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ECR SOURCE FOR THE HHIRF TANDEM ACCELERATOR

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INTRODUCTION

Electron Cyclotron Resonance, ECR, ion source technology has developed rapidly since the original pioneering work of R. Geller and his group at Grenoble in the early 1970s. These ion sources are capable of producing intense beams of highly charged positive ions and are used extensively for cyclotron injection, linac injection, and atomic physics research. In this paper, the advantages of using an ECR heavy-ion source in the terminal of the Holifield Heavy Ion Research Facility (HHIRF) 25-MV tandem accelerator is discussed. A possible ECR system for installation in the HHIRF tandem terminal is described.

An ECR source in the terminal of an electrostatic accelerator is advantageous if it could provide larger currents of higher charge states than with conventional sources. Comparison of source performance is straightforward for single-ended electrostatic accelerators. For tandem accelerators, the comparison is more complicated, since negative ions are injected and then stripped to a positive charge state in the terminal. Furthermore, for the most interesting cases, the ions are foil stripped, and the maximum beam current in the terminal is, in fact, usually limited by foil lifetime considerations.

The improved performance with a terminal ECR source is particularly marked for the HHIRF with very heavy beams during coupled operation in which ORIC is injected with the tandem beam by a second foil stripping. The charge state available for acceleration down the tandem high-energy tube determines tandem beam energy. This energy constrains the charge state from the ORIC injection foil and thus the maximum energy per nucleon from ORIC. In particular, a terminal ECR source will allow very heavy beams, such as lead, to be

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accelerated in coupled operation to energies and intensities of interest for nuclear structure physics. A terminal ECR source would also allow ions of inert gases to be accelerated by the tandem accelerator, as well as other elements for which negative ion production is difficult. The construction and successful testing of the simple, low-power, all-permanent magnet, NEOMAFIOS source at Grenoble[1] has demonstrated that a terminal ECR source for the HHIRF tandem accelerator is technically viable at this time. Such an ECR source would augment the existing negative ion sources and would not replace or interfere with the present normal operation of the tandem accelerator.

EXPECTED IMPROVEMENT IN PERFORMANCE

The expected performance improvement from a terminal ECR source, emphasizing a ^{208}Pb beam, is illustrated in Fig. 1, which shows ^{208}Pb current available in the high-voltage terminal of a tandem accelerator for acceleration down the high-energy tube as a function of charge state. Results for six cases are shown. The three lower curves are for tandem accelerators with foil strippers operated at terminal voltages of 6, 12, and 24 MV. As the terminal voltage increases from 6 to 24 MV, the peak charge state for an equilibrium distribution from foil strippers increases from 9 to 17 and the corresponding beam energy increases from 0.29 to 2.16 MeV/nucleon. Equally important, the higher beam energy for stripping increases the foil lifetime and, hence, current from 10 pnA to 35 pnA. For the results of Fig. 1, a foil lifetime of 30 minutes was required, assuming beam-current-lifetime products of 1.4, 2.8, and 5.6 pμA-min for 6-, 12-, and 24-MeV lead beams, respectively. These beam-current-lifetime products were estimated for 5 μg/cm^2-thick, glow-discharge foils from the work of Auble et al.[2] Clearly, the beam currents available with foil stripping are foil-lifetime limited, and are not necessarily limited by negative ion source intensity.

The three upper curves in Fig. 1 are for terminal ECR sources, for which the available beam current is independent of terminal voltage. Results for three ECR sources are shown: (1) Measured Bi currents from the all-permanent magnet, lower power, compact, 8-GHz NEOMAFIOS source[1]; (2) Measured Au currents from the ORNL 10.6-GHz source[3]; and (3) Measured Bi currents from the large, high-power, 6.4-GHz LBL source with a 700°C oven vapor feed.[4] The HHIRF tandem accelerator can presently operate stably for long periods with a terminal potential of 24 MV. For any given charge state, an ECR source can provide at least 20 times more beam current in the terminal than conventional negative ion source operation with foil stripping using the foil lifetime estimates of Auble et al.[2]

A lead beam above the Coulomb barrier, with an energy between 4.5 and 6.0 MeV/nucleon, and an intensity in the order of one pnA, is of strong interest for nuclear structure physics. Such a beam cannot be produced with the HHIRF 25-MV tandem accelerator in stand-alone operation with or without an ECR ion source. However, acceleration of a lead beam to this energy range at the HHIRF can be accomplished in coupled operation using the ORIC energy booster. The product of the transmission, foil fraction, and bunching factor through ORIC is about 5%. Consequently, to deliver one pnA of beam on target would require about 40 pnA of lead beam in the tandem terminal to inject into ORIC, assuming a 50% beam loss in the tandem high-energy tube. As shown in Fig. 1, 40 pnA of lead cannot be obtained in the tandem terminal at 24 MV with the Auble et al.[2] foil lifetime limits. However, the three ECR sources all produce at least 40 pnA of beam over a wide range of charge states. In particular, the NEOMAFIOS, ORNL, and LBL ECR sources produce over 40 pnA of lead for charge states less than 23+, 25+, and 29+, respectively. The charge states of interest for tandem acceleration followed by ORIC injection are between 17+ and 24+ for nuclear physics studies.

