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NORTH-AMERICAN MP TANDEM ACCELERATORS

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Résumé. — Les accélérateurs tandem MP en Amérique du Nord sont au nombre de six. Serial § 1. Yale; § 2. Minnesota; § 3. Chalk river; § 4. Rochester; et § 6 et § 7. Brookhaven. L'état actuel et les caractéristiques de fonctionnement de ces six accélérateurs sont discutés. L'augmentation en performance et les améliorations particulières des différentes machines sont examinées et les développements nouveaux apparus depuis la dernière conférence électrostatique sont discutés en détail. Les caractéristiques du fonctionnement au cours de la dernière année pour les différentes machines sont comparées entre elles.

Abstract. — The North-American MP Tandem accelerators are six in number. Serial § 1. Yale; § 2. Minnesota; § 3. Chalk river; § 4. Rochester; and § 6 and § 7. Brookhaven. The current status and operating characteristics of these six tandem accelerators will be discussed in the order of their serial numbers. Upgrade and special improvements of the different machines will be reviewed and new developments since the last Electrostatic Conference will be discussed in detail. The overall operating characteristics of the different machines during the last year of operation will be compared.

The Second International Conference on Electrostatic Accelerator Technology will review the improvements and progress in accelerator technology since the first conference held four years ago [1]. At the time of the first conference only a few of the MP accelerators had been upgraded with the new large diameter stainless steel acceleration tubes and relatively limited experience had been obtained at that time with these tubes in the different laboratories, with the exception of Chalk River which had the first such installation. Previous to this upgrade capability all of the MP accelerators were operating with aluminium electrode acceleration tubes and the performance was limited to the 8-10 MV region because of breakdown difficulties with this type of tube. Now, four years later, we can report that most of the North-American MP's that have been upgraded in one way or another are operating at voltages in the vicinity of 12-13 MV on a routine basis for their associated research programs. A number of improvements and innovations have also been developed over the last four years and have contributed to improved performance and ease of operation of these accelerators as well. Some of the improvements discussed in this paper were also reported in the special issue of *Nucl. Instrum Methods* edited by D. A. Bromley [2].

By serial number, the North-American MP machines are as follows : § 1. Yale University; § 2. University of Minnesota; § 3. Chalk River Laboratories in Canada; § 4. University of Rochester; and § 6 and § 7. Brookhaven National Laboratory. My review of the current operating characteristics of these machines and the various improvements in design and capability carried out over the last four-year interval will be in the order of their serial numbers.

1. The MP tandem accelerator at Yale University [3] ⁽¹⁾. — The Yale MP-1 tandem accelerator was the first of the MP machines to change from the conventional charging belt to the NEC-developed pelletron chain-charging system [4]. Typical charging currents at 13 MV operation are reported to be 260 μA of charging current shared between the low and high energy resistor strings, 80 μA each, the control corona, 40 μA and 60 μA of losses associated with a 4 curie ^{137}Cs radiation source. At present the charging current appears to be limited to a maximum of 400 μA with the six chain pelletron system.

The accelerator has also been upgraded with the large diameter stainless steel acceleration tubes [5] and the special so-called *blue* resistors [6] which are part of the standard upgrade kit provided by the High Voltage Engineering Corporation. They have installed

(*) Work supported by the U.S. Energy Research and Development Administration.

⁽¹⁾ P. D. Parker, private communication.

separate tube resistors on tube sections 4 and 5, immediately adjacent to the high voltage terminal on the low and high energy end, respectively, and § 6 section as well. Their operating experience to date shows that the parallel isolated resistor networks on the acceleration tubes do not suffer any spark damage which so far has been limited exclusively to the column resistors. Installation of similar separate tube resistors on the rest of the acceleration tubes is planned for the future.

The blue epoxy-embedded resistor strings initially showed a gradual development of shorting paths through the epoxy material between the ends of the resistors opposite the series gaps. A number of the resistors were modified with diamond-saw cuts through the epoxy so that an additional insulating gas space was provided between adjacent resistors. This modification eliminated that particular breakdown problem. Subsequently, an additional protecting spark gap was designed and installed across the resistor strings arranged with an inductive loop connection to the resistor strings as shown in figure 1. This additional protection has eliminated the breakdown problem originally encountered within the epoxy so that the saw cuts are no longer necessary for reliable performance.

