BNL 33116
CONF-830405--5

The Brookhaven Double MP Facility

Recent Developments and Plans for the Future

BNL--33116
DE83 013279

P. Thieberger

Abstract

The Brookhaven Tandem Van de Graaff facility consists of two model MP accelerators which have been extensively modified and improved over the years. Recent accelerator developments leading to a maximum terminal voltage of 16.5 MV for one of the machines include an increase of the active length of the acceleration tubes, installation of vacuum pumps at intermediate field-free sections, installation of smooth high-voltage-terminal shields and the implementation of a system for individual acceleration-tube conditioning. A new cylindrical voltage-divider resistor-shield arrangement has been tested and will be installed. A novel 4-stage mode of operating the tandems provides variable low-energy highly charged heavy ions used for atomic-physics experiments. This type of operation has been improved by the addition of a removable gridded lens at the exit of the last acceleration tube. Plans for the future include the production of relativistic heavy ions by injecting beams from the tandems into the AGS 30-GeV proton accelerator at BNL either directly or via a tandem booster cyclotron. For this purpose, a high-intensity pulsed-beam system was developed and tested.

1. Introduction

The two model MP tandem Van de Graaff accelerators at Brookhaven National Laboratory (MP6 and MP7) can be operated separately or jointly in several different configurations. The highest energies are obtained with the three-stage mode for which an ion source system is used that has been installed inside of the high voltage terminal of the first accelerator (MP6) operated at a negative potential. The negative beam accelerated by MP6 is then injected into MP7, further accelerated to the positive high voltage terminal where the first stripping takes place. A second stripper can be used which is located in the first field-free section after the terminal. The two accelerators are also used in a four-stage accel-decel configuration to produce highly stripped low energy heavy ions of interest for atomic physics experiments. Finally, negative atomic and molecular ions are available at energies up to 11 MeV by using the ion source in the high voltage terminal of MP6 and a single acceleration stage.

This facility has provided a large variety of heavy ion beams for many years. The list of available projectiles has been steadily increasing and, to date, over 60 different isotopes have been accelerated (fig. 1). Also, the maximum energies have increased over the years (fig. 2), as a result of many large and small accelerator improvements [1-10], the last of which have led to some experiments successfully performed at 16.5 MV MP7 terminal voltage and to reliable operation at terminal voltages in the vicinity of 16 MV.

The latest developments will be summarized here and a recent improvement of the four-stage mode of operation will be described. The possibilities for producing relativistic heavy ions at Brookhaven will be reviewed and test results will be discussed of a new high intensity pulsed beam system developed for this purpose.

2. Accelerator developments

Most of the recent MP7 accelerator improvements are schematically indicated in fig. 3 and will be described in the following sections. The new terminal shield and the column shorting system have also been installed in the MP6 accelerator.

2.1. Acceleration tube extension

The longitudinal acceleration tube gradient is still the main limiting factor for the terminal voltages that can be achieved with tandem Van de Graaff accelerators [9]. It is thus important to make effective use of the available longitudinal space by increasing the active acceleration tube length as much as possible. A major step in this direction was first taken at Strasbourg [11] by allowing the tubes to protrude into the previously field-free column dead sections and into the terminal. A similar approach was followed here, but new acceleration tube terminations were developed in order to allow the installation of vacuum pumps and strippers inspite of the drastically reduced space. The active length of the six central acceleration tube sections (section numbers 2 through 7) was increased from 72" to 88", leaving only 8" between insulators in the dead sections. The first and last acceleration tube sections (numbers 1 and 8) were extended to 96". Of these 96", 16" correspond to half-gradient straight-electrode sections and therefore the gradients on the inclined field sections of all tubes are the same. The exit of tube number 8 has been provided with these 16 straight electrodes to improve the 4-stage accel-decel mode of operation [12] described in section 2.6.

The new acceleration tube termination which can be seen in fig. 4 incorporates for the first time an integral flexible bellows. This arrangement decouples mechanical stresses from the first metal-glass glue joint and is much shorter than the conventional terminations which, in addition require separate bellow sections.

2.2. Dead section vacuum pumps

Due to the small vacuum conductance of the acceleration tubes, vacuum pumps are required at intermediate locations between the ends of the accelerator and the high voltage terminal in order to increase the heavy ion transmission and also to improve the acceleration tube performance.

Specially designed Varian ion pumps [13] rated at 110 liters/second and tested to an external pressure of 15 atmospheres were installed underneath the spring planes and just inside the hoop rings as shown in fig. 5. All the dead sections on the low energy side of MP7 were provided with these pumps while only one pump was installed in the central dead section of the high energy side.

Motor powered 2" diameter lucite drive shafts operate generators in the high voltage terminal and in the dead sections provided with vacuum pumps. The drive shaft systems were purchased [14] and installed in both the low and high energy sides of the accelerator.

2.3. Shorting system for individual tube section voltage conditioning

Many large tandem Van de Graaff accelerators have systems which allow voltage to be applied to individual acceleration tube sections for voltage conditioning. The advantages of such systems are that there is less energy available to cause damage during discharges, that the probability of tank to column breakdowns is reduced, during conditioning, and that the section being conditioned cannot be affected by discharges in neighboring sections. At high voltage terminal potentials up to 14 MV the conditioning characteristics of the MP7 acceleration tubes were such that the need for a shorting system was not felt. However, at higher voltages such a system has proven to be useful.

Two spring-loaded windup pulleys were installed in the terminal in order to provide an electrical shorting system from the terminal down the column to successive dead sections in sequence from the terminal to ground. A 1/8" steel cable contained in the terminal mounted, windup pulley is coupled to a 1/8" monofilament nylon pull cable by crimping each end into a short section of copper tubing. The nylon pull cable is reeled in and out on a Slosyn motor powered drum at each of the ground ends of the machine. At each dead section the cable pulls through a three pulley system to insure good electrical contact as shown in fig. 5. The nylon pull cable is arranged to go through the open region available in the outside section of the column structure and is well away from any of the mechanical components of the column.

Quarter-inch diameter shorting rods as shown in fig. 3 are also provided at each dead section that slide through a Teflon compression seal and are equipped with 1" diameter balls to contact the dead section.

2.4. Improved high voltage terminal shield

A series of solid panels and spun ends fitted together to form smooth skin terminal shields were installed to replace the parallel bar cage structures originally provided with both accelerators. The new terminal shield is 80" in diameter as compared to 74" for the old system. The shield consists of fifteen 24° contoured panels that form the cylindrical section. Each of the 24° panels is fastened with four captured screws and can be easily removed. This design reduces the electric field strength at the surface and at the ends of the terminal and at the adjacent equipotential rings, thus reducing the probability of sparking in the terminal region. For negative terminal operation the onset of corona discharge, which before limited the maximum voltage to about -9 MV, now occurs at -11 or -12 MV.

The solid skin also provides better protection to all internal terminal components against surge damage from terminal sparks and it contains solid particles that would otherwise fall to the bottom of the tank, increasing the spark probability.

2.5. Test of cylindrical resistor shields

The present arrangement of spark-gap protected Caddock resistors mounted between parallel plates attached to the tubes and to the columns through inductive connections [10] allows reliable operation up to the highest MP7 terminal voltages. However, there are occasional resistor failures and a gradual value change is noticed for many of the units closest to the high voltage terminal. This indicates that still better protection is desirable.

Previously a cylindrical shield configuration had been successfully tested [4] with the RPC resistors originally delivered with the accelerators. A similar system designed for the Caddock resistors can be seen in fig. 6. The coils and the cylindrical caps surrounding the ends of each resistor form an LC filter which attenuates very high transient frequencies while protection against lower frequency components is achieved by the annular spark gaps. Twenty such units have been installed close to the high voltage terminal and no measurable changes in resistor value have occurred over a six month period. Installation along the entire length of the accelerator column is now being planned and the acceleration tube resistors will also be protected by a similar system.

2.6. Improvements in the four-stage production of highly stripped low energy heavy ions

The principle for the accel-decel production of low energy highly stripped heavy ions [12,15] is illustrated in fig. 7. The first accelerator is used as a normal positive terminal tandem and the heavy ion beam is then further accelerated toward the negative terminal of the second accelerator. At that point a second foil stripper produces the desired high charge states and the beam then loses energy as it returns to ground potential. By adjusting the voltages and charge state combinations appropriately, a wide range of energies and charge states becomes available. Ions with the highest charge states at the lowest possible energies form the most unusual, most difficult and most sought-after beams. The three main factors which reduce the available beam intensities as one approaches this limit are residual gas charge exchange losses in the accelerator and beam transport, beam size growth and inadequate beam optics.

The very slow highly stripped ions are very far from charge state equilibrium and the electron pick-up cross sections become very large. The losses in the residual gas at the exit of the deceleration stage and in the beam transport line are thus often very substantial. The vacuum in the acceleration tubes has been improved by the addition of dead-section ion pumps (see section [illegible]). Also, additional vacuum pumps have been installed along the beam transport line where the vacuum is now between ~[illegible] and ~5x10^{-7} torr, while it had been between .5 and 1.0x10^{-6} torr before.

