Summary of the second international conference on electrostatic accelerator technology

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SUMMARY OF THE SECOND INTERNATIONAL CONFERENCE ON ELECTROSTATIC ACCELERATOR TECHNOLOGY

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Résumé. — Dans cette conclusion, les informations et les nouveaux résultats présentés à cette Conférence sont passés en revue, et une comparaison est faite entre l'état actuel des caractéristiques générales des principaux accélérateurs électrostatiques et celui d'il y a quatre ans, lors de la dernière conférence. La discussion des progrès de la technologie des accélérateurs électrostatiques, réalisés au courant de cette période de quatre ans, englobe les tubes des accélérateurs, les systèmes de transport de charges et les sources d'ions, et mentionne également d'autres aspects de la conception et du fonctionnement des accélérateurs.

Abstract. — This summary reviews the information and new results presented at this Conference and compares the present overall performance of the major electrostatic accelerators to that at the time of the last Conference, four years ago. The advances in electrostatic accelerator technology in the four year period are discussed in terms of accelerator tube improvements, electrostatic charging system improvements, ion source developments, and other aspects of machine design and operation.

Ladies and gentlemen, it is indeed a pleasure and honor to be the summary speaker of this Conference. We have now reached the end of the Conference on Electrostatic Accelerator Technology even though there is an additional session this afternoon which I strongly recommend you all attend. This afternoon we will be talking about boosters for electrostatic accelerators that will increase the energy over what is available out of the electrostatic accelerator. These boosters take the form of linear accelerators or cyclotrons and then either conventional or superconducting of both varieties. When an electrostatic accelerator is used to inject another accelerator as a booster, it is no longer a subject of electrostatic accelerator technology. The accelerator is simply lowered in energy until it operates with essentially 100 % reliability as an ion source for the booster accelerator. Its operation is no longer of interest in electrostatic accelerator technology because all the problems will lie with the booster accelerator. It will be much easier to get the necessary energy out of the booster rather than operating the electrostatic accelerator at its extreme limit which is the normal operational mode when used singly as research accelerator. It is important that all the members of this Conference be knowledgable about the current status and situation with booster accelerators and we will be updated on these matters by the speakers this afternoon. It is entirely possible that by the time of the next Electrostatic Accelerator Conference, four years from now, the trend will be towards the utilization of booster machines and abandonment of the technology of electrostatic accelerators in favor of their use as reliable ion sources for other kinds of accelerators.

On behalf of all of the participating members of this Conference, I would like to first thank the various people and organizations that have made this Conference possible. The Director of the *Centre de Recherches Nucléaires de Strasbourg,* Professor Gallmann, the Director of *L'Institut National de Physique Nucléaire et de Physique des Particules,* Professor J. Yoccoz and the *Commissariat à l'Énergie Atomique.* Many other people have also contributed to this Conference with their time and energy and we must recognize the Chairman of the Organizing Committee, G. Frick and his right-hand helper, F. Wechselgaertner. This beautiful conference room and its fine organization has been maintained by G. Gerardin with his many pleasant helpers like M. Resch, G. Weiss and any others. And, of course, if any of you have had problems with travel or questions of other matters you have always been able to get the answers at the desk operated so capably by D. Kueny and N. Gross. Finally, special thanks is offered to the Organizing Committee for arranging such perfect weather during the entire time of the Conference in such a delightful setting. We thank you one and all.

It is only appropriate in summarizing a conference of this type to remind us all how this technology got started. In 1932 a post doc named R. Van de Graaff, working at the Department of Terrestial Magnetism of Carnegie Tech, built a small electrostatic machine with a high voltage terminal approximately 2 meters

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in diameter and support column about 3 meters long. This machine had a special acceleration tube designed and built by G. Bright and was able to operate up to 1.2 MV outside in an open yard where there was adequate clearance for sparking from the high voltage terminal to various objects. The main problem was reported to be June bugs that would land on the high voltage terminal and provide a corona load that would often limit the voltage to 500 or 600 kV.

In 1933 a graduate student in Wisconsin, named R. Herb, took over a vacuum electrostatic experimental device and tried pressurizing it with air with a little mixture of carbon tetrachloride. He was able to hold up to one million volts in this first pressurized electrostatic machine. He then installed an acceleration tube 1.5 meters long and was able to operate the machine at 400 kV on that length tube which made it possible for him to complete his PhD. thesis work.

We have certainly come a long way from those early days and at present we now have some very large machines under construction. In Japan, there is a 20 MV machine under construction by NEC; at Oak Ridge National Laboratory, a 25 MV accelerator under construction by NEC; and in Daresbury, England, a 30 MV machine currently under construction by the Daresbury research group.

