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Tandems as Injectors for Synchrotrons

A. G. Ruggiero

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Collider Accelerator Department

Brookhaven National Laboratory

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Accelerator Development Department
Accelerator Physics Division
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, NY 11973

Accelerator Physics Technical Note No. 42

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A.G. Ruggiero
Accelerator Development Department
Brookhaven National Laboratory
Upton, NY 11973, USA

ABSTRACT

This is a review on the use of Tandem electrostatic accelerators for injection and filling of synchrotrons to accelerate intense beams of heavy-ions to relativistic energies. The paper emphasizes the need of operating the Tandems in pulsed mode for this application. It has been experimentally demonstrated that at the present this type of accelerators still provides the most reliable and best performance.

1. Introduction

The conventional mode of operation of Tandems, for application and experiments in sub-atomic and nuclear physics, is the acceleration of *continuous* beams of heavy ions. Typical currents in the range of several particle-microamperes are available for a large variety of beam species. This mode of operation provides good beam quality, high momentum resolution and 100% duty cycle for utilization; nevertheless it is not recommended for injection and filling of a subsequent circular accelerator, like a fast cycling synchrotron. In this case, it is more convenient pulsing the source to generate high-current beam pulses at repetition rates matching that of the synchrotron, typically between 1 and 10 Hz. Each pulse can have a duration of few hundred microseconds corresponding to injection of several turns. It is possible to obtain large pulse currents of

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few hundred of particle-microamperes without deteriorating beam quality and performance. The paper describes methods and performance for the use of the Tandem as the injector to a circular accelerator.

2. Motivations

There are proposals to accelerate intense beams of heavy ions to relativistic energies in circular accelerators, for instance fast cycling synchrotrons, for high-energy and nuclear physics experimentation and other applications. In particular we mention:

1. The experimental program with heavy-ions [1] in the facilities of Brook-haven National Laboratory (Fig. 1). Light-ion beams, like O^{+8} and Si^{+14} have already been accelerated to 15 GeV/u in the AGS [2]. Very recently ^{197}Au ions have been accelerated into the AGS Booster to 200 MeV/u, to be fully stripped and then also accelerated in the AGS to 12.5 GeV/u. The ultimate goal is injection and filling of the RHIC [3] for collision of fully stripped ions of gold at 100 GeV/u per beam. The entire program is based on the use of two MP Tandem Van de Graaff accelerators as the pre-injector [4].
2. The experimental program with heavy-ions in CERN [5]. Few years ago [6] beams of light-ions like O^{+8} and S^{+12} have been accelerated in the PS and the SPS to energies of about 200 GeV/u for experimentation with fixed target. The near future plane [5] includes acceleration of fully stripped heavier ions like ^{208}Pb and collision of ion beams in the Large Hadron Collider [7] at the energies of few TeV/u. The proposed pre-injector for this facility is a combination of an ECR source and an RFQ linac.
3. The GSI facility, with the SIS accelerator and an Experimental Storage Ring (ESR) [9,10]. Ion beams are obtained with an ion-source, an RFQ and a linac of Alvarez structure. In this facility, ions are accelerated to few GeV/u and mainly used to produce exotic fragments which are then stored and cooled in the ESR.

4. The future development of the Laboratori Nazionali di Legnaro [11,12,13], in particular the ADRIA proposal for acceleration of heavy ions to energies of few GeV/u and intensities of 10^{11}-10^{12} particles per second (Fig. 2). The main application of the project is the production of exotic fragments. The pre-injector is an XTU Tandem combined to the post-accelerator ALPI (Fig. 3) [14-15].
5. The use of heavy ion beams for inertial fusion [16]. The main requirement of this project is the very high intensity of short beam burst at high repetition rates. Moreover, to circumvent space charge problems in fast cycling synchrotrons where the beams are accelerated and compressed, a very low charge state is required.

All these projects and proposals, and others similar to these, require very particular set up and mode of operation of their pre-injectors. In this paper we describe the use of Tandem Van de Graaff accelerators for the injection of ion beams in circular machines. Recently, alternatives like ECR sources and RFQ linacs are also being considered as injectors [17]. Though the field of research of these devices is proceeding very fast, nevertheless we believe that they are not yet at a level of performance to compete with the old-fashion but extremely reliable Tandem accelerators. In particular, two good examples of the use of Tandems we shall refer to are the BNL facility and the ADRIA proposal.

3. The Tandem Accelerator

The Tandem accelerator is an electrostatic machine that works on an old, but still very effective, principle which was first proposed by R.J. Van de Graaff [18] in 1931. The principle is schematically shown in Fig. 4. A high voltage is generated on a terminal by making use of the convective currents carried by a belt charged up by another lower voltage electrostatic generator. In the example of the BNL accelerator the terminal is set at the voltage of 15 MVolt. The source of ions is located near ground where it can be easily reached for replacement and maintenance. The beam of ions of the required species is obtained by letting an intense flow of positively charged ions of Cesium impinge a target of the same material of the wanted species (Fig. 5). The ions of Cesium release more electrons to the ions being delivered from the target changing them to a negative charge state (usually −1). The beam is then extracted by a relatively low voltage (~ 25 kV) set between the target and an extraction anode. The same voltage difference helps to push the ions of Cesium toward the target. This process is called "sputtering". The negative ions are then accelerated toward the positive high-voltage terminal, traveling along the axis of a drift tube penetrating the terminal itself.

