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RADIOACTIVE ION BEAMS WITH THE HHIRF ACCELERATORS*

M. J. MEIGS,† G. D. ALTON, C. BAKTASH, D. T. DOWLING, J. D. GARRETT, D. L. HAYNES, C. M. JONES, R. C. JURAS, S. N. LANE, I. Y. LEE, G. D. MILLS, S. W. MOSKO, D. K. OLSEN, B. A. TATUM, K. S. TOTH
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6368, USA

H. K. CARTER††
Oak Ridge Associated Universities
Oak Ridge, Tennessee 37831, USA

1. Introduction

Our present understanding of nuclear structure is almost completely based on facts obtained for nuclei that can be produced with stable projectiles and targets which have equilibrated for a significant fraction of the lifetime of the universe. The use of Radioactive Ion Beams (RIB) could overcome this limitation and provide unique opportunities for the study of nuclear structure with nuclei far from stability. These nuclei could answer critical issues concerning some of the most fundamental current nuclear structure themes and allow the study of entirely new phenomena, unobservable with current techniques and not derivable from our present knowledge of nuclear theory. RIB will also open new opportunities for the study of processes taking place at less equilibrated astrophysical sites, such as supernovae, cataclysmic binaries, and accreted shells of neutron stars. Widespread interest in RIB has developed in the last few years and a steering committee has recently been established to consider the construction of a large radioactive beam facility in North America. With this interest in mind, we have performed a feasibility study for a low-cost extension of the Holifield Heavy Ion Research Facility (HHIRF) accelerators which would provide access, on a short time scale, to much of the physics of proton-rich nuclei.[1]

2. Radioactive Beams from the HHIRF Accelerators

The two coupled accelerators of the HHIRF provide a unique opportunity to quickly and economically develop a medium-intensity radioactive beam facility in North America using an isotope separator on line (ISOL). Presently, the Oak

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† Instrumentation and Controls Division, ORNL.
†† Oak Ridge Associated Universities, Oak Ridge, TN, contract DE-AC05-76OR00033.

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Ridge Isochronous Cyclotron (ORIC) serves as an energy booster for heavy ions and is injected directly from the 25-MV tandem accelerator. To produce radioactive beams with the HHIRF accelerators, this process could simply be reversed. The tandem accelerator would be injected with heavy ions produced by ORIC. In this case, the two accelerators will be coupled by a thick target, ion source, and mass separator mounted on a high-voltage platform. Light ions from ORIC, with an internal ion source, would produce radioactive heavy ions for tandem injection. Moreover, the University Isotope Separator-Oak Ridge (UNISOR) with its FEBIAD ion source[2,3] provides the capability to immediately investigate and develop the target-ion source hardware and chemistry required to produce useable radioactive beams.

Because of its high terminal voltage, the tandem accelerator can accelerate 5-MeV/amu beams with high efficiency up to about mass 80. This is illustrated in Fig. 1, which shows maximum energy and corresponding total transmission efficiency, including terminal stripping charge state fraction, for operation with terminal gas stripping and terminal foil stripping. It is important to appreciate that since the tandem accelerator is inherently a dc machine, no bunching is required for the injected beam. This property is a perfect match to the low-intensity dc beams available from an ISOL source. In addition, the other inherent advantages of the tandem accelerator, such as simplicity, reliability, flexibility, and excellent accelerated beam quality, are also available. No modification to the tandem accelerator would be required for service as a radioactive beam postaccelerator.

It is also important to note that most, but not all, elements are easily formed as negative ions for tandem injection. The use of negative ions provides an additional physical factor to help select a specific product atom with respect to its corresponding isobars. This fact has led to the development of ISOL negative ion sources[4,5] even in cases where negative ion sources were not required for other reasons.

ORIC[6] was designed for the acceleration of both light and heavy ions and was used extensively for the production of intense light-ion beams in the first years after its completion in the early 1960s. It should be noted that continued use of the ORIC as an energy booster in normal coupled operation is planned and that the modifications required for stand-alone light-ion operation with an internal ion source are not expected to interfere with this present operating mode.