The advent of the sputter-type ion source, as developed by R. Middleton, has now provided over 50 elements in the form of negative ions that can be easily accelerated by tandem accelerators. In the near future with the automation and computer controls available nowadays, we will be able to *dial an isotope* for whatever kind of beam is desired with the tandem accelerator.

The electrostatic accelerators in the world today are now running better than they have ever run before from down under in Australia to up and over in the United States and on into Europe. The main challenge to this summary speaker is to somehow characterize how much better these machines are operating now in comparison to where they were at the time of the last Conference and where the technology is going in the future.

At the time of the last Conference the TU accelerator seemed like an extremely large machine compared to MP's and, at that time, the 14 UD machine was just under construction in Australia. Today, visitors to Daresbury can stand inside the accelerator vessel for a 30 MV machine which easily contains two or more of the previously large TU-class machines, demonstrating that increases in size have certainly been made. The Oak Ridge pressure vessel, now being assembled, is even more impressive in terms of its large diameter. Generally speaking, there have been little or no problems from a structural or electrostatic voltage generator point of view of building larger machines.

The main problem over the years has been with acceleration tubes and it is interesting to see where we stood four years ago and where we stand today on the design of a reliable, working acceleration tube. Quoting one of the authors of the last Conference, he commented *What is the secret of a good acceleration tube? The most vexing problem of building a good accelerator is getting a good tube for it. Reasonable tubes are available, but none of them will work at a gradient of 3 to 4 MV par meter*. Certainly, this gradient desired by the speaker at the last Conference is still desired by most of the people in this room and is yet to be attained. At the time of the last Conference, R. Herb was quoted by others to believe that the lifetime of his new kind of acceleration tube was infinite; however, that expectation is now not quite so clear. The new tube just developed by HVEC at the time of the last Conference was deemed to fail just like all previous HVEC tubes, but over the last four years has turned out to fail in only one case with the other five installations working unbelievably well. The characteristics of all these new tubes still are not completely understood as we will discuss in more detail later.

At the time of the last Conference, a review of the acceleration tubes at that time concluded that although many cutouts in the electrodes of the acceleration tube was good for pumping and consequently very good for heavy ion acceleration, these same cutouts were very bad for holding voltage reliably. Very small holes through the electrodes just large enough to pass a beam were very good for voltage holding, but very bad for heavy ions because of the obvious difficulty of providing adequate vacuum through the small hole. We have now heard at this Conference of the success of a new kind of acceleration tube at Rochester that does use large cutouts for good pumping and is performing satisfactorily and reliably with over 2 000 hours on a complete set of such acceleration tubes.

In 1975, at a review of accelerators at the Electrostatic Conference, I ventured to say, and I quote, *In 1969 we were contemplating 12 to 15 MV operation with considerable skepticism. In 1975 we exceeded 15 MV operation with acceleration tubes and* now understand *acceleration tube loading and other electrostatic phenomena sufficiently well so that we can* now confidently *construct 25 to 30 MV machines*. In view of the discussions and papers presented at this Conference I am afraid that that statement was a little more optimistic than it should have been.

It always turns out that when acceleration tubes are operated in an accelerator, *in situ*, providing accelerated ions for research operations the situation is always different than it seems to be with just a few tubes running largely under test conditions rather than research conditions. We are now in a much better position to evaluate and diagnose acceleration tubes under actual operating conditions than we were four years ago. We have heard of the photomultiplier method of directly observing conditioning phenomena in acceleration tubes from its associated light production as developed by Rochester and also in use at BNL and other places. We have also heard of high-resolution mass spectrometer applications of accelerators as developed by Purser and colleagues at Rochester, independently by Thieberger and Schwarzschild at BNL and also at Daresbury where various kinds of ions produced during the conditioning process can be detected and analyzed with extreme sensitivity and may very well lead to a more basic understanding of conditioning phenomena.

Although our basic understanding of how acceleration tubes work, how they condition, how they hold voltage, why they breakdown, and so on has greatly improved over our understanding in 1973, we still have a long way to go to 4 MV per meter and we probably have considerably more work to understand all of the phenomena going on with our present newest design of acceleration tubes, even though they are working much, much better than any kind of tubes that were available back at the time of the last Conference. The large diameter stainless steel tubes manufactured by HVEC are now in use in seven different MP accelerators and performing quite well as we will see later. In fact, the original installation of this new set of tubes had just occurred at the time of the last Conference in the Chalk River accelerator and have now performed for over 20 000 hours and are still in what might be called *new condition.* They have suffered essentially negligible damage and are working today as well as when they went through their acceptance tests.

In contrast, the same tubes in the Heidelberg accelerator have operated for over 15 000 hours, but have now suddenly started developing extreme damage to the insulating glass, as shown in figure 1. Why this damage is occurring in the Heidelberg machine and not in the other working machines is not clear at this time. It only points up the fact that we still have things to learn about the reliability of acceleration tubes under research operational conditions.

