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PROGRESS, STATUS, AND PLANS FOR THE HRIBF PROJECT[1]

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Abstract

Over the last three years, the Holifield accelerator system has been reconfigured into a first-generation radioactive ion beam facility, the HRIBF, a national user facility for RIB research. The construction and reconfiguration have been completed and the equipment commissioning and beam development phases have started. The progress to date, the present status, and future plans will be given. The special problems connected with the production and acceleration of RIBs will be discussed.

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1. Introduction

In June 1992, the Holifield Heavy Ion Research Facility was closed and became a project to reconfigure, construct, and develop the accelerator system into a radioactive ion beam, RIB, facility using the on-line isotope-separator technique [1,2]. The name of this new national user facility for RIB research will be the Holifield Radioactive Ion Beam Facility, HRIBF. The construction phase of the project is complete and a first-floor layout of the new facility is shown in Fig. 1.

The reconfiguration of the two existing accelerators has provided a quick and inexpensive first-generation RIB facility for North America. In the past, the Oak Ridge Isochronous Cyclotron, ORIC, served as an energy booster for stable heavy ions injected from the tandem accelerator. To produce RIBs, this process has been reversed. The tandem accelerator will be injected with radioactive heavy ions produced by ORIC. In particular, intense light-ion beams from ORIC will produce proton-rich radioactive atoms for the tandem accelerator from fusion reactions in a thick target on the new RIB injector. The RIB injector consists of an ISOLDE-type [3] thick-target positive-ion source assembly, a first-stage mass separator to select a single mass number, a charge exchange cell to produce negative ions, and beam diagnostics, all mounted on a 300-kV high-voltage, HV, platform system. The resulting negative RIBs will be accelerated to ground potential and analyzed to separate isobars with a second-stage high-resolution mass analyzer installed in the beam transport line to the tandem accelerator. The resulting isotopically pure beam will be injected into the tandem and accelerated to energies of interest for nuclear physics, astrophysics studies, and applied studies.

In addition to using existing accelerators, the HRIBF has used existing shielded space and has required no major civil construction. The shielding for the original ORIC vault and target rooms was originally designed for 75-MeV, 1-mA proton beams. These rooms are also equipped with single-pass HVAC systems appropriate for high-radiation areas. One of these rooms, as shown in Fig. 1, was used to house the RIB injector.

The potential RIB intensity from the HRIBF could be near 1 pnA of beam on target for an ideal case. Such a case is outlined in Fig. 2, which quantitatively summarizes the process with average efficiencies for a 50-μA proton beam from ORIC. The process will require about 1000 protons to produce one radioactive atom in a thick target with a (p,n) reaction. These radioactive atoms, with the tandem accelerator, can be delivered as beam-on-target with about a 1% efficiency. This gives a factor of 100,000 between the ORIC beam intensity and the RIB intensity. An ORIC beam intensity of 50 μA could, therefore, produce a RIB intensity of 0.5 pnA. This estimate assumes optimum ionization, charge exchange, and transmission efficiencies. More importantly, this estimate does not include any release, surface sticking, or decay losses of radioactive atoms in the target ion source. These losses could be large.

The many reconfiguration, construction, and development aspects of the facility are discussed below, with emphasis on the special problems to make RIBs. The reconfiguration and construction phase of this project is essentially completed and the commissioning phase to produce usable radioactive ion beams has started.

2. RIB Injector

The major additional equipment required to produce radioactive ion beams are a RIB injector [4] and connecting beam lines. The HV platform system for the RIB injector is shown in Fig. 3 and is rather complicated for two reasons. First, the tandem was optimized for a high injection voltage and recent measurements have verified that an injection voltage of at least 200 kV is required for good transmission through the tandem. Secondly, the neutron fluence from the RIB target has been estimated to be in the order of 0.07 fast neutrons for each 60-MeV proton stopping in a medium mass target. This corresponds to a neutron fluence of about 10^{15} n/cm^2, one meter from the target, for 2000 hours of high-intensity operation. This radiation level would destroy nearly all unshielded semiconductor devices near the target-ion source in one year of operation.

The RIB injector solves these problems by mounting the injector on a two-platform system. The RIB target, ion source, and related beam line mechanical equipment are mounted on a source platform. A second instrumentation platform, electrically connected to the ion source platform, houses electronics associated with the RIB injector. A shielding wall separates the two platforms to protect electronic components from radiation damage. Electrical signal and power cables are transported through the shielding wall in two HV conduits, one biased at the platform potential and the other biased at the source potential. The injector, including the two platforms, a 300-kV, 1-mA power supply, two HV conduits, two 300-kV acceleration tubes for the ORIC beam and RIB beam, and two 40-kVA motor-generator sets were built to our specification by the National Electrostatics Corporation, NEC. The system was delivered in October of 1993 and installation and acceptance testing were completed in January of 1994.

