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ADVANCES IN ELECTROSTATIC ACCELERATORS*

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Summary

Advances in the design and performance of electrostatic accelerators since 1969 are reviewed with special emphasis on the "forefront" accelerators that are currently leading in voltage capability. A comparison of the acceleration tube design offered by the National Electrostatics Corporation and the High Voltage Engineering Corporation will also be made. Other methods of increasing heavy ion energy by means of dual foil stripping will be discussed as well as the performance of a newly developed sputter ion source for the production of negative heavy ions with reliability and flexibility that greatly exceeds all other present systems. Finally, new developments in terms of both booster systems and very high voltage electrostatic accelerators (25-60 MV) are discussed.

Introduction

The status of tandem electrostatic accelerators was last reviewed for this Conference in 1969.[1] Some of the expectations, predictions, planned projects, and construction have been realized while others have passed onto oblivion like so many favorite new ideas in the accelerator field. A recent special issue of Nuclear Instruments and Methods, edited by D. A. Bromley,[2] contains many of the details of my talk since the purpose of this special issue was to provide a communication medium and review for both research people and accelerator designers of the latest performance, construction details, and future plans for all the larger electrostatic accelerator systems. This paper could simply highlight and summarize the wealth of information in this recent journal; however, instead, a special emphasis and discussion of the forefront tandems and some of the trials and tribulations leading to the improved performance of today will be made. Many of the accelerator systems discussed in the special issue have been further improved and the current status in terms of research capability will be updated as much as possible.

The description of performance and improvements in electrostatic accelerators since 1969 can be broken down into several categories: improvements in maximum operating voltage and new kinds of charging systems; special methods for increasing the energy of heavy ions; new ion source capabilities for heavy ion production; and finally, future developments and plans. The most dramatic change since 1969 is in our understanding of the limitations and capabilities for higher and higher voltages. In 1969 we were contemplating 12 and 15 MV operation with skepticism; in 1975 we exceeded 15 MV operation and now understand acceleration tube loading and other electrostatic phenomena sufficiently well that we are now confidently constructing 25 and 30 MV machines.

I. Operating Voltage Improvements and New Kinds of Charging Systems

Some of the accelerator systems which were described[1] as under construction or planned in 1969 have now been tested and many impressive test results have been obtained by both the High Voltage Engineering Corporation[3] (HVEC) and the National Electrostatics Corporation[4] (NEC).

A. Voltage Improvements by HVEC

The High Voltage Engineering Corporation has tested their large TU class machine up to 21 MV without an acceleration tube and to 16 MV with an acceleration tube. They have also successfully accelerated protons at 16 MV and both ^{16}O and ^{127}I ions at 15 MV under test conditions.[5] Because of budget limited operational time which forced intermittent operation, most of the diagnostic tests were carried out at 14 MV or lower voltages. These impressive record voltage tests were carried out with a new kind of 14-inch diameter acceleration tube made with stainless steel electrodes. The early tests were carried out with tubes that were eventually installed in the Canadian Chalk River Laboratories accelerator (MP-3) as part of an "upgrade kit" and later tests were carried out with a second set of similar tubes eventually installed in the University of Heidelberg accelerator (MP-5). This new type of acceleration tube is now operational in five different MP accelerators: Chalk River, MP-3; Heidelberg, MP-5; Orsay, MP-9; Strasbourg, MP-10; and just recently at Yale, MP-1. The only large HVEC machines in research operations are of the MP class which have an ultimate operational voltage limit, without acceleration tubes, of approximately 17 MV as demonstrated at Strasbourg (MP-10), while the TU limits at approximately 21 MV. At present, there is no TU accelerator operational in research and the only machine of that size in existence is at HVEC.

The Chalk River machine has carried out some research at 13 MV, however, a series of difficulties of various kinds associated with the new higher voltage capability has forced their operation down to voltages of 12 to 12.5 MV. Actually, all of the upgraded machines have passed acceptance tests at 13 MV and appear to be operating in support of research programs mostly in the region of 11-12 MV at present. The second of the two MP accelerators at Brookhaven National Laboratory (BNL), MP-7, was upgraded with special smaller 8-inch diameter stainless steel acceleration tubes,[6] however, they have not performed as well as the large tubes. Initially, the machine operated smoothly at 12 MV but after a year of operation is now capable of only 11 MV for reliable research operations, which is still a considerable improvement over the previous performance with aluminum electrode tubes.

The only difficulty to date with the larger diameter tubes is their expense, however, the investment appears to be very sound because none of these new tubes have shown any evidence for the kind of insulator damage that has ultimately led to limited maximum performance lifetime for all other kinds of acceleration tubes in this class machine. Ultimately, all of the MP machines expect to operate reliably in the 14 to 15 MV region. It would appear that the tubes are capable of such performance at present but the overall system must be able to operate at these voltages reliably in order to realize a practical heavy ion research program at the corresponding high energies.

B. Voltage Improvements by NEC

The National Electrostatics Corporation does not have a test capability for their large high voltage

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accelerators at the plant. The internal parts of the machines are assembled at the plant for mechanical testing and shipped to the customer for installation in the high pressure vessel for high voltage testing and performance demonstration, which indicates the extreme confidence they have in their design. The first such large machine (14 UD) has been installed and is now operational at the Australian National University (ANU) at Canberra, Australia.[7] A second 14 UD is now under construction at the Weizmann Institute in Rehovot, Israel. Although the Canberra machine operates at 14 MV and has passed acceptance tests at that voltage, the research program at present utilizes the machine more in the 11 to 12 MV region. The difficulty with the higher voltage operation is the higher probability of occasional sparks which in turn cause damage inside the machine that require maintenance before the machine can continue in operation. Consequently, the research programs cannot operate successfully at the highest voltages. It is expected that these machines will eventually operate up to voltages in the 15 to 16 MV region when problems having to do with surge damage are corrected.