The new kind of acceleration tube developed by the National Electrostatics Corp. was just about ready for its first extensive test in a large machine at Canberra at the time of the last Conference and although in use at a smaller accelerator facility in Sao Paulo, had not been tested extensively because of other difficulties with the machine installation at that time. We can now report on the successful operation of these tubes in Australia at Canberra and in Japan at Tsukuba and as we have heard at this Conference, In Israel at the Weizmann Institute. Although these tubes have performed quite well with a fair number of operational hours, there are still problems that are not completely understood. These same tubes in use at both Tsukuba and Munich suffered extensive damage in some sections presumably due to contamination from packing material. At present, the damage problem has not been completely demonstrated to be due only to contamination in terms of satisfactory *research* operation of a large machine at rated voltage. There are annoying questions still to be answered concerning the performance of these tubes. Figure 2 shows one of the damaged tubes and indicates the extensive coloration in the electrodes as well as the insulating sections which require sand blasting and cleaning for satisfactory operation.

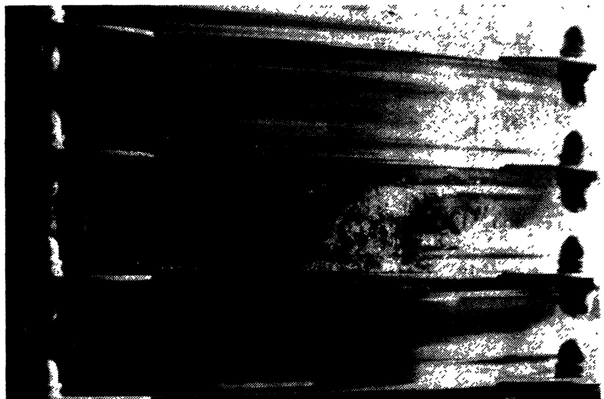

FIG. 1. — Severely damaged glass insulator section in one of the large diameter stainless steel acceleration tube sections of the Heidelberg MP-5 tandem.

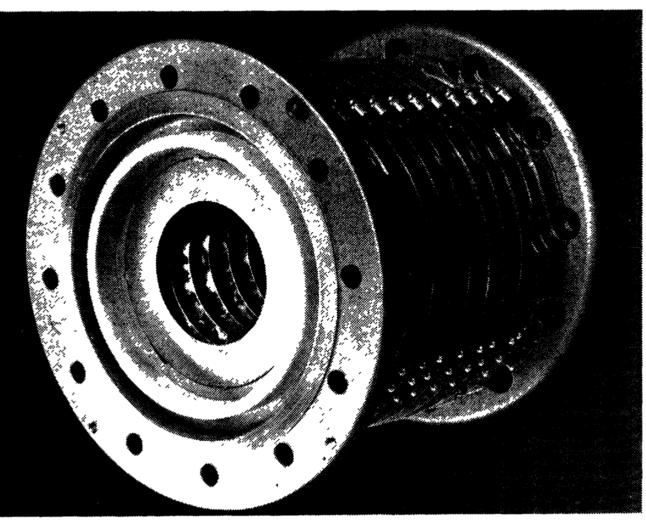

FIG. 2. — Acceleration tube section (NEC) from the Munich (MP-7) tandem showing the damaged and discolored electrodes presumably caused by organic contamination inadvertently introduced during shipping.

The main conclusion of this discussion is that the different designs and approach to the problems of manufacturing reliable acceleration tubes by the National Electrostatic Corp., High Voltage Engineering Corp., Dowlish Developments Limited, Megavolt Ltd. and other independent groups like Rochester and Daresbury will ultimately lead to a much better and thorough understanding of acceleration tubes. Consequently, we will be able to look forward to long and reliable operation at much higher voltages in the 25 to 30 MV region in our newest accelerators now under construction.

One of the more important aspects of reliable acceleration tube operation is the vacuum capability of the pumping system provided with the acceleration tubes. On most machines there is only a vacuum system inside the high voltage terminal and outside the machine at both ends. The operating vacuum inside the acceleration tubes when in operation is very difficult to measure without having specially pressurized ion gauges and local power supplies for their readout at various stations along the tube. However, the effects of good or bad vacuum along the length of the acceleration tube can now be measured because the sputter ion source allows convenient and quick changes of one kind of ion to another over a wide range of masses. Rochester has diagnosed the vacuum characteristics of the acceleration tube system in their machine by studying the transmission efficiency of various heavy ions from oxygen to gold. It was found that the transmission efficiency gradually decreased with increasing ion mass very much as you would expect if gas stripping were the source of the lowered efficiency, as shown in figure 3. These data can be

