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BEAM TRANSPORT
A Selected, Annotated Bibliography

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BEAM TRANSPORT

A Selected, Annotated Bibliography

The primary criterion used in selecting the references for this bibliography was their applicability to the problems of transporting charged particles in the areas external to accelerators. Specifically, this included the various focusing components associated with particle optics, the dynamics of particles passing through these components, and the achromatic properties and aberrations of beams.

The period covered is 1949-1961, although a few references both prior and subsequent to this period have been included. The sources consulted include Science Abstracts, sections A and B, Nuclear Science Abstracts, Engineering Index, Applied Science and Technology Index, Dissertations in Physics, and numerous bibliographies. Additional references were obtained from the internal report files of the Particle Accelerator Division at the Argonne National Laboratory and by corresponding with other major accelerator installations both in the United States and in Europe.

Part I is concerned with the more general aspects of electron optics and includes much fundamental material on the subject as well as work that was done in regard to electron microscopy. Part II contains the references that deal more directly with applications to particle accelerators. Although, as stated above, the primary concern is with the beam external to the accelerator, a few basic references concerned with the focusing of the beam within the accelerator have been included.

Arrangement within each part is by broad subject with cross references listed at the end of each section. Additional cross references have been made to related articles by providing the journal citation followed by the item number if the article is also included in the bibliography. Thus in the example,

Optik 11 (9), 423-43 (1954) 277.

the cross referenced article would appear in the journal as indicated and also in this bibliography as item #277.

The efforts of Mr. C. H. M. Turner, who assisted in selecting and arranging many of the references, are gratefully acknowledged.

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PART I - ELECTRON OPTICS

BOOKS AND REVIEW ARTICLES

1.

"The deflection and focusing of charged particles in magnetic and electric fields," K. T. Bainbridge, Experimental Nuclear Physics, Part V, Segré, E., Ed., John Wiley and Sons, New York (1953), pp. 566-614.

Includes following topics: Combined cylindrical condenser electric field and uniform magnetic field; the focusing of charged particles by a spherical condenser; sectorial magnetic field; ion optics; mass spectrographs; double focusing for all masses; crossed electric and magnetic fields; trochoidal trajectories; focusing in nonuniform fields.

2.

Optics of high-energy beams. O. Chamberlain, Ann. Rev. Nuclear Sci., 10, 161-192 (1960).

Summarizes information of methods for setting up beams of charged secondary particles. Discusses: basic components of purely magnetic systems; determination of a trajectory in the central plane; focusing properties of magnetic fields; matrix method for combining components; use of wire orbits to test components; examples of purely magnetic systems; measurement of transmission of a magnetic beam-forming system; aberrations; separated beams; extremely cleanly collimated beams.

3.

Introduction to electron optics; the production, propagation and focusing of electron beams, Cosslett, Vernon Ellis, 2nd ed., Oxford University Press (1950).

4.

"Elektronen- und Ionenoptik," (W. Glaser) Handbuch der Physik, 33, 123-395 (Flugge, S. ed Springer, Berlin, 1956). (In German.)

5.

Foundations of electron optics (Grundlagen der Elektronenoptik), W. Glaser, Springer-Verlag Vienna: (1952), 699 pp. (In German.)

A very complete and profound treatment of electron-optical theory. There are three parts: (1) lens fields and Gaussian di-optics; (2) the theory of geometrical aberrations; (3) electron optics and wave mechanics. The first part is mostly standard material, but given in an unusually complete and rigorous form. The second part deals with caustic surfaces, problems of electron intensity, and the theory of deflection, as well as with the ordinary third-order aberrations of the image. In the last part, the wave-mechanical aspects of electron optics are developed sufficiently to discuss the resolving power of electron devices. The book includes 445 figures and extensive bibliographies. It does not deal with experimental questions, except those concerned with measurements of fields in lenses, nor with electron optical instruments in any detail. Neither are problems encountered with high current beams discussed.

6.

Electron lenses, P. Grivet, Adv. Electronics 2, 47-100 (1950).

A review of the development of electron lens theory over the last ten years. Section headings: image formation in a thin lens; magnetic lenses; relativistic lenses; image defects; third-order aberrations; mechanical defects; some typical lenses. 100 refs.

7.

Electron optics. I. Electron lenses, P. Grivet, M. Y. Bernard, and A. Septier, Bordas (1955) 184 pp. (In French.)

This monograph in the series Bibliothèque de la Science Moderne deals with the properties of electron lenses. Most of the ten chapters comprise an up-to-date review of the methods for obtaining lens focal properties and aberration, particularly the mathematical methods. A limited amount of design data is given in illustration. Electrostatic lenses are dealt with in a more detailed manner than magnetic. Much of the most recent work on the latter is not adequately covered.

8.

An introduction to electron optics, Jacob, L., John Wiley and Sons, New York (1951).

9.

Theory of electromagnetic system with curvilinear axis,
P. P. Kas'yankov, LETI Leningrad State University Press (1956).

10.

Electron optics, O. Klemperer, Cambridge University Press (1953),
471 pp. (Cambridge Monographs on Physics).

An enlarged and completely revised version of the 1939 edition, it covers the e.o. characteristics of a comprehensive range of applications, with practical rather than theoretical emphasis. Subjects include: paraxial e.o., field plotting, ray tracing, types of e.s. and mag. lenses, aberrations, space charge, emission systems, "cylindrical" lenses, deflection focusing, miscellaneous applications. 600 refs.

11.

Contribution to the study of the numerical calculation of fields and trajectories in the electron optics of cylindrical systems, M. Laudet, Ann. Fac. Sci. Univ. Toulouse, 20, 111-230 (1956; publ. 1957). (In French.)

An extensive treatise giving, in the first part, full details of the relaxation method of potential determination with square, triangular and other meshes, together with applications to several particular practical problems. The treatment of boundary conditions at infinity is discussed. Extrapolation of potentials obtained with successively smaller nets is shown by comparison with analytical solutions to lead to high accuracy. In the second part, the trajectory equations of cylindrical electron lenses (electrostatic and magnetic) are fully developed and expressions for aberrations are tabulated. The particular case of the symmetrical three-electrode slit lens is treated both analytically and numerically.

12.

Some designs in electron and ion optics, J. B. Le Poole, Technische Hogeschool, Delft (1954) 98 pp.

The booklet describes some new features of electron-optical devices developed at the Technische Hogeschool. Included are an achromatic electron-diffraction apparatus, which can be operated under pulsed conditions, a simplified electron microscope using a very short focal-length objective lens, and a new type of mass spectrograph using dynamic deflecting fields and electrostatic focusing. A separate chapter is devoted to focusing aids for the electron microscope.

13.

Field plotting and ray tracing in electron optics. A review of numerical methods. G. Liebmann, Adv. Electronics, 2, 101-49 (1950).

A comprehensive resumé of analytical, numerical, graphical and experimental methods, including also automatic ray-tracing methods (rubber membrane, etc.). 129 refs.

14.

"Beam optics," D. Luckey, in Techniques of high energy physics, D. M. Ritson, ed., Interscience, New York, (1961), pp. 403-463.

Includes the following topics: various elements for beam optics; combination of simple elements; magnetic field design; experimental determination of system performance; and high-intensity pulsed magnetic fields in particle physics, by R. Schluter.

15.

Einführung in die Theorie der Elektronenoptik, Johannes Picht, 2nd ed., J. A. Barth, Leipzig, (1956).

16.

Theory and design of electron beams, John Robinson Pierce, 2d ed., D. Van Nostrand and Co., New York (1954).

17.

Optique Electronique, H. Piraux, Electricite' 41, No. 240, 169-76 (July-Aug 1957)

Fundamentals of electron optics; influence of homogeneous electric fields; electron-optic simulators; influence of magnetic fields; applications of theory of electron optics in microscopy and in other instruments.

18.

Molecular beams, Norman F. Ramsey, Oxford, Clarendon Press (1956), 466 p. References on pp. 435-453.

19.

The proceedings of the third international conference on electron microscopy, London, 1954, Royal Microscopical Society, London (1956).

Electron optics, pp. 46-109.

20.

Strong-focusing lenses, A. Septier, Advances in electronics and electron physics 14, 85-205 (1961).

Discusses: 1) The theoretical properties of quadrupole lenses, the distribution of their field, and their optical properties, and more especially the elementary or grouped lenses. 2) The calculation of the third-order aberrations of these lenses. 3) Review of the practical realization of these lenses and the distributions of field which may be obtained in practice. 4) A review of the experimental results obtained, which show that the calculations carried out in the first section are valid to a good approximation. The methods of study are described.

21.

Electron Physics, U.S. Bur. Standards Cir. No. 527 (Mar 17, 1954). 416 p.

Includes the following articles:

Fundamental problems of theoretical electron optics.

W. Glaser.

Formation of images in electron microscope. H. Boersch.
(In German.)

Theoretical study of quality of images. A. Marechal.

Electron lenses. P. Grivet. (In French.)

Note on theory of electrostatic lenses with central elliptic electrode. E. Regenstreif. (In French.)

Note on theory of elliptic electrostatic lens operating in transgaussian region. E. Regenstreif. (In French.)

Characteristics of symmetrical magnetic electron lenses.
G. Liebmann.

Controlling of electron beam by means of rotating electric field and its application. K. Owaki.

Experiments with adjustable magnetostatic electron lenses.
E. Ruska.

Correction of field measurements in electron lenses.
A. Bruaux.

22.

Electron optics and the electron microscope, V. K. Zworykin et al., John Wiley and Sons, Inc., New York (1945).

766 p. Includes references at the end of each chapter.

BEAM OPTICS

23.

Periodic focusing of electron beams, C. W. Barnes, Jr., Ph.D. Thesis, Stanford University (1954).

The possibility of focusing electron beams by means of electric or magnetic fields which are periodic in the axial direction is investigated for four specific cases: axially symmetric and quadripolar electric field systems, and axially symmetric and quadripolar magnetic field systems. The principal emphasis and experimental results are on the axially symmetric electric system. The theory of the axially symmetric magnetic system is in agreement with results obtained at the Bell Telephone Laboratories and is included primarily for completeness.

In general, the electron motion in each of the three coordinate directions will have a periodic component with the same period as the focusing field. As a result of the interaction of the periodic field and the three periodic components of motion, the electrons experience a time-averaged inward force. This average inward force can be balanced against the outward space-charge force to keep the electrons in equilibrium. The equilibrium will be a stable one since the focusing force is an increasing function of radius and the space-charge force is a decreasing function of radius.

Because of the periodicity of the forces on the electrons, radial oscillations are an inherent property of periodic focusing systems. The radial motion of the electrons can be separated into two parts, one of which has the same period as the focusing field and corresponds to the particular integral of the radial equation of motion, and a second part which has a period much longer than the field period and corresponds to the complementary function of the radial equation of motion. The particular integral represents the irreducible minimum radial oscillation which can be set up under optimum initial conditions.

Periodic focusing systems have the advantage that the focusing fields can be excited by structures which are light in weight, compact, and have low power consumption as compared with the axially uniform magnetic focusing systems, either of the "brute-force" or of the Brillouin type. In many cases, a periodic electric focusing field can be produced by providing a dc isolation between parts of the periodic rf structure. Periodic magnetic fields can easily be produced by sets of small permanent magnets.

Of the four focusing systems considered, the axially symmetric electric and the axially symmetric magnetic systems appear to be the most promising. Both of these systems are found to be subject to perveance-limiting effects, however, the electric system being much more limited in this respect than the magnetic system. The axially symmetric electric system is found to be quite sensitive to initial radial velocities in the injected beam; this is true to such an extent that the normal aberrations in the electron gun are apt to cause the beam flow to become nonlaminar. In the nonlaminar-flow condition, the space-charge effects will usually be small compared to the effects of the initial conditions.

The theory indicates that for both of the quadripolar systems the beam will not be uniformly sensitive to initial conditions around the periphery of the beam.

All of the experimental results are devoted to the axially symmetric electric system. The focusing structure was adapted from the rf structure of an interdigital backward-wave oscillator. Because of the aberrations in the electron gun, the resulting beam was apparently nonlaminar, and, insofar as possible under these conditions, the experimental results give qualitative verification of the theory.

24.

Determination of sign of power flow in electron beam waves,
W. R. Beam, Proc. Inst. Radio Engrs., 48, 1170 (June 1960).

By considering the transformations of energy in a coordinate system moving with the wave phase velocity v_1 so that - for typical electron beams - only quasistatic fields need be considered, the author obtains the condition $v_b/v_1 > 1$ for the wave to carry negative power (v_b = beam velocity).

25.

Self-focusing streams, W. H. Bennett, Phys. Rev., 98, 1584-93 (1955).

Streams consisting of a mixture of ions and electrons in which the average velocity of the electrons in the direction of the stream is different from the average stream velocity of the ions can be magnetically self-focusing. The random velocities of the electrons and ions about their respective average stream velocities do not need to be Maxwellian. The only condition which must be met is that the total electric current in stream must exceed a critical value which can be calculated in terms of the stream velocities and the average kinetic energies of the particles due to components of velocity transverse to

the axis of the stream. Streams containing both slow and fast particles of like kind tend to eject the slow particles and keep the fast ones. Streams of particles of one kind only, entering an ionized or ionizable region, can be self-focusing. Axial asymmetries grow in arcs but disappear in low-density self-focusing streams.

26.

Focusing polar molecules, H. G. Bennewitz, W. Paul, and C. Schlier, Z. Phys. 141, 6-15 (1955) (In German.)

A beam of molecules with electric dipole moments is directed along the axis of an electric field whose transverse gradient is such that the restoring force on the molecules is proportional to their distance from the beam axis when the exact Stark effect is considered. The molecules then execute cosine curves and are refocused on the axis every half wavelength. This condition can be reached with low J and M values, and the nature of the four-pole field, the effect of oven aperture and other variables are discussed. The construction of such a focusing device is described; it incorporates mechanical stops for nonfocused molecules, a mechanical velocity selector, and a Langmuir-Taylor detector. Detector current-voltage curves to 8kV indicate for KBr successive focusing of (J,M) (1,0), (2,0), (3,0), and (2,1) states and for KF the (1,0) and (2,0) states with signals about 60 times the null signal.

27.

On the focusing of high-current electron beams, G. R. Brewer, J. Appl. Phys., 25, 243-51 (1954).

The focusing of high-current electron beams by means of a system of periodically spaced magnetic lenses has been studied. The trajectories of the electrons under the influence of magnetic and space-charge forces have been obtained by the use of an analogue computer. Graphs have been prepared which permit the design of a lens focusing system for given values of current, voltage, and beam diameter. The solutions are obtained for the Glaser magnetic lens with longitudinal field variation of the form $B_z = B_0 [1 + (z/a)^2]^{-1}$. The conditions of operation appropriate to the minimum chromatic aberration are obtained, and the entrance conditions to the lens system discussed.

28.

An experimental investigation of ion beam focusing, W. W. Buechner, E. S. Lamar, and R. J. Van de Graaff, J. Appl. Phys. 12, 141-148 (1941).

An experimental investigation has been made of the initial focusing of ions from capillary sources of the diffusion type described by the authors in J. Appl. Phys., 12, 132-140. The lens system used consisted of a 90-degree cone at the ion source followed by three coaxial cylinders which were arranged at various potentials up to 25 kilovolts. Since the beams are rendered slightly luminous by traces of gas in the high-vacuum region, they have been studied by a photographic method. The beams have also been studied by an electrical scanning method. Both types of investigation were made as functions of the electrode potentials and arc variables, and are in good agreement. Based on these observations, a focusing and canal arrangement suitable for differential pumping has been tested. This arrangement has been embodied in a design for a projected ion-gun assembly.

29.

Production and focusing of intense proton beams, W. W. Buechner, Ph.D. Thesis, Mass. Inst. of Technology (1939).

30.

Behavior of intense relativistic electron beams, R. H. Capps, Phys. Rev., 114, 1203-17 (1959).

A theoretical investigation is made of intense, relativistic, partially neutralized, self-focusing electron beams. Approximate equations are derived that express the time derivatives of the beam radius and mean electron energy as functions of these parameters, the densities of the electrons, ions, and neutral atoms, and the impressed electric and magnetic fields. The equations are numerically integrated for various values of the parameters. It is shown that the radiation damping leads to a shrinkage of the beam radius to a value of order 0.05 m in a time of order 10^{-2} - 10^{-1} sec. If the longitudinal electric field is constant, the beam approaches the "equilibrium state" discussed by Budker (1956), in which the increase in electron transverse momentum caused by scattering from the ions is compensated by radiative loss, and the energy lost by radiation is restored by the longitudinal field. The various instability problems associated with dense systems of charged particles are not discussed.

31.

Methods of focusing electron beams in modern ultra high-frequency (microwave) devices, Z. S. Chernov. Radiotekh. i. Elektron, 3, 1227-42 (1958).

The existing systems of focusing electron beams can be classified as homogeneous and periodic. In the first class of the devices, the focusing fields which compensate the Coulomb forces are constant along the beam, whereas the second class ensures the required configuration of the beam by passing it through a periodic system of magnetic or electrostatic lenses or mirrors. The focusing systems can also be divided into magnetic and electrostatic or combined devices. A classification diagram is included and described. The method of employing a longitudinal magnetic field is the simplest and consists of employing a strong field in order to equalize the electron trajectories. The Brillouin beam is a development of this system; in this case, an electron beam having a circular cross section is rotated around the axis whose direction is parallel to the magnetic field. This method permits the focusing of electrons by employing comparatively low fields, but there are practical difficulties in constructing appropriate focusing systems. The centrifugal, electrostatic focusing system is based on the use of a helical electron gun and a pair of helical focusing electrodes. It is concluded that the sharpness of the Brillouin beam and that of the centrifugal, electrostatic focusing are almost the same, whereas the focusing by longitudinally magnetic field is slightly sharper. The rotating beams in a periodic, electrostatic system have the highest focusing sharpness.

32.

Focusing of an electron beam by periodic fields, A. M. Clogston and H. Heffner, J. Appl. Phys. 25, 436-47 (1954).

The problem of focusing long electron beams by means of magnetic or electric fields which vary periodically along the beam is considered. Four specific cases are discussed: periodic fields of the axially symmetric and quadrupole type with either electric or magnetic fields employed. The equations of motion are written and solutions obtained which show beam trajectories corresponding to essentially parallel flow. Under certain specified conditions only small ripples are present. Actual trajectories as plotted by the analogue computer are shown and charts and equations are presented to aid in the design of practical periodic focusing systems.

33.

Axially symmetric electron beams of uniform axial velocity, E. J. Cook, J. Appl. Phys., 30 860-5 (1959).

Since the initial work of Brillouin, interest in long, dense electron beams with a uniform velocity profile has increased steadily. In this paper, the general member of this class of beams is derived. Various special cases become the equilibrium systems of current interest. In addition to these known systems, the analysis leads to new possibilities. One of these is of particular interest in that it is the first of this group of beams in which the axial velocity is important to the balance of forces on the electrons. The new beam has properties ideal for M-type interaction and should be of considerable future importance.

34.

Elektronen- und Ionenbuendel mit krummer Achse- Willenmechanisch betrachtet, H. Grümm, Optik, 12 (4), 153-65 (1955).

Electron and ion beams with curved axis considered from point of view of wave mechanics; calculation of Schroedinger equation representing static flow of loaded particles influenced by electromagnetic field along arbitrary curve in space.

35.

On the optical properties of electron and ion beams with circular axes, H. Grümm, Acta phys. Austriaca, 8 (2), 119-40 (1953) (In German.)

The author investigates the electron-optical properties of beams whose central trajectory is a plane normal to the axis of symmetry of electric and magnetic fields of rotational symmetry. The paraxial properties and aberrations are derived from the Fermat principle and relevant mixed characteristic function (eikonal). The first-order contributions to the velocity and mass dispersions are calculated and so are the second-order aberrations; the resultant intensity distribution in image-space is investigated. The author also establishes formulae for the third-order aberrations, which involves a second-order perturbation calculation, and for the second-order dispersion. [The latter formulae are obtained by second-order methods whereas the problem must be considered as one involving a third-order perturbation, as is shown in Sturrock, Proc. Roy. Soc., A210, 269-89 (1951).] 394

36.

Production of high intensity proton beams, R. N. Hall, Ph.D. Thesis, California Institute of Technology (1948).

37.

Use of scanning slits for obtaining the current distribution in electron beams, K. J. Harker, J. Appl. Phys., 28, 1354-7 (1957).

In axially symmetric electron beams, the current density (as a function of radius) may be rather easily related to the current through a narrow slit (as a function of slit position) by means of an integral equation. A similar equation applies to scanning by a straight edge. The solution of the integral equation is obtained, and a simple technique for rapid numerical evaluation of the resulting ordinary equation is included. The relations derived are of particular interest in the large number of cases where the mechanical simplicity of slit or straight-edge scanning makes these methods preferable to the more common pinhole method. The resolving powers for slit and pinhole scans are compared.

38.

Optical theory of thermal velocity effects in cylindrical electron beams, G. Herrmann, J. Appl. Phys., 29, 127-36 (1958).

The present theory is based on a nonlaminar optical model which treats thermal velocities as an integral part of the motion. A Maxwellian distribution of initial transverse velocities is assumed at the cathode, and a first-order focusing theory is applied in order to calculate trajectories at any point in the beam. It is shown that whenever a long beam is confined by a focusing field, images of the cathode are formed repeatedly along the axis. When applied to uniform magnetic focusing fields, the theory predicts the periodic formation along the axis of cathode images and cross-overs, and relative rotation of successive images. Such effects have been reported. Values of required focusing fields are derived for given space-charge and thermal-velocity conditions, and relations are established between beam spread and transverse velocities. The resulting picture differs radically from the laminar model of beam flow.

39.

The interaction of electron beams in crossed electric and magnetic fields, C. L. Hsieh, Ph.D. Thesis, Stanford University (1951).

40.

Optimal focusing of electron beam in a T. W. T. periodical focusing system, A. L. Igritskii, Radiotekh, i Elektron., 6, 137-45 (1961) (In Russian.)

A new analytical method is suggested for determining parameters for a periodic focusing device (mechanism of spatial interaction of electrons with plasma LBV) for electron beams. It is shown that

the suggested method is capable of achieving considerably smaller electron beam undulation than has been achieved by the commonly used Chang method. The method permits the development of an accurate electron beam configuration, depending on the conditions under which the electron is injected into the periodic field. It is shown that much better focusing can be achieved with maximum electron induction into the field.

41.

On the displacement of an ion beam image by magnetic fringing fields, L. Kerwin, Can. J. Phys., 36 711-20 (1958).

Some of the methods proposed for calculating the effect of the magnetic fringing field on the image position of an ion beam are reviewed and applied to the case of a particular instrument. The differences between the calculated corrections and the observed image suggest an improved method of calculating the image position. Applied to the case under consideration, this method gives essentially the correct image position.

42.

Focusing of electron beams by magnetic fields, W. Kleen and K. Poschl, Arch. elekt. Übertragung, 9, 295-8 (July 1955). (In German.)

If in a cylindrical electron beam focused by longitudinal magnetic fields the boundary electrons are slightly oscillating about a mean radius, a simplified method can be developed for obtaining this radius and the maximum deviation from it. The results apply to general initial conditions at the cathode and to constant as well as to periodic magnetic focusing fields.

43.

On the adiabatic self-constriction of an accelerated electron beam neutralized by positive ions, J. D. Lawson, J. Electronics and Control, 3, 587-94 (Dec 1957).

An analysis is made of the behavior of a space-charge-neutralized electron beam under the influence of a longitudinal electric field. The energy lost by radiation and collision is neglected, and transverse velocities are assumed small compared with the drift velocity. It is found that the buildup of the self magnetic field causes the transverse oscillation of the electrons to be damped, but that this damping is counteracted to some extent by an outward diffusion due to multiple scattering of the electrons on the ions. Inductive effects appear as an apparent increase of mass of the electrons. The importance of the problem lies in the fact that such a beam represents

a possible intermediate state in setting up a steady-state relativistic beam of the form described by Budker [Proceedings of the C. E. R. N. Symposium on High Energy Accelerators and Pion Physics, Geneva, Vol. 1, 68 (1956).] 605

44.

The relaxation time for the contraction of a relativistic self-constricted electron beam, J. D. Lawson, AERE-GP/M-200 (June 1957).

The rate of contraction of the beam which occurs when the electron energy is increased above its steady-state value was calculated. No attempt to formulate the general problem of the beam behavior under nonsteady conditions is made; rather, a simple specific calculation which illustrates the physics of the problem and the order of magnitude of the time constants involved is presented.

45.

Some experiments on a cylindrical electron beam constrained by a magnetic field, J. D. Lawson, J. Electronics, 1, 43-52 (July 1955).

A study has been made of the optics of an electron beam with a perveance of $10^{-6} \text{ A/V}^{3/2}$ constrained by an axial magnetic field. Measurements of the beam contour for different conditions of entry into the field were made with the aid of a screen which could be moved to intercept the beam. Rough measurements of the radial current distribution, and a measurement of the efficiency of transmission through a drift tube, were also made. Fair agreement with theory was found, although there were significant discrepancies which have not been explained.

46.

Magnetic forces and relativistic speeds in stationary electron beams. B. Meltzer. J. Electronics and Control 4, No. 4, 350-4 (April 1958).

The assumption usually made that self-magnetic forces may be neglected in non-relativistic electron beams is shown to be unjustified in general. As an example, it is proved that Child-Langmuir space-charge-limited flow between infinite parallel planes is impossible. If one starts with a thin beam section of such flow, as produced for example in a Pierce gun, and broadens it indefinitely, the magnetic attraction of the current filaments will increase without limit and constrict the beam. The limitation on beam size for magnetic constriction to be negligible is $r/a \ll 6c^2/v^2$, where r is beam radius, a diode spacing, v maximum electron speed and c speed of light. The limitation on size for relativistic beams is also calculated, use being made of Acton's analysis of relativistic diodes¹ which also neglected

magnetic forces. For planar diodes of potentials 51 kV, 511 kV, and 5.11 MV, the restrictions required are respectively $r/a \ll 29$, 5.6 and 1.1.

- ¹J. A. Prins, J. Mulder and J. Schenk. Appl. Sci. Res. A2, 431-8 (1951). (See also Winwood, J. Electronics and Control 5, 161-2 (1958). 57.)

47.

Simplified methods in the statistical mechanics of stationary electron beams. B. Meltzer, J. Electronics and Control, 3, No. 4, 355-66 (Oct 1957).

The statistical mechanics of axially symmetrical electron beams from isotropically emitting cathodes is critically developed. Calculation of current density is reduced to the evaluation of simple integrals over a "phase-plane," of which the coordinates are respectively the forward and transverse kinetic energy of a beam electron. Applications are made to retarded and accelerated beams from a secondary-emission and thermionic cathodes, to the problem of improved cathode-loading in high-vacuum devices, and to explanation of anomalously high "beam temperatures" experimentally observed in cathode-potential-stabilized, television pick-up tubes.

48.

Sufficient and necessary trajectory conditions for dense electron beams. P. Meltzer and A. R. Lucas. J. Electronics and Control, 4, No. 5, 454-6 (May 1958).

A pair of sufficient conditions were given by Lucas et al., (J. Electronics and Control, 4, No. 2, 160-4 (Feb 1958) for a given set of trajectories to be possible ones in a laminar, irrotational, electrostatic, non-relativistic beam; it is now shown that these conditions are not necessary in spite of a contrary conjecture in the earlier paper. A new necessary condition is derived. See also J. Electronics and Control, 4, No. 5, 457-9 (May 1958). P. T. Kirstein. 551.

49.

A combined slow-wave circuit and beam focusing structure. P. Rice, Letter in J. Appl. Phys. 25, 680-1 (May 1954).

An experimental beam-focusing tube was built using alternate N and S magnetized rings which formed also alternate projections

inside a waveguide suitable for reducing the velocity of an electromagnetic wave. A circular beam of electrons was directed at 750 V into a 4.6 mm dia copper tube, 5.7 cm long, axially traversing this system. With a cathode current of 7.8 mA, a final beam of over 6 mA could be obtained at a sharply defined magnetic field of 150 gauss.

50.

Quantitative measurements of ion beam properties. P. H. Rose, et al. Nuclear Instruments and Methods 14, 79-82 (1961).

A device is described which can be used to determine the profile, position and emittance of beams of charged or neutral particles.

51.

Splitting of a beam of particles by an electrostatic biprism, A. Septier, Compt. rend. 249, 662-4 (1959). (In French.)

A method of calculating the deviation of a beam of particles by an electrostatic biprism is given, and the predictions are found to agree with experimental results. The deviation is brought about without any distortion of the beam.

52.

Focusing of extended intense electron beams by combined periodic magnetic and electric fields, P. I. Strel'nikov, A. I. Fedorenko, and B. M. Charnyi, Zh. tekhn. Fiz. (USSR) 31, 394-9 (April 1961). (In Russian.)

A focusing system was investigated in which the combined effect of magnetic and electric fields makes it possible to confine an electron beam which is accelerated to 100 kV; the beam current is 10 amp (pulsed). The beam is confined over a distance of 1 m from the cathode (at the collector) without change in beam diameter. By means of this system it is possible to obtain high-density electron beams of fixed diameter over any desired distance. [English translation in: Soviet Physics - Technical Physics (USA) 6, 285-8 (1961)]

53.

The imaging properties of electron beams in arbitrary static electromagnetic fields, P. A. Sturrock, Phil. Trans. Roy. Soc. London, A245, 155-87 (1952).

Aims at constructing a complete theory of aberrations in electron-optical systems with curved axes, and demonstrating, by an example, its application to practical problems. An appropriate coordinate system

is set up by means of a ray axis together with its normal and binormal. The electric and magnetic fields are then investigated with the help of tensor calculus; the variational principle of electron optics is also put into tensor form. The integrand of the variational equation may be separated into a series of polynomials, one of which determines the paraxial imaging properties of the system and the rest of which determine the aberrations. The condition is established for which, upon an appropriate transformation, either of the paraxial ray equations contains only one off-axis co-ordinate. Subsequent investigations are restricted to systems, which are termed "orthogonal," for which this condition is satisfied. It is shown that, in a certain sense, no orthogonal electron-optical system can be wholly divergent. The second-order aberration and the zero-order and paraxial chromatic aberrations are then investigated by the method of perturbation characteristic functions. All formulae are given in their relativistic forms, but their nonrelativistic forms are indicated; formulae are therefore given for the calculation of the zero-order and paraxial relativistic correction. It is indicated to what extent one forfeits control over the second-order aberration - and hence over the paraxial chromatic aberration also - by specifying that the paraxial behavior of rays should be Gaussian. As an example, the imaging properties of a helical beam moving in the field of a pair of coaxial cylindrical electrodes are calculated. There is also an appendix which gives formulae for the effect upon aberrations of a change in the aperture position.

54.

Theory of the focusing of sheet beams in periodic fields,
P. A. Sturrock, J. Electronics and Control, 7, 153-61 (Aug 1959).

Equations determining the paraxial behavior of sheet beams in periodic focusing fields are established. Space charge is taken into account, and its effect upon stability is investigated. It is proved that, if space charge is neglected, any such focusing system is convergent. A procedure for determining optimum lamellar-flow configurations is set out, and approximate formulae for the perveance of such focusing systems are presented.

55.

Electron beams in axially symmetrical electric and magnetic fields,
C. C. Wang, Proc. Inst. Radio Engrs., 38, 135-47 (1950).

Considers the formulation of the equations governing the motion of an electron beam in axially symmetrical magnetic and electric fields. The equations are obtained for the trajectories of the electrons along

the outer edge of the beam for the most general case, in which there are both axial and radial components of the fields. It is shown that, as a result of symmetry, the combined effects of the electric and the magnetic fields can be expressed as a single generalized potential function which depends only on the axial and radial space coordinates. This enables the axial and radial force components to be expressed as the axial and radial components of the gradient of this potential function. Numerical solutions have been obtained by numerical integration for the trajectories in a uniform magnetic field. Curves are presented in normalized form, giving the results of these solutions for practical cases. It is shown that there exists an equilibrium radius for which the net radial forces acting on the electrons are zero, and that the outer radius of the beam will oscillate about this equilibrium value, the amplitude being nonsymmetrical and depending upon the initial conditions, and the wavelength (distance between successive maxima) depending upon the amplitude.

56.

On the properties of the electron beam in the presence of an axial magnetic field of arbitrary strength, H. Wilhelmsson, Chalmers Tekn. Hogsk. Handl., No. 205, 31 pp. (1958)

Presents unusually general small-signal theory of ac disturbances of a circular cross-section beam travelling parallel to a uniform magnetic field in a neutral ionized medium, collisional effects being neglected. Angle-dependent asymmetrical modes are taken into account, as well as drift Lorentz and relativistic terms in the electrodynamic equations. Special results on longitudinal space charge, TE, TM, and magneto-ionic waves are obtained. The case of a circular waveguide filled by the beam is considered. Another specialization gives the magneto-ionic refractive indices.

57.

Comment on magnetic forces and relativistic speeds in stationary electron beams, J. M. Winwood, J. Electronics and Control 5, 161-2 (Aug 1958).

Criticism of discussion by Meltzer [J. Electronics and Control, 4, 350-4 (April, 1958) 46] of relative magnitudes of magnetic and electrostatic forces in electron beams. Three errors in the application of the theory of the Lorentz transformation lead to an estimate of the ratio of magnetic to electric force between two moving electric charges, different from Meltzer's.

See also Meltzer, J. Electronics and Control 5, 348-9 (1958). 510

See also 2, 3, 4, 14, 16, 18, 21, 126, 127, 128, 331, 335, 538, 541, 559, 561, 562, 563.

ELECTRON LENSES - THEORY

58.

"Electron optical properties of electrode systems of four- and eight-fold symmetry," G. D. Archard, Proc. Intern. Conf. on Electron Microscopy, London. pp. 97-109 (1954).

Electrode systems of four-fold symmetry act as crossed, cylindrical electron lenses. Some focal properties are computed. A magnetic analogue and the effect of electrode shape are discussed. Systems of eight-fold symmetry act as electron-optical fourth-order plates; the effect of electrode shape on these is discussed.

59.

Regenerative deflection as a parametrically excited resonance phenomenon, S. E. Barden, Rev. Sci. Instr., 25, 587-93 (1954).

The phenomenon termed regenerative deflection¹ is treated as a resonance mechanism forming only one of a larger class of similar mechanisms. Conditions of optimum coupling to promote the growth of radial oscillations are described, and the results of some numerical calculations are given. The causes of the axial spreading of the beam during the extraction period are analyzed, and methods of reducing such spreading are discussed. An electrodynamic system for creating the coupling inhomogeneities is also described.

¹K. J. Le Couteur. Proc. Phys. Soc., London, B64, 1073-84 (1951). 752.

60.

A method for the determination of nuclear moments with focused atomic rays, H. G. Bennewitz and W. Paul, Z. Phys., 139, 489-97 (1954). (In German.)

The atom focusing method of Friedburg and Paul [Naturwissenschaften, 38, 159-60 (1951)] is incorporated into an atomic beam apparatus with a four-pole magnet to provide the inhomogeneous focusing field. This is followed by a mechanical velocity selector. The number and positions of the focused rays give the spin and nuclear moment and the results with Cs¹³³ agree to 4% with the Rabi resonance methods. Intense atom streams are involved, and photographic detection of radioactive nuclei is possible.

61.

Exact determination of the cardinal elements of strongly converging lenses, M.-Y. Bernard, Compt. rend., 240, 1612-14 (1955). (In French.)

The cardinal elements of an electron-lens combination (strongly converging in one plane and diverging in the plane at right angles) are determined by approximating the true potential distribution to a flat-topped bell shape which allows exact solution of the electron trajectories. A further simplification involving a rectangular potential distribution is envisaged.

62.

An analytical method for designing multipole magnets, M. H. Blewett, Accelerator Development Department. Brookhaven National Laboratory. Internal Report BNL-MHB-8. 22 p. (Oct. 27, 1957).

A two-dimensional analytical method for designing sextupole and quadrupole magnets is outlined, including the effects of exciting coils with uniform current density. Several specific cases have been calculated for each type of multipole and the resultant shapes and computed parameters are given.

63.

The derivation of paraxial constants of electron lenses from an integral equation, H. Bremmer, Appl. Sci. Research, B2, 416-28 (1952).

The Liouville-Neumann expansions of the solutions of this equation lead to expressions for the magnification, the focal distances, and the positions of the focal points and cardinal points. The numbers of integrations to be performed in the individual terms of the expansions used to describe lens characteristics are reduced to half, as compared with the normal treatment. The focal and cardinal points are defined as osculating elements similar to those introduced by Glaser (1950).

64.

Characteristic curves on planes in the image space, N. Chako, Chalmers Tekn. Hogsk. Handl., No. 191, 49 pp. (1957).

By a characteristic curve is meant the curve in which a bundle of rays from a single object point and a narrow ring in the pupil intersect a plane in the image space. They are shown to be epicycloids and their general forms in the Seidel region are derived as functions of the aberration coefficients. Systems of finite aperture and small field are discussed, and the generalized sine condition is obtained. The analysis includes aberrations of electron-optical systems.

65.

On electron-optical systems with a rectilinear axis not having rotational symmetry, I. I. Chukkerman, Zh. tekhn. Fiz., 24, 2261-63 (1954). (In Russian.)

The systems studied are defined as systems of static electric and magnetic fields, such that one of the trajectories of an appropriately directed beam of charged particles is a straight line, which is the axis of the system. The equations of motion for paraxial electrons are obtained. The condition for a rectilinear axis is stated. Another condition is found in order that a beam radiating from a point on the axis be brought again to a focus.

66.

Electron optical image (formation) by orthogonal systems under the application of a new field model with exact assignable paraxial paths, H. Dusek, Optik, 16, 419-45 (1959). (In German.)

A rigorous solution of the orthogonal system of differential equations for paraxial electron paths and rectilinear axis is given for fields of nonrotational symmetry. The image properties of an orthogonal system and the asymptotic image formation by an arbitrary number of orthogonal systems are investigated. A detailed discussion of two-stage image formation is given in greater detail, and the possibility of an electrical correction of mechanical adjustment errors, as well as the combination of stigmator and projective, are pointed out.

67.

The refractive index in electron optics, W. Ehrenberg and R. E. Siday; W. Glaser. Letters in Proc. Phys. Soc., London, B64, 1088-9 (1951).

Correspondence relating to criticisms made by Ehrenberg and Siday of the validity of some generalized expressions for μ derived by Opatowski from extensions of Glaser's 1933 result.

68.

The refractive index in electron optics and the principles of dynamics, W. Ehrenberg and R. E. Siday. Proc. Phys. Soc., London, B62, 8-21 (1949).

The origin of the refractive index in electron optics is discussed in some detail, and the uniqueness of an expression given is demonstrated. On this basis, some general properties of electron optics are investigated. A relation between ray direction and wave normal is

obtained. Whereas the refractive index is unique in terms of the magnetic vector potential A , this itself is arbitrary to some extent. It is shown that A must, for purposes of electron optics, be chosen so as to satisfy Stokes' theorem and that, if it does, no observable effects result from the arbitrariness of A . An expression for the optical path difference is given in terms of the magnetic flux enclosed. The results are applied to a number of questions, viz. the differential equations for trajectories, the focusing properties of an axially symmetric field and the interference pattern produced by two converging bundles of rays which enclose a magnetic flux.

69.

Experimental determination of focal lengths and principal planes of asymmetric electron einzel lenses, C. W. F. Everitt and K. J. Hanssen. *Optik*, 13, No. 9, 385-98 (1956). (In German.)

Focal length and principal point determinations of symmetrical lenses by the shadow method require two shadow pictures. Asymmetrical lenses, in general, require four. For the special case of the asymmetrical einzel lens, this number can be reduced to three. A simple experimental arrangement for measuring the properties of these lenses is described, and a few results are given.

70.

Poincaré's invariant and Particle optics, H. R. Fechter. Argonne National Laboratory Internal Report HF-7. (September 25, 1958) 8 p.

71.

Spectrographic and electron optical features of directional double focusing. H. W. Franke. *Ost. Ingen.-Arch.*, 6, 105-13, No. 2 (1952). (In German.)

Mass and velocity dispersion, the inclination of the collecting plane and the size of the aperture disk error are expressed in terms of the coefficients derived by writing the field components in the form of series. The conditions for directional double focusing and for velocity- and extended directional double focusing are also given. The possibility of second-order focusing is indicated.¹

¹W. Glaser, *Ost. Ingen. Arch.* 4, No. 5, 354-62 (1950). 151.

72.

On Newton's image relationship in electron optics, P. Funk. *Acta Phys. Austriaca*, 4, No. 2-3, 304-5 (1950). (In German.)

Gives a simple mathematical solution to the problem of determining the conditions under which Newton's image relation is satisfied.

73.

Electron-optical systems with helical axis, D. Gabor. Proc. Phys. Soc., London, B64, 244-55 (1951).

As the chromatic error of focus has the same sign in all electron lenses with straight axis, achromatic combinations do not exist. It is shown, however, that systems with curved axes can be designed which are equivalent to centered systems in the Gaussian approximation, but have chromatic error of opposite sign, and thus may be useful as correcting elements. Systems with a helical axis, with a helical electrostatic field so shaped as to eliminate first-order astigmatism, have particular advantages. In such systems, images of unit magnification are produced at equal intervals along the helical axis. Under certain conditions the transverse chromatic shift can be made zero in every second, or third, ..., image, while the longitudinal error of focus can be given any negative value by suitable choice of the pitch. Such systems may find application in secondary emission and dark-field electron microscopes, and particularly in diffraction microscopy. At a certain pitch the chromatic error becomes infinite. This system is particularly easily realized by means of two coaxial cylindrical electrodes. It is useless as a chromatic corrector, but may find application as a velocity spectrograph.

74.

Electron optics at h.f. and relativistic velocities, D. Gabor, Rev. optique, 29, 209-31 (1950). (In French.)

Is limited to electrons in axial symmetric fields. The field is described by two vector potentials, the usual magnetic vector potential and Born's "antipotential." The field equations are developed and the difference between dc and h.f. conditions explained. Relativistic dynamics is then discussed, leading to an expression for the focal length of a long magnetic field. This tends to $L = 2.1 \times 10^4 MV^{1/2} H^{-1}$ (MV = energy in MeV units, cm, gauss⁻¹) for small energies and $L = 2.1 \times 10^4 MVH^{-1}$ for high. Problems in varying fields are then discussed and applications to the behavior of lenses in particle accelerators made. A dissertation on the stability of linear accelerators concludes the work.

75.

The caustic surface of electron lenses, W. Glaser and H. Grümmer, Optik, 7, 96-120 (1950). (In German.)

The properties of the caustic surface of an electrostatic and a magnetic lens are investigated mathematically. There is general

similarity to the light optical case, especially for the electrostatic lens; the magnetic lens, however, gives rise to different symmetry characteristics and disposition of the surface. The results, which were deduced for a system including a diaphragm, may be extended to apply to a system without a diaphragm. The general relations are numerically evaluated for a typical case and illustrated by photographs of a scale model.

76.

On the significance of the concepts "focal point" and "focal distance" in electron optics, and on strong electron lenses with Newtonian image equations, W. Glaser and O. Bergmann, Z. angew. Math. Phys., 1, 363-79 (1950). (In German.)

The idea of focal distance in the case of electron lenses is examined, and it is pointed out that the usual definition does not in general specify the formation of the image in dealing with strong electron lenses. The relations between the positions of object and image are more complicated than those of light optics. These relations are investigated mathematically, and the conditions under which the ordinary optical equations are valid are discussed. The second part of the paper is devoted to the study of strong fields and the circumstances in which the term focal distance retains physical significance. The experimental determination of focal distances is briefly examined.

77.

On the significance of the concepts "focal point" and "focal distance" in electron optics, and on strong electron lenses with Newtonian image equations, W. Glaser and O. Bergmann, Z. angew. Math. Phys., 2, 159-88 (1951). (In German.)

For earlier report see ¹. It is shown that the usual definition of focal distance is inapplicable in strong electron lenses and is more complicated than in light optics. The correct expressions are approximated to fourth-order terms, in the neighborhood of two conjugate points by the "Newtonian equation for the image function." If the choice of conjugate points does not influence the resultant cardinal points, the latter are identical with the usual parameters. Strong fields are then studied, and a technique for approximating the empirically determined field by a "Newtonian" field (one which obeys the usual expressions) is given. Finally, experimental methods for determining the cardinal points for the approximate fields are discussed.

¹W. Glaser and O. Bergmann, Z. angew. Math. Phys., 1, 363-79 (1950). 76.

78.

On the wave mechanical theory of electron optical image formation, W. Glaser, S. B. Öst. Akad. Wiss., IIa, 159, 297-360 (No. 9-10, 1950). (In German.)

The material in this paper was presented in a set of lectures at the German University of Prague in 1942/43. Geometrical electron optics is treated as a limiting case of wave mechanics. The calculation of wave surfaces up to the third order, in an axially symmetric field, is carried out. The Schrödinger equation is solved for a "Seidel" electron beam. The electron density in the image plane is determined, and representations of wave functions are given.

79.

The refractive index of electron optics and its connection with the Routhian function, W. Glaser, Proc. Phys. Soc., London, B64, 114-18 (1951).

The derivation of the electron-optical refractive index from Hamilton's Principle is discussed. It is stated that the criticisms¹ of the author's method, whose derivation (1933) is correct, are invalid. To prove that it is generally applicable, the isotropic refractive index of an axially symmetrical field is obtained.

¹W. Ehrenberg and R. E. Siday, Proc. Phys. Soc., London, B62, 8-21 (1949). 68.

80.

A wave mechanical determination of the intensity relations in the image space of electron lenses. I. Determination of the electron intensity for given geometrical-optical imagery. V. Glazer (W. Glaser) and G. Gryumm (Grümm.), Zh. Tekh. Fiz., 21, 1427-43 (1951). (In Russian.)

By an extension of the WKB method, Schrödinger's equation is shown to lead, for a slowly varying refractive index, to corrections of the amplitude and phase as compared with the usual solution for locally constant refractive index; the conditions of validity of these corrections are shown to hold in existing electron microscope lenses. The corrected solutions are to be applied to rotationally symmetric systems having Seidel aberrations and also to systems with imperfect rotational symmetry.

81.

Wave-mechanical theory of electron-optical imaging, I., W. Glaser and G. Braun, *Acta Phys. Austriaca*, 9, 41-74 (1954). (In German.)

A method is given, in direct analogy with wave optics, for determining the Schrödinger wave function in any image plane from its value in a given (object) plane with the aid of Green's theorem; it corresponds to a generalization of Kirchhoff's treatment of diffraction. As the required Green's function cannot be rigorously derived, it is obtained as a series in powers of h , asymptotic for $h \rightarrow 0$, by a method akin to the WKB method in wave mechanics. The method of stationary phase is used to evaluate the resulting diffraction integrals. The meaning of the points of stationary phase in terms of geometrical optics is indicated, the number of solutions is discussed, and the relationship with geometrical electron optics and wave mechanics demonstrated. The laws of the former follow from those of the latter when the de Broglie wavelength is vanishingly small ($h \rightarrow 0$). The physical significance of the method of stationary phase is discussed. The results will be used in a later paper for a complete wave-mechanical treatment of paraxial focusing in electromagnetic fields of rotational symmetry.

82.

The wave-mechanical theory of electron-optical imaging, II., W. Glaser and G. Braun, *Acta Phys. Austriaca*, 9, 267-96 (1955). (In German.)

The general theory developed in Pt. I.¹ is now applied to the calculation of the wave-mechanical intensity distribution in the paraxial region of a rotationally symmetrical electromagnetic field. The behavior of the wave function in the Fraunhofer plane and its immediate neighborhood is first discussed ("strong diffraction"), and expressions are then derived for the components of the wave function at points sufficiently far from the Fraunhofer plane ("weak diffraction"), in the directly illuminated field, in the shadow, and at the shadow boundary as given by geometrical optics. The geometrical-optical part of the wave function is described by a series which can also be obtained from the treatment of optical diffraction due to Bremmer.² By means of this series it can be shown that the image formed by the paraxial region of an electromagnetic field of rotational symmetry is stigmatic in the Gaussian image plane. The diffraction part of the wave function is represented by a series of integrals over the edge of the aperture. It is shown how these integrals can in principle be evaluated by the method of stationary phase for points which lie (a) far enough from the

shadow boundary, (b) in the neighborhood of the shadow boundary, and (c) at the shadow boundary. The imaging of an infinite slit, a straight edge, and angular corner and a circular aperture is discussed in turn.

¹W. Glaser and G. Braun, Acta Phys. Austriaca, 9, 41-74 (1954). 81.

²H. Bremmer, Physica, 18, 469-85 (1952).

83.

In connection with the criticism by P. P. Kas'yankov of my method of obtaining the principal electron-optical equations for beams with a curvilinear axis, G. A. Grinberg, Zh. Tekh. Fiz., 27, 2425-31 (1957). (In Russian.)¹

The author discusses step by step the various objections raised by Kas'yankov in his book Theory of electromagnetic systems with a curvilinear axis (Leningrad University, 1956) and disproves them by showing that Kas'yankov's conclusions are based on erroneous premises, in the first place on the identification of the local system of Cartesian coordinates x, y, z with the curvilinear system s, p, q used by Kas'yankov. As a matter of fact, a correct treatment of the author's equations yields exactly the equations derived by Kas'yankov. In a note appended during proof-reading the author deals in the same way with Kas'yankov's criticism contained in a later paper [Optika i Spektrosk., 3, 169-79 (1957)]. 502.

¹English Translation in: Soviet Physics - Technical Physics, 2, 2259-65 (1957).

84.

On some classes of static axially symmetric electric and magnetic fields, for which the basic equation of electron optics admits of solution in terms of known functions, G. A. Grinberg, Zh. Tekh. Fiz., 23, 1904-14 (1953). (In Russian.)

It is shown that Picht's equation $\rho'' + \frac{3}{16} (\phi'/\phi)^2 \rho = 0$ has solutions of the form $\rho = (\phi/\phi') \frac{1}{2} C_v(\phi)$, where $C_v(\phi)$ is an arbitrary Bessel function of order v and ϕ is also related to z through Bessel functions. In a particularly simple case, the potential function reduces to $\phi = \frac{1}{2} (\phi_1 + \phi_2) + \pi^{-1} (\phi_2 - \phi_1) \tan^{-1} (z/a)$. In all cases, ϕ is a monotonic function of z , tending to ϕ_1 as $z \rightarrow -\infty$ and to ϕ_2 as $z \rightarrow +\infty$. A similar theory applies to magnetic fields of the form $H_0 [1 + (z^2/a^2)]^{-1} [1 + \alpha^{-1} \tan^{-1} (z/a)]^{-1}$; Glaser's bell field is the limiting case of $\alpha \rightarrow \infty$. It is also shown that $\rho = \sqrt{z} C_{1/2n} \left[\frac{1}{4} \sqrt{3} (z/a)^n \right]$ for an electrostatic potential $\phi = \phi_0 \exp [-(z/a)^n]$.

85.

A new mathematical model of an electron lens, P. Grivet, J. Phys. Radium, 13, 1A-9A (Feb. Suppl., 1952). (In French.)

A fuller version of^{1,2} [$H = H_0 \operatorname{sech} (z/b)$], giving some comparisons with experiment. It is shown in an appendix how $P_V (\cos \theta)$ may be computed for v not integral or half-integral.

¹P. Grivet, Compt. rend., 233, 921-3 (1951). 156.

²P. Grivet, Compt. rend., 234, 73-5 (1952). 155.

86.

On the question of the geometrical-optical intensity distribution in the image space of electron lenses. I-II, H. Grömm, Optik, 9, 281-8; 289-311 (1952). (In German.)

For background see Glaser and Grömm.¹ Expressions for the surfaces of equal intensity (isophots) are developed in the sense of Seidel's dioptics. The connection between this theory of the intensity distribution and the much more difficult wave-mechanical theory is discussed. An appendix gives some possibilities for the measurement of caustic dimensions and their use in determinations of aberrations.

¹Optik, 7, 96-120 (1950). 75.

87.

Perfect imaging dynamical systems, G. Iwata, Progr. Theoret. Phys., (Kyoto), 19, 375-88 (1958).

Perfect imaging dynamical systems are classified from the viewpoint of particle optics and their properties are studied. Examples illustrating inversion, translation, and rotation are given.

88.

In connection with the letter of Professor G. A. Grinberg, P. P. Kas'yankov, Zh. Tekh. Fiz., 28, 915-18 (1958). (In Russian.)

A reply to G. A. Grinberg's letter [Zh. Tekh. Fiz., 27, 2425-31 (1957). 83]. The author maintains his criticism [Optika i. spektrosk., 3, 169-79 (1957). 502] of Grinberg's method described in the latter's book on selected problems of the mathematical theory of electric and magnetic phenomena. The polemics are terminated by the editor who believes that it was begun owing to a misunderstanding on the part of the author.

89.

On certain focusing problems in electron optics theory, P. P. Kas'yankov, Dokl. Akad. Nauk SSSR, 108, No. 5, 813-16 (1956). (In Russian.)

Fully relativistic equations are formulated for electron trajectories in general electro- and magneto-static potentials. The conditions that these potentials must satisfy in order that the electron-optical image be planar can be obtained from a fundamental matrix property of the coordinates. In the paraxial region these conditions assume a relatively simple form.

90.

On the conditions for the existence of stigmatic imaging in electron optical systems with curved axes, P. P. Kas'yankov, Dokl. Akad. Nauk SSSR, 120, No. 3, 497-500 (1958). (In Russian.)

Conditions for stigmatic imaging in electron optical systems with curved axes are derived and applied to the correction of electron lenses with elliptical bores.

91.

Theoretical method of investigation characteristics of stigmator, P. P. Kas'yankov. Acad. Sciences USSR-Bul.-Phys. Ser. (English translation), 23, No. 6, 706-10 (1959). (Columbia Tech. Translations, New York, N.Y.)

Method is presented for determining compensating fields by means of which uniformly focused image can be obtained in absence of axial symmetry of field; method can also be used, with modifications, for investigating systems deviating from given system with curvilinear axis.

92.

"Schlieren" optics in the electron microscope, H. Konig. Naturwissenschaften, 37 (No. 21), 486-90 (1950). (In German.)

A general description of the electron optical analogue of the "Schlieren" method.

93.

Electron lenses in relativistic mechanics, J. Laplume. Rev. Opt. (Theor. Instrum.), 29, 106-11 (Feb., 1950). (In French.)

The relativistic equation of motion for electron trajectories in an axially symmetric field is derived. The Gauss approximation is

then introduced, and the equations for the cases (1) a magnetic lens, (2) an electrostatic lens, are written down explicitly. These clearly show the departure, at high electron speeds, from the ordinary equations. A formula is given for the relativistic correction to the focal length of a lens.

94.

Paraxial lens-action in electric ion optics or geometrical optics, L. J. Laslett. Brookhaven National Laboratory. (February, 1955) 6 p. BNL-LJL-O.

Useful for extended (diffuse or thick) lenses.

95.

The analysis of rotational-symmetric potential fields in electron lenses, F. Lenz, Ann. Physik, 19, 92-8 (1957). (In German.)

Contains a critical discussion of two recent papers. Regenstreif's analysis of the three-electrode electrostatic aperture lens¹ is shown to imply incorrect boundary values of the assumed axial potential at infinity. A modified distribution is advanced, and the extension to the case of a thick central aperture considered. The results of Ehinger's analysis of the two-diameter magnetic lens² are compared with those derivable from a previous publication by the author,³ and shown to be less accurate, particularly with regard to the prediction of the position of maximum field strength, by reference to Liebmann's resistive network measurements.⁴

¹E. Regenstreif, Ann. Radioelectricite 23, 51-83 (1951). 313.

²P. Ehinger, Compt. rend., 238, 1306-8 (1954). 272.

³F. Lenz, Z. angew. Phys., 2, 337-40 (1950). 179.

⁴G. Liebmann, Proc. Phys. Soc., London, B68, 679-81 (1955). 183.

96.

Magnetic electron microscope projector lenses, G. Liebmann, Proc. Phys. Soc., London, B65, 94-108 (1952).

The results of an earlier paper¹ are extended to the special case of the electron microscope projector and similar type lenses. It is shown that the focal properties of symmetrical projector lenses with different ratios of gap width S to lens bore D can be represented by a single curve. This is then applied to the discussion of various cases of practical interest. The calculated results are found to be in excellent agreement with measurements by Ruska. The question of image distortion as a function of design parameters and lens excitation is then discussed; it is shown that all the types of lenses investigated can

be operated at a point where they are free from "radial distortion." A consideration of scaling operations shows that there is little difference between the optimum performance of lenses of different geometry, but equal focal length. Certain results of use in practical lens design are combined in a design chart from which the relevant design or operational parameters can be read directly. In conclusion, design rules are given for the optimum design of projector lenses covering a wide range of magnifications.

¹G. Liebmann and E. M. Grad, Proc. Phys. Soc., London, B64, 956-71 (1951). 184.

97.

Zur Berechnung des Polschuhprofils bei Magnetischen Quadrupollinsen.
(On the calculation of the poleshoe cross section in magnetic quadrupole lens), D. Lubow, DESY-A2.78 (Aug. 1, 1961). 45 p.

The form of the solenoid, which produces in a magnetic lens an exact quadrupole field, was calculated. A method was given by which the poleshoe profile necessary for the production of as good a quadrupole field as possible can be calculated, when a specified coil form is determined in advance.

98.

On solution of equation of electron optics, B. Meltzer. J. Electronics, 1, 53-9 (July 1955).

Analytic solution is given of class of differential equations, one of which is ray equation determining focusing in X-ray tube; equations originate from expressions obtained by F. Ollendorf in analysis of X-ray tubes.

99.

On the focusing of charged-particle beams using high-frequency fields, M. A. Miller, Dokl. Akad. Nauk SSSR, 119, 478-80 (1958). (In Russian.)

Beams of charged particles can be focused by periodic magnetic and electric fields as shown by Clogston and Heffner. The present paper develops mathematically the conditions to be satisfied by the fields for focusing in the presence of space charge. The high frequencies required can be produced in waveguides provided with periodic structures.

100.

Researches on electron streams. I., J. Müller, Z. angew. Math. Phys., 5, 203-32 (1954). (In German.)

Matrix representations of known electron flow properties are deduced, and the conditions imposed by the conservation of charge and energy are derived for small departures from the stationary state (small-signal theory). Only linear phenomena are considered, i.e., electron collisions in the gas kinetic sense are neglected. Streams with one or more discrete velocities and with velocity distributions are considered. In the Maxwellian case these results are of use in the study of noise. Strong magnetic fields are used to define the electron paths, and therefore only the electric field components in the direction of motion are considered.

101.

Researches on electron streams. II., J. Müller, Z. angew. Math. Phys., 5, 409-19 (1954). (In German.)

For Pt I, see ¹. The laws of conservation of energy and charge are used in a perturbation theory for longitudinally controlled streams of electrons. Space charge, the electromagnetic field, and the relativistic change of mass are taken into account. The relations in the classical field are found from a matrix form. Impedances of the streams are used. On terminals they are identical with the impedances of the electronic device. It is shown how Nyquist's noise formula can be derived from the shot noise for a system in thermal equilibrium with potential minimum in the electron streams and high transit time angles. Noise formulae are presented for a system not in thermal equilibrium. A simplification of the calculation of the noise convection currents of the electrons coming at the electrodes can be made. When in all emission points the emission fluctuations are concentrated in the streams with maximal transit time, the noise in the convection currents has the same value as the real noise. When a potential minimum is present, the current is important, which passes over the potential minimum. The noise of this current must be concentrated in the streams with maximal transit time beginning in the potential minimum.

¹Z. angew. Math. Phys., 5, 203-32 (1954). 100.

102.

Note on the use of point cathodes in electron optics, Y. Sakaki and G. Mollenstedt, Optik, 13, 193-200 (1956). (In German.)

The point cathode developed by Müller and Hibi emits electrons from an effective area of only a micron or so in diameter. The present

authors have improved the technique for making such cathodes and incorporated them into an electron microscope. With such a small electron source, multifringe Fresnel diffraction patterns can readily be obtained without the use of auxiliary lenses or apertures.

103.

Optical power of short electron lenses, O. I. Seman, J. Tech. Phys., USSR, 20, 1180-93 (1950). (In Russian.)

It is shown that Bruche and Scherzer's well-known approximation formula for focal length, $f^{-1} = 0.125 \phi_1^{-1} \int_{z_0}^{z_1} \phi^{1/2} \phi^{-3/2} dz$, where $\phi(z)$ is the electric field potential along axis z and $\phi' = d\phi/dz$, can lead to a 100% error in the case of short lenses. Corrected formulae are derived which are accurate within 5-13% in all cases for electrostatic and magnetic lenses, and contain a new constant $R = r\phi^{1/4}$. It is shown that the assumption $R = \text{const}$ instead of the usual $r = \text{const}$ is particularly useful for short, single, symmetrical electron lenses, and that $\Delta f/f$ and relative radial displacement $\Delta r/r$ of the electron beam in a short magnetic lens are always below lens thickness $1/f$.

