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AMU-ANL WORKSHOP ON
HIGH-VOLTAGE
ELECTRON MICROSCOPY

HELD AT
ARGONNE NATIONAL
LABORATORY
JUNE 13-JULY 15, 1966

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June 13-July 15, 1966

Raymond K. Hart
Workshop Chairman

Dorothy Carlson
Administrative Arrangements

Organizing Committee

D. Cohen, University of Illinois at Chicago Circle
J. M. Donhowe, University of Wisconsin
R. K. Hart, Argonne National Laboratory
E. D. Klema, Northwestern University

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Preface

This volume contains the proceedings of the Summary Session and individual reports by participants at the Summer Workshop on High-Voltage Electron Microscopy. The workshop was held at Argonne National Laboratory from June 13 through July 15, 1966, and was jointly sponsored by Argonne National Laboratory and the Associated Midwest Universities. The workshop consisted of fifty invited participants from the United States, Europe, and Japan. Participants worked in three groups which discussed High-Voltage Problems (Chairmen: E. D. Klema, Northwestern University; and J. M. Donhowe, University of Wisconsin), Lens Problems (Chairmen: D. Cohen, University of Illinois at Chicago Circle; H. Fernandez-Moran, University of Chicago; and C. Laverick, Argonne National Laboratory), as well as Specimen Facilities and Recording Problems (Chairmen: J. Gilroy and R. K. Hart, Argonne National Laboratory). At a two-day Summary Session the findings of the Workshop were presented to an audience of 96 persons. These proceedings are the second in a series of conferences on High-Voltage Electron Microscopy to be held at Argonne National Laboratory. The first conference was held on February 13 and 14, 1964.

These proceedings have been edited by J. Gilroy, R. K. Hart, M. Weber, and Joyce Kopta. Due to a technical fault in the recording system, a number of the Summary Session papers could be transcribed only with the utmost difficulty. These transcriptions were sent to the speakers so that any necessary corrections could be made. The editors hope that a reasonable portrayal of the actual discussion has been accomplished.

I would like to take this opportunity to express my sincere appreciation to all who participated in this workshop and helped make it a success. Special thanks are due to the three workshop secretaries, Dorothy Bodden, Florence O'Neill, and Jean Sims, who did a superb job of keeping the workshop running smoothly and coping with the voluminous amount of work that it entailed.

Raymond K. Hart
Chairman

Foreword

A. V. Crewe

Argonne National Laboratory

In my experience, this has been one of the most exciting periods we have had recently at the Laboratory. At least it has been one of the most enthusiastic gatherings of people that we have seen. Perhaps it is a symbol of the need for a system of communication by those who are occupied with the development of the technology of electron microscopes as opposed to the use of them. Usually if one proposes another conference these days, a great sigh goes up and not many people show much enthusiasm. But in this case there has been a great deal of enthusiasm in spite of the fact that there are meetings of various microscope societies coming up in the next few months. This indicates to me a need that these societies perhaps do not satisfy—that of the instrumentalist. I hope then, that we have been able to add our bit to the communication system relating to electron microscope development.

This month we started out with a meeting at which the various problems as people saw them were described and at which a few solutions were proposed. During the month many people have studied each of these problems and the proposed solutions as well as others of their own. New solutions to some of the problems have been developed and now we are planning to record them.

I should perhaps emphasize that we do not intend in the next two days to present the solution to the problem of designing and building a five million volt electron microscope. Rather, I believe, the speakers will present the various alternatives which are possible if one wishes to build such a microscope. There is, obviously, no unique solution to the problem. There are systems which appear good to some people and alternatives that appear good to others. Many of the solutions, however, have already been eliminated in favor of more promising ones. Ultimately it will be left to us here at the Laboratory to make a choice from among the very attractive alternatives for building such an instrument.

For those who don't know the background, I should explain why we are interested at all in a five million volt microscope. Our interest developed some time ago because of a suggestion of the Associated Midwest Universities, who are co-sponsoring this conference; this is an AMU-ANL conference, not strictly a Laboratory one.

Associated Midwest Universities is an organization representing a group of universities who are interested in working with Argonne National Laboratory for the mutual benefit of themselves and the Laboratory. This interaction has taken a great many forms and when the possibility of a high voltage microscope arose and in particular when the account of the French microscope at one million volts appeared, it seemed that such a program could be another of these interactions. Our thought was that Argonne could undertake to design and construct a very large microscope of this character which would then be available to any scientist in the Midwestern universities to use. Also, because of my personal interest in the development of a particular kind of microscope—the scanning microscope—there was a strong mutual interest that led to preliminary discussions. We held a conference here about two years ago, which was in the nature of an exploratory conference, to find out what the reaction would be to such a proposal and we have kept the idea of a cooperative project alive since then by the publication of our High Voltage Microscope Newsletter. In this Newsletter various sporadic thoughts by people within and outside the Laboratory have been recorded, thoughts that were relevant to the high voltage microscope problem. Finally, in order to firm up the ideas, we suggested this summer workshop.

I would like to express my gratitude and thanks to those who organized this workshop. I know it required a substantial effort on their part. Those who played the largest part in organizing the workshop are Raymond Hart, Ernest Klema, David Cohen, Jack Donhowe, and John Roberson. If you contemplate the problems of running two two-day meetings like this, of organizing a one month's conference where people float in and out, and of trying to make some sense out of the scientific output of the whole group, you can see that it is a non-negligible task, and I think these men deserve credit for a splendid job. Also, of course, I do not intend to omit

thanking those who have actively participated in the workshop during the past month; we will never be able to repay adequately our debt to these people.

I think our own ideas—those of us who are here at the Laboratory—have been changed substantially by this workshop. I know that mine have, and I think the influence that the people have had upon one another and the mutual interaction of the groups has been extremely healthy. It is possible that the future of the whole of microscopy has been changed by this interaction.

It is the privilege of the opening speaker of a conference to act either as a wise old man or as a public jester. One never knows quite how to perform at an opening. I suppose that I am going to make a jester out of myself by illustrating perhaps how foolish we have been in the past and how simple our ideas were, and then allow the rest of the conference to correct these silly ideas and put you on the right track.

Originally, for example, it seemed to us—to me in particular—that above one million volts one runs into substantial problems of a new power supply. It is relatively simple to build a power supply of one million volts; it is not so simple to regulate it. But there are people who claim that it has been done. If we contemplate going to energies higher than one million volts, one is faced with a huge structure of indeterminate properties, or one must change the character of the power supply and get something utterly different. If we must change the character of the power supply in going beyond one million volts, we might as well go at least a half an order of magnitude higher and go to five. This, in fact, is the reason why we suggested five million volts.

It seemed to us, then, that the Van de Graaff generator was the only solution. Van de Graaff generators have been worked on for a long time—particularly by people like Ray Herb in Wisconsin. Ray Herb is, in fact, working in the direction of this particular problem by trying to build a one million volt Van de Graaff generator and to regulate it accurately. So we felt that this was the obvious solution. Then, too, we felt that if one were going to buy, build, design or construct the five million volt microscope, the obvious thing would be to put several different microscopes on the one high voltage power supply. This would look rather like a cow, with a Van de Graaff generator on the top and various microscope columns dangling from the high voltage generator.

This was our general idea, and I must say that at that time the microscope lens seemed to be the easiest problem that was facing us. If I may present Figure 1—this is a slide that I foolishly, or perhaps wisely, showed at the first meeting—you can see what one has to do to get one angstrom resolution as a function of the voltage of the microscope. The solid line is the magnetic field in the lens and the broken line is the gap in the lens.

We see that at low voltage the problem is really tough; you need several hundred thousand gauss and you need a fraction of a millimeter gap. But at about five million volts the problem is simple; one needs one thousand gauss and about fifteen centimeter gap for one-angstrom resolution. So, as you can see, the lens problem was no problem at all about a month ago.

I had at that time a personal interest in the subject of energy-loss microscopes, and I must say that at that time there was very little external support for this particular solution to the general problem of microscopy, and certainly to me the problem of producing an image didn't look all that difficult at the beginning.

So, there you are. I have presented what several people thought were the general problems and the general types of solutions at the beginning of the conference. Now the task for the rest of the speakers is to show how foolish we were at the beginning

FIGURE 1

and what the correct solutions of these various problems are. They will show that in some cases we didn't even ask the right questions to begin with.

Now I would like to mention something general about the justification for building a high voltage microscope.

The Argonne National Laboratory and the academic community which is working with us are interested in a whole variety of scientific problems. Microscopy is an area in which we really should take an interest because we have the whole fields of biology, material sciences, etc., to cover. A very high energy microscope clearly has the advantage of high penetrating power. One should be able to inspect thick material samples and, if not living samples, at least biological material which is closer to its original natural state than that which one normally uses in conventional electron microscopes. These were the basic reasons for investigating the high voltage machine in the first place.

There is one further idea of course—that is the possibility of better resolution. Can one improve the resolution of conventional electron microscopes by going to higher energy?

A few of us were discussing this problem last night and I would like to present to you the general trend of thought. Scientists in this world are interested in the objects which surround them—both the physical scientist and the biological scientist. These objects range in size from the largest imaginable galaxy to the smallest imaginable particle. The range of sizes covered by this spectrum is truly enormous—from 10^{-13} centimeters to millions of billions of light years. The very large objects are readily available to us. Using our eyes and telescopes we can see these objects quite clearly and distinctly and gain a great deal of information about them. As we come down the scale, we can use our eyes and various other inspection techniques down to the range of a micron or less. Using the electron microscope we can go down as far as two or three angstroms. Further down the scale, high energy electron scattering experiments with protons and neutrons, etc., have given us a picture of the proton. The proton is, in this sense at least, understood; we have a picture of the proton with about a hundred bits of information across the radius of the proton. I think it has been inspected with wave lengths of better than 10^{-14} centimeters.

There is only one gap missing, because there is no object intermediate in size between the proton and the atom. There is one small octave of sizes which is inaccessible to date, a mere factor of two between one angstrom and two angstroms. In that whole spectrum of objects, everything else is available except that, and it is precisely in that region, the region of one angstrom, that we know there is an enormous amount of information. A tremendous analytical power will be available to us if we can only achieve resolutions of one angstrom or better. So here again is another primary reason for being interested in this kind of development.

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The Generation of High Voltages

ERNEST D. KLEMA

*Northwestern University
Evanston, Illinois*

I am sure I speak for all the members of the High-Voltage Group in saying that we have very much enjoyed this opportunity of working together. We have had a stimulating time, and I hope that we have come to some useful conclusions.

We have considered the specific problem of furnishing a source of electrons for the microscope, of let's say from 0.5 to 5.0 MeV, which would be stabilized in energy to the order of one part in 10^5 to one part in 10^6 , for periods of the order of one minute, which would be of suitable optical quality and, hopefully, which would be readily available.

We would like to emphasize that one very important consideration is that of making the source of electrons essentially a switch on and off device so that one doesn't spend 90 percent of his time trying to get the electron beam going. We would like to have the problems be in the microscope itself and be able to furnish a really reliable electron source.

What we did initially was to try to consider all the possible ways of furnishing such an electron beam we could think of, and then we narrowed them down into five possible sources, which we looked at in detail. We looked at the pressurized Cockcroft-Walton generator, the pressurized Van de Graaff, commercially-available linear electron accelerators, the Los Alamos LINAC, and superconducting LINACS. In each case, we looked at the accelerator as a possible source of electrons to charge up a terminal to high voltage, and also as a source of electrons directly for the microscope itself. In addition, we tried to determine the present state of commercial units—what you can buy from a company now and how it will perform. Secondly, we tried to look at what is the present state of the art, wherever the art is the most advanced. Thirdly, what are the future possibilities for development of this type—what are the problems that have to be solved, and what is the likelihood of their solution? Dr. Smith has summarized these considerations in Table I.

We have here some of the general characteristics of the five generators. On the Cockcroft-Walton we have put a voltage limit of 4.5 MeV, since this is the highest energy unit commercially available right now. On the Van de Graaff, as Dr. Crewe has indicated, one

can go beyond 5; and likewise with the ordinary LINAC as well as with the superconducting LINAC.

The next consideration was the voltage range over which these instruments are capable of operating without changing any major adjustment. One finds that the Cockcroft-Walton can easily cover this factor of 10 that we are looking for, from 0.5 to 5.0 MeV, and so can the Van de Graaff. With the LINAC, one has to change injector conditions to get capture over this energy range, but this is an easy change. One can get a factor of 5 without changing the injector.

Now we come to the problem of the size of these pressurized generators, which is of course extremely large—we are talking about pressure tanks 20 to 30 feet long for a pressurized Cockcroft-Walton or a Van de Graaff. The ordinary LINAC is comparatively small on this scale and is something like a tube about 10 feet long; and in the case of the superconducting LINAC we are talking about a very small accelerator indeed, about 3 to 4 feet of accelerator tube for 5 MeV.

Then we come to the problem of the stored energy in the system. In the case of the Cockcroft-Walton it is very large. There are thousands of micromicrofarads of capacity along the set. This is all charged up and when a voltage breakdown occurs, an awful lot of energy is dumped into the accelerator tube. On the other hand, the stored energy in the Van de Graaff is small—only a few micromicrofarads capacity—so the problem is very much alleviated. Of course there is no stored energy in the LINAC since there is only an electron beam.

From the vibration standpoint, which is an important one, the Cockcroft-Walton is very good because it just sits there. The LINACS are also good in this respect. In the case of the Van de Graaff, the problem is serious because one has to have some mechanical means of moving the charge from ground up to the high-voltage electrode. Ordinarily this is done by a motor-driven belt, and there are very large vibrations associated with this system.

If one wishes to provide power for accessories in the top terminal of one of these high-voltage systems, it is quite difficult in the case of a pressurized Cockcroft-Walton, although Dr. Smith says that one can use

TABLE I. COMPARATIVE TABLE OF HIGH VOLTAGE GENERATORS.

	Cockcroft-Walton (Pressurized)	Van de Graaff (Pressurized)	LINAC ⁽¹⁾	Superconducting LINAC ⁽¹⁾
Voltage limit	4.5 MeV	>5 MeV	>5 MeV	>5 MeV
Voltage range	10:1	10:1	2:1 ⁽²⁾	2:1 ⁽²⁾
Size	Large	Large	Small	Very small
Stored energy	Large	Small	—	—
Vibration	Good	Bad ⁽³⁾	Good	Good
Provision of power in top terminal	Difficult ⁽⁴⁾	Easy	— ⁽⁵⁾	— ⁽⁵⁾
Power consumption	Large	Moderate	Moderate	Small ⁽⁶⁾
Cooling required	Yes ⁽⁷⁾	Probable	Yes	Liquid He
<i>Stabilization</i>				
Compatibility with resistor	Yes	Yes	—	—
Compatibility with spectrometer	Yes	Yes	Yes ⁽⁸⁾	Yes ⁽⁸⁾
Coupling between generator and measuring device	Large	Small	None	None

NOTES: ⁽¹⁾Considered as generator-accelerator combination. Used as charging device—rather different considerations apply.

⁽²⁾For constant injector conditions.

⁽³⁾Has been tried (Tadano) and found wanting.

⁽⁴⁾Batteries can be used in a variety of ways.

⁽⁵⁾No top terminal.

⁽⁶⁾Excluding cryogenic power.

⁽⁷⁾Gas circulation may be required, in which case vibration may arise.

⁽⁸⁾Beam deflector required to split beam for microscope and accelerator—brightness halved.

batteries, and we would agree. In the case of the Van de Graaff, it is very easy because you have the mechanical charging system. All that is required is to attach a generator to the top belt pulley. Of course there is no power in the case of the LINAC.

When one comes to the power consumption, that of the pressured Cockcroft-Walton is rather large because of its relative inefficiency. It is moderate in the case of the Van de Graaff. For example, several horsepower are required to drive the charge transporting system. It is still moderate in the case of the linear accelerator of the conventional type, as will be discussed later, and it is very small in the case of the superconducting LINAC. If we are talking about electrical power—we will get to this point later on—the power in the LINAC goes into the liquid helium system. The Cockcroft-Walton must also be cooled because of the large power loss in the system itself. This power loss amounts to many kilowatts, which must be removed from the pressure tank by cooling the circulating gas. In the case of the Van de Graaff, cooling is probably necessary. The reason we say probably is that in conventional systems in which one uses a belt which is dissipating, say, ten horsepower in the windage, one must remove this power. However, new and more clever means of charging have been developed which considerably reduce the windage losses, and one may not have to cool. The LINAC must be cooled, and we'll

talk about this later on. Of course the superconducting LINAC must be operated at liquid-helium temperature.

Table I also summarizes the compatibility of these generators with several methods used for high-voltage stabilization. If one wants to use a resistor for stabilization, then this can be done with either the Cockcroft-Walton or the Van de Graaff. Of course, there is no high-voltage terminal with the LINAC, and one can use the Haine spectrometer, which Dr. Donhowe will talk about. The spectrometer is suitable for stabilization of each type of generator, although in the case of the LINAC one loses half the beam current. This will be dealt with later on.

The last entry in Table I is a very important one. The coupling between the generator and the measuring device is a very serious problem in the case of the Cockcroft-Walton, since the components have to be physically close together in order to minimize the size of the pressure tank. With the Van de Graaff, this coupling is not nearly so bad, and in the case of the LINAC this problem doesn't exist.

To summarize our feelings on the various systems, we would say that the Cockcroft-Walton would need a very great deal of development to reach 5 MeV reliably, primarily because of the stored energy problem. It is extremely hard to make an accelerating tube that will stand the sort of discharge that is to be expected.

However, the Japan New Electric Company has been quite successful in manufacturing a 1-MeV system

for the JEM-1000, and rumor is that a 3-MeV Cockcroft-Walton system is going to be available. The other commercial system is the Haefely at 4.5 MeV, but Dr. Smith's feeling, and ours, is that this system has solved neither the problem of the coupling discussed above nor the problem of voltage regulation. Their regulation is far less stringent than we would require for the microscope.

We will say then that the Cockcroft-Walton would require a very large amount of really hard development work before it can be successfully used to power a 5-MeV electron microscope.

We now come to the Van de Graaff, and I think Dr. Crewe's comment about this type of generator is correct. The Van de Graaff can be used since it performs just about as well as is required in this particular application. There have been a number of improvements made in Van de Graaffs recently, and although these have been tested out, they are not yet commercially available. Some of these improvements, such as bakeable accelerating tubes, ultrahigh vacuum operation, and other ways of charging the terminal, will be discussed by Dr. Donhowe in the following presentation. Since we can't buy a Van de Graaff of suitable high quality at present, we think that this is not the way to venture at the moment.

Now we turn to the problem of using the linear accelerator. It was just about a year ago that Dr. Herb and I started considering the possibility of charging up a high-voltage electrode with a LINAC. The real problem with the LINAC is that one ordinarily can't furnish enough RF power to be able to operate the accelerator continuously, so one pulses it instead. With this pulsing, you are sending up charge to the high-voltage terminal intermittently, which puts a very severe ripple on the potential of the electrode, and this has to be filtered out. When Dr. Herb and I looked at the problem, we were quite optimistic because we felt if the LINAC could be pulsed at 10 kilocycles, we could use it as a source. We called Varian, a company that makes these accelerators commercially, and asked if they could furnish a LINAC operating at 10 kilocycles. The highest that they wanted to go was 3 kilocycles, and we essentially lost interest in the linear accelerator.

Subsequently, Dr. Hanson at the University of Illinois, who was the one who originally developed the concept of regulating a high-voltage terminal by pointing a needle at the terminal and using a vacuum tube in a control circuit to vary the amount of current drawn from the terminal, got the idea that you could split the high-voltage electrode into two parts and use a vacuum tube (there are vacuum tubes now that will hold 50 kV) to regulate the one part of the high-voltage

electrode with respect to the other. This summer he looked into this quantitatively and came to the conclusion that one can only gain about a factor of five in ripple reduction, which he feels is not enough to make it worthwhile. One would have to have a linear accelerator at a repetition rate of 100 kilocycles before he would be willing to say that it would be a suitable source for charging up a high-voltage terminal.

The conclusion we reached was that linear accelerators are not useful for this purpose unless one can operate them continuously. The development of the Los Alamos meson factory has been very important to us in this respect. Los Alamos is working for a high-intensity beam. They are trying to get a milliamperere of protons, at 800 MeV, coming out of their linear accelerator. They have designed an accelerating structure that is extremely efficient—which means that the impedance is very high, and they get a lot of energy gain in the particles per unit of RF power put into the accelerator. Now, just to keep the record straight, this sort of a solution was not available to SLAC, the two-mile electron LINAC at Stanford. One could not go in this direction for that accelerator because the way one gains this very good electrical efficiency is by designing an extremely complicated accelerating structure. The cost of building this structure for two miles would be prohibitive. The Stanford people were forced to go to a very much less efficient accelerating system, just because they were planning for two miles of tube.

Los Alamos is going to pay a price because, if I remember correctly, the tube at Los Alamos is supposed to be about 1100 feet long.

They have solved the design and production problems, and it is very nice because they now have running a model of the first section. They are testing it with electrons, and solid numbers have come out of this design. Up to the moment, they have achieved an electron energy of 4 MeV, and they are putting in 400 kilowatts of RF power to do this. They are doing it in 3 feet of tube. If one uses this design and thinks of an accelerating tube 10 feet long to provide 6-MeV electrons, the amount of RF power one has to furnish is between 100 and 200 kilowatts. We say 100 but we are probably going to have to put another 20 in for some bunching that we won't talk about here. The injection problem is really quite simple, although one probably should be somewhat clever about it. Talking of between 100 and 200 kilowatts of RF power to get 6-MeV electrons out of a 10-foot accelerating tube turns out to be a very practical device, because there are klystrons available that will furnish 100 kilowatts quite easily, and they cost of the order of five to ten thousand dollars each. They are sealed off and have a lifetime of several thousand hours, so they really are a shelf item. Thus,

the 100 to 200 kilowatts can be furnished by two off-the-shelf klystrons. One can operate this accelerator in the carrier-wave manner, and going to the 10-foot length gives advantages in dissipating this power. One has to be able to dissipate this power by water cooling, and if one goes to the 10-foot length this is a simple problem, whereas if you have to take out very much higher power per unit length, one gets into a problem.

This LINAC design is a very close approximation to an ideal device, and estimates of the cost are under a hundred thousand dollars. We are asking for only very simple requirements on the LINAC as to the current, as to the energy, and, of course, for charging of an electrode, as to regulation. We are talking in terms of having the energy constant to ten percent. This would be good enough for charging up the electrode, although one can do very much better if one wants to put more money into it.

This looks like an eminently practical solution to the problem of generating high voltage, one which is available now, and the recommendation we make at the present time is that one should think seriously of charging up a high-voltage electrode with 6-MeV electrons with a continuously operating, room-temperature LINAC.

The real advantage in this approach, as we see it, is that it allows one to separate the optics of the beam and the optics of acceleration. If one has a terminal sitting there quietly—we hope at 5 MeV—one can put a field emission source in the high-voltage electrode for the microscope and then tailor the beam strictly for its use in the microscope all the way down. One should then be able to get the optimum solution for the optical properties of the beam one wishes to use in the microscope.

Another advantage is that one can easily use the field emission source in such a high-voltage terminal because, as Dr. Donhowe will tell us later on, the vacuums are such now that one can operate long sections of the tube with the new pumps at the very good vacuums that are required to operate the field emission source. We feel there is a reasonable chance that one can pump at ground—that one won't have to furnish a pump at high voltage. If one needs some power at the terminal to extract current from the field emission source, one can use batteries for the extraction. Dr. Donhowe will talk about some possible layouts on this. As far as we can see, this will be a rather neat solution to the problem; and we don't see any real developmental work that would be required for this purpose.

In a certain sense, this still is the hard way to do the job. It would be very much nicer if one never had to generate this five million volts DC at all, but could

just furnish a beam of 5-MeV electrons with suitable optical properties.

Let's now go into the possibilities, which we have looked at fairly carefully, of producing an electron microscope beam directly—a beam of suitable quality to be used in a microscope—by means of a LINAC.

The first thing is to see if one can make the output energy of the LINAC sufficiently homogeneous. We will require that the energy homogeneity of the LINAC be one part in 10^6 and then ask, if the energy of the electrons is regulated to one part in 10^6 , how many are left? Are enough electrons left to be useful in the microscope, namely, what is the brightness? We first looked to see what sort of brightness is wanted. Figure 1 shows how we get at the brightness. We will say that the microscopist wishes to have a certain height irradiated, at a particular angle, and he tells us the intensity that he wants for the specimen. This tells us the intensity we have to furnish from the source. We have to furnish him a certain brightness given in terms of the current per square centimeter per steradian. The number that we have taken to satisfy microscopists is that our source has to have a brightness of 3×10^5 amperes per square centimeter per steradian. If we can get this sort of brightness, we have a useful device.

To get a first estimate, we have looked at the injector now in operation in the two-mile accelerator at Stanford. We have taken the parameters from this SLAC injector and evaluated them for a microscope. If we reduce the energy spread on this injector from its measured value of 1.8% to one part in 10^6 , we find that the brightness of the source is down by a factor of 20 over what is required for the microscope.

The SLAC injector uses an oxide-coated cathode as an electron source. If a field emission source is used instead of an oxide-coated cathode, the brightness can be increased by a factor of about 100. This would give more than the required brightness to operate an electron microscope.

If one reduces the energy spread on this LINAC to one part in 10^6 , the phase angle over which one can inject is roughly 0.04 degree. This is an extremely small phase angle, and the question is whether one can really do this on a LINAC. It is really a moot question because no one has attempted it, but there seem to be ways of getting around it. We'll talk about some of them. We think that this is an important enough problem that it ought to be looked at experimentally. No one has really looked carefully at the energy spread from a linear accelerator because nobody to date has been interested in using the linear accelerator with a very small energy spread.

Our suggestion is that we should design a suitable

bunching and sweeping system for an optimum injection system into a suitable linear accelerator. This linear accelerator would be part of an optical bench, with the injection system at one end and slit arrangements at the output end. With such a system we could explore the beam and determine where the source is located. These systems are so complicated that it would be an extremely difficult job to calculate the optics, yet it should be rather easy to determine experimentally with an optical bench what the optics look like. One could measure the energy homogeneity of the beam and see what sort of optical quality it has. We are suggesting that this ought to be done at Varian, since these people have all the know-how to design bunchers and choppers and can make cavities. We would suggest that we have this injector for such a machine designed and built there and have them use it on one of their existing 5-MeV accelerators to get the information. It seems to us that one should know how far one can push linear accelerators, that this is an important question, even independent of the microscope.

If this is really not the right way to go, if the problems are just too severe to try to get a linear accelerator regulated with this kind of energy homogeneity, we would like to consider the possibility of the superconducting LINAC. Table II shows just what sort of factors we can talk about, as the increase in Q by cooling is just fantastic. For our purposes we are talking about frequencies something like a thousand megacycles, and if we go down to 4.2°K, we pick up a factor of over four orders of magnitude. If we go down to 2°K, we pick up another order of magnitude, and at 1.5°K still another. One LINAC is operating right now at 2°K. The fact that one can operate an extremely high Q cavity at superconducting temperatures means a number of things. One thing it means, primarily for our purposes, is that one has an extremely stable system with respect to time. The Q is so high that nothing much can happen in a short time as far as RF fields

TABLE II. THEORETICAL Q IMPROVEMENT FACTORS FOR LEAD-PLATED CAVITIES AT SEVERAL FREQUENCIES AND TEMPERATURES

$T, ^\circ\text{K}$	10,000 Mc/sec	3,000 Mc/sec	1,000 Mc/sec	300 Mc/sec
4.2	6×10^2	3×10^3	1.5×10^4	1×10^5
2.0	2×10^4	1×10^5	5×10^5	3×10^6
1.5	2×10^5	1×10^6	5×10^6	3×10^7

1 INCH

FIG. 2. Superconducting Accelerating Cavities

go. Looking at the problems in detail, several tricks can be used, for instance, velocity bunching of the electrons after they come out of the accelerator as well as before they go in to make the energy more homogeneous. This possibility really ought to be considered for future development because of these inherent advantages. In addition, the RF power requirement is reduced three orders of magnitude.

I would like to show some of the mechanical problems involved in making these cavities. Figure 2 shows two types of cavities that have accelerating fields. Dr. Wilson and his co-workers at Stanford have been able to accelerate electrons in a superconducting cavity. They have obtained 0.5-MeV electrons and are at the

$$h\alpha = h'\beta$$

$$\text{BRIGHTNESS } B = \frac{I}{h^2 \pi \alpha^2} = \frac{I}{h'^2 \pi \beta^2} \quad \text{A cm}^{-2} \text{ steradian}^{-1}$$

FIG. 1. Formula for Brightness

moment working on two sets of problems. These cavities have to be machined as separate sections and then joined together. This is turning out to be a difficult job for two reasons. The first is that the cavities have to be machined and put together at room temperature and then cooled down to liquid-helium temperature and still remain in one piece. The second problem is that they have to be machined extremely perfectly at the joint, because one then has to put a layer of lead on the inside surface of these cavities. The requirements on the lead are that it be very pure and its thickness between 0.0002 and 0.001 in. Tests were made on cavities that did not have current going across a joint. Of course, they were not accelerating-mode cavities, and Q's were observed when they had high RF power and high electric fields in them. These Q's were within a factor of two of the theoretically possible Q's listed in Table II.

If one can solve the problems associated with the manufacture of these cavities, what sort of a microscope can one make out of them? We have a tentative drawing of a superconducting microscope (Fig. 3). We start with a field emission source, extracting with 2 kV. With the next electrode we accelerate the electrons to 80 kV right away because that is the injection energy we want. We use a lens to get hold of the beam, then we use an RF buncher driven by the same klystron that runs the LINAC to bunch the electrons. To get the small phase angle of acceptance into the accelerator we pass the electrons through a radio-frequency chopper, so that through the exit slit we pass only that fraction of the beam corresponding to the phase angle we wish to inject. The electrons pass through another lens before injection into the superconducting LINAC, which

FIG. 4. Possible Layout for LINAC "Gun" System

accelerates them to 5 MeV. They then pass through an RF sweeper operating a half frequency, which deflects alternate bunches of electrons in opposite directions. One bunch of electrons goes to the microscope, the following one to an energy-measuring device and so on. This system has the really nice feature of sampling in energy the very beam that is used in the microscope. The whole system lends itself very nicely to being a bakeable cryogenic system. For the energy-measuring device, we are thinking of using a Haine spectrometer. This spectrometer needs an extremely constant magnetic field, which can be obtained with a superconducting coil. Also, an electron multiplier running

FIG. 3. Proposed Superconducting Electron Microscope

cryogenically can be used to detect the electrons. The multiplier would remain constant in time, both with respect to the secondary electron coefficient and the dark current.

A problem with this system is that when somebody wants to come in and use the microscope, he would like just to push a button and start using it. This means that we have to keep the LINAC superconducting all the time. The only practical way to operate this is to use a continuously operating liquid-helium compressor to keep the cavity cooled to liquid-helium temperatures all the time. For the present superconducting electron accelerator, extrapolated to our conditions, we would have to furnish 100 watts of cooling, at 2°K and this is quite expensive. As a matter of fact, there is no such system as yet operating; the present best estimate of its cost is two hundred thousand dollars. This is a large number; however, it should be possible to reduce the power load of the LINAC to 25 watts at 2°K. The guess is that the cost of the liquid-helium system for this load would be fifty thousand dollars. The best estimate for the accelerator itself at present is of the order of ten to twenty thousand dollars. It looks as if

in the long-term future this might be a very useful device. The other problem we have talked about is that of optically tailoring the beam. There are quite a few possibilities here. For example, it could well be that what one really wants is to do the bunching and chopping at very low energy, and then do the accelerating before going into the LINAC. In addition, one can also do things to the beam to make the energy more homogeneous after it comes out of the accelerator. One ought to be able to do quite a few things to improve the system. There is a reasonable possibility of separating the fields used for acceleration and those used for shaping and making the image. There is at least a finite chance of coming up with a rather clever device that would have the optical quality for a really good microscope; and, just for fun, we have done a little drawing (Fig. 4) on how such a system might look in practice. This is such a cheap device that we would like to have a microscope like this just as a plaything in addition to the other big microscope.

This is quite a promising system, and we think one of these days we might get from it a very useful electron microscope.

Accelerator Tube Design

JOHN M. DONHOWE

*University of Wisconsin
Madison, Wisconsin*

Beam Optics

I must disclaim any responsibility for concocting the topic listed in the brochure as "Beam Ejection." It conjures in my mind the problems we sometimes have with Van de Graaffs and long accelerating tubes, but don't like to discuss: to wit, a man can be so clumsy in injecting a charged-particle beam into an accelerating tube that he fails to get the beam out of the tube at all. The problem is properly one of injection.

Dr. Smith emphasized the requirements of the high-voltage electron source:

- (a) The source must be compatible with the rest of the microscope. In describing the beam optics of the 750-kV microscope at the Cavendish Laboratory (Fig. 1), he depicted a conventional sequence of: (1) injection; (2) acceleration; (3) condensing to match components of the lens column. I say this is conventional because it is familiar to those of us who rarely speak of acceleration from cathode to anode, but who think in terms of acceleration of a charged particle beam through a tube 5 or even 15 feet long. The first-order characteristics of these "injection-acceleration" systems have been calculated by M. M. Elkind [R.S.I., **24**, 129 (1953)] and by Timm [Zeitschrift für Naturforschung **10**, 593, 603 (1955)], but I know of no published calculations of the third-order aberrations.
- (b) The system must have good focusing characteristics over a wide range in energies. The microscope at the Cavendish Laboratory, for instance, is operable from 75 keV to 750 keV. The injection voltage is about 5 kV.

Dr. Herb enumerated many of the requirements in tube design such that the tube hold high-potential gradients without breakdown and damage to the tube. Development of accelerating tubes at Wisconsin, aimed at maintenance of high gradients, has been toward a nominally uniform field.

Dr. Butler, at this Laboratory, developed a computer program designed to prescribe an electrode shape that would minimize the spherical aberration for a given set of first-order parameters and a given axial potential distribution. The electron gun that was fabricated according to these specifications has been termed the

Butler gun (ominously, I believe). This gun, with a field-emission tip as the source, has been operated successfully in Dr. Crewe's scanning microscope.

Only recently, Dr. Butler obtained results from his computer which predicts the beam spot size, referred back to the source, and the spherical aberration (again referred back to the source) of a column of 20 Butler guns. Each lens accelerates 50 kV and would be similar to that shown in Fig. 2.

Dr. Langsdorf suggested that if Butler-type electrodes be chosen to give rise to a quintic potential distribution down the axis (analogous to Butler's cubic potential distribution), the tube could be back-biased and so suppress electron loading, or the "long-tube effect." The back-bias technique has been used by Dr. McKibben at Los Alamos, with some success. This design should be examined further, even though it may raise problems in fabrication or in holding high voltage.

Some of our experience at Wisconsin with voltage breakdown in many-electrode tubes has led us to be wary of introducing any metal at all into the vacuum. In high, or even moderate fields, whiskers develop on the electrode, electrons are emitted, which knock off ions, and the chain reaction that issues in breakdown has begun. The plasma-like discharge of these positive ions seems to be the cause of eventual rupture of the tube. Dr. Nixon has added, helpfully, that Gabor and Goldstone have observed this effect: the appearance of whiskers and a chain reaction of ion discharge at a pressure of 10^{-10} to 10^{-11} torr. He suggested that heating an accelerating tube fabricated of Al_2O_3 ceramic and thin (0.002-inch thick) aluminum electrodes could help in two ways:

- (1) Increase the conductivity of the insulator,
- (2) Free the surface of the insulator from contaminant buildup, which can bind electrostatic charge and perturb the electron beam. If this can be done successfully, accelerating tubes built in this simple way would not require the customary shielding electrodes in the interior.

Dr. Symon has suggested that a tungsten tip immersed in a uniform field could well provide one with a means of distributing the potential along the axis during injection so as to minimize the spherical aberration for a given set of conditions. Fig. 3 shows that the

FIG. 1. Electron Optics in Accelerating Tubes (Suggested by J. Donhowe, July, 1966).

electron trajectory in a uniform field is parabolic. Neglecting fringing fields due to perturbation of the field due to the presence of the tip, the spherical aberration coefficient for a field emission tip biased at 3 kV and in a nominally uniform field of 50/3 kV/cm is less than 1 mm, referred back to the source. Mr. Moses then calculated the spherical aberration for a system in which the second derivative of the potential along the axis is positive in the injection region, the trajectory is nominally parallel to the axis in the uniform-field region, and a condenser is used to introduce the beam into the magnetic lens column. If we include a condenser lens at the exit of the accelerating tube, with $C_s \sim$ focal length ($f \sim 8.8$ cm), then $\delta_1 = 2.5$ Å. This choice of focal length of the condenser lens was chosen to conserve brightness. If some brightness can be sacrificed in the interest of ultrahigh resolution, as in the scanning microscope, this δ_1 could be reduced from 2.5 to 1 Å. Then $f_{\text{cond}} \sim 0.64$ cm and $C_s \sim 0.64$ cm.

The potential gradient for an accelerating tube 3 meters in length, for acceleration to 5 MeV, is 16.7 kV/cm. If bias of the tip for field emission is, say, 3 kV, and the axial potential distribution $\Phi(z)$ is assumed to be of the form $\Phi(z) = \Phi_0 \cdot (z/a)^\lambda$ (see Fig. 4), then for $\lambda = 2.58$, $z_p/a = 4.18$, $a = 3$ cm, and the focal

FIG. 2. Accelerating Tube with Quintic Potential Distribution (Suggested by J. Donhowe, July 1966).

FIG. 3. Field-Emission Tip Immersed in a Uniform Field (Suggested by J. Donhowe, July, 1966)

length $f \sim 2.5$ cm, the following calculated values of the coefficient of spherical aberration are obtained, for this set of conditions:

$$C_s (\text{source} + \text{tube}) \sim C_s (\text{condenser lens})$$

$$C_s (\text{source}) = 1.6 \text{ Å} \quad C_s (\text{tube}) = 4.8 \text{ cm}$$

$$C_s (\text{total}) = 9.2 \text{ cm}$$

All values of C_s are referred back to the source.

FIG. 4. Axial Potential Distribution in an Accelerating Tube.

FIG. 5. Beam Trajectory

FIG. 6. The University of Wisconsin Orbitron Pumps

FIG. 7. 7.6-cm-diameter Orbitron Pump and (p,γ) Nuclear Reaction Target Chamber

If one introduces into the system a condenser lens, as shown in Fig. 5, with a focal length of 8.8 cm, with a coefficient of spherical aberration of the order of that focal length, then

$$C_s(\text{total}) = C_s(\text{cond}) \frac{p_{1\text{col}}^4}{p_{0\text{cond}}^4} + C_s(\text{column})$$

where $C_s(\text{cond})$ refers to the third-order aberration of the condenser lens, and $C_s(\text{column})$ is the total spherical aberration for the source and accelerating tube, including the fringing-field at the exit terminal of the tube. With a half-angle of divergence of the beam $\alpha = 1 \times 10^{-3}$ radian, and a magnification of

$M = 1/30$, for acceleration to 5 MeV, the beam spot size will be

$$\delta_{0_{\text{total}}} = 75\text{\AA}, \quad \delta_{1_{\text{total}}} = \delta_{0_{\text{total}}}/M, \quad \text{and} \quad \delta_{0_{\text{total}}} = 2.5\text{\AA}$$

I shall ask Dr. Butler to comment during the discussion time on his tube, which was designed for an acceleration to 1 MeV. Comparison must be made with the traditional method of injection from, say, a Butler gun into a uniform field, and the calculations presented by Mr. Moses and Dr. Symon.

The Ultrahigh Vacuum System

The use of a field-emission tip in the electron gun implies a vacuum system capable of maintaining a pressure below 1×10^{-10} torr. Pumps with this capability are now available commercially.

With the recent development of orbitron pumps at the University of Wisconsin (see Fig. 6), high pumping speeds were attained down to 1×10^{-10} torr, which was the lowest pressure at which pumping speeds could be measured. These pumps gave evidence of being capable of maintaining an ultimate pressure below 1×10^{-11} torr, deduced from Bayard-Alpert and orbitron gauge measurements.

Three of these pumps were installed on the University of Wisconsin Model 51, electrostatic generator, electrostatic analyzer, and target chamber. Each was characterized by ease in starting and low maintenance requirements. The larger pumps, at the accelerating tube and the electrostatic analyzer, were baked out at 250°C , each cold-trapped to a fore-pump.

The 20-cm pump, shown in Fig. 7, operated at 200 watts (10-kV potential at the anode and 20-mA filament emission) and maintained a pressure of 6×10^{-8} torr in the electrostatic analyzer vacuum box for over 6 months without service. The 7.6-cm target-chamber pump operated at 50 watts for periods of one to two months without service.

The target-chamber pump was initially baked out at 500°C , although after several of these hard bake-

outs, it was no longer necessary to raise the temperature so high, nor to maintain the high temperature longer than 3 hours. During each bake-out, the target chamber was evacuated by a fore-pump in series with a cold trap. The pump was started at 100 watts immediately after the oven was removed, and 1×10^{-9} torr was achieved within 90 minutes. The high performance characteristics of this pump may be observed in noting that targets were formed by evaporation *in situ* at a maximum pressure of 3×10^{-9} torr, and recovery of the vacuum to 9×10^{-11} torr was made in 8 minutes. An indicated static pressure of 5×10^{-11} torr, corrected, was maintained during proton bombardment.

The orbitron pumps are manufactured by the National Research Corporation under the trademark "ORB-ION" pumps. Being off-the-shelf items, they are immediately adaptable to the ultrahigh vacuum system of the electron microscope. Several of the 6-inch-diameter pumps, placed horizontally in spoke-fashion around the beam tube at the ground terminal of the accelerating tube, should be sufficient for maintaining a pressure below 1×10^{-10} torr in a baked-out accelerating tube. It is hoped that no pumping would have to be done at the high-voltage terminal of the accelerating tube; but if efficient use of the Butler gun should require it, the regular 10-cm orbitron pump that operates efficiently on 50 watts, or less, could be used. The main problem would be constructing a 5-kV power supply for this pump at the high-voltage terminal.

Because the "ORB-ION" pumps require no associated magnetic fields for their operation, they are suitable for the lens column as well. The only associated ancillary parts of the ultrahigh vacuum system would be molecular adsorption roughing pumps, and provision for bake-out of the pump at 250°C .

Components of the electron microscope that require an ultrahigh vacuum for efficient operation would be separated from low-vacuum components by means of differential pumping through a high-impedance capillary.

Stabilization of the High-Voltage Generator

JOHN M. DONHOWE

*University of Wisconsin
Madison, Wisconsin*

A 5-MeV microscope of conventional design requires a high-voltage source to be regulated to better than three parts per million/10 seconds. If the microscope is to be used as a high-resolution scanning microscope, a 5-MeV supply must be stabilized to plus or minus 15 volts/10 seconds, or better. Dr. Crewe asks for one volt (plus or minus) in 5 million.

Whatever method of stabilization is to be used, a means of analyzing and controlling the high-voltage beam must be devised. This could be achieved by a high-precision resistive voltage divider; or, as suggested by Dr. Rymer, by means of a magnetic spectrometer.

The Haine Magnetic Spectrometer

The magnetic spectrometer of Haine and Jervis [Proc. Inst. Elect. Engrs. 102B, 265 (1955)] is based on the principle of semicircular focusing of electrons passed through a uniform magnetic field. The general scheme is shown in Fig. 1. The electron beam is directed into a uniform magnetic field, in a direction perpendicular to the field. The beam is then deflected in the field in the arc of a circle.

The incident beam is collimated with slits, and falls on a knife-edge at the boundary of the magnetic field. The knife-edge is placed so as to intercept approximately half the beam. The portion of the beam passing the knife-edge is deflected round a semicircular path by the magnetic field and falls on a second knife-edge, which intercepts most of it. The small portion of the beam that passes the second knife-edge enters a Faraday cage, or other collecting device, and produces a small current, which serves as a signal for operating the stabilizer of the high-voltage source.

To detect a fractional change in voltage of two parts per million, changes in the position of the beam at the output must be detected of the order of one part per million of the radius of the electron path. In a conventional velocity analyzer, such measurements are made by defining the width of the beam at the analyzer input with a slit system. In the system proposed here, a slit system could be used, but the simpler arrangement was adopted by Haine since the virtual image of the first knife-edge is seen as a second jaw of a pair of virtual slits at the position where the beam leaves the magnetic field.

The fringing field has not been indicated, but its effect can be compensated by inclining the beam a few degrees from the normal degree of incidence on the magnetic field. The required inclination is independent of the energy of the electron beam, provided the fringing field is always proportional to the main magnetic field.

An increase in energy of the electrons deflected in this spectrometer causes an increase in the diameter of the beam orbit; hence the collected current is increased, producing an error (negative) signal to the amplifier.

Dr. Rymer's reports, contained in the literature of this workshop, include a discussion of the effect of: (a) inhomogeneities of the magnetic field; (b) roughness of the knife-edges; (c) precision of setting of the beam on the entrance knife-edge; (d) fluctuations in current incident on the knife-edge (e.g., uniform to 1% for an ultimate stabilization of voltage to one part per million); (e) lack of parallelism of the knife-edges; (f) noise current; and (g) angular divergence of the beam.

Haine and Jervis report stabilization of a 50-keV electron beam to a few parts in a million using two electron guns and two spectrometers, one being a stabilizing analyzer and the other a measuring analyzer.

Fluctuation in beam intensity leads to a difficulty, because the electron beam is not well defined at the edges, but has an approximately Gaussian distribution of current density. If one edge only is used, the low-current density leads to a low sensitivity, and hence to low signal output and an inefficient use of the electron beam. For this reason, a second defining-edge is placed at the analyzer input. This edge is arranged to bisect the beam so that the edge of the beam spilling over the second defining-edge is sharp and of maximum current density. The input defining-edge also serves to position the beam at analyzer input, so that drifts in position of the beam illuminating the analyzer produce only second-order disturbances in the system.

A major source of error in such a system appears to be the determination of the changes in diameter of the electron beam that passes through the analyzer to *twice* the accuracy one wishes to achieve in stabilization of the high-voltage source. This requires temperature regulation of the metal bar, the ends of which form the two knife-edges, to reduce error due to variations in

FIG. 1. Schematic of the Haine and Jervis Magnetic Spectrometer

length of this bar caused by ambient-temperature variations.

Another difficulty with this device, as applied to use with an electron microscope, is the homogeneity of magnetic field that is required. Haine and Jervis used permanent magnets, thus fixing the usable electron beam at one given energy. A variable high-voltage source could be analyzed only by means of an electromagnet, which requires an ultrastable current source to drive the magnet.

If a superconducting magnet were constructed, persistent currents would be stable to one part in 10^9 , and the strength of the magnetic field could be adjustable to suit a wide range of energy of the electron beam. Dr. Fernandez-Moran has demonstrated the stability of the magnet field, over a period of 12 hours, in his electron microscope which uses a superconducting objective (without pole-piece).

An Invar bar, approximately 10 cm long, can be used to define the two knife-edges. In a cryogenic system this bar would be safeguarded against fluctuations in length due to thermal expansion. If a superconducting

magnet were designed to accommodate such a bar, then the Josephson junctions, which are capable of detecting current fluctuations of the order of 10^{-9} A, could be incorporated into the reading of an error signal which is used for stabilization.

Dr. Laverick has constructed a superconducting magnet which produced a stable magnetic field of one-foot diameter. He assures me that a magnet for the purpose I have just outlined presents no insurmountable problems; rather, he leads me to understand it would be easy to construct. He has furnished a first approximation design of a magnet: cavity, 1 cm x 12 cm x 6 cm, $NI = 5000$ Amp-turns, or $N = 24$ turns, $I = 200$ Amp.

Resistive Voltage Dividers

Recently, extremely high quality resistors became available commercially in this country. These resistors, in the one-megohm range, were used in the Park volta divider and were manufactured by Julie Research Laboratories, New York. The resistors, JRL type HV-106, had a rated stability to 1 ppm, and a temperature coefficient of resistivity of less than 2.5 ppm/ $^{\circ}\text{C}$.

FIG. 2. Beam Analysis and Control Schematic, Wisconsin Model 51 Electrostatic Accelerator

Experiments at two different laboratories have been carried out in an attempt to measure the stability of high-voltage proton beams, which have been controlled in energy by means of resistive voltage dividers. Figure 2 shows the beam analysis and control schematic at the University of Wisconsin, where a one-meter-radius, cylindrical, electrostatic-energy analyzer was used for voltage measurement. To avoid time-dependent drifts in the voltage-division ratio due to ambient temperature changes or self-heating of the resistors, temperature regulation of the resistors was incorporated in design of the Lucite enclosure to permit forced-air recirculation.

Resonance-energy determination for proton capture in the nuclear reaction $\text{Al}^{27}(p, \gamma)\text{Si}^{28}$ was used as a measure of the stability of the energy of the proton beam (Fig. 3). The resonance energy was determined by fitting a datum point in the one-half to two-third range of the rise in the yield curve to a calculated yield curve. This method prevents the introduction of errors due to inaccuracy of the potentiometer, and voltage drifts in the high-voltage components of the electrostatic analyzer. The proton beam was varied in rapid rotation, about four sharp resonances between 750 and 1500 keV (Fig. 4).

Although this method is limited by the quality of the proton beam itself, as well as the resolution of the analyzer, voltage fluctuations of several parts per million are discernible, and *standard error* in reproducibility averaged 5 ppm.

Part of this experiment was repeated here, at ANL, in cooperation with Dr. Langsdorf this last week. Extremely carefully designed voltage dividers, using the Research Laboratories components, were used to stabilize the potential on the electrodes of the one-meter-radius, spherical electrostatic analyzer. Fluctuations in the reproducibility of the resonance energy

FIG. 3. Shape of Gamma-ray Yield Curve Over a Nuclear Resonance.

determination near the 1364-keV resonance were less than 15 ppm, and long-term drift was less than 40 ppm/hour. Again, since the nominal resolution of the analyzer could be set at only 6000 because of the quality of the proton beam, the poor resolution of the inspecting instrument (electrostatic analyzer) prevented a more precise measurement of the accuracy of these voltage dividers. A proton beam from a RF ion source, with an inherent energy distribution of ~ 100 eV full-width at half maximum, is much more difficult to focus than an electron beam from a tungsten filament with a beam width less by two orders of magnitude.

The potentiometer and resistors used in these tests are rated as being stable to 1 ppm for over 5 years. These same high-voltage components, stabilizing a crude proton beam to 5 ppm accuracy, should be capable of stabilizing a high-quality electron beam to at least 2 ppm because of the increased resolution of the energy analyzer which could be achieved by narrowing the slits (one order of magnitude).

However, it is difficult to see how stabilization to

Fig. 4. Irreproducibility of Resonance-Energy Measurements at Several Energies

better than 1 ppm could be achieved with resistors, unless one could solve the problem of thermal fluctuations. We could cool to absolute zero, I suppose. But then one would have no resistance at all. Resistance itself is a thermal phenomenon, intrinsically chaotic. A breakthrough in voltage stabilization perhaps could be won by going to a superconducting magnetic spectrometer, where order and stability are characteristics of the state. That, it seems to me, is preferable to "harnessed chaos."

I wish to add a note in comparison of resistive voltage dividers and the Haine spectrometer, regarding gain in the instrument, and required amplification of the error signal.

The gain in the UW electrostatic analyzer is 100. Voltage stability at the point of tapping into the resistive voltage dividers must be to better than 100 microvolts for stabilization to 1 ppm. In the Haine analyzer, resistors would be used to stabilize the input to the amplifier to, say, plus or minus 1 mV, since the sensitivity of the instrument is about 10 microAmps/V, and $\Delta V = \pm 1$ V implies stabilization of 5 MeV to 3 ppm.

These methods of voltage stabilization, based on the brute-force method of beam deflection, have been adapted successfully to voltage regulation to, say, 5 ppm.

Three worthy suggestions on possible means of voltage stabilization have been suggested in this workshop. I mention them in this sequence, not to imply that they be secondary alternatives to beam-bending techniques. They are ingenious and perhaps direct us to a real breakthrough in achieving high-voltage stabiliza-

tion. Their only insufficiency is that, at present, only one of these methods has been proven by experiment. Nevertheless, they should be examined in detail, I feel. Details of these proposals have been described in the literature of this conference, and I will only summarize them here.

Dr. L. L. Marton:

Two possible ways of high-voltage regulation may be considered:

The Pradal Monochromator

The information serving as input for the feedback circuit is provided by the main microscope beam. This necessitates a sensitive monochromator, whose beam, when having the correct value, passes through an aperture into the microscope and is used to form the image. Any deviation (+ or -) is picked up by suitably placed sensors, and the information activates the correcting circuits.

A possible version of the monochromator is based on a recent thesis of Pradal (Toulouse). It consists of a homogeneous, slablike magnetic field, and with sufficient lever arm it should be possible to reach the necessary dispersion. The sensors can be cathodes of symmetrically placed secondary-electron multipliers, with the main (unperturbed) beam passing between them. (Approximate calculation available.)

The High-Q Cavity Serving as an Electrometer

The information reaching the feedback circuit consists in a frequency sensing of the deviations from the

standard. One way of doing it consists of making one wall of a high-Q cavity part of an electrostatic voltmeter. The forces exerted by the electrostatic field change the shape of the cavity and with it the frequency of the associated circuit. Noise problems can be minimized by immersing the components in transformer oil, compressed gas, or the like.

Dr. H. Stanley Bennett:

Use of the Electro-Optical Effect for Regulation of Voltages

A voltage regulator based on a Kerr or Pockels cell, wherein the strains engendered in a dielectric medium are caused to modulate a polarized laser beam as to phase, offers attractive features since the high coherence of the laser beam and the sensitivity of a good polarimeter provide possibilities of detecting and measuring voltage perturbations of one part in 10^7 or more. To realize this capability, several difficulties would have to be overcome. In a Kerr cell the most serious difficulty seems to threaten from the high-temperature coefficient of the Kerr constant and the resistive heating of a

FIG. 5. Beam Analysis and Control Schematic, University of Wisconsin 1-MeV Electron Accelerator.

FIG. 6. Possible Layout for Two LINAC Charged High-voltage Systems (with Two Lens Columns) (Suggested by J. Gilroy, July 4, 1966).

nitrobenzene cell with immersed condenser plates. There are prospects of ameliorating these and other defects, but considerable development work will be necessary before one can determine the extent to which these difficulties can be overcome. Until this is done, the method cannot safely be recommended as a means for detecting small voltage fluctuations for purposes of regulation.

Conclusion

For comparison with what Dr. Klema and I have presented regarding high-voltage design, I want to show a slide of the Wisconsin 1 MeV test design. The accelerator is a tandem, decoupled at the high-voltage terminal. It accommodates two tubes in each section of the tandem (Fig. 5). It is arranged so that one tube may lead to a magnetic spectrometer, and another parallel tube may lead to an optical bench. A third tube, in the upper part of the tandem, is to be used for voltage control, by way of telemetering devices which would discharge the high-voltage terminal through a tungsten filament.

Dr. Laverick has sketched a design of a magnet for a Haine-type spectrometer, and as soon as costs can be estimated, I want to get to work on the spectrometer. Then, if someone can locate a spare LINAC, or other source of 1 MeV electrons, we can test charging of the high-voltage terminal by use of an electron beam. The third tube, illustrated in Figure 5, could be used, only in this instance for charging the high-voltage terminal with an electron beam. For control, the error signal from the magnetic spectrometer could be fed back to the LINAC.

We would have all the essential parts of a Tandem Van de Graaff, you see, only without the objectionable motors and moving belt that cause vibration. In fact,

our plans to build a two-meter electrostatic analyzer are pretty nearly scrapped now, since Dr. Rymer apprised us of the Haine spectrometer.

With a little work we can test: (a) suitability of a LINAC for charging; (b) charging an electrode with an electron beam, and (c) energy analysis by way of a magnetic spectrometer. This, we believe, is the most reasonable design, and really nearest to us in terms of successful escalation to five million volts.

A 5-MeV electron-microscope installation using a LINAC for charging, and a magnetic spectrometer for energy control, and utilizing parallel accelerating tubes in the manner of the 1 MeV test design, is depicted in Fig. 6.

Remarks on Electron-Gun and Accelerating-Tube Design

JAMES W. BUTLER

Argonne National Laboratory

Work on electron-gun design has been carried out during the past three years in connection with the scanning electron microscope being developed at Argonne National Laboratory,^{1, 2} while the impetus for the column design studies was furnished by the AMU-ANL Electron Microscope Workshop.

A schematic view of the existing microscope is shown in Fig. 1, its salient feature for the present purpose being the use of a tungsten field emitter as a source of electrons.

The basic problem is the design of an electron gun with aberrations as low as possible, or, to put it another way, to design an electrostatic accelerator capable of producing 50-100-kV electrons while maintaining the "beam quality" at a level comparable to the high quality available from the field emission source.

The obvious way to approach this problem might seem to be to simply try different electrode configurations and select one with the best performance. However, field calculations are always messy and unsatisfactory, even in axial geometry. Another point is that the principal mathematical entity involved in this kind of calculation is the paraxial trajectory equation which only involves the behavior of the field in the immediate neighborhood of the axis of rotation of the system.

When these two factors are taken into account, the natural way to attack the problem is to devise an analytic procedure with the potential function along the axis as input, both the paraxial trajectories and the required electrode shape being determined from this input. Once this is decided, the only remaining task is to produce an actual computer code to perform the necessary calculations.

The first step is to solve the well-known paraxial ray equation:

$$r''(z) + U(z)r = 0 \quad (0 \leq z \leq 1),$$

where the nonrelativistic form of U for an electric lens is

$$U(z) = 0.1875[\Phi'(z)/\Phi(z)]^2$$

in which $\Phi(z)$ is the electrical potential along the axis. This form of U is displayed only for orientation; the actual computer codes in current use are relativistically correct and allow for the introduction of magnetic as well as electric fields.

Since it is difficult to obtain adequate error control in "step-by-step" or "marching" methods, the solution of the ray equation is computed by a "global" technique due to Lanczos,³ which rests ultimately on Chebyshev polynomial expansions. Briefly, the solution proceeds as follows:

Pick an integer N (this is the number of z values at which the solutions are to be calculated) and define "weights"

$$w_k = 0.25 \sin [\pi(2k - 1)/4N] \quad (k = 1, 2, 3, \dots, 2N)$$

and abscissas

$$z_k = \sin^2 [\pi(2k - 1)/8N] \quad (k = 1, 2, 3, \dots, 2N)$$

(these are the points on the z -axis at which the solutions will be determined).

The whole process is based on the indefinite-integration formula

$$\int_0^{z_m} dz g(z) = \frac{1}{N} \sum_{k=1}^{2N} w_k g_k [A_{m-k} + B_k] \quad (m = 1, 2, 3, \dots, 2N)$$

and the corresponding definite-integration formula

$$\int_0^1 dz g(z) = \frac{\pi}{N} \sum_{k=1}^{2N} w_k g_k.$$

In these formulas, g is any function that needs to be integrated, $g_k = g(z_k)$, and the A 's and B 's are certain coefficients that depend also on the chosen value of N .

With these integration rules in mind, the ray equation is integrated twice and rearranged slightly to yield the equivalent integral equation

$$h(z) + z \int_0^z d\xi U(\xi) h(\xi) - \int_0^z d\xi \xi U(\xi) h(\xi) = h(0) + zh'(0).$$

Use of the indefinite-integration formula converts this integral equation into a system of linear equations for the $2N$ quantities $h(z_k) = h_k$, after which the system is solved by direct matrix inversion.

Three solutions are needed for the complete analysis, these satisfying the three sets of boundary conditions:

$$\begin{aligned} h(0) &= d \quad h'(0) = 1, \\ S(0) &= 1 \quad S'(0) = 0, \end{aligned}$$

FIG. 1. Schematic View of Scanning Microscope

and

$$t(1) = 1 \quad t'(1) = 0.$$

The first two solutions are determined "simultaneously" by the matrix-inversion code, and the third solution t is then found as a linear combination of h and s . After these solutions are calculated, the various quantities of interest are computed from standard formulas as derived by Sturrock.⁴

Some kind of convergence criterion must obviously be applied to find the correct value of N . In the present case, the value of N is determined by intrinsic convergence of the spherical aberration coefficient, since this is the principal quantity of interest. This simply means that the calculation is carried out for a sequence of increasing values of N until two successive determinations of the spherical-aberration coefficient agree to a specified accuracy.