The shielding for the original ORIC facility[7] was designed for 75-MeV, 1-mA proton beams; consequently, the ORIC vault, and the original ORIC target areas, rooms C110 and C111, are shielded to this original standard. These rooms are also equipped with single-pass HVAC systems appropriate for high-radiation areas. In this study, room C111 was assumed to house the ISOL target-ion source and mass separator on a 300-kV platform, as well as the associated storage caves and remote handling equipment which may be required for the irradiated target-ion sources. While rearrangement of stacked block shielding may be necessary, no civil construction would be required.

3. Expected Energy and Intensity Performance

Primary beams will be accelerated in ORIC. The maximum energy of these beams is limited by the maximum ORIC bending power given by $K = ME/Q^2 = 105$, as well as rf frequency and focusing limitations for protons. The assumed maximum energy for the light-ion beams of interest are: 55-MeV ^1H, 52-MeV ^2H, 140-MeV $^3He^{2+}$, 105-MeV $^4He^{2+}$, 70-MeV $^6Li^{2+}$, 60-MeV $^7Li^{2+}$, 94-MeV $^{10}B^{3+}$, and 86-MeV $^{11}B^{3+}$. The maximum available intensity of ^1H, ^2H, ^3He, and ^4He beams is presently believed to be limited by heat dissipation and activation in the beam extraction system, specifically the septum of the electrostatic deflector. For this study, a maximum value of 1 kW for heat dissipation in the deflector septum and a beam extraction efficiency of 67% were assumed. These assumptions limit the extracted beam power to 2 kW; consequently, the corresponding extracted beam intensity is given by $I\ (p\mu A) = 2000/E\ (MeV)$. It was also assumed that the available intensity of Li and B beams will be ion-source limited to 10 pμA for both elements, independent of energy.

The thick target production rates listed in Table 1 for radioactive atoms were estimated using a cross-section model based on nuclear systematics along with the stopping powers of Northcliffe and Schilling.[8] Production rates for proton-rich beams were calculated using (H, xn), (He, xn), (Li, xn), and (B, xn) reactions on C, N, O, Si, and Ge targets. Other target elements and reactions are also possible, but were not considered in this study.

In principle, 118 proton-rich radioactive beams between ^7Be and ^{84}Rb could be accelerated with energies > 5 MeV/amu from an ISOL facility[9] based on the existing HHIRF accelerators. For this study, we have restricted the initial radioactive beams to those isotopes of oxygen, fluorine, phosphorus, sulfur, arsenic, and selenium which are identified in Table 1. These isotopes were chosen because they could be obtained using target-beam combinations with favorable chemical and physical properties and their half-lives were not too short, nor so long as to pose activation problems. Taking into consideration the maximum accelerated beam intensity, the intensity and half-lives of the activation products, and other factors where appropriate, the most favorable reaction was chosen for each radioactive beam. Information on these most favorable reactions is summarized in Table 1. It is important to note from Table 1 that the maximum required primary beam energies are generally quite low. These low energies will result in low ORIC operating costs and low system activation. Other factors contributing to the maximum accelerated RIB intensities given in Table 1 are listed below:

(1) Conversion efficiency of atoms to negative ions was considered for either direct surface ionization or charge exchange. Direct surface ionization was assumed for elements with electron affinities greater than about 2 eV. For these elements, conversion efficiencies were estimated from the Langmuir-Saha relation for a LaB_6 surface ionizer operated at 1370°K. The actual operating efficiency was taken to be 50% of this calculated value.

Conversion efficiencies for atoms to negative ions using the charge-exchange technique are the product of two factors: the efficiency for conversion from atoms to positive ions and the efficiency for conversion of positive ions to negative ions. For this study, the efficiencies for converting neutral radioactive atoms into positive ions were estimated by scaling the efficiency of the species in question to a 30% value measured for calcium.[10] The efficiencies for positive to negative ion conversion through sequential charge exchange were based on experimental measurements by Heinemeier and Hvelplund for Na and Mg[11] exchange vapors and on measured values by Greenway for Cs exchange vapor as reported in Ref. 12.

(2) A 50% loss factor has been included to account for anomalous losses in beam transport.