The injector bias voltage noise must be extremely low for high-resolution mass separation. The short-term periodic and random deviations of the bias voltage are less than 10 V when the injector is operated at 300 kV. The HV platform system has met all performance specifications.

The most important component mounted on the RIB injector is the target-ion source. Beam from the circular aperture of this source is focused by four quadrupoles into a thin vertical line on the object slits of a first-stage mass separator. The beam envelope of the RIB injector transport system is shown in Fig. 4. The double-focusing, first-stage mass separator consists of two 76-degree dipoles with edge-angle focusing. Between the two dipoles, the beam is wide in the horizontal plane for maximum resolution and has a crossover in the vertical plane for a minimum dipole gap. Object slits select a beam of a single unit mass for further development. This positive-ion beam is refocused by a quadrupole triplet into a round spot for charge exchange with a Cs vapor cell. After the charge-exchange cell, the negative-ion beam is focused to a waist at the entrance of the acceleration tube to accelerate the beam to ground potential. The RIB injector has been completed and tested using stable ions. The new equipment is controlled with a recently installed VISTA control system. Without any fine tuning, the mass resolution FWHM of the first-stage separator has been measured to be about 1/1000.

3. RIB Injection Beam Line

The negative-ion beam line from the RIB injector to the tandem accelerator includes a high-resolution, second-stage isobaric mass separator to separate elements and molecules having the same unit mass number. This capability can provide an isotopically pure beam for tandem injection and RIB research. The beam line is shown in Fig. 5. Four electrostatic quadrupoles will focus the beam from the RIB injector to a circular waist. At this waist, a tape system and gamma-ray detector, 300-keV diagnostics, have been installed for radionuclide identification. Another four electrostatic quadrupoles will focus the beam to a narrow vertical line on the object slits of the second-stage separator. The two dipoles have bend angles of 55°, radii of curvature of 2.8 m, vertical gaps of 7.6 cm, and a total mass of 25 tons. The system is designed to provide a beam spot on the image slits giving a mass resolution in the order of 1/20,000. The separator will have unit magnification using the four edge angles for double focusing. In the horizontal plane, the beam will be 25 cm wide and in the vertical plane there will be a beam crossover between the two dipoles minimizing the gap.

Directly below the tandem accelerator, another quadrupole triplet after the second-stage separator will focus the beam to a round spot which will be transported through a 90° vertical bend. Tandem injection will be accomplished by focusing the beam through the existing, de-energized, stable injector bending magnet onto its image slits. The injection line has been completed and commissioned with a stable beam.

4. Target Ion Source

A target and electron-beam-plasma ion source, based on modifications to a similar source [3] in use at ISOLDE CERN, has been designed for positive RIBs. Three sources have been fabricated and tested, and one has been operated on the RIB injector. A recirculating charge-exchange cell has been constructed, tested, and installed on the RIB injector. A variety of other ion source concepts is being developed and tested. This work is discussed in Ref. 5.

5. Low-Intensity Diagnostics

Initial RIB intensities are expected to be much smaller than the lower-current limit of Faraday cups; therefore, a concept for a new beam diagnostic system [6] has been developed and tested. The system combines a Faraday cup to integrate current and a continuous dynode-electron multiplier, CDEM, to directly count either secondary electrons or Rutherford backscattered ions. These new systems will be used throughout the RIB injection system, the tandem accelerator, and the experimental beam lines as a beam tuning aid.

The present logarithmic amplifiers for the Faraday cups are being replaced with Keithley amplifiers with a dynamic range of 10^{-4} to 10^{-12} A. In addition, the electron suppression for these Faraday cups, which is normally negative to capture electrons, will be bipolar and can be switched positive to provide amplified current readings from escaping electrons. This amplification is about a factor of 10 and depends on the ion species and energy.

Beam currents less than 1 pA, 6 x 10^6 ions/s, can not be measured with Faraday cups and will be measured with a CDEM. The beam will be stopped in a metal target and the CDEM will count either electrons or Rutherford backscattered ions, depending on the beam intensity. For beam currents less than 10^5 ions/s the CDEM entrance will be biased to attract electrons. These secondary electrons from the beam striking the target will be counted with about a 50% efficiency which will allow measurement down to a few ions/s. For more intense beams, in the 10^4 to 10^7 ions/s range, the entrance bias of the CDEM will be reversed so that electrons will be repelled and Rutherford backscattered ions will be counted. The efficiency for this process has been measured to be about 0.1%. A moveable target, shown in Fig. 6, was designed to eliminate confusion from beta emitters that may be deposited on the target. The system has been tested with beams from the 25-URC stable-ion injector and also the EN tandem accelerator.