After the convergence criterion is satisfied, the quantities printed out by the computer program are the magnification and image position, the cardinal and transfer matrix elements, and the spherical- and chromatic-aberration coefficients *referred back to the object*. Also, for the values of z_k used in the final solution, the values $\Phi(z_k)$, $U(z_k)$, and $h(z_k) = h_k$ are printed, the last being a typical ray. If the ray h_k crosses the axis inside the lens region, the magnification and the three aberrations are also computed at the image point represented by the first crossover.

A separate computer program calculates the electrode shapes and furnishes output in the proper form for feeding into a numerically controlled machine tool for making the rough electrode surfaces.

These computer programs have been used to investigate a number of parametric families of electric and mixed electromagnetic lenses. The lowest spherical aberration thus far found for an accelerating lens is associated with the axial potential

$$\Phi(z) = [P_3(z)]^b \quad (b \geq 1),$$

in which P_3 is a cubic polynomial. For this form of $\Phi(z)$, oddly enough, the spherical aberration is a minimum (one-sided) for the simple cubic $b = 1$. This means that the potential function itself, and hence the electrode structure, is symmetrical about $z = \frac{1}{2}$. Results of the calculations show that the aberration depends strongly on the position of the source (object), the lowest spherical-aberration figure of about 0.01 (lens length) being obtained by immersing the emitter tip in the lens field, resulting in the design shown in Fig. 2. This is a rather weak lens; however, the addition of a modest magnetic field moves the image to any desired point without sensibly affecting the spherical aberration. Table I lists some representative numbers

FIG. 2. Electron Gun with Immersed Field Emission Source

TABLE I. SELECTED LENS CHARACTERISTICS
(All lenses accelerate from 4000 to 50,000 volts)

Source Distance from Entrance Plane*	Magnetic Field Maximum, gauss	Image Distance from Exit Plane*	Magnification	Spot Size for a 1-in. Lens
0.5	0	5.49	4.15	142.7
0.5	800†	1.69	1.56	55.2
0.5	1200†	0.72	0.91	33.0
0.5	1600†	0.25	0.60	22.5
-0.21 (immersed)	0	Virtual	0.75	8.7
-0.21 (immersed)	3600‡	5.14	12.96	154.4
-0.21 (immersed)	4000‡	0.80	3.66	43.4
-0.21 (immersed)	4400‡	0.12	2.25	26.8

* Units of lens length.

† Broad, bell-shaped field.

‡ Linear field, maximum near source.

relating to this configuration and also to the same lens with the object point outside the field region.

Studies relating to accelerating columns originated from a suggestion by Dr. Crewe that it might be interesting to consider a column made up of a stack of lenses similar in design to the already developed electron gun. Accordingly, the lens-design programs were incorporated as subroutines into a program which performs calculations for all lenses in the stack and combines the results into one effective lens.

The calculation begins at the gun end and proceeds down the column, the virtual image produced by a given lens being taken as the virtual source for the next. Following a conversation with Dr. Hawkes, simple recursion formulas were derived for the propagation of first- and third-order properties down the column.

Denoting by M_n , CS_n , and CC_n the magnification, spherical aberration, and chromatic aberration, respectively, for the n th lens in the stack, one has

$$X_n = X_{n-1}M_n \quad (X_o = 1),$$

$$S_n = S_{n-1}/M_n^3 + CS_n \quad (S_o = 0),$$

$$C_n = C_{n-1}/M_n + CC_n \quad (C_o = 0),$$

in which X_n , S_n , and C_n are, respectively, the magnification, spherical aberration, and chromatic aberration for a column of n lenses. If there is a crossover in the last lens, the immersion properties are also computed relative to the crossover point. The program outputs values of X_n , S_n , and C_n and, in addition, the quantity $S^{1/4}\lambda^{3/4}$ (λ is the DeBroglie electron wavelength) which is a measure of the diffraction-limited spot size from a point source in the gun.

On the advice of Dr. Langsdorf and others, it was considered unwise to rely on each lens section to hold

more than about 50,000 volts. Accordingly, several 1,000,000-volt column calculations were done assuming a stack of 20 lenses each holding 50,000 volts. A thickness of one inch was taken for each lens section in order to obtain a definite value for the diffraction-limited spot size. Such a stack of lenses with cubic axial potential functions gave a diffraction-limited spot size of 163 Å with no real image. To see if the situation could be improved by inducing more crossovers, a parabolic magnetic field with a maximum value of 8000 gauss was added to each lens except the gun, whereupon the spot size increased to 260 Å. Upon inspection of these results, it became apparent that the large aberration values were arising from the long distances between the virtual sources and corresponding lens elements. To test the validity of this observation, another column was investigated in which the magnetic field increased from 8000 to 14,000 gauss at the high voltage end. This produced a reduction in spot size to 25 Å. The program is being modified to optimize the system by making an automatic adjustment of the magnetic field in each lens section, hopefully yielding a further substantial decrease in spot size.

This kind of accelerating tube could also be constructed (following a suggestion of Dr. Langsdorf) by separating the accelerating lens sections and placing magnetic lenses in the "drift spaces" between. Such a tube would be longer but might be easier to build.

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Discussion of Session I

Discussion of Paper by E. D. Klema

D. Hess: I was wondering why you didn't consider a modern version of the old cascaded transformer.

E. D. Klema: We did consider them, and they were not left in the last five because they are essentially very high-current machines. We don't need much current, and they need an awful lot of power.

A. Langsdorf: I just think you should not have left out the Radiation Dynamics machine in the comparison. The Dynamitron does not compare unfavorably on a whole lot of scores with all the others, I believe.

E. D. Klema: The others are quite a bit cheaper. We are talking about less than one hundred thousand dollars.

A. Langsdorf: Not on the cryogenic one, because you have a hundred thousand dollars for the cryogenic system, too.

E. D. Klema: The only purpose for which we would use a Radiation Dynamics unit is for charging an electrode.

L. L. Marton: I just want to warn against the Haine analyzer, which has not been proven.

J. M. Donhowe: Oh, it has been proven experimentally. It has stabilized a high-voltage source, at 50 kV, to 2 ppm. For this purpose they used two spectrometers; one for stabilization and one for calibration. However, they used permanent magnets. Now if we were to use a superconducting magnet, and if we were to use an Invar bar, all held at liquid-helium temperatures, it looks like a very good device.

L. L. Marton: Who did the testing?

E. D. Klema: Haine and Jervis.

Discussion of Papers by J. M. Donhowe

D. Cohen: The 2.5 Å that Mr. Moses has calculated, is that the total image size including diffraction, first-order size, and aberrations, or is that just aberrations?

J. M. Donhowe: It includes only third-order calculations of the spherical aberration. Incidentally, that condenser lens was chosen so that it had a rather large spherical aberration, in order to save on brightness. If one were willing to sacrifice brightness in the interest of ultrahigh resolution for a scanning microscope, this could be reduced to 1 Å if one were willing to shorten the focal length of 8.8 cm in the condenser lens an order of magnitude.

A. V. Crewe: That 2.5 Å calculation, does that assume a perfect condenser lens, or is that spot size just from the characteristics of the lens rather than the crossover?

J. M. Donhowe: It assumes a condenser lens that has third-order aberrations, in this case, equal in magnitude to its focal length of 8.8 cm.

A. V. Crewe: It's not clear that we have an accurate comparison between the two columns. We'll have to get this straightened out.

R. K. Hart: Referring to the Butler gun, is there any reason why one could not reduce the number of lenses and increase the accelerating potential from 50 to 100 kV?

J. W. Butler: There is no mathematical reason why we can't have a million volts, these days, but I am told by the Engineering Department that we are limited.

R. K. Hart: Well, from an engineering point of view, we are limited to about 200 kV/cm.

J. M. Donhowe: That is rather high, for a Langsdorf-type tube. You would surely develop whiskers on the electrodes, triggering a discharge, at that high a gradient.

A. V. Crewe: I think it would be worth it for the record of the meeting to have a calculation of Butler's gun at 5 MeV using the same lens.

T. N. Tahmisian: I am sure that you have the particle acceleration realm well under hand, but what is bothering me very much is that for a pressure of 10^{-11} torr, how are we going to maintain any biological objects in the column? How are they going to look at chemicals? For metals this may be all right, but are we going to interpose into the beam a chamber in which we have, let's say, almost 1 atm of pressure, and if we do this, how do we get any kind of an image on the other side?

H. Fernandez-Moran: Actually this works all in our favor, because if we do look at an object, we would probably look at it either in the frozen state or at liquid-helium temperatures. Already at liquid-nitrogen temperatures, it would have 10^{-18} torr, which may very well do it. If we look at it through a microchamber of the type that we have been using, of different sizes, then the conditions are even more favorable for the 5 MeV because we have greater penetrating power and it would be actually possible to maintain the object in the hydrated state. So I would add a note of encouragement here.

D. B. Wittry: I would like to know if the calculations made by Mr. Moses are particularly sensitive to the form of the focusing field assumed between Z_0 and Z_c .

R. Moses: It definitely is sensitive to this field. What I did was to get a potential distribution that minimized C_s in this region, for a reasonable tip bias and acceler-

ating field, and yet focused to a parallel beam in the uniform part of the tube. I did make an approximation within the integral itself because I did not want to integrate the sine of the log of z over a .

A. V. Crewe: I guess you are suggesting that this number of 2.5 Å is not an accident.

R. Moses: Definitely not.

D. B. Wittry: As I understand it then, this expression for the field was an analytical expression; have you considered whether this can be physically realized?

J. M. Donhowe: The first reason we are holding to an accelerating tube design that maintains a nominally uniform field is that this is the kind of tube Dr. Herb at the University of Wisconsin knows how to build, which will tolerate high potential gradients satisfactorily. The diagram that I displayed earlier shows electrodes which would intercept the beam. We would tie down the potential by way of resistors. This brings us into the experimental problem of always having perturbations in the field whenever we have a beam present. But we felt that this configuration for shaping the field was realizable experimentally, and that we could come within reasonable limits of achieving any given sensible potential distribution from the point of injection down to the high-voltage terminal.

A. Langsdorf: Have you considered the problems of keeping a tube like that hot and at high voltage?

J. M. Donhowe: You mean at 250°C, I presume. I was stricken when Dr. Nixon suggested this, for it recalled to me an experiment we began about three years ago in which we tried to heat the tube. We never completed the experiment because the Tandem, an older accelerator, was constructed in part of Lucite, and sagged under heat. I had since forgotten to try it again. The accelerating tubes designed and built in Dr. Herb's laboratory at Wisconsin are bakeable at over 250°C.

A. V. Crewe: Let me assure Dr. Donhowe that a LINAC, in the 1- to 2-MeV range, happens to be available here at Argonne.

Voice: That accelerator is a Dynamitron, a 1.2 MeV accelerator.

A. V. Crewe: At any rate, it could be used for an experiment with an electron beam charging a high-voltage terminal.

Voice: What aberrations are to be expected with the Haine and Jervis spectrometer, due to the knife-edges?

J. M. Donhowe: Asperities, or roughness of the knife-edge, are an aberration. So is misalignment. One would use the best possible means of making these knife-edges and arranging them parallel, but I don't know what order aberrations would be involved, and I don't know whether you can calculate it or not. I think it would have to be tried experimentally. It would be a problem,

but it beats the problems resistors give. I've had more acquaintance with resistors, and I'm tired of it.

C. E. Cohn: You might have to try to use a different slit geometry than a sharp edge, so that the beam would have more of a tendency to cut off sharply as it moved.

J. M. Donhowe: Did you have a suggestion?

C. E. Cohn: The boundary of the slit might be parallel to the electron orbit.

J. M. Donhowe: That's fine. That's the way we make slits for high-energy protons, using ground flat edges in steps.

A. V. Crewe: This problem may not be too bad, because the electrons that lose energy at the first slit get lost on the next slit.

C. E. Cohn: That consideration takes care of the first slit, but it doesn't take care of the second slit.

L. L. Marton: Why not replace the slit with a Wollaston wire sensor? The wire would sense only the part that you would collect in the Faraday cage.

C. E. Cohn: You could extend Dr. Marton's idea further. Instead of a wire, for 5 MeV electrons you would need a large chunk. If you had a large chunk with a well-defined edge, and used this as a collector, collecting only those electrons stopped in the chunk, then the thing that defines how sharp this edge must be is essentially the range-straggling of the electrons, which is about 10 or 20%. Perhaps this could make the geometrical requirements less stringent than trying to operate this with a slit.

M. Beer: How sensitive are the optics of the spectrometer? Maybe one way of looking at it is that we should build two identical columns side by side, and the function of one of them would be only to act as a probe for the instabilities that affect the other image. If we put into one a thick specimen and looked at the image produced under conditions identical to those of the others, and used some scanning device across the image of some sharp boundary, we could lead that into a feedback system.

J. M. Donhowe: That is true. Dr. Symon was intrigued, after his visit to Dr. Moran's laboratory, with the fantastic stability of the image with a superconducting lens. He said, "Why can't you program the problem, so that you measure instability of voltage by the quality of image? The eye can do it, why can't the computer do it?"

D. B. Wittry: Let me come back to an older subject, which I feel is perhaps not as attractive as some of these newer approaches. With regard to the resistor stabilization, you have given a great deal of consideration to the stability of the divider network. Are you now at a point where the stability limit is the reference voltage, and if so, what references have you used?

J. M. Donhowe: We have used Julie Research stand-

ard cells: three standard cells, enclosed in two thermally-lagged ovens, stabilized to 0.01°C . Calibrated voltages of these cells are stable to one part per million for a period of over five years. We have three of them, so we calibrate our system against them separately. Incidentally, I don't mean to say that we would throw out resistive dividers at all; because we could beat the problem with the Haine spectrometer, incorporating what little we do know about resistors, by correcting the problem I felt was the deficiency in my system in Madison. Namely, that was in the amplification stage of the error signal. If we could stabilize the voltage in the amplifier by means of a good, high-quality resistor stack, then we would steal a march on previously used spectrometers. We would use both.

L. L. Marton: How stable was that cell? Was it good enough for one part per million?

J. M. Donhowe: Well, I had nothing better to measure it with. We checked one against the other. These are CdS saturated standard cells, certifiable by the National Bureau of Standards to one part per million.

A. Langsdorf: Isn't it true that the Bureau of Standards have standard cells, and if one of them has shifted a few parts per million, they throw it away? And they only do that after years, usually?

C. E. Cohn: I wanted to ask one question pertinent to regulating schemes one might consider, especially those that have a long time constant such as the scanning

scheme that Dr. Beer proposed; i.e., what is the noise-power spectrum of the high-voltage fluctuations? What is the RMS amplitude fluctuation, that is, the function of the frequency of the fluctuations? Are they the fluctuations you would expect from a raw, unregulated power source? Are these fluctuations in voltage predominantly slow or predominantly fast?

J. M. Donhowe: They are of the order of one millisecond in the Van de Graaff that I was using. We controlled the voltage of the high-voltage terminal by sampling the current to the exit slits of the electrostatic analyzer with a 700-cps chopper. This frequency was dependent on the time of migration of negative ions (SF_6) from the corona needle at the pressure tank wall to the high-voltage terminal of the Van de Graaff. Fluctuations of the raw beam were no better than 0.1 %. Perhaps Dr. Langsdorf could comment on this, based on his experience with the ANL Van de Graaff.

A. Langsdorf: I made some measurements on our Van de Graaff and found that it has a natural hunting cycle—the whole feedback loop—between 40 and 80 cycles per second depending upon the gas pressure which determines the ion transit time, and the amplitude of the hunting is from one to two thousand volts operating at two million. That I think is characteristic of almost all Van de Graaffs. If you work very hard, you can make it better. Henry Newson presumably has his down to a few hundred volts.

Summary of Lens Systems for High-Voltage Electron Microscopes

DAVID COHEN

*University of Illinois at Chicago Circle
Chicago, Illinois*

General

The lens group has been involved in gathering information and exchanging ideas on lenses that could be used at higher accelerating voltages, such as 3 or 5 MeV. For purposes of reporting, we may think of the lens activities as divided into five categories.

- 1) Gathering information and evaluating "conventional" lenses, where "conventional" here means a round lens with an iron shroud and copper coils.
- 2) Gathering information and evaluating magnetic quadrupole lenses.
- 3) Gathering information and evaluating "round" superconducting lenses, where "round" is used to distinguish things from, say, superconducting quadrupoles.
- 4) Working out some problems involving aberrations in the accelerating column.
- 5) Exchanging ideas on how lenses at the higher voltages interact with other components of a microscope, such as the specimen chamber, recording stage, main support column, etc.

The fourth category, involving work of Mr. Moses and Dr. Symon, has already been reported this morning in Dr. Donhowe's high-voltage talk. I will briefly report on and perhaps compare the other categories, after which Dr. Hawkes and Dr. Laverick will give detailed reports on quadrupole and superconducting lenses, respectively, and Dr. Nixon will briefly discuss the fifth category.

Workshop Activities on Conventional Lenses

At the beginning of the Workshop, some of us thought it would be useful to have some sort of high-voltage standard or reference lens. This lens would be conventional, that is, iron and copper and round, and only using conservative and well-established techniques so that we could say "here is a lens that we certainly know we can build, and we know how it will work." We would then have a starting place, and we could compare superconducting lenses and quadrupoles with this reference to see what features are better or worse; that is, to know if a certain quadrupole lens or certain superconducting lens is relatively good or bad.

Dr. Tadano offered to present details of such a reference lens, and in fact had already just worked out the scheme for not only a single lens but also an entire lens column for an electron-beam energy of 3 MeV. This lens column should be viewed as a conservative and feasible structure, immediate constructability being the major advantage over other lens systems, and the major disadvantage being the inconveniences of large power consumption and weight, and not much possibility of further and interesting developments. We will first see the entire lens column, then look in detail at the 3 MeV reference lenses.

Figure 1 shows the accelerated electron beam entering the microscope column from the top, and some details of the column.

Figure 2 shows the 3 MeV reference objective lens which, again, is one of the lenses from the column of Fig. 1. This suggested design was derived by assuming the conservative current density of 100 amps/cm²; this assumption produces the stated weight and wattage of 1 ton and 2 kW, respectively. Dr. Foss recently pointed out that some newly developed copper-tubing techniques probably make it safe to increase the 100 amps/cm², perhaps to as much as 1000 amps/cm², without changing the focusing properties. In that case, he calculated that the copper weight could drop by a factor of 10 and the iron weight by a factor of 3, so that the one-ton weight drops to about 350 lb, but the power would rise from about 2 kW to about 15 kW. The lens power consumption for the entire 3 MeV column would change from about 12 kW to about 90 kW, but the total weight would drop from 6 or 7 tons to about 1 ton.

Dr. Tadano has also extrapolated the suggested 3 MeV design to 5 MeV, using also 100 amps/cm² for a conservative design. The numbers change as shown in Table I.

Dr. Tadano has pointed out that in going from 3 to 5 MeV, new mechanical difficulties appear, such as dimensional "creep" or change, because of the increased size and weight; but he believes that construction of such a 5 MeV lens is still feasible.

As with the 3 MeV case, changing from 100 to 1000 amps/cm² can trade weight for power. We will return to the Tadano 5 MeV extrapolated lens a bit farther on,

THIS DESIGN WAS MADE BY THE HITACHI ELECTRON MICROSCOPE GROUP IN MAY 1966 FOR AMU-ANL ELECTRON MICROSCOPE WORKSHOP.

FIG. 1. A First-order Suggested Design of a 3 MeV Electron-microscope Column, Using Conventional Lenses Only. The total lens weight is 6 or 7 tons, the total power consumption is about 12 kW, and the theoretical limiting resolution is about 1.5 Å.

$B_{MAX} = 25,000$ GAUSS
IN = 45,000 A.T.

THEORETICAL RESOLVING POWER

$\delta = 1.5 \text{ \AA}$
COIL WATTAGE = 2 kW
WEIGHT ≈ 1 TON

$f_o = 10$ mm
 $z_o = 5$ mm
 $c_s = 10$ mm
 $c_c = 6$ mm

FIG. 2. A Suggested Design of a Conventional 3 MeV Objective Lens. The wattage and weights were derived by assuming the conservative current density of 100 amps/cm².

as a standard for comparison with superconductors and quadrupoles.

Workshop Quadrupole Activities—General Comments

Nine or ten Workshop participants had a strong or direct interest in quadrupole magnet lens systems; a large amount of detailed calculation was done in the Workshop by Drs. Deltrap, Hawkes, and Meads, using the Meads aberration computation program. The calculations were executed by Dr. Meads on the 7094 Computers at both the Lawrence Radiation Laboratory (Berkeley) and The University of Chicago.

As we sorted out our thoughts on quadrupoles in the first week or so, it began to appear that we really didn't have three or four types of systems to consider and evaluate, but in fact had dozens of systems. That is, before choosing some systems to evaluate, we found it necessary to classify things, and found that there were a large number of groups and subgroups. I don't believe the quadrupole people had much occasion to do such classifying before. By classification, we mean there were triplets of this type and triplets of that type; there were many types of quadruplets, etc. If we speak of quadrupoles for high-voltage electron microscopes, do we consider symmetric doublets, or do we consider a particular type of quadruplet with one crossover in each plane?

TABLE I

	3 MeV	5 MeV
B_{max} , gauss	25,000	25,000
IN, ampere-turns	45,000	85,000
Wattage	2,000	8,000
Weight, tons	1	4
Diameter, mm	700	1,200
Height, mm	450	600
D , mm	10	10
s , mm	20	40
f_o , mm	10	14
z_o , mm	5	12
C_s , mm	10	20
C_c , mm	6	10
Resolution δ , $\text{\AA}$	1.5	1.2

Table II shows some aspects of classification, up to and including some quintuplets. The first column is only a partial division of combinations. For example, only two types of triplets are listed, yet the nonsymmetric triplet can, if we wished, be further subdivided into several symmetries which are not as severe as the "Symmetric Triplet." There are perhaps six symmetry types lumped into "Quadruplets (Other Symmetries)." Only two quintuplets are listed, although there may be a dozen or more symmetry types. Types of combinations are listed by names; these names refer to the

TABLE II. CLASSIFICATION OF QUADRUPOLE MAGNET COMBINATIONS

Each subgroup is further subdivided by the number of x and/or y crossovers. The two availability columns refer *only* to zero crossovers. There is almost no information on one or more crossovers.

Quadrupole Combination	No. of Elec. Knobs	No. of Mech. Choices	Availability of Linear Information	Availability of Aberration Information
Symmetric Doublet	1	2	Yes	Yes (ANL)
Nonsymmetric Doublet	2	3	Yes (ANL)	Yes (ANL)
Symmetric Triplet	2	2	Yes	No
Nonsymmetric Triplet	3	5	Some	Some (Wkshp)
Quadruplet (Multiple Doublet)	2	4	Yes	Yes (Wkshp)
Quadruplet (Russian)	2	4	Yes	Yes (Wkshp)
Quadruplet (Dhuicq)	2	4	Yes	No (?)
Quadruplet (Other Symmetries)	2-3	4-6	No	No
Quintuplet (Bauer)	5	9	Some (Wkshp)	Some (Wkshp)
Quintuplet (Strong)	5	9	Some (Wkshp)	Some (Wkshp)

groups (e.g., Russian) or investigator (e.g., Dr. Dhuicq) who first solved and published the linear properties.

Each combination can be further subdivided by the number of orbit crossovers for the particular double-focusing condition dealt with. For example, the symmetric triplet behaves differently for each crossover situation; four crossovers in x and/or y are a different lens than zero crossovers.

The second column shows the number of electrical "knobs" for the combinations listed. Each knob is meant to represent an independent magnet current control. There are both advantages and disadvantages to either less or more knobs. The symmetric doublet, for example, has only one electrical knob. This is a good thing for a microscope lens in terms of simplicity and convenience—an easy lens to use. However, that one knob is not enough to produce a stigmatic double-focus if the mechanical lengths of the magnets are not completely identical, and in practice some trimmer knobs would be necessary to electrically trim the mechanical lengths. Another way of looking at this is to say that the more electrical knobs inherent in a given system, the less trimming knobs are necessary.

The third column shows the number of mechanical choices for the combinations listed. Two choices, for example, means that two different lengths or spacings must be chosen. The pros and cons of less or more mechanical choices are complicated, and we will not discuss these here any further.

The last two columns list whether or not the linear and aberration properties are available for evaluation and comparison, but only for the case of no crossovers. None of the combinations has much useful and available information for more than zero crossovers. In these columns, "(ANL)" means the work of Drs. Meads and Cohen, which was reported at the opening session one month ago. "(Wkshp)" means that the work for zero crossovers was performed during the Workshop, using

the Meads' program, and will shortly be reported by Dr. Hawkes.

The number of quadrupole combinations is therefore large if one or more crossovers are taken into account, and in the Workshop it was decided to evaluate only those combinations that were guessed at as being promising. Some of the cases, as we shall see, turned out to be surprisingly good and very useful for high-voltage microscopy; there may well be combinations that are even better than those dealt with by the Workshop, and we recommend that more work be done in evaluating the aberrations of most of the combination-crossover situations.

Unfortunately, guesswork does not do too much in evaluating the aberrations. The number of parameters to be juggled around in one's head are too large, and one is forced to use an elaborate computing program, such as that of Dr. Meads. Mr. Moses, working with Dr. Symon, is formulating the aperture aberrations of quadrupoles in several new ways, and there is hope that he will find simplifications that will allow us to use easy rules for evaluating the aberrations.

One important combination is not listed in Table II because it contains a round lens. In the Workshop, we have called this combination the "Deltrap Corrector" because Deltrap was the first to have built and tried this combination. (It was, however, originally suggested by others.) It consists of four quadrupoles and three octopoles following a round lens. The round lens does nearly all the focussing, and the seven multipole magnets correct the round-lens aberrations. This system has some appeal because it allows "small" round lenses to be used at high voltages. For example, a 5 MeV objective would consist of a round lens powered for 0.5 MeV, followed by the Deltrap Corrector. The focal length of the "small" round lens would be large under these conditions and hence also the aperture aberrations. The appeal rests in the fact that for a variable-voltage,

high-voltage microscope, the round lens may be used uncorrected at, say, 1 MeV or less. As the voltage is increased, the Deltrap Corrector would be brought in and would play a larger part with the higher voltages.

We will soon show some advantages of quadrupoles for high-voltage objectives.

Activities on Relationship between Lenses and Other Components

It is difficult in a short time to cover all the work and discussions that took place in this category, and to list everyone's contribution. Drs. Marton, Nixon, and Tadano were especially active in general lens column arrangements. Some of their particular contributions will be presented in tomorrow morning's session.

Participants in the lens group had many opinions on many issues involving lenses and other components. In order to gather these opinions in some sort of meaningful way, a questionnaire was given to these participants. Here are some of the questions and answers:

- Q. What high-voltage range would be desirable?
 A. Variable, to 5 MeV maximum. (Unanimous)
 Lower limit 3 kV to 1 MeV. (Spread of answers)
- Q. What theoretical limiting lens resolution should we consider?
 A. 0.5 Å units to 2 Å units. (Spread of answers)
- Q. How many separate microscope columns would be advisable?
 A. At least two completely separated microscopes, each used for a different purpose. (Unanimous)
 Both of these microscopes would have interchangeable components.
- Q. What about general construction?
 A. A complete spread of answers all over the map, showing that this area involves quite a bit of individual tastes, and that engineering-design numbers cannot tell the whole story.

So much for a brief summary of the questionnaire. I would now like to discuss some Workshop activities in comparing different lenses. Earlier I had mentioned that Dr. Tadano had worked out a conventional lens design as a reference at 3 MeV, and that he extrapolated this design to 5 MeV. We will now compare a particular suggested superconducting lens and one of the better Russian Quadruplets with this particular reference lens, all at 5 MeV. Table III shows the comparison.

The first column of numbers lists the numbers I discussed a short time ago. The middle column of numbers is a particular 5 MeV, superconducting lens suggested by Drs. Tadano and Kitamura during the Workshop period. This lens will be discussed in some detail later by Dr. Laverick. For the moment, let me say that it is of fairly conservative design and uses Permandur shroud and pole pieces. The last column of

TABLE III. 5-MeV OBJECTIVE LENS COMPARISON

Lens Type	Conventional (Tadano)	Superconducting (Tadano-Kitamura)	Quadrupoles Russian Quadruplet
Outer diameter, in.	50	8	6
Length, in.	25	5	8
Weight, lb	8000	100	200
Wattage, W	18,000	15,000 (incl. cryo.)	500
Focal length, cm	1.4	<1.0	0.8 → 8.0
C_s , cm	2.0	0.3	~160
Resolution, Å	1.2	0.8	(3.5 (no corr.) 1.0 (with corr.))
Tolerances	Lax	?	Tight
Engineering problems	O.K.	Development nec.	O.K. except tol.
Feasibility	Probable-certain	Probable	Probable

numbers lists one of the better Russian quadruplets; better quadruplets than this one might well be found in the future.

The listed weights include the superconducting cryogenic container, and octopole correctors with quadrupoles. The wattage also includes the same items. The resolutions are, of course, only approximate, and there are two shown for the quadrupoles. The resolution of 3.5 Å units is for the case of no octopole correctors, while the insertion of two or more octopole correctors would certainly bring the resolution down to less than 1 Å unit. It is fairest to compare conventional and superconducting lenses without correctors to quadrupoles with correctors; this is because the aperture aberrations of a quadrupole system can be completely corrected with only octopoles, while round lenses need both quadrupole and octopole correctors. That is, it isn't much of a job to put in two octopole magnets with four quadrupoles, compared with adding four quadrupoles and three octopoles to a round lens.

The tolerances are listed as "Lax" for the conventional lens, "?" for the superconducting lens, because they had not yet been worked out (but one can guess that they will be somewhat tighter than for the conventional lens), and "Tight" for the quadrupoles. The latter numbers have not been scrutinized from the computing output as yet, but we know from previous studies that rotational tolerances, for example, are very severe. The comments in the category of Engineering Problems reflect some of the above points. Quite a bit of development work would be necessary to evolve a good, high-resolution, 5 MeV superconducting lens, and the tolerance problems would have to be dealt with for the quadrupole system.

The comments on Feasibility reflect the Workshop

FIG. 3. Magnetic Shield System to Reduce Outer $\Delta B = 10^{-3}$ gauss to inner $\Delta B < 10^{-6}$ gauss (Suggested by D. Cohen, July 11 1966).

optimism on the 5 MeV lens problem. If a conventional 5 MeV lens were to be built, it is almost certain to be a good workable lens; quite probably, 5 MeV superconducting lenses and quadrupole quadruplets would make good workable objectives. With some development work, the superconducting and/or quadrupole quadruplet lens would be preferable to the conventional lens in almost every category.

I would now like to discuss a particular topic in this category (of the relationship between lenses and the rest of the microscope) in which I have been especially interested during the past several years; this particular topic is the technology of magnetic shielding.

For a high-voltage microscope, we are forced to ask the following question: How much magnetic fluctuation (say in gauss) can be tolerated along the electron path? Dr. Möllenstedt deals with this question quite generally in a recent paper in *J. Microscopie* **4**, 413 (1965). He shows, for example, that if one wishes to have a resolution of $0.4 \text{ \AA}$ units at 50 kV and an objective focal length of 2.4 cm, then fluctuations greater than 0.8×10^{-7} gauss cannot be tolerated. He calculated this number by restricting the phase shifts of the fringes to be less than $\pi/10$ at the image, and assuming an object with repetitive structure, such as a crystal. Dr. Hawkes made the same calculation a few days ago for 5 MeV,

and arrived at a limiting fluctuation of about 1×10^{-6} gauss. Dr. Zeitler pointed out that the same physics is really used when the object structure is not repetitive, for example, a single molecule. So we may conclude: If one wishes a theoretical limiting resolution of less than $1 \text{ \AA}$ unit for a microscope with variable energy up to 5 MeV, for any kind of object structure, then the maximum allowable magnetic-field fluctuation averaged over the electron flight path is about 1×10^{-6} gauss. A safe and conservative restriction would probably be about 1×10^{-7} gauss, although 1×10^{-6} gauss may be good enough.

This takes us into the technological area of large-volume magnetic shielding. Until a few years ago, people did not like this area because the engineering problems were considered formidable. For example, magnetically-shielded rooms had not been very successful. A few years ago, however, Mr. Robert Patton of the Socony Oil Research Laboratory in Dallas, Texas, experimented with various types of high-permeability joints and found a technique that worked. He then built a two-layer shielded room with moly-permalloy, which was successful in the sense that it behaved as theory said it should, and four or five copies of this room have now been successfully built. Figure 3 shows how this technique could be used to shield the electrons in a high-

voltage microscope. Two layers of shielding are involved, using angles and joints with a square cross section preferred to cylinders. This is because of annealing difficulties with curved surfaces in the currently available ovens.

Let me explain the use of solenoids shown in Fig. 3. It is a little-known fact, however important, that the maximum permeability of ferromagnetic material occurs at zero field if one is only considering small fluctuations. The familiar curve of permeability versus field, where the permeability has a maximum at several thousand gauss, only applies to large hysteresis loops and not small incremental permeability loops. The permeability involved with small changes of magnetic field is a maximum at zero field inside the ferromagnetic material, and drops quite rapidly with increasing "d.c. bias," so that if shields are to be effective against fluctuations, they must involve only small fields inside the material. For the suggested design in Fig. 3, the earth's field can easily produce several hundred gauss or more within the material of the outer shield, and so a simple solenoid is shown which is meant to roughly buck out the earth's field and allow the outer shield to operate at maximum permeability. It is supposed that there is a one-inch steel cylinder wall for the lens column of the

microscope, and this structural wall performs the magnetic function of partially shielding the inner permalloy layer from the fringing fields of the lenses; a solenoid system immediately outside this cylinder would complete the job of keeping the stray fields out of the inner layer.

The suggested shielding system is easily disassembled, and has a shielding factor of more than 1000. It is assumed that a similar two-layer shield would exist around the high-voltage section, although the size would, of course, be greater.

There appears to be no published data on the magnetic noise within an enclosure generated by the inner wall of that enclosure. That is, the shielding factor alone does not tell the whole story, and one must consider the new source of magnetic fluctuations produced by the shield itself. Several phenomena which could be involved in producing such fluctuations are the spontaneous flipping of ferromagnetic domains, and seismically-produced vibrations of the inner walls. Some measurements should be made within large-volume magnetic shields of the noises produced by the inner walls before one can safely design the shielding for a 1 Å electron microscope.

The Roles of Quadrupole Lenses and Quadrupole Correctors in High-Voltage Microscopy

PETER W. HAWKES

*University of Cambridge
Cambridge, England*

During the past few weeks, three of us (Deltrap, Meads, and myself) have been studying the properties of quadrupole-lens combinations with a view to using them in the high-voltage microscope either as complete lenses or as correctors for normal or superconducting round lenses. I should like to make it clear from the outset that all the computations I shall describe were performed by Dr. Meads, using the IBM 7094 program he, himself, wrote, and without this program, few if any of these results could have been obtained.

The rectangular model is used throughout. If a different model is used, the results will be different numerically, of course, but I see no reason why the trends we have uncovered should not be maintained.

At very high voltages, conventional round lenses have a number of shortcomings: they are heavy, their focal lengths increase and their spherical aberration becomes large. These can only be overcome by sacrificing many of their convenient features, in particular, their relatively simple construction and their freedom from first-order astigmatism.

These drawbacks of conventional round lenses used at very high voltages can be avoided by introducing quadrupole systems for two reasons. Firstly, quadrupole lenses focus the beam directly, whereas the focusing property of round lenses is a differential effect. This means that in any given situation, the excitations of quadrupole lenses will be rather lower than those of their round counterparts. Secondly, quadrupole lenses are probably the simplest kind of lenses with which spherical aberration can be completely cancelled.

We have tried therefore to design quadrupole systems that are similar in action to round lenses; that is to say, they produce undistorted images and are free of first-order astigmatism, but they differ from round lenses in one way. Their spherical aberration is no longer a necessary evil, for with the aid of octupoles, this aberration can be wholly corrected. Quadrupoles therefore offer two major advantages, despite the fact that they introduce formidable new problems, concerned with alignment and the task of altering the focal lengths: with them, spherical aberration can, in principle, be reduced to an unlimited extent, and the maximum magnetic fields are still manageably small.

Let me now describe the quadrupole combinations we have analyzed and the reasons why we have selected these from the large number mentioned by Dr. Cohen. There are (at least) two schools of thought concerning quadrupoles. The first school reasons along the following lines.

Round lenses can be improved if a corrector is added to them which cancels their spherical aberration just as a stigmator cancels their astigmatism. One convenient way of designing such a corrector obliges us to depart from rotational symmetry. The beam is thus astigmatic in some region, and in this region the aberrations of octupoles are superimposed on to those of the quadrupoles. The sums of these aberrations can be controlled independently so that if they are arranged to be equal and opposite to those of the round lens, the aggregate spherical aberration will vanish. This has been the attitude of Dr. Deltrap, and he has designed a four-quadrupole system for use with a high-voltage, electron-microscope round lens. Such a corrector might be used in conjunction with a lens that works well at 1 or 2 MeV, say, and it could be made to improve the lens considerably, whatever the accelerating voltage.

A general view of a magnetic quadruplet is shown in Fig. 1. The optical properties of various possible correctors have been computed by Dr. Meads; two of these take advantage of the presence of the quadrupoles to shorten the focal length of the round lens. I shall describe this system in more detail later.

Let me now describe the attitude of the second school of thought, to which I belong. If we have to tolerate the inconvenience of quadrupoles anyway, can they not be used to do all the focusing required so that the round lens can be eliminated? More exactly, can a quadrupole system be designed to give much the same focal length as the ideal round lens we should have used if it had been available, and with small enough geometric aberrations for correction to be feasible without our having to use intensely strong octupoles? The reason why the latter are undesirable is that octupoles are difficult to align and adjust and the fewer sources of parasitic aberrations, the better! If we can design such a quadrupole combination, how can we ensure that it is convenient to use in practice? We must arrange it in such a way

FIG. 1. Magnetic Quadrupole Quadruplets (July 12, 1966)

that the focal length can be changed fairly easily and that such changes will not spoil the good correction conditions.

So much for our general approach, then. I shall now describe in detail the various systems we propose.

The Quadrupole Corrector

Let me now describe the corrector which Dr. Deltrap has designed for use with a round lens. One such system was in fact built by Dr. Deltrap in Cambridge in 1963 and was shown to work well. This type of corrector was first proposed by Archard in 1955. Dr. Deltrap's specific suggestions for the high voltage microscope are shown in Figs. 2 to 6.

Figure 2 shows the general appearance of a quadrupole for use at 5 MeV, and Fig. 3 shows a quadrupole-octupole unit. To give you some idea of the scale of these quadrupoles, this cylinder, kindly lent by Dr. Crewe, contains two quadrupoles and three octupoles; it could cope with 2 MeV electrons. Figure 4 shows how four of these quadrupole-octupole units would be combined to form a corrector. The details of three

FIG. 3. 5 MeV Quadrupole-Octupole Combination (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 2. 5 MeV Quadrupole (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 4. Quadrupole-Octupole Corrector (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 5a. One-, Two-, and Three-Power Telescopic Systems (Suggested by J. H. M. Deltrap, July 9, 1966).

possible correction systems are shown in Fig. 5a. Each of these behaves like a telescope; that is, a parallel incident beam emerges from the system parallel to the axis. However, the height of the emergent beam differs in the three cases and the three correctors behave like a one-, two-, or three-power telescope. Ray paths through the two- and three-power systems are illustrated in Figs. 5b and 5c (taken directly from the oscilloscope plotter attached to the IBM computer). The aberrations of the quadrupoles in these combinations, when referred to the focal plane of the round lens they are designed to correct, are roughly equal to one another and of the same order of magnitude as the spherical aberration of the round lens.

The role of the octupoles, therefore, is to introduce new aberrations opposite in sign to those of the quadrupoles, but roughly equal to them in magnitude, so that the total aberrations in the focal plane of the round lens are very small, or, ideally, zero. A practical difficulty, incidentally, is that the present-day methods of measuring spherical aberration are not sensitive enough to tell us when correction has been satisfactorily achieved.

The excitations and geometric parameters are shown in Fig. 6 for the two-power and three-power cases, and the numbers corresponding to the excitations are very easily obtainable. With the three-power corrector, the

2 MeV lens described by Tadano could be used at 5 MeV, and any conventional lens could only benefit from a good corrector of this kind.

Quadrupoles as Objective Lenses

The problem of designing quadrupole combinations capable of performing as well as, or preferably better than, a round-lens objective has been attacked by a

FIG. 5b. Beam Profile Plotted by a Computer

FIG. 5c. Beam Profile Plotted by a Computer

number of groups—notably in Leningrad, East Germany, Paris, Cambridge, and, with projector lenses in mind, in Professor Siegel's laboratory here in the United States.

Let us consider what quadrupole systems are available. Why should we choose one system rather than another? The optical properties of quadrupole combinations depend acutely upon their symmetry; before describing the kind of combination we believe to be best adapted to the present task, I will explain briefly what I mean by this.

An isolated quadrupole possesses two planes of symmetry. An electron moving in either of these planes remains in it but follows a different path in each. The focal lengths and focal distances are thus different in these planes, and if combinations are to be used having equal focal lengths and distances (so that their gaussian properties are identical with those of a round lens), the various excitations will be interrelated. For certain quadrupole combinations these relationships are relatively simple. Any system containing an even number of lenses and arranged so that the second half of the system is a mirror image of the first half, both electrically and geometrically, except that the polarities are reversed in the second half, has the following important properties: The object and image cardinal elements are situated symmetrically about the center of the system, and the x and y focal lengths are equal. The two independent excitations have then to be chosen only so that the foci coincide and lie outside the lens field. We have therefore concentrated on quadrupoles possessing this symmetry, which I shall call "Russian quadruplets," since their properties were first elucidated by a Russian team in Leningrad. Figure 7 shows schematically the general arrangement.

We have studied the third-order properties of a very

FIG. 6. Telescopic Corrector Systems Used with Round Lens (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 7. The Russian Quadruplet

FIG. 8. Dependence of Spherical Aberration on Drift Space

wide range of high-magnification Russian quadruplets varying all the numerous geometric parameters, and we have found a most significant dependence of the minimum value* of C_s/f upon the lens lengths and drift spaces between them. We have always required the computer to calculate the pair of excitations for which the foci both lie at the end-face of the last quadrupole, for each set of geometrical parameters; having obtained these excitations, we then compute all the aberration coefficients for a parallel incident beam.

If I had given this talk yesterday, I should have told you (with considerable pride at having discovered it) that the following system is one of the best obtainable:

The ratio C_s/f for this system is 177, and you will realize that this is very good when I tell you that in Paris, M. Dhucq is correcting a similar lens with the aid of octupoles for which C_s/f is equal to 48,920.† However, when we plotted the dependence of C_s/f upon the central drift space, we obtained a curve as in Fig. 8, where the particular system is the lowest point on the curve. We immediately wondered whether the curve continued to drop towards the origin if the central drift was made still shorter.

Last night, therefore, Dr. Meads went into Chicago to see how C_s/f varies when we continue to reduce this parameter. He found a further dramatic improvement, so that with a quadruplet consisting of four quadrupoles in contact, their length chosen so that the second and third quadrupoles are about twice as long as the first and fourth, C_s/f can be as small as 32 (Fig. 9). For

* The number I call C_s is the largest of the aperture aberration coefficients.

† The comparison is not wholly fair, since he uses much higher excitations than we do, which enables him to obtain much smaller f/L ratios (L = length of first quadrupole).

FIG. 9. Quadruplet for Low Spherical Aberration

FIG. 10. The Multiple Doublet (Suggested by P. F. Meads, July 4, 1966).

FIG. 11. Beam Profile Plotted by a Computer

such a lens, the focal length is 2.8 in. when the first quadrupole is $\frac{3}{4}$ inch long. This compares very favorably with the kind of round lens that has been proposed for a 5 MeV microscope. Since the resolution depends upon the one-fourth power of the spherical aberration, such a quadruplet will resolve almost as well as the round lens for a considerable saving in weight, volume, and excitation. Furthermore, there is no way of correcting the round lens without introducing quadrupoles and octupoles, whereas for the quadruplet, such small aperture aberrations could be easily overcome by weakly excited octupoles. I think you will agree that such a quadruplet is worth investigating further.

Although we devoted most of our time to the Deltrap corrector and the Russian quadruplet, we have considered a few other systems. The triplet was the first of these. We did not expect it to be very useful because the

first-order requirements can be satisfied only if three excitations are independently variable, whereas in the quadruplet systems there are only two independently variable excitations. Of the triplets we examined, none had its foci outside the system; therefore these combinations could be used solely as projector lenses.

We also considered a system suggested by Dr. Meads (Fig. 10), which we have called the "multiple doublet"

FIG. 12. Beam Profile Plotted by a Computer

FIG. 13. Beam Profile Plotted by a Computer

because it consists of two identical doublets placed one behind the other, the second rotated through 90° with respect to the first. Such a combination has only two independent excitations, and if the distances are arranged as shown in Fig. 10, the system will be automatically orthomorphic, since the magnifications of the second doublet are equal and opposite to those of the first. Such a system might perhaps be used as a replacement for the conventional condenser lens. We have found sets of excitations and drift spaces for which the effective source size is most satisfactory, but a lot more work would have to be done on this kind of system before it could be used in practice, for, as Dr. Nixon has pointed out, the quality of the electron beam is erratic in a microscope near the electron source, and the beam might well be difficult to "condense" with quadrupoles.

We also considered quadruplets similar to the Russian quadruplet so far as the sequence of excitations is concerned, but different from the Russian quadruplet in that the first and third drift spaces are not equal. By altering these lengths, we are deliberately throwing away the convenient first-order properties of the Russian arrangement, but it seemed worthwhile to see whether such combinations can have even lower C_s/f ratios than the Russian system as such a lens might be convenient for some special purpose. However, even when the foci coincide and the focal lengths are equal in image space, the foci are still separated in object space, and this means that such a combination will be difficult to use in practice.

With such a quadruplet we found that C_s/f can be

even smaller than the best Russian quadruplet. The best value we encountered was 26.54.

Finally, I should mention that we examined the properties of a five-quadrupole combination, the quintuplet, which promises to be of interest because such a combination is being successfully used by Bauer in Professor Recknagel's laboratory in Dresden. I shall not quote the figures we obtained here, but Figs. 11 and 12 show the traces through such a combination. In fact, we calculated the properties of a pair of triplets, and then the computer removed one of the quadrupoles without altering the first-order properties. We have considered two sequences of polarities: in one, the polarities alternate through the system (Bauer's arrangement); in the other, the diverging planes of the second doublet lens and the first triplet lens are the same.

To sum up, therefore, quadrupoles seem potentially useful in high-voltage microscopy in two very different ways. Perhaps their most immediate use is as correction systems. Such a corrector would be useful at any voltage, and it would probably be convenient to use the corrector both to reduce spherical aberration and to shorten the focal lengths of round lenses at these high voltages. The more exciting proposition, however, is to use quadrupoles alone. Figure 13 shows ray traces for the best Russian quadruplet, and I hope that the figures that we have obtained will have convinced you that there are indeed quadrupole combinations, which (even without the octupoles, which are normally regarded as obligatory when quadrupoles are being used) can rival the image-forming qualities of round lenses.

Superconducting Lens Studies

CHARLES LAVERICK

Argonne National Laboratory

It is true that with a bit of luck and a lot of support from Argonne, we've made large magnets practical. The superconducting magnet business really began in 1961, although, of course, Kamerlingh Onnes began the business way back in 1911. In fact, he didn't just discover superconductivity—he was looking for it and found it, which was very good. Drs. Fernandez-Moran, Tadano, Kitamura, Foss and the other experts here are really the people whom I'm representing and speaking for, although perhaps I will misrepresent them enough to put in an original contribution of some sort.

The great thing about an electron microscope is that it is one of the best measuring devices for checking lenses, and so it is really the finished picture, which shows whether or not the lens is any good. Dr. Fernandez-Moran has been able now, for almost two years, to demonstrate in practical electron microscopes the feasibility of superconducting lenses.

The advantages of the superconducting lenses are:

- 1) High current density
- 2) High magnetic field
- 3) High stability
- 4) Low weight
- 5) Compactness
- 6) Controlled low-temperature environment

The disadvantages are:

- 1) Liquid-helium environment.
- 2) Low-temperature refrigeration system.
- 3) A new technology to which microscopists must adapt.

It was obvious during the workshop that a number of skeptics still tended to think that superconducting magnets were things you built and played with. Therefore, outside in the lobby, arranged so you don't quite fall over them, are a number of large superconducting magnets, which work very well. In fact, the biggest is a 30-kG system with 10,000 ft of cable, and a total cost of probably something around \$25,000. The 4-inch coil outside contains another new conductor, also first wound and operated during the period of this workshop. It demonstrates that heavy section niobium titanium can, in fact, be stabilized and used in coils. The coil operated at 1,300 amps in a central field of about 55 kG for a current density of 9,000 amps per square centimeter. There are also two small coils, two of the several hun-

dred I made and tested in the early days, and these coils are about the size that will be required for electron microscopes. The current densities, averaged throughout the coils, ranged from something like 20–45,000 amps per square centimeter, which is some advance over the 100 amps per square centimeter that can be obtained with copper in microscope systems.

The systems will be smaller and probably easier to construct, align, and so on.

Typical possibilities for superconducting systems are:

- a) Replace windings of conventional coils with high-density, superconducting windings.
- b) As a), above, but work at 50 to 70 kG with high-saturation-field ferromagnetic material as insert between coil and iron.
- c) Use opposing currents in coils adjacent to the main coils to reduce half-width of the field-axial length characteristic. Iron can still be used for screening and containment.
- d) Use superconductors in bulk forms with induced persistent currents, with or without iron.

I suggest, in (a) above, that if you replace the winding of the conventional coils with high-density superconducting windings and do nothing else, you should have a good lens—a very compact lens. There are now two possibilities: Merely cool the winding down as Dr. Crewe wanted to do with a lens recently, in which case the iron is at room temperature, and those of you who feel you have specimen loading problems will only have the same problems you have now. Alternatively, do as Dr. Tadano and others have suggested, and cool the iron.

In (b) above, the suggestion is to work at 50 to 70 kG with high-saturation-field ferromagnetic materials inserted between the coil and the iron to give you a good field profile by preventing saturation in the region between the coil and the iron. This has already been proposed, and later I shall discuss a design of this type. The other possibility, is to use opposing currents in trimming coils which are adjacent to the main coils. This reduces the field near the central coil. Iron can be used with this system because there will now be repulsive force between the various coils. If the coils are used without any iron, satisfactory lenses can be made and the system made much lighter, as Dr. Foss has pointed

out. If you do this, some severe errors introduced in the winding have to be examined and overcome. Alternatively, one can use the trimming coils to replace the dysprosium or holmium which is proposed for the 60–70 kG system and this, again, will have the effect of reducing the saturation in that region while maintaining the actual field profile.

Superconductors can also be used in bulk form. In this case, one induces persistent currents and uses the systems with or without iron. The advantage here is that now you use an external field to induce the persistent current system in the bulk material, and this is now a permanent magnet. The disadvantage, which has been mentioned by Dr. Grivet and during the last week here in my conversations with Dr. Foss, is this question of how one knows that the persistent current will follow the same path each time the system is charged or discharged. Dr. Kitamura has an answer to that one, which is to make, very carefully, very small disks with very thin films of superconductor, which are also very thin in the radial as well as the axial direction. However, there is some feeling that if one just uses coils with persistent switches, the system is easier to control. My experience has been that the sort of innovation that has led to the dramatic growth in the use of superconducting magnets has come about by people trying things, and so I prefer not to recommend only one direction of development.

Now I'm listing here some of the problem areas as I see them, but first, I would like to mention that Dr. Fernandez-Moran in 1965, Dr. Tadano during this conference, and others elsewhere, have shown that superconductors can be used in microscope lenses.

The problem areas are as follows:

- 1) Superconducting lenses (conventional design) are not yet as good as commercially available lenses (resolution).
- 2) At highest resolution, Dr. Tadano has had problems, as yet unsolved, due to vibration associated with helium boiling. This should be $\leq 2 \text{ \AA}/\text{min}$.
- 3) High stability is difficult to attain because of change in temperature distribution near objective and specimen.
- 4) Symmetrical superconducting lenses are difficult to make; this may give high astigmatism.

The problem there is that superconducting lenses are not yet as good as commercially available conventional lenses and resolutions. They're good, as Dr. Fernandez-Moran will show you later. They are almost there, but not quite. Now, Dr. Tadano has had problems due to vibrations associated with helium boiling. He considers that the vibrations should be less than $2 \text{ \AA}/\text{min}$. (He actually said $1 \text{ \AA}/\frac{1}{2} \text{ min}$, but since I was the draftsman, it was easier to write the former.) He thinks that high

stability is difficult to obtain because of changes in the temperature distribution between objective lens and specimen. The figure I recall is that the temperature stability for something like half a minute should be about 0.0001°C , and this is the temperature stability that is necessary for the very highest resolution. There is this other comment, again from Dr. Tadano, which is that symmetrical superconducting lenses are difficult to make; and this may lead to higher astigmatism. Dr. Foss has looked into this and indeed it is so, but the lenses can be made; and of course, if one can use iron without saturation, many of the errors inherent in the coils are smothered out by the influence of the iron. This would be one argument in favor of trying to use iron or some other paramagnetic material below the saturation level.

Here are some interesting points for consideration by people who wish to design high-resolution, high-voltage microscopes.

- 1) A 1- or 2-cm change in focal length has little effect on column length.
- 2) High fields are required to give short f_0 .
- 3) Short f_0 minimizes C_s .
- 4) A good, low field shape at $f_0 \sim 1 \text{ cm}$, $B \sim 20\text{--}25 \text{ kG}$, is better than a poor, high field shape at $f_0 \sim 0.7 \text{ cm}$.
- 5) Bell-shaped field profiles are better than rectangular profiles of equal $\int B dl$.
- 6) Improvements in voltage stability yield greater dividends in final performance than increases in B .

At first it looked to me as though one or two centimeters change in focal length had little effect on the length of the column but a large effect on the aberration. There are many arguments for making the focal length as small as possible throughout. However, since the columns in some cases are higher than many buildings, if there are advantages to be gained by using slightly longer focal lengths (say by changing five millimeters into ten), then I think that this may make the lens design problems easier while having little effect on column length. It is obvious that high fields are required to give short focal length, yet short focal lengths minimize the aberrations. However, it would appear to me—again, without claiming to be an expert—that a good low field stage with a one-centimeter focal length at 25 kG would be much better than a poor high field stage, say 0.7 centimeter with 70 kG. Now, again I do not want to do any other than present ideas. Dr. Fernandez-Moran has stated “Well, we're so near every limit on this instrument, that we should do the best we can everywhere.” Perhaps that is what we really should do. During the conference I asked the question, “What sort of field profile do you like?” since with good luck and some help, I could probably design the right field

Fig. 1. Layout of ANL Coil Construction Facilities

profile or the desired field profile. The question was put to three experts. There were three possible answers, and I received each answer with sufficient reference to prove that they were right. Dr. Butler, with the use of his computer program, came to the conclusion that the bell-shaped axial field distribution was the best possible shape. Most of the experts (independently, I must say) also came to this conclusion, reading different books. Thus, bell-shaped field profiles are better than rectangular field profiles of equal f Bdl. Bell-shaped profiles have specific definitions and meanings for electron microscopes. The thing which impressed me (this has nothing to do with superconducting lens design) is that improvements in voltage stability seem to yield greater dividends in final performance than increasing the field strength in the lens. For instance, if the $\Delta V/V = 10^{-7}$ could be obtained, the lens problem would be trivial. However, again, many of you pointed out that indeed,

that is probably not attainable, so I suppose we should try to make the best lenses.

I came to try to find out how we should go about doing something. It was immediately obvious that everyone had a different opinion, so I grouped them conveniently as pessimists or optimists. Assuming that one seriously wants to build a microscope, and at the time the microscope has to be built, has given up on the quadrupole lenses that look so very promising or on the conventional lenses that work, then here would be a way of doing it according to the people I've marked down as realists or pessimists. The suggested development plan A (realists or pessimists) is:

- 1) Use conventional lenses if a microscope must operate at high resolution as soon as possible.
- 2) Use superconducting windings with conventional yokes until current lens performance is equalled or bettered.

FIG. 2. Supercon Nb25%Zr and Nb33%Zr Short Sample Characteristics for 0.010-in.-diam Wire

- 3) Develop high field systems, with or without ferromagnetic yokes.
- 4) Investigate the possibilities of fully superconducting ring systems with permanent circulating currents.
- 5) Improve superconducting contact design.
- 6) Develop refined current-controlling systems.
- 7) Develop lens-correction systems.

The next important thing is to include superconducting contact designs. If very high-current persistent superconducting joints have to be made at zero resistance, then all one really needs is a ring of superconductor and a heater. Charge up the ring by switching off the heater in an external magnetic field; then, if the joint is good enough, you can have 10,000 amps or so circulating in the superconductor. If made correctly, one can, I think, hopefully attain 100,000 amps per square centimeter at 50 kG or 100 kG with bulk niobium-tin. I've listed also that we should develop refined current-controlling systems, and the reason for saying this is that Dr. Foss, among others, has said, "Well, there's something nice about coils—you can always change the current, and you can always control the current, and maybe, you don't always need a precision fit." But whether you do or don't, we have the capacity with zero-resistance coils to make very sophisticated current-controlling systems, if required. Then, I've also said, develop lens correction systems. This is

especially necessary if we discard the iron completely, which might be silly, but is worth thinking about.

Now having called the other people pessimists or realists, I thought I'd better call these optimists or realists. These include Drs. Crewe and Fernandez-Moran, for certain. Development plan B (optimists or realists) is:

- 1) Install conventional type lenses with superconducting coils immediately because
 - a) They are already almost as good as conventional lenses.
 - b) Working supermagnets are now a fact of life.
- 2) Develop acceptable high field systems as soon as possible.

Commenting on the statements, 1a and 1b, I would say that 1a-1b is probably the way Dr. Fernandez-Moran would put it, and 1b-1a is probably the way Dr. Crewe would put it. On the other hand, perhaps neither of them would put it that way at all. Perhaps an even better way would be to design these lenses for 1 MeV only (since this results in a further gain in size), and use the Deltrap quadrupole corrector if, in fact, theory holds out in practice. Since it takes some time to make a proposal, and since it is possible to move quickly in this business, I don't think this is such a silly approach; but it remains for those who have the decisions to make, to judge.

Dr. Fernandez-Moran suggested that the magnet display outside might show you that things are really

FIG. 3. Supercon NbTi Short Sample Characteristics for 0.010-in.-diam Wire.

FIG. 4. RCA Nb₃Sn Ribbon Short Sample Characteristics for 0.00025-in.-thick Nb₃Sn Deposited on 0.002-in.-thick Hastelloy and Electroplated with 0.001-in. Niobium.

in a practical state; consequently, Fig. 1 shows a general view of the ANL workshop from which you can see that, at least in Argonne, we are able to make these magnets easily and fairly quickly.

Present-day superconducting magnets use either NbZr, NbTi, or NbSn as the superconducting material, and the choice is governed by the magnetic field desired and the economics of the situation. The upper critical fields and critical temperatures for these materials are: NbZr ~ 60 kG, $T_c \sim 10^\circ\text{K}$; NbTi ~ 120 kG, $T_c \sim 9^\circ\text{K}$; Nb₃Sn ~ 300 kG, $T_c \sim 18^\circ\text{K}$. At 20 to 30 kG, NbZr is cheapest at present prices and Nb₃Sn is most expensive, but the materials-supply situation is highly competitive and the economics situation can change overnight.

The transition from the normally conducting to the superconductor is governed by the magnetic field, temperature, or current density. An excess of any one of the quantities or some combination of these is sufficient

to cause a rapid transition. It is usual to discuss the current-carrying capacity of a superconductor in terms of its short sample characteristic. This is the current-

FIG. 5. Short Sample Characteristics of Brittle General Electric Cables of Nb₃Sn Formed by Heat Treating 7- and 49-strand Tin-coated 0.003-in. Niobium.