To further characterize the overall development problem of electrostatic accelerators it is interesting to contrast the NEC and HVEC philosophy of design for the most crucial part of the accelerator, the acceleration tubes. The tube developed by NEC, a section of which is shown in Fig. 1, is ~ 4 inches in diameter and assembled to any desired length from the standard section as shown.

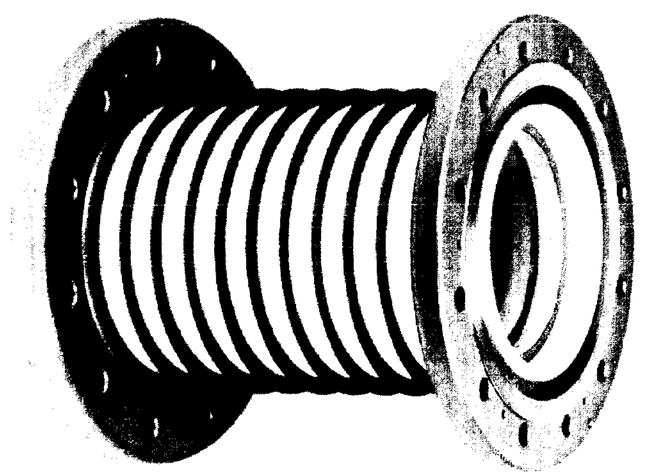

Fig. 1 Basic acceleration tube structure manufactured by NEC. The metal rings are titanium and are bonded by a proprietary process directly to the ceramic insulator sections. The assembly is approximately 10 inches long.

It is made with titanium electrodes and ceramic insulators which are bonded by a proprietary metal-to-ceramic bonding technique. This kind of joint allows the tube to be baked out resulting in a capability for attaining extremely good vacuums. The tube sections are assembled with metal-to-metal ultra-high vacuum joints and arranged with integral heating systems for high vacuum bake out. The NEC acceleration tube system can be made operational in the vacuum region of 10^{-8} torr or less. This basic design, as shown in Fig. 1, has special internal electrodes which clip into the inside and external torroidal spark gaps which clip onto the outside, as shown in Fig. 2. The electrodes are simple diaphragms without specially polished surfaces and when assembled form what is called a straight field tube. In the past, other straight field tubes have

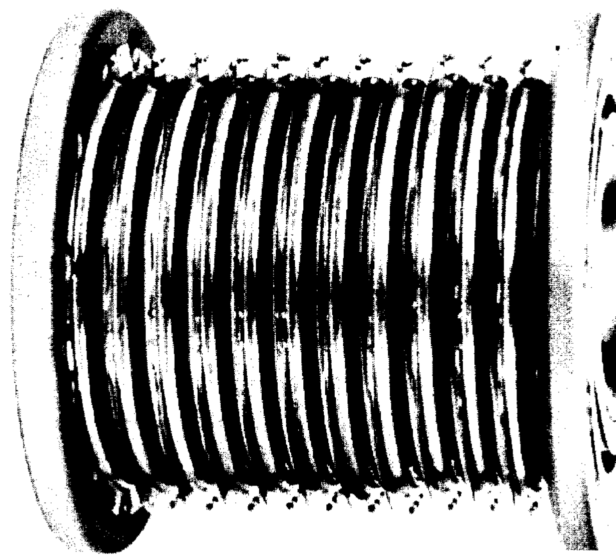

Fig. 2 Acceleration tube section of Fig. 1 equipped with external spark gaps and internal electrodes.

suffered from excess electron loading problems which NEC believes was mainly due to inadequate vacuum. So far, the performance characteristics of both the Sao Paulo[8] and Canberra[7] machines when operated within design vacuum levels do not exhibit excessive loading which shows that this design concept is basically sound. There are still some questions about the loading characteristics for very heavy ion performance in the 14 UD machine at ANU, however, these early loading problems have now been traced to vacuum pumping limitations in both the tubes and high voltage terminal.[9] The machine is now doing research and appears to be operating reasonably well at voltages in the 12-13 MV region without any special acceleration tube problems.

The new HVEC acceleration tube is also operating in this voltage region at very similar voltage gradients without any kind of special problems. It is made of highly polished stainless steel (rather than unpolished titanium) that is bonded to glass (rather than ceramic insulators) with vinyl acetate cement thereby not allowing any kind of vacuum bake out procedure. This means that the acceleration tube operates at a poorer vacuum than is possible in the NEC metal-ceramic baked out system. The operational pressure region is 10^{-6} to 10^{-7} torr depending on the vacuum history of the acceleration tube in contrast to the 10^{-7} to 10^{-8} torr of the NEC tube. The electron loading problem is taken care of by inclining the central electric field of the accelerator tube as shown in Fig. 3 so that the electrons are swept out of the acceleration tube soon after they are formed. The large diameter keeps the glass insulating surface well away from the sweeped out electrons so that they cannot interfere with the insulator performance of the glass or result in any damage.

These two completely different kinds of acceleration tubes operate successfully for reasons which have been outlined in this brief description. However, it is important to emphasize that there probably are many more processes going on inside acceleration tubes than have yet been imagined by physicists. Although these explanations for good tube performance seem reasonable and plausible, the unknown element of "witch craft" should not be discounted. The voltage conditioning "witch craft" process that allows an acceleration tube to operate smoothly and quietly at much higher voltages than it is initially capable of holding is a process that is not completely understood in the sense that very few people would care to predict good conditioning prospects for a new design, however, a simple explanation can usually be easily made for designs that either fail or are successful in test.