The beam size growth at low energies is due to the phase space invariance of the beam spot area times the solid angle divided by the energy. This is therefore a fundamental property and one can only remove unnecessary beam transport restrictions to avoid losing too much of the beam intensity. In fact, the beam defining slits at the object and image points of the double focussing 90° analyzer magnet are set at openings several times wider than during normal operation.

The conventional beam optics at the exit of the second accelerator was not adequate for producing the lowest energies with the accel-decel mode of operation. First of all, the last inclined field acceleration tube sections produced too much vertical deflection as the ions slowed down and acquired electrostatic rigidities comparable to the ones normally encountered at the injection point. As was mentioned in section 2.1, this problem was solved by installing a tube at the end of the second accelerator in which the last 8 inclined field, full gradient sections were replaced by 16 half gradient straight electrode sections. In fact, this tube is the mirror image of the acceleration tube at the entrance of the accelerator. The second beam optics problem that was recently solved is due to the electrostatic lens effect at the exit of the last acceleration tube. These very "soft" beams are strongly overfocussed by this lens and therefore a removable grid was installed, electrically connected to the last electrode (fig. 8), the potential of which is controlled by a variable high voltage supply. This arrangement is then similar to the gridded lens system at the entrance of the accelerator. During 2- and 3-stage tandem operation the grid is rotated into the stored position where it does not interfere with - and is not affected by - the normal beams. The steerer plates following this arrangement correct for residual vertical deflections and are automatically connected to ground potential when the grid is rotated into the stored position.

Results obtained after these improvements were implemented are summarized in table 1.

3. High intensity pulsed beam tests

When discussing methods of producing heavy ions at energies above the ones available from tandem Van de Graaff accelerators, one can either consider injecting other accelerators with beams from a tandem or directly from a positive ion source at much lower energies.

The advantages of tandem injection have to do with this higher initial energy, with the excellent beam quality and with the versatility, reliability and ease of operation of negative ion sources. One disadvantage of tandem injection of CW machines such as cyclotrons or linacs is that the beam intensities are limited by the maximum DC beam capabilities of the tandems. To get the highest energies, cyclic machines such as synchrotrons must be used. The possibility of using tandems to inject such accelerators has not been generally recognized in the past.

These synchrotrons accept injected current for only a small fraction of the acceleration period: the AGS, Brockhaven's 30 GeV proton accelerator for instance, will accept the input beam during 200 sec out of a 2 sec period, or 1 part in 10^4 of the time. In principle, it should be possible to make use of this fact by accelerating short, high intensity beam bursts through the tandem without exceeding its average beam capabilities. The capacitance of the accelerator structure should tend to preserve the voltages sufficiently during short times, even when the charging and voltage distribution systems would be totally incapable of sustaining them for a DC beam of the same intensity. Of course, there could well be other problems when very large beam bursts traverse the acceleration tubes, operated close to their maximum voltage gradients. For instance, it is easy to imagine how breakdowns or instabilities could be triggered.

Until recently there was no good way to find out what the problems might be because the available negative ion sources were well matched to the limited current DC beam capabilities of the Tandems. This situation changed dramatically with the development by Roy Middleton (University of Pennsylvania) of his MARK VII sputter ion source [16] which provides over 200 μA of a variety of negative ions; an increase of more than one order of magnitude over older sources.

Prior to these tests this ion source had only been used in the DC mode. In this mode, positive cesium ions are accelerated through a potential difference of 3 to 5 kV and focussed onto a sputter target from which the negative ions originate. These negative ions are accelerated by the same 3 to 5 kV and then further accelerated by an additional extraction voltage of about 20 kV.

In the pulse mode developed here [17] (see fig. 9), the total negative ion acceleration voltage is kept constant so as to preserve a constant beam energy independent of any pulse shape imperfections. Only the cesium acceleration voltage is pulsed from a DC base level of about 1.5 kV to a maximum intensity level of about 4.5 kV. The lower value is adjusted so as to generate a low intensity DC beam used for tuning the accelerator and the beam transport. The pulse amplitude is adjusted to obtain maximum beam pulse intensity and the optimum amplitude varies with the sputter target material and other ion source operating conditions.

The pulsed beam intensities observed are similar to beam intensities obtained for DC operation. Beam pulse rise times between 2 and 10 μsec were observed while the applied high voltage pulse had a rise time less than 1 sec.

The pulse length for these tests was adjusted to 230 μsec and ten pulses per second were injected into the accelerator. Examples of pulse shapes and intensities for ^{16}O and ^{32}S beams can be seen in fig. 10.

For instance, in the case of ^{32}S - 170 μA negative ion beam was injected and the total instantaneous accelerator output current was 900 μA, of which 240 μA (27 particle μA) was in the most abundant charge state. The operation of the accelerator was completely normal, even though instantaneous intensities were over two orders of magnitude larger than conventional DC beams.

While DC beams must always be much smaller than charging and voltage divider currents, these pulsed beams are in fact much larger (see fig. 11). The terminal voltage is kept nearly constant by the terminal-tank capacitance. The total calculated voltage droop at the end of the pulse is 1 kV and the deviation from the average is ±0.5 kV or $\pm 3.5\times10^{-5}$ of the total voltage. The emittance of the analyzed beam was approximately determined by adjusting a set of slits located at a focal point so as to transmit 80% of the beam and by probing the beam profile with a beam scanner located 4 meters beyond the slits. The values obtained for oxygen and sulphur are 18 and 6 π mm mrad $MeV^{1/2}$, respectively.

In spite of the very large instantaneous beam intensities, the operation of the accelerator was completely normal, and the measured beam quality was excellent. From these results one can conclude that if necessary, even higher intensities could be obtained.

4. Proposed future developments and conclusions

In the three-stage mode of operation with MP6 at -11 MV and MP7 at 16, the heavy ion beam energies using single stripping are roughly equivalent to the energies from a single 15 MV tandem. Even higher energies will become available if an intershield system similar to the Strasbourg Vivitron [18] is implemented in MP7.

Now, plans are being made for accelerating heavy ions to much higher energies. A booster cyclotron has been designed [19,20], based on a large existing room-temperature magnet. This cyclotron would multiply the tandem energies by approximately a factor of 20. To get relativistic heavy ions, there is a proposal [21] to inject the beams from this cyclotron into the AGS, which could accept heavy ions up to iodine without any vacuum improvements. Some of the lighter ion beams such as oxygen or sulphur could actually be injected directly from the tandems [22].

The very good beam quality would allow many more turns to be injected into the AGS than is customary with linac injection. This, together with the now demonstrated heavy-ion intensities from the tandems (see section 3), provides a large safety margin to assure that oxygen intensities of 4×10^{10} particles per pulse can be reached. For iodine beams, which require the cyclotron booster, the intensity would be 10^9 particles per pulse.

Beyond AGS injection and beams at 15 GeV/AMU, considerations have been made of possible injection of heavy ions into the future Colliding Beam Accelerator proposed for Brookhaven [23]. There appear to be no technical problems in accepting AGS Heavy Ion Beams - passage of heavy ion beams through transition during acceleration can be accommodated by all presently considered CBA designs. The range of heavy ion beams with reasonable luminosities (see fig. 12) that would become available is truly impressive - involving center of mass energies of order 10^5 GeV.

This work was supported by the U.S. Department of Energy, under Contract No. DE-AC02-76CH00016.

Acknowledgements

I gratefully acknowledge the enthusiasm, dedication and ingenuity of all members of the Brookhaven Tandem Operations and Development Group, so essential for the successful upgrading and operation of this facility. The efforts of Mike McKeown, Mario Manni, Robert Lindgren, Charles Carlson, and Irving Feigenbaum were particularly crucial for the implementation of the work described here. I am grateful for helpful discussions with Chellis Chasman, who headed the cyclotron design group and also the group in charge of the AGS injection proposal. Comments by Harvey Wegner about tandem injection for synchrotrons are gratefully acknowledged as well as his contributions to the removable gridded lens design and to the high intensity pulsed beam measurements. I am grateful to J. Barrette, B.M. Johnson, K.W. Jones, and M. Meron for collaborating in the development and improvement of the four-stage system.

References

[1] P. Thieberger and H.E. Wegner, Nucl. Instr. & Methods 122 (1974) 205.

[2] P. Thieberger, H.E. Wegner, M. McKeown, M. Manni, and I. Feigenbaum, Nucl. Instr. & Methods 122 (1974) 291.

[3] P. Thieberger and H.E. Wegner, Nucl. Instr. & Methods 126 (1975) 231-233.

[4] P. Thieberger, R. Lindgren, M. McKeown, T. Robinson, and H.E. Wegner, IEEE Trans. on Nucl. Sci., Vol. NS-24 (1977) 1081-1083.

[5] H.E. Wegner and P. Thieberger, Revue de Physique Applique 12 (1977) 1291.