FIG. 6. Short Sample Characteristics of General Electric Flexible Nb₃Sn Tape with 0.001-in. Copper Strips Soldered to Each Side of $\frac{1}{2}$ -in.-wide, 0.00009-in.-Thick Nb₃Sn Strip Formed in a 0.002-in.-thick Niobium Core.

carrying capacity of a short sample of the material tested in liquid helium and plotted as a function of the magnetic field. These characteristics are normally obtained by increasing the current through the specimen at given values of field until a transition occurs. They can also be obtained by increasing the field through the specimen at certain fields or by varying field and current together. The characteristics obtained by these various methods may not always agree. The current-carrying capacities of typical commercial materials as a function of magnetic field at 4.2°K are given in Figs. 2-6. Current densities where quoted are for the superconductor and are not averaged over the total cross section of the conductor.

The current-carrying capacities of NbZr wires are enhanced by heat treatment, but heat-treatment durations in excess of 8 min at 600°C for NbZr can cause embrittlement of the material even though the current-carrying capacity is enhanced.

The temperature of the superconductor has a profound effect upon its short sample characteristic. Momentary rapid increases of temperature occur in small local regions of a superconducting wire as the magnetic field or current is increased, and these increases are due to sudden re-adjustments in the distribution of mag-

FIG. 7. Variation of Short Sample Characteristics with Operating Temperatures (Graph by courtesy of Z. J. J. Stekly of AVCO).

FIG. 8. Variation of Resolution with Accelerating Voltage for Various Volumes of $\Delta V/V$ (by courtesy of N. Kitamura).

FIG. 9. Variation of Resolution with $\Delta V/V$ for Various Volumes of Peak Sample Fields (by courtesy of N. Kitamura).

netic flux within the superconductor. Known as flux jumps, these local hot spots can cause large changes in the operating characteristics of a superconducting wire and even result in premature transitions to the normal conducting state at low currents. The effect of temperature changes on the short sample characteristics of NbZr is shown in Fig. 7.

Figure 8 shows resolution against accelerating voltage for $K^2 = 3$ at 30 kG. At 5 MeV and the 1 Å, 1 Å can be

FIG. 10. Variation of Half-width with Peak Sample Field or Various Volumes of Accelerating Voltage and Field Gradient.

FIG. 11. Variation of Spherical Aberration with Peak Sample Field for Various Volumes of Accelerating Voltage and Field Gradient.

FIG. 12. Typical Pole-Piece Arrangements and Axial Field Distribution for Conventional and Superconducting Pole-Pieces

obtained theoretically at least with a $\Delta V/V = 10^{-6}$; $2 \text{ \AA}$ is not obtainable with $\Delta V/V = 10^{-5}$.

For a bell-shaped field, at 5 MeV with $K^2 = 3$, we need 80 kG central field at $\Delta V/V = 10^{-6}$; 10 kG is adequate at $\Delta V/V = 10^{-7}$ (Fig. 9).

In comparing half-width of axial field, a , with peak central field H_0 for various values of accelerating voltage (Fig. 10), we see that for a half width of 0.7 cm at a peak field of 70 kG, a field gradient of 60 kG/cm is required for a bell-shaped field with $k^2 = 3$. Similarly (Fig. 11) for 70 kG central field at 60 kG/cm ($k^2 = 3$), the spherical aberration at 5 MeV $\approx 3 \text{ mm}$.

The above results are theoretical only, but indicate desirable practical configurations. Typical field profiles and pole arrangements for conventional and superconducting lenses are shown in Fig. 12. Naturally superconducting windings can be used with a conventional pole piece in the region up to about 20 kG, but the superconducting arrangement with the coil surrounded by iron is better at higher fields, since less iron is in the saturation region. The increase in field gradient and in peak field, obtained when a winding of the type shown as superconducting in Fig. 12 is used with iron, is shown in Fig. 13, although this is for the lower field region up to 20 kG. At higher fields, the field profile would deteriorate because of saturation effects in the iron. The values of Fig. 13 are measured values obtained with a trapped flux system built up from thin discs of Nb_3Sn deposited on platinum.

Some parameters for superconducting objective lenses have been listed in Tables I and II by Dr. Kitamura. Table I gives some calculated fields and field gradients for some possible systems for 100 to 1000 kV. The various parameters of a superconducting objective lens for various accelerating voltages and maximum fields are estimated in Table II. The variations in spherical aberration with peak central field for rectangular and bell-shaped field profiles are given in Fig. 14, from which it can be seen that bell-shaped profiles are preferable.

The superconducting discs used at Cornell consist of thin films of vapor deposited Nb_3Sn on platinum discs. The film is cut into a large number of circular annuli to confine the circulating currents to circular paths. These discs have to be made precisely. A number of these discs are then stacked together to make a coil.

When a trapped flux system is enclosed on two sides by other discs containing circulating currents to form a coaxial system of three sets of circular discs, the field due to the central disc system can then be compressed by moving one or both sets of outer discs axially with respect to the central disc. The results of a typical experiment of this type are portrayed in Fig. 15, where

FIG. 13. Axial Field Profile Produced by a Stack of 100 Nb_3Sn Discs with and without Pole Pieces.

the axial positions of the discs are shown and the variation in axial field profile with axial position of the compressing discs is also shown. Thus this is one possible technique for adjusting focal length, but there will be additional problems at 70 kG. A possible objection to these trapped flux systems is that the motion may not be identical each time the position of a movable disc is changed, so that slight differences in circulating current and field profile may occur for what are supposed to be identical adjustments.

The Tadano-Kitamura proposal for a 5 MeV superconducting lens is shown in Fig. 16. Dysprosium inserts are used between coil and iron to minimize saturation effects, and the maximum proposed central field is 70 kG with a cross-sectional area of 5 cm^2 for the main coil winding. Shim coil inserts for field adjustment and stigmator sets for aberration adjustments are required. The peak field at the winding will be 15 to 20% greater than the central field; therefore, even with dysprosium or holmium inserts, the system will be run well into saturation. This proposal is meant to be a starting point for discussion, and such a lens could be made for experimental purposes. Alternatively, a similar lens design could be used and the peak field reduced to 50 kG to get a higher probability of success in initial experiments.

TABLE I. SOME CALCULATED FIELDS AND FIELD GRADIENTS FOR POSSIBLE SUPERCONDUCTING SYSTEMS FOR ACCELERATING VOLTAGES BETWEEN 100 kV AND 1000 kV

	Superconductor	Ferromagnetic Material	$H_{\max}$ kG	$(dH/dz)_{\max}$, KG/cm
100 kV	Nb-Zr coil, 350 turns ID = 4 mm, OD = 25 mm 30 A 100 Nb ₃ Sn discs, trapping flux. Nb ₃ Sn coil, 150 turns. ID = 6 mm, OD = 40 mm	In free space	9.7	16
		In free space	11.0	16
		Fe; D = 5 mm, S = 3 mm	22.3	70
		In free space $i = 80$ A	10.00	10
		Fe-Co; D = 5 mm, S = 3 mm. $i = 80$ A	23.4	67
		Fe-Co	21.3	70
		Shielding discs $i = 144$ A		
200 kV	Nb ₃ Sn coil.	In free space $i = 80$ A	10.0	10
		Fe-Co $i = 80$ A	23.4	67
		Fe-Co	22.0	70
		Shielding Discs $i = 144$ A		
500 kV	Nb ₃ Sn coil.	Dy + Fe-Co $i = 170$ A	35.0	64
		Fe-Co $i = 170$ A	35.9	62
		Dy + Fe-Co $i = 170$ A	35.9	64
		Dy + Fe-Co $i = 175$ A	37.5	67
1,000 kV	Nb ₃ Sn coil.	Dy + Fe-Co	37.5	67

TABLE II. LIMITATION OF SUPERCONDUCTING OBJECTIVE LENS

Energy of Electrons, keV	Field ^a , Maximum, kGauss	Half-width of Field, mm	Maximum Slope, kG/cm	C_s , mm	δ_s , ^b Å
100	33	1.2 ^c	150	0.40	2.3
200	37	1.5 ^c	125	0.54	1.95
500	43	2.0 ^c	90	0.88	1.48
1,000	48	2.8	75	1.3	1.08
2,000	60	5.2	60	1.8	0.83
5,000	70	10.0	50	3.2	0.50

^a Bell-shape Field; $k^2 = 3$, RCA Superconducting Discs (Nb₃Sn).

^b $\delta_s = 0.65 \lambda^{3/4} \cdot C_s^{1/4}$.

^c Compression of field required.

Norihisa Kitamura, Cornell University.

FIG. 14. Variations of Spherical Aberration with Peak Sample Field for Linear and Bell-shaped Axial Field Distribution.

Dr. Foss considered multiple-coil systems with the idea of seeing if more accurate profiles can be obtained in this way. He concluded that three coil systems offered the most promise and suggested that some iron be retained for screening and for holding the windings in position. His proposal is shown in Figs. 17 and 18, where the calculated profiles for the main coil itself and for the clipped field system are given. The reduction in field due to the reverse currents in the clipping coils adjacent to the main coil is now considerable, and 100% more ampere-turns are now required for the same field. Higher field gradients and axial field compressions are obtained with this system, and saturation effects can be eliminated in this way. Since the coil errors add, the problem of reducing coil errors is more difficult but can probably be solved.

FIG. 15. Adjustment of Axial Field Distribution by Relative Motion of Sets of Bulk Conductors Containing Permanent Circulating Currents.

FIG. 16. A Tadano-Kitamura Proposed 5 MeV Superconducting Lens-Design.

FIG. 17. Arrangement and Calculated Field Profiles for a Bell-shaped High-field System Using Clipping Coils.

The Fernandez-Moran objective stage (Fig. 19) has a complete cryogenics system with helium-cooled pole-piece and coil. Nitrogen cooling is also provided with this system. The system has operated well, as has already been mentioned, and demonstrates fully the practicability of superconducting lenses. While not yet as good as conventional lenses in resolving power, it is a useful first step and perhaps would justify a decision to eliminate conventional windings and plan immediately on using superconducting windings.

FIG. 18. A Coil System to Give Short Half-width by means of Adjacent Coils Operated in Reverse Current.

FIG. 20. Conventional Objective Lens Corrected for Spherical Aberration (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 19. The Fernandez-Moran Superconducting Microscope Objective

The Deltrap Quadrupole corrector (Fig. 20) has already shown its value in correcting lens aberrations over a wide range of incident energies. In view of this, the sizes and weights of all microscope lenses could be reduced considerably by using this corrector in con-

junction with lower-power superconducting lenses. Thus a 5 MeV microscope could utilize a 1 MeV lens with corrector, and a 3 MeV microscope could use 500 kV lens with corrector.

Experiences at Cambridge in Operating Electron Optical Systems in Various Orientations

WILLIAM C. NIXON

*University of Cambridge
Cambridge, England*

So far, we have heard two or three schemes for individual lenses, but no time really has been spent on how they all fit together. Coming under Group II, we have Dr. Tadano's 3 MeV complete column, with an extra lens over that of normal columns because, as he has pointed out, if we are going for high resolution and have moderately long focal lengths, we do not want high magnification; therefore we must be sure we have sufficient lenses.

Electron optical systems can be put together in several ways. The electron source can be at the top, the electron beam coming down vertically as in normal, conventional electron microscopes. We can also have the electron source at the bottom and the electron beam coming up, or we can have the system horizontal as a bench form. We have heard the term electron optical bench used, and we have heard of columns used that can be tilted around the beam.

A previous speaker pointed out that there is no really firm majority of opinion as to whether it should be vertical, horizontal, or somewhere in between, and I think because of the size of the lenses and the weights, this is perhaps the most important decision to make. If it is the conventional lens, can we support other than vertical? If it is to be as small as the superconducting lens, perhaps it can be tilted at a convenient angle. The lens decision must be made first, but almost immediately thereafter, the decision must be made as to how they are put together in the system.

We teach electron optics to undergraduates in the Engineering Laboratory at Cambridge, and in doing this, we use a simple, vertical electron optical bench to compare the light microscope and the electron microscope. To get an exact comparison, we use a tungsten filament, which acts as the light source for a test specimen grid, which is viewed by a normal glass objective and a glass eyepiece on a ground glass plate if one wants the exact analogy with the electron optical system. After students have familiarized themselves with this, the glass microscope is moved to one side, and the equivalent is put in place. For the objective lens, the magnetic field replaces the glass, the iron casing of the coil and the intermediate spacer is equivalent to the

tube, a projector lens equivalent to the eyepiece, and then a fluorescent screen on the glass plate.

With this, one can get information from the undergraduates' point of view. They have not handled electron microscopes before, they're teaching themselves what some of you had to teach yourselves when you inherited or purchased a hundred-kilovolt microscope. I think this sort of instrument, scaled up, of course, for higher voltages, should be used to collect the sort of information that so far is missing on how these various newer proposals will operate in practice.

In the type of system I have just described, the specimen is moved by two micrometers. The pole-piece of the projector lens is symmetric so that it can be placed either way up in its housing; in this way we can form magnified images or reduced images on the fluorescent screen. This, in turn, can be viewed through binoculars to pick out fine detail in the image. The operator, a student, sits at a chair and views the screen. I don't recommend this at 5 MeV. The instrument is operated at 30 kV usually, but with the scaling down of the bulk and mass of the lenses using quadrupoles, superconducting lenses, or a combination of the two (aside from the necessary shielding, which probably will be the most massive thing in this new microscope), the dimensions are not too far away.

This has been extended into a more elaborate system, which is commercially available in Britain, where the two lenses are within a cage or outer case formed by four supporting rods and horizontal face-plates or cage-plates. The lenses themselves can be moved sideways, since all the weight is taken by the supporting rods, and there is merely a vacuum seal between the lens and the plate above and below. By removal of one rod, a lens can be extracted. Again the lenses are asymmetric and can be put together either way up, each one containing an aperture and a removable pole piece. Thus, standing with an electron gun at the bottom, one can add components in a do-it-yourself fashion and produce an instant microscope.

The electron gun in this equipment is very simply detached for replacement of filaments. I don't think we worried too much about the replacement of the

field emission tips, and I can't remember a specific statement on their lifetime. However, in a 5 MeV instrument the replacement of filaments can be a major task, and considerable thought should be given to this detail. A scanning electron-diffraction system is an attachment to the basic gun, and two lenses allow diffraction display of the type used by Dr. Grigson,¹⁻⁸ where the results come out onto an x - y plotter, using a scanning rack and a velocity-analysis rack so electron-diffraction information can be displayed in terms of discrete energy losses. This is the counterpart of Dr. Crewe's scanning electron microscope with energy loss, and there are places where each individual method of obtaining information is of value.

We have in Cambridge, at the Engineering Laboratory, five of this type of scanning microscopes in operation. I mention five because it is extremely easy to make, once you have trained your workshop. You go in and say, "I will have another lens," and a couple of weeks later they produce one; these are strictly conventional. There are antivibration mountings at floor level, and a second stage of antivibration mounts further up the column on which it is suspended. There are three lenses; the gun is at the bottom, a first reducing lens, a second reducing lens, and the final lens before the beam strikes the specimen. We have measured our vibration and it is about 4 microns at 5 cps, and I think one must measure the particular frequency of vibration in any of these electron-optical systems, so that you know what you are shielding against mechanically. With the antivibration mounts, we drop this by a factor of 100 to 400 Å at this frequency, but, of course, the specimen and objective are both moving with this displacement, and so we can get a resolution of 50–100 Å with this system. Again, it can be thought of as a vertical electron bench.

Now we move to a more universal vertical electron-optical bench, entitled "Electron Optical Column for Surface Microscopy." Because scanning is one way of getting information, a second way is to operate in the mirror-microscope mode where the electron beam comes from a gun at the bottom through a double condenser system, through a hole in the fluorescent screen, and through two more lenses and the objective, and finally reaches the specimen held at the same negative high voltage. The electron beam is then reversed at this point, comes back down through the objective, through the projectors and onto the fluorescent screen. So, this is a folded electron optical column with five lenses in

the upward direction, three in the reverse direction, making eight lens in all.

I leave it to you who have had practical experience to imagine the alignment problems, but they are solvable. We attempt to solve them before we start by a four-poster bed principle of construction where there are long tie rods with accurately ground spacing collars that fit over these rods, and horizontal reference planes, again accurately ground, at several places in the column. This means we have a reference system to which we can fit the various lens combinations. We have the gun at the bottom, a double condenser system on a bed plate, the viewing chamber and projectors on the next plate, and the objective and specimen on the top plate. Each piece can be moved separately and replaced without disturbing the others. The vacuum is taken up by a simple bellows arrangement. By having a horizontal reference plane, we feel that gravity is neutral. We can move the lens around fairly easily, align, and do experiments on the electron optical design.

We have had horizontal columns. One has an electron gun at the left and an electron gun at the right. There are six lenses in the center, and both beams are on at the same time. We can see, on a fluorescent screen in the viewing chamber, the specimen and also the image of the electron probe striking the specimen. Our experience with this horizontal column has led us to feel that most columns should be vertical. There may be some special reasons why they must be horizontal. Perhaps in the 5 MeV microscope there are such reasons, but, I think for the number of columns I have mentioned, vertical vs. horizontal is about the sort of probability that I would prefer. By all means try to have it vertical. If there are strong reasons for a horizontal column, I would certainly like to know them.

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Electron Microscopy with Superconducting Lenses

HUMBERTO FERNÁNDEZ-MORÁN

*The University of Chicago
Chicago, Illinois*

Dr. Crewe pointed out that in the field of structural dimensions, the 1 Å level has special significance in terms of information content. In the scale of temperature, there is an octave that harbors a corresponding singular measure of information content, namely, the temperature range of liquid helium. The physicists and chemists were the first to realize this. However, the biologists are now keenly aware that the amplitude of thermal vibrations in the lattice of biological objects at room temperature can be as great as 1 Å. This happens to be in the size range of the atomic domain we hope to be able to visualize directly by electron microscopy. Therefore, if we are going to attain the ultimate resolution, we have to go into the low-temperature domain.

Dr. M. Beer has made promising attempts to resolve the base-pair separations in DNA, which are of the order of 3.5 Å. This particular problem is a very important one. To achieve this type of direct readout of the genetic code at the molecular level, we will have to work at liquid-helium temperatures, if for no other reason than to eliminate the uncertainty introduced by thermal vibration.

The resolving power of the electron microscope has already enabled investigators to see directly structures of molecular dimensions and the atomic spacing in crystalline lattices. In our new electron-microscope facility, using improved point-cathode sources and short-focal-length objective lenses with improved stability,⁴ we have been able to consistently attain point resolutions of 2.8 to 3 Å and to record phase-contrast, high-resolution images of carbon atom arrays (hexagonal cells of 5 Å) in ultrathin (10 to 20 Å) single-crystal graphite (Fig. 1).

Based on previous work in low-temperature electron microscopy,¹⁻⁹ I have indicated the unique advantages to be derived from the use of superconducting electromagnetic lenses operating at liquid-helium temperatures, with regard to both instrumentation and specimen preservation. With the new high-field superconducting solenoids of niobium-tin and niobium-zirconium now available, it is possible to obtain large uniform magnetic fields, which are highly homogeneous to better than one part in 10^6 to 10^7 . Furthermore, these mag-

netic fields are extremely stable and noise-free, when the solenoids are operated at liquid-helium temperatures short-circuited, or in the persistent current mode under appropriately controlled conditions. The first successful electron-microscopy experiments with high-field superconducting solenoid lenses have been performed as part of a comprehensive program carried out in our new facility. As a result of this initial work, it became apparent to us that numerous instrumental problems had to be overcome before the specific advantages of this approach could be sufficiently established for high-resolution electron microscopy.

The major problems included: (a) incorporation of superconducting solenoid lenses and associated cryogenic components into high-performance electron-microscope systems; (b) precise control and reproducible current settability for focusing superconducting solenoid lenses; (c) satisfactory specimen mounting to prevent temperature drift and achieve high degree of stability during irradiation; (d) stabilization of lens excitation currents and accelerating voltage, and improved electron source characteristics for low-temperature microscopy; (e) reduction of magnetic, electrical, and mechanical perturbations under carefully controlled conditions in the requisite cryogenic environment; (f) adequate continuous recording of images without breaking high vacuum under cryogenic conditions.

A comprehensive research program on different types of cryo-electron microscopes is being pursued in our laboratory, trying to meet these requirements. The program is based on our earlier work,¹⁻⁴ extending and confirming the exceptional stability of high-quality images with 50 to 100 Å resolution, which were recorded exclusively with superconducting solenoid lenses in special "cryo-electron microscopes" (Fig. 2), operating at 4 to 32 kG and 4 to 50 kV accelerating potential. As described in our publications,^{4,5} we have also used a superconducting niobium-zirconium objective lens operating in a liquid-helium cryostat of special design, which was equipped with superconducting stigmators and regulating circuitry (Fig. 3). With this instrument we recorded, for the first time, electron micrographs of biological specimens at 4.2°K, and were repeatedly able to reach resolutions of 10 to 20 Å with a minimum

FIG. 1. (a, b) Electron Micrograph of Uranylacetate Thin Film Test Specimen Showing Point Resolution of $2.8\text{--}3 \text{ \AA}$ in Focal Series, $70 \text{ \AA}$ Steps, 100 kV . (c) High-resolution Phase Image of Array of Hexagonal Cells Carbon Atoms in Ultrathin Lamella of Single-crystal Graphite. El. opt: $300,000\times$; Elmiskopla, Obj. $f = 1.8 \text{ mm}$. Focal Steps $30 \text{ \AA}$; 80 kV . Point cathode.

of specimen modifications. Moreover, the unique combination of high magnetic fields, liquid-helium temperature, and high electron-optical magnifications has enabled us to make preliminary observations on characteristic electron-optical phenomena, associated with trapped fluxes in thin superconducting films.⁵ This work has been reported in a number of publications from which I will select a few representative illustrations. Although we incorporated suitable commercially available electronic and cryogenic components, all the equipment used was specially developed and tested in our laboratories. Even special superconducting equipment, though built to our specifications by commercial firms, had to be extensively modified and adapted in our workshops.

Our research program has, in general, followed two approaches:

The first is a *cryo-electron microscope, optical bench system*. This system comprises a modified air-core liquid-helium Dewar in which different types of niobium-zirconium solenoid lenses operate at 4 to 32 kG without pole pieces. It also contains modified objective and objective-projector pole pieces, the objective pole pieces being of conventional design with focal lengths of 1.6 to 2.6 mm . It was necessary to improve the available 25-amp regulated power supplies and storage batteries and to use them in conjunction with additional current vernier control circuits. This system, when operated under suitable conditions, permits adjustable current changes of 10^{-9} , whereby "superfine" focusing

of the objective lens can be achieved reproducibly. These results are far better than those obtained with conventional electron-optical systems. The current vernier control comprises a low-field, two-winding, superconducting toroid, which has its secondary in series with the main solenoid. The entire system is placed in a loss-free and completely stable condition when the toroid primary is transferred to the persistent current mode after optimum focusing is achieved. We used improved point-cathode sources⁴ to provide stable coherent microbeam illumination of small spot size, high specific brightness, and low energy spread, along with highly stabilized power supplies operating mainly at 50 kV. These were connected to a central regulated motor-generator set in which the main line voltage stability is kept at better than 0.1% by solid-state regulators.

To keep mechanical, electrical, and particularly, magnetic field perturbations at a minimum, special precautions were taken throughout the experiments. Extensive moly-Permalloy 4-79 shielding was used to reduce magnetic-field perturbations. We developed and tested several types of specimen holders so that they would provide optimum stability in a cryogenic environment and eventually allow for multiple sample holders and piezoelectric specimen manipulation within the Dewar.

FIG. 2. Cryo-electron Microscope with High-field Nb-Zr Superconducting Solenoid Lenses, Regulating Circuitry and Power Supply Controls.

SUPERCONDUCTING OBJECTIVE LENS AND LIQUID HELIUM COLD STAGE ASSEMBLY FOR CRYO-ELECTRON MICROSCOPE

FIG. 3. Sketch of Superconducting Objective Lens with Stigmators and Vernier Coils of Special Design.

The second major aspect of our program involved a superconducting objective lens in a specially designed liquid-helium Dewar. This lens, which was designed and built to our specifications by Westinghouse, may be used as an integral part of cryo-electron microscopes or may replace the objective lens in a modified commercial, high-resolution electron microscope. The lens is made up of niobium-zirconium main and vernier coils of 32,580 ampere-turns with superconducting stigmators, persistent current switches, and improved current-control devices. In our experiments, microstages maintained at 4.2°K were used for mounting specimens that could also be inserted within different types of pole pieces. These will include short focal length ($f = 1.5$ to 1.8 mm), single-field condenser-objective pole pieces of iron or dysprosium, and trapped-flux Nb₃Sn miniature lenses.

Our cryo-electron microscope IV is mounted on a 10-ton vibration-isolated base and features extensive magnetic shielding, ultrahigh-vacuum ion-pump system, improved field and T-F emission source, 50 to 100 kV highly stabilized accelerating potential, and image intensifier with provision for videotape recording. High-resolution Kodak or Ilford plates and Kodak High Definition 70-mm films with thin polyester base were generally used for photographic recording. The test specimens included replicas of diffraction gratings of 2160 lines/mm, fenestrated carbon films of niobium, niobium-zirconium, or lead. The results were based on evaluation of more than 1,000 plates and films directly recording the electron-optical images.

It was possible, once the experimental difficulties were overcome, to operate these cryo-electron micro-

scopes on a routine basis. Reproducible results were obtained while operating at 4 to 32 kG preferably in the persistent current mode and at 50 kV. We first focused a specimen image on the fluorescent screen, using the precision settability circuitry at electron-optical magnifications of 200 to 20,000 $\times$ using only superconducting lenses. Then the solenoid was switched into the persistent-current mode. At first there were slight shifts in the image, but these could be readily corrected while still in the persistent-current mode. The images maintained without any external current source are of an unprecedented degree of stability and high quality, with resolutions of 50 to 100 Å. Correction of astigmatism could have considerably improved the images. This exceptional stability allowed for exposures of 30 seconds to several minutes when using microbeam illumination of low intensity and high-resolution plates. The integrated long-term exposure, made possible by the superstability of the lenses, resulted in the recording of fine detail which can be observed in micrographs displaying a very large field recorded with only a single lens. This detail is normally only discernible in the best high-resolution micrographs at higher magnifications. The same area can be recorded continuously at 5- to 15-minute intervals over periods of 10 to 20 hours under carefully controlled conditions without detectable image changes (Fig. 4). Other sources of mechanical, magnetic, and electrical perturbations were discovered as a result of this typical long-term superstability. Lens fluctuations and ripple had previously masked these perturbation sources.

This unique stability, as well as the improved cryogenic vacuum and reduced specimen damage, already represent major advantages of the superconducting lens system. Preliminary experiments have shown that application of the exceptional stability of superconducting lenses with coherent microbeam illumination to high-resolution electron microscopy and diffraction appears promising for practical realization of Gabor's wave-front reconstruction microscopy.¹⁷

Improved objective lens and cold-stage assemblies have now made it possible to examine biological and other types of specimens at 4.2°K. Specimen drift, which previously presented a major problem, has been largely overcome by combined use of adequate cryogenic shielding, stable specimen mounting, and microbeam illumination of low intensity and small spot size. In addition, it is possible to compensate our superconducting objective lens, operating in the persistent current mode at 4 to 8 kG, by using special superconducting stigmators and shim coils. When the superconducting lens is used in conjunction with standard projector and intermediate lenses, excellent electron-optical images can be recorded

at magnifications of 200 to 40,000 $\times$ under optimum conditions. Clearly resolvable details in the size range of 10 to 20 Å point resolution are seen in test specimens of catalase with asbestos fibers of about 100 to 200 Å diameter with central channel of 20 to 50 Å, stained with uranylacetate (Fig. 5). The 80 to 90 Å periodic structure of the catalase crystals can also be detected in certain areas. After prolonged exposure, the lack of contamination and the transparency and clarity of the images are amazing. In specimens shadowed with lead, we could confirm the characteristic electron transparency at low temperatures first described by Boersch.¹¹

Thin films of niobium or niobium-zirconium (200 to 500 Å) evaporated on fenestrated, thin-film carbon substrates, exhibit interesting phenomena when examined at low temperatures (4.2°K) and relatively high fields of 4 to 8 kG without pole pieces and up to 20 kG with pole pieces. As shown in Fig. 6a, the control micrograph recorded at liquid-nitrogen temperature and low fields differs markedly from micrographs of the same area (Fig. 6b) examined at 4.2°K and higher fields of about 8 kG. A series of characteristic fringe patterns is observed under the latter conditions. These patterns vary in configuration and dimension according to the applied field strength. It is tentatively assumed that this reproducible effect is associated with the Lorentz deflections induced by the trapped flux patterns, resembling the imaging of magnetic domains in conventional microscopy at normal temperatures. Under conditions of higher beam intensity, close to critical transition temperatures, preliminary observations reveal unexpected dynamic phenomena displaying a state of flux of vortex-like regions resembling the "bee-swarm" effect,¹¹ described by Dove in thin carbon and Permalloy films. These interesting observations, which can now be readily made over a wide range of temperatures and electron-optical conditions, are being continued and will be reported in detail elsewhere.

In summary, the unique stability and relatively high quality of the images recorded at low temperatures with superconducting solenoid lenses is revealing and encouraging, considering the advanced state of development of conventional, high-resolution electron microscopy. It clearly indicates the potentialities of a highly promising experimental approach, which has opened up with recent advances in superconducting technology but which is only now emerging from the confines of timid or skeptical speculation. To reiterate, our own experimental approach is primarily designed to provide essential data for the development of high-resolution electron microscopy of biological specimens, examined in the frozen hydrated state under the ideal low-temperature

FIG. 4. Electron Micrographs of 2160 Lines/mm Diffraction Grating Replicas Recorded at 50 kV (10-20,000 $\times$ electr. opt.) with Superconducting Lens in Persistent Current Mode Continuously over 10-hour Period. Unaltered images of First (a, c) and Final (b, d) Series Demonstrate Lens Superstability. Fine Detail Discernible in (e) Resulting from Long-term Exposure is Only Found in Control Standard Micrographs (f) at Higher Magnification (g) 500,000 $\times$.

conditions of minimized specimen contamination, radiation damage, and thermal noise. However, now that the advantages of superconducting lenses in electron microscopy have been demonstrated, the way is open for new approaches that are unique to superconductors as

perfect diamagnetic materials. Thus, the possibility of using superconductors for correction of spherical aberration, as first suggested by Marton, becomes susceptible of experimental verification.

Moreover, the obvious advantages of high-field super-

FIG. 5. Electron Micrographs of Stained Catalase Asbestos Specimen on Carbon Film Recorded at 4.2°K Using Superconducting Objective Lens Without Pole Piece in Persistent-current Mode at 75 kV, Demonstrating 10 to 20 Å Resolution in Asbestos Filaments (c). (a) 20,000 $\times$; (b) 60,000 $\times$; (c) 800,000 $\times$.

conducting lenses for both high-voltage and low-voltage electron microscopy enter into the realm of practical realization. Cryo-electron microscopes should also prove to be a powerful tool for direct visualization of fundamental phenomena in thin superconducting films.

In principle, such a cryo-electron microscope would also be an ideal device for controlled application of electron microbeams (ca. 50 to 500 Å diameter) of precisely defined intensity and duration for ultraminiaturization, for storage of information, and in general, for controlled

FIG. 6. Electron Micrographs of Thin Niobium Film on Fenestrated Carbon Substrate Recorded with Superconducting Objective Lens. Compare Control Images at Low Field, 90°K, with Corresponding Areas (b, c) Examined at 4.2°K and High Fields, Showing Characteristic Fringe Patterns Presumably Associated with Trapped Flux. 60,000 $\times$.

observation, irradiation, and manipulation of hydrated biological systems at the molecular level under conditions of minimum perturbation.

It is therefore hoped that despite the inherent experimental difficulties and uncertainties, further critical and constructive work will continue in this field.

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Discussion of Session II

Discussion of Paper by P. W. Hawkes

H. Fernández-Morán (Chairman): As an outsider, I cannot help but be profoundly impressed by the remarkable amount of work that has gone into a very complex field. I am doubly impressed by the fact that this is a field that because of its complexities has been forbidden, and being weaned on symmetrical lenses I must confess that after hearing this and looking at some of the slides, I for one, am converted to some of the virtues of the quadrupoles. The amount of work that has gone into this is just remarkable, and I am sure that out of this will come benefits not only for the specific field that you have been entrusted with but for the whole field. The remarks that Dr. Cohen made on magnetic shielding were also very revealing to me. The papers are open for discussion.

D. B. Wittry: Will you care to elaborate on the problem of using quadrupoles of varying focal length?

P. W. Hawkes: This is a feasible problem to solve, I think, if you have one of these systems with a high symmetry already built in. Otherwise, every time you want to change the focal length, you have to change something else as well. If you did have a relatively simple design such as this, you would eventually design it, I imagine, so that you would have one knob physically and also a piece of other electronics which would then alter the other excitations according to prescribed rules, and these rules could be prescribed very exactly. I think this is how this kind of thing would have to be done. I ought to mention too that one of the major problems that goes with your question is doing this kind of thing systematically. There are no rules yet for changing focal lengths systematically; furthermore, you have to alter your correction condition, and this changes in a way that is far from obvious.

P. F. Meads: I would like to add one thing. It seems to me that comments we mentioned to Dr. Crewe are relevant: the obvious answer is a superminiaturized, superconducting quadrupole system. If you look at this figure we have here for a Russian quadruplet, you see that the length of these lenses is large. The field in the pole tip is very small, about 500 G. If one can be clever enough to make the system on a very small scale with quadrupoles made of loops of wires and no metal in a superconducting environment and the fields run up to 10 or so kG at the pole tip, I think you can see that you can run the focal length down by a factor of 50 or so. I suspect that this might be done.

Voice: I want to be sure we have these numbers right.

In the one you designed for minimum spherical aberrations, do the first two quadrupoles have the same direction of excitation?

P. W. Hawkes: No, they are plus-minus-plus-minus.

Voice: On the Russian and on the Meads quadrupoles they are not mirror symmetric about the center?

P. W. Hawkes: No, they are not mirror symmetric; they are mirror symmetric *plus* rotation.

A. V. Crewe: There seems to be a remarkable family similarity between the Deltrap corrector and this thing you ended up with. Is it possible to make them the same thing?

P. W. Hawkes: This is one thing we just didn't have time to do. I think if you are going to design a Deltrap corrector, you would certainly arrange it so that perhaps three of the excitations were equal. I am not sure how far one can go in this way, but I think that these correctors could be designed with higher symmetry than the ones I have described.

C. Turner: Would you like to comment on the symmetry? The focal length remains the same. I wondered whether the effective thickness of the lenses is the same in both planes and whether the transfer matrices are the same, or whether they are the same in both planes only for a specific object-image position.

P. W. Hawkes: The transfer matrices are made to be the same in both planes so that the transformation of object into image is stigmatic and othomorphic independent of object position. In the relationships we have been calculating we always have as a condition that the transfer matrix elements be identical. Incidentally, for the more general system I mentioned, where the drift spaces are different, the best we could do was to get the cardinal elements in image space identical, but you have lost the identity in the object space so that you could only tolerate a nearly parallel beam.

P. F. Meads: I have two more comments, one for the accelerator people. The arrangement of lenses in this Russian system is the same as that in the long, straight section as applied to high-energy synchrotrons, consisting of four quadrupoles for those of you who are keeping up with 200 BeV machines. Secondly, the number 32 is the ratio of the largest of the four coefficients to the focal length. Actually, if we do want to make a comparison with the round lens, we should choose a number smaller than that because, after all, the other three are much smaller and one is doing only part of the imaging. So really we are using a much more pessimistic number there.

P. W. Hawkes: I might also add that one of them is so small that although in theory you need three octopoles, I expect one could get away with two, but I have no figures to substantiate that.

L. L. Marton: Would it be possible to use a Deltrap corrector with lenses built for a much lower energy such as a 100 keV as we have at NBS?

P. W. Hawkes: The one that was originally built was for 40 kV and there is no reason, in principle, why one shouldn't be able to work to a higher voltage just as easily as at a low voltage.

H. Fernández-Morán: Going back to that question of the actual manipulation of this. You mentioned the twiddling of a few knobs; is it really that simple? Wouldn't you have too many complicated situations, because when one looks at the papers by Mollenstedt on the correction using the Scherzer corrector, it appears to be a prodigious feat experimentally.

P. W. Hawkes: This is a much simpler system than that. In fact, it has designed into it a number of tricks of which the specific purpose is to make things simpler. Here both rays cross the optical axis in the center of quadrupoles, whereas in the Seeliger-Mollenstedt system each change in magnification affects everything. Here you have two octopoles, which are effectively changing the things you would like to correct, and you are only left with the third aberration to correct.

H. Fernández-Morán: That's very heartening—it's easier than Russian roulette.

P. W. Hawkes: It's still very difficult.

K. Vosburgh: Is the focal point of the lens inside or outside the lens?

P. W. Hawkes: It's always outside. In fact, just for convenience we have always arranged that the focal point falls at the end of the last quadrupole.

K. Vosburgh: Do you have a numerical figure on that?

P. W. Hawkes: About 10^{-6} or 10^{-7} inch from the end of the lens.

K. Vosburgh: That's very striking.

P. F. Meads: I should mention that the lens length is really the effective length of the lens which extends a little beyond the real end of the lens. This point is really accessible.

K. Vosburgh: That effective length takes care of the fringing field.

P. F. Meads: One more comment on that. I think there is a correction term necessary in the computing program for having an immersed image in the field. I think for this case it goes to zero because every one of those terms has a displacement in it, and if the image is real, all those correction terms go to zero.

Discussion of Paper by C. Laverick

P. F. Meads: Is there a plan C by which you start to make superconducting quadrupoles, thereby achieving

the advantages of quadrupoles and superconducting magnets?

C. Laverick: I believe it should be easy to make these magnets, so if you want some superconducting quadrupoles and somebody gives us some money and some staff and some space, we'll make them. We need a good development program that looks at all these things. Yes, you can have a plan C.

P. W. Hawkes: Could you say more about why there is this problem of astigmatism in superconducting lenses?

C. Laverick: I don't think that the problem for superconducting lenses is any greater than with conventional lenses. Dr. Foss was speaking of the simple case of winding the lens, and instead of having a pure cylinder, you have a helix, so you effectively have a cylindrical field with an additional field going in another direction. Then, if you propose to do as I've done in these magnets and wind back, you now have a helix in the other direction; furthermore, you have crossover points, and these lead to further errors.

M. Foss: The high-field lenses require that the coil be nearer the electron beam; therefore the beam will see errors in the coil, so care is required in the coil construction. I don't really know how difficult it is. With the steel lenses, the steel has to be very accurate, but you don't have to worry about the leads and positioning the wires in the coil.

C. Laverick: With the high-field lenses, we could make a slightly different bore and reduce these errors to some extent.

N. Kitamura: Using niobium-tin discs, we can make a very precise inside diameter.

M. Foss: Dr. Crewe suggested that in a system similar to yours you might machine a spiral groove and obtain the precision of the coil that carries current.

C. Laverick: That was in my notes, but I didn't want to take time to go into it.

H. Fernández-Morán: Stigmators of the ordinary type can be used in a superconducting lens and, in fact, there they are more useful because once you have stigmated you switch them into the persistent-current mode, and if time permits, I will show pictures that have been taken without pole pieces. The very high quality of these pictures is primarily attributable to the stigmators, so that the problems of introducing stigmators into a high-field lens are no greater, and, in fact, it may be easier because you don't have to worry about the drift. Also, the suggestion of Dr. Kitamura and the way he's going about it, using high precision mask techniques of vapor deposition, rather than the chemical ones, would ensure close tolerances. We've been checking on this by examining, at high magnifications, the holes produced. So the answer is that you can stigmatize, and it would not pose any untoward problems.

P. W. Hawkes: What does a good superconducting stigmator look like?

H. Fernández-Morán: In appearance, it's the counterpart of an electrostatic stigmator of the Haine or RCA type, only that you have small superconducting windings and perhaps, if you want to get stronger effects, a small iron piece. Essentially you need coils the equivalent of your octupoles or quadrupoles. That's why I was so interested in your Deltrap corrector.

P. W. Hawkes: That's why I'm so interested in your stigmator.

H. Fernández-Morán: Once you have this, then the only other thing you require, which is unique, is a persistent-current switch, and that is very important. Otherwise, you will be introducing a drift.

L. L. Marton: You mention the difficulty of vibrations due to boiling of the helium. It would be advantageous to operate at lambda point, where I understand boiling is much reduced and vibrations would be partly eliminated.

C. Laverick: That certainly can be done, and coils can be operated. I have operated coils below the lambda point. Some don't work too well, but they can be made to work well. On the other hand, one expert doesn't have any vibration problems, and another one does.

H. Fernández-Morán: The vibration problem exists, only there are much more serious effects. For example, Dr. Tadano points out, and his pictures bear out, the thermal drift that he gets with his low-capacity system which, incidentally, was practically the identical system as shown last year by Boersch with high resolution. This type of system gives you such a high thermal drift that the bubbling of the helium is a second-order effect. We have come across this and peculiarly enough the boiling of the helium is not as important as the boiling of the nitrogen. By pumping on the nitrogen, or by using a very ingenious method of bubbling helium through the nitrogen so that you get its temperature down, you practically cut it out. So much so, that it is a second- or third-order effect. I sympathize with your suggestion of operating below the lambda point, because several years ago at Professor Collin's laboratory we went to or below the lambda point, among the other things, for that reason.

C. Laverick: That is another complication. Dr. Foss did have some comments to make on that subject.

M. Foss: I was suggesting gas-phase cooling. You can use cold gas at, say, 4.5°K, circulated to keep the coil cool.

H. Fernández-Morán: I have to speak for a man who has done a remarkable piece of work and has not been represented here either in the reports or otherwise, and that man is Boersch. Boersch has done precisely this.

FIG. 1. Use of a Superconductor for Field Correction (Suggested by L. L. Marton, July 1966).

He has used cold gas, and it is primarily due to this and many other refinements that he has obtained some of the most significant data in this domain. He probably will report at a forthcoming meeting. He has a very ingenious system of cooling his specimen holder to liquid-helium temperatures with reflux of gas. This is a system that was designed by his group and has been described in the *Zeitschrift für Physik*.

L. L. Marton: I would like to submit a proposal for correction of spherical aberrations. Usually when one looks at the field distribution of a rotationally symmetric lens, we have the typical bell-shaped curve as shown in Fig. 1a. For the purpose of correction, I would like to consider a radial field distribution where the field is constant in the region of the pole piece and has a minimum on the optical axis as shown in Fig. 1b. If introduced on the optical axis, the first choice of diamagnetic material is a superconductor. Let's assume an ideal superconductor, which repels completely lines of forces and, therefore, the flux is reduced to zero on the optical axis. A short radial distance away, at the surface of the superconductor, the flux is large, and then a bit smaller at larger radii between the superconductor surface and the poles, as shown in Fig. 1c. There is, therefore, a reversal of the z -field gradient in the region between the superconductor and the poles, and this reversal in the inner radial regions may be used for the correction of aperture aberration.

Discussion of Cross Sections of Possible Contrast Mechanisms in the Electron Microscope

ELMAR H. ZEITLER

*Armed Forces Institute of Pathology
Washington, D.C.*

Any electron-optical device, such as an energy spectrometer, an electron microscope, or a combination of both (scanning microscope) can be described by an acceptance function, which determines the probability (transmission) for an electron entering the instrument with a given energy under a given angle to hit the recorder. Instrumental data will be contained in the acceptance function in form of the energy and angular acceptance for which the instrument is set or designed. Hopefully, the energy acceptance is a steep and narrow function of the difference of the particle and design energy only (i.e., ideally independent of the entrance angle), whereas the angular acceptance is a cone whose opening is determined by a physical aperture.

If a target is inserted in the optical path, the originally parallel and monoenergetic electron beam will interact with the constituents of the target. The beam will emerge from the target with a certain angular spread and distribution in energy. The beam intensity may optimally be envisaged as a topographic plot over the energy-angle plane. For different interactions different plots result. There might be no change in energy, degenerating the energy-angle region into a line parallel to the one axis; there might be a strong correlation between energy and angle resulting in a curve, or there might be no correlation yielding an area in this energy-angle plane.

The different distributions are given by the differential cross section of the particular interaction. Into the formulas for the cross section, enter parameters defining the incoming beam in terms of energy and incident angle, parameters pertaining to the target, and parameters defining the emerging beam also in terms of energy and angle.

The instrumental acceptance punches a cylinder out of this three-dimensional intensity distribution. The cross-sectional area of this cylinder is determined by the design of the electron-optical device. (The example mentioned above would exhibit a rectangularly shaped area of acceptance.) We see now how the electron-optical contrast comes about. The target transforms the energy-angle coordinates of the electron in accordance with the local cross section, so that some of

the electrons fall outside the instrumental acceptance. Contrast is generated by excluding a fraction of electrons from the optical tract. This fraction of "successfully" lost electrons will change locally with the target composition and hence reveal information on the target. The contrast will be higher the smaller the area of acceptance and also more specific, since the cross section is averaged only over this smaller area of acceptance.

This introduction was to show how both instrumental design and the interaction of the electron beam with the target determine contrast. However, we will deal only with the problem of contrast mechanisms. We will exclude phase contrast for two reasons. First of all, it is extensively treated in many books, most outstanding in the book by R. D. Heidenreich.¹ Secondly, phase contrast is very much dependent on the internal structure and order of the target.

We divide the cross sections into three classes, namely, cross sections of:

1. Elastic processes
 - 1.1 Single elastic scattering
 - 1.2 Plural-multiple scattering
2. Inelastic processes, characteristic energy losses
 - 2.1 Single-electron transition
 - 2.2 Plasmon excitation
3. Inelastic processes, noncharacteristic energy losses
 - 3.1 K-shell ionization
 - 3.2 Bremsstrahlung

The inelastic cross sections are particularly interesting for scanning microscopy because the energy losses bring about a "new dimension" for characterizing the target composition. These cross sections are found in the literature only as intermediate results in studies of the stopping power of a target or in the papers on the generation of bremsstrahlung, whereby the path of a primary electron is of subordinate importance, whereas in our case this electron is the carrier of information and our prime concern.

Units

We use relativistic units; i.e., we measure Lengths in Compton wavelength

$$\lambda_c = \hbar/m_0c = 3.87 \cdot 10^{-11} \text{ cm};$$

Momentum in m_0c ;
 Energies in $m_0c^2 = 0.511$ MeV.

Useful Relations

Bohr radius $a_0 = 137 \lambda_c$
 $\hbar c / \theta^2 = 137$;
 Classical electron radius $r_0 = e^2 / m_0 c^2$;
 Compton wavelength $\lambda_0 = 137 r_0$.

Classification of Cross Sections

We start out with a "responsive system" characterized by an atomic number Z . An incoming electron, described by its total energy E_1^* or its kinetic energy T_1 and its momentum $\vec{p}_1$, will leave the system, with an energy E_2 (T_2) and a momentum $\vec{p}_2$.

$$1. E_1 - E_2 = T_1 - T_2 = 0$$

This is the idealized case of elastic scattering. The responsive system is the Coulomb potential of the nucleus. The atomic electrons enter the picture only in modifying (screening) the Coulomb potential.

In reality, every electron being scattered in a Coulomb field has lost energy by emitting photons. Yet the photon energies are so low that the finite energy resolution inherent in all measurements makes the case $T_2 \rightarrow T_1$ indistinguishable from the idealized case $T_1 = T_2$.

$$2. T_1 - T_2 - \Delta_{ou}^n = 0$$

2.1 The responsive system is an atomic electron, which can uptake only definite energy quanta Δ_{ou}^n . The Coulomb potential enters the picture only indirectly in providing the discrete energy levels.

2.2 The responsive system is the nearly free electrons in metals, which form a plasma. This plasma performs collective oscillations under the influence of the primary electron. The oscillations are quantized (plasmons).

$$3. T_1 - T_2 - \Delta = 0$$

3.1 The responsive system is an inner-shell electron, which has to be removed from the atomic compound. Since at least the binding energy must be overcome, this process exhibits a threshold. Above this threshold, the secondary electron carries away kinetic energy.

3.2. The responsive system is the screened Coulomb potential, which deflects the incoming electron with emission of a bremsstrahlung's quantum, whose energy is derived from the energy of the primary electron. In contrast to the photon emission mentioned under (1),

FIG. 1. Notation for Electron Scattering by an Atom

the photon energy in this case is readily measurable; or, in other words $T_2 < T_1$.

Before we introduce explicitly the expressions for the various cross sections, let us repeat what was said in the introduction, however, in a mathematical fashion.

We are interested in two quantities:

a. The differential cross section $d^2\sigma/d\Omega dT_2$, which determines the probability for the scattered primary electron to appear within an energy interval dT_2 centered around T_2 , and within a solid angle $d\Omega$ centered around the direction of $\vec{p}_2$.

b. The cross section σ , which gives the probability for an electron to fall into the energy-angle region of instrumental acceptance A ,

$$\sigma = \iint_A \frac{d^2\sigma}{d\Omega dT_2} d\Omega dT_2.$$

This expression can be related to the total cross section σ_0 in writing $\sigma = k\sigma_0$, whereby $1 - k$ is the fraction of all scattered electrons that contribute to contrast.

i. In the case of elastic scattering and of characteristic energy losses, T_2 can have only discrete values, which is mathematically taken care of by a δ -function in the differential cross section $d^2\sigma/d\Omega dT_2 = d\sigma/d\Omega \cdot \delta(T_1 - T_2 - \Delta_{ou})$. The interaction itself does the energy selection; hence, we can immediately integrate over T_2 and obtain the differential cross section $d\sigma/d\Omega$ pertinent to these cases. Wherever T_2 appears explicitly in $d\delta/d\Omega$, the proper value has to be used.

In this case, only the angular acceptance plays a role and σ becomes

$$\sigma = \int_0^\alpha \frac{d\sigma}{d\Omega} d\Omega = \sigma_0 - \int_\alpha^\infty \frac{d\delta}{d\Omega} d\Omega,$$

whereby α is the restricting aperture angle. (We can extend the integrals to infinity since in electron optics only small angles are permitted anyway; i.e., $\sin \theta \simeq \theta$; $\pi \simeq \infty$.)

* Subscripts 1 and 2 refer to initial and final state, respectively.

The energetic acceptance function plays a role only in the question of whether two adjacent energy losses can be resolved.

ii. In the case of noncharacteristic energy losses, the cross section σ also determines the contrast, yet the latter depends more intricately on the acceptance function. Since we don't want to go into a discussion of this function, we must restrict ourself to deal only with the differential and perhaps the total cross section. In concluding this paragraph, we will show the mentioned complication. The probability, P , for getting an electron through the optical device differs from σ and is

$$P = \iint W(T_2; T_1; \Omega) \frac{d^2\delta}{d\Omega dT_2} d\Omega dT_2.$$

We generously simplified $W(T_2; T_1; \Omega)$ to unity when T_2 and Ω fall into the region A , and to zero, when they fall outside.

The Various Cross Sections

The Rutherford cross section, which describes the probability for deviating an electron in the Coulomb potential of another particle Z , plays a central role for the following discussion. The main parameter is the momentum change

$$\underline{q} = \underline{p}_1 - \underline{p}_2,$$

which has to be absorbed by the system.

The scattering angle θ is related to q and so is the solid angle $d\Omega$:

$$q^2 = p_1^2 + p_2^2 - 2p_1p_2 \cos \theta$$

$$q dq = p_1 p_2 \frac{d\Omega}{2\pi}.$$

Since q bears more physical significance than the angle θ , we will switch to q as the variable, and conceivably obtain simpler expressions

$$d\sigma_{\text{Ruth.}} = 8\pi \left(\frac{Z}{137\beta} \right)^2 \frac{1}{q^4} q dq.$$

We recognize the famous $1/q^4$ dependence and also the fact that the Rutherford cross section is only dependent on the velocity β of the incoming electron.

1. Elastic Scattering

$$a. \quad p_1 = p_2 = q; \quad q = 2p \sin \theta/2 = p\theta; \quad d\Omega = 2\pi/p^2 q dq;$$

$$d\sigma = 8\pi \left(\frac{Z}{137\beta} \right)^2 \frac{[1 - F(q)]^2}{q^4} q dq.$$

We obtain the Rutherford cross section except for the factor $1 - F(q)$, which is the "response function" of the electron cloud screening the nuclear Coulomb potential.

The very same function occurs in the scattering cross section for X rays. It is called the atomic form factor.

To discuss this formula, we describe the atomic potential approximately by a Yukawa (Wentzel) potential,

$$V(r) = - \frac{Z}{137r} e^{-\Lambda r},$$

which reveals the general features of screening (exponential screening). For more exact calculations, Hartree-Dirac-Fock distributions for the atomic electrons have to be applied, which in turn can be approximated by a sum of Yukawa potentials. The parameter $1/\Lambda = 0.885 \cdot 137 \cdot Z^{-1/3}$ is the Thomas-Fermi radius,

$$a_{\text{TF}} = 0.885 Z^{-1/3} a_0.$$

With these values we get

$$\frac{1 - F(q)}{q^2} = \frac{1}{\Lambda^2 + q^2} = \frac{1}{\Lambda^2} \cdot \frac{1}{\left(1 + \frac{q}{\Lambda}\right)^2}.$$

We see that the screening action of the electrons suppresses the predominance (divergence) of small momentum transfers. Since $q/\Lambda = 2p/\Lambda \sin \theta/2$, the expression $\Lambda/2p$ suggests the introduction of an angle θ_0 , the so-called screening angle by defining

$$\Lambda/2p = \sin \theta_0/2,$$

or in small-angle approximation

$$\Lambda/p = \theta_0.$$

This angle determines the spread of the angular distribution; the distribution is down to its 25 % value at an angle $\theta = \theta_0$. If we return, for a moment, to usual units, θ_0 becomes $\lambda/2\pi a_{\text{TF}}$ and corresponds to the angle by which waves of the wavelength λ are diffracted by an obstacle of the size a_{TF} .

The angular distribution concentrates in the forward direction with decreasing wavelength of the electrons. Let us see what the forward intensity does in this case, namely,

$$d\sigma(q = 0) = 8\pi \left(\frac{Z}{137\beta} \right)^2 \frac{q dq}{\Lambda^4} = 4 \left(\frac{Z}{137\beta\Lambda} \right)^2 \frac{d\Omega}{\Lambda^2 \theta_0^2}.$$

Except for the factor β^{-2} , the forward intensity increases in the same rate as the angular spread decreases or

$$\theta_0^2 \left(\frac{d\sigma}{d\Omega} \right)_{\theta=0} = 4 \left(\frac{Z}{137\beta\Lambda} \right)^2 = \left(\frac{2 \cdot 0.885 \cdot Z^{2/3}}{\beta} \right)^2$$

changes only with β^{-2} . For electron energies T_1 above 1 MeV, β is nearly constant ≈ 1 , making the product of forward intensity and spread also constant. We expect this product related to the total cross section σ_0 .

TABLE I. ELASTIC SCATTERING SCREENING ANGLE θ_0 IN MRADS TOTAL CROSS SECTION σ_0 IN UNIT $10^3\lambda_c^2$ DIFFERENTIAL CROSS SECTION $d\sigma/d\Omega$ IN UNIT $10^3\lambda_c^2$

Z	6						29						79					
keV	100	200	500	1000	2000	5000	100	200	500	1000	2000	5000	100	200	500	1000	2000	5000
θ_0 in 10^{-3} rad	22.86	15.49	8.78	5.39	3.16	1.40	38.66	26.19	14.84	9.11	5.27	2.36	53.99	36.58	20.73	12.72	7.36	3.30
σ_0 in $\lambda_c^2 \times 10^{-2}$	5.57	3.46	2.25	1.89	1.75	1.69	52.00	32.3	21.00	17.6	16.3	15.8	230.2	143.1	92.9	78.1	72.2	69.8
θ/θ_0	$(d\sigma/d\Omega) \times 10^6$																	
0.1	0.56	0.75	1.52	3.40	9.40	45.3	4.30	5.82	11.8	26.3	72.6	349.8	14.3	19.3	39.1	87.3	241.1	1161.1
0.5	0.29	0.39	0.80	1.78	4.91	23.7	0.86	1.16	2.35	5.25	14.5	69.8	1.98	2.69	5.43	12.1	33.5	161.4
1.0	0.03	0.11	0.22	0.49	1.35	6.50	0.19	0.26	0.53	1.19	3.28	15.8	0.37	0.50	1.00	2.24	6.18	29.8
1.5	0.204	0.032	0.066	0.15	0.40	1.9	0.064	0.09	0.18	0.39	1.09	5.23	0.11	0.15	0.30	0.66	1.82	8.79
2.0	0.009	0.012	0.024	0.054	0.15	0.72	0.026	0.035	0.071	0.16	0.44	2.12	0.042	0.057	0.12	0.26	0.71	3.42

b. Applying the formula given for the differential cross section, yet with angular rather than momentum variables, we obtain for an aperture α (in small-angle approximation):

$$\sigma(\alpha) = 8\pi \left(\frac{Z}{137\beta\Lambda} \right)^2 \int_0^\alpha \frac{1}{[1 + (\theta/\theta_0)^2]^2} \frac{\theta d\theta}{\theta_0^2}.$$

This formula shows that we get roughly (except for this β^{-2}) the same values $\sigma(\alpha)$ and hence roughly the same contrast, if we scale the aperture α by the screening angle θ_0 :

$$\sigma(\alpha) = 4\pi \left(\frac{Z}{137\beta\Lambda} \right)^2 \frac{\alpha^2}{\theta_0^2 + \alpha^2}.$$

The total cross-section $\sigma_0 = \sigma(\infty)$ becomes

$$\sigma_0 = 4\pi \left(\frac{Z}{137\beta\Lambda} \right)^2 = \pi \left(\frac{2 \cdot 0.885 Z^{2/3}}{\beta} \right)^2.$$

The last formula tells us three facts:

(1) $\sigma(\alpha) = k \cdot \sigma_0$, the contrast-determining factor

$$1 - k = \frac{\theta_0^2}{\alpha^2 + \theta_0^2}$$

is the larger screening angle in comparison to the aperture.

(2) Forward intensity times θ_0^2 equals σ_0/π .

(3) The total cross section goes down with increasing *velocity* of the electron; yet this decrease reaches saturation like the increase in β . If we increase the energy over, let us say, 1 MeV, all the costs are put into increasing the mass of the electron rather than its velocity. The total cross section σ_0 is related to the mean number of impacts m in a target of thickness t (in atoms per unit area); namely,

$$m = \sigma_0 \cdot t.$$

This number decides whether single, plural, or multiple scattering applies. In normal electron microscopy, this number is small compared to unity or in the order of unity, depending on whether the object is amorphous or crystalline. To compare fairly the permitted target thicknesses for different electron energies, this number should be kept constant. Hence t becomes proportional to $1/\sigma_0$, which aptly can be called penetration. This definition is independent of the particular type of interaction.

Numerical values exemplifying the results of this section are given in Table I. Hartree-Fock potentials are applied.

2. Inelastic Scattering

After this lengthy treatment of elastic scattering, we can proceed more quickly since all the following formulas show a strong relation to the formulas given so far.

2.1. Because we have to transfer the energy Δ_{ou} , $P_1 \neq P_2$, and

$$q^2 = p_1^2 + p_2^2 - 2p_1p_2 \cos \theta.$$

On account of the energy transfer the minimum momentum transfer ($\theta = 0$, head-on collision) will not be zero but finite:

$$q_{\min}^2 = (p_1 - p_2)^2 = \Delta_{ou}/\beta^2.$$

Applying the small angle approximation $\cos \theta = 1 - (\theta^2/2)$, $p_1 \cdot p_2 \sim p_1^2$, we obtain

$$q^2 = q_{\min}^2 + p_1^2 \theta^2.$$

a. We can directly write down the differential cross section

$$d\sigma = 8\pi \left(\frac{1}{137\beta} \right)^2 \frac{|\epsilon_{ou}(q)|^2}{q^4} q dq$$

as the Rutherford law for deviating an electron by the potential of an atomic electron ($Z = 1$) and accounting for the probability of a transition of the atomic electron from a state 0 to a state n by a response function ϵ_{ou} .