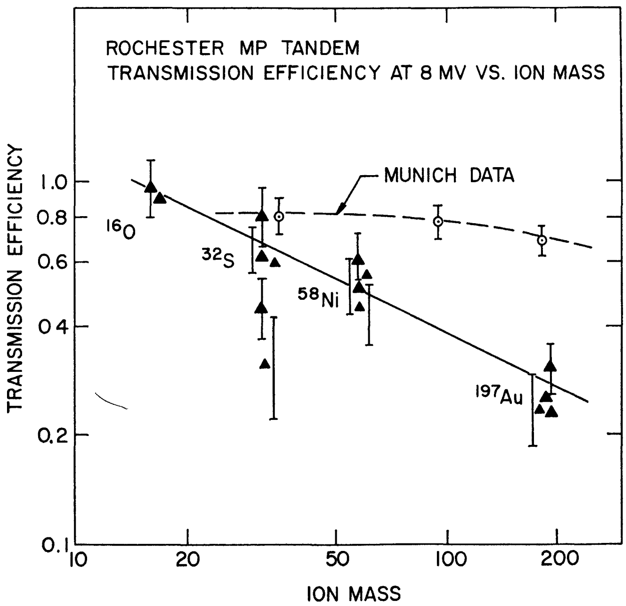

FIG. 3. — Transmission efficiency *vs.* ion mass compared for the Rochester (MP-4) and Munich (MP-8) tandems.

contrasted with similar measurements on the Munich machine where the vacuum is maintained and monitored at each dead section from one end of the acceleration tube to the other. In this case the operating pressure is 10^{-7} or better at each dead section so there is no question about the quality of the vacuum throughout the machine. The attenuation of gold ions was for all practical purposes no different than that for oxygen as indicated by the dashed line on figure 3 and strongly infers that some kind of additional pumping along the acceleration tube is certainly worth while in providing better transmission and performance of the MP machines.

There is additional information from the Heidelberg MP provided by Roland Repnow who has a fibre optics telemetry system that controls and reads out a Faraday cup in the high voltage terminal. This terminal Faraday cup allows a measure of the transmission efficiency from the low energy end of the machine to the terminal and from the terminal to the image cup at the high energy end of the accelerator. He reports that there is no measurable loss in transmission from the terminal to the image cup of the 90° analyzing magnet other than what would be expected from the object and image slits for both oxygen and nickel beams. A one microampere nickel beam injected into the machine shows a transmission efficiency from the high voltage terminal to the object slit of over 90 % with the slight loss due to the finite slit settings of the analyzing magnet. This means that the primary loss of ions due to limited tube vacuum is not in the high energy end of these machines but the low energy end. If additional pumping is going to be provided, the first place to install it is in the low energy end of the accelerator and it would appear that all machines without such pumping should start planning now for such improvements.

The final aspect of acceleration tube reliability has to do with maintaining the voltage gradient along the acceleration tubes and we have heard at this Meeting that the new blue resistor systems provided by HVEC and modified suitably by protectrice spark gaps as shown at this Meeting by Yale and BNL are working quite reliably in the capacity of both tube and column resistors. We have also heard that the new closed corona system provided by NEC is working quite well at Argonne National Laboratory on the FN tandem and at the Weizmann Institute during their recent successful demonstration of acceptance specifications. Although J. Yntema has reported long lifetime and reliability in the FN accelerator with the closed corona, it remains to be seen what the lifetime and reliability will be in the much higher energy storage machines like the 14 UD at the Weizmann Institute. At present, both the new resistors and corona seem to be able to handle whatever unusual loading conditions arise in the present operating accelerators and the tube and column gradient reliability appears not to be a problem at this time which is a great improvement over the situation four years ago.

Another hardly noticed but important change in electrostatic accelerator design in the last four years has been the total elimination of any kind of spring electrical contact on any column or tube components. The larger machines now operating at higher gradients all use SF_6 either pure or in some mixture. The SF_6 electrical breakdown products rapidly degrade spring type connections to where the connection becomes an intermittent spark gap that destroys the stability of the machine and also leads to damaging terminal-to-tank breakdowns. The existing machines have had all such spring contacts replaced by hard connections or eliminated altogether. The new machines under construction will not have any such contacts in their design.

One of the most notable changes in design of electrostatic accelerators from the time of the last Conference has been in the basic charging system of the machine. The original belt charging system developed by the High Voltage Engineering Corp. has always suffered from various problems from time to time. At the time of the last Conference the arbitrary performance of one belt as compared to another was a common complaint. The most definitive study and demonstration of how charging belts work in detail has been carried out by M. Letournel on the Strasbourg machine, MP-10 and we can now understand many more of the idiosyncracies of charging belts as Letournel has shown by his study of the charging characteristics under many different configurations. This extensive belt study is the first carried out on a modern large machine and may lead to much more reliable service from charging belts.