(3) Total tandem accelerator efficiencies were taken from Fig. 1. These efficiencies are the product of the tandem transmission for either gas or foil terminal stripping and terminal charge state fraction.[13] The charge state and charge state fractions were taken at the peak of the charge state distribution. A maximum terminal potential of 26 MV was assumed.

(4) The results summarized in Table 1 do not contain any decay losses for short-lived isotopes and assume a 100% release efficiency of radioactive atoms from the target material.

4. Additional Equipment

The additional equipment required to produce radioactive beams at the HHIRF is shown in Figs. 2 to 4. Figure 2 shows the ISOL target-ion source and mass separator located on a high-voltage platform situated in the south end of room C111. Except for a necessary change in elevation, the high-voltage platform could be fed by an existing 43-ft-long beam line from ORIC. The high-voltage platform would be operated at potentials up to 280 kV, with respect to building ground, and, in conjunction with the ISOL source potential of 20 to 80 kV, with respect to platform ground, would provide the nominal 300 keV energy presently used for tandem injection. ORIC beams would be transported from ground potential to the platform, and the ISOL source, through an acceleration tube. Depending on the element, either positive or negative ions would be formed in the ISOL source. These ions would be accelerated to platform potential, gaining 20 to 80 keV, and then transported through a 90° analyzing magnet where ions of the desired mass would be selected. This mass-analyzed beam would then be transported through the charge exchange cell, if required, and through an acceleration tube to ground potential. At this point, the beam would be ready for injection into the tandem accelerator with the normal injection energy of 300 keV. As shown in Fig. 2, the north end of room C111 could, if required, be configured as an ion source service area with appropriate shielding and remote-handling equipment.

Figures 3 and 4 show a beam line to transport the negative ion beam through the east experimental area, room T106, from the high-voltage platform to the tandem accelerator. Injection into the tandem accelerator would be accomplished by transporting the beam through the existing, de-energized, mass-analyzing magnet as shown in Fig. 4. A second mass analysis would be performed on the negative ion beam prior to tandem injection with the 65° magnet shown in Fig. 3. The negative ion beam transfer line will use components identical to, or very similar to, those used in the existing tandem injection line and will be of all-metal construction. This beam line will be pumped with sputter ion pumps, and operating pressures in the low 10^{-8} Torr range are expected.

Controls for components on the ISOL high-voltage platform and the negative ion beam transfer line would be provided by a straightforward extension of the existing tandem accelerator CAMAC-based control system. Since the tandem accelerator is now equipped with two independent control consoles, one of these could easily be used for ISOL operations. It is important to note that the proposed ISOL system could be operated independently of the tandem accelerator, so that radioactive beams could be developed off-line without disturbing conventional tandem-only operation.

The most important additional component required for producing radioactive beams with the HHIRF is, of course, the ISOL target-ion source. The detailed choice of target type and composition, ion source type, materials and geometry, component operating temperatures, possible support gases, etc. depend on the desired radioactive beam and target isotope. Clearly, the general techniques developed at the ISOLDE facility,[14] UNISOR, GSI,[15] and other on-line isotope separators, are directly applicable. However, the specific techniques required for a low-energy, light-ion primary beam producing relatively light radioactive ions in thick targets will require considerable research and development. Efforts are now under way to begin this research and development using the existing UNISOR facility and the tandem accelerator as a source of beams for the implantation of elements of special interest.

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Table 1. Radioactive Beams Considered for Initial Operation