FIG. 1. — Auxiliary protective spark gap with inductive connection to resistor string for the Yale MP-1 column resistors.

The accelerator has also been provided with a terminal cryo pump system manufactured by the General Ionics Corporation [7] utilizing the CTI cryopump. A foil-stripper assembly of the NEC type [8] was recently installed in the first dead section after the high voltage terminal, between tube sections 5 and 6 thereby providing a dual-stripping capability. The accelerator operation is 82 % heavy ions ($A \geq 6$) and 18 % light ions ($A \leq 4$). Most of the beams used in the research programs are provided by a sputter ion source which has provided μA currents of Ni, Ge and NbO beams for the research programs. Particle transmission for most ion beams is 50-60 % in terms of the high energy to low energy cup ratio. The insulating gas mixture in use in the machine is 33 % SF_6 , 12 % CO_2 and 55 % N_2 at a pressure of 150 PSIA.

A plot of percent operating time *versus* terminal voltage in MV for the last year of operation is shown

in figure 2 and indicates a major amount of operation in the 11-12 MV region which is a major improvement over that reported at the last accelerator conference.

FIG. 2. — Per cent operating time vs. terminal voltage for the Yale MP-1 tandem accelerator from January 1976 to May 1977.

2. The MP tandem accelerator at the University of Minnesota ⁽²⁾. — The Minnesota MP-2 tandem accelerator, which was the second to be manufactured of ten, now appears to be the first of this class machine to be closed down. The facility recently lost its ERDA funding and alternate funds for continuing operation have not been approved by the National Science Foundation. Present plans are to close down all operations in the fall of 1977.

The machine was never upgraded to the extent of the other MP accelerators; however, some interesting innovations have been carried out. At present, a specially modified design of the old, large diameter aluminium tubes is being used in the machine [9]. These new tubes provided some improved performance capability over the older aluminium design and were relatively inexpensive compared to the standard upgrade acceleration tubes. This means that they could be disposed of if necessary when contaminated with special kinds of radioactive ions like tritium and ^{14}C which were being planned for future experiments.

A special radioactive ion source enclosure was added to the rear end of the ion source cage in the form of a steel tank, $12 \times 8 \times 10$ feet, which is accessed solely from the building and provided with hot lab ventilation and glove-box facilities. With this kind of arrangement and appropriate differential pumping, virtually any kind of radioactive material desired can be accelerated with the special sputter source installed inside the radioactive containment vessel. With the imminent close down of the facility it

(2) J. H. Broadhurst, private communication.

FIG. 3. — Crossed field magnetic triplet designed to stop up to 4 MeV electrons in the dead sections of the Minnesota MP-2 tandem accelerator.

is not clear that the radioactive source capability will ever be tested to any extensive degree which would be very interesting in terms of the degree of radioactive contamination that will migrate into the acceleration tubes.

The dead sections are equipped with a magnetic suppression system to provide electron isolation from one tube section to the next. The crossed-field magnetic triplet design as shown in figure 3 is in a configuration that allows beam particles to pass without deflection but is capable of trapping electrons up to 4 MeV in energy. With this magnetic suppression individual tube conditioning added up arithmetically on the full set of tubes. At present the accelerator will operate up to 11.6 MV, but suffers from tank sparks beyond that voltage for reasons which have not yet been determined.

The acceleration tubes are decoupled from the column by replacing the regular spring connections from the column to the tube with straight lengths of resistive spark plug wire that is used in automobiles to aid in interference suppression from the ignition system. Each wire connection is approximately 20 in. long and equivalent to around 15 k Ω resistance. After 6 000 hours of operation with the new tubes there were no tracks and at the end of 8 000 hours there

were two light tracks in tube section 4. This technique may be an alternate solution to independent resistive strings as is now used in the other machines; however, the long-term stability of the resistive wire could be a problem especially in the presence of SF₆ corrosive breakdown products.