Other people at the time of the last Conference simply felt they were unable to pay for the expense of belts which would only work reliably for 2 000 to 3 000 hours and Yale was the first customer to abandon the charging belt for the new pelletron charging system just then being offered by the National Electrostatic Corp. as a modification for an MP machine. The pelletron worked extremely well for Yale while operating at relatively low gradients in the 9-10 MV region and Chalk River, with the first upgraded acceleration tubes, also decided to install a pelletron because of the extensive difficulties with charging belts that appeared to onset at voltages above 12 MV in operation.

Just to indicate the kind of problems that Chalk River was facing with the charging belt, in a period of a few months they had destroyed what is called an old black belt, a new black belt, three tan belts, two new black belts and finally, a special combination tan-black belt. Although the tan-black belt was working satisfactorily at the time of shut down with relatively few hours of operation, the pelletron from NEC arrived at that time and was installed.

Unfortunately, the higher energy storage of the MP machine, operating at the 12 to 13 MV level, caused new kinds of problems with the pelletron resulting in pulley damage, chain breakage, etc., for a period of several months. These were finally eliminated by various redesigns and rework of the pelletron charging system. After these changes were made the pelletron behaved very reliably and has continued to do so for the last several years with only occasional changes of pulleys due to bearing failure during the year. There are now pelletron-charging systems in five of the ten MP accelerators in existence; three in the North-American machines and two in the European machines and Orsay has expressed an interest in a pelletron system because of the excessive series of belt failures that have plagued their machine, MP-9, recently. It is interesting to note that all of the new large machines now offered by the High Voltage Engineering Corp. are offered with a laddertron mechanical-type charging system developed in conjunction with the Daresbury group rather than the older belt charging system which was always the previous standard of the Company.

Another major change from 1973 to today has been in the kind of ion sources used with these accelerators. In 1973 the off-axis duoplasmatron and Penning-type source were the main stays for heavy ion operation and we now find that most accelerators are operating with the sputter-type source as developed by R. Middleton. Just to indicate the complex situation of source operation at one laboratory in 1973; at Brookhaven National Laboratory we had in use four different direct extraction duoplasmatron ion sources, one Heinicke source, one Hortig source, one General Ionics helium-lithium source and one Extrion Mark I sputter source. All of these different ion sources had different idiosyncracies and operating characteristics not to mention completely different operating controls with the result that the set up and operation was complex and the difficulties in changing from one source to another for different kinds of ions caused various problems and delays because of all the different mechanical and operational difficulties. Today, we use principally two Extrion Mark VI sputter sources for conventional two-stage operation of our two accelerators and one General Ionics sputter source in the high voltage terminal for three-stage operation. The same situation is true in most other tandem laboratories because of the flexibility, rapid change capability and long life and reliability of the sputter-type ion source for heavy ion operation. In the next four years we would expect to see higher currents available for many of the different ions as well as higher efficiency in producing the ions. Increased flexibility will allow us to essentially dial up most any isotope of any element throughout the periodic table and in five minutes have that isotope available on target.

It is interesting to compare quantitatively the performance improvement of the various machines now in operation. The Tsukuba machine is reported to be operating satisfactorily in the 11 to 12 MV region; we have heard at this Meeting that the Canberra machine is working well in the 12 to 13 MV region; and also that the Weizmann machine has successfully passed its acceptance tests at 14 MV operation. The MP machines throughout the world have also shown remarkable improvement in the four-year period from the last Conference to the present.

Figure 4 compares the performance of the Yale machine, MP-1, with the old aluminium acceleration tubes in 1973 to the present. Recently, they increased the SF_6 concentration in their insulating gas mixture and have started research operation in the 12.5 to 13 MV region. Their operation record for the last year

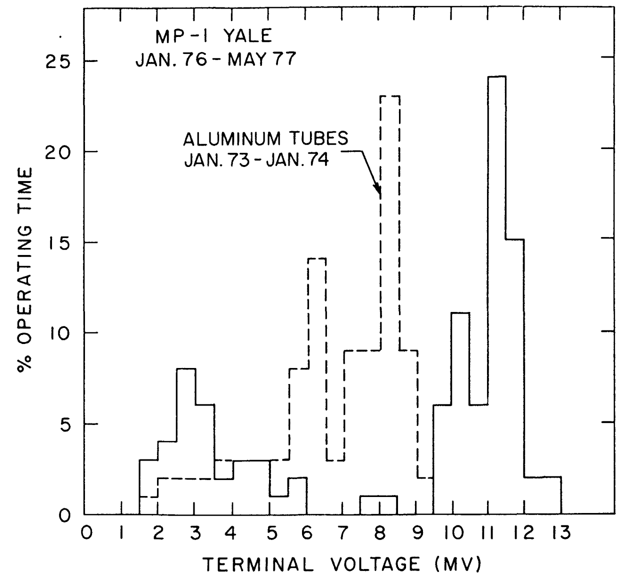

FIG. 4. — Comparison of aluminium and stainless steel acceleration tube performance for the Yale (MP-1) tandem.

shows an average operating voltage increase of 2 to 3 MV.