[6] P. Thieberger, Nucl. Instr. & Methods 150 (1978) 329.

[7] P. Thieberger, Nucl. Instr. & Methods 150 (1978) 327.

[8] P. Thieberger, M.A. Manni, R. Lindgren, M. McKeown, C. Carlson and H.E. Wegner, Proc., Third Intl. Conf. on Electrostatic Accelerator Technology, April 1981, IEEE Catalog No. 81CH1639-4, p. 46.

[9] P. Thieberger, Proc., Third Intl. Conf. on Electrostatic Accelerator Technology, April 1981, IEEE Catalog No. 81CH1639-4, p. 35.

[10] P. Thieberger, H.E. Wegner, M. McKeown, R. Lindgren, N. Burn, J.H. Brodhurst, T.S. Lund, T.E. Miller, K. Sato, C.E.L. Gingell, T.A. Barker, P.D. Parker, and D.A. Bromley, Nucl. Instr. & Methods 184 (1981) 121-144.

[11] M. Letournel;, Proc., Third Intl. Conf. on Electrostatic Accelerator Technology, April 1981, IEEE Catalog No. 81CH1639-4, p. 9.

[12] J. Barrette and P. Thieberger, Proc., Third Intl. Conf. on Electrostatic Accelerator Technology, April 1981, IEEE Catalog No. 81CH1639-4, p. 202.

[13] Varian Vacuum Division, 611 Hansen Way, Palo Alto, CA 94303, U.S.A.

[14] National Electrostatic Corporation, Graber Road, Box 117, Middleton, WI 53562, U.S.A.

[15] P. Thieberger, J. Barrette, B.M. Johnson, K.W. Jones, and M. Meron, 7th Conf. on Applications of Accelerators in Research and Industry, Denton, TX, November 8-10, 1982; IEEE Trans. Nucl. Sci. (to be published).

[16] R. Middleton, Proc., "Symp. of Northeastern Accelerator Personnel", Univ. of Wisconsin, Oct. 13-15, 1980; also, Nucl. Instr. & Methods (to be published). Ion source fabricated by General Ionex Corp., Newberry, MA.

[17] P. Thieberger, M. McKeown, and H.E. Wegner, Proc., 1983 Particle Accelerator Conference, IEEE Trans. on Nucl. Sci. (to be published).

[18] M. Letournel, Proc., Third Intl. Conf. on Electrostatic Accelerator Technology, April 1981, IEEE Catalog No. 81CH1639-4, p. 247.

[19] Proposal for a Heavy ion Facility at Brookhaven, Informal Report, BNL-30630.

[20] C.E. Thorn, C. Chasman, and A.J. Baltz, IEEE Trans. Nucl. Sci. NS-28 (1981) 2089, and BNL Informal Report 30630.

[21] Proposal for a 15 A·GeV Heavy Ion Facility at Brookhaven. Informal Report, BNL-32250.

[22] M.Q. Barton, Proc., 1983 Particle Accelerator Conference, IEEE Trans. on Nucl. Sci. (to be published).

[23] M.Q. Barton, Proc., 1983 Particle Accelerator Conference, IEEE Trans. on Nucl. Sci. (to be published).

Figure Captions

Fig. 1 Elements which have been accelerated by the BNL tandems are enclosed in circles, with dots indicating individual isotopes.

Fig. 2 Maximum energies for three typical beams as a function of time.

Fig. 3 Schematic representation of the main components involved in the recent upgrade program.

Fig. 4 New acceleration tube termination incorporating an integral flexible bellows.

Fig. 5 Schematic representation of the configuration of a dead section containing a 110 liters/second ion pump.

Fig. 6 Cylindrical shielding arrangement for column resistors.

Fig. 7 Schematic diagram of four-stage accel-decel system and equations describing the beam energy at the strippers and at the exit of the accelerator.

Fig. 8 Removable grid system installed at the exit of the last MP7 acceleration tube for improved four-stage accel-decel production of highly stripped low energy heavy ions.

Fig. 9 Simplified schematic diagram of the pulsing system for the MARK VII Middleton sputter ion source. The indicated voltages are typical and can be adjusted for optimum performance. The energy of the negative ions is determined exclusively by the extraction supply and therefore does not vary during the pulse. The 1.5 kV DC voltage in series with the high voltage pulser provides a low intensity DC beam used for tuning the accelerator and beam transport.

Fig. 10 Test results for high current pulsed heavy ion beams obtained by injecting ^{32}S and ^{16}O beams from a MARK VII Middleton ion source into the Brookhaven MP7 Tandem Van de Graaff accelerator. The oscilloscope traces show a) the injected negative beam currents, b) the total beams containing all charge states at the exit of the accelerator, and c) the analyzed most abundant charge state components. These analyzed beams were 43 particle μA of 100 MeV $^{16}O^{6+}$ and 27 particle μA of 140 MeV $^{32}S^{9+}$ The emittances were also measured for both beams and were found to be about 18 π mm mrad MeV $^{1/2}$ in the worst case. This excellent emittance and the pulsed beam intensities two orders of magnitude larger than normal DC tandem beams assure that the beam intensities for AGS operation quoted in the text can be reached with large safety margins.

Fig. 11 Simplified diagram of currents entering and leaving the high voltage terminal. The relative magnitudes of the currents are indicated by the length of the heavy arrows. During a beam pulse these currents are not balanced and charge must be supplied by the terminal-tank capacitance. The resulting total voltage droop for the present example is ~1 kV.

Fig. 12 Energy/nucleon for the present BNL tandems, for proposed systems involving a large booster cyclotron and heavy ion injection into the AGS 30 GeV BNL proton synchrotron and for possible future colliding beam accelerator performance. The Bevalac energy curve is shown for comparison.

Table 1. Examples of Accel-decel Beams

Ion	Final Charge State	Final Energy (MeV)	Final Current (nA)
$_{17}Cl$	16	20	3.4
	16	10	2.[illegible]
	16		0.9
	16	2.5	5.0+
$_{16}S$	5 to 16	20	#
	15	15	12
	15	8	0.5

+ The production of this beam would have been impossible without the gridded exit lens arrangement shown in fig. 8 and described in the text. The other beams were produced before the installation of this system.

Depends on charge state. Typical currents are 4 nA, increasing to 110 nA for the most probable charge state, [14]