For large q 's, $\epsilon_{ou}(q)$ is related to the incoherent scattering of X rays (Compton effect). Here, however, we are not interested in this case, because a secondary electron is ejected and may absorb the entire momentum of the incoming electron, thus falling into the continuum (analogous to the Compton effect). For small-momentum transfer q , we obtain the desired discrete-energy losses. The response function ϵ_{ou} is then related to the transmission probability X_{ou} for optical excitation of the atom (X_{ou} matrix element of dipole moment):

$$\frac{1}{q^2} |\epsilon_{ou}|^2 = |X_{ou}|^2; \quad q \rightarrow 0.$$

For hydrogen, $|\epsilon_{ou}/137q|_{q=0}^2$ is essentially the intensity of the Lyman series. To obtain a discrete loss, the momentum transfer must be smaller than the upper limit of ou ,

$$q_{\max} = \sqrt{2\Delta_{ou}}.$$

We go on to the angular distribution:

$$d\sigma = 8\pi \left(\frac{1}{137\beta}\right)^2 \frac{|X_{ou}|^2}{q^2} q dq,$$

or, written in angles,

$$d\sigma = 4 \left(\frac{1}{137\beta}\right)^2 \frac{|X_{ou}|^2}{q_{\min}^2 + p_1^2 \theta^2} p_1^2 d\Omega,$$

$q dq$ being $(p_1 p_2 d\Omega / 2\pi) \simeq p_1^2 \theta d\theta$.

Again we introduce an angle characteristic for the spread of the distribution

$$\theta_1 = \frac{q_{\min}}{p_1} = \frac{\Delta_{ou}}{2T_1},$$

and obtain

$$d\sigma = 8\pi \left(\frac{1}{137\beta}\right)^2 \frac{|X_{ou}|^2}{1 + (\theta/\theta_1)^2} \frac{\theta d\theta}{\theta_1^2}.$$

Observe that this distribution is extremely narrow since the energy loss Δ_{ou} is small compared to the kinetic energy T_1 of the incoming electron $\theta_1 \sim 10^{-4} - 10^{-6}$. Furthermore, the product of forward intensity and θ_1^2 again is nearly constant, indicating a high peak in forward direction.

If the energy resolution is not sufficient, or if we are interested in all the inelastically scattered electrons, we must add all possible transitions, and $\Sigma |X_{ou}|^2$ becomes Z . The ratio of inelastically to elastically scattered electrons in forward direction is then

$$\left(\frac{d\sigma_{inel}}{d\sigma_{el}}\right)_{\theta=0} \sim \frac{1}{Z} \frac{\theta_0^2 \Delta^2}{\theta_1^2} = \frac{\Delta^2 \beta^2}{Z \Delta^2},$$

where Δ is the ionization energy. The ratio increases with β , since θ_1 decreases faster than θ_0 and decreases for heavier elements.

$$\begin{aligned} b. \quad \sigma(\alpha) &= 8\pi \frac{|X_{ou}|^2}{(137\beta)^2} \int_0^\alpha \frac{1}{1 + (\theta/\theta_1)^2} \frac{\theta d\theta}{\theta_1^2} \\ &= 4\pi \frac{|X_{ou}|^2}{(137\beta)^2} \ln \left(\frac{\alpha^2 + \theta_1^2}{\theta_1^2} \right). \end{aligned}$$

For obtaining the total cross section σ_0 , we have to observe the restrictions on q ; therefore,

$$\begin{aligned} \sigma_0 &= 8\pi \frac{|X_{ou}|^2}{(137\beta)^2} \int_{q_{\min}}^{q_{\max}} \frac{1}{q} dq \\ &= 4\pi \frac{|X_{ou}|^2}{(137\beta)^2} \ln \left(\frac{2\beta^2}{\Delta_{ou}} \right); \\ \theta_{\max}^2 &= \frac{2\Delta_{ou}}{p_1^2} - \frac{\Delta_{ou}^2}{\beta^2 p_1^2} \simeq \frac{\Delta_{ou}}{T_1} - \frac{\Delta_{ou}^2}{4T_1^2} \approx 2\theta_1. \end{aligned}$$

Also, we have

$$\sigma(\alpha) = k\sigma_0; \quad k = \ln \left(\frac{\alpha^2 + \theta_1^2}{\beta\theta_1} \right).$$

2.2. Plasmon Excitation

a. We can directly apply the results of Section 2.1, with the exception that the response function $|X_{ou}|^2$ is now determined by the plasmon oscillator strength. The formula has become slightly more difficult, since X_{ou} cannot be replaced by its value for $q = 0$ but remains a function of q , and furthermore a critical cutoff momentum q_c arises. Here q_c is of the order of the momentum of an electron at the Fermi surface. The definition of θ_1 remains valid; the energy loss Δ is now related to the electron density n of the material (remember units!),

$$\Delta = \frac{1}{137} \sqrt{4\pi n}.$$

(In cgs units, Δ W $\hbar\omega_p$ with the plasma frequency

$$\omega_p = \sqrt{4\pi n \frac{e^2}{m_0}}.$$

b. The total cross section for a free electron plasma is approximately

$$\sigma_0 = \frac{4\pi}{(137\beta)^2} \frac{1}{\Delta} \ln \left(\frac{q_c \beta}{\Delta} \right).$$

Comparing this result with the one for single-electron excitation, we see that $|X_{ou}|$ corresponds to $1/\Delta$. Since the energy losses are comparable in both cases,

TABLE II. BREMSSTRAHLUNG DIFFERENTIAL CROSS SECTION $d^2\sigma/d\Omega dT_2$ IN UNITS $10^{-4}\lambda_c^2$ $\theta = 87.3 \text{ mrad}$

T_2/T_1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$Z = 13$									
$T_1 = 100 \text{ keV}$	5.83	14.67	31.16	63.46	130.5	281.4	661.2	179.19	6265.3
$T_1 = 1000 \text{ keV}$	0.205	0.875	2.25	5.32	12.21	27.91	63.28	141.5	359.3
$Z = 79$									
$T_1 = 100 \text{ keV}$	204.7	504.6	1048.5	2084.8	4177.9	8748.3	19851.4	51437.5	17202.5
$T_1 = 1000 \text{ keV}$	9.55	31.08	78.48	181.6	409.4	922.0	2076.5	4656.3	11975.6

the total cross section for plasma losses will be smaller than for single electron excitation, for $q_c \ll 2\beta$.

3. Inelastic Scattering Noncharacteristic Energy Losses

In both cases we have a secondary particle, an electron or bremsstrahlung quantum, leaving the atom carrying away a momentum p and an energy Δ .

3.1. K-shell Ionization

$$\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2, \quad \Delta = E_1 - E_2 = T_1 - T_2,$$

$$p_1^2 = E_1^2 - 1,$$

$$p_2^2 = (E_1 - \Delta)^2 - 1 = p_1^2 - 2E_1\Delta + \Delta^2.$$

a. Again we obtain

$$d^2\sigma = \frac{8\pi}{(137\beta)^2} \frac{I(q)}{[q^2 - \Delta^2]^2} q dq dT_2,$$

a formula reminding one of the Rutherford law. The momentum q is now replaced by the four-dimensional momentum change $Q^2 = q^2 - \Delta^2$. The kinetic energy T_2 can vary between zero and $E_1 - |E_k| - 1$, E_k being the binding energy in the K-shell.

The response function $I(q)$ is very complicated and can be discussed only by means of numerical values, which, however, are scarce (we are in the process of computations). This function is related to the response function in Section 2.1; here, however, we are interested in large momentum transfers, which lead to the continuum.

One disadvantage of this process for scanning electron microscopy is that two electrons emerge from the atom and that the primary can exchange roles with the secondary. This is the reason why the accompanying characteristic X rays were more suitable and are indeed used for target characterization. The excitation of characteristic X rays is proportional to β^{-2} and E_k^{-1} .

b. See a.

3.2. Bremsstrahlung

a. With the abbreviations of Section 3.1, we have

$$d_2\sigma = \frac{8\pi}{137} \left(\frac{Z}{137\beta} \right)^2 \frac{R(q)}{Q^4} q dq dT_2.$$

Again the four-dimensional momentum transfer is the important variable. Observe that the production of the quantum invoked a factor $1/137$. The response function $R(q)$ is not too complicated but cannot readily be discussed in physical terms. Graphical representation of the formula must be awaited.

The differential cross section for two elements $Z = 13$ and $Z = 79$ and two energies $T_1 = 100$ and 1000 keV is compiled in Table II. The angle of observation θ is fixed to 87.5 mrad , and the kinetic energy T_2 of the electron is given in fractions of T_1 . The quantum energy is then $T_1 \cdot (1 - T_2/T_1)$. The values reach a peak towards small energy losses. Yet even the maximum values are smaller by orders of magnitude than the corresponding values of the elastic cross section.

b. See a.

Conclusion

We have seen that the discussed cross sections can be written in a unified form. This form permits quick and rough comparison in terms of magnitude and general trends. It also makes the physical event more apparent. But we also have seen that there is much work to be done before we can gain a good insight into the entire picture. The best articles ever written on this subject are by H. Bethe² and by U. Fano,³ from which the author has drawn heavily.

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FIG. 1. Differences in Resolution of Structures at Top and Bottom Surfaces of Thick Crystalline Specimen.

Dr. Hashimoto has asked me to report briefly some of the work he has been doing during the Workshop on the scattering of high-energy electrons.

It is well known that the transmission of electrons increases with increasing voltage. This has been measured using 300-kV, 500-kV, and 1-MeV electron microscopes (H. Hashimoto,¹ R. Uyeda *et al.*,² G. Dupouy *et al.*³).

Since electron-microscopic images are recorded generally on photographic film, images of thick crystalline specimens appear bright with sufficient exposure. But the contrast and resolution of the images become poor due to the inelastic scattering of electrons in the crystal.

Most of the observations on crystalline material have been carried out by the use of anomalous transmission of electron waves. In such a situation the electrons that have passed through the specimens suffer heavy inelastic scattering. Since these electrons are incoherent to each other they become divergent in the crystal. Each inelastically scattered electron, however, is Bragg reflected by the crystal-lattice planes and forms the Kikuchi pattern in the diffraction pattern. Therefore

the structures near the top surface will be projected to the bottom surface as a diffused image.

Since the electron-microscopic images of the crystals are the projection to the image plane of the intensity distribution of electrons that have appeared at the bottom surface of the crystal, the diffused image at the bottom surface is projected to the image plane. Therefore, structures near the top surface will appear with different contrast and resolution from those in the bottom surface.

Using Both's formula (Rutherford scattering) for multiple scattering, Marton⁴ calculated a "depth-resolving power" for specimens placed on the gun side of the support, as well as for density variations for a specimen of uniform thickness. He pointed out the need for placing the specimen on the objective side in the case of thick supports.

Several theories of inelastic scattering have been proposed for the transmission of fast electrons through crystals when fast electrons are described by Bloch waves so that Bragg reflection is also considered. Howie,⁵ Whelan,⁶ Hirsch and Hall,⁷ and Yoshioka and Kainuma,⁸ discussed the inelastic scattering of electrons

FIG. 2. Relative Intensity Maxima of Images from Top and Bottom of Thick Specimen.

TABLE I. VALUES USED FOR CALCULATIONS OF RESOLUTION AND CONTRAST AT VARIOUS VOLTAGES

E , volts	5×10^5	1×10^6	3×10^6	5×10^6	Measured at $E =$ 300 kV
θ_i , rad	9.025×10^{-5}	5.536×10^{-5}	2.266×10^{-5}	1.434×10^{-5}	
ξ_i , Å	9.193×10^2	1.003×10^3	1.054×10^3	1.061×10^3	
C_{sp} , Å	0.35×10^8	0.4×10^8	1.0×10^8	2.1×10^8	Tadano
C_{ch} , Å	0.35×10^8	0.4×10^8	0.6×10^8	1.0×10^8	
α , rad	4×10^{-3}	3.7×10^{-3}	2.6×10^{-3}	1.6×10^{-3}	
ΔE , volts	15 for aluminum				

in crystals by plasma excitation, interband excitation, and phonon scattering, respectively. These theories could estimate the amount of anomalous absorption effect due to their models for inelastic scattering.

Most crystals have structural imperfections such as dislocations, interstitial atoms, and vacancies, which are also formed by irradiation with high-energy electrons. These imperfections will also produce angular divergence of elastically scattered electrons.

Since the angular distribution of scattered electrons in crystals with different thicknesses can be known from their diffraction patterns, and the energy dependence of mean free path of inelastically scattered electrons can be estimated from the measured values of elastic scattering, the simple estimation of resolution and contrast of thick specimens can be done using these values.

The present paper shows, in Fig. 1, expected resolutions of structures near the top and bottom surfaces of a thick crystalline specimen, when observed by high-voltage electron microscopes. Figure 2 shows peak intensities of the images of the top and bottom surfaces.

The treatment is confined to structures in the crystal whose images are formed by the interference of plane waves such as stacking fault fringes, moiré patterns, and grain-boundary fringes. For the images of small particles in the crystal, such as precipitation particles, the spherical waves will propagate from the particles with the semiangle of divergence $\theta \simeq \lambda/d$, where d is the diameter of the particles. In such cases, the term due to the diffraction of the wave

$$\delta_{\text{diff}} = \lambda/\sin \alpha$$

must be added. For thick crystals, δ_{diff} becomes negligibly small compared with other errors.

Table I shows the numerical assumptions used.

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During the Workshop, at a Group III seminar, Dr. Crewe pointed out that four general types of energy-loss spectra have been observed:

I = NO. OF ELECTRONS/UNIT TIME WITH LOSS ΔE

Fig. 1

Fig. 4

Fig. 2

Fig. 5

Fig. 3

Fig. 6

FIGS. 1-6. Typical Energy Loss Spectra for Various Materials (Suggested by A. V. Crewe, June 1966).

FIG. 7. Differences in Appearance of a Specimen when Observed by Electrons of Increasing Image Loss

1) Bulk Losses

- a) Losses due to microscopic properties in heterogeneous material (see Fig. 1). A distributed curve, with low peak losses from a thin, predominantly low Z , material—larger peak losses with “thick” specimen, higher Z ’s.
- b) *Plasma type losses in metals* (Fig. 2). Here we may find repetitive “band” structure at low energy losses.
- c) Somewhat discrete losses in amorphous materials (Fig. 3). A plasma-like peak, for “thick” specimens, superposed on a type *a*) curve.

2) Molecular Losses

Here a peak is found at slight energy loss, on the general distribution, corresponding to an ultraviolet absorption process (Fig. 4).

3) Atomic Losses

Here sharp increases of scattered electrons are found at energy losses corresponding to K , etc., X-ray edges (Fig. 5).

4) Gas Specimen Losses

Sharp line spectra have been observed, corresponding to energy losses in optical absorption (Fig. 6). Perhaps non-organized heavy molecules in a light matrix will give similar spectra.

Dr. Crewe illustrated some of these effects as seen in a series of scans of a single specimen, nominally aluminum, taken with electrons of discrete energy losses from about 7 to 700 eV. Some of these are illustrated in Fig. 7. He recommended that since comparable information may be expected from 5 MeV electrons, energy resolution of better than 1 V should be provided.

Specimen Facilities for Very-High Voltage Microscopes

RAYMOND K. HART

Argonne National Laboratory

Firstly, I would like to review some of the reasons that have been discussed during this workshop why a very high-voltage microscope should be constructed, as these features have a bearing on the specimen facilities that should be provided. These features may be listed as follows:

- 1) Better theoretical resolution than is possible with conventional microscopes. I am going to use the word conventional to refer to microscopes operating in the region of 100 kV.
- 2) Improved penetrating power of electrons in matter.
- 3) Improved chromatic aberration, assuming highly stabilized high voltage and lens currents.
- 4) Greater accuracy in electron diffraction techniques.
- 5) Improved dark-field observation of both crystalline and "amorphous" materials.
- 6) Employment of other contrast mechanisms.
- 7) Radiation damage studies—less damage to thin biological specimens, more damage to thick metal specimens.
- 8) Investigation of living cells and complete molecules in their natural form.
- 9) High-pressure gas reactions without excessive beam deterioration.

The resolution of an electron microscope is simply determined by the spherical aberration of the objective lens and the wavelength of electrons by the relation:

$$R = k(C_s \lambda^3)^{1/4}.$$

The value for the "constant" k is usually about 0.5, although values used by various workers have varied from 0.47 to 0.78, with an average of 0.5. Considering this expression it does not seem profitable to go to beam voltages above 3 to 5 MeV since the wavelength of electrons ceases to change rapidly with voltage, as is shown in Fig. 1. Thus, going to voltages much above 5 MeV, the advantages would be small compared to the additional expense involved.

Spherical aberration of the objective lens can nominally be kept within the range of that obtainable in conventional microscopes, i.e., from 0.5 to about 1.0 cm, without too much difficulty. With technological

advancements it may be possible to improve these figures.

Using these values in the above expression, we can show that a conventional microscope should have a theoretical resolution of about 2 Å, and this has already been approached in practice. With a 3- to 5-MeV microscope, it should be possible to obtain a resolution of about 0.5 Å.

Although experimental results from electron microscopes in the 0.5- to 1.0-MeV range have shown that metal specimens a few microns thick can be investigated, the increase in thickness over that most profitably used in 100 kV instruments is largely dependent on the resolution and contrast requirements. If you wish to use a 5 MeV microscope for obtaining the ultimate resolution, you will still be restricted to about 0.1 micron thickness of metal with an atomic number, Z , of about 40.

On the other hand, if we are willing to sacrifice resolution for specimen information, i.e., to go from 1 Å to, say, the 20 or 30 Å level, then it should be possible to go to much thicker specimens than can be investigated in a conventional microscope. At 1 MeV the French have taken good pictures of aluminum approximately 10 microns in thickness, and extrapolating these figures up to 5 MeV, we should be able to view aluminum in the vicinity of 50 microns in thickness. This would be a definite improvement over the conventional microscope.

The thickness of the specimen is also tied in with the chromatic effect. If we view a very thick specimen in a high-resolution microscope, i.e., one which has excellent high-voltage and lens-current stability, the chromatic effect caused by energy loss of electrons passing through the specimen will decrease resolution. These energy losses can occur by a number of different processes of inelastic scattering. The distribution of energy-loss electrons over angle and energy is quite complicated and not thoroughly investigated as yet, even for electrons in the 100 kV range.

If the thickness of a specimen used in a very high-voltage microscope is kept below an upper limit of a few microns, the chromatic aberration due to the specimen can be kept to a minimum since very high-energy electrons suffer maximum forward-scattering as shown

FIG. 1. Electron Wavelength vs Accelerating Voltage

TABLE I

<i>E</i> , MeV	0.1	0.5	1.0	2.0	5.0
2 <i>θ</i> , rad	0.016	0.0061	0.0037	0.0022	0.00096

by Dr. Zeitler. The result is that a maximum number of single inelastically scattered electrons are confined to a small angle of spread. Also, one must consider the chromatic effect introduced by the specimen with reference to the absorption contrast. With thin specimens, the contrast is likely to decrease in comparison with that obtained with 100-kV electrons. On the other hand, thick specimens are more likely to yield images of good contrast, as has been shown by the French at 1 MeV, due to the chromatic effect mentioned previously. If the contrast, however, is due to diffraction, as is usually the case with crystalline material such as metals, then one should expect an improvement by going to higher voltages.

This brings up the question of the accuracy of diffractions that one can obtain. Normally, in a conventional microscope one can observe a selected area by selected area diffraction of 0.5 micron or so. At 1 MeV one can look at an area of about 0.1 micron as both French and Japanese investigators have shown, and at 5 MeV this would be reduced to a few hundred angstroms. The minimum size that can be analyzed is limited by the spherical aberration of the objective lens, as shown by the expression

$$d_s = C_s \theta^3,$$

where θ is the Bragg angle.

The decrease in Bragg angle of a diffracted beam from (111) aluminum as a function of λ is given in Table I. The smaller diffraction angles allow smaller apertures to be used in the intermediate lens. Also, the beam is closer to the optical axis when it goes through the objective lens, so the spherical aberration is kept to a

minimum. Small diffraction angles are also beneficial to dark-field microscopy. In dark-field microscopy, the main electron beam is tilted so that the diffracted beam goes axially down the column. When the diffraction angle becomes very small, as is the case when you go up into the MeV range, the tilting angle becomes much smaller. Therefore, instead of tilting the whole gun-condenser system, as in a conventional microscope, it should be possible to do all this by several deflection coils without introducing any severe aberration into the beam.

One important problem in microscopy is how to distinguish different regions of a specimen from each other given that the microscope has sufficient resolution and that the regions are different in some interesting way. This is the problem of contrast. A number of physical effects can be used to produce contrast in microscopes operating below 500 keV. The most important of these effect are incoherent scattering, diffraction, and characteristic X-ray production. All of these effects are of course available to a high-energy microscope as are the elaborate staining and shadowing techniques developed for conventional electron microscopes. In addition, several effects available only at energies of over 1 MeV have great interest for scanning microscopy. Among these are the following:

A. Scattering from Free Nuclei. When this recoil energy as given to a nucleus by a high-energy electron scattered by the nucleus, exceeds about 50 eV the nucleus may be considered as essentially free for the calculation of the kinematics of the scattering. In this case the energy lost by an electron scattered at a particular angle is characteristic of the nuclear mass. Thus an energy analyzer accepting the electrons scattered at a particular angle in a scanning microscope could show what nucleus they have been scattered from. This could have an interesting application in biology, for example, in tracing deuterium and perhaps some other stable isotopes with microscopic resolution. Because the cross sections for this process are relatively low, it could not give very high resolution but a resolution of 500 Å seems possible; this is much better than any other method of tracing stable isotopes and is as good as the best that can be done with radioactive isotopes.

B. Nuclear Reactions. A number of nuclear reactions produced by electrons of 1–5 MeV energy, such as electrodisintegration of the deuteron and Coulomb excitation of low levels of many nuclei, produce characteristic radiation which could be identified and in a scanning microscope give the location of the nuclei in question. The cross sections for these processes are admittedly quite low, but they may have value even if only relatively poor resolution can be obtained because of their unique selectivity.

C. Cerenkov Radiation. Cerenkov radiation is essentially only produced by electrons of greater than 500-keV energy. In specimens of greater than about 10 microns thickness, it is a unique way of measuring the optical index of refraction in an area equal to the beam diameter. This would be done by measuring the angle between the Cerenkov light and the beam direction. In very thin specimens, however, this angle is indeterminate.

D. Electron Positron Pair Production. Since the positron is a relatively easily identified particle, there may be some usefulness in this reaction whose cross section has the property of depending on Z^2 where scattering, bremsstrahlung, etc. depend on Z . It has a quite high threshold, which may help in maintaining resolution in thick specimens.

At very high voltages, damage to the specimen due to beam irradiation can be kept at a level low enough so that living cells can be investigated, as has been shown by Professor Dupouy and his associates at Toulouse. This again is possible because with very high voltages, the beam current can be significantly reduced to that used at 100 kV, and it should also be possible to extract more information from individual electrons because of their greater elastic range in matter.

On the other hand, very high-energy electrons can be used to produce radiation damage in metals and other crystalline substances and by controlling the dosage, it should be possible to make detailed examinations *in situ*.

When carrying out gas reactions in an electron microscope, we found that the gas molecules cause considerable electron scatter. Figure 2 shows some results that Dr. Hashimoto has obtained with 50-, 80-, and 100-kV electrons. These curves show that at a given pressure, the amount of electron scatter will reduce with increasing accelerating voltage. Thus it should be possible to carry out chemical reactions at quite high pressures when very high accelerating voltages are used. These values were obtained with a differentially pumped microscope and the specimen in a gas-chamber, and the only entrance between the gas chamber and the rest of the microscope was by means of small apertures. Three aperture sizes were used: 50, 100, and 150 microns.

The next question that arose is where to locate a specimen in an electron-microscope column. The normal position is, of course, either just above the modal plane of the objective lens, or in the modal plane if it is a single field condenser-objective lens. As shown in Fig. 3, the beam diameter at this point in a conventional microscope is about 2 microns, if both condenser lenses are used. By placing scanning coils between the specimen and condenser II, we can also perform scanning

FIG. 2. Intensity Decrease due to Gas Inlet

FIG. 3. Ray Path in a Conventional Electron Microscope (R. K. Hart, July 11, 1966).

microscopy with the specimen in this location, though the resolution will be poor.

Dr. Nixon has pointed out that a very fine probe exists in the back focal plane of the projector lens and should be very suitable for both high-resolution scanning microscopy and scanning electron diffraction, which has been developed by Dr. Grigson and his co-workers.

I have made some calculations of the beam size at this point in a conventional microscope as well as in the same place of Dr. Tadano's 3 MeV column. The reduction in size of an electron beam passing through a magnetic lens can be expressed by

FIG. 4. Projector Lens Scanning Microscope (W. C. Nixon, June 30, 1966); Projector Lens Scanning Diffraction (C. W. B. Grigson, June 30, 1966).

$$d = Md_0 + C_s\alpha^{3/2},$$

where M is the lens' magnification, d_0 the primary source size, and $C_s\alpha^{3/2}$ the effective increase in spot size due to the disc of confusion created around the principal beam.

Starting with an effective source size of 50 microns and assuming that the spherical aberration constants are the same as the focal lengths of the lenses, we can theoretically obtain a beam of about 20 Å diameter at this location in the microscope column. It is also theoretically possible, with Dr. Tadano's 3-MeV column, to obtain a beam of similar dimensions at this location.

The theoretical beam current at this location in both columns was calculated using the expression

$$I_2/I_1 = (rM_1)^2/(S\alpha_1)^2$$

and was found to be approximately 10^{-11} Amp. This

figure agrees well with experimental values measured in a conventional microscope if the measured intensity in a suitably reduced area of the final image is extrapolated back to the back focal plane of the projector lens.

Although this very fine beam has not been used to date in scanning microscopy or diffraction, it has been used in static form by Haine and Mulvey (J. Opt. Soc. Amer. **42**, 763, 1952) in an attempt at electron holography. Experiments are under way at Cambridge to use such a beam in the scanning mode for scanning electron microscopy.

Scanning coils can be placed either in the projector bore or above it and a projector stigmator fitted as shown in Fig. 4. For rough work, scanning could be fed to the objective stigmator if electrostatic or electromagnetic and astigmatism corrected as well. The viewing chamber has ample room for insertion of specimen

FIG. 5. Vacuum Interlock for Specimen Change (Suggested by W. C. Nixon and R. J. Miller, July 1966)

stage and electron detectors. In addition, it is suggested that a small aperture be placed in the projector bore to act as a differential pumping hole, if such is required.

Dark-field scanning electron microscopy is a method that has been tried at low voltages, to 50 kV, but not yet worked through. In this case, only the elastic electrons are collected, all loss electrons excluded, and only elastic electrons that have also been deviated through a selected angle. These angles may be big enough at 5 MeV to permit analysis. In any case, dark-field methods show the best detection limit, and the resolution need not be inferior to that in bright field.

The next consideration is how to get a specimen, or specimens, into an ultrahigh-vacuum environment without destroying the existing vacuum conditions. Drs. Miller and Nixon worked on this problem and produced the system shown in Figs. 5, 6 and 7. This system, to a large degree, makes use of commercially available components. Such a system would allow a

minimum of air into the ultrahigh-vacuum system and allow as many as nine specimens, or more, to be available for immediate use. Multiple specimen loading was considered to be very desirable by the majority of participants. It was also strongly recommended that several of these specimens be test specimens such as holey carbon films.

Another type of mechanism that could be used to transfer specimens, or other equipment such as photographic plates, etc., from the atmosphere into an ultrahigh-vacuum system is shown in Fig. 8. This mechanism is somewhat complicated, but it does have the advantage that it allows straight-through entry into the vacuum. The internal flange is held down by a series of bolts, and these bolts are allowed to be tightened down by bellows, so all rotary motion, (i.e., tightening of the bolts) can be kept outside the vacuum system. To open the system, the plate turns through a

FIG. 6. Schematic of Specimen Storage Bank (Suggested by R. J. Miller, July 1966)

FIG. 7. Specimen Holder Mounting for Specimen Storage Bank (Suggested by R. J. Miller, July 1966)

FIG. 8. Design for Blank-off Flange (Suggested by R. K. Hart, June 15, 1966)

small sector so that the bolt heads clear the "keyhole," and then the plate can be lifted and swung to one side.

The movement and manipulation of specimens in the stage were also discussed, bearing in mind that operation of a very high-voltage microscope would necessitate remote control. Four types of motions were seriously considered, these being

- Extended manual controls
- Mechanical activation from servomotors
- Hydraulic controls
- Piezoelectric movements.

Of these, piezoelectric crystals were quickly dismissed, except where very small movements would be involved and where the field created by the voltage to the crystal would not be detrimental.

Both Drs. Marton and Rymer were strong advocates for hydraulic controls. Hydraulic movements, similar to that shown in Fig. 9, have been constructed and found to work effectively. They have the advantage that they can duplicate the movement of the human hand. In electron microscopy one usually likes to scan specimen rapidly until an area of interest is located and then have very fine control to look at this area in detail. Such an arrangement as this can give this kind of control very nicely. Here you have a "joy stick,"

which is capable of moving the specimen over its entire field in the matter of a few seconds, and once an area of interest has been located, the fine adjustments can be used for very precise setting. The system is capable of movements to at least 1 micron and possibly even less.

Servomechanisms have one advantage: they can be programmed, and alignment as well as the movement of specimens can be left to a computer, so that if we want to come back to a specific area of which the coordinates are known, we can ask the computer to set the whole system up.

Most electron microscopes, which are at present operating in the 0.5- to 1.0-MeV range, today use extended manual controls, and there was considerable advocacy for this type of control.

For most applications it was considered essential that goniometer motion of the specimen be included. Also, it was considered essential that dark-field capabilities be included.

However, the inclusion of other specimen facilities such as heating and cooling stages in one instrument was considered somewhat inadvisable, especially if we are going to the ultimate of resolution, i.e., in the vicinity of 1 Å or less. A number of participants suggested

FIG. 9. Hydraulic Specimen Stage Movement (Suggested by L. L. Marton, June 15, 1966)

that the electron optical column should be designed so that the specimen-objective lens system could be easily inserted or removed from the rest of the column, and that these lens-stage combinations should then be designed for specific types of experiments. Much of the preliminary setting up of the systems could be done outside the actual column and thus not tie up the rest of the microscope, which could be used for other purposes, while the setting up is in process. It was repeatedly stressed that, to achieve a resolution of $1 \text{ \AA}$ or less, the relative movement between the specimen and the objective lens must be kept to $1 \text{ \AA}$ or less. This suggests that the specimen stage should be rigidly tied down to the objective lens during the time of the recording of a very high-resolution micrograph.

Even after this precaution is taken, we still have the problem of thermal gradients within the specimen itself. The use of very high-energy electrons should ease this problem compared to conventional microscopy, but it will certainly not eliminate it. The reason is

that we can use much smaller beam currents at the higher energies than possible at 100 kV. Also, as Dr. Fernandez-Moran mentioned yesterday, the keeping of a specimen at liquid helium temperatures would reduce the thermal vibration within the material itself to below $1 \text{ \AA}$. I would like to conclude by reading an extract from Mollenstedt's paper, which appeared in *J. Microscopie*, **4**, 413 (1965). "The electron interferometer—and the same would apply to an electron microscope of extremely high resolution—betrays the step of a walker in a distance of 20 m. If an observer lays his hand onto the instrument, his heart beat can be seen as a fringe shift in the interferometer.

"For these reasons I would suggest that an electron microscope for a resolution limit of $1 \text{ \AA}$ or less should be arranged far from all civilization in the solitude of nature on a foundation of concrete well immersed in the ground, and that, during observation, the interaction between the observer and the instrument should be of optical nature."

Mechanisms for Contrast Formation in High-Voltage Microscopy

DAVID B. WITTRY

*University of Southern California
Los Angeles, California*

I would first like to add to "Mechanisms for Contrast Formation for High-Voltage Microscopy" the word "possible," because many of the mechanisms I would like to discuss may not, in fact, be practical so far as attaining useful information from the specimen. I am sorry that I do not have any slides. I have a great many slides back in California that show the virtues of observing X-ray signals from specimens at an angle of $52\frac{1}{2}^\circ$, but I want to stress here more fundamental questions than how to instrument the observation of some of these sources of contrast.

I am one of those who came here to find out what the high-voltage microscope is good for. It is not entirely clear to me that the 5 MeV electron microscope has a significant advantage over the 1-MeV electron microscope, which is considerably easier to construct and undoubtedly much more reliable in operation. I asked one of my metallurgist friends, who has electron-microscope experience, what he thought about this question. He said, "Well, perhaps you can look at thicker samples, but once you find out that the things you see from a thicker sample are the same as you might see in a thin sample, then it seems to me to be a lot less expensive to find how to make thinner samples."

Now this undoubtedly represents only a limited view, particularly with respect to biological applications, for example, where entirely different considerations apply, because a biologist has known for a long time how to make specimens adequate for examination in the conventional electron microscope. So, new advantages, some of which were discussed by earlier speakers, must be investigated carefully as to the advantages of 5 MeV vs 1 MeV, or alternatively down as low as 500 keV.

I would like to present in the rest of the discussion some of the feelings that emerged from my interaction over the brief period I have been here with some other members of Group III. In the first place, I felt that Group III was at a slight disadvantage with respect to Groups I and II, because much of what Group III ultimately is able to recommend will depend on what comes out of Groups I and II, in the form of the amount of space actually available in the specimen region, and regulation of the electron beam. Secondly, I think that

we lack certain basic information necessary to evaluate the use of some of the possible mechanisms for contrast formation using a 5 MeV electron beam.

We need not restrict the present considerations with regard to the location of the specimen along the electron optical column, but can divide the discussion into two categories: the specimen located in the normal position, and the specimen located in a new position. In the normal specimen position, that is, with the specimen between the final condenser lens and the objective lens, the configuration corresponds to a conventional transmission electron microscope. In a 5 MeV transmission electron microscope, the specimen thickness can be several microns—a distance that corresponds roughly to the order of the generation depths for characteristic X rays at about 3 kV. In this lies one definite advantage of high-voltage microscopy; namely, when the specimen thickness becomes as large as 1 to 5 microns, a quantitative electron-probe microanalysis can be performed using electrons of 10 to 3 kV. This may be one of the most powerful tools at our disposal to find out what is in the several cubic microns of specimen that is observed typically in electron-probe microanalysis.

Transmission electron microscopy is, of course, one of the most important cases involving a specimen in the normal position, and sources of contrast formation have been discussed by the previous two speakers in this session. However, other ancillary techniques have also achieved importance in the normal transmission electron microscope. As indicated in part A of Table I, these include selected area diffraction, Kikuchi line patterns, and the possibility of performing energy analysis of the electrons making up the transmitted electron beam. The latter technique is relatively new and has been accomplished with electrons that form a complete two-dimensional image by Castaing and Henry and also by Watanabe and his co-workers, using a slightly different approach. With regard to specimen facilities and accommodations in a very high-voltage microscope, it appears that the use of heating, cooling, and tilting stages, or stages that can be used for ion or for molecular bombardment, may be very important for many of these ancillary techniques.

TABLE I. IMPORTANT TECHNIQUES IN TRANSMISSION ELECTRON MICROSCOPY

A. Normal Specimen Position
Transition Electron Microscopy
Ancillary Techniques
Selected area diffraction
Energy loss spectra
Kikuchi line patterns
B. New Specimen Position
Electron Diffraction of Surfaces
Emission Microscopy
Reflection Microscopy
Back-reflection Diffraction
Scanning Electron Microscopy or Electron
Probe Microanalysis

Next let us consider the possibilities for a new specimen position. One case of this has already been suggested by Dr. Nixon, wherein the very small crossover that occurs below the projection lens could be used as an electron probe. But we must note that some conventional electron microscopes have also been equipped for utilizing accessories at positions different from the normal specimen position. I refer, for example, to electron diffraction of surfaces for a thick specimen where one would normally locate the specimen farther down the electron-beam column. Various additional possibilities for the "new" specimen are listed in part B of Table I. For convenience, I choose to include in the category of "new" specimen position, techniques not commonly used with conventional electron microscopy, such as various types of emission microscopy (because the specimen is located in a region of different potential energy if not in a different position physically). I would also include in this category reflection electron microscopy, where the specimen is tilted at an angle that is extremely large compared to the tilt angles used in normal transmission electron microscopy.

Along these lines we might consider also the possibility of using back-reflection electron diffraction. Such a technique cannot use a parallel incident beam because, as I am sure you are all aware, the diffraction pattern is highly concentrated in a forward direction. However, if we have a diverging source of electrons, as used in the formation of Kikuchi line patterns, and in addition have an extremely penetrating electron beam, the possibility of formation of Kikuchi line pattern in the backward direction then exists. Moreover, those electrons that have suffered selective energy losses will be diffracted by the crystal lattice, and perhaps these may also form a Kikuchi line pattern. I am referring here to losses, for example, corresponding to excitation of K or L levels, which would be completely unfeasible with the voltages commonly used (because of the small range of 50 to 100-keV electrons). I recognize that

there will be severe background, which may, in fact, prevent the observation of the back reflection of the Kikuchi line patterns. Nevertheless, I think it well to be aware of those things we might look for even though their ultimate value remains to be seen.

Finally, of course, we have scanning electron microscopy or electron-probe microanalysis. Now, this can be done to a certain degree in a conventional transmission electron microscopy with the specimen in a normal position. The advantage of moving the specimen further down the column was pointed out by Dr. Nixon. Therefore I put this technique into the "new" specimen position category, partly for that reason, and partly because in scanning electron microscopy, or in scanning electron-probe microanalysis, there are additional sources of "contrast" that are not normally available in the transmission electron microscope.

For further discussion, I would like to take a very broad view of the meaning of the term contrast. I suggest that contrast is simply a way to tell one thing from another, and this may be either quantitative or qualitative. It is convenient in this discussion to assume that all sources of information other than electron signals must use some form of scanning in order to get the desired spatial information. Now this is not necessarily true. For example, the Kossel line patterns are a good case in which diffraction information can be obtained. In fact, you don't need to use an electron probe, but if you do, the local information is much more significant and useful.

Another good example of a source of contrast that does not require scanning is cathodoluminescence. If we were to excite a large area, optical radiation could be focused with an appropriate optical system to form an image and we could get local information without the necessity for scanning. In fact, some of the people using electron microprobes do precisely that. They expand the electron beam to cover a relatively large field of view and they observe the cathodoluminescence of minerals through an ordinary optical microscope. So, it is not necessary that all other signals than electrons employ scanning for localization of the information, but it is convenient for purposes of discussion to make this assumption. We then have available for the function of contrast all the signals with which we have experience using electron microprobe instruments at 30- to 50-kV energy.

Figure 1 shows schematically various types of signals from which we can get different kinds of information in the scanning electron microprobe. I have tried to assess in Table II some of these signals from the point of view of whether they will be useful when one extends the voltage of the primary electron beam from what we

customarily use in the 100 kV range or less up to energies above 1 MeV. A crucial question which I think remains to be answered in this regard is: "What is precisely the distribution of excitation by a 1 MeV electron probe?" This question, of course, was similar to the first question that people asked themselves in the use of the conventional electron-probe microanalyzer, but we are now faced with not only knowing how much is the penetration of the electron beam, but also what is the three-dimensional distribution of the excitation produced by a focused electron beam.

In 30- to 50-kV electrons, you may get one of two possibilities, roughly speaking (there are many variations in between). We can get a volume element for excitation roughly hemispherical in shape, the center being something less than half the radius below the surface. We may also get excitation particularly in very low atomic-number targets, where the beam seems to penetrate somewhat before the scattering begins to become important. These two extreme cases are shown in Fig. 2. Now the point I would like to raise at this time is this: The utility of a high-voltage scanning electron microscope for thick specimens depends to a large degree on which of these two shapes we have for the volume element with a particular signal.

Many sources of signal information are localized to smaller volumes than the volume in which the bulk of the electron-beam energy is dissipated. Secondary electron emission is an extreme case wherein secondaries come from an escape depth of the order of 100 or 200 Å. The X-ray information in the typical wavelength range we are accustomed to using (1–10 Å) may come from

TABLE II. SIGNALS AVAILABLE IN THE SCANNING ELECTRON MICROSCOPE

Signal	Useful at 5 MeV?	
	Thin Spec. (<5 μ)	Thick Spec.
Secondary Electrons	yes	?
Specimen Current	no	no
Backscattered Electrons	yes	yes
Transmitted Electrons	possibly	no
Optical Excitation		
Cerenkov and Transition Radiation	doubtful	
Line Spectra	yes	no
Hole-electron Pair Effects		
Recombination Radiation	limited	limited
Junction & Conductivity Effects		limited
X-Radiation		
Line Radiation	yes	?
Continuum	yes	?
Nuclear Effects	?	?

FIG. 2. Volume Element for Excitation in *a*, Hemispherical Distribution of Excitation; *b*, Pear-shaped Distribution in Very Low Atomic-number Targets.

FIG. 1. Schematic Diagram Showing Various Types of Signals that Can Be Generated in a Thick Specimen by an Electron Beam.

tens of microns, but with the very soft characteristic x radiation, 10 to 100 Å in wavelength, we are looking at surface layers whose thickness is one micron or less. This being the case, if we are fortuitous enough to have a distribution as in Fig. 2b, then we can preserve the highly local character which is made available by the focused electron beam, and we don't have to worry about the spreading of the electron beam in the thick target. For that reason, secondary electron emission has a possibility of being used for a thin specimen, but one is not sure, in fact, whether this will be useful for the thick specimen. The same question exists regarding the utility of characteristic radiation from a thick specimen. If we are willing to use very long wavelengths for the X-rays, we could take advantage of the local

character of the beam at the surface if the excitation distribution is as in Fig. 2b.

Specimen current I feel, is not useful for either thick or thin specimens. In thin specimens most of the beam goes through the specimen, and in the thick specimens we are dependent, to a large degree, on the effects that occur over a relatively large volume so that the attainable resolutions, I feel, will be particularly poor.

Back-scattered electrons certainly can be a possible source of information in a thin specimen without serious degradation of resolution and, you will notice, I've indicated in Table I the feasibility of using this signal with a thick specimen. This requires some explanation because it is more than a probable source, but I think a rather certain potential source of information. The information from back-scattered electrons can be made reasonably independent of the volume element in which most of the energy is dissipated, provided we look at back-scattered electrons, which have suffered relatively little energy loss. This is possible through the use, for example, of proportional detectors such as the *p-n* junction solid-state detector. We may hope at 1 MeV to achieve an energy resolution in such a proportional detector of about 1%, which means we will be looking at electrons that have lost about 3 keV of energy from their primary energy of the order of 3 MeV. Therefore, the range in the specimen will be about half the distance required for the electron to lose 3 keV of energy. So, I think we can preserve the local character of the back-scattered electron signal by using pulse-height analysis of the back-scattered electrons.

Transmitted electrons, I think, have no possibility of use for an infinitely thick specimen because there aren't any. For a thin specimen, this is a potential source of information. One important possibility, then, is to measure the energy distribution of the transmitted electrons as was done first by Hillier. Hillier was the first to observe characteristic energy losses corresponding to K and L shell excitation. Over a period of many years, there has been a great deal of work on small energy losses of transmitted electrons. However, we encounter additional problems when we try to do this at energies of 1–5 MeV, particularly with regard to the small energy excitation, because we're still looking for an energy loss that is the same amount, but we have now increased the energy of the electron by a factor of at least 100. This means that we must have an electron spectrometer with resolution that is a hundred times better if we want to see the same amount of detail in the energy-loss spectrum.

The applications of secondary-electron emission have already been mentioned, but I would like to point out further that one of the most useful sources of informa-

tion from the secondary electron was derived from the possibility of obtaining contrast depending upon the local variation in potential of the surface. To some degree this technique may be thought of as energy selection of the secondary electrons. Voltage contrast was first demonstrated at Cambridge by the observation of *p-n* junctions with reverse bias, and has subsequently given rise to a number of practical applications demonstrated by the work of Everhart and others at Westinghouse and at the University of California at Berkeley. The secondary-electron emission and voltage contrast are an extremely important tool to the electrical engineer who is building solid-state devices and would like to be able to examine the local potential distribution in an integrated circuit, for example.

Optical radiation has not, I think, been utilized in the conventional electron microprobe as much as possible. In our own work at The University of Southern California, we have found certain forms of optical radiation, particularly that which results from the recombination of excess hole-electron pairs in semiconductors, to be very useful. As to whether we can obtain information from Cerenkov radiation of Lilienfeld radiation (sometimes called transition radiation), this is somewhat doubtful. I think there is insufficient time to go into the details on some of these points. Perhaps they will be discussed in the appendixes of the proceedings.

Line radiation of optical frequencies can be very useful for thin specimens, I think, if the intensity is adequate, and depending upon the transitions that give rise to this radiation we may or may not be influenced by surface recombination. For radiation that results from electron hole-pair recombination, we may be seriously limited in what we can do with a sample a few microns thick by the loss of carriers due to non-radiative surface recombination. The diffusion length of excess minority carriers in gallium arsenide ranges from about 0.6 to 3 microns (which is roughly the distance over which the carriers normally recombine radiatively), so if the specimen is thinner than the diffusion length, the intensity suffers drastically. On the other hand, because surface recombination may occur, this effect can be used to obtain information on thick targets with the electron microprobe. By increasing the accelerating voltage and measuring the intensity of the cathodoluminescence, we can measure the diffusion length and surface recombination velocity of minority carriers. Still, I would qualify this as being relatively limited in potential because when we do this at 1–5 MeV, we may spoil spatial resolution. The spatial resolution again will depend on the self-absorption of radiation and on the shape of the volume element excited at the surface. If we have a distribution as in Fig. 2b and large self-absorption, the method may still

provide resolution limited only by the diameter of the electron probe.

If this is not the case, such signals can still be potentially useful on thick targets, provided we can vary the voltage of the electron beam and observe changes in the emission of recombination radiation as a function of the average depth at which excitation occurs. Hence, for cases that are essentially one-dimensional, junction effects and conductivity changes resulting from excess carrier generation in semiconductors may be useful for study of thick specimens, but some questions remain to be answered. (Note that some of these experiments can be performed with a 5 MeV Van de Graaff generator more readily than in an electron microscope.)

Now, one of the most interesting sources of information in electron microscopy we have seen so far stems from the development of the electron-probe micro-analyzer. For example, as early as 1951 the possibility of doing X-ray analysis on a highly localized area of a thick target was recognized. For a "thin" target and 5 MeV electrons we can estimate the intensities to be expected. We have roughly a factor of 16 decrease due to increased beam energy assuming the cross section for production of characteristic X-rays decreases as $1/E \ln(E/E_K)$. To compensate for this, we have an increased thickness by roughly a factor of 100 over the sections normally used in transmission in electron microscopy because a "thin" section for the high-voltage microscope may be of the order of 5 microns thick. In other words, we should expect to find a signal of the order of possibly 3 to 10 times greater for the X-ray intensities from the "thin" target with the high-energy electron microscope, compared with the thin target in the normal transmission electron microscope. This makes it a potentially useful technique; the counting rates are rather low for thin samples in ordinary microanalysis (that is, on the order of a few hundred counts per second), but one can still get quantitative information.

Regarding the X-ray continuum, I would like to suggest that the information to be derived is quite similar to the information derived from back-scattered electrons, namely the local variations in average atomic number. In fact, in the use of semiconductor particle detectors the X-ray continuum would contribute to the signal that I previously assumed was only the back-scattered electron signal. I suspect that with such a detector, we measure an unknown portion of the X-ray continuum from the target as well. It would be rather difficult to discriminate between the X-ray continuum and back-scattered electrons. Indeed it may not be necessary to discriminate between these signals since they both provide information on the local variations in average atomic number.

Finally, I would like to deal with what are called

nuclear processes. It is not quite clear as to what type nuclear processes one might use. They could be such processes as the photodisintegration of a neutron, pair production, etc. Regarding these, I don't think we have enough information about the appropriate cross section to determine whether we can use them as a practical source of information.

Before summing up, I would like to mention some calculations by Dr. Ringo with respect to the transmitted electron signal. He has considered the energy loss of electrons elastically scattered through small angles by free nuclei. He finds, for example, that if we have scattering angles that exceed a few degrees in such an interaction, we can determine whether a proton or deuteron did the scattering by measuring the energy loss. For scattering at 6° by a proton, the energy loss is estimated to be 125 eV, and for scattering by a deuteron, it would be about half of this value, or 60 eV. The cross section in this case is $0.4 \times 10^{-23} \text{ cm}^2 \text{ steradian}$. Since the cross section varies as E^2 and as the reciprocal of the atomic weight, extending this technique to the detection of the isotopes of the heavier atoms is somewhat unlikely. We must note also that the mechanism for observing contrast from protons or deuterons by this scheme depends on recoil of the nucleus in Rutherford scattering. The binding energy of the proton or deuteron in a solid would modify the foregoing estimate. Moreover, the existence of this form of contrast implies displacement of the nuclei and the production of irradiation damage.

In summary, I would like to make several remarks, some of which I have already mentioned and others which I feel are conclusions that may be drawn from this discussion.

First, staining or tracer methods are equally applicable to all sources of contrast discussed. In specific problems, if we have a source of contrast that is sensitive to particular elements, then we can use tracers to evaluate where these elements go in a chemical or biochemical reaction.

Second, I feel none of the processes available for contrast is sufficiently promising to justify at the present time for the construction of a special scanning-electron microscope column. (This is a point that Dr. Crewe may wish to debate in the discussion.) I think that at 1 to 5 MeV, it is not quite as simple as putting a field emission source together with a lens, and that the instrumentation required would be just a little more complicated. The amount of information to be obtained by such a scanning-electron microscope might not be worth the cost of a separate electron-probe column.

Third, we should evaluate some of the mechanisms for contrast formation at 1-5 MeV before the development of the high-voltage electron microscope is too far

along. In this way it would be possible to incorporate means by which these signals could be observed in the same instrument. By knowing the most useful sources of information well in advance, the electron lens design, for example, could take account of the required specimen positions and provide space for the necessary ancillary detectors.

Fourth, it seems that one should make the specimen region as large as possible, and it is gratifying to find that some people are thinking in terms of extremely large lens bores, which, of course, makes it much easier to incorporate some of the ancillary sources of contrast into such an instrument.

Fifth, the desirability of adding facilities for measuring new signals or for accommodating heating and tilting stages makes it important to consider interchangeable pole pieces for the objective lens, particularly if the final lens design requires small bores for high resolution.

Finally, I might come back to a point that was made, I believe, by Dr. Reisner of RCA some years ago. I believe he noted then that the attainment of very low magnification with the electron microscope is just as important as high magnification when questions of interpretation of the image are concerned. If we are aiming at an instrument with 1 Å resolution, we may be tempted to make the magnification 1,000,000, to minimize the problem of recording the image, but we should not neglect to make provision to go to low magnification as well. The technical feasibility of an instrument covering a wide range of magnification at 5 MeV must be investigated.

I want to say that I have enjoyed very much the four days that I've spent here, and that the interaction and contact with many people of widely different backgrounds who are undertaking this work was very stimulating.

Recording Systems for the High-Voltage Electron Microscope

JOHN GILROY

Argonne National Laboratory

In the opening session, Dr. Marton set forth the preferred goals for image recording systems, and suggested several mechanisms for further consideration. The most important detector criteria were "quantum" efficiency, i.e., the ability to utilize the information from every electron, high signal-to-noise ratio, and high spatial resolution.

Since then there has been extensive work on the problems of recording, comprising about 50 pages of reports and summaries of discussions. Within a reasonable time, I can only touch on some of these.

With one exception, there seems to be none of the suggested recording mechanisms that has the capability of utilizing the full energy of a 5 MeV electron directly and effectively. However, it does appear that there are various mechanisms that will give an excellent signal-to-noise ratio for a single electron, even though only a small fraction of the electron energy is utilized.

FIG. 2. Schematic Representation of Energy Distribution from 100 keV and 5 MeV Electrons.

FIG. 1. Image Size and Radiation of 5 MeV Electrons in Various Materials.

Perhaps most significant of the Group III work is the clearer realization of the difference, due to penetration and scattering, between image systems for 5 MeV and common electron-microscope voltages. Figure 1 shows computations, by C. E. Cohn and J. H. Roberts, of the effective image size for 5 MeV primaries in various thicknesses of various materials, and of the accompanying radiation loss. We see that resolution of 0.001 cm will be possible only in detectors of a thickness less than 0.030 cm of plastic or 0.015 cm of emulsion (neglecting graininess). In such a photographic emulsion, about 20 % of the energy loss is by radiation, so that the background problem may be severe even in a thin detector.

Figure 2 depicts schematically the difference in the photographic problem for electrons of 100 keV and 5 MeV, using dimensions representative of a commonly used slide. However, the spreading shown is for plastic—for glass it would be far greater. Only about 40 keV of

FIG. 3. Large Fibre Optic Screen Coupled to Small Fibre Optic Image Intensifier by an Oil Film of Matching Refractive Index to Allow Inspection of a Large Field of View by Moving the Intensifier Across the Stationary Viewing Screen (Suggested by W. C. Nixon, July, 1966).

the energy loss of a 5 MeV electron occurs even in this thick emulsion.

With this introduction let's consider the observation of an enlarged image. For alignment, etc., rapid visual observation is essential, and most, if not all, of the viewing must be done remotely. A suggestion for covering a large field of observation using presently available devices, was made by Dr. Nixon, and is shown in Fig. 3. This enables high resolution (referred to the specimen), without enormous scanning resolution, by successive viewing of portions of the image. This conforms with opinions expressed during the Workshop, that remote imaging should be capable of depicting 5000×5000 or more picture elements. For lesser overall resolution, conventional image intensifiers will undoubtedly be readily adaptable.

Despite the difficulties, most of the participants felt that photographic recording must be available to permit comparison with results of current microscopy. In addition to the spreading problem associated with thickness, this involves sensitivity and vacuum problems. For other

portions of the microscope, vacua of 10^{-9} Torr or less are wanted, and this is considered incompatible with open emulsion. Dr. Nixon has suggested differential pumping, as shown in Fig. 4.

To improve the efficiency, Dr. Marton has suggested enhancement by use of secondary electrons in an auxiliary electric field.

Dr. Hashimoto has pointed out that loading the emulsion or base film with fluorescent material or heavy atoms, or coating with a heavy material, or adding a material with anomalous Auger effect, will improve sensitivity. Figure 5 illustrates the importance of fluorescence even at 100 keV. In the right exposure, since the base film thickness exceeds the electron range, the exposure must be due to X rays or fluorescence. Figure 6 demonstrates that the principal contribution is optical fluorescence, since a predeveloped film will inhibit the image when placed blackened emulsion down, but is relatively ineffectual when the emulsion is up. No confirmation of this will be provided later, during the discussion.

FIG. 4. Differential Pumping of Ultrahigh Microscope Column for Use with Photographic Plates (Suggested by W. C. Nixon, June 30, 1966).

Dr. Roberts has pointed out that very high-resolution detection could be obtained by optical microscopic observation of individual electron tracks in "nuclear" emulsion.

Other recording techniques for extended images have been given consideration, such as Cerenkov radiation in fiber optics, arrays of Bendix type small multiplier tubes, and metallized scintillation fibers. For various reasons, these do not look inviting for 5 MeV electrons. On the other hand, available figures indicate that thin scintillator screens may readily be observed through orthicons, and perhaps through vidicons, with good signal-to-noise characteristics for individual high-energy electrons.

For output of such systems, there was agreement that numerous devices should be provided; storage tubes, photography, tapes, and computer loading all seem eventually needed.

A scanning type of observation can be used, at a

great sacrifice of time, for observing enlarged images. The only limiting factor to resolution then becomes the scanned aperture, since the detector may receive ample energy from each high-energy electron, so that theoretically this method may have the highest resolving capacity. Time can be conserved by using an array of apertures and detectors. Then only a portion of the image, analogous to one square of a checkerboard, need be scanned across each aperture; but computer unscrambling of the data would probably be required for on-line observation. Making fine apertures, in material sufficiently thick to give substantial energy loss, may be very difficult.

For scanning systems, a multiplicity of operating modes was considered essential by most participants. Conductivity [Oatley, Nixon, and Pease, *Scanning Electron Microscopy*, Advan. Electronics and Electron Phys. **21**, pp. 181-247, Academic Press, 1965], back-scattering [Wright and Trump, *Back-Scattering of*

FIG. 5. Image Production by Fluorescence (H. Hashimoto, July 8, 1966)

Megavolt Electrons from Thick Targets, *J. Appl. Phys.* **33**, p. 687, February 1962], electron diffraction [Denhigh and Grigson, *Scanning Electron Diffraction with Energy Analysis*, *J. Sci. Instrum.* **42**, p. 305, 1965], and energy-analysis observations all should be available, and simultaneous usage of two or more should be provided.

Similarly, it was felt that numerous display systems should be available, such as energy-loss image displays [Brookshier and Gilroy, *IEEE Trans. Nucl. Sci.*, p. 104, April 1965], energy scanning showing the energy loss spectrum for small areas, multiple-energy-level displays, and Y-modulation.

Figure 7 shows six of a series of successive energy-loss image displays observed during the Workshop in the CSEEM. [A. V. Crewe, in *Proc. AMU-ANL High Voltage Electron Microscope Meeting*, 63, 1964.] Obviously, the informational content of each image is quite

different. The specimen is nominally aluminum, about 300 Å thick, but the presence of other materials, and perhaps crystal information, is variously indicated best at diverse energy losses. The energy "window" used was about 1 volt, with primary energy of about 24 keV. Since similar information can be expected with 5 MeV electrons, energy analysis to about 1 volt appears needed.

The advantage of multiple display is illustrated in Fig. 8 (not reproduced here) for which color contrast was used, photographically, to compare directly the first two images of the series shown in the previous slide. In the long range, multiple-display systems appear to have an enormous potential.

Another display technique giving enhanced information content is scanning with y-modulation of the display, shown in Fig. 9, which was loaned to us by Dr. Nixon from the work of Philip Chang. This displays a

FIG. 6. Optical Fluorescence in Image Production. (H. Hashimoto, July 8, 1966)

scratched cobalt surface, with upward displacement of each "horizontal" oscilloscope trace by a chosen function of the secondary emission. The result may be analyzed accurately to provide a contour map of the modulating parameter.

Some consideration was given to data-handling problems. Because of operating time and cost, multiple detectors will probably be wanted, though they will probably require sophisticated data handling such as tapes or a computer, or both.

Figure 10 suggests a possible multiple detector, using a series of scintillators coupled individually by fiber-optics bundles to a corresponding series of photomultiplier tubes. By observing the light from the individual scintillators at 90° to the electron-beam direction, the scintillator thickness in the beam direction, and hence the electron path length and spreading, can be kept small. Such a device could be used either for enlarged

image observation, by scanning the image across a single transverse slit, or for observation of the output of a linear-dispersion energy analyzer. Figure 11 gives crude estimates, for 5 MeV electrons, of the energy losses per channel for various thicknesses in the electron-beam direction. We see that channel identification by pulse-height discrimination looks hopeful if a reasonable light collection can be achieved. In such a system, we might hope to use the image spreading to advantage to compute, by pulse-height analysis of the contributions from various layers, the position of an incoming electron beam to a fraction of the layer width.

Similarly, if remote controls are digitized, or are coupled to digital feedback devices, computer control of alignment may be highly advantageous.

I mentioned previously that 5000×5000 picture elements were considered useful. If, in the longer view, you want to think of obtaining complete data concern-

0 eV loss

9 eV loss

20 eV loss

100 eV loss

250 eV loss

600 eV loss

FIG. 7. CSEEAM Images at Various Energy Losses

FIG. 9. Scanning Display with Y-modulation by Secondary Electrons

FIG. 10. Proposed Multiple-Detector System

ing such a picture, you might wish to have as many as 100 logarithmic levels of intensity at various energy losses for each picture element, and perhaps for each of 100 energy-loss values. This may set an ultimate goal for digital on-line storage as high as 2.5×10^7 fourteen-bit words. This is a major problem.

Numerous areas remain to be given further consideration. Simple preliminary experiments on detectors were strongly recommended by most members of Group III, and some specific proposals were made. For example, sensitivity, spreading, etc., can be studied using a high-energy β spectrometer.

FIG. 11. Estimated Energy Loss, Averaged for One 5 MeV Electron, in Multiple-detector System.

Discussion of Session III

Discussion of Paper by R. K. Hart:

A. V. Crewe: You mention the problem of chromatic effect through a thick specimen in the high-voltage microscope. I think that it is possible that the scanning microscope will at least partially overcome this because your optical elements are above the specimen and you don't have to rely on the transmitted electrons to make your picture. You may get better resolution than with a scanning microscope on a thick specimen.

R. K. Hart: This, I think, is certainly true. Theoretically one should not have any contrast at all in a conventional electron-microscope image. It is actually due to these chromatic effects that one can get an image at all. If one goes to scanning systems, you can use other forms of getting contrast, such as energy loss, as Dr. Crewe has shown to be quite startling.