Once the high-voltage terminal has been reached, the beam of ions traverses a target thick enough to provide an initial stripping to the desired positive charge state. The target is made of gas for the light ions and can be made of solid material, like carbon, for heavier elements. The target is entirely located in the high-voltage terminal and stripping occurs here. The ions are then accelerated again from the positive voltage down to ground traveling along the second stage of the drift tube. At this point the beam is carried to some distance where, if required, it can cross a second stripping target to obtain a larger charge state.

At the end of acceleration, taking the BNL case as the example, the final kinetic energy is (1 + QT) × 15 MeV, where QT is the charge state after the first stripping at the terminal. The Tandem has very good stability of the high-voltage, better than one part in ten thousand, and the beam accelerated is expected to have a very small energy spread.

The stripping target, which is required to remove the desired number of electrons or, eventually, to fully strip ions of light mass, may also cause some negative side effects. The thickness has to be adjusted to reach the wanted charge state for the given available energy; the higher the energy and easier it will be to remove electrons. For a given thickness there is an energy loss accompanied by a transverse angular spreading and by a spreading of the energy distribution. Despite all this, the resulting momentum spread is better than 0.1% and the rms emittance does not exceed 1 π·mm·mrad in each transverse plane, also with two stripping targets, the second of them located after the Tandem. A more serious effect is that there is a wide distribution of charge states in exit of a target and, by selecting only the required one, one looses a considerable amount of beam. If the target thickness is properly chosen for the required charge, survival rates of 10-20% have been demonstrated.

A summary of cases which are taken as examples of the experimental programs of the BNL and LNL heavy-ion facilities is given respectively in Tables 1 and 2. The tables show the charge state QT after the stripping target at the terminal, the survival rate or stripping efficiency ST, the specific kinetic energy in exit and the relativistic velocity factor β. Table 2 shows also the charge state QF and the stripping efficiency SF of a second stripping target located in the ALPI post-accelerator. It shows also the increase in energy and β due to the post-accelerator.

4. Pulsed Mode of Operation

The standard mode of operation of a Tandem is to accelerate continuous (dc) beams of ions, as required by the experimental program of low-energy atomic and nuclear physics. Typical currents in output are around several particle-μA. The limitation is caused by either the available negative ion sources or by the beam loading of the high-voltage terminal. Indeed, as charged particles are accelerated by the terminal they have a tendency to lower the potential by an amount proportional to the total charge being accelerated. The voltage drop is compensated by the recharging of the Van de Graaff generator which nevertheless has a limited rate. A maximum current is then obtained when the two rates equal each other.

As an injector to a circular machine, the Tandem can be operated more conveniently in a pulsed mode, providing beam in burst of short duration just enough for filling of the subsequent accelerator. The bursts will repeat in succession to match the repetition rate of the circular accelerator and with much larger instant current. This mode of operation was first demonstrated at BNL [19].

In order to understand this mode of operation we have to explain in more detail the functioning of the heavy-ion source. First of all an important step in the required direction was obtained with the development by Roy Middleton of his MARK VII sputter ion source which provided over 200 μA negative-ion beams of a large range of species [20]. These sources are presently manufactured by General Ionex Corporation (Model 860). Despite the large output current, the beam quality and performance remained unchanged, that is small emittance and energy spread. The negative-ion source (Fig. 5) is made of three components: the vessel with the sputter target kept at a constant negative voltage of at most 1.5 kV; the Cesium tank in front of the target kept at a positive voltage pulsed rapidly up to 3 kV; and an extraction column at the constant positive voltage of 25 kV with respect to the sputter target. Thus the negative-ions produced at the sputter target are accelerated at the same constant voltage of 25 kV whereas their intensity depends on the voltage through which the ions of Cesium are accelerated toward the target; if this voltage is pulsed with the desired duration and repetition cycle, also the negative-ion beam will take the same pulse shape. Indeed it has been demonstrated that a risetime of 1μs of the Cesium tank voltage corresponds to a variation of the beam intensity of about 10 μsec. As already said, this pulsed method has amply been demonstrated at BNL [19]; actually the whole heavy-ion program of this laboratory is based on its implementation.

It is possible to pulse the ion source at the repetition rate of ten pulses per second, as it is indeed required for filling circular accelerators at both BNL and the ADRIA project. The pulse duration can be made as large as one millisecond. In this mode of operation the same high level of negative-ion current can be sustained through acceleration with no alteration of the already good beam properties. It may be possible also to increase the source current to about 1000 μA, but it is still to be demonstrated that at this higher value the beam performance remains unchanged. Table 3 gives a summary of performance of heavy-ion beams from the Tandem facility at BNL, and Table 4 those from the Tandem at the Legnaro Laboratory. A major difference between the two facilities is that whereas in the BNL case the ion beam is taken directly from the Tandem to the following circular accelerator (either AGS or Booster), at

Legnaro, in the case of the ADRIA project, there is one intermediate state of acceleration with the ALPI superconducting Linac.