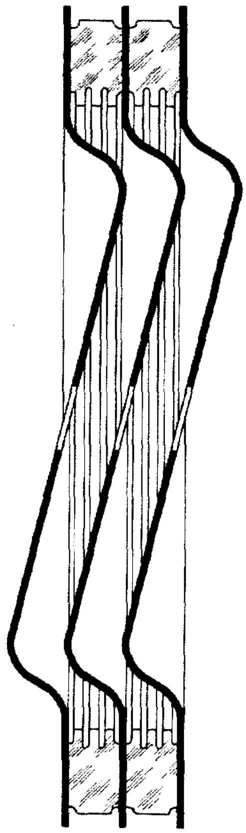

Fig. 3 Cross section of a portion of the new HVEC high gradient stainless steel acceleration tube. The slant of the electric field in the central region sweeps out any electrons formed by gas or electrode collisions by ions. The outer diameter is approximately 14 inches.

Since electrostatic accelerators have acceleration tubes that can hold voltages up to the 14-15 MV region and the electrostatic generators are also capable of smooth operation in the same region, why aren't the machines carrying out research at energies corresponding to these voltages? The reason is that for a succesful research program it is essential for electrostatic accelerators to operate extremely reliably. This means 24 hours continuous operation for several days on a particular experiment with relatively little interference or downtime during the course of the measurements. For these reasons, the research people have all programmed their research interests and requirements into the 11 and 12 MV region of operation. If they try to carry out research at higher voltages they soon find that they have little actual realizable research time during the course of the experiment because of malfunctioning of the machine one way or the other.

Most of the problems are caused by high voltage surging which apparently must always occur in any machine. It would appear impossible at this time to conceive of a large electrostatic generator that would not occasionally spark almost regardless of operating voltage. Fortunately, lower voltage sparks do not cause much damage because energy dissipation is proportional to the square of the terminal voltage. Photographs taken of terminal sparks for diagnostic purposes are shown in Fig. 4.

Fig. 4 High voltage sparks from terminal to ground at 9 MV photographed from the end of the accelerator through special windows.

These are what cause most problems in electrostatic accelerators and limit the practical operating voltage in terms of carrying out research in all of the forefront machines of today. Even though the machines can be taken to higher voltages for short term testing periods especially when everything is in the newest of operating condition they simply will not continue to operate at these high test voltages on a long-term basis for routine operation in support of research programs.

Extensive experience at BNL with the highest voltage terminal ion source in the world has provided some perspective in regards to high voltage surge damage. After initial operation at voltages in excess of 10 MV the operation has gradually settled down to reliable operation between 7 and 9 MV for negative operation of the terminal. At this voltage, most of the power supplies with their protective spark gaps and other protection systems survive occasional sparking. Some of these successful systems, when installed in the terminal of MP-7 worked well in the 9-10 MV region, however, as soon as the machine was upgraded with the new small diameter stainless tubes to a performance capability of 11 to 12 MV, some of the units began to fail from voltage surging, simply because of the increased energy dissipation.

The other MP accelerators with upgraded capability, utilizing the new acceleration tubes have also developed new problems associated with the higher energy storage and greater spark damage capability. After the first set of new stainless steel acceleration tubes were installed in the Chalk River MP accelerator and operated under research conditions, it was found that the old reliable charging belt system, invented by Robert J. Van de Graaff, suffered from premature failure at voltages in the region of 12 to 13 MV.[10] This premature failure problem with different kinds of charging belts tested at both Chalk River and at Brookhaven is still not completely understood which has led to the installation of alternate charging schemes for many MP accelerators.

The pelletron chain charging system pioneered by NEC[11] can be installed in an MP and the first such system was installed in the Yale accelerator and operated successfully in the 8 to 10 MV region before their acceleration tube upgrade program.[12] Figure 5 shows three of the six pelletron charging chains as they appeared during installation.

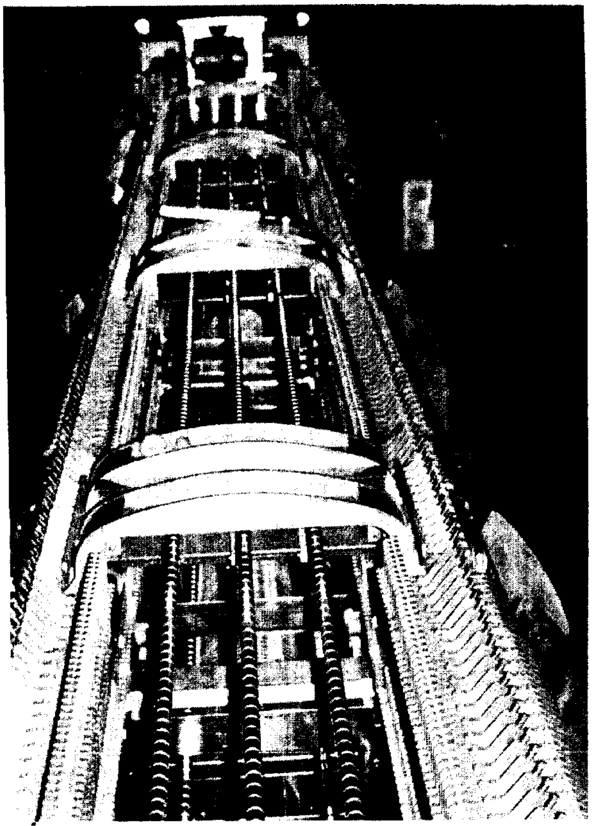

Fig. 5 First pelletron installation in the Yale (MP-1) tandem. There are three chains installed in both low and high energy ends of the machine.