The operating terminal voltage of the machine as a function of running time is shown in figure 4 and

FIG. 4. — Per cent operating time vs. terminal voltage for the Minnesota MP-2 tandem accelerator during 1976.

shows that the principle operational voltage utilized during the last year of operation has been between 9 and 10 MV. Total beam-on time was about 58 % of the overall 24-hour, 7-day operation time including all maintenance, holidays, etc.

3. The MP tandem accelerator at the Chalk River Laboratories in Canada ⁽³⁾. — The Chalk River MP-3 accelerator was the second such machine to be modified from a belt to a pelletron-charging system. The pelletron has worked quite well after early problems with chain oscillation and idler damage which was subsequently corrected by design changes of the system. Currently the pelletron is providing reliable operation to voltages as high as 13.4 MV and the voltage ripple is routinely 500 V or less. This machine is also provided with a second foil stripper between tube sections 5 and 6 and features a special cup valve that allows the foilchanger system to be sealed off from the acceleration tube for reloading so that the tube does not have to be let up to air during the reloading process. A schematic of the cup-type seal is shown in figure 5 and detailed construction plans are available from Chalk River on request. After the initial cup installation, it was found that the O-ring seal of the cup suffered from radiation damage from the secondary electrons in the vicinity of the foils and suitable modifications have been made to eliminate this problem.

FIG. 5. — Special dead section cup valve for removal of the second foil stripper while maintaining tube vacuum in the Chalk River MP-3 tandem accelerator.

Another interesting improvement was in the NEC foil changer used for the terminal and second foil stripper [8] and also used in many different MP facilities. The foil capacity of the changer was doubled by welding additional foil support tabs inbetween each of the present existing tabs. This kind of development can be readily used in all the machines using this foil

changer because they all suffer from the problem of running out of foils too quickly, especially when the heaviest ions are being used in the research programs.

The transmission of heavy ions through the machine was improved by a factor of two by special modifications of the electrode assembly at the front end of tube section § 1 and the installation of a quadrupole doublet in front of the gridded lens.

The insulating gas for this machine is pure SF_6 . The original liquid storage system was recently converted to gas storage with a purchase of a 5 000 cubic foot storage tank. The gas-storage system has greatly simplified the gas handling with exchange of 40 some odd valves necessary for the liquid storage by 4 valves required for the gas storage.

The performance characteristics of the machine from september 1974, about the time of the last Electrostatic Accelerator Conference, to april 1977 is shown in figure 6 and indicates a predominant amount of operation up to 12.5 MV with an appreciable amount as high as 13.5 MV.

FIG. 6. — Per cent operating time vs. terminal voltage for the Chalk River MP-3 tandem accelerator from septembre 1974 to april 1977.

4. The MP tandem accelerator at the University of Rochester ⁽⁴⁾. — The Rochester MP-4 tandem accelerator features a number of special design improvements most of which were made on or before the time of the last conference [10]. The accelerator has a completely enclosed terminal area larger in diameter than the column diameter so as to properly minimize the potential gradient non-uniformity at the ends of the terminal. The complete enclosure also provides additional protection for terminal components from sparking as well as more volume for terminal component installation and is being considered as

⁽³⁾ N. Burn, private communication.

⁽⁴⁾ T. S. Lund, private communication.

an appropriate modification for the two MP accelerators at Brookhaven.

A special RPC resistor for both column and tube has worked quite successfully in MP-4; however, subsequent production of these resistors has not worked out in other accelerators presumably because of some change in the fabrication details of the resistors. The Rochester group pioneered the use of separate tube resistors now used on many other machines and has had great success with this arrangement.

Cryogenic terminal pumping was first used in the Rochester machine and the two cryogenic cold heads are just now being overhauled after 18 000 hours of operation with complete reliability over this period of time.

