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A BEV HIGH CURRENT ACCELERATOR

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56-6-36

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An Invited Paper presented at the
Southeastern Section Meeting of the APS
at Nashville, Tennessee
March 30, 1956

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Date Issued

JUN 20 1956

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A Bev High Current Accelerator

During the last two years we have been attempting at Oak Ridge to assess the feasibility of producing high intensity beams of protons at an energy in the vicinity of one bev. Although several types of accelerators, linear accelerator, synchrotron, and f-m cyclotron may be capable, in principle, of accelerating protons to such an energy, the one which appears most attractive for a number of reasons is a fixed frequency cyclotron. As many of you are aware it was first proposed by L. H. Thomas some eighteen years ago that the energy limitation for ordinary fixed frequency cyclotrons, then thought to be less than 20 Mev for protons, could be circumvented by a fairly complex magnetic field configuration in which the average magnetic field increases with radius and there is a symmetrical series of azimuthal variations in this field.

Although the detailed design of a cyclotron of this type is impressively complex, as I will explore further in a few moments, the basic idea is both simple and elegant. When a particle is accelerated to increasingly higher velocities, its mass increases, of course, due to the relativistic effect. At velocities experienced by a particle in the multi-Mev range this increase becomes a large fraction of the rest mass; at 937 Mev the mass of a proton is doubled. The frequency of rotation of a charged particle in a magnetic field is, of course, affected by this change in mass, as shown in the well known relation

$$f = eH/2\pi mc$$

where the letters have their usual significance. In Thomas' proposal the magnetic field, H, is increased with radius at just the proper rate to compensate for the increase in mass which occurs as the particle spirals outward to higher energies. The cyclic azimuthal variations are added, then, to serve as a series of magnetic wedge-type lenses which serve to correct for any motion away from the desired orbit and thus keep the particles properly focused at higher energies.

For various reasons, no attempt was made to obtain experimental verification of Thomas' ingenious idea until rather recently. During the period 1950 through 1953 two electron models of this AVF cyclotron system were built and tested at the Radiation Laboratory, Berkeley, California. The initials AVF which we have tentatively adopted stand for "azimuthally varying field" cyclotron. The latter of these Berkeley models succeeded in accelerating electrons for more than 1000 revolutions and obtained 75,000 volt electrons with a dee voltage of less than 25 volts. The successful operation of these model electron machines was highly encouraging but left many unanswered questions, particularly with respect to the upper energy limit of this type of cyclotron.

An exposition of the background for bev cyclotrons would be incomplete without a reference to the independent proposals of the Midwestern Universities Research Association (MURA) arising from their work on the FFAG (fixed field alternating gradient) proton synchrotron. The unique feature of the FFAG machine which was described at the New York meeting of the American Physical Society last year is that the "hill-and-valley" fields are spiralled. This effectively increases the angle at which the particles enter and leave the magnetic wedges and thereby greatly increases the amount of focusing obtained. With these spiral azimuthal variations the amplitude of the variation in the alternate strong and weak field regions need not be nearly so large. In principle this makes the design of the magnet much less demanding and therefore more practicable.

At Oak Ridge we first became interested in these "hill and valley" cyclotrons in 1950 through an interest in obtaining very high currents of protons at about 30 Mev. A little later, when we were able to solve the high current problems on our ORNL 86-Inch Cyclotron with very high dee voltage, our motivation for using a Thomas-type field machine was diminished. Our interest revived shortly, however, when the idea occurred to several of us that a machine of this sort, at higher energy, might be an ideal avenue for the Laboratory to enter the field of meson physics.

While Ted Welton has just completed an exposition in considerable detail of a very extensive calculation and theoretical program on the characteristics of AVF cyclotrons, I would like to comment relative to the importance of some of his early work. When we embarked on the investigation, about two years ago, the energy limit for protons was 160 Mev, as established both experimentally and theoretically. This is, of course, impractically low for the meson field. Theoretical work then underway at Berkeley on four-sector machines eventually revealed a higher but still unimpressive limit of 360 Mev for protons. Welton initiated a study of the general features of an n -sector machine and at a very early date established that the energy limit is closely related to the number of poles, the upper energy limit increasing as n increases. This new insight, I think, is the first major contribution of new knowledge from the South to this field. As you have already heard, the actual energy limit may well be somewhat above two bev.