When a similar system was installed in the Chalk River accelerator operating in the 12 to 13 MV region, various kinds of chain sparks, pulley damage, and vibration problems developed which required major design modifications of the chain support system. One recent problem was from high energy sparks, presumably going down the chain, jumping across the pulley to the ball bearings which were then instantaneously welded to their races. They then failed in a relative short time because of the ball damage and high speed bearing loads. Again, the increased energy dissipation at higher voltages led to new problems which were not evident with the lower voltage at Yale. These problems have now been resolved and the Chalk River machine is operating quite reliably in the vicinity of 12.5 MV. The machine still exhibits occasional mysterious sparks which are not tube or terminal sparks and presumably have something to do with the chain charging system, however, at the moment these sparks are not interfering with the research operation and only occur on rare occasions.[13]

Another important electrostatic generator component is the resistor or corona system that provides the uniform potential gradient from the terminal potential to ground. Both resistors and corona systems have worked moderately reliably on smaller machines over the years. The standard MP resistor would occasionally open or drift to higher unusable values at 9-10 MV, however, at 13 MV they opened regularly and spectacularly by blowing into little pieces! A special three-wire corona system designed for long life at approximately constant voltage drop, independent of erosion, tested well but suffered instant destruction when field tested under surge conditions.[13] The resistor systems pioneered by HVEC have been improved and further protected by new designs incorporating multiple spark gaps and the corona systems pioneered by NEC have also been improved. Many other tandem groups have devised different potential dividing systems that are now in use,[15,16,17,18] however, this paper will only review the two commercially available systems for simplicity.

In the resistor improvement program one of the main problems may be production control of the basic resistor. Figure 6 shows the damage caused by surging to a resistor used in MP-7.

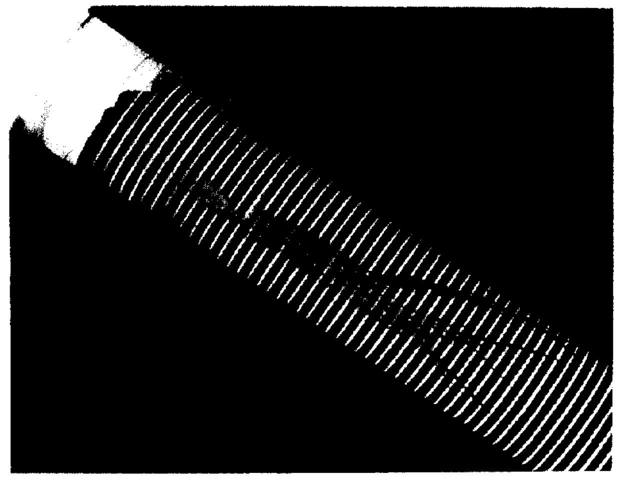

Fig. 6 Metal film 800 megohm resistor damaged by high voltage surges. The protective epoxy coating has been carefully removed to show the resistive film condition.

The protective epoxy covering has been removed to show the spark erosion.[19] It is not known whether this kind of damage occurs instantaneously with one surge or gradually with many. The basic problem with resistors is that under surge conditions they are subjected to severe over voltage. Resistor manufacturers that supply the basic product to electrostatic generator manufacturers generally do not respond favorably to performance guarantees at 1000% over voltage - to say the least. Protective spark gaps take many nanoseconds to conduct in high pressure insulating gas thereby providing little or no protection in the first few nanoseconds of a fast rising voltage surge.

A new kind of multiple component, spark gap protected, resistor system has been developed by HVEC and is shown in Fig. 7. Both a 20 and 40 element version is sold and although largely successful in research operations at 12 MV there have still been some problems.[20] Yale has recently modified this design with an additional spark gap across the resistor which in turn has additional inductive protection plus carefully made saw cuts through the epoxy encapsulation between unconnected resistor pairs in order to suppress internal breakdown through the epoxy.[21]

A complete tube and individual pressurized corona control assembly for the Weizmann 14 UD installation is shown in Fig. 8. Although NEC has incorporated the latest design features in this system it has yet to be tested under 14 UD surge conditions and consequently its reliability for research support at voltages in the range of 12-14 MV is still to be demonstrated.

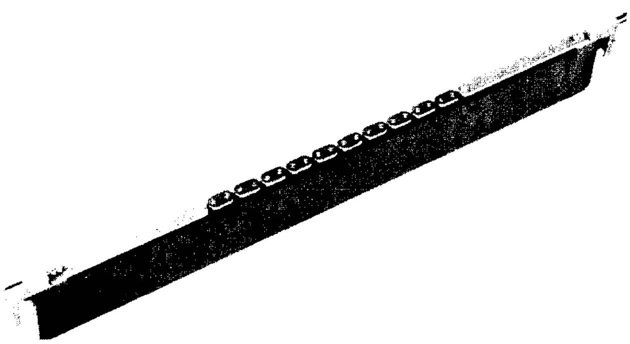

Fig. 7 New upgrade resistor design developed by HVEC. This unit contains 20 small encapsulated resistors in the epoxy block. Alternate series connections are protected by a series of spark gap connections as shown.