6. 300-kV Diagnostics

Another crucial diagnostic is a device to characterize the specific radioactive isotopes in an isotopic mass chain and to optimize the production of a specific RIB prior to the second-stage mass separator and tandem injection. The device is located at the first beam focus after the RIB injector, and consists of a moving tape system and gamma-ray counting chamber [7]. The moving tape is a continuous loop of 6-mm audio tape, whose motion is controlled by a stepper motor and associated sequencer. A 25% Ge detector, well shielded from potential background in the beam transport pipe, is located at the counting chamber, in a position 1 cm from the tape. The counting chamber also accommodates plastic detectors for positron decays. Activity is implanted into the tape at a collection position which is directly in the path of the RIBs. After the desired collection time, the activity is moved to the gamma-ray counting chamber and monitored by the gamma-ray detector at the counting position, while a new sample is implanted at the collection position. The collection point of the tape can be moved out of the direct beam path by lowering the internal support structure for the tape, which is attached to the external vacuum chamber for the 300-keV diagnostics system by means of a bellows. This diagnostics has been tested and is operational.

7. Tandem Accelerator

The 25-URC tandem Pelletron accelerator, manufactured by NEC, was placed into routine operation in 1982. The original acceleration tubes were replaced with a compressed-geometry tube design in 1986, which allowed an increase in the effective insulator length by 17%. With this improvement, the maximum operating terminal potential with beam has been increased to 26 MV. Over the years, the charge state fractions and transmission efficiencies through the tandem have been extensively measured. With gas stripping, beams of mass 52 can be accelerated above 5 MeV/A with a total efficiency of over 20%. With foil stripping, beams of mass 80 can be accelerated above 5 MeV/A with an efficiency of over 8%. In addition, the tandem is inherently a dc machine, maximizing the beam available from the RIB target ion source. The accelerator's simplicity, reliability, and excellent beam quality are unmatched by other types of accelerators.

Nuclear astrophysics measurements will require beam energies as low as 2 to 3 MeV. In the past, operation at the low terminal potentials needed for these measurements was a problem because of the point-plane corona-discharge voltage-grading system. At low terminal potentials, the grading currents tend to disappear and the column tends to be graded by capacitance. This has led to instabilities resulting from spurious ionization-induced currents in the insulating gas. To address this and other problems, the corona system was replaced in June 1994 with a resistor-based voltage-grading system [8]. In initial tests, operation with this resistor system has been smooth and beam was quickly provided for development studies at terminal potentials up to 20 MV. As a result of the improved voltage grading provided by the resistor system, it is believed that the maximum terminal potential capability will be increased and HV tests will be conducted in 1996.

The first test of low-voltage operation with the resistors has been completed and the overall transmission efficiency for an ^{16}O beam was measured in the beam energy range 50.3 to 2.3 MeV. The essential result of these measurements is that the accelerator can be operated at a terminal potential of 1.0 MV, without shorting units or changing the SF_6 pressure, to produce 2.3-MeV beams. Overall beam transmission efficiency at 2.3 MeV was only a factor of two lower than the usual transmission efficiency at higher energies. More tests and development are planned.

One concern with the tandem accelerator is terminal potential control with very-low-intensity RIB beams. With stable beams, the stability of the terminal potential has been excellent with typical RMS deviations of a few hundred volts. The terminal potential is controlled by a feedback loop which includes a capacitive pickoff, and either a generating voltmeter, GVM, or energy-analyzing slit currents, or both. A new terminal potential stabilization system was installed in 1991 which allows operation using the GVM only with no measured beam current. Preliminary tests indicate that the terminal potential should be stable in this mode for RIB acceleration. In addition, the new diagnostics for low-intensity beams will be installed.

8. ORIC Accelerator

The ORIC is a K = 100 cyclotron with 22 trim and harmonic coils allowing both proton and heavy-ion acceleration. The ORIC was commissioned in 1964 and originally produced intense light-ion beams with an internal ion source. Parts of ORIC were originally designed to accelerate a 1-mA, 75-MeV proton beam, whereas proton intensities in the order of 30 μA were extracted for experiments with energies up to 65 MeV. In 1970, the experimental program and ORIC operation changed to mostly heavy-ion research. In 1980, with the construction of the 25-URC tandem accelerator, the internal ion source was removed and ORIC was modified for use as an energy booster. ORIC has now been reconfigured for intense light-ion beams for the HRIBF.