Figure 5 shows the operating situation for the first two years of operation with aluminium tubes in the Chalk River machine, MP-3, *versus* the last three years of operation with the new stainless tubes. The improvement is remarkable, going from an average operating voltage in the vicinity of 7-9 MV to a routine operating voltage of 12 which represents a 3-4 MV basic improvement in performance.

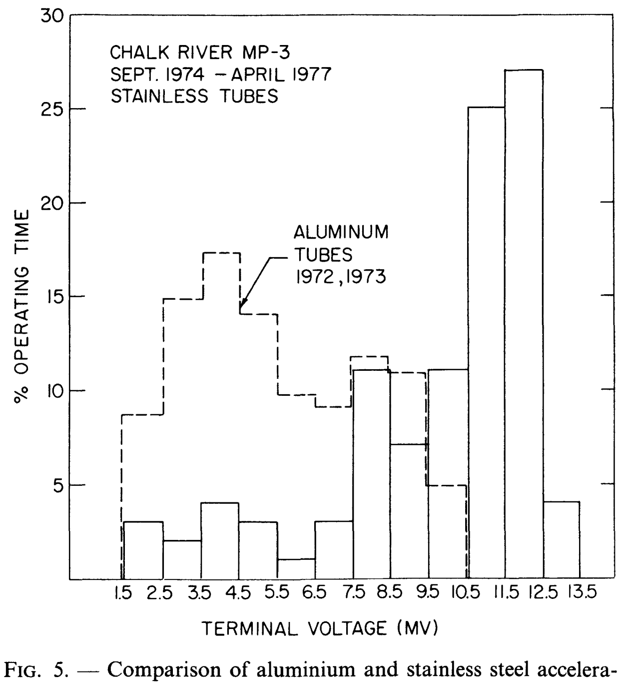

FIG. 5. — Comparison of aluminium and stainless steel acceleration tube performance for the Chalk River (MP-3) tandem.

Figure 6 shows the improvement in the Rochester machine, MP-4, from the old aluminium tubes to the new titanium tubes. As we have heard at this meeting from T. Lund they have just recently completed the full installation of titanium tubes which now allows 12 MV operation and again we see a solid 3 MV improvement in performance over the last four years.

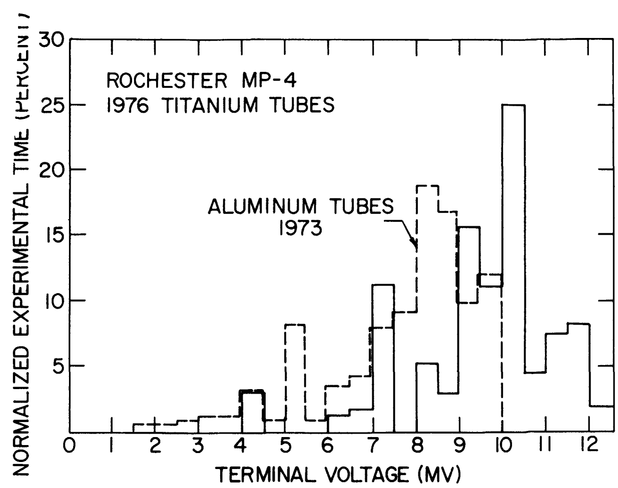

FIG. 6. — Comparison of aluminium and stainless steel acceleration tube performance for the Rochester (MP-4) tandem.

Figure 7 shows the improvement at Brookhaven National Laboratory in MP-7 from the old aluminium tubes in 1972-1973 to the interim upgrade of small stainless tubes in 1975-1976 and the further