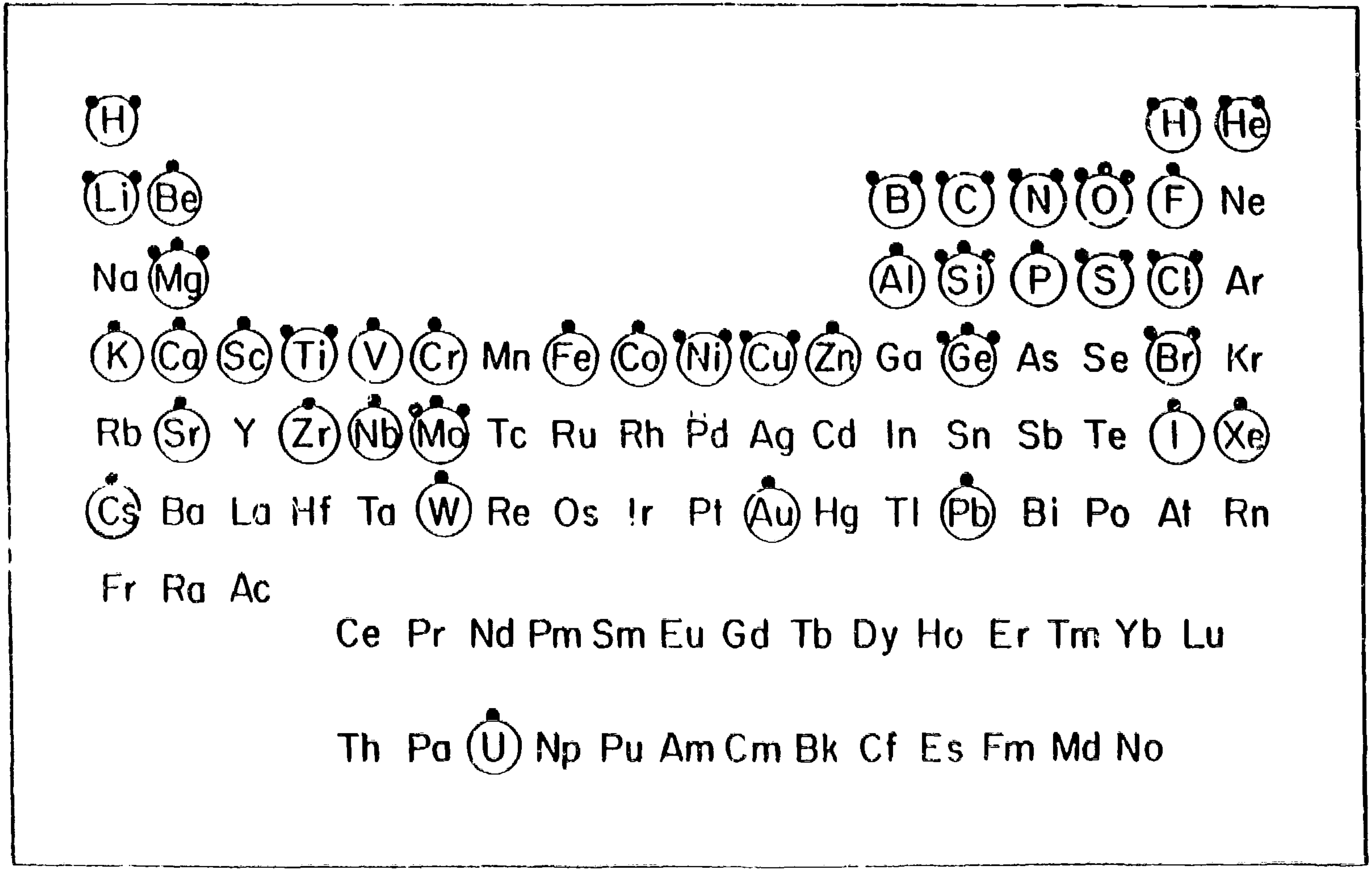

H H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No

Fig. 1

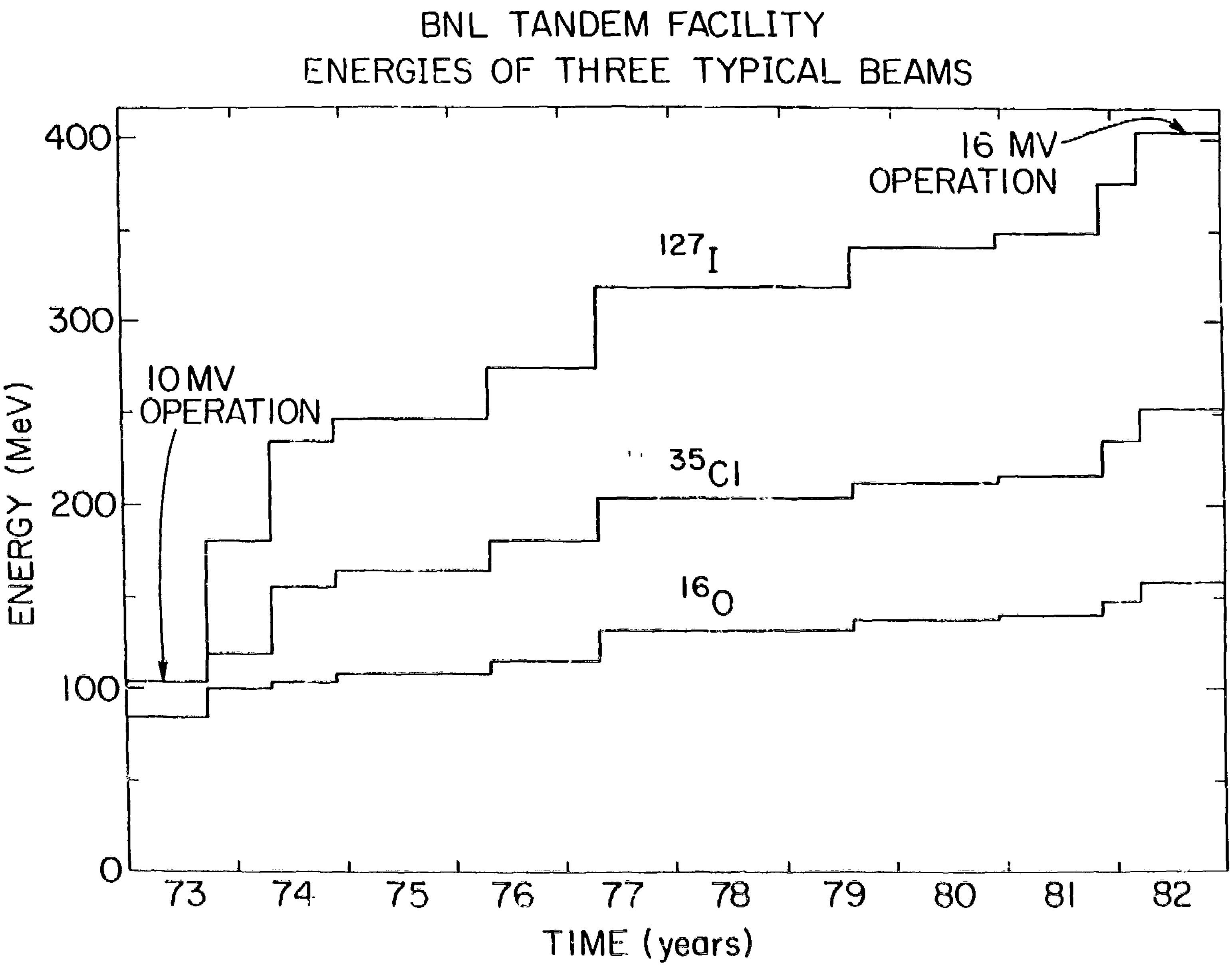
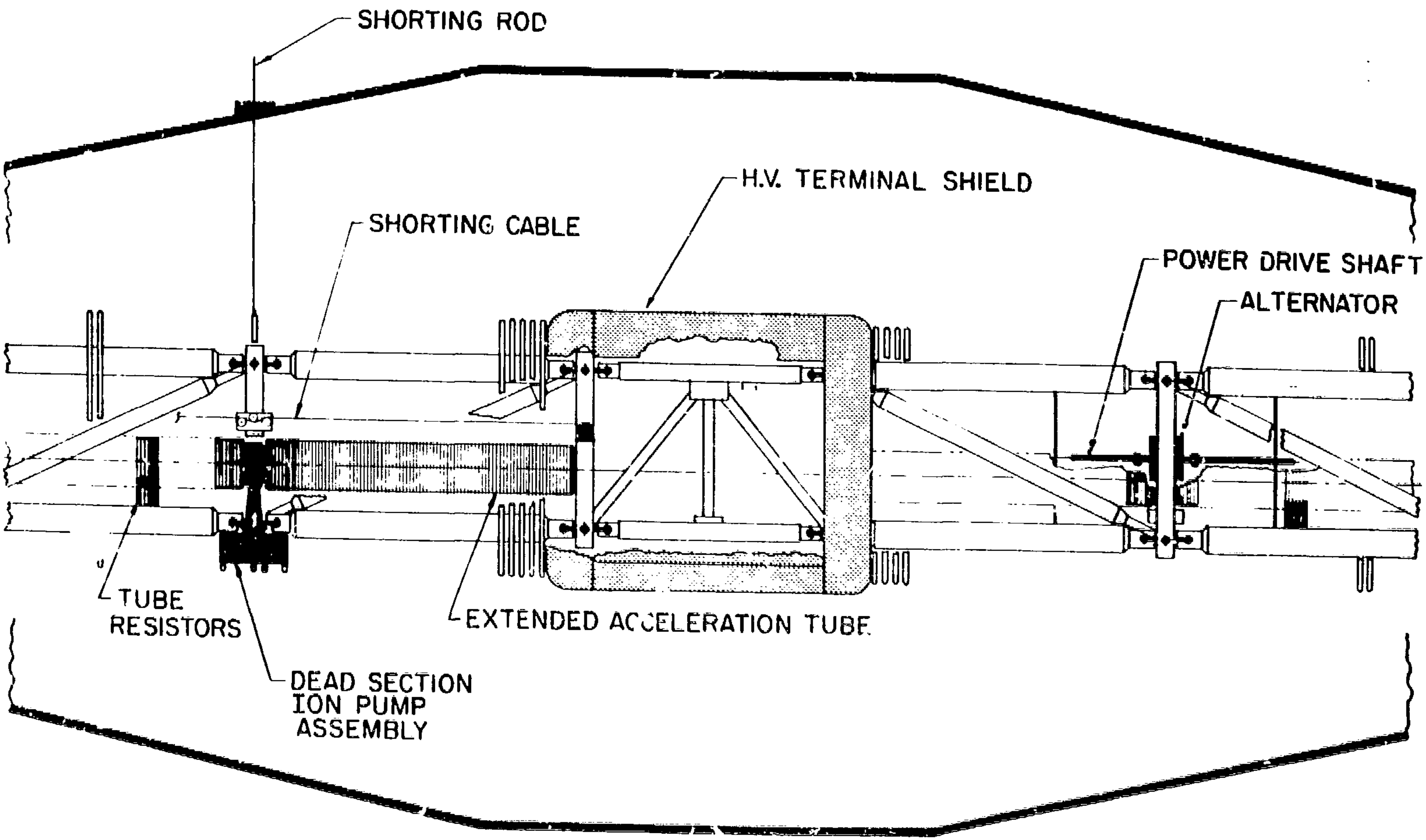