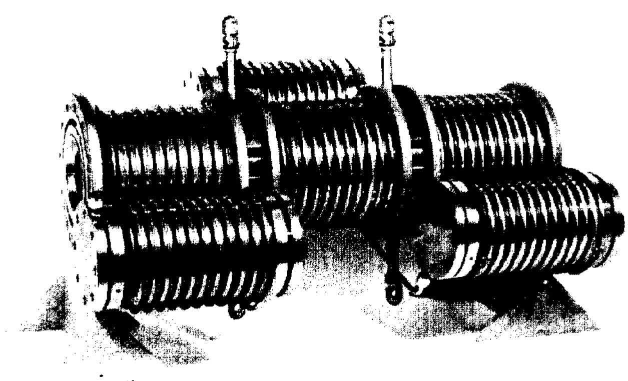

Fig. 8 Acceleration tube assembly with individual pressurized corona tube assemblies for each tube section. The whole assembly is a standard 1 MV section for any of the NEC accelerators.

All of the MP accelerators will try to achieve the mystical 13 to 15 MV capability that this overall structural design should be able to handle, however, as the voltage is raised, new and interesting kinds of surge failures will be discovered. Unfortunately, the complex machines now in use depend on all kinds of specialized internal electrical and mechanical hardware in order to achieve optimum performance. Some of the future machines being designed will depend on complex internal components for any performance whatsoever. Consequently, these internal components will have to be made extremely reliable under conditions which are generally so complex that they cannot be completely predicted.

II. Special Methods for Increasing the Energy of Heavy Ions

Special techniques can provide more heavy ion energy for a given limited terminal voltage. One recently demonstrated method is through the use of multiple stripping. This technique is not a new idea[22,23] however, the direct comparison of single and double foil efficiencies and capabilities and routine use in support of research programs has only recently been demonstrated.[24] The most probable charge state of a heavy ion produced by a stripping foil in the terminal of a tandem accelerator is not utilized in most experiments unless maximum possible current is necessary. The maximum energy is attained by compromising the maximum beam current and utilizing a less probable but higher charge state which provides higher energy. Quite often, the charge state chosen is produced at an intensity of approximately a fifth of the most probable charge state. This situation can be exploited by stripping heavy ions twice in succession.

A second foil stripper was installed at the 3/4 V_t point in the high energy acceleration tube of the second BNL tandem. This second stripper was then used to strip the most probable charge state ion from the high voltage terminal to even higher charge states after acceleration through the first tube section after the high voltage terminal. The higher charge produced by the second foil more than compensates for the lower energy gain between foils as illustrated in Fig. 9. The data in this figure show that the dual foil strippers provide an increase in heavy ion energy of approximately 10% over what would otherwise be available at comparable intensities with a single foil in the high voltage terminal.

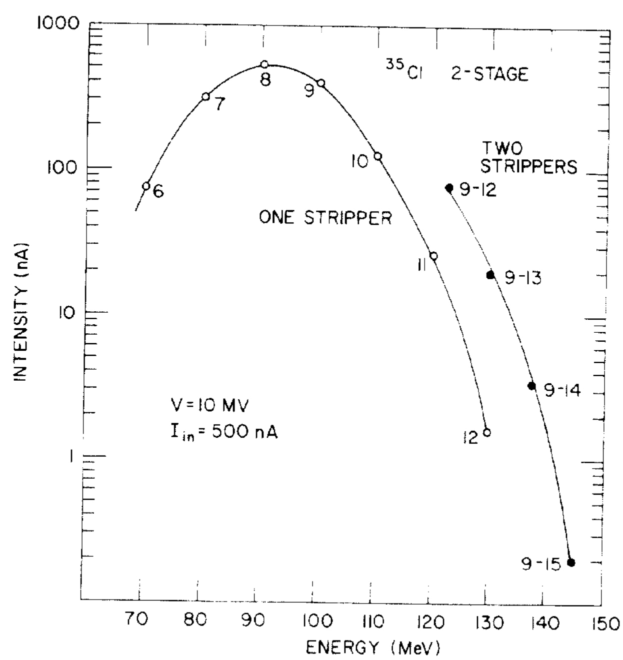

Fig. 9 Analyzed beam intensity (current nA) of ^{35}Cl ions as function of energy (MeV) for single (terminal) and dual (terminal + 3/4 V) foil stripping. The 9^{+}-13^{+} dual stripping point shows a factor of 10 increase in current for the same energy (single stripper 12^{+}) or 10 MeV more energy at the same current (single stripper 11^{+}).

In the early history of the operation of these large electrostatic machines, they were mostly used for proton and light particle acceleration but now are used mostly for heavy ion acceleration all the way to the mass of uranium. The carbon stripping foils were not any special operational problem for proton acceleration and had appreciable long lifetimes, however, with the advent of increased heavy ion operation they were found to have operationally useless, short lifetimes. For ions as heavy as Ni or Cu and modest injected beam currents like .3 μA, the foil lifetime was extremely short like five to ten minutes. Although gas stripping has no lifetime problem or current limitation, the most probable charge state is approximately half or less than that provided by foils for the heavier ions[25] which means that experimental necessary energies cannot be provided by gas stripping either. This basic foil lifetime problem can now be alleviated by using the combination of gas stripping in the high voltage terminal followed by foil stripping at the V 3/4 point[26] as indicated in Fig. 10.