At the time of the last conference, a new set of specially designed acceleration tubes which are a spiral slant electron suppressed tube had just been installed and are shown in figure 7. These tubes initially were made with aluminium electrodes with only one section of titatium. At high voltage, the aluminium tended to sputter and cause sparking problems and subsequently the tubes have been gradually changed to an all titanium system which now allows operation at voltages as high as 12 MV. These tubes have worked out quite successfully with 18 000 hours on § 4, the original titanium tube, and varying lesser hours on other sections as they were purchased with tube section 1, the most recent, with 5 000 hours. The titanium tubes have not shown any form of damage from high voltage surging and the present operating

FIG. 7. — Special titanium spiral slant electrode acceleration tube design as used in the Rochester MP-4 tandem accelerator. The outer diameter of the tube is 8 in.

voltage limitation appears to be instabilities that are induced by the belt charging system resulting in terminal and knee sparks.

The sensitive method of monitoring conditioning by observing microdischarges in the acceleration tube sections with photomultiplier tubes looking at each section was also innovated by Rochester and is now used on other accelerators as well. Figure 8 shows the photomultiplier-tube arrangement on the machine which observes the tube sections through specially installed light pipes and the shorting rod cable arrangement used for individual conditioning of tube sections, two at a time. The metal cables are pulled out of the spring-loaded reels in the terminal with a monofilament nylon line approximately 2 mm in diameter. The fixture on the end of the cable can then be used to connect the terminal to the different dead sections selectively so that a particular section, defined by the cable and shorting rod, can be conditioned as an individual unit. They have found that individual tube sections condition quickly to 3 MV in two to three hours while 3.5 MV takes as much as twice as long. After the individual conditioning, the machine goes up to 12 MV quite easily; however, voltages in excess of 12 MV have been limited by sparking as discussed previously.

FIG. 8. — Layout of the photomultiplier conditioning monitors, shorting bars, and shorting cable drums on the Rochester MP-4 tandem accelerator.

The Rochester group has studied the transmission efficiency of the accelerator for various heavy ions ranging from ^{16}O to ^{197}Au [11]. The results of these measurements are shown in table 1. The observed particle ratio *versus* the predicted ratio for the most probable charge state after allowance for the entrance grid, decreases from 0.892 for ^{16}O to 0.611 for ^{32}S , to 0.522 for ^{58}Ni , to 0.228 for ^{197}Au . This decrease in transmission efficiency appears to correspond to a gas scattering or stripping loss effect and shows that external and terminal pumping are not sufficient for good particle transmission of the heavier ions in the MP configuration. These data make a strong case for dead section pumping along the tube as is now being done on the Munich MP-8 tandem accelerator [12].

The performance of the accelerator during 1976 is shown in figure 9 and indicates that most of the operational time was in the vicinity of 9.5 to 10.5 MV with a more recent capability in the 11.5 to 12.5 MV region

TABLE I
Heavy Ion Transmission Data

Beam Type	Charge State Q^+	Injected Current I_{LE} (μA)	Analyzed Current $I_Q +$ (μA)	Particle Ratio	Predicted Ratio	Predicted Ratio After Allowance For Grid	Transmission Efficiency
^{16}O	+ 4	0.500	0.740	0.370	0.461	0.415	0.892
^{16}O	+ 5	0.500	0.820	0.328	0.377	0.339	0.968
^{32}S	+ 4	8.0	4.6	0.1438	0.2011	0.1810	0.794
^{32}S	+ 5	6.2	6.2	0.2000	0.3637	0.3273	0.611
^{32}S	+ 6	6.2	4.0	0.1075	0.2790	0.2511	0.417
^{32}S	+ 7	6.1	1.1	0.0258	0.0908	0.0817	0.316
^{32}S	+ 8	6.0	0.32	0.0067	0.0125	0.0113	0.593
^{32}S	+ 9	7.8	0.085	0.0012	0.0007	0.0006	—
^{58}Ni	+ 4	0.600	0.300	0.125	0.2269	0.2042	0.622
^{58}Ni	+ 5	0.700	0.460	0.131	0.2788	0.2509	0.522
^{58}Ni	+ 6	0.700	0.360	0.0857	0.2099	0.1889	0.454
^{58}Ni	+ 7	0.650	0.220	0.0483	0.0968	0.0871	0.555
^{58}Ni	+ 8	0.650	0.130	0.0230	0.0274	0.0247	0.931
^{197}Au	+ 6	1.80	0.300	0.0277	0.1346	0.1214	0.228
^{197}Au	+ 7	2.30	0.380	0.0236	0.0840	0.0756	0.312
^{197}Au	+ 8	2.20	0.175	0.0099	0.0424	0.0382	0.259
^{197}Au	+ 9	2.17	0.070	0.00358	0.0173	0.0156	0.229
^{197}Au	+ 10	2.05	0.020	0.00097	0.0057	0.0051	0.190
^{197}Au	+ 11	1.90	0.005	0.00024	0.0015	0.0013	0.185
ADDITIONAL DATA WITH LE DEFINING APERTURE REMOVED							
	+ 7	4.00	0.600	0.0214	0.0846	0.0756	0.283