BNL TANDEM FACILITY
ENERGIES OF THREE TYPICAL BEAMS
16 MV OPERATION
127I
10 MV OPERATION
35Cl
16O
ENERGY (MeV)
400
300
200
100
0
73
74
75
76
77
78
79
80
81
82
TIME (years)

Fig. 2


SHORTING ROD
H.V. TERMINAL SHIELD
SHORTING CABLE
POWER DRIVE SHAFT
ALTERNATOR
TUBE RESISTORS
EXTENDED ACCELERATION TUBE
DEAD SECTION ION PUMP ASSEMBLY

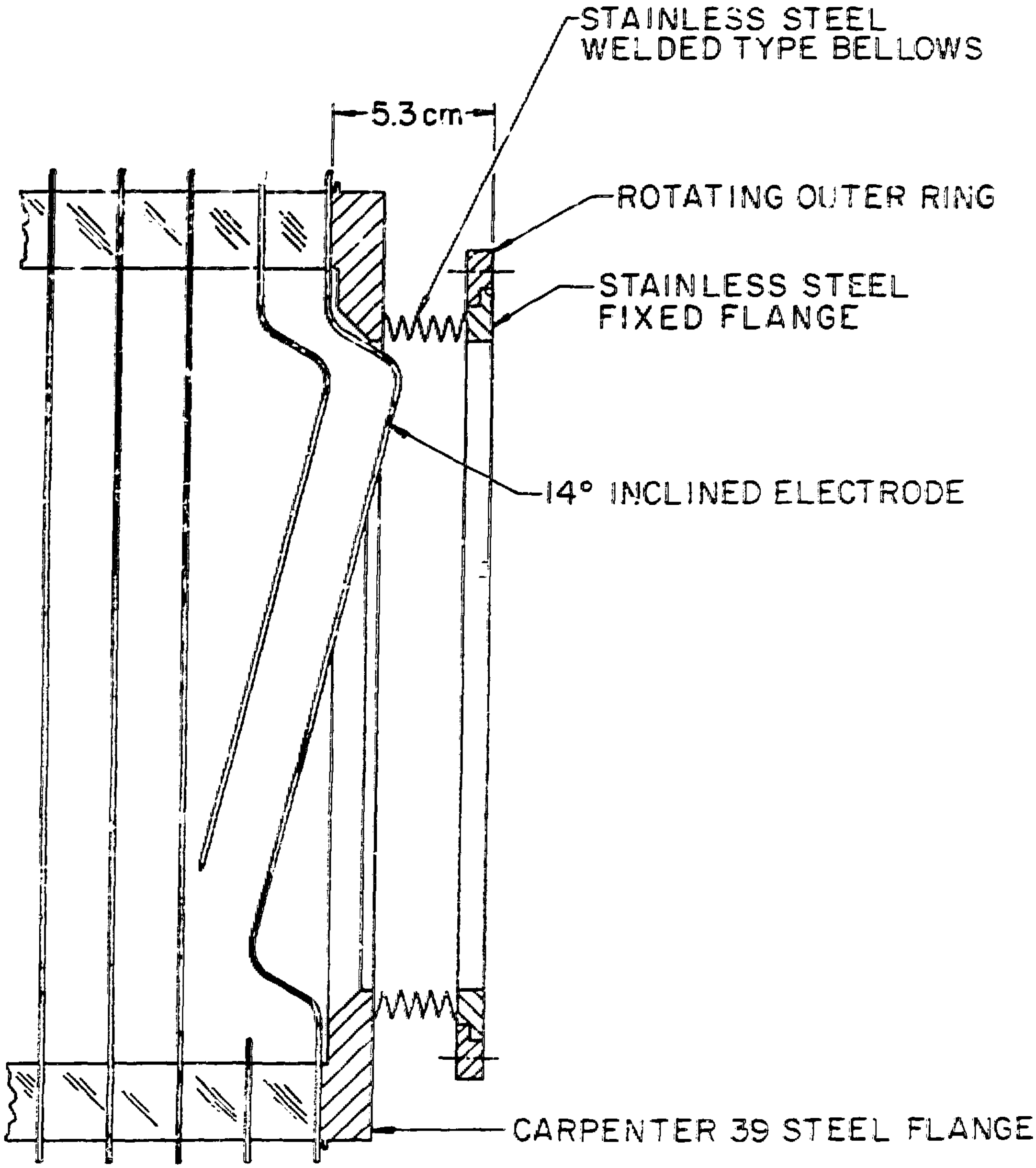
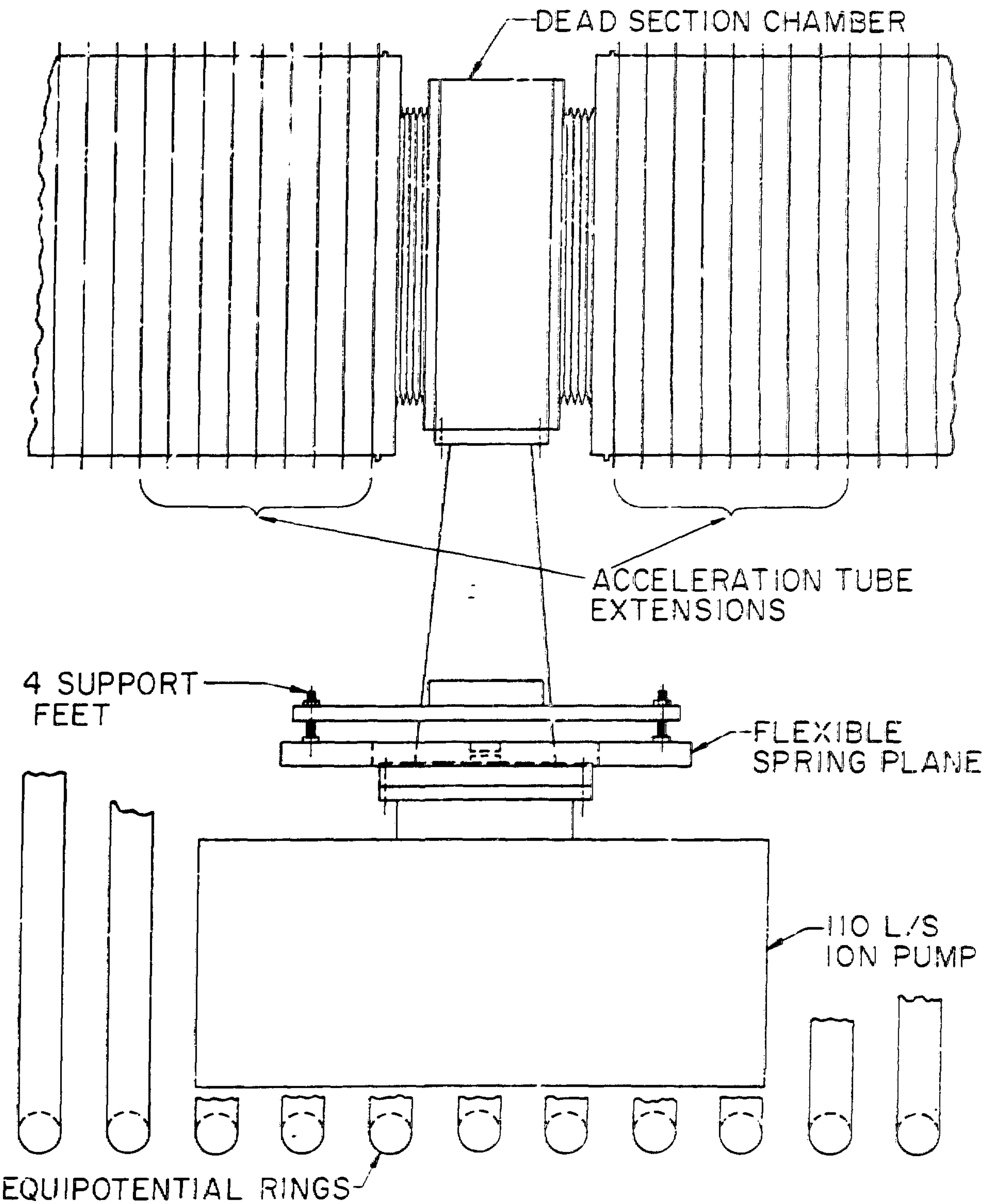

STAINLESS STEEL
WELDED TYPE BELLOWS
5.3 cm
ROTATING OUTER RING
STAINLESS STEEL
FIXED FLANGE
14° INCLINED ELECTRODE
CARPENTER 39 STEEL FLANGE

Fig. 4


DEAD SECTION CHAMBER
ACCELERATION TUBE EXTENSIONS
4 SUPPORT FEET
FLEXIBLE SPRING PLANE
110 L/S ION PUMP
EQUIPOTENTIAL RINGS