104.

Investigation of field distribution in symmetrical electron lens, J. R. Shah and L. Jacob, J. Appl. Phys., 22, 1236-41 (1951).

High accuracy of measurement in the electrolytic tank can be achieved by a suitable ratio of impedance as between tank and measuring circuit. With this requirement fulfilled, the axial distribution of the symmetrical lens was explored and found to satisfy a relation $V_z = V_0 + Ae^{-Vz}$, where V_0 is the potential of the outers with respect to the middle electrode, z distance from the centre of the lens, while A and b are constants from any one geometry. The effect of varying the separation between the elements was specially investigated. It was found that the maximum value of the gradient between electrodes increases as the separation between them increases, reaches a flat maximum between 0.8 and 0.4 D (D bore diameter), and then decreases with further increase in spacing. This means that a decrease in separation produces a weaker field and an increased focal length. The potential at the saddle point is very sensitive to changes in separation in the region up to about 0.5 D; it was also found to vary linearly with bore up to 3 D. The relaxation method of field plotting was also applied to map the distribution; the results are compared with those given by the tank.

105.

Theory of electron-optical systems with arbitrarily curved axes,
I. I. Tsukkerman, Zh. Tekh. Fiz., 24, 258-73 (1954). (In Russian.)

The general problem has been treated by Cotte (1938), Wendt (1943), and Grinberg (1942-3); Grinberg's method is adopted here, Cotte's being more complicated and Wendt's wrong except when the axis is a plane curve. The paraxial ray equations, a simultaneous pair, involve the radii of curvature and of torsion of the axial ray, as well as the potential functions. The coordinates used are the arc length along the axial ray and the displacements along its principal normal and binormal; the arc length is the independent variable of the ray equations. Consideration is confined to stigmatic focusing with magnification independent of orientation, for which conditions are given. Particular cases include focusing in and near the median plane between 2 antisymmetric magnetic poles, and the astigmatism produced by magnetic scanning coils. The author's solution of the problem of determining the field required to produce a given family of rays in the case of rotational symmetry is extended to the present case.

106.

Electron-optical systems whose fields are independent of one coordinate, Yu. V. Vandakurov, Zh. Tekh. Fiz., 26, 2578-94 (1956).
(In Russian.)

The fields involved are either cylindrical or they have a symmetry of rotation. It is shown that, for electron-optical systems with fields of this kind, one of the two second-order differential equations determining the deviation of the particle path from the axial trajectory can be substituted by a first-order equation. The results obtained have been used for the study of fields whose electric potential is symmetrical with respect to the median plane, whereas their scalar magnetic potential is antisymmetrical with respect to that plane. The following fields have been investigated in more detail: (1) fields of the linear current, (2) fields of a spherical or cylindrical condenser, and (3) combinations of a heterogeneous magnetic field with the field of an electrical condenser.

107.

An arrangement for focusing electrically neutral particles, R. Vauthier, Compt. rend, 228, 1113-14 (1949). (In French.)

Harzog [Z. Physik, 89, 447 (1934)] showed that between the plates of a cylindrical condenser a monoenergetic beam of ions can be focused. An analogous arrangement is now proposed for particles

having a magnetic dipole moment, which may be focused in a curved region in which the gradient of the magnetic field is constant. For particles having a magnetic moment of one Bohr magneton, the radius of curvature of the trajectories is $52,000 T / (\partial H / \partial X)$, where T is the absolute temp and the particles have the most probable thermal velocity. Such an arrangement would facilitate the investigation of the distribution of thermal velocities. Expected difficulties include the attainment of a uniform $\partial H / \partial X$ over 2 or 3 mm of air gap, and of a value of $\partial H / \partial X$ sufficiently great for the size of the electromagnet not to become prohibitive. Application would be confined to molecules having one Bohr magneton moment.

108.

A method for the numerical integration of a class of equations of mathematical physics and its application to electron optical problems, Yu. V. Vorob'ev, Zh. Tekh. Fiz., 22, 1166-73 (1952). (In Russian.)

The class of equations considered is $y'' + yQ(x) = 0$, where $Q \rightarrow \infty$ not more rapidly than x^{-2} as $x \rightarrow \infty$. A solution is assumed of the form $y = ux\rho$ and with the help of the Newton-Gregory forward interpolation formula the auxiliary function uQx^2 is determined at a few points near the singularity. A forward difference extrapolation formula is then used until the solution has been carried far enough for other well-known numerical methods to be applicable. Details, including numerical coefficients in the extrapolation formulae, are given for the solution of the paraxial ray equation, in Picht's "reduced" form, for the case in which the initial electron energy $\rightarrow 0$. The method here proposed differs, e.g., from that of Recknagel (1941) in that the latter involves axial derivatives of the potential, which is disadvantageous, where the potential is not given analytically.

109.

Lens equation and image curve of a cylindrical condenser when the entry and exit of an ion beam is oblique at field boundaries, H. Wende, Z. Naturforsch. 12a, 967-70 (1957). (In German.)

The ion-optical lens equation of Herzog¹ is extended to the case of oblique entry and exit, using the theory of second approximation. The position of the image curve and the properties of an "energy spectrograph" are discussed.

¹R. Herzog, Z. Physik, 89, 447 (1934).

See also: 1-22, 487, 493, 500, 502, 503, 508, 515, 517, 519, 520, 521, 522, 524-528, 531, 601, 640.

ELECTRON LENSES - DEFLECTION SYSTEMS

110.

Probleme general de la deflection d'une particule chargee de haute energie par un champ electromagnetique. Iere Partie: Ondes deflechissantes en coordonnees cartesiennes, R. Gabillard (Institut Radiotechnique Faculte des Sciences de Lille) N-2877a (Mai 1961). 29 p. (In French.)

111.

Probleme general de la deflection d'une particule chargee de haute energie par un champ electromagnetique. 2eme Partie: Cavites pour ondes deflechissantes, R. Gabillard, (Institut Radiotechnique Faculte des Sciences de Lille) N-2877b, 15 p. (In French.)

112.

Investigation of a special deflection system for electron beams, R. Gain, *Optik*, 14, 49-71 (1957). (In German.)

Describes a new system for the deflection of electrons. This consists of a flat plate and a single wire held at a potential differing from that of the acceleration electrodes. Approximate formulae for the potential distribution in several arrangements of the system are worked out, and the deflection characteristics and aberration figures are deduced. An experimental model is shown to produce results comparable with conventional cathode-ray-tube deflection systems.

113.

Graphical solution for high-frequency electrostatic deflection, M. H. Greenblatt, *Am. J. Phys.*, 27, 348-51 (1959).

A graphical analogue, which obeys the same equations as an electron beam during deflection, is described. The transverse displacement and velocity of the beam can be calculated from this analogue, and certain details which are not obvious in the straightforward solution are apparent in the graphical-analogue solution. A proposal for a charged-particle beam-velocity measuring device is made. This proposal is based on behavior revealed by the graphical-analogue solution.

114.

Errors of magnetic deflection, I. J. Haantjes and G. J. Lubben, *Philips Res. Rep.*, 12, 46-68 (Feb 1957).

Deals with the errors caused by magnetic deflection of the electron beam in a cathode-ray tube. It appears that image distortion,

astigmatism, curvature of the image field, and coma may occur corresponding to the errors of the third order in conventional optics. It will be shown that in most cases one may influence and even eliminate these errors by a suitable distribution of the deflecting field. The only error which can never be eliminated by a special field distribution is the error known as curvature of the image field. This error would not appear if the screen face of the tube coincided with the image field. However, the curvature of the image field is such that it is generally impossible to fulfill this condition. Therefore, this error has to be taken into account in the design of cathode-ray tubes for television purposes.

115.

The electron optical theory of the deflection of an extensive electron optical picture by means of a crossed electrical deflection system, J. Himpan, Ann. Physik, 8, 405-22 (1951). (In German.)

A rigorous mathematical formulation of the problem, including the 3rd-order errors. Conditions for distortion-free deflection are given and the 6 3rd-order errors are classified, 3 giving rise to distortions of the picture and 3 to deformations of the spot. Expressions for the error constants are given.

116.

Double electro-static deflection of electron beams without aberrations, K. Kanaya and H. Kawakatsu, Denki Shikensho Iho, 25, 241-52 (1961). (In English.)

An electron beam passing through a deflecting field is, in general, subject to aberrations such as distortion, astigmatism, and coma. The deflection equations are formulated by developing the theory of deflection. Furthermore, it is shown that the caustic figures of the deflected beam converged at the focal point show complicated patterns of aberration. It is suggested that deflections free from coma, astigmatism, and distortion can be achieved by means of a double deflection system, since the aberration of deflection in such systems can, in principle, be compensated if the deflection fields are properly distributed.

117.

Some considerations concerning the transverse deflection of charged particles in radio-frequency fields, W. K. H. Panofsky and W. A. Wenzel, Rev. Sci. Instr., 27, 967 (1956).

Presents general theorems restricted to a beam of fast particles passing through a cavity parallel to its axis excited either in a TM (no component of magnetic field parallel to the axis) or a TE (no component of electric field parallel to the axis) mode.

118.

Calculation of properties of magnetic deflection systems, S. Penner, Rev. Sci. Instr., 32, 150 (1961).

A convenient matrix method for calculating properties of magnetic deflection systems is presented. This method is applicable to particle beams of small spatial and angular extent, and small energy spread. Equations for quadrupole lenses and for deflecting magnets are given. Examples are given to show the procedure for calculating the parameters of magnet systems.

See Rev. Sci. Instr., 32, 1068-9 (1961) for errata to the above article.

119.

Experimental and theoretical investigation of a new electron-optical deflecting device, J. Picht and R. Gain, Exper. Tech. der Phys., 4, 262-8 (1956). (In German.)

In the device the electron beam is deflected during its passage between two plates at the same potential. This is achieved by shaping the plates so that the equipotentials assume the form of a prism. The theory is supplemented by a field study in an electrolytic tank and by measuring deflections in an experimental tube.

120.

Extension of the electron-optical theory of deflecting electrostatic systems to the case of relativistic particles, A. M. Strashkevich, Zh. Tekh. Fiz., 24, 2264-70 (1954). (In Russian.)

The systems considered have two perpendicular planes of symmetry. The field is symmetrical with respect to one plane, and anti-symmetrical with respect to the other. The trajectories of fast paraxial electrons are determined from relativistic equations of motion. The results are carried out to the second order of approximation. The deflection sensitivity is determined. It is higher than in the nonrelativistic case. Two cases are given as illustrations: the parallel plate condenser, and the system of two electrodes in the same plane. End effects are disregarded for entering as well as for emerging electrons. The results are intended for application, e.g., to cathode-ray-tube design, but their usefulness is restricted because of end effects on entering electrons.

121.

Magnetic deflection focusing, P. A. Sturrock, J. Electronics and Control, 7, 162-8 (Aug 1959).

A scheme for focusing sheet beams by means of a periodic configuration of magnetic fields directed transverse to the beam is presented. Discussion of a particular model gives information about stability limits and perveance. This scheme, which lends itself to the incorporation of intense magnetic fields, should be immune to the space-charge instabilities of beams focused in longitudinal fields. The focusing mechanism is such as to produce coupling between the beam and electromagnetic waves of phase velocity exceeding the velocity of light. Application to millimetre-wave tubes is anticipated.

122.

Electron deflection systems and their aberrations, G. Wendt, Onde elect., 33, 92-106 (Feb 1953). (In French.)

Deflection systems are classified in two categories: (1) static or systems with a curved axis; examples are spectrographic systems and Gabor's helicoidal system; (2) dynamic systems: television deflection systems, polar deflection, etc. The author confines his study to systems with two planes of symmetry. The third-order aberrations are discussed as functions of the deflection angle and beam aperture. Aberrations are calculated for a coil with a sinusoidal distribution of turns and the measured aberrations for the plates of a super-icoscope are discussed. A mathematical appendix gives the detailed calculations for third-order aberrations in systems of double symmetry set at 90° to one another.

See also: 1, 240, 284, 500.

ELECTRON LENSES - ELECTROMAGNETIC SYSTEMS

123.

First order optics of thin magnetic cylindrical lenses, G. Bacquet, P. Gautier, and A. Santouil, Compt. rend., 252, 522-4 (1961). (In French.)

A simple rectangular model of the field is used for a theoretical study of the essential optical properties of thin magnetic cylindrical lenses. Experimental investigations of such lenses, made with an electron-optical bench, have confirmed the theoretical deductions.

124.

On paraxial electron-optical image formation, F. Borgnis, *Helv. Phys. Acta*, 22, 261-4 (1949). (In German.)

The results of an earlier paper [*ibid.*, 21, 461 (1948)] are extended. It is shown that if the paths of two rays through the system are given, the potential and magnetic field at all points can be derived. Further references to the literature are given.

125.

A simple approximation formula for the field distribution along the axis of magnetic electron lenses with unsaturated pole pieces, H. Bremmer, *Optik*, 10, 1-4 (1953).

Further discussion of a result due to Lenz¹ which depends only on the total flux and the ratio of pole spacing to aperture diameter. Formulae valid for various conditions are given, together with a table of an integral required in the calculation.

¹*Optik*, 7, 243-53 (1950). 178.

126.

Some characteristics of a magnetically focused electron beam, G. R. Brewer, *J. Appl. Phys.*, 30, 1022-38 (1959).

The detailed behavior of a solid, cylindrical electron beam focused by a uniform magnetic field (Brillouin flow) was studied experimentally. These studies included the influence of the optics of the electron gun on the beam-focusing characteristics, the effects of transverse "thermal" velocities, the change in the internal beam dynamics with increasing values of magnetic focusing field, etc. A simple model of the beam is used to explain certain of the observed characteristics. It is found that an optically good electron gun will produce a focused beam which closely resembles the theoretical Brillouin-flow model. A brief analysis of the electron motion in a magnetically focused beam is given.

127.

The behavior of an electron beam at entry to a coaxial magnetic field, L. Bruck, *Telefunken Ztg.*, 26, 85-8 (March 1953). (In German.)

In electron guns used for setting up Brillouin flow (cylindrical beam), the cathode must be shielded from the magnetic field. The problem of the transition region in the polepiece aperture is discussed using an (assumed) simple magnetic field variation. It is shown that

the beam must be converging at entry to the field. It should converge, when the magnetic field is switched off, to a point where the field reaches 70% of the final, uniform value. The final diameter, with field on, is less than the final diameter with field off.

128.

The focusing of electron beams by a periodic longitudinal magnetic field, O. Cahen, Ann. Télécomm., 11, 142-50 (July-Aug 1956). (In French.)

It is shown that, if a magnetic field directed along the axis of an electron beam changes its sense periodically in space, the beam may be focused as well as it would have been by a unidirectional field. The optimum form and intensity of the field (viz., those which reduce the beam to a minimum diameter) are discussed, and practical arrangements for its production are detailed.

129.

Focusing properties of the Biot-Savart field, E. R. Caianiello and G. Gatti, Nuovo Cimento, 12, 469-76 (1959). (In Italian.)

The focusing properties of magnetic fields produced by rectilinear currents of very high intensity are investigated. The results seem to indicate that such fields might prove of practical use in the design of particle accelerators.

130.

Double focusing with wedge-shaped magnetic fields, M. Camac, Rev. Sci. Instr., 22, 197-204 (1951).

Geometric focusing in two directions for charged particles of a single energy is produced with a wedge-shaped magnetic field. The uniform field in the gap focuses in the plane of the pole faces, while the fringe fields focus perpendicular to the pole faces. With a single wedge, the energy dispersion is too large for the weak electron intensities available with the source; i.e., for a reasonably sized slit at the collector only a narrow energy width and, thus, a small number of electrons is accepted. With the use of two wedge-shaped fields the energy dispersion can take a wide range of values, even zero in the first order. General formulae for either one or two magnet systems are derived for the focusing conditions, the energy dispersion, the second-order beam spread, and the effect of source width. These formulae are then applied to two special cases from which practically all design requirements can be obtained. Finally, a design is recommended for which the following requirements are fulfilled: 5% energy spread in an inch collector slit, large angular collection and the same size source and collector slits.

131.

The spin kinematics for a charged particle in a uniform magnetic field, M. Carrassi, Nuovo Cimento (Ser 10), 5, 955-60 (1957).

The influence of a uniform magnetic field on the spin orientation of electrons in a beam is calculated according to the Dirac theory. It is shown that when the field is perpendicular to the electron beam path, the spin orientation does not change with respect to the direction of propagation. The calculations are performed using the exact solution of the Dirac equation.

132.

Permanent magnet for atomic beam focusing, R. L. Christensen and D. R. Hamilton, Rev. Sci. Instr., 30, 356-8 (1959).

A compact six-pole permanent magnet useful for focusing of atomic beams is described, together with the equations of motion of atoms in its field as used in its design. The method of construction, magnetization, and measurement of its field are discussed.

133.

Two-directional focusing of charged particles with a sector-shaped uniform magnetic field, W. G. Cross, Rev. Sci. Instr., 22, 717-22 (1951).

For a sector-shaped, uniform magnetic field with source and detector outside the field, the nonuniform fringing fields can be employed to give simultaneous focusing of charged particles in two perpendicular directions. Equations for determining the position of the doubly focused image are developed and graphs are given for some representative arrangements. This double focusing can be combined with the methods recently developed for second-order focusing to increase further the useful solid angle of a uniform-field mass or momentum analyser. Fringing-field focusing can also be used in concentrating to a point a parallel beam of finite cross section.

134.

Construction of electromagnetic lenses, P. Durandeau, J. phys. radium, 17, 18A - 25A (March Suppl., 1956). (In French.)

The axial field distribution in electromagnetic lenses is investigated for varying geometry of the pole pieces and the iron circuit. Optimum conditions for constructing short-focus lenses using high-speed (250-kV) electrons are given.

135.

General expressions and curves representing the electron optical characteristics of magnetic electron lenses, P. Durandeu, *Compt. rend.*, 242, 1710-12 (1956). (In French.)

The focal properties and chromatic aberration constants of magnetic lenses are plotted in the form of universal curves against a parameter proportional to (ampere turns)/(relativistically corrected accelerating voltage)^{1/2}, the unit of length being taken as $(S^2 + 0.45 D^2)^{1/2}$ (S = spacing, D = diameter of bore).

136.

Magnetic electron lenses, P. Durandeu and C. Fert, *Rev. optique*, 36, 205-34 (May 1957). (In French.)

Comprehensive survey of the rules of design for electron lenses for electron microscopes and similar instruments.

137.

Magnetic electron lenses: simple general expressions for the axial field and the electron-optical characteristics, P. Durandeu, *J. phys. radium*, 17, 33S-35S (June 1956). (In French.)

For symmetrical lenses it is convenient to express parameters in terms of $\sqrt{(S^2 + 0.45 D^2)}$, where S is the gap in the iron circuit and D is the bore.

138.

A method of measuring the induction and its derivatives on the axis of magnetic electron lenses, P. Durandeu, B. Fagot, and M. Laudet. *Compt. rend.*, 247, 2316-18 (1958). (In French.)

A method is described for measuring the axial field strength and its derivatives along the axis of a magnetic electron lens. The accuracy of the method (0.1%) is limited by the accuracy with which the flux can be determined and not by the finite dimensions of the search coil.

139.

Measurement of two-dimensional fields. Part I: Theory, W. C. Elmore and M. W. Garrett, *Rev. Sci. Instr.*, 25, 480-485 (1954).

An arbitrary two-dimensional magnetic field may be uniquely specified by listing all coefficients of the power-series expansion of its complex potential function. An experimental procedure is described

in which the first N coefficients are derived from an N -point harmonic analysis of the radial component of field or gradient, as measured with a dipole or quadrupole search coil at N equally spaced angular positions about an arbitrary longitudinal axis. The method may be refined by mounting two coils coaxially on a radial arm, so connected as to balance out the strongest component present and permit more accurate determination of the higher harmonics. With four coils, odd or even harmonics also may be suppressed. Analysis of the symmetry of various magnet pole structures shows that many of the coefficients vanish identically. Procedures are outlined for measuring with a quadrupole search coil the five independent elements of the magnetic gradient dyadic at a point in an unrestricted field. It is shown that in the fringing region at the ends of a long magnet gap the axial average of the transverse field can be treated as a two-dimensional field. It is correctly measured using line dipole or quadrupole search coils, whose design is prescribed. The procedure is identical with that for the two-dimensional case. A further extension of the same method to measurements made with the electrolytic tray analog increases greatly their speed and accuracy.

For Part II see I. E. Dayton, Rev. Sci. Instr., 25, 485-489. 213.

140.

Optical focusing of neutral atoms, H. Friedburg, Z. Physik, 130, 493-512 (1951). (In German; see also NSA 5-5752.)

The theory of focusing of beams of neutral paramagnetic particles by an inhomogeneous magnetic field is discussed and an experimental apparatus is described.

141.

Magnetic analysis of scattered particles, H. P. Furth, Rev. Sci. Instr., 26, 1097-1100 (1955).

The theory of conditioned probabilities is applied to the problem of momentum, charge, and mass determination from Coulomb-scattered tracks in a magnetic field. An optimum procedure is derived, which makes use of both random and systematic track curvature. It is shown that application of this procedure to a highly relativistic nuclear emulsion track of 1-cm length in a field of 300,000 gauss will yield the momentum information of a 9.2-cm track in zero field. If the scattering information were neglected, the effective length of the track would be 8.2 cm. At 100,000 gauss, the improvement in effective track length due to the inclusion of scattering information is shown to be by a factor of 2.3.

142.

Energy selection of charged particles by a magnetic field,
J. W. Gardner, Can. J. Phys., 31, 459-68 (1953).

Examines the problem of obtaining a sharply defined mono-energetic beam of particles from an omnidirectional, polyenergetic source without the use of slits. A magnetic field is suggested which will achieve this in the idealized case when the source and counter are of vanishingly small dimensions and the particles are confined to the median plane. The proportional spread in energy ($\Delta E/E$) of particles arriving at the counter, due to the finite dimensions of the source and counter and a small component of particle velocity out of the median plane, is then investigated. Finally, some numerical estimates are made of $\Delta E/E$ and of the magnetic fields required in particular cases.

143.

Theoretical and experimental study of the field of a series of magnetic cylindrical lenses, P. Gautier and C. Latour, Compt. rend., 248, 1637-40 (1959). (In French.)

By means of two successive transformations the field in a magnetic cylindrical lens is calculated theoretically. The results are in good agreement with experiment and this is taken to justify the assumption that the permeability of the pole pieces may be taken as infinite.

144.

Second-order focusing in a wedge-shaped magnetic field, J. Geerk and C. Heinz, Z. Phys., 133, 513-23 (1952). (In German.)

It is shown that second-order focusing may be obtained in a homogeneous wedge-shaped magnetic field at the cusp of the caustic for first-order focusing, and the necessary conditions are derived and simplified by introduction of the angular magnification for a narrow beam as parameter.

145.

Methods of developing focusing fields, Ya. L. Geronimus, Zhur. Tekh. Fiz., 32, 3-14 (Jan 1962). (In Russian.)

Methods are suggested for developing focusing fields (all trajectories pass through the same field point after changing their initial rate) in which charged particles in a stationary external electromagnetic field are in motion from a given field point. Interactions between the particles are not considered, and focusing is analyzed from a purely geometric point of view. The studies are limited to motion in one plane.

146.

Investigation of magnetic lenses having the axial field $H(0, z) = y/z^n$,
U. F. Gianola, Proc. Phys. Soc. (London), B65, 597-603 (1952).

Examination of the requirements for reducing the spherical aberration of an electron lens by modifying the field shows that the hypothetical lens field $H(0, z) = y/z^n$ should have small aberrations. It is shown that the properties of a certain class of this general field configuration can be described in terms of an exact analysis. In particular, the electron-optical properties of the y/z^2 field are described in detail. The y/z^2 field is found to have small aberrations, but practical conditions limit appreciable improvement in resolving power. The characteristics of the y/z^3 field are also examined and are found to give little further advantage.

147.

Apertures and diaphragms in magnetic electron microscopy, W. Glaser and H. Robl, Ost. Ingen.-Arch., 5, 36-48 (No. 1, 1951). (In German.)

Crossover formation is discussed in generalized axially symmetrical fields. The aperture of the incident beam in magnetic microscopes is defined as a function of the powers of condenser and objective, and the properties of three special types of diaphragms, "largest diaphragm," "diaphragms of equal aperture," and "contrast diaphragms" are discussed.

148.

Calculation of the optical constants of strong magnetic electron lenses, W. Glaser, Ann. Phys., 7, 213-27 (1950). (In German.)

Expressions are derived for the focal length, magnification, chromatic aberration, and aperture defect of the strong magnetic lenses used in electron microscopy. The process of computation of the electron-optical constants is reduced to the solution of an eigenvalue problem.

149.

Computation of the electron optical focusing of three typical strong magnetic lenses and their relation with the usual lens equation, W. Glaser and F. Lenz, Ann. Phys., 9, 19-28 (1951). (In German.)

$H_z = H_0 [1 + (z/a)^2]^{-\mu}$, with $\mu = 1, 3/2, 2$ and ∞ .^{1,2} Graphs show object and image positions, focal lengths, positions of "osculating foci"³ v. magnification, with lens strength as parameter. It is pointed

out that the circular conductor (i.e. $\mu = 3/2$), like the systems with $\mu = 2$ and ∞ , is non-Newtonian. The (paraxial) ray equation was solved numerically except for $\mu = 1$.

¹N. Svartholm, Ark. Mat. Astr. Fys., 28B, 4 (1942).

²F. Lenz, Z. angew. Phys., 2, 337-40 (1950). 179.

³W. Glaser and O. Bergmann, Z. angew. Math. Phys., 1, 363-79 (1950). 76.

150.

Correction to Walter Glaser's paper, "Calculation of the optical constants of strong magnetic lenses," W. Glaser, Ann. Phys., 8, 423 (1951).¹

¹W. Glaser, Ann. Phys. Lpz., 7 (No. 5) 213-27 (1950). 148.

151.

Direction double focusing of electron beams in inhomogeneous electromagnetic fields, W. Glaser, Öst. Ingen. Arch., 4, 354-62 (1950).
(In German.)

Focusing by electron beams, the main beam of which is a circle situated symmetrically to the axis of an axially symmetrical electromagnetic field, is investigated. The focusing is in general an astigmatic one. The conditions for the variation of the field in the immediate neighborhood of the main beam, to get an anastigmatic image formation, are described. The possibilities for application of the device in velocity- and mass-spectroscopy are indicated.

152.

Strenge Berechnung magnetischer Linsen der Feldform $H = \frac{H_0}{1 + (Z/a)^2}$,
W. Glaser, Z. Physik., 117, 285-315 (1940-41). (In German.)

Exact computation of magnetic lenses in the field shape
$$H = \frac{H_0}{1 + (Z/a)^2}.$$

153.

Isotropic and anisotropic distortion of weak magnetic electron lenses,
R. Gobrecht, Exper. Tech. der Phys., 6, 97-109 (1958). (In German.)

In an apparatus for the measurement of magnetic lens image distortion, the eccentrically located electron source is made capable of rotation about the optical axis. The position of the image point for various orientations is measured, and the rotational and radial components of the distortion are deduced.

154.

Contribution to the study of a cylindrical electromagnetic electron lens, J. A. Gomez Garcia, An. Real Soc. Esp. Fis. y Quim., 47, 15-28 (Jan-Feb 1951). (In Spanish.)

Conditions of bidimensionality are imposed on scalar and vector potentials by selecting an appropriate system of reference. Formal expressions for V and A are obtained in the form of potential series of y . By applying the minimum action principle, differential equations of the semiparaxial trajectories are obtained. These equations are solved by the constant variation method. Agreement between the equations obtained and those of Gratsiatos is shown for paraxial trajectories.

155.

Cardinal points of a new model of a (magnetic) electron lens, P. Grivet, Compt. rend., 234, 73-5 (1952). (In French.)

Focal lengths and mid-focal distances for the field¹
 $H = H_0 \operatorname{sech}(z/b)$ are tabulated, mostly to 1 in $\sim 10^3$, against v , the order of the Legendre function in the ray equation. The real values are given for $v = 0.1$ (0.1), 1.5 and 2.0, the virtual (i.e., asymptotic) for $v = 0.1$ (0.1), 0.9, and 0.95.

¹P. Grivet, Compt. rend., 233, 921-3 (1951). 156.

156.

A new mathematical model of an electron lens, P. Grivet, Compt. rend., 233, 921-3 (1951). (In French.)

$H = H_0 \operatorname{sech}(z/b)$ describes the axial field of an unsaturated magnetic lens. The differential equation of paraxial rays may be solved in terms of Legendre functions, the order of which is a measure of the lens strength. The order is < 1 if the strength of the lens is not sufficient to produce multiple foci. Expressions are given for the positions of the cardinal points when object and image are outside the strong field, and the case of high magnification is also discussed. Aberration is not considered.

157.

Axially symmetric electron beam and magnetic field systems (Technical Report No. 170), L. A. Harris (Aug. 29, 1950) 78 p. (NP-3106).

The theory of longitudinally uniform and axially symmetric electron beams focused by a uniform axial magnetic field is presented. A general graphical method is described for obtaining the potential

distribution required for the design of hollow beams. The necessity of bringing the beam through a transition region where electrons acquire their angular velocity restricts the problem to two categories in which the cathode is either in a uniform magnetic field or in a magnetically shielded region. Special cases are the solid beam, the hollow beam with uniform radial charge density, the hollow beam between coaxial electrodes at the same potential, and the hollow beam inside an outer electrode only. Of interest is the case of a hollow beam focused with a magnetic field in the cathode region only. Explicit design equations are presented for all cases. The possible effects of incidental ionization are briefly considered. Experimental results confirm the theory qualitatively and to a considerable extent quantitatively, and indicate the importance of the cathode flux condition and the need for a good method of bringing the beam through the transition region.
20 references.

158.

New information on the (paraxial) electron-optical properties of (homogeneous) magnetic (sector) prisms, R. F. K. Herzog, *Acta Phys. Austriaca*, 4, 431-44 (1951). (In German.)

A sector prism is treated as composed of a part bounded by edges perpendicular to the principal ray and of, in general, 2 wedges. For the radial focusing these act as thin lenses (converging or diverging according to the sign of the angle of refraction) whose effect is added to that of the perpendicularly bounded sector. The axial focusing action of the wedges is also calculated - it is claimed, for the first time.^{1,2} The axial focal length of a wedge = -(radial focal length). Some special cases of stigmatic focusing are considered and application to electron microscopy is suggested. Experiments to be described later have confirmed the occurrence of stigmatic focusing.

¹Kelman et al., *J. Exp. Theor. Phys. USSR*, 9, 681-4 (1939).

²Ya. L. Khurgin, ibid., 9, 824 (1939).

159.

The calculation of magnetic lens fields by relaxation methods, M. B. Hesse, *Proc. Phys. Soc. (London)*, B63, 386-401 (1950).

The field and lens constants are calculated for 2 typical magnetic lenses as used in electron microscopes, using the relaxation method developed by Southwell for the solution of potential problems. The results are compared with those based on simple analytic approximations to the field distribution in the work of Glaser and Ramberg, and are shown to agree closely as regards those characteristics on which the discussion of the performance of the lens is based.

160.

The aperture defect in the ion-optical imaging of a point by means of an arbitrarily bounded magnetic field, H. Hintenberger, Z. Naturforsch., 6a, 275-6 (1951). (In German.)

An expression for the aperture defect is given following earlier work.^{1,2}

¹H. Hintenberger, Z. Naturforsch., 3a, 125 (1948).

²H. Hintenberger, Ibid., 3a, 669-70 (1948).

161.

Annular correction of a magnetic lens, P. Hubert, P. Grivet, and J. Seiden, Physica, 18, 1136-8 (1952). (In French.)

A short coaxial coil is placed inside the lens coil, so that the 2 coils have a common mid-plane.¹ Although correction was obtained in practice, the gathering power was low. This is attributed to the use of too small an angle of emission.

¹P. Hubert, Compt. rend., 233, 943-5 (1951).

162.

On the focusing of electrified particles, A. Yu. Ishlinskii[✓], Dokl. Akad. Nauk SSR, 96, 721-4 (1954). (In Russian.)

Given a magnetic field which is everywhere normal to the plane xy and which in that plane is a function of x only, the problem is to determine $H(x)$ such that all particles leaving $x = 0$, $y = 0$ and travelling in the plane with "specific momentum" (H_p) shall arrive at $x = 0$, $y = l$, the y axis itself being included as a ray. It is shown that the required form is $H(x)/(H_p) = (\pi^2/l^2)[x - (\pi^2 x^3/2l^2) + (9\pi^4 x^5/40l^4) \dots]$.

163.

Further improvements in magnetic focusing, L. Kerwin and C. Geoffrion, Rev. Sci. Instr., 20, 381 (1949).

The general theory of magnetic focusing in a plane developed in a previous paper is extended to asymmetric cases. The general asymmetric case being developed, several particular examples are considered, including one which eliminates second-order aberrations, and requires a smaller magnet than the normal design. Methods of minimizing aberrations are discussed.

164.

Improved magnetic focusing of charged particles, L. Kerwin, Rev. Sci. Instr., 20, 36 (1949).

A general theory of geometric magnetic focusing of charged particles is developed. Some special cases are discussed. One proves to be the type of focusing in general use; another, equally simple, eliminates second-order aberrations.

165.

On the influence of quantum fluctuations on the path of electrons in a magnetic field, A. A. Kolomenskii and A. N. Lebedev, Zh. éksper. teor. Fiz., 30, 205-7 (1956). (In Russian.)

Quantum characteristics become important when the energy is greater than about 10^{15} eV, and above this quanta of radiation are emitted. The effect of this on the path of an electron is discussed mathematically.

166.

The image properties of magnetic sector-fields including the fringing field, L. A. König and H. Hintenberger, Z. Naturforsch., 10a, 877-86 (1955). (In German.)

An abbreviated account of a dissertation by L. A. König is given.¹ First, the fringing fields at the boundaries of sector magnets of several types are investigated experimentally. Formulae for magnification, velocity, and direction focusing are given with reference to H. Ewald and H. Hintenberger, Methoden und Anwendungen der Massenspektroskopie, Weinheim/Bergstrasse, Verlag Chemie (1953). The optical properties with fringing fields² are related to those of ideal sector fields and extensive formulae are given. The changes due to the fringing field are calculated for the mass spectrograph of Bainbridge and two other types. They depend strongly on magnet dimensions. For typical magnets of double-focusing spectrographs the exact formulae of the paper differ only by a few % from the calculations done by means of equivalent homogeneous sector fields. This method of accounting for fringing fields leads to much greater errors with other types of magnets.

¹Mainz (1955), D77.

²N. D. Coggeshall, J. Appl. Phys., 18, 855-61 (1947). 487.

167.

The motion of ions in an axial magnetic field of the $H_z = H_1 r^{2s} - H_2 r^{2s+2}$ type, M. I. Korsunskii, Trudy Khar'kov, Politekh. Inst., 14: 103-10 (1958).

The motion of ions in axial magnetic difference-type fields of the $H_z = H_1 r^{2s} - H_2 r^{2s+2}$ type is investigated in order to find magnetic fields with a high dispersion and resolution power. The components H_z and H_r of the difference-type field are determined. Conditions for focusing a diverging ion beam are established. At the focusing spot the beam is decomposed into spectrum with a dispersion exceeding by one order the dispersion in a homogeneous magnetic field. A high degree of dispersion can be obtained for a difference-type field with various values of the s parameter. A difference-type field with parameters $s = 0$ has a minimum aberration for ions moving outside of the plane $z = 0$. Difference-type fields have the property of double focusing in direction (in z and in r). Conditions for double focusing are established. The form of the pole surfaces for obtaining the most significant particular case of the difference-type field ($s = 0$) is determined.

168.

Helical lenses, F. Krienien, CERN-57-28 (July 1, 1957) 8 p.

The helical lens may be used as a high-pass filter with $\omega^2 = |A|$ determining the cutoff momentum; or as a transmission line in which the configuration of particles with a given momentum repeats itself periodically along the line with $\cos \omega_1 T = \cos \omega_2 T = \pm 1$ determining the parameters; and, finally, positive focusing may be obtained, however, with unit magnification under rather strict conditions given by formulae.

169.

Testing of some adjustable permanent-magnet electron lenses, G. Langner, Optik, 12, 554-62 (1955). (In German.)

Methods of regulating the strengths of electron lenses formed from permanent magnets are described. For a condenser lens, the flux in the magnetic circuit is varied by adjusting the width of an air gap. For the individual adjustment of several lenses excited by the same magnet, auxiliary regulating pieces are provided. Lens strengths can thus be varied over a wide range and the same instrument used for microscopy and diffraction. Measurements of typical lenses are given.

170.

Calculation of induction and its derivatives on the axis of a rotationally symmetrical magnetic lens, M. Laudet, *Compt. rend.*, 243, 1855-7 (1956). (In French.)

It is shown that if the axial distribution of the induction in a magnetic electron lens of a particular simple form is known, then, by virtue of the principle of superposition, the distribution for any other form can be simply deduced.

171.

Electron optics of cylindrical systems with a plane of symmetry. I. First order approximation, M. Laudet, *J. phys. radium*, 16, 118-24 (1955). (In French.)

Since the electromagnetic field of cylindrical systems with a plane of symmetry depends only on two variables, the electron trajectories in such cases may be derived using a Lagrangian treatment. Certain simple image-object relationships in a magnetic lens are obtained using first-order approximations.

172.

Method of calculating the flux density and its derivatives on the axis of a magnetic electron lens with axial symmetry, M. Laudet, *J. phys. radium*, 18, Suppl. No. 7, 73A-77A (July 1957). (In French.)

It is shown how it is possible to calculate the values of the flux density B and of its derivatives B' and B'' , on the axis of a magnetic electron lens with rotational symmetry after measuring the flux density with simple matrix products. The numerical values are then given for the "elementary matrices" and the method is applied to the case of a circular current whose mathematical expressions of the flux density and its derivatives are already known. In this way, a precise idea of the accuracy of the results is obtained. Finally, stress is laid on the practical interest of this method which allows measurement of B , B' , and B'' with one search coil having only one winding, the diameter of which is limited only by that of the bore of the pole pieces of the lens used.

173.

Numerical calculation of the induction of a non-rotating magnetic electron lens, M. Laudet, *Compt. rend.*, 241, 1728-30 (1955). (In French.)

The field distribution of a magnetic electron lens, which does not produce rotation of the image, is calculated by an iteration method. Values of the field at various points are shown diagrammatically.

174.

Confinement of charged particles by a magnetic field, B. Lehnert, *Nature*, 181, 331-2 (1958).

Confinement of charged particles by axially symmetrical, stationary magnetic fields and electric fields is discussed. It is shown that if the coil connections are made as small as possible and if the magnetic field, in the neighborhood of the connections, from the supply current predominates over the field from the coil, particles will be reflected and will not be absorbed by the connections. The field from the supply current gives an additional drift in planes through the z axis, but since the connections carry current in opposite radial directions, a cancellation of the drift takes place for particles passing around the z axis repeatedly.

175.

An analytical approximation of axially symmetric potential fields with cylindrical equipotentials, F. Lenz, *Ann. Phys.*, 8, 124-8 (1950). (In German.)

The method, utilizing the zeros of the Bessel function of zero order, is explained, and illustrated by an application to the field distribution near the poles of an electromagnet. The formulae are used, in the case of a weak magnetic lens, to calculate the optical constants.

176.

Calculation of optical constants of magnetic electron lenses from pole-piece dimensions and operating conditions, F. Lenz, *Z. angew. Phys.*, 2, 448-53 (1950). (In German.)

Gives the results of the calculation of such quantities as focal length, depth of focus, and spherical and chromatic aberration, under various conditions. The results on focal length are compared with measurements reported in the literature and the differences discussed.

177.

Calculation of the electron-optical characteristics of a special magnetic lens field without numerical ray tracing, F. Lenz, *Ann. Phys. (Lpz.)*, 9, 245-58 (1951). (In German.)

Same problem and same paraxial solution as in Grivet.¹ Graphs are given of the paraxial properties and of the coefficients of spherical and chromatic aberration, over a wide range of lens strengths; the aberration coefficients refer to high magnification and the first axial intersection.

¹P. Grivet, *Compt. rend.*, 233, 921-3 (1951). 156.

178.

Calculation of the field-distribution along the axis of a magnetic electron lens from pole-piece measurements and total flux, F. Lenz, Optik, 7, 243-53 (1950). (In German.)

In order to calculate the optical properties of electron lenses it is necessary to know the field distribution. This can be obtained approximately from a knowledge of the pole-piece dimensions and the magnetic properties of the pole-piece material when saturated.

179.

Calculation of the optical constants of magnetic electron lenses with a generalized bell-shaped field, F. Lenz, Z. angew. Phys., 2, 337-40 (1950). (In German.)

The experimentally determined axial field is approximated by $H(z) = H_0 \{1 + (z/a)^2\}^{-\mu}$ by fitting the maximum, half the maximum, and the integral

$$\int_{-\infty}^{+\infty} H dz \quad .$$

The optical constants are tabulated for $\mu = 1, 2, \infty$, and $k = 0, 3, 1.0, 1.5, 2, 3$ ($k^2 = eB^2 d^2/8mV$, d = width at half maximum field). The constants given are the focal lengths, focal distance, magnification, chromatic and spherical aberration constants. For earlier work see Glaser.¹

¹W. Glaser, Ann. Phys., Lpz., 7, 213-27 (1950). 148.

180.

A mathematical field model for a permanent magnet "unipotential" electron lens, F. Lenz, Z. angew. Phys., 8, 492-6 (1956). (In German.)

A magnetic analogue of the electrostatic "unipotential" lens is proposed, in permanent magnet form, i.e., a series of three magnetic elements (with or without polepieces) with the central one of opposite polarity to the outer two. The field along the axis can be closely approximated by the expression $B(z) = Cz/(1 + z^4/a^4)$, for which the differential equations of the ray path can be directly solved. The optical constants of the lens have been evaluated in this way and are given in graphical form. The results are applicable also to "rotation-free" lenses that are excited by windings in the usual way.

181.

A simple procedure for determining the field in magnetic electron lenses, F. Lenz, *Optik*, 9, 3-18 (1952). (In German.)

A method of determining the field by means of a probe electron beam is described, with full mathematical details. The objective diaphragm is removed and the voltage for a sharp point focus with a diffuse halo is measured for several values of the lens current. This corresponds with "telescopic" ray paths, i.e., paraxial paths which are parallel at entry are parallel at exit.

182.

Velocity analysis with high resolving power, using a magnetic electron lens, F. Lenz, *Naturwissenschaften*, 38, 524-5 (1951). (In German.)

In this method of making a velocity analysis the cathode is brought closer to the objective lens than one focal length so that a ring focus is obtained. A section of the ring is focused by the decentered projection lens on to the screen. The width of the resulting bright line serves as a measure of velocity range, which is calibrated by injecting an ac voltage on the beam. A resolving power of 5×10^{-5} has been obtained.

183.

The field distribution in asymmetrical magnetic electron lenses, G. Liebmann, *Proc. Phys. Soc. (London)*, B68, 679-81 (1955).

The field distribution of asymmetrical magnetic electron lenses comprising two pole pieces with differing bore radii are plotted. The maximum axial field strength, and hence the refracting power, is shown to increase as the ratio of the bores is made smaller. The asymmetry of the field distribution is shown to be a function of the ratio of the bores only, not depending on their relation to polepiece separation.

184.

Imaging properties of a series of magnetic electron lenses, G. Liebmann and E. M. Grad, *Proc. Phys. Soc. (London)*, B64, 956-71 (1951).

The paraxial lens data and the more important first-order lens aberrations were determined for a series of symmetrical magnetic lenses of equal lens diameter D but variable air gap width S for a wide range of lens excitations. The range of gap widths covered was $S/D = 0.2$ to $S/D = 2$. The field distribution within the lenses was measured to a high degree of accuracy with a resistance network

analogue, and the lens data were then obtained through numerical trajectory tracing. The results, represented as a series of graphs, are representative of the most common magnetic electron lenses. An approximate formula for the focal length is $f \approx 50(DS)^{1/2} V_r / (NI)^2$. A few design examples are discussed.

185.

The magnetic pinhole electron lens, G. Liebmann, Proc. Phys. Soc. (London), B68, 682-5 (1955).

An asymmetrical magnetic electron lens having the bore of one pole piece much smaller than that of the other is considered as the combination of one half of a symmetrical lens with a pinhole lens. It is shown that the pinhole lens does not greatly affect the refracting power of the combination, but that, when it is located on the emergent side of the electron beam, it may make a considerable contribution to the spherical aberration.

186.

A unified representation of magnetic electron lens properties, G. Liebmann, Proc. Phys. Soc. (London), B68, 737-45 (1955).

It is shown that the focal lengths of all known iron-shrouded magnetic electron lenses lie between two fairly close limit-curves, if f is measured in the unit $S + D$ for symmetrical or $S + R_1 + R_2$ for asymmetrical lenses of bore radii R_1 and R_2 and gap length S , f being plotted as function of $(NI)^2 / V_r$. The lenses of the more usual S/D ratios ($0.5 \leq S/D \leq 2$) lie very close to the lower limit-curve, i.e., all these lenses can be represented by a single focal-length curve. A similar representation can be given for the other lens constants.

187.

On the effect of the transition region upon an electron beam constrained by Brillouin flow, B. W. Manley, J. Electronics, 2, 241-6 (1956).

The introductory conditions of an electron beam into an axial magnetic field are derived. Design conditions for a useful range of beam parameters are given.

188.

Electron beam focusing with periodic permanent magnet fields, J. T. Mendel, C. F. Quate, and W. H. Yocom, Proc. Inst. Radio Engrs., 42, 800-10 (1954).

Presents experimental and theoretical results on focusing a long electron beam with a permanent magnet structure which produces

a periodic magnetic field along the axis of the electron beam. In principle, the periodic permanent magnet made up of N cells will be reduced in weight by a factor of N^2 over a permanent magnet producing a uniform field over the same length. The periodic focusing results are comparable to results obtainable with a uniform field. In addition, the periodic fields for certain combinations of beam voltage and magnetic field exhibit regions of "stop bands" in which the beam becomes unstable and no current reaches the collector.

189.

Variable magnetostatic lens systems for electron microscopes, K. Muller, Z. Wiss. Mikr., 63, 303-28 (1957). (In German.)

Various types of permanent magnet systems suitable for electron microscope lenses were investigated in detail. Variation in strength is obtained by use of adjustable gaps and magnetic shunts. The construction of a three-lens and a four-lens electron microscope is described, in which a number of different pole-piece designs were tried out. The best results show a resolution approaching 20 Å, when a stigmator was incorporated.

190.

Notes on the focusing properties of homogeneous magnetic sector fields, R. Persson, Ark. Fys., 3, 455-69 (Paper 24, 1951).

Fields with straight and circular boundaries are considered, using the graphical construction of Cartan.¹ Dispersion, aberration, and the locus of mass foci are derived for symmetrical arrangements, and first- and second-order focusing conditions are given for these and for one asymmetrical case. Resolving power is calculated for systems using one fixed collector, and it is shown that, even in a special case with third-order focusing, the resolving power may decrease appreciably with increasing beam divergence. A mass spectrometer giving second-order focusing is described briefly. It uses 90° deflection with normal incidence, and the ion source may be used with solid or gaseous samples. Scanning is by voltage variation.

¹J. phys. radium, 8, 453 (1937).

191.

Permanent magnet lenses, J. H. Reisner, J. Appl. Phys., 22, 561-5 (1951).

Permanent magnets have been successfully used to energize magnetic-lens pole pieces for high-resolution electron microscopy at direct magnifications of 7,000X with 30-kV electrons, and 6,000X at

50-kV. Stray magnetic fields, which have previously limited high magnification and high resolution, have been minimized by using two circuit gaps in parallel and by surrounding the assembly with a magnetic shield connected to the external pole pieces of the two gaps. Magnetomotive forces of 1,400 gilberts have been obtained. A single magnet, magnets in bucking arrangement, and configurations involving magnets disposed either radially or parallel to the optical axis of the lens have been successfully utilized. The effects of various magnetic circuit parameters on the design and operation of the lens system have been studied.

192.

Two-directional focusing with short uniform magnetic fields,
C. Reuterswärd, Ark Fys., 4, 159-71 (Paper 3, 1951).

The 3-dimensional ion-optic properties of the uniform magnetic fields with boundaries are investigated in the case of ion paths near the plane of symmetry, and the results are given in terms of the dioptrics of ion lenses. The conditions of simultaneous focusing of pencils of rays perpendicular and parallel to the lines of flux are stated in a somewhat specialized class of fields. The second-order aberrations in planes parallel to the plane of symmetry are given. The existence of fields in which these cancel in points of the optic axis is pointed out. The same second-order aberrations due to the fringing fields are calculated to the first approximation.

193.

The electron optics of a magnetic lens of the Glaser type, J. Schlögl, S. B. Öst. Akad. Wiss., Abt. IIa, 157, (No. 6-10) 237-62 (1949). (In German.)

The Glaser lens has a field given by $H(z) = H_0 [1 + (z/a)^2]^{-1}$. The present work treats a generalized case in which $H(z) = H_0 [1 + (z/a)^2]^{-\mu}$, $\mu = 1, 1.5, 2, 2.5, 3$, etc. This leads to a differential equation of Hill type which has been solved by Svartholm¹ by an infinite series. An integral equation solution is given, and the results are found to agree with the earlier ones. The problem of calculating the field required to give specified focal lengths, etc., is then treated as an eigenvalue problem which is solved by the Rayleigh-Ritz method.

¹Ark. Mat. Fys., 28B, 4 (1942).

194.

Strong-focusing lens with cylindrical pole pieces, I. A. Shukeilo, Zh. tekhn. Fiz., 29, 1225-7 (1959). (In Russian.) English translation in Soviet Physics - Technical Physics, 4, 1123-5 (1960).

An estimate is made of the field nonlinearity of lenses in which the pole-piece cross section is defined by an arc which is almost hyperbolic. The arc radii for which the field nonlinearity is a minimum are determined.

195.

Double focusing of charged particles by a system of two magnets with nonuniform fields, R. M. Sternheimer, Rev. Sci. Instr., 24, 573-85 (1953).

Equations are obtained for the focusing by a system of two magnets with nonuniform fields such that $n > 0$ in the first magnet and $n < 0$ in the second. For each magnet a lens equation is set up, and then the system of the two magnets is itself treated as a thick lens. It is shown that for very large n there is in general one object distance for which double focusing takes place. The theory is also applied to deflecting systems with moderate values of n , and it is shown that the entrance and exit angles can be reduced to values of the order of 20° even for small deflections (20°) of the charged particle.

196.

Double focusing of charged particles with a wedge-shaped, non-uniform magnetic field, R. Sternheimer, BNL-1177,¹ 24 p.

The pole faces of a wedge-shaped magnet can be shaped so as to reduce the image distance for simultaneous horizontal and vertical focusing, and thereby increase the intensity at the image. The field inside the magnet is assumed to behave as r^{-n} , where r is the distance from the center of curvature of the normal path and n is a constant parameter. Equations are obtained for the image distance for double focusing, and the results of calculations for several representative cases are shown. It is shown that by appropriate choice of the non-uniform field, the image distance can be appreciably reduced in all cases of interest.

¹Also in: Rev. Sci. Instr., 23, 629 (1952).

197.

Note on the focusing of electron beams in certain magnetic fields,
P. A. Sturrock, Proc. Phys. Soc. (London), B63, 954-7 (1950).

Equations are set out which determine the focusing properties of electron beams in magnetic fields whose scalar potential has a plane of antisymmetry. From these is derived the condition that a proposed ray-axis and associated focusing requirements should be physically realizable. It is also shown that the fringe effect of fields with sharply defined boundaries may be characterized by a pair of focal lengths for which formulae are given.

198.

Optical properties of axially symmetric magnetic fields of the forms
(on the optic axis): $H = H_0/[1 - (z/a)^2]$ and $H = H_0/[(z/a)^2 - 1]$,
P. Sturrock, Compt. rend., 233, 401-3 (1951). (In French.)

Glaser's formulae for $H = H_0/[1 + (z/a)^2]$ are transformed to the present cases, the first of which may be applied to the Siegbahn, Slätis β -spectrograph¹ and the second to an electron microscope objective.

¹H. Slätis and K. Siegbahn, Ark. Fys., 1, Paper 17, 339-57 (1949).

199.

Calculation of the ion optical properties of inhomogeneous magnetic sector fields, including the second order aberrations in the median plane, H. A. Tasman and A. J. H. Boerboom, Z. Naturforsch., 14a, 121-9 (1959).

Investigation is made of the ion-optical properties of inhomogeneous magnetic sector fields. In first-order approximation the field is assumed to vary proportional to r^{-n} ($0 \leq n < 1$); the term in the magnetic field expansion which determines the second-order aberrations is chosen independent of n , which makes possible the elimination of the second-order angular aberration. From the Euler-Lagrange equations, the second-order approximation of the ion trajectories in the median plane and the first-order approximation outside the median plane are derived for the case of normal incidence and exit of the central path in the sector field. An equation is presented giving the shape of the pole faces required to produce the desired field. The influence of stray fields is neglected. The object and image distances are derived, as well as the mass dispersion, the angular, lateral, and axial magnifications, the resolving power, and the inclination of the plane of focus of the mass spectrum. The maximum transmitted angle

in the z-direction is calculated. The resolving power proves to be proportional to $(1-n)^{-1}$, whereas the length of the central path is proportional to $(1-n)^{-1/2}$. An actual example is given of a 180° sector field with $N = 0.91$, where the mass resolving power is increased by a factor of 11 as compared with a homogeneous sector field of the same radius and slit widths.

200.

Calculation of the ion optical properties of inhomogeneous magnetic sector fields, II. The second order aberrations outside the median plane, H. Wachsmuth, A. J. H. Boerboom, and H. A. Tasman, Z. Naturforsch., 14a, 818-22 (1959).

The second-order aberrations are calculated outside the median plane referring to focusing in the radial direction. The influence of fringing fields is neglected, and the field boundaries are supposed to be plane and normal to the main path at the point where it enters and leaves the field.

201.

Calculation of the ion optical properties of inhomogeneous magnetic sector fields, part 3: oblique incidence and exit at curved boundaries, H. A. Tasman, A. J. H. Boerboom, and H. Wachsmuth, Z. Naturforsch., 14A, 822-7 (1959).

Previous calculations are extended to include the effect of oblique incidence and exit at curved boundaries. The influence of the fringing fields on axial focusing when the boundaries are oblique is accounted for. It is shown that the second-order angular aberration may be eliminated by appropriate curvature of the boundaries.

202.

Calculation of the ion optical properties of inhomogeneous magnetic sector fields: Note on the trajectories outside the median plane with oblique incidence, and on the second order angular aberration coefficient, H. A. Tasman, A. J. Boerboom, and H. Wachsmuth, Z. Naturforsch., 15, 78-9 (1960).

203.

"Non-optical" theory of focusing in axially symmetric magnetic fields, I. I. Tsukkerman, Zh. Tekh. Fiz., 22, 1843-7 (1952). (In Russian.)

Refers chiefly to the image-converter type of system, with mixed electric and magnetic fields. It is indicated how, given $V(z)$, and

also $r(z)$, for rays non-skew at the cathode, the necessary $H(z)$ can be determined to satisfy the condition that an image of the cathode is formed in the plane $z = z_1$. The conclusions of ¹ are accepted, but are said to have been essentially contained in ².

¹D. L. Klaminskii^v and V. M. Kelman, Zh. Tech. Fiz., 22, 703-8 (1952).

²I. I. Tsukkerman, Letter in J. Tech. Phys. USSR, 21, 599-601 (1961).

204.

On some antisymmetrical magnetic fields with double focusing,
Yu. V. Vandakurov, Zhur. Tekh. Fiz., 25, 2545-55 (1955). (In Russian.)

Equations were obtained for antisymmetrical fields with symmetrical rotation, producing double focusing of charged-particle paraxial beams. The field character depends on the direction and initial radius of the beam axis trajectory which lies in the middle of the field plane. Calculations were made of focal points, magnification, dispersion, and aberration for some values of these parameters. The possibility of realizing double focusing in antisymmetrical fields, independent from a single Descartes coordinate, was investigated.

205.

Some antisymmetrical magnetic fields with double focusing. II.,
Yu. V. Vandakurov, Zh. tekhn. Fiz., 26, 1599-610 (1956). (In Russian.)

The preceding abstract, 204, discusses the focusing properties of the antisymmetrical magnetic fields with rotation symmetry for the case when the basic trajectory of the beam, positioned in the median plane of the field, is, at its initial point, perpendicular to the radius. Fields with double focusing are studied in which several intermediate images, obtained as a result of focusing in only one (horizontal or vertical) direction, are found between the source and the final image. It is shown that in some fields of this type the dispersion is strong and that no aberration of the second order, which depends on the angle of the beam in the median plane, is found.

206.

An investigation of axially symmetric magnetic fields for focusing a three-dimensional beam with a spiraling central trajectory of slowly changing radius, Yu. V. Vandakurov, Zh. Tekh. Fiz., 27, 1319-29 (1957). (In Russian.) English translation in: Soviet Physics - Technical Physics, 2, 1217-28 (1957).

Axially symmetric magnetic fields with a median plane (with the plane of symmetry between the pole pieces) are studied, whose shape is

determined by the requirement of focusing of a wide, flat beam with noncircular central trajectory. It is shown that for a nearly circular central curve the field distribution can be such that the aberrations which depend on the angle of spread in the median plane will be small compared with other aberrations. In these fields it is possible to focus a beam at a large angle. With increased focusing angle the dispersion increases as its square, whereas the aberration, which depends on the width of the source and the initial angle between the trajectory and the median plane, changes little. At some angles, two-directional focusing occurs. Thus the fields under investigation here can be used to construct spectrometers of large resolving power and quite high luminosity.

207.

Focal properties and resolving power of magnetic fields defined by parallel planes, R. Vauthier, *Compt. rend.*, 229, 181-3 (1949). (In French.)

The theory is developed, and it is shown that such a device should have practical applications in mass spectrographs, especially those used for abundance measurements.

208.

Convergence of magnetic sectors with shaped edges, M. Vivargent, *J. phys. radium*, 18, 537-8 (1957). (In French.)

The particle-converging properties of magnetic sectors with shaped edges, earlier obtained for the very general case, are listed in a simplified notation conveniently applicable to practical cases.

209.

Predetermination of magnetostatic electron optical imaging systems, B. von Borries and F. Lenz, *Optik*, 13, 264-76 (1956). (In German.)

A study has been made of magnetic lenses for the electron microscope in which a permanent magnet provides the excitation. The problem is to design the magnetic circuit for maximum refractive power in the lens, but using a minimum amount of permanent magnetic material. The calculations are illustrated by practical examples of successful permanent magnet lenses. An arrangement is described for varying the strength of such a lens by means of a mechanically operated soft iron shunt.

See also: 1, 2, 9, 10, 11, 21, 23, 27, 31, 32, 34, 35, 38, 42, 45, 49, 53, 56, 81, 82, 93, 95, 101, 121, 372, 406, 479, 480, 484, 491, 492, 496, 497, 498, 500, 504, 506, 507, 509, 511, 512, 513, 514, 518, 523, 528, 529, 530, 535, 540.

ELECTRON LENSES - ELECTROMAGNETIC SYSTEMS QUADRUPOLES

210.

The quadrupole magnet as a focusing device, R. N. Carlile, HEPL-33 (Stanford Univ.)

211.

On plasma compression in a magnetic quadrupole field, J. Christiansen, Z. Naturforsch., 13a, 951-61 (1958). (In German.)

The conditions in which charged particles are "compressed" along the axis of a stationary magnetic quadrupole field were studied. The ion paths were investigated, using hf excitation of the plasma, and approximate results obtained for the equilibrium density distribution of ions. A simple relation was found among apparent plasma column diameter, the central gas temperature, and the magnetic flux density at the magnet surface. The theoretical results agree reasonably well with practice for weakly ionized gases.

212.

A network analogue for a quadrupole lens system, C. F. Coleman, Nuclear Instruments and Methods, 14, 53-62 (1961).

An analogue model for a system of quadrupole lenses is described. If such a lens system has two planes of symmetry through its axis, the action of the system on displacements from these two planes is equivalent to that of two corresponding sets of cylindrical lenses. In the model these cylindrical lenses and the intervening distances are represented by successive parallel and series impedors in an ac network. From the model, direct information can be obtained on those transformations of elliptical phase-space boundaries which are used to describe the transport of particle beams through lens systems. It can be used to investigate the restrictions which slits within the system impose on the available phase space at the input, and leads to a particularly straightforward method for finding a system which will accept a beam with given characteristics and produce an output with waists at specified positions.