FIG. 9. — Per cent operating time vs. terminal voltage for the Rochester MP-4 tandem accelerator for 1976.

utilizing the full complement of titanium acceleration tubes.

5. The three-stage facility at Brookhaven National Laboratory. — The three-stage tandem accelerator facility at Brookhaven National Laboratory consists of two model MP Van de Graaff accelerators, serial numbers 6 and 7, arranged in line so that MP-6 can inject negative ions up to 10 MeV energy into MP-7 providing a three-stage mode of operation. The injec-

tor accelerator, MP-6, may also be used as a standard two-stage accelerator having been equipped with an external ion source and target room facility. The Brookhaven upgrade program was recently reviewed by Thieberger *et al.* [13] and will again be summarized here.

The BNL Tandem staff had originally designed, constructed, and installed into the MP-6 high voltage terminal an off-axis, direct-extraction duoplasmatron negative ion source for the initial three-stage operation in 1969 and has now upgraded the three-stage performance by the installation of a terminal mounted negative ion source based on the cesium sputter principle as originally developed by R. J. Middleton [14]. In addition, both accelerators have new stainless steel acceleration tubes and other improvements that allow for negative operation of MP-6 to 10 MV and positive operation of MP-7 to 13.25 MV. These improvements in operation have now provided record electrostatic accelerator heavy ion energies for the research program of 125 MeV $^{16}O^{8+}$, 200 MeV $^{32}S^{16+}$ and 255 MeV $^{63}Cu^{19+}$.

5.1. MP-6 IMPROVEMENTS. — **5.1.1. Acceleration Tubes.** — The injector accelerator, MP-6, had been equipped with standard large diameter aluminium tubes since the beginning of the facility, with all previous upgrade efforts concentrated on MP-7. When the MP-7 small diameter stainless steel accele-

ration tubes were upgraded to the large diameter stainless steel tubes, the smaller tubes were reconditioned and installed in MP-6 as an interim upgrade. Since the positive voltage operation is limited to the maximum negative capability (10 MV negative at present) in order to maintain optimum reliability for injector operation, separate resistor strings for the tube sections are not necessary for reliability and long life.

5.1.2. Terminal ion source improvements. — The advent of the Middleton-type sputter ion source for two-stage operation considerably reduced the utilization of three-stage operation because of the limited selection of available heavy ions from the terminal off-axis duoplasmatron and the inability to quickly change from one ion species to another. Several years of development, modifications, and improvements to achieve a reliable two-stage operation with sputter sources have indicated the main design elements necessary for a high voltage terminal system. Such a system, utilizing a Hiconex negative ion source [15], was designed, constructed, successfully bench tested, installed in MP-6, the injector accelerator, and used successfully in support of the research program. The entire electrical power-interlock system for the terminal source was also redesigned and upgraded for the new source installation.