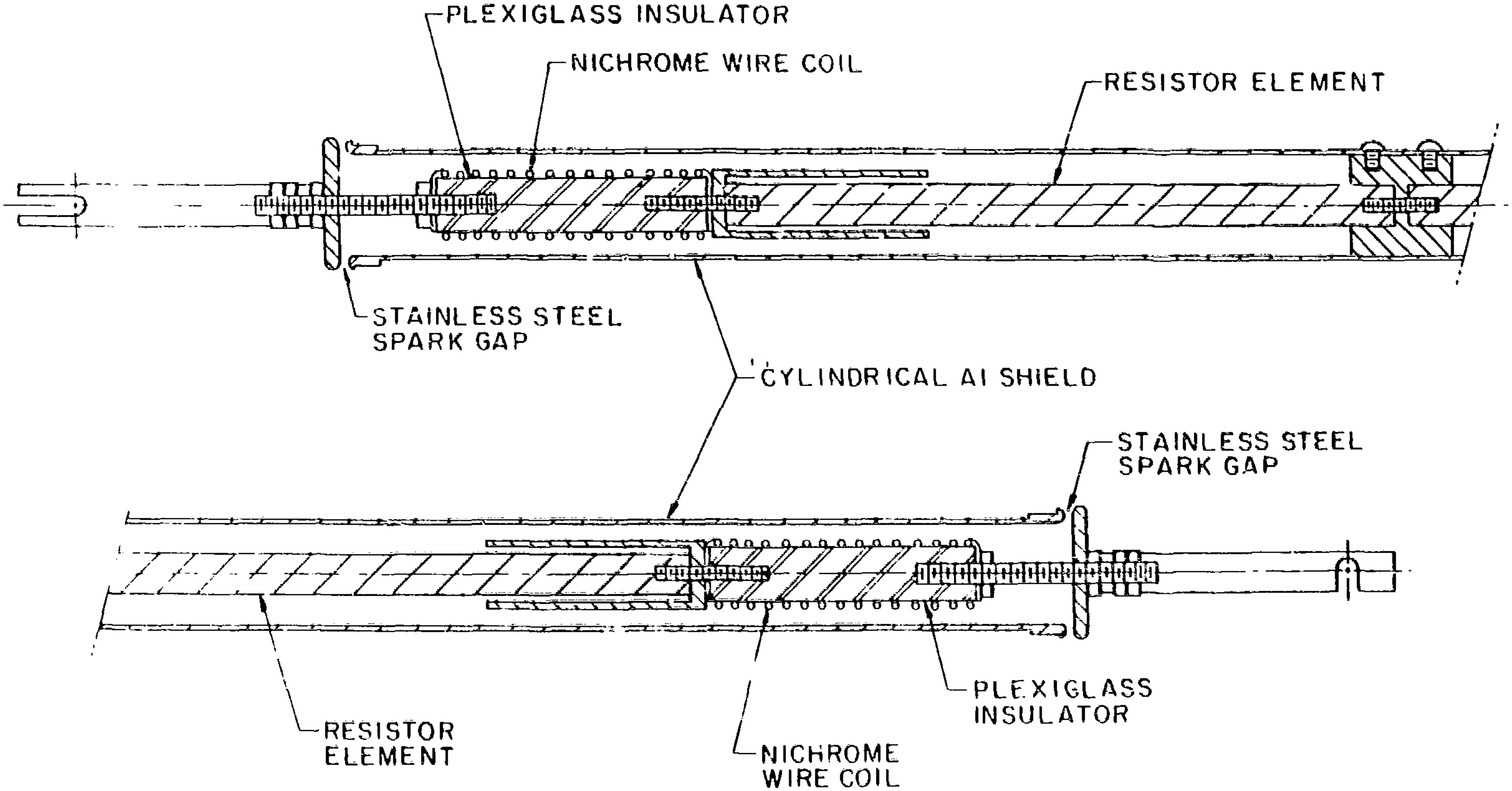
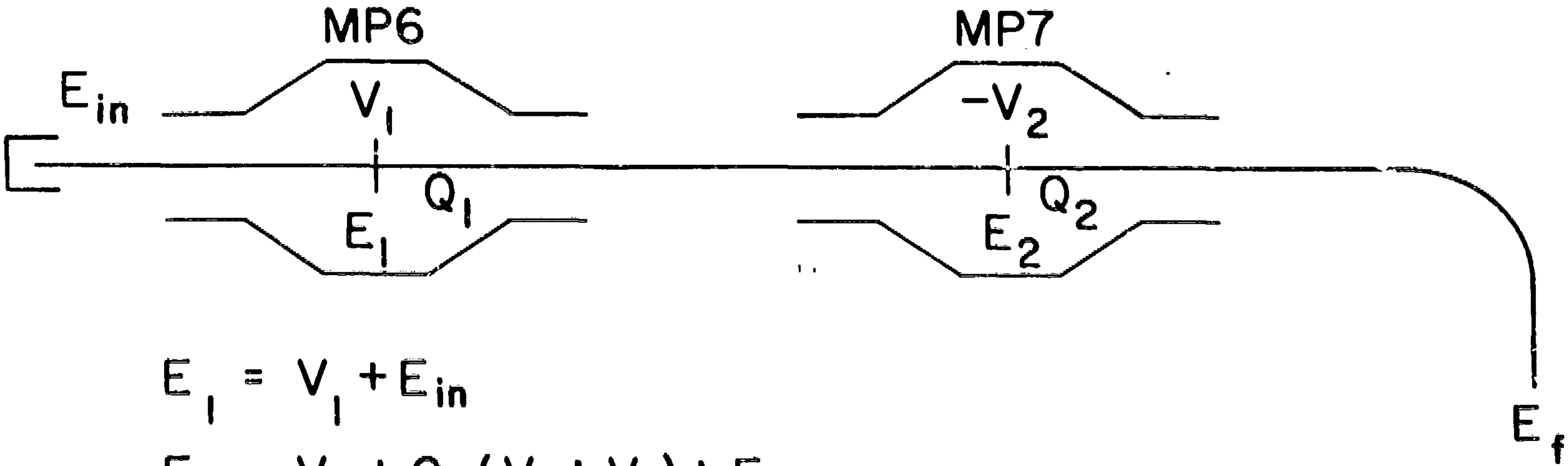

PLEXIGLASS INSULATOR
NICHROME WIRE COIL
RESISTOR ELEMENT
STAINLESS STEEL SPARK GAP
CYLINDRICAL Al SHIELD
STAINLESS STEEL SPARK GAP
PLEXIGLASS INSULATOR
RESISTOR ELEMENT
NICHROME WIRE COIL