The determination of the ORIC output energy is somewhat complicated. Injection into ORIC is achieved by stripping from the tandem charge state to a higher charge state Q through an injection foil. The maximum energy/ nucleon from ORIC is then given by $E/M = 105\ (Q/M)^2$. Consequently, the maximum energy from ORIC is determined by the charge state Q from the injection foil,[5] which is energy dependent and determined by the tandem energy which, in turn, is determined by the tandem terminal charge state. These relationships are illustrated for ^{208}Pb in Fig. 2, which shows the maximum current one can obtain from ORIC in coupled operation as a function of energy per nucleon. Five curves are shown: conventional tandem operation with a terminal gas stripper, conventional tandem operation with a terminal foil stripper, and tandem operation with a terminal ECR source using the NEOMAFIOS, ORNL, and LBL current results. The numbers on the curves give the terminal charge state, whereas the bottom scale gives the ORIC charge state Q. The energy range of greatest interest for nuclear structure physics is also shown. Clearly, the installation of a terminal ECR source would allow the HHIRF coupled accelerators to produce lead beams for nuclear structure physics with intensities above one pnA.

Figure 3 shows the expected energy per nucleon as a function of mass for 1-pnA and 5-pnA beams from coupled operation using the NEOMAFIOS ECR source. All masses would be available for nuclear structure studies.

INSTALLATION OF AN ECR IN THE HHIRF TANDEM TERMINAL

There are many factors to consider in the installation of an ECR source in a tandem terminal, among which are space, weight, power, cooling, vacuum, control, bunching, reliability, and beam optics requirements. The solutions to some of these problems have been studied for the HHIRF tandem. The power constraints in the HHIRF tandem terminal make an all-permanent magnet NEOMAFIOS-type source compelling.

The NEOMAFIOS source was designed with low power consumption to operate on a high-voltage platform. The magnetic structure is fabricated entirely of NdFeB permanent magnets and is designed for resonance at 8 GHz, B = 0.29 T, a frequency for which powerful air-cooled microwave generators exist. About

0.8 kW of rf power is required and the total power consumption for the source is less than about 3 kW. The ECR chamber is 8 cm in diameter and 15 cm long. The source is a single-stage device, is vacuum pumped only through the extraction electrode, and requires a space 66 cm long and 50 cm in diameter. The magnetic structure weighs 722 pounds. The NEOMAFIOS source operates at 12 kV and the position of the extraction electrode is adjustable. The NEOMAFIOS source was designed, built, and tested by the Grenoble group and is used to inject into the RIKEN variable-frequency heavy-ion linac in Tokyo. The measured beam currents from this source are available and are used in this study. A more optimum source for the HHIRF tandem accelerator would perhaps operate at 10 GHz with a controllable oven vapor feed for metallic beams.

The beam transport system between the ECR source and the high-energy tube would be similar to that of the ORNL ECR facility[3] and would select a single charge state prior to injection into the high-energy tube. A possible system is shown in Fig. 4, and would transport the expected 30 π mm·mrad·MeV$^{1/2}$ emittance from the source into the corresponding 96 π mm·mrad·MeV$^{1/2}$ acceptance of the high-energy tube. The source potential would be at 50 kV positive with respect to the terminal voltage, with a variable energy 10 kV extraction electrode. An einzel lens would focus the beam from the source to the object point of a 40-cm radius, 110°, double-focusing dipole magnet. The dipole would have end angles of 35.5° and focal length of 56 cm. Variable apertures and Faraday cups would be located at both the object and image positions of this magnet. The variable aperture at the image position would select a single charge state to be focused by a second einzel lens through an electrostatic mirror. This mirror would bend the ions by 90° to merge the beam into the existing tandem terminal optics system. Two sets of magnetic steerers would align the beam.

With the voltage of the electrostatic mirror off and the ECR transport system valved off, the tandem accelerator would operate without interruption in the normal mode. A two-mode vacuum system would be required. During operation, the ECR source and transport system would be evacuated by oil-free turbo-molecular pumps, backed by an oil-free mechanical pump. This mechanical pump would exhaust into a compressor discharging into either a holding tank or the SF_6 gas itself. This system would pump large gas flows, including inert gases, either as support or beam gas. When the ECR source is not operating, the source and transport line would be valved off and evacuated with sublimation and sputter-ion pumps.