5. Filling of Circular Accelerators

At injection, the beam of heavy ions is a pulse lasting few hundred of microseconds. The duration of the pulse is chosen so that the beam wraps around the accelerator a number n of revolutions (turns), using a betatron stacking technique by which subsequent turns are placed next to each other in the phase space until the whole available aperture is filled. Typically $n = 20$ to 40 turns can be injected in this faction. From the accelerator circumference C and the velocity βc of the ions at injection it is possible to determine the revolution period $T = C/\beta c$ and the required pulse duration τ by multiplying the revolution period per the number of turns to be injected, that is

$$\tau = nC/\beta c \tag{1}$$

Eventually there is a limit on the maximum intensity that can be reached during injection, which is due to the depression of the betatron tunes due to space charge forces. This is estimated according to the following formula

$$\Delta\nu = \frac{N r_0 Q^2}{2\beta^2\gamma^3 B A \epsilon} \tag{2}$$

where N is the total number of ions injected, A the mass number, Q the charge state, $r_0 = 1.5347 \times 10^{-18}$ m the classical proton radius, B the bunching factor defined as the ratio of the average beam current to the peak current after rf capture and bunching, and β and γ are the usual relativistic factors. Finally ϵ is the beam emittance, which measures the phase space area occupied by the beam. An important design consideration is the relation between the circulating beam emittance and the value ϵ_T of the pulse at the Tandem exit

$$\epsilon = n\epsilon_T/\eta \tag{3}$$

where η is a betatron stacking efficiency of about 0.5. At most the beam emittance will equal the acceptance of the circular accelerator defined essentially by the vertical gap of the bending magnets.

Equation (2) is used to determine the maximum number N of ions that can be injected by allowing as an upper limit $\Delta\nu \sim 0.5$. In turns, it is possible to determine the required negative-ion source current I_s from the following relation

$$nI_sS_TS_FS_L = Ne/T \tag{4}$$

where S_T and S_F are the stripping efficiencies respectively of the stripping target at the terminal location and of the one after the Tandem exit; S_L is an overall transport efficiency which includes losses in the Tandem, in the subsequent transport line and in the post-accelerator; typically $S_L \sim 0.5$ or better.

Interesting to note that the AGS-Booster and the ADRIA-Booster have about the same size and capability; a comparison of performance between the two is given in Table 5 for the case of injection, accumulation and acceleration of ions of gold.

6. Momentum Distribution

The energy stability of the Tandem accelerators is good and the momentum spread in the beam is small, mostly the result of the scattering in the stripping targets. These are good features which need to be preserved for an efficient injection in the circular accelerator. To minimize the amount of voltage needed for capture, bunching and the early stage of acceleration a small momentum spread is required.

In the case of the BNL facility, the beam pulse in exit of the Tandem is continuous with no internal high frequency structure. A major difference exists with the Tandem-ALPI complex at Legnaro; prior to acceleration in the post-accelerator, the heavy ion beam is pre-bunched at the frequency of 5 MHz and then ulteriorly bunched and compressed at 80 and 160 MHz. It results a beam pulse which is made of a train of microbunches separated by 200 nsec each with a length of only few nanoseconds. This then becomes an ideal beam for injection into the subsequent circular accelerator. By choosing conveniently the accelerating rf system, one has available a sequence of small "brushes" that can be used to "paint" the rf buckets of the accelerator to minimize beam losses and space charge effects.

7. Conclusions

Few years ago, several institutions which had their activities centered around a Tandem accelerator saw their experimental programs being exhausted. Recently, the experimental evidence, especially at Brookhaven National Laboratory, that Tandems can be used very effectively as injectors to circular accelerators has caused a renewed interest in these electrostatic devices. At the moment of writing this paper, for the first time the MP-7 Tandem has delivered pulses of ^{197}Au ions for acceleration in the Booster and in the AGS at BNL; for the first time very heavy ions, fully stripped, were accelerated to 12.5 GeV/u and delivered to several experiments.

Waiting that other ions sources and other methods of acceleration (e.g. ECR and RFQ) will become more competitive and will present higher performance alternatives, Tandems still remain very useful especially in those facilities with long range plans of heavy-ion programs.

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References

[1] A.G. Ruggiero, "The BNL Heavy-Ion Beam Facility" The Physics of Particle Accelerators, AIP Conf. Proc. 249, Vol. 2, p. 2129.

[2] C. Gardner, et al., Proceedings of the 1989 IEEE Particle Accelerator Conference, March 20-23, 1989, Chicago, IL, Vol. 3, page 1850.

[3] RHIC Conceptual Design, May 1989, BNL 52195.

[4] P. Thieberger, NIM 220 (1984), 45-53.

[5] D. Brandt et al., Proceedings of EPAC, Nice, France, June 1990, Vol. 1, p. 49.

[6] N. Angert et al., Proceedings of EPAC, Rome, Italy, June 1988, Vol. 2, p. 1367.

[7] Design Study of the Large Hadron Collider (LHC), May 1991, CERN 91-03.