Reaction	Lifetime	Primary Energy Range (MeV)	Production Rate* (Atoms/s/puA)	Source Type	Positive Ionization Efficiency (%)	Negative Ion Conversion Efficiency (%)	Tandem Transmission E ≥ 5 MeV/amu (%)	Accelerated*** Beam (ions/s/puA)	Max. Primary Beam Intensity (puA)	Max. Accel. Beam Intensity (ions/s)
$B^{14}_{7}N(p,n)^{14}_{8}O$	1.18 m	18-33	0.23×10^{10}	CE	8.5	45	35(G)	1.7×10^{7}	61	1.0×10^{9}
$B^{15}_{7}N(p,n)^{15}_{8}O$	2.03 m	11-22	0.41×10^{10}	CE	8.5	45	35(G)	2.7×10^{7}	91	2.5×10^{9}
$Si^{16}_{8}O_2(d,n)^{17}_{9}F$	64.5 s	13-29	0.86×10^{10}	SI		100(50)**	32(G)	6.9×10^{8}	69	4.7×10^{10}
$Si^{18}_{8}O_2(p,n)^{18}_{9}F$	1.83 h	8-15	0.26×10^{10}	SI		100(50)**	32(G)	2.1×10^{8}	100	2.1×10^{10}
$^{29}_{14}Si(d,2n)^{29}_{15}P$	4.14 s	19-33	0.19×10^{11}	CE	15	70	26(G)	2.6×10^{8}	61	1.6×10^{10}
$^{30}_{14}Si(d,2n)^{30}_{15}P$	2.5 m	16-25	0.11×10^{11}	CE	15	70	26(G)	1.5×10^{8}	80	1.2×10^{10}
$^{28}_{14}Si(^{3}_{2}He,n)^{30}_{16}S$	1.24 s	15-28	0.16×10^{10}	SI		15.8(7.9)**	26(G)	1.6×10^{7}	71	1.2×10^{9}
$^{29}_{14}Si(^{3}_{2}He,n)^{31}_{16}S$	2.56 s	11-14	0.23×10^{9}	SI		15.8(7.9)**	26(G)	2.4×10^{6}	100	2.4×10^{8}
$^{70}_{32}Ge(p,3n)^{68}_{33}As$	2.65 m	36-43	0.28×10^{11}	CE	26	60	8.5(F)	1.8×10^{8}	47	8.7×10^{9}
$^{70}_{32}Ge(p,2n)^{69}_{33}As$	15.2 m	23-31	0.24×10^{11}	CE	26	60	8.5(F)	1.6×10^{8}	65	1.0×10^{10}
$^{72}_{32}Ge(p,3n)^{70}_{33}As$	52.6 m	38-40	0.31×10^{11}	CE	26	60	8.5(F)	2.0×10^{8}	51	1.0×10^{10}
$^{72}_{32}Ge(p,2n)^{71}_{33}As$	2.7 d	20-27	0.20×10^{11}	CE	26	60	8.5(F)	1.3×10^{8}	74	1.0×10^{10}
$^{72}_{32}Ge(p,n)^{72}_{33}As$	1.08 d	11-15	0.72×10^{10}	CE	26	60	8.5(F)	4.8×10^{7}	100	4.8×10^{9}
$^{74}_{32}Ge(p,2n)^{73}_{33}As$	80.3 d	18-24	0.18×10^{11}	CE	26	60	8.5(F)	1.2×10^{8}	83	1.0×10^{10}
$^{76}_{32}Ge(p,3n)^{74}_{33}As$	17.8 d	25-31	0.19×10^{11}	CE	26	60	8.5(F)	1.3×10^{8}	65	8.2×10^{9}
$^{76}_{32}Ge(p,n)^{76}_{33}As$	1.1 d	9-10	0.18×10^{10}	CE	26	60	8.5(F)	1.2×10^{7}	100	1.2×10^{9}

Reaction	Lifetime	Primary Energy Range (MeV)	Production Rate* (Atoms/s/puA)	Source Type	Positive Ionization Efficiency (%)	Negative Ion Conversion Efficiency (%)	Tandem Transmission E ≥ 5 MeV/amu (%)	Accelerated*** Beam (ions/s/puA)	Max. Primary Beam Intensity (puA)	Max. Accel. Beam Intensity (ions/s)
$^{70}_{32}Ge(^{3}_{2}He,3n)^{70}_{34}Se$	41.0 m	27-37	0.43×10^{10}	CE	27	50	8.2(F)	2.4×10^{7}	54	1.3×10^{9}
$^{70}_{32}Ge(^{3}_{2}He,2n)^{71}_{34}Se$	4.7 m	18-22	0.13×10^{10}	CE	27	50	8.2(F)	7.2×10^{6}	91	6.5×10^{8}
$^{72}_{32}Ge(^{3}_{2}He,3n)^{72}_{34}Se$	8.4 d	22-31	0.37×10^{10}	CE	27	50	8.2(F)	2.0×10^{7}	65	1.3×10^{9}