Figures 5 and 6 show an ECR source and beam transport in the tandem terminal mounted in a horizontal plane above the highest casting. Many other orientations are also possible since the bend angles of the 110° dipole magnet and 90° electrostatic mirror are variable, and the orientation of the plane of the dipole magnet is arbitrary, as well as the azimuthal angle of the electrostatic mirror with respect to the high-energy tube. In any event, the required apparatus would fit into the tandem terminal which has a diameter of 3.9 m. This ECR system is estimated to have an installed weight of less than 11,000 pounds and require less than 30 kW of power. About 38 kW of power are presently available in the tandem terminal.

Also shown in Fig. 6, directly below the electrostatic mirror, is a double-drift bunching system to prepare the ECR beam for the ± 3° phase acceptance of ORIC. The first buncher would operate between 6 and 14 MHz and produce a peak voltage of 4.0 kV with 200 W of rf power. The second buncher, located 22 cm below the first buncher, would operate between 12 and 28 MHz and will produce a peak voltage of 2 kV with 100 W of rf power. The system would be controlled with an extension of the existing CAMAC control system. The entire system would be assembled, tested, debugged, and optimized on the ground before final assembly in the tandem terminal.

DISCUSSION

It should be fully appreciated that the motivation for installing an ECR source in the HHIRF tandem terminal would be to produce, in coupled operation, very heavy beams with energies above 4.5 MeV/nucleon with intensities in the order of 1 pnA. Presently, such beams are foil lifetime limited with negative ion injection using the foil lifetime estimates of Auble et al.[2] for 5 $\mu g/cm^2$-thick glow-discharge foils. The results shown in Figs. 1 and 2 are based on this assumption. Improvements in foil lifetimes may also be possible. Measurements made in the terminal of the tandem accelerator operating at 20 MV with a gold beam indicate that a small increase in foil thickness, from about 5 to 7 $\mu g/cm^2$, can significantly increase foil lifetime without serious degradation of beam quality and transmission. In addition, a new foil changer has been developed for the HHIRF tandem accelerator which will allow the foil to be rotated in a 6-mm-diameter circle, thus increasing the effective area of the beam spot on the foil by about a factor of 6. With these two changes, an improvement in foil lifetime of at least a factor of 4.5 may be possible. A determination of the achievable foil lifetime with these two improvements will be made in the near future.

Nevertheless, there appears to be no fundamental problem in installing and operating an ECR source in the tandem terminal. The main concern would be reliability and the general inaccessibility of the source during operation. Presently, it takes 30 hours to access the tandem terminal. Most of this time is spent transferring the SF_6 gas in and out of the tank. However, it should be appreciated that the tandem terminal presently contains a great deal of apparatus similar to that required for an ECR source. This apparatus works well and has been demonstrated to operate with excellent reliability.

In addition, it should be appreciated that an ECR source would be meant only to augment and not replace the existing negative ion source operation. Only very heavy or very special beams would be produced with an ECR source; probably only a few runs per maintenance cycle. Most beams would be produced with the standard negative ion source operation and this operation would not be affected by the installation of a terminal ECR source.

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3. F. W. Meyer and J. W. Hale, Proc. 1987 IEEE Particle Accelerator Conference, Washington, DC (1987) p. 319.

4. D. J. Clark and C. M. Lyneis, Proc. of Int. Conf. on the Physics of Multiply Charged Ions and Int. Workshop on ECR Ion Sources, Grenoble (1988) p. 759.

5. The charge state distributions used in this paper are consistent with recent measurements, both published and unpublished, at the HHIRF at energies required for ORIC injection.