[8] H. Haseroth (Ed.) CERN Yellow Report 90-01, Feb. 1990.

[9] D. Böhne et al., Proceedings of EPAC, Nice, France, June 1990, Vol. 1, p. 18.

[10] B. Franzke et al., Proceedings of EPAC, Nice, France, June 1990, Vol. 1, p. 46.

[11] The ADRIA proposal. LNL-INFN (REP) 58/92.

[12] Feasibility Study of a Hadron Facility. LNL-INFN (REP) 57/92.

[13] CRYSTAL. LNL-INFN (REP) 59/92.

[14] G. Fortuna et al., NIM A287 (1990) 253-256.

[15] R.A. Ricci and C. Signorini, NIM 184 (1981) 35.

[16] See, for instance, Proceedings of the Heavy Ion Fusion Workshop, Brookhaven National Laboratory, October 1977, BNL 50769.

[17] K. Prelec et al., NIM A295 (1990) 21-23.

[18] R.J. Van de Graaff, Phys. Rev. 38, 1919 (A).

[19] P. Thieberger et al., IEEE Trans. on Nuclear Science, Vol. NS-30, No. 4, Aug. 1983.

[20] R. Middleton, Proc. "Symp. of Northeastern Accelerator Personnel," Univ. of Wisconsin, Oct. 13-15, 1980.

Table 1. MP Tandem at BNL (15 MV)

	A	Z	QT	ST	MeV/u	β
Deuterium	2	1	+1	70%	15.0	0.177
Oxygen	16	8	+6	39	6.56	0.118
Silicon	28	14	+9	30	5.36	0.107
Copper	63	29	+11	27	2.86	0.078
Iodine	127	53	+13	20	1.65	0.059
Gold(*)	197	79	+14	12	1.07	0.048
			+33	20		
Uranium(**)	238	92	+35	3.4	0.88	0.043

(*) Two stripping stages: one at the Tandem terminal and the second at the Tandem exit.

(**) Result of two stripping stages.

Table 2. XTU Tandem (16 MV) and ALPI (40 MV) at LNL

	A	Z	QT	ST	QF	SF	MeV/u	β
Sulfur	32	16	+9	34%	+16	50%	5.00 - 16.40	0.103 - 0.185
Copper	63	29	+11	27	+27	46	3.05 - 10.39	0.081 - 0.148
Iodine	127	53	+12	20	+40	21	1.64 - 6.11	0.059 - 0.114
Gold	197	79	+13	20	+51	16	1.14 - 4.58	0.049 - 0.099
Uranium	238	92	+13	20	+54	14	0.94 - 3.86	0.045 - 0.091

Table 3. Tandem - Booster Performance at BNL

Pulse Length for Gold			110 μs
Current of Negative-Ion Source			200 μA
	Ions/Cycle$^{(+)}$	Space-Charge Limit	Kinetic Energy
Deuterium	2.0×10^{10}	81×10^{11}	1.86 GeV/u
Oxygen	1.7	3.8	1.25
Silicon	1.4	2.4	1.00
Copper	1.75	1.9	0.38
Iodine	1.7	1.1	0.14
Gold$^{(*)}$	0.84	0.9	0.072
$^{(**)}$	0.25	0.16	0.35
Uranium	0.40	1.1	0.28

(+) Transfer transmission of 75%. No stripping between Tandem and Booster.

(*) Charge state +13, for RHIC injection.

(**) Charge state +33, for other programs.

Table 4. Tandem - ALPI - Booster Performance of ADRIA

Pulse Length for Gold			360 μs
Current of Negative-Ion Source			200 μA
	Ions/Cycle(*)	Space-Charge Limit	Kinetic Energy
Sulfur	2.0×10^{10}	18.9×10^{10}	2.53 GeV/u
Copper	1.8	13.2	2.08
Iodine	0.79	6.6	1.37
Gold	0.68	4.9	1.03
Uranium	0.68	4.6	0.85

(*) Transfer transmission of 50% including ALPI. Second stripping target in ALPI.

Table 5. Comparison between AGS and ADRIA Boosters for the case of Au ions*

	AGS-Booster	ADRIA-Booster	
Circumference	201.8	266.7	m
max $B\rho$	17.52	22.25	T·m
Repetition Rate	7.5	10	Hz
Charge State	33	51	
Injection Kin. En.	1.1	4.6	MeV/u
β	0.048	0.099	
Top Kin. En.	0.035	1.0	GeV/c
β	0.69	0.88	
Tandem pulse length	110 (300)	360	μs
No. of turns injected	8 (20)	40	
Intensity	1.9×10^{10}	6.8×10^{10}	ions/sec
Space Charge Limit	1.2×10^{11}	4.9×10^{11}	ions/sec
Norm. Emittance	4	12	πmm·mrad

* Assuming a negative-ion source current of 200 μA. Overall transmission is 75% for AGS-Booster and 50% for ADRIA-Booster which also includes the ALPI post-accelerator.

Figure Captions

Fig. 1 The BNL facility for heavy-ions.

Fig. 2 The ADRIA complex on the LNL site.

Fig. 3 XTU Tandem and ALPI at LNL.