213.

The measurement of two-dimensional fields. Part II: Study of a quadrupole magnet, I. E. Dayton, F. C. Shoemaker, and R. F. Mozley, Rev. Sci. Instr., 25, 485-489 (1954).

The characteristics of a dc quadrupole magnet have been measured using some of the techniques for measuring two-dimensional

fields and gradients proposed by W. C. Elmore and M. W. Garrett [Rev. Sci. Instr., 25, 480 (1954)].* Saturation curves and measurements of the flux distribution in the magnet are presented. The characteristics of the magnet have been determined both in the interior and in the fringing region at each end. It is shown that by using a pole tip of circular cross section and correctly chosen radius it is possible to produce a magnetic field with gradient constant to ± 1 percent out to 0.8 of the radius of the gap.

*139.

214.

An optical system of rotational symmetry convergence, D. Dhuicq and A. Septier, Compt. rend., 249, 2031-3 (1959). (In French.)

Two crossed-quadrupole lenses can be made to act as a single strong lens of rotational symmetry, but the focal points are inaccessible. By combining two such systems it might be hoped that the focal point could be made to fall outside the lens system without loss of strength. Such a lens could be used as an objective in an electron microscope. Unfortunately, under the special conditions chosen for this calculation it turns out that an external focus is not possible.

215.

Ion focusing properties of a quadrupole lens pair, H. A. Enge, Rev. Sci. Instr., 30, 248-251 (1959).

The focusing properties of a quadrupole lens pair have been studied, and the results of thick-lens calculations are presented in the form of graphs showing the field-strength parameters and magnifications as functions of object and image distances.

216.

Ion-focusing properties of a three-element quadrupole lens system, H. A. Enge, Rev. Sci. Instr., 32, 662-6 (1961).

Results of thick-lens calculations are presented in the form of graphs showing the field-strength parameters and magnifications, as functions of object and image distances.

217.

The use of a 4-pole magnetic lens to reduce the "distortion" of the image in reflection electron microscopy, C. Fert and R. Saporte, Compt. rend., 243, 1107-10 (1956). (In French.)

In a previous paper,¹ a sphero-cylindrical electrostatic lens was described which corrected the characteristic "distortion" that

occurs in reflection microscopy. The same correction can be made more conveniently with a four-pole magnetic lens placed after the projector lens. Design data are given and an example of its use in reflection microscopy described.

¹C. Fert and B. Marty, Compt. rend., 241, 1454-6 (1955).

218.

L'Evolution des polygones et des ellipses d'acceptance le long d'un canal de lentilles magnetiques quadrupolaires. Rapport interne No. 611
(The evolution of the polygons and ellipses of acceptance along magnetic quadrupole lens channels. Internal Report No. 611), Jean Fronteau (April 1961) 20 p. (NP-10774).

Surfaces of acceptance are defined in general terms followed by definitions for polygons and ellipses. Each case is then treated separately using the program "GAUUA ET" BULL.

219.

Magnetic quadrupole with rectangular aperture, L. N. Hand and W. K. H. Panofsky, Bull. Am. Phys. Soc., 3, 421 (1958).

A magnetic quadrupole lens has been designed and is being built which defines the desired field shape by a current distribution on the inside faces of a rectangular box; the current emerges on one set of opposite faces and returns along the other set. The motive for such a design is the need for a quadrupole lens in a strong-focusing system where the radial excursion in the focusing plane generally greatly exceeds the excursion in the defocusing plane. The particular design of 40-in. length employs an aperture of 23 x 4 in. at a gradient of 400 gauss/in. This quadrupole in combination with a conventional 6 x 6-in. quadrupole and a bending magnet constitutes a 1-Bev/c magnetic spectrometer of 0.013-sterad aperture and a target-to-focus distance of 20 ft. It is intended to correct the aberration of the quadrupole by differential shunting of the windings.

(The above constitutes the report in its entirety.)

220.

On the expansion of the quadrupole lens, H. Hultschig, DESY-A2.73 (Dec. 20, 1960) 12 p.

Three lens shapes derived from the Panofsky lens, which yield theoretically an exact quadrupole field, permit a rectangular cross section, and are comparable costwise with the classical lens, are examined. All these lenses are linear.

221.

On the development of quadrupole lens. Part II, H. Hultschig,
DESY-A-2.76 (Apr. 20, 1961) 11 p.

The quadrupole lens discussed in Part I, 220, required too large a power consumption. In the present article a quadrupole lens with increased coil cross section and rectangular coil shape is considered. The lenses discussed are symmetrical. A quadrant of the quadrupole lens with coil corrector and a 200-mm coil is shown. The profile was measured in the analog model, and the potential lines show a quadrupole field within the measurement accuracy of 5%.

222.

Effects of current fluctuations in quadrupole doublet systems,
P. Kalmus, Argonne National Laboratory Internal Report PK-4
(June 7, 1961). 10 p.

Calculations show that image blurring arising from current fluctuations in quadrupole lenses can be minimized by connecting the elements of a doublet in series.

223.

Use of rectangular quadrupoles in doublet systems, P. Kalmus,
Argonne National Laboratory Internal Report PK-2 (Feb. 15, 1961).
10 p.

Using thin-lens optics, relations between the required apertures of quadrupoles in a doublet are derived under certain specified conditions.

224.

A large bore quadrupole magnet for low momentum particles,
S. Marcowitz, Argonne National Laboratory Internal Report SM-3
(Apr 7, 1961). 4 p.

Describes a 36-in. long, 24-in. aperture (2a) quadrupole.

225.

The imaging properties of crossed magnetic quadrupoles, E. Reisman,
PhD. Thesis, Cornell University, 1957. (University Microfilms.
Pub. No. 24,773).

226.

Optical properties of a helical magnetic quadrupole (lens), G. Sacerdoti, Elettrotecnica, 47, 322-8 (May 10, 1960). (In Italian.)

Describes a device for focusing beams of charged particles. The lens consists of a four-pole magnetic yoke, carrying energizing coils, whose pole faces are curved helically around the axis of the lens. The theory of the device is given, together with a sketch of the suggested construction.

227.

An A. G. Channel with four quadrupole magnets, H. Schneider, Nuclear Instr., 1, 268-273 (1957).

The known formalism of transformation matrices for the path of a charged particle in a magnetic quadrupole field is used to deduce the formulae for focus, image, and object distances for a single magnet and solid angles for a system. The magnets are treated as lenses and a focusing system is constructed. From the paths in this system, conditions for the magnetic fields are found, and these conditions are shown to correspond to a simple set of equations, which are solved graphically. The usefulness of this method was checked in an experimental setup with monochromatic electrons from an electron gun. The caustic was measured, and the working conditions were found to be in agreement with the calculations. The approximations made in calculation and experiment are discussed.

228.

Constant gradient iron-less quadrupolar lenses, A. Septier, Nuclear Instr. and Methods, 7, 217-18 (May 1960). (In French.)

229.

Construction of quadrupolar magnetic lenses without iron, A. Septier and G. Chartier, Compt. rend., 249, 64-6 (1959). (In French.)

Magnetic field distributions with quadrupolar symmetry due to linear currents or surface currents were studied. This solution leads to a satisfying approximation of the ideal distribution with constant radial gradient and permits consideration of strong-focusing lenses without iron.

230.

Les Lentilles Magnetiques Quadrupolaires Sans Fer: Realisation de Repartitions D'Induction a Gradient Constant. (Quadrupolar Magnetic Lenses without Iron: Construction of Induction Sectors with Constant Gradient.), A. Septier, CERN 60-6 (Mar. 10, 1960) 47 p.

The usefulness of magnetic lenses with strong convergence without iron cores for magnetic-induction sectors with constant radial gradient is pointed out, and an investigation is made of the possibilities. To simplify the energization problems, the field created by systems of conductors with uniform current density is considered. The expressions for the potential and for the field of systems with quadrupolar symmetry are given, and a study made of the approximations more and more nearly obtained in a larger and larger space surrounding the axis, using 4 wires, then 4 levels of current, and finally 4 thick coils of rectangular cross section. The conductors are supposed to be indefinite according to an Oz axis, which leads to induction sectors with only two dimensions.

231.

Magnetic quadrupole lenses without iron. Producing a constant gradient induction distribution, A. Septier, J. phys. radium, 21, Suppl. No. 3, 1A-15A (March 1960). (In French.)

Recalls the general properties of the fields in a system with quadrupolar symmetry and gives expressions for the magnetic field and its radial gradient, in a system consisting of four current sheets, or four thick coils without iron. By properly choosing the transversal dimensions of the coils, it is possible to obtain for the gradient, in the whole space around the axis, a flatness which is better than 10^{-2} . From this point of view, strong-focusing lenses without iron are better than quadrupole lenses of classical design.

232.

Optical properties of a doublet formed by two strong focusing magnetic lenses, A. Septier, Compt. rend., 246, 1835-8 (1958). (In French.)

Two crossed quadrupole lenses can be arranged to simulate the properties of a rotationally symmetrical lens. Theoretical and experimental results are presented in support of this. Simple formulae for focal lengths are provided.

233.

Practical realization of a quadrupole magnetic lens for high-energy particles, A. Septier, Compt. rend., 243, 132-5 (1956). (In French.)

A magnetic quadrupole lens is formed from four pole pieces having rounded tips so designed as to approximate the hyperbolic cross section demanded by theory. Measurements by search coil (presented graphically) show that the theoretical distribution of the transverse field is closely approached.

234.

Study of the effective focal length of a 4-pole magnetic lens and the variations in the gap, A. Septier, Compt. rend., 243, 1297-300 (1956). (In French.)

From measurements of the field and field gradient in certain quadrupolar magnetic electron lenses the "effective lengths" along various lines parallel to the axis are determined. It is shown that these correspond to negative spherical aberration.

235.

Study of the stray fields of a 4-pole magnetic lens, A. Septier, Compt. rend., 243, 1026-9 (1956). (In French.)

The field distribution of a quadrupolar magnetic electron-lens near its ends is examined. Within distances from the ends roughly equal to half the separation of opposite pole pieces considerable variations are shown to occur. It is deduced that for favorable operation electrons should be kept well away from the magnetic material.

236.

Use of a strong focusing doublet in electron microscopy, A. Septier, Compt. rend., 246, 1983-5 (1958). (In French.)

Two properly excited neighboring quadrupole lenses are shown to be equivalent to a rotationally symmetric lens capable of being used for projection. Photographs taken in an electron microscope using such a system are presented.

237.

A quadrupole magnet with non-circular aperture and linearized end fringing field, K. G. Steffen, Desy-Notiz A 2.81 (Aug. 14, 1961). 19 p.

A new type of quadrupole magnet cross section is suggested and compared with the standard circular aperture. It is shown that a significant improvement of acceptance in phase-space is gained by this

design. Formulae for the acceptance per unit cost are given for the two quadrupole types. A general investigation of the acceptance of a long periodic strong-focusing channel is used as an approach to optimizing standard quadrupole parameters. Special end field configurations are suggested for quadrupole and for bending magnets. They eliminate to a large extent the nonlinear aberrations which are generally caused by the fringe fields.

238.

Short quadrupole magnetic lenses, I. I. Tsukkerman, Zh. Tekh. Fiz., 28, 1809-12 (1958). (In Russian.)

Expressions for the focal lengths and magnifications of short quadrupole magnetic electron lenses are given, and applications to focusing in cathode-ray tubes are described.

239.

On the design of quadrupole focusing systems, W. Weidemann, Nuclear Instr. and Methods, 9, 347-353 (1960).

The theory necessary for the design of a quadrupole focusing system is set out, followed by a practical design example and the conclusions that can be drawn from the results.

See also: 20, 118, 347, 387, 444, 455.

ELECTRON LENSES - ELECTROSTATIC SYSTEMS

240.

Construction and calibration of a cylindrical electrostatic analyzer, S. K. Allison et al., Rev. Sci. Instr., 20, 735-44 (1949).

A cylindrical electrostatic deflector has been constructed with average radius 15 cm, spacing 0.5 cm, and deflection 90° , in which the deflecting potential can be in the neighborhood of 50 kV. Thus protons up to 0.75 MeV can be focused. Movable slits have been incorporated in the design, and the geometry of the entrance and exit apertures of the deflecting channel is such that the stray field may be calculated analytically. This has been done for the case in which the deflecting plates are symmetrically charged above and below zero potential. The predictions have been compared with experiments on the focusing of electron beams by the instrument under controlled conditions. Agreement with the calculations is demonstrated within the accuracy of the experiments, which is about 0.3%. Experiments with asymmetric charging of the electrodes are reported and shown to agree with a

plausible extension of the theory. Further experiments investigated the effect of small displacements of the slits from the computed focal positions. A set of factors, or calibration constants, has been measured so that, given the co-ordinates of the centres of the entrance and exit slits, and the potentials applied to the deflecting plates, the kinetic energy of the focused ion beam, as it left its source at zero potential, can be calculated to within 0.3%.

241.

An unconventional electron lens, G. D. Archard, Proc. Phys. Soc. (London), 72, 135-7 (1958).

An electrostatic lens system is described which is free from primary spherical aberration. The required field distribution is obtained from four nonrotationally symmetric elements. These elements contain either four or eight electrodes. The proposed arrangement is simpler to construct than the one first proposed by Scherzer [Optik, 2, 114 (1947)].

242.

Potential distribution of symmetrical cylindrical electron lenses, G. D. Archard, Brit. J. Appl. Phys., 5, 179-81 (May 1954).

Expressions are developed for the distribution of axial potential and potential derivatives in the two-dimensional "unipotential" electron lens. Comparison is made with expressions obtained in simpler cases, and an example is illustrated.

243.

Some properties of symmetrical slit ("cylindrical") electron lenses, G. D. Archard, Brit. J. Appl. Phys., 5, 395-9 (Nov 1954).

The focal lengths of a series of symmetrical slit electrostatic lenses are determined as a function of aperture size and applied potential. It is shown that all practical lenses may be represented on a single curve by means of a parameter simply related to potential and geometry. It is deduced that lens strength depends more on the size of the central aperture than on that of the outer apertures.

244.

Ueber die relativistische Elektronenoptik elektrostatischer Beschleuniger, E. B. Bas, L. Preuss, and W. Schneider, Z. angew. Mathematik u. Physik, 10, 533-44 (1959).

Relativistic electron optics of electrostatic accelerator; relativistic and nonrelativistic data for coaxial 2-cylinder, electrostatic

electron-lens are compared; values of potential along axis were measured on resistance analog network, while trajectories were calculated on high speed digital computer; significant optical quantities have been calculated.

245.

The axial potential in gridded lenses, M. Bernard, Compt. rend., 233, 298-9 (1951). (In French.)

An analytic expression for the potential in a lens consisting of two symmetrical electrodes at ϕ_1 , separated by a planar grid at ϕ_0 . This is:

$$\phi = \phi_0 \{1 + [2(\sigma - 1)G(d, z)/\pi d]\} \quad ,$$

where

$$G(d, z) = 0.587 \log \{[\cosh 1.315 (\chi + d)]/[\cosh 1.315 (\chi - d)]\} \quad ,$$

$\sigma = \phi_1/\phi_0$ and $2d$ = distance between planes. The holes in the planes are circular, equal, and of unit radius.

246.

On certain formulae in electron optics, M. Bernard, J. phys. radium, 12, 761-2 (1951). (In French.)

An electrostatic lens is treated as a system of refracting surfaces, whose curvature is that of the equipotential surfaces; hence integral expressions are obtained for the focal length.

247.

Electron lenses useful for particles of high energy. Calculation of trajectories, M. Y. Bernard, Compt. rend., 236, 902-4 (1953)(In French.)

Calculates the trajectories of high-energy particles in the lenses described [Compt. rend., 236, 185 (1953)]. The converging power is greater than for other types of lens with the same potentials.

248.

Electrostatic lenses for focusing particles of very high energy, Field distribution, M. Y. Bernard, Compt. rend., 236, 185-7 (1953)(In French.)

Describes theoretical work on lenses which are the electrostatic analogue of the magnetic lenses described by Courant [Phys. Rev., 88, 1190 (1952)]. This note derives expression for the field in one unit and in a lens made up from two units separated by earthed screens.

249.

The focusing of high-energy particles by grid lenses. I. The strength of grid lenses. II. Lens aberrations, M. Y. Bernard, J. phys. radium, 14, 381-94; 451-8 (1953). (In French.)

In Pt. I, the strengths of various forms of electrostatic grid lenses is calculated from analytic field distributions. It is shown that the lens strength is appreciably greater than any conventional lens, particularly when the excitation voltage is a small fraction of the total particle energy.

Pt. II discusses the effect of the grid apertures on the image. It is shown that the resulting disk of confusion is smaller than the grid holes.

250.

Focusing of high energy particles by the grating lens. I. The convergence of the grating lens, M. Y. Bernard, J. phys. radium, 14, 381-94 (1953). (In French.)

The properties of an electrostatic lens designed to focus particles of high energy are studied by using a source having a potential much lower than the acceleration potential. This setup, in which one of the electrodes is made from a metallic membrane permeable by the particles, is useful in linear ion accelerators to overcome the defocusing effect of the high-frequency fields.

251.

Focusing of high energy particles by the grating lens. II. Defects of the lens, M. Y. Bernard, J. phys. radium, 14, 451-8 (1953). (In French.)

The defects caused by the presence of a grating are discussed. It is impossible to obtain a lens with a continuous membrane. It is necessary to replace it by a grating with apertures as fine as possible. It is shown that the defects which result are not as important as they first appear and do not make the use of these lenses impossible as a focusing device.

252.

Gaussian elements of gridded lenses, M. Bernard, Compt. rend., 233, 1354-6 (1951). (In French.)

The expressions for the axial potential developed earlier¹ are used to deduce the Gaussian optical formulae, using an approximation due to Glaser for the function $T = \phi'/\phi$. The theory agrees well with experiments by Knoll and Weichard.

¹M. Bernard, Compt. rend., 233, 298-9 (1951). 245.

253.

On a potential model useful in the study of the three electrode lens,
M. Bernard, Compt rend., 233, 1438-40 (1951). (In French.)

In a bell-shaped field, very simple expressions for the focal length and image plane are derived, which give results in good agreement with the more accurate expressions due to Regenstreif.¹ Two coefficients only have to be deduced from a curve giving the axial potential variation.

¹Ann. Radioelectricite, 23, 51-83 (1951). 313.

254.

Field asymmetry in electrostatic lenses due to the high tension lead,
F. Bertein, Compt. rend., 229, 291-3 (1949). (In French.)

A calculation is made, in which the effect of the axial apertures and the part of the connection inside the lens is neglected. Perceptible effects can be produced for practical values of beam aperture.

255.

On a method of approximation for the strongly curved trajectories of highly convergent lenses, F. Bertein, J. phys. radium, 13, 309 (1952). (In French.)

The polynomial representation of ¹ is unsuitable in this case. A suitable approximate functional form is therefore obtained, the polynomial terms being retained to represent corrections to it. As an example, an electrostatic field which is an even function of z is considered.

¹F. Bertein, J. phys. radium, 13, 41A-49A (Feb Suppl. 1952). 481.

256.

On certain methods of determining the field at the axis in electron optics, F. Bertein, Compt. rend., 234, 417-19 (1952). (In French.)

Discusses results which may be obtained by developing the potential due to each individual electrode in a series of Legendre polynomials and superposing these potentials to obtain the overall result. A system of coaxial cylinders is used as an example.

257.

On the correspondence between electron lenses and electric quadripoles, F. Bertein, Compt. rend., 236, 2047-9 (1953). (In French.)

Further discusses the analogy between electron lenses and electric artificial lines.¹

¹See also A. Hampikian, Compt. rend., 236, 1864-6 (1953).

258.

On the general properties of weak electron lenses: the first approximation, F. Bertein, J. phys. radium, 12, 595-601 (1951). (In French.)

If the electrostatic field on either side of a defining aperture is different, there will be a focusing action which it is evidently necessary to know over the whole aperture. The lens is treated as perfectly thin. Its mean convergence is defined as the relative reduction in cross-sectional area of a beam on passing through it. This is shown to be the difference of field on each side and, to the approximation considered, to be uniform all over the aperture. Several simple cases are discussed, including an astigmatic corrector of zero mean convergence. To the same approximation, all weak, thin magnetic lenses (i.e., field discontinuities) have zero mean convergence.

259.

On the representation of optical or electron lenses by pure resistance quadripoles, F. Bertein, Compt. rend., 236, 2494-6 (1953). (In French.)

The similarity between the paraxial ray equation for an electron in an electrostatic field of axial symmetry, and the differential equation describing the potential distribution in a chain of series and parallel connected resistors, suggests a resistor-network method for solving the electron trajectories. A difficulty arises because of dissimilarity in sign between the equations. A method of avoiding this by a transformation of variables is outlined.

260.

(Theoretical) studies of weak electrostatic lenses: the second approximation, F. Bertein, J. phys. radium, 12, 25A-31A (Oct 1951). (In French.)

The method presented previously¹ of calculating electron trajectories is placed on a more rigorous and general basis, and is extended by including in the equations higher order derivatives of the potential. The results are expressed in terms of the differences between the positions and slopes of the extrapolated asymptotic trajectories

at the plane of the lens. The method is applicable to two-dimensional and axially symmetrical lenses; calculations of the aberrations of non-axial trajectories in these two types of lens are given.

¹F. Bertein, J. phys. radium, 12, 595-601 (1951). 258.

261.

Use of marginal rays for the study of asymmetry in electrostatic lenses, F. Bertein and E. Regenstreif, Compt. rend., 228, 1854-6 (1949). (In French.)

262.

A modified ion slit lens for virtual variation of slit widths, A. J. H. Boerboom, Z. Naturforsch., 15, 350-5 (1960).

It is shown that a slit lens system can be greatly improved by introducing a potential on one of the electrodes, which previously was at zero potential. The focusing at the collector is unaltered within optical aberrations of the third order, and the range of adjustment is increased as compared with the original system. Experimentally, it was found that the virtual collector slit width could be adjusted from 1 mm down to 0.15 mm, maintaining a fair peak shape.

263.

Numerical calculation of the potential distribution in ion slit lens systems. I., A. J. Boerboom, Z. Naturforsch., 14a, 809-16 (1959).

The potential distribution is calculated in an ion lens, consisting of three parallel collinear slits in three parallel electrodes. The slit system is supposed to be infinite in the direction of the slits, so the problem becomes two-dimensional in a plane perpendicular on the direction of the slits. In this plane the potential distribution is calculated by the method of conformal transformation. The Schwarz-Christoffel transformation is used to map conformally the region between the projections of the electrodes of the slit system. It proves to be very simple to perform this transformation. Formulae are given for the case of an ion lens consisting of slits in three parallel plates. A series expansion and an iteration method are developed to find the necessary parameters. Both methods prove to be satisfactory if the slit widths are smaller than the distance to the neighboring electrodes. Symmetrical lenses, not satisfying this condition, will be treated in a second paper. In a third paper, slit system will be treated with an arbitrary number of electrodes. In the transformed region Laplace's equation is solved, having as boundary conditions the potentials on the electrodes. In this way the exact potential distribution in the lens system is found. In a typical example the potential distributions are calculated along the axis for several potentials on the electrodes, together with the corresponding fields.

264.

Numerical calculation of the potential distribution in ion slit lens systems. II., A. J. H. Boerboom, Z. Naturforsch., 15a, 244-52 (1960).

For Part I see Z. Naturforsch., 14a, 809-16 (1959). The potential distribution is computed in certain ion slit lens systems, consisting of three parallel slits in three parallel electrodes. In Part I, the case was treated where the slit widths were smaller than the distances to the neighboring electrodes. In the present paper, this requirement is relaxed; for the sake of simplicity, however, the computations are confined to the case where the central electrode represents a plane of symmetry. Various approximation and iteration methods are given to find the necessary parameters to perform the Schwarz-Christoffel transformation. Several typical examples are given.

265.

Numerical calculation of the potential distribution in ion slit lens systems. III., A. J. H. Boerboom, Z. Naturforsch., 15a, 253-9 (1960).

The computing methods are generalized to slit systems of an arbitrary number of electrodes, the only restrictions being that slits broader than the distances to neighboring slits are separated by slits narrower than the respective distances, and that a pair of electrodes with a mutual distance smaller than their slit widths are separated from the neighboring slits by distances greater than the respective slit widths. For slit systems satisfying this condition, the parameters are computed which are necessary to perform the Schwarz-Christoffel transformation. Formulae are given to compute the potential distribution and field strength. In a typical example the potential distribution and field strength are computed in the region around two parallel electrodes with slits broad compared with the distance between the electrodes.

266.

On the electrostatic lens, H. Bruck and P. Grivet, Rev. optique, 29, 164-70 (1950). (In French.)

The lens was studied by measuring the axial field in an inclined trough. The lens properties were found as a function of the diameter of the central hole and the thickness of the centre electrode. The resolution is discussed and a qualitative description of the effects of eccentricity of the central hole given.

267.

Electrostatic strong-focusing lens, M. L. Bullock, Am. J. Phys., 23, 264-268 (1955).

The basic principles of an electrostatic strong-focusing lens are described in order to illustrate a modern application of several classical concepts. The motion of an ion in the electrostatic field is described in terms of optical analogies to thick lenses. The astigmatism of such lenses is discussed, and the two-section lens designed for use with the Naval Research Laboratory 5-Mev Van de Graaff proton beam is described.

268.

Correction of electrostatic lenses by departure from rotational symmetry, J. C. Burfoot, Proc. Phys. Soc. (London), B66, 775-92 (1953).

It is known that departures from rotational symmetry may offer correction possibilities for certain aberrations which limit the resolving power of present-day electron microscopes. The geometrical optics of such departures in electrostatic systems and the general correction condition are investigated. The minimum number of design parameters is taken, in order to ensure a simple structure, and a theory is developed for the correction of third-order spherical aberration in the particular type of objective lens evolved. This theory is simple enough for computation, yet applies to lenses with four electrodes capable of a high magnification. An example shows a tolerance of $\frac{1}{5}$ micron for the correcting electrode if the resolution limit is to be reduced to 10% of its rotationally symmetric value. A better example could probably bring this within engineering practice, but first-order astigmatic electrodes are also needed, and the tolerances of these are one or two factors of ten more exacting. It is, therefore, here that the difficulties will arise in the application of nonrotational symmetry.

269.

Electrostatic lens, N. P. Carleton, Rev. Sci. Instr., 28, 9-10 (1957).

A possible electrostatic lens consists of a cylindrical surface along which the potential varies as the square of the distance from some original plane. If the cylinder is very long or is terminated without distorting the field within, the trajectories of charged particles inside it can be calculated analytically. These calculations show that a small-diameter source of electrons inside the cylinder can be imaged, with magnification unity and slight aberration, at another point in the cylinder. A short section of the cylinder with open ends serves as a thick lens for focusing a beam of particles, the focusing effect

being due to the main field inside the cylinder plus end effects. Such a lens was constructed, the boundary condition being realized by a succession of closely spaced rings maintained at the proper potentials. This lens was more efficient in focusing a highly divergent beam of ions than were several combinations of conventional lenses which were also tried.

270.

First-order study of an optical system consisting of four electrostatic quadrupole lenses, D. Dhuicq, *Compt. rend.*, 251, 1989-91 (1960). (In French.)

An experimental study has been made of the optical properties of a system of four quadrupoles, arranged symmetrically and acting as a projector. The results are compared with calculations made by a method previously described.* The lack of close agreement is ascribed to the use of a simple rectangular model for the shape of the field, as well as to experimental error. There exists only one set of conditions in which the system is stigmatic, and the focus is then immersed in the lens.

*214.

271.

Potential and field of a particular type of cylindrical lens, E. Durand, *Compt. rend.*, 232, 314-16 (1951). (In French.)

Considers theoretically the case of an electrostatic lens composed of two parallel half-infinite planes situated between two infinite planes parallel to the first two and at a different potential. Equipotential surfaces are drawn.

272.

Calculation of the axial potential of a three-electrode electrostatic lens, P. Ehinger, *Compt. rend.*, 238, 1306-8 (1954). (In French.)

By a modification of a method of Bernard¹ expressions are derived for the axial potential of an electrostatic three-electrode lens. The theory requires the electrodes to be in the form of long cylinders, but an experimental check shows that the expressions hold also for the case of a thin central electrode.

¹P. Ehinger, *Compt. rend.*, 238, 879-81 (1954).

273.

Current carrying deflector-plates for rotating a beam of charged particles, P. A. Einstein and A. G. Edwards, J. Sci. Instr., 31, 222-3 (1954).

A method is described for rotating a flat beam of charged particles about an axis in the direction of travel. The beam is passed between two resistive plates arranged parallel to it. A current is passed through the plates in a direction perpendicular to the direction of motion of the beam, and parallel to its flat side. The current in opposite plates is opposed. The electrostatic field resulting from the potential drop across the plates results in the rotation or twisting of the beam. Application to slit alignment in mass spectrometers is suggested.

274.

Paraxial electron trajectories in electrostatic lenses, C. Fert, J. phys. radium, 13 (Suppl. No. 7-8-9), 83A-90A (July-Aug.-Sept. 1952). (In French.)

The classical step-by-step method of integration for obtaining electron trajectories can be formulated in such a way that all the constants of any lens system can be expressed in terms of the coefficients of a characteristic matrix (second order and square). It is the product of several similar matrices each associated with a plane of discontinuity of the system. The theory is illustrated by a number of examples.

275.

Plasma penetration boundary and plasma focusing, M. D. Gabovich, L. L. Pasechnik, and L. I. Romanyuk, Soviet Physics - Technical Physics, 6, 61-66 (1961).

A probe method is described for determining plasma penetration boundaries. It is found possible to produce a plasma boundary configuration which is favorable for the focusing of ions from the plasma penetration surface in an immersion lens.

276.

An electrostatic spectrograph based on an electron microscope, B. Gauthe, Compt. rend., 239, 399-402 (1954). (In French.)

The adaptation of an electrostatic electron microscope for velocity analysis of an electron beam is described. A cylindrical lens

used in the telefocal condition with an off-axis slit is employed in a system closely following that previously described by Möllenstedt.¹ The resolution obtained is better than 1 : 20,000.

¹Optik, 5, 499-517 (1949).

277.

Rigorous calculation of a typical electrostatic unipotential lens, W. Glaser and P. Schiske, Optik, 11, 422-44 (1954). (In German.)

The rigorous calculation of magnetic electron lenses has been carried out previously using the bell-shaped field function of Glaser. The present paper carries out the analogous calculation for the electrostatic lens. The equations of image formation are derived and the principal parameters of the lens calculated, including spherical and chromatic-aberration coefficients. Applications such as electron-velocity analysis and electron-velocity filter are discussed.

278.

Rigorous calculation of typical electrostatic electron lenses, W. Glaser and H. Robl, Z. angew. Math. Phys., 2, 444-69 (1951). (In German.)

Exact solutions of the differential equation of the trajectories of electrons close to the axis are given for potentials along the axis determined by rotationally symmetrical electrostatic fields; these potentials have a configuration analogous to those of cylindrical lenses. Expressions are derived for the most important optical characteristics of these lenses.

279.

Rigorous calculation of a typical electrostatic unipotential lens (continued), W. Glaser and P. Schiske, Optik, 11, 445-67 (1954). (In German.)

Continues the exact calculation of the preceding article (see 278) with an analytical field distribution. The results are shown graphically in the form of trajectories. Trajectories are also shown for the lens acting as a velocity spectrograph.

280.

Gaussian characteristics of the electrostatic lens formed by two coaxial cylinders of equal diameter, P. Grivet and M. Bernard, Compt. rend., 233, 788-90 (1951). (In French.)

If the separation of the cylinders is infinitely thin, the axial potential is given in terms of a hyperbolic function of the axial coordinate.¹ By a suitable change of coordinate, the function Φ'/Φ may

be made symmetric about its maximum; it is then approximately represented by Glaser's "bell" function. Formulae for the paraxial characteristics and a numerical table of focal lengths are given.

¹S. Bertram, Proc. Inst. Radio Engrs., 28, 418-20 (1940).

281.

On the axial potential of a three-electrode lens, P. Grivet and M. Bernard, J. phys. radium, 13, 47-8 (1952). (In French.)

Calculation of the lens parameters is greatly simplified when Regenztrief's¹ expression for the axial potential is replaced by an empirical function.

¹Ann. Radioelectricité, 23, 51-83 (1951). 313.

282.

Theory of the electrostatic lens formed by two coaxial cylinders, P. Grivet and M. Bernard, Ann. Radioelectricité, 7, 3-9 (1952). (In French.)

The first part of this paper is a fuller version of ¹. It is also shown that Φ'/Φ is approximately proportional to $\text{sech}(z/b)$, so that the results of ^{2,3} are applicable. Numerical results from each method are given and compared with calculations of Goddard⁴ and observations of Spangenberg and Field.⁵ The discussion is paraxial but it is suggested that the method of Sturrock for 3rd-order aberrations^{6,7} might be applied to either of the present approx. ray equations.

¹P. Grivet and M. Bernard, Compt. rend., 233, 788-90 (1951). 280.

²P. Grivet, Compt. rend., 233, 921-3 (1951). 156.

³P. Grivet, Compt. rend., 234, 73-5 (1952).

⁴L. S. Goddard, Proc. Phys. Soc. (London), 56, 372-8 (1944).

⁵Elect. Commun., 21, 194 (1943).

⁶P. Sturrock, Compt. rend., 233, 146-7 (1951). 393.

⁷P. Sturrock, Compt. rend., 233, 243-5 (1951). 392.

283.

Examples of rigorously calculable ion and electron paths in plane electrostatic fields, H. Grümmer and H. Spurny, Acta phys. Austriaca, 11, 11-22 (1957). (In German.)

Staeckel's method for the separation of the Hamilton-Jacobi differential equation leads to rigorous solutions for electron trajectories in particular plane fields. The cases of homogeneous and hyperbolic fields are fully treated, and by a change of coordinates the method is applied to a field in which the equipotentials are cardioids.

284.

Plane electrostatic fields for which rigorous calculation of electron trajectories is possible, H. Grüm m, Ann. Phys., 17, 269-74 (1956). (In German.)

Only very few field distributions are known for which particle trajectories can be rigorously calculated. The problem is now attacked systematically in the most general terms, starting from a result of Staeckel (1893) on the conditions for separability of the Hamilton-Jacobi equation. The necessary conditions are more fully formulated for the case of plane fields (electron prisms and cylindrical lenses) and explicit expressions given for the types of field which are found to satisfy them. Among them are the special cases of an electrostatic cylindrical lens, an immersion cylindrical lens, and a deflection system.

285.

A rigorously soluble model for cylindrical immersion electron lenses, H. Grüm m, Optik, 13, 277-88 (1956). (In German.)

Electron paths through an analytical potential distribution similar to that of a two-dimensional immersion lens are calculated rigorously. Criteria are established to distinguish between operation as lens and mirror, respectively. Expressions are given for paraxial focal properties.

286.

Rotationally symmetrical electrostatic fields for which rigorous calculation of electron trajectories is possible, H. Grüm m, Ann. Phys., 17, 275-80 (1956). (In German.)

The method developed in the preceding paper¹ is extended to fields of rotational symmetry, as encountered in practical electron lenses. Explicit expressions are given, in a number of coordinate systems, for the fields which satisfy the necessary conditions. These fields will be investigated in more detail in a subsequent paper.

¹H. Grüm m, Ann. Phys., 17, 269-74 (1956). 284.

287.

Measurement of electron energies by deflection in a uniform electric field, G. A. Harrower, Rev. Sci. Instr., 26, 850-4 (1955).

The well-known principle that the deflection of electrons in a uniform electric field can serve to measure the distribution of their energies has been investigated both theoretically and experimentally.

Simple theory suggests a particular choice of parameters for an instrument intended for such measurements. Design equations are presented, dimensions of a practical device are given, and the necessary associated electric circuits are discussed. An instrument of this type employs only an electric field, is small in size, is easily constructed, and provides a linear scale of energy values. An analyser built to this design with an overall length of 5 in. was able completely to separate electrons having a difference in their energies of 2%.

288.

Electrostatic potential plotting for use in electron optical systems, K.-C. Ho and R. J. Moon, J. Appl. Phys., 24, 1186-93 (1953).

A noniterative numerical method has been found for solving a partial differential equation when its boundary conditions are not known on the entirety of a closed boundary. Under such conditions, the iterative numerical methods which are generally used, such as the relaxation technique, are not applicable. As an example, this noniterative numerical method has been used to calculate the shapes of a pair of beam forming electrodes for use in an electron gun in which rectilinear flow is desired. The calculated shapes are in almost complete agreement with Pierce's experimental results (1940). Equipotential surfaces calculated by this method have been checked by means of an electrolytic trough which employs a semiautomatic detecting and plotting system.

289.

The calculation of electron lenses from given paraxial focusing properties, P. P. Kas'yankov, Zh. Tekh. Fiz., 23, 531-40 (1953). (In Russian.)

For an electrostatic lens, let $R = r\Phi^{1/4}$; then if $R(z)$ is given,

$$\Phi = \Phi_0 \exp \left[\pm \int_{z_0}^z (-16R''/3R)^{1/2} dz \right] ,$$

where z_0 is the axial coordinate of the object. What will actually be given is the magnification and the separation of object and image; the problem of choosing a suitable functional form for R is discussed in detail; special functions as those of Mathieu, Bessel, and Legendre are considered. Electrode shapes may be calculated from the axial potential by a process which is the inverse of the relaxation method. The possibility of imposing the condition that a certain primary aberration coefficient be minimized is mentioned, but is not enlarged upon.

290.

The electron optics of electrostatic accelerators in the relativistic range, J. Kessler, Z. Naturforsch., 16a, 1138-46 (1961). (In German.)

The properties of electrostatic lenses for relativistic particles are described by means of transfer matrices. Using Gans' polygon method, the matrices are calculated by integrating the equation of motion of relativistic particles in electric fields that have rotational symmetry. These general results are used for calculating the first-order approximations of the characteristic data for two-cylinder lenses. Numerical evaluation shows that the lens properties at a fixed V_2/V_1 vary only slowly with increasing energy (V_1 and V_2 being the potentials of the lens). The results are compared with those calculated by Timm for the nonrelativistic case, which can be seen in our results as a special case. The easiest way of applying the derived formulas to the case of multistage accelerator tubes is discussed.

291.

Investigation of the ion-optical properties of the sector electrostatic field of the dispersive type, M. I. Korsunskii and V. A. Bazakutsa, Zh. Tekh. Fiz., 28, 1510-25 (1958). (In Russian.)

An electrostatic analyzer of the sector type has been built, but using curved walls instead of the usual cylinders. The focusing properties of such an analyzer have been investigated theoretically and experimentally. The instrument has been applied to the spectral analysis of a beam of charged particles.

292.

Potential and field of a cylindrical electrostatic lens with three apertures, M. Laudet, Cahiers de Phys., No. 41, 73-80 (1953). (In French.)

Presents a theoretical analysis of the potential and field distributions in the general case of a cylindrical lens formed by apertures in three parallel plane electrodes. The important case of a symmetrical lens is studied and a numerical calculation of the potential and field distributions in the plane of symmetry is shown graphically. Anabacus gives the relationship between the theoretical parameters and the geometry of the system. Finally, the procedure for studying immersion objectives is given.

293.

The electrostatic field of an immersion electron lens formed by two diaphragms, N. N. Lebedev, Zh. Tekh. Fiz., 27, 2097-104 (1957). (In Russian.) English transl: Soviet Physics - Technical Physics, 2, 1943-50 (1957).

This work gives an exact calculation of the field of an electron lens formed of two parallel planes with circular openings of radius a separated by a distance $2b$ from each other. It is shown that the potential on the lens axis is given by quadratures involving an auxiliary function which is the solution of a one-dimensional integral equation of the second kind with a continuous kernel. An effective method is proposed for solving this integral equation, and the results are presented for several relations between the geometric dimensions. The method developed in the present work can be applied in calculating the fields of more complex lenses made of circular diaphragms.

294.

Chart for solution of a problem with electric or magnetic alternating gradient lenses, P. Levy, J. phys. radium, 17, Suppl. No. 6, 60A-61A (June 1956). (In French.)

A chart is described aiding in selection of parameters for an alternating-gradient focusing channel, for the case where focusing takes place at the same point in both planes. The chart has been used in designing an electrostatic lens for the beam from an accelerator ion source.

295.

On the determination of the electron optical characteristics of electrostatic lenses. I., W. Lippert and W. Pohlit, Optik, 9, 456-62 (1952). (In German.)

Deals with the electrostatic "eigenlinse." Experimentally determined curves for the focal length and position of the principal planes are given, as are the conditions which the lens geometry must obey for achromatic correction.

296.

On the determination of the electron-optical characteristics of electrostatic lenses. II., W. Lippert and W. Pohlit, Optik, 10, 447-54 (1953). (In German.)

For Pt. I, see 1. Further results on the lenses treated in Pt. I are given, including the image distortion, spherical aberrations, the

variation of lens power, and position of focal plane with the potential of the center electrode. Experimental results are compared with results deduced from a simplification of the formulae due to Regenstreif. Fair agreement is obtained.

¹Optik, 9, 456-62 (1952). 295.

297.

On the determination of the electron-optical characteristics of electrostatic lenses. III., W. Lippert and W. Pohlit, Optik, 11, 131-6 (1954). (In German.)

For Pt. II, see ¹. This paper completes the work of the previous parts. The experimental results are compared with the theoretical results of Regenstreif. It is concluded that agreement exists between the theoretical and experimental results only over a limited range of geometry, and therefore Regenstreif's solutions cannot yet be regarded as complete.

¹Optik, 10, 447-54 (1953). 296.

298.

Theory of the ion beam in electrostatic fields taking space-charge into account, N. Pucker, Acta Phys. Austriaca, 12, 475-91 (1959). (In German.)

Firstly, presents a matrix formalism of Timm¹ for calculating the paths of paraxial rays in a given electrostatic field, and applies it to an ideal two-cylinder lens with linear variation of potential between two field-free regions. Then a first-order perturbation calculation of the effect of the space-charge field of the beam, assumed small, is carried out, results being given explicitly in terms of measurable quantities.

¹V. Timm, Z. Naturforschung, 10a, 593-602 (1955). 334.

299.

Electron-optical properties of electrostatic systems with apertures deviating from an ideal shape, B. M. Rabin, A. M. Strashkevich, and L. S. Khin, J. Tech. Phys., USSR, 21, 438-44 (1951). (In Russian.)

The apertures are elliptical, and the potential field is found by an extension of the method of Strashkevich¹ for various electrode arrangements. Two examples are tabulated and compared with measurements in an electrolytic tank. A series development valid near the axis is also obtained and the differential equations of the ray are set up. In the usual way, an integral expression is obtained for the longitudinal axial astigmatism, when the lens is thin and weak.

¹J. Tech. Phys., USSR, 10, 91 (1940).

300.

On a mechanically adjustable electrostatic einzel lens, B. Rajewsky and W. Lippert, *Optik*, 14, 72-3 (1957). (In German.)

The normal method of altering magnification by changing the potential of the middle electrode of an electrostatic lens involves certain difficulties. It is suggested instead that a lens comprising three cylinders should be used in the "einzel" condition, one cylinder being made capable of displacement in an axial direction.

301.

The adjustment of electron-optical filter lenses, O. Rang, *Optik*, 11, 327-34 (1954). (In German.)

The development of electron optics has led to the use of more complicated lens systems. The paper discusses the adjustment and use of electrostatic filter lenses of the type described in previous papers.¹

¹G. Möllenstedt and O. Rang, *Z. angew. Phys.*, 3, 187-9 (1951).

302.

The independent electrostatic lens for non-paraxial rays (regime transgaussien)., E. Regenstreif, *Compt. rend.*, 230, 1650-2 (1950). (In French.)

The properties of the "Einzelinse" are calculated, retaining terms in ξ^3 . Relations giving the principal surfaces, caustic surfaces, etc., are derived in terms of the fundamental parameter $x = \Phi(0)/\Phi(z_0)$ and the parameter giving the incidence ξ_0/z_0 . The limiting value of ξ_0/z_0 beyond which the lens acts as a mirror is also determined.

303.

Non-paraxial theory of the elliptic electrostatic lens, E. Regenstreif, *Ann. Radioelectricité*, 6, 299-317 (1951). (In French.)

Fuller version of ¹. The effect of ellipticity is supposed to be confined to the central region of the lens; where the refraction is weak, axial symmetry is assumed. Within this limitation, however, the theory is exact, i.e., it is not a perturbation theory, so that the ellipticity is not necessarily extremely small. Some discussion of aberration figures is given.

¹E. Regenstreif, *Compt. rend.*, 233, 854-6 (1951). 304.

304.

On the non-paraxial theory of the elliptic electrostatic lens,
E. Regenstein, Compt. rend., 233, 854-6 (1951). (In French.)

Extends the theory of ¹ to "trans-gaussian" rays, in the sense defined in ². Expressions are given both for lenses analogous to the cylindrical lens of light optics and for lenses slightly deformed from axial symmetry.

¹E. Regenstein, Compt. rend., 232, 1918-20 (1951). 310.

²E. Regenstein, Compt. rend., 230, 1650-2 (1950). 302.

305.

On the theory of independent electrostatic lens with thick central electrode, E. Regenstein, Compt. rend., 232, 604-6 (1951). (In French.)

An extension of the author's theory for lenses with thin electrodes.

306.

The optical properties of the electrostatic "einzelinse" with a thick central electrode, E. Regenstein, Compt. rend., 232, 710-12 (1951). (In French.)

The expressions developed in earlier papers^{1,2} are extended to the case of the thick centre electrode, and it is shown that absolute values of converging power considerably greater than those for thin centre electrodes can be obtained.

¹E. Regenstein, Compt. rend., 230, 1262-4 (1950). 307.

²E. Regenstein, Compt. rend., 230, 1650-2 (1950). 302.

307.

Principal rays for a family of electron lenses and mirrors,
E. Regenstein, Compt. rend., 230, 1262-4 (1950). (In French.)

See ¹ for recent papers on same subject. Gives the explicit expressions for the Gaussian trajectories in the family of "Einzelinsen" previously studied. The coefficients depend directly on the dimensions and voltages.

¹E. Regenstein, Compt. rend., 230, 734-5 (1950). 309.

308.

Simple expressions for the focal distance and chromatic aberration for an extended family of electrostatic lenses, E. Regenstreif, *Compt. rend.*, 230, 630-2 (1950). (In French.)

See ¹. The expressions derived for the axial potential distribution in the "einzelinse" are used to calculate the focal distance and chromatic aberration for medium and small focal powers. The agreement between the calculated values and those deduced from trough plots is good for the focal distance but only fair (error about 15%) for the aberration constant.

¹E. Regenstreif, *Compt. rend.*, 229, 1311-13 (1949). 312.

309.

Synthetic representation of the properties of a family of electrostatic lenses and mirrors, E. Regenstreif, *Compt. rend.*, 230, 734-5 (1950). (In French.)

A theoretical study of the isolated 3-electrode lens. The equation for the Gaussian trajectory is deduced from a synthetic expression for the axial potential, and by a change of variable is transformed into an equation which is soluble in terms of generalized hypergeometric series. The dimensions of the lens appear as a parameter, the system being a lens for values of the parameter >1 and a mirror for values <1 .

310.

Theory of electrostatic lens with central elliptical aperture, E. Regenstreif, *Compt. rend.*, 232, 1918-20 (1951). (In French.)

Explicit formulae are given for deriving the Gaussian trajectories of electrons passing through an infinitely thin, 3-electrode electrostatic lens, the central electrode having an elliptical aperture.

311.

A theory of the electrostatic "einzelinse" with perturbed symmetry of revolution, E. Regenstreif, *Ann. Radioelectricité*, 6, 244-67 (1951). (In French.)

Deals with thin lenses with an elliptic central hole. The results for a perfect lens are reviewed before the field and ray equations for the elliptic lens are established. The ray equations are integrated for paraxial electrons and explicit formulae for the optical properties are deduced.

312.

The theory of the independent electrostatic lens with three diaphragms ("einzelinse"), E. Regenstreif, *Compt. rend.*, 229, 1311-13 (1949). (In French.)

Derives an analytical expression for the potential in an einzellinse consisting of 3 plane parallel electrodes with circular apertures by superposing the potentials due to each plate. The constants are determined by requiring that the potentials remain continuous as the hole radii $\rightarrow 0$. Good agreement with trough measurements is obtained.

313.

Theory of the three-electrode electrostatic lens, I, E. Regenstreif, *Ann. Radioelectricité*, 23, 51-83 (1951). (In French.)

A complete derivation of the results announced in 1,2. The theory is generalized covering both lens and mirror and starts from an analytical expression for the axial potential. This part gives the results for the parameters of the lens with thin electrodes in the Gaussian approximation.

¹E. Regenstreif, *Compt. rend.*, 230, 630-2 (1950). 308.

²E. Regenstreif, *Compt. rend.*, 230, 1650-2 (1950). 302.

314.

II. E. Regenstreif, *ibid.*, 6, 114-55 (1951). (In French.)

The following subjects are discussed here: the lens used as mirror, lenses with slight axial asymmetry, lenses with small holes, the optical parameters of the lens as determined by the position of the inflection in the axial potential, lenses with thick central plates, and the transgaussian state in lens mirror assemblies. All the calculations are given in detail and many of the lens parameters are given in graphical form so that the paper contains design information in a readily available form.

315.

An electrostatic lens permitting rigorous calculation, P. Schiske, *Nature*, 171, 443-4 (1953).

A lens for which $\Phi(z) = \Phi_0 - \Phi_0 x^2 / [1 + (z/a)^2]$, $0 < x^2 \leq 1$ (the electrostatic equivalent of a solvable magnetic lens) can be calculated rigorously. The equation for the trajectories is given.

316.

A certain property of the image curvature in short electron-optical lenses, O. I. Seman, *Optika i Spektrosk*, 7, 113-115 (July 1959). (In Russian.)

The author shows that the meridional curvature of the image formed by "short" electrostatic lenses can be corrected, at certain magnifications, by means of diaphragms between the second focus and the object, or between the second focus and the image.

317.

Calculation of an electron slit lens for use in an electron-velocity analyzer, A. Septier, *Compt. rend.*, 239, 402-4 (1954). (In French.)

An analysis is given of the electrostatic cylindrical einzel lens used in the telefocal condition for electron velocity analysis. The optimum operating conditions are deduced.

318.

An electrostatic immersion objective with high resolving power, of a new type, A. Septier, *Compt. rend.*, 235, 652-4 (1952). (In French.)

Describes an objective which is, essentially, a unipotential lens placed in front of a plane cathode, for which the cathode field is large and sensibly independent of the focusing potential. The objective, when corrected for coma, can resolve objects with a separation of 100 m μ .

319.

On the resolving power of the electrostatic immersion objective, A. Septier, *Compt. rend.*, 235, 609-11 (1952). (In French.)

The resolving power of an emission electron microscope was measured, using a microscope with a classical immersion objective and an object heated by electronic bombardment of its front face. The results obtained were better than those predicted by a given approximate formula.

320.

Theoretical resolving power of an electrostatic immersion lens, A. Septier, *Compt. rend.*, 240, 1200-2 (1955). (In French.)

The resolving power of an electrostatic immersion objective lens considered as the diameter of the disk of least confusion is five times that of the resolving power considered as the diffraction limit.

Calculations of the angular distribution of electrons leaving an object, however, show that the most favorable plane for viewing an image is not where the overall diameter of the beam is smallest but where an intense central spot is surrounded by a large but weakly illuminated halo. This gives a resolving power of the order of the diffraction limit.

321.

The theoretical resolving power of an electrostatic immersion objective, A. Septier, J. phys. radium, 15, 573-81 (1954). (In French.)

A geometrical treatment of the aberrations of a simple three-electrode immersion objective is given. Calculations indicate that without a limiting aperture the theoretical resolution limit is about $300 \text{ \AA}$. With such an aperture, this limit may be reduced only to about $100 \text{ \AA}$, because of the intrinsic spherical aberration of the system. For all practical purposes, the resolution limit lies between these two values.

322.

The radius of curvature method for construction of space trajectories of charged particles in electrostatic fields, N. I. Shtepa, Zh. tekhn. Fiz., 26, 2281-6 (1956). (In Russian.)

323.

Improved electron filter lens, J. A. Simpson and L. Marton, Rev. Sci. Instr., 32, 802-3 (1961).

A filter lens of improved characteristics obtained by use of an intermediate image is described. The design has the advantage of longer focus and increased aperture while maintaining an energy resolution, at 5-kev primary energy, of less than thermal spread of the initial beam.

324.

Investigation of electron optical properties of an electrostatic focusing system, W. E. Spear, Proc. Phys. Soc. (London), B64, 233-43 (1951).

It is shown that the combination of paraxial ray tracing and a dynamical determination of the electron trajectories in the cathode region leads to a complete analysis of electron-optical immersion systems, once the potential distribution is known. The method is applied to an electrode arrangement recently described.¹ In particular, it is shown that a demagnified image of the emitting area of the outer electrode of the system is at cathode potential. A magnified image is

formed near the emitter if this electrode is at anode potential. The results are in good agreement with experiment. A discussion of aberration and crossover is included.

¹W. Ehrenberg and W. E. Spear, Proc. Phys. Soc. (London), B64, 67-75 (1951).

325.

Basic relations of relativistic electron optics of non-axially symmetric electrostatic fields, A. M. Strashkevich, Zh. tekhn. Fiz., 22, 1848-56 (1952). (In Russian.)

The discussion is paraxial and the general formulae are applied particularly to cylindrical lenses and to fields of diad symmetry.¹

¹A. M. Strashkevich, Zh. tekhn. Fiz., 22, 487-97 (1952). 326.

326.

Electron optical properties of electrostatic fields having diad symmetry, A. M. Strashkevich, Zh. tekhn. Fiz., 22, 487-97 (1952). (In Russian.)

Seman¹ showed for axially symmetric fields that the applicability of the thin lens approximation can be extended if $\gamma\Phi^{1/4}$ is taken as constant instead of r . This is adapted to the present case and integrals are given for the focal length and the magnification in the planes of symmetry. ² gave a formula for the potential near the axis of a system of coaxial apertures in electrodes, one of the apertures being elliptical; an improved formula is now given, especially advantageous at small separations of the apertures. From it expressions are derived for the focal lengths.

¹O. I. Seman, J. Tech. Phys., USSR, 20, 1180-93 (1950). 103.

²B. M. Rabin, A. M. Strashkevich, and L. S. Khin, J. Tech. Phys., USSR, 21, 438-44 (1951). (In Russian.) 299.

327.

Electron optical properties of quadrupole electrostatic lenses, A. M. Strashkevich, Acad. Sciences USSR - Bul. - Phys. Ser. (English translation) 23, 701-5 (1959). (Columbia Tech. Translations, New York, N. Y.)

Basic relativistic relationships are derived; general methods of calculation applicable to any arbitrary configuration of electrodes in quadrupole lens are considered.

328.

Multiply symmetric and multiply anti-symmetric (electrostatic) electron-optical systems, A. M. Strashkevich, Zh. tekhn. Fiz., 24, 274-86 (1954). (In Russian.)

Analytical expressions for the potential are given for a number of cases in which it is independent of z , the axial coordinate, as well as the form of the z -dependent solution as a series in the radial coordinate. For the z -independent case an iterative method is developed for solving the paraxial ray equations, explicit expressions being given for the coefficients required, as far as the third approximation. The manner of dealing with the z -dependent case is indicated.

329.

Quadrupole lenses, the fields of which do not possess antisymmetry, A. M. Strashkevich, Zh. Tech. Fiz., 30, 1199-1206 (1960). (In Russian.)

The lateral potential distribution of two asymmetrical electrostatic quadrupoles is analytically determined. The relativistic equations for the motion of charged particles through these are applied on the assumption that the potentials do not depend on distance measured along the optical axis of the system. Focal lengths are obtained and compared with those holding for symmetrical quadrupoles. [English translation in: Soviet Physics-Technical Physics, 5, 1136-42 (1961)].

330.

Hydrogen supply and beam focusing for electrostatic generator, C. J. Strumski et al., Rev. Sci. Instr., 25, 514 (1954).

Describes two helpful devices: a supply of hydrogen for the rf ion source, and an alternating gradient electrostatic lens on the separated mass-one beam.

331.

Beam focusing by RF electric fields, E. Sugata et al., Proc. Inst. Radio Engrs., 48, 1169 (1960).

On the assumption of small perturbations, it is deduced that the periodic field pattern of a waveguide propagating an E_{01} wave can focus an electron beam, provided the wave is either backward or, if forward, slower than the electrons. Power requirements are calculated.

332.

An electrostatic energy filter, R. Taubert, Z. Naturforsch., 12a, 169-71 (1957). (In German.)

A "strong focusing" electrostatic system, of alternately focusing and defocusing fields, is shown to act as an energy filter for particles of the same mass. Two simple four-pole models are analyzed, and stability properties of the Mathieu-type equations involved are used to provide some design data.

333.

Focusing of a long cylindrical electron stream by means of periodic electrostatic fields, P. K. Tien, J. Appl. Phys., 25, 1281-8 (1954).

The use of a bifilar helix or a series of annular rings to produce periodic electric fields is considered. The potential distribution at the position of the electrons is expanded in a power series, and an equation of electron motion is written. The solutions obtained indicate that the flow of electrons is essentially parallel, provided that the electrons enter the focusing structure practically without transverse velocities and are distributed across the stream such that the space charge fields decrease radially toward the axis in a manner similar to that of the periodic electric fields. The method of periodic electrostatic focusing is of particular interest in connection with travelling wave tubes. The possibility of using a bifilar helix as both the slow wave and the focusing structure is discussed.

334.

Computation on electrostatic lenses, U. Timm, Z. Naturforsch., 10a, 593-602 (1955). (In German.)

Develops a matrix formulation for the determination of lens characteristics. The elements of a lens matrix can be simply related to the usual lens parameters. The properties of lens combinations are then found by matrix multiplication. The method lends itself to numerical computation by approximating the axial potential distribution by a series of linear elements, whose matrix representation is known. A number of examples are discussed in some detail.

335.

The production and focusing of intense positive ion beams, M. A. Tuve, O. Dahl, and L. R. Hafstad, Phys. Rev., 48, 241-256 (1935).

Based on a suggestion by Dr. F. L. Mohler, a high-intensity source of positive ions utilizing a gaseous low-voltage arc constricted by a metal capillary has been developed. With 250-w input and 10-cc gas flow per hour, this source delivers controllable positive ion

currents up to 1.5 milliamperes through a probe canal, 1 mm in diameter. The focusing of weak and intense positive ion beams by various electrostatic lens arrangements has been empirically investigated, giving additional data on quantitative design concerning the multiple-section, high-voltage tubes long in use in the laboratory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and indicating the requirements met in delivering the total ion current from the source onto a target at the far end of such a tube.

336.

Diffusion patterns in electrostatic immersion lenses, Yu. V. Vorob'ev, Zh. tekhn. Fiz., 26, 2269-80 (1956). (In Russian.)

In the first part, the author deals with a new mathematical treatment of the problem of how to solve the nonlinear equation for the trajectory of beams of electrons leaving the cathode in the neighborhood of the symmetry axes, in the case of immersion lenses, i.e., of an optical system where the source is placed in a strong electric field. In the second part, an original set of results for the diffusion patterns of an arbitrary beam is obtained.

337.

On the dioptrics of electrostatic electron-lenses, G. Wendt, Z. angew. Phys., 3, 219-25 (1951). (In German.)

The investigation of electron lenses is much simplified by transformation of the standard differential equation. The expression for the axial potential is written in the form $\Phi = \text{const} + f(z) = \text{const} + S$. It is then established that, for several common electrode arrangements, $dz = (1 - s^2)^n ds$, $\frac{1}{2} < n < \frac{3}{2}$. The transformed equation has solutions which are Riemann functions of the second order and are of a type studied by Heun. When the $\text{const} = +1$, the differential equation becomes a hypergeometric equation. This case corresponds with a plane cathode and circular aperture, which is discussed in detail.

338.

Investigation of nonrotationally symmetrical electrostatic electron optical lenses, R. F. Whitmer, J. Appl. Phys., 27, 808-15 (1956).

Electrostatic lenses which are nonrotationally symmetric, constant in time, free of space charge, and in which the electrostatic potential along the axis of the lens does not fall to the cathode potential are investigated. In general, nonrotationally symmetric lenses suffer from first-order distortion and astigmatism. A method is given for determining lenses of the assumed symmetry which are free of these first-order aberrations. This is accomplished by deriving an imaging

relationship between $\Phi_2(Z)$, an arbitrary field parameter introduced from the assumed field symmetry, and $\Phi(Z)$, the rotationally symmetric component of the axial potential distribution, from the paraxial ray equations. The equations for the spherical aberration of such a lens are derived by standard methods. A method is given for finding lenses of reduced aberration and specific examples are discussed.