ORNL DWG-90-6361

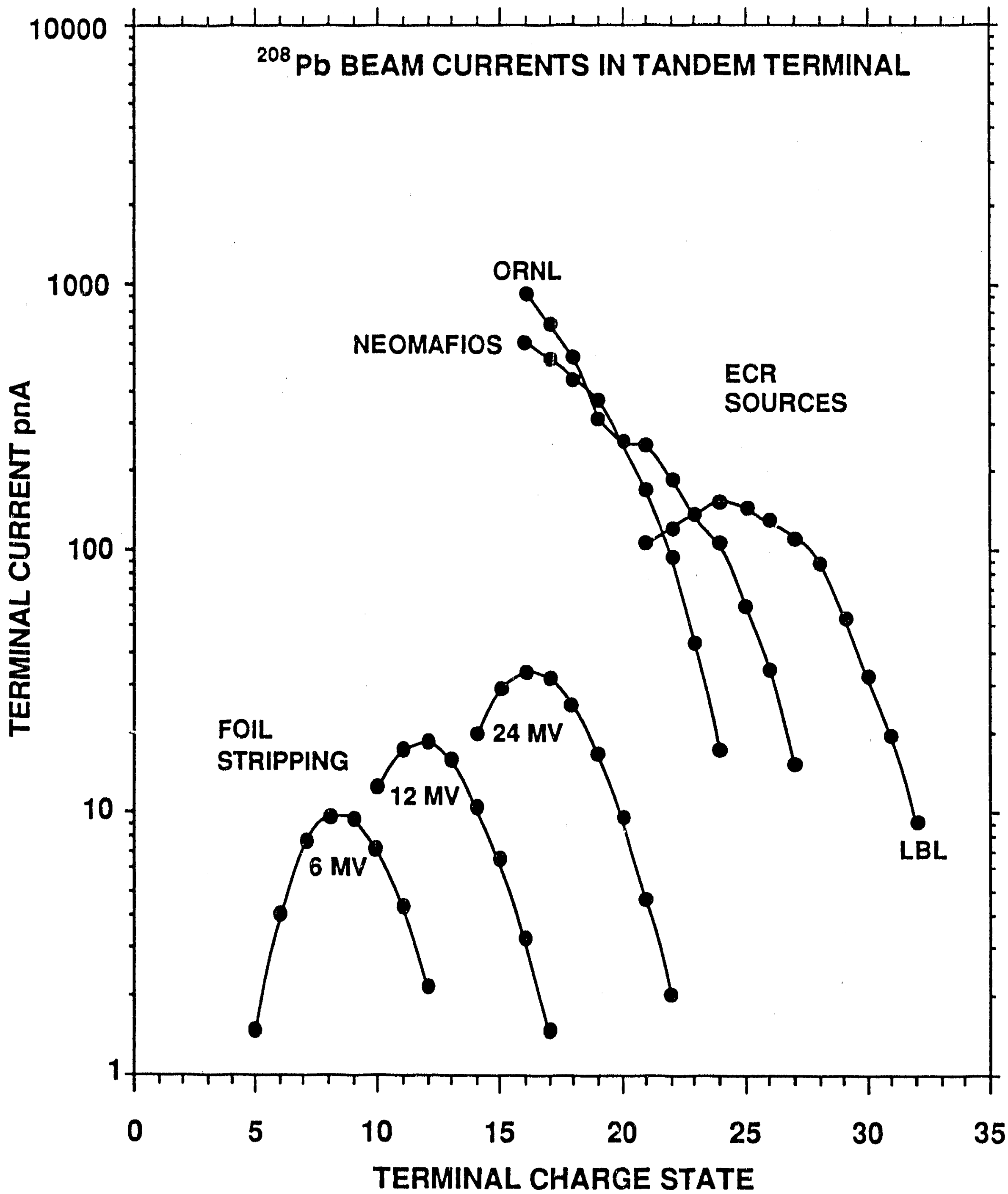

Fig. 1. Comparison of expected ^{208}Pb beam currents in the terminal of a tandem accelerator between conventional negative ion injection with foil stripping and a terminal ECR source. Results for 6-, 12-, and 24-MV terminal voltages are shown. The maximum beam current in this case is limited by the foil lifetime. Measured results for beams in the lead region for three ECR sources are shown. Over a factor of 20 more current could be expected from the ORNL ECR source than with foil stripping at 24 MV.

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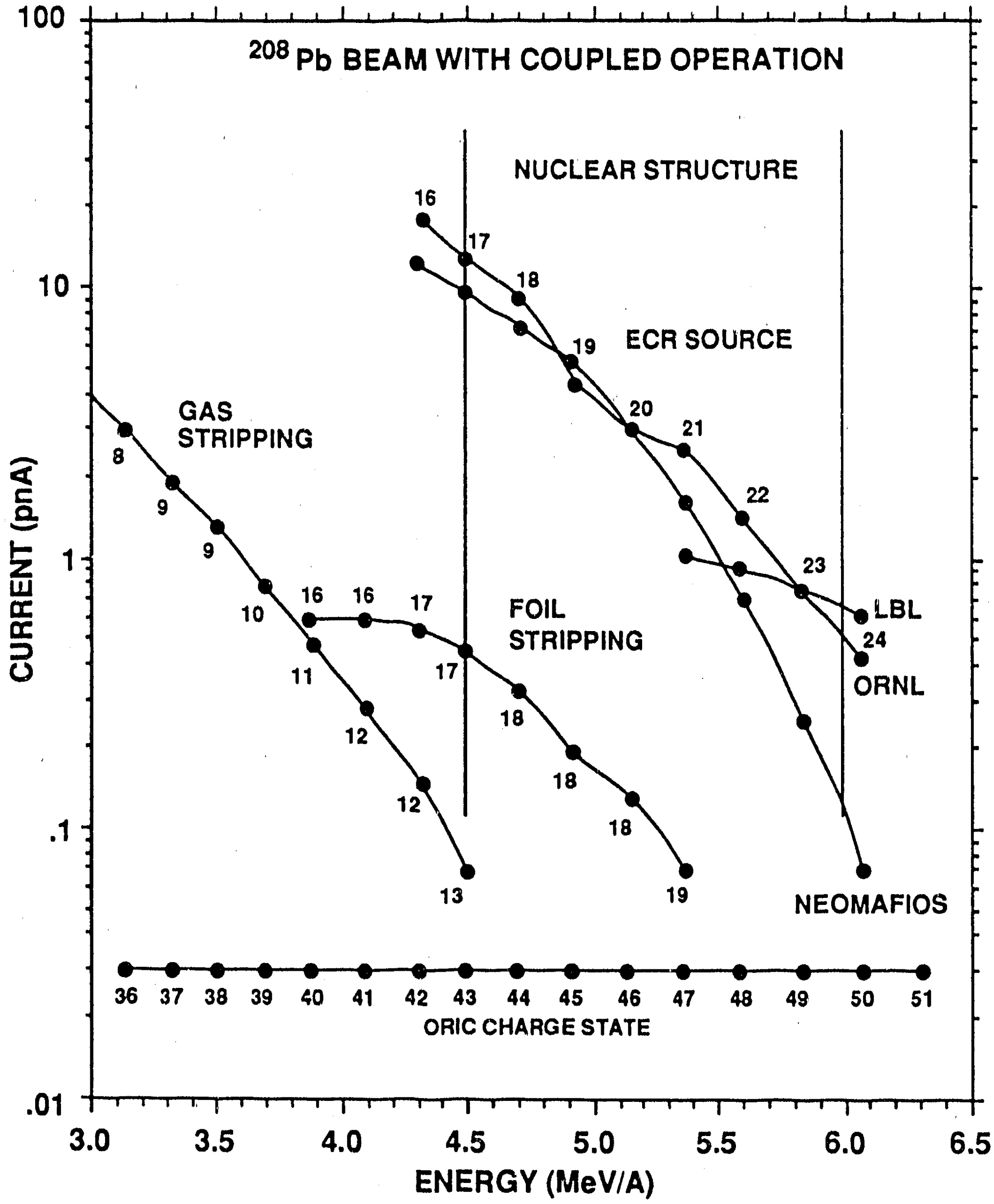