The DOE safety approval for the facility allows 50 μA of proton and deuteron beam intensity to be extracted from ORIC. A development program is under way to achieve that intensity. The main problems will be activation of internal components and improving the extraction efficiency. A new PIG internal ion source has been installed with the original central-region geometry. With this hardware, 2 μA of K = 100 Q/A = 1/2 beams have been readily extracted. These beams correspond to 25-MV protons from H_2 molecules, 50-MeV deuterons, and 100-MeV alpha particles. The highest extraction efficiency has been around 40%. These beam intensities are sufficient for low-intensity commissioning of the facility.

In order to extract 50 μA of beam, a new central-region geometry will be required to provide better beam centering, orbit definition, focusing, and extraction efficiency. Phase and axial slits will also be required. These improvements will optimize the ion source geometry in order to minimize beam losses and maximize extracted light-ion beam. Figure 7 shows a much improved central-region geometry and resulting central-region orbits. This central region will be implemented in ORIC over the next year. A total of three different geometries may be required to accelerate all the desired ORIC beams. One of these geometries will be for the highest possible proton-beam energy. Activation problems and high-efficiency operation at high beam intensities will be addressed through a FY96-97 AIP Project.

9. Target Ion Source Remote Handling System

After bombardment with a 50-μA ORIC proton beam for a few weeks, the RIB target-ion source, TIS, may contain up to 20Ci of residual activation, giving a radiation field which will prohibit entry into the RIB injector room and prohibit manual removal of the TIS for examination, repair, or replacement. This radiation will decay with time; however, for many targets, the time delay for this decay will be prohibitively long. Consequently, a remote handling system for activated TISs has been designed and ordered. This system will remotely remove the TIS from the RIB injector, place the TIS in a metal contamination control box, CCB, move the loaded CCB to a low-radiation area, and place the CCB into a lead shielding cask.

The central element of this remote handling system is a remote handler which will be permanently mounted on the RIB injector. After bombardment of the TIS with an ORIC beam and before personnel access to the RIB injector, the TIS will be remotely back-filled with inert gas, isolated from both the ORIC and RIB beam lines with shutters, and mechanically disengaged. The remote handler will grasp the TIS and lower the TIS into an open CCB on a roller-conveyer system that will extend from an opening in the wall to ORIC. The roller-conveyer system will move the sealed CCB through the ORIC vault into room C110. A second remote handler in C110 will then place the CCB containing the TIS into a lead cask and place a lid on the cask. The sealed and shielded TIS can then be safely stored, shipped for disposal, or shipped for disassembly for examination, repair, or retrieval of enriched target material. Disassembly of activated TISs can occur at an ORNL hot-cell facility or a HRIBF glove-box facility. Television monitors will be used to monitor TIS loader and conveyer operations.

The remote handling system which was ordered from PAR Corporation in July, will be delivered in December, and installed and commissioned in January. Many of the components are used in the commercial nuclear power industry. High-intensity operation with most target materials will be limited until this installation is completed. During low-intensity commissioning, development and maintenance operations on the TISs will be performed in a low-level radiological laboratory in the HRIBF containing a radiological glove box and hood.

10. Actinide Target Upgrade

In order to expand the physics capability of the facility, neutron-rich fission fragment radioactive beams will be accelerated, probably beginning in 1998. These beams will be produced using proton-induced fission reactions on thick actinide targets, probably 60-MeV protons on a ^{238}UC target. These new beams will not require major hardware upgrades; however actinide targets will increase the radiation levels by at least an order of magnitude. In addition to the radiation hazard, some reaction products will increase the safety concerns and oversight of the facility. Most fission fragment masses are larger than those which can be accelerated with single-foil stripping above the Coulomb barrier with the tandem. Consequently, double-foil stripping will be used which reduces the tandem transmission and hence RIB intensity. The second column of Table 1 lists some of the RIB intensities which can be expected with actinide targets using the existing facility.

11. HRIBF Phase II Upgrade

In the longer term, a major expansion of the facility is possible. The recently completed NUSAC long-range plan for the next five years calls for a "cost effective" second-generation ISOL facility as it's highest priority for new DOE construction, after the completion of RHIC. In response to this priority, a proposal is being prepared to upgrade the first-generation HRIBF, with minimum civil construction and modest cost, into a second-generation facility. This upgrade builds on the existing facility and consist of four major improvements described below. These improvements could be constructed simultaneously or separately, if needed, to match a given funding profile and to minimize the impact on the operation of the existing HRIBF. A possible layout of the upgraded facility is shown in Fig. 8.