Fig. 4 The principle of operation of a Tandem.

Fig. 5 Schematic of a sputtering negative-ion source.

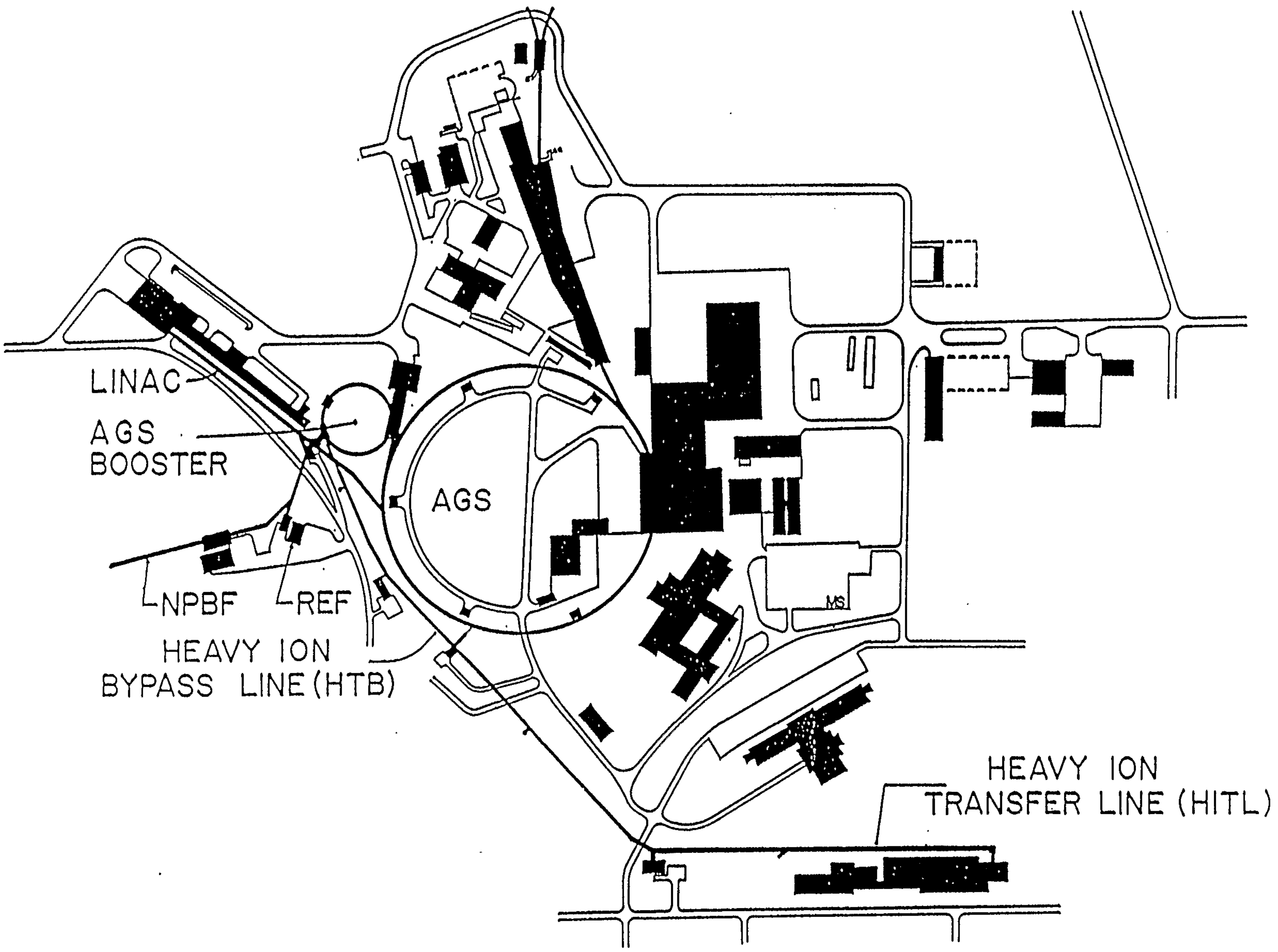

LINAC
AGS BOOSTER
AGS
NPBF
REF
HEAVY ION BYPASS LINE (HTB)
HEAVY ION TRANSFER LINE (HITL)
MS

Figure 1