Fig. 2. Expected ^{208}Pb beam currents from the HHIRF tandem and ORIC accelerators operated in the coupled mode. Results for the tandem operated at 24 MV with either gas or foil single stripping are shown, as well as results for the NEOMAFIOS, ORNL, and LBL ECR sources mounted in the tandem terminal. The charge states in the tandem terminal are listed along the curves, whereas the ORIC charge states for K = 105 are given on the bottom of the figure. For these calculations, ORIC transmissions of 0.42, 0.42, and 0.35 were assumed with tandem transmission of 0.49, 0.26, and 0.50 for the gas, foil, and ECR cases, respectively. The current injected into the tandem for the gas stripping was limited to 2000 nA, whereas the injected current for foil stripping was limited to 183 nA because of the need to have at least a 30-minute lifetime for a foil with an expected 5.6-μA-min beam-current-lifetime product.

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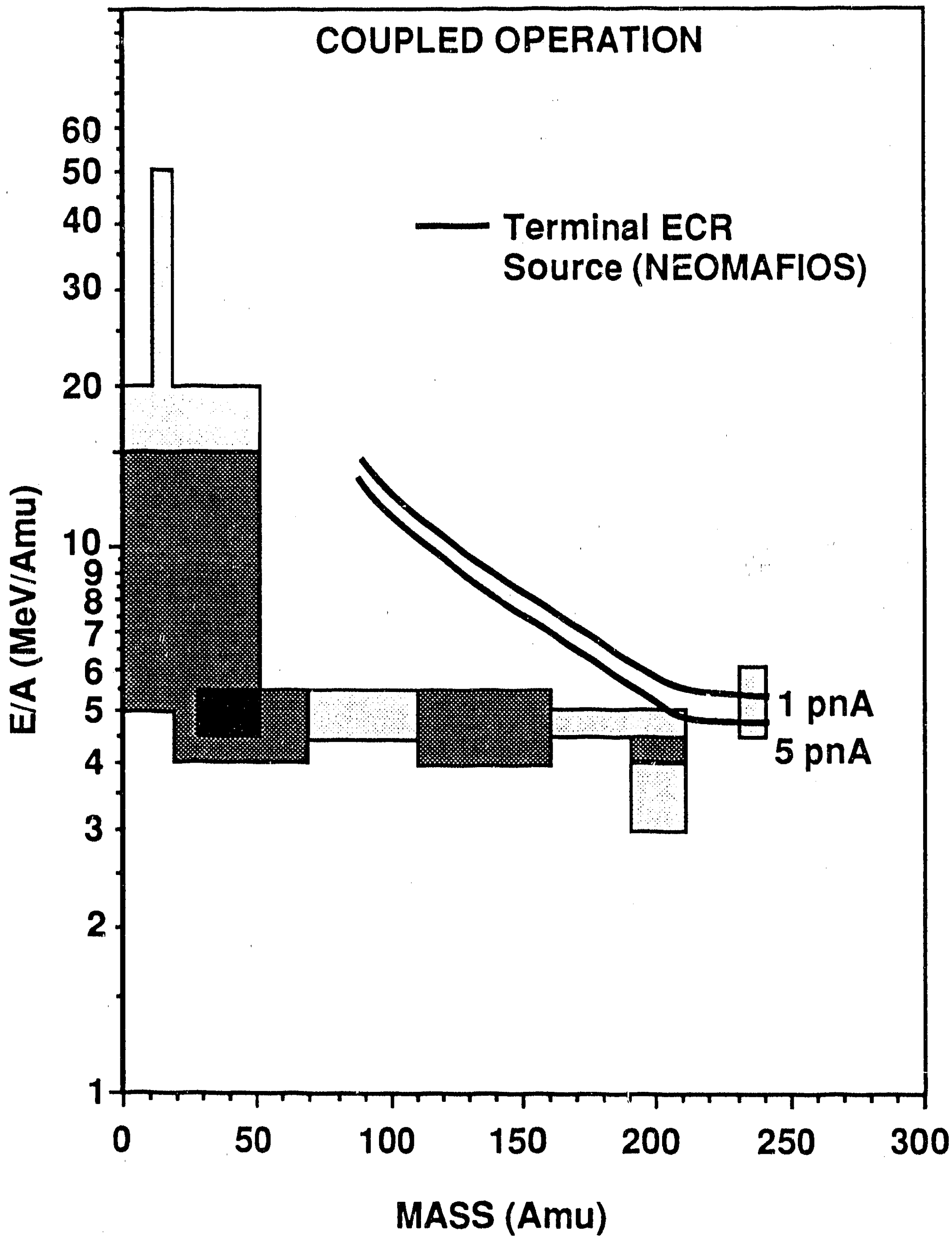