See also: 1, 7, 10, 11, 21, 23, 26, 31, 32, 35, 43, 93, 95, 113, 120, 339, 341, 365, 366, 369, 372, 380, 389, 390, 397, 401, 402, 407, 408, 425, 429, 433, 449, 457, 458, 483, 500, 584.

ELECTRON LENSES - RAY TRACING

339.

Numerical ray-tracing in electron lenses, J. C. Burfoot, Brit. J. Appl. Phys., 3, 22-4 (1952).

For the solution of the paraxial ray equation, a very simple step-by-step method is given, using a procedure due to Fox and Goodwin for equations of the type $d^2y/dx^2 = f(x)y$. The accuracy of the method can be increased to any desired extent without increasing the complexity. All sources of inaccuracy except those present in the given field data can thus be avoided, and the aberration integrals can be accurately evaluated. If required, an approximate solution may be obtained initially, which is easily modified later for better accuracy, without redundancy of the early work. Graded intervals are easily introduced. A worked example is given for a strong electrostatic lens.

340.

An improved method of numerical ray tracing through electron lenses, G. Liebmann, Proc. Phys. Soc. (London), B62, 753-72 (1949).

An improved method is described for the tracing of electron trajectories through electron lenses by integrating the general ray equation with the help of Taylor's series, taking the series up to and including fourth-order terms. The paraxial trajectory is obtained by progressing from point P_n on the trajectory to point P_{n+1} with the help of recurrence formulae $r_{n+1} = Q_1 r_n + Q_2 r'_n$ and $r'_{n+1} = Q_3 r_n + Q_4 r'_n$ where the coeffs. $Q_1 \dots Q_4$ are functions of the electrostatic or magnetic field distribution along the axis. The deviation of the first-order trajectory from the paraxial trajectory is built up with the help of similar recurrence formulae. The method is first developed for combined electrostatic and magnetic lenses, using the "equivalent potential" $U = \Phi - (eA^2/2m)$, and then specialized for pure magnetic or pure electrostatic lenses. The case of space charge within lenses is also

considered. Comparison of the improved method with other methods shows that it is faster and capable of high accuracy. The factors influencing the accuracy are considered in detail, and a short-cut method using extrapolation is given. A fully calculated example is appended.

See also: 10, 13, 27, 324, 565, 598.

ELECTRON LENSES - ANALOG AND DIGITAL COMPUTATION

341.

Electron-trajectory tracer for use with resistance network analogue, M. E. Haine and J. Vine, *Instn. Elec. Engrs. - Proc.* 106, Pt. B (Electronic & Communication Eng.), n. 30, p. 517-25 (Nov. 1959). (Discussion) 525-7.

Constructional details of instrument for direct analog computation of electron trajectories for which resistance network provides necessary field data; results obtained for two typical electrostatic lenses. Paper 2800M.

342.

An analogue computer for the study of trajectories in electron lenses, A. Hampikian, *Compt. rend.*, 236, 1864-6 (1953). (In French.)

Describes a simple "transmission line analogue" calculator¹ with which the cardinal points of a symmetrical lens have been determined to an accuracy of better than 1.5%.

¹P. Grivet and Y. Rocard, *Rev. Sci.*, 87, 85 (1949).

343.

Covariant phase-space factors for reactions involving four to six secondary particles, T. H. Hoang and J. Young, UCRL-9050 (Jan 1960). 24 p.

A set of programs for computing covariant phase-space factors with the IBM-605 is described. Originally, the programs were written to investigate K production in antiproton annihilation in terms of the statistical model. They were written with enough flexibility to permit their use on similar problems involving four to six secondary particles of another nature provided the particles can be ordered so that the last two particles in the successive integrals are identical.

344.

Analogue study of electron trajectories, B. F. Logan, G. R. Welti, and G. C. Sponsler, J. Assoc. Comput. Mach., 2, 28-41 (Jan 1955).

Describes an automatic computer used in conjunction with an electrolytic tank, giving both field maps and trajectory plots. Circuit components, tank, and probe assembly are described. The most serious error is due to the drop in tank water level by evaporation. Errors in the measured field components, and those due to finite probe dimensions, are removed by corrective networks. The system was calibrated with a special tank with concentric cylindrical electrodes. A tracer was used to assess the merits of different electrode configurations in c.r. tubes using postdeflection acceleration; 250 trajectories for 6 different configurations were plotted in 2 days, with reproducibility of better than $\frac{1}{2}\%$. Several improvements are suggested.

345.

The "Mechanical Particle," an analog computing machine, B. Rankin, Rev. Sci. Instr., 25, 675-678 (1954).

A machine is described which solves the equations of motion for a charged particle in a two-dimensional magnetic field. Its accuracy is not limited by the steepness or the asymmetry of the field. Guided by remote control, the mechanism moves continuously over a contour map just as a particle would move through the field itself. The operator matches position, or local field value, with a parameter of the steering control, or curvature of the trajectory. He is able to interpolate continuously between lines of constant field value, thus speeding the process of solution and increasing the accuracy. In five minutes a 40-in. orbit can be drawn over which the field values vary through 23,000 gauss. Five minutes are required for introducing initial conditions including momentum. For regions in which the field is more than half maximum, the orbits of the mechanical particle and the electromagnetic particle coincide in their radii of curvature to within 0.5 percent. Accuracy is less for low field values. The performance characteristics have been determined from a working instrument which is fully described. An alternative computer design to the one already in use is also discussed.

346.

Numerical investigation of range of unipotential electron lenses, J. Vine, Brit. J. Appl. Phys., 11, 408-11 (1960).

Digital computer has been applied to computation of focal lengths and spherical aberration constants of unipotential lenses;

results presented in graphical form are in good agreement with published experimental results, but not, in case of spherical aberration constants, with results based on analytical approximation to axial potential distributions; sources of error are discussed, and accuracy of results estimated.

347.

Optical analog for a symmetric quadrupole, J. D. Young, UCRL-9054 (Jan. 22, 1960). 22 p.

The construction of an optical analog to a symmetric quadrupole by use of an IBM 650 computer program is described.

See also: 27, 244.

LENS ERRORS

348.

Focal properties and chromatic and spherical aberrations of the three-electrode electron lens, G. D. Archard, Brit. J. Appl. Phys., 7, 330-2 (1956).

Published theoretical and experimental values of the focal length of simple three-electrode electron lenses are compared and found to be in general agreement. These are presented in the form of graphs which show directly the dependence of focal length on lens geometry and voltage ratio. Analogous graphs are derived for spherical and chromatic aberrations in the form of the ratios C_s/S and C_c/S (S being the separation of adjacent electrodes), and the general relation between the various curves is discussed.

349.

Magnetic electron lens aberrations due to mechanical defects, G. D. Archard, J. Sci. Instr., 30, 352-8 (1953).

The electron-optical aberrations due to mechanical defects in magnetic lens pole pieces are calculated for several lens geometries and a range of excitations, by a slight modification of the computational procedure of Sturrock.¹ The condition that these aberrations shall not predominate over the combination of spherical aberration and diffraction is taken as a criterion of mechanical tolerance. Tolerances for the alignment of the pole pieces are shown to be well within the limits of normal workshop practice (for a typical lens: the axes of the two pole pieces must not be laterally separated by more than 30μ , nor must the angle between them exceed 0.005 radian). Tolerances for ellipticity of the bore and corrugation of the pole faces are more stringent (typically: the variation in radius or in distance of the pole face from the midplane must not exceed 0.1μ). The results are generalized in the form of universal curves designed to facilitate the assignment of tolerances in the case of lenses of any magnitude or accelerating voltage.

¹Phil. Trans. Roy. Soc. London, A243, 387-429 (1951). 391.

350.

Properties of two-aperture electron lenses, G. D. Archard, Brit. J. Appl. Phys., 8, 127-30 (1957).

Spherical and chromatic aberrations and focal properties of two-aperture ("immersion") electron lenses investigated theoretically, and results presented graphically as functions of lens geometry and voltage ratio.

351.

An approximation method for image aberration calculation in electron optics, M. Barbier, Diss. E. T. H., Zurich No. 1932, 88 pp. (1951), Mitt. Inst. Tech. Phys. No. 3 (In German).

The author first investigates the errors introduced into the calculated paraxial paths by the assumption of an axial potential distribution different from the correct value. It is shown that the axial field can be piecewise approximated by fields for which the path is known. The results are sufficient for the calculation of chromatic errors. The third-order aberrations are then treated, and it is shown that only the second derivative of the axial potential is required since the fourth derivative can be eliminated by partial integration. Formulae for the third-order aberrations are given, and the dependence on object and diaphragm positions is investigated. Two examples are treated in detail: the magnetic field of Glaser's type $y = (1 + x^2)^{-1}$, and the equal cylinder electrostatic lens.

352.

The practical calculation of third-order aberrations in the centered systems of electron optics, M. Barbier, Ann. Radioelectricité, 8, 111-33 (1953). (In French).

The well-known method of trajectory tracing (in which the space is divided into successive intervals for which the potential variation can be approximated by a potential law corresponding with a known trajectory) is extended to the third-order aberrations. It is shown that the expressions for the aberrations can be completely integrated under these conditions, and the results obtained agree, for all known cases, with results obtained directly. As an example, the aberrations are calculated, as a function of lens power, for magnetic and electrostatic lenses.

353.

Some aberrations of an ion beam when passing through an electric field of the $E_r = E_0 r^{-1} (1 - kr^2)$ type, V. A. Bazakutsa and M. I. Korsunskii, Trudy Khar'kov. Politekh. Inst., 14, 83-101 (1958).

The motion of ions in an electrical field of the difference type, with the components $E_r = -E_0 r^{-1} (1 - kr^2)$; $E_z = -2kE_0 z$, where E_0 and k are parameters of the field, is considered in the second approximation. Insofar as the motion of the ions is considered near the equilibrium trajectory, the method of perturbations is applied to the solution of the problem. The calculation of the side shift of the ion beam from the equilibrium trajectory makes possible the establishment of its dependence on the inconstancy of the value of the ion energy (β), their angle of divergence (ψ_r), and the width of the input slit (Δr_0). The aberration coefficients have the highest value at β^2 and ψ_r^3 . The aberration coefficients of a difference-type field are compared to the corresponding

coefficients of a cylindrical field. If the dispersion of a difference-type field increases by one order compared with the dispersion of a cylindrical field, the aberration coefficients increase 100 times. The absolute aberration value of the difference-type field, however, is comparable with the dimensions of the slits usually employed in spectroscopy; an increase of dispersion in the difference-type field leads, therefore, to a practical increase of the resolution power.

354.

Aperture aberrations of strongly converging electron lenses, M. Y. Bernard and J. Hue, *Compt. rend.*, 244, 732-5 (1957). (In French).

It is shown that the cross section of an electron beam emerging from a strong electrostatic or magnetic lens may take one of several complicated forms. These are calculated, to the third order, by a perturbation method, and the resulting expressions are applied to a particular practical case.

355.

Geometrical aberrations in strong electron lenses, M.-Y. Bernard and J. Hue, *Compt. rend.*, 243, 1852-4 (1956). (In French).

A perturbation method for the determination of the geometrical aberrations of strong electron lenses, in terms of a certain potential coefficient which can be accurately measured, is briefly described.

356.

On the aberrations of ion lenses in ion sources, F. Bertein, *Compt. rend.*, 231, 1448-9 (1950). (In French.)

Studies theoretically the aberrations introduced by the use of a focusing diaphragm, by considering it as a weak lens.

357.

Theory of the aberrations in the focusing properties of a magnetic field with one plane of symmetry, A. J. H. Boerboom, *Appl. Sci. Research*, B7, 52-62 (1958).

A general theory is given of the aberrations in focusing properties occurring in fields with one plane of symmetry. It appears that line-to-line imaging is possible and that ten geometrical aberrations of the second order exist, together with five chromatic aberrations. Names for these aberrations are proposed. The beam intensity distribution in the image is calculated.

358.

Third-order aberrations of "doubly symmetric" systems, J. C. Burfoot, Proc. Phys. Soc. (London) B67, 523-8 (1954).

The third-order geometric aberrations of nonrotationally symmetric imaging systems are classified, and their characteristics given diagrammatically for the case of a circular exit aperture. The systems are "doubly symmetric," that is, they retain symmetry about each of two mutually perpendicular planes. Eleven new aberrations occur, three of which are third-order distortions, three give curved image surfaces, three are analogous to coma, and two to spherical aberration.

359.

Investigation of fifth-order aberration in electron optical systems of axial symmetry, Wu My Chang, Scientia Sinica, 6, 833-46 (1957). (In Russian).

The eikonal method is used to deduce the total aberration of the fifth order in combined electric and magnetic fields of axial symmetry. Expressions are developed for the various components of the aberration. Finally, the fifth-order distortion is evaluated for two particular cases. This aberration is important, for example, in electron image tubes.

360.

Distortion in electron lens, M. L. De and D. K. Saha, Indian J. Phys., 28, 263-8 (1954).

The distortion produced by an electromagnetic lens of an electron microscope has been measured in different parts of the image field. From the data obtained, the distortion coefficient of the lens has been evaluated and compared with similar values obtained by other workers.

361.

Third-order aberration and focusing with sector-shaped magnetic fields, D. F. Dempsey, Rev. Sci. Inst., 26, 1141-5 (1955).

A divergent beam of monoenergetic charged particles can be refocused by a homogeneous magnetic field whose sharply defined boundaries are straight lines or circles. The transverse aberration of order α^3 at the image point is evaluated and a general third-order focusing condition is given. Design equations for third-order instruments are obtained and the results presented graphically. Many third-order focusing designs follow, both symmetrical and asymmetrical.

362.

A simple presentation of the general theory of systems of revolution in electron optics (relativity and aberrations included), E. Durand, *Rev. Optique*, 33, 617-29 (1954). (In French).

The author gives a simple demonstration of formulae about all sorts of aberrations in the most general case (electric field, magnetic field, relativity, object and image in the field, etc.). Lagrange equations are invariable for any change in coordinates. Computations are much simpler when complex combinations are introduced in the Lagrangian itself. The two Lagrange equations are reduced to only one, for the other is then the conjugate complex equation. Optical analogy and iconal functions are not used. Aberrations are calculated by the classical method which gives a special solution of a differential equation with a second member, when the general solution of the equation without second member is known.

363.

Interference and diffraction fringes in electron optics: Fresnel diffraction, Young's pinholes, Fresnel biprism, J. Faget and C. Fert, *Compt. rend.*, 243, 2028-9 (1956). (In French).

Describes the equipment necessary to illustrate the electron-optical equivalents of the optical effects mentioned.

364.

The aberration constants of an electron optical imaging system without aperture, W. Glaser and H. Grümmer, *Osterr. Ingen. Arch.*, 6, 360-72 (1952). (In German).

As it is usual in electron microscopy not to employ an objective aperture, the earlier derivation of aberration coefficients for an apertured system¹ is here extended to the apertureless system. The expressions obtained are used in conjunction with numerical values for the coefficients of the apertured system, repeated here in full, to obtain tables and graphs of values for the coefficients of the apertureless system for various values of the lens-strength parameter, k^2 . Values are also given for the separation of the cusps of the caustics (the astigmatic difference) and the distance of the midpoint between the cusps from the Gaussian image plane. The results are used to evaluate the effect upon the lens resolving power of a misalignment of the imaging beam. Numerical values are given at several aperture angles for varying degrees of decentration.

¹W. Glaser, *Z. Phys.*, 83, 104 (1933).

365.

The aberrations of the third order of a typical electrostatic einzel lens, W. Glaser and P. Schiske, *Optik*, 12, 233-45 (1955). (In German).

In previous papers^{1,2} the authors worked out the paraxial focal properties of a typical electrostatic lens. The present paper extends the calculations to five Seidel aberrations as a function of the lens potentials and the position of the object.

¹W. Glaser and P. Schiske, *Optik*, 11, 423-43 (1954). 277.

²W. Glaser and P. Schiske, *Optik*, 11, 445-67 (1954). 279.

366.

Distortion in weak electrostatic electron lenses, R. Gobrecht, *Exper. Tech. der Phys.*, 6, 1-10 (1958). (In German).

Although much work has been done on the distortion of weak magnetic lenses, little has been done on the analogous case of electrostatic lenses. The paper describes an electron-optical arrangement for measuring the distortion. Two immersion lenses were investigated in this way and the Seidel distortion coefficients obtained.

367.

Application of the "knife-edge" method to the estimation of aberrations of deflected electron beams, H. Gr $\ddot{u}$ mm, *Optik*, 12, 544-53 (1955). (In German).

Expressions are given for the shapes of the shadows of certain test objects (straight edges, wires) when the electrons forming them pass through simple deflecting fields. It is shown that by measuring the shadows, the "coma" and "astigmatism" of the deflecting system can be determined. Diagrams of typical shadows are given.

368.

The geometrical optical intensity distribution in the focal spot of the deflected electron ray pencil, H. Gr $\ddot{u}$ mm, *Optik*, 11, 32-43 (1954). (In German).

Expressions are given for the intensity distribution near a focal spot when an electron beam is deflected by electrostatic or magnetic fields. Cases are considered in which the total aberration is made up of the sum and difference, respectively, of particular aberration terms. The former leads to a channel-shaped caustic surface; the latter to a caustic of triangular cross section.

369.

Determination of the field distortion and aperture errors in electrostatic lenses by means of the principal planes and an equivalent focal plane, F. Heise, *Optik*, 5, 479-89 (1949). (In German).

Continues the work described earlier¹ by a similar method using mesh grids instead of wires. One of the lenses already investigated was used and measurements made as a function of voltage ratio. For a particular voltage ratio, in this case 11%, the field distortion is zero. The spherical aberration goes through a minimum at the same value. The minimum focal length is also obtained at the same value, but the spherical aberration constant exhibits a minimum at this point even when re-defined as a dimensionless constant. It is concluded that lenses should be worked at the minimum focal length for best resolution.

¹F. Heise and O. Rang, *Optik*, 5, 201-16 (1949).

370.

The ion-optical aberrations of a uniform magnetic sector field for arbitrary entry and exit angle of the principal ray, H. Hintenberger and L. A. Konig, *Z. Naturforsch.*, 11a, 1039-40 (1956). (In German).

In previous investigations of the deflection of ions in the magnetic sector field, aberrations were evaluated only for normal exit of the beam; for arbitrary entry and exit angle only the spherical aberration was found by Hintenberger.¹ A general expression is now derived for the mixed directional- and momentum-dependent aberration, the pure momentum-dependent aberration, and the spherical aberration. It is shown how the earlier results of other authors for one or other of these aberrations, at normal entry or exit, follow from this general expression.

¹*Z. Naturforsch.*, 6a, 275-6 (1951). 160

371.

Calculation of the aberration coefficients of magnetic electron lenses as functions of pole-piece geometry and of operating conditions, O. Jandeleit and F. Lenz, *Optik*, 16, 87-107 (1959). (In German).

Glaser's third-order aberration coefficients and the three coefficients of chromatic aberration are calculated numerically for different lens strengths of three magnetic electron lenses of given field distributions. Apart from third-order aberration coefficients in the system with an aperture in the back focal plane, the aberration coefficients in the system without aperture are also computed,

and integrals for the asymptotic aberration coefficients given. A graphical representation of the dependency of aberration coefficients on lens strength can be made approximately independent of the geometry of pole pieces, i.e., the ratio of gap width s to bore diameter b , by making the aberration coefficients dimensionless after multiplication with an appropriate power of Durandeau's unit of length $l = (s + \frac{4}{9} b^2)^{1/2}$ and measuring the lens strength in units of its telescopic value. The telescopic lens strength was numerically determined for these three field distributions. The result supplies additional information about the connection between telescopic lens strength and field form factor.

372.

Angular aberrations in sector-shaped electromagnetic lenses for focusing beams of charged particles, E. G. Johnson and A. O. Nier, *Phys. Rev.*, 91, 10-17 (1953).

The general expression for the second-order angular aberration of sector-shaped electromagnetic lenses consisting of superimposed uniform magnetic and radial electric fields used for the plane focusing of diverging beams of charged particles is derived. The result is applied to the special cases of pure magnetic and pure electric field lenses. The ion optics of a mass spectrometer employing sector electric and magnetic lenses in tandem and which has first-order velocity focusing and second-order angular focusing is obtained.

373.

The calculation of an electron lens for a given third-order aberration, P. P. Kas'yankov, *Zh. tekhn. Fiz.*, 22, 80-3 (1952). (In Russian).

A method is outlined whereby the axial potential of an electrostatic lens has been computed numerically, subject to given conditions of paraxial focusing and to the vanishing of primary coma, astigmatism, or distortion, the coefficients of which are expressed as integrals involving the potential and its axial derivatives and 2 paraxial rays. Unsuccessful attempts have been made to find a potential distribution without infinities and giving zero curvature of field.

374.

Calculation of the aberrations of electrostatic lenses by the method of calculating electron trajectories, P. P. Kas'yankov, *J. Tech. Phys.*, USSR, 20, 483-8 (1950). (In Russian).

Differential equations convenient for practical work are given for the calculation of the sagittal and orbital foci of an infinitely thin beam (pencil). Some hints are also given aiming at the simplification

of the calculating work when determining electron trajectories. In one of the examples higher orders of spherical aberration are evaluated and a correction is introduced for the mean curvature of the image.

375.

On the imaging defects of arbitrarily bounded homogeneous magnetic sector fields, L. A. König and H. Hintenberger, Z. Naturforsch., 12a, 377-84 (1957). (In German).

As an extension of earlier work on the particle-deflecting properties of magnetic sector fields with straight boundaries, the properties of such fields with curved boundaries are studied. Expressions are given for aberrations, and it is shown that at least some of these can be removed by suitable choice of boundary curvature.

376.

Electron optics of cylindrical systems with a plane of symmetry. II. aberrations, M. Laudet, J. phys. radium, 16, 908-16 (1955). (In French).

The first-order treatment of electron trajectories in Pt I¹ is extended to derive expressions for the coefficients of the various aberrations.

¹M. Laudet, J. phys. radium, 16, 118-24 (1955). 171

377.

Aberrations in the electron optical diffraction pattern, F. Lenz, Optik, 16, 457-60 (1959). (In German).

The aberrations of diffraction patterns produced by axially symmetric lenses can be calculated using methods similar to those used to calculate the aberrations of the ordinary electron-optical image. Small deviations of the lens fields from axial symmetry cause two additional first-order aberrations: the diffractive distortion and diffractive displacement. The distortion effects an affine deformation of the pattern, e.g., it deforms a circle to an ellipse. The partial diffraction patterns originating from different parts of the specimen are displaced opposite to one another, together with their primary reflex. The vector describing this displacement is connected with the position vector of its origin in the specimen by a linear transformation.

378.

On asymptotic image defects, F. Lenz, *Optik*, 14, 74-82 (1957).
(In German).

The determination of the aberrations of a system of electron lenses requires more than a simple combination of the aberration of individual lenses. In an electron microscope, for example, electrons come under the influence of the projector lens before reaching the geometrical image position pertaining to the objective lens. The effect of this interaction is worked out rigorously and applied to the case of the "bell" field. It provides an explanation for discrepancies between earlier calculations of Liebmann and Glaser.

379.

On the diffraction theory treatment of electron optical imaging aberrations, J. Picht, *Optik*, 13, 494-501 (1956). (In German).

Referring back to concepts developed in his optical diffraction theory (1925), the author shows how these may be adapted to electron-optical aberrations. The chief difference lies in that electron optics involves media of continuously changing refractive index; it therefore proves convenient in various applications to imagine media of fictitious refractive index, and to replace conventional wave surfaces by surfaces of constant phase.

380.

On the theory of third-order rays in independent electrostatic lenses, E. Regenstreif, *Compt. rend.*, 233, 1588-90 (1951). (In French).

Following work^{1,2} establishing Gaussian and trans-Gaussian ray paths, formulae are given for the third-order ray paths. From these, an expression for the geometrical aberration is obtained which is more suitable for numerical calculation than that used hitherto.

¹E. Regenstreif, *Ann. Radioelectricité*, 23, 51-83 (1951). 313.

²E. Regenstreif, *Ann. Radioelectricité*, 6, 114-55 (1951). 314.

381.

On the chromatic and spherical aberrations of electron-optical cylinder lenses, M. Rheinfurth, *Optik*, 12, 411-16 (1955). (In German).

It is shown analytically that the spherical and chromatic aberrations of cylindrical (i.e., two-dimensional) electron lenses are essentially finite. As in the case of rotational symmetry, the cylindrical lenses are weaker for paraxial rays and for fast electrons than for peripheral rays and for slow electrons.

382.

Correction of spherical and chromatic aberration in electron lenses, O. Scherzer, *Optik*, 2, 114-32 (1947). (In German).

Chromatic and spherical aberration cannot be corrected in electron lenses which are (1) rotationally symmetric, (2) charge-free, (3) without alternating potentials. By altering one of the 3 above conditions the correction becomes possible. The paper discusses all types of correction and finds them, theoretically, of equal usefulness. In practice, all introduce considerable complication into the microscope, but the author suggests that methods (1) and (3) should be the first choice for experiment.

383.

Aberrations of electron optical systems with charged surfaces in the refracting region, O. I. Seman, *Zh. tekhn. Fiz.*, 22, 1581-91 (1952). (In Russian).

The problem relates to proposals to correct aberrations by means of grids, which are here idealized as curved conducting surfaces, perfectly transparent to electrons. Expressions are derived for the primary aberrations, by the method of the characteristic function, in the formulation of 1. Distinction is made between two effects of the "grids": (a) change of axial potential distribution due to their presence, affecting paraxial and aberrational properties, and (b) effects on aberration associated with the curvature of the "grid" surfaces. In an immersion objective the latter effects do not significantly correct spherical aberration.

¹O. I. Seman, *Dokl. Akad. Nauk SSSR*, 81, 775-8 (1951). 385.

384.

Limits to aberration coefficients in electron optics, O. I. Seman, *Dokl. Akad. Nauk SSSR*, 93, 443-5 (1953). (In Russian).

The coefficients are those of the primary aberrations of axially symmetric, static fields free from space charge. The limits are imposed by the condition that the fields are Laplacian and are obtained by consideration of the reduced eikonal.¹ In addition to the well-known limitations, such as that on spherical aberration, limits have been found for the astigmatism and for the Petzval curvature. Numerical values are given, for electric and magnetic fields, of the constants which, together with values at object and image of the electric potential and field and of the height and slope of a paraxial ray, determine the lower limit of the curvature of the appropriate image surface.

¹See Seman, *Dokl. Akad. Nauk SSSR*, 81, 775-8 (1951). 385.

385.

Reduced form of the fourth order eikonal and of the aberration coefficients in electron optics, O. I. Seman, Dokl. Akad. Nauk SSSR, 81, 775-8 (1951). (In Russian).

Expressions are given for the 8 Seidel coefficients of an axially symmetric magnetic + electric lens field, the paraxial equation being set up in the "reduced" form (Scherzer, 1936) in which $rV^{1/4}$ replaces r so that the term in r' is eliminated. This is found advantageous when solving numerically by the method of Motz and Klanfer.¹

¹Proc. Phys. Soc. London, 58, 30-41 (1946).

386.

Relativistic aberration functions and the normal coefficients of electron-optical aberrations. O. I. Seman, Dokl. Akad. Nauk SSSR, 96, 1151-4 (1954). (In Russian).

"Normal" here has the same meaning as "reduced" in 1. Relativistically correct expressions are given for the fourth-order point eiconal and for the eight third-order coefficients of transverse aberration, for an axially symmetric electric + magnetic lens field. The electrostatic field appears to be restricted to that of the unipotential type of lens.

¹O. I. Seman, Dokl. Akad. Nauk SSSR, 81, 775-8 (1951). 385.

387.

The correction of aperture aberrations in a system of two magnetic quadrupole lenses, A. Septier, Compt. rend., 245, 2036-9 (1957). (In French).

It is shown that the aperture aberration of this system can be totally corrected by placing steel rods in the gap between the pole pieces at a certain critical distance from the axis. A similar effect could be produced by the use of octupole lenses.

388.

The third-order aberrations of cylindrical electron lenses, N.I. Shtepa, Zh. tekhn. Fiz., 22, 216-26 (1952). (In Russian).

Mixed electrostatic + magnetic fields are considered, analogous to a cylindrical lens of light optics: $\phi(y, z) = \phi(-y, z)$; $H_z(y, z) = H_z(-y, z)$; $H_y(y, z) = -H_y(-y, z)$. The variational function μs [μ = refractive index, s = path length] is expanded as a power series in y, y', x' , the first approximation leading, via the Euler-Lagrange equations, to the Gaussian ray

equations and the second approximation leading to differential equations for Δx and Δy , which may be solved by successive approximations. Expressions are given for the ten aberration coefficients in terms of integrals involving paraxial rays. Four of them are analogous to distortion, spherical aberration, curvature of field and tangential coma; the remainder depend on the initial value of x' [i.e., on "skewness"]. Four of these "skew" coefficients (viz., those associated with odd powers of x') are absent in the purely electrostatic case.

389.

The aberrations of corpuscular beams of arbitrary form in an arbitrary electrostatic field, A. M. Strashkevich and I. M. Pilat, *Izv. Akad. Nauk SSSR, Ser. Fiz.*, 15, 448-66 (1951). (In Russian).

By ray methods, expressions are obtained from which the second- and third-order transverse aberrations may be calculated in the following cases: (1) field having one plane of symmetry, whence the cylindrical lens is obtained as a special case;¹ (2) cylindrical condenser; (3) the general case; (4) field having two planes of symmetry; (5) field having axial symmetry; in this case the formula reduces to that of Scherzer (1936).

¹I. M. Pilat, E. E. Reznik, and A. M. Strashkevich, *Zh. Tekh. Fiz.*, 21, 1149-52 (1951).

390.

Aberrations of relativistic electron beams, A. M. Strashkevich and N. G. Gluzman, *Zh. Tekh. Fiz.*, 24, 2271-84 (1954). (In Russian).

A beam consists of a set of moving electrons with the same initial velocity and trajectories close to an axial trajectory. Relativistic equations of motion are derived for a wide beam in an arbitrary electrostatic field. In this the axis may be straight or bent, e.g., a helix. The systems with a bent axis are specially interesting since they may give rise to negative chromatic aberration. The special cases considered are an axially symmetrical field, a flat field, the field of a cylindrical lens and the field of a cylindrical condenser. Image aberrations are computed for the relativistic case of an axially symmetric lens and a cylindrical lens.

391.

The aberrations of magnetic electron lenses due to asymmetries, P. A. Sturrock, *Phil. Trans. Roy. Soc. London*, A243, 387-429 (1951).

Electron-microscope objective lenses are considered; the asymmetries are due to misalignment and to distortion of the pole pieces, not to inhomogeneity of the iron, the surfaces of which are

regarded as magnetic equipotentials. Each pole piece is assumed to be bounded by a semi-infinite cylinder, the surfaces of which are subjected to perturbations which are developed as Fourier series in the azimuthal angle, corresponding expressions being obtained for the potential field in the presence of these perturbations and of nonskew misalignments. The primary aberrations are derived by a variational method. Distortions of period π (elliptic distortions) lead only to axial astigmatism (i.e., astigmatic focusing of an object point on the axis); distortions of higher order, which are less important, are not discussed. Misalignment leads to axial coma, which varies linearly, and to axial astigmatism, which varies quadratically with the misalignment. Examples are worked with a lens having a pole separation = bore diameter ($2a$), (1) as an immersion lens with a focal length $\approx 4a/3$, and (2) as a weak lens, the magnification being great in each case. The potential field is found by a relaxation method, some difficulty being experienced at the sharp edges formed by the surfaces $r = a$ and $z = \pm a$ (cf. also the discussion Sturrock-Le Poole,¹). Referring the aberration to the object, it is found for case (1) that the variation $\delta a (=a_{\max} - a_{\min})$ must be $< \frac{1}{4} \delta f$ (δf = permissible longitudinal astigmatism); the astigmatism is due almost entirely to the image-side pole piece. In case (2) if the major axes of the ellipses are parallel, $\delta f/f \approx 4\delta a/a$, while, if they are perpendicular, $\delta f/f \approx 4(\delta a/a)(f/a)^{1/2}$. When the major axes are parallel, the ellipticity of the equipotentials near the axis $\approx$ that of the pole piece bore, at least in the present example.

¹Proceedings of the Conference on Electron Microscopy, Delft, July 1949, p. 93.

392.

New formulae for the third-order aberrations of (axially symmetric) electrostatic lenses, P. Sturrock, *Compt. rend.*, 233, 243-5 (1951). (In French).

Analogous expressions are given to those of ¹.

¹P. Sturrock, *Compt. rend.*, 233, 146-7 (1951). 393.

393.

New formulae for the third-order aberration of (axially symmetric) magnetic lenses, P. Sturrock, *Compt. rend.*, 233, 146-7 (1951). (In French).

Integral expressions, better suited to numerical computation than were those of Glaser and of Scherzer, are given for the aberration coefficients; the integrands are functions of the axial field and of 2 solutions of the paraxial ray equation.

394.

Perturbation characteristic functions and their application to electron optics, P. A. Sturrock, Proc. Roy. Soc. (London), A210, 269-89 (1951).

Attempts to systematize and extend to higher orders the aberration theory of electron optics. Hamilton's "equation of the characteristic function" is derived in the usual way from the variational equation for an unperturbed system. It is then assumed that the variational function, i.e., the integrand of the variational equation, depends on a "perturbation parameter" and the corresponding perturbations of Hamilton's point characteristic function and of Hamilton's differential relation are obtained. The first-order terms, when separated, lead to the introduction of a pair of characteristic functions whose arguments may be - among other choices - the coordinates in the object and aperture surfaces; from these one may obtain the perturbation of the ray throughout its length. The perturbation of rays at a surface which is an image surface of the unperturbed system may be derived from a single characteristic function. Formulae simplify considerably if the unperturbed system is Gaussian or otherwise orthogonal. It is found that there exist two distinct pairs of second-order characteristic functions; this duality offers a means of checking second-order calculations. Once again, perturbations at an image surface may be evaluated from a single characteristic function when calculations are taken beyond the first order, it is necessary to consider more than one parameter, since perturbation effects are then no longer additive. The theory is used to establish formulae for the geometrical, chromatic, and mixed aberrations of two classes of systems; one contains all systems of rotational symmetry, the other all systems with curved axes. Certain transformations which may be applied to the perturbations of a variational function, the use of complex coordinates, and a classification of electron-optical systems according to their aberration calculations are treated in appendices. Although the theory is developed only to the second order, the extension to higher orders is straightforward.

395.

On the theory of aberrations in electron-optic focusing systems with a curvilinear axis. Yu. V. Vandakurov, Zh. tekhn. Fiz., 27, 1850-62 (1957). (In Russian). English Translation in: Soviet Physics - Technical Physics, 2, 1719-33 (1957).

The method of trajectories is applied to derive equations which may be used to compute the second- and third-order geometric aberrations and the first- and second-order chromatic aberrations in the case of arbitrary electric and magnetic fields. Formulae are derived for the above aberrations and for the mass and velocity dispersions. Conditions are found under which geometric aberrations of the second order are absent. All derivations of the general formulae are performed for the relativistic case.

396.

Second-order aberrations in sector shaped electromagnetic analyzers, H. G. Voorhies, Rev. Sci. Inst., 26, 716-17 (1955).

The expressions for the second-order velocity aberration and the second-order angle-velocity aberration are given for a sector-shaped analyzer with superimposed electric and magnetic fields. Focusing is in one plane.

397.

Concerning the nature of the aberrations in electron sheet beams, W. E. Waters, J. Opt. Soc. Am., 49, 304-7 (1959).

A power-series expansion is used to derive expressions for the aberrations up to the third order in electron sheet beams, subject to purely electrostatic focusing. The "ray axis" is considered to be curvilinear in general. Chromatic effects are considered but space charge is omitted. The treatment reveals the presence of four purely geometric aberrations and four others due to chromatic effects. No attempt is made to derive expressions for the aberration coefficients.

See also: 2, 6, 7, 10, 11, 20, 35, 64, 86, 114, 116, 122, 153, 163, 164, 184, 190, 192, 200, 201, 204, 206, 217, 249, 251, 260, 268, 282, 289, 296, 303, 321, 324, 338, 339, 542, 558, 570, 572, 573, 574, 578, 580, 583, 587, 590, 597, 601, 611, 722, 723.

LENS ERRORS - ASTIGMATISM

398.

Magnetic deflexion of electron beams without astigmatism, G. D. Archard and T. Mulvey, J. Sci. Instr., 35, 279-83 (1958).

An electron beam passing through a magnetic deflecting field is, in general, subject to astigmatism. For circular pole pieces, this takes the form of focusing in the plane of deflection; for square pole pieces, focusing perpendicular to the plane of deflection. Deflection free from astigmatism can be achieved by means of circular pole pieces from which semicircular portions have been removed. An application of this to reflection electron microscopy is described.

399.

The detection and direct measurement of the axial astigmatism (astigmatisme d'ellipticite) of an electron lens, R. Castaing, Compt. rend., 231, 894-6 (1950). (In French).

Measurements on an electrostatic lens have confirmed the theory given.¹ The object was a metallized Perspex ("plexiglass") thread,

$\sim 0.1 \mu$ in diameter. Measurements of the distorted line observed gave the astigmatic constant in terms of the spherical aberration. Correction of axial astigmatism by Berstein's method² could be detected with fair exactitude.

¹Compt. rend., 231, 835-7 (1950).

²Compt. rend., 225, 801-3 (1947).

400.

Image aberrations due to asymmetry in (magnetic) electron lenses, W. Glaser and P. Schiske, Z. angew. Phys., 5, 329-39 (1953). (In German).

The astigmatic aberrations arising from geometrical asymmetry of the pole pieces of magnetic lenses are treated for the most general conditions. Lack of rotational symmetry in the bore, lateral displacement, and inclination of one pole piece with respect to the other are all discussed. Equations are set up for the form of the pole-piece surfaces in the disturbed conditions. The boundary value problem is solved by using an expression for the axial potential within the polepieces due to Pertram.¹ The departure from rotational symmetry of the magnetic field, in function of the ratio of bore to pole-piece gap, is then found by Fourier transformation. The astigmatism coefficients follow from the axial distribution of the disturbed field. Tables of these coefficients are given for various values of bore/gap ratio and of an excitation parameter. Numerical comparison is made with the results obtained for a special type of magnetic lens by Sturrock² using a different method of calculation.

¹J. Appl. Phys., 13, 496 (1942)

²Phil. Trans. Roy. Soc. (London), A243, 387-429 (1951) 391

401.

Measurement of the astigmatism of electrostatic lenses, R. Gobrecht, Exper. Tech. der Phys., 6, 241-9 (1958). (In German).

The astigmatic aberrations of an electrostatic immersion lens were experimentally investigated in both accelerating and retarding conditions. The aperture diameter, focal length, and distance of the object point from the axis were independently varied. Agreement with the third-order theory was reasonably good, but better for the retarding than for the accelerating lens. The Seidel coefficient S_4 is not constant but falls rapidly with increasing focal length; its value is greater for a retarding than for the corresponding accelerating lens.

402.

Conditions for the correction of astigmatism and of curvature of field in (axially symmetric electrostatic) electron lenses, P. P. Kas'yankov, J. Tech. Phys., USSR, 20, 1426-34 (1950). (In Russian).

Starting from the differential ray equation, necessary and sufficient conditions are formulated for the correction of astigmatism, meridional and sagittal curvature of field. These conditions are expressed in terms of explicit functions of the axial potential and its derivatives, and have to be satisfied throughout the lens.

403.

An electron lens system excited by permanent magnets with a new astigmatism compensator, H. Kimure and S. Katagiri, Optik, 16, 50-6 (1959).

In the HS-5 electron microscope (Hitachi Central Research Laboratory, Japan) all the lenses are excited by permanent magnets. The objective and projection lenses are of the single-gap type, the condenser and intermediate of the double-gap type. The construction is reported. The astigmatism of the objective lens is compensated with a new compensator. The compensator is a nickel-plated copper cylinder with a slitted head. The strength of the asymmetric magnetic field in the compensator is controlled by the thickness of plated nickel. To find quickly the compensating condition, the vector representation of the astigmatism is used.

404.

On astigmatism in electron lenses, S. Leisegang, Optik, 10, 5-14 (1953). (In German).

The caustic surfaces calculated by Glaser enable a simple test of the axial astigmatism to be made. The agreement between the calculated and experimental results is shown. Regenstreif's formulae for the caustic cross section allow higher order errors to be quantitatively investigated. The results lead to a simple test for a magnetic stigmator.

405.

Stigmatic imaging in rotationally asymmetrical electron lenses, F. Lenz, Optik, 15, 393-7 (1958). (In German).

A small asymmetrical disturbance in an otherwise rotationally symmetrical field introduces a first-order astigmatism and a first-order distortion, additional to the normal aberrations of the undisturbed lens. In the object plane of such an asymmetric lens there will exist a

point for which the normal (Seidel) astigmatism is balanced by the adventitious astigmatism due to the disturbed field. Such a point will be imaged stigmatically, being affected only by spherical aberration, provided that the imaging beam can be properly centered on it; that is, it now has the properties of the axial point in a rotationally symmetrical field. If this point can be found experimentally and the beam aligned upon it, a resolution should be obtained equal to that reached by using a stigmator to correct rotational asymmetry. A numerical example, assuming a bell-shaped field of strength k^2 equal to unity, and a degree of astigmatism (2μ) normal in a magnetic lens, shows that the stigmatic object point would be about 130μ off the axis.

406.

Singular astigmatic electron optical systems. I and II, A. Melkich, S. B. Akad. Wiss. Wien, 155, Abt. IIa (Nos. 9-10) 393-71 (1947). (In German).

Electromagnetic cylindrical lenses having one plane of refractive index symmetry, and then systems with two perpendicular planes of symmetry are considered. This enables the simultaneous focusing of several independent electron beams by a common electric or magnetic lens. The potentials, fields, electron-optic properties, and picture distortion of these systems are calculated. Methods of compensating the axial astigmatism of the electric and magnetic fields are given. The necessary conditions for picture formation by systems having two perpendicular planes of symmetry of refractive index are investigated. The special system giving a twist-free image is considered, and conditions for optimum picture representation given. A geometrical discussion of characteristic picture distortion is included.

407.

An astigmatic electron lens which can be simply adjusted for refracting power and azimuth, O. Rang, Phys. Bl., 5, (No. 2) 78-80 (1949). (In German).

Following a suggestion of Scherzer a correcting field which can be rotated electrically is used. Six electrodes are arranged symmetrically around the optic axis. Opposite pairs are connected together, one pair being connected to the anode and the others to variable potential sources. This electrical eccentricity corrects the mechanical eccentricity of the main lens.

408.

The electrostatic "Stigmator," a corrector for astigmatic electron lenses, O. Rang, *Optik*, 5, 518-30 (1949). (In German).

Describes an experimental arrangement for carrying out Scherzer's¹ proposal to correct a lens by using two cylinder lenses with focal powers oriented in opposing directions. Six axial electrodes are connected to a potentiometer system which allows the focal power and angular position to be independently adjusted.

¹*Optik*, 2, 114-32 (1947).

409.

On an independent electrostatic lens with minimum elliptic astigmatism, E. Regenstreif, *J. phys. radium*, 12, 760-1 (1951). (In French).

See Regenstreif.¹ The longitudinal astigmatism is proportional to the ellipticity, the factor of proportionality depending only on the axially symmetric lens.

¹*Compt. rend.*, 232, 1918-20 (1951). 310.

See also: 114, 116, 267, 299, 367, 384, 391, 582.

LENS ERRORS - CHROMATIC ABERRATION

410.

A possible chromatic correction system for electron lenses, G. D. Archard, *Proc Phys. Soc.*, (London), B68, 817-29 (1955).

It is shown that a suitably arranged group of four electrodes has properties which make it a useful integral part of a system for the correction of axial chromatic aberration. Its application to the correction system proposed by Scherzer and to a new simplified system having certain advantages over that of Scherzer is discussed. Curves are given for the chromatic and focal properties of the corrective electrode group, and an example of a corrective system is considered numerically. The effect of this system on off-axial chromatic aberration is investigated, and the possibility of combining it with a system for spherical correction is envisaged.

411.

Asymmetric magnetic electron lenses, P. Durandeu, C. Fert, and P. Tardieu, *Compt. rend.*, 246, 79-81 (1958). (In French).

The focal properties and chromatic aberrations of asymmetric magnetic lenses are presented in the form of reduced curves, in which the minimum focal length obtainable is used as the unit of length.

412.

On the chromatic aberration of electron lenses, H. Grümme, *Ann. Phys.*, 14, 193-200 (1954). (In German).

The chromatic aberration of electron lenses is investigated by the methods of wave mechanics.¹ In this way it is possible to evaluate the intensity distribution in the image, which cannot be done in geometrical optics. As in the latter method, certain simplifications are introduced in order to obtain results of practical significance. The case of a simple amplitude object (circular hole) is taken, and expressions are obtained for the "first" chromatic coefficient, relating to the shift of the image plane, and the "second" coefficient, relating to the change in magnification. It is shown that in the ideal case correction can be obtained, since the coefficients are of opposite sign. In the practical case of a bell-shaped magnetic field, the compensation is not perfect but has a minimum when the lens strength parameter $k^2 = 1$. It is concluded that previous estimates of the chromatic aberration have been too pessimistic.

¹W. Glaser and P. Schiske, *Ann. Phys.*, 12, 240-280 (1953).

413.

Experimental investigation of chromatic aberration in the electron microscope, S. Katagiri, *Rev. Sci. Instr.*, 26, 870-3 (1955).

Experimental results on the reduction of chromatic aberration in the magnetic electron microscope are described. It is proved that the chromatic field aberration can be completely compensated by a proper combination of two lenses with adequately designed pole pieces and the voltage stabilization tolerance is greatly improved. Micrographs with a resolution of about $5 \text{ m}\mu$ can be obtained even under a voltage fluctuation as large as $\Delta E/E = 1 \times 10^{-2}$.

414.

On the chromatic resolving power of electron lenses used for velocity analysis, F. Lenz, *Optik*, 10, 439-46 (1953). (In German).

The chromatic aberration in rotational symmetric lenses is evaluated in relation to the results of Möllenstedt. For $V = 40$ kV the limit of resolving power is $\approx 0.03V$ for electrostatic and $1V$ for magnetic lenses. However, for a source at 2700°K the initial thermal fluctuations are at least $0.23V$, so they will normally be the limiting factor in electrostatic lens systems.

415.

The magnetic electron microscope objective lens of lowest chromatic aberration, G. Liebmann, *Proc. Phys. Soc. (London)*, B65, 188-92 (1952).

The shortest focal length f and smallest chromatic aberration constant C_c of an objective lens is directly proportional to the square root of the (corrected) accelerating voltage V_ν and inversely proportional to the maximum magnetic field strength H_ρ in the parallel part of the pole piece gap. For given values of V_ν and H_ρ , both f and C_c fall monotonically with the relative pole-piece separation S/D , although the reduction is insignificant for $S/D > 2$. For each lens geometry there exists an optimum set of lens dimensions.

416.

Chromatic aberration and resolving power of electron microscopes, W. E. Meyer, *Optik*, 15, 43-6 (1958). (In German).

The effect of chromatic aberration on the resolving power of electron microscopes is calculated approximately. In contradiction to the usual estimations, the resolution limit in the case of very large chromatic aberration is found to exceed the one resulting in the case of vanishing chromatic aberration by only a factor of 1.4.

417.

On the chromatic field aberration of the magnetic electron lens in the electron microscope, N. Morito, *J. Appl. Phys.*, 25, 986-94 (1954).

The chromatic field aberration of the magnetic lens in the electron microscope is theoretically studied. Good results are obtained for the coefficient of the chromatic difference in magnification of the objective, taking into account the inclination of the principal illuminating rays. The same coefficient of the intermediate lens increases rapidly as the magnification is reduced by the intermediate lens. The calculated

results agree well with experimental results. Calculated results are given for the coefficients of chromatic difference in rotation of all lenses as well as for the coefficient of chromatic difference in magnification of the projection lens.

418.

The lower limits of focal length and chromatic errors in magnetic electron lenses, O. Scherzer, Z. Phys., 118, 461-6 (1941). (In German).

The lower limits are primarily determined by mechanical considerations. A characteristic length is defined as $S = -H^{-1}(\partial H / \partial x)$. If the upper limit of S is put $= \ell^{-1}$ then $\ell/100$ is the length in which the axial field changes by 1%. This length should be of the order of dimensions of the lens aperture. It is shown that $f > 0.8\ell$. The chromatic aberration $\simeq \ell/2U$ (U = velocity).

419.

The lower limit of the chromatic-aberration of magnetic lenses having a prescribed maximum field strength, P. Schiske, Optik, 13, 502-5 (1956). (In German).

The minimum chromatic aberration of magnetic electron lenses with given maximum field strength is calculated and compared with earlier estimates. The field form required for this could be approached, but never quite reached in practice.

420.

O teoreticheskikh granitsakh koeffitsienta khromaticheskoi aberratsii v ogranichennykh magnitnykh polyakh elektronnoi optiki, O. I. Seman, Radiotekhnika (i Elektronika,) 4, 1702-7 (1959). See also English translation in Radio Eng. & Electronics, 4, 235-44 (1959).

Theoretical boundaries of chromatic aberration coefficient in limited magnetic fields of electron optics; use of variation method to determine such boundary fields for given projection, system length, and magnetic field not exceeding specified maximum.

421.

Effective region (Existenzbereiche) of rotationally symmetric electron lenses, W. Tretner, Optik, 16, 155-84 (1959). (In German).

By applying the calculus of variations, it is shown how the chromatic aberration and the aperture defect of an electron-optical system are restricted by parameters of the field and of the Gaussian dioptrics.

422.

The measurement of the chromatic aberration constant of magnetic lenses, H. Watanabe and N. Morito, *Optik*, 12, 166-72 (1955). (In German).

The axial chromatic aberration constant of a magnetic lens is difficult to measure experimentally since it usually appears as a disk of confusion. The authors show that the axial chromatic aberration causes an image shift if the contrast aperture of the objective is displaced sideways from the optical axis. This image shift varies linearly with change in accelerating voltage and with the angle that the electrons make with the optical axis. To measure the latter, a magnesium oxide crystal is used as an object, and a diffracted ray of known inclination is selected by the contrast diaphragm and imaged by a second lens on to a photographic plate. The values of chromatic aberration obtained from the shift of this ray with change in accelerating voltage agree well with theoretical calculations.

423.

Compensation of the chromatic field aberration in the electrostatic electron microscope, W. Weitsch, *Optik*, 15, 492-9 (1958). (In German).

Projection lenses of electrostatic type are usually designed to be free from distortion and also from chromatic difference in magnification across the field. The objective has to be operated in slightly different conditions, to ensure that the front focus is in field-free space, and it may then have considerable chromatic field aberration, which causes undue confusion in the image when the specimen is thick enough to produce appreciable voltage loss of the electron beam. Partial compensation can be made by operating the projection lens in conditions giving distortion of opposite sign to that of the objective. Compensation over a wider field can be obtained if two projection stages are employed, and the operating points of the two projectors are correctly chosen. A slight distortion of the final image, or a greater restriction of the image field, must then be tolerated, however.

See also: 27, 73, 135, 148, 176, 177, 179, 308, 348, 350, 351, 371, 381, 382, 390, 394, 395, 494, 558, 573, 611, 806, 818.

LENS ERRORS - SPHERICAL ABERRATION

424.

Fifth order spherical aberration of magnetic lenses, G. D. Archard, *Brit. J. Appl. Phys.*, 11, 521-2 (1960).

Knowledge of the fifth-order spherical aberration of magnetic lenses is required in order to show how much error is left when

third-order aberration is corrected. This is found theoretically for lenses of the bell-shaped field type. It is found that, for lenses of moderate strength, third- and fifth-order coefficients are numerically very similar.

425.

Requirements contributing to the design of devices used in correcting electron lenses, G. D. Archard, Brit. J. Appl. Phys., 5, 294-9 (1954).

The voltage requirements for a modification of the spherical correction system of Seeliger are given. The potential changes introduced by unintentional asymmetries of nonrotationally-symmetrical elements are calculated, and an expression is given for the resulting aberrations. It is shown that some of these can be removed by the Stigmator of Rang,¹ but that others remain which would necessitate positioning to 1μ in order to attain a resolution improvement of three times. With the addition of certain other elements, tolerances could be raised to 10μ for a resolution improvement of ten times. In the course of the work, the mechanism of Seeliger's system and its suggested modification are compared with another system proposed by Burfoot.

¹Optik, 5, 518-30 (1959) 408.

426.

Two new simplified systems for the correction of spherical aberration in electron lenses, G. D. Archard, Proc. Phys. Soc., (London) B68, 156-64 (1955).

Two new simplified electrostatic systems for the correction of third-order spherical aberration in electron lenses are described and related to earlier systems of Seeliger and Burfoot. Numerical examples are given in which the voltages and positioning tolerances of the various electrodes are calculated. The effects of scaling and change of electrode shape are discussed.

427.

"Some results of mass-spectrum analysis," K. T. Bainbridge, Proceedings of the Seventh Solvay Conference, 55 (Stoops, R. ed. Brussels, Belgium, 1948).

Presents a method for eliminating the second-order spherical aberration for the horizontal plane for bending magnets.

428.

Spherical aberration coefficient of asymmetrical magnetic electron lenses, J. Barthere, J. Dugas, and P. Durandeu, *Compt. rend.*, 250, 3461-3 (1960). (In French).

The spherical-aberration coefficient has been calculated for a series of magnetic lenses in which the ratio of the bores (D_1/D_2) of the pole pieces varied from 1:3 to 3:1, whilst their sum ($D_1 + D_2$) was constant and equal to the separations of the pole pieces. The axial field distributions needed for the calculation were taken from the measurements of Durandeu, Fagot, Barthere and Laudet (*J. phys. radium*, 20, 80A, 1959). A similar calculation for symmetrical lenses was in good agreement with the results of Liebmann and Grad.

See:

1. G. Liebmann, and E. M. Grad, *Proc. Phys. Soc. (London)*, B64, 956-71 (1951). 184
2. G. Liebmann, *Proc. Phys. Soc. (London)*, B64, 972-7 (1951). 442.

429.

Spherical aberration of gridded lenses, M. Bernard, *Compt. rend.*, 235, 1115-17 (1952). (In French).

The aberration coefficient is calculated for the approximation of a continuous membrane transparent to electrons. The coefficient is positive for converging lenses and negative for diverging lenses.

430.

Principle of a lens spectrometer with envelope diaphragms, H. Daniel, *Z. Naturforsch.*, 12a, 940-1 (1957). (In German).

Use is made of the spherical-aberration properties of a thin magnetic lens. Expressions for the electron deflection are given and approximate conditions for the diaphragm positions discussed.

431.

Spherical aberration of weak magnetic lenses, P. Durandeu, B. Fagot, and C. Fert, *Compt. rend.*, 248, 946-9 (1959). (In French).

The focal properties of weak magnetic lenses are evaluated using the measured axial field distribution. The results are in agreement with calculations by previous authors.

432.

The rotating beam method for investigating electron lenses, D. E. George, R. G. E. Hutter, and M. Cooperstein, *Sylv. Techn.*, 4, 41-3 (April 1951).

If a narrow electron beam is scanned elliptically and the lens under test is of such a strength that the paraxial image of the centre of deflection is on the fluorescent screen, then spherical aberration will produce an approximate figure of 8. This will be unsymmetrically distorted if the alignment is faulty or if the lens lacks axial symmetry. In the absence of these 2 defects, circular scanning will give a circular trace whose radius is the transverse spherical aberration. (Aberration of the scanning system is not discussed.)

433.

The correction of the spherical aberration of electron lenses using a correcting foil element, U. F. Gianola, *Proc. Phys. Soc. (London)*, B63, 1037-9 (1950).

The negative spherical aberration produced by a pair of plane parallel conducting foils suitably placed in an electron-lens system is described and analyzed mathematically. The use of such foils as correcting elements and the problems arising in the design of a foil-corrected lens are briefly discussed.

434.

Reduction of the spherical aberration of magnetic electron lenses, U. F. Gianola, *Proc. Phys. Soc. (London)*, B63, 703-8 (1950).

The dependence of the resolving power of the asymmetrical bell-shaped magnetic field on the lens parameters is examined for varying degrees of field asymmetry. It is shown that a high asymmetry index favours high resolution, and a preferable value of lens power is specified. By suitably reinforcing the lens field with that of a small air-cored coil, the theoretical resolving power of the lens is increased. On account of the small size of the coil, the coil current must be pulsed intermittently if an appreciable reinforcing field is to be produced. The basic factors governing the design and operation of a suitable coil are discussed.

435.

On the spherical aberration of magnetic electron lenses, W. Glaser, *Optik*, 13, 7-12 (1956). (In German).

It is shown that the lower limits of spherical aberration derived by Tretner¹ cannot be upheld since a "trough-shaped" field (analytically

complementary to a "bell-shaped" field) yields considerably lower values. The trough-shaped field possesses inferior refractive power, but useful imaging is still possible, though the concept of "focal length" loses its normal meaning.

¹W. Tretner, *Optik*, 11, 312-26 (1954). 459

436.

A comparison of the spherical aberration of weak electrostatic and magnetic electron lenses, R. Gobrecht, *Exper. Tech. der Phys.*, 4, 215-31 (1956). (In German).

The spherical-aberration coefficient of electrostatic (cylinder) immersion lenses and air-cored magnetic lenses is determined experimentally and compared from the point of view of cathode-ray-tube practice. Extensive data are given in tabular form.

437.

On the estimation of the lower limit of spherical aberration of magnetic electron lenses, H. Grümmer, *Optik*, 13, 92-3 (1956). (In German).

The theory of Tretner,¹ which gave a lower limit to the spherical aberration of magnetic lenses, failed to consider one specific type. It was therefore hoped that this type would yield a lower aberration, but numerical calculations reveal that Tretner's limitations apply to this also.

¹W. Tretner, *Optik*, 11 312-26 (1954). 459

438.

Comparative study of the spherical aberration of symmetrical and asymmetrical unipotential electron lenses on the basis of measurements of the tangent to the exit ray, K. J. Hanssen, *Z. Naturforsch.*, 13a, 409-14 (1958). (In German).

The investigation of the differing properties of symmetrical and asymmetrical electrostatic lenses is now extended from the paraxial¹ to the marginal rays. Instead of using the normal cardinal elements of a focusing system, the position of which varies rapidly with the height of the incident ray, the lens properties are described in terms of the tangents to the entrant and exit rays. The axial spherical aberration of an asymmetrical lens, according as the effective centre of the former lies on the object or the image side of the system, is considered.

¹K. J. Hanssen, *Optik*, 15, 304-17 (1958).

439.

Spherical aberration due to initial path angle and lens curvature in aperture electron lenses, L. A. Harris, Proc. Inst. Radio Engrs., 48, 368-9 (1960).

Thin lens electron optics of an aperture in (a) a spherical and (b) a cylindrical electrode are discussed: an extension of the Davisson-Calbick theory for a plane electrode is given, assuming zero field on the exit side but not making the paraxial approximation.

440.

An aberration phenomenon in electrostatic lenses, S. Harrison, J. Appl. Phys., 20, 412-14 (1949).

An explanation, based on spherical aberration, of the kidney-shaped dark patches observed in c.r.t.s. subjected to an extreme degree of de-focusing.

441.

On a new test method for spherical aberration of electron lenses, O. Klemperer, Proc. Phys. Soc. (London), B64, 790-4 (1951).

The focus of rays from a lens with spherical aberration appears as a spot surrounded by a discrete halo ring if a diaphragm with fine circular aperture is placed across the beam in front of the focus. The diameter of the halo allows an estimate of the magnitude of the aberration involved. The geometry of rays forming the halo is explained here by schematic drawings. The practical application of the halo test is illustrated by some examples. In particular, the negative spherical aberration produced by an electronic space charge in a saddle field lens is demonstrated.

442.

The symmetrical magnetic electron microscope objective lens with lowest spherical aberration, G. Liebmann, Proc. Phys. Soc. (London), B64, 972-7 (1951).

Each of the investigated symmetrical magnetic lenses¹ has an optimum value of the lens excitation parameter for which the spherical aberration constant is smallest. Taking account of the dependence of the maximum obtainable axial field strength H_0 on the maximum field strength H_p in the pole-piece gap, one finds that there is an optimum design of electron microscope objective lens of conventional type which gives a lowest value of spherical aberration and highest resolving power. A modification of this optimum lens as adapted for practical use is described.

¹G. Liebmann and E. M. Grad, Proc. Phys. Soc. (London), B64, 956-71 (1951). 184

443.

The focal properties and spherical aberration constants of aperture electron lenses, M. M. MacNaughton, Proc. Phys. Soc. (London), B65, 590-6 (1952).