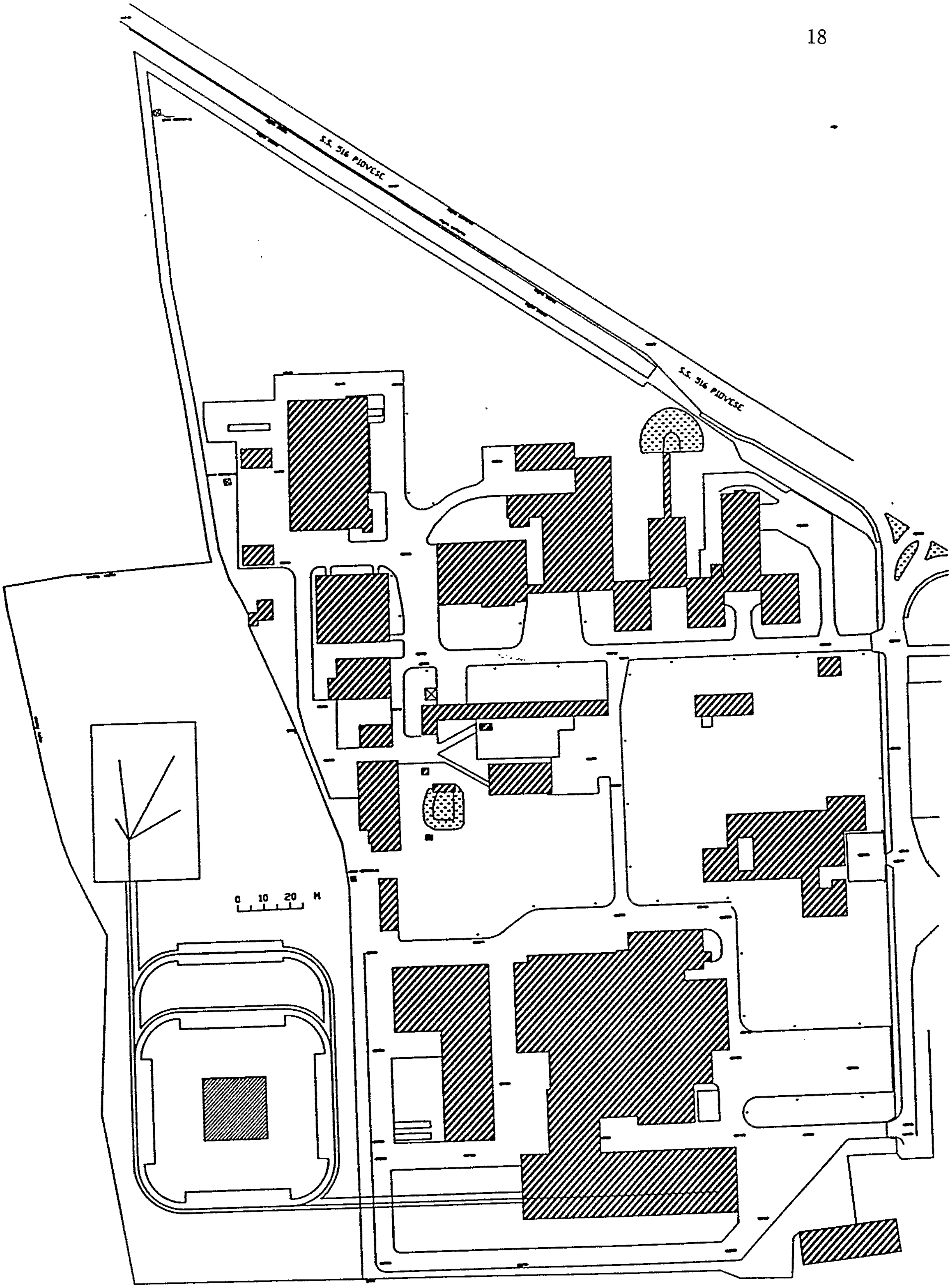


Figure 2

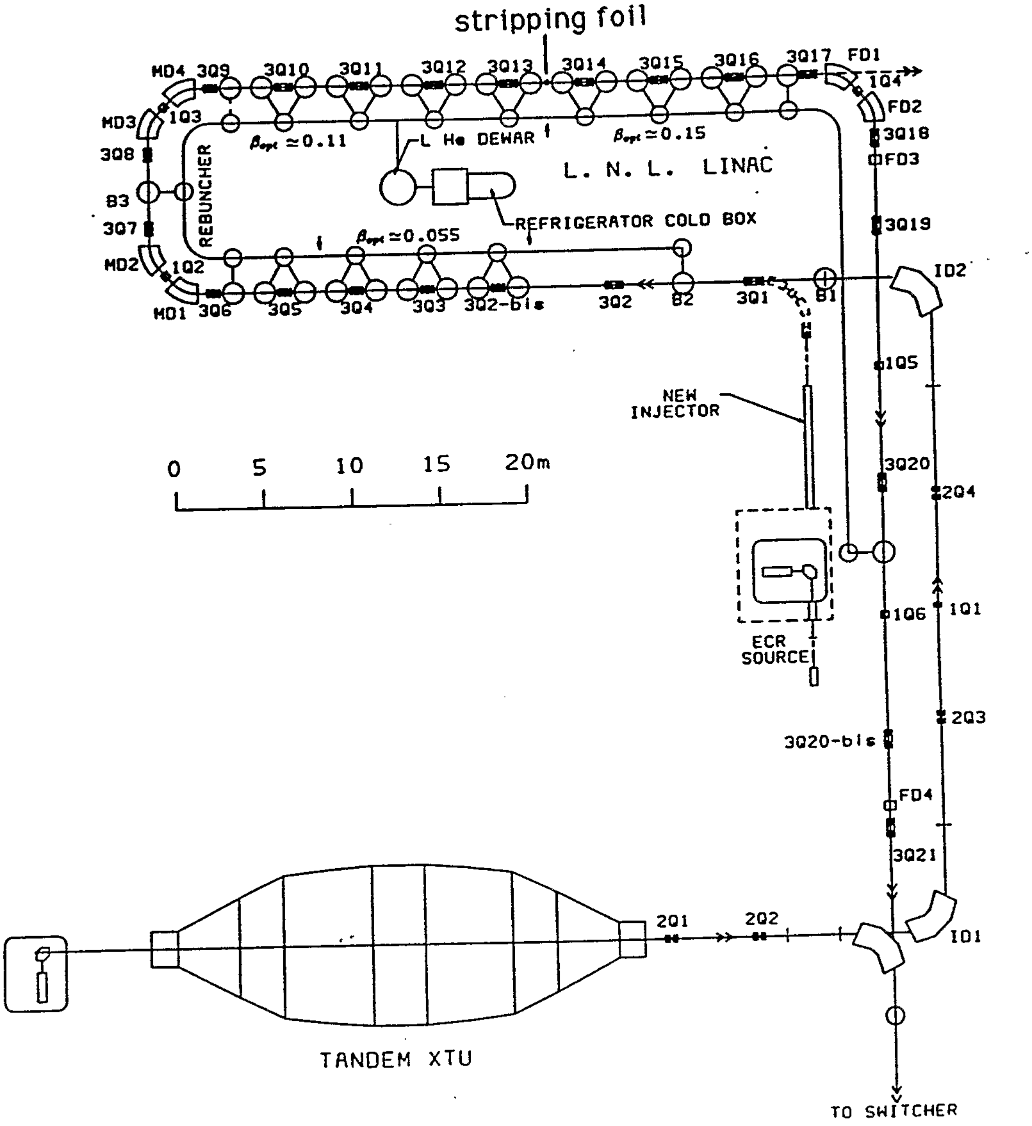
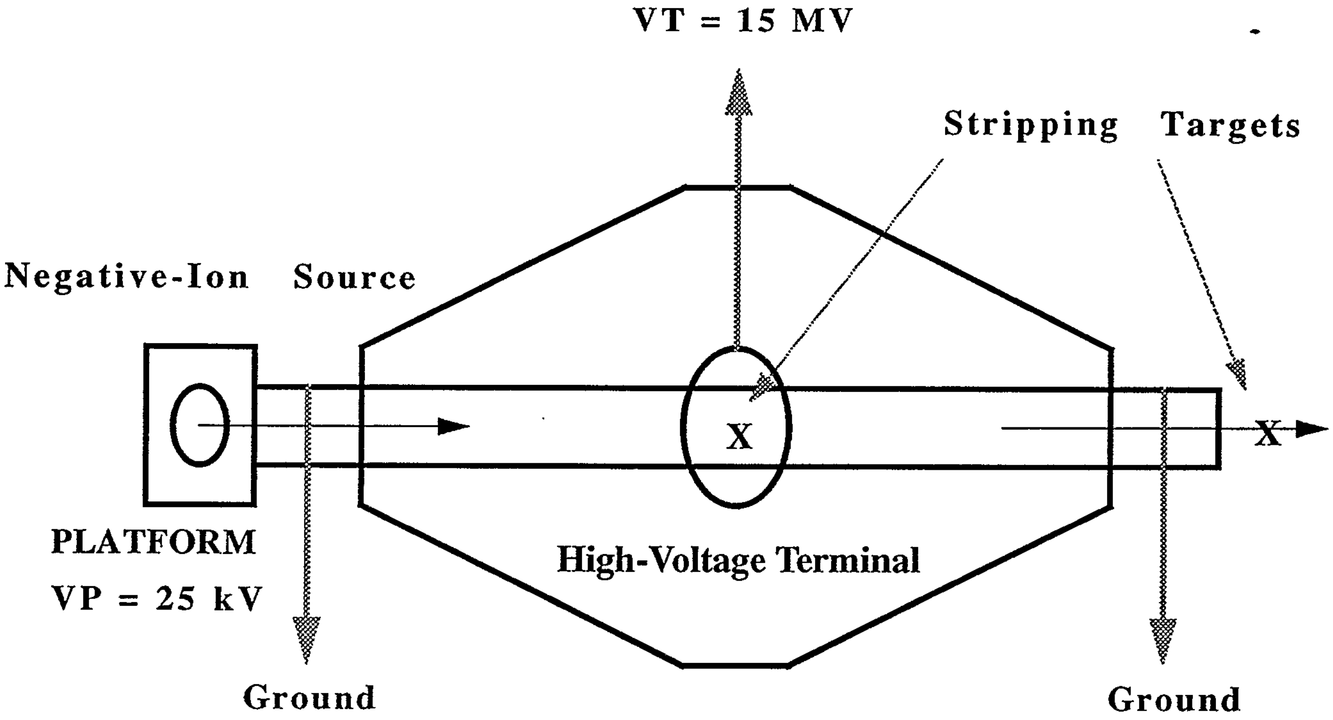

stripping foil
MD4
3Q9
3Q10
3Q11
3Q12
3Q13
3Q14
3Q15
3Q16
3Q17
FD1
1Q4
FD2
3Q18
FD3
3Q19
MD3
1Q3
3Q8
B3
3Q7
MD2
1Q2
MD1
3Q6
3Q5
3Q4
3Q3
3Q2-bis
3Q2
B2
3Q1
B1
ID2
REBUNCHER
$\beta_{opt} \simeq 0.11$
L He DEWAR
$\beta_{opt} \simeq 0.15$
L. N. L. LINAC
REFRIGERATOR COLD BOX
$\beta_{opt} \simeq 0.055$
NEW INJECTOR
1Q5
3Q20
2Q4
0
5
10
15
20m
ECR SOURCE
1Q6
1Q1
2Q3
3Q20-bis
FD4
3Q21
2Q1
2Q2
ID1
TANDEM XTU
TO SWITCHER