Fig. 3. Expected energy per nucleon as a function of mass for 1-pnA and 5-pnA beams from coupled operation using a NEOMAFIOS ECR source in the tandem terminal. A 5.5-MeV/nucleon ^{238}U beam would be available with an intensity of 1 pnA. The shaded areas show mass-energy regions of particular interest for nuclear structure physics.

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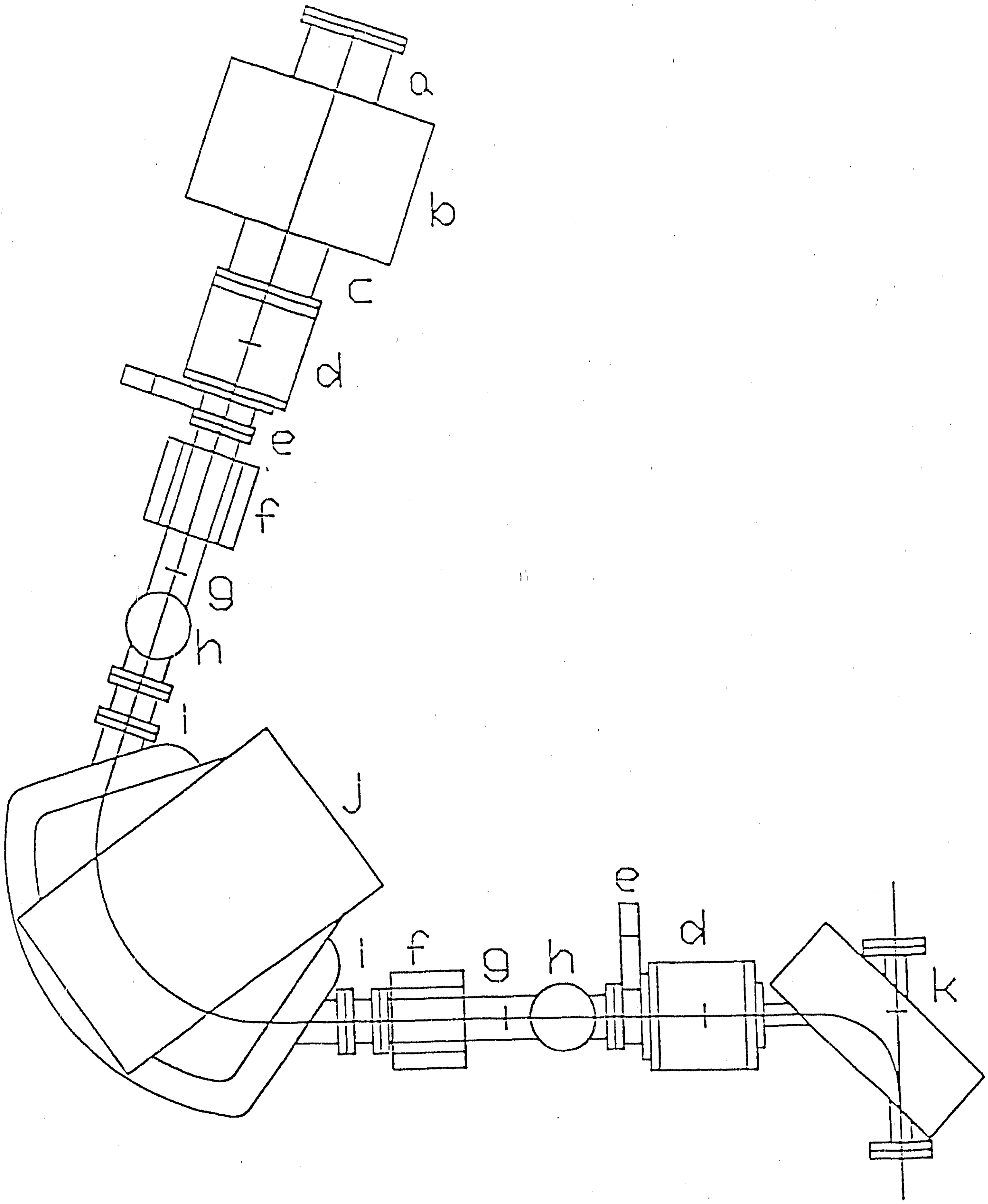