The focal properties and spherical-aberration constants of a number of aperture electron lenses of varying diaphragm thickness and varying strength were determined numerically with potential distributions obtained (a) from a rigorous solution due to Ollendorff (1932), and (b) on a resistor network analogue. The focal lengths of "weak" aperture lenses of finite diaphragm thickness agree closely with those given by Davisson and Calbick's (1931, 1932) formula for the "infinitely" thin aperture lens; "strong" aperture lenses of all thicknesses show systematic deviations from this formula. The primary spherical aberration constants of diverging aperture lenses are small, and of such sign that they cannot be used for the correction of the spherical aberration of converging electron lenses.

444.

Spherical aberration of quadrupole magnetic lenses, M. G. Markovich and I. I. Tsukkerman, Zh. Tekh. Fiz., 30, 1362-8 (Nov. 1960). (In Russian). (English translation in: Soviet Physics-Technical Physics, 5, No. 11, 1292-7 (1961).

Expressions for the spherical aberration of asymmetrical magnetic quadrupoles are given, special attention being paid to terms of negative sign. It is shown that, by altering the degree of asymmetry the relative magnitudes of positive and negative terms can be altered, and it is further claimed that under suitable conditions, the overall aberration may be made negative.

445.

The spherical aberration of fifth order of spherically corrected electron microscopes, W. E. Meyer, Optik, 13, 86-91 (1956). (In German).

The effect of fifth-order spherical aberration in a system incorporating third-order correctors is calculated and found to agree with experiment. Partial correction of the fifth-order terms could be most simply achieved by placing one of the third-order correctors inside the lens under correction, and properly siting the remaining correctors. The theoretical resolving power of a typical lens (10 Å without correction) would become 1 Å.

446.

Electron optical images with an objective connected according to O. Scherzer, G. Möllenstedt, Optik, 13, 209-15 (1956). (In German).

The lens system proposed by Scherzer for correcting spherical aberration and constructed by Seeliger [Optik, 4, 258, (1948-49)] has been improved further. The operating voltage has been increased from 25 to 40 kV, and a magnetic condenser lens has been fitted. Up to now, a resolving power of 30 Å has been attained, but it is hoped by removing stray varying magnetic fields and other disturbing effects to attain a resolving power of 2 Å.

447.

Zonal correction of spherical aberration in magnetic lenses, G. Nadeau, Atti accad. nazl Lincei, 10, 225-9 (March 1951). (In French).

Following the suggestion of Persico,¹ the correcting action of dipole fields is considered. The r - z differential equation of nonskew rays has been numerically integrated, by a method which is described, for coaxial combinations of a circular conductor and 2 dipoles, respectively, between object and conductor and between image and conductor. Graphs are shown of the axial displacement of the marginal focus v . aperture angle, in the zone of correction, for 3 unsymmetrical combinations of dipole strengths and positions, and one value of the current, the magnification being close to unity; it is assumed that the 3 fields do not interfere. Each graph shows a maximum between 2 minima. If a displacement tolerance of 0.013 of the "focal length" (defined on the assumption that the combination is a thin lens) is allowed, the systems collect solid angles of 0.12 to 0.19 steradians, compared with 0.004 for the conductor without dipoles.

¹E. Persico, Atti accad. nazl. Lincei, 7, 191-5 (Nov 1949) 448.

448.

The dipole as a diverging magnetic lens, E. Persico, Atti accad. nazl. Lincei, 7, 191-5 (Nov 1949). (In Italian).

A magnetic dipole along the axis of an electron microscope behaves as a diverging lens of high spherical aberration. Its focal length for electrons at a distance from the axis is given approximately by $f = -(16\pi/9)a^5(1 + a^{-4})$. It is suggested that diverging lenses of this type may be used for correcting the spherical aberration of an ordinary magnetic lens.

449.

On some aberrations of electrostatic systems having diad symmetry,
I. M. Pilat, E. D. Reznik, and A. M. Strashkevich, Zh. tekhn. Fiz., 21,
1149-52 (1951). (In Russian).

Formulae are given resulting from the application of theory described previously¹ to these fields, and in particular to the perturbed unipotential lens. An integral expression is given for the spherical aberration so that conditions for its correction (Scherzer, 1947) may in principle be found.

¹A. M. Strashkevich and I. M. Pilat, Izv. Akad. Nauk SSSR, Ser. Fiz., 15, 448-66, (1951). 389

450.

Adjustment of spherically corrected electron optical systems,
R. Seeliger, Optik, 10, 29-41 (1953). (In German).

An electrostatic electron microscope is described which has third-order spherical correction. The system comprises 2 ring lenses, 2 cylindrical lenses, a "stigmator" (an 8-electrode device for removing first-order astigmatism), and 3 "corrector" electrodes. The method of adjusting the potentials of the various components to obtain correction is described. At an angular aperture of 2.6×10^{-2} , the use of the correcting system reduced the image defects to 6% of their original magnitude.

451.

Experiments on the spherical correction of electron lenses by means of image elements which are not rotation-symmetrical, R. Seeliger, Optik, 5, 490-6 (1949). (In German).

Tests on an arrangement proposed by Scherzer¹ are described. This consists of 8 axial plates connected alternately positive and negative. The radial field in such an arrangement is $E_R = -4aR^3 \cos 4\theta$ so the third-order aberration can be eliminated in two perpendicular directions, but is doubled in two perpendicular directions at 45° to the first pair. Scherzer further proposed the use of a strongly astigmatic region to eliminate the last effect. The tests showed that the 8-electrode collector functioned as desired and, although some fifth-order distortion was introduced, it was too small to be of importance. No further improvement as found when the astigmatic system was inserted.

¹Optik, 2, 114-32 (1947). 382.

452.

The spherical correction of electron lenses by means of a non-rotationally symmetric image element, R. Seeliger, *Optik*, 8, 311-17 (1951).

The correction of a third-order aperture error in an electron lens with a fourfold "correction" piece consisting of two principal sections perpendicular to each other was demonstrated. This error was also successfully corrected in all axis intersections by a tele-central system consisting of 2 cylindrical lenses, a spherical lens, and 3 "correction" lenses. A new, practical form for a correction piece of higher precision is given. By the correction of the aperture error of the third order, an error of the fifth order occurs, whose error constant C_5 lies, by different axis intersections, between 11 m and 35 m.

453.

On the existence of an extremum of the coefficient of spherical aberration for axially symmetric systems in electron optics, O. I. Seman, *Zh. eksper. teor. Fiz.*, 24, 581-8 (1953). (In Russian).

The question of the existence of an extremum is treated as a variational problem, and the corresponding Euler equations are set up, the electrostatic and magnetic fields being taken as variable but other conditions (e.g., potentials and fields at object and image, magnification, separation of principal planes) fixed. It is shown that there cannot be real focusing if the spherical aberration is an extremum, assuming there to be no space charge. The author draws attention, however, to some doubt in the case where the magnetic field is given and an extremal electrostatic field sought. When there is no extremum, there is still a lower bound to the spherical aberration, but if there is no restriction on the fields this bound is zero. The problem of finding limiting values of the aberration for realizable fields has not yet been solved.

454.

Correction of the spherical aberration of electrostatic quadrupole lenses functioning astigmatically, A. Septier and J. van Acker, *Compt. rend.*, 251, 1750-2 (1960). (In French).

Three methods are proposed for correcting the effect of spherical aberration on the focal lines formed by a quadrupole lens (or a doublet): by introducing a degree of asymmetry in the applied potential, by slight modification of the electrode form, or by adding an octupole lens to the system.

455.

An experimental study of the spherical aberration of a system of two magnetic quadrupole lenses, A. Septier, *Compt. rend.*, 245, 1905-8 (1957). (In French).

The aberrations of a system of two magnetic quadrupole lenses were investigated experimentally using the electron optical bench (See 732*). The lenses were 15 cm long and spaced 50 cm apart. The lens aperture was 4.0 cm. Accurate calculation of such a system is not feasible owing to the complex end effects of the magnetic circuit. In addition, the effective length of the lens decreases with increasing ray height. This leads to a negative spherical aberration. The experimental results show that such a quadrupole system of short focal length has a spherical aberration comparable with the best classical round lenses. It should be possible to correct the spherical aberration of the system by introducing positive spherical aberration by suitably altering the field distribution in one of the quadrupoles.

*A. Septier, *Compt. rend.*, 245, 1406 (1957).

456.

Measurement of the spherical aberration of electrostatic quadrupole lenses, A. Septier and J. van Acker, *Compt. rend.*, 251, 346-8 (1960). (In French).

Describes measurements of the spherical aberration of an electrostatic quadrupole lens operating at 10 kV and traversed by 50-keV electrons. It is shown that the electrical symmetry about the optical axis of the voltage applied to the quadrupole influences the spherical aberration coefficient.

457.

Calculation of spherical aberration for the electrostatic electron lens, D. W. Shipley, *Sylvania Technol.*, 5, 87-93 (Oct 1952).

Integral expressions for the coefficient of spherical aberration of an electrostatic electron lens contain the axial potential distribution of the lens and a particular solution of the paraxial-ray equation. The axial potential distribution is determined by means of the electrolytic tank; the particular paraxial-ray path is obtained by a method of successive approximations. The coefficient of spherical aberration of the lens is calculated by numerical integration. Finally, the result is compared with a value which was measured experimentally.

458.

A method for the measurement of spherical aberration of an electrostatic electron lens, D. W. Shipley, J. Appl. Phys., 23, 1310-16 (1952).

A relatively simple method for the experimental determination of spherical aberration of electrostatic electron lenses is described. This method uses an effective point source of electrons at the centre of deflection of a magnetic deflection yoke; the yoke deflects the beam through any desired aperture angle. From the measurement of the displacement of the electron-beam in the Gaussian image plane as a function of the aperture angle, the coefficient of spherical aberration can be calculated. The value for this coefficient obtained from the measurement of a unipotential lens and that calculated for this lens by numerical integration are compared; the agreement is within 12%. An effective method for the detection of axial astigmatism (which is due to an ellipticity of the lens field) of a lens is described. Diagrams and photographs are given which qualitatively substantiate the method.

459.

The lower limit of spherical aberration in magnetic electron lenses, W. Tretner, Optik, 11, 312-26 (1954). (In German).

It is shown, by a thoroughly discussed variation method from which the relevant externals are carefully selected, that the spherical-aberration constant C^3 is always greater than or equal to the greater of two quantities involving respectively the parameters $H_{\max}$ and $(H'/H)_{\max}$. The optimum value of C^3 would lead to a resolving power of $\sim 2\text{\AA}$, but would involve unattainable values of the parameters. It would moreover be undesirable to approach this condition as the focal length would simultaneously tend to infinity.

460.

On the lower limit of spherical aberration in magnetic electron lenses, W. Tretner, Optik, 13, 516-19 (1956). (In German).

Following criticism of his earlier work by Gr $\ddot{u}$ mm,¹ the author expands this and discusses in detail the various factors affecting the minimization of spherical aberration in magnetic lenses.

¹H. Gr $\ddot{u}$ mm, Optik, 13, 92-3 (1956). 437.

See also: 146, 176, 177, 179, 185, 234, 296, 321, 338, 346, 348, 350, 369, 370, 374, 381, 382, 384, 388, 410, 499, 547, 558, 576, 695, 806.

INSTRUMENTATION

461.

Crossed electric and magnetic field multichannel ion analyzer,
L. E. Bailey, Rev. Sci. Instr., 31, 1147-52 (1960).

A multichannel mass and energy analyzer with crossed electric and magnetic fields for ion separation has been constructed to analyze plasmas produced in conjunction with a magnetic-mirror machine. Ions are piped between the strong magnetic field of the mirror machine and the weaker magnetic field of the analyzer by auxiliary magnetic coils, and they enter the analyzer traveling in a direction nearly parallel to the magnetic field. There, the ions are accelerated by the electric field and assume cycloid-like trajectories in the plane perpendicular to the magnetic field. The ions are collected by detectors located at the top of the cycloid. The amplitude of the cycloid is determined by the e/m of the ion; the distance traversed parallel to the magnetic field before collection is proportional to the velocity of the ion.

462.

Resonator particle separator, J. P. Blewett, U. S. Patent 3, 016, 458
(Jan 9, 1962).

A wave-guide resonator structure is described for use in separating particles of equal momentum but differing in mass and having energies exceeding one billion electron volts. The particles are those of subatomic size and are generally produced as a result of the bombardment of a target by a beam such as protons produced in a high-energy accelerator. In this wave-guide construction, the particles undergo preferential deflection as a result of the presence of an electric field. The boundary conditions established in the resonator are such as to eliminate an interfering magnetic component, and to otherwise phase the electric field to obtain a traveling wave such as one which moves at the same speed as the unwanted particle. The latter undergoes continuous deflection over the whole length of the device and is, therefore, eliminated while the wanted particle is deflected in opposite directions over the length of the resonator and is thus able to enter an exit aperture.

463.

La Separation des particles au Moyen de Champs H. F. (The Separation of Particles by means of HF fields), M. Geiger, P. Lapostolle, and B. Montague, CERN-61-26 (Sept 28, 1961). 23 p.

Discussion is given on the selection of a hf separator, the definition and calculations of deviations and separations in hf electrostatic separators, methods of calculation, and various types of separators utilizing hf.

464.

Separation of high-energy particles by means of strong interaction processes, G. Goldhaber, S. Goldhaber, and B. Peters, CERN-61-3 (Jan 27, 1961) 18 p.

Studies of strongly interacting particles in the Bev region produced experimental results which can be extrapolated to 10 Bev. These results indicate that there are many interactions in which a particle, belonging to the same isotopic multiplet and carrying the same baryon number as the incident particle, emerges within a narrow cone around the forward direction with a large share of the available energy. In collisions between high-energy π -mesons with nucleons, a baryon is emitted in the backward hemisphere in the center-of-mass system. Applications of these two experimental results to obtain enriched anti-neutron, antiproton, and positive K-meson beams are discussed.

465.

The design of calorimeters for the determination of ion beam intensities, E. R. Harrison, J. Sci. Instr. 34, 242-4 (1957).

Calorimetric methods for determining the total particle flux of ion beams are discussed. Three types of calorimeter are described which, from experience gained with 25-50-mA, 10 kev and 0.2-mA mean, 500-kev proton beams, have proved suitable for this purpose. The sensitivity of the calorimeters can be either calculated from elementary theory or obtained directly by a convenient method of calibration.

466.

On two directional focusing magnetic analyzers, S. B. Karmohapatra, Indian J Phys., 29, 393-7 (1955).

Design parameters for a symmetrical two-directional nonuniform magnetic analyzer are considered. Suggestions are made for achieving second-order radial focusing effect by properly shaping the pole edges of the first-order focusing conical magnets having an angle $< \sqrt{2}\pi$. The advantage of such a 180° magnet for mass spectrometry is discussed in consideration with the resolving power and solid angle.

467.

On the possibility of reducing the aberration coefficients in analyzers with non-uniform fields, M. I. Korsunskii and V. V. Zashkvara, Priboi i Tekh. Eksper., 1959, No. 3, 21-5 (May-June). (In Russian.)

A theoretical examination is made of the ion-optical properties of an electrostatic analyzer with n sectors. The angles subtended by

successive sectors are independent. It is shown that by choosing correctly the field in a single sector the fundamental coefficient of aberration can be reduced to zero in an instrument of high dispersion.

468.

Ion beam collimator, A. S. Langsdorf, U. S. Patent 2,814,728 (Nov. 26, 1957)

A device is described for defining a beam of high-energy particles wherein the means for defining the beam in the horizontal and vertical dimension are separately adjustable and the defining members are internally cooled.

469.

A magnetic analyzer for high energy particles, A. Lovati and H. Tyren, J. Sci. Instr., 33 151 (1956).

A magnetic analyzer for accurate measurement of momentum of nuclear reaction products, employing two-directional focusing with a sector-shaped uniform magnetic field, is described. The instrument is useful for analyzing particles with magnetic rigidity up to $2 \cdot 10^6$ G cm (corresponding to 180-MeV protons and α particles, 90-MeV deuterons, etc.).

470.

Electron-optical bench, L. Marton, M. M. Morgan, D. C. Schubert, J. R. Shah, and J. A. Simpson, J. Research Natl. Bur. Standards, 47, 461-4 (1951).

A versatile electron-optical bench has been constructed for the extensive study of electron-optical elements. Three carriages for magnetic lenses and four holders for apertures, objectives, and meshes are arranged appropriately in the vacuum chamber, while provision is made for external positioning with 3 degrees of freedom for each element. The design and experimental technique are discussed in detail. A set of measurements of the focal length of a magnetic lens is presented to illustrate the practical employment of the bench and to indicate the limits of accuracy that can be attained.

471.

Magnetic analyzer for nuclear reaction products, O. Meier, Jr., et al., Rev. Sci. Instr., 29, 1004-8 (1958).

A magnetic analyzer for nuclear reaction products has been built which employs a sector-shaped uniform magnetic field. The shaped sectors are inserted in the 8.5-in. gap of a C-shaped magnet

with a 12 x 12-in. cross section. The iron core is 54 x 33 in., and 69,360 ampere-turns give 13,500 gauss across a total air gap of $1\frac{5}{8}$ in. In the notation of Cross,¹ the parameters were: $p = 15$ in., $\phi = 60^\circ$, useful gap = 1.5 in., $\ell' = 22.5$ in., $\ell'' = 45$ in., $\epsilon_1 = +46^\circ 38'$, $\epsilon_2 = -18^\circ 21'$, max usable $\alpha = \pm 3^\circ$, max usable $\omega = \pm 1.6^\circ$. The entrance boundary was straight, and the exit boundary had a convex curvature of 123.7 in. The boundaries of the sector and the locations of the object and image positions were corrected for the effect of the fringing field. The observed ℓ'' was 46.5 in. Fringing-field focusing in the direction of perpendicular to the plane of deflection was not as strong as calculated; the maximum image height was 2 in. The magnet is capable of bending 12-Mev protons and has an energy resolution of 300 for the maximum useful solid angle of $1/2000$ of 4π steradians. The observed maximum energy resolution was 400. The advantages of this magnet are simplicity of construction and ease of adaptation to other sector parameters. The core is also an adaptable laboratory magnet.

¹W. G. Cross, Rev. Sci. Instr., 22, 717-22 (1951). 133.

472.

Improvement of the optics of the high-resolution electrostatic velocity analyzer, G. Möllenstedt and W. Dietrich, Optik, 12, 246-9 (1955). (In German.)

The high-resolution electrostatic velocity analyzer previously described by Möllenstedt¹ has been further developed. Originally, the resolution decreased with increasing distance from the optical axis. By applying a suitable potential to the central electrode of the analyzing lens, each part of the spectrum can be brought on to the axis in turn, where it falls on to a second slit. This gives a constant resolution for all parts of the spectrum and enables larger apertures to be used. By the use of a fluorescent screen under the second slit, a multiplier photocell, and a pen recorder, the spectrum can now be recorded in a convenient manner. The energy-loss spectrum of aluminum is given as an example.

¹G. Möllenstedt, Optik, 5, 499-517 (1949).

473.

Microwave separator for high energy particle beams, P. R. Phillips, Rev. Sci. Instr., 32, 13-16 (1961).

The design and construction are described of a microwave separator for high-energy particle beams, following the original ideas of Panofsky and Wenzel. A TM_{012} rectangular cavity with a Q of 15,000 and a maximum power dissipation of 1.3 Mw was used. With this

electrons of 150-Mev/c momentum through $\frac{3}{4}$ in. at the final focus of the analyzing magnet could be deflected. The available aperture is so small that the technique is not immediately useful, but it is anticipated that it may become so at higher energies, when other methods of beam separation become unfeasible.

474.

A magnetic analyzer for charged-particles from nuclear reactions, C. W. Snyder et al., Rev. Sci. Instr., 21, 852-66 (1950).

A double-focusing magnetic spectrometer for detecting and analyzing charged particles from nuclear reactions is described. The magnetic field, varying as $r^{-1/2}$ near an average radius of 10.5 in. extends over a semicircle, yielding object and anastigmatic image positions some distance outside of the region of strong field. The acceptance solid angle is $\Omega = 0.0061$ sterad and the momentum resolution with an 8-mm slit at the detector is $R = 128$. The ultimate resolution determined by spherical aberration and some residual astigmatism is about 1,000. Applications to the study of the energy and yield of nuclear reaction products are discussed.

475.

Electron-optical design of a mass-separator, P. A. Sturrock AERE-T/M-89 (Oct 1953) 11p.

The design of a magnetic mass separator which is to focus a line source into a line image is investigated. It is assumed that all rays of the beam leave the line source normally. The curvatures of the entrance and exit boundaries of a uniform magnetic field are adjusted so that broadening of the image due to second-order aberrations is eliminated, and the position of the plane of best focus is determined. Calculations are based on a previous paper by Sturrock appearing in Phil. Trans. Roy. Soc. London, A245, 155-87 (1952).

476.

Nonsaturable high-energy beam monitor, G. W. Tautfest and H. R. Fechter, Rev. Sci. Instr., 26, 229-31 (1955).

The monitor uses the phenomenon of secondary emission. The primary beam to be monitored passes through a set of foils alternately phased in voltage. The current produced by secondary electrons ejected by the beam passage is collected on to the one set of foils and measured. Results of tests with high-energy electrons are given. The monitor gives no indication of saturation up to peak current densities of 16 mA/cm², and is independent of the primary beam energy in the range over which the monitor was tested (111-235 Mev).

477.

High-order focusing by a uniform magnetic field with straight-line boundaries, E. T. S. Walton, Proc. Roy. Irish Acad., 57A, 1-13 (1954).

A special drawing instrument has been constructed with which to study the focusing of rays of charged particles by a uniform magnetic field extending over a limited area. This instrument will draw the ideal exit boundary of the field corresponding to any arbitrary entrance boundary. It has been used to determine what straight line boundaries will give the best focusing of rays diverging over as wide an angle as possible. The results have been given in graphs suitable for use in the design of sector-shaped magnetic analyzers which combine large aperture with good focusing. It has been shown that these designs also give convenient and high-order focusing of particles of nearby magnetic rigidity.

478.

Electrostatic analyzer for selection of homogeneous ion beam, R. Warren, PhD Thesis. University of Washington (1947).

See also: 50, 142, 169, 181, 182, 240, 277, 287, 291, 317, 323, 332, 570, 594.

PARTICLE MOTION

479.

Electron orbits in hyperbolic magnetic fields, E. Astrom, Tellus, 8, 260-7 (May 1956).

Electron motion in the field of cylindrical pole pieces, with the section in the shape of a rectangular hyperbola and its conjugate, is treated. The accessible region is discussed. For the motion in the asymptote planes to the hyperbola, the orbits are characterized by two parameters: one (k) characterizing the shape, and the other the amplitude. The solution is given in elliptic functions. The orbits may be divided into two groups, one composed of orbits resembling trochoids and the other orbits of a meander type. There exists a periodic orbit similar to the digit 8. The drift is in opposite directions on different sides of this orbit, as characterized by k . The trochoidal motion is stable if the orbit is not stretched too much. For the meander orbits, the criterion used gives a main stability region. This region is bounded by the periodic orbit and the orbit the branches of which just touch each other. For both groups of orbits there exists an infinite number of stable regions.

480.

On the asymptotic series expansion of the motion of a charged particle in slowly varying fields, J. Berkowitz and C. S. Gardner, NYO-7975 (Dec 23, 1957) 28 p.

The asymptotic series expansion for the motion of a charged particle in a slowly varying magnetic field was determined by Kruskal. Kruskal showed that the series formally satisfies the equations of motion. It is proved that the series is in fact a valid asymptotic development of the exact solution.

481.

A method of calculation of trajectories in electron optics. Generalization to linear homogeneous differential equations, F. Bertein, J. phys. radium, 13 (Suppl. No. 7-8-9) 91A-98A (July-Aug.-Sept., 1952). (In French.)

A generalization of the method described in 1. An estimation of the error involved at any stage is given, and the factors affecting the choice of the base polynomials for lens and mirror problems are discussed.

¹F. Bertein, J. phys. radium, 13, 41A-49A (Feb Suppl. 1952). 482.

482.

Trajectories in electron lenses: a method of approximation,
F. Bertin, J. phys. radium, 13, 41A-49A (Feb. Suppl., 1952).
(In French.)

Paraxial rays are assumed to have the form of a polynomial in z (the axial coordinate), the coefficients being determined by a method which requires the evaluation between fixed limits of $\int v z^n dz$, where v is the potential function and n takes various integral values. Although the method is discussed with reference to electrostatic lenses, it is equally applicable to magnetic ones.

483.

Model for the motion of charged particles in a two-dimensional electric field, taking account of space charge, B. V. Bobykin, V. M. Kel'man, and D. L. Kaminskii, Zh. Tekh. Fiz., 22, 736-43 (1952).
(In Russian.)

If a membrane, stretched by a surface tension T , is subjected to a nonuniform pressure $P(x, y)$, the normal displacement z , if small, obeys $(\partial^2 z / \partial x^2) + (\partial^2 z / \partial y^2) = -P/T$, which is formally identical with Poisson's equation. Hence, space charge can be represented as a distributed load. The distribution is found by successive approximations, the effects of space charge on the trajectories being initially neglected; the velocity distribution of the spheres, representing charged particles, then enables the first approximation of the space-charge distribution to be calculated. An experimental model is described, in which the space-charge loads are applied to a set of hexagonal pads on the underside of the rubber sheet. A test on an arrangement having a known analytical solution was satisfactory.

484.

On the motion of a charged particle in an almost homogeneous magnetic field, L. J. F. Broer and L. Van Wijngaarden, Appl. Sci. Research, B8, No. 3, 159-76 (1960).

First the motion of a particle in a slowly varying homogeneous field is studied. An expansion is given for the dominating spiralling part of the motion. It is found that the center of this motion will drift slowly. Calculation of the drift amounts to the determination of the reflection in an equivalent wave-propagation problem. Next, the motion in constant, nearly homogeneous fields is treated, partly using the same method. In a few representative cases it is shown that the first approximation reproduces results given by Alfven (1950) and by Spitzer (1956), while some results are given in second approximations.

485.

Floating wire measurements on the SC magnet, A. Čitron et al.,
CERN-59-8 (Feb 20, 1959) 43 p.

The method of simulating trajectories of charged particles moving with uniform speed in a magnetic field by means of a wire under tension and carrying constant current has been described by Loeb. The conditions of stability are discussed, and it is shown that any particle trajectory can be represented by a stable wire if the wire is sufficiently light and if its two points of support are not separated by the image of one of them. The particular case of the magnetic field of the CERN 600-Mev synchrocyclotron is considered.

486.

Velocity-dependent potentials for particles moving in given orbits,
M. L. Coffman, Am. J. Phys., 20, 195-9 (1952).

Velocity-dependent potential functions can sometimes be used to determine the field of force that can be applied in order that particles may move in specified paths. In particular, the electromagnetic field vectors E and B can be determined from such a potential function if the paths on which charged particles move are specified. The velocity-dependent potential U is related to the kinetic energy T and the Lagrangian function L by the equation $U = T - L$, where L is an arbitrary solution of the Lagrange equation $(d/dt)(\partial L/\partial p') - (\partial L/\partial p) = 0$, where $p = \text{constant}$ represents the orthogonal trajectories of the curves which describe the paths the particles are to follow. From the velocity-dependent potential function U , the field of force can be calculated by the definition $Q_p = -(\partial U/\partial p) + (d/dt)(\partial U/\partial p')$.

487.

Fringing flux corrections for magnetic focusing devices, N. D. Cog-
geshall, J. Appl. Phys., 18, 855-861 (1947).

When a charged particle approaches a region of uniform magnetic field, the trajectory is affected by the fringing field. Compensation for the effect of the fringing field may in some cases be achieved by the use of virtual-field boundaries which are outwardly displaced from the actual boundaries. A definition of the virtual boundary in terms of the effect of the fringing field upon the trajectories is formulated. A procedure for calculating the displacement d of the virtual from the actual field boundary is given using the methods previously developed for calculating ion trajectories in nonuniform magnetic fields. Using this procedure, several values of the displacement for various magnet dimensions and conditions have been calculated. A method of altering the geometry of sector-type mass spectrometers to correct for the

effects of the fringing fields is proposed. It is shown that the angular and spatial separations of the individual ion trajectories in an ion beam of small angular spread as it approaches a uniform field region through a fringing field are approximately the same as for the ideal case wherein the magnet field changes discontinuously at the boundary.

488.

Particle optics of ray systems with curved axes, H. Dormont, Ann. Phys. 4, 1341-87 (1959). (In French.)

The particle optics of systems involving curved axes is reviewed fundamentally. Equations for the motion of particles are derived and the conditions for image formation obtained. The nature and extent of aberrations is discussed. Particular attention is paid to chromatic effects and isochronism in klystrons; space charge is also extensively discussed. A few special applications are worked out.

489.

Determination of an electron trajectory by successive integration, E. Durand, Compt. rend., 236, 364-6 (1953). (In French.)

A combination of step-by-step integration and iteration methods for the solution of second-order differential equations. The magnetic lens and the Glaser lens are taken as illustrative examples.

490.

Determination of an electron trajectory by successive differentiation, E. Durand, Compt. rend., 236, 471-3 (1953). (In French.)

A method of trajectory plotting based on successive differentiation of the trajectories defined by the paraxial ray equation is derived. This method has the advantage over standard plotting methods in that the required interval Δ can be determined a priori to yield the required accuracy.

491.

Differential geometry of the trajectories of charged particles, H. Figueras, Compt. rend., 250, 2143-5 (1960). (In French.)

Using a moving frame of reference, studies the trajectories of charged particles in an electromagnetic field.

492.

Allowed and forbidden regions for the motion of electrically charged particles in axially symmetrical magnetic fields, H. Fisser and R. Kippenhahn, Z. Naturforsch., 14a 37-46 (1959). (In German.)

The motion of charged particles in a rotationally symmetric magnetic field is characterized by their kinetic energy and generalized angular momentum. If these quantities are used as coordinated to define a plane, the boundaries between allowed and forbidden orbits are clearly seen. This is of particular value in considering the loss of particles from a region in which circular currents flow.

493.

Direction double focusing of particles varying in velocity and mass in rotationally symmetric electromagnetic fields, H. W. Franke, Öst. Ingen-Arch., 5, 371-87 (1951). (In German.)

The Glaser theory of the motion of charged particles in ordinary electric-magnetic fields is extended to the case of particles divergent in velocity and mass. The magnitudes, characteristic for dispositions of velocity and mass spectrography, are calculated according to the case of double direction focusing.

494.

Numerical computation of the trajectories in the axial symmetric electron-optical system, P. Gautier, J. phys. radium, 14, 524-32 (1953). (In French.)

A three-point recurrence formula for the numerical calculation of electron paths in central systems (electrostatic and magnetic) is derived from the ray equation. Its application to a particular case yields results comparable with those obtained from the two-point formula of Liebmann [Proc. Phys. Soc. (London), B62, 753-72 (1949)], but with greater ease of computation. The method is extended to consider space charge and chromatic aberration.

495.

Charged-particle orbits in varying magnetic fields. E. I. Gordon, J. Appl. Phys., 31, 1187-90 (1960).

A solution for the paraxial orbits of charged particles in varying magnetic fields is given. The magnetic field is assumed to be azimuthally symmetric but is allowed to vary arbitrarily with time or axial distance. The instantaneous guiding centre and radius vector of the orbit are given in terms of the initial guiding centre and radius vector and two parameters which are determined from the solution of

a first-order differential equation containing the magnetic-field variation. One exact and two approximate constants of the motion are evaluated and discussed.

496.

Improved magnetic focusing of charged particles, H. Hintenberger, Rev. Sci. Instr., 20, 748-50 (1949).

A general second-order focusing condition is given for particles passing through a region of uniform magnetic field with foci outside the field. Previously published cases¹ are special cases of this condition. Diagrams show some possible field shapes for deflection angles of 90° and 60°.

¹L. Kerwin, Rev. Sci. Instr., 20, 36-41 (1949). 164.

497.

Orbits of an electron in static electromagnetic fields, I. G. Iwata, Prog. Theor. Phys. (Kyoto), 15, 513-22 (1956).

Static electromagnetic fields in which the Hamilton-Jacobi equation of an electron is integrable by separation of variables are determined. The field for a perfect imaging system is rediscovered.

498.

Separable dynamical systems of Staeckel in flat space, G. Iwata. Prog. Theor. Phys. (Kyoto), 19, 369-74 (1958).

For previous work see Prog. Theor. Phys. (Kyoto) 15, 513-22 (1956). 497. To assist in the study of the orbits of a high-energy charged particle in an electromagnetic field, coordinate systems and respective potential functions are determined where the Hamilton-Jacobi equation of the particle is integrable by separation of variables.

499.

Trajectories in the symmetrical electron lens, L. Jacob and J. R. Shah, J. Appl. Phys., 24, 1261-6 (1953).

The complete field plot obtained by "relaxation" was used to determine electron trajectories for parallel incidence, at heights up to one-third the bore diameter, from a numerical integration of the trajectory equation using the method of differences. The accuracy attained in this method yields cardinal points to within 1%. It was found that the focal length f_n for a ray of height r_n was given by $f_n = f_0 - br_n^2$ where b is a constant; also, because of the curvature of the principal planes, the distance d_n to the midplane follows a law $d_n = c - dr_n^2$, where c

and d are constants. A consequence of this is that for the same variation in focal length, the greater the curvature of the principal plane the larger the spherical aberration of the lens. The trajectory tracings indicate that spherical aberration is small at heights up to $\frac{1}{12}$ the bore diameter, but increases with height till at a value of $\frac{1}{3}$ the bore, the percentage change in focal length has decreased by some 40%. Confirmation of focal properties was obtained using the lens in a single-stage electron microscope and examining the pincushion distortion in the image of a gauze object. Evaluation of the spherical aberration using the weak-lens approximation of Scherzer leads to gross errors both in magnitude and variation, e.g., the aberration does not remain constant with voltage ratio. The experimental data with the electron microscope indicate little or no change in aberration with increase in the power of the lens; this does not agree with the results of the mathematical analysis of Ramberg.

500.

Movement of charged particles in the magnetic field of a linear current and the electric field of a cylinder capacitor, V. M. Kalman and I. V. Rodnikova, Zh. Eksper. i Teoret. Fiz., 21, 1364-9 (1951). (In Russian.)

The Hamilton-Jacobi differential equations of the nonrelativistic problem of the movement of a charged particle in a constant electromagnetic field (cylinder capacitor and current-carrying conductor along its axis) permit of solutions in the form of quadratures. For certain relations between field strength and initial particle velocities such a system has the property of focusing beams of charged particles. It is shown that a linear, current-carrying conductor acts on the movement of charged particles the initial velocities of which are at right angles to the conductor as a deflecting electron-optical element. It has in this respect much in common with a short magnetic lens, and the simplest magnetic lens is a conductor bent into a ring. The deflection of the linear conductor then becomes a focusing into the axis of the ring. The displacement parallel to the current may be compensated by the methods used with magnetic lenses for compensating image rotation. The deflecting systems must for this purpose consist of two linear and parallel conductors carrying opposing currents. The great advantage of the deflecting systems considered in the paper over the known types is that their characteristics do not change in a direction parallel to the current. Therefore, such systems do not impose any limitations on the height of the beams to be deflected as do all the usual deflecting systems owing to the leakage fields at the edges of the poles.

501.

Model for the motion of charged particles in magnetic fields with axial symmetry, D. L. Kaminskii and V. M. Kel'man, Zh. Tekh. Fiz., 22, 703-8 (1952). (In Russian.)

The contours of the rubber model correspond to the equivalent potential, which includes the skew constant. The magnetic lens formed by a single circular conductor has been investigated, with special reference to the problem of Tsukkerman.¹ It is shown that although rays, emitted parallel to the axis from a source in the field, diverge from the axis on leaving the field, yet a family of paraxial rays from any given point near the axis is brought to a real focus, or at least has its divergence diminished.

¹J. Tech. Phys. USSR, 21, 559-601 (1951).

502.

On the electron-trajectory equations in electron-optical systems with curved axis, P. P. Kas'yankov, Optika i Spektrosk., 3, 169-79 (Aug 1957). (In Russian.)

The author derives exact relativistic equations for electron trajectories in an arbitrary electron-optical system with a curvilinear optical axis, and shows that these equations can be simplified for the region close to the axis (the paraxial case). The trajectory equations are derived by two methods: (a) starting with the equations of motion in tensor form, and (b) using the electron-optical analogue of Fermat's principle (variational method). The author critically discusses Grinberg's method (1948) for obtaining the paraxial electron-trajectory equations in the first-order approximation and shows that Grinberg's method cannot be used to derive the exact equations.

503.

The motion of charged particles in a homogeneous magnetic field with a superimposed linear current magnetic field and an electric field from a cylindrical condenser, V. M. Kel'man and S. Ya. Yavor, Zh. Tekh. Fiz., 24, 1329-32 (1954). (In Russian.)

Certain particle trajectories are obtained by numerical integration for given values of the field strengths. Curves of the selected trajectories are given.

504.

Similar trajectories of charged particles in magnetic fields,
V. M. Kel'man and K. V. Lyubimov, *Izv. Akad. Nauk SSSR Ser. Fiz.*,
18, 155-60 (1954). (In Russian.)

Conditions are found such that rays in a 2-dimensional field are functions only of initial geometrical conditions and are independent of momentum. Two particular fields satisfying these conditions are (1) $H_x = 0$, $H_y = zH_0$, $H_z = yH_0$; (2) $H_x = 0$, $H_y = 2yzH_0$, $H_z = (y^2 - z^2)H_0$. The first of these was among the cases considered by Coggeshall and Muskat (1944). The present authors show that the ray equation in the second field can be expressed as an integral, which they have solved numerically for a number of values of the parameters. A description is given of magnets which reproduce these fields and of an investigation of their behavior as electron mirrors, by means of cathode rays of various energies.

505.

Cyclic motion of charged particles in an electric field, A. A. Kolomenskii and Fong Soy-cen, *Zhur. Eksp. i Teoret. Fiz.*, 36, 271-6 (1959). (In Russian.)

Formulas are derived which describe cyclic motion of charged particles in an electric guide field. A field of this type can be created by a system of special lenses (strong or weak focusing). Resonance acceleration of the particles and in particular their phase stability (auto-phasing), which is similar to the familiar magnetic auto-phasing, are considered. The effect of electromagnetic radiation (including quantum fluctuations) on the motion of the electrons in the electric field is examined. A case is also discussed when the particle moves part of the way in an electric field and part in a magnetic field.

506.

Crooked trajectories for charged particles in a magnetic field with a plane of symmetry, J. Lafoucriere, *J. phys. radium*, 13, 392-400 (1952). (In French.)

With the restriction of an inhomogeneous magnetic field with a plane of symmetry, and a strong radial field with a plane of symmetry, and a strong radial fall-off, a general method is given for the construction of the crooked trajectories of charged particles in this field. These trajectories are systematized, and the problem of axial focusing for stationary orbits discussed.

507.

The different types of trajectories of charged particles in inhomogeneous axially symmetrical magnetic fields, J. Lafoucriere, Compt. rend., 229, 823-5 (1949). (In French.)

If there is a strong field gradient, viz., if rH decreases as r increases, 3 types of trajectories in the plane of symmetry are possible: (1) Aperiodic, eventually escaping from the region of the field; this applies to high energy particles. (2) For a given source position and H_p , one ray becomes asymptotic to a circle centered on the axis of symmetry. (3) Particles of relatively low energy describe trochoids, in which for the slowest particles the loop width exceeds the precession, whilst the converse holds for faster particles. For a given H_p , all rays of type (3) initially making small angles with the circle, centered on the field axis and passing through the source, follow the same trochoid; thus a new type of focusing arises.

508.

Numerical integration of the electron trajectory equation, M. Laudet, J. phys. radium, 14, 604-10 (1953). (In French.)

A three-point recurrence formula for electron paths in rotationally symmetrical electrostatic and/or magnetic fields is developed. Various approximate expressions are given for the coefficients involved, and, with each of these, ray paths are computed in the case of a magnetic lens for which an exact solution is known. Each computation is carried out with two interval sizes, and an extrapolation formula is applied. The residual errors are compared.

509.

The motion of charged particles in magnetic fields with rotational symmetry, R. Lust and A. Schluter, Z. Naturforsch., 12a, 841-3 (1957). (In German.)

Conditions are derived for a particle to remain within a finite volume.

510.

Reply to letter by J. M. Winwood. B. Meltzer, J. Electronics and Control, 5, 348-9 (Oct 1958).

Winwood's calculation [J. Electronics and Control, 5, 161-2 (Aug 1958)]* of the ratio of magnetic to electric force exerted by one moving electron on another, is shown to contain three errors in the use of the Lorentz transformation of special relativity. It is also

shown that the value obtained by Meltzer [J. Electronics and Control, 4, 350-4 (April 1958)]** is unaltered when relativistic corrections are taken into account.

*57
**46

511.

Motion of particles in a screw-form toroidal magnetic field,
A. I. Morozov and L. S. Solov'ev, Zh. Tekh. Fiz., 30, 271-82 (1960).
(In Russian.)

A magnetic trap designed to restrict particles to a specified region is formed by a magnetic field in the form of a screw wound around a toroid. Equations of motion for the particles are derived and their behavior discussed. Motion in a figure-of-eight system is also considered.

512.

Motion of particles in a toroidal corrugated magnetic field,
A. I. Morozov and L. S. Solov'ev, Zh. Tekh. Fiz., 30, 261-70 (1960).
(In Russian.)

A magnetic trap for confining moving particles into a specified region is formed by disposing a corrugated magnetic field around a toroid (Stellarator). It is shown that for sufficiently large radius of the toroid the trap can become absolute by the establishment of a magnetic surface which no particles, whatever their direction of motion, can penetrate.

513.

The motion of electrons in two combined magnetic fields, S. G. Nilsson,
K. Tekn. Högsk. Handl., No. 72, 11 pp. (1953).

In previous calculations¹ the author has investigated the focusing properties of the toroid field. Here the toroid field is combined with a homogeneous field perpendicular to the toroid plane (in accordance with an idea of Professor Kai Siegbahn). The ratio between the strength of the two fields is an available parameter. It was now anticipated that one might find a ratio, giving either two-directional focusing or one-directional focusing of a rather high order, or both. The results of the calculations are mainly negative. For the two limiting cases of dominating homogeneous field and toroid field, the properties of the semicircular spectrometer and the solenoid spectrometer, respectively, are obtained. Ratios lying between these extremes either tend to lower the resolving power of the semicircular spectrometer or

make the apparatus lose the two-directional focusing property of the solenoid type. There exists no specially suitable intermediate choice of the ratio between the two fields. The technique developed for finding periodical solutions to differential equations of the type $\ddot{y} + Ay + By^2 + Cy^3 + \dots = 0$, where $[y] \ll 1$, may be of some general interest.

¹Ark. Fys., 4, 347-51 (Paper 17, 1952).

514.

On a method for systematically calculating an electron-optical potential distribution with specified imaging properties, J. Picht, Optik, 12, 433-40 (1955). (In German.)

The general equation of the trajectory of electrons in a magnetic field is expressed in a simplified form, and conditions corresponding to fixed object and image points and to a specified magnification are impressed upon it. It is shown that a hyperbolic trajectory containing several free parameters constitute a solution of the equation, and a method for determining the shape of the polepieces needed to produce this is given. Judicious choice of the free parameters may be used to minimize aberrations.

515.

An integrable case of electron motion in electric and magnetic field, H. Poritsky and R. P. Jerrard, J. Appl. Phys., 23, 928-30 (1952).

Electron motion is studied in a two-dimensional electric field of potential $V = AB(x^2 - y^2)/2$ and a uniform magnetic field $H = (0, 0, -H)$ normal to the electric field, where $A, B, -H$ are constants. The equipotential lines of the electric field in any plane $z = \text{const.}$ consist of rectangular hyperbolas with a point of zero field strength at $x = 0, y = 0$. The differential equations of motion are integrated, and expressions are given for the electron paths. For this type of field, the electron motion consists of superposition of elliptic and hyperbolic motions, that is, of a simple harmonic motion along an ellipse whose center moves along a hyperbola. The latter hyperbolas intersect the equipotential hyperbolas, so that, unlike the uniform crossed-field case, the electron may drift into regions of higher or lower potential.

516.

The trajectories of charged particles slightly deviated from their initial direction by an electrostatic field, B. M. Rabin and A. M. Strashkevich, J. Tech. Phys., USSR, 20, 1232-40 (1950). (In Russian.)

The time-independent differential equations of such trajectories are set up and are shown to lead to the known results when applied to a lens with rotational symmetry or a cylindrical lens. Applied to a

transgradient system, they reduce to a form which may be solved by quadrature. A numerical example is worked and compared, inter alia, with the formulae of Hutter.¹

¹J. Appl. Phys., 18, 740-58, 797-810 (1947).

517.

Determination of ion paths in crossed electric and magnetic fields, M. E. Reinders, C. J. Zilverschoon, and J. Kistemaker, Appl. Sci. Res., B2, 264-8 (1952).

Ion paths in crossed electric and magnetic fields were calculated by a step-by-step method. Two examples are given: the ions in a Nier source; and the ions passing the acceleration electrode of an electromagnetic isotope separator. The magnetic field was homogeneous; the electric field was determined by means of a resistor network.

518.

The study of the motion of a charged particle in the magnetic field of a toroidal solenoid, G. Sacerdoti, Atti Accad. Sci. Torino, 1, 93, No. 1, 72-83 (1958-9). (In Italian.)

Gives detailed calculations of the motion in a plane perpendicular to the lines of force, with formulae for the orbit shape, the period of rotation, and the mean velocity in the direction perpendicular to the field gradient. The formulae are expansions in powers of the ratio of the Larmor radius to the major radius of the torus.

519.

Third-order paths in electron mirrors, P. Schiske, Optik, 14, 34-45 (1957). (In German.)

For computing third-order trajectories in electron lenses, the trajectories are generally assumed to be inclined at small angles to the axis. This assumption is not valid for electron mirrors in the neighborhood of the reversal point. A fully described perturbation procedure, based on the eiconal method, and using axial distance as the independent variable, is here shown to be capable of overcoming this difficulty.

520.

Graphical-analytical construction for the trajectories of charged particles in alternating electric and steady magnetic fields, N. I. Shtepa. Zh. Tekh. Fiz., 28, 178-87 (1958). (In Russian.)

A method is presented for finding the trajectory of a charged particle. Analytical expressions for the velocity are used in connection with a graphical step-by-step process. This involves certain errors, but these can be allowed for. An example is given of a proton moving in a steady magnetic field combined with an alternating electrostatic field of sinusoidal waveform.

521.

Graphical-analytical constructions of trajectories of charged particles in electrostatic and magnetic fields, N. I. Shtepa, Zh. Tekh. Fiz., 28, 2587-603 (1958). (In Russian.)

Trajectories of charged relativistic particles are considered. The method of incremental velocities and the method of radii of curvature, as well as a combination of the two, are used. The approximations involved are considered and the way of accounting for the resulting errors. Examples of trajectories constructed in this way are given.

522.

Grapho-analytical constructions of trajectories of charged particles in magnetic fields; N. I. Shtepa, Radiotekhnika i Elektronika, 2, 790-5 (1957). (In Russian.)

Two methods of constructing trajectories of relativistic charged particles are described: the method of velocity increments, and the method of radii of curvature. An example illustrating the use of both methods is given.

523.

Numerical determination of the trajectories of charged relativistic particles in electric and magnetic fields, N. I. Shtepa. Zh. Tekh. Fiz., 30, 121-4 (1960). (In Russian.)

A numerical extrapolation method is applied directly to obtain the solution of a system of second-order differential equations. The accuracy is estimated through given recurrence relations.

524.

Motion of a charged particle in an optically active anisotropic medium, I., A. G. Sitenko and A. A. Kolomenskii, *Zh. Eksp i Teoret. Fiz.*, 30, 511-17 (1956). (In Russian.)

The Fourier method is applied to determine the electromagnetic field components and the total energy loss of a charged particle moving in an optically active anisotropic medium.

525.

The freely moving electron in electric and magnetic fields. A. Spork, *Osterr. Z. Telegr.-Teleph.-Funk-Fernsehtech (OTF)*, 7, 85-98 (July-Aug 1953). (In German.)

The trajectories of electrons in different types of electrostatic and magnetic fields are discussed mathematically, with special reference to television systems. The general solution of the equations of motion is first obtained and then applied to a variety of conditions: the electrostatic or magnetic field alone, both fields crossed normally or at an arbitrary angle and both fields in the same direction. In each case, differing initial directions of electron injection with respect to the field vectors are discussed. There appears to be nothing new in the treatment or in the results, but it is valuable to have all the possible types of trajectory collected together and logically related.

526.

Velocity and two-directional focusing of charged particles in crossed electric and magnetic fields, I., N. Svartholm, *Ark. Fys.*, 2, Paper 20, 195-207 (1950).

Field systems with cylindrical symmetry are treated mathematically by the path equation method. Equations are calculated for the equipotentials of electric and magnetic fields, both having cylindrical symmetry with respect to the z-axis and mirror symmetry with respect to the xy-plane; the field strengths are expressed by series expansions in annular regions. Nonrelativistic equations of motion of particles in such fields are solved, and conditions for radial, axial, and double-directional and velocity focusing are given generally and with special cases. Aberrations are calculated, and it is shown that there is an important special case of a cylindrical combination which gives both first-order velocity focusing and second-order, two-directional focusing. The conditions are $\alpha_1 = \frac{1}{4}$, $\beta_1 = \frac{1}{2}$, $\beta_2 = 2\alpha_2 + \frac{1}{2}$, where α_n, β_n are the coefficients in $E(r) = E_0(1 + \beta_1 p + \beta_2 p^2 + \dots)$, $H(r) = H_0(1 + \alpha_1 p + \alpha_2 p^2 + \dots)$ and $p = (r - r_0)/r_0$.

527.

Lagrangian formulation of the motion of a charged particle in an electromagnetic field, L. C. Teng, Argonne National Laboratory Internal Report LCT-17 (March 7, 1960). 10 p.

528.

Simulation of trajectories of charged particles in magnetic fields, G. H. Vineyard, J. Appl. Phys., 23, 35-9 (1952).

A ball rolling on a rotating surface is shown to simulate the motion of a charged particle in a magnetic field. The theory is given for the case of warped surface undergoing arbitrary rotation about a fixed axis and translation perpendicular thereto, while the system from which the ball is observed partakes of similar but independent motion. With approximations based on not too large departure of the surface from flatness, the following cases can be simulated: (a) The magnetic field is homogeneous and constant. The electric field is perpendicular to the magnetic field, and irrotational, but otherwise arbitrarily spatially dependent, and arbitrarily time-dependent within certain limits. (b) The magnetic field is homogeneous but arbitrarily time-dependent. The electric field is perpendicular to the magnetic field and may have a variety of space and time dependences, including a part which encircles the axis and has just the right magnitude to produce acceleration in a circular orbit as in the betatron. Results of rudimentary experiments are presented which indicate that the method is capable of good accuracy.

529.

Stable orbits of charged particles in an oscillating electromagnetic field, E. S. Weibel, Phys Rev, 114, 18-21 (1959).

Orbits in a field of the cylindrical waveguide driven in the TE_{01} -mode were studied. The radial components of the Lorentz force acting on the particle is never positive regardless of its charge; thus, it is attracted toward the axis of the waveguide around which it moves in a complicated path. Sufficient conditions are given under which the orbits are stable, that is remain bounded for all times.

530.

Focusing in high-voltage beam-type electron devices, S. V. Yadavalli, J. Electronics and Control, 5, 65-87 (1958).

The paraxial electron-trajectory equation applicable at relativistic speeds, including the effects of self-magnetic field and space charge of the beam, is derived. Problems concerning beam spreading,

electrostatic lenses (the unipotential Pierce gun being an example), magnetic lenses, Brillouin flow, and beam stability are treated using this equation. Most of the results are presented graphically and discussed in detail. Their applications to practical situations are indicated.

531.

Motion of electron along self-intersecting trajectories, G. E. Zil'berman, Zh. Eksp. i Teoret. Fiz., 34, No. 3, 748-9 (1958). (In Russian.)
English translation: Soviet Physics-JETP, 34 (7), 513-14 (1958).

A general form of the motion of an electron along a closed self-intersecting curve is considered, including the case when this "figure-eight" trajectory has a narrow neck and breaks up into two regions. The region of applicability of the quasi-classical approximation is determined and the level separation for varying deformation of the "figure-eight."

532.

Use of space charge in electron optics, E. A. Ash, J. Appl. Phys., 26, 327-30 (1955).

Electron-optical properties of cylindrical space-charge cloud are derived; possibility of achieving system free from either spherical or chromatic aberration by combining space-charge lens with space-charge-free converging lens; it is found that achromatization of thin electric or magnetic lens is possible only if resultant action of combination is divergent.

See also: 65, 89, 131, 167, 267, 329, 345, 353.

SPACE-CHARGE EFFECTS

533.

Space charge neutralization by ions in linear flow electron beams, N. C. Barford, J. Electronics and Control, 3, 63-86 (1957).

The integro-differential equation of linear electron space-charge flow in the presence of ions is obtained, using an empirical formula for the cross section for ion production by electrons based on experimental results. The influence of the ions may be represented by a single parameter, ϕ , which is a function of the potential and current density of the electron beam and of the gas pressure. Solutions of the flow equation are obtained for a wide range of values of ϕ . These show that for $\phi \geq 0.01$ ions are produced at such a rate that they can neutralize the electron space charge even when there exist appreciable fields to draw them off, whereas for $\phi \leq 0.01$ this neutralization is only achieved when the ions are trapped. Two examples are given of the numerical application of the theory to problems of practical importance.

534.

On the neutralization of space-charge in positive ion beams, R. Bernas and J.-L. Sarrouy, Compt. rend., 233, 1092-4 (1951). (In French.)

The conditions under which electrons can be used to maintain the concentration of a beam of positive ions are investigated. The method has been applied to a magnetically focused isotope-separating apparatus.

535.

Corrections of Davisson-Calbick aperture-lens formula for space charge and magnetic field, V. Bevc and C. Susskind, Proc. Inst. Radio Engrs., 47, 336-7 (1959).

Results of a very approximate analysis, compared with earlier ones of Birdsall [IRE Trans. Electron Devices, ED-4, 132-4 (1957)] and of Pöschl and Veith [Arch. elekt. Übertragung, 12, 45-8 (1958)], suggest that a uniform axial magnetic field of about the magnitude required for Brillouin flow should cancel out the space-charge and aperture-size corrections of the classical formula $f = 4V/(E_2 - E_1)$ for the focal length of an aperture lens.

536.

Remarks on the influence of space-charge on the phase-focusing of electron beams and the work of J. Labus with the same title, F. Borgnis, Z. Naturforsch, 5a, 175 (1950). (In German.)

Discusses the effect of assuming that there is no longitudinal electric field in the drift space when a dense electron beam is injected, an assumption which was criticized by Labus.¹

¹Z. Naturforsch., 3a, 52-61 (1948). 554a.

537.

The non-existence of straight, parallel compressible space-charge flow, O. Buneman, J. Electronics and Control, 5, 561-2 (1958).

The present note¹ shows that straight-parallel flow cannot depend on the longitudinal coordinate at all and must therefore be incompressible, whatever its (irrotational) origin.

¹A. R. Lucas, J. Electronics and Control, 5, 245-50 (1958). 555a.

538.

Stability of periodic-field beam focusing, K. K. N. Chang, J. Appl. Phys., 27, 1527-1532 (1956).

By taking into consideration both the effects of space-charge and large-amplitude scalloping, an analytic solution for periodic-field beam focusing is obtained through use of successive approximation and Fourier series expansion. The stability limit is then determined by studying a perturbation of the obtained solution. The perturbation results in a Hill's differential equation for the incremental beam radius. This equation yields a stability criterion for periodic-field beam focusing. It is found that instability starts at some degree of beam scalloping and ends at a higher one, and thus forms an unstable band.

539.

Space-charge effects in electron optical systems, K. T. Dolder and O. Klemperer, J. Appl. Phys., 26, 1461-71 (1955).

Beams consisting of charged particles which are all directed towards a given virtual focus will generally not reach this focus but, due to their mutual repulsion, they will pass through a waist and then become divergent. Ray tracing shows that either positive or negative spherical aberration is introduced in a beam passing through a waist. This aberration is caused by the interaction of the electrons; its sign depends on voltage, current, and the angle of initial convergence of the

beam. For sufficiently high voltages or low currents, waist formation no longer occurs, but the electron rays cross the axis of the beam. With decreasing current density, the transition from waist to crossover is found to occur first for the inner rays of the beam while the outer rays still form a waist. All experimental results are found to be in approximate agreement with theoretical predictions.

540.

Instability of electron beams under a magnetic field, B. Epsztein, Compt. rend., 242, 1425-8 (1956). (In French.)

An electron beam travelling parallel to a magnetic field develops instability and splits up into several parts. This is explained as the result of a travelling wave which becomes amplified as the beam progresses, the energy of the wave being derived solely from the mutual repulsions of the electrons.

541.

Transverse instability of electron beams, B. Epsztein, Compt. rend., 246, 586-8 (1958). (In French.)

Unstable, transverse plasma oscillations may exist in electron beams in addition to the well-known longitudinal oscillations. These may constitute a new limitation to resolution in electron microscopy.

542.

The aberration of axially symmetrical electron-optical system in presence of space charges, Yao Fu-Den, Scientia Sinica, 7, 31-44 (1958).

Formulae for aberrations in electron-optical systems beset by appreciable space charge are derived in a form more easily adapted to numerical evaluation than those of earlier workers. The contribution of space charge to the aberrations is separated from the geometrical contributions and this offers hope of application to correction systems.

543.

Calculation of optimum focusing of a beam by an electron lens, taking account of space charge, M. D. Gabovich, J. Tech. Phys., USSR, 21, 363-8 (1951). (In Russian.)

A method is given of calculating the focal length of the lens, such that the spot on the screen shall have the smallest radius, on the assumption that the lens-screen space is field-free. A graph is given of spot size as a function of screen distance, beam current, and

accelerating voltage. For the case in which there is a uniform accelerating field between lens and screen, an approximate solution is given, valid when the energy of electrons at the screen is not much greater than the energy on leaving the lens.

544.

The effect of space charge during the propagation of intense beams of charged particles, M. D. Gadovich. *Uspekhi fiz. Nauk*, 56, 215-56 (1955). (In Russian.)

The article brings together the results of published fundamental work on the topic and appears to have been successful in assembling information and in deriving formulae likely to be of use in work with intense beams. 81 refs.

545.

Scaling of space-charge limited electron-optical systems, M. E. Haine, *Brit. J. Appl. Phys.*, 8, 44 (1957).

The scaling laws for a space-charged-limited electron-optical systems are derived from simple field considerations.

546.

On the space-charge divergence of an axially symmetric beam, E. R. Harrison, *J. Electronics and Control*, 4, 193-200 (1958).

An examination is made of the assumptions customarily used in estimating the effect of space charge in an axially symmetric beam. It is shown that, subject to certain restrictions, the assumptions are consistent with a coaxial, cylindrical conducting boundary. For small amounts of divergence in an initially parallel beam, a hyperbola solution is proposed as an alternative to the usual solution which involves a tabulated function. It is then argued that in some cases there is reason for believing that the hyperbola solution may be as good an approximation as, or better than, the usual solution, even when the divergence is not small.

547.

Correction of the spherical aberration of electrostatic lenses by space charge, G. Haufe, *Optik*, 15, 521-37 (1958). (In German.)

A space-charge lens has been constructed, the basic elements of which are a ring cathode, grid, and anode, concentrically arranged about the axis of an electrostatic electron microscope. The space charge formed at the axis, consisting of both electrons and positive

ions, acts as a weak lens having spherical aberration of opposite sign to that of the normal objective lens. Experiments on the imaging of a metal mesh show that the space-charge conditions can be controlled so as to correct the spherical aberration of the final image. The magnification was 2500 times the accelerating voltage of the microscope, 10-20 kV, and the prevailing pressure of 10^{-3} mm Hg. No blurring of the image, due to scattering in the space charge, was observed.

548

Nullification of space-charge effects in a converging electron beam by a magnetic field, M. E. Hines, Proc. Inst. Radio Engrs., 40, 61-4 (1952).

Presents the conditions necessary for maintaining a uniformly converging, conical electron beam in the presence of space charge. It is an extension of the Brillouin focusing condition to conical flow, requiring a converging rather than a uniform magnetic field. In this type of electron flow, the diverging effects of space charge are balanced against magnetic reaction forces for reasonably small cone angles of convergence. Though the balance of forces is exact only for infinitesimal angles, it is reasonably accurate for cones of half-angle of 10 degrees. The minimum beam size will be limited only by the effects of thermal velocities, by gun aberrations, and by the magnetic field obtainable.