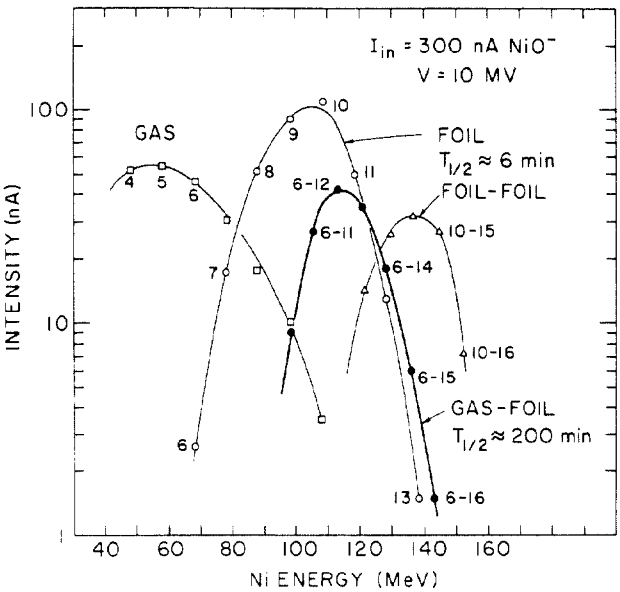

Fig. 10 Analyzed beam intensity for ^{58}Ni ions as function of energy (MeV) for single gas and foil stripped ions and also double stripped by gas-foil and foil-foil combinations. The 6^{+}-14^{+} gas-foil stripping current and energy is equivalent to that of the 12^{+} single foil stripping condition with a lifetime improvement of approximately 30 times.

The data show that for the acceleration of NiO ions providing a 120 MeV Ni 8^{+} beam, the current and energy are completely equivalent to a single foil stripper as long as the usual high side of the charge state distribution is used to obtain the desired energy. This gas foil combination was found to increase the foil lifetime, now in terms of the second foil stripper, 20 to 30 times over that experienced with a single foil stripper in the high voltage terminal. This kind of "trickery" with additional stripper foils has consistently extended the performance and capability of tandem accelerators both in terms of the overall beam current and energy for all varieties of heavy ions. This technique is not new and has been proposed for other facilities,[27,28] however, it is important to demonstrate the practical operation of such a system and utilization in regular research operations.

III. Ion Source Improvement

The epitome of ion "sourcery" is negative heavy ion "sourcery". The production of negative heavy ions usually involves "atomic trickery" while the production of high charge positive state heavy ions more usually involves "brute force". The capability for producing negative heavy ions of all varieties with quick change capability from one ion to another and long term stable operation is as important to the major heavy ion physics programs of tandem accelerators as their stable and reliable operation. Until recently, heavy ion negative ion sources were all based on some kind of plasma discharge from which negative ions were directly extracted or else gas or vapor charge exchanged with positive ions. Although many such sources reported at this Conference and others have all produced many varieties of negative heavy ions, many have operational problems with long term reliability and capability for rapid change from one heavy ion species to another. For many source designs a change from typically $^{32}S^{-}$ to $^{18}O^{-}$ might require as much as 6 or 8 hours including the conditioning time necessary to achieve optimum operation. Although a special source dedicated to a particular ion could in principle be "plugged in" to operation as needed, the real world of budget limitations does not allow this method of time saving. This time is generally lost for research purposes and comes out of the operating period assigned to the particular research team that is trying to carry out a research program. Consequently, most research teams in the past have been reluctant to change beams during a run and possibly lose a large part of their research time because of ion source tuning.

A completely new kind of negative heavy ion source has recently been developed by R. Middleton[29] of the University of Pennsylvania, and is now commercially available[30,31] for tandem operation. The source utilizes an application of space-age technology in the form of a cesium boiler system that ionizes cesium ions by diffusing them through hot porous tungsten. This technique was developed to practical levels as one means of providing ion thrusters[32] for the purpose of correcting satellite positions on a long-term basis. The positive ions diffusing through the hot porous tungsten are accelerated to 30 keV and arranged to impinge on various solid materials. The heavy cesium ions sputter out atoms or compounds from target material with which they collide and simultaneously produce large quantities of negative ions of the sputtered atoms or compounds. One of the more exotic materials sputtered recently at Brookhaven was XeF_2 forming XeF^{-} ions and thereby allowing the acceleration of xenon in a tandem accelerator.

The first commercially available version of the Middleton sputter source was offered by the Extrion Corporation[30] as a UNIS source, initials standing for "Universal Negative Ion Source", and more recently a somewhat different design has been offered by the General Ionex Corporation.[31] The Extrion UNIS source has been in operation at Brookhaven for over a year, however, a number of mechanical modifications and design changes were necessary in order to achieve long-term reliable operation. The source now operates routinely for 2 weeks at a time on a 24 hr./day, seven day/week basis. The record continuous running time on research without any maintenance is 4 weeks. The source allows a change from one type of heavy ion to another in approximately five minutes and 18 different selections are available with one setup of the source. On one experiment as many as 12 different heavy ion beams ranging from ^{32}S to ^{98}Mo were provided at different energies for calibration purposes in an eight hour period. Similar performance by any other kind of heavy ion source would be virtually impossible.

Now that the source is in routine use, many research programs need or require several ion changes during the operational period of a specific experiment. The fast change capability allows the research teams to make exploratory measurements with contrasting reactions. In the event that the accelerator performance is limited or there is some other difficulty with the experimental equipment the scientist can rapidly change the experimental plan to an alternate beam ranging from ^{6}Li to ^{18}O to ^{45}Sc or literally to whatever heavy ion beam is desired. This method of operation especially exploits the dynamic range and capability of the tandem accelerator and was not previously possible because of the limited capability and changeover time required by more conventional heavy ion sources. The dynamic capability of this new source has generated a pressing need for the same capability for three-stage operation at the BNL tandem facility and a high voltage terminal version is being designed.

A partial list of UNIS source operating characteristics for experiments carried out on the machine over the last year is in Table 1. The tabulated performance characteristics were extracted from the accelerator operational logs and are representative of normal operations in support of the heavy ion research programs.