* Excluding decay and target release losses.
** Theoretical (assumed) surface ionization efficiency.
*** For surface ionization negative ion production, values in this column were calculated using assumed negative ion conversion efficiencies for surface ionization. For charge exchange negative ion production, values in this column were estimated from the product of the positive ionization efficiency and negative ion conversion efficiency for charge exchange. A 50% loss factor for transport from the source or charge exchange cell to the tandem accelerator was also assumed for both methods of negative ion production.
In the Source Type column, CE denotes charge exchange and SI denotes surface ionization.
In the Overall Tandem Transmission Efficiency column, F denotes operation of the tandem in the foil stripping mode, and G denotes operation in the gas stripping mode.

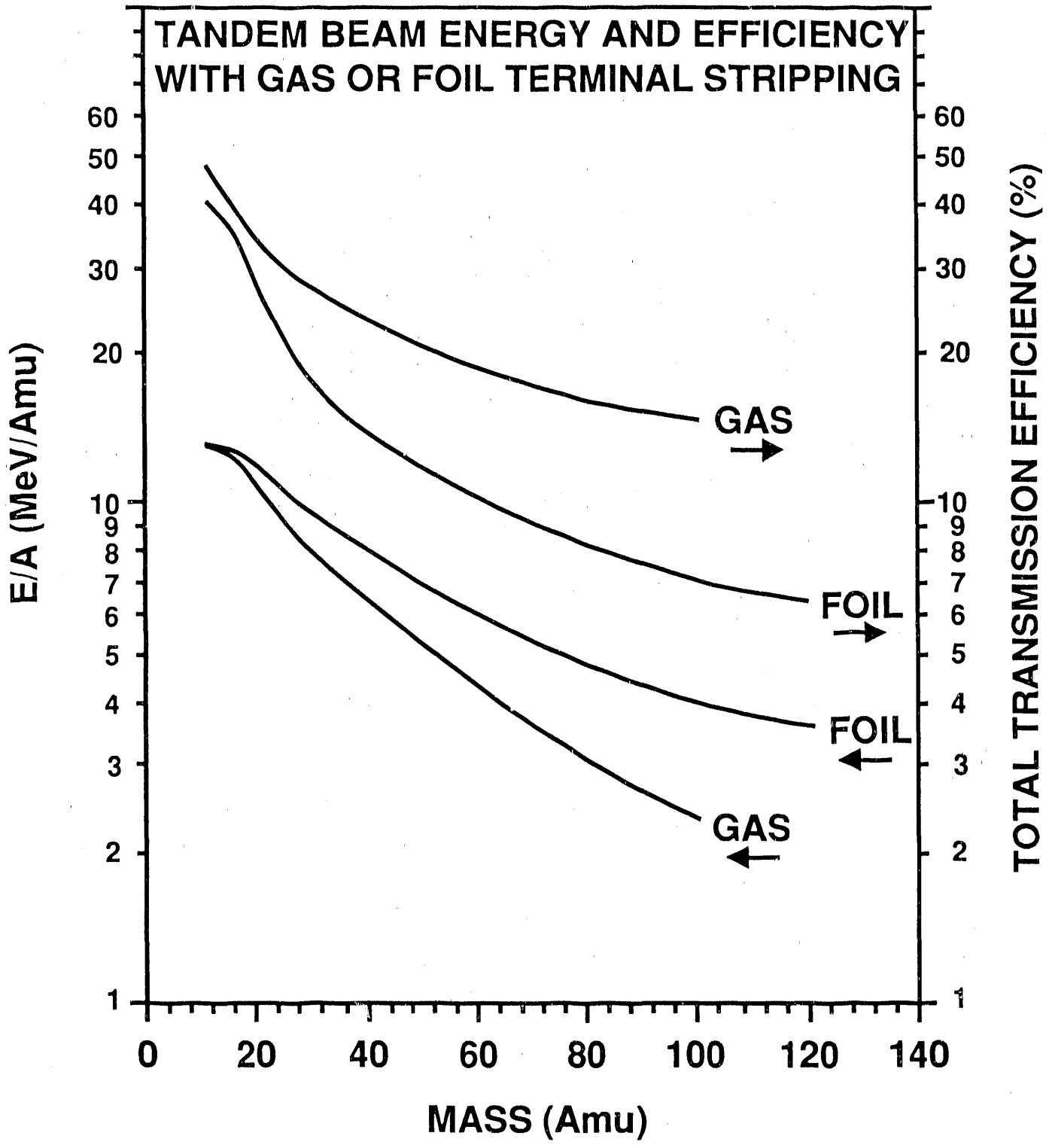

Fig. 1. Maximum beam energy per nucleon and total transmission efficiency of the most probable charge state for the tandem accelerator operated with gas and foil stripping with the terminal potential at 26 MV.

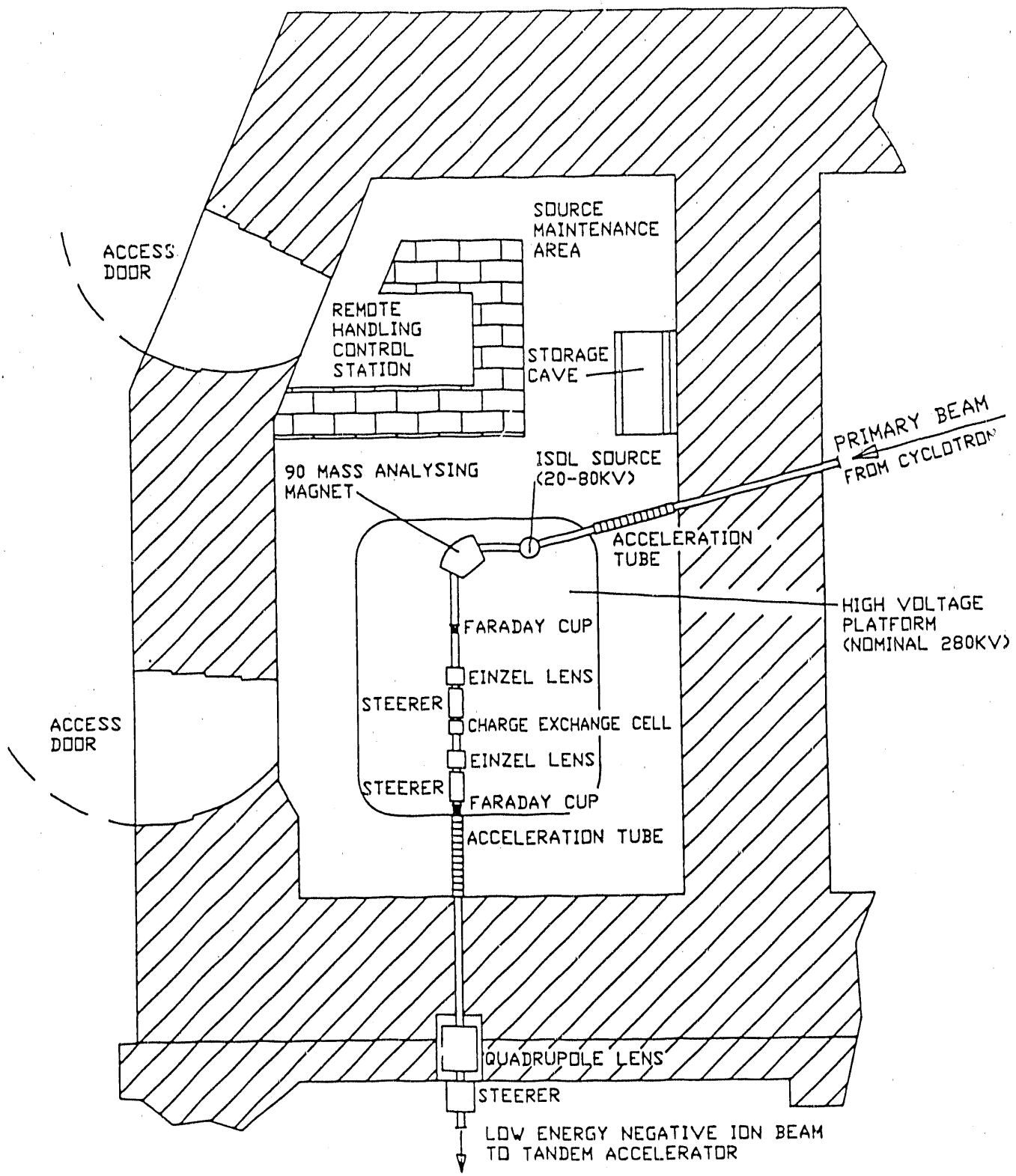

Fig. 2. Plan view of target room C111 showing details of the proposed radioactive beam facility high-voltage platform and source maintenance area.