Fig. 4. HHIRF tandem terminal ECR source consisting of: a) material, rf, water and power feeds; b) ECR chamber and permanent magnet structure; c) extraction and acceleration electrodes and vacuum manifold; d) einzel lens; e) valve; f) magnetic steerer; g) variable aperture and Faraday cup at 110° dipole focus; h) pumping tee; i) bellows; j) 110° dipole magnet; and k) 90° electrostatic mirror.

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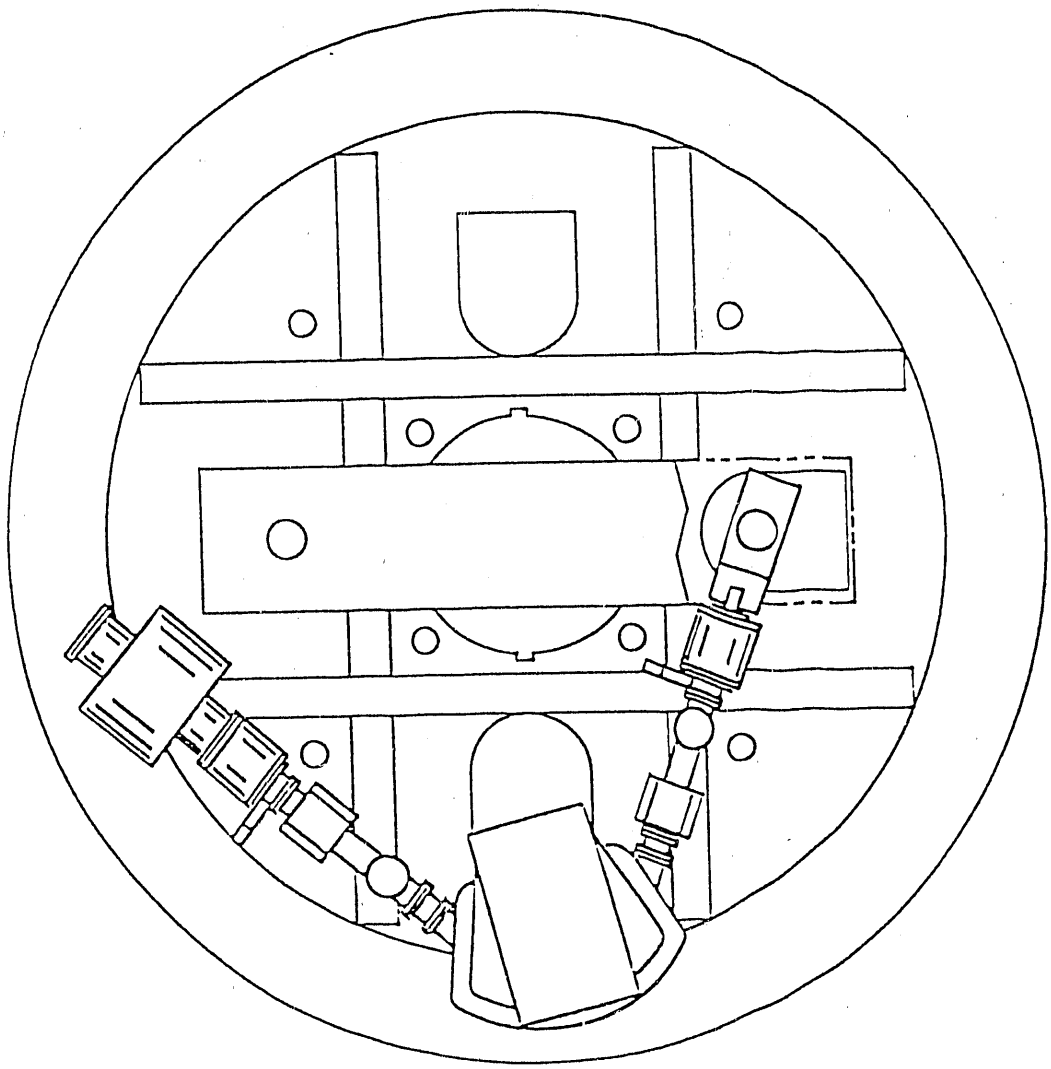

Fig. 5. Top view of the 3.9-m-diameter terminal of the HHIRF tandem accelerator. The proposed ECR source and beam transport system are shown positioned in a horizontal plane above the top casting of the accelerator. Beam is injected into the high-energy tube with a 90° electrostatic mirror. Many other orientations of the source and transport system are also possible.