I want to describe two machine design studies now in a little more detail. The first is an 850-Mev, 8-sector AVF cyclotron; the second is a 220-kev 4-sector cyclotron analogue, using electrons. I need to emphasize that this work is still exploratory and in the nature of a feasibility study. It is intended to study the 850-Mev machine carefully enough to develop an appreciation for the major physical and engineering problems involved. We do not want to freeze specifications for a serious proposal for some time yet. We would like to get energies much higher than 850 Mev, perhaps 2.5 bev if possible, and will certainly not rule them out until we have firm experimental grounds for doing so.

An artist's conception of how the bare magnet for an AVF cyclotron would appear is shown in Fig. 1. One of the major advantages of this general system is the distribution of iron. The bulk of the iron, including the return yoke, is concentrated near the rim of the machine. There is no need for a large amount of iron for the hugh central area. The coils which energize the magnet may be seen in section. An unusual feature of this magnet, to which I will refer later, is that the magnet

Fig. 1. Artist's Conception of Magnet for AVF Cyclotron.

actually consists of four quadrants, each isolated from the others. Two S-shaped slots run all the way through, thus dividing the magnet into quarters. In connection with this conceptual sketch, I would like to itemize the basic parameters of the accelerator. They are as follows:

Maximum orbit diameter	21 ft
Central flux density	7.9 kgauss
Maximum flux density	20 kgauss
Applied radio frequency	24.4 mc/sec
Total weight of iron	1850 tons

A view of a vertical section through the cyclotron is shown in Fig. 2. Here is shown the dome-shaped vacuum tank which is designed to prevent vacuum forces from distorting the pole faces. The volume of the vacuum tank is 8000 cu ft. This is large but not as large as other vacuum tanks which have been built.

A point of interest is the amount of shielding required for such an accelerator as this. At 100 μ a, which is the estimated current, it would take 45 feet of ordinary concrete or an equivalent amount of dirt or other material. This estimate assumes the deflected beam will all impinge on about a square yard of surface. For scattered neutrons away from the median plane it is expected that 15 ft of concrete would suffice. Obviously, serious consideration would be given to installing the machine below ground or in a hillside to reduce this problem to manageable proportions.

A plan view, showing the spiralled hills and valleys, is seen in Fig. 3. A section through one of the main coils may be seen in one of the eight sectors. The two S-shaped slots through the magnet will contain the large resonant cavities. These cavities will require no clearance for electrical insulation and will represent a large advance in technology, if proven feasible. Vacuum tank extensions are provided at four places to receive the end sections of the resonant cavities. Note, that section line AA, which shows the location of the next view, line cuts through two cavities and three magnetic hills.

Fig. 2. Section Through Magnet and Vacuum System.

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Fig. 3. Plan View of Magnet Showing Spiralled Sectors.

In Fig. 4 may be seen some details of the two cavities and the three hills. In order to obtain the necessary variation in magnetic field it is necessary to supply auxiliary current-carrying conductors located on the surfaces of the iron pole faces. In this design these pole-face windings would require 16 tons of copper, as compared with 82 tons for the main field coils. The power for the pole-face windings is 1.8 Mw; for the main field coils 0.75 Mw. The slot opening and the minimum gap are both four inches.

Because of the difficulty of visualizing the nature of the resonant-cavity accelerating system an additional view is given in Fig. 5. This is a sketch in three dimensions of the two cavities removed from the magnet but in their proper relative orientation. The dark line represents the accelerating slit across which the high rf potential is generated and through which the protons pass as they spiral outward.

Obviously the engineering problems on a machine of this sort are impressively severe. Perhaps the most formidable of all is the requirement for tailoring or shimming the complex magnetic patterns to the required precision. If an accuracy of $\sim 0.05\%$ is required it is estimated that 160,000 readings, each accurate to substantially better than this, must be taken for just one survey of the field. If no more than ten trials surveys are required this would be 2×10^6 readings. At one reading per minute, the total job would require 26,000 hrs or 3 years. Obviously, a rapid measuring, recording, and analysis system must be developed. Such systems as feeding the data to a magnetic tape and thence to the Oracle, or the development of an electronic analogue computer which reads the average field and the amplitude of various harmonics directly are under consideration. This is one of the most fertile areas for new ideas, and we hope some of you will be suitably motivated and properly inspired in the near future on this matter.