The original terminal source was mounted off-axis at an angle of 90° to the beam direction and injected onto the axis with a special electrostatic reflector which was also transparent for the normal two-stage beam. The sputter source, because of its prolific production of both carbon and oxygen ions as well as many other negative ions throughout the periodic table, requires a crossed-field analyzer for appropriate mass analysis in order to avoid loading the

accelerator with large numbers of unwanted ions when particular desired ions are being produced. The basic source design makes the assembly too long for 90° off-axis mounting as it would protrude outside of the high voltage terminal enclosure. Therefore a new installation was designed so that the ion source axis is parallel to the beam axis but offset beneath it approximately 40 cm as shown in figure 10. A layout of the various source components including an outline of the beam envelope is also shown in figure 10. The heavy ion beam is extracted with 20 kV, focussed, mass analyzed, preaccelerated by 80 kV, and then reflected through two 106° bends onto the beam axis with symmetric electrostatic reflectors similar to that originally used with twice the available aperture. A Faraday cup is provided in line with the source beyond the first 106° reflector so that proper mass selection and focussing can be provided before injecting the beam into the acceleration tube. The beam optics are arranged for a crossover between the two reflectors through a 0.6×2.5 cm slit aperture which provides excellent caesium vapour isolation between the source and the acceleration tubes and in the 0.6 cm direction determines the mass resolution of the crossed field analyzer which is approximately 1 part in 5.

The oven-ionizer system used in sputter sources provides the basic reliability and long life, but can always fail at an unpredictable time and could result in the instantaneous release of gram quantities of caesium vapour into the ion source vacuum system and associated components, including the acceleration tubes. This possibility has been reduced in this terminal source design by the two reflections and small beam defining aperture between the reflectors.

5.1.3. Open belt charging arrangement. — Part of the MP-6 upgrade was the installation of a new

FIG. 10. — Negative ion sputter source arrangement within the high voltage terminal; see text for details.

belt, replacing the original belt which had been operated for 26 740 hours. The belt was installed with a radical modification of the belt guide configuration similar to that devised by M. Letournel which is presently in use in the Strasbourg MP-10 accelerator [16] (5). The basic idea is to reposition the guides from their normal position where they rub the belt lightly to a clearance of one to two cm so that the belt runs completely free. The only column components in contact with the belt in this modified arrangement are the charging and pick-off screens and the belt pulley motor and generator. The new belt arrangement has operated satisfactorily since its installation (2 000 hours) and has not experienced any spark damage to date similar to the performance experienced by Letournel, however, terminal voltage has been limited to 9 MV negative and 10 MV positive where little if any belt damage would be expected. Since the belt is no longer rubbed by the belt guides the production of belt dust is greatly reduced.

5.2. MP-7 IMPROVEMENTS. — 5.2.1. *Acceleration tubes, resistors and column improvements.* — The special small 8" diameter stainless steel acceleration tubes that were used to provide an interim upgrade capability in MP-7 were removed and reconditioned for subsequent installation in MP-6, the injector accelerator, and new large diameter 14 inch stainless steel tubes were installed in MP-7 [13].

The new accelerator tube sections are equipped with separate resistor strings so that the only connections between tube and column are made at the end of each tube section. This separated gradient arrangement increases accelerator tube protection during terminal discharges and provides improved electrical stability. Figure 11 is a photo of acceleration section § 5 that shows both the column and tube resistors mounted in place. Both tube and column resistors are

FIG. 11. — Photo looking up at tube section § 5. The tube resistors, 1, are mounted on support rods, 2, which are fastened on each side of the tube electrodes, 3, auxiliary spark gaps, 4, limit overvoltage on resistor gaps, 5. The column resistors, 6, are mounted on the column girders below the acceleration tube and are also provided with auxiliary spark gaps, 7. Vertical gradient bars, 8, on each side of the column enclose and shield the tube electrostatically.

(5) M. Letournel, private communication.

equipped with additional single spark gaps for further protection against surging as shown.

In the standard HVEC design the tube electrodes and diagonal column elements are connected by springs which have proved to be quite unreliable in an SF_6 environment. There are also vertical gradient rods (Fig. 11) that are spring loaded into position rather than being securely fastened. All of these spring-type connections have been replaced by a bolted or riveted contact and the tube connections have been eliminated by the separate resistor strings as previously described. These modifications represent an extensive effort because there are over 4 000 connections, but in the end, guarantee much more stable operation and a complete elimination of miscellaneous column sparking, breakdown and corrosion.