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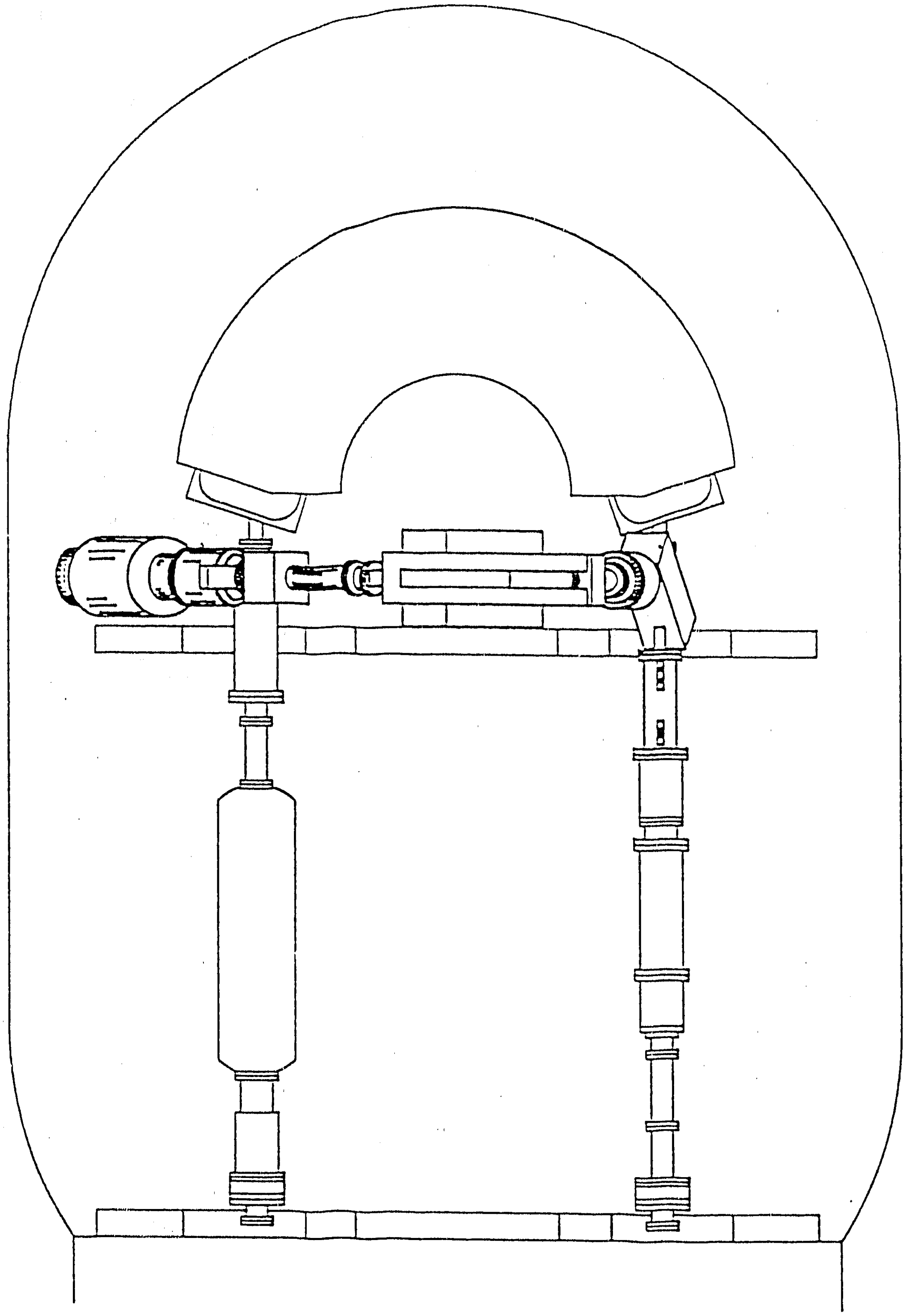

Fig. 6. Side view of the 3.9-m-diameter terminal of the HHIRF tandem accelerator. The proposed ECR source is shown in a horizontal plane above the top casting of the accelerator. Directly below the 90° electrostatic mirror is a double-drift buncher to prepare the beam for the ± 3° phase acceptance of ORIC.

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