The huge cantilevered beams of the magnet represent a somewhat unreasonable demand on the mechanical engineer. Movements of $0.001''$ could represent a gap change of as much as 1 part in 4000 or 0.025% .

Fig. 4. Section A-A of Fig. 3.

Fig. 5. Resonant-Cavity Accelerating System.

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The method for calculating deflections in beams of such odd shapes are not well established and it probably will be necessary to build strain models in order to obtain data of adequate accuracy.

The radio-frequency system proposed represents a novel approach, and no experience on this scale exists. A square cavity operating in the TE_{011} mode, and at twice the frequency of the rotating ions, is one of the promising systems; it has been portrayed in the previous figures. The cavities would need to be driven with a 180-deg. phase difference to provide properly phased voltages. Special shaping of the cavities would be required to provide an energy gain uniform with radius. Although no serious problems are expected here, the rf power required for obtaining 1 Mev per turn is 4 megawatts, just for exciting the cavity. Obviously, at these power levels, considerable rf development is to be expected.

I would now like to turn to the second piece of machinery, the Cyclotron Analogue. This is essentially an electron cyclotron which can be designed to serve as an efficient and accurate analogue computer for determining particle orbits, characteristics of resonances, deflection properties, threshold voltage, and many other features. The principle area of uncertainty insofar as technical feasibility of a large AVF machine is concerned is the question of beam stability at the several resonances which occur between the ion orbital frequency and the betatron radial oscillation frequency, or "focusing frequency" as it is sometimes called. When in a four-sector machine this ratio is $3/2$ (imperfection resonance) or $4/3$ (non-linear resonance), a coupling may be experienced which can cause the amplitude of the radial oscillations to grow destructively. It is possible that many particles passing through the machine will be lost in these regions. The imperfection resonance arises due to the third harmonic component of the field. Careful shimming can reduce this to arbitrarily small values. The loss of beam is somewhat a matter of the degree of accuracy which it is practical to achieve. The $4/3$ resonance arises from non-linear effects and cannot be affected by magnetic shimming. It is still important to measure accurately what the ion transmission through this $4/3$ region will be.

The Cyclotron Analogue will be a four-sector, non-spiralled electron cyclotron. It should produce approximately 220-kv electrons, equivalent relativistically to about 400 Mev protons. It is hoped that the method of design will permit later extension of the work on the same machine, perhaps to eight or more sectors with the appropriate amounts of spiral.

The prescribed magnetic field shape is shown in Fig. 6. The average field is 40 gauss at the center and increases with radius the appropriate amount to compensate for the increase in electron mass, with 220-kv electrons at about 12 inches. The choice of the central field is somewhat arbitrary but represents a compromise between the ease of measuring fields or minimizing stray fields and, on the other hand, keeping the apparatus large enough for convenience of experimentation.

The hill fields go up to about 120 gauss, the valley fields to -25 gauss. The half integral resonance, occurs at 156 kv, or at 9.7-in. average radius. The integral resonance occurs at 220 kv, or 10.0-in. average radius; this orbit swings out to about 12 in. at the hills.

For threshold voltages of the order of 50 kv, in the equivalent proton machine for 400-Mev protons, an accuracy of $\sim 0.05\%$ is required in the average field. The azimuthal field amplitudes need, however, be accurate to only 0.5%. Because of this difference it was decided to produce the two fields separately.

The general layout of the electron cyclotron is shown in Fig. 7; some features to be noted are:

1. A solid supporting structure is used; it isolates the magnet from the vacuum forces.
2. The removable lid and side ports provide easy access; all leads and connections come through the bottom.
3. The dish-shaped 30-in. poles produce the average field.
4. Adjustments of the ion source can be made from the outside.
5. The radio frequency is 112 Mc/sec from a 5786 tube which provides up to about 1-kv acceleration per turn.
6. The pumping speed is about 500 L/sec.

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Fig. 6. Magnetic Field of Cyclotron Analogue.