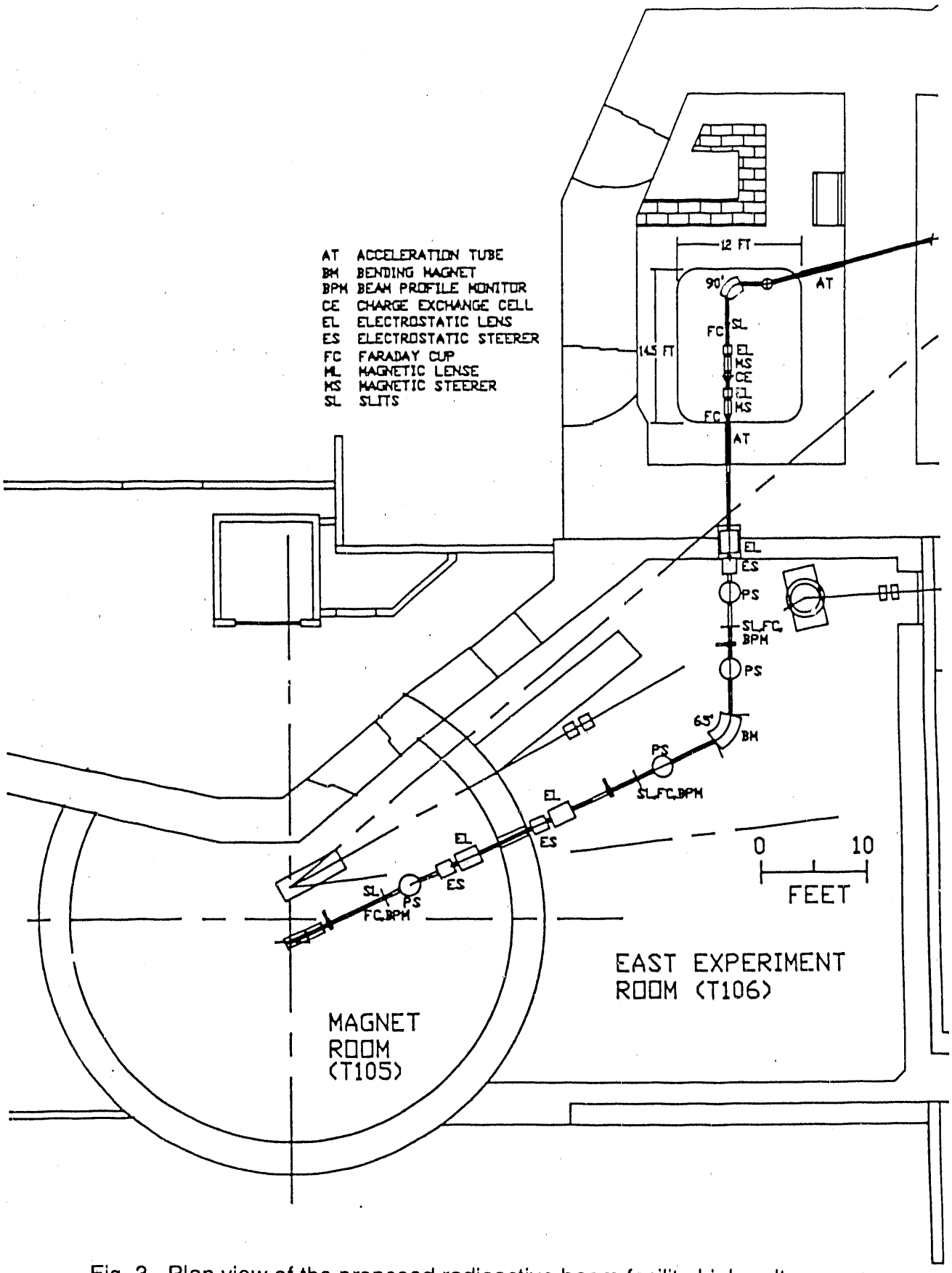

Fig. 3. Plan view of the proposed radioactive beam facility high-voltage platform and negative ion transfer line.