Table 1

Accelerated Ion	Ion Mass	Injected Negative Ion	Injected Current (μA)	Final Energy (MeV)	Analyzed Beam Current (nA)	Ion Charge State
H	1	H	2.300	23	60.00	1
Li	7	Li	0.900	40	360.00	3
Be	9	BeO	0.650	39	80.00	4
C	12	C	0.900	65	500.00	5
C	13	C	2.000	68	500.00	6
N	14	NH	0.120	42	100.00	5
O	16	O	0.500	60	120.00	6
O	18	O	0.500	65	800.00	6
F	19	F	1.800	63	500.00	6
Si	28	Si	0.300	121	20.00	10
S	32	S	2.000	110	400.00	10
Cl	35	Cl	2.700	96	100.00	10
Ca	40	CaO	0.250	118	8.00	10
Sc	45	ScO	0.030	98	3.00	8
V	51	VO	0.060	92	5.00	8
Fe	56	FeO	0.480	98	70.00	9
Ni	58	NiO	0.640	97	90.00	10
Zn	64	ZnO	0.200	103	15.00	9
Ge	74	Ge	2.000	42	500.00	5
Br	79	Br	0.200	125	10.00	10
Br	81	Br	0.200	125	10.00	10
Sr	88	Sr	0.650	84	200.00	8
Nb	93	NbO	0.200	42	180.00	6
Mo	98	MoO	0.300	41	70.00	6
I	127	I	2.500	90	300.00	9
Xe	132	XeF	0.020	90	2.00	9
Au	197	Au	3.000	99	40.00	10
Pb	208	Pb	0.030	110	2.00	10
U	238	U	0.024	113	0.45	11

Improvements in the future may provide even further increases of intensity so that low percentage isotopes of various elements might be provided in adequate intensities and thus rare isotope beams would be available without the expense of separated isotopes. Fortunately, even in some cases where separated isotopes are necessary, they now can be used at modest cost because of the small amount of materials necessary to provide relatively large quantities of negative ions.

IV. Further Developments and New Construction Now Underway

A. Booster Systems

Instead of working on the voltage improvement of tandems, different research groups around the world are actively pursuing the development of specialized pulsed accelerators designed for injection by specially pulsed tandem accelerators that would provide a "giant leap" to a much higher energy heavy ion capability. The idea is to greatly extend the range of heavy ion energy capability over that provided by the tandem in normal operation. R. H. Stokes and coworkers at LASL have worked out a spiral resonator LINAC operating CW at room temperatures with the purpose of providing a major increase in performance capability over what at present is possible with a tandem.[33] A superconducting helical resonator has been used to accelerate protons and ^{16}O ions during a test run at Argonne National Laboratory[34] and other groups at Stanford,[35] at Heidelberg and Karlsruhe,[36] and at Cal Tech[37] are also designing and testing superconducting systems. Groups at Heidelberg[38] and Munich[39] are also studying room temperature LINAC systems as other possible booster accelerators for their tandem facilities.

Superconducting cyclotrons are also being considered by groups at Chalk River,[40] Michigan State,[41] and Berkeley[42] as possible boosters for tandems and other cyclotrons as well. All of these different systems are being designed to maintain as well as possible the high quality beam properties of the tandem which mainly depends on the ability to bunch the beam down to picosecond lengths. Bollinger has recently reported bunch lengths of 70 picoseconds or less for tandem accelerated ^{16}O ions[43] which means that practical high quality booster acceleration is possible if all the other problems of the superconducting systems, control, beam transport, etc. can be worked out. Finally, the group at Indiana, building the first separated radial sector focused cyclotron in the U. S. is also considering the possibility of utilizing an FN tandem as an injector in order to provide a wide-ranging heavy ion capability.[44]

B. Very Large Electrostatic Systems

Instead of resorting to booster accelerators, other groups are taking giant leaps (factor of 2-3 over present performance capability) in the direction of increasing electrostatic voltage capability.

1. The Daresbury 30 MV Nuclear Structure Facility (NSF). The electrostatic machine development team at Daresbury, England is constructing a 30 MV vertical tandem accelerator. It is well on schedule and planned for completion in 1978. The machine design has been described in detail,[18] however, it is now under construction and further design developments have been made. A completely new design for the support column, acceleration tubes, and charging system have resulted from the efforts of the Daresbury group. They have developed a chain type charging system called the "Laddertron" wherein flat conducting slats are transported at high speed from ground to the high voltage terminal by a chain-like structure arranged for inductive charging. One of these laddertron chains is equivalent to approximately 3 pelletron chains in charging current. Figure 11 shows the type of structure used in laddertron construction.

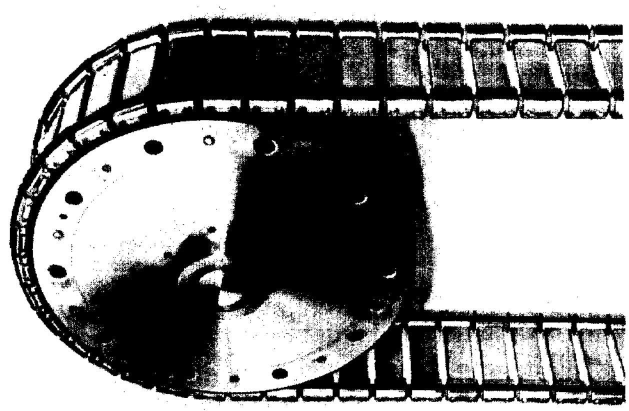

Fig. 11 Laddertron chain charging system developed by the Daresbury accelerator group. Each of the flat plate sections is inductively charged at ground and discharged at the high voltage terminal. This new charging system will be used in the 30 MV electrostatic accelerator now under construction in Daresbury, England.