5.2.2. *Photomultiplier voltage conditioning monitors.* — Photomultiplier tubes have been installed at some window ports of the accelerator to detect any light generated in the vicinity of the mid-section of each of the eight acceleration tubes, similar to the system developed by the University of Rochester [17]. This method of observing the illumination produced by the micro discharges resulting from the voltage conditioning process within the acceleration tubes appears to be one of the most sensitive for monitoring the conditioning phenomena. This system allows for the machine to be voltage conditioned at a maximum possible rate commensurate with minimizing the possibility of initiating tube sparks that can cause serious damage.

5.2.3. *Magnetic electron suppression of inclined field tubes* [18]. — When the new stainless steel tubes in MP-7 were first conditioned up to voltage utilizing the photomultiplier voltage conditioning monitors, it was found that tube section 4 would not condition properly at 13 MV. Although the tube section could be conditioned to normal operation at 12.5 MV the micro discharges characterizing the conditioning phenomena persisted at a steady state at 13 MV. Although the persistent conditioning phenomena in this tube section could be stopped with the introduction of stripping gas in the tube or so-called conditioning gas, it still could not be permanently decreased to an acceptable value without gas.

Coincidence measurements between an NaI detector and the photomultiplier optical output indicated that most of the conditioning light phenomena were strongly correlated with x rays corresponding to voltages across the entire tube section. This fact led to the conclusion that the electron suppression in this particular tube section was not sufficient to handle the electron production from the conditioning phenomena. Consequently, additional electron suppression was provided in the form of the usual clip on permanent magnets developed by the High voltage Engineering Corporation for suppression usually used at the entrances and exits of their acceleration tubes. Three

magnet pairs were installed at the midsection of each of the electrostatic inclined field sections in the tube arranged so that the electron sweeping action was in the same direction as that of the inclined field. This arrangement then provided for an average sweeping field of approximately 10 gauss for a distance of 5 to 6 inches at the midpoint of each of the four inclined field sections in the overall tube section. Since the average magnetic field through these four mutually inverted pairs is approximately zero, the net beam deflection is negligible for any ion.

These magnets immediately eliminated the conditioning phenomena previously observed at 12 MV and the tube section behaved in a manner similar to the other tube sections in terms of its conditioning capability with noticeably less conditioning light phenomena at any given voltage during the usual routine conditioning procedures when raising the machine in energy. This magnetic suppression has not interfered with the operation of the accelerator in any way and has worked successfully for almost a year at this time. Consequently, similar magnets are now planned for installation on the other tube sections to help reduce the conditioning phenomena in those sections and possibly allow for an overall operation of the acceleration tube to voltages reasonably in excess of 13 MV.

5.2.4. Post stripper installation. — A second foil stripper, or post stripper, was installed at the 3/4 terminal potential point in the dead section between tube sections 5 and 6 in the high energy end of the accelerator. The initial performance of the post stripper both with terminal gas and foil stripping has been reported elsewhere [19,20]. Over the last year of operation, dual-foil stripping has been used extensively for many different heavy ions and has greatly extended the performance capability of the facility, as will be described in more detail in section IV on accelerator performance. Besides the obvious improvement in yield and energy for heavy ions like ^{32}S , ^{35}Cl , ^{63}Cu , etc., it has also been found that $^{12}\text{C}^{6+}$ and $^{16}\text{O}^{8+}$ yields can be increased by factors of two or three over single stripper yields.

Since the presence of carbon foil fragments in some acceleration tubes contributed to premature tube failure, special shrouds were installed that completely encloses the stripping foil changer mechanism with entrance and exit apertures only large enough to pass the beam. These shrouds have effectively eliminated the migration of foil fragments into the acceleration tubes and also serve as excellent shields against possible air current foil damage during foil loading operations.