D. B. Wittry: In the use of the ordinary electron microscope to obtain a very small probe, I understand that the aberration calculation has included the spherical aberration. I wonder if the chromatic aberration has also been estimated. It seems to me that at the normal accelerating voltages, even the thermal energy of the electron might be a significant factor in the achieving of a 10 Å crossover.

R. K. Hart: In the crude calculation that I made I just assumed or just considered the Airy disc of confusion. Of course there are diffraction effects and chromatic effects that would increase this figure. In the geometrical reductions of the beam in a conventional microscope using this part of the formula and available data, one obtains a figure of 0.98 Å for 100 keV instrument. With the 3 MeV column of Dr. Tadano's, the geometrical figure is about 1.25 Å. Assuming that you have a regular hairpin filament of spot size 50 microns, this part of the formula increases the geometrical size by a factor of 20. I have no definite figures of Dr. Tadano's column to check the demagnification factor. I used the factor that I obtained from the 100 keV instrument and multiplied this a factor of 20 to come up with the 30 Å figure. The chromatic and diffraction effects certainly will increase this again, but I think the point is that you have a very fine probe, much smaller than one normally uses, i.e., 0.1 to 1 micron, that is used in microprobe analyzers. This is sitting there and has been sitting there ever since people have used conventional electron microscopes, and no one has made use of it except for the case cited by Haine and Mulvey.

W. C. Nixon: On the chromatic-aberration point, we

have looked into this with a scanning microscope that we made ourselves and changed over to magnetic lenses completely, partly for this reason. The earlier microscopes in Cambridge used electrostatic lenses, and the chromatic aberration there was sufficient to limit the resolution 200–300 Å. We went to an all-magnetic system that Pease and I put together a few years ago, and the resolution fell to between 50 and 100 Å. Due in large part to the improvement of the chromatic-aberration theory for those lenses, the high-voltage supply for this particular microscope (we were looking for high resolution in transmission) was also stabilized sufficiently well that I am sure that it would be adequate for an electron probe size approaching 10 Å, if one hopes to get 1 Å or better in transmission. Of course, in the scanning system there is no specimen in the normal object position to cause loss electrons. So, we have, we hope, free space vacuum at 10^{-10} all the way down.

A. V. Crewe: Needless to say, I don't really understand the interest in that particular scanning-microscope system for several reasons. One is the enormous demagnification from the number of lenses one has to use, and therefore one has to stabilize to a high degree in order to get that kind of picture, the alignment problem, and so on. I think the whole situation is much simpler with Jim Butler's gun and one single lens.

W. C. Nixon: The particular point of this system is that a normal transmission microscope to produce magnification has to have these lenses anyway. They are going to exist; therefore, whether they are superconducting, quadrupole, or what not, we can use the same column for scanning. The projector lens is the only one that need be stabilized in this situation, and I am sure the projector lens will be very similar to the objective lens in the normal transmission. I am sure that, particularly in this Laboratory, there will be a small additional column with the Butler gun and a single lens producing scanning, just tapping a few microamps or less from the main high-voltage power supply.

P. F. Meads: From our analysis of quadrupoles, I should like to point out that quadrupole strength is proportional to one over the square root of the momentum, while round-lens strength is proportional to one over the momentum. A quadrupole is therefore roughly half as sensitive to voltage changes as a round lens.

R. Ringo: Has anyone any idea how to use a hydraulic manipulator in a liquid-helium environment, or is this just for room temperature?

R. K. Hart: No, the way to use this is with push rods,

and you take these out through bellows so that the hydraulic fluid is at room temperature.

Discussion of Paper by D. B. Wittry:

J. Butler: I would like to say a word to combat the slightly negative approach that you gave to scanning microscopy. I think the point of the scanning microscope is a little different to what has been presented here. Actually, if you want to do quantitative work, the overwhelming advantage of the scanning microscope is that the information is obtained in serial order. You can actually do something with it. If you are just going to look at pictures, the advantages might be doubtful.

D. B. Wittry: Yes, I'm sorry. I didn't mean to convey the impression that the scanning-electron microscope does not have important advantages, but only that some of the value of scanning-electron microscopy is reduced by using 5 MeV electrons instead of 5- to 50-keV electrons.

L. E. Welter: I think that you can get information from the transmitted low-energy-loss electrons that is still worthwhile looking for.

D. B. Wittry: Yes, this may be the case, but the resolution required in the spectrometer is much greater if you want to see a given energy loss in an electron at several MeV than at 30 keV. May I ask what is the best energy resolution that has been used in the scanning-electron microscope?

L. E. Welter: Right now, the best we've measured is about 0.6 volt operating at about 30 kV.

D. B. Wittry: If we scale this up, of course, at, say, 3 MeV, you are looking at a 60-volt loss.

L. E. Welter: Let me add that this is purely the result of the design of the instrument. We had nothing better intended; this is just the way it came out. We hope to get one part in 10^6 .

D. B. Wittry: Yes, but even if you achieve one part in 10^6 for the spectrometer resolution, you also need better than one part in 10^6 for the beam voltage regulation.

A. Voice: This can be achieved.

D. B. Wittry: Perhaps so, but that is also a question that has been debated in the other sessions.

R. K. Hart: Would you like to put some figures on the minimum magnification that we should consider in an electron microscope?

D. B. Wittry: It should overlap the range of the optical microscope, that is 600-1,000.

R. K. Hart: I would like to mention that back-reflection electron diffraction patterns were obtained, I believe in 1953 or thereabouts, by Dr. Pashley at Imperial College, London. This work was written up, I believe, in the Proceedings of the Royal Society.* To my knowl-

edge, this is the only work that has been done on this aspect of electron diffraction. It was a very nice piece of work, and I think it should certainly be looked into.

D. B. Wittry: Yes, I'm very interested to know that. Of course, the back-reflection electron diffraction was also demonstrated at the very beginning of electron diffraction by Davisson and Germer, with low-energy electrons. But I wonder whether anyone has observed characteristic energy losses in a Kikuchi line pattern.

W. C. Nixon: During the middle period of the workshop, we discussed low magnification range, and I advocated that there should be a trial microscope using an unregulated, perhaps one part in 1000, high-voltage supply, 1 to 3 MeV, on what is available with, say, a single lens. This lens should be made up with the three various possibilities, so that we could measure the aberrations of this lens, and also get some information about penetration and the recording of images. This would be something with a resolution of a few hundred angstroms, but would be very useful in getting separate pieces of information.

D. B. Wittry: This appears to be a very sound suggestion in view of the lack of certain information we require to evaluate some of the sources of specimen contrast, particularly with respect to scanning techniques.

Discussion of Paper by J. Gilroy

H. S. Bennett: I have heard it stated that fiber-optic systems are rapidly degraded when subjected to ionizing radiation. Do you know anything about this particular problem?

J. Gilroy: Basically this is true. However, I understand the industry has made some effort to use radiation-resistant glass. I believe available glasses differ by orders of magnitude in their radiation resistance. Presumably, if essential, an enormous improvement could be reached. Even so, I think taking typical radiation damage figures, and extrapolating them to the microscope problem, except for a concentrated primary beam, you probably would have hours of operating time without any blackening problems.

L. L. Marton: I would like to show one slide (Fig. 1).

FIG. 1. Suggestion for Use of Bendix-type Multiplier Tubes for Image Recording.

* Alam, N. M., Blackman, M., and Pashley, D. W., Proc. Roy. Soc. **A221**, 224 (1954).

This suggests using Bendix-type channel multipliers, which can be made into very small elements so that, ultimately, perhaps 50-micron image elements can be recorded. The proposal uses a scatterer, suitably shaped to minimize the effects of cross reference between the individual multipliers. The multipliers are long capillaries, which provide up to 10^8 multiplication and can feed the information into suitably shaped anodes, in a corresponding area of insulating matrix, and can be scanned to get the final information. I believe that by suitable shaping of the scatterer, some of the problems can be licked to reach the performance required.

J. Gilroy: One of the reasons I felt that this did not look immediately promising, although undoubtedly it should have more consideration, is that, for example, if the material above the array of multipliers were, say, 0.010 in. of platinum, the energy loss would still be only about 1 MeV for 5 MeV electrons; and we would have 4 MeV electrons plowing into the multipliers and spreading off through the array. If the material were very thin, again, the direct primaries would spread for any reasonable length of multipliers. If you could make the multipliers very short, you would avoid this difficulty.

L. L. Marton: I forgot to mention one advantage of the system—that it is already existing and available—and that presents a definite advantage.

R. M. Fisher: At the opening session, Prof. Hashimoto described some of his experiments on the exposure of emulsions. At his suggestion we took some color film, tungsten-type Ektachrome, and exposed it directly in the electron microscope. I'll hold them up so you can see them. You will notice they are essentially pale blue in color. One was exposed in the correct way, and the

other was loaded upside down. You'll notice they are essentially the same, and the exposure time was the same in both cases. As he points out, the fluorescent radiation will be predominantly blue in color. At least it will be a fairly short wavelength, 3500 Å, and will expose the film in the blue range. This suggests to me that the electrons are relatively inefficient, in the case of this film, for directly exposing the film, but it is due to fluorescence. Because the color emulsions are in layers, and the electron, in passing through, is exposing them all uniformly you would not expect this predominantly blue color. I think this is strong support, as you indicated, of Prof. Hashimoto's concept of the case for film. In glass, this must be somewhat different, I believe.

J. Butler: I would like to take some issue with your unrealistic figure for the amount of storage required for pictures. I think, in the first place, no reasonable picture contains this much information. In the second place, the most elementary data-compression techniques one would ordinarily use would give you a factor of 10,000 to 1 million on this figure right away. You just don't store pictures that way.

J. Gilroy: What you say is very true, and I should, perhaps, not have presumed to use such figures. My figures, however, were geared on the simplest on-line usage, which probably would not be desirable. I think if you wanted (and this is a question now, I will admit) to put all that information directly on to a tape without any further consideration, that my figure is something comparable to the necessary extent of storage.

C. E. Cohn: I might point out that this amount of information is about what you can store on one reel of magnetic tape at the present time, which is not an unreasonable amount of storage for later reduction.

General Considerations for Electron-Microscope Columns

RAYMOND K. HART

Argonne National Laboratory

I would like to take a few minutes to discuss the general concept of the electron column. Until seven to ten days ago, I thought we had come to a conclusion that there would be, at the most, two alternative types of electron-optical columns to consider. Then, a number of participants who had been here at the beginning and then went away for a month or so started to come back, and I think that everyone of them seriously considered what an electron-optical column, operating at 5 MeV, should look like. This consideration of two columns went up, and it appears now that it can be split up into at least four different types of columns. If we consider that a column can either be placed vertically or horizontally, we get up to eight possibilities at the moment as to how to build a 5 MeV electron-microscope column, so I thought I'd take this opportunity to briefly run through these various designs.

First of all, I will briefly describe a two-column arrangement using LINAC-charged high-voltage systems, which is shown in Fig. 1. In this configuration, two charging LINACs are employed, and bending magnets are used to deflect the beams from these LINACs to the charging domes of the high-voltage systems of either microscope. From each charging dome, the electrons are led away through beam tubes to either the microscope column or a magnetic analyzer. A resistor network is also incorporated as another beam-stabilization device.

A scaled-up version of a conventional microscope column is shown in Fig. 2. This is the 3 MeV column designed by Dr. Tadano during the Workshop. In this type of column the lenses are bolted together to produce a rigid column. The section of this column that is under vacuum is up the center, and the whole column is kept vacuum-tight by many O-ring seals between the lenses, not to mention those required for bringing mechanical motions into the region of the beam.

The other type of column that has been given considerable thought during this Workshop uses shelves to support individual column components in a manner similar to that described by Dr. Nixon yesterday. A schematic diagram of this type arrangement is shown in Fig. 3. The solenoid of each lens is encapsulated so that the windings are not in vacuum. The column vacuum is maintained by means of a large tank surrounding the whole system.

The lens stack can either be supported on a base plate, as shown in Fig. 3, so that the entire column can be removed from the vacuum container, or the stack can be rigidly mounted at the top and the vacuum container removed for access to the column. If superconducting lenses are used instead of conventional lenses, the vacuum container can be made in the form of a large liquid-nitrogen dewar, as is shown on the left-hand side of Fig. 3.

Another possibility, which Dr. Nixon suggested, when conventional lenses are used, is to restrict the vacuum to within the bore of the lenses by means of a tube and eliminate the necessity of having vacuum seals between

Fig. 1. Possible Layout for Two LINAC-Charged High-voltage Systems (with Two Lens Columns) (Suggested by J. Gilroy, July 4, 1966).

THIS DESIGN WAS MADE BY THE HITACHI ELECTRON MICROSCOPE GROUP IN MAY 1966 FOR AMU-ANL ELECTRON MICROSCOPE WORKSHOP.

FIG. 2. A First-order Suggested Design of a 3 MeV Electron-microscope Column, using Conventional Lenses Only. The total lens weight is 6 or 7 tons, the total power consumption is about 12 kW, and the theoretical limiting resolution is about 1.5 Å.

FIG. 3. Suggested Vacuum Housing for Conventional and Superconducting Lenses

the lenses. This tube could be attached to the base of the accelerator tube by a flexible coupling and also to the specimen chamber. Another tube could run from the base of the specimen chamber, through the objective, intermediate, and projector lenses, into the viewing chamber.

With 3- or 5-MeV conventional magnetic lenses, the bore of the pole pieces would be large enough to allow quite a large tube to be used, and pumping would thus be greatly eased. Moving controls could be brought inside the vacuum tube by means of bellows, keeping the activating parts outside in the atmosphere.

This last type of column looks quite inviting but it might be quite difficult to build in such a way that the lens could be readily interchangeable.

It is, of course, possible to construct any of these columns lying horizontal instead of vertical. With columns of the dimensions and weight being considered, it might indeed be preferable to mount the whole system on a very heavy concrete slab, as suggested by Dr. Marton.

Although there were arguments in favor of and against both these attitudes in which the column can be placed, the final decision will be determined in a large degree by other design factors.

Proposed Layout of an Electron-Microscope Facility

JOHN W. ROBINSON

Argonne National Laboratory

One of the jobs of Plant Engineering at the Workshop was to prepare papers for construction of facilities. During the Workshop, quite a number of problems arose, and we are going to discuss some of them today. We will show some possible locations.

Figure 1 shows an aerial view of the Argonne site. I am going to take a counterclockwise rotation in discussing certain areas. To the north we would be confronted with a Nike Site, radar installations, etc. In the northwest is swampland, and this calls for pilings, caissons, and whatnot. Along the west we have U.S. 66 and Lemont Road. Here we have a traffic problem, causing vibration. So we finally end in the southwest.

This space was originally set up to receive the ZGS complex. This is not the final location, but was picked for a basis of estimate only. After the facilities are considered in detail, another site probably will be selected. A more detailed map of this area, which is called Water Tower Road, is shown in Fig. 2; the area lies just south of the 800 area. You see that we have divided the facility into three buildings: conventional microscope and support building, equipment building, and high-voltage microscope building. This was done on the premise of reducing vibrations from other buildings. Between the buildings you see dotted sections, representing underground tunnels between the buildings. We also have an above-grade connection.

Our concept of the Conventional Microscope and Support Building is shown in Fig. 3. Throughout the sessions of the Workshop, we covered power, lens design, microscope column design. One thing we did not cover is: What is needed in this facility? We said we needed a microscope building. We need other areas. Another question to be answered: How many people are going to be at this facility? Starting with the Conventional Microscope and Support Building, we consider this the administrative area, the reception room, and the main entrance. We show a conference room, a computer room, a file room, a dock and storeroom area, a library, and five laboratories. Now the question might arise in your mind: What are these laboratories? We do not know. We will probably have people coming from all over the country, perhaps from all over the world to use this facility. Are they going to prepare their specimens, say in Japan, or other parts of the U.S.? Or are they going to bring materials and prepare specimens

here for use in the microscope facility? These laboratories can either be chemical, metallurgical, or whatever, or they can be changed to preparation rooms. In this area you have offices—probably fourteen. We may need more; we do not know.

As we leave the main floor of the microscope building, we go down to the service floor, and to "access control." We have talked with Dr. Fernandez-Moran and to others and they asked that the microscope spaces be relatively "clean." In the access-control area, you will put on lab coats and probably plastic overshoes. Dust is going to be a problem.

After we leave the access control area, we have M.S. No. 1, No. 2, No. 3, and No. 4. These are conventional microscope spaces—Siemens, RCA, etc. We have over here Crewe No. 1, Crewe No. 2. Crewe No. 1 is the microscope that Dr. Crewe has now. Crewe No. 2 is for the second microscope. Separating the areas we have readout rooms and darkrooms. In the area labeled "microscope and building services" would be power supplies and any small vibrating equipment. We have preparation rooms, and print storage. You will notice there is no mechanical equipment space in this building whatsoever, other than the microscope and building services.

On each side of the building we have tunnels. The utility tunnel takes off to the equipment building. The only thing in this tunnel will be the air conditioning, piping, process piping, and other items used with the laboratories in the microscope area. This other tunnel is a personnel-access tunnel from the support building to the microscope building.

Figure 4 shows the equipment building, in which all rotating equipment would be housed. The mechanical aspects will be discussed in just a few minutes. We have provided a high-bay mockup area for the preparation of additional columns; the consensus is that the initial microscope facility would have two microscope columns. In the high-bay space, probably 25–30 feet high, you can have a high crane. We have a machine shop for light work—heavy work could be done in our regular Central Shops facility. We have electronics and vacuum equipment repair areas. The high-bay space has rotating equipment, to keep it away from the microscope facility. We have a few offices for the people in charge of the

Legend

▲ INFORMATION CENTER

BUILDING

- 2 Administration
- 3 Cafeteria
- 4 & 5 Receiving and Central Warehouse
- 6 Garage
- 8 Firehouse
- 10 Executive Offices
- 11 Reactor Engineering
- 12 Remote Control Engineering
- 14 Industrial Hygiene and Safety
- 15, 22, 24 & 25 Office for College and University Cooperation

BUILDING

- 16, 17, 20 & 40 Central Shops
- 19 Electronics
- 21 Security
- 22 Radiobiology Experimental Station
- 23 Communications and Special Services
- 24 U. S. Branch Post Office
- 25 Guard Post
- 26 Central Heating Plant
- 27 & 28 Meteorology
- 29 Chemistry - Solid State Science

BUILDING

- 202 Biological and Medical Research
- 203 Physics, Radiological Physics and Library
- 205 Chemical Engineering
- 206 Reactor Engineering
- 208 Reactor Physics - Reactor Engineering
- 211 Cyclotron
- 212 Fuels Technology Center
- 213 Cafeteria
- 221 Applied Mathematics
- 301 Hot Laboratory
- 306 Reclamation

BUILDING

- 308 Reactor Engineering
- 310 Chemical Engineering
- 316 Reactor Physics
- 330 Research Reactor (CP-5)
- 331 Experimental Boiling Water Facility
- 335 Juggernaut Reactor Facility
- 340 Experimental Animal Cuslers
- 350 Plutonium Fuel Fabrication
- 360-365 Zero Gradient Synchrotron Complex

BUILDING

- 362 High Energy Physics
- 583 & 584 Canal Water Treatment Plant
- 600-621 Lodging Facilities
- 801 Accounting, Plant Engineering
- 805 Particle Accelerator Division
- 806 Plant Services
- 808 Industrial Hygiene and Safety
- 817 & 818 Electronics
- 829 Hydrogen Test Facility
- 891 Guard Post
- 951 Argonne Recreation Center

FIG. 1. Schematic Map of Argonne National Laboratory Site

Proposed Layout of an Electron-Microscope Facility

FIG. 2. Suggested Location of Microscope Facility at Argonne National Laboratory

FIG. 3. Conventional Microscope and Support Building

FIRST FLOOR PLAN

SECOND FLOOR PLAN

SERVICE FLOOR PLAN

SECTION A-A

Fig. 4. Equipment Building

FIRST FLOOR - GRADE LEVEL

SERVICE FLOOR

SECTION A-A

SECTION B-B

Fig. 5. High-voltage Microscope Building

building, probably a small conference area, storage, freight elevators, stairs, and electric equipment areas.

On the service floor we have put in process equipment, heating, air-conditioning and plumbing equipment, boiler room, etc.

The second floor, along with the upper part of the high-bay mockup, has air-handling equipment, storage areas, stairs, freight elevator. This building is attached to the Conventional Microscope and Support Building by an above-grade, covered walk; process piping, heating, air-conditioning, ventilation, etc. pass through an underground tunnel.

Our conception of the High-Voltage Microscope Building is shown in Fig. 5. In the opening session, Drs. Klema and Donhowe brought out the use of the LINAC as an accelerator for their power-generating equipment. The facility we have shown here is based on using pressure tanks for Van de Graaff or Cockroft-Walton. We have done this only as a basis for estimate. Starting with the service floor area, we enter through the personnel corridor from the Support Building, and come back through an access control area. This area here is all "clean," calling for lab coats and plastic overshoes. We have two access-control areas for one reason: you can enter this building, under the present design, from the outside.

Coming in from the main floor, down the stairs, it is necessary to go through this access-control area. In this building we have the operator's offices, readout room,

darkroom areas, lens storage areas, and the microscope areas. Between the two microscopes we have a control room, with shielding windows, and walls of conventional concrete, possibly, for shielding purposes.

Notice the microscope transfer pit. When we need to work on the microscopes, we have a hydraulic ram, which comes up, attaches to the microscope, and lets it down into this pit. It is then transferred across to the mockup area. As we bring the microscope over, we can again raise the column to working level. The columns are shown suspended from inertia blocks. These columns, such as Dr. Hart discussed, are about 15 feet long. When the microscope column is in use, from the control console a man may watch what is going on. With another console, you can operate both microscopes at one time.

Section A-A shows the pits for transferring the microscopes from the microscope room to the mockup area. We took the extreme on this pressure tank about 27 feet. We need approximately twice that for pulling this tank off by crane, so this area is about 60 feet high. If we go to a LINAC, this area would probably drop down to 25 feet. The dimension from the floorline to the pit where the ram sits is about 16 feet.

In Section B-B is shown the other elevation. We can take either the columns or accelerator tanks out of the building. Also shown are workrooms, offices, the personnel passage back to the Conventional Microscope Building, and the utilities tunnel. All walls are of shielded construction.

Structural Considerations for an Electron-Microscope Facility

WILLIAM R. RIORDAN
Argonne National Laboratory

The immediate structural problem associated with the design of the electron-microscope facility is the isolation of the high-voltage microscope column from vibration. In the frequency range of perhaps a tenth of a cycle per second to 30 cps, the vibration damping problems would be the most severe. Some of the usual causes of building vibration are pumps, fans, compressors, elevators, motors, and miscellaneous mechanical and electrical equipment operating within a building. External causes of vibration are nearby railroad traffic, earth-moving equipment, seismic disturbances, etc.

As has been previously shown, we have split the facility into three buildings. One building would house the high-voltage microscope; the second would house the conventional microscopes and preparation area; and the third, the conventional, mechanical and electrical equipment as far as possible. A remote location was chosen to minimize external vibrations.

The supporting structures for the high-voltage microscope and the high-voltage accelerator column would have to be designed to reduce the displacements, associated with low-frequency vibrations still present in the building after all the obvious steps have been taken, within limits in which the microscope could operate satisfactorily. One design criterion that must be set down is what displacements can be tolerated by the microscope and the accelerator at the frequencies previously mentioned, if indeed these are the frequencies that adversely affect the microscope. The site chosen will have to have readings made, covering a range of frequencies, to determine how much displacement would have to be eliminated to keep the microscope within the limits set.

The general practice of isolating a delicate instrument from building vibrations is to place the instrument on a heavy table suspended by long, flexible springs, able to deflect several inches. In a similar fashion, the microscope column and the high-voltage column could be fastened to a large inertia block, hung by springs from a series of horizontal beams as shown in Fig. 1. These horizontal beams would be supported by columns on a solid foundation, separated from the rest of the building structure, or depending on how serious the problem is, from the sidewalls of the building. If the differential settlement of these supports is an overriding considera-

FIG. 1. Schematic of Suspension for Reducing Vibration

tion, it may be desirable to carry these foundations to bedrock.

In Fig. 2, one question concerns the walls around the microscope room and the accelerator floor. Should we make these walls thick enough to act as a biological shield, eliminating the need for local biological shielding around the microscope and accelerator?

All secondary microscopes shown in Fig. 3 are placed on the service floor because we believe vibration would be much less severe at this elevation, the floor slabs being continuously supported.

A structural problem associated with the building shown in Fig. 4, and with the others, would be the determination of floor loadings, particularly in the high-bay mockup area. The loadings in the machine shop and electronics and vacuum equipment repair shop would be about 150 lb/sq ft, with provisions for certain concentrated loads.

Dr. R. J. Miller, in conjunction with personnel from Argonne's Plant Engineering and Industrial Hygiene and Safety Divisions, made some vibration measurements in three existing buildings at Argonne. The equipment used was a Phillips Vibration Meter, PR-9252, and electrodynamic pickup, PR-9260, giving peak amplitudes of mechanical vibration. The pickup was firmly clamped to all surfaces measured. The scale used most was 0-10 microns. Readings to a tenth of a micron are

FIG. 2. High-voltage Microscope Building

FIG. 3. Conventional Microscope and Support Building

FIG. 4. Equipment Building

readily made with this equipment. Readings in the vertical plane and in both x and y directions on the horizontal plane were attempted.

The first area visited was in ZGS, at Magnet Ring 1.256. We could not get a vertical reading since sections of the magnet ring were being replaced. We picked up a single 0.5-micron reading in the horizontal direction; it did not repeat itself over a period of time. The conclusion at ZGS was that the magnet-ring base was singularly free of vibration, and it is isolated from the building housing it. The ring is supported from bedrock to maintain a constant elevation around the ring itself.

In Bldg. 212, on the second floor, there are Siemens and RCA microscopes. We took vertical readings on the floor at the base of the microscope, and horizontally in the x and y directions at the anode assembly of the gun. The vertical readings were a constant 0.4 micron. The electron gun anode assembly, gave constant readings of 1 micron, horizontally, with jumps as high as 3 microns. On the second floor there is a rather heavy construction of laboratory pipe and waffle floor; the microscope itself does not have any vibration mounts. In the basement, readings of 0.2 micron were taken underneath the

microscope, on the floor. The main-building column in the horizontal direction gave a reading of 1 micron. There is a large air-conditioning air-intake duct directly beneath the scope, and we picked up a reading of 0.03 micron. On the column supporting this air-conditioning unit, a rather slender column, we picked up a reading of 90–120 microns.

In Bldg. 202, on the ground floor, all instruments in Biology have vibration mounts. At the Siemens we found a floor reading of 0.8 micron. On the vibration mounts the reading was generally zero, and the x and y direction vibrations were too small for significant readings. The RCA microscope gave readings at the floor and at the electron gun of 0.2 micron in the x and y directions, and only a very small reading in the vertical direction.

In conclusion, based on our findings, the magnet ring base of ZGS, is with the exception of the building housing, extremely free of vibration. The commercial electron microscopes installed without vibration mountings are adversely affected by the building vibrations, and those with vibration mountings are virtually free of it.

Mechanical Design Concepts for an Electron-Microscope Facility

PAUL R. HIRSCH

Argonne National Laboratory

The mechanical services for the facility can be divided into two broad categories. One includes heating, ventilating, air-conditioning, and plumbing systems to serve the building; the second includes process systems to serve the equipment located in the building. I will discuss the heating and ventilating systems first.

A rough schematic diagram of the ventilating and air-conditioning systems (Fig. 1) shows the three separate buildings connected by tunnels. The heating, ventilation, and air-conditioning for the nonmicroscope areas are conventional in nature, and, in designing the systems, we will follow the standard Laboratory criteria for the particular occupancy involved.

The High-Voltage Microscope Building and the basement of the Conventional Microscope and Support Building will be considered as "clean" areas with low relative humidity as a requirement. The maximum allowable relative humidity is 30% at 75°F. The air

supply to these areas will pass through AEC absolute filters that have a filtration efficiency of 99.7% for 0.3-micron particle size. In addition, we will maintain the "clean" areas at a positive pressure with respect to their surroundings, to minimize the entry of dirty air when the doors are open. We also anticipate a means of access control to reduce dirt contamination—possibly electrically interlocked doors.

The air-handling units are located on the second floor of the equipment building because of the vibration problem, and the ducts pass through the tunnel into the other two buildings. In the air ducts will be hot-water reheats for each zone to control temperature.

In addition, we will have separate hot-water heating systems for areas of the building that have outside exposures. Because of the vibration problem, all the other mechanical equipment will be located in the equipment building, with special design consideration to reduce

FIG. 1. Ventilation and Air-conditioning Schematic Diagram

FIG. 2. Equipment Building

transmission of vibrations through the piping, and to reduce transmission from rotating equipment to the equipment-room floor. This vibration could be transmitted through the ground to the other buildings. Figure 2 shows the Equipment Building. The other heating, ventilating, and air-conditioning equipment will be located on the service floor: refrigeration system, boilers, hot-water heating systems, compressed-air systems, domestic water, laboratory water, gas metering, hot-water heaters, and possibly distilled water.

The process equipment is shown as close as possible to the High-Voltage Microscope Building. The equipment to be located in this area is dependent upon the type of electron-microscope lens and high-voltage generator finally selected, and might include: liquid-helium regeneration system, liquid-nitrogen regeneration sys-

tem, equipment for cooling, purifying, transferring and storing the insulating gas used in high-voltage accelerator tanks, rough vacuum systems, and low-conductivity water equipment.

I am sure that our present concept of what mechanical services to provide will undergo considerable change as engineering progresses on the facility. I think the changes will be due partly to clarification of requirements and partly to engineering evaluations that point up alternate methods.

Some examples that I feel fall in this category are the possibility of extending piping from our central heating plant in lieu of a boiler installation, of purchasing liquid nitrogen rather than regenerating, and of using electrostatic precipitators instead of absolute filters.

Electrical Design Considerations for an Electron-Microscope Facility

HENRY KACINSKAS

Argonne National Laboratory

It is planned to supply the high-voltage electron-microscope facility with electric power from the Laboratory's existing 13 kV network. The 13 kV system has a relatively good reliability record, and its voltage is regulated automatically with the $\pm 10\%$ range in steps of $\frac{5}{8}\%$. However, this regulating equipment cannot compensate for voltage transients.

The power supply and distribution system within the facility is rather conventional, with the exception of the special consideration for stray alternating magnetic fields because these would have an adverse effect on the performance of a microscope.

Possible sources of magnetic interference are: ac and dc motors and generators; power cables carrying large currents; power transformers, etc.; audiofrequency,

radiofrequency, and pulsed circuits, especially in the lower frequency range.

Careful attention will be necessary to reduce stray magnetic fields by shielding and other means. Figure 1 is a simplified diagram of the proposed electric power supply system. An aerial line is planned to bring the 13 kV power to a point approximately 200 feet from the facility. Between this point and the Equipment Building an underground steel conduit is proposed. This will improve general appearance and provide substantial shielding. In the Equipment Building the 13 kV power will be stepped down by two transformers for distribution within the facility. The building utilities' load and some other motor loads will be separated from the electron-microscope power in order to reduce transients.

FIG. 1 HVEM Facility Electric Supply System

With a normally open tie circuit breaker, in case of failure of one transformer, its output bus can be energized from the other bus.

Emergency Power. To cope with the problem in case of a normal ac power-supply loss to the facility, a diesel-driven emergency generator is proposed which, upon sensing the loss of the normal power supply, would start up automatically and in 10–15 sec be able to assume loads from the emergency power bus.

In conclusion, I would like to mention the grounding

system that would be required for this facility. The Y-connected transformer secondaries will be grounded at one location only—at the source location—right at the transformer. To ground the various other equipment, such as a high-voltage generator, a very reliable and low-resistance grounding system will be required. It is recommended that a suitable means be provided to disconnect the ground electrode system for periodical tests.

Proposal for a Super-High-Voltage Electron-Microscope Facility

K. C. A. SMITH

*University of Cambridge
Cambridge, England*

(Presented by: A. W. R. Oswald, Argonne National Laboratory)

As you can see, our job is really the simplest, as all of the answers have already been provided by the other groups. All we have to do is carry these answers out to build the facility. One regret I have had, and the only one really, is that the people who will be using the microscopes were not represented as a group per se and most of our design will depend on the answers we would get from such a group. However, I think that it is quite fortunate that Dr. Smith was able to attend the Workshop, and he has, I believe, taken into account in his proposal some of the problems associated with the operation of such a facility. I would like also to point out at this time that he has limited his paper to the High-Voltage Electron Microscope Building alone and has not touched upon any of the auxiliary facilities.

The essential requirement of the first super-high-voltage electron-microscope facility is experimental flexibility. Initially, an instrument is required with which to explore the possibilities of microscopy in the regions above 1 MeV—in many different fields and in many different modes of operation. For these purposes an extremely high resolving power is a necessary flexibility required by the majority of workers intent upon exploring this new region of microscopy. Ultimately, there may be a need for a microscope with a resolving power of 1 Å or better at 5 MeV, but the feasibility of such an instrument would appear to depend upon a number of new technologies, the development of which—for the purposes of electron microscopy—has only just begun.

What is required, therefore, is an instrument that will allow the testing and development of new components and methods while allowing a program of research into the application of super-high-voltage microscopy to be carried on with a minimum of interruption. These requirements could be met by a conventional instrument along the lines suggested by Dr. Tadano. Such an instrument, fed by a pressurized Cockroft-Walton generator, together with a conventional accelerator, could be made to give a resolving power better than 5 Å at 3 MeV and better than 10 Å at voltages approaching 5 MeV.

The complete facility must be so designed and con-

structed as to be capable of supporting an instrument operating at 1 Å level. Nevertheless, since such a resolution would be achieved with only a small fraction of specimens observed, it would be unnecessary and uneconomical to design on the basis of requiring the facility to be capable of 1 Å operation at all times and under all conditions. Thus, it might be satisfactory to aim for ultrahigh resolution conditions only for certain periods at night when major sources of electrical and mechanical interference might be switched off.

A facility in which provisions were made for only a single, high-voltage instrument would not satisfy the requirement of experimental flexibility for the exploratory stage of super-high-voltage microscopy. Neither, in the long run, would a single instrument meet the multivarious needs of a large body of research workers. The needs of, say the metallurgist studying thick specimens at elevated temperatures, and the biologist looking at the ultra structure of nucleic acids, cannot be met within a single instrument. At the very least, radically different objective lenses and specimen chamber arrangements would be required. Thus, with a single instrument, the downtime between different experiments would be appreciable, leading to very uneconomical operation of such a facility. It might also be reasonably supposed that such a unique facility would attract large numbers of researchers whose demands in time alone could hardly be met by a single instrument.

Various proposals have been made for a facility in which, for example, one high-voltage generator might feed a number of different microscope columns. Such an arrangement must require considerable engineering complexity involving increased capital expenditure, and it is doubtful whether any substantial economy could be effected this way. Moreover, it appears unlikely that a generator with sufficient stability to meet the requirements of an ultra-high-resolution microscope could be constructed at present. A single generator further restricts the use factor of the facility. Other combinations of generators, accelerators, and columns are conceivable, but all appear to suffer grave disadvantages when compared with the advantages accruing from completely separate instruments.

FIG. 1. Layout for Two-instrument H.V.E.M. Facility Plan (Suggested by K. C. A. Smith, June 25, 1966)

FIG. 2. Layout for Two-instrument H.V.E.M. Facility Plan (Suggested by K. C. A. Smith, June 25, 1966)

For the reasons outlined above the proposals made here concern a facility in which provision is made for, ultimately, two instruments, which may be operated separately or together without mutual interference. The initial instrument would be of relatively conventional design with provision for rapid modification to allow testing of new lenses and other components. The form and nature of the second instrument would arise as a

result of experience gained with the initial instrument and from the innovation of new techniques.

The facility, illustrated in Fig. 1, comprises a two-story building. The upper story accommodates the high-voltage generating and accelerating equipment, and the lower story—preferably at ground level—contains the microscope columns. Below each column is a pit or basement, which facilitates the removal and/or trans-

FIG. 3. High-Voltage Electron Microscope (Suggested by K. C. A. Smith, June 25, 1966)

FIG. 4. Housing for 1-5-MeV Electron Microscope (Suggested by R. J. Miller, June 17, 1966)

port of complete columns or sections of columns. This level may also be used to accommodate ancillary equipment such as beam analyzers, etc., if required. A centrally situated control room serves both instruments while effectively separating them so that one instrument may be set up and prepared while the other is in full operation.

In Fig. 2, a passage at one end of the control room connects the two instrument areas. A passage also runs beneath the control room to provide a connection between the two pits along which column sections may be transported. Both passages are provided with radiation-shielding doors.

The columns are placed immediately adjacent to the walls of the control room, in which situation, direct operation of the microscope may be provided through control rods and links. Direct-screen viewing systems are also possible with this arrangement.

The floor of the high-voltage room consists of a massive reinforced concrete slab, supported on outer walls that are relatively thin and flexible.

The column and generator tank of the conventional instrument illustrated in Fig. 3 are bolted together and

suspended at relatively the center of gravity from this massive slab. In this way, considerable attenuation of earth-borne vibration might be achieved. Suspension of the column and the deep pit below also allow various lengths of columns to be accommodated without difficulty.

Figure 2 shows work areas at both ends of the building in which column components and other apparatus associated with each of the two instruments may be prepared or modified. Individual column components are transported between all areas of the building by means of a forklift trolley designed to enable components to be withdrawn from or inserted into the column with precision—an arrangement that has worked extremely well at the Cavendish Laboratory high-voltage installation.

Again, as shown in Fig. 3, in order to further facilitate the mechanical handling of the columns and to allow sections of the columns to be opened up for withdrawal by the forklift, hydraulic rams are provided at each location. Their length and carrying capacity might be sufficient to allow a complete column to be lowered to the floor of the pit. The ram heads may be fitted with

CONDITION I
WHERE H.V. SOURCE PRODUCES VIBRATION AND MUST BE ISOLATED FROM COLUMN.

CONDITION II
WHERE H.V. SOURCE DOES NOT PRODUCE VIBRATION—THEN THE TWO SUPPORTS ARE RIDGIDLY FASTENED TOGETHER. (CONDITION I CAN BE TRIED AND WITH MINIMUM COST CONDITION II ATTAINED.)

tables providing traverse and tilt in order to allow precision alignment of adjacent column sections. In addition, each head might be fitted with a demountable trolley designed to engage in rails in the floor of the pit areas. Thus, after the ram is fully lowered, the trolley carrying part or all of the column might be translated from one instrument area to another through the connecting passage, or across the floor of the pit to a position beneath a crane by means of which the column might be hoisted out of the pit. Such an arrangement might be extremely valuable, for example, in the testing of a new high-voltage generator system. A new generator could be assembled and partly tested in the second instrument area with little interruption in the operation of the first instrument. With the mechanical handling facilities described it would then be possible to transfer and attach the column of the first instrument to the new generator for further tests.

Figure 2 shows a single story, along the front of the building, containing a number of preparation rooms, darkrooms, and offices. At the rear there is another single-story building for accommodating the various power supplies, required for the microscopes and other ancillaries.

Access between the control room and each instrument area is obtained via a labyrinth formed by extending the walls of the control room on either side. This obviates the need for heavy radiation-shielding doors between control room and instrument areas and at the same time provides an extra shielding wall between the instruments, offices, and preparation rooms.

I would like to take this opportunity to observe, and I am sure you have already observed, some of the differences in these two concepts presented. The one of Dr. Smith provides for local shielding around the generators, whereas the previous concepts call for the shielding in the walls of the building. There are other differences, but shielding and vibration, along with the design of the auxiliary buildings and requirements there, seem to be the major items we should be concerned about. Now, other suggestions have been made during the course of

the Workshop, and several of these will be commented on by Dr. R. J. Miller.

* * *

R. J. Miller: I guess it is quite obvious that I am vibration-minded. Figure 4 shows a silo-type of construction for one column which is down in the ground, but the structure supporting the high voltage is completely independent of it. If the upper one vibrates, this vibration will not be transmitted into the column.

Secondly, the concept I had in the upper right corner of Fig. 4 is a cross section of the silo, which probably would be very much like Dr. Smith's except that I have done away with the hydraulic ram. There are four long, threaded screws (very heavy) and individual platforms (there can be as many as you like) that are tied together by some mechanism. Possibly even something like a bicycle chain could be used to turn the journals in these lead screws in the four corners, which would make it possible to elevate any portion of this column or the entire column from the bottom platform. There are many possibilities with this arrangement. If for any reason, since these two structures are separated by only a matter of possibly an inch or so, it is desired to tie them together, this can be done at a later date. But, I would hope that at the beginning we try to isolate these two structures and help ourselves as much as possible to avoid the vibration problem. There is no biological shield since all radiation will be absorbed in the concrete walls of the silo and the surrounding ground. I can't envision anyone working inside this structure while the equipment is running. Secondly, the magnetic shield is in the outer structure of this silo, and there has also been some objection to that. The consideration here is that this arrangement allows ready access to the microscope column. But if there are tons of steel shielding material surrounding the column, this access is going to be difficult. There will be a great deal of remote control on this instrument. I think that going through these heavy shields is going to create a bit of a problem.

Discussion of Session IV

H. S. Bennett: Dr. Fernandez-Moran at The University of Chicago has interposed alternators and motor generator sets with regulated output between his electron microscopes and the regular commercial line. These depend on the momentum of rotating elements to protect the secondary line emerging from the generator, from the surges that are present, of course, in the main line. He has the output, which is fed to his microscopes, regulated to somewhere in the neighborhood of a tenth of a percent or better. This greatly reduces the load on the regulators in the microscopes themselves. My own view is that this is an excellent idea that it would be wise to provide for in the installation you are contemplating here.

A. V. Crewe: I would like to mention one source of ac pickup that has not been mentioned. When we moved into Bldg. 818, our greatest source of ac pickup was a steamline that ran close to the microscope and had several amperes of ac in the steamline.

G. R. Ringo: Did you say anything special was being done on the ventilation ducts to minimize this as a noise source?

P. R. Hirsch: We would probably provide some kind of acoustic insulation in the design. Placing the ducts far enough away would be one way of eliminating the noise.

G. R. Ringo: Could large ducts with low velocity be used?

P. R. Hirsch: This would depend on how big they got, and how much space is available in the tunnels. It will be either extra large, low velocity, or there will be higher velocity with some effort made to eliminate the noise.

G. R. Ringo: Air turnover requirements should not be very high in this building as there are no radioactive sources.

P. R. Hirsch: I don't see where they would be very large. It is a rather large building.

H. Kacinskas: I would like to ask Dr. Crewe—to your knowledge is this ac still existing on the steamline? Or was there a solution? Could there have been a neutral ground at several locations and a ground loop created inadvertently?

R. J. Miller: From experience here, it would indicate that your frequency of steamline running above ground is not too uncommon. Many a ground circuit around the City of Chicago is not grounded at all. Some of them we found as much as 20 volts above ground. Putting a meter between the electrical ground and the plumbing ground would be pretty frightening—in fact could be

almost lethal. There is a question I would like to ask these ventilation people. Why not go to a round type of duct? Those ducts in Bldg. 212 actually have standing waves in them in their long, flat sections.

H. S. Bennett: Comment was made about the importance of grounding electrical circuits, and this has been emphasized in the discussion. I'd like to comment that it is very important to provide an excellent low-resistance ground for the electron microscope itself. Perhaps this does not fall within the plans of the electrical outfit, but it should be an important feature in the plans of the facility.

H. Kacinskas: I think I mentioned that the low-resistance grounding system will be required for this facility.

H. S. Bennett: One feature of Dr. Miller's silo, it seems to me, is that it offers an opportunity to pump out the chamber in case one wants to reduce pressure in the immediate environment of the microscope itself as an aid to achieving high vacuum in the system and, perhaps, reducing leaks into it.

J. Gilroy: Since specifics of shielding were not mentioned in the last two days, I would like to point out that Group III did have a quick look at this particular problem, especially by Dr. Ringo. Before one can give exact figures one would have to know the currents and materials upon which these currents might impinge. Now, considering a 5 MeV high-voltage system and microscope, the necessary shielding would be in the range of 4 inches of lead, and this corresponds to something like 15 inches of steel and I don't know how many inches of concrete. Minor differences, such as having equipment extensively lined with beryllium, etc., could cut down the necessary shielding somewhat, but the overall level will have to be in that level throughout—in other words, for the high-voltage portion where sparkovers may occur, as well as in the lens column itself.

R. K. Hart: I would like to take this opportunity to sincerely thank the co-chairmen who have helped me so much in these past weeks and Dr. John Roberson of the Associated Midwest Universities, whose help has been most valuable and also the six secretaries who have done such a fantastic job to keep up with the work load placed upon them. Finally, I would like to thank Dr. Crewe for making this High-Voltage Electron Microscopy Workshop possible in the first place. Thank you very much.

Aperture Aberrations of an Accelerating Tube with a Section of Uniform Field

RONALD W. MOSES, JR.

*The University of Wisconsin
Madison, Wisconsin*

In one type of high-voltage electronmicroscope, the high-voltage scanning microscope, the aperture aberrations of the accelerating system must be carefully dealt with. In this paper, we are interested in accelerating electrons to 5 MeV and focusing the beam into a probe spot size of about 1 Å. We will assume that this is an electrostatic accelerating tube, which forms a beam of 5 MeV electrons into trajectories nearly parallel to the beam axis, and we will work out the aberrations for this particular type of system. We also assume there is a magnetic condensing lens, which focuses the beam to a spot. Here we are primarily concerned with the aperture aberrations of the accelerating tube. It is believed that they will be small for the particular type of accelerating tube with a uniform electric field (constant and parallel to the beam axis). The source of electrons will be a field-emission tip. We assume that the radius of the tip is so small that it acts as a point source of monochromatic electrons. Our particular type of accelerating system will then contain three basic sections. We call the first the collimator, which extends from z_0 (the source) to z_1 in Fig. 1. The purpose of the collimator is to electrostatically focus electrons into a nearly parallel beam. Section II is the closed interval $[z_1, z_2]$. We assume this to be a tube about 3 meters long. To obtain 5 MeV electrons, the electric field is parallel to the axis and constant in the Section II with a value of 16.7 keV/cm. We treat one example where there is no collimator since the uniform field of Section II focuses the electrons into approximately parabolic trajectories.

Section III consists of the fringing field at the high-energy end of the tube and the condenser. The defocusing effect of the fringing field is discussed in the appendix.

We will work with cylindrical coordinates r , θ , and z . The electric potential is Φ , and we define the electric field as $E = -\nabla\Phi$. In Section II, $E = \Phi'/z$ is constant; hence, $\Phi = Ez$. Primes on functions indicate derivatives with respect to z .

Since the system is rotationally symmetric, and we are concerned with aperture aberrations here, only the radial coordinate $r(z)$ will be discussed, and we will require $r(z_0) = 0$. We define the paraxial solution $h(z)$

such that $h(z_0) = 0$ and $h'(z_0) = 1$. The initial slope of a ray is defined as α ; hence, a paraxial ray has the trajectory $r_s(z) = \alpha h(z)$. The magnification of a system up to the point z is defined as $M = [p_0/p(z)][1/h'(z)]$, where p_0 and $p(z)$ are the magnitudes of the momentum for electrons on the axis at z_0 and z , respectively.

The third-order solution is defined as

$$r(z) = r_s(z) + \epsilon,$$

where ϵ is the aberration. The aperture-aberration coefficient referred to the source, C_s , is defined so that $\epsilon = MC_s\alpha^3$. The aperture aberration causes an object on the axis to have an apparent displacement from the axis equal to $C_s\alpha^3$. The aperture-aberration coefficient for Sections I and II combined may be expressed in terms of the coefficients for each separate section, as follows:

$$(C_s)_{1,2} = (C_s)_1 + \frac{h'^3(z_1)}{M(z_1)} (C_s)_2 = (C_s)_1 + \frac{p_1}{p_0} h'^4(z_1) (C_s)_2. \quad (1)$$

$(C_s)_1$ is calculated with an object at z_0 . Section I places an image at z'_0 (either real or virtual). The image relative to I is the object for Section II, and its location enters in the calculation of $(C_s)_2$.

$(C_s)_2$ may be obtained directly from the analytic solution of the relativistic equations of motion for an electron in a uniform field. Assume there is a virtual object on the axis at z'_0 , (Fig. 2) and we define

$$s_1 \equiv z_1 - z'_0.$$

Likewise, there is a virtual image at z'_3 with $s_2 \equiv z_2 - z'_3$.

Since all rays have a virtual object at z'_0 , they can be defined by the slope, α_1 , at z_1 . Let $\alpha_1 k(z, \alpha_1^2)$ be an exact solution, which satisfies $k(z_1, \alpha_1^2) = 0$ and $k'(z_1, \alpha_1^2) = 1$ for all values of α_1 . Then the exact solution as a function of α_1 and z is

$$r(\alpha_1, z) = \alpha_1[s_1 + k(z, \alpha_1^2)]. \quad (2)$$

The paraxial ray is the linear solution

$$r_s(\alpha_1, z) = \alpha_1[s_1 + k(z, 0)].$$

FIG. 1. Beam Trajectory in Various Sections of Acceleration Tube

FIG. 2. Beam Trajectories from Virtual Object and Virtual Image

The image distance is

$$s_2(\alpha_1^2) = \frac{r(z_2, \alpha_1^2)}{r'(z_2, \alpha_1^2)} = \frac{s_1 + k(z_2, \alpha_1^2)}{k'(z_2, \alpha_1^2)}, \quad (3)$$

where the paraxial image distance is $s_2(\alpha_1^2 = 0)$. The aperture-aberration coefficient is related to the image distance by the equation

$$(C_s)_2 = \frac{r'_s(z_2, \alpha_1)}{r'_s(z_1, \alpha_1)} \frac{ds_2}{d\alpha_1^2} \Big|_{\alpha_1^2=0} = k'(z_2, 0) \frac{ds_2}{d\alpha_1^2} \Big|_{\alpha_1^2=0} \quad (4)$$

The relativistic Hamiltonian is

$$H = -\Phi + m_0 c^2 \left[1 + \frac{\vec{p}^2}{m_0^2 c^2} \right]^{1/2} = E_0, \quad (5)$$

where $\Phi = E(z - z_1) + \Phi_1$, and we choose Φ_1 such that $E_0 = m_0 c^2$. The relativistic mass is $m = \gamma m_0$, where

$$\gamma = \left(1 - \frac{\vec{v}^2}{c^2} \right)^{-1/2} = \left(1 + \frac{\vec{p}^2}{m_0^2 c^2} \right)^{1/2}. \quad (6)$$

The momentum is $\vec{p} = m\vec{v}$. When the z -coordinate is taken as the independent variable, the Hamiltonian becomes¹

$$K = -\{ (E_0 + \Phi)^2 / c^2 - m_0^2 c^2 - p_r^2 - p_\theta^2 / r^2 \}^{1/2} = -p_z. \quad (7)$$

The equations of motion are

$$r' = \frac{\partial K}{\partial r} = -\frac{p_r}{K} = \frac{p_r}{p_z}, \quad (8a)$$

$$p_r' = -\frac{\partial K}{\partial r} (=0 \text{ if } p_\theta = 0), \quad (8b)$$

and

$$p_\theta' = -\frac{\partial K}{\partial \theta} = 0. \quad (8c)$$

Since we must consider a trajectory that crosses the axis in order to obtain $(C_s)_2$, we must have $p_\theta = 0$. The magnitude of the momentum at z_1 is taken as a constant, p_1 . Hence, we have

$$p_r = \frac{\alpha_1}{\sqrt{1 + \alpha_1^2}} p_1, \quad (9a)$$

and

$$r'(z, \alpha_1) = \frac{\alpha_1 p_1}{\sqrt{1 + \alpha_1^2}} \frac{1}{p_z(z, \alpha_1^2)}. \quad (9b)$$

Now the displacement may be obtained as a function of z and α_1 ,

$$\begin{aligned} r(z, \alpha_1) &= \alpha_1 s_1 + \int_{z_1}^z r'(\xi, \alpha_1) d\xi \\ &= \alpha_1 s_1 + \frac{\alpha_1 p_1}{\sqrt{1 + \alpha_1^2}} \int_{z_1}^z \{ (E_0 + \Phi)^2 / c^2 - m_0^2 c^2 - \alpha_1^2 p_1^2 \}^{-1/2} d\xi. \end{aligned} \quad (10)$$

The notation is simplified by the following definitions:

$$\zeta = E / p_1 c, \quad (11a)$$

$$Z = (z - z_1) + E_0 / E, \quad (11b)$$

¹ K. R. Symon, Hamiltonian Foundation of the Equations of Electron-Optics, Lecture Notes, April 27, 1966, MURA-591.

and

$$Z_{m_0} = m_0 c^2 / E. \quad (11c)$$

On carrying out the integration, we have

$$r(z, \alpha_1) = \alpha_1 s_1 + \frac{\alpha_1}{\xi \sqrt{1 + \alpha_1^2}} \cdot \ln \left\{ \frac{\xi Z + \sqrt{\xi^2 (Z^2 - Z_{m_0}^2) - \alpha_1^2}}{\xi Z_1 + \sqrt{\xi^2 (Z_1^2 - Z_{m_0}^2) - \alpha_1^2}} \right\} \quad (12)$$

$$= \alpha_1 [s_1 + k(z_2, \alpha_1^2)];$$

$$s_2 = \frac{r}{r'} \Big|_{z_2} = [\xi^2 (Z_2^2 - Z_{m_0}^2) - \alpha_1^2]^{1/2} \times \left\{ s_1 \sqrt{1 + \alpha_1^2} + \frac{1}{\xi} \cdot \ln \left[\frac{\xi Z_2 + \sqrt{\xi^2 (Z_2^2 - Z_{m_0}^2) - \alpha_1^2}}{\xi Z_1 + \sqrt{\xi^2 (Z_1^2 - Z_{m_0}^2) - \alpha_1^2}} \right] \right\}. \quad (13)$$

By applying Eqs. (4), (8a), and (13), we get the aperture-aberration coefficient

$$(C_s)_2 = \frac{p_1}{p_2} \frac{ds_2}{d\alpha_1^2} \Big|_{\alpha_1=0};$$

$$(C_s)_2 = \frac{p_1^2}{2E} \frac{c}{p_2} \left[\frac{p_2}{m_1 c + p_1} - \frac{p_1}{m_2 c + p_2} - \frac{p_1}{p_2} \cdot \ln \left(\frac{m_2 c + p_2}{m_1 c + p_1} \right) \right] + \frac{1}{2} s_1 \left(1 - \frac{p_1^2}{p_2^2} \right). \quad (15)$$

On noting that $s_1 = h(z_1)/h'(z_1)$ and combining (1) and (15), we get

$$(C_s)_{1,2} = (C_s)_1 + \frac{1}{2} \frac{p_1}{p_0} h(z_1) h''(z_1) \left(1 - \frac{p_1^2}{p_2^2} \right) + \frac{p_1}{p_0} h''(z_1) \frac{p_1^2 c}{2E p_2} \left[\frac{p_2}{m_1 c + p_1} - \frac{p_1}{m_2 c + p_2} - \frac{p_1}{p_2} \ln \left(\frac{m_2 c + p_2}{m_1 c + p_1} \right) \right]. \quad (16)$$

It is clear that $(C_s)_{1,2} = (C_s)_1$ if $h'(Z_1) = 0$.

A system of interest is one in which the field-emission tip is immersed directly in the uniform field. Assuming the tip to be a monochromatic source of electrons with momentum p_1 , Eq. (12) gives the radial coordinate $r(z, \alpha_1) = \alpha_1 k(z, \alpha_1)$. Note that $s_1 = 0$. For a field of 16.7 keV/cm, an initial kinetic energy of 2 keV and a final kinetic energy of 5 MeV, we have

$$k(z_2, 0) \simeq 8 \text{ cm.}$$

On examining Eq. (15), one may note that $(C_s)_2$ has an upper bound $(C_s)_2 < p_1^2 / 2m_1 E$. For nonrelativistic

electrons at the source, this is Φ_1/E . For the above beam parameters, we have $(C_s)_2 < 0.12$ cm. This is an extremely small aperture-aberration coefficient; however, we shall see later that one must sacrifice intensity to take full advantage of it.

At this point we backtrack to discuss the collimator. The next system to be considered in this paper is a slightly nonuniform field near the source, which focuses the electrons into a parallel beam without trajectories that cross the axis. The electrons are assumed to be non-relativistic in Section I. The paraxial ray equation is

$$R''(z) + \frac{3}{16} \frac{\Phi'^2}{\Phi^2} R(z) = 0, \quad (17)$$

where

$$R(z) = \Phi^{1/4}(z) r(z). \quad (18)$$

An analytic solution exists for

$$\Phi(z) = \Phi_0 \left(\frac{z}{a} \right)^{\frac{4}{\sqrt{3}} B}.$$

where a and B are adjustable parameters. The solution is $R = R_0(z/a)^A$, where A satisfies $A^2 - A + B^2 = 0$ and z_0 is set equal to a . If we are to obtain $r'(z_1) = 0$, A must be complex; hence,

$$A = \frac{1}{2} \pm i \sqrt{B^2 - \frac{1}{4}}, \quad B > \frac{1}{2}.$$

With the boundary condition $r(z_0 = a) = 0$, the solution for r is

$$r(z) = r_0 \left(\frac{z}{a} \right)^{1/2 - \frac{1}{\sqrt{3}} B} \sin \left[\sqrt{B^2 - \frac{1}{4}} \ln \left(\frac{z}{a} \right) \right]. \quad (19)$$

The boundary condition $r'(z_1) = 0$ places the following requirement on the system:

$$\cot \left[\sqrt{B^2 - \frac{1}{4}} \ln \left(\frac{z_1}{a} \right) \right] = \frac{\frac{2}{\sqrt{3}} B - 1}{\sqrt{4B^2 - 1}}. \quad (20)$$

To match Sections I and II, $\Phi'(z_1)$ is set equal to the uniform field in II. Our desire to specify the uniform field, the source potential, and the approximate length of Section I places another boundary condition on the system. It may be related to the solution in I by the equation

$$z_1 \frac{\Phi'(z_1)}{\Phi_0} = \frac{4}{\sqrt{3}} B \left(\frac{z_1}{a} \right)^{\frac{4}{\sqrt{3}} B}. \quad (21)$$

Now we have two equations, (20) and (21), and two unknowns, a and B .

For this paper we are interested in $\Phi'(z_1) = 16.7$ keV/cm, $\Phi_0 = 2$ keV, and $z_1 \simeq 10$ cm. Several values

of B were chosen to examine $z_1\Phi'(z_1)/\Phi_0$. It appears that $z_1\Phi'(z_1)/\Phi_0$ has a minimum of about 100, which gives $z_1 \simeq 12$ cm. $B = \frac{\sqrt{5}}{2}$ was used in the following calculations.

It gives $z_1\Phi'(z_1)/\Phi_0 = 103$ and $\sqrt{B^2 - \frac{1}{4}} = 1$.