Fig. 7. Section through Cyclotron Analogue.

A top view of the system is shown in Fig. 8. Here may be seen the method of supporting the upper portion of the magnet with six stanchions. The viewing and probe ports and the locations of access holes through the lower base are also shown.

A section near the edge of the gap is shown in Fig. 9. In sequence are the copper dee wall, the insulators, the copper ground-plate liner, the sector coils for producing increased or decreased fields at the appropriate azimuthal angles, the water-cooled copper plate for cooling the sector coils, the circular trimming coils for correcting the average field, and the iron pole piece. The clear gap for experimental work is 1 1/4 inches. The magnet gap is 3 1/4 inches.

A plan view of the coils of one sector, Fig. 10, shows a series of triangular coils overlaid by a smaller number of trapezoids. Placement of the coils is fixed by pins located in the corners of the triangles or trapezoids. Because of the smaller iron gap near the edge of the machine, the field tends to be too high there, so that a second layer of coils was necessary to obtain greater field variation near the center. The cost of a complete set of these coils, including the circular windings which provide correction for the average field, is quite nominal. The sector we have wound for tests is held together with a resin, "Laminac." The resin in turn bonds the windings to a water-cooled copper sheet which also supports the coil. Each set of 16 series windings will be controlled by a current-regulated power supply. Provision is made for controlling, independently, the current in any coil or group of coils.

The magnetic field will be measured with a flux-gate magnetometer to an accuracy of about 5 milligauss or 0.05%. The magnetometer pick-up will rotate along circles of various radii. Knowledge of the Fourier components of field produced by each coil will permit determination of currents required in each coil to set the field to prescribed values in the median plane.

Fig. 8. Plan View of Cyclotron Analogue.

Fig. 9. Detail Section of Cyclotron Analogue.

EACH COIL CONSISTS OF 55 TURNS OF NO. 24 WIRE. COIL CROSS-SECTION: $\frac{1}{4} \times \frac{1}{8}$ in.

FIRST LAYER OF SECTOR COILS

SECOND LAYER OF SECTOR COILS

Fig. 10. Sector Coils for Cyclotron Analogue.

It is hoped that after an appropriate period of study sufficient data will be available from the Cyclotron Analogue to make it possible to proceed with confidence in the design of a large cyclotron of this general type.

I would like to close by considering for a moment how an accelerator producing 100 μ amperes of protons at upwards of 850 Mev would fit into the pattern of other accelerators now existing or proposed. All the known proton accelerators with energies above 240 Mev are tabulated in Fig. 11. Note that the currents tend to be very small; the largest is 1 μ a, at 435 Mev. At 1 bev the current in prospect is $\sim 10^{-3}$ μ a. It is fairly clear that, on an AVF cyclotron, we can hope for an intensity increase in π and μ mesons of at least a factor of 1000 and perhaps 10,000-100,000. It is our expectation that this will open the door for a wide variety of new experiments and for repeating with increased accuracy many previous measurements. It seems possible that this could permit the physicists of the South to become leaders in precision meson scattering, as they have to a considerable extent already in the area of particle physics below 6 Mev.

F-M CYCLOTRONS

	<u>μa</u>	<u>Mev</u>
University of Rochester	0.1	240
UCRL (Berkeley)	1	350
UK (Univ. Liverpool)	1	380
Columbia University	0.1	385
Carnegie Inst. Tech., Pa	> 1	435
University of Chicago		450
Brazil	?	450*
CERN (Geneva)	?	600*
Russia	0.3	680
UCRL (Berkeley)	~ 0.1	730*

PROTON SYNCHROTRONS

Netherlands	?	1000*
UK (Birmingham)	$\sim 10^{-3}$	1000
Australia	?	2000*
Brookhaven	$\sim 10^{-3}$	3000
Princeton	$\sim 10^{-1}$	3000*
UCRL (Berkeley)	$\sim 10^{-3}$	6400
Russia	?	10,000*
Argonne	?	10,000*
Brookhaven	?	25,000*
CERN	?	25,000*
MURA	?	25,000*

F-F CYCLOTRONS

ORNL	~ 100	900*
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* Proposed or under construction

Fig. 11 High Energy Machines