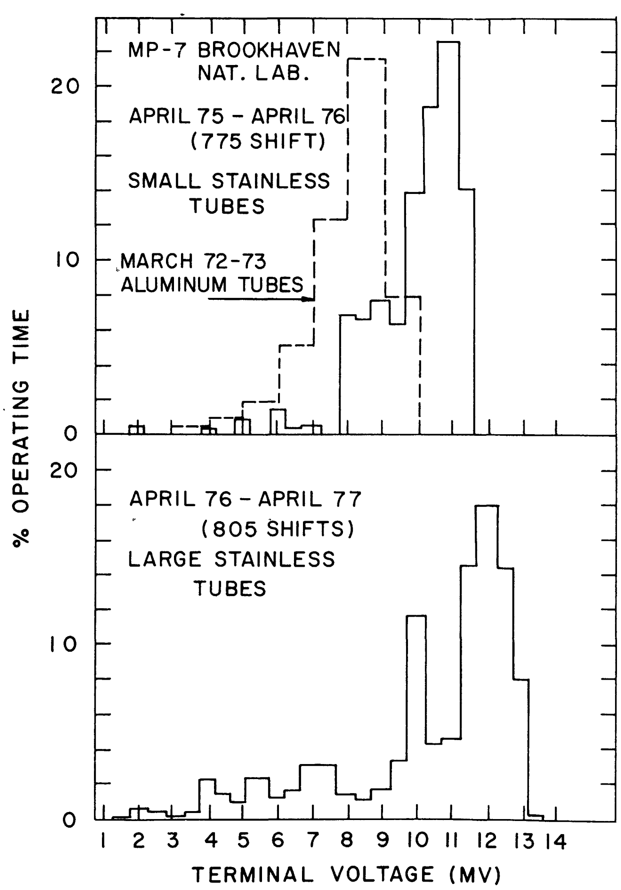

FIG. 7. — Comparison of aluminium and stainless steel acceleration tube performance for the BNL (MP-7) tandem.

improvement from 1976 to now with the large stainless tubes that allow routine operation in excess of 12 MV.

The situation is quite similar with the European machines. At Heidelberg, MP-5, the aluminium tube operation as compared with the 1976 operation shows again a 2 to 3 MV improvement as illustrated in figure 8; Strasbourg, MP-10, shows an appreciable part of their operations in the 13 MV region which is a definite improvement over their aluminium tube operational period as shown in figure 9; and perhaps the record of improved performance is shown in figure 10 for the operating record of the Orsay machine, MP-9. The contrast vith their aluminium tube operation is striking and their operating record of almost 40 % of their running time between 12.5 to 13 MV is indeed impressive.

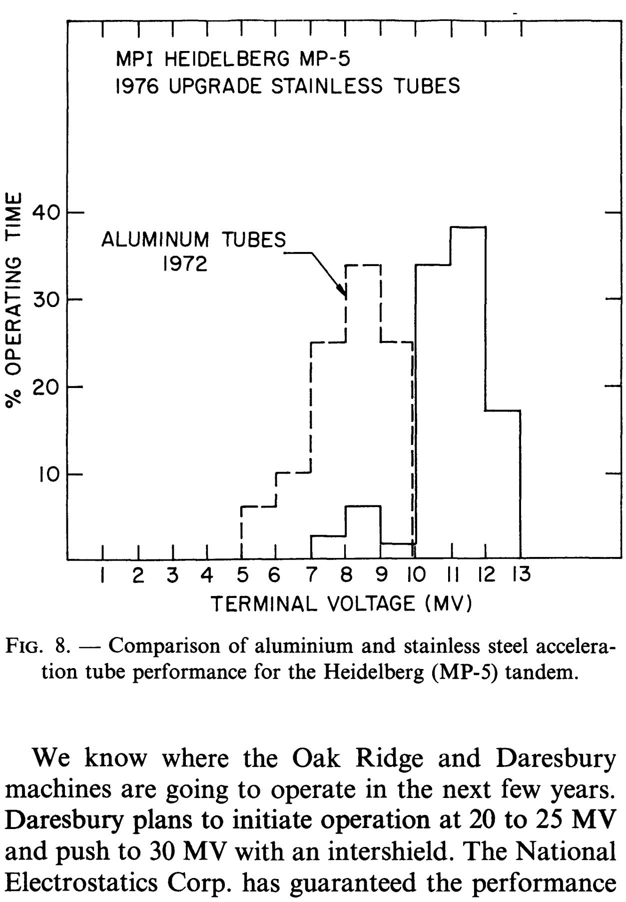

FIG. 8. — Comparison of aluminium and stainless steel acceleration tube performance for the Heidelberg (MP-5) tandem.

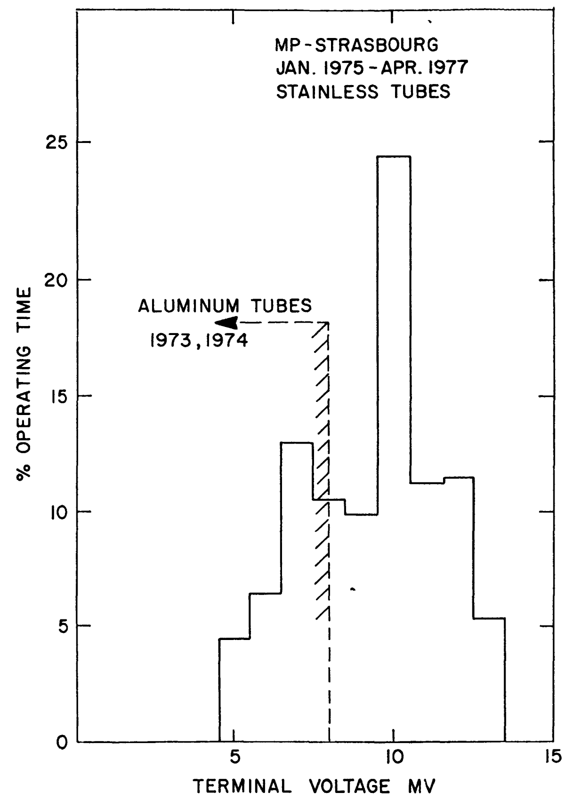

FIG. 9. — Comparison of aluminium and stainless steel acceleration tube performance for the Strasbourg (MP-10) tandem.