Performance tests with this new charging system on an 8 MV test generator at Daresbury have shown that the present design exceeds the necessary performance for the 30 MV design. This kind of charging chain may very well be used as an alternative to the pelletron system in the future and will be offered commercially in the U. S. by HVEC. The machine design will incorporate many new features of beam transport technique through the machine as well as more elaborate internal control and diagnostics that have not been previously possible in smaller machines.

C. HNL 25 MV Tandem

A large tandem rated at 25 MV is being proposed for construction at the Holifield National Laboratory (HNL) and planned for completion in 1979. This machine will be of a folded rather than the customary straight through design which has been standard till now for most large tandem accelerators. In this vertical design, the beam will be accelerated up to the terminal from the ground, turned 180° and accelerated back to ground after stripping and charge selection in the terminal with both the low and high energy acceleration tubes parallel and inside the same support structure. This arrangement makes the vertical machine much shorter because only one support column is needed for both acceleration tubes and additional height of one or two stories is not required on the top of the accelerator for the ion source laboratory. A comparison of relative size for the two basic machine designs as proposed for HNL is shown in Fig. 12. Perhaps the main problem of the folded design is that the performance depends completely upon the proper operation of the large 180° bending magnet that turns the beam around. If the performance of this magnet is interrupted in any way by damage from a terminal spark the machine must be opened for repair before any kind of performance is possible. At this time, bids have been received by HNL from both HVEC and NEC for the construction of this accelerator with guaranteed performance. The reader is referred to several papers in this Conference for details on the status of this new large machine.[45,46,47] This machine will have an additional booster capability by being arranged to inject the ORIC cyclotron with an expected heavy ion energy gain of up to four times.[48]

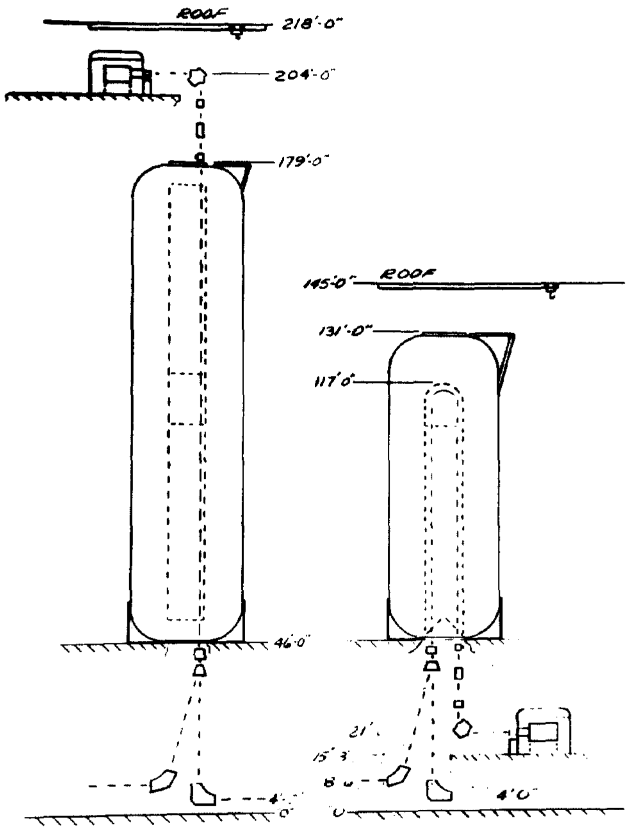

Fig. 12 Relative size comparison for a 25 MV conventional and new folded design of tandem. The building that houses the conventional vertical tandem must have an additional two stories for the ion source laboratory and associated structures as shown.

If the scientific needs of the country for heavy ion physics in the future require even larger tandems, they can, in principle, be built. For example, a 60 MV tandem could easily provide uranium ions of several GeV, well over the Coulomb barrier of uranium, thereby allowing the study of the reactions of any nuclei combinations throughout the entire Periodic Table. Such a large machine would only be practical if built on the basis of a separation column design as pioneered by McKibben[15] in the large vertical Van de Graaff accelerator at Los Alamos. This design isolates the outer part of the support column from the inner part containing the charging system, acceleration tubes, etc. in terms of the insulating gas in such a way that only the inner portion of the accelerator ever needs to be pumped up and down for maintenance. Even though the voltages are well beyond all present available experience, even with 25 to 30 MV machines yet to be tested, it is interesting to speculate that surge protection might even be more easily arranged than in smaller machines because of all the space inside the high voltage column structure and terminal region. This extra space could be used to provide multi-layer shield systems with multiple alternate paths to ground for protection of internal hardware components from 60 MV surges on the exterior separation column. The large column diameter would also be convenient for elevator access for maintenance, modification, and adjustments to the internal components inside the multi-layered shielding system.

Conclusion

In conclusion, it is clear that a number of solid advances and improvements have been made over the last five years in the performance capabilities of electrostatic machines. Even though these improvements have been modest from the standpoint of increased terminal voltage, they have definitely demonstrated a solid reliability for most of the basic components of electrostatic accelerators that previously were too unreliable for present considerations involving the building of much larger machines.

In one sense, a lot of the witch craft has now been removed from the basic design of acceleration tubes and it would appear that much larger machines, double the present operating voltage capability, will be built and operated successfully in support of the wide ranging heavy ion research programs pursued in this country and throughout the world.

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