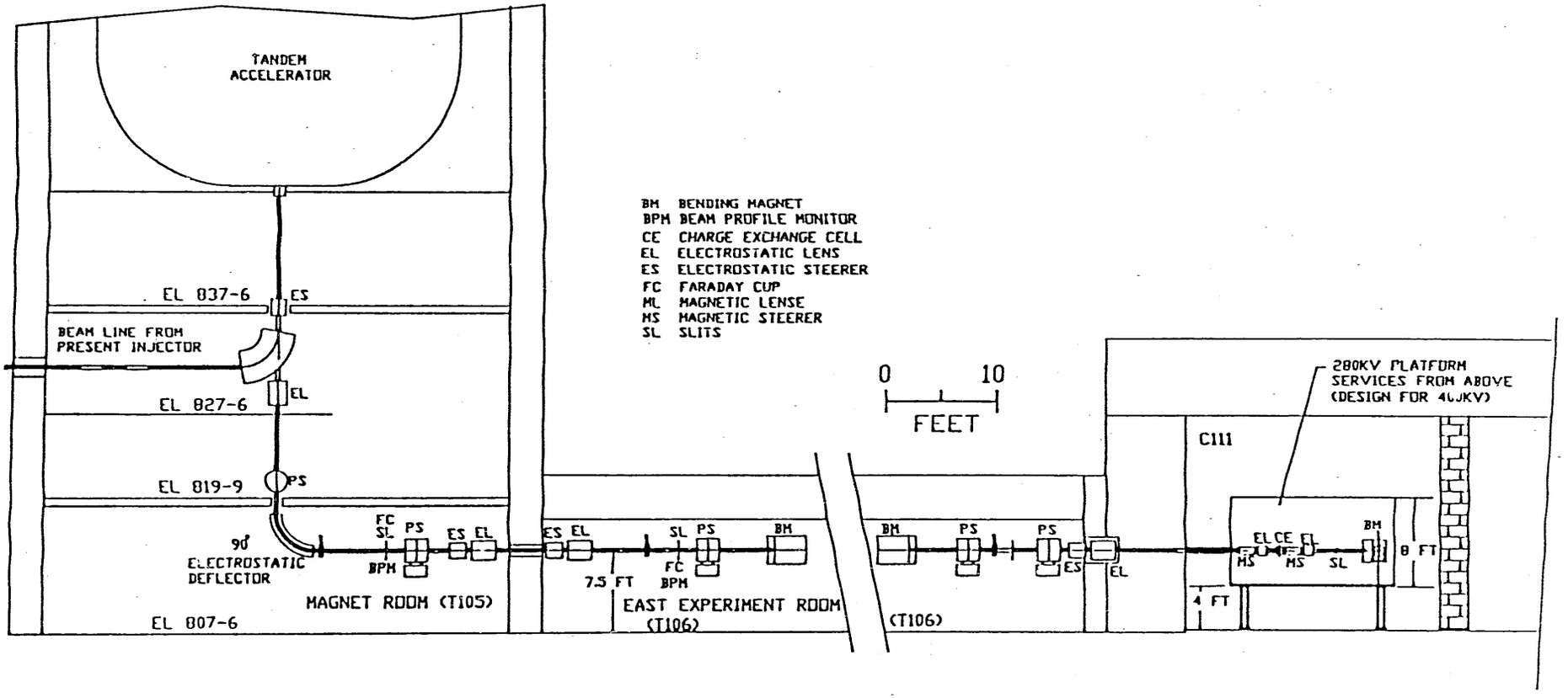

Fig. 4. Elevation view of the proposed radioactive beam facility high-voltage platform and negative ion transfer line.

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