5.2.5. Two-stage sputter ion source. — A middle-ton-type sputter ion source has been the main source used in support of the heavy ion research program. The original Extrion Mark II UNIS Source was replaced by an improved model, Mark VI, which is much simpler in construction and easier to use, but

still required some modifications in order to achieve reliable operation [21]. The quick change capability of the source from one heavy ion to another, the excellent yield of most heavy ions produced, and the long-term reliability has changed the nature of the research program. It is now common for the operation schedule to call for two or more different ions during an eight-hour shift period. On one occasion ten different ions were provided during one shift for calibration purposes. This dynamic and rapid change capability allows the accelerator to be used more efficiently in support of the research program. When questions arise from preliminary analysis of data utilizing one kind of heavy ion, they can be checked quickly by producing other ions the scientist may need for comparisons.

5.2.6. Present performance. — The new acceleration tubes in MP-7 have been demonstrated to operate smoothly in excess of 13 MV and experiments have been carried out at 13.15 MV. Under normal operating conditions the accelerator can be conditioned from 10 MV or less to 12 MV in approximately 1 hour/MV and 13 MV in 2 hours/MV. The insulating gas is a mixture of 47 % SF_6 , 42 % N_2 and 11 % CO_2 at 9-10 atmospheres.

The voltage history of MP-7 for the last two years is shown in figure 12 and indicates a modest percent of

FIG. 12. — Per cent operating time vs. terminal voltage for the Brookhaven MP-7 tandem accelerator for april 1975 to april 1976 (small stainless tubes) and april 1976 to april 1977 (large stainless tubes). Improved performance with the larger tubes is appreciable.

operating time at voltages in excess of 12 MV with the new large diameter stainless tubes. The main limiting factor in exceeding 12 MV in operation has been due to the charging belt failures or interactions of one kind or another which are now being eliminated by the present installation of a pelletron-charging system similar to that of the other pelletron-MP installations.

5.2.7. Three-stage performance. — The performance of the overall upgraded three-stage facility is shown in figure 13. Curve A represents the most

FIG. 13. — Heavy ion performance characteristics for the upgraded BNL tandem facility compared to previous capability.

probable charge state beam energies attainable with a 13 MV tandem. Curve B shows the performance of the three-stage two-stripper BNL facility before the present major upgrade program. Curve C is the performance after upgrading. These curves correspond to the most probable charge state components, but usually less intense higher energy components can be used. Curve C' corresponds to higher energy components such that the intensity is 10 particle nA (6.2×10^{10} particles/second) for injected beams (I_{in}) of 1 μ A. The solid points on curve C represent ion species that have actually been obtained at BNL and all of which are available from the injector. Most of the missing ion species have simply not been requested in the past and several of them are expected to become available in the future. The open square points represent scheduled beams used to date in the research

program since the completion of the upgraded three-stage facility.

The curves labelled $Z_{target} = 5, 10 \dots 90$ show the beam energy necessary to overcome the Coulomb repulsion to allow a collision between given beam and target nuclei to take place. The vertical distance from a point on a Z_{target} curve defined by a particular Z beam up to the performance curves A, B, C and C' defines the range of energy above the Coulomb barrier available for inducing nuclear reactions with heavy ions.

6. Conclusion. — The demonstrated operating characteristics of the North-American MP accelerators have shown an overall improvement of 2 to 3 MV in reliable operating capability during the four-year period since the last Electrostatic Accelerator Conference. Four years ago the main limitation in operating capability appeared to be mainly acceleration tubes with a new capability just on the market at that time in the form of the HVEC upgrade kit. Now other new acceleration tubes have also been developed and the acceleration tube limit seems to be mostly in the distant past of the MP-class machines with the new limitation in the form of charging belts which is now being eliminated by the pelletron-charging system. Hopefully, the appropriate coupling of pelletron-charging systems and the most optimum kind of acceleration tubes will lead to a further increase in operating voltage which optimistically might be another 3 MV in the next four-year period before the next Conference. At present, routine operation of an MP-class accelerator for research in the vicinity of 15 to 16 MV seems quite far fetched; however, the TU accelerator planned for installation at Padua is guaranteed to perform at 16 MV and is the same physical length as an MP although much larger in diameter. Greatly increased understanding of the details of how these machines work along with other improvements in their charging systems and other construction aspects may very well lead to the MP's performing reliably in the region of 15 to 16 MV in a reasonable time period like three to four years.

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