Fig. 6

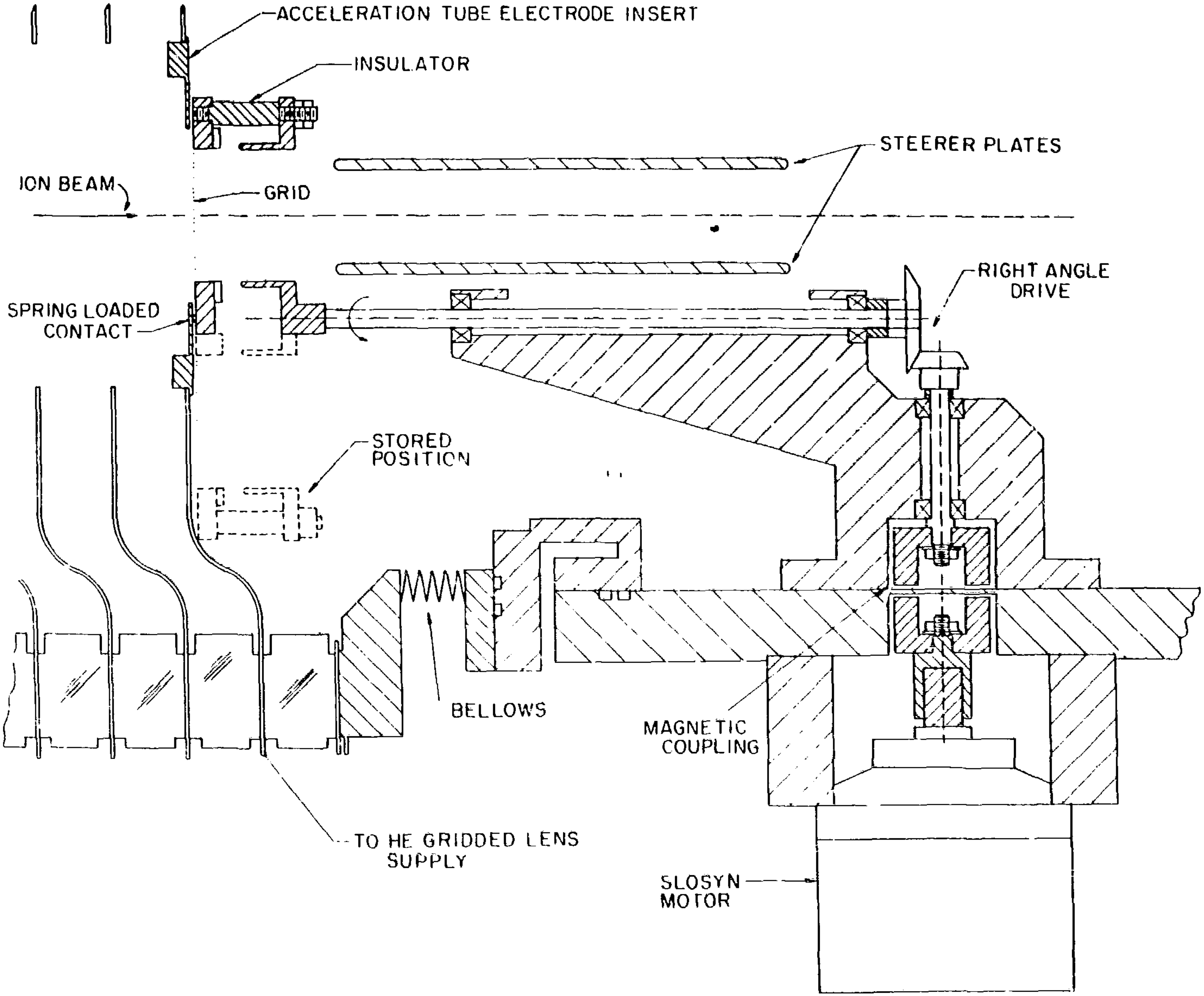


$$E_1 = V_1 + E_{in}$$

$$E_2 = V_1 + Q_1(V_1 + V_2) + E_{in}$$

$$E_f = V_1 + Q_1(V_1 + V_2) - Q_2V_2 + E_{in}$$

Fig. 7


ACCELERATION TUBE ELECTRODE INSERT
INSULATOR
STEERER PLATES
ION BEAM
GRID
RIGHT ANGLE DRIVE
SPRING LOADED CONTACT
STORED POSITION
BELLOWS
MAGNETIC COUPLING
TO HE GRIDDED LENS SUPPLY
SLOSYN MOTOR

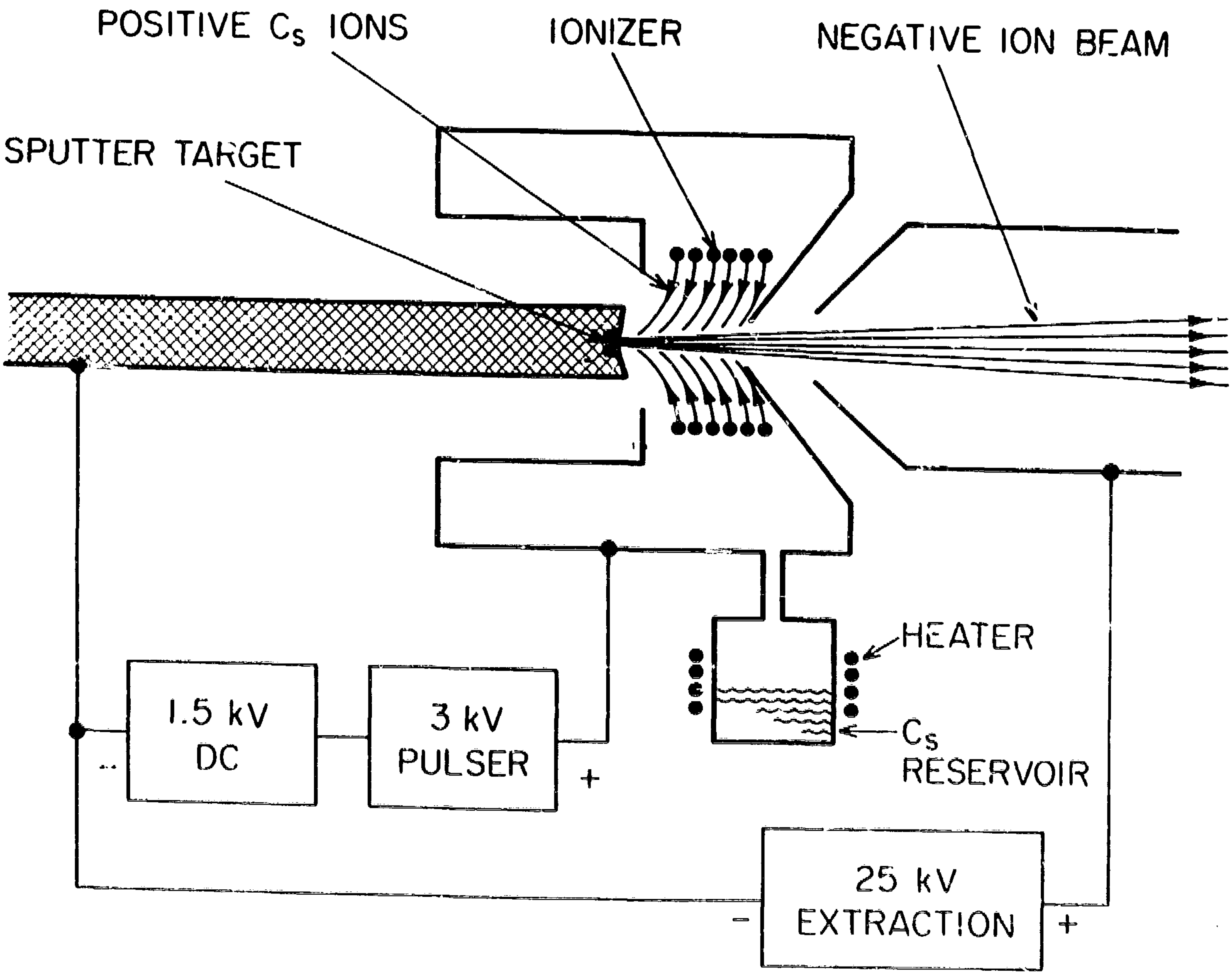
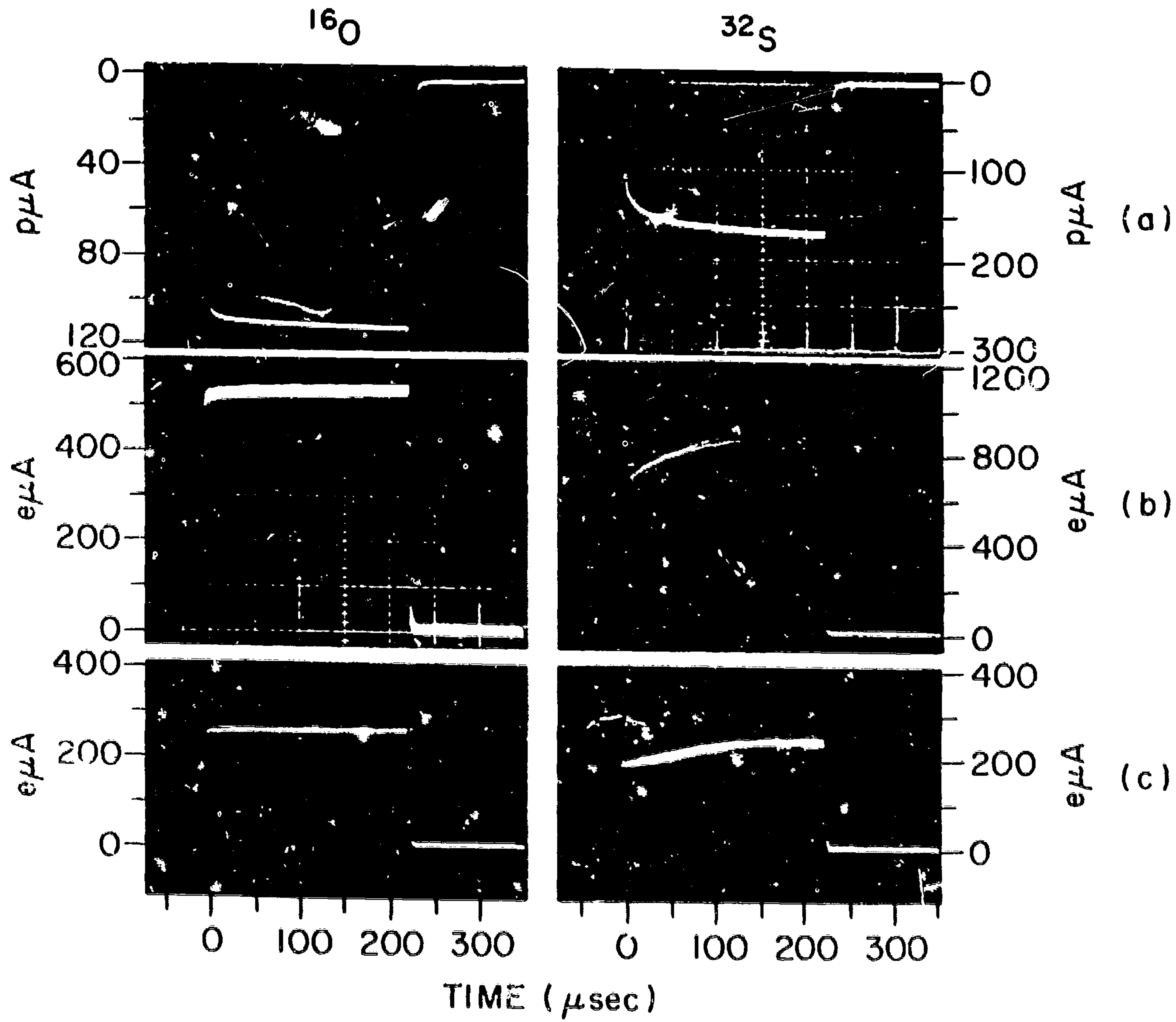