549.

Determination of electron trajectories in presence of space charge, D. L. Hollway, Australian J. Phys., 8, 74-89 (1955).

Method of representing space charge in electron-trajectory tracing by use of currents injected from sources spaced at intervals in electrolytic tank; experimental application of principle to plane diode, axially symmetric electron beam, and general asymmetric beam. Bibliography.

550.

The optimum space-charge-controlled focus of an electron beam., D. L. Hollway, Austral. J. Sci. Research, A5, 430.6 (1952).

The problem of space-charge defocusing of circular electron beams is considered, and expressions for the condition of optimum focus are derived from the equations of the beam profile. It is shown that, over a wide range of spot radii, the optimum-focus expressions may be replaced by much simpler relationships suited to electron-beam design problems.

551.

Comments on "A general theorem for dense electron beams" by A. R. Lucas, B. Meltzer, and G. A. Stuart, P. T. Kirstein, J. Electronics and Control, 4, 457-9 (1958).

Two new solutions of the equations of electrostatic, nonrelativistic stationary space-charge flow are given as counter-examples to refute the conjecture of Lucas et al. [J. Electronics and Control, 4, 454-6 (1958)] that their two general sufficient conditions are also necessary ones for such flows.

552.

Paraxial formulation of the equations of electrostatic space-charge flow, P. T. Kirstein, J. Appl. Phys., 30, 967-75 (1959).

The equations of electrostatic irrotational space-charge flow are set up in a paraxial manner. Given an arbitrary trajectory, and the potential distribution along that trajectory, the variation of such quantities as potential and beam convergence in the vicinity of the specified trajectory are investigated. A detailed analysis is carried out for beams from a space-charge-limited cathode in the form of a cone. The agreement between the paraxial theory and the exact theory for particular beams is investigated. Numerical results are presented for beams from a conical cathode which predict beams with a microperveance of about 15 and a very large area convergence. It is felt that by use of this method much higher perveances and beam convergences could be obtained for hollow and sheet beams than have heretofore been possible.

553.

Solution to the equations of space-charge flow by the method of the separation of variables, P. T. Kirstein and G. S. Kino, J. Appl. Phys., 29, 1758-67 (1958).

The equations for irrotational, electrostatic laminar space charge (no thermal velocities or normal magnetic field at the cathode) are set up in terms of the action function. The resulting nonlinear partial differential equation is first reduced, by the method of the separation of variables in cylindrical polar coordinates, to the solution of a set of first-order, nonlinear, ordinary differential equations in one coordinate. It is shown that it is possible to predict axially symmetric, electrostatic, hollow beams from the inside of hollow cylindrical cathodes with space-charge-limited emission which asymptote, theoretically, to other extremely thin cylinders - though thermal velocities would, in practice, limit such a convergence. The characteristics of a particular beam and the electrode system to produce it are shown.

The beams which result from the separation of variables in other coordinate systems are described. In spherical polar coordinates, one obtains hollow axially symmetric beams from a conical cathode, which may asymptote to other cones; in a less familiar coordinate system, spiral coordinates, sheet beams from equiangular spiral cathodes result. It is shown how the method may be extended to include magnetic fields transverse to the cathode. Some new solutions to space-charge flow in crossed electric and magnetic fields from a space-charge-limited cathode are mentioned.

554.

Remarks on the influence of space-charge on the phase-focusing of electron beams, J. Labus, Z. Naturforsch., 5a, 176 (1950). (In German.)

Reply to discussion in:

F. Borgnis, Z. Naturforsch., 5a, 175 (1950) 536

See also:

J. Labus, Z. Naturforsch., 3a, 52-61 (1948) 554a

554a.

Influence of space charge on the phase focusing of electron beams, J. Labus, Z. Naturforsch., 3a, 52-61 (1948). (In German.)

An electron beam enters a velocity-bunching apparatus. A mathematical analysis, based on Poisson's equation, the equation of motion, and the continuity equation, is made of the effect of space charge on velocity bunching and the efficiency. If the space charge is greater than a certain critical value, the efficiency is 44%; but, whatever the space charge, the efficiency cannot exceed 58%.

555.

Exact electrode systems for the formation of a curved space-charge beam, R. J. Lomax, J. Electronics and Control, 3, 367-74 (1957).

An analytical method of determining the shape of the (Pierce) electrodes required to maintain a two-dimensional space-charge beam is given, which is valid when the edge of the beam is curved. The method is applied to a solution of the space-charge equations given recently by Meltzer,¹ in which the flow pattern is a family of arcs of concentric circles. It is found that a completely enclosed electrode system results, making it unnecessary to adopt the usual approximation of terminating the electrodes at some arbitrary distance from the beam in order to make them finite.

¹B. Meltzer, J. Electronics, 2, 118-27 (1956)

555a.

The relativistic flow of electrons in parallel and radial straight lines with no externally imposed magnetic field, A. R. Lucas, J. Electronics and Control, 5, 245-50 (1958).

Four cases of rectilinear dense flows are considered: a parallel "ribbon" beam, a parallel beam of cylindrical symmetry, a beam radiating virtually from a point, and a beam radiating virtually from a straight line. A rigorous treatment, taking into account both the relativistic mass and the self-magnetic field, shows that these flows could not be generated from a space-charge-limited cathode. The proof includes the general theorem that electrons from a space-charge-limited cathode must leave it at right angles.

556.

Single component relativistic space-charge flow, R. J. Lomax, J. Electronics and Control, 5, 563-4 (1958).

The work of Lucas¹ is generalized to single-component flow in any orthogonal coordinate system. See also Buneman, J. Electronics and Control, 5, 561-2 (1958). 537.

¹J. Electronics and Control, 5, 245-50 (1958). 555a.

557.

Electron flow in curved paths under space-charge conditions, B. Meltzer, Proc. Phys. Soc. (London), B62, 813-17 (1949).

Further developments in a method of obtaining solutions of space-charge flow, described in a previous paper,¹ are presented. A single example of 3-dimensional flow is given, as well as a number of general theorems. A distinction is drawn between "normal" flow, in which all electrons have the same energy (example: a thermionic device with a unipotential cathode), and "abnormal" flow, in which they may have different energies. It is shown that in the case of the former the application of the general method simplifies considerably.

¹B. Meltzer, Proc. Phys. Soc. (London), B62, 431-7 (1949).

558.

The space-charge aberration and the resolving power of the electron microscope, W. E. Meyer, Optik, 15, 398-406 (1958). (In German.)

The aberration due to space charge is calculated in conditions typical of electron microscopy, under certain simplifying assumptions. When the aperture of the illuminating beam, α_L , is equal to that of the objective, α_0 , the only effect is a shift of focus. If the illuminating aperture is smaller than that of the objective, as is usual, the

strength of the outer zones of the lens is weakened less than that of the inner zones, i.e., an effect in the same sense as a spherical aberration. An integral expression is obtained for the effect on the focal length and is evaluated for the simple case of uniform current density in any cross section of the beam; thus, the actual space-charge error will be rather greater than that calculated. For typical conditions of high-resolution operation of the magnetic electron microscope, it is found that the error rises sharply with angle, above the value of α_L . It is approximately proportional to α/α_L , and would amount to 5 or 6 Å in conditions in which the resolution limit due to spherical aberration and diffraction would be 3.5 Å. In the electrostatic microscope, its value is calculated to be 14-15 Å when the resolution limit should be 10 Å. The space-charge effect is, therefore, a limiting factor in practical conditions of electron microscopy, contrary to the conclusions of Gr $\ddot{u}$ mm,¹ who considered only the external rays of the imaging beam. The space-charge error can be reduced to negligible proportions by using lower current density (longer exposure), smaller area of illumination in the object plane, or by arranging for the current density in the incident beam to increase with radius. In principle, the last method could be utilized for correcting the spherical aberration of the lens. Experimental tests showed that the resolution of an electrostatic electron microscope was appreciably improved by reducing the current density to about one-tenth of that normally used. Micrographs are reproduced having a resolving power of 15 Å, equal to that calculated from the known spherical and chromatic aberration of the objective lens; this is the first time that the theoretical limit of an electrostatic system has been reached in practice.

¹Optik, 9, 281-8; 289-311 (1952) 86.

559.

On space charge waves, R. H. C. Newton, J. Electronics, 2, 441-50 (1957).

Theoretical analysis of the behavior of an electron beam in a uniform magnetic field, without making the usual assumption of neutralization by a positive space charge. A general wave equation is derived, and various types of small perturbations are shown to give the same results as previous work using the positive ion neutralization assumption. Some qualitative remarks are made on the effects of "sausageing" and of large signals.

560.

Die Brennweite einer Lochblende von endlicher Oeffnung fuer Electronenstrahlen endlicher Raumladung, K. Poeschl and W. Veith, Archiv der Elektrischen Uebertragung, 12, 45-8, (Jan 1958).

Focal length of diaphragm with finite aperture for electron beam of finite space charge; improved formula for cylindrical stream of electrons, which takes into consideration focal length reducing effects of finite aperture and of space charge; influence on focal length of longitudinal magnetic field for guiding beam.

561.

Longitudinal oscillations of electron-ion beams, R. V. Polovin and N. L. Tsintsadze, Zh. Tekh. Fiz., 27, 2615-23 (1957). (In Russian.)

It is known that an electron-ion beam can exist in the case where the density of the electrons is not equal to the density of the ions. The beam will exist only if the electromagnetic forces acting on the beam are directed towards the center of the latter. This gives rise to a fluctuation in density resulting in an electromagnetic wave being propagated along the beam. The problem of the stability of such a beam is solved qualitatively by a method not requiring solution of the differential equations involved.

562.

The influence of the space charge in an electron beam accelerated in a constant electrostatic field up to energies of several Mev, M. Sangster, Appl. Sci. Res., B4, 261-70 (1955).

To realize a pulsed electron beam of high energy (2.5 Mev) and great intensity (~ 1 amp), the influence of space charge has to be taken into account. A calculation in this article shows that at an average field strength in the acceleration tube of 10^6 V/m the influence of the space charge begins to play a dominating part at a current density of 2 amp/cm^2 .

563.

Practical application of the defocalizing influence on the space charge. Application to the case of relativistic electron beams, A. Septier, J. phys. radium, 22: Suppl. to No. 6, 79A to 82A (June 1961). (In French.)

Using the equation of motion of a relativistic particle situated on the surface of the beam, some formulas are obtained along with a chart permitting calculation, for any initial conditions, of the radius of the beam at a point of the axis of a drift space. The method is applied here to electron beams of 2 and 100 Mev.

564.

On space charge waves, D. H. Trevena, J. Electronics and Control, 6, 50-64 (1959).

The existence is shown of four sets of space-charge waves on a uniform electron beam focused by an axial magnetic field with arbitrary, but uniform cathode flux. The magnetic field affects the results only through the cathode flux. Expressions for the plasma frequency reduction figures are given. Some discussion is given for the case of a beam in a propagating drift tube.

565.

Graphical method for the approximate determination of trajectories in electrostatic lenses taking account of space charge, W. Walcher, Z. angew. Phys., 3, 189-90 (1951). (In German.)

The applied field is treated as a series of potential steps, at each of which refraction occurs. In the intervening space free of applied field, the space charge alone is supposed to operate. Appropriate expressions for ray tracing are given. The method has been applied to lenses used with a high-intensity mass spectrograph.

566.

The measurement of space charge wavelength in an electron beam, D. Walsh, J. Electronics, 2, 436-40 (1957).

A method is described of measuring the wavelength of space-charge waves in an electron beam by comparing the klystron gain between cavities unequally spaced along the beam.

567.

Space charge requirements in some ideally focused electron-optical systems, N. Wax, J. Appl. Phys., 24, 727-30 (1953).

A selected set of points on the trajectories of charged particles traversing an electron-optical system may be considered to be an object space, and another set an image space. Electron-optical lenses are said to be ideally focused if the transformation of the points in object space to those in image space is one to one and continuous. A necessary condition for ideal focusing is used to prove that a number of electron-optical systems require the presence of space charge in order to be ideally focused. Expressions for some ideally focused electron-optical lenses are given, in particular those for cylindrical lenses without space charge derived from spherical lenses with space charge.

568.

Space charge effects in dense, velocity modulated electron beams,
M. Weinstein and H. M. Von Foerster, J. Appl. Phys., 27, 344-6 (1956).

By assuming the bunching process of electrons in the drift region of a klystron as being space periodic, rather than time periodic, it is possible to describe the debunching mechanism in a finite diameter beam on a large signal basis. It is shown that such beams have a discrete spectrum of oscillations with the plasma frequency as series limits. This makes it impossible to assign a unique bunching parameter to all electrons. These results check with a velocity-phase analysis of high-density electron beams carried out with a beam analyser at a frequency of 3000 Mc/s.

569.

Space-charge expansion of a positive hydrogen ion beam leaving a duoplasmatron ion source, A. B. Wittkower et al., Rev. Sci. Instr., 33, 515-520 (1962).

Space charge is shown to be the controlling influence in the expansion of a positive hydrogen ion beam leaving a duoplasmatron source aperture. This implies that there is an optimum source-aperture radius for each application. In particular, when high currents are required, this aperture may be large, i.e., greater than 0.05-in. radius. The gas flow from the source into the vacuum system may then become excessive; an extraction system which allows the aperture radius to be increased without this attendant gas flow is described.

See also: 10, 38, 54, 99, 101, 211, 298, 483, 488, 494, 530, 601, 844.

SPECTROMETRY

570.

Ionic optics, ion focusing in the mass spectrometer, F. Bertein, Bol. Radiactividad, 23, 86-100 (1950). (In French.)

Description of mass spectrometers, with a short discussion of the magnetic separation of the ions, their separating power, aberrations, and double focusing.

571.

Transverse convergence created by the slits of ion optical instruments, F. Bertein, Compt. rend., 231, 766-7 (1950). (In French.)

An expression is derived for the transverse convergence arising from the limited dimensions of the slits in such instruments as mass spectrometers.

572.

Broad-range magnetic spectrograph, C. P. Browne and W. W. Buechner, Rev. Sci. Instr., 27, 899 (1956).

A broad-range magnetic spectrograph for precise measurement of the energies and intensities of charged particles from nuclear reactions is described. A uniform magnetic field with a circular boundary focuses particles from a source outside the field along a hyperbolic focal surface. Particles with energies varying by as much as a factor of 2.5 may be simultaneously recorded on nuclear-track plates. Under routine operating conditions, an energy resolution of better than 1000 is obtained over the length of the focal surface. The design, construction, testing, and operation of the spectrograph are described, and plots of dispersion, magnification, aberration, and calibration are given.

573.

On the theory of the 90° mass spectrometer, I. ideal magnetic field, D. Charles, Ann. Radioélect., 11, 249-67 (1956). (In French.)

Simple theory is used to examine image formation for single and double collection; the influence of objective slit width, the required source stability, and the tolerances on chromatic aberration are deduced. Second- and third-order aberrations are evaluated, and the simplest practicable conditions for second-order correction discussed. The influence on image formation of mechanical and electrical adjustments and mechanical tolerances is considered.

574.

On the theory of the 90° mass spectrometer. II. real magnetic field, trajectories in the plane of symmetry, D. Charles, *Ann. Radioélect.*, 12, 62-77 (1957). (In French.)

The influence of end-effects and nonuniformity of the analyzer field on image formation is examined.¹ It is concluded that end effects lead to loss of symmetry which may be corrected by suitable displacement of the magnet. Increase of the field in the gap with radius affects symmetry, and the second-order aberration, α , becomes more serious; if the field is made to decrease with radius, α may be reduced by adjusting the position of the slits. Variation of field along the mean ion trajectory leads to a slight image displacement, and α is not appreciably affected. The effects are illustrated by numerical examples.

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1. A. M. Clogston, *Bell System Tech. J.*, 34, 739-60 (1955).

575.

Combined magnetic spectrograph and spectrometer, H. A. Enge, *Rev. Sci. Instr.*, 29, 885 (1958).

A combination instrument is proposed in which a broad-range magnetic spectrograph can be operated as such or in connection with a magnetic quadrupole lens to form a high-intensity spectrometer. A solid angle of approximately 10^{-2} steradian can be attained with this spectrometer without use of very large magnet gaps.

576.

Spherical condensers free from spherical aberration, H. Ewald, *Z. Naturforsch.*, 14a, 680-1 (1959). (In German.)

Discusses the use of spherical and toroidal condensers in spectrometers. It is shown that a toroidal condenser system can be constructed in which the mean zero potential is part of a sphere, thus eliminating spherical aberration, while retaining stigmatic focusing.

577.

Further mass spectrometers with complete double focusing of the second order, H. Hintenberger and L. A. König, *Z. Naturforsch.*, 13a, 236-7 (1958). (In German.)

It is shown that double focusing in mass spectrometers can be achieved to a second order if the magnetic deflector is assigned curved boundaries. Optimal radii of these are determined by the geometry of the rest of the apparatus, and the relative dimensions of a number of such systems are given in tabular form.

578.

Mass spectrometers with double focusing of the second order, H. Hintenberger and L. A. Konig, Z. Naturforsch., 12a, 773-85 (1957). (In German.)

The authors propose a double-focusing mass spectrometer free from second-order aberration, whether due to aperture defect or to chromatic error. The design follows the solution of a complicated set of equations containing five arbitrary design parameters; these equations have been solved numerically. Designs using complementary deflection appear to be a practical possibility.

579.

On mass-spectrometers with perfect double focusing of the second order, H. Hintenberger and L. A. Konig, Z. Naturforsch., 12a, 443 (1957). (In German.)

Some examples of design data for double-focusing mass spectrometers free from second-order aberrations are given; they were obtained by solution of the five equations given in the author's previous paper.¹

¹Z. Naturforsch., 12a, 773-85 (1957). 578

580.

On the aberrations in double-focusing mass spectrometers and mass spectrographs, H. Hintenberger and L. A. Konig, Z. Naturforsch., 12a, 140-7 (1957). (In German.)

The aberrations of a double-focusing spectrometer are evaluated neglecting end effects. The system analyzed consists of a radial electrostatic field followed by a uniform magnetic field. The conditions for freedom from aberration are stated.

581.

Second-order properties of double-focusing spectrometer with nonuniform magnetic field, H. Ikegami, Rev. Sci. Instr., 29 943-8 (1958).

Second-order focusing properties are considered for a nonuniform magnetic field with arbitrary circular boundaries in the case of normal entry and exit. The formula obtained agrees with that obtained by Hintenberger for the special case $\alpha = \beta = 0$. It is also shown that the double and second-order focusing can be achieved simultaneously. The numerical results are represented graphically for a symmetrical double-focusing spectrometer with an arbitrary deflection angle.

582.

Focusing properties of a generalized magnetic spectrometer,
D. L. Judd, Rev. Sci. Instr. 21, 213 (1950).

The first-order focusing properties of a magnetic spectrograph similar to that of Siegbahn and Svartholm, but differing in that both source and collector lie outside the field, are investigated. The parameters of the analogous thick-lens optical system are derived. General expressions for image distance, astigmatism, magnification, solid angle, dispersion, and resolution of lines with a spread in momentum are obtained. Factors affecting the compromise between intensity and resolution are discussed. The possibility of increasing resolution without loss of intensity by introducing some astigmatism is considered. Second-order effects have not been included since they are thought to be of the same order as corrections for the fringing field. The first approximation proved adequate for the design of an instrument in which satisfactory focusing was obtained by simple empirical adjustments.

583.

Variation of image aberration coefficients and line broadening along the photographic plate in mass spectrographs having double focusing of the first order for all masses, L. A. Konig, and H. Hintenberger, Z. Naturforsch., 13a, 1025-34 (1958). (In German.)

Aberrations and line broadening are worked out for spectrometers of the Mattauch-Herzog type. The results are expressed in diagrammatic form and numerical examples given.

584.

On the use of differential electrostatic fields in the spectroscopy of beams of charged particles, M. I. Korsunskii and V. A. Bazakutsa, Doklady Akad. Nauk SSSR, 113, 1029-31 (1957). (In Russian.)

The development of the doubly focusing mass spectrometer is briefly reviewed and attention directed to the focusing properties of a differential electrostatic field of the type discussed by Barber.¹ An electrostatic mass spectrometer based on these principles is described. The particles, which are focused axially and radially, follow a circular path between suitably shaped electrodes. The dispersion is said to be an order of magnitude better than that obtainable from ordinary cylindrical electrodes.

¹N. F. Barber, Proc. Leeds. Phil. Soc., 2, 427 (1933).

585.

High-dispersion two-directional-focusing β -spectrometers,
G. E. Lee-Whiting, Can. J. Phys., 35, 570-5 (1957).

Momentum spectra of charged particles are often analyzed with the aid of magnetic focusing; in one type of spectrometer the particles move along a circular arc roughly perpendicular to the lines of force. It is shown that when the beam is turned through an angle of $\pi(n^2 + 1)^{1/2}$ radians in a suitably shaped magnetic field a two-directional focus is obtained. For this type of instrument the dispersion increases rapidly as n is increased, while the aberrations remain roughly constant. Even for values of n in the range 3 to 7 an enormous gain in "luminosity" and a useful increase in the permitted source width should be obtained. Although practical difficulties are introduced by the use of paths of more than one complete revolution, these should not be insuperable if the size of the apparatus is large enough relative to the size of the source, especially if an odd value of n is used.

586.

The large-angle two-directional focusing of the beta spectrometer,
G. Lehr and S. B. Gesell, Naturwissenschaften, 78, No. 2, 47-82.
(1955). (In German.)

It is shown that for arbitrary focusing angles, higher-order focusing can be obtained independent of the aperture. Formulae for the suitable magnetic field are given to the fifth order. The equations for the paths of charged particles in an inhomogeneous, cylindrically symmetrical field have been calculated to the fourth order. From this it is possible to obtain the inhomogeneity of the field, which yields simultaneously the focusing of the first order, the vertical focusing, and the higher-order focusing. It is shown that axial defocusing of the second order can be reduced by means of an elliptic baffle. Furthermore, a field of reasonably good focusing property is given for cases of equally large radial and axial apertures.

587.

The image aberrations of double-focusing mass spectrographs,
H. Liebl and H. Ewald, Z. Naturforsch., 12a, 538-40 (1958). (In German.)

The second-order radial aberrations are calculated for a double-focusing mass spectrometer which has a toroidal electrical condenser and a magnetic field of circular boundary at entry. Cylindrical and spherical condensers, and rectilinear magnetic field boundary, are special cases to which the results are applicable.

588.

Mass spectrographs with double focusing of the second order. H. Liebl and H. Ewald, Z. Naturforsch., 14a, 199-200 (1959). (In German.)

The conditions for double focusing of the second order were numerically calculated, and the results are tabulated.

See also Ewald, Z. Naturforsch., 14a 198-9 (1959).

589.

Particle spectrography of high intensity: dispersion and resolving power, H. Liebl, Z. Naturforsch., 14a 843-4 (1959). (In German.)

Continues the calculations referred to in 588 and shows that the production of a point intermediate image leads to an increase of intensity. An example is given of a point-focusing, aberration-free toroidal condenser which produces an axial intermediate image. Such condensers have five times greater dispersion than a comparable spherical condenser.

590.

Point focusing aberration-free mass-spectrometer, H. Liebl and H. Ewald, Z. Naturforsch., 14a, 842-3 (1959). (In German.)

Briefly describes the conditions to be satisfied in a point-focusing mass spectrometer using a toroidal condenser and a magnetic sector field if it is desired to form an intermediate radial image between the electric and magnetic fields. Aberration-free operation and point focusing are maintained.

591.

Stigmatic-imaging mass spectrographs with double-focusing practically of second order, H. Liebl and H. Ewald, Z. Naturforsch., 12a, 541-4 (1958). (In German.)

Results of the article [Liebl and Ewald, Z. Naturforsch., 12a, 538-40 (1958)*] are applied to a discussion of conditions for the vanishing of second-order radial aberrations. It is shown how three of the four aberrations may be eliminated, while the fourth, depending only on ion-energy spread, is minimized.

*587

592.

The intersection angle of direction- and energy-focusing curves in double-focusing mass spectrographs, H. Liebl, *Optik*, 16, 19-26 (1959). (In German.)

Derives formulae for this angle at the point of double focusing and gives its values for existing and proposed spectrometers. Discusses the condition for zero angle.

593.

Alternating-gradient magnetic spectrometer, H. J. Martin and A. A. Kraus, *Rev. Sci. Instr.*, 28, 175-177 (1957).

An alternating-gradient magnetic spectrometer has been constructed. The spectrometer consists of two magnetic lenses that deflect the analyzed particles through a total angle of 30° . It is able to analyze protons with energies up to 6 Mev and has a solid angle of 0.012 sterad and a momentum resolution $R = p/dp = 77$ for 0.5-mm exit slit. The distance between the source and image positions is 85 cm.

594.

The electric mass filter as mass spectrometer and isotope separator. W. Paul, H. P. Reinhard, and U. von Zahn, *Z. Phys.*, 152, 143-82 (1958) (In German.)

An electric quadrupole lens is used as a mass spectrometer by placing alternating potentials across the electrode pairs. A resolution of 1500 is obtained in agreement with theory. The method can also be used in isotope separation.

595.

A new mass spectrometer without a magnetic field. W. Paul and H. Steinwedel, *Z. Naturforsch.*, 8a, 448-50 (1953). (In German.)

The ions move in the z-direction in an alternating electric field with a potential distribution of the form

$$\phi(x,y,t) = \frac{U + V \cos \omega t}{a^2} \frac{(x^2 - y^2)}{2}$$

generated between four hyperboloidal electrodes. The stability of the particle orbits is discussed.

596.

Investigation of the focusing properties of a double directional-focusing magnetic spectrometer with conical pole surfaces, R. Pauli, Ark. Fys., 10, 175-85 (1955).

The spectrometer uses a 180° sector field with a field distribution $H(\gamma) = H_c(2\gamma_c)/(\gamma_c + \gamma)$, where γ_c is the mean orbit radius, and H_c the field at $\gamma = \gamma_c$. The field is obtained by conical pole surfaces with suitable spacing. Focusing is slightly astigmatic. The best position for the photographic plate was determined experimentally and agreed with calculation. The resolving power was about three times worse than the calculated value.

597.

Elimination of the radial second-order angular aberrations in inhomogeneous field mass spectrometers by inclined plane boundaries, H. A. Tasman and A. J. H. Boerboom, Z. Naturforsch., 15a, 736-8 (1960).

Extension of previous work. See: 1. Tasman and Boerboom, Z. Naturforsch., 14a, 121-9 (1959); 2. Wachsmuth, Boerboom, and Tasman, Z. Naturforsch., 14a, 818-27 (1959); 3. Tasman, Boerboom, and H. Wachsmuth, Z. Naturforsch., 15, 78-9 (1960).

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598.

Ion optics of the ion source of mass spectrometers, R. Vauthier, Compt. rend., 231, 764-5 (1950). (In French.)

The trajectories of the ions are calculated by considering the slit system of the ion source as a system of cylindrical lenses.

599.

Optics of the ion source of mass spectrometers, R. Vauthier, Compt. rend., 231, 1218-20 (1950). (In French.)

Formulae are derived for the angular width of the emergent beam and its intensity. The influence of the geometrical dimensions of the source (thickness) is shown to be almost negligible with regard to the resolution of the mass spectrometer.

600.

Double-focusing aberration-free mass spectrometer with particularly high resolving power and dispersion, H. Wachsmuth, H. Liebl, and H. Ewald, Z. Naturforsch., 14a, 844-6 (1959). (In German.)

Describes a practical realization of a mass spectrometer based on the calculations of the work by Liebl [Z. Naturforsch., 14a, 843-4 (1959)]. A toroidal condenser was followed by a magnetic sector field with conical pole pieces in such a way that between the fields the ions followed parallel paths in the radial direction and came to a point focus in the axial direction. In this system the resolving power is determined entirely by the electric field and the dispersion by the magnetic field. The calculated resolving power and dispersion are nearly an order better than that from a cylindrical condenser and homogeneous magnetic field with comparable radius of trajectory.

601.

Ion optics and mass spectrometry, W. Walcher, Nucleonics, 5, 42-51 (Oct 1949).

The optical constants of magnetic and electric sector fields are derived by a simple method. The magnetic case is developed in some detail for sectors of any central angle; by drawing the normal trajectory as a straight optical axis, the system becomes analogous to a thick optical lens, with the usual familiar expressions. A variation of particle momentum is equivalent to a parallel displacement of the axis. Expressions for mass dispersion and resolving power are given. The combination of electric and magnetic sectors to compensate for inhomogeneity in particle energy is demonstrated. The effects of boundary spreading of magnetic fields and space-charge repulsion in intense beams are discussed, also second-order aberrations in magnetic sectors.

602.

Aberration-free mass spectrometer with radial intermediate image, H. Wollnik and H. Ewald, Z. Naturforsch., 15a, 265-7 (1960). (In German.)

The results of calculations, on an electronic computer, of the characteristics of 69 double-focusing mass spectrometers are presented in 8 graphs.

See also: H. Liebl and H. Ewald, Z. Naturforsch., 4a, 843-4 (1959). 589

603.

A mass spectrometer of second-order focusing, M. Yokata, M. Nagatani, and I. Nonaka, Mem. Fac. Sci. Kyusyu Univ., B2, 22-31 (1956).

Detailed account of construction and circuitry, also some performance data, of a symmetrical mass spectrometer.

See also: 71, 73, 151, 190, 206, 207, 273, 276, 279, 372, 430, 466, 474, 487, 565, 615.

PART II - ACCELERATOR APPLICATIONS

BOOKS AND REVIEW ARTICLES

603a.

International Conference on high energy accelerators, Sept., 6-12, 1961. M. H. Blewitt, ed., TID-7636, 499 p.

604.

"Cyclotrons and synchrocyclotrons," B. L. Cohen, pp. 105-69 of Handbuch der Physik, Band XLIV. Instrumentelle Hilfsmittel der Kernphysik I. [Encyclopedia of Physics, Vol. XLIV, "Nuclear Instrumentation," I. S. Flugge, ed., Springer-Verlag, Berlin (1959). 480 p.]

Theoretical discussions are presented on three classes of cyclotrons: the standard cyclotron, the synchrocyclotron, and the azimuthally varying field (AVF) cyclotron. The various orbital stability and phase problems of the three types of cyclotrons are discussed in detail. The physical problems involved in the design of magnets, radiofrequency systems, ion sources, vacuum systems, beam-deflection systems, targets, shielding, and controls and interlocks are described. Several miscellaneous subjects are considered.

605.

European Organization for Nuclear Research, Sur les Accelérateurs de Haute Energie et la Physique des Mesons.. (CERN Symposium on high energy accelerators and pion physics.), Geneva, 11th - 23rd June, 1956, Proceedings. Volume 1. "High Energy Accelerators."

See especially pages 129-158; problems of ejection of particles from machines; and pages 159-236, linear accelerators and injection techniques.

606.

Conceptual advances in accelerators, D. L. Judd, [Ann. Rev. Nuclear Sci., 8, 181-216 (1958)].

Includes a discussion of phase-space concepts applied to accelerator problems, and on p. 195 there are presented applications to electron and ion optics.

607.

"Instrumentation for high-energy physics," Proceedings of an international conference, held at the Ernest O. Lawrence Radiation Laboratory. Berkeley, Calif. Sept. 12, 13, and 14, 1960, Interscience, New York (1961).

See the following:

Electromagnetic mass separation at higher energy,
M. L. Good

A high-intensity μ -meson beam from the 600-Mev CERN synchrocyclotron (Citron et al.) Presented by A. Citron

Some features of beam-handling equipment for the CERN proton synchrotron, C. A. Ramm

A new 800-Mev/c K^- beam of high purity at the Bevatron (Bastien et al.) Presented by P. Schlein

Use of generalized amplitude and phase functions in designing beam-transport systems, K. G. Steffen

Reliability of beam monitors, F. A. Bumiller

608.

High-energy accelerators, M. S. Livingston, Interscience Publishers, Inc., New York (1954) 157 p.

The development of recent high-energy accelerators is reviewed by a discussion of physical, particle-orbit, and design principles. The principles are demonstrated by recourse to particular machines. The mathematical analysis of particle motion is presented in a separate chapter, where common features of acceleration, focusing, and stability are derived from the equation of motion.

609.

Particle accelerators, M. S. Livingston, and J. P. Blewett, McGraw-Hill Book Co., Inc., New York (1962) pp. 96-132.

Chapter 5. Particle motion in electric and magnetic fields. Four focusing systems are discussed: the electrostatic lens, the axial magnetic field lens, the alternating-gradient lens, and the magnetic edge-focusing lens.

610.

Proceedings of the CERN symposium on high energy accelerators and pion physics, held in Geneva, June 11-23, 1956, Volume 1: "High-energy accelerators," E. Regenstreif, ed., Geneva, European Organization for Nuclear Research (1956). 567 p. (This publication is composed of several papers by various authors. Most of the papers are in English but a small number are in French.)

...Discussions on ejection problems include topics such as the external proton beam at the Cosmotron, deflection of the beam of a 7-Bev strong-focusing proton accelerator, ejection problems for the CERN-AG machine, regenerative action in high-energy accelerators, the USSR 6-meter synchrocyclotron, and a synchrocyclotron ejector. Papers on linear accelerators and injection include those on injectors for proton synchrotrons, alternating-gradient focusing in linacs, proton orbits in the Brookhaven linear accelerator, computation of drift-tube shapes, study of magnetic lenses, a chromatic injector for the Saclay synchrotron, design of high-current linacs, proton linacs, methods of acceleration, a microwave linear accelerator, beam stability, and proton injection by molecular dissociation...

611.

Static and dynamic electron optics. An account of focusing in lens, deflector and accelerator. P. A. Sturrock, The University Press, Cambridge: (1955), x + 240 pp. (Cambridge Monographs on Mechanics and Applied Mathematics).

In the first part (static), units convenient for electron-optical calculations are defined; a variational equation is derived and applied to the paraxial focusing of magnetic and electrostatic lenses. Classical geometrical optics are then reviewed (Hamilton's point characteristic function, Lagrange and Poincaré invariants) and interpreted in terms of electron optics. A "perturbation characteristic function" is introduced to take account of small departures from simple focusing, and adapted to a form convenient for determining aberrations in instruments with curved or straight axes. This is used to determine the chromatic and third-order geometrical aberrations, and aberrations due to manufacturing inaccuracies of rotationally symmetrical systems; it is also applied to systems with mirror symmetry, particularly β -ray and mass spectrographs and cathode-ray tube deflectors.

In the second part (dynamic), adiabatic invariants and matrices are used in addition to the foregoing theory to determine the motion of particles in the synchrotron, linear accelerator, and strong-focusing synchrotron. Phase acceptance, tolerances, and stability conditions are discussed.

SOURCES: ION AND PROTON

612.

Theory and performance of the radiofrequency ion source. Part I. Theory and mechanism of the low-pressure plasma used in radiofrequency ion sources, M. E. Abdelaziz, Argonne National Laboratory Internal Report MEA - 1 (April 14, 1960) 19 p.

An efficient ion source is characterized by two fundamental functions: i) the creation of an intense plasma with relatively high electron and ion densities, and ii) the extraction from the plasma and proper focusing of the positive ion beam into an exit canal so that the maximum possible current can be obtained at a minimum of absorbed power and consumed gas in the source. In this paper the first fundamental function, i.e., the plasma theory, is to be treated. (See MEA-2 for part II; 613.)

613.

Theory and performance of the radiofrequency ion source. Part II. Extraction of ion beams from the r.f. plasma, M. E. Abdelaziz, Argonne National Laboratory Internal Report MEA-2 (September 1, 1960) 34 p.

The analysis of the extraction problem in a radiofrequency ion source is considered in three sections: 1. Design charts for the exit canal of the source are prepared to give characteristics of the extracted ion beam corresponding to different canal sizes and running conditions of the source. 2. The focusing properties of the beam between the plasma boundary and the canal are analyzed considering the theory of conical flow of proton beams between spherical surfaces; from such analysis the dimensions of the beam-forming cathode shield are determined. 3. The theory of radial potential distribution in an intense beam is applied to find out its effect on design calculations from the first-order theory and how the resulting blow-up forces contribute to the losses in beam current inside the metal canal. (For part I see MEA-1; 612.)

614.

Development of a 100-ma proton source and lens system for the bevatron mark-II injector. R. W. Allison, Jr., B. Cork, R. M. Richter, J. F. Smith, G. E. White, and E. Zajec, Rev. Sci. Instr., 32, 1331-6 (1961). [See also UCRL-9743 (Rev.).]

A Von Ardenne-type ion source and lens system is developed for use as a preinjector to the 18-Mev strong-focusing linear accelerator. Proton beams of 120 ma at an ion production efficiency of 83%

are obtained. A magnetic beam-confining system is built, and a beam of 85 ma is transported 82 in. The beam energy is 370 kev and its emittance is 100 mrad-mm. The beam diameter is 1 cm. This is within the linear accelerator's calculated acceptance of 179 mrad-mm.

615.

Strong-focusing ion source for mass spectrometers, C. F. Giese, Rev. Sci. Instr., 30, 260-261 (1959).

An ion source has been developed, using strong-focus principles, with a view toward obtaining high transmission through sector-shaped magnetic fields. The lens described, starting with an ion beam 0.375 in. square, produces a line focus 0.60 in. long and 0.025 in. wide, with a half-angle of divergence beyond the crossover of 0.034 rad.

616.

A new method to produce a polarized proton beam, T. K. Khoe and A. Yokosawa, Argonne National Laboratory Internal Report TKK-AY-1 (January 10, 1962) 4 p.

In order to overcome the difficulties created by the polarized proton sources constructed at Harwell, Oak Ridge, etc., namely, an insufficient amount of dissociated hydrogen atoms and too low an ionization efficiency, a new scheme has been devised. This comprises a duoplasmatron proton source, focusing electrode, H₂ gas, separation magnet, He gas, and finally the polarized proton beam.

617.

A high current proton source, P. C. Thronemann and E. R. Harrison, AERE-GP/R-1190 (Jan. 25, 1955) 18 p.

Proton currents approaching 20 ma at 10 kv can be produced from a moderately simple form of ion source in which the beam divergence is sufficiently small to be focused by an electrostatic lens. The increased gas flow requires high pumping speeds to maintain suitably low pressures below the ion source.

SOURCES: EMITTANCE MEASUREMENT

618.

Beam emittance measurement, E. A. Crosbie, Argonne National Laboratory Internal Report EAC-5. 3 p.

In a memorandum from A. Yokosawa, dated April 9, 1962,¹ mention is made of two methods for determining the phase-space area by means of slit and image measurements. Quite different phase-space figures and areas are obtained depending on which method is used. It should be pointed out that both methods must be used in order to arrive at the correct phase-space figure. Method I will give the correct result in some positions, Method II in others. The purpose of the present note is to show an approximate method for determining which method to use at various positions in the phase-space plane.

¹621

619.

A study of a focused beam from the duoplasmatron proton source, R. McKeever and A. Yokosawa, Argonne National Laboratory Internal Report AY-RM-2. 17 p.

Aberrations of the preaccelerator focusing electrodes were studied experimentally by obtaining emittance diagrams for a beam of 38 and 60 ma. Aberrations observed were similar to those obtained from previous ray-tracing calculations. According to the calculations, the cause of aberrations is improper distribution of the radial field in the exit portion of the lens. More distortion of the phase-space diagram was observed for the higher beam current than the lower one. The observed emittance area increased by more than a factor of two when the beam current was changed from 38 to 60 ma. Even if aberrations were entirely eliminated, this fact may raise a serious problem in beam matching for a large beam current. A technique for measuring the emittance of the beam at 200 kv was developed, and the details are described.

620.

Beam emittance measurement, C. H. M. Turner, Argonne National Laboratory Internal Report CHMT-11 (May 2, 1962) 8 p.

A variation and extension of the argument presented in EAC-5 (Crosbie, Beam emittance measurement, ANL internal report, 4/16/62)¹ and in response to the memorandum of A. Yokosawa, 4/9/62.²

¹618
²621

621.

Beam emittance measurement, A. Yokosawa, Argonne National Laboratory Internal Memo (Unnumbered) (April 9, 1962). 3 p.

Presents two methods of measuring beam emittance. See also C. Turner, CHMT-11,¹ 5-2-62; E. Crosbie, EAC-5, 4-16-62;² and A. Yokosawa, AY-RM-1, 5-10-61.³

¹620

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³622

622.

Emittance measurements of beams extracted from the duoplasmatron ion source, A. Yokosawa and R. McKeever, Argonne National Laboratory Internal Report AY-RM-1 (May 10, 1961) 12 p.

Describes the method and results of emittance measurements of protons extracted from the ion source.

INJECTION

623.

Der Injektionsweg (The injection method), DESY-A2.40 (Jan 27, 1959)
18 p.

The requirements for the establishment of an injection method from the linear accelerator into the synchrotron are briefly reviewed. The limiting values for the injection system are given with a consideration of the integration of the orbit curve, the theoretical orbit, particles with energy deviations, energy adjustment system, transformation of the phase surface, and the phase-surface adaptation system.

624.

The effect on injection of a linear build-up of the accelerating voltage, C. Alley, CA-1 (Sept. 6, 1949).

625.

Focusing system for injection of electrons in the national synchrotron, U. Amaldi, Jr., R. C. 1st. Super. Sanita, 21, Pt 10, 896-914 (1958). (In Italian.)

The electron-optical system is described which has been designed and constructed for focusing electrons of 2 MeV injected into a synchrotron. The electron beam is accelerated by a Cockcroft-Walton set, focused by an iron-clad magnetic lens and a quadrupole lens, and issued through an electrostatic deflector. The instantaneous electron current is 200 mA in a pulse duration of 1-5 μ sec, the exit diameter of the beam being about 5 mm and its divergence 3×10^{-3} rad. Calculations were made in Gaussian approximation, ignoring edge effects. The feeds to the magnetic lenses are mounted in a new and very simple way, which allows a stabilization of better than 1% for load resistance variations of 20%.

626.

Fokusirovka i Yustirovka Puchka Inzhektora Lineinogo Uskoritelya. (Focusing and Adjusting Linear Accelerator Injector Beam.), Yu. N. Antonov et al., Joint Inst. for Nuclear Research, Dubna, USSR Lab of High Energy (1961). 19 p.

The focusing and alignment of an injector beam in a linear synchrophasotron accelerator is described. The distance between the ion source and the resonator pipe is 5000 mm. The beam diameter at the accelerator entrance is ≤ 5 mm and the angular divergence is

$\leq 3 \times 10^{-3}$ rad, with a proton pulse current of 50 to 70 ma (pulse time = 450 μ sec at a proton energy of 570 kev). The design of the device is included.

627.

Injection into the 7-GeV synchrotron, M. Bell, AERE-T/M-155 (Jan. 1958) 21 p.

Calculations were made on a linear approximation to determine the best choice of Q_R and of field rise at injection into the 7-Bev proton synchrotron. It is found that at the commensurate values of Q_R of $2/3$ and $3/4$, the acceptance area for the injected beam has small radial width and large angular divergence. Between these values the area has larger width and smaller divergence but is roughly of the same magnitude. Consideration of injection optics suggests the latter as the better choice. The optimum choice of field rise appears to lie between 2 and 4 kilogauss/sec.

628.

A lens system for use between the 15-Mev Linac and the 7-GeV synchrotron, M. Bell, TAG/3.

The variation in the frequency of the accelerating field needed to take advantage of the increase in the number of protons captured in stable orbits accompanying a linear build-up in amplitude during injection. N. M. Blachman, NMB-13 (Jan. 17, 1950).

630.

Procedures for injection into an alternating-gradient synchrotron, J. P. Blewett, BNL-JPB-4 (Sept. 9, 1954) 16 p.

In this report it will be shown that injection into the proposed BNL alternating-gradient synchrotron can be accomplished either from inside or outside the ring. The general procedure in either case involves a final inflection into the orbit by a pulsed inflector in one of the 10-ft straight sections. The beam is curved into the magnet-ring building on a radius of the order of 20 ft and is released by the bending field just outside of the four-pole lens in the 5-ft straight section immediately preceding the 10-ft section in which the pulsed inflector is located. From this "release point" the beam travels on a roughly straight trajectory into the inflector.

631.

Spiral path of injected particles in the Cosmotron, M. H. Blewett, MHB-11 (Mar 11, 1952).

632.

Injection optical system, H. N. Brown, BNL-4646 (Aug 21, 1957) 18 p.

The general requirements of the injection system between the linear accelerator and the synchrotron are discussed. The specific equipment necessary to meet these requirements is described. It is felt that the system as described is close to its final form although the detailed design and drawings have not been done.

633.

Optical system controlling the Van de Graaff beam in the synchrotron chamber, H. Bruck, G. Gendreau, and M. Salvat, Onde elec., 39, 505-11 (1959) (In French.)

The reasons leading to the selection of the achromatic and afocal optical system in the Saturne injector and the theory of this system are discussed in detail. The component parts of the optical system are described. Experimental data on the system are in good agreement with the theoretical data.

634.

Review of some concepts involved in ZGS injection, D. Cohen, Argonne National Laboratory Internal Report DC-3 (March 11, 1959). 14 p.

Using Cartesian coordinates, discusses injector properties in terms of phase-space figures. Concludes that 1) an effort should be made to insure that the emittance from the column will blanket the linac uniformly in phase space; the resulting radioactivity on the drift-tube bore surfaces should be viewed as a necessary evil. Serious consideration should be given to increasing the radial focusing strength in the column, perhaps by the use of solenoids enclosed by the accelerating electrodes or by a Helmholtz coil arrangement. 2) If the blanketing procedure takes place, the linac should operate in the $+-+$ mode with the highest gradients allowed by power and saturation limitations, and care should be taken to minimize radial misalignments of quadrupole magnets in order to increase the effective bore size; otherwise the low-power $++-$ mode operation is adequate. 3) Several percent of ripple can be tolerated in the quadrupole power supply. 4) For the cases

mentioned, precision control of the quadrupole matching system between linac and synchrotron is not as necessary as was previously felt; nonlinearities in these magnets need not be painfully minimized.

635.

Radial oscillation induced by injection conditioning, E. D. Courant, EDC-12 (March 26, 1952).

636.

Linac injection for the 340-Mev Berkeley electron synchrotron, Part I - Theoretical, K. C. Crebbin and J. R. Hiskes, UCRL-9057 (Jan 1960) 24 p.

The problem of multiturn injection into the 340-Mev electron synchrotron utilizing the 2-Mev beam from the rf linear electron accelerator is discussed. The details associated with inflection are ignored; primary attention is given to estimating the acceptance requirements for the betatron and synchrotron oscillations. Two methods of injection are examined: injection at constant energy, and injection with energy increasing with the magnetic field. Under somewhat idealized assumptions regarding the output properties of the linac beam, it is estimated that a trapped-beam current could be obtained which is several factors larger than the present beam using betatron injection. Since the angular properties of the beam from the linac are appreciably poorer than the idealized assumption, it appears that the probability of increasing the present synchrotron beam intensity using these injection methods is small.

637.

Tuning up the zero gradient synchrotron, A. V. Crewe, Argonne National Laboratory Internal Report AVC-2 (May 10, 1960) 6 p.

Presents a method for tuning up the ZGS with the following objectives: 1) to achieve vertical and radial frequencies of oscillation of the correct values, 2) to adjust the particle orbits at injection to utilize the full vacuum chamber width, 3) to inject as many turns as possible.

638.

Injection dans le synchrotron. Reglage de l'acceptance du synchrotron. (Injection in the Synchrotron. Regulation of the Acceptance of the Synchrotron), CERN-PS/PL-3 (Feb 1955) 35 p.

639.

Injection dans le synchrotron. Aberrations. (Injection in the Synchrotron. Aberrations), CERN-PS/PL-4 (Apr 1955) 28 p.

Second-order aberrations of the particle beam between the linear accelerator and the synchrotron are studied in connection with the maximum acceptance of the synchrotron. Particular attention is given to the aberrations introduced by the passage of the beam through the synchrotron leakage flux, and it is concluded that some rearrangement of the magnetic sectors is necessary to deal with this problem.

640.

Electron-optical properties of homogeneous magnetic and radial electric fields, A. A. Garren and Lloyd Smith, UCRL-599 (Feb 8, 1950) 34 p.

For various purposes it is often desired to change the direction or alter the characteristics of a given beam of ions. This can be done with various combinations of magnetic and electric fields, of which a homogeneous magnetic field and a radial electric field, such as is found inside an electrostatic deflector, are among the easiest to produce. It is the purpose of this report to summarize the optical properties of these two types of fields and of various combinations thereof. It is always assumed that the electric and magnetic fields are perpendicular wherever they are superimposed, are plane bounded, and that the beam is in what shall be called the horizontal plane, which is defined as the plane perpendicular to the magnetic field and/or parallel to the electric field. The discussion is confined to effects of the first order in the deviations in position, direction, velocity, and mass of the ions from reference values. The theory of focusing effects in the horizontal plane is based on a paper by R. Hertzog, who was interested chiefly in applications to mass spectroscopy. Parts of his discussion have been generalized somewhat; further, the focusing effects in the vertical plane (the plane parallel to the magnetic field and/or perpendicular to the electric field) are given. All optical properties are expressed by equations which show the analogy with thick lenses, and so far as possible Hertzog's notation has been used. Lastly some discussion of the application of the theory to the problem of injection into the bevatron has been included.

641.

Betatron injection into synchrotrons, F. K. Goward, Physical Society of London, Proceedings, 62A, 617-631 (1949).

The paper states simply the factors influencing the proportion of electrons which may be trapped and accelerated in a transition from betatron to synchrotron operation; this transition is a vital factor influencing the design of the normal electron-synchrotron. Machines of various energies are studied, and it is shown that the important considerations in the design are quite different in different energy ranges. The theoretical predictions are compared with experimental evidence obtained on 14- and 70-Mev synchrotrons, and the agreement is sufficient to give confidence in the simplified theory.

642.

Bevatron injector measurements, H. G. Heard, UCID-907 (Oct 16, 1956). 8 p.

Further measurements have been made of some of the critical parameters in the Bevatron injector system. The variation of the rf level of the linear accelerator during a pulse and from pulse-to-pulse has been examined in some detail. The effect on beam transmission of varying the linear accelerator rf voltage is reported. Measurements of the regulation of the Cockcroft-Walton accelerator voltage during a beam pulse have been made. The effect of varying the Cockcroft-Walton voltage on the acceptance of the linear accelerator has been measured.

643.

Effect of inner radius obstructions on the acceptance of injected charge in the Bevatron, H. Heard, Bevatron report 384 (12/8/58).

644.

The effect of rate of rise of magnetic field on the acceptance time of the Bevatron, H. G. Heard, UCRL-3682 (Feb 12, 1957) 13 p.

The acceptance time of the Bevatron has been measured for three different rates of rise of magnetic field. These data indicate that the acceptance time varies inversely with rate of change of magnetic field. An analysis is given of the variation of the probability of an injected proton's striking the inflector on successive turns. This analysis, which is idealized to a circular machine and assumes linear betatron oscillations shows that the probability of missing the inflector varies slowly with the rate of change of magnetic field.

645.

A note on injection timing and tolerances, H. G. Hereward, CERN/PS/HGH-5 (May 1955).

646.

An injection optical system for the Argonne synchrotron, J. R. Hiskes, Argonne National Laboratory Internal Report JRH-2 (Oct 1958). 17 p.

Discusses the problem of matching the output beam from the linear accelerator to the admittance requirements of the Argonne synchrotron. The parameters for a particular set of matching lenses and steering magnets are given, as well as tolerances on magnetic field values and quadrupole alignment.

647.

Magnetic strong focusing proton linear accelerator for the Bevatron. J. R. Hiskes, UCID-914 (Feb 3, 1959) 3 p.

The parameters are listed for a Bevatron injection system utilizing a 200-Mc quadrupole focusing linac. The quantities listed are calculated on the basis of a ten- or fifteen-Mev linac of the Argonne-Brookhaven type.

648.

Injection philosophy for synchrotrons, K. Johnsen, CERN-PS/KJ 30 (Nov 1956) 20 p.

The injection system is a very important part of any accelerator, and the beam intensity one can expect to get out of the accelerator depends very much on having the right design for the injector. By injector is in this respect meant everything up to the synchrotron. In most large synchrotron projects one plans to use a linear accelerator as injector. Designs for such linear accelerators exist, both for electrons and for protons. However, such machines are constructed for nuclear physics experiments, for medical purposes, or even for industrial applications, and the requirements put on these machines for such purposes may be quite different from the requirements one would like to impose on an injector. The purpose of this lecture is to show the principles one should follow in analyzing the injection problems to find the special features one would like an injection system to have.

649.

"Beam injection into a 50-Gev strong-focusing proton synchrotron," D. G. Koshkarev, p. 656-9 of International Conference on High-energy Accelerators and Instrumentation-CERN 1959. Geneva, European Organization for Nuclear Research, 1959.

The effectiveness of injection depends largely on the beam characteristics at the outlet of the injector, a linear accelerator. The ion guide, injection, and injector design are discussed. Some beam characteristics at the linear accelerator outlet and in the ring accelerator chamber at the moment of injection are given.

650.

Summary of the CERN-PS injection philosophy, G. Lüders, CERN-PS/GL11 (Dec 1953) 19 p.

A summary is given of the present state of thinking in general terms of injection (optimum fit, "admittance," etc.). The dependence of the admittance on the mode is shown in a curve. Further, the transfer matrix for optimum fit is written down but no attempt is made to realize this transfer matrix by magnetic or electric fields.

651.

The theory of particle capture into synchrotron acceleration regime with account of nonconservation of motion equations, V. K. Malnikov and Yu. S. Sayasov. Joint Inst. for Nuclear Research, Dubna, USSR Lab. of Theoretical Physics (1958) 14 p.

A calculation of the capture region for accelerators is given taking into account the nonconservation of the equation of motion of the particles. The calculation is based upon the assumption that the change of $m(t)$ and $f(t)$ is slow in the equation $d/dt[m(t)\psi] + f(t)U'(\psi) = 0$.

652.

The CERN proton synchrotron. Part II. Chapter V. Injection, E. Regenstreif, CERN-60-26 (1960) 193 p.

Discussions are given of the general arrangements of the injection system, the principles of the Alvarez structure of the proton accelerator, the ion source, the 500-kev pre-accelerator, beam focusing between the source and the accelerator, the beam buncher, beam steering coils and apertures, the linear accelerator, rf power supply to the cavities, the adjustment of the accelerating field in the cavities,

focusing the accelerator, phasing the accelerating cavities, matching the beam to the synchrotron, the beam debuncher, injection optics, and ancillary apparatus between the accelerator and the synchrotron.

653.

Injection of fast neutral beams into the three-stage tandem accelerator, P. H. Rose *et al.*, *Rev. Sci. Instr.*, 31, 1052-3 (1960).

An experiment is described in which a beam of fast neutral atoms was injected into the terminal of a tandem accelerator. A second tandem was arranged in line with the first. By taking advantage of charge-exchange mechanisms these atoms were accelerated to 15 MeV by a three-stage process.

654.

Electronic-optical electrode systems for injectors of electronic accelerators, I. M. Samoilov, *Pribery i Tekh. Eksperimenta*, 1959, No. 1, 24-7.

Systems of electrodes for injectors of betatrons and synchrotrons in which spiral and ribbon cathodes are used were found to have better electron-optical parameters than the usually applied Kerst injector. These systems permit obtaining of practically parallel electron beams so that the angular dispersion can be changed to 15-20°. The spiral is made of W wire of 0.3 mm wound around a frame of 0.5 mm, 48 windings per 24-mm length. The ribbon cathode consists of a W ribbon, 0.1 x 1.0 x 28 mm. The electrodes are made of 0.3-mm Ta.

655.

Effects of rotational misalignments on the radial acceptance of the LINAC injector for NIMROD, R. Taylor, AERE-R-3096 (Oct 1959) 7 p.

A method is given for computing the radial acceptance of a linac in which the focusing quadrupole magnets may be rotated through arbitrary angles from their nominal position, while retaining their axial location and strengths. Results show that the acceptance should be scarcely affected provided the errors in angular alignment do not exceed one degree.

656.

Interturn space-charge coupling during multiturn injection, L. C. Teng, Argonne National Laboratory Internal Report LCT-27 (Sept 21, 1961) 13 p.

During the multiturn injection into a synchrotron, the space-charge interaction between various injected turns of the ion beam constitutes an interturn coupling of the betatron oscillations. Since

the betatron oscillations of ions in different turns have identical frequencies and are, therefore, in perfect resonance, the effect of this interturn space-charge coupling is expected to be rather pronounced. This effect has been observed on the synchrotron "Saturne" in Saclay, and an attempt has been made to interpret the experimental result quantitatively. In this report we shall make a more or less detailed calculation of the effect of this coupling on the betatron oscillation amplitudes.

657.

The proton synchrotron "Saturne," Onde Elect., 39, 425-634 (1959)
(In French.)

Injector-injection optics-vacuum chamber. Injector. R. Vienet, (487-492). Principles of injection. G. Bronca, et al., (492-505). Injection-Optics system. H. Bruck (505-511).

Experimentation and associated equipment. Experiments with Saturne. A. Berthelot, (606-606). Electromagnets employed with Saturne. B. Tsai and H. Desportes, (605-607).

658.

The use of a debuncher with the injector, T. R. Walsh, HAG/INJ/10

659.

On the advisability of injection from a cyclotron, A. I. Yavin, MURA-496 (Aug 10, 1959) 23 p.

A survey of some of the factors which determine the properties of a cyclotron beam is given. An effort was made to determine the characteristics of a beam as far as injection is concerned, and it is indicated why a 50-Mev cyclotron is at the present inferior to the 50-Mev linac. An 850-Mev cyclotron, however, is shown as a possible replacement for the 50-Mev linac injector.

See also: 605, 700.

BEAM OPTICS

660.

Physics Div. Quarterly Report. May, June, July, 1957, UCRL-3914
(Aug 20, 1957). 58 p.

Includes details of beam focusing and separation of the Bevatron in connection with antiproton studies where emulsion was exposed to flux of 4×10^{13} . Also includes a description of an electrical-mechanical beam-pattern indicator developed for the 60-in. cyclotron.

661.

An accurate determination of the P. L. A. beam energy by a time-of-flight method, C. J. Batty and D. J. Warner, National Institute for Research in Nuclear Science. Theoretical Group, Rutherford High Energy Laboratory, Harwell, Didcot, Berkshire (July 1961), 22 p.

An accurate time-of-flight method for measuring proton energies has been developed and used to determine the output proton energy of the P. L. A. operating at 30 MeV. A detailed analysis shows that the precision obtainable ($\pm 0.16\%$) compares favorably with other available methods in the 10-MeV to 50-MeV region.

662.

"Strong focusing" in ion linear accelerators, M. Y. Bernard, Ann. phys., 9, 633-82 (1954). (In French.)

Main aspects of ion dynamics in a linear accelerator are given, and various types of focusing reviewed, with emphasis on the properties of the "strong-focusing" system.

663.

An achromatic inflector system for NIMROD, R. Billinge, AERE-R-3475, (Sept 1960) 21 p.

The need for achromatic inflection into NIMROD is outlined, and the fundamental design of a suitable arrangement of four magnets followed by an electrostatic element is described.

664.

The phenomena affecting the cosmotron beam in the course of its acceleration, N. M. Blachman, NMB-28 (Aug 25, 1950).

665.

Radial focusing in the linear accelerator, J. P. Blewett, Phys. Rev., 88, 1197-1199 (1952).

The focusing mechanism described by E. D. Courant [Phys. Rev., 88, 1190 (1952)¹] is applied to the linear accelerator. The defocusing forces in the linear accelerator are derived, and the particular example of a 4-million-volt accelerator, 10 meters long, is discussed. It is shown that the defocusing forces can be compensated by magnetic or electric lenses of the alternating-gradient type using easily attainable field gradients. For example, a defocusing field gradient of 1000 volts per centimeter on a 100-kv proton beam can be compensated by a lens, 10 cm long, with field gradients of the order of 1000 gauss per centimeter.

1671.

666.

Ion optics of the beam of the Van de Graaff generator, H. Bruck and G. Gendreau, Onde elect., 35, 1009-21 (1955). (In French.)

A detailed discussion, with special reference to the 5-MeV machine of the Centr d' Etudes Nucleaires at Saclay. A Philips-type source is used. The design of the focusing lens and accelerator tube are briefly described. A consideration of the relative merits of electrostatic and magnetic monochromators concludes in favor of the latter. In the system adopted, a 90° uniform field sector, trajectory radius 60 cm, is preceded by a collimating lens consisting of two four-pole (hyperbolic field) magnets. In this way the aperture angle of the incident beam can be controlled and, taking aberrations into account, optimized for maximum intensity for a given required resolution. The design of apertures capable of adequate heat dissipation, methods of observing the beam, and of aligning the components are briefly considered. So far resolutions of one part in 10³ have been attained, but this is not regarded as an upper limit.