The trajectory is

$$\begin{aligned} h(z) &= a \left(\frac{z}{a} \right)^{1/2 - \sqrt{5/12}} \sin \left[\ln \left(\frac{z}{a} \right) \right] \\ &= a \left(\frac{z}{a} \right)^{-0.144} \sin \left[\ln \left(\frac{z}{a} \right) \right]; \end{aligned} \quad (22)$$

$$\frac{z_1}{a} = 4.18, \quad a = 2.96 \text{ cm};$$

$$z_1 = 12.4 \text{ cm},$$

The potential is

$$\Phi = \Phi_0 \left(\frac{z}{a} \right)^{2\sqrt{5/3}} = \Phi_0 \left(\frac{z}{a} \right)^{2.58}. \quad (23)$$

In the present collimator, electrons are accelerated to 80 keV; hence, Schenzer's nonrelativistic integral for aperture aberrations may be used. If the integration is terminated with the trajectory off axis in a region of nonzero field, the expression for C_s referred to the source is

$$\begin{aligned} (C_s)_1 &= \frac{1}{16\sqrt{\Phi_0}} \int_{z_0}^{z_1} \Phi^{1/2} \left\{ \frac{5}{4} \left(\frac{\Phi''}{\Phi} h^2 + \frac{\Phi'}{\Phi} h h' \right. \right. \\ &\quad \left. \left. - \frac{\Phi'^2}{\Phi^2} h^2 \right) + \frac{\Phi'^2}{\Phi^2} \left(h h' + \frac{7}{8} \frac{\Phi'}{\Phi} h^2 \right) \right. \\ &\quad \left. + \frac{1}{64} \frac{\Phi'^4}{\Phi^4} h^4 \right\} d\xi + \frac{1}{16\Phi_0^{1/2} \Phi^{1/2}(\xi)} \\ &\quad \cdot \left[16\Phi'(\xi) h^2 h'^2 - \frac{1}{2} \Phi'''(\xi) h^4 \right. \\ &\quad \left. - \frac{1}{4} \frac{\Phi'(\xi) \Phi''(\xi)}{\Phi(\xi)} h^4 + \frac{13}{16} \frac{\Phi'^3(\xi)}{\Phi^2(\xi)} h^4 \right] \Big|_{z_0}^{z_1}. \end{aligned} \quad (24)$$

Let us carry the integration across the boundary between I and II. Then the only integrated term appearing is

$$\frac{13}{256} \frac{\Phi'^3(z_1)}{\Phi_0^{1/2} \Phi^{5/2}(z_1)} h^4(z_1) = 0.1 \text{ cm}.$$

Since there are no singularities in the integrand, this does not change the value of the integral. We can now combine $(C_s)_1$ with the uniform field expression, which is zero, to give $(C_s)_{1,2} = (C_s)_1$. An upper bound may be obtained for $(C_s)_1$ by replacing h and $h'h$ with expressions that are larger at all points in I and by adding the absolute values in all terms of (24). Expressions that will give this and are easy to integrate are

$$\begin{aligned} h_a &= 1.03 \sqrt{\frac{2a}{4.18}} \left(\frac{z}{a} \right)^{-0.144} \\ &= 0.51 a \left(\frac{z}{a} \right)^{0.356}, \end{aligned} \quad (25)$$

and

$$h'_a/h_a = 1/z; \quad (26)$$

$$\begin{aligned} (C_s)_1 &\leq \frac{1}{16} \int_{z_0}^{z_1} \left(\frac{z}{a} \right)^{1.29} \left\{ \frac{5}{4} (4.1 + 2.58 + 6.7)^2 \right. \\ &\quad \left. + 6.7(1 + 2.26)^2 + 0.7 \right\} \frac{1}{15.4} \\ &\quad \cdot \left(\frac{z}{a} \right)^{-2.58} dz + 0.1 \text{ cm} \end{aligned} \quad (27)$$

$$= 1.2a \int_1^{4.18} \left(\frac{z}{a} \right)^{-1.29} d \left(\frac{z}{a} \right) + 0.1 \text{ cm}$$

$$= 1.41a + 0.1 \text{ cm};$$

$$(C_s)_1 \leq 4.3 \text{ cm}.$$

From now on we treat Eq. (27) as an equality.

Since the trajectory is parallel to the axis in Region II, the total aperture-aberration coefficient referred to the source may be easily expressed in terms of $(C_s)_1$, and the aberration coefficient of the condenser referred to the image and the image aperture angle, $(C_s)_I[\text{cond.}]$. The total aperture aberration is

$$(C_s)[\text{total}] = (C_s)_1 + \frac{p_3 h'^4(z_3)}{p_0 h'^4(z_0)} (C_s)_I[\text{cond.}]. \quad (28)$$

As an example, let us assume that $(C_s)_I[\text{cond.}]$ is equal to the focal length of the condenser, $f[\text{cond.}]$. The focal length of the collimator relative to the source side is $f_1 = h(z_1) = 2.5$ cm. (Note: $(C_s)_1$ is the spherical aberration of the collimator, i.e., source and accelerating tube. It corresponds to $(C_s)[\text{col.}]$) We also note that

$$\frac{h'(z_3)}{h'(z_0)} = \frac{f_1}{f[\text{cond.}]};$$

hence, we have

$$(C_s)[\text{total}] = (C_s)_1 + \frac{p_3}{p_0} \frac{f_1^4}{f^3[\text{cond.}]} \quad (29)$$

A system that accelerates electrons to 5 MeV is considered; hence, $p_3/p_0 = 123$. To further the example, we take a system in which the condenser contributes an aberration term referred to the source equal to that of the collimator. Then we have

$$(C_s)_1 = \frac{p_3}{p_0} \frac{f_1^4}{f^3[\text{cond.}]},$$

and

$$f[\text{cond.}] = 10 \text{ cm.}$$

The magnification is

$$M = \frac{p_0}{p_3} \frac{1}{h'(z_3)} = \frac{p_0 f[\text{cond.}]}{p_3 f_1}; \quad (30)$$

$$M = \frac{1}{31}.$$

For a point source, the minimum spot size to which this system can focus is

$$\Delta r_I = M (C_s)_I^{1/4} [\text{total}] \lambda_0^{3/4},$$

with

$$\lambda_0 = 0.277 \text{ \AA}$$

and

$$(C_s)_I [\text{total}] = 8.6 \text{ cm};$$

then

$$\Delta r_I = 2.1 \text{ \AA}.$$

The optimum aperture angle at the source is

$$\alpha = \left(\frac{\lambda_0}{(C_s)_I [\text{total}]} \right)^{1/4}. \quad (31)$$

For the above system we have

$$\alpha = \left(\frac{0.28 \text{ \AA}}{8.6 \text{ cm}} \right)^{1/4} = 4 \times 10^{-3} \text{ rad.}$$

The beam current is proportioned to α^2 .

Now let us examine the problem of getting 1 \AA resolution at 5 MeV. The equation for minimum resolution, $\Delta r_I = \eta (C_s)_I^{1/4} [\text{total}] \lambda_I^{3/4}$, gives

$$(C_s)_I [\text{total}] = \eta^{-4} \Delta r_I^4 / \lambda_I^3.$$

For

$$\lambda_{I \text{ 5 MeV}} = 2.26 \times 10^{-3} \text{ \AA}$$

and

$$\Delta r_I = 1 \text{ \AA},$$

we get

$$(C_s)_I [\text{total}] = 0.87 \text{ cm } \eta^{-4},$$

where η depends on the chosen definition of resolution. We take $\eta = 1$, with the realization that a slight variation of η will cause a great variation of $(C_s)_I [\text{total}]$ for any one desired Δr_I . If $(C_s)_I [\text{cond.}] = f[\text{cond.}]$, we must have a condenser with $f[\text{cond.}] \leq 0.87 \text{ cm}$. The total aperture-aberration coefficient referred to the image is

$$\begin{aligned} (C_s)_I [\text{total}] &= \frac{p_0 h'^4(z_0)}{p_3 h'^4(z_3)} (C_s)_I [\text{total}] \\ &= (C_s)_I [\text{cond.}] + \frac{p_0 h'^4(z_0)}{p_3 h'^4(z_3)} (C_s)_{I,2} \quad (32) \\ &= f[\text{cond.}] \left(1 + \frac{p_0 f^3[\text{cond.}]}{p_3 f_1^4} (C_s)_{I,2} \right). \end{aligned}$$

Clearly, good resolution may be obtained by reducing the focal length of the condenser, but this is at a loss of beam current. The optimum aperture angle is

$$\alpha = \left(\frac{\lambda_0}{(C_s)_{I,2} + \frac{p_3}{p_0} \frac{f_1^4}{f^3[\text{cond.}]}} \right)^{1/4}. \quad (33)$$

For the collimator described above and $\Delta r_I = 1 \text{ \AA}$, we have $\alpha = 8 \times 10^{-4} \text{ rad}$. If we consider the source immersed in the uniform field, and take $f_1 \simeq k(z_2) = 8 \text{ cm}$, we get $\alpha \simeq 2.5 \times 10^{-4} \text{ rad}$.

To increase the intensity and have 1 \AA resolution, we must reduce the focal length of the collimator. This can be done either by keeping the trajectory parallel to the axis in Section II and shortening and strengthening the collimator, or by slightly increasing the strength of the present collimator so the beam is converging as it enters II. It is beyond the scope of this paper to analyze these more general systems.

In conclusion, we have presented several simple examples to demonstrate techniques for analytically discussing aperture aberrations of a collimator-uniform field-condenser type of accelerating system. With a collimator 8.5 cm long ahead of a 5 MeV uniform-field tube, we have obtained an aperture-aberration coefficient $C_s \leq 5.4 \text{ cm}$ for the collimator and tube combined. The focal length at the low-energy end of this system is 2.5 cm. When it is combined with a condenser of focal length 10 cm, we get a theoretical resolution of 2 \AA and an optimum aperture angle at the source of $4 \times 10^{-3} \text{ rad}$.

More extensive studies of this type of accelerator should be made in order to optimize resolution and intensity while maintaining an experimentally realizable system. More precise calculations for this system and similar ones should be made with iterative techniques using a computer.

Appendix

The fringing field at the high-energy end of the accelerating tube acts as a defocusing lens. Its focal length is easily determined with the thin-lens approximation. The relativistic paraxial-ray equation is²

² P. A. Sturrock, *Static and Dynamic Electron Optics*, Cambridge University Press (1955).

$$r'' + \frac{\Phi'(mc^2 + \Phi)}{2mc^2\Phi + \Phi^2} r' + \frac{1}{2} \frac{\Phi''(mc^2 + \Phi)}{(2mc^2\Phi + \Phi^2)} r = 0. \quad (A1)$$

We assume that $r' \simeq 0$ through the fringing field. Hence, we have

$$\begin{aligned} \Delta r' &= - \int_{z_3}^{z_3+} \frac{1}{2} \frac{\Phi''(mc^2 + \Phi)}{(2mc^2\Phi + \Phi^2)} r \, d\xi \\ &\simeq - \frac{1}{2} \frac{(mc^2 + \Phi)}{(2mc^2\Phi + \Phi^2)} \Big|_{z_3} r \Delta\Phi'. \end{aligned} \quad (A2)$$

The focal length is

$$f = - \frac{r}{\Delta r'} = + \frac{2(2mc^2\Phi + \Phi^2)}{mc^2 + \Phi} \Big|_{z_3} \frac{1}{\Delta\Phi'}. \quad (A3)$$

If the accelerating potential is 5 MeV and the electric field goes from 16.7 keV/cm to 0, we have

$$f \simeq -6.6 \text{ m.}$$

For the above energy and field, the accelerating tube is 3 m long; hence, the focal length of the fringing field lens at the high-energy end of the tube is over twice the length of the tube. We have neglected the effect of this lens on the first-order properties of the beam and have assumed that its contribution to aperture aberrations is negligible.

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Addendum: The Haine and Jervis Spectrometer as an Energy Analyzer

The possibility of using the Haine and Jervis analyzer to determine the energy spectrum of a beam is considered. It is concluded that, for a given particle-gathering power, the Haine and Jervis analyzer has an energy resolution worse by a factor of 16 than a conventional

double-slit spectrometer of the same diameter. The use of the Haine and Jervis instrument for spectrum analysis is, therefore, justified only if there are other reasons for not using a double-slit spectrometer.

The theory of the Haine and Jervis energy analyzer has been given in the AMU-ANL High-voltage Electron Microscopy Workshop paper "The Magnetic Spectrometer as a Voltage Stabilizer." The following are the important results for our present purpose. If a monoenergetic beam of energy v electron volts enters the spectrometer, the current output I' is given, as a function of v , by

$$\begin{aligned} I' &= 0, & v &\leq V; \\ I' &= g(v - V), & v &> V; \end{aligned} \quad (1)$$

where V is the cutoff energy of the device. V is given in terms of the magnetic field B , and the distance x_0 between the knife-edges by

$$\frac{1}{2} B x_0 = [2mV(1 + eV/2mc^2)/e]^{1/2}. \quad (2)$$

The mutual conductance $g = dI'/dV$ is given by

$$g = \frac{I x_0 a}{\pi^{1/2} r_0 V}, \quad (3)$$

where I is the total beam current, r_0 is the effective radius of the beam entering the spectrometer, and a is the relativistic correction factor,

$$a = \frac{1 + eV/mc^2}{2 + eV/mc^2}. \quad (4)$$

If the beam entering the spectrometer is not monoenergetic, then let the current carried by particles of energy range v to $v + dv$ be $I(v) dv$. Then the output current will be given from (1) and (3):

$$I' = \int_V^\infty k I(v)(v - V) dv, \quad (5)$$

where

$$k = \frac{x_0 a}{\pi^{1/2} r_0 V}. \quad (6)$$

The Magnetic Spectrometer as a Voltage Stabilizer

T. B. RYMER

University of Reading
Reading, England

The magnetic spectrometer of Haine and Jervis [Proc. Inst. Elec. Engrs. **102B**, 265 (1955)] is based on the principle of semicircular focusing in a magnetic field. The general scheme is shown in Fig. 1. An unfocused beam of electrons from a gun falls on a knife-edge situated at the boundary of a magnetic field, which is directed perpendicular to the plane of the paper. The knife-edge is placed so as to intercept approximately half the beam. The portion of the beam passing the knife-edge is deflected round a semicircular path by the magnetic field and falls on a second knife-edge, which intercepts most of it. The small portion of the beam, which passes the second knife-edge enters a collecting cylinder (Faraday cage) and produces a small current, which operates the stabilizer.

The fringing magnetic field has not been indicated in Fig. 1. Its effect is that the incident electron beam has to be inclined at a few degrees to the direction shown in the diagram. The precise inclination can be found by a detailed calculation of the electron trajectories in the fringing field, or by experiment. The required inclination is independent of the energy of the electron beam, provided the fringing field is always proportional to the main magnetic field.

We now consider in more detail the theory of this analyzer. Let

x_0 = diameter of electron orbit, i.e., distance between knife-edges;

V = high tension required to give electron orbit diameter x_0 ;

B = magnetic field;

and

V^* = relativistic potential = $V(1 + eV/2mc^2)$.

Then

$$\frac{1}{2}Bx_0 = (2mV^*/e)^{1/2}. \quad (1)$$

A change in voltage δV will change the diameter of the orbit by δx , where

$$\begin{aligned} \frac{\delta x}{x_0} &= \frac{1}{2} \frac{\delta V^*}{V^*} = \frac{\delta V}{V} \frac{1 + eV/mc^2}{2 + eV/mc^2} \\ &= a \frac{\delta V}{V}, \end{aligned} \quad (2)$$

where the relativistic factor,

$$a = \frac{1 + eV/mc^2}{2 + eV/mc^2}$$

is about $1\frac{1}{2}$ for 5 MeV electrons.

If the beam overlaps the exit knife-edge by an amount x , corresponding to a voltage change V' , a fractional change i in the beam current results in a spurious voltage change, iV' . This must be less than V/S , where S is the stability required. Hence $V' < V/iS$.

If g is the mutual conductance of the device, the current I' passing the second knife-edge is

$$\begin{aligned} I' &= gV' \\ &< gV/iS. \end{aligned} \quad (4)$$

From (2) and (3),

$$x < ax_0/iS. \quad (5)$$

From an examination of the spherical aberration of the device, we find that for a cone of rays of semiangle α , the aberration is $\frac{1}{2}x_0\alpha^2$. If this is to be less than half the maximum permitted overlap given by (5),

$$\alpha^2 < a/iS. \quad (6)$$

If we assume $i = 10^{-2}$, $S = 10^6$, this gives for the maximum permissible value of α

$$\alpha_{\max} = 10^{-4}.$$

The angular spread of the beam will usually be less than this unless the beam is focused on the knife-edge, and we conclude that spherical aberration is negligible.

Let the beam at the entrance knife-edge have a gaussian distribution of intensity, so that the current density at a distance r from the center of the beam is

$$J = J_0 e^{-(r/r_0)^2}. \quad (7)$$

The current passing into the detector is derived from the portion of the beam that passes between the exit knife-edge and the virtual image of the entrance knife-edge (Fig. 2). The current passing through the area $dx dy$ is

$$J_0 e^{-(r/r_0)^2} dx dy = J_0 e^{-x^2/r_0^2} e^{-y^2/r_0^2} dx dy.$$

FIG. 1. Schematic of the Haine and Jervis Magnetic Spectrometer

Hence the current passing the exit knife-edge is

$$I' = \int_{x=0}^x \int_{y=-\infty}^{y=+\infty} J_0 e^{-x^2/r_0^2} e^{-y^2/r_0^2} dx dy.$$

But

$$\int_{-\infty}^{+\infty} e^{-y^2/r_0^2} dy = \pi^{1/2} r_0.$$

Thus

$$I' = J_0 \pi^{1/2} r_0 \int_0^x e^{-x^2/r_0^2} dx,$$

so that

$$\begin{aligned} \frac{dI'}{dx} &= J_0 \pi^{1/2} r_0 e^{-x^2/r_0^2} \\ &\approx J_0 \pi^{1/2} r_0. \end{aligned} \quad (8)$$

Now the total beam current from the gun is obviously

$$\begin{aligned} I &= \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} J_0 e^{-x^2/r_0^2} e^{-y^2/r_0^2} dx dy \\ &= J_0 \pi r_0^2. \end{aligned} \quad (9)$$

Thus

$$\frac{dI'}{dx} = \frac{I}{\pi^{1/2} r_0}. \quad (10)$$

The mutual conductance of the device is given by combining (10) and (2):

$$\begin{aligned} g &= \frac{dI'}{dV} = \frac{dI'}{dx} \frac{dx}{dV} \\ &= \frac{I}{\pi^{1/2} r_0} \frac{x_0 a}{V}. \end{aligned} \quad (11)$$

The maximum permissible current to the detector is obtained by combining (11) and (4):

$$I'_{\max} = \frac{I x_0 a}{\pi^{1/2} r_0 \delta S}. \quad (12)$$

On the other hand, a *minimum* value of I' is set by the consideration that the rms shot noise current must be less than iI' . Thus,

$$(iI')^2 < 2eI'f,$$

FIG. 2. Alignment of Beam on Entrance Knife-edge, and Location of Virtual Exit Knife-edge.

FIG. 3. Schematic of Control Amplifier Arrangement

where f is the bandwidth. Hence,

$$I'_{\min} = 2ef/i^2. \quad (13)$$

If we take as typical values

$$x_0 = 20 \text{ cm},$$

$$S = 10^6,$$

$$i = 10^{-2},$$

$$f = 10^3 \text{ cps},$$

$$I = 1 \mu\text{A},$$

and

$$r_0 = 2 \text{ mm},$$

we obtain

$$I'_{\max} = 5.6 \times 10^{-9} \text{ A},$$

and

$$I'_{\min} = 3.2 \times 10^{-12} \text{ A}. \quad (14)$$

That noise is therefore not likely too serious.

With the data given, the mutual conductance of the device is about 10^{-11} A/V . Let us suppose that the output of the spectrometer is connected to an amplifier-control system of gain M and input resistance R . Then if changes ΔV in the high-voltage output are to be reduced to δV by the control system, a simple consideration of the circuit in Fig. 3 shows that

$$\Delta V - \delta V g R M = \delta V,$$

or

$$\frac{\Delta V}{\delta V} = 1 + g R M$$

$$\approx g R m.$$

Let us suppose that our generator has an inherent stability of one part in 10^3 and we wish to stabilize it to one part in 10^6 . Then $\Delta V/\delta V = 1000$. If we suppose $R = 10^7 \text{ ohms}$, $g = 10^{-11} \text{ A/V}$, we obtain $M \leq 10^7$.

Let us now consider the noise generated by the input resistor R . Figure 3 shows that the output-voltage fluctuations produced by a noise voltage v in the resistor R are given by

$$\delta V = M(v - g R M \delta V),$$

or

$$\delta V = \frac{M v}{1 + M g R} \approx \frac{v}{g R}.$$

Now the noise voltage developed across a 10-megohm resistor at room temperature in a 10^3 -cps bandwidth is $13 \mu\text{V}$. Hence,

$$\begin{aligned} \delta V &= \frac{1.3 \times 10^{-5}}{10^{-11} \times 10^7} \\ &= 0.13 \text{ volt}. \end{aligned}$$

This is appreciably less than the limit within which we seek to stabilize the high voltage (5 V). If the output from the spectrometer is passed into a scintillation-photomultiplier detector, or a solid-state particle detector, we shall achieve a current gain of the order of 10^4 , and the noise problem will become insignificant.

The magnetic field required for the device specified is given by (1). For 5 MeV electrons, it is about 1500 G.

We now consider some other aspects of the device.

Lack of Parallelism of Knife-edges

If the knife-edges are perfectly parallel, the current-voltage relation of the device is as given by the solid line in Fig. 4, the upper limit of current being set by (4), and the upper limit over which the device stabilizes being given from this in conjunction with the value 10^{-11} A/V for the mutual conductance.

If the knife-edges are inclined, then Fig. 5a shows that when the voltage is low, so that there would have been no current if the knife-edges had been parallel, we shall obtain a small current due to the portion of the beam shown shaded. Figure 5b shows the corresponding situation at high voltage. Comparing the situations prevailing with parallel knife-edges, as compared with inclined knife-edges, we see that inclining the knife-edge has uncovered the portion A of the beam and obscured the portion B. The latter region is somewhat nearer the

center of the beam, and therefore has a greater current density than the region A. The overall effect is that inclining the knife-edge has reduced the current. The current-voltage characteristic is therefore as shown by the dotted line in Fig. 4; it is asymptotic to the characteristic obtained with parallel knife-edges. The current corresponding to the point P can easily be calculated. The positions of the knife-edges are as shown in Fig. 5c. It is obvious that a fraction $\alpha/4\pi$ of the total beam current is then passed.

We may suppose that if the ordinate at P is about 1% of the maximum current, the dotted curve will not be significantly different from the solid one. Since we have assumed a beam current of 10^{-6} A, this would require

$$\alpha = 4\pi \times 5.6 \times 10^{-5}.$$

Precision of Setting of Beam on Entrance Knife-edge

The maximum amount of overlap of the beam which is permissible at the exit knife-edge is given by (5):

$$\begin{aligned} x &= 2 \times 10^{-3} \text{ cm} \\ &= r_0/100. \end{aligned}$$

The effect of an error in the setting of the beam is seen in Fig. 6. It is clear that such an error will result in a reduction in the current passed into the collector. An examination of a table of error functions shows that this reduction of current will not exceed 1% if the error in the position of the beam does not exceed $r_0/100$ or 0.2 mm.

FIG. 4. Current-Voltage Distributions with Parallel and Nonparallel Knife-edges.

FIG. 5. Leakage Current with Nonparallel Knife-edges

FIG. 6. Positions of Beam with Respect to Knife-edges

FIG. 7. Distortion of Current Voltage Curve by Magnetic Field Variation.

Roughness of Knife-edge

Asperities on the knife-edges are serious only if they are comparable in height with the gap between the exit knife-edge and the image of the entrance knife-edge. Since the upper limit of this gap is 2×10^{-3} cm, we may suppose that the knife-edges should be true to better than one-tenth of this, i.e., to about 1 micron.

Power Dissipation at Knife-edges

Assuming a beam current of $1 \mu\text{A}$ at 5 MV, each knife-edge will be subjected to a power loading of 2.5 W. With a beam of radius $r_0 = 2$ mm, this gives a peak power density of $2.5/[\pi \times (0.2)^2]$ or about 20 W cm^{-2} . Although this will not cause damage to the knife-edges, it might cause a local deformation. It is difficult to formulate the process in a manner that is mathematically

tractable, but if we suppose that the surrounding cool metal exerts no elastic constraint on the expansion of the heated part (this is obviously the most pessimistic assumption), then the deformation can depend only on the beam power, the thermal conductivity, and the thermal-expansion coefficient of the knife-edge material. From dimensional considerations, therefore, the linear deformation must be given by an expression of the form

$$L = \text{Const. } W\alpha/K,$$

where W is the beam power, α is the expansion coefficient, and K is the thermal conductivity. For molybdenum, $K = 1.5 \text{ watt cm}^{-1} \text{ deg}^{-1}$, and $\alpha = 5 \times 10^{-6} \text{ deg}^{-1}$, so that for $W = 2.5 \text{ W}$, L must be of order of magnitude 10^{-5} cm. This is clearly not of consequence.

Effect of Inhomogeneities of the Magnetic Field

The most important effect arises from a variation in the strength of the magnetic field in a direction perpendicular to the plane of Fig. 1. This has the result that the diameters of the electron trajectories vary slightly in a direction perpendicular to the plane of the figure. The effect of this is that in Fig. 2 the image of the entrance knife-edge is slightly curved. This would result in the current-voltage characteristic of the device being as represented by one of the dotted lines of Fig. 7, instead of the ideal characteristic shown by a solid line. If the lower limit of the linear portion V' is to be not less than 10% of V'_{max} , then the field must not vary by more than about $iS/10 = 10^{-5}$ of its mean value over the cross section of the beam $2r_0$. Note, however, that a small nonlinearity in the characteristic of the device will not materially affect the stabilization.

Addendum: The Haine and Jervis Spectrometer as an Energy Analyzer

The possibility of using the Haine and Jervis analyzer to determine the energy spectrum of a beam is considered. It is concluded that, for a given particle-gathering power, the Haine and Jervis analyzer has an energy resolution worse by a factor of 16 than a conventional double-slit spectrometer of the same diameter. The use of the Haine and Jervis instrument for spectrum analysis is, therefore, justified only if there are other reasons for not using a double-slit spectrometer.

The theory of the Haine and Jervis energy analyzer has been given in the AMU-ANL High-voltage Electron Microscopy Workshop paper "The Magnetic-Spectrometer as a Voltage Stabilizer." The following are the important results for our present purpose. If a monoenergetic beam of energy v electron volts enters the spectrometer, the current output I' is given, as a function of v by

$$\begin{aligned} I' &= 0, & v &\leq V; \\ I' &= g(v - V), & v &> V; \end{aligned} \quad (1)$$

where V is the cutoff energy of the device. V is given in terms of the magnetic field B , and the distance x_0 between the knife-edges by

$$\frac{1}{2} Bx_0 = [2mV(1 + eV/2mc^2)/e]^{1/2}. \quad (2)$$

The mutual conductance $g = dI'/dV$ is given by

$$g = \frac{Ix_0a}{\pi^{1/2}r_0V}, \quad (3)$$

where I is the total beam current, r_0 is the effective radius of the beam entering the spectrometer, and a is the relativistic correction factor,

$$a = \frac{1 + eV/mc^2}{2 + eV/mc^2}. \quad (4)$$

If the beam entering the spectrometer is not monoenergetic, then let the current carried by particles of energy range v to $v + dv$ be $I(v) dv$. Then the output current will be given from (1) and (3):

$$I' = \int_V^\infty kI(v)(v - V) dv, \quad (5)$$

where

$$k = \frac{x_0a}{\pi^{1/2}r_0V}. \quad (6)$$

Thus

$$I' = k \int_V^\infty Iv dv - kV \int_V^\infty I dv. \quad (7)$$

Now let

$$\int_0^v I dv = F(v). \quad (8)$$

Then

$$I' = k \int_{F_0}^{F_\infty} v dF - kV \int_{F_0}^{F_\infty} dF, \quad (9)$$

where the limits of integration are

$$\begin{aligned} F_\infty &= \int_0^{v'} I dv, \\ F_0 &= \int_V^{v'} I dv, \end{aligned} \quad (10)$$

v' being large enough to satisfy the condition

$$I(v) = 0, \quad v \geq v'.$$

Integrating the first term by parts, we obtain

$$I' = k(v' - V)F_\infty - k \int_V^{v'} F dv. \quad (11)$$

Now the cutoff potential V of the spectrometer can be varied by changing the magnetic field B according to (2). We can therefore regard (11) as the equation connecting the output of the spectrometer I' as the dependent variable with V the independent variable. Then

$$\frac{dI'}{dV} = -kF_\infty + kF. \quad (12)$$

Hence,

$$\begin{aligned} \frac{d^2I'}{dV^2} &= k \frac{dF}{dV} \\ &= kI \end{aligned} \quad (13)$$

from (8).

Thus the energy spectrum $I(V)$ of the beam is given by the second derivative of the $I' - V$ characteristic. We also see from (12) that

$$\left(\frac{dI'}{dV}\right)_{V_1} - \left(\frac{dI'}{dV}\right)_{V_2} = k \int_{V_1}^{V_2} I dv; \quad (14)$$

i.e., the difference between the slopes of the $I - V$ characteristic at two points is directly proportional to the total intensity of the beam contained in this energy range.

The simplest way of determining d^2I'/dV^2 is to superpose a small sinusoidal magnetic field on the steady field so that the cutoff voltage varies about a mean value V_0 ,

FIG. 8. Current-Voltage Characteristic for Two Spectral Lines

$$V = V_0 + b \cos pt. \quad (15)$$

If I'_0 is the current output from the spectrometer corresponding to a cutoff potential V_0 ,

$$I' = V_0 + b \frac{dI'}{dV} \cos pt + \frac{1}{2} b^2 \frac{d^2 I'}{dV^2} \cos^2 pt + \dots \quad (16)$$

If the output from the spectrometer is passed into a phase-sensitive detector that responds only to the component of angular frequency $2p$, then, provided b is sufficiently small, the output recorded will be

$$\begin{aligned} i &= \frac{1}{4} b^2 \frac{d^2 I'}{dV^2} \cos 2pt \\ &= \frac{1}{4} \frac{b^2 x_0 a I}{\pi^{1/2} V} \cos 2pt \end{aligned} \quad (17)$$

from (6) and (13).

Now if the energy spectrum consisted of two sharp lines separated by ΔV electron volts, the $I' - V$ characteristic would appear as in Fig. 8. If the output i is to fall to zero at some voltage between the break points A and B, it is necessary that the amplitude b of the sinusoidal voltage variation should not exceed $\Delta V/2$. We may therefore rewrite (17) in terms of the energy resolution ΔV :

$$i = \frac{\Delta V}{V} \frac{x_0 a}{16\pi^{1/2} r_0} I \Delta V \cos 2pt. \quad (18)$$

If the breadth of a spectrum line is comparable with ΔV , then $I\Delta V$ is approximately the amount of current in this spectrum line. We may therefore rewrite (18) as

$$\frac{\Delta V}{V} = Q \frac{16\pi^{1/2} r_0}{x_0 a}, \quad (19)$$

where $Q = |i|/I\Delta V$ is the ratio of the output current from our phase-sensitive detector to the input current of the appropriate energy. Q is therefore a measure of the particle-gathering power of the device. If instead of using a Haine-Jervis analyzer, we had used a double-slit instrument with an entrance slit of width S , then the fraction Q of the incident beam entering the slit would be $Q = S/\pi^{1/2} r_0$ and, from (2) and (4), the energy resolution would be

$$\begin{aligned} \frac{\Delta V}{V} &= \frac{1}{a} \frac{S}{x_0} \\ &= Q \frac{\pi^{1/2} r_0}{x_0 a}. \end{aligned} \quad (20)$$

Comparing (19) and (20), we see that the energy resolution of the Haine and Jervis instrument is worse by a factor of 16 than a conventional double-slit instrument of the same particle-gathering power.

A Superconducting Magnetic Spectrometer

MARTYN H. FOSS

*Carnegie Institute of Technology
Pittsburgh, Pennsylvania*

AND

CHARLES LAVERICK

Argonne National Laboratory

The possibility of using a Haine and Jervis Magnetic Spectrometer¹ to determine the energy spectrum of an electron beam and then to act as a high-voltage power-supply stabilizer has been considered at the AMU-ANL High-Voltage Electron Microscope Workshop.

If an electromagnet is used, the spectrometer can be adjusted to stabilize over a wide range of voltages by suitable adjustment of the magnetic field. Present instruments are limited in stability to a few parts per million. This limit can be increased by several orders of magnitude if superconducting windings are used and a truly superconducting joint can be fabricated. In addition to this, the winding cross section can be very small since high average current densities are attainable. Two possibilities exist: either the iron can be cooled, or the winding only. In view of the high dimensional stability required, it may be better to adopt the former solution and immerse most of the instrument in liquid helium.

A typical design is shown in Fig. 1. The D-shaped coils are inserted at the top and bottom of the gap, and the central space is for the vacuum chamber. This is the simplest type of design, but is adequate. More efficient designs with coils on the midplane and the straight section windings distributed equally above and below this gap are possible. The mild-steel shroud is built up from small slabs of the required shape and size, but precision machining is not required.

A peak central field of about 3 kG is required, which

FIG. 1. A Magnetic Spectrometer with Superconducting Windings.

necessitates a maximum of 5000 Amp-turns/coil. Using heat-treated, 0.25-mm-diameter, copper-coated Nb-33%Zr wire, it may be possible to operate at wire currents as high as 250 A so that only 20 turns would be required for each coil. Assuming about 0.25 cm/turn, we need about 50 meters of wire per coil, and a single layer winding is probably adequate.

These figures suffice to indicate approximately what is involved. A more compact instrument can be designed and constructed if required.

REFERENCE

1. Haine, M. E. and Jervis, M. W., *Proc. Inst. Elec. Engrs.*, **102B**, 265 (1955).

The Brightness of a Linear Accelerator used as an Electron-Microscope Source

T. B. RYMER

University of Reading
Reading, England

General Considerations

In any electron-optical system, let us suppose we have an object O in the form of a square of side h (Fig. 1). From any point of the object, electrons are diverging within a cone of semiangle α . After passing through the imaging system, the electrons converge in a cone of semiangle β to a corresponding point of the image, which is a square of side h' . A general theorem of electron optics states that, if the energy of the electrons is the same in the object and image spaces,

$$h\alpha = h'\beta.$$

If no electrons are lost in passing through the system, the same total current I passes through both the object and image planes. Hence the quantity

$$B = \frac{I}{\pi h^2 \alpha^2} = \frac{I}{\pi h'^2 \beta^2}$$

is a characteristic of the beam and is termed the "brightness." I/h^2 is the current density in the object plane and, since α is small, $\pi\alpha^2$ is the solid angle formed by a cone of semiangle α . Hence the brightness of a beam is measured in amps per square cm per unit solid angle, or $\text{A cm}^{-2} \text{steradian}^{-1}$.

Brightness of Conventional Microscope Beams

The Elmiskop I has at the source

current density: 1.5 A cm^{-2}

angular divergence: $1.3 \times 10^{-3} \text{ radian}$,

so that its brightness is

$$B = \frac{1.5}{\pi(1.3 \times 10^{-3})^2} \approx 3 \times 10^5 \text{ A cm}^{-2} \text{steradian}^{-1}$$

Brightness of Linear Accelerator

An experimental injector for the Stanford 2-mile linear accelerator is described in IEEE Transactions on Nuclear Science, NS 12, p. 804. This gave an output energy of 6 MeV, and may be taken as typical of what is to be expected from a source for a 5 MeV microscope. The optics of the beam are described in Fig. 4 of the

$$h\alpha = h'\beta$$

$$\text{BRIGHTNESS } B = \frac{I}{h^2 \pi \alpha^2} = \frac{I}{h'^2 \pi \beta^2} \quad \text{A cm}^{-2} \text{steradian}^{-1}$$

FIG. 1. Formula for Brightness

paper referred to. The area of the outer contour, within which 90% of the beam current is contained, is 10^{-3} cm^2 . This in our notation is the quantity $\pi h\alpha$. The beam current from this injector was 0.1 A. Hence the brightness is

$$\frac{\pi 0.1}{(10^{-3})^2} \approx 3 \times 10^5 \text{ A cm}^{-2} \text{steradian}^{-1}.$$

The accelerator beam therefore has exactly the same brightness as the beam from a typical low-voltage electron-microscope gun.

Energy Spread of Beam

The injector for SLAC produced bunches extending over 5 degrees in phase angle, and the energy spread was 1.8% (see Fig. 5 of article referred to). For the 5 MeV microscope, we aim at an energy spread of one part in 10^6 . This means that we must improve on SLAC by a factor of 2×10^4 . Now (see Eq. 1 of paper referred to) the energy spread is given by

$$\frac{\Delta E}{E} = \frac{\theta^2}{8},$$

where θ is the spread of the beam in phase angle. Hence, to improve the energy homogeneity by a factor of 2×10^4 , we must reduce the phase-angle acceptance by a factor of 140. Thus the brightness of the SLAC test injector is smaller than that of a conventional microscope by a factor of 140.

The above figure can be materially improved by accepting only half the beam. Figure 4 of the paper cited indicates that the 48% contour has about $1/3.5$ of the area of the 90% contour; i.e., by reducing the beam current utilised by a factor of two we also reduce the

denominator of the expression for the brightness by a factor of $3.5^2 \approx 12$. The overall gain in brightness is therefore 6:1. Under these conditions, the brightness of the SLAC beam is lower than that of a typical microscope by a factor of only 23 approximately.

Separated High-Voltage Charging and Accelerating Systems

A. O. HANSEN

*University of Illinois
Urbana, Illinois*

The advantage of using separated charging and accelerating systems was discussed by DeGeeter and Yokosawa (in Newsletter No. 3 of February 10, 1965), who pointed out its advantages in precision regulation of a high-voltage electrode. Langsdorf and Rymer have discussed possible reference systems. This note will attempt to discuss some important properties of several charging systems which include:

- I. Conventional Van de Graaff,
- II. Split Electrode Van de Graaff,
- III. Cockroft-Walton, Dynamitron charging systems,
- IV. Pulsed LINACS,
- V. Conventional Cockroft-Walton LINACS
- VI. Superconducting Cockroft-Walton LINACS,

The use of separated but adjacent charging and accelerating electrodes in the same pressure tank is also considered as a method of supplying charging currents for voltage control much larger than the average current carried up by the charging system.

I. Single Electrode Van de Graaff

This system is the one commonly used, and performance figures are available. For purposes of discussion it is shown schematically in Fig. 1, where i_c represents the charging current, i_b the beam current, and i_l the load. When the system is conservatively operated, so that there is no tendency to spark, the change in the potential of the high-voltage electrode is obtained by the net current into it. The time constant $\tau = RC$ for the relaxation of the high-voltage electrode is typically of the order of 10 seconds ($C = 100$ pf, $R = V/I = (5 \times 10^6)/(50 \times 10^{-6}) = 10^{11} \Omega$). If the charging current is intermittent with a period T , the maximum ripple would be $\Delta v_r = v(T/\tau)$. If $\Delta v_r/v$ is to be 10^{-6} , T should be less than 10^{-5} second, corresponding to a charging frequency of about 10^5 per second.

In considering systems for stabilizing a dc high-voltage electrode, one notes that the time delay in changing the current carried up by a belt is around 0.1 second and can be used in a slow control only. A controlled electron beam load, such as planned for the 1-MeV system, has intrinsic delays of less than 0.1 microsecond, and it is possible to reduce overall time delays to less than 1 microsecond.

The control electron beam, however, introduces an additional load on the charging system and could also be a source of instability in the system. This beam load can discharge the electrode at a high rate. Its maximum effective charging rate is obtained by cutting off the load completely. This is necessarily a fraction of the charging current. This system will operate very well if the current carried up by the charging belt has a ripple that can be compensated for by the discharge current and if other variations in discharge currents are less than the current in the control beam.

II. Van de Graaff with Separated but Adjacent Charging and Accelerating Electrodes

This system is shown schematically in Fig. 2, where c_1 and c_2 are the electrode capacitances, c_{12} the interelectrode capacitance, and i_{12} the electronically controllable interelectrode current. It would be desirable to reduce the interelectrode capacity to a negligible amount. For adjacent electrodes the interelectrode capacity, c_{12} , is about one-fifth of that for c_1 and c_2 . The effect of this coupling capacity is that an abrupt voltage slip Δv_1 would result in a step of $\Delta v_2 \approx \Delta v_1/5$, which cannot be removed by controlling the current i_{12} . One may note, however, that if the duty factor on a pulsed charging current is greater than 1/5, it becomes possible to regulate v_2 precisely. In the case of a Van de Graaff charging system there should be no step-charging effects, and it seems that electronic control of the interelectrode current i_{12} could improve regulation without introducing another high-energy electron beam load on the system. Since the control-current tube would operate across the voltage ($v_1 - v_2$) which may be of the order of 100,000 volts, the output of X radiation would be much reduced over that for an electron beam to ground potential.

III. Cockroft-Walton and Dynamitron Charging Systems

Systems at 1 MeV have claimed stability to ± 1 volt. These systems are likely to introduce some difficulty with ripple and with the response time of the basic charging circuit. If the voltage fluctuations and ripple are sufficiently low, the accelerating electrode voltage can be regulated by using an electron beam

FIG. 1. Schematic of Single Electrode Van de Graaff

FIG. 2. Schematic of Double Electrode Van de Graaff System

load or an interelectrode current control as in the Van de Graaff charging systems.

These systems are not as highly developed for voltages of 5 MeV as the belt-type charging device. These can be made to supply large currents, but large currents do not appear to be required.

IV. Pulsed Electron LINACs

A pulsed LINAC can be set up for 6 MeV with adequate electron current to charge a high-voltage accelerating electrode by directing the beam through an accelerating tube against the electric field. The cost for such a system would be less than \$100,000 and could be obtained commercially. The available repetition rates up to about 2000/sec, however, would give a ripple which is above one in 10^6 .

V. Conventional Cockcroft-Walton LINACs

Any charging system carrying bunched charges at a rate of 100,000 per second or more would be very satisfactory. This could be done by a conventional S-band LINAC operating with 100 kW Cockcroft-Walton. The parameters for such a LINAC can be expressed by the relation $V = \sqrt{Prl}$, where V is the energy gained by the electron in MeV, P is the power in megawatts, r is the shunt impedance in megohms/meter, and l is

length of the accelerator in meters. Standard disc-loaded, S-band accelerating sections have an effective impedance r of around 30 megohms/meter so that for a length of 3 meters one could get 6 MeV with rf power $P = v^2/rl$ of $36/303 = 0.4$ megawatts. The dissipation of 40 kW/ft is too high, according to present practice. If, however, one is willing to increase the length by a factor of 4 to 40 ft, one finds the power down to 100 kW and the dissipation quite manageable. The basic cost of such a Cockcroft-Walton system for this energy is not much more than a pulsed system since one does not need a modulator. The cost may again be less than \$100,000.

Cavities having a shunt impedance of 42 megohms/meter at 805 megacycles/sec are being operated at Los Alamos, achieving 4 MeV/meter with 400 kW peak pulsed power. The power dissipation in this system is again a problem for Cockcroft-Walton operation, which could be solved by going to a longer length. In this case one could use a 100 kW power source, with a 9-meter accelerator section, to achieve 6 MeV. Since the effective shunt impedance for the same shape of cavity varies directly with the square root of the frequency, one can obtain a shunt impedance of 80 megohms/meter at around 3000 mc/s and get 6 MeV in 4.5 meters. This seems to be a reasonably convenient size and power consumption.

A Cockroft-Walton Microtron arrangement is also possible as a charging device. The main advantage of this system is that one could use the accelerating cavity more efficiently. A possible arrangement would be to use an 805-mc, 1 MeV accelerating section, sending the beam through five or six times. This might involve an accelerating section 75 cm long, using around 35 kW of rf power. The guide field for such a device has not yet been designed, but it seems feasible if one is satisfied with a fixed energy output.

A discussion of this type of microtron has been presented by B. A. Wiik, H. A. Schwettman, and P. B. Wilson, International Conference on High Energy Accelerators, 1965.

VI. Superconducting LINACs

Superconducting cavities can be used to obtain high rf fields for accelerators, and much work toward the

development of such LINACs is progressing at Stanford. A three-wavelength, 1265 mc/s standing-wave section is also being assembled and tested at the University of Illinois during the summer of 1966. Such an accelerator could have a very convenient size. For a length of two meters one may expect to get 6 MeV, with a cooling load of 20 watts, at 1.8°K. The main cost of such a setup would be that for a refrigeration system, which may be more than \$100,000. Intermittent operations, however, could be carried out using stored liquid helium and some kind of recovery system.

Any of the Cockroft-Walton LINACs or similar devices by which the charging current is quickly and accurately adjusted seems to offer a simple method of achieving a stable and accurately controlled dc electrode. There would be no advantage to introduce a current regulator between electrodes in these cases, since the charging current available is more than sufficient.

Use of the Electro-Optical Effect for Regulation of Voltages

H. STANLEY BENNETT

*The University of Chicago
Chicago, Illinois*

This section discusses the merits and problems anticipated in an attempt to explore the feasibility of the electro-optical effect for regulation of voltages in an electron microscope. Use of this principle offers some salient advantages, the most important of which is very high sensitivity to small voltage changes. In principle, the method should be able to detect voltage variations of the order of one part in 10^8 or better, but depends on overcoming in sufficient measure a number of difficulties. In this discussion, the method is examined from the point of view of detecting voltage changes of one part in 10^7 .

The method proposes to use a highly coherent monochromatic linearly polarized laser beam as the basic information carrier. This beam is to be phase modulated by causing it to traverse a transparent, dielectric optical medium inserted between the two plates of a condenser, one at the voltage to be measured, or a known proportional sample thereof, and one at ground. As the condenser is charged, the dielectric medium is put under strain and exhibits a submicroscopic distortion of structure which gives changes in birefringence. This birefringence is used to modulate the laser beam. The resulting phase difference, θ , may be measured by a suitable polarimeter, which is fitted with a light transducer, counter, and logic circuit suitable for converting the light signals from the polarimeter into electrical analog for the control of the voltage.

The method seeks to capitalize on the attractive features of high coherence of a laser beam and high accuracy of a good polarimeter. Laser beams have demonstrated coherence out to 10^9 fringes. Polarimeters have been devised that measure accurately phase differences of 10^{-4} wavelength. A combination of these devices, then, affords an opportunity to split a signal reliably into a large number of bits of information, and hence to detect small changes with high sensitivity.

At present, reliable helium-neon lasers emitting linear polarized light of a wavelength of 6238 Å are available, and appear to be the most promising laser for this application, though shorter wavelengths would provide some advantages. There is a wide choice of polarimeters, but the most attractive possibility seems to be one based on the quarter-wave plate method for detecting ellipticity, developed in the last century by de Sénarmont and Friedel. This method has been studied thoroughly

by Goranson and Adams [*J. Franklin Inst.*, **216**, 475-504 (1933)]. It has the required accuracy, and the advantage of displaying the phase lag, θ , in a beam of linear polarized light, which rotates as a linear function of θ . By means of suitable half-shade devices, ambiguities of sign and order can be resolved and high sensitivity achieved by allowing a photo-detector system to match intensities of different fields, which monitor the emergent linear beam at points separated in phase by a chosen amount.

Problems of a carrier beam and of a modulation detector, then, are well in hand. There remains the task of examining the properties of the modulation mechanism itself.

Two broad classes of transparent, dielectric media can be considered as modulators, to transduce voltage changes into optical signals. These two classes are:

1. Random gases, liquids, and solids, such as glass, which follow the Kerr formula,

$$\theta = k l E^2, \quad (1)$$

where θ is the phase retardation, K is the Kerr constant, l is the length of the optical path between the charged plates, and E is the electric field strength.

2. Crystals which display the Pockels effect; namely, a change in birefringence when subjected to electrostatic strain. This effect varies with different crystals and along the several crystal axes. The strongest effects of this kind now known are displayed by certain potassium phosphate crystals complexed with hydrogen, ammonia, or deuterium, when the voltage is imposed along a crystal axis, and the polarized light traverses the crystal in the same direction. The birefringence so produced is independent of crystal thickness and is a linear function of the applied voltage. The effect is rather weak, as 5,000 to 10,000 volts is required to produce a value of θ of $\frac{1}{2}$. Hence high voltages and many Pockels cells in series would be necessary to produce a value of θ sufficient to achieve a sensitivity of one part in 10^7 . A 100-kV Pockels cell would produce a θ of 5 to 10. Thus 100 to 200 of these would be necessary to produce a θ of 1000. The last fringe might be cut into 10,000 parts, giving a sensitivity of one part in 10^7 . Since the beam is parallel to the direction of the field, transparent condenser plates are a necessity. One may be able to develop

arrangements involving several reflections of the carrier beam through the same cell, but reflection of a polarized beam can introduce ellipticities and noise. Thus a number of problems would have to be overcome before the Pockels cell could be used at the desired sensitivity.

A Kerr cell offers interesting advantages and problems. The basic Kerr formula (1) offers an attractive advantage in that θ varies as the square of the voltage. For any given ΔE , $\Delta\theta$ varies as follows:

$$\theta + \Delta\theta = Kl(E + \Delta E)^2.$$

Solving for $\Delta\theta$, we have

$$\Delta\theta = 2KlE(\Delta E) + Kl(\Delta E)^2. \quad (2)$$

For small values of $\Delta E/E$, the last term becomes negligible. Hence it follows that, for small values of $\Delta E/E$, $\Delta\theta/\theta$ is about twice the value of $\Delta E/E$.

θ varies directly with the Kerr constant and with the length of the optical medium under electrostatic strain. The material with the largest Kerr constant known is nitrobenzene, a clear, yellowish liquid with properties as follows:

Refractive index for Na D line	1.5562
Dielectric constant	~ 35 at room temperature
Resistivity	$\sim 1.4 \times 10^{10}$ ohm-cm
Specific heat	~ 0.34
Breakdown voltage	$\sim 45,000$ V/cm
Light absorption	Strongly absorbing in ultraviolet and violet, with cutoff at around 4200–4700 Å; transparent to wavelengths longer than 4700 Å.

There are many published values for the Kerr constant of nitrobenzene. The most careful measurements seem to be those of Szivessy [Zeitsch. J. Physik, **2**, 30–48 (1920)], who determined values of K at five wavelengths at three temperatures.

From his data, one can obtain an estimated value for the Kerr constant of nitrobenzene at 6°C, for the He-Ne-laser wavelengths of 6328 Å, of about 28.7×10^{-6} . One can also estimate the temperature coefficient for the Kerr constant at 633 mμ and 6°C to be about $-0.5 \times 10^{-6}/^\circ\text{C}$. This is a large temperature coefficient and engenders some special considerations.

Let us examine the properties of a Kerr cell using nitrobenzene operated at a voltage gradient of 45,000 V/cm. Such a cell, letting $\theta = 1$, gives a value of l of 1.55 cm for $K = 28.7 \times 10^{-6}$. Thus the retardation per cm equals a θ of 0.645 wavelength. An optical path 15.5 meters long would be required for θ to be 1000 wavelengths.

To achieve a sensitivity sufficient to detect a ΔE of

$10^{-7} E$, Eq. (2) gives $\Delta\theta$ as 1.29×10^{-7} wavelength. From this, an optical path length of 8 meters will be sufficient to yield the desired sensitivity of voltage detection. An 8-meter Kerr cell would be inconveniently long; therefore one is led to consider reflecting the polarized light beam back and forth several times through a shorter cell.

There remain the questions of variations of K and l with temperature. Temperature variations result in rather large variations of K ; thus, to avoid significant error the temperature of the nitrobenzene must be held to the order of 10^{-5} degree if regulation to 10^{-7} is desired.

With dc voltages fluctuating only slightly, heating from dielectric loss would be small. However, in a Kerr cell of conventional design, with condenser plates immersed in the liquid, heating from resistive losses must be considered.

In a cell with 1 cm between plates immersed in nitrobenzene with a resistivity of 1.43×10^{10} ohm-cm at 45,000 volts, the power dissipation per cm³ is 0.141 watt. With a specific heat of about 0.34, the temperature rise would be about 0.1°C/sec, receiving in that short time about 10,000 times the temperature change that can be tolerated. To deal with such a strong heating effect would require a rapid and accurately controlled exchange and circulation system for the dielectric.

Fused quartz has a resistivity more than a hundred million times greater than that of nitrobenzene. One can consider a Kerr cell with nitrobenzene enclosed in quartz sheets of suitable thickness as a means of increasing the resistivity. Quartz, with a dielectric constant of about 3.8, causes unfavorable losses in field strength when interposed between the liquid and the condenser plates.

Such an arrangement poses problems of three leaky capacitors in series, the solution of which seems to be uncertain in the face of scanty data on the resistivity of nitrobenzene and quartz as a function of field strength.

Summarizing, a voltage regulator based on Kerr or Pockels cells, wherein the strains engendered in a dielectric medium modulate a polarized laser beam as to phase, offers attractive features, since the high coherence of a laser beam and the sensitivity of a good polarimeter provide possibilities of detecting voltage perturbations of 1 part in 10^7 or more. To realize this capability, a number of difficulties would have to be overcome. In a nitrobenzene Kerr cell the most serious difficulties are the high temperature coefficient of the Kerr constant and the resistive heating. There are prospects of ameliorating these and other defects, but considerable development work would be necessary to determine the extent to which these difficulties can be overcome. Until this is done, the method cannot safely be recommended as a means for detecting small voltage fluctuations for purposes of regulation.

Insulation of High Voltages in Vacuum

WILLIAM C. NIXON

*University of Cambridge
Cambridge, England*

A general review paper on "Insulating Properties of High Vacuum," R. Hawley, A. A. Zaky, and M. E. Z. Eldine, *Proc IEE (London)* Vol. **112**, 1237, June 1965, summarized the rather uncertain theories of electrical breakdown in vacuum. More recent work has been done by L. Goldstone in a Ph.D. thesis for Professor D. Gabor, Imperial College of Science and Technology (Department of Electrical Engineering) London, 1965-1966.

Goldstone used ultrahigh vacuum $\approx 10^{-10} - 10^{-11}$ torr and carefully prepared electrodes to measure breakdown potentials under various surface conditions. He concluded that field emission from the cathode led to vaporization at the anode where the electrons struck, ions formed and positive ions accelerated to the cathode, establishing an unstable situation leading to an arc. This agrees with the work of Bas, at Zurich. Using an emission microscope, he saw fine points emerge from polished molybdenum, even under moderate field stresses, probably due to defects in crystal structure. All of this has led me to the conclusion that a cross-magnetic field at the *cathode* surface of all electrodes in an accelerating tube, for instance, would prevent the field-emitted electrons from reaching the anode and so stop this chain reaction before it started. The magnitude of the magnet field would be such that the emitted electrons of only a few volts at a short distance from the surface would be bent back into the cathode. The $\beta\rho$ value for a 10-volt electron is approximately 10 gauss-cm (Grivet p. 745); therefore a relatively weak field supplied by permanent magnets would deflect the emitted electrons, but not be enough to affect the main electron beam at, say, 50 kV from the first stage up to 5 MeV at the final stage. A small-scale experiment with a

single pair of electrodes and an external electromagnet could produce evidence of any change in the breakdown potential with and without the crossed magnetic field.

To prevent contamination and subsequent charging and to provide variable resistance in the insulator, it is suggested that the Al_2O_3 ceramic-type accelerator tube be heated during operation to 150-200°C.

The high-voltage source, if of the Cockcroft-Walton or Van de Graaff type, should have an additional corona shield and accelerating tube down beside the column so that a 180° magnet may be used below the main microscope column to bend the beam back vertically but moving upwards. This beam would be decelerated by the second tube, and the electrons reaching the top of the column would be almost at rest and could be used for energy analysis of the specimen area through which they passed. The *same* tube and magnet might be used for the Haine and Jervis voltage stabilizer scheme, with two beams, one in each direction. A small magnetic prism near the electron source would separate the two beams, one going down the column to be accelerated and used for stabilization, the second having come up the column and about to be used for energy analysis, having been decelerated.

In initial trials we should include the 2 MeV surge generator plus field-emission source made by the Field Emission Corp. McMinnville, Oregon, for X-ray purposes. This high-voltage and electron emitter could be matched to a *single* lens, conventional, superconducting or nonrotationally symmetric (quadrupoles-octupoles), and the beams chopped to get single-shot tests of lens parameters, recording devices, X-ray shielding, etc., and even resolution better than the optical microscopes

Conventional Magnetic Lenses

RAYMOND K. HART

Argonne National Laboratory

From the beginning of electron microscopy 35 years ago up to and including the present time, cylindrical magnetic lenses have been used almost exclusively to produce electron images. The only other lenses that have been used to any appreciable degree are electrostatic lenses, and several commercial instruments use this type of lens system.

For the highest-resolution work, electrostatic lenses have a number of drawbacks. The most severe of these is that their resolving power is limited to about $15 \text{ \AA}$, which is about 10 times worse than a magnetic lens; i.e.,

$$d = 4.2/X_m^{1/4}V_r^{1/8},$$

where X_m is the electric stress, which has a maximum of 200 kV/cm , and V_r is the relativistic voltage. This voltage is given by the following:

$$V_r = V(1 + \epsilon V);$$

$$\epsilon = e/2M_0C^2 = 0.978 \times 10^{-6}.$$

Contamination of the electrodes is also a severe problem in electrostatic systems.

The development of efficient magnetic lenses has been rapid. The earliest microscopes built by Ruska and his co-workers between 1931 and 1933 operated at 75 kV and resolved $500 \text{ \AA}$ at $12,000 \times$ magnification. Present-day microscopes usually operate at 100 kV with a resolution of $2\text{--}4 \text{ \AA}$ at $200,000 \times$ magnification. In the past few years, microscopes using conventional lens have been operated up to 1.2 MeV . Several commercial manufacturers are presently offering microscopes that operate in the half-million- and one-million-volt ranges.

Nearly all current electron microscopes employ five magnetic lenses. A double-condenser lens system is placed between the electron gun and the specimen to control the illumination of the specimen. With these two lenses, the size of the irradiated area, the beam intensity, and angular aperture can be precisely controlled.

The projection train consists of an objective lens, an intermediate lens, and a projector lens. By selecting suitable energizing currents in these three lenses, magnifications between $200 \times$ and $200,000 \times$ can be readily obtained. Also, by suitable aperturing and energizing of the intermediate lens, electron-diffraction patterns from

a very small selected area of the specimen can be recorded.

Two forms of magnetic lens are typically encountered in an electron microscope. These are shown in Fig. 1. Type a is commonly used for condenser II and intermediate lenses; type b is used for condenser I, objective, and projector lenses. Since the objective lens is by far the most important lens in an electron microscope, the rest of this report will be concerned only with strong lenses containing pole-piece inserts.

The performance of a magnetic lens depends on its pole-piece, the essential geometry of which is illustrated in Fig. 2. The important parameters are the radii R_1 and R_2 of the bores and the spacing, S , between them. The values for these parameters for 100 kV microscopes range from 2.5 to 7.0 mm .

Owing to the radial-velocity component of the electron and the axial field H_z , the plane of motion of the electron also rotates, as is shown in Fig 3. This rotation, in radians, is given by

$$\theta = 0.148/E^{1/2} \int_{\text{gap}} H_z dz.$$

This and the formula for focal length indicate that these properties depend on the z -component of the magnetic field in the gap. By using a resistance network analog, Liebmann and Grad,¹ in the early 1950's, developed a unified diagram for pole-piece design. For an unsaturated pole-piece, H_z is proportional to NI , the ampere turns energizing the lens; i.e.,

$$H = 4\pi NI/10S.$$

Now, the focal length of the lens can be expressed in terms of several geometrical parameters and ampere turns; i.e.,

$$f/(S + D) = \alpha V_r/(NI)^2.$$

The factor α is not a true constant, however, and has been found to vary between about 10 and 100.

Electron lenses, like those used for light microscopy, have aberrations that limit their resolution in a number of ways. Aberrations that are of any consequence in electron microscopy are usually third-order errors according to the term in the expansion on which they depend; i.e.,

$$\sin \alpha = \alpha - \alpha^3/3! + \alpha^5/5! - \dots$$

These third-order aberrations are listed in Table I. Of the aberrations listed in Table I, the most important (since it limits the resolution of the microscope) is spherical aberration, which does not vanish on the axis of the lens. In addition, one should also be concerned with astigmatism, which is caused by defects in the pole-piece, and chromatic aberration, which can be introduced by the specimen itself or by instability in the high-voltage and lens supplies.

Let us now consider briefly these three types of aberrations. Spherical aberration is the chief defect of an objective lens since at present there is no convenient way of correcting it. Due to the increased bending of marginal rays compared to axial rays, a disc of confusion of radius

$$\Delta r_i = MC_s \alpha^3$$

is produced at the Gaussian image plane.

Liebmann² has shown that the spherical-aberration

FIG. 1. Typical Construction of (a) a Weak Magnetic Lens and (b) a Magnetic Lens of Short Focal Length.

FIG. 2. Pole-piece Geometry and Magnetic Field Distribution. a, The geometry of an objective pole-piece; b, the axial distribution of the z -component of magnetic field. To a good approximation,

$$H_z = H_{\max}/[1 + (z/a)^2], \text{ and } 1/f = (e^2/4c^2p^2) \int_{\text{gap}} H_z^2 dz,$$

where p = electron momentum.

FIG. 3. Rotation of an Electron Passing through a Magnetic Lens.

TABLE I. MAGNETIC-LENS ABERRATIONS

Third-order aberrations causing image defects due to geometrical effects of the refracting fields:

1. Spherical aberration
2. Distortion
3. Anisotropic distortion
4. Curvature of field
5. Astigmatism
6. Anisotropic astigmatism
7. Coma
8. Anisotropic coma

Other aberrations causing image defects:

1. Chromatic aberration
2. Rotational chromatic aberration
3. Space-change distortion

constant can be expressed simply as

$$C_s/f = 3130V_e^2/(NI)^4.$$

For a limiting flux density of 18,000 G, the limiting value of C_s becomes about 0.3 cm.