Figure 3



-1	*Charge State*	QT	QF
	Stripping Efficiency	ST	SF

$$\begin{aligned} \textit{Energy Gain} &= VP + VT + QT \times VT \\ &= 25\ \text{kV} + 15\ \text{MV} \times (1 + QT) \end{aligned}$$

Figure 4

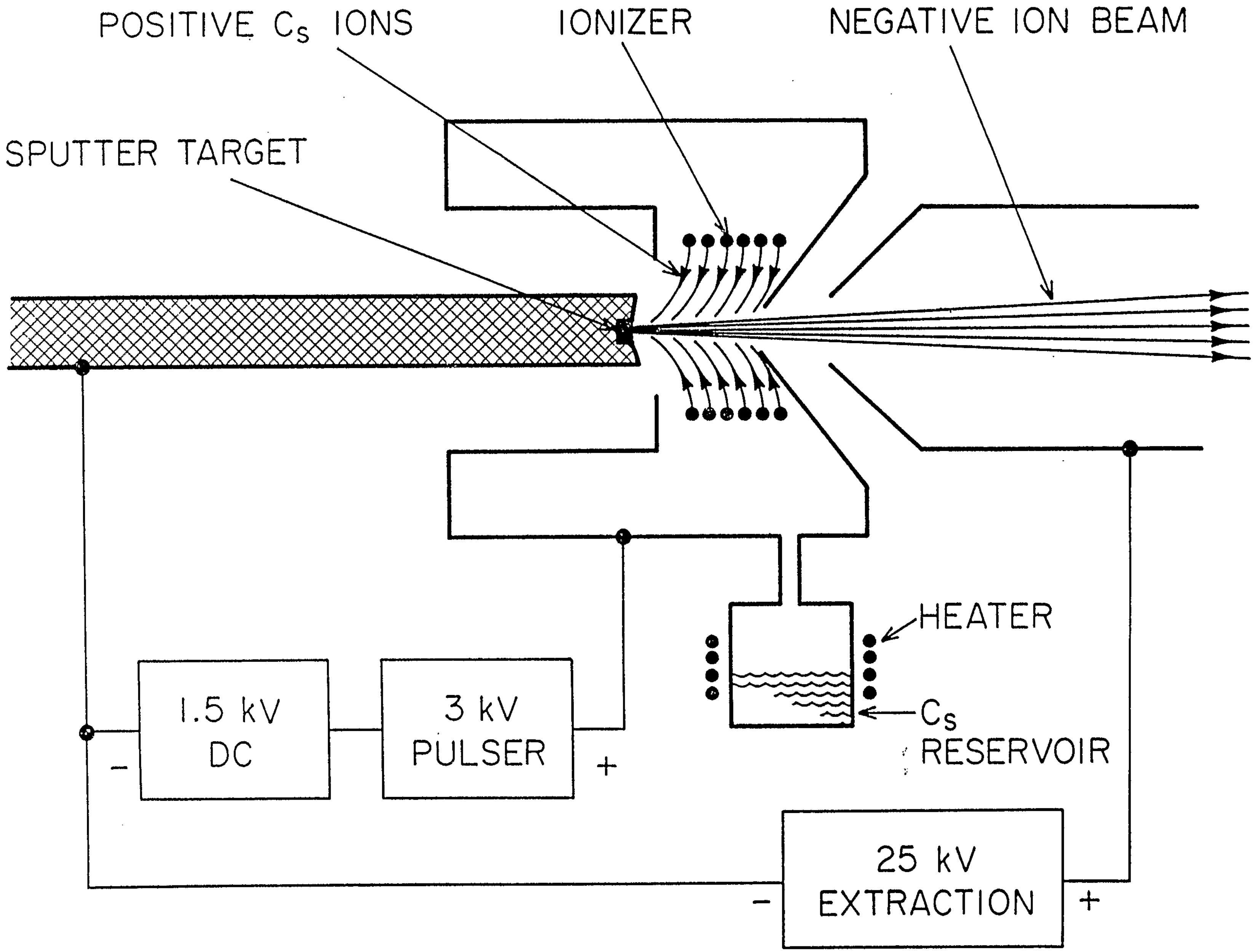

POSITIVE C_s IONS
IONIZER
NEGATIVE ION BEAM
SPUTTER TARGET
HEATER
C_s RESERVOIR
1.5 kV DC
3 kV PULSER
25 kV EXTRACTION
−
+
−
+

Figure 5