667.

Stanford high-energy linear electron accelerator (Mark III), M. Chodorow et al., Rev. Sci. Instr., 16, 134-204 (1955).

A composite paper by the members of the Hansen Laboratories staff, Stanford University. The main sections are: basic design features; the accelerating structure; generation and transmission of r.f. power; auxiliary systems; interlock system; beam dynamics; research facilities; radiation shielding; operational results.

668.

On a focusing channel for collecting μ -mesons from π - μ decay in flight,
A. Citron and H. Overas, CERN/SC 143 (March 1957).

669.

Focusing system for the electrostatic generator, H. S. Cockroft,
AERE-N/R-716 (June 4, 1951), 20 p.

The focusing effects and energy resolution obtainable from a 90° deflecting magnet on a positive ion beam are considered, and it is shown that for best resolution and beam shape the slit should be a distance about $1.2 p$ from the out-put face of the magnet. The angles of the magnet faces and the width of the slit must be adjusted to suit the beam entering the magnet, and the best resolution obtainable is then given by $(\delta p/p)_{\min} = 0.6 a/\mu$, where a/μ is the minimum angle subtended by a beam diameter at the input face of the magnet and p is the radius of curvature of the beam in the magnet. The accelerator tube is considered and the constants of the equivalent lens are determined. These results are used to find what conditions the beam at the top of the tube must satisfy in order to use all the beam and get best resolution. The lens system at the top of the tube is considered and the best position for the ion source determined.

670.

Production of V particles by 3-Bev protons, R. L. Cool et al., Phys. Rev., 108, 1048 (1957).

Included in this article is a description of the design methods employed to produce a pencil beam of protons from the Cosmotron.

671.

The strong-focusing synchrotron - a new high energy accelerator,
E. D. Courant, M. S. Livingston, and H. S. Snyder, Phys. Rev., 88, 1190-1196 (1952).

Strong-focusing forces result from the alternation of large positive and negative n -values in successive sectors of the magnetic guide field in a synchrotron. This sequence of alternately converging and diverging magnetic lenses of equal strength is itself converging and leads to significant reductions in oscillation amplitude, both for radial and axial displacements. The mechanism of phase-stable synchronous acceleration still applies, with a large reduction in the amplitude of the associated radial synchronous oscillations. To illustrate, a design is proposed for a 30-Bev proton accelerator with an orbit radius of 300 ft, and with a small magnet having an aperture of 1×2 in. Tolerances on nearly all design parameters are less critical than for the equivalent uniform- n machine. A generalization of this

focusing principle leads to small, efficient focusing magnets for ion and electron beams. Relations for the focal length of a double-focusing magnet are presented, from which the design parameters for such linear systems can be determined.

672.

Theory of the alternating-gradient synchrotron, E. D. Courant and H. S. Snyder, Ann. Phys., 3, 1-48 (1958).

The equations of motion of the particles in a synchrotron in which the field gradient index

$$n = -(\nu/B) \partial B / \partial r$$

varies along the equilibrium orbit are examined on the basis of the linear approximation. It is shown that if n alternates rapidly between large positive and large negative values, the stability of both radial and vertical oscillations can be greatly increased compared with conventional accelerators in which n is azimuthally constant and must lie between 0 and 1. Thus aperture requirements are reduced. For practical designs, the improvement is limited by the effects of constructional errors; these lead to resonance excitation of oscillations and consequent instability if $2\nu_x$ or $2\nu_z$ or $\nu_x + \nu_z$ is integral, where ν_x and ν_z are the frequencies of horizontal and vertical betatron oscillations, measured in units of the frequency of revolution. The mechanism of phase stability is essentially the same as in a conventional synchrotron, but the radial amplitude of synchrotron oscillations is reduced substantially. Furthermore, at a "transition energy" $E_1 \approx \nu_x Mc^2$ the stable and unstable equilibrium phases exchange roles, necessitating a jump in the phase of the radiofrequency accelerating voltage. Calculations indicate that the manner in which this jump is performed is not very critical.

673.

Beam characteristics of the 12.5-Bev accelerator, A. V. Crewe, R. H. Hildebrand, U. E. Kruse, S. C. Wright, and C. M. York, Argonne National Laboratory Internal Report CHKWY 5 (Feb 1958) 7 p.

This report deals with the beam characteristics which are needed to make the accelerator useful for a wide range of experiments. To summarize, the machine must produce beam pulses whose energy and intensity are adjustable. The length of the beam pulses must also be adjustable, because counter experiments require very long pulses to reduce accidental coincidences and count rate losses, whereas bubble chambers often require very short pulses.

674.

Coupling of betatron and phase oscillations in a synchrotron,
E. A. Crosbie and M. Hamermesh, Argonne National Laboratory
Internal Report EAC-MH/MAC-1 (Aug 1954) 16 p.

The coupled equations for radial position, momentum, and phase oscillations in a synchrotron are treated by use of difference equations. The effect of a radial variation in the accelerating radio-frequency voltage is included in the treatment; and resultant damping of one type of oscillation is shown necessarily to be accompanied by equal antidamping of oscillations of the other type. A simple treatment of the adiabatic variation of parameters for systems of linear differential or difference equations is given.

675.

Method of charged particle focusing in accelerators, V. I. Danilov
and O. V. Savchenko, Joint Inst. for Nuclear Research, Moscow.
Laboratory of Nuclear Problems, NP-6903. (1958) 18 p.

A variant of charged-particle focusing obtained with a synchrocyclotron is considered. The particle focusing is achieved by the magnetic field formed in the gap of the deviating electromagnet with the help of iron bars. It is shown that the effect of the focusing arrangement is equivalent to that of the magnetic quadrupole lens if the definite ratio of the dimensions of these bars is maintained. By means of such lenses the density of the 600-MeV polarized proton beam intensity was increased three times in the place where the detecting arrangement was set up; the density of the ~ 300 -MeV meson beam intensity was increased 2.7 times.

676.

An electrostatic focusing device for use with the Harwell F. M. Cyclotron, A. O. Edmunds and F. Uridge, AERE-GP/R-1246 (Sept 2, 1953)
11 p.

An electrostatic-focusing device for use with Harwell cyclotron is described. For 146-MeV protons the focal length of the unit is approximately 2.8 m, using a maximum electrode voltage of 60 kV relative to ground. A gain factor of over 40 has been obtained, giving a flux of 2.5×10^7 protons/cm²/sec at a point 13 m from the cyclotron. At the working point the beam has a square cross section of 2 x 2 cm.

677.

A new method to evaluate phase space integrals with special application to angular momentum effects, T. Ericson, CERN-61-22 (pp. 205-11)

An outline is given of an approximation technique for use in the evaluation of phase-space integrals, and which becomes asymptotically exact for large multiplicities. The method has the additional advantage that it can be generalized to permit the incorporation of the angular momentum conservation in the statistical model.

678.

Operation and development quarterly report No. 3 July-Sept. 1960, CERN-60-42 (Nov 17, 1960) 24 p.

A study was made of random variations of rf levels and phases during operation and of their effects on beam mean energy and energy spread. The grid-control equipment of the static converters was modified in order to improve "Flat-top" operation. The trapping behavior with early beam control takeover was investigated. Various new target shapes were tried in an attempt to obtain better spot geometry and longer counter bursts. The extra skewed quadrupole windings for cancelling the coupling between vertical and horizontal betatron oscillations were added to the octupole lenses. (For preceding period see CERN-60-29).

679.

Afocal achromatic bending, H. Fechter, Argonne National Laboratory Internal Report HF-9 (Oct 23, 1958) 7 p.

Based on the work of Bruck (CERN Symposium, 1956. Vol. I. p. 200), an achromatic, but not afocal, 94.5° bend design is executed.

680.

An electron accelerator in pressurized tank for 3 mA at 1.5-MV direct voltage, G. Henneberke, Nuclear Instr. and Methods, 7, 89-98, (1960).

A 14-stage accelerating tube is supplied by a 7-stage Cockcroft-Walton generator with selenium rectifying units. The potential distribution across the accelerating tube is ensured by a parallel resistor. Special care has been devoted to the electron-optical part and this makes it possible to control a 3-mA electron beam with a current of 110 μ A through the parallel resistor at a generator load of 3.2 mA. Focussing and intensity of the beam are independent of the high tension. X-ray intensities of 300 r/min. at a distance of one metre from the target are readily attainable.

681.

Focusing procedures for electrostatic accelerators, C. H. Johnson, J. P. Judish, and C. W. Snyder, Rev. Sci. Instr., 28, 942-8 (1957).

Ion optics for Van de Graaff accelerators are reviewed in elementary terms of geometric optics with particular reference to the Oak Ridge 3-Mv accelerator. This machine produces well-focused beams of over $100\ \mu\text{a}$ and pulsed peak currents of several hundred μa . The beam diameter measured at a distance of 2.7 tube lengths from the accelerator tube exit decreased from 0.26 in. at 0.38 Mv to 0.10 in. at 2.47 Mv. The beam divergence at 1.8 tube lengths from the exit is nearly constant, $\approx 2.8 \times 10^{-3}$ rad. The system is analyzed in terms of five separate lenses: (1) einzel lens, (2) gap lens, (3) accelerator tube, (4) 90-degree analyzing magnet, and (5) strong-focusing lens. It is shown that the crossovers formed in the gap lens and near the exit of the analyzing magnet are of fundamental importance. Brief reference is made to the small energy spread, $\approx 0.025\%$, for the beams obtained from this accelerator in spite of the large control slit spacing demanded by a large crossover.

682.

A neutrino beam design, L. W. Jones, MURA-590 (Aug 5, 1960) 12 p.

A neutrino beam is designed for use with accelerators, such as the MURA FFAG, using only quadrupoles. A very feasible system with 25% momentum resolution is described which could produce one neutrino-induced reaction every 10 min in a large hydrogen bubble chamber.

683.

Application of magnetic slits in the production of circular particle trajectories, V. M. Kel'man, V. A. Kolyunov, and M. V. Karpov, Zhur. Eksper. i Teoret. Fiz., 35, 1113-15 (1958). (In Russian.)

An electron-optical system consisting of magnetic slits arranged in a circle is proposed which can be employed to obtain almost circular charged-particle trajectories. The magnetic field strength in such a system rapidly increases with the distance from the axis but this does not lead to defocusing in the vertical direction. Thus a system of this type can be employed in an accelerator with a constant guiding field. The path of an electron beam during its first circuit in the system under consideration was studied experimentally.

684.

On the influence of radiation in the movement of relativistic electrons in a magnetic field. A. A. Kolomenskii and A. N. Lebedev, Doklady Akad. Nauk SSSR, 106, 807-10 (1956). (In Russian.)

Discusses the effect of electrons emitting photons on the action of the betatron.¹

¹A. A. Kolomenskii and A. N. Lebedev, Zhur. Eksper. i Teoret. Fiz., 30, 205-7 (1956). 165.

685

Alternating gradient focusing in proton linear accelerator. Report No. 80/VII, S. Kulinski (Apr. 1959) 25 p. Polish Academy of Sciences. Inst. of Nuclear Research, Warsaw. NP-7811.

It appears that in existing ion linear accelerators the best focusing system is a succession of electric or magnetic quadrupole lenses. These strong focusing or alternating gradient focusing systems are considered in detail.

686.

Electron trajectories in high current strip beams constrained by a magnetic field, J. D. Lawson, AERE GP/M 154 (1953) 8 p.

687.

An approximate lens for high-energy particles, D. Luckey, Rev. Sci. Instr., 31, 202-3 (1960).

A magnetic lens was constructed by arranging 19 conductors in hexagonal array parallel to the optic axis. The length of the lens was 1 m, the outside diameter 25 cm, and the focal length for 100-MeV electrons was about 1 m when the current through the conductors was 500 amp. The focal length is not very sharply defined, the transparency of the lens is about 80-90%, and the image of a 2-in.-dia source was 3 x 4 in. Compared with a standard quadrupole, the new lens uses no iron and requires less stored energy for given focal power, but the focusing is less perfect and the transparency less.

688.

Electrical and magnetic fields with strong focusing in application to the high-energy accelerations. N. Martalogu, Acad. rep. populare Romine Inst. fiz. Studii cercetari fiz., 8, 70-83 (1957). (In Romanian.)

After a review of methods of strong focusing, the application of strong focusing to accelerators is discussed. Various accelerators with alternant gradients are briefly shown.

689.

On the focusing system of the INS cyclotron, K. Matsuda et al., INSJ-14 (Jan. 15, 1959) 26 p.

The design and the construction of the focusing system for the INS 160-cm cyclotron are described. In order to fulfill the requirements of the variable energy external beam and to facilitate various experimental arrangements, a combined lens of a pair of quadrupole magnets and a sector magnet was constructed. An analysis of the focusing properties of quadrupole magnets is described.

690.

A method of focusing electron beams, B. T. Murphy, Proc. Inst. Elec. Engrs., Paper 2719R (1959) (Part B Suppl. No. 12, 1033-9, 1040).

Describes a method of using reversing magnetic fields to focus electron beams in which considerably smaller permanent-magnet structures are required than with focusing using unidirectional fields. The structures needed are more convenient than those necessary for periodic focusing systems, being applicable to klystrons, for example, and the range of beam parameters over which the method can be used is greater than for periodic focusing systems. It is also probable that beam focusing by reversing-field systems of the type described with few reversals will be less critically dependent on field and beam parameters than in periodic focusing, although the weight-saving advantages of the latter system would be largely retained. The use of an experimental system with one field reversal to focus an electron beam is described.

691.

Achromatic beam translation systems for use with the linear accelerator, W. K. H. Panofsky and J. A. McIntyre, Rev. Sci. Instr., 25, 287-90 (1954).

The beam of a linear accelerator has desirable geometrical properties, but frequently contains secondaries produced in the machine and has an unsuitable energy spectrum. Two systems have been designed which translate the accelerator beam without energy dispersion. In the one system, now in operation, the emergent beam has an "energy focus," i.e., a point at which the initial beam shape is reproduced independent of energy. The second system is designed to produce a beam translated but otherwise unmodified in shape, independent of beam energy to the first order. Both systems permit easy control of energy width and produce a beam free from secondaries.

692.

Linear accelerator beam dynamics, W. K. H. Panofsky, UCRL-1216 (Feb 1951) 32 p.

General equations of motion of a charged particle, basic geometry of the linear accelerator, synchronous conditions, types of stability for a "long" accelerator, the "incompatibility" theorem, velocity focusing, radial oscillations, phase oscillations, large oscillations, and unstable operation are treated.

693.

Proposal for the construction of a beam-hardener for a gamma-ray by the application of a constant magnetic field. (Vorschlag zum Bau eines Strahlhärter für einen Gamma-Strahl unter Verwendung eines konstanten Magnetfeldes), C. Passow, Desy-Notiz A 2.83 (Nov 1, 1961) 5 p. (In German.)

693a.

El deflector magnetico del has del sincrociclotron de Buenos Aires. Informe No. 45. (Magnetic deflector system of Buenos Aires Synchrocyclotron Beam. Report No. 45), J. Rosenblatt and R. J. Slobodrian, (Argentina. Comision Nacional de Energia Atomica, Buenos Aires). (1960) 22 p. NP-11693.

694.

Production of magnetic fields for strong focusing, by means of nonferrous coils, J. C. Schnuriger, J. phys. radium, 22: Suppl. to No. 2, 68A-9A (1961) CEA-1732. (In French.)

A method is developed for calculating the magnetic field of a rectilinear conductor with a cross section of any given shape, which gives the potential vector in the form of a series of "multipolar" magnetic fields. This method is applied to the calculation of nonferrous coils producing the magnetic fields used in particle optics; deflection field, fields used in strong focusing (quadrupolar, hexapolar, octopolar, and those of the alternating-gradient synchrotron). An example shows that a quadrupolar nonferrous lens of constant current density may be obtained, of which the first sign on nonlinearity in the field is of the ninth order.

695.

Spherical aberration of some electrostatic lenses with symmetry of revolution for beams of large aperture, A. Septier, CERN-60-39, (Oct 13, 1960) 59 p.

The purpose of this study was to measure the aberration of the aperture of the different lenses used on the CERN accelerator and then

study lenses with low aberrations. The methods of measurement are given for the determination of the principal elements of lenses and of the diameter of the aberration region in a given plane image. The lenses actually employed at CERN are used as an example. Proposals for obtaining a lens with the lowest aberration are given. Two different lenses are envisaged: hyperbolic and dissymmetric; the latter leads to extremely interesting results.

See also Compt. rend., 249, 2746-8 (1960). (In French).

696.

Strong-focusing lenses, A. Septier, Ind. Atom, 2, No. 7-8, 79-90 (1958). (In French.)

The development of high-energy particle accelerators required the development of a lens to channel the rays for a great distance, to concentrate the particles on targets or to the entrance of an analyzer, and to focus the beam during acceleration. After showing that the classical lens is insufficient to perform these tasks, the theoretical properties of strong focusing lenses are discussed and the experimental study to attain them is described. Possible applications of strong-focusing lenses are reviewed.

697.

Magnetsektor mit Konstantem Feldgradienten, (Magnet Sector with Constant Field Gradients), K. G. Steffen, DESY-A2.37 (Oct 17, 1958) 16 p.

Analyzing magnets with constant-field and magnetic quadrupole lenses are the customary elements for the separation and focusing of particle beams of high energy. With respect to its focusing properties, the magnet sector is represented as a lens with predetermined focusing width and principal axis, and the equations for this are given. The acceptance surface of the elements are investigated for a constant opening width and are represented graphically for various cases. In a sector magnet with constant field, which is described as a pulse analyzing magnet, the beam emittance received depends on extended pulse resolution. This relationship is represented in dependence on various parameters and discussed for various cases.

698.

Strong-focusing synchrotron magnet with tilted focusing planes, K. G. Steffen, Desy-Notiz A2.82 (Aug 14, 1961) 9 p.

A strong-focusing synchrotron magnet design of the type suggested by Sigurgeisson¹ is considered, in which the two focusing planes

are tilted by 45° with respect to the conventional orientation. When used in a FODO-electron synchrotron, this magnet type would eliminate classical radiation antidamping of betatron oscillations. Some advantages and disadvantages of the magnet are discussed. A magnet of this type may also be used as a strong-focusing pair spectrometer.

¹T. Sigurgeisson, CERN 55-14 (1955).

699.

Alternating gradient electrostatic focusing for linear accelerators, L. C. Teng, Rev. Sci. Instr. 25, 264-268 (1954).

The properties of the focusing systems using alternating convergent and divergent electrostatic lenses which were proposed by Courant et al. and Blewett are studied in detail, applied to Alvarez type of linear accelerators. It is found that the introduction and the removal of the focusing force of the system can be made approximately adiabatic by using half-length injection and extraction lenses. The appropriate choice of the parameters of the lenses in practical cases and the behavior of the ion beam going through such a system are discussed. The results can easily be reinterpreted to apply to magnetic lens systems.

700.

Modified achromatic bending magnet system for ZGS, L. C. Teng, Argonne National Laboratory Internal Report, LCT-25 (May 3, 1961) 11 p.

The studies, made in ANLAD-48, of the achromatic bending magnet system for steering the exit beam from the Linac into the ZGS did not take into account the focusing properties of the system. It is true that, in principle, the optical (focusing) properties of the system can always be modified by quadrupole magnets to any desired prescription. However, for this specific design the physical restrictions on the available space for quadrupole magnets makes the necessary parameters of these modifying quadrupole magnets rather unreasonable. This study puts the optical properties of the magnet system on equal footing with its chromaticity (dispersion) property. The result is applied to revise the design of the achromatic bending magnet system to achieve desirable optical properties as well.

701.

Phase spaces and beam qualities, L. C. Teng, Argonne National Laboratory Internal Report LCT-16. (March 3, 1960) 10 p.

A clarification of the terminology "beam quality."

702.

The beam guide, a device for the transport of charged particles,
S. van der Meer, CERN 62-16 (Apr 17, 1962) 29 p.

A coaxial transmission line, fed with direct current or pulsed, may be used as a focusing channel for charged particles. The particles will follow a screw-type trajectory around the inner conductor. The most important properties of the trajectories are described, and normalized diagrams are given for computing all important parameters for high-energy applications. A method of calculating the acceptance is outlined and some examples are given. It is shown that both angular acceptance and phase acceptance may be an order of magnitude higher than that of a quadrupole channel. Some remarks are made about the method of excitation and the direction in which applications might be found.

703.

A directive device for charged particles and its use in an enhanced neutrino beam, S. van der Meer, CERN 61-7 (Feb 1961) 20 p.

It was found that divergent beams of charged particles can be made nearly parallel by a magnetic horn that is analogous to an internally reflecting conical surface in geometrical optics. Trajectory calculations showed that it would accept a strongly divergent beam of charged particles over a wide momentum range. The current and power necessary for excitation indicate that the design must include pulsed operation. Data are presented for a horn designed for increasing the intensity of a neutrino beam. It would concentrate mesons (π) from an external target in the direction of the detectors. It was shown that this device would accept nearly all pions of one sign produced in the target. It was calculated that with this horn the neutrino interaction rate could be increased by an order of magnitude.

704.

Magnetic cylindrical lenses with plane of antisymmetry, S. Ya. Yavor, E. V. Shpak, and R. M. Minina, Zhur. Tekh. Fiz., 30, 395-404 (1960). (In Russian.)

Magnetic cylindrical lenses, formed from current-carrying conductors so arranged as to produce a field with a plane of antisymmetry, provide focusing for particle accelerators. The field distribution and imaging properties of typical examples are calculated and measured.

705.

The optical design of beam matching systems, T. R. Walsh,
AERE-A/R-2711 (Oct 1958) 19 p.

Beam matching is considered with reference to beams which may be represented by ellipses in phase space. A general expression for the profile of such beams is obtained and used to examine the parameters of a single-lens system. Extension of the treatment to more complex systems is discussed.

706.

Design of fringing shims for magnet poles, J. J. Wilkins and
A. H. Spurway, NIRL/R/6 (May 1961) 30 p.

Dimensions of fringing shims for uniform-field magnets have been computed using two-dimensional (conformal transformation) theory. Tables and graphs of design data are given for single shims and for shim-antishim combinations, appropriate to various required degrees of uniformity of field and field gradient. The computations were restricted to very simple pole and shim geometries, but methods of extrapolation to more refined geometries are indicated. Application of the data to still more general magnet designs, e.g., quadrupole magnets, is also discussed.

See also: 74, 192, 247-251, 290, 485, 756, 764, 787, 838, 843.

BEAM OPTICS - QUADRUPOLES AND SEXTUPOLES

707.

Minutes of meeting of accelerator development department, Brookhaven National Laboratory, N-2871a (Sept 22, 1958) 3 p.

Discusses analytical work performed on the design of quadrupole magnets by M. H. Blewett to obtain information on saturation behavior, stored energy, and inductance. G. T. Danby described the measurements program on the $\frac{1}{4}$ -scale quadrupole magnet. C. Lasky outlined the specifications which have been prepared to accompany the bid solicitations for the quadrupole fabrication.

708.

The focal properties of certain quadrupole lenses, J. P. Blewett,
BNL-4654 (May 11, 1959) 32 p.

The focal properties of a quadrupole lens system can be described by a tabulation of the locations of principal planes and of the focal lengths for various gradient strengths in the lens elements. In

this report is presented a derivation and a tabulation of these parameters for the following standard lens systems:

- a. A single quadrupole.
- b. Two quadrupoles of equal length in sequence with opposite gradients of different strengths. Several different quadrupole spacings are studied.
- c. Three quadrupoles of equal lengths separated by equal distances. The gradients in the first and third quadrupoles are equal and of the same polarity. The gradient in the center quadrupole is reversed and has different strength from the gradients in the other two quadrupoles. Again, several different quadrupole spacings are considered.
- d. A symmetrical triple quadrupole lens as in (3) except that the length of the center quadrupole is twice the length of the first and third quadrupoles.

709.

On the design of quadrupole focusing systems, J. P. Blewett, Brookhaven National Laboratory Internal Report, BNL-JPB-11 (Oct 2, 1958) 12 p.

Solutions are presented to the design problem in which a system of quadrupole lenses is required to carry a particle beam from given focal lines in the x and y planes to other given focal lines. Particular attention is given to the case of the anastigmatic lens system which takes a beam from one focal point to another focal point.

710.

Magnetic quadrupole lens component arrangement in focusing and bunching μ mesons at CERN, E. Brauersreuther, CERN 61-12 (April 11, 1961) 70 p.

The floating-wire method is used for the direct determination of the elements of the linear transformation of a μ meson beam and the limits of the beam to which the transformation is applied. The floating-wire method is described in detail, and the properties of a thick quadrupole lens are reviewed as an introduction to the results obtained with this method. The construction of the lens is briefly described, and the magnetic measurements made by the Hall effect and the floating-wire measurements are given. The source of linearity faults detected with the floating wire could be determined from the Hall effect. The validity and utility of these two measurement methods are established.

711.

The quadrupole magnet as a focusing device. Technical report on linear electron accelerator project, R. N. Carlile, HEPL-33 (Feb 1957) 60 p.

The basic concepts of the first-order dynamics of a particle in the field of a quadrupole magnet are reviewed. Descriptions are included on the suspended-wire method of measuring parameters which describe the focusing properties of a quadrupole. The results of applying these methods to a specific quadrupole are presented. Discussions of the principal planes and focal length in the horizontal plane of a wedge magnet are included in an appendix.

712.

The Linac quadrupole system, D. Cohen, Argonne National Laboratory Internal Report DC-1 (March 18, 1958) 24 p.

Discusses the many phases of the development program for the 124 quadrupole focusing magnets which will be situated inside the 124 drift tubes of the 50-Mev linac injector. Covers some aspects of the evolution of the quadrupole system to be used, the work which has already been completed, and some of the plans for the completion of the program up to the point of installation of the drift tubes inside the linac cavity.

713.

Quadrupole magnet forces, D. Cohen, Argonne National Laboratory Internal Report DC-2 (Feb 4, 1959) 8 p.

Discusses the forces involved due to magnetic fields with the 124 linac quadrupole magnets. These are classified into two groups: 1) Forces between magnets and hence, longitudinal forces between drift tubes; these forces, if large, may significantly displace drift tubes longitudinally when the fields are present, and thereby change accelerating gradients in the gaps with resulting extra energy spread in the exit linac beam. 2) Forces within a particular magnet; these may be divided up into two groups, the first dealing with radial forces on the steel poles and yokes, and the second with radial forces on the coils. Forces in the first group have a bearing on steel construction and junction details, while forces in the second group have a bearing on coil-potting methods and long-range coil-tubing reliability. Non-radial forces, with construction errors of the order 0.002 in., are expected to be negligible.

714.

Quadrupole focusing lenses for charged particles, B. Cork and E. Zajec, UCRL-2182 (Apr. 15, 1953) 22 p.

A set of four strong-focusing magnetic-quadrupole lenses has been constructed and operated. Each lens consists of four air-cooled electromagnets with pole tips having a hyperbolic cross section. Each lens is 4 in. long and has an aperture 2 in. in diameter. Measurements of the magnetic field demonstrate that the hyperbolic cross section satisfies the requirements of a constant magnetic field gradient very well. The technique of deflecting a current-carrying flexible wire has been used to measure the trajectory of charged particles through the system of lenses. It has been observed that the strong-focusing requirements are satisfied. The system of lenses was then used to focus 0.5-Mev protons, 20-Mev deuterons, and 40-Mev α particles. The parallel beam of 0.5-Mev protons was detected by observing the incandescence of a quartz plate while the protons were bombarding it. The focused beam was less than 1 mm in diameter. The astigmatic 20-Mev deuteron beam from the 60-in. cyclotron was increased in current density by a factor greater than 30.

715.

Alignment of the magnetic centers of quadrupole focusing magnets in a linear accelerator, J. G. Cottingham, BNL-5429 (Apr 17, 1956) 6 p.

Methods for alignment of magnets in linear accelerators are examined. One method consists of passing a proton beam through a lens and observing the deflection produced, moving the lens a calculated amount, and repeating until there is no deflection. Optical factors in this method are discussed along with target shape, the effects of the Earth's magnetic field, and results of an alignment confirmation experiment.

716.

Quadrupole and sextupole requirements, E. D. Courant, BNL-4644 (July 12, 1957) 4 p.

In the AGS, quadrupoles are required to correct variations in $\underline{n}$, and sextupoles are required to correct nonlinearities in the field, both arising at injection and saturation. Twenty-four quadrupoles and thirty-six sextupoles, both of length 22 in. and aperture 6 in., are required for adequate corrections.

717.

Possible alternative to quadrupole magnet focusing, A. V. Crewe,
Argonne National Laboratory Internal Report AVC-1 (May 6, 1960) 9 p.

The use of quadrupole magnets for the focusing of beams of particles is now in widespread use. The system has many advantages, but its prime disadvantage would appear to be the fact that one must combine two strong lenses in series in order to achieve a weak lens. One might suspect, therefore, that a better focusing system would exist, and in fact such a system does exist, but in a rather inconvenient form. The best lens to use for this purpose would be an electric current of uniform current density flowing on the same axis as the beam of particles. If this current is confined into a cylindrical region, then the magnetic field perpendicular to the direction of the particles rises linearly with the distance from the axis. Focusing can therefore be achieved in all planes simultaneously. The major disadvantage of this system is the difficulty of achieving the current densities required by means of, for example, an electric discharge. With the use of very high-energy particles, however, it becomes feasible to pass a beam of particles through a conducting material in which the focusing current is passing, provided the net focusing action predominates over the multiple scattering. The purpose of this report is to show that this can, in fact, happen.

718.

Quadrupole magnets and their uses, A. V. Crewe, Argonne National Laboratory Internal Report AVC-3 (Aug 19, 1960) 20 p.

Quadrupole focusing magnets have now been in use for several years and have proved to be of immense value for controlling beams of charged particles. This report is intended to be an introductory answer to the question: "What is a quadrupole magnet and how is it used?" It is not intended to be an exhaustive or detailed discussion, but rather a collection of thoughts on the subject and manipulative tricks which have proved to be of value to the author.

719.

Curves for the stigmatic focusing of quadrupoles, B. de Raad, CERN-PS/Int. EA 60-5 (Aug 1960).

720.

Magnetic measurements on the beam transport quadrupoles for the CERN P.S., CERN-PS/Int. EA 60-5 (Aug 11, 1960) 37 p.

Presents the details and methods of measurement, both inside and outside, of the two 1-m-length beam-transport quadrupole magnets.

The cooling has been designed so that the coils can support 830 A, which is the maximum rating of the beam transport generators.

721.

Magnetic quadrupole lenses, I., P. Grivet and A. Septier, Nuclear Instr. and Methods, 6, 126-56 (1960). (In French.)

The first part discusses the properties of quadrupole lenses. Integration of the equations of motion is possible if the characteristic function of the transverse gradient is represented by simple mathematical models, i.e., rectangular or bell-shaped models. Formulae of the main elements of a lens and of a system of two crossed lenses are given. The second part is devoted to measures of field and gradient on typical magnetic lenses for CERN's 50-MeV linear proton accelerator, i.e., determination of the various components of field and transverse gradient inside the lens and in the leakage fields, calculation of equivalent lengths relative to the transverse field and to the gradient, and correction of the variations of these equivalent lengths in the useful space. Measurements made with very high intensities on saturated lenses show that the poles do not saturate, and thus the field configuration is not disturbed. The measuring instruments used are described in detail, and results are given in graphical form.

722.

Quadrupolar magnetic lenses,¹ P. Grivet and A. Septier, CERN-58-25, (Oct 15, 1958) 162 p.

An investigation of quadrupolar magnetic lenses by experimental and mathematical means is described. The objects of the study were: practical realization of relatively low-power lenses for the synchrotron injection beam; precise determination of the distribution of the magnetic field; determination of the possible influence of saturation on the topography of the field in the useful zone; determination of the first-order optical properties of a two-lens system; measurement of the aberrations directly; and correction of the aberrations. Results of calculations of the aberrations by electronic computers are given.

¹See also Nuclear Instr. and Methods, 6, 126-56 (1960). 721.

723.

Quadrupole magnetic lenses. Part II, P. Grivet and A. Septier, Nuclear Instr. and Methods, 6, 243-75 (1960). (In French.)

The optical properties of quadrupole lenses are discussed and the results of magnetic measurements of the field configuration in the spaces crossed by the particles are given. A method of direct study

of optical properties and of aberrations in a system of two crossed lenses by means of a special ionic-optical bench are described. It is shown that the aperture defect can be corrected in this type of lens, by correcting the profile of the polar pieces. The calculation of the aperture defects by different methods is demonstrated. After giving the equations of motion to the third order, a method of calculation which is based on representing the characteristic function of the lens by a rectangular model is presented. The results of calculations made by different electronic machines are compared. Agreement between experimental and calculated results was obtained.

For part I, see Nuclear Instr. and Methods, 6, 126-56 (1960). 721.

724.

Cost optimization of doublet and triplet quadrupole systems, P. Kalmus and S. Marcowitz, Argonne National Laboratory Internal Report PK-SM-2 (Dec 20, 1960) 19 p.

The conditions are examined for producing parallel beams in both planes, from a point source on an object, using two or three conventional quadrupole elements of equal diameters. Each element is treated as an optical thin lens. The system is then optimized to give the lowest cost per solid angle of acceptance. The effect of this optimization on the size of a bending magnet which could follow such a system is estimated.

725.

Parameters for large aperture quadrupole magnets, P. Kalmus, Argonne National Laboratory Internal Report PK-3 (May 10, 1961) 15 p.

The effectiveness and feasibility of design of large aperture quadrupoles are examined. It is shown that large apertures do not always give rise to greater acceptance of particles. Design parameters for a 60-cm-bore quadrupole are given.

726.

Tests and analysis of magnetic quadrupole lenses, P. J. Lynch and D. J. Zaffarano, ISC-927 (Aug 1957) 53 p.

A pair of strong-focusing magnetic lenses are used to focus the electron beam from the Iowa State College Synchrotron. Each lens has four poles, alternately north and south. An electron, directed away from the principal axis in, say, the horizontal plane of the lens, is therefore converged in the vertical plane. The two lenses are rotated 90 degrees with respect to one another, principal axes coincident, so that each electron is subject to both a converging and a

diverging field, the order depending on the plane of initial entry. However, two equally strong convergent and divergent lenses produce a real image in both planes, for a suitable adjustment of parameters. In general, the images do not coincide, but for each value of the magnetic field, there is a unique source distance for coincident focusing. To determine the properties of these lenses, a current-carrying wire is employed. The wire, placed under a constant tension in the magnetic field, feels a force proportional to the strength of the field and the current. It adjusts to an equilibrium position, which is the trajectory of an electron with the corresponding magnetic rigidity. By noting the intersection of the wire with the principal axis of the lens system, the image distance for any given object distance can be determined. If the object distance is infinite, the image distance will be the focal length. A theoretical analysis allows comparison with the experimental findings. Results from the measurements of focal length show that the magnetic field does not cut off sharply at the face of a lens, but extends 2.0 cm beyond it. With this information taken into account, the agreement between theory and all experimental data is good.

727.

A note on the infeasibility of long effective focal lengths in both planes with quadrupole lenses. S. Marcowitz, Argonne National Laboratory Internal Report SM-1 (Feb 23, 1961) 4 p.

A beam of several types of particles from a small target may be separated by first focusing it into an essentially parallel beam, then deflecting the different types of particles through different angles (electric or magnetic deflection), and then refocusing the parallel bundles into separated images of the target. The focal length of the first lens system is the most important one for separation and should be long. For velocity selection in the vertical plane it is desirable to have a long effective focal length in the vertical plane. For momentum analysis it is desirable to have a long effective focal length in the horizontal plane. Both conditions would best be fulfilled if the first principal plane in both horizontal and vertical planes were on the side of the lens system away from the source. The conclusion is reached, however, that long focal lengths in both planes are not possible for doublets or triplet quadrupole systems.

728.

A sextupole magnet design, S. Marcowitz, Argonne National Laboratory Internal Report SM-5 (Nov 16, 1961) 6 p.

729.

Quadrupole magnets for focusing beams of charged particles John Marshall, Argonne National Laboratory Internal Report JM-13 (June 12, 1957) 12 p.

Describes the properties of quadrupole magnets and provides a recipe for calculating their focusing properties.

730.

Experimental study of helical quadrupole lenses for focusing μ -mesons M. Morpurgo and A. Septier, Compt. rend., 245, 2496-9 (1957). (In French.)

A succession of quadrupole lenses of alternate signs is capable of confining a beam of high-energy particles, those of lower energies being eliminated. The same effect can be obtained by means of a helix wound with many parallel wires bearing currents of specified relative magnitudes. Experiments with this system are described.

731.

Design of alternating gradient quadrupole lenses, J. Rosenblatt, Nuclear Instr. and Methods, 5, 152-155 (1959).

A graphical method is described by means of which it is possible to design quadrupole lenses once locations of object and image are given. It is shown that similar procedures would be valid in the paraxial (Gauss) approximation, when applied to electron optical devices of any kind.

732.

An ion-optical bench for the study of magnetic quadrupole lenses and deflectors for particle accelerators, A. Septier, Compt. rend., 245 1406-9 (1957). (In French.)

Magnetic quadrupole lenses for focusing and deflecting high-energy nuclear particles have long focal lengths and large apertures, conditions not normally encountered in classical electron optics and which make accurate calculations difficult. An optical bench was therefore devised to study the properties of these lenses experimentally. A beam of ions is formed into a hollow cone by means of a rotating deflector field. The beam is then focused by the quadrupole lens. The image, which is formed on a fluorescent screen, may be observed visually or photographed by an external camera, and the aberrations evaluated.

733.

Effect of quadrupole correcting lenses, K. G. Steffen, CEA-34(M-H) (AECU-3735) (June 3, 1957) 12 p.

The effect of correcting quadrupole lenses on the betatron oscillation characteristics of an AG synchrotron was studied, and general formulas are given for the fractional changes of the amplitude and phase functions. Calculations performed for different setups of different numbers of lenses for the CEA synchrotron structure point out that one may correct for sizable errors in the n -value by means of 8 pairs of quadrupole lenses in two consecutive straight sections with the focusing lens between defocusing sectors, and vice versa. An increase of $\beta_{\max}$ of about 5% is obtained for $\Delta n/n \approx 0.04$. It was found that the necessary corrections can probably be obtained satisfactorily with lenses of 6-in. length.

734.

A quadrupole magnet with noncircular aperture and linearized end fringing field, K. G. Steffen, DESY-A2.81 (Aug 14, 1961) 21 p.

A new type of quadrupole magnet cross section is suggested and compared with the standard circular aperture. It is shown that a significant improvement of acceptance in phase space is gained by this design. Formulas for the acceptance per unit cost are given for the two quadrupole types. A general investigation of the acceptance of a long periodic strong-focusing channel was used as an approach to optimizing standard quadrupole parameters. Special end field configurations are suggested for quadrupole and for bending magnets. They eliminate to a large extent the nonlinear aberrations which are generally caused by the fringe fields.

735.

Beam rotating quadrupole magnet system, L. C. Teng, Argonne National Laboratory Internal Report LCT-26 (May 15, 1961) 7 p.

Momentum- and velocity-analyzing magnets and electrode systems generally bend and spread the beam in the horizontal direction. Therefore, the analyzed beam is generally a thin horizontal sheet. When a bubble chamber or any other trajectory-registering chamber with vertical window and, hence, horizontal camera is used to perform experiments with such a beam, the camera will be looking edge-on at the beam sheet unless the beam is rotated 90° to form a vertical sheet. This can be accomplished by a quadrupole magnet system with poles placed at 45° with respect to the horizontal-vertical directions. A two-section system was proposed by M. Good of Wisconsin. Such a system, while being able to rotate the beam, cannot transform a parallel

incident horizontal beam sheet to a parallel outgoing vertical beam sheet of the same width. To do this, the three-section quadrupole magnet system studied in this report is required.

See also: 62, 132, 220, 221-224, 237, 706, 738, 772.

EXTRACTION

736.

The deflection of protons from the Harwell synchrocyclotron, J. B. Adams, A. O. Edmunds, and K. J. Hill, AERE G/R 681 (1951) 16 p.

Various ways of extracting the circulating protons in a synchrocyclotron are described in general, and the method used in the case of the Harwell synchrocyclotron is described in detail.

737.

An achromatic system of extraction for proton synchrotrons, R. G. T. Bennett and J. W. Burren, J. of Nuclear Energy, Part C: Plasma Physics, 3, 14-16 (1961).

An achromatic modification of the Piccioni extraction system for weak-focusing synchrotrons is described. A quadrupole magnet placed between the target and the extraction magnet is used to cancel the momentum resolution of the extracted beam produced by the synchrotron magnet. The extraction magnet is made radially focusing to give a beam of small dimensions in the exit region.

738.

Projet D'Ejection des protons de Saturne. (Proton Ejection Project for "Saturne"), G. Bronca and G. Gendreau, CEA-1081 (1959) 176 p.

The reasons for choosing the ejection system are given. The characteristics required for the ejected beam are followed by a description of the ejection process, in chronological order from the view point of the protons: movement of the particles, taking into account the various elements which make up the system (internal magnet, external magnet, quadrupoles, ejection correction coils, thin and thick cables, ...) and specification of these elements. Then follows an estimation of the delay in manufacture and the cost of the project. Finally, the characteristics of the magnets and quadrupoles are listed in an appendix.

739.

Extraction and focusing of Beam III, G. Chadwick, BNL-5497 (Dec 16, 1960) 4 p.

A summary is included of the characteristics of the third external proton beam extracted from the Cosmotron. The beam was brought to a first focus at energies of 1.35, 2.06, and 2.87 Bev. The parameters found optimal in extracting and focusing the beam are tabulated.

740.

Deflection of the Bevatron beam, W. Chupp and W. W. Salsig, Jr., UCID-904 (Bevatron-82)(May 24, 1955) 8 p.

A description of the deflecting system to provide a clean external beam of 6.3-Bev protons.

741.

The extraction of the beam from the Liverpool synchrocyclotron. II. Experimental work, A. V. Crewe and J. W. G. Gregory, Proc. Roy. Soc. (London) A232, 242-51 (1955).

The paper gives the practical application of the principles of the preceding paper to the Liverpool synchrocyclotron, and the designs of the various components of the extraction system are described, as well as the procedure for optimizing the extracted proton-beam current. In the final result, 3% of the circulating beam was extracted from the cyclotron tank. The beam has an energy of 383 Mev with no measurable energy spread. By the aid of an auxiliary focusing magnet, the beam has been focused into a fairly well-defined spot, and the proton flux per sq in. is at least 1000 times greater than that obtained from any similar machine.^{1,2} For part I see 3.

¹R. Gabillard, CERN-PS/RGb-8 (Sept 1955).

²D. H. Tomboulion, Nov. 15, 1955. DA Project No. 5B99-01-044. Contract DA-30-115-ORD-669, NP-5805.

³E. J. LeCouteur, Proc. Roy. Soc. (London), A232, 236-41 (1955). 751.

742.

Regenerative beam extraction on the Chicago synchrocyclotron, A. V. Crewe and U. E. Kruse, Rev. Sci. Instr., 27, 5-8 (1956).

The proton-beam extraction system of the 450-Mev synchrocyclotron is described. The nonlinear theory of LeCouteur has been applied and an external beam of 10¹¹ protons per second has been obtained.

743.

Extraction of protons from the Birmingham 1000-MeV synchrotron, G. A. Doran et al., Nuclear Instruments and Methods, 7, 225-236 (1960).

An electromagnetic deflecting channel for protons is described. This is moved close to the circulating beam in the synchrotron vacuum box after the accelerating cycle has commenced. Protons are induced

to enter the deflector by Coulomb scattering through a very small angle, and when the current flowing through the deflector is ~ 35 kA the protons are deflected through an angle of ~ 0.03 radian and escape from the synchrotron. The number of protons available per pulse in the experimental area has been increased by a factor of ~ 1000 from that obtained previously by nuclear scattering from internal targets.

744.

The ejection of the electron beam from the betatron, S. L. Fawcett, PhD Thesis, Case Institute of Technology (1950).

745.

Use of the strong-focusing principle for the shaping of electric deflectors, V. V. Krotov, Zhur. Tekh. Fiz., 29, 716-25 (1959). (In Russian.) English translation in Soviet Physics-Technical Physics, 4, 643-50 (1959).

The defocusing effect of the fringing magnetic field of a cyclotron may be counteracted by suitable shaping of the electric deflector responsible for extracting the beam. Balancing of the focusing and defocusing effects can be improved by splitting the extractor into two parts. This in effect provides a chain of three strong-focusing lenses and allows greater concentration of the beam.

746.

Magnetic measurements on the bending magnets of the beam transport system of the CERN P. S., B. Langeseth, G. Pluym, and B. de Raad, PS/Int. EA 60-14 (Oct 13, 1960) 35 p.

For the deflection of charged particle beams from the CERN P. S. a number of bending magnets have been constructed. Their pole faces are plane and rectangular. Most of the magnets have straight poles. To obtain a somewhat higher flux density over a narrower width some of the magnets have tapered poles. The axial length of the poles is 1 m for some of the magnets and 2 m for the remaining ones. In terms of pole profile and length there are thus four different types. The nominal distance between the pole faces is 0.14 m. It can be changed, however, to 0.11 m, 0.17 m, or 0.20 m, by changing the spacing plates. The coils have hollow, water-cooled conductors. The nominal resistance is 0.2 ohm for all magnets. The magnets are mounted on concrete supporting blocks. The blocks which also may act as radiation shielding are fitted with special devices for fine adjustment of position and orientation of the magnets.

747.

Sur la deflection d'une particule rapide par un champ electromagnetique, P. Lapostolle, CERN-PS/Int. AR/60-2 (March 14, 1960) 20 p. (In French.)

748.

Sur l'effet d'un deflecteur haute frequence applique a des particules se deplacant dans un systeme de focalisation - un type de separateur parametrique. P. Lapostolle, CERN-PS/Int. AR/PSep 60-2 (July 20, 1960) 18 p. (In French.)

749.

Two distinct deflecting structures including alternating-gradient focusing, P. Lapostolle, CERN. (To be published.)

750.

Proposed scheme for extracting the electron beam from the Malvern 30-MeV synchrotron, J. D. Lawson, AERE G/M 117 (Jan 1949) 5 p.

It should be possible to eject the electron beam from the 30-MeV synchrotron with the aid of two moderate-sized modulators and coils. The first will disturb the guide field in such a way that the radially unstable region moves inwards, causing the electrons to spiral very rapidly outwards; the second will produce a stable track of zero field along which the electrons can move out of the donut.

751.

The extraction of the beam from the Liverpool synchrocyclotron. I. Theoretical, E. J. LeCouteur, Proc. Roy. Soc. (London) A232, 236-41 (1955).

The beam has been efficiently extracted from the Liverpool synchrocyclotron by a magnetic deflector designed to produce radially unstable orbits while maintaining vertical stability. The theoretical specification of the apparatus is described. For part II, see A. V. Crewe, Proc. Roy. Soc. (London) A232, 242-51 (1955). 741.

752.

The regenerative deflector for synchrocyclotrons, K. J. LeCouteur, Proc. Phys Soc. (London) B64, 1073-84 (1951).

Tuck and Teng have proposed to extract the beam from a synchrocyclotron by modifying the normal magnet field in such a way as to build up the amplitude of radial oscillations until protons can escape from the magnet. In the present paper the method is studied

analytically, and formulae are derived which express the performance in terms of the magnetic field perturbations: these formulae have been evaluated numerically in sufficient detail to guide practical design.

753.

Beam-deflecting magnet, John Marshall, Argonne National Laboratory Internal Report JM-1 (July 24, 1956) 5 p.

Describes a deflection magnet to be used for extracting protons from one of the long straight sections of the proton synchrotron.

754.

Two distinct deflecting structures combined with focusing lenses, B. W. Montague, CERN. (To be published.)

755.

Optics of the deflection of a beam of high-energy charged particles, J. Pinel, Ann. Radioelect., 14, 230-49 (1959). (In French.)

A study of theoretical and practical problems arising in the deflection, analysis, and refocusing of a beam of accelerated particles. After an exposition of the problem an examination is made of certain of the solutions proposed, followed by the methods of calculation established for this study, and of the various essential elements: electromagnets, four-pole lenses. As an example, a description is given of the calculation of the essential elements of the "250-MeV" station of the Orsay linear accelerator.

756.

Optics of the deflection of a beam of high-energy charged particles. II, J. Pinel, Ann. Radioelect., 15, 3-27 (1960). (In French.)

The principles outlined in Part I¹ are applied to a particular case. An examination is made of defects due to optical elements, of which field structure defects are the most important. Debunchers are dealt with and some essential properties of systems using two electromagnets with parallel faces are given. Several solutions to the problem of triple focusing are given and defects of these various systems are examined. One optical system was tested using a hodoscope. The conditions of application of the method and its possibilities are examined. One application is the adjustment, measurement of resolving power, aberrations, and mixed focusing of the 250-MeV beam in the Orsay linear accelerator.

¹J. Pinel. Ann. Radioelect., 14, 230-49 (1959). 755.

757.

The leakage field of magnetic deflectors. Shape of magnetic fronts, correction of aberrations, A. Septier, CERN-59-1 (1958).

The leakage fields of the extremities of the magnetic deflectors can be taken into account by defining an effective length d on the mean trajectory. In a magnet with pole pieces sufficiently large, the imaginary magnetic fronts of entry and outlet are planar in the useful zone because d is constant. However, the narrowing of the pole pieces causes the deformation of this front. In the case where the magnetic fronts are planar and normal to the direction of the mean trajectory, the magnetic fronts are curved and possess at each point two equal and opposed curvatures. Their section by the median plane of the air gap is a convex curve towards the exterior. One can correct this curvature by giving to the mechanical face an equal and opposite curvature; the approximation obtained with the aid of plane faces is sufficient. When the correction of the aberration of the second order necessitates the use of curved mechanical faces, the parasite effect must be considered in the calculation of the curvature radius. For the deflectors of the CERN, the double curvature of the face leads to troublesome aberrations much stronger than the aberrations of the second order. In the case where the mechanical faces are inclined by an angle α_0 on the direction of the same trajectory ("vertical" focusing), the magnetic fronts have a weaker average inclination. The "drag" Δx increases very rapidly with α_0 and causes a distortion of the magnetic faces. The correction of the flaw is possible with appropriate correctors, and for a given magnet a method of correction can generally be perfected for all used values of α_0 .

758.

On the form of the faces of a magnetic sector with homogeneous field and the correction of aperture aberration, A. Septier, Compt. rend., 247, 1577-80 (1958). (In French.)

The effective ends of conventional deflecting magnets are not planes parallel to the mechanical surfaces but are curved surfaces. At low energies when the gap dimension can be made large in comparison with the beam dimension, it is justified to consider these surfaces as planes parallel to the mechanical surfaces. At high energy and large beam dimension the above condition is not satisfied and we have to consider the curved surfaces.

759.

Magnetic deflector for the bevatron, B. T. Wright, UCRL-2238
(June 4, 1953) 13 p.

A magnetic deflector for the Bevatron is described. Particles initially circulating at some distance from the deflecting field are caused to enter the field during the course of a single turn because of a small energy loss in a suitably placed target. The estimated efficiency is about $1\%/in.^2$ at a detector located 20 ft from the circulating current.

See also: 59, 605, 610, 870.

SEPARATION

760.

Minutes of meeting of accelerator development department, Brookhaven National Laboratory, N-2871b (May 4, 1959) 2 p.

R. L. Cool gave a talk on the general features of the use of the AGS machine for research. He described the general concept of the present program, which is intended to arrive at a set of magnets and electromagnetic beam separators which could be used as "building blocks" for producing beams required for a variety of experimental purposes. The general experimental requirements for such beams as they applied to various methods of detection were described.

J. P. Blewett described a method for beam separation by means of radiofrequency deflecting.

761.

The production and use of beams of particles. "Particle photography" conference, Montreal, 1958, p. 413. (In French.)

A summary of methods used to obtain beams suitable for the study of elementary particles by means of nuclear emulsions. Focusing and separation techniques are considered together with the instrumentation required for each type of separator. Factors limiting the quality of the beams are briefly examined.

762.

A nanosecond time-of-flight circuit utilizing the inherent modulation of a synchrotron beam, R. L. Anderson and B. D. McDaniel, Laboratory of Nuclear Studies, Cornell Univ. Paper presented at Brookhaven International Conference on high-energy Accelerators. Sept. 6-12, 1961. TID-7636.

A relatively simple circuit having a resolution of less than one nanosecond has been built and used to separate particles of different mass generated by the Cornell 1.3-Bev electron synchrotron. The circuit employs the coincidence principle of Cottini and Gatti, so that no high-speed electronics is required. The method utilizes the inherent radiofrequency bunching of the synchrotron beam to produce a pulse-modulated photon beam. The radiofrequency itself is used to perform the timing. The circuitry may also be used to make a direct coincidence between two counters with a resolution of 0.4 nanosecond.

763.

Design and performance of a 3.3-Bev/c separated antiproton beam, C. Baltay, E. C. Fowler, J. R. Sanford, and J. Sandweiss, Brookhaven National Laboratory. 19 p. (Paper presented at the Brookhaven International Conference on high-energy accelerators. Sept. 6-12, 1961.) TID-7636.

A description of a high-energy, high-purity antiproton beam set up at the Brookhaven AGS for use with the 20-in., liquid-hydrogen bubble chamber, in order to study the $\bar{p} + p$ reactions in an energy range where the antiparticles of all the presently established particles can be produced.

764.

A new 800-Mev/c K^- Beam of high purity at the bevatron, P. Bastien et al., "Instrumentation for high-energy physics," Proceedings of an international conference. New York, Interscience (1961) p. 299-301.

Describes the development of the beam utilizing glass-cathode parallel-plate spectrometers and with a sufficiently narrow momentum spread to permit a reasonable fraction of stopping particles in a bubble chamber. The final beam width is variable from approximately 2 to 5 in. in order that it can be used with different detection devices, particularly with either a horizontal-window (15-in. hydrogen) or vertical-window (8-in. helium) bubble chamber.

765.

Beam separators for Bev particles, J. P. Blewett, Brookhaven National Laboratory. Internal Report. BNL-JPB-12 (March 16, 1959) 8 p.

A description of the problem of separation of beams of particles of different masses but of the same momentum at Bev energies. Presents a tabulation of some of the cogent parameters.

766.

A device for separation of negative protons and negative pions at high energies, J. P. Blewett, Brookhaven National Laboratory. Internal Report. BNL-JPB-10 (April 1, 1958) 5 p.

Considers the possibility of separating the beams in an rf deflecting system in which the slight difference in velocity between the two beams allows the negative protons to fall out of step with the deflecting field and to emerge with no transverse velocity while the negative pions continue to experience deflection and so diverge on emergence from the deflector.

767.

A new type of resonant cavity for deflection of particle beams,
J. P. Blewett, Brookhaven National Laboratory. Internal Report.
BNL-JPB-9 (March 31, 1958) 5 p.

Ordinary wave-guide resonators whose field patterns include an electric field component normal to the axis usually include magnetic field components normal to the axis and to the transverse electric field. If particle beams travel along the axis they will undergo transverse forces due both to the electric field and the magnetic field components. The net deflection is discussed by Panofsky and Wenzel [Rev. Sci. Instr., 27, 967 (1956)]¹ who conclude that "in a TE mode the deflecting impulse of the magnetic field always cancels the impulse of the electric field, while in a TM mode it multiplies the electric impulse by a factor independent of the velocity." Evidently, such cavities are useless for separating particle beams of the same momentum but different masses. This report presents a new resonator in which this limitation should be removed.

¹117

768.

A radiofrequency beam separator for complete separation of high-energy particle beams, J. P. Blewett and J. D. Kiesling, Brookhaven National Laboratory. Internal Report. BNL-4658 (Aug 18, 1959) 16 p.

Describes a combination of traveling-wave deflectors which can give complete separation between the desired and the undesired particle types. A possible deflector configuration is described and the necessary dimensions and power requirements are estimated. Although the discussion is aimed at the problem of removing the π -meson component from a beam of negative protons, the equations are stated with sufficient generality that the results can be applied to other similar problems. It is also shown that the radiofrequency separation technique is applicable in the energy range from 1 Bev to 20 Bev or higher.

769

"A radiofrequency mass separator for complete separation of high-energy particle beams," J. P. Blewett, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959, 422 p. (L. Kowarski, ed., CERN, Geneva, 1959).

By passing a beam of high-energy particles already analyzed in momentum through a deflector in which a deflecting wave travels with the beam, it is possible to reduce the relative intensity of an undesired particle component. This is accomplished by matching the

velocity of the traveling wave to the velocity of the unwanted particles. The desired particles have a different velocity and will then fall out of step with the deflecting field so that they experience less total deflection. This paper shows that a combination of two such deflectors can give complete separation of two particle types. For clarity, the discussion is aimed at the problem of removing the π meson component from a beam of antiprotons. The method can obviously be applied to other similar problems of beam separation.

See also: J. P. Blewett and J. D. Kiesling, BNL-4658. 768.

770.

A scheme for particle separation in high-energy beams, H. M. Brody, NYO-2810 (Feb 19, 1960) 6 p.

A high-energy particle separator is proposed for separation of particles at momenta up to the highest produced by the Brookhaven AGS.

771.

Limitations of accelerator magnetic analyzing systems, B. L. Cohen, Rev. Sci. Instr., 33: 85-92 (1962).

The relationship between the best resolution obtainable with an accelerator magnetic analyzing system and the rate at which reaction product particles are received at the detector is studied. For cyclotrons and linear accelerators (but not for Van de Graaffs), the beam from the accelerator in all ordinary cases more than fills the phase-space volume accepted by the analyzing system; the optimum resolution depends on the phase-space density of the accelerator beam to the $1/6.5$ power. For Van de Graaffs, the optimum resolution depends on the total accelerator current to the $1/2.5$ power. For all typical cases with all accelerators, the best obtainable resolution, for situations where good resolution is needed from the nuclear physics standpoint, is between 3 and 10 kev. AVF cyclotrons should obtain about the same resolutions as Van de Graaffs, but with more difficulties in alignment and stability.

772.

Mass separation of high-energy particles in quadrupole lens focusing systems, E. D. Courant and L. Marshall, Rev. Sci. Instr. 31, 193-6 (1960).

In systems for mass separations of high-energy particles, the separation achieved depends not only on the applied electric field but also on the characteristics of the systems of magnetic lenses which

may be used to contain and focus the beam of particles. Quantitative relations for the mass separation and momentum dispersion are derived. It is shown that systems can be designed involving a module of magnetic lenses and electric field such that, when the module is repeated indefinitely, the mass separations at successive foci increase linearly with the number of modules.

773.

Magnetic spectrometer for 450-Mev protons, A. V. Crewe, Rev. Sci. Instr., 29, 880-4 (1958).

A 60° wedge-focusing magnetic spectrometer has been built for use with the 450-Mev proton beam of the Chicago synchrocyclotron. It has curved pole edges to produce good focusing in one plane only. The minimum line width obtainable is $\sim \frac{1}{4}\%$ with an available solid angle of $\sim 1/2000$ sterad. The deflection is vertical, and angular distributions can be measured from 7° to 173° without allowing the primary beam to strike the magnet yoke.

774.

A separated 1.17-Bev/c K^- meson beam, P. Eberhard, M. L. Good, and H. K. Ticho, UCRL-8878 (Aug. 25, 1959).

The design and testing of a 1.17-Bev/c separated K^- beam for use with a 15-in. hydrogen bubble chamber experiment are described. At the target the K^-/π^- ratio was 1/140. At the chamber, after two stages of electromagnetic separation and 4.0 K^- meson decay lengths, the K^-/π^- ratio was 12.5, corresponding to a total pion suppression by a factor of about 10^5 . The K flux at the chamber was $0.87K^-$ per 10^{10} protons on the target.

775.

Low-energy particles from the CERN PS, CERN 62-19 (May 17, 1962) 8 p.

The production of low-energy particles by 19.2-GeV/c protons from an internal Be target was studied at the CERN PS. The K1-beam in the North experimental hall was used to separate the different kinds of particles ($\pi^\pm$, $K^\pm$, p, $\bar{p}$) from each other. The target emission angle varied according to the beam momentum and charge. At 0.8 GeV/c, it was $\sim 14^\circ$ for positive particles, $\sim 16^\circ$ for negative particles, but the angle for higher energy particles for both signs was nearly 15° . The purity of the different separated beams was determined by measuring the time of flight of the particles with scintillation counters. The τ and μ contamination was also measured on the hydrogen bubble chamber photographs.

776.

The Cosmotron parallel plate velocity spectrometer (beam separator),
 W. J. Fickinger, J. Sandweiss, and J. R. Sanford, BNL-5757
 (Oct 15, 1959).