By substituting numerical values in this relationship, we can show that the spherical-aberration constant does not improve at very high voltages. For this reason other types of lenses should be investigated for very high-voltage microscopes. A comparatively new idea for decreasing spherical aberration by using a zone plate has been put forward by Hoppe.³ It consists of a system of concentric circular rings, which obstructs all parts of the wave surface whose contributions to the wave amplitude in the image point are in opposite phase to the paraxial part of the wave front, and leaves through all parts that are in phase with it.

FIG. 4. Single-field Condenser Objective Lens, due to Glaser⁶

Lenz⁴ modified Hoppe's idea by suggesting a zone plate in which the outer rings leave through the parts of the beam in opposite phase and obstruct the in-phase ones. This type of plate is expected to improve the contrast without any appreciable loss of resolving power.

Astigmatism results from asymmetry in the magnetic field produced by either inaccuracies in pole-piece manufacture or inhomogeneities in the iron itself. This produces different focal lengths for paraxial rays in two principal planes of asymmetry. Computations by Archard⁵ have shown that astigmatism can be expressed as a ratio Z_a/δ in the form

$$Z_a/\delta = 100(2 + 3S/D) V_r/(NI)^2$$

where Z_a is the axial difference between the tangential and sagittal foci, and δ is the peak error in symmetry. To obtain a resolution of 5 Å limited only by astigmatism, pole-pieces have to be constructed to an accuracy of 0.05 micron or approximately 2 microinches.

Astigmatism can be compensated for by the use of stigmators, which are either of the magnetic-slug type or of the electrostatic type.

The change in focus caused by chromatic effects have

scale: 1=5

FIG. 5. Schematic Diagram of a 5 MeV Conventional Lens

little effect on resolution if these effects are kept to a value that is smaller than the focal length of the lens. They do, however, have a considerable effect on contrast and naturally should be kept to a minimum.

A unified formula for the chromatic constant C_c can be expressed as

$$\delta f = C_c(\delta V/V - 2\delta I/I).$$

Expressed as a function of resolution, the limits of these variations are

$$\delta V/V - 2\delta I/I < 0.7d^2/\lambda C_c.$$

It can be shown that for a resolution of 5 Å the high voltage must be stable to approximately 5 ppm and the lens current to about 2 ppm.

With the aim of increasing the resolution of electron microscopes, considerable attention has been paid recently to single-field condenser objective lenses which were initially considered by Glaser⁶ in 1943. Such a lens is shown in Fig. 4. Considerable work has been done in

TABLE II. PARAMETERS OF A SINGLE-FIELD CONDENSER OBJECTIVE LENS ($k^2 = 3$) WITH POLE-PIECE SYSTEM OF $D + S = 4.5$ MM FOR VARIOUS VOLTAGES

V	kV	20	50	100	200	500	1000
NI	kA	4.17	6.57	9.68	14.29	25.22	41.10
A	mm	1.51	1.64	1.82	2.08	extrapolated	
C_s	mm	0.45	0.49	0.55	0.62	0.81	1.08
B_{max}	kG	11.0	16.0	21.5	27.5	37.5	45.5
Glaser ⁶ :							
$\alpha_{opt} = 1.13\sqrt{\lambda/C_s}$	10^{-2}	1.33	1.16	1.03	0.90	0.73	0.62
$d_{lim} = 0.56\sqrt{\lambda^3 C_s}$	Å	4.00	2.94	2.29	1.77	1.23	0.98
$\left(\frac{\Sigma \Delta V}{V} + \frac{\Sigma \Delta I}{I}\right)_{max}$	$p \times 10^{-6}$	21.3	16.0	12.6	9.7	6.4	4.4

Ruska's laboratory with this type of lens, and some of the data pertaining to it are given in Table II.

Using the foregoing information, one can now design a cylindrical lens for a 5 MeV microscope. Such a lens is shown in Fig. 5.

Operating parameters are as follows:

$$V_r = 2.95 \times 10^7 \text{ volts;}$$

$$\lambda = 0.0022 \text{ \AA;}$$

$$\left(\frac{\Sigma \Delta V}{V} + \frac{\Sigma \Delta I}{I} \right) = 5 \text{ ppm;}$$

$$B_{\max} = 20 \text{ kG.}$$

Then, according to Grivet,⁷

$$(NI)_0 = 13.5 V_r^{1/2}$$

$$= 73.3 \times 10^3 \text{ AT.}$$

If we assume that $(NI)_0 = NI$, then

$$NI = 73.3 \times 10^3 \text{ AT.}$$

The space between the pole-pieces is given by

$$S = 4\pi NI / 10 B_{\max}.$$

Setting $B_{\max} = 20 \text{ kG}$ results in

$$S = 4.6 \text{ cm.}$$

Placing S and D equal results in

$$\begin{aligned} f_{\min} &= 0.5 \sqrt{S^2 + 0.45 D^2} \\ &= 2.8 \text{ cm.} \end{aligned}$$

For spherical aberration,

$$\begin{aligned} (C_s)_{\min} &= 4.05 \sqrt{V_r / B_{\max}} \\ &= 1.1 \text{ cm.} \end{aligned}$$

For chromatic aberration,

$$C_c / f_{\min} \simeq 1;$$

i.e.,

$$C_c = 2.8 \text{ cm.}$$

Resolution using Glaser's formula results in

$$d = 0.56 \sqrt{\lambda^3 C_c}$$

$$= 0.6 \text{ \AA.}$$

Winding Data

In normal design work, No. 20 gauge copper wire will carry 1 Amp in a closed solenoid without excessive heating.

$$\begin{aligned} \text{Wire required for } 73.3 \times 10^3 \text{ AT} \\ = 5.32 \times 10^5 \text{ ft.} \end{aligned}$$

Total resistance at 50°C

$$= 6038 \Omega;$$

$$\text{voltage} = 6038 \text{ volts for 1 Amp flowing through the coil;}$$

$$\text{wattage} = 6038 \text{ watts;}$$

$$\text{current density is } 160 \text{ \AA/cm}^2.$$

In conclusion, note that with conventional lenses in very high-voltage microscopes, one encounters the problem of saturation. Because of this, the focal length will be greater than with lenses operating at lower voltages. Consequently their magnification will be reduced.

The ultimate criteria for high-resolution microscopy is the resolution of the human eye, which is only about 0.1 mm. Thus the magnification required in an electron micrograph for 1 Å resolution is given by

$$R_u = R_{\text{eye}} / R_{\text{microscope}};$$

i.e.,

$$R_u = 1,000,000 \times.$$

About 10 % of this magnification can be accomplished either light-optically or by electronic amplification in a display system. However, the remainder has to be done by the electron optics of the microscope. To obtain such a high magnification at the 5 MeV level, an additional projector lens will have to be added to the column.

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Conventional 3 MeV and 5 MeV Electron-Microscope Design

BUNYA TADANO

Hitachi, Ltd.
Tokyo, Japan

I. 3 MeV Electron-Microscope Design; A First-order Estimation

A. Design of Magnetic Lenses

To design magnetic lenses, both conventional and superconducting lenses, the following conditions will be taken as a starting point.

1. The maximum magnetic field strengths B_0 at lens pole-piece for the used material are as follows:

Soft iron	$B_0 < 17,000$ G
Permendar	$B_0 < 22,000$ G
Dy*	$B_0 < 30,000$ G
Ho*	$B_0 < 35,000$ G.

2. Exciting ampere-turn $IN/\sqrt{V^*}$, where V^* is relativistically corrected accelerating voltage.

The focal length f_o , spherical-aberration constant C_s , and chromatic aberration constant C_c strongly depend on the value of $IN/\sqrt{V^*}$.

The larger the value of $IN/\sqrt{V^*}$, the shorter the length of lens system and the smaller the aberration constants. On the other hand, the leakage flux increases as the value of $IN/\sqrt{V^*}$ increases. This means that the alignment of electron-optical system is very difficult. We usually take $IN/\sqrt{V^*}$ between 10 and 15 for commercial electron microscopes.

3. For objective lens design, we used figures by Liebmann¹ which agree fairly well with experimental value. For condenser and projector lenses, we used the design data by Hitachi Electron Microscope Group, since available published data are not reliable.

B. Actual Values Adopted for Objective Lens Design

1. $B_0 \simeq 25,000$ G. This means that we are going to use specially treated Permendar as lens pole-piece and core material.
2. The magnetic saturation at pole-piece is ignored.
3. $IN/\sqrt{V^*} = 13$ (see Table I)
where $V = 3$ MeV or $V^* = 11.8$ MeV

Although the smallness of the value of C_c is important for the thick specimen observation, we

* These materials depend on the temperature and the orientation of crystals.

chose 13 from the practical point of view. This gives the coil wattage 2 kW.

NOTE: If this electron microscope is operated under ideal conditions with a very thin specimen, we can use Fig. 1 to find the optimum α and the minimum δ . From Fig. 1, we have

$$\alpha_{\text{opt}} \simeq 2 \times 10^{-3} \text{ radian}$$

and

$$\delta_{\text{min}} \simeq 1.5 \text{ \AA},$$

provided that $V = 3$ MeV and $C_s = 10$ mm.

When the electron microscope is operated with a thick specimen, the chromatic aberration due to the inelastic scattering increases and the scattering angle becomes large.

Assuming that the objective aperture diameter corresponding to $\alpha_{\text{opt}} \simeq 2 \times 10^{-3}$ rad is adopted and the specimen is 10μ Al, we have the resolving power δ :

$$\delta = (\delta_{\text{diff}}^2 + \delta_s^2 + \delta_c^2)^{1/2} \simeq \delta_c \simeq 100 \text{ \AA},$$

where we assumed that $\Delta V = 3000$ V.

As is shown at Table II, there are several ways to spoil the final image quality. Perhaps the point-to-point resolution with a thin specimen will be about $10 \text{ \AA}$.

C. Design Considerations

1. Electron-beam Alignment

The incident beam from the electron gun into the top of microscope column with a beam diameter of 10 mm and an angle between the microscope axis and the beam of less than 3° is desirable. The alignment will be done using the magnetic deflector coil shown in Fig. 4.

2. First and Second Condenser Lens

Beam-spot size of about 2μ on specimen is favorable. Assuming that the beam cross-over size is 50μ and it is located at 750 mm above from the first condenser lens center, we have the focal length 20 and 85 mm and the wattage of coil 0.5 and 0.25 for first and second condenser lenses, respectively.

TABLE I. VARIATION OF PARAMETERS WITH AMPERE TURNS

$IN/\sqrt{V^*}$	10	13	15
$IN(AT)$	34,000	45,000	51,000
Bore diameter, mm	10	10	10
Pole spacing, mm	18	22	25
Focal length, mm	12	10	7.5
Z_o , mm	9	5	3
C_s , mm	16	10	7
C_c , mm	9	6	5

FIG. 1. Variation of Spherical Aberration and Resolution with Accelerating Voltage.

3. Magnetic Deflector for Dark-Field Illumination

This deflector can also be used to align a beam. An example is shown in Fig. 5.

NOTE: As stated in the appendix, high-voltage electron microscopes have advantages for dark-field observation.

4. Selected area diffraction

Because of the small spherical aberration, selected area diffraction becomes significantly easier in comparison with 100 kV electron microscope (see appendix).

NOTE: The minimum diameter of selected area on the specimen d_s is given by

$$d_s = C_s \left(\frac{\lambda}{d} \right)^3.$$

Since C_s is very roughly proportional to λ^{-1} , we have approximately

$$d_s \propto \lambda^2.$$

This gives

$$\frac{d_s(V = 3 \text{ MeV})}{d_s(V = 100 \text{ keV})} \approx \frac{1}{100}.$$

To make a selected area diameter 200 Å on a specimen using a selected area aperture of its diameter 10 μ, the camera length should be longer than 2000 mm. This is a principal reason for using a five-stage lens system. The focal length of these lenses are as follows:

First objective lens	$f_{o1} = 10 \text{ mm}$
Second objective lens	$f_{o2} = 30 \text{ mm}$
Intermediate lens	$= 20 \text{ mm}$
First projector lens	$f_{p1} = 13 \text{ mm}$
Second projector lens	$f_{p2} = 13 \text{ mm}$

- A. ASSUMED POLE PIECE SURFACE CONFIGURATION
 B. THE EXTENDED SURFACE CONFIGURATION WHICH GIVES THE MAGNETIC FIELD STRENGTH 10 kG AND 20 kG AT $Z = 224$ AND POLE PIECE HEAD RESPECTIVELY, AND GIVES THE UNIFORM GRADIENT OF MAGNETIC FLUX DENSITY BETWEEN THEM
 C. THE SURFACE CONFIGURATION WHICH GIVES THE UNIFORM MAGNETIC FLUX DENSITY FOR EVERY CROSS SECTION PERPENDICULAR TO Z AXIS

NOTE: THESE ARE DONE BY USING RESISTANCE-NETWORK

FIG. 2. Maximum Magnetic-flux Distribution to Determine the Configuration of 3 MeV Second Objective Lens.

THIS DESIGN WAS MADE BY THE HITACHI ELECTRON MICROSCOPE GROUP IN MAY 1966 FOR AMU-ANL ELECTRON MICROSCOPE WORKSHOP.

FIG. 3. A First-order Suggested Design of a 3 MeV Electron-microscope Column, Using Conventional Lenses Only. The total lens weight is 6 or 7 tons, the total power consumption is about 12 kW, and the theoretical limiting resolution is about 1.5 Å.

TABLE II. IMAGE DEFECT DUE TO INSTRUMENTAL INSTABILITIES. TOLERANCE TO SAVE THE MOVEMENT OF IMAGE WITH 2 Å

Sources of Image Defect	Method of Measurement and Reasoning to Determine Tolerance	Tolerance	Remarks
Movement due to varying static electric charges and high temperature caused by electron beam	Measure the moved distance on the picture which is exposed three times every 30 or 60 sec.	$\leq 2 \text{ Å}$	
Vibration of specimen holder with respect to objective lens			
Movement due to high voltage or lens-current instabilities	$\sqrt{\delta_c = C_c \left(\frac{\Delta V}{V} \right)^2 + \left(\frac{\Delta I}{I} \right)^2}$ <p>where δ_c = disc of confusion due to chromatic aberration $\cong 2 \text{ Å}$; α = electron beam angle $\cong 0.015 \sim 1 \times 10^{-2} \text{ rad}$; C_c = chromatic aberration constant $\cong 1 \sim 2 \text{ mm}$; $\frac{\Delta V}{V}$ and $\frac{\Delta I}{I}$ are instabilities.</p>	$\frac{\Delta V}{V} \leq 1.5 \times 10^{-5}/30 \text{ s}$ $\frac{\Delta I}{I} \leq 0.8 \times 10^{-5}/30 \text{ s}$	Room-temperature fluctuations $\pm 0.5 \sim 1^\circ\text{C}$
Astigmatism	$2\delta_A = \Delta f_A$, where δ_A = disc of confusion due to astigmatism Δf_A = astigmatism.	$\Delta f_A \leq 0.05 \mu$	
Misalignment	$r_0 \cong C_c \cong 10^{-2} \text{ mm}$ where r_0 = the shifted distance of the center of coil current.	$r_0 \leq 10 \mu$	
Mechanical vibration	Measure the moved distance on the picture which is taken under the known model disturbance	$\leq 2 \text{ Å}$	Mechanical vibration of the room $\geq \text{few } \mu$
External magnetic field			External magnetic field in the room $\geq \text{milligauss}$

5. Electronic magnification

a. First low-magnification image observation:

Location: just above intermediate lens.

Screen diameter = 50 mm.

Magnification = 100.

b. Second low-magnification image observation:

Location: between intermediate lens and first projective lens.

Screen diameter = 50 mm.

Magnification = up to 40000.

c. Final image magnification = 15×10^6 .

D. Magnetic Design

There are three steps to reach the final design:

1. Resistance-network method (see Figs. 2 and 6);
2. Direct measurement of flux distribution using actual lens determined by 1);

3. Electron-optical properties check by electron beam.

E. Other Items

1. The pole-piece, stigmator, aperture, and fine-position alignment mechanics are joined into one block, similar to the "polar block" or Toulouse electron-microscope structure. By adjusting the polar block, we align lenses.
2. To make the X-ray problem easy, we use a beryllium plate for the condenser lens aperture and an aluminum tube inside the microscope column.
3. X-ray shielding and vacuum system will be left for some other time.
4. Microscope column height: 4000 mm.
Total weight: 10 tons.
Total coil wattage: 8 kW.

FIG. 4. Magnetic Deflector Coils

FIG. 5. Deflection of Illuminating Beam for the Dark-field Observation, at 500 kV. (Deflecting-angle maximum 3°).

II. 5 MeV Electron-Microscope Design; A Zero-order Estimation

This is called a zero-order estimation because in first-order estimation, we normally use the formulas

$$\frac{f_o}{S + D} = 25 V^*/(IN)^2,$$

and

$$H_o = \frac{4\pi NI}{10S}$$

where V^* is the relativistically corrected accelerating voltage in volts,

NI is the ampere-turns excitation,

H_o is the maximum axial field strength in gauss,

D is the bore diameter,

and

S is the pole spacing.

From practical reasons, D is around 10 mm.

If we use Permendar as pole-piece material, we have

$$H_o = 25,000 \text{ G.}$$

Therefore, when we try to get a practical focal length f_o with the accelerating voltage 5 MeV, S becomes more than 30 mm. This gives

$$S/D > 3.$$

The lens design constants for first-order estimation are functions of S/D , and there are no reliable data in the range $S/D > 3$.

This is the reason for calling this a zero-order estimation.

FIG. 6. Hitachi Resistance-network Analyzer

The design constants for 5 MeV objective lens are as follows†:

$$\begin{aligned} H_0 &= 25,000 \text{ G;} \\ IN &= 85,000 \text{ ampere-turns;} \\ IN/\sqrt{V^*} &= 15; \\ S &= 40 \text{ mm,} & D &= 10 \text{ mm;} \\ f_o &= 14 \text{ mm;} \\ Z_o &= 12 \text{ mm;} \\ C_s &= 20 \text{ mm;} \\ C_c &= 10 \text{ mm;} \end{aligned}$$

Coil wattage = 18 kW.

III. Short Note on the Design Considerations of Short Focal Length Lens

A. Requirements to Design Short-focal-length Lens

1. Use high B_0 material for pole-piece top (for example, dysprosium or holmium).
2. Design the lens with a small half-width field strength. There are several ways to obtain a small half-width:
 - a. Design the lens with small $(S + D)$.
 - b. Compress the field flux with diamagnetic material.
 - c. Minimize the cross section of the coil.
 Conventional lens: 100 Amp/cm^2 .
 Superconducting lens: $5 \times 10^4 \text{ Amp/cm}^2$.

That is, the coil cross section of superconducting lens is about 1/500 of conventional lens. The main coil size of 5 MeV objective lens will be about 2 cm^2 if we use superconducting coil.

B. Problems Involved in Superconducting-lens Construction

1. Lens astigmatism is a problem. Because of the difficulty in making a symmetric superconducting lens, astigmatism will play an important role.
2. Mechanical vibration due to the bubbling in the liquid helium is a new trouble for electron-microscope design.
(Specimen stage instability $\leq 1 \text{ \AA}/30 \text{ sec.}$)
3. Heat is a problem. To obtain high stability of specimen stage with respect to objective lens might be serious because very small temperature-distribution change around objective lens and specimen stage affects the final image.
4. Objective-aperture change system is a problem. Since there is not much space to insert an aperture, we have to find a new system for objective-aperture changing.

If these problems are solved, the superconducting-lens system will be attractive for the high-voltage electron microscope.

† Data from Hitachi Electron Microscope Group are used.

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APPENDIX

Features of High-Voltage Electron Microscope*

The penetrating power of the electron is extremely small. Thus, a 100 kV instrument enables observation of specimens with thicknesses less than approximately 0.5 micron.

By way of example, the direct-observation technique developed by Dr. Hirsch *et al.*¹ of crystal-thin film specimens has made it possible to study dislocation, precipitation, and other defects in crystals. However, the specimen must be very thin to allow sufficient electron penetration under 100 kV operation. This prerequisite results in dislocation movement within bulky

FIG. A-1. Penetration Curve Proposed by Dr. Hirsch

material during the specimen thinning process, necessitating the use of thicker specimens (as much as 1 micron or more) and a higher accelerating voltage. Research and development of the high-voltage electron microscope^{2-7, 10} were conducted with these conditions in mind.

In addition to the above application, the high-voltage instrument effected valuable results relative to theoretical studies of electron diffraction.^{5, 8, 9} This suggests latent possibilities for future utilization of the high-voltage electron microscope.

As a result of recent studies involving this high-voltage instrument, advantages related to the following characteristics have become apparent: a) theoretical resolution; b) penetrating power; c) specimen damage; d) accuracy of electron diffraction; and e) chromatic aberration.

* H. Tsuchikura *et al.* This report was circulated at the annual meeting of Japanese Society of Electron Microscopy, Hokkaido Division, on February 12, 1966.

NOTE: This is a viewpoint of Nagoya University and Hitachi Electron Microscope groups, April, 1966.

A. Theoretical Resolution

Resolution of an electron microscope, when spherical aberration is considered, is given by

$$\delta = A (C_s \lambda^3)^{1/4}, \quad (1)$$

where δ is theoretical resolution, A is a constant, C_s is spherical-aberration coefficient, and λ is electron wavelength.

The C_s value is roughly proportional to λ^{-1} , and this results in a relationship of $\delta \propto \lambda^{1/2}$, from Formula 1.

Actual resolution of the electron microscope depends rather heavily on inherent characteristics such as chromatic aberration, astigmatism, and other effects such as mechanical vibration, thermal expansion, and magnetic disturbance. As a result, the value of Formula 1 in relation to practical improvement of resolution in high-voltage instruments is not reached yet.

However, theoretical resolution improves with a higher accelerating voltage, and this assures maximum resolution of the instrument along with technical efficiency.

B. Penetrating Power

Although electron penetrating power increases as a function of accelerating voltage elevation,¹¹ it is limited by the fact that electron mass increases with respect to electron-energy development. This results in greater interaction within specimens.

By simple calculation, Hirsch¹² proposed that the electron-penetration curve as a function of accelerating voltage illustrates saturation, and that maximum penetration at infinite voltage is only 3.3 times that at 100 kV (see Fig. A-1).

This may be reasonable under simple circumstances, but does not take into consideration effects of inelastic scattering and simultaneous reflection. Experimental values including these factors were obtained through use of the following method.^{8, 13-16}

When an electron beam penetrates the wedge-shaped section of a crystal specimen, the extinction contour (equal-thickness fringe) always appears in the electron-microscope image due to Bragg reflection. By measuring intensity of the striped pattern of the image, a mean absorption coefficient (μ_0) can be obtained. The reciprocal (μ_0^{-1}) is considered to represent penetrating power of the electron beam.

Figure 2 shows measured values obtained from several sources.^{8, 11, 13-16} These values differ from each other and deviate from the theoretical value to some extent. All experimental curves, however, approximately coincide with theoretical values. Since μ_0^{-1} is proportional $(v/c)^2 - v$ represents electron velocity, and c represents photon velocity—according to conventional theory, the

FIG. A-2 Measured Values of the Penetrating Efficiency. Plots must be linear theoretically (By courtesy of Prof. Uyeda, Nagoya University¹³).

abscissa in Fig. A-2 is graduated in a $(v/c)^2$ arrangement. These data also confirm the saturation of penetrating efficiency with respect to the crystalline specimen. It can thus be concluded that the penetration of a 1000 kV instrument is about 20% better than that of a 500 kV instrument.

C. Specimen Damage

Under higher accelerating voltages, specimen damage due to electron irradiation is greatly reduced. This permits free study of materials that deteriorate quickly due to irradiation. For example, the following experiment was conducted by Prof. Kobayashi *et al.*⁹

When single-crystal polystyrene film is placed under an electron microscope with a 3-micron spot size for selected area diffraction study, the initial net pattern gradually broadens. It becomes round and finally disappears, evolving into a halo pattern in response to total irradiation.

These critical total doses were experimentally measured under various accelerating voltages, and plotted as shown in Fig. A-3. The curve clearly demonstrates positive reduction of specimen damage under high-voltage operation.

The high-voltage instrument not only reduces specimen damage but also produces a brighter image under identical beam intensity. This makes the instrument extremely valuable for the study of materials that are sensitive to irradiation.

However, high-energy electrons produce radiation damage in metal and semiconductor specimens. (Threshold energy of incident electron needed to dis-

FIG. A-3. Specimen Damage Reduction (By courtesy of Prof. Kobayashi, (Kyoto University)

place a copper atom is about 490 keV and displacement energy of the copper atom is of the order of 22 eV.) Under operating conditions of the 500 kV instrument, however, the possibility of damage is very slight due to the low intensity used. Radiation damage study can be conducted under extended irradiation with the high-voltage instrument.

D. Accuracy of Electron Diffraction

The selected area-diffraction technique by electron microscope enables analysis of the crystal nature of one or several particles within a small specimen area. How-

FIG. A-4. Selected Area Diffraction Limited due to Spherical Aberration.

FIG. A-5. Wavelength of Electron

TABLE I. BRAGG-ANGLE VARIATION

$E(\text{kV})$	100	200	300	400	500
$2\theta \text{ (rad)} \times 10^{-2}$	1.58	1.08	0.84	0.70	0.61

ever, the minimum size is limited due to spherical aberration of the objective lens, as shown in Fig. A-4. The size is expressed by the following formula:

$$\delta_s = C_s \theta_B^3 = C_s (\lambda/d)^3, \quad (2)$$

where δ_s is minimum selected area, C_s is spherical aberration coefficient, θ_B is Bragg angle, λ is electron wavelength, and d is specimen lattice spacing corresponding to diffraction spot.

In this formula, C_s is proportional to λ^{-1} under rough approximation as expressed in Formula 1. Hence, δ_s becomes proportional to λ^2 and diminishes rapidly under higher accelerating voltages (see Fig. A-5.).

Table I illustrates the Bragg angle variation for (111) lattice plan of aluminum specimen as a function of λ . Although the spherical-aberration coefficient of the high-voltage instrument slightly increases according to a relationship of $\lambda^{-1} \propto E$, the 500 kV instrument features extremely small spherical aberration. This is one-tenth or less than that of a 100 kV instrument.

By way of example, the minimum selected area of a specimen under 100 kV operation is derived from Formula 2, and its size is one or several microns. However, the high-voltage instrument makes it possible to limit the area to 0.1 micron or less.

Professors Dupouy, Uyeda, *et al.*¹⁷ confirmed experimentally this accuracy through use of a magnesium oxide crystal specimen.

Nishigaki *et al.*¹⁸ have obtained results of selected area-diffraction analysis for pearlite structure which clearly demonstrates characteristic diffraction patterns of ferrite and cementite components. A 3-micron field-limiting aperture is used in this experiment, and this value corresponds to 540 Å on the specimen.

E. Chromatic Aberration

Chromatic aberration greatly decreases under high-voltage operation of an electron microscope.^{6, 19}

As penetration in the high-voltage instrument has been a serious problem, another important aspect—reduction of chromatic aberration—of the instrument has been overlooked to a certain extent.

Better penetration brings about clear and bright observation of thick specimens, but does not effect better image quality. For obtaining good image quality, it is essential to minimize chromatic aberration. Chromatic aberration is generally expressed by the following formula:

$$\delta_c = C_c \alpha \frac{\Delta E}{E} \quad (3)$$

where δ_c is chromatic aberration, C_c is chromatic-aberration coefficient, α is scattering angle of electrons, ΔE is inherent mean-energy loss of electrons based on specimen characteristics, and E is energy of incident electrons.

In the high-voltage instrument, the high-energy electron beam suffers maximum forward scattering during

specimen penetration. This results in increase of single inelastic-scattering electrons within a small angle.

This single inelastic-scattering angle of electrons is usually several times smaller than a multiple one. Hence, this effect contributes to the reduction of chromatic aberration in the image by decreasing the α angle.

In addition, ΔE in Formula 3 generally decreases with the E increment for a specimen having the same thickness. For this reason, higher accelerating voltage results in less chromatic aberration. This greatly enhances performance of the high-voltage instrument.

Professor Uyeda²⁰ has suggested that chromatic aberration will decrease with the increase of accelerating voltage and that plotting will not result in saturation as shown in the penetration curve (Figs. A-1 and A-2).

As an example of efficiency in the high-voltage instrument, outstanding image quality under dark-field observation and high accelerating voltage is clearly illustrated. This has not been possible with 100 kV instruments.

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Current Superconducting Lens Studies for Electron Microscopes

BUNYA TADANO

*Hitachi, Ltd.
Tokyo, Japan*

AND

CHARLES LAVERICK

Argonne National Laboratory

Introduction

Recent developments in superconducting-magnet design offer another degree of freedom to the designer of electron-microscope lenses. The advantages claimed for the use of superconductors in these lenses include high stability and high average-current densities at high magnetic fields. Lenses of conventional type can be reduced considerably in size if the copper windings are replaced by superconducting windings. High magnetic-field gradients are desirable in electron-microscope lenses, and it is possible to achieve these gradients at high magnetic fields by using superconducting windings or superconductors in bulk in conjunction with iron or with other superconductors that act to limit the spatial extent of the fringing field.

Present-day superconductors are usually operated at 4.2°K in liquid helium, and it is necessary to provide a cryogenic *containing* system with low heat loss to the room-temperature environment when superconductors are used. Liquid-nitrogen shielding at 77°K in conjunction with high-vacuum insulation spaces are in common use, but superinsulation techniques that eliminate the nitrogen shielding and use multiple layers of aluminum foil in conjunction with high-vacuum spaces are also available.

The liquid-helium environment can be provided by means of a liquid-helium storage vessel (helium dewars) or a closed-cycle helium refrigeration system.

The three types of suitable, currently available, high-field superconductor for electron-microscope lenses are niobium zirconium (NbZr), niobium titanium (NbTi), and niobium stannide (Nb₃Sn). Approximate values for the upper critical fields, critical temperatures, and attainable current densities for these materials are:

- i) NbZr, 55 to 70 kG, 10°K, 10⁵ A/cm² at 50 kG;
- ii) NbTi, 120 kG, 9.2°K, 10⁵ A/cm² at 50 kG;
- iii) Nb₃Sn, 190 kG, 18°K, 10⁵ A/cm² at 100 kG.

These figures are typical short-sample characteristics. A safe average density for an electron-microscope coil is 20,000 A/cm², with higher figures possible in future development.

The first two materials can be made in wire form, have high ductility, and are easy to interconnect with zero-resistance contacts. The brittle Nb₃Sn has the advantage of higher upper-critical field and high critical temperature and can be used to best advantage where closed circulating-current loops can be induced in the material. The problem of producing zero-resistance contacts between successive lengths of Nb₃Sn tape has not yet been solved but is capable of solution. Typical contact resistances at the moment are of the order of 10⁻⁸ ohm.

Superconducting windings or superconductors in bulk can be formed into permanent magnets by setting up systems of permanent circulating currents in the materials. These are known as the persistent currents, and this mode of operation is the persistent-current mode. The magnetic flux in a persistent mode system is easily redistributed if other conductors, magnets, or circulating systems are moved into the neighborhood of the system. This forms the basis of one method of adjusting the magnetic field of a persistent-current system. Good magnetic screening is required with superconducting lenses, and this can be provided either by iron or by superconducting sheets.

Several groups have studied the possibility of applying superconductors in electron-microscope lens design. Dr. Fernandez-Moran has operated a Westinghouse NbZr coil system successfully in objective lens pole pieces in a working electron microscope. S. Katagiri, S. Ozasa, and H. Kimura of Hitachi have also operated a superconducting objective lens experimentally in a 0.5 MeV electron microscope. Experimental lens arrangements are under investigation at Cornell by C. N. Kitamura, M. P. Schulhos, and B. M. Siegel. A. Leberigue and P. Levinson of the College de France, Paris, have also reported on the possibilities of using superconductors in electron-microscope lens design.

The data in this paper have been assembled principally by B. Tadano to provide some account of the approaches being adopted by the several investigators and the results being obtained.

I. UNIVERSITY OF CHICAGO INVESTIGATION:

H. Fernández-Morán Department of Biophysics, The University of Chicago

A comprehensive research program is being pursued with different types of cryo-electron microscopes concentrating on two approaches.

1. *Cryo-electron microscope optical bench system* using high-field superconducting, niobium-zirconium solenoid lenses in liquid-helium Dewars, operating at 4 to 32 kG without pole-pieces and with modified objective and objective-projector pole-pieces. An additional current vernier-control circuit for the superconducting objective solenoid is used in conjunction with a 25 A regulated power supply to permit adjustable current changes of 10^{-9} A for achieving reproducible "superfine" focusing orders of magnitude better than conventional systems. This device, specially developed for the lenses by D. Kasun and associates of Westinghouse Cryogenics Div., consists of a low-field, two-winding, superconducting toroid with its secondary connected in series with the main solenoid. Energizing the toroid primary changes the total flux linkage in the solenoid circuit, altering the persistent-current value, and results in an incremental change of field in the main solenoid. After optimum focusing adjustment is achieved, transfer of toroid primary to persistent mode places the entire system in a lossless, completely stable condition. Improved point-cathode sources and highly stabilized 50 kV accelerating potential are used, taking special precautions to minimize mechanical, magnetic, and electrical field perturbations. Once correct focus of test specimens at electron-optical magnifications of $200\times$ – $20,000\times$ is attained, the superconducting solenoid system is switched into persistent-current mode. The high-quality images (50 – 100 Å resolution) thus maintained without any external lens-current source are of an unprecedented degree of stability, permitting exposures of up to several minutes with low-intensity illumination for direct photographic recording on high-resolution films. The same area can be continuously recorded at 5- to 15-minute intervals over a 10-hour period under carefully controlled conditions without detectable image changes, demonstrating typical long-term superstability. Combination of this unique stability of superconducting lenses with coherent microbeam illumination appears promising for practical realization of Gabor's wavefront-reconstruction microscopy.

2. *Special superconducting objective lens in liquid-helium cryostat*, which may be used as an integral part of cryo-electron microscopes or replace the objective lens in modified high-resolution, commercial electron microscopes. The superconducting objective lens in a special Dewar, designed and built to the required specification by Westinghouse Co., comprises a main Nb-Zr

coil (27,220 ampere-turns) with vernier coil, superconducting stigmators, persistent current switches, and improved current-control devices. Specimens are mounted on microstages of special design maintained at 4.2°K, together with pole-pieces of different types including short focal length, single-field condenser-objective pole-pieces of iron or dysprosium, and trapped-flux Nb₃Sn lenses. The microscope mounted on a 10-ton, vibration-isolated base, features extensive magnetic shielding, ultrahigh-vacuum ion-pump system, improved field and T-F emission source, image intensifier, and photographic recording. It is primarily designed for high-resolution electron microscopy of biological specimens, examined preferably in the frozen hydrated state under ideal low-temperature conditions of minimized specimen contamination, radiation damage, and thermal noise.

II. HITACHI INVESTIGATIONS: B. Tadano, Hitachi Central Research Laboratory

A. Preliminary Investigations

Preliminary experiments on superconducting lenses have been carried out using copper-plated, nylon-covered Nb-25 Zr or Nb-40 Zr-10 Ti superconducting wires produced by the Hitachi Company. The arrangement of a superconducting lens with shim coil is shown in Fig. 1, and the electrical schematic diagram for the system is given in Fig. 2.

The measured axial magnetic-field distribution obtained by changing the currents in the main coil and keeping the shim coil open are given in Fig. 3. After

FIG. 1. Arrangement of the Hitachi Superconducting Electron-microscope Objective Lens.

FIG. 2. Electrical Schematic Diagram of the Hitachi Lens

FIG. 3. Magnetic-field Distribution for the Hitachi Lens for Different Persistent Currents in the Main Coil.

each current adjustment, the main coil was switched into the persistent mode.

The possibility of controlling the focal length by adjusting the shim-coil currents has been examined using a superconducting lens that was slightly different from that shown in Fig. 1. The magnetic field was adjusted by changing the shim-coil current with the main coil operating in the persistent mode. It can be seen that the change in half-width, a , is adequate to adjust the focal length of the lens (Figs. 4 and 5).

The half-width can be changed considerably by inserting a Nb-40 Zr-10 Ti superconducting tube into the main

coil as shown in Fig. 6, where both lens arrangement and the degree of adjustment are shown.

B. Experiments with a Superconducting Lens in the 500 kV Electron Microscope

The diffraction chamber of the 500 kV electron microscope was replaced by a superconducting lens. The

FIG. 4. Variation of Magnetic Field with Current for the Main Coil and Shim Coil.

FIG. 5. Magnetic-field Control by Shim-coil Current Adjustment.

FIG. 6. Lens Arrangement and Degree of Adjustment of Half-width for Magnetic-field Variations due to Movement of a Superconducting Tube in the Lens System.

FIG. 7. Characteristics of RCA SR2101 Ribbon

FIG. 8. Nb_3Sn Spirally Wound Tape Coil

FIG. 9. Technique of Depositing RCA Nb_3Sn on a Platinum Disc.

FIG. 10. Disc Assembly for Permanent-magnet Coil Utilizing Persistent Current.

FIG. 11. Superconducting Tape Coil with Permendar Yokes

FIG. 12. Superconducting Tape Coil with Permendar Yoke and Dysprosium Insert.

FIG. 13. Variation of Magnetic Field with Axial Distance from Coil Center for Various Central Peak Fields in the Nb_3Sn Tape Coil.

TABLE I. RESULTS FOR VARIOUS ENCLOSURES

	Superconductor	Ferromagnetic Material	$H_{\max}$, kG	$(\frac{dI}{dz})_{\max}$, kG/cm	a , mm	H_{obj} , kG	f , mm	C_s , mm	C_e , mm	k^2	δ_s , Å
100 kV	Nb-Zr coil, 350 turns. ID = 4 mm, OD = 25 mm 30 A 100 Nb ₃ Sn discs, Trapping flux.	In free space	9.7	16	3.6	9.4	3.5	1.10			
		In free space; Fe; $D = 5$ mm, $S = 3$ mm	11.0 22.3	16 70	4.3 2.6	10.4 21.4	3.6 1.5	1.14 0.66			
		Nb ₃ Sn coil, 150 turns. ID = 6 mm, OD = 40 mm	10.00 23.4	10 67	5.3 2.5	10.0 21.3	5.4 1.6	1.86 0.66	3.23 1.08	3.6 5.8	3.6 2.8
		In free space; $i = 30$ A Fe-Co; $D = 5$ mm, $S = 3$ mm; $i = 80$ A	21.3	70	2.4	20.2	1.6	0.69	1.10	5.0	2.8
		Fe-Co shielding discs; $i = 144$ A									
200 kV	Nb ₃ Sn coil.	In free space; $i = 80$ A	10.0	10	5.0	9.9	5.3	1.81	3.26	4.5	2.7
		Fe-Co; $i = 80$ A	23.4	67	2.5	23.4	1.9	0.89	1.29	6.1	2.1
		Fe-Co shielding discs; $i = 144$ A	22.0	70	2.4	22.0	2.0	0.90	1.37	5.0	2.3
500 kV	Nb ₃ Sn coil.	Dy + Fe-Co; $i = 170$ A	35.0	64	3.6	34.6	2.4	1.05	1.65	4.6	1.5
		Fe-Co; $i = 170$ A	35.9	62	3.5	34.6	2.5	1.11	1.71	4.8	1.5
		Dy + Fe-Co; $i = 170$ A	35.9	64	3.5	35.4	2.4	1.03	1.62	4.8	1.5
		Dy + Fe-Co; $i = 175$ A	37.5	67	3.8	35.9	2.5	1.02	1.66	5.6	1.5
1000 kV	Nb ₃ Sn coil.	Dy + Fe-Co	37.5	67	3.8	35.4	3.1	1.58	2.19	2.2	1.2

$S/D = 0.8$, and $k^2 = 0.0 = HR/V$, are assumed where $D (=2R)$ is lens bore diameter; $Z_0 \approx 1.1$ mm.
 f , C_s , and C_e are calculated by Glaser's equations.

microscope was used as a two-lens system, with the superconducting lens as an objective lens and a conventional second projector lens. Design data for this superconducting objective lens are as follows: $f_o = 6$ mm, $IN = 4000$ AT, $N = 370$, $I = 11$ amp, $M_o = 20 \times$, and $M_p = 50 \times$.

A micromesh film was used as a specimen in this two-lens system at an accelerating voltage of 300 kV. The micrographs, however, were not satisfactory due to movement of the specimen holder with respect to the objective lens; attempts are being made to solve this problem.

III. CORNELL UNIVERSITY GROUP: C. N. Kitamura, M. P. Schulhos and B. M. Siegel

A. Experiments with RCA Nb₃Sn Ribbon Coil

A cross section of RCA type SR 2101 ribbon is shown in Fig. 7. This ribbon can be supplied with the following mechanical characteristics: width, 0.091 ± 0.001 inch; thickness, 0.0044 ± 0.0004 inch; length, this ma

FIG. 14. Axial Field Profile Produced by a Stack of 100 Nb₃Sn Discs with and without Pole Pieces.

material can be supplied in continuous lengths suitable for coil applications; weight, approximately 4.5 lb/1000 meters.

This ribbon has been found to vary slightly in thickness from the center to the edge of its cross section. The thickness given above is the maximum value for the entire cross section.

A small superconducting coil made of this ribbon is shown in Fig. 8. This coil contains 150 turns.

B. Experiments with RCA Nb₃Sn Deposited on Platinum Discs

Nb₃Sn was evaporated on a thin platinum sheet, as shown in Fig. 9, and a disc coil was made by assembling 100 such discs together (Fig. 10).

The coils described above were tested under the following conditions:

- a. Unshielded (coil only);
- b. Coil with Permendar yokes (Fig. 11);

- c. Coil with Permendar yokes with Dysprosium inserts (Fig. 12).

C. Experimental Results

1. Tape Coil

It was not possible to make zero-resistance superconducting joints with Nb₃Sn tape; therefore, persistent-current operation was impossible. The axial-field strength produced by the Nb₃Sn tape coil above is given in Fig. 13. The results for various types of enclosures are given in Table I.

2. Disc Coil

A separate coil system was used to induce diamagnetic currents in the disc assembly. The field due to these induced circulating currents is given for the case of the system unshielded and with Permendar shielding (Fig. 14). The lens constants were calculated from the observed axial-field distributions; the results are listed in Table I.

High-Field Superconducting Lenses

MARTYN H. FOSS

*Carnegie Institute of Technology
Pittsburgh, Pennsylvania*

Introduction

The design and construction of high-field lenses will be quite different from those of conventional lenses. This is because steel can no longer function well in pole tips of these lenses and high current densities must be used in the conductors. Also, precision in coil design and construction will determine the precision of the lens.

In conventional lenses the pole tips almost completely determine the lens characteristics, and the effect of coil errors is shielded out of the lens region by the pole tips. This function cannot be served by steel, which operates well above saturation. Steel will still play an important role in the yokes. For example, where the flux density is low enough, steel can improve the effective position of the coil. Steel can also reduce stray fields from the lens coils, which will keep external effects outside the lens field. The required number of ampere-turns can be somewhat reduced. Besides, the steel yoke can give mechanical support.

Because steel cannot direct the flux, high current densities are required to produce high local fields. A current density in excess of 10^4 amp/cm² can be used in copper conductors. Edgewise-wound sheet might give the required precision. Recent developments have made well-regulated (10^{-5} or better), high-current power supplies available. However, there will still be major problems connected with powering and cooling such a coil. Superconducting coils seem to be better suited to use in a microscope using a current density in excess of 10^4 amps./cm². Current regulation is simple particularly in the persistent current mode.

A Lens

The actual design of a lens is not undertaken, although some of the problems are brought out by the following example. Figure 1 shows the field due to three wires. A 200,000-Amp loop in the midplane has a radius of 2 cm. The top curve gives the field due to this coil. A 50,000-Amp current flows in the opposite direction in each of two other coils. These also have a radius of 2 cm and are above and below the midplane

by 1.8 cm. The lower curve in Fig. 1 gives the field due to the system. This resembles the field required for a high-voltage microscope. Figure 2 suggests how an actual coil might look. The effect of the yoke is to shift the effective position of the main coil toward the desired position. The coil areas are such that a current density of about 50,000 Amp/cm² is required.*

Coil Design and Construction

The coil must be designed so that undesired fields are not generated. For example, field ripple due to the individual wires in a layer will smooth out in a distance equal to the turn spacing. This will usually not be important. Thus a uniform helix may be thought of as a cylinder with desired current plus an axial current. This is good except for possible errors at the ends of the helix. However, it is common practice to go from one turn to the next at one azimuth, as shown in Fig. 3a. This practice makes the error current flow down one side of the cylinder. This generates an error field.

It is convenient to think of the current flow as the sum of a set of currents. Part of this set should be a satisfactory current as close to the real current as possible. A second example is given in Fig. 3b. This illustrates the effect of displacing a group of wires in a layer. The desired current and the backwards flowing current loop A would make a good lens. Thus the current loop B is the source of error.

A coil designed to be free of (low-order) errors is shown in Fig. 4, where the turns are made of 16 parallel wires. These are wound side by side to form a layer. Sixteen pins at either end of the coil define the axial length and are convenient tie points for moving from one layer to the next. Some sort of a winding machine will be required to make this coil. The lowest-order systematic error is of 32nd order. Such an error decreases by 10^9 at half the coil radius. Figure 5 shows an eight-wire mockup of this type of coil.

Again, it is not sufficient to design a satisfactory coil. Accurate construction is also necessary. Careful arrangement of the leads, accurate wire size, and other details must be attended to. If the insulation on every N^{th} wire had a different color, this might help in winding and inspection.

* I gave this incorrectly as 17,000 during the Workshop summary.

FIG. 1. Arrangement and Calculated Field Profiles for a Bell-shaped High-field System Using Clipping Coils.

FIG. 2. A Coil System to Give Short Half-width by Means of Adjacent Coils Operated in Reverse Current.

FIG. 3. Typical Current Flow Through a Coil. (a) The error current that flows from one end of a layer to the other will be a trip down one side if the coil is wound as shown. (b) The error due to the displacement of a group of wires as indicated is approximately equal to a reverse turn at A-A and a circulating current B-B. The error current is the wire current times the displacement of the wires divided by the wire diameter.

FIG. 4. Projected Views of a Lens Coil that is Free of Low-order Errors.

FIG. 5. Eight-wire Mockup

Protection

Superconducting coils are subject to normal excursions during the charging process. Efforts are made to negate the effect of these excursions. The word protection is applied to these efforts because self-destruction of the coil was the original concern. At present, protection is built into a coil so that it can be reliably taken up to full current.

FIG. 6. Circuit Utilizing Protection by Mutual Inductance. R = variable resistors + meter shunts used to measure and regulate currents to coils. S = low resistance ($10^{-3} \Omega$) protecting shunts. Switch = persistent mode switch. Coil = one of the parallel elements in the lens coil.

FIG. 7. Normal Conductor Test

FIG. 8. Bond Test. Voltage probes on either side of a break in the superconductor can determine how current gets from the superconductor to the normal conductor. When all the current is out of the normal conductor, the voltage between adjacent probes will vanish.

Coils are protected by adding high-conductivity normal material. This reduces the space available for a superconductor. Thus it increases the current density in the superconductor at a given average current density. An optimum protection system is important in many coils. The high current density required in a microscope lens makes efficient protection particularly important.

A coil may be protected by having a cooled high-conductivity normal conductor in electrical contact with the superconductor. The coil is fully protected if the superconductor remains cool enough to be superconducting while the normal conductor carries the full current. (This is not quite sufficient.) Cooling also requires space.

The coil shown in Fig. 4 is protected by efficient cooling. With enough wires in parallel, the coil can be wound so that wires do not nest between wires of the previous layer. The result will be a coil with a large area in contact with the coolant. Also, there will be passages between the wires for circulation of the coolant.

The mutual inductance between conductors of the coil shown in Fig. 4 is very high. This will be particularly true if each wire has a nonintegral number of turns per layer. This helps the conductors to protect each other. If this is sufficient the coil might be wound with alternate wires of normal and superconducting material in each layer. This would improve the cooling of the superconductor and would make it possible to choose a superior normal conductor. Also, the problem of obtaining accurate wire sizes would be simplified. A circuit that takes advantage of this mutual inductance is shown in Fig. 6.

Design of the Conductor

The best way to check conductor designs is to wind test coils. Since a relatively small amount of superconductor is required for a lens coil, this may be satisfactory. However, indirect tests may be useful.

A conductor can be tested by measuring the temperature at the position of the superconductor while the normal part of the conductor is carrying the full current. The current-carrying capacity of superconductor can be used as a thermometer. For this purpose, it must be insulated from the normal conductor under test, as illustrated in Fig. 7. This sample must be placed in an environment similar to that in the proposed coil when it is tested.

A good electrical bond between the normal and superconductor is advantageous. This can be tested as shown in Fig. 8.

Quadrupole Lens Properties

PETER W. HAWKES

University of Cambridge
Cambridge, England

A. Definitions

A quadrupole system is, in general, astigmatic or anamorphic. In an astigmatic system, a point object is imaged as two perpendicular line images lying in separate z -planes. In an anamorphic system, rays leaving the object point in the converging and diverging planes with the same slopes emerge from the system with different slopes.

The system may be designed to be stigmatic (or "double-focused") for one pair of conjugate (object and image) planes in which case it is called "pseudo-stigmatic." The magnifications may be (simultaneously) equal, in which case it is said to be "orthomorphic."

A quadrupole lens system is said to be *equivalent to a round lens* if it produces a stigmatic and orthomorphic image for all pairs of conjugate (object and image) planes (without any changes of excitation or spacing). Even when this is the case, it may not be possible to design the system so that a real object produces a real image if the number of quadrupoles is too small, or if the excitations and geometry are badly chosen.

B. Properties of Individual Systems (summarized in Table I)

1. The Single Quadrupole

The single quadrupole is suitable only for producing a line image. It is divergent in one plane, convergent in the other.

2. The Symmetrical Doublet

The focal lengths are always equal in the converging and diverging planes. (This is true of all systems consisting of an even number of quadrupoles possessing mirror symmetry about the center plane, except that the second half of the system is rotated through 90° with respect to the first half.)

For each quadrupole separation, an excitation can be found such that the doublet is equivalent to a round lens, but in this situation, a real object can *never* produce a real image. Such a doublet is only useful as a projective lens, or as one stage of a multiple condenser

system. Even here, it seems to be of limited promise as it is very inflexible.

3. The Symmetrical Triplet

The symmetrical triplet does not automatically have equal focal lengths in the two planes, since it can obviously never have mirror symmetry about the center plane plus 90° rotation. Probably a symmetrical triplet can not be designed to produce a real image of a real object; therefore, it would not be suitable as an objective lens.

It is difficult to see how the excitations and spacing could be selected to make such a triplet strong and, given all the alignment problems associated with quadrupoles, there might well be little to be gained by using a quadrupole system with such inherent optical shortcomings.

An unsymmetrical triplet does not suffer from so many defects; this lens-combination might well be suitable for a projector lens.

4. The Two Types of Symmetrical Quadruplet

a. *Mirror Symmetry Alone.* The symmetric triplet is a degenerate case of the symmetric quadruplet, and the latter seems to suffer from the same drawbacks as the former. No system producing a real image of a real object is known (despite fairly extensive calculation by D. Dhucq), and since the two central lenses have the same diverging plane and the same converging plane, the problem of designing a strong lens will again be hard to solve.

b. *Mirror Symmetry Plus 90° Rotation of the Second Half of the System.* The focal lengths of such systems are automatically equal. The requirement that the foci coincide can be satisfied for ranges of geometries and excitations, and solutions are known for which the focal length is very short and the focus lies outside the system.

C. Requirements for the Various Kinds of Lenses

NOTE: I assume that any quadrupole system will be required to provide the same imagery as a round

TABLE I. PROPERTIES OF VARIOUS LENS SYSTEMS

System	Stigmatic	Orthomorphic	Real Image Real Object	Comments
Single quadrupole	Never	Never	One real line image	—
Symmetrical doublet	Yes	Yes	No	Very inflexible; conditions very restrictive.
Unsymmetrical doublet	Yes	Yes		Correction difficult; no good systems known.
Symmetrical triplet	Yes	Yes	No	Weak.
Unsymmetrical triplet	Yes	Yes	—	Correction now easier; could provide a good projective or second condenser. Not suitable as objective.
Mirror symmetry quadruplet	Yes	Yes	No (?)	Similar to symmetrical triplet.
Quadruplet with mirror symmetry +90° rotation	Yes	Yes	Yes	Good correction possibilities; focal lengths automatically equal; very short focal lengths possible; aberrations seem to be high.
Unsymmetrical quadruplet	Yes	Yes	Yes	As preceding quadruplet; it should now be possible to choose a system with low aberrations at the sacrifice of automatic equality of focal lengths.

lens, and hence that its foci must coincide and its focal lengths must be equal. (This requirement is arguable. It would certainly be convenient if it were fulfilled, but it is by no means obvious that there is nothing to be gained by abandoning it.)

1. Condenser

The condenser must be strong and employ a virtual object; a real image is only acceptable if this is one stage of a multiple-condenser system. (This could perhaps be convenient for modes of microscope operation where the aberrations need to be corrected at this level.) Possible quadrupole systems are: doublet (inflexible), triplet (possible but is strength compatible with tolerable aberrations?), and quadruplet (fulfills all requirements and provides good possibilities for correction—good sites for octupoles—but strength and quality are not easy to obtain simultaneously).

2. Objective lens

Aperture (i.e., spherical) aberrations matter most in the objective lens. If quadrupoles are to be used, they will have to be very well corrected for aberrations, and this requires three octupoles to be built into the lens. A triplet is the simplest of the possible systems, but no satisfactory triplet has yet been discovered. Furthermore, the task of correcting the aperture aberrations of a triplet is liable to be exacting. A quadruplet has the advantage of equal focal lengths, and the symmetry ought to make correction simpler. However, alignment and accurate assembly will be crucial in this lens and this could militate in favor of systems of fewer lenses.

3. Projector lens

Aperture aberrations scarcely matter. A triplet is now a workable system, since the object can be virtual and correction limitations matter less.

Quadrupole-Octupole Correction System

J. H. M. DELTRAP

*Aerojet Corporation
Plainview, L.I., New York*

I. Introduction

The possibility of correcting the spherical aberration of a round lens by means of a quadrupole-octupole system has been considered. A preliminary design of such a system will be presented here.

Studies of quadrupole objectives so far did not result in systems comparable to a round objective lens as regards third-order spherical aberration. The number of possible systems has not yet been exhausted. Nevertheless, it seems opportune to investigate the combination of a good round objective lens of conventional design with a quadrupole-octupole arrangement.

Because of the rather drastic departures from normal imagery associated with the use of quadrupoles, they may be better employed as elements facilitating correction. It has, in fact, already been demonstrated that the third-order spherical aberration of a round lens can be corrected by means of a quadrupole-octupole arrangement.¹⁻³ The question of its usefulness depends on the magnitude of the parasitic aberrations, which are inevitably present because of inaccuracies in construction and alignment.

A correction system can, in principle, be designed with any round lens one cares to choose. However, in order to have some definite data available, the Tadano lenses⁴ have been chosen as examples, and his line of thought was followed to obtain other designs.

Tadano gives explicitly the parameters for a 3 MeV and a 5 MeV conventional objective lens. Other lenses follow directly from the data he collected. In Table I the characteristics of 1, 2, 3, and 5 MeV are presented.

Lenses optimized for 5 MeV become rather unmanageable, and it is of interest to investigate the properties of 1, 2, and 3 MeV lenses used with a 5 MeV beam. In Table II the performance characteristics of the 1, 2, and 3 MeV lenses described above are given when used with a 5 MeV beam. Clearly, the lens performance is degraded when employed in this manner. However, it turns out that the 3 MeV lens used at 5 MeV has approximately the same characteristics as the heavier lens designed for 5 MeV. The latter does not seem to be optimized and, indeed, Tadano only claims a zero-order estimation.

In order to use the smaller, lighter lenses at the full

beam potential of 5 MeV, they have to be corrected. For the spherical aberration this can be accomplished by a combination of quadrupole and octupole elements. Chromatic correction could be achieved with combined electrostatic and magnetic quadrupoles. This, however, will not be considered here. Another factor that may become disadvantageous is the increased focal length, but this, too, may be remedied with a quadrupole system.

Consider the 2 MeV lens, whose characteristics are not yet too discouraging even when used at 5 MeV. In Table III the performance characteristics of this 2 MeV lens are given when used at 0.5, 1, 2, 3, and 5 MeV.

II. Corrective System

To correct the aberrations, one can use the one-power telescopic system suggested by Archard.⁵ This is schematically outlined in Fig. 1. It offers the possibility of systematic correction by means of octupole elements, which could be combined with the quadrupoles. Only three octupoles are required, but one may as well give the system a modular construction and make all elements mechanically identical. The system also gives efficient correction because the octupoles at the positions 2 and 3 each affect only one of the aberration coefficients. This is not a necessary requirement, but it avoids unnecessary compensation of one octupole with another.

However, because it is a one-power telescopic system, it will not change the effective focal length of the following round lens. To accomplish this, one needs a system with a power different from one. It would be of interest to obtain an effective reduction of the focal length of the round lens by a factor three for the 5 MeV beam and a factor two for the 2 MeV beam. Two- and three-power telescopic systems that could accomplish this are outlined in Fig. 2. The separation between the quadrupoles can, in principle, be of arbitrary value. In practice one likes the system to be as short as possible, and the separation will be determined by the physical size of the coils. Because the elements will be mechanically identical, the separations in the outline drawings have been kept constant for the two- and three-power

TABLE I. OPTIMUM LENSES FOR 1, 2, 3, AND 5 MeV, ACCORDING TO TADANO

	1 MeV	2 MeV	3 MeV	5 MeV
$IN/\sqrt{V^*}$	13	13	13	15
IN	10,000	32,000	45,000	85,000
Bore, mm	10	10	10	10
Gap, mm	9	16	22	40
S/D	0.9	1.6	2.2	4.0
k^2	1.1	0.58	0.35	—
f_o , mm	6	8	10	14
Z_o , mm	3	4	5	12
C_s , mm	4	7	10	20
C_c , mm	4	5	6	10

TABLE II. 1, 2, AND 3 MeV LENSES USED AT 5 MeV

	1 MeV	2 MeV	3 MeV
IN	10,000	32,000	45,000
$IN/\sqrt{V^*}$	3.8	6.8	9.7
S/D	0.9	1.6	2.2
k^2	0.08	0.16	0.20
f_o , mm	38	17	13
Z_o , mm	35	15	10
C_s , mm	850	43	18
C_c , mm	38	14	9

TABLE III. 2 MeV LENS USED AT 0.5, 1, 2, 3, AND 5 MeV

	0.5 MeV	1 MeV	2 MeV	3 MeV	5 MeV
IN	32,000	32,000	32,000	32,000	32,000
S/D	1.6	1.6	1.6	1.6	1.6
$IN/\sqrt{V^*}$	36.5	22.5	13	9.2	6.8
k^2	3	1.9	0.58	0.27	0.16
f_o , mm	4	4.5	8	12	17
Z_o , mm	-2	-1	4	9	15
C_s , mm	1.8	2.4	7	18	43
C_c , mm	2.8	3.2	5	9	14

systems. Again, efficient correction is possible with combined elements although the line foci are no longer exactly at the center of the second and third quadrupoles.

III. Quadrupole Design

In the most effective and efficient correction system, the physical parameters of the quadrupoles are of the same order of magnitude as those of the round lens to be corrected.