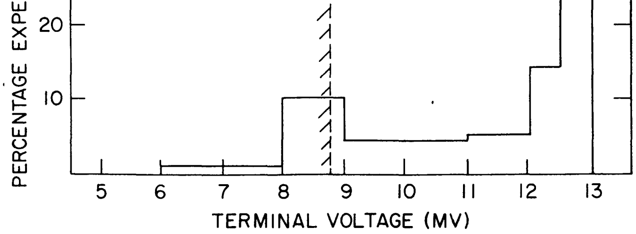

FIG. 10. — Comparison of aluminium and stainless steel acceleration tube performance for the Orsay (MP-9) tandem.

We know where the Oak Ridge and Daresbury machines are going to operate in the next few years. Daresbury plans to initiate operation at 20 to 25 MV and push to 30 MV with an intershield. The National Electrostatics Corp. has guaranteed the performance of the Oak Ridge machine at 25 MV which means that it must operate satisfactorily at that point. In the next few years, how high a voltage will be possible with the MP accelerators or have we now achieved the maximum performance capability? It is interesting to speculate on what MP capabilities might be possible four years from now or perhaps even farther into the future.

Figure 10 shows a plot of terminal voltage *versus* SF_6 pressure for two different test runs without acceleration tubes, the Strasbourg machine with a belt charging system and the Munich machine with a pelletron. The lower dashed line indicates the performance in 1973 with the aluminium-type tubes and the upper dashed line is the present performance with the new stainless and other kinds of tubes.

It would appear that the machines as electrostatic generators will go right on up in voltage to even beyond 20 MV since the MP's are capable of up to 15 atmospheres of pressure unlike most new machines which are limited to 8-9 atmospheres; however, it is certainly not clear that acceleration tubes will work up at that point. Perhaps we can confidently think of 16 MV operation with tube X in four years; however,

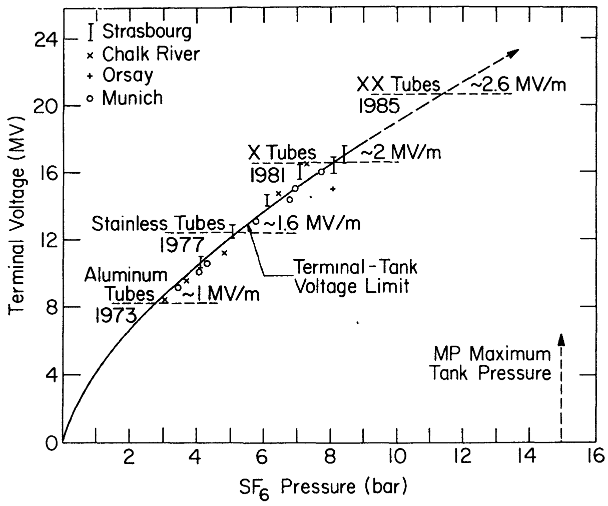

FIG. 11. — Terminal-tank voltage limit for MP tandem accelerators (without acceleration tubes) as a function of pure SF_6 insulating gas pressure.

it is quite clear that we are in sore need of that *idealized acceleration tube* that is capable of reliable operation at a gradient of 3 to 4 MV per meter. With such an XX tube we should be able to operate at 20 MV or higher by 1985. Perhaps what is really needed is the *ideal* acceleration tube insulating material as described by D. McK. Hyder at this Meeting and a proper mixture of black magic.

In conclusion, we have all accomplished a great deal in improving the performance of electrostatic accelerators over the last four years. This improved performance has greatly expanded the heavy ion research capabilities of the entire research community. From the evidence in the papers presented at this Conference we can confidently look forward to a much greater expansion in capability for research in the future as provided by electrostatic accelerator technology.

Acknowledgments. — I would like to acknowledge the cooperation of all the conferee's in helping to provide the information for this summary talk. I would also like to apologize for any oversight or error on my part in interpreting or presenting other conferee's data or comments since it is not possible in the publication time scale to solicit independent opinions and corrections to this text. References are not included in this paper, however, all the material is completely referenced in the contributed and invited papers published in the proceedings.