An electromagnetic velocity spectrometer or beam separator was designed for the Cosmotron to create a meson (π^+) beam. Physical principles of beam separator operation, beam separator design features, aspects of operation, and use in the meson (π^+) beam are discussed.

777.

Design for a 6-BeV/c separated K^- beam, T. H. Fields, E. L. Goldwasser, and U. E. Kruse, Argonne National Laboratory, Internal Rept. THF/ELG/UEK-1 (Oct 3, 1961).

A beam-transport system for high-energy separated particle beams has been designed for use with a bubble chamber at the ZGS. The basic design consists of two sections symmetrical about the half-way point, each incorporating an electrostatic particle separator followed by a narrow slit. The beam is designed to operate with a source 15 mils high and $\frac{1}{2}$ in. wide; and with magnets and separators allowing a vertical full aperture of 2 milliradians and a horizontal full aperture of 20 milliradians. The momentum acceptance of the system is $\pm 1\%$, and a sextupole correcting lens is used in each section to correct for chromatic aberration in the vertical focusing. The overall length of the system to the second slit is 343 ft. It is estimated that 10^{11} protons striking the target will supply about four 6-BeV/c K^- particles to the bubble chamber.

778.

Particle separation by means of a chain of RF-deflection cavities,
 M. Geiger, CERN-PS/Int. AR/PSep/60-4 Part I and Part II, Oct 20,
 and Dec, 1960. Part I-16 p, Part II-11 p.

An extension of the investigations presented in PS/Int.
 AR/60-13 (M. Geiger) 780.

779.

La Separation des particules au moyen de champs, H. F. M. Geiger,
 P. Lapostolle, and B. Montague, CERN 61-26 (Sept 28, 1961) 21 p.
 (In French.)

780.

Some considerations on particle separation by means of RF-deflection using cavities. M. Geiger, CERN-PS/Int. AR/60-13 (June 20, 1960) 16 p. (Also includes ADDENDUM, dated Sept. 8, 1960. 5 p.)

Considers the problem of the maximum obtainable difference in rf deflection of particles of very high energy having the same momentum and different masses so that $\beta \sim 1$ for all particles considered and that $\Delta\beta$ is a small quantity. The expressions developed apply to the fundamental case of cavities with rf fields such that the particles on their passage through them encounter a sinusoidal variation of the deflecting force. That opens a large range of cavities and cavity structures to which this case applies. [See also Panofsky's calculations on deflection separators in HEPL-82, May, 1956 and CERN-PS/Int. AR/PSep/60-4 (M. Geiger) 778.]

781.

Model studies for the electrostatic separator design, C. Germain and R. Tinguely, CERN. (To be published.)

782.

Principe du separateur electrostatique. (Principle of the electrostatic separator.) C. Germain, CERN-59-38 (Dec 7, 1959) 14 p.

It is proposed to construct an electrostatic particle separator to be used with a proton synchrotron to supply a purified beam of antiprotons. The separator is actually a velocity spectrometer since it uses a continuous electric field to act on the particles as a function of their velocity. The principle of the device is stated, and the optics of the beam feeding the separator is treated. The device and preliminary experiments with a model are described.

783.

"Electromagnetic mass separation at higher energy," M. L. Good, Instrumentation for high-energy physics, Proceedings of an international conference. New York, Interscience (1961) p. 34-36.

Separation of K mesons and antiprotons from pions at energies up to 15 BeV/c is possible if reasonable extrapolation of existing dc separator techniques is made and with careful attention to tolerances $[1/(2 \times 10^4)]$.

784.

Electromagnetic separation of secondary beams at the MURA accelerator, M. L. Good, MURA-584 (Aug 15, 1960) 19 p.

The problems of electromagnetic separation at Midwestern Universities Research Assn. machine energies are examined. It is concluded that dc separation will handle all foreseeable needs and poses essentially no special problems other than precision tolerances on components and, for the case of pulsed beams, a rather special target arrangement.

785.

A radiofrequency separator for high-energy particles, M. L. Good, UCRL-8929 (Oct 28, 1959) 19 p.

A preliminary version of the rf separation scheme outlined was given at the MURA Users' Conference of June, 1959. At that conference the group on beam separators discussed the problem of whether particle separation could be achieved at the machine energies under consideration. The scheme described has an overall acceptance (at 10 Bev/c) comparable to Bevatron separated beams (at 1 Bev/c). It would seem to be applicable to the BNL AGS and the CERN and ANL accelerators as well. The separation of π and K mesons is considered.

786.

Particle separation using internal bunching. ("Veksler Separator"), H. G. Hereward, CERN-PS Int. TH 58-8 (Dec 16, 1958) 13 p.

Discusses a transverse rf deflector at the end of the flight path, locked in frequency and phase to the proton bunches in the synchrotron, deflecting different particles different amounts according to their flight times. This can be regarded as an improvement on the older idea of travelling-wave velocity selection, and was suggested by Veksler.¹

¹Starting up of a 10-BeV Synchrophasotron and first results of physical research. V. I. Veksler, Proc. 2nd UN Int'l. Conf. on Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958) Vol. 30, p. 3.

787.

450-Mev/c K^- and $\bar{p}$ beams at the northwest target area of the Bevatron separated by the coaxial velocity spectrometer. N. Horwitz et al., UCRL-8269 (June 1958) 19 p.

Enriched beams of 450-Mev/c K^- mesons and antiprotons have been produced by separation with the coaxial static electromagnetic velocity spectrometer. Characteristics of the final separated beams as observed in the 15-in. hydrogen bubble chamber are given, together with a detailed description of the beam optics and apparatus.

788.

3-BeV/c spectrometer with a sloped window in the p-O-plane (Preliminary design), W. Kern and K. Steffen, Desy-A 2.72 (Jan 4, 1961) 15 p.

Describes the system which is 14.80 m long and has an estimated total power at 3 GeV/c and $\sigma = 0.42 \text{ rad}^{-1}$ ~950 kW. The quadrupole apertures are 40 cm wide and 15 cm high. Gives focusing properties and the acceptances of the system for $\Delta p/p = 0$

789.

Basic concepts in the design of electrostatic velocity separators. N. M. King, NIRL/R/2 (Nov 1960) 45 p.

Properties and limitations of an isolated parallel-plate crossed-field single-stage velocity separator are examined. The design objective is taken to be optimization of wanted-particle transmission through the separator in the plane of separation. In relation to certain acceptance and separation criteria, a treatment of beam behavior in phase space is developed, leading to a suitable optimization procedure. For given particles at given momentum, separator length is recommended in terms of the voltage and separator aperture, it is suggested that both these latter parameters should be as large as possible, consistent with practical limitations. Two types of beam contour - parallel and focused - are considered and compared. Two cases are discussed: first, where the wanted particles are stable, second, where they are subject to decay. Wanted-particle decay is a major consideration in determining optimum lengths. These cases are exemplified by particular treatment of $(\bar{P}, \bar{\pi})$ and $(\bar{K}, \bar{\pi})$ separation, and appropriate data are derived at various momenta. It is emphasized that the $(\bar{P}, \bar{\pi})$ data is closer to practical specification than that for $(\bar{K}, \bar{\pi})$. Basic assumptions of the theory are critically reviewed, and a future theoretical program is suggested.

790.

Finite separation ratio in electrostatic velocity separator design,
N. M. King and R. G. Cox, NIRL/R/10 (July 1961) 32 p.

The phase-space theory of electrostatic velocity separators is extended to cover cases where several beam widths of separation are provided at the selecting slit. Data are derived for $(\bar{p}, \bar{\pi})$ and $(\bar{K}, \bar{\pi})$ systems, typifying stable and unstable wanted particles. In the stable case, these studies yield practical design estimates, but the investigation is not yet complete for unstable particles.

791.

Focalisation alternee dans un separateur haute frequence separateurs parametriques, P. Lapostolle, CERN-PS/Int. AR/PSep 60-5 (Nov 2, 1960) 12 p. (In French.)

792.

Quelques relations approximatives concernant la separation de particules de meme quantite de mouvement mais de masse differente au moyen de champs de haute frequence, P. Lapostolle, CERN-PS/Int. AR/60-15 (June 24, 1960) 9 p. (In French.)

793.

RF Separators; proposed program, P. Lapostolle, CERN - PS/Int. AR/PSep/60-3.

Discusses the following: 1. Properties of rf separators; comparison with electrostatic separators; 2. Various types of rf separators; 3. First rf separator proposed for CERN; 4. Proposed program; 5. Budget, and 6. Future projects.

794.

Deviations from adiabatic behavior during capture of particles into an rf bucket, C. G. Lilliequest and K. R. Symon, MURA-491 (July 20, 1959).

Capture of particles into stable synchrotron oscillations for a constant-frequency accelerating voltage is studied for various voltage turn-on programs. Results are given for various linear voltage turn-on rates, and for two rates of turn-on with a nonlinear voltage function $V(t)$ designed to insure a constant degree of adiabaticity for all particles captured. A satisfactory form of the voltage turn-on function $V(t)$ is found for which particles are captured into stable synchrotron oscillations along curves in the phase space whose areas differ from the adiabatic value by an rms deviation of about 12%.

795.

Separation scheme for high-energy particles by differential energy loss and momentum analysis, S. Marcowitz and L. Ratner, Rev. Sci. Instr., 33, 552-554 (1962).

A simple, low-cost separation scheme using differential energy loss is described. The expected parameters of the ANL-ZGS secondary beams provide a framework for the design of a $\bar{P}$, K^- beam at 6 Bev/c for bubble chamber use. Magnet stabilities of the order of 0.01% are required. The π^- , $\bar{P}$, K^- ratio at the chamber is about 1:8:8 with 3.2 $\bar{P}$ and 3.0 K^- per pulse for a $\pm 0.25\%$ initial momentum "bite". A calculation is also made for a 50-Bev/c beam to show that it seems feasible to use this method at energies higher than any that have hitherto been produced.

796.

Resonant method of mass separation for high-energy particles, L. Marshall, BNL-LM (1958?) 5 p.

797.

RF Travelling wave particle separators. A matrix formalism and general phase-space properties. B. W. Montague, AR/PSep/60-1 (July 11, 1960) 16 p.

Velocity separators for particles of high momentum require deflecting structures of considerable length. In order to maintain sufficient acceptance in the system it may be necessary to combine a focusing structure with the deflection system. This report represents such a system by a 3×3 matrix with rather simple properties. The formalism appears to be almost useful in the case of rf deflecting structures but is equally applicable to dc deflection. The investigation of the phase-plane properties of the matrix leads to some interesting possibilities for the separation of different particle types, including a method for the elimination of first-order scattering contamination by the edge of a slit. (See also Blewett and Kiesling, BNL-JPB/JDK-1).

798.

A coaxial static-electromagnetic velocity spectrometer for high-energy particles, J. J. Murray, UCRL-3492 (May 7, 1957).

An apparatus is described in which crossed E and H fields will be used to separate high-energy charged particles of different masses. It is shown that use of coaxial geometry is expected to effect satisfactory separation within a considerably shorter system

than would be possible in a parallel-plate system with a comparable separation criterion. A summary is given of the operational characteristics of a spectrometer now under construction.

799.

"Experience with a microwave separator," W. K. H. Panofsky, Proc. Intern. Conf. High-energy Accelerators and Instrumentation, CERN, 1959, 428 (L. Kowarski, ed., CERN, Geneva, 1959).

A description of a microwave separator designed, constructed, and tested in connection with the Mark III 700-MeV linear accelerator, according to general principles described in 1956. (See W. K. H. Panofsky, A mass-sensitive deflector for high-energy particles, HEPL-82.)

800.

"Radiofrequency particle separators," D. S. Robertson, Brookhaven National Laboratory. Internal report, BNL-IA-8. 1961 summer study on 300-1000-Bev accelerators. No. 8. August 8, 1961. 4 p.

Describes the principle of operation of a radiofrequency separator where the incoming beam consists of a mixture of π^- mesons and antiprotons and that their momenta fall into a narrow momentum range. Also, describes an alternative method using a conventional disc-loaded linac section to take the place of the former drift space.

801.

Electrostatically separated beams for use with a 1000-Bev proton synchrotron, J. Sandweiss, Internal report, BNL-IA-7, 1961 Summer study on 300-1000-Bev accelerators, No. 7, (Aug 8, 1961) 26 p.

Considers the extension of the current-beam-purifying technique of electrostatic velocity selection to an energy range ~ 15 Bev/c to 150 Bev/c. The desired particles are $\bar{p}$, $K^\pm$, $\pi^\pm$, and the final beam purity is 15 tracks of the desired type of particle.

802.

Discussion of a radiofrequency particle separator for the CERN proton synchrotron. W. Schnell, CERN 61-5 (1961) 44 p.

Design parameters and possible performance figures are discussed for a Panofsky rf particle separator planned for bubble chamber experiments with the CERN synchrotron. The principle of a Panofsky particle separator is two relatively short transverse deflecting rf cavities separated by a lens system and a drift space. A three-cavity system is also considered and applied to the problem of separating one kind of particle from p, K and π .

803.

Teilchenseparator mit Gekreuzten Elektrischen und Magnetischen Feldern. (Vorläufige Untersuchung), [Particle Separator with Crossed Electrical and Magnetic Fields. (Preliminary Investigation.)],
K. G. Steffen, DESY-A2.34 (Sept 29, 1958) 12 p.

At particle energies of several Bev it is difficult to separate from each other particles of equal momentum but different rest masses. For this purpose a particle separator with crossed electrical and magnetic fields was proposed, in which the electrical and magnetic power compensates for the desired particle, and particles with varying rest mass are deflected. The basic equations for this separator are derived and illustrated by numerical examples. The question of the technical feasibility is not considered.

804.

Achromatic beam optics for particle separator, S. Van der Meer, CERN report 60-22 (1960).

The maximum momentum at which a particle separator can give a useful separation is partly determined by the aberrations of the associated beam transport system. The various factors limiting the image sharpness are discussed. It is shown how the chromatic aberration of the lenses can be compensated by using a sextupole lens in combination with a momentum analyzing magnet. A description is given of two possible beam-transport systems for the CERN electrostatic separator, one for the South Hall and one for the East Experimental Area. These designs aim at a maximum momentum value of 6 GeV/c and 8 GeV/c, respectively (separation of antiprotons and π mesons).

805.

Deflection plates of the electrostatic beam separator, A. Yokosawa, Argonne National Laboratory Internal Report AY-9 (June 22, 1961) 11 p.

Presents an analysis to be used in designing the parallel deflection plates of the beam separator. The high vertical field $\partial v / \partial y$ found at the edge can be eliminated by using the Rogowski electrode for part of the width.

Deflection plates of the electrostatic beam separator. A. Yokosawa, Argonne National Laboratory Internal Report AY-9 Suppl, (Sept 28, 1961) 11 p.

Supplement to above report.

806.

Transmission of particles of the electrostatic separator, A. Yokosawa, Argonne National Laboratory Internal Report ANLAD-70, (March 30, 1962) 26 p.

Basic beam optics involved with the electrostatic beam separator is discussed. Calculated values of transmission of $\bar{P}$ and K particles, which are just separated from π 's, are given in terms of the phase-space area for different momenta. The transmission is also discussed for different values of gap distance between parallel plates. Chromatic and spherical aberrations in the associated magnets with the beam separator are investigated for different gap distances.

See also N. M. King, NIRL/R/2. 789.

807.

Physical principles of antiproton channel, V. N. Zubarev et al., Joint Inst. for Nuclear Research, Dubna, USSR Lab. of High Energy, JINR-P-371, 23 p.

A method for separating high-energy antiprotons from a π -meson background in a synchrotron is described. Conditions for producing a satisfactory ratio of average pulse spacing to average pulse duration, the ion-optical system, the deflecting device, and other conditions necessary for realizing the suggested method are studied. A spatial separation of antiprotons and π mesons with 3.1 ± 0.1 Bev/c was achieved. The divergence between the image centers of antiproton and π meson beams is 13.5 cm with a clearance between the image inner edges of about 9 cm. The anticipated π background damping coefficient is $\gtrsim 700$.

808.

The division of electrons in outlet from linear accelerator by means of electromagnetic wave in waveguide, A. I. Zykov, Zhur. Tekh. Fiz., 30, 971-4 (1960). (In Russian.)

A method is suggested for separating accelerated electron beams in such a way that successive electron bunches deflect in various directions at small equal angles in relation to the original beam. The method is based on electron-bunch interactions with transverse electric waves of H_{10} type in a waveguide where the frequency is 2-fold lower than the bunch frequency, and the phase rate v_f is twice the bunch transmission rate v_1 . Hence, the spatial wave in the waveguide is 4 times larger than the distance between the centers

of the bunches. The length of the waveguide is equal to 2λ [or to an odd number $(2n + 1 \text{ times } 2 \gamma_0)$], and the bunches enter the waveguide according to the corresponding phase (at the moment when the electric field in the waveguide equals zero). During the waveguide flight time, the electrical forces act on successive bunches and deflect them into different directions. [English translation in: Soviet Physics-Technical Physics, 5, 909-11 (1961)].

See also: 607, 809, 838, 867, 870.

EXTERNAL BEAM SYSTEMS

809.

Beam handling at Saturne, Centre d'Etudes Nucleaires de Saclay.

Consists of the following three items:

- 1) NT 223 CA/FM
Parc Electro-Aimants de Saturne Caracteristiques
Generales (2/9/62).
- 2) S.E.F. A-F. 30.005
Drawing: "Experiences - Physiciens Janvier 1962"
(Jan 1, 1962).
- 3) Contrat C.E.Z. 3787
Separateur de Particules. R. Liot (March 1961).

Presents a listing of the Saturne magnets with their main characteristics, a recent map of the hall indicating the beams, and a brief description of their second electromagnetic separator, which is of a conventional type.

810.

Characteristics of the K2 beam in the North Hall, Lundby (27 Oct 1961)
6 p. (Unnumbered report) Available in the Argonne-ZGS Reading Room.

Describes the experimental setup and the procedure used to establish the beam characteristics essential for the experimental work.

811.

Beam-transport system for the Berkeley 88-inch cyclotron,
H. Atterling, UCRL-10077 (May 4, 1962) 21 p.

812.

Description of AGS experimental beams as of February 1, 1961,
W. F. Baker, E. D. Courant, and R. H. Phillips, BNL-5283 27 p.

A description of the channels installed for the beam survey studies at the Brookhaven Alternating-Gradient Synchrotron is given. Maps showing the layout of the shielding and the parts through it are included, along with data on the beam collimators and bending magnets.

813.

A circle diagram for beam transport calculations, A. P. Banford.
NIRL/R/8 (June 1961) 17 p.

A chart consisting of two families of circles is described, which facilitates the calculation of the optics of focusing systems for finite emittance beams. The chart can also be used to demonstrate certain properties of the optics of such beams, which differ from the corresponding properties of point-source beam optics.

814.

Deflection coil for an external accelerator beam, R. Benaroya and W. J. Ramler, Nuclear Instr. and Methods, 10, 113-20 (1961)

A compound vertical and horizontal deflection coil using a motor-stator-type iron core and a winding with a sinusoidal distribution of turns makes a useful tool for precisely positioning and sweeping the external beam of an accelerator. The design, method of construction, performance, and characteristics of this coil are discussed.

814a.

"Beam facilities planned for the ORIC," R. S. Bender, p. 270-1 of Sector-focused cyclotrons. Proceedings of an Informal Conference, Sea Island, Georgia, Feb. 2-4, 1959.

The external optics and facilities for the ORIC are briefly discussed. Present plans for the machine are shown.

815.

157-Mev synchrocyclotron, C. Bergamaschi et al., J. phys. radium, 21, 305-14 (1960) (In French.)

The general characteristics of the synchrocyclotron de la Faculte des Sciences (157-Mev protons) and its setting up are described. The main properties of the external proton beam (focusing, energy definition, time structure with or without additional high modulation frequency at the end of acceleration, intensity measurements with ionization chamber and Faraday cup) and of the neutron beam (energy spectrum, intensity) are given. The characteristics of a magnetic analyzer of secondary particles under construction and a summary of the main uses of the machine are also given.

816.

Fine time-structure of beams from the Birmingham proton synchrotron, N. E. Booth and G. W. Hutchinson, Nuclear Instr, 1, 80-85 (1957).

The radiofrequency time-structure of beams scattered from internal targets in the Birmingham proton synchrotron has been investigated using a delayed self-coincidence technique. The degree of bunching of all the beams commonly used in counter experiments has been investigated, and methods of increasing the burst length and destroying the radiofrequency structure are discussed.

817.

The design of a focusing and analyzing system for the 27-in. cyclotron beam, D. A. Bromley and J. A. Bruner, NYO-3823 (1954).

818.

Technique of obtaining monochromatism of an ion beam from an accelerator, H. Bruck, J. phys. radium, 14, 251-6 (1953) (In French.)

The optimum adjustment of an ionic prism monochromator is discussed, and the relations between characteristics of the beam, of the monochromator, and of the final current to the target are established. Some numerical examples are given.

819.

"A high-intensity μ -meson beam from the 600-Mev CERN synchrocyclotron," A. Citron et al., Instrumentation for high-energy physics, Proceedings of an international conference, Interscience, New York (1961) p. 286-288.

A description of the beam-optical system at the CERN synchrocyclotron. This system provides strong fluxes of μ -mesons, of both high and low energy, with a low π -meson contamination.

820.

An experimental facility: A mu meson beam of 1 Bev, R. Cool, E. D. Courant, and L. Marshall, BNL-RC/EDC/LM (1959?) 11 p.

It is proposed to produce as an experimental facility at the Cosmotron a high-energy mu-meson beam. Briefly, the method of production is to contain a beam of momentum-analyzed pions in a system of quadrupole lenses extending for a distance equivalent to one pion lifetime at the appropriate velocity and to collect the decay

muons in the same lens system. At the end of it, the decay muons are separated from the remaining pions, and at the same time selected in energy by means of a momentum-analyzing magnet. The main features of the lens system and the expected characteristics of the muon beam are described here.

821.

The external proton beam of the Cosmotron, R. L. Cool et al., BNL-498 I24 (March 1958) 34 p.

This report on the external beam program at Brookhaven is divided into six parts. Section I describes the internal targeting, Section II the magnet M1, Section III the magnetic shim system, Section IV the beam trajectory calculations, Section V the known experimental facts concerning the external beam which is produced, and Section VI the monitoring methods by activation.

822.

Tentative plans for experimental equipment at the AGS, R. L. Cool and E. D. Courant, BNL-4653 (April 9, 1959) 11 p.

Presents a brief resume of the present tentative plans for general experimental equipment to be used during the first year of operations of the AGS. Items discussed include: Magnets and Beam Separators and Suggested Beams. The latter include Beam I - 5 Bev/c positive or negative separated beam. Beam II - 25 Bev/c negative particle beam, Beam III - 10 Bev/c positive or negative beam. Beam IV - 5 Bev/c positive or negative beam, and Beam V - θ° neutral beam.

823.

Analyzed secondary beams from AGS magnet, E. D. Courant, BNL-EDC-13 (June 25, 1954) 5 p.

Considers a target in the AGS bombarded by 25-Bev protons, where fast secondary particles emerge mostly at small angles near the forward direction. Describes provisions for obtaining secondary particles of both signs (and neutral).

824.

"Transport and separation of beams from AG synchrotron,"
E. D. Courant and R. Cool, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 403 (Kowarski, L. ed. CERN, Geneva, 1959).

Beams of various particles (protons, π and K mesons hyperons, antinucleons, neutrons, and photons) at various energies can be produced by placing appropriate targets into the path of the proton beam inside the machine and analyzing and focusing the energetic secondaries by means of bending magnets, quadrupole magnets, and mass separators. In this paper the possible layouts of some of these beams are presented, together with some of the considerations that led to the particular choices.

825.

External particle beams, A. V. Crewe, R. H. Hildebrand, U. E. Kruse, S. D. Warshaw, and S. C. Wright, Argonne National Laboratory Internal Report CHKW-2, n.d. 3 p.

The purpose of the present report is to recommend a system of particle beams which will insure efficient and flexible use of the accelerator. Several aims of the recommendation are: 1) to limit accelerator down time to accelerator maintenance time; 2) to allow the deliberate and careful setup of experimental apparatus by avoiding successive experiments in a single area; 3) to meet requests for low-intensity beams at the same time as those for high-intensity beams; 4) to allow the long-term setup of major devices such as antiproton beam facility without prejudicing the performance of other experiments.

826.

Layout of the experimental areas of the 12.5-Bev accelerator, A. V. Crewe, R. H. Hildebrand, U. E. Kruse, S. D. Warshaw, S. C. Wright, and C. M. York, Argonne National Laboratory Internal Report CHKWY 3 (Jan 1958) 11 p.

An overall layout is suggested for the experimental areas which surround the machine. A guiding principle in devising this arrangement has been that it should never be necessary to shut off the machine in order to set up or remove experimental apparatus. This principle is essential in order that several experiments may be efficiently performed at one time. In Section A, we discuss the two external proton beams and the surrounding experimental areas. In Section B, we discuss the meson beams and associated facilities. The experimental area for the 50-Mev LINAC will be discussed in a separate report.

827.

"Notes on external particle beams from the Argonne 12.5-BeV synchrotron," A. V. Crewe, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 400 (Kowarski, L. ed. CERN, Geneva, 1959)

Describes: beam height, proton beams, meson area, general facilities.

828.

Method of focusing charged particles from an accelerator, V. I. Danilov and O. V. Savchenko, Pribory i Tekh. Eksper., 1959 17-20 (May-June). (In Russian.)

Charged particles emerging from an accelerator and passing into a magnetic deflecting field can be deflected and focused simultaneously if suitably disposed ferromagnetic blocks are placed between the deflecting pole pieces. These blocks have the effect of magnetic quadupole lenses, and by their use the intensities of high-energy protons and mesons received by the collecting device have been trebled.

829.

On a method of increasing the density of an external proton beam from the six-meter synchrocyclotron, V. I. Danilov, V. P. Dmitrievskii, and I. V. Chestnoi, Trans. from Pribory i Tekh. Eksper., No. 3, 9-13 (1956) 11 p.

The estimation of increasing the average density was performed by comparing the cross sections of the external beam in the absence or presence of the focusing magnetic field. The calculation of the focusing effect of the magnetic field was made on the basis of the analysis of particle motion along the beam trajectory. The focusing field was created in the nonworking region of the accelerator's magnetic field with the help of iron masses of certain configurations.

830.

An external proton beam at the CERN proton synchrotron, B. Dayton et al., Helv. Phys. Acta, 33: 544-6 (1960).

Trajectories of the external beam of the CERN proton synchrotron in the horizontal plane were calculated and show a moderate defocusing. The vertical motion, obtained for three trajectories by graphical piecewise integration, show positive focusing. These predictions on particle directions were checked on nuclear emulsions placed in arrays at several distances from the target. At 19 m from

the target, the observed focal point for the horizontal flux distribution is precisely the calculated value. Vertical profiles of the scattered proton flux at 37 m distance shows the most nearly parallel beam corresponds to a scattering angle of 28 mradians. A target diagram giving the angular distribution in space of scattered 24-Bev protons indicates that half the tracks lie within a space angle of 1 mradian from the average direction. The beam intensity at 90 m from the target is as high as 4000 protons/cm² per pulse.

831.

Scattered-out external proton beam at the CERN proton synchrotron,
B. Dayton and H. Winzeler, CERN-61-17 (May 17, 1961) 32 p.

Trajectories were calculated in both horizontal and vertical planes for the proton beam elastically scattered from target No. 1 in the CERN proton synchrotron. The momentum distribution of the beam was determined. Means of increasing the intensity of the beam is discussed.

832.

An extension of the transfer matrix method to a beam-transport system containing a solenoid, D. N. Edwards and B. Rose, Nuclear Instr. and Methods, 7, 135-144 (1960).

The transfer matrix method of calculating beam-transport problems is outlined and extended to the case in which one of the elements is a solenoid, as is used in certain polarization experiments. The theoretical results are compared with measurements made with a proton beam and semiquantitative agreement found.

833.

Design studies for the Nimrod external proton beam, J. W. Gardner, N. M. King, and D. Whiteside, NIRL/R/12 (Jan 1962) 31 p.

A flexible external beam system is proposed, in which focal spots suitable for target location may be provided at any convenient point along the path through the experimental area. A target spot close to the machine, in front of the main shield wall, is also provided. The beam-transport problem is solved in terms of widely separated singlet quadrupole elements, and matching problems are solved using quadrupole doublets. It is shown that target spot sizes of order $\frac{1}{8} - \frac{1}{4}$ in. should be feasible, provided that the achromatic extraction system performs satisfactorily.

834.

Bevatron operation and development. Part XIX for Aug, Sept, Oct 1958, W. D. Hartsough, UCRL-8564 (Apr 1959) 19 p.

A new secondary-particle beam facility was completed which will allow negative particle beams in the momentum range from 0.77 Bev/c to 6 Bev/c to be brought out of the Quadrant III curved section. The initial phase involved in the installation of a plunged beam clipper within the magnet aperture in Quadrant I was completed. Continued improvement in ignitron performance was recorded.

835.

Slow and fast structure of secondary-particle beams of the Bevatron, H. G. Heard, UCRL-3428 (July 5, 1956) 18 p.

A coordinated investigation of the structure of the secondary-particle beams of the Bevatron was made. The debunching and spiral in time of the primary beam have been determined for typical experimental conditions. Two of the methods of secondary-beam production, which are discussed here, have been used extensively in cloud-chamber and counter-type experiments. Three new methods of secondary-beam production have been studied in some detail. The radiofrequency structure, synchrotron oscillation structure, magnet-ripple structure, and duration of the secondary-beam pulse are reported for each of these methods.

836.

Alternating gradient focusing of the 20-inch cyclotron external beam, E. L. Hubbard and E. L. Kelly, UCRL-2818¹ (Apr 23, 1953) 23 p.

The 0.75-Mev external proton beam from the 20-in. cyclotron appeared to diverge from an astigmatic source. With a series of 3 alternately converging and diverging electrostatic lenses of hyperbolic cross section, it was possible either to focus the external beam to a spot or to make it parallel.

¹See also Rev. Sci. Instr. 25, 737-9 (1954).

837.

Secondary beams from the ZGS, P. Kalmus, Argonne National Laboratory Internal Report PK-1 (Feb 6, 1961) 7 p.

Describes the three secondary beams planned for the meson area. These beams will leave the machine with exit angles of 7° , 17° , and 30° .

838.

Some beam transport considerations, P. Kalmus and S. Marcowitz, Argonne National Laboratory Internal Report PK-SM-1 (Dec 1, 1960) 8 p.

Report of a trip to Berkeley and the discussions held on quadrupole lenses, bending magnets, power supplies, electrostatic separators, high-voltage supplies, of separators, and beamology.

839.

Observation of the deflected ion beam trajectory from a cyclotron, K. Kimura, J. Kokame, and S. Yamashita, Rev. Sci. Instr., 29, 142-3 (1958).

A simple and convenient method has been employed to determine the trajectory of the deflected ion beam from a cyclotron. Using several mesh screens across the beam path, the location and angular divergence of the beam in various places can be obtained simultaneously by the holes made by the ion bombardment on these meshes.

840.

"External beam problems in the 6-BeV electron synchrotron," M. S. Livingston, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN 1959. (Kowarski, L. ed. CERN, Geneva, 1959)

Describes the beam properties of the electron synchrotron, internal targets, emergent electron beams, and shielding and the beam channels.

For a more detailed description see: "Stanford two-mile linear electron accelerator." R. B. Neal (Stanford Univ.) Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 349 (Kowarski, L. ed. CERN, Geneva, 1959.) 845

841.

External magnetic focusing devices for the Mark 3 accelerator,
J. A. McIntyre, R. L. Kyhl, and W. K. Panofsky, ML-202 (July 1953) 48 p.

Beam loss in the 1-Bev Stanford linear accelerator appears to be in excess of that predicted by theory. Theoretical calculations are presented in attempts to overcome this problem by strong-focusing applications. The theory of strong focusing is first applied to the accelerating region in a manner similar to that used by Bell,¹ after which the image-forming properties of a system of thin quadrupole lenses are examined. Some typical numerical results are presented for the 200-ft 1-Bev electron accelerator. The achromatic double-prism deflection system in use at the 100- and 130-ft points, which is described in detail, transforms an essentially parallel, nonhomogeneous beam into a beam converging to a focus. The possibilities of applying strong-focusing principles to this system so as to effect a parallel, rather than a converging, beam are discussed.

¹AERE-T/R-1114

842.

Focusing secondary beams from the ZGS, S. Marcowitz, Argonne National Laboratory Internal Report SM-2 (March 9, 1961) 9 p.

The first two elements in each of the three secondary beams in the ZGS meson area form doublets. It is useful to know the field gradients in each magnet necessary to produce essentially parallel beams in both vertical and horizontal planes from very small targets. Since the field region in the octant has not yet been accurately mapped, for the present, only a target in the field-free region common to all three beams will be considered. The magnet lengths may change slightly but new calculations can be performed when they are well known.

843.

An application of a ribbon lens to the focusing of the external beam of a cyclotron, Ye. S. Mironov, L. M. Nemenov, S. B. Zvyagin, and R. A. Meshcherov, *Pribory i Tekh. Ekspt.*, No. 5, 18-21 (1957). (In Russian.)

An electrostatic focusing device for the external beam of the 1.5-m cyclotron is described. The system, consisting of molybdenum ribbons, is shown. The system focuses the beam in the vertical direction, focusing in the perpendicular direction being carried out by a magnet (not described). Performance measurements were obtained

using 12-Mev protons. The ribbon lens increases the current density by a factor of 10. Particle losses did not exceed 10%. The current density at the target was $15 \mu\text{a}/\text{cm}^2$.

844.

Space-charge effects in cylindrical beams with uniform acceleration, C. D. Moak, AERE-R-3255¹ (Feb 1960) 28 p.

An evaluation was made of the integral which describes the profiles of cylindrical beams of particles, converging toward parallel emergence from a uniform voltage gradient accelerator. Tables are presented which cover variations of the parameters.

¹See also: Nuclear Instr. and Methods, 8, 19-22 (1960).

845.

"Stanford two-mile linear electron accelerator," R. B. Neal, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 349 (Kowarski, L. Ed. CERN, Geneva, 1959).

Presents the present ideas about the external beam lay-out for the proposed 2-mile Stanford electron linear accelerator.

846.

"Beams from high-energy linear accelerators," W. K. H. Panofsky, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959 (Kowarski, L. ed. CERN, Geneva, 1959).

This paper contains some general remarks about the properties of beams from high-energy linacs and about the use of these beams.

847.

A focusing device for the external 350-Mev proton beam of the 184-inch cyclotron at Berkeley, W. K. H. Panofsky and W. R. Baker, UCRL-499¹ (Nov 15, 1949) 12 p.

The external beam of the 184-in. synchrocyclotron is produced by a pulsed electrostatic deflector displacing the cyclotron orbits to enter a magnetic shield which channels the beam to the outside of the magnetic field. The beam thus produced covers an area of approximately 8 sq in. at the bombarding position (about 46 ft from the center of the cyclotron). Since the total beam attained thus far is only of the order of 10^{-9} amp, the resultant beam density is insufficient for many experiments or at least leads to long run times. Since in most experiments beam density rather than total current is the determining factor, a focusing device is considered of advantage. Both horizontal and vertical focusing is possible by means of a wedge-shaped deflecting magnet.

The use of such a device, although practical in principle, was rejected here since it involved re-location of the target facilities and also since the physical size of a focusing magnet at this energy and aperture is very considerable. It was, therefore, decided to study an "in-line" focusing device, i.e., a device focusing without deflection. The device chosen consists essentially of a current-carrying cylindrical conductor whose axis is parallel to the beam and which is transparent to the passage to the beam. If the current density is uniform, the magnetic field will increase linearly with the radius and a linear restoring force on the beam will result. A current carrying conductor transparent to the proton beam was realized physically in the form of an arc inside a cylindrical glass tube 3 in. in diameter and 48 in. in length. The operation of this focusing device is discussed.

¹Also in Rev. Sci. Instr., 21, 445-7 (1950).

848.

Energy degrading-focusing of cyclotron beam, W. J. Ramler, J. L. Yntema, and M. Oselka, Nuclear Instr. and Methods, 8, 217-20 (1960).

The Argonne National Laboratory 60-in. cyclotron is a fixed 10.8-Mev/nucleon accelerator. To increase machine flexibility, it was desired to obtain variable energy projectiles 25 to 40 ft from the accelerator without severely reducing particle number and beam definition. Sacrificing energy resolution, a focused variable energy beam can be obtained by using the technique of a foil-absorption system close coupled with strong focusing provided by quadrupole magnets. The system described can readily degrade a deuteron or α beam to about 2.5 Mev/nucleon with about 5% of the original particles focused a distance of 35 ft from the accelerator.

849.

"External beam-focusing system - Argonne 60-in. cyclotron," W. J. Ramler, p. 266-9 of Sector-focused cyclotrons. Proceedings of an Informal Conference, Sea Island, Georgia, February 2-4, 1959.

The external beam of the Argonne 60-in. cyclotron can consist of either deuterons (21.6 Mev), helium ions, or molecular hydrogen (H_2). The experimental machine requirements have established a range of beam operation from the nominal quoted currents down into the region of 1×10^{-11} amp. The external beam-focusing system is described.

850.

Beam production and transport, L. G. Ratner, Argonne National Laboratory Internal Report LGR-1 (Nov 8, 1960) 19 p.

An estimate is made of the amount of secondary particles which can be produced by the 10^{13} protons per pulse in the ZGS on an internal target. Target positions and exit channels are investigated and operating parameters for the first element of the transport system are calculated. This element is a conventional quadrupole doublet, and its dimensions have not been optimized as to cost. It is, however, a feasible magnet.

851.

Vertical focusing in bending magnets, L. G. Ratner, Argonne National Laboratory Internal Report LGR-2 (March 28, 1961) 6 p.

Consideration of the magnetic-field requirements in bending magnets for highly separated beams leads to a severe requirement on the vertical-focusing properties as outlined by M. L. Good (Univ. of Wisconsin). This report considers Good's criteria and discusses the feasibility of such a magnet and the measurement techniques which are necessary to determine the magnetic field to the required accuracy.

852.

ZGS proton areas. Parameters for proton beam transport elements, L. G. Ratner, Argonne National Laboratory Internal Report LGR-3 (Sept 5, 1961) 5 p.

853.

"External beam-focusing system," F. H. Schmidt, p. 257-61 of Sector-Focused Cyclotrons. Proceedings of an Informal Conference, Sea Island, Georgia, Feb. 2-4, 1959.

The external beam-focusing system of the University of Washington cyclotron is briefly described. The cyclotron ejects the beam through a target chamber, a focusing magnet, then a water-filled shielding room. In the target box and in the shutter box just ahead of the focusing magnet there is a system of remotely adjustable beam-delimiting slits. The focusing magnet employs "edge focusing," so that it focuses in both the horizontal and vertical planes. An analyzing magnet directs the beam into one of two scattering chambers.

854.

Concentration of a cyclotron beam by strong focusing lenses, F. B. Shull, C. E. MacFarland, and M. M. Bretscher, *Rev. Sci. Instr.*, 25, 364-367 (1954).

A pair of strong-focusing magnetic lenses has been used to concentrate a part of the external beam from the Washington University cyclotron. The lenses focus the beam at distances up to more than four meters beyond the end of the cyclotron. This produces approximately an eightfold improvement in beam intensity.

855.

"Cosmotron beams," L. W. Smith, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 397 (Kowarski, L. ed. CERN, Geneva, 1959).

Describes the external experimental beam layout. The Cosmotron is back in operation after an extended shutdown because of coil failures due to copper fatigue. Modifications to experimental arrangements and facilities accomplished during shutdown are discussed. External beams one, two, and three are considered.

856.

Use of generalized amplitude and phase functions in designing beam-transport systems, K. G. Steffen, H. Hultschig, and W. Kern, *DESY-A-2.70* (Aug 1960) 14 p.

The method of amplitude and phase functions used in AG synchrotron theory is generalized for application in high-energy beam transport systems. The beam is represented by phase ellipses, and the ellipse parameters are transformed through the system. A complete description of the beam as a whole, rather than of single-particle trajectories, is thus obtained. The method allows a quick estimate of the cost of a system and appears to be useful in looking for close-to-optimum systems satisfying given experimental requirements. Some suggestions are made concerning the use of an analog computer for treating this problem.

857.

Calculations on a new proposed external proton beam, R. Sternheimer, *BNL-RMS-72* (Dec 26, 1957) 11 p.

In connection with the projected extension of the Cosmotron building, it has been suggested to obtain a new external proton beam by deflecting the proton beam in magnet M_1 by an appropriate amount

to make it emerge from the vacuum chamber at the first pump station past the East straight section (in quadrant #3). The purpose of this report is to give the results of calculations of the trajectories and focusing properties of this new proposed external proton beam. It appears from the calculations that the horizontal defocusing of the beam before it arrives at the pump station will be a serious problem. As a result, the intensity of the beam is estimated to be only 40% of the present external proton beam (from quadrant #2).

858.

Focusing of secondary beams from the AGS, R. M. Sternheimer, Internal Report, BNL-RMS-6 (Feb 12, 1959) 9 p.

Presents the results of calculations on the double focusing by a general system of two quadrupole magnets, for particles of momenta of order 10 Bev/c.

859.

Focusing of the external proton beam, R. Sternheimer, BNL-RMS-67 (Oct 16, 1956) 6 p.

It has been suggested to place several strong focusing magnets in the path of the external proton beam, so as to provide a small image for several experiments, running simultaneously, with one possible target location (and experimental area) between each pair of successive strong focusers. With such an arrangement, the beam envelope tends to increase rapidly as the number of focusing units is increased. This report discusses the spreading of the beam in two successive strong focusing units of the type now used at the Cosmotron (12-in. diameter) and it will be shown that the displacement of the beam envelope from the central axis is generally less than 6 in. in the second magnet pair, so that this set up will be adequate for providing two alternate target locations in the external beam.

860.

Asymmetric achromatic bending magnet systems, L. C. Teng, Argonne National Laboratory Internal Report LCT-15 (Nov 1959) 10 p.

A study of the design of an achromatic system which will lead an incident beam with fixed position and direction to prescribed exit position and direction.

861.

"The production, transport and separation of beams," H. K. Ticho, Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959, 387 (Kowarski, L. ed. CERN, Geneva, 1959).

Discusses the characteristics of counter and chamber beams. Topics included are: target considerations; beams for counters; a separated 1.17-BeV/c K^- beam, septum separator.

The characteristics of a beam are strongly influenced by the nature of the investigation for which it is constructed and the research technique which will be used. Of the three most common tools, scintillation counter arrays, bubble chambers, and nuclear emulsions, the requirements of the last are usually less stringent than those of the other two. The characteristic requirements of counter beams are long beam duration and the largest possible flux, while those of chamber beams are short beam duration and sharp images. These two beams are discussed in detail.

862.

"A beam of π^- mesons with a momentum of 7 GeV/c from the synchrotron," W. Tso-tsiang et al., Proc. Intern. Conf. High-Energy Accelerators and Instrumentation, CERN, 1959. 412 (Kowarski, L. ed. CERN, Geneva, 1959).

Discusses the determination of the direction of the π^- meson beam and the focusing of the π^- meson beam.

In order to set up a 7-BeV/c π^- beam, trajectories of π^- mesons, emitted from a Be target at an angle of 0° with respect to the circulating proton beam, were calculated. The trajectories were obtained with a graphical method and by numerical integration of the equations of motion of a charged particle in an inhomogeneous magnetic field. To focus the beam four quadrupole magnets, each 1 m in length and with an aperture of 30 cm and a maximum field gradient of 600 G/cm, were used.

863.

Focusing of the synchrotron scattered-out beam, H. B. Van Der Raay, Nuclear Instr., 1, 351-3 (1957).

A means of focusing the scattered-out beam of the Birmingham proton synchrotron by modifying the magnetic fringing field is outlined. The beam is brought to a spot focus of about 20 sq cm at a distance of 5 m from the exit port and has a mean intensity of 5×10^3 particles per sq cm per pulse.

See also: 607, 670, 673, 681, 689, 777, 804.

EXTERNAL BEAM SYSTEMS - EQUIPMENT AND POWER SUPPLIES

864

Particle accelerator division summary report for October 1, 1957 through April 15, 1958, ANL-5864 63 p.

Includes recommendations for the layout of experimental areas, the power requirements for these areas, and the characteristics of the various beams are presented.

865.

Power required for beam handling and experiments, A. V. Crewe, R. H. Hildebrand, U. E. Kruse, S. D. Warshaw, S. C. Wright, and C. M. York, Argonne National Laboratory Internal Report CHKWY-4 (Dec 17, 1957) 6 p.

An estimation is made of the delivered power required for all magnets outside the machine itself. Although all the magnets listed will not necessarily be running at full power simultaneously, the installed power should be at least the equivalent of the calculated values since it is anticipated that future developments will increase the power requirements.

866

Beam-handling equipment at Brookhaven, P. Kalmus, S. Marcowitz, and A. Yokosawa, Argonne National Laboratory Internal Report PK-SM-AY-1 (Jan 1961) 4 p.

Presents information about magnets, separators, and power supplies obtained while visiting Brookhaven National Laboratory on January 9-11, 1961.

867

Magnets in the experimental areas, S. Marcowitz, Argonne National Laboratory Internal Report SM-4 (May 26, 1961) 3 p.

A discussion of the status and design of some of the components of the beams from the ZGS.

868.

Power requirements for magnets and bubble chambers in Cosmotron department, A. C. Nerenbert, BNL-5036 (Sept 27, 1960) 2 p.

A table is presented which indicates the power requirements for the existing magnets and bubble chambers and those units on order for the Cosmotron Department.

869.

"Some features of beam-handling equipment for the CERN proton synchrotron," C. A. Ramm, Instrumentation for high-energy physics, Proceedings of an international conference. Interscience, New York (1961) p. 289-298.

The CERN proton synchrotron (CPS) accelerates about 3×10^{11} protons per pulse to a maximum kinetic energy of 28 Gev, with a repetition rate of once per 5 sec. At lower energies, higher repetition rates are possible, up to a limit of once per second. This paper reviews work in progress on the momentum analysis, focusing, separation, and extraction of particles.

870.

P. L. A. Progress Report. 1961, P. L. A. Group, Rutherford High Energy Laboratory, Harwell, Didcot, Berkshire, NIRL/R/15.

On pages 32 and 33 a brief description is given of the beam-handling equipment for the experimental area.

871.

High-voltage cable estimates for 6-Bev/c $\bar{p}$ beam, J. Sandweiss, Internal report, BNL-JS-1 (April 21, 1961) 5 p.

Presents an estimate of the beam layout and the lengths of high voltage cable required for this layout.

See also: 652, 657, 838.

INSTRUMENTATION

872.

Design characteristics of beam current monitors, M. E. Abdelaziz, Argonne National Laboratory Internal Report MEA-3 (Jan. 26, 1961) 15 p.

It has been a normal practice to measure beam currents from ion sources in cylindrical Faraday-cup collectors. This method seems to be unsatisfactory with high beam currents (probably higher than 50 milliamperes). The efforts involved in the Faraday-cup measurement are i) emission of secondary electrons from the cup due to bombardment by beam particles (a dc bias or a magnetic field is normally used to reduce this error), ii) ionization by collision of the beam with gas molecules trapped in the cup, and iii) scattered beam particles which leave the cup. In addition, a Faraday cup has the disadvantage that it cannot be easily used for current measurement when the source is put into operation with a particle accelerator. A non-destructive method must therefore be used for the beam-current measurement at different points along the beam path and during its acceleration. The best-known method is the use of current pulse transformers to monitor the beam and measure its amplitude. The purpose of this paper is to give the experimental characteristic curves of such transformers which will be located at the following positions: a) exit of ion source, b) end of preaccelerator, c) linac entrance and exit, d) entrance to a chromatic magnet, and e) inflector entrance and exit.

873.

Design characteristics of beam current monitors. Part II, M. E. Abdelaziz, Argonne National Laboratory Internal Report MEA-4 (July 24, 1961) 17 p.

Deals with a further experimental study connected with the calibration of beam monitors designed for operation with the final machine. (For Part I see MEA-3, 872).

874.

Cosmotron external beam monitor, C. Brand and C. Swartz, Rev. Sci. Instr., 29, 247-8 (1958).

A device of sufficiently low density so that it could be left in the beam for continuous monitoring by the Cosmotron operators is described. The device is an 8-in.-diameter ionization chamber with Mylar walls. One wall is coated with Al and the other has a silk-screened silver mosaic of 64 spots. In the control room, 64 bulbs

are arranged in an array corresponding in position and size to the 64 spots of the chamber. Each time the bulb passes through the chamber the appropriate bulbs light in the control room. The device is useful in locating the emerging beam and in monitoring the pencil beam

875.

Multipurpose magnetic particle analyzer, R. L. Burman and A. I. Yavin, TR-6 (March 1959).

876.

Mass analysis of the secondary particles produced by the 25-GeV proton beam of the CERN proton synchrotron, V. T. Cocconi et al., CERN Geneva, Switzerland.

Presents some results of a mass analysis of the secondary particles produced at 15.9° to the circulating beam in an aluminum target bombarded by 25-GeV protons in the CERN proton synchrotron.

877.

Velocity selection using internal bunching, H. G. Hereward, CERN-PS Int. Th 58-5 (Nov 10, 1958) 7 p.

Describes a fast counter technique in which a delayed gate or pulse-instant analysis is used to find the velocity along the flight path of whatever particle caused the event counted.

878.

A transistorized hodoscope for setting up fast pulsed beams, G. Kuhn and B. Voss, CERN (To be published).

879.

A proposed search coil for measuring the harmonic coefficients of magnetic quadrupole fields, W. H. Lamb, Jr., Argonne National Laboratory Internal Report WHL-1 (Jan 25, 1962) 10 p.

The scalar magnetic potential, and hence the magnetic field intensity, of a quadrupole magnet can be found from a direct solution of Laplace's equation by employing the method of harmonics. A rotating search coil has been developed which, along with a wave analyzer, can measure a large number of these harmonic coefficients and thereby enables one to determine the contribution of each term to the total magnetic field.

880.

Current regulator for "floating" wire used in magnet calibration, I. Lutz and C. Pike, *Rev. Sci. Instr.*, 30, 841 (1959).

Describes method for calibrating a beam-analyzing magnet.

881

A method of measuring the velocity of high-energy electrons, M. Papoular, *Compt. rend.*, 239, 1194-6 (1954). (In French.)

The electrons are made to pass in proximity to a broad-band slow wave line, and the frequency of the waves excited on the line is measured. This frequency is related to the velocity by formulae familiar in the theory of the carnotron.

882.

Faraday cup monitor for the Iowa state college synchrotron electron beam, R. D. Riggs and C. L. Hammer, *ISC-1008* (Dec 1957) 38 p.

The design, construction, and testing of two high-energy electron beam monitors are described. One, a Faraday cup, is an absolute measuring device, and the other is a secondary emission monitor. The procedure and results necessary to calibrate the secondary emission monitor against the Faraday cup are included. Since the secondary emission monitor is portable, it is an adaptable instrument for the absolute measurement of high-energy electron beams after it has been so calibrated.

883.

The focusing and analyzing magnets of the Saclay cyclotron, J. Thirion and J. Saudinos, *Nuclear Instr., and Methods*, 5, 165-9 (Sept 1959). (In French.)

Two strong gradient magnets deflect and refocus the beam of the cyclotron in both directions. The beam is then analyzed by a double-focusing magnet which gives a definition in energy of 1.5/1000 for 2-mm slits. This analyzer can also be used for analyzing secondary particles.

See also: 607, 660, 721, 761, 763, 764, 711, 773.

ANALOG AND DIGITAL COMPUTATION

884.

Optik: an IBM 709 computer program for the optics of high-energy particle beams, T. J. Devlin, UCRL-9727 (Sept 15, 1961) 30 p.

A program was developed for the IBM 709 digital computer to handle many of the problems encountered in the optical design of high-energy particle beams. The program employs a six-dimensional vector space that takes into account the position and direction in both planes perpendicular to the beam direction, chromatic aberrations, and particles of different mass. The quadrupole problem with one or two degrees of freedom (i.e., one or two singlets, a doublet, or a symmetric triplet) is solved for the field gradients necessary to yield given beam conditions. The vectors are evaluated at the end of each element in the system. Effects higher than first-order, with the exception of second-order chromatic aberrations in the quadrupoles, are not included. The effect of apertures is calculated in terms of the limitations on the phase-space volume that can be transmitted by the system.

885.

OPUS - Optimization program for separated particle beams, J. W. Gardner and D. Whiteside, Internal Report, Rutherford High Energy Laboratory, Harwell, Didcot, Berkshire (April 1962) 10 p.

The program OPUS has been written in Fortran for the 709-7090 IBM computers to assist in the design of one- or two-stage separated beam systems. It will optimize a quantity T , related to the flux of wanted particles transmitted through the system (including the effects of W -particle decay). The quantity T is of the form:

$$T \sim \theta_r \theta_H \frac{\Delta p}{p} \exp \{-L/\lambda\} ,$$

where $\Delta p/p$ is the momentum spread, and θ_r and θ_H are the vertical and horizontal acceptance angles.

886.

TRAMP (Tracking and Matching Program), J. W. Gardner and D. Whiteside, NIRL/M/21 (July 1961) 19 p.

A MERCURY program has been developed for tracking and matching beam properties in high-energy beam design. It will track particle trajectories and beam ellipses in phase space through systems of quadrupoles, bending magnets and velocity separators. It also contains a number of matching routines for adjusting quadrupole strengths or positions in order to obtain desired beam configurations.

887.

Analog computer for charged particle trajectories, R. H. Good and O. Piccioni, Rev. Sci. Instr., 31, 1035-9 (1960), also BNL-4526.

An analog computer was applied to the problem of tracing the trajectories of a beam of charged particles such as is produced by high-energy accelerators. The electrical circuit involved employs analogs for both quadrupole magnets and bending magnets, and thus it facilitates the determination of both the focal properties and the dispersion characteristics of the magnets; an accuracy of 2% was attained for some of the calculations made with the present instrument.

888.

A fast analog computer for beam envelopes and particle trajectories. W. Kern and K. Steffen, DESY-A2.80 (Aug 14, 1961) 10 p.

An analog computer method for the calculation of beam envelopes was developed and a system consisting of an analog computer with some additional electronic equipment was constructed. The computer is capable of calculating beam-transport systems composed of the following elements: quadrupoles, bending magnets, synchrotron-type magnets with combined focusing and bending action, and electrostatic mass separators. The use of the beam envelope method is demonstrated by a specific example. The sources of error in the system and design improvements are discussed.

889.

Phase-space analogue computer for beam matching problems, B. W. Montague, CERN-60-24 (May 25, 1960) 24 p.

An electronic analog computer built for the solution of problems connected with the injection of the 50-Mev beam into the CERN Proton Synchrotron is described. The apparatus consists of a sequence of voltage-adding networks and buffer amplifiers which simulates the continued multiplication of 2×2 matrices with unity determinant. The electronic design is described, and a section devoted to operation is included.

890.

Beam optics analysis using the IBM 650, P. E. Schlein, AFOSR-TN-60-1480 (Nov 1960) 27 p.

An IBM 650 computer program, BOMMIT (Beam Optics Matrix Multiplication and Iteration), is described for facilitation of precision particle beam optics system design. A beam system consisting of an arbitrary ordering, type, and number of optical elements up to a maximum of 50 can be considered. The matrix method is used.

891.

A mercury subprogramme for high-energy beam optics, S. Vander Meer, CERN-NPA/Int. 61-5 (March 8, 1961) 15 p.

In evaluating the focusing and bending properties of optical systems consisting of quadrupole lenses and bending magnets, much time may be lost in tedious calculations of such quantities as: lens strength necessary for fulfilling required image conditions, effect of bending magnets on focusing (edge focusing), magnification of system, shape of beam envelope, chromatic dispersion in systems with bending magnets, chromatic aberrations of lenses, tolerances on constancy and linearity of lenses and magnets and on positioning. The computer subprogram described here was written in order to speed up these calculations. All calculations are made under the assumption of aberration-free components, but the effect of aberrations can easily be evaluated using the results of the program. In part A of this report the method used is described without going into details of programming, since it is possible, without understanding its exact composition, to use it as part of another program. Part B describes in some more detail how this can be done. In the Appendix an example is given.

See also: 856.

PROGRESS REPORTS ISSUED BY MAJOR ACCELERATOR INSTALLATIONS

Argonne National Laboratory - Particle Accelerator Division

Previous formal reports. Earlier activities of the Particle Accelerator Group (largely in the shape of informal theoretical reports) from December 1952 to March 1956 have been recorded in the following Physics Division Quarterly Reports:

ANL 5031	ANL 5273	ANL 5497
ANL 5080	ANL 5317	ANL 5498
ANL 5140	ANL 5412	ANL 5554
ANL 5174	ANL 5420	

ANL 5573 - Quarterly Report on Physical Sciences

ANL 5610 - ANL Annual Report of 1955, Page 50.

Summary reports.

ANL 5630	Apr 1956 - Sept 1956	ANL 5956	Apr 1958 - Oct 1958
ANL 5713	Oct 1956 - March 1957	ANL 6032	Nov 1958 - May 1959
ANL 5803	Apr 1957 - Sept 1957	ANL 6152	May 1959 - March 1960
ANL 5864	Oct 1957 - Apr 1958	ANL 6427	Apr 1960 - Sept 1960

Brookhaven National Laboratory

Quarterly progress reports.

BNL 51	Jan 1950 - March 1950	BNL 337	Jan 1955 - March 1955
BNL 64	Apr 1950 - June 1950	BNL 355	Apr 1955 - June 1955
BNL 82	July 1950 - Sept 1950	BNL 367	July 1955 - Sept 1955
BNL 93	Oct 1950 - Dec 1950	BNL 375	Oct 1955 - Dec 1955
BNL 103	Jan 1951 - March 1951	BNL 388	Jan 1956 - March 1956
BNL 117	Apr 1951 - June 1951	BNL 406	Apr 1956 - June 1956
BNL 132	July 1951 - Sept 1951	BNL 419	July 1956 - Sept 1956
BNL 149	Oct 1951 - Dec 1951	BNL 430	Oct 1956 - Dec 1956
BNL 177	Jan 1952 - March 1952	BNL 439	Jan 1957 - March 1957
BNL 189	Apr 1952 - June 1952	BNL 455	Apr 1957 - June 1957
BNL 209	July 1952 - Sept 1952	BNL 473	July 1957 - Sept 1957
BNL 219	Oct 1952 - Dec 1952	BNL 484	Oct 1957 - Dec 1957
BNL 232	Jan 1953 - March 1953	BNL 502	Jan 1958 - March 1958
BNL 243	Apr 1953 - June 1953	BNL 515	Apr 1958 - June 1958
BNL 259	July 1953 - Sept 1953	BNL 526	July 1958 - Sept 1958
BNL 270	Oct 1953 - Dec 1953	BNL 537	Oct 1958 - Dec 1958
BNL 289	Jan 1954 - March 1954	BNL 550	Jan 1959 - March 1959
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BNL 314	July 1954 - Sept 1954	BNL 632	July 1959 - June 1960
BNL 326	Oct 1954 - Dec 1954	BNL 682	July 1960 - June 1961

California University. Radiation Laboratory. Bevatron Operation
and Development

Progress reports.

UCRL 2692	May 1954 - July 1954	UCRL 8114	Aug 1957 - Oct 1957
UCRL 2822	Aug 1954 - Oct 1954	UCRL 8261	Nov 1957 - Jan 1958
UCRL 2954	Nov 1954 - Jan 1955	UCRL 8334	Feb 1958 - Apr 1958
UCRL 3033	Feb 1955 - Apr 1955	UCRL 8563	May 1958 - July 1958
UCRL 3212	May 1955 - July 1955	UCRL 8834	Nov 1958 - Jan 1959
UCRL 3236	Aug 1955 - Oct 1955	UCRL 8927	Feb 1959 - Apr 1959
UCRL 3332	Nov 1955 - Jan 1956	UCRL 9011	May 1959 - July 1959
UCRL 3444	Feb 1956 - Apr 1956	UCRL 9058	Aug 1959 - Oct 1959
UCRL 3519	May 1956 - July 1956	UCRL 9220	Nov 1959 - Jan 1960
UCRL 3614	Aug 1956 - Oct 1956	UCRL 9221	Feb 1960 - Apr 1960
UCRL 3913	Nov 1956 - Jan 1957	UCRL 9418	May 1960 - July 1960
UCRL 8021	Feb 1957 - Apr 1957	UCRL 9671	Nov 1960 - Jan 1961
UCRL 8022	May 1957 - July 1957	UCRL 9721	Feb 1961 - Apr 1961

European Organization for Nuclear Research, Geneva.

CERN Proton Synchrotron Machine Group Operation and
Development Quarterly Report

CERN-60-23	Jan 1960 - March 1960
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