We therefore choose the bore radius of the quadrupole, $a = 10$ mm, and the mechanical length $l = 20$ mm. The effective length of the quadrupole field is then approximately 30 mm. The excitation parameter is given by

$$\beta^2 = \frac{\mu_0^* NI}{a^2} \sqrt{\frac{2e}{MV^*}},$$

where s is a correction factor determined by the value of a/l . In the particular case $s \simeq 0.7$ with $V^* = 29.5$ MeV, one finds

$$\beta^2 = NI \quad (\beta \text{ in } m^{-1}).$$

The quantity determining the strength of the quadrupole is βL . As a practical maximum value, we set $\beta L = 1.5$. With $L = 30 \cdot 10^{-3}$ m, it follows that

$$\beta_{\max} = 50 \text{ m}^{-1}, \text{ or } NI_{\max} = 2500 \text{ AT per pole.}$$

The flux in two gaps of the quadrupole configuration is estimated at

$$\Phi = 2.4 \times 10^{-4} \text{ Weber, for } NI = 2500 \text{ AT.}$$

Considering a cylindrical pole with a radius of 10 mm near the tip, or a cross-section area of $3.2 \times 10^{-4} \text{ m}^2$, it follows that the flux density in the pole resulting from the flux in the gap is

$$\beta_{\text{iron}} = 0.75 \text{ Weber/m}^2 = 7500 \text{ G.}$$

Even at maximum excitation there appears to be a sufficient margin for stray flux. Nevertheless it may still be advantageous to increase the diameter of the poles with increasing distance off-axis.

Fig. 1. Archard's Telescopic Corrector

FIG. 2. Three- and Two-power Telescopic Systems (Suggested by J. H. M. Deltrap, July 9, 1966).

A preliminary design for a 5 MeV quadrupole based on the above considerations is shown in Fig. 3.

In order to decrease the overall length of the corrector system, it is desirable to combine the quadrupole elements with octupoles. This also reduces the alignment problems and provides a modular approach. For proper action the poles of the octupole are rotated 22.5° with respect to the poles of the quadrupole. Thus, to combine quadrupole and octupole, one pole of the quadrupole configuration should be formed by two adjacent poles of the octupole configuration. If the pole tips are made mechanically symmetrical as in Fig. 3, the effective "pole" of the quadrupole configuration becomes concave near the tip rather than convex as is desired. It has been verified, however,³ that this does not influence the third-order aberrations as long as the proper symmetries are maintained, but it does increase significantly the fifth-order aberrations. In an electron microscope, fifth-order aberrations are not of great concern, but excessively large values should be avoided if third-order correction is to have any effect. Shaping the poles in pairs has the desired effect of reducing fifth-order aberration (see Fig. 4).

The same quadrupole strength as in the simple quadrupole is obtained with eight coils of 1250 AT. The required octupole strength depends very critically on the focal length of the lens to be corrected. In an efficient corrector system, however, the number of ampere-turns for the octupole should not exceed that of the quadrupole. In the preliminary design of a quadrupole-octupole combination, we have chosen a total of 2500 AT per pole, 1250 AT for the quadrupole configuration, and 1250 AT for the octupole configuration. In practice, it is convenient to divide each coil in two so that the quadrupole coils can be connected together and the octupole coils can be combined. The quadrupole and octupole can then be independently

FIG. 3. 5 MeV Quadrupole (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 4. 5 MeV Quadrupole-Octupole Combination (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 5. Quadrupole-Octupole Corrector (Suggested by J. H. M. Deltrap, July 9, 1966).

adjusted and regulated. The combined element is outlined in Fig. 4.

The power per coil = 11 watts maximum.

The power per element = 88 watts maximum.

The weight of one element = 80 lb.

The outer diameter of the coils = 80 mm.

The minimum separation between elements therefore is 80 mm from center to center. With an effective length of the field of 30 mm, it follows that the "drift space" between elements equals 50 mm. An outline of a four-element corrector is presented in Fig. 5.

IV. Aperture Aberrations of the Corrector

To determine the aberrations of the system, one first needs to solve the first-order equations for a realistic model. The rectangular model was chosen. The overall

configuration is shown in Fig. 6. The round lens is introduced as a first-order matrix effective at the position indicated. This position is not critical because the beam emerging from the corrector system is collimated in a first-order approximation. The set-up shown in Fig. 6 was subjected to a computer treatment guided by Meads' ⁶ program. The desired matrices of the correctors are

	QUAD	QUAD	QUAD	QUAD	ROUND LENS

	30mm	50mm				
2 POWER SYSTEM	.923	.820	.758	.704	6.7	3.35
3 POWER SYSTEM	1.05	.845	.750	.679	20.0	6.7
	βL	βL	βL	βL	$f_o(\text{mm})$ ROUND LENS	$f_o(\text{mm})$ TOTAL SYSTEM

FIG. 6. Telescopic Corrector Systems Used with Round Lens (Suggested by J. H. M. Deltrap, July 9, 1966).

FIG. 7. CRT Picture Showing Result of Combining 2 x System with Round Lens of 7 mm.

FIG. 8. CRT Picture Showing Result of Combining 3 x System with Round Lens of 20 mm.

$$\begin{pmatrix} -2 & x \\ 0 & -1/2 \end{pmatrix} \text{ and } \begin{pmatrix} -3 & x \\ 0 & -1/3 \end{pmatrix} \text{ in both planes,}$$

and the computer achieved this without difficulty. The resulting excitations are:

	βL_1	βL_2	βL_3	βL_4
2 x system	0.923	0.0820	0.758	0.704
3 x system	1.05	0.845	0.750	0.679

Clearly, the required values of βL are significantly lower than the maximum value allowed for in the design of the quadrupoles.

Combining the 2 x system with a round lens of 7 mm reduces this to 3.5 mm. The first-order trajectories are shown in Fig. 7 (taken off CRT). Similarly, the combination of the 3 x system and a round lens of 20-mm focal length is shown in Fig. 8.

Thanks to Meads' program, the computer proceeded to calculate the quadrupole aberrations at the image plane of the aberration-free lens. The following results were obtained.

	C/f	C_{zzz}	C/f	C_{yyy}	C/f	$C_{zyy} = C_{yzz}$
2 x System	6.4×10^{-2} $f = 3.35 \text{ mm}$	0.21 mm	2.6×10^{-2}	0.087 mm	3.6×10^{-2}	0.12 mm
3 x System	2.1 $f = 6.7 \text{ mm}$	14 mm	0.57	3.8 mm	0.99	6.7 mm

The largest quadrupole aberration coefficient referred to the image plane of the round lens in the 3 x system is 14 mm. This system is intended to be used with the 2 MeV lens at 5 MeV (see Table III) which has a $C_s = 43$ mm. Thus the quadrupole system aberration is approximately one-third of the C_s of the round lens. This is the right order of magnitude. If the quadrupole aberration is large compared to C_s , the non-inherent aberrations will become large as well, and correction of the inherent aberrations does little good. If the quadrupole aberrations are too small, very strong octupoles—compared with the strength of the quadrupoles—have to be used to correct the round lens. It seems that the present 3 x system will provide the right compromise at 5 MeV.

The 2 x system is intended for use with the same round lens at 2 MeV. The C_s is then equal to 7 mm, which is rather large compared with the maximum aberration of the quadrupole system, namely, 0.21 mm. This will involve strong octupoles. However, one is working here at 2 MeV, and the elements are designed for 5 MeV. A considerable margin exists, therefore, in this case.

V. Tolerances

Tolerances required in the construction and alignment of quadrupoles have been studied⁷ but not very extensively. In Ref. 3, relatives between the noninherent or additional aberration coefficient and deviations from the ideal symmetry are given for simple elements. For given parameters the ratio of the maximum additional over the inherent aberrations can be determined. Summary experimental and computational evidence suggests that the same ratio may be used as a guide to determine tolerances in compound systems. However, this is by no means conclusive. Nevertheless, let us make use of this.

The quadrupoles are excited such that their focal length is between L and $2L$. We then have for the additional second-order aberrations,³

$$\frac{C_{(2)} a^2 f}{C_q L^2 \delta} = 3 - 10,$$

and for the additional third-order aberrations,

$$\frac{C_{(3)} a^3}{C_q L^2 \delta} = 6 - 18,$$

where C is the inherent aberration to be corrected, $C_{(2)}$

and $C_{(3)}$ are the additional aberration coefficients of second and third order, respectively, f = typical focal length of an element, q = correction factor = 0.3, and δ is the deviation from ideal symmetry.

Substituting the relevant values, we find

$$\frac{C_{(2)}}{C} \approx 0.3 \delta \text{ and } \frac{C_{(3)}}{C} \approx 3 \delta \text{ } (\delta \text{ in mm}).$$

Now, in order to achieve improvements in resolution of a factor 2-3 when C , the inherent aberration, is corrected, it is required that

$$\frac{C_{(2)}}{C} \approx 10^{-3} \text{ and } \frac{C_{(3)}}{C} \approx 10^{-2}$$

before correction.

Thus it follows that $\delta \approx 3\mu$.

This will insure that the second- and third-order additional aberrations do not destroy the effect of corrected inherent aberrations. Not considered here is the additional 1° order astigmatism due to misalignment of the quadrupoles. This requires extremely severe tolerances. However, the effect is easily compensated with a stigmator, which is normally incorporated any way in a good round lens.

VI. Conclusions

Whenever electromagnetic aberration can be disregarded, it is believed that, with the above correction system, one lens optimized for some intermediate beam potential can be used over the complete range from 0.5 to 5 MeV; a performance can then be achieved that is at least as good as can be obtained with different lenses for each beam potential and is conceivably better because there is little doubt that C_s can be corrected in this way. But to have full benefit of this correction, stringent tolerances in construction and adjustment have to be met.

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General Comments on the AMU-ANL Electron Microscope Workshop Lens-Design Considerations

DAVID COHEN

*University of Illinois, Chicago Circle
Chicago, Illinois*

AND

CHARLES LAVERICK

*Argonne National Laboratory
Argonne, Illinois*

A 3 or 5 MeV electron microscope offers the theoretical possibility of resolving distances less than $0.5 \text{ \AA}$ so that each atom will separately become visible and new fields of research will be opened. The instrument requires the highest stability of accelerating voltage that can be attained and magnetic lenses of improved design. Considerable development is necessary to attain the desirable $\Delta V/V = 3 \times 10^{-6}$, but it would appear to be worthwhile attempting to make a significant breakthrough in high-voltage design by working towards $\Delta V/V = 10^{-7}$. The variation in theoretically attainable resolution with accelerating voltage stability is shown in Fig. 1 for various magnitudes of lens fields. This would indicate that resolutions less than $1 \text{ \AA}$ can be attained at 20 kG. In fact, higher-field lenses will improve both contrast and resolution and are desirable. This would improve the actual resolution by lowering chromatic aberrations. Short focal-length lenses are essential in a high-voltage instrument to reduce aberrations to a minimum. This necessitates high field, short half-length, conventional lenses.

The lens-design group considered conventional cylindrical lenses, super-conducting cylindrical lenses, and many types of quadrupole-octupole systems.

Cylindrical lenses have been used almost completely in electron microscopes since the first development of the instrument. They are less sophisticated and less efficient than the other possible candidates. They utilize second-order focusing as the beam paths, and field lines are roughly parallel. Such lenses are still the best currently available, as they have been improved continually for the instruments over about 30 years.

The newer systems offer far greater potential and should be developed as soon as possible. These include the application of superconductors to lens-design problems, and the development of high-quality multiple-pole systems.

Information on the best currently available lens

systems and on recent new lens developments was assembled before possibilities for the new instrument were considered. Objective lenses were considered in greatest detail since they are the most difficult lenses to design. Projector and condenser systems are simpler to design, and the design ideas developed for objectives can be used.

Some important criteria in magnetic lens design are as follows:

1. Lens aberrations must be reduced as much as possible.
2. The highest degree of stability in magnet current should be attained.

The maximum attainable magnetic field should be used for cylindrical lenses with the field very contained.

Sophisticated beam-transport systems have been developed for high-energy physics studies, and, in particular, quadrupole and other multipole lenses have been developed. These have significant advantages in focusing charged particle beams since they utilize first-order focusing in which the field lines act directly on the particles as the beam paths and field lines are mutually perpendicular.

It is now obvious, from the studies that have been carried out, that many promising multipole systems can be developed for use in electron microscopes.

Some typical lens designs of each type were formulated and compared (Table I) to assist the Workshop in its deliberations. A good quadrupole system, a possible superconducting lens system, and a good conventional system were considered. No recommendations were made at the meeting as to which avenues should be pursued, but it is obvious that parallel developments of multipole systems and superconducting systems should be pursued simultaneously and energetically because of their potential value in all beam-transport technology as well as in the present high-voltage instrument design.

FIG. 1. Theoretical Resolution vs Accelerating Voltage for Various Voltage Stabilities.

TABLE I. COMPARISON OF 5 MEV OBJECTIVE-LENS SYSTEMS

Lens Type	Conventional (Tadano)	Superconducting (Tadano-Kitamura)	Quadrupoles (good quadruplet)
Outer diameter, in.	50	8	6
Length, in.	25	5	8
Weight, lb.	8,000	100	200
Power, watts	18,000	15,000 (including cryo)	500
Focal lengths	1.4	< 1.0	0.5-8.0
C_s , cm	2.0	0.3	~160
Resolution, Å	1.2	0.8	3.6 (no corrector) < 1.0 (with corrector)
Tolerances	Lax	?	Tight
Engineering problems	OK	Development Necessary	OK except tolerance
Feasibility	Probable to certain	Probable	Probable

FIG. 2. A 3 MeV Conventional Lens Design due to B. Tadano

FIG. 3. A Superconducting Lens System Used by H. Fernandez-Moran

A typical 3 MeV conventional lens design due to B. Tadano, from Hitachi, is shown in Fig. 2. Some possibilities for superconducting lens design were considered but these require further study. Superconductors reduce the size of conventional magnets since they can be operated at average current densities of the order of 5×10^4 A/cm², as opposed to the 100 A/cm² used in the copper windings of conventional lenses. A possible arrangement of a superconducting lens system in a microscope is that (Fig. 3) used by H. Fernandez-Moran, Department of Biophysics, The University of Chicago, in recent studies. While the resolution is not

yet as good as that attainable with conventional lenses, resolutions of between 10 and 20 Å have been obtained, and the unique long-term stability of the system has been demonstrated. The advantages of superconductors in electron microscopy have, therefore, been clearly demonstrated.

Superconductors are not of great value with multipole systems since high magnetic fields are not required with first-order focusing. Consequently, the development of satisfactory multipole systems would eliminate the need for superconducting systems.

General Construction—A Dissenting Opinion

L. L. MARTON

*National Bureau of Standards
Washington, D.C.*

Consensus appears to be crystallizing toward constructional guidelines that are ultraconservative and do not even offer the advantage of being economical. I would like to limit my remarks to aspects such as: a) flexibility of the column (easy replacement of components); b) shielding (radiation and magnetic); c) remote control and operation; and d) general arrangement (vertical or horizontal).

A. Flexibility

Agreement is unanimous that the optical components should be easily exchangeable, substituting for each other with a minimum of work and loss of time. This implies facilities for handling large and cumbersome components, means for easily disconnecting and connecting the electrical and cooling junctions, and means for rapid and exact alignment of the newly installed components. To my mind the best solution is divorcing the shielding problems from other problems and relying on remote control means for *all* the operations connected with the manipulation of the instrument. This requires a common vacuum chamber, easily accessible, with a sufficient number of large ports for installation of the components. The way I visualize it, the main vacuum chamber may resemble an outsize and odd-shaped refrigerator with many access ports. Opposite the access ports and protruding through the walls are the fixed installations, such as electrical and cooling connections, hydraulic centering means, means for exchanging apertures, etc.

B. Shielding

Radiation shielding is best achieved by light construction of the instrument for accessibility and housing it in a concrete building with at least 8-inch walls. Coating of the walls with magnetically shielding materials is cheaper than a solid-steel enclosure for the optical parts. (Question: efficiency of magnetic shielding.)

C. Remote Control and Operation

Hydraulic means for remote control have been tried successfully. The argument that a hydraulic system is not compatible with bake-out or with cryogenic operations is not valid. The hydraulic means can be kept outside the vacuum enclosure, and motion can be transmitted via rigid members passing through bellows.

Hydraulic means can be used for: 1) aligning of optical components; 2) stage motion; 3) specimen insertion; 4) aperture insertion; 5) exchange of burned-out filaments from a filament bank; 6) operation of any moving parts inside the instrument, such as shutters, fluorescent screens, variable slits or apertures, etc.

D. General Arrangement

I would like to put in a word in favor of horizontal mounting. The argument that gravity helps in the vertical column is sufficiently contradicted by the prevailing trend in building linear accelerators. The same kind of problems in alignment are met successfully in their construction. The advantage of horizontal arrangement is more easy accessibility to the components for servicing and replacement.

It is proposed, therefore, to mount the microscope on top of a large horizontal baseplate, through which all the supports, connections, etc., reach the components. The lens supports can consist of two plates at a 90° angle to each other and 45° angles to the baseplate. These lens-supporting plates are at the upper end of two rods, passing through the base with bellows providing the vacuum-tight enclosure, forming the upper arms of hydraulic jacks. The dimensions of the plates, rods, and jacks depend on the dimensions and weights of the components they are supporting. Since the two plates are at 90°, they form a cradle in which the components rest (with gravity helping). The jacks provide *x-y* motion for alignment.

Similarly, all other means for alignment or motion, together with electrical and cooling connections, can be brought in through the baseplate. All vacuum pumps can be attached to the bottom of the baseplate, where service is easily available. The vacuum enclosure is an oversized bell jar, which is lifted for servicing and dropped in place and bolted to the baseplate for operation.

The baseplate is mounted on legs of sufficient length above a large concrete block. This concrete block, which (through the hydraulic jacks) is the main support of the microscope column, can be anchored relatively deep and be independent of the surrounding housing of the instrument. Flexing of such a large block is extremely unlikely and can thus be neglected. The independent anchoring shall help eliminate mechanical vibrations.

Enhancement of Photography of High-Voltage Electrons

H. HASHIMOTO

*Kyoto Technical University
Kyoto, Japan*

When ordinary photographic film is exposed to 100 keV electrons, the darkening starts from the surface of the emulsion during developing. But film exposed to electrons accelerated by voltages higher than 300 keV shows that darkening starts from the back of the emulsion when it is developed. This phenomenon can be explained by the high penetration power of high-energy electrons.

Improvement of the sensitivity of photographic film to high-energy electrons can be achieved by the following methods.

1. Using Fluorescence

As is shown by Dr. Gilroy's report of my observations, fluorescence of emulsion and substrate film play an important role in the sensitivity of the film.

The fluorescent wavelength of polyester base is about $\lambda = 3500 \text{ \AA}$, and the wavelength will not change with the energy of irradiating electrons. A fluorescence material can be included in the emulsion, as for instance, by dyeing the emulsion with an alcoholic solution of *p*-amino benzoic acid.

Using fluorescent basal film as well as fluorescent emulsion may be useful.

2. Using an Emulsion Containing Heavy Atoms, Such as Lead

Since the emulsion of X-ray film contains lead bromide, use of such emulsion seems advisable. JEM will

send me the X-ray film that was exposed to 1 MeV electrons in the 1 MeV electron microscope.

Prof. Mitchell suggests that using lead bromide in the emulsion will lower the sensitivity to light but increase the sensitivity to X-ray and high-energy particles. He also suggested thallous bromide as being effective for increasing the sensitivity, but it decreases the contrast and the image tends to appear foggy.

3. Coating the Surface of Emulsion by a Layer of Heavy Atoms

According to the suggestions of Prof. T. Mitchell of the University of Virginia [J. Phys. Chem. **66**, 2359 (1962); J. Photograph Science **6**, 57 (1958); and Report on Progress in Physics **20**, 433, (1957)] it is easy to deposit chemically a thin layer of gold particles. Such a layer will increase the photographic effect of high-speed electrons.

4. Using Auger Process (Multiple Ionization)

The krypton¹⁹ atom has anomalous Auger effects, and may be included in the emulsion to increase the ionization process. Since the Fuji-Film Co. is producing special photographic plates for the electron-microscopic studies, I think we can ask Dr. Mizuki of Fuji Co. to make special photographic plates that are sensitive to high-energy electrons, or we may be able to make a special emulsion that contains lead bromide, fluorescent compounds, and heavy atoms with Auger effect.

Digital-Computer Applications to Electron Microscopy

JAMES W. BUTLER

Argonne National Laboratory

Computers can accelerate progress in the design and application of electron microscopes in a number of ways.

1. The time required for the design process itself may be greatly reduced.
2. The time required for setting up and aligning may be reduced by supplying data for assistance in construction and adjustment.
3. Computer techniques can be used effectively to control and monitor operation.
4. Exciting new vistas are opened up by the prospective use of computer methods to interpret the large amounts of data produced. This is especially true of the scanning microscope, since it produces information serially in time and is therefore ideally adapted for quantitative work.

Techniques 1 and 2 are now well understood and in some routine use. There has been a time lag in applying computer-design methods to electron microscopes, presumably because satisfactory commercial instruments were being produced using traditional methods. The achievement of substantial improvements in performance will require the use of computer design, and the aforementioned gap is rapidly being closed.

It is a reasonably straightforward task to implement a digital scanning and data output system. As far as I know, this has not been done, and I believe this development would have very important consequences in the use of the scanning microscope.

There are two prongs to the subject of digital processing of pictorial data. One relates to the processing of images to aid in direct human interpretation, and the other to the derivation of quantitative information from pictorial data to support scientific hypotheses.

Image processing to aid human interpretation may be accomplished by such techniques as contrast improvement, noise reduction, and discrimination. For example, these methods were used very successfully by NASA engineers in processing the Ranger (Moon) and Mariner IV (Mars) television images. It is possible that such techniques will be easier to apply to the microscope, since it may be feasible to combine the results of multiple scans.

The conversion of pictorial information into numerical forms permits the application of statistical methods for parameter estimation and hypothesis testing. This

is equally important for scientific progress, since it is by statistical methods that a tentative scientific conclusion can be verified and supported. Examples in this area are the automatic processing of spark and bubble-chamber photographs and of chromosome images. I am not familiar enough with electron microscopy to be more specific about this application, but I am certain that many quantitative results are theoretically deducible from sufficiently accurate and numerous measurements on electron micrographs.

The digital scanning and image processing system could be modeled closely after the existing CHLOE system [Robert Clark and W. F. Miller, "Computer Based Data Analysis Systems," *Methods in Computational Physics* **5**, 47-98 (Academic Press, 1966)], although modifications will be necessary because of the extremely high resolution of the microscope.

Two features of this machine are a coordinate representation of the picture to effect data compression, and scanning voltages derived from digital-to-analog converters driven by digital counters.

Use of coordinate representation in scanning presupposes that pictorial information is being abstracted from the viewing field. This principle is well known to television engineers and is, in essence, the same as the "associative" data-storage technique used in multiparameter analyzers. In the CHLOE machine, the principle is implemented by transmitting information to the computer memory only when the light transmission observed at two adjacent points in the viewing field (film) differs in a specified manner. For reasonable pictures, this results in data-compression factors of 1,000 to 10,000 over allocating one memory cell for each picture element. Larger compression factors can be obtained by modifying the hardware to reflect additional *a priori* knowledge about the kind of measurements to be made.

A few rough calculations will illustrate these points and other general features of the scanning microscope. If the beam were deflected over a square $\frac{1}{4}$ mm on a side, a spot size of 10 Å would lead to a raster of 250,000 or approximately 2^{18} (262,144) elements on a side. This is a very large "Field of view" and is an inconvenient (>68 billion!) number of points to be scanned in one sweep. Consequently, two deflection systems

may be necessary; a slow system to define a particular subfield to be scanned, and a fast-scanning system to develop information from that subfield. A convenient raster for the fast-scan subfield is 4096×4096 , leading to a maximum of 2^{24} points. Applying a data compression factor of 2^{10} (1024), the probable yield of data from one scan would be 2^{15} (32,768), a reasonable amount for computer processing. Allowing for overlap, the slow-scan system has to position the beam over 128×128 subfields, a low number in view of the extreme stability requirement on the slow-scan system. The implication is that $\sim 16,000$ "pictures" can be obtained from one sample, a striking illustration of the large amounts of data potentially available.

In a cathode-ray-tube scanner such as CHLOE, the ultimate limitation on scanning speed is the decay time constant of the phosphor. In the electron microscope, since there need be no conversion to light, the scanning speed is limited only by the engineering of the deflection system and the necessity of detecting enough electrons to reduce the counting error to an acceptable value. The deflection counters may conservatively run at one megacycle/second, to a scanning time of ~ 17 seconds for the subfield. This can be reduced by employing a more complex scanning strategy or by running the counters faster.

The main advantage in driving the deflection system from counters is that the scan can be made asynchronous. Areas of the specimen where no information is detected may be covered at the maximum speed, while if information is detected the counters may stop and wait until the corresponding data words have been received by the computer, the dwell time varying for sufficient electrons to be received by the detector.

Digital control of operating conditions is similar to computer control of a Van de Graaff accelerator [J. F. Whalen, R. Roge, and A. B. Smith, "A Digital Computer System for the Executive Control of a Fast Neutron Laboratory," *Nucl. Instr. Methods* **39**, 185-193 (1966)], but is probably more difficult. Assuming that the

microscope operation is governed by a finite number of "knobs," it should be straightforward to place these under computer control and to write computer programs to investigate and reset the various operating points in an appropriate sequence. As I see it, the more difficult problem is monitoring the performance of the microscope so that the computer program can tell how to adjust the "knobs." One way would be to have a standard specimen adjacent to the actual specimen. The computer program could then deflect the beam to the standard specimen and compare the observed performance with appropriate fixed indices held in memory. If this process were continuous, at any time the microscope will have automatically corrected for voltage drifts, temperature variations, etc., and will be ready for immediate use.

The cost of such a system depends on the necessary length of data words in the control computer. Specification of a coordinate on a 4096×4096 raster uses 12 bits; in a 16-bit machine (15-bit fraction + sign), three bits would be left to encode eight output levels of a single detector or the response of eight discriminators. The slow deflection system coordinates (14 bits) are listed at the beginning of each data block.

If a 16-bit data word is adequate, an IBM 1800 or equivalent would be a reasonable choice, and the control and data-processing system could be produced for \$250K, including the necessary interface equipment. A 24-bit machine, such as the ASI 6020, would add about \$40K to the system cost. If more computing capacity for data analysis directly associated with the instrument is necessary, an IBM 360 Model 44 would bring the total cost to about \$450K. Any of these machines is capable of running the control and monitoring program and processing image information on an interrupt basis.

I do not feel that it is necessary to have a powerful computer directly connected to the microscope. It is probably more economical to run the data-processing programs on other large computers.

Notes on a Survey of Digital and Related Techniques

CHARLES E. COHN

Argonne National Laboratory

Comparative present and expected data on digital devices is shown in Table I. Information on motion transducers is summarized in Table II. Figure 1 shows possible transducer usage with digital devices. A reasonably accurate theoretical model of the influence of position of elements, etc., on a microscope, combined

with digital sensors and drives, might make computer-governed alignment preferable to manual alignment. Indeed, arbitrary manipulation of a "digitized" conventional microscope might suffice to establish the necessary regime for computer alignment.

During Workshop discussions, Dr. Nixon pointed out

TABLE I. DIGITAL STORAGE DEVICES*

	Transfer Rate, Bits/sec		Capacity, Bits/file		Cost, \$/bit	
	Today	1970	Today	1970	Today	1970
Flip-flops	10^6 - 10^7 (10^9)	2×10^7			0.5-10	2.5×10^{-2}
Magnetic Core	0.2 - 1×10^6	0.2 - 10×10^6 (words)	2 - 64×10^3 (words)	1 - 20×10^5 (words)	5 - 5×10^2	0.2 - 3×10^{-2}
Magnetic Tape	10^5 - 10^6	2×10^6	0.03 - 0.16×10^9	0.3×10^9	10^{-4} - 10^{-3}	10^{-5} - 10^{-4}
Magnetic Discs (Access times ~ 10 - 100 ms)		5×10^6	0.02 - 1.2×10^9	0.3 - 6.0×10^9		

* L. C. Hobbs, Impact of Hardware in the 1970's, Datamation 12(3), 36 (March 1966).

TABLE II. SUMMARY OF INFORMATION IN AVAILABLE TRANSDUCERS

1. INPUT TRANSDUCERS—ELECTRICAL

Instant-sampling A-D Converters

Resolution to 1 part in 10^5

Conversion Time 10^{-6} -1 sec.

Voltage-to-Frequency Converters

Range 0-0.1 or 0-1 volt

Max. frequency 10^4 - 10^6 /sec.

Linearity error 0.01% full scale

Stability 0.01% full scale/day

Temperature drift 0.001% reading/ $^{\circ}\text{C}$

2. INPUT TRANSDUCERS—MECHANICAL

Digital	Cm/bit, min.	Usual Form
Brush-Contact	0.1	Rotary
Optical	5×10^{-5}	Rotary
Magnetic		
Laser interferometer	1.5×10^{-6}	Linear

Analog

Potentiometer		Either
Differential transformer	10^{-4} (30-cm travel)	Linear

3. OUTPUT TRANSDUCERS—MECHANICAL

Stepping motors

200 steps/revolution, 10^2 - 10^3 steps/second

Torque $\sim 10^7$ dyne-cm

Step error 3% nonaccumulative

a. DIRECT

b. INDIRECT

Fig. 1. Suggested Transducer Usages

that magnetic-beam alignment (rather than mechanical movement of lens and apertures) might be preferable, and could readily be adapted to digital control. Also, digital control of specimen dosage might be advisable, particularly for radiation damage studies.

Similarly, Dr. Gilroy reported that a digital scanning system was developed for the CSEEAM, without substantially greater effort than the ramp function system. It has not yet been used.

Threshold Sensitivity of Television Camera Tubes

CHARLES E. COHN

Argonne National Laboratory

If the sensitivity of TV camera tubes, as limited by internally generated noise, is calculated in terms of incident photons required for a given signal-to-noise ratio, the light output needed for a scintillator may be estimated, and the need for image intensification may be evaluated.

It is desirable for the viewing system to be able to record individual electrons; i.e., the image of a single electron should be visible over the system noise. Just how far above system noise need the signal from an individual electron be? This can be answered in terms of the inherent noise component resulting from the randomness of the arrival of electrons. The response to a single electron need only be sufficient to make the electron shot noise predominate over the system noise. Since the two noise components are uncorrelated, they add in quadrature, so that the effect of the smaller of the two components is weakened. If the rms level of the system noise is one-half that of the electron shot noise, then the rms amplitude of the overall noise will be only 12% greater than if the system noise were completely absent. This ratio of the two noise components appears to be a reasonable figure for system design.

Noise generation in camera tubes has been analytically treated by E. G. Ramberg [A Theoretical Analysis of the Operation of Flying Spot and Camera Tube Microscopes in the Ultraviolet, IRE Trans. on Med. Elec., *PGME-12*, 58 (1958)]. For the image orthicon, his formula for the signal current (referred to the multiplier input) may be written

$$i_e = N_e QMT (\delta - 1) qe,$$

where N_e is the mean number of electrons incident per picture element per scan, Q the number of light quanta received at the photocathode per incident electron (noise due to fluctuations in Q is neglected), M the number of picture elements scanned per second, T the transmission of the target screen, δ the secondary-emission ratio for photoelectrons landing on the target, q the quantum efficiency of the photocathode, and e is the electron charge. The signal-current noise-component rms amplitude due to the electron shot noise is given by

$$\sqrt{i_e^2} = \sqrt{N_e} QMT (\delta - 1) qe.$$

Ramberg's formula for the rms amplitude of the system

noise (referred to the signal current) may be written

$$\sqrt{i_s^2} = 3.54 Me \sqrt{N_e QT (\delta - 1) q}.$$

Ramberg assumes that the scanning beam current is adjusted so that 20% of the incident beam is deposited on the target in areas with illumination N_e .

The ratio between the electron shot noise and system noise amplitudes is then

$$R = \frac{\sqrt{i_e^2}}{\sqrt{i_s^2}} = 0.282 \sqrt{QT (\delta - 1) p}.$$

(Note that this is independent of N_e and M .) Ramberg suggests values of 0.65 for T , 4 for δ , and 0.2 for q . For a minimum R of 2, the minimum Q becomes 129 photons. A variant of this tube, known as the isocon [A. Cope and E. Luedicke, "Camera Tubes for Recording Stratoscope II Telescope Images," RCA Review, Vol. 27, 41 (March 1966)], might allow a smaller Q . For the vidicon, Ramberg points out that the noise originating in the tube itself is overshadowed by the noise generated in the first video-amplifier stage. He assumes that the target load resistor is made greater than 100,000 ohms so that its thermal-noise contribution will be negligible, and that the resulting high-frequency attenuation due to shunt capacitance is compensated in the video amplifier, with the overall bandwidth made commensurate with the value of M .

At the output of the video amplifier, the signal voltage will be

$$\bar{V}_e = BN_e QM qe,$$

where B is the ratio of voltage out to current in for the video amplifier at low frequencies. The rms amplitude of the electron shot noise at this point is then

$$\sqrt{v_e^2} = B \sqrt{N_e} QM qe.$$

The system-noise amplitude at that point is given by

$$\sqrt{v_s^2} = 2.485 BC \sqrt{kt R_t M^3},$$

where k is Boltzmann's constant, t the absolute temperature, R_t the equivalent noise resistance of the amplifier, and C the total shunt capacitance of the vidicon output circuit. The ratio between the two noise components is then

$$R = \frac{\sqrt{v_e^2}}{\sqrt{v_s^2}} = 0.401 \frac{Qqe}{C} \sqrt{\frac{N_e}{ktR_iM}}$$

Ramberg recommends values of 18.5×10^{-12} farads for C , 103 ohms for R_i , 1 for q , $kt = 4 \times 10^{-21}$ joules, and $e = 1.6 \times 10^{-19}$ coulombs. Also, assume $N_e = 1$ and $M = 1.1 \times 10^7$ picture elements/sec (broadcast TV standards). For $R = 2$, this gives $Q = 1220$ photons per electron.

Note that, unlike the image orthicon, the threshold sensitivity of the vidicon depends on N_e and M . The dependence on N_e is easily understood, since the electron shot noise is competing with the amplifier noise which is independent of the signal; and the dependence on M , since a faster scanning rate requires the system to operate at higher frequencies. (At higher frequencies, the coupling from the vidicon to the amplifier is less efficient because of the shunt capacitance, so the vidicon signal competes less effectively with the amplifier noise.)

The vidicon is less sensitive than the image orthicon by about a factor of 10 under the conditions assumed, and might be still less with practical vidicons with smaller quantum efficiencies. On the other hand, the M -dependence implies that vidicon sensitivity can be improved by slow-scan operation, for which it has been pointed out [R. E. Johnson, "Vidicon Performance Characteristics at Slow Scan Rates," RCA Review,

Vol. 27, p. 57, March 1966] that vidicons are well adapted. Standard tubes show good reciprocity for exposure times to 1 second, and optimum resolution for scanning rates of about 1 frame per second. Some "sticking" of the picture is noticeable at these rates, since it takes a few scans to remove a charge pattern completely. However, this might be eliminated by a few fast scans between each slow-scan frame, with the video signal blanked.

Another advantage of the vidicon is that tubes are available having electrostatic focus and deflection. This might reduce stray magnetic field problems.

A recent study [N. A. Talpis and D. L. Burge, "Television System Study for Nuclear Accident Recovery (Phase I)" Report IDO-10047/EGG 1183-1210, April 1966] on the expected radiation resistance of vidicon cameras indicates it is possible to build a camera that can withstand gamma-ray fields of 10^4 roentgens/hr with a total accumulated dose of 10^8 roentgens, with a fused-silica faceplate. Radiation-resistant glass could be used in the optics, but might start to darken after 10^5 roentgens and require annealing. Active elements in the camera circuits could be limited to nuvistor tubes and high-frequency germanium diodes.

With a sufficiently effective scintillator for 5 MeV electrons, the image orthicon should not need image intensification, nor should the vidicon, if light collection is sufficiently good.

A Computer Code for Calculating the Spreading of High-Energy Electrons in Detector Materials

CHARLES E. COHN

Argonne National Laboratory

AND

J. H. ROBERTS

Northwestern University
Evanston, Illinois

A CDC-3600 FORTRAN code has been written to calculate the spreading of electron paths in various detector materials due to multiple scattering. This allows an estimate of the electron-image resolution and energy deposition in a detector of a given thickness.

The theory of multiple scattering provides means for calculating the mean-square lateral spreading distance, $\bar{y}^2$, after traversal of material of thickness t .

However, this is an overly pessimistic estimate of the spreading, since this is a maximum distance and most of the energy is deposited with less spread. Therefore, the code calculates an effective spreading diameter $\bar{D}$ by dividing the total thickness into layers.

The multiple-scattering formulation used is that of Rossi and Greisen [B. Rossi and K. Greisen, *Rev. Mod. Phys.* **13**, 240 (1941)]. Here, the mean square lateral spreading distance $\bar{y}^2$ is given by

$$\bar{y}^2 = \frac{1}{6} t^2 \bar{\theta}^2 \text{ (cm}^2\text{)},$$

where $\bar{\theta}^2$ is the mean-square total scattering angle (in radians), and t is the detector thickness in cm. The quantity $\bar{\theta}^2$ is given by

$$\bar{\theta}^2 = E_s^2 \int_0^x \frac{dx'}{p(x')^2 \beta(x')^2},$$

where x is the detector thickness measured in radiation lengths, P is the electron momentum in energy units, β is the electron velocity in units of the velocity of light, and E_s is a characteristic energy equal to 21.205 MeV. (This overestimates the multiple scattering.) [E. Segre, *Experimental Nuclear Physics* (Wiley, New York, 1953), Volume I, pp. 285-6, 292.]

To evaluate this integral, the thickness x is broken up into M layers of thickness Δx .

We assume that in each layer the energy loss and momentum loss are linear, and that β is constant over any one layer. We then have

$$\bar{\theta}^2 = E_s^2 \sum_{j=1}^M \frac{\Delta x}{\beta_j^2 P_j P_k},$$

where P is the momentum.

The code is given a value of Δx , and results are computed for all values up to a prescribed M .

If the electron kinetic energy is E_j at the front face of the layer, the code calculates

$$P_j = \sqrt{E_j(E_j + 1.02196)}$$

and

$$\beta_j = P_j / \sqrt{P_j^2 + 0.26110},$$

with all energies and momenta in MeV, and the electron mass 0.51098 MeV.

The rate of energy loss $E' = E'_{\text{ion}} (1 + R)$, where E'_{ion} is the energy loss due to ionization and R is the ratio of radiative to ionization energy loss. The ionization loss is given by [R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1955), p. 582]

$$E'_{\text{ion}} = 0.50984 \times 10^{-24} N_e$$

$$\cdot \left\{ \ln \left(\beta_j \frac{E_j + 0.51098}{I} \sqrt{\frac{E_j}{0.51098}} \right) \right\} / \beta_j^2 - 0.5 \},$$

and the radiative component is given by [R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1955), p. 610]

$$R = \bar{Z} E_0 / 817.568,$$

where N_e , $\bar{I}$, and $\bar{Z}$ are described later.

For each chemical element in the material under consideration, the code requires the atomic number Z_i , the atomic weight A_i , and a parameter K_i giving the relative number of atoms of element i in the material. (For a pure compound, K_i is a whole number equal to the multiplier in the chemical formula.) The code also requires the density ρ of the material in grams per cc.

The code calculates the number of atoms per cc, N_i , for each element, from

$$N_i = \frac{6.02472 \times 10^{23} \rho K_i}{\sum_i K_i A_i}$$

the number of electrons per cc

$$N_e = \sum_i N_i Z_i,$$

the average ionization energy (MeV),

$$\bar{I} = 1.1 \times 10^{-5} \sum_i N_i Z_i / \sum_i N_i,$$

the effective radiative atomic number,

$$\bar{Z} = \sum_i N_i Z_i^2 / \sum_i N_i Z_i,$$

and the radiation length, cm,

$$x_0 = \rho \sum_i \frac{\sum_i K_i A_i}{1.3959 \times 10^{-3} Z_i (1 + Z_i) K_i \ln (183 Z_i^{-1/3})} \cdot \frac{1}{1 + 0.12 \left(\frac{Z_i}{82} \right)^2}.$$

The code prints out for each element: input information, plus atoms/cc. For the material, it prints density, radiation length (cm), electrons/cc, and $\bar{Z}$. For each thickness it prints E_j , P_j , β_j , R , total ionization loss, total radiative loss, total energy loss, rms scattering angle, full-width final rms spread ($2\sqrt{y^2}$ in cm), and effective spread in cm.

Since this computer code was written, it was found that a more accurate estimate of the angular spread could be obtained by a direct application of the multiple scattering of Molière and Snyder and Scott. [G. Molière, *Z. Naturforsch.* **3a**, 78 (1948); W. T. Scott, *Rev. Mod. Phys.* **35**, 231 (1963).]

The Molière theory uses an angle θ_a , which depends on the screening of the atomic field. It is

$$\theta_a^2 = \left(\frac{\lambda}{0.885 a_0 Z^{-1/3}} \right)^2 (1.13 + 3.76 \alpha^2),$$

where $\lambda = \hbar/p$ for the electron. The denominator is the characteristic radius of the Fermi atom, and $\alpha = Z/137\beta$. An angle θ_1 is chosen by the statistics so that there will be many collisions with $\theta < \theta_1$ but not many with $\theta > \theta_1$. The theory then gives

$$\left(\frac{\theta_1}{\theta_a} \right)^2 = 7800 \frac{(Z+1)Z^{1/3}}{\beta^2 A (1 + 3.35 \alpha^2)} t,$$

where t is measured in grams/cm². The fraction is close to unity for fast electrons and any Z .

TABLE I. INFORMATION CALCULATED BY THE COMPUTER CODE

Primary Electron Energy: 5.0 MeV

Material	Thick- ness, cm	Ion Loss, MeV	Rad. Loss, MeV	RMS Angle, degrees	Final Spread, microns	Effec- tive Spread, Microns
Cesium Iodide	0.0050	0.028	0.0094	11.5	8.2	4.1
	0.0100	0.057	0.019	16.3	23.2	9.9
	0.0200	0.113	0.037	23.2	66.1	26.8
Zinc Sulfide	0.0050	0.319	0.0049	8.5	6.0	3.0
	0.0100	0.0637	0.0098	12.0	17.1	7.3
	0.0200	0.1273	0.0194	17.1	48.6	19.7
Cadmium Tungstate	0.0050	0.0550	0.0176	15.2	10.8	5.4
	0.0100	0.1100	0.0348	21.7	30.9	13.1
Anthracene*	0.0050	0.0122	0.0004	2.6	1.8	0.9
	0.0100	0.0243	0.0008	3.6	5.2	2.2
	0.0200	0.0486	0.0016	5.1	14.6	5.9
	0.0300	0.0729	0.0024	6.3	27.0	10.9
	0.0400	0.0972	0.0032	7.3	41.6	16.7
Nuclear Emul- sion (Ilford)	0.0050	0.0265	0.0068	9.7	6.9	3.4
	0.0100	0.0529	0.0134	13.8	19.7	8.3
	0.0200	0.1058	0.0267	19.6	56.0	22.7

* Plastic almost the same.

Molière introduces an auxiliary function B tabulated by Segre [Segre, *Experimental Nuclear Physics*, Vol. 1, pp. 287-290 (Wiley)] as a function of

$$\log_{10} \left(\frac{\theta_1}{\theta_a} \right)^2.$$

A. O. Hanson, L. H. Lanzl, E. M. Lyman, and M. B. Scott, *Phys. Rev.* **84**, 634 (1951)] give typical angular-distribution curves, and a simple formula for the angle θ_w at which the distribution function has fallen to $1/e$ of its maximum:

$$\theta_w = \theta_1 (B - 1.2)^{1/2}.$$

The Molière theory was used to estimate the spreading for cesium iodide 0.01 cm thick; θ_w was calculated as 13.4° . This compares with the rms angle of 16.3° given by the computer code.

If anything, the theory used for the computer code overestimates the spreading, but gives values sufficiently accurate for our present purpose if thicknesses such that θ is small are used (i.e., $\theta \approx \tan \theta$).

Useful information may be extracted from Table I, calculated by the computer code.

Magnetic-Tape Storage System for Scanned Images

CHARLES E. COHN

Argonne National Laboratory

When specimens may be exposed to only a limited beam current, it may be necessary to accumulate image information over several scans, and store the final result for extended viewing. This is now done with storage tubes. However, these tubes have certain disadvantages; they are expensive and easily damaged, the screen is nonuniform, and if the contrast and brightness are set correctly for the first scan, the tube will rapidly saturate as more scans are accumulated.

It is felt that these disadvantages could be eliminated by the magnetic-tape system proposed here. A simplified block diagram of the system is shown in Fig. 1. The heart of the system is a recirculating magnetic-tape loop, long enough to store the information from one complete scan. This tape carries two tracks, one with the video data, the other with a clock pulse for each picture element scanned.

As each picture element is scanned, the video information for that element accumulated from previous scans is read off the data track, added to the video signal from the current scan, and rewritten on the erased tape. The information may be continuously monitored by a picture tube scanned in synchronism with the scanning microscope.

A counter shows the number of scans completed. The count controls the settings of the two attenuators, which insure that the information recorded on the tape will be a uniform average over all scans, and that the dynamic range of the system will be fully used. They could be readjusted as more information became available by suitable control of the attenuators.

After scanning of the specimen is complete, the image can be viewed at length by disconnecting the video input, the erase heads, and the write heads. The information is then repeatedly read from the tape and displayed on the picture tube, and may be permanently recorded in a variety of ways. The information may then be cleared by erasing the tape.

Synchronization is maintained by the clock track. The clock pulses are counted in digital counters, connected to digital-to-analog converters, which produce the scanning waveforms for both the input and the

FIG. 1. Block Diagram of Magnetic-tape System

monitor. Thus the synchronization will be independent of tape-speed variations. The clock pulses are rewritten on the erased tape as they are read, in synchronism with the data. For the first scan, they could be generated by a master oscillator.

This arrangement allows accurate interlacing to assist in reducing flicker, if the number of picture elements per line is made even, and last stage of the horizontal counter is made a scale-of-two. Pulses at a rate of two per line may then be taken to the vertical counter, which counts down by an odd number. The use of interlace, plus the long-persistence phosphor, should allow a slower scan rate than for broadcast television, since the object is not moving.

The system could be used for a color display in a straightforward manner. It would require three data tracks on the tape and three data channels working into a conventional three-gun picture tube.

Proposed Experiments to Study Detection of High-Energy Electrons

CHARLES E. COHN

Argonne National Laboratory

AND

J. H. ROBERTS

*Northwestern University
Evanston, Illinois*

The problem of detecting single electrons with adequate spatial resolution in the detector of a 5 MeV electron microscope does not appear to be extremely difficult, but there are questions that should be answered through experimentation before the optimum systems can be selected. This report suggests experiments that would test the crucial points.

From our studies, it appears that a system consisting of a thin (~ 0.1 -mm) scintillator, such as cesium iodide, coupled optically to an image orthicon, would be satisfactory. One possibility is a thin mirror placed behind the scintillator and a lens placed out of the electron beam to focus an image on the photocathode of the image orthicon. This is sufficiently marginal, however, that one may need an image intensifier followed by a vidicon or image orthicon. Coupling by fiber optics offers better optical coupling, but this places the fiber optics in the electron beam. Complications resulting from this would have to be investigated. Extensive studies on such systems may lead to the conclusion that direct photography is not necessary.

Studies on the spreading of 5 MeV electrons might be undertaken as a test of Moliere's [G. Moliere, *Z. Naturforsch.* **3a**, 78 (1948); see also Segre, *Experimental Nuclear Physics*, Vol. 1, pp. 287-292 (1953)] theory for electrons in this energy range. Studies at higher energies have been made [Hanson, Lanzl, Lyman, and Scott, *Phys. Rev.* **84**, 634 (1951); Gottstein, Menon, Mulvey, O'Ceallaigh, and Rocabat, *Phil. Mag.* **42**, 708 (1951)].

A series of experiments is needed as a guide to the performance of certain elements common to most of the useful detection schemes.

A simple experiment could be done by using a β -ray and spectrometer to expose nuclear emulsion to monoenergetic 5 MeV electrons. If a collimated beam of electrons bombards a hypersensitized nuclear emulsion

[see W. H. Barkas, *Nuclear Research Emulsions*, Vol. 1, pp. 131-132 (1963)] at an angle of $\sim 30^\circ$ to the emulsion surface, the lateral displacement from the original electron path as a function of distance from the point of entry could be measured. This gives a direct measurement of the spreading. Diluted emulsion could be used to check the effect of atomic concentrations on spreading.

The source described above could be used to bombard thin scintillators (~ 0.1 mm thick) to determine the area over which light is produced. One possible method of measuring the spreading is to use a magnifying lens, thick enough to stop the electrons, forming an image of light produced in the scintillator on a photomultiplier. A diaphragm of variable size could be put over the photomultiplier, and the size of the pulse measured as a function of aperture size.

A β -ray emitter with spectrometer should again be adequate as a source of monoenergetic electrons for studying the effectiveness of obtaining images at the output of a television system of light produced in a scintillator sheet by using single electrons. Characteristics of the video signals could also be analyzed.

One also could investigate the special electronic circuits that might be useful in a television system for this application. Examples are scanning beam current control for image orthicons, fast interframe erasure scans in a slow-scan vidicon system, contrast expansion, characteristic curve modification, and optimum video bandpass. The optical aspects of the system could also be investigated.

A Van de Graaff generator producing 5 MeV electrons could be used to test the radiation damage produced in scintillators, fiber optics, and Bendix multiplier systems. Another factor to investigate is the buildup of space charge in detector materials.

Suggestions on Image Observation

WILLIAM C. NIXON

*University of Cambridge
Cambridge, England*

1. Magnified Image Observation

The fiber optic faceplate used by Burroughs and Kennedy ["Electron Microscope Camera with Fiber Optic Output," *Rev. Sci. Inst.* **37**, 771 (1966)] is available up to 30 cm diameter. Such a viewing screen could be coupled to an RCA fiber optic input, three-stage image intensifier by using a thin film of immersion oil. The image intensifier could be moved across the fiber optic end window to inspect a larger image than covered by the intensifier. Vidicon or orthicon viewing, or photography of the image intensifier output, could be used.

2. Scanning Electron Microscopy

Scanning electron diffraction should be available on the main microscope column for readout of crystalline information as developed by Dr. Grigson [Denbigh and Grigson, "Scanning Electron Diffraction with Energy Analysis," *J. Sci. Inst.* **42**, 305 (1965)]. An energy analyzer is necessary, both for thin films and for solids.

This type of scanning achieves achromaticity in the recording since the decrease in Bragg angle for higher voltage is matched by a decrease in scanning angle for the same scanning waveform. Therefore, useful diffraction information might be extracted even if the high-voltage supply is not suitable for microscopy. As an extension, it might be possible to record electron interference patterns or "holograms" and retain the achromaticity since space information would be converted into angular information. The reconstruction, which might be done with a laser, would be achromatic if the angular display were reconverted to a spatial distribution.

Scanning-electron microscopy need not involve a second column. A very fine electron probe exists in the back focal plane of all electron microscopes, and has been used in static form by Haine and Mulvey [*J. Opt. Soc. Am.* **42**, 763 (1952)] in an attempt at electron holography. We are now trying at Cambridge to scan with this electron probe. The scanning coils can be

placed in the projector bore and a projector stigmator fitted. For rough work, scanning could be fed to the objective stigmator.

In addition, it is suggested that an adjustable aperture be placed in the projector lens bore to act as a differential pumping hole, separating the ultrahigh vacuum of the column necessary for field emission from the normal high vacuum of the recording area. This aperture would be of use in all three modes of operation: conventional transmission microscopy, scanning microscopy, and scanning electron diffraction.

Scanning of the specimen in the normal objective plane is also feasible by several methods. If a 180° sector magnet is used for analysis, then this magnet may be used in reverse on a beam of electrons sent downwards adjacent to the column. The lenses then reduce the beam to form a fine probe at the specimen [Buchanan and Nixon, *Proc. European Re. Conf. On Electron Mic.*, Prague (1964) p. 119].

Scanning electron microscopy of solids should also be considered at high voltage. The resolution achieved is much less than the electron range [Pease and Nixon, *J. Sci. Inst.* **42**, 81 (1965)]. The contrast is produced by collecting secondaries. Oatley, Nixon, and Pease discuss [*Adv. in Electronics and Electron Physics* **21**, pp. 181-247, Academic Press (1965)] various forms of voltage contrast, including the electron-beam induced-current method of Czaja and Wheatley. Recent results from the Bell Laboratories show that the electron penetration in silicon may be used to image defects below the surface.

Any form of scanning electron microscope, even with a field emission source, should have two lenses, to permit variation of the effective source position on the axis with respect to the final lens.

Dark-field scanning electron microscopy is a method that has been tried but not yet worked through. In this case, only those elastically scattered electrons that have been deviated through a selected angle are collected. Dark-field methods show the best detection limit (i.e., the actual presence of matter) and the resolution need not be worse than in bright field.

Electrical Service Provisions to Minimize Stray Fields

CHARLES E. COHN

Argonne National Laboratory

The proposed 5 MeV microscope would require considerable magnetic shielding to minimize defocusing by stray alternating magnetic fields, originating from electrical power apparatus and wiring in the vicinity. Since a building is to be designed and built specifically for the microscope, it would seem appropriate to minimize the generation of such fields and thus reduce the shielding requirements. The following measures seem appropriate:

1. The building should be located as remotely as possible from major power lines, accelerators, etc.

2. Generation of stray fields within the building could be minimized by use of dc power instead of ac power. Lights, for example, could all be dc, and many motors could be dc.

3. Unusual wiring practices would be desirable. Normally, the neutral wire is tied to ground at every fuse box or breaker cabinet. As a result, part of the

return current flows through the ground system and part through the neutral wire, the division depending on the relative resistances of the two parts. This part of the return current follows a very different path from the outgoing current, so that a loop is set up and magnetic flux is generated.

If the neutral wires are connected to ground at only one point, no return current will flow in the ground system. With the hot and neutral wires close together in the same conduit, the area of the loop and the resultant flux generation are minimized, particularly if the wires are twisted together. The conduit might also provide some magnetic shielding.

The same precautions should be followed in dc wiring to avoid strong field transients due to switching.

4. Transformers, substations, motor generators, rectifier sets, etc. should be located as remotely as possible, despite increased wiring losses.

Workshop Participants and Attendees at Open Sessions of the AMU-ANL Workshop on High-Voltage Electron Microscopy

June 13–July 15, 1966

Argonne National Laboratory

<i>Name</i>	<i>Affiliation</i>
ADLER, H. C.*	ANL—Plant Engineering
BEER, M.*	Johns Hopkins University
BENNETT, H. S.*	The University of Chicago
BIBB, W.	AEC Biology and Medicine—Washington
BISKIS, B. O.	ANL—Experimental Radiation Pathology
BREWER, J.	ANL—Electronics
BROOKSHIER, W. K.*	ANL—Electronics
BRUES, A. M.	ANL—Biological and Medical Research
BUTLER, J. W.*	ANL—Applied Mathematics
CHEN, V.	The University of Chicago
CHISWIK, H. H.	ANL—Metallurgy
CHURM, A. A.	AEC—Chicago Operations Office
COCKS, G. G.	Cornell University
COHEN, D.*	University of Illinois at Chicago Circle
COHN, C. E.*	ANL—Reactor Physics
COREY, C. L.*	Wayne State University
CREWE, A. V.*	ANL—Laboratory Director
CULIK, A. E.	ANL—Security
DELTRAP, J. H. M.*	Aerojet Corp., New York
DEPARRY, T.	ANL—Particle Accelerator
DONHOWE, J. M.*	The University of Wisconsin
DOOLIN, P. F.	Veterans Administration Hospital—Hines, Ill.
EGGENBERGER, D. N.*	ANL—Electronics
EVINS, D. J.	Perkin-Elmer Corporation
FERNANDEZ-MORAN, H.*	The University of Chicago
FERRY, J. A.*	The University of Wisconsin
FISHER, R. M.*	U. S. Steel Corporation
FLAUMENHAFT, E.*	ANL—Chemistry
FOSS, M. H.*	Carnegie Institute of Technology
FOURIE, J. T.	General Motors Corporation
FREEDMAN, M.*	ANL—Chemistry
GILROY, J.*	ANL—Electronics
GLOS, M. B.	McGraw-Hill, Nucleonics
GREENSPAN, HAROLD	ANL—Applied Mathematics
HALVERSON, S. L.*	ANL—Electronics
HANSON, A. O.*	University of Illinois—Urbana
HART, R. K.*	ANL—Metallurgy
HARTMAN, R. E.	New York Medical College
HARTMANN, J. F.	Presbyterian-St. Luke's Hospital
HASHIMOTO, H.*	Kyoto Technical University
HAWKES, P. W.*	University of Cambridge, England

* Workshop Participants.

<i>Name</i>	<i>Affiliation</i>
HERB, R. G.*	The University of Wisconsin
HESS, D.	ANL—Physics
HEWSON, R. E.	ANL—Security
HIRSCH, P. R.*	ANL—Plant Engineering
HSU, J.	ANL—Electronics
ISAACSON, M.	ANL—Electronics
KACINSKAS, H.*	ANL—Plant Engineering
KAMINSKY, M.	ANL—Physics
KAWAKATSU, H.*	Cornell University
KELSCH, J. J.	Brookhaven National Laboratory
KESSIE, R. W.	ANL—Chemical Engineering
KITAMURA, N.*	Cornell University
KLEMA, E. D.*	Northwestern University
LALLY, J. S.	U. S. Steel Corporation
LANGSDORF, A.*	ANL—Physics
LAVERICK, C.*	ANL—Particle Accelerator
LAWLESS, K.*	University of Virginia
LAYTON, J. M.	University of Iowa
LEIGHLY, H. P., JR.	University of Missouri at Rolla
McGEE, T. D.	Iowa State University
MARSHALL, W. R.	The University of Wisconsin
MARTON, L. L.*	National Bureau of Standards—Washington
MEADS, P. F., JR.*	Wm. M. Brobeck & Associates
MEYER, E.*	The University of Wisconsin
MILLER, R. J.*	Radio Corporation of America—Chicago
MILLER, W. C.*	University of Notre Dame
MIZUHIRA, V.	Tokyo Medical and Dental University
MONROE, E.	ANL—Metallurgy
MONTET, G. L.	ANL—Solid State Science
MOSES, R. W., JR.*	The University of Wisconsin
NIXON, W. C.*	University of Cambridge, England
O'BOYLE, D. R.	ANL—Metallurgy
OSWALD, A. W. R.*	ANL—Plant Engineering
PLOMP, F.*	Cornell University
REISNER, J. H.*	Radio Corporation of America—Camden, N. J.
RHUDE, H. V.	ANL—Metallurgy
RINGO, G. R.*	ANL—Physics
RIORDAN, W. J.*	ANL—Plant Engineering
ROBERSON, J. H.	Associated Midwest Universities
ROBERTS, J. H.*	Northwestern University
ROBINSON, J. W.*	ANL—Plant Engineering
ROHDE, R. E.	ANL—Electronics
RONNE, E.	ANL—Information Services
ROSS, H. V.	ANL—Technical Services—Manager's Office
ROWLAND, R. E.*	ANL—Radiological Physics
RUDNICK, S. J.	ANL—Electronics
RYMER, T. B.*	Reading University—England
SAMBE, H.*	The University of Chicago (Secretary to B. Tadano)
SCHUSTER, F. L.	ANL—Biological and Medical Research
SEATES, R.	ANL—Solid State Science
SIEGEL, B. M.*	Cornell University
SIMANTON, J. R.	ANL—Particle Accelerator
SLAUGHTER, G. G.	Oak Ridge National Laboratory

<i>Name</i>	<i>Affiliation</i>
SMITH, K. C. A.*	University of Cambridge, England
SMOLER, M. H.	ANL—Biological and Medical Research
SUN, C. N.	St. Louis University, School of Medicine
SWALLOW, E. C.	ANL—High Energy Physics
SWIFT, H. H.	The University of Chicago
SYMON, K. R.*	The University of Wisconsin
TADANO, B.*	Hitachi, Ltd.—Tokyo
TAHMISIAN, T. N.	ANL—Biological and Medical Research
TENG, L. C.	ANL—Particle Accelerator
TURNER, C. H. M.	ANL—Particle Accelerator
VOSBURGH, K.	Cornell University
WALL, J.	ANL—Electronics
WELTER, L.*	ANL—Electronics
WELTON, T. A.*	Oak Ridge National Laboratory
WILEY, C. M.	John Wiley & Sons, Publishers
WILSON, P. B.*	Stanford University
WINSBERG, L.	University of Illinois at Chicago Circle
WITTRY, D. B.*	University of Southern California
WOOD, R. W.	AEC Biology and Medicine—Washington
YOKOSAWA, A.	ANL—Particle Accelerator
ZEITLER, E. H.*	Armed Forces—Institute of Pathology