POSITIVE Cs IONS
IONIZER
NEGATIVE ION BEAM
SPUTTER TARGET
HEATER
Cs
RESERVOIR
1.5 kV
DC
3 kV
PULSER
+
25 kV
EXTRACTION
−
+

Fig. 9



16O
32S
pμA
eμA
eμA
(a)
(b)
(c)
0
40
80
120
600
400
200
0
400
200
0
100
200
300
1200
800
400
0
400
200
0
100
200
300
TIME (μsec)

Fig. 10

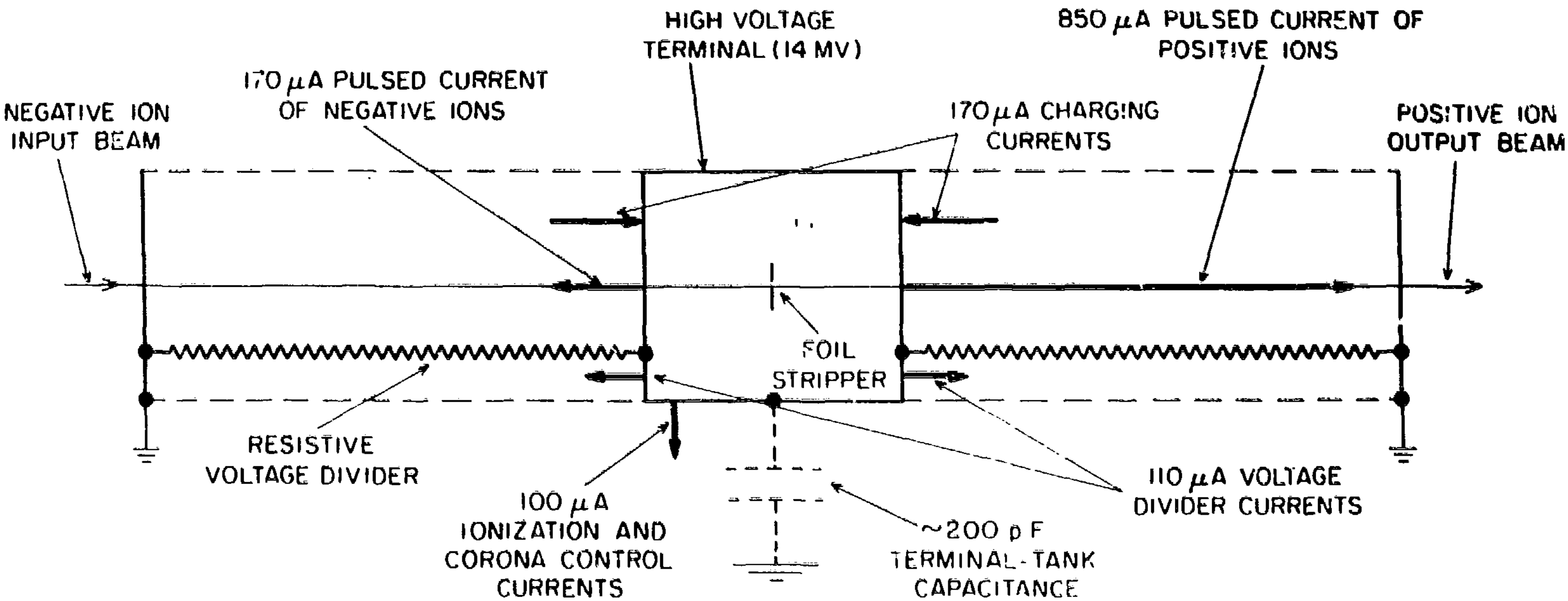

HIGH VOLTAGE TERMINAL (14 MV)
850 μA PULSED CURRENT OF POSITIVE IONS
170 μA PULSED CURRENT OF NEGATIVE IONS
NEGATIVE ION INPUT BEAM
170 μA CHARGING CURRENTS
POSITIVE ION OUTPUT BEAM
FOIL STRIPPER
RESISTIVE VOLTAGE DIVIDER
100 μA IONIZATION AND CORONA CONTROL CURRENTS
~200 pF TERMINAL-TANK CAPACITANCE
110 μA VOLTAGE DIVIDER CURRENTS

Fig. 13

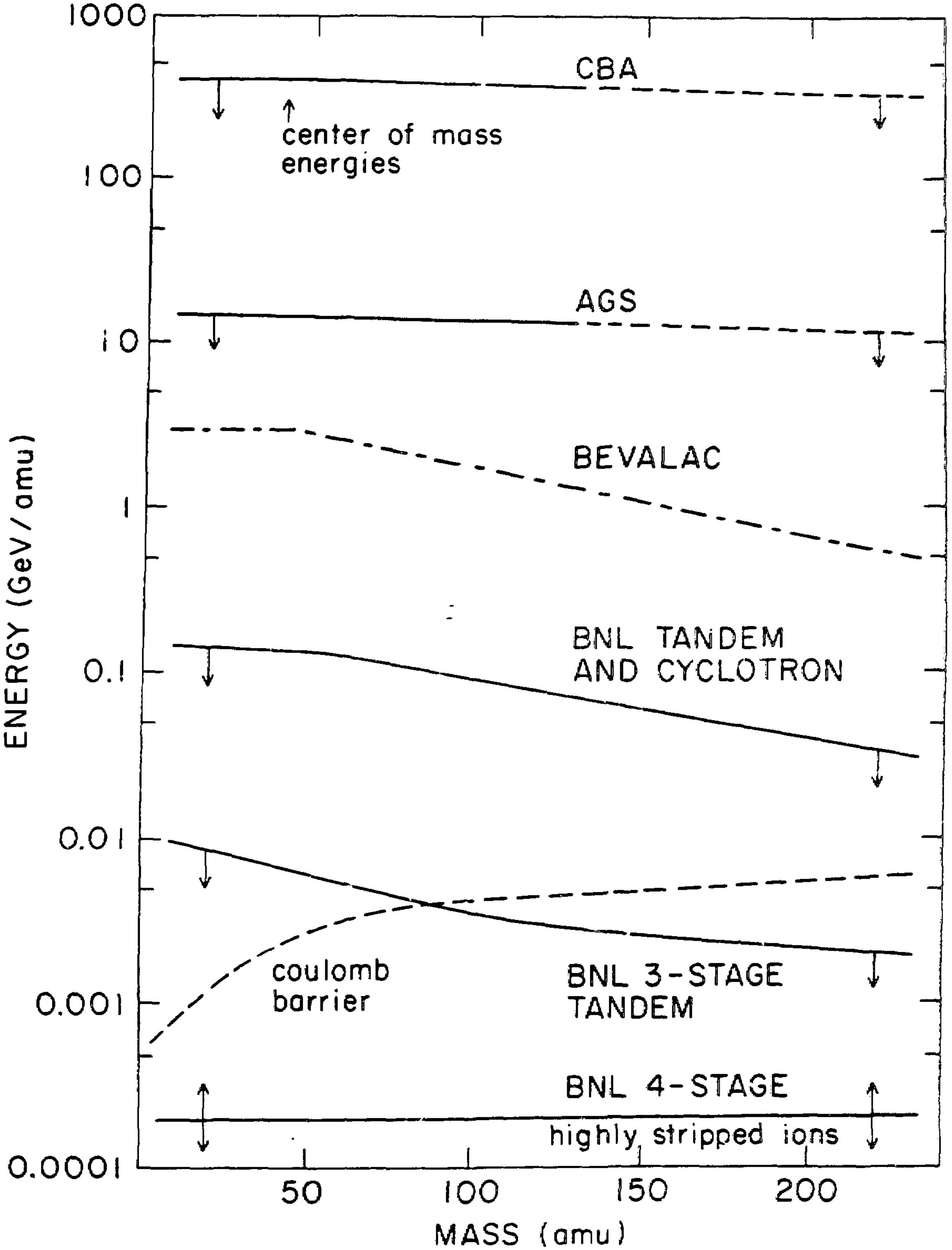

1000
100
10
1
0.1
0.01
0.001
0.0001
ENERGY (GeV/amu)
CBA
center of mass
energies
AGS
BEVALAC
BNL TANDEM
AND CYCLOTRON
coulomb
barrier
BNL 3-STAGE
TANDEM
BNL 4-STAGE
highly stripped ions
50
100
150
200
MASS (amu)

Fig. 12