11.1 K = 200 Cyclotron

ORIC would be replaced with a K = 200, 200-uA, 200-MeV commercial proton cyclotron, based, in part, on the existing proton therapy machines. The cyclotron would be installed in an existing shielded experimental area. In addition to accelerating protons for fission and spallation reactions to produce neutron-rich RIBs, the cyclotron would also accelerate 50-MeV/A Q/A = 1/2 light-ion beams for fusion reactions to produce proton-rich RIBs. The machine will operate at room temperature and have about the same mass as ORIC and greatly reduced power consumption.

11.2 High Power Actinide Target

Neutron-rich fission fragments would be produced using the 200-MeV proton beam from the cyclotron to bombard a high-power ^{238}U target on a recycled RIB injector. As is the case for Phase I, the target, the ion source, and the first-stage mass separator will all be located on a HV platform system. Use of existing shielding can be optimized by locating the target in the present ORIC vault, as shown in Fig. 8. Preliminary shielding studies indicate that sufficient local shielding could be added to this configuration to accommodate 100 uA of 200-MeV protons on a ^{238}U target. The remaining highly shielded ORIC space could be used to handle highly activated targets.

11.3 Superconducting Linac Booster

Fission-fragment RIBs would be accelerated above the Coulomb barrier with the tandem and a new 40- to 50-MV linac booster based on independently phased superconducting cavities. The design of an appropriate superconducting linac booster that is matched to post-tandem-beam velocities is straightforward, and several similar boosters have been constructed. The booster will probably operate near 100 MHz, have a length of 20 to 35m, utilize niobium quarter-wave resonators, and will operate in the $\beta = 0.05$ to 0.15 range. The only stripper in the system for RIB beams would be in the tandem terminal. A new building may be needed to house the booster. The configuration shown in Fig. 8 allows the operation of the tandem accelerator with or without the booster.

11.4 New Experimental Space

The facility outlined in Fig. 8 is compatible with the utilization of considerable experimental equipment specific to nuclear structure, nuclear astrophysics, and applied measurements. Additional experimental areas will be constructed to fully utilize the additional capabilities of the Phase II HRIBF.

12. Summary

The construction and reconfiguration of the Holifield accelerator system into a first-generation radioactive ion beam facility has been completed. Equipment commissioning and beam development have started. The development of the 25-URC tandem and ORIC into RIB and driver accelerators, respectively, is well under way. First scheduled experiments with radioactive beams are planned for the summer of 1996. After the successful acceleration of proton-rich RIBs from light-ion fusion reactions, an actinide target will be installed to produce heavier neutron-rich radioactive beams from proton-induced fission. In the longer term, a substantially upgraded facility with a superconducting linac booster accelerator and higher power driver cyclotron is planned.

Acknowledgments

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Figure Captions

Fig. 1. First floor layout of the Holifield Radioactive Ion Beam Facility, HRIBF.

Fig. 2. Summary of the potential HRIBF beam intensity with average efficiencies for RIBs produced with 50 μA of protons. About 1/100,000 of the primary beam particles, or 0.5 pnA, could be produced as beam-on-target.

Fig. 3. Detailed layout of the new RIB injector.

Fig. 4. Beam envelope of the RIB injector beam transport.

Fig. 5. Second-stage mass separator and negative-ion beam line from the RIB injector to the tandem accelerator.

Fig. 6. Simplified drawing of the moveable belt used for the low-intensity diagnostics system.

Fig. 7. Orbit calculations for a new ORIC internal ion source and central-region geometry for high-intensity light-ion beams.

Fig. 8. Possible layout of a second-generation HRIBF with a K = 200 cyclotron, high-intensity actinide target, and SC linac booster. A proposed new experimental hall is not shown.

Table I. Comparison of projected neutron-rich RIB intensities for the existing HRIBF and the proposed Phase II upgrade.

RIB	HRIBF	Phase-II
$^{82}Ge^{50}$	8×10^7	2×10^9
$^{88}Se^{54}$	1×10^8	4×10^9
$^{90}Br^{55}$	6×10^8	2×10^{10}
$^{122}Ag^{75}$	1×10^7	6×10^9
$^{132}Sn^{82}$	1×10^7	4×10^9
$^{135}I^{82}$	9×10^7	4×10^{10}
$^{140}I^{87}$	4×10^7	2×10^{10}

Assumes energy above Coulomb barrier with predicted ionization and charge-exchange efficiencies and a 50% isobaric analyzer efficiency. No release, sticking, or decay losses are included for 50- and 100-µA proton beams, respectively, for the HRIBF and the Phase II upgrade.

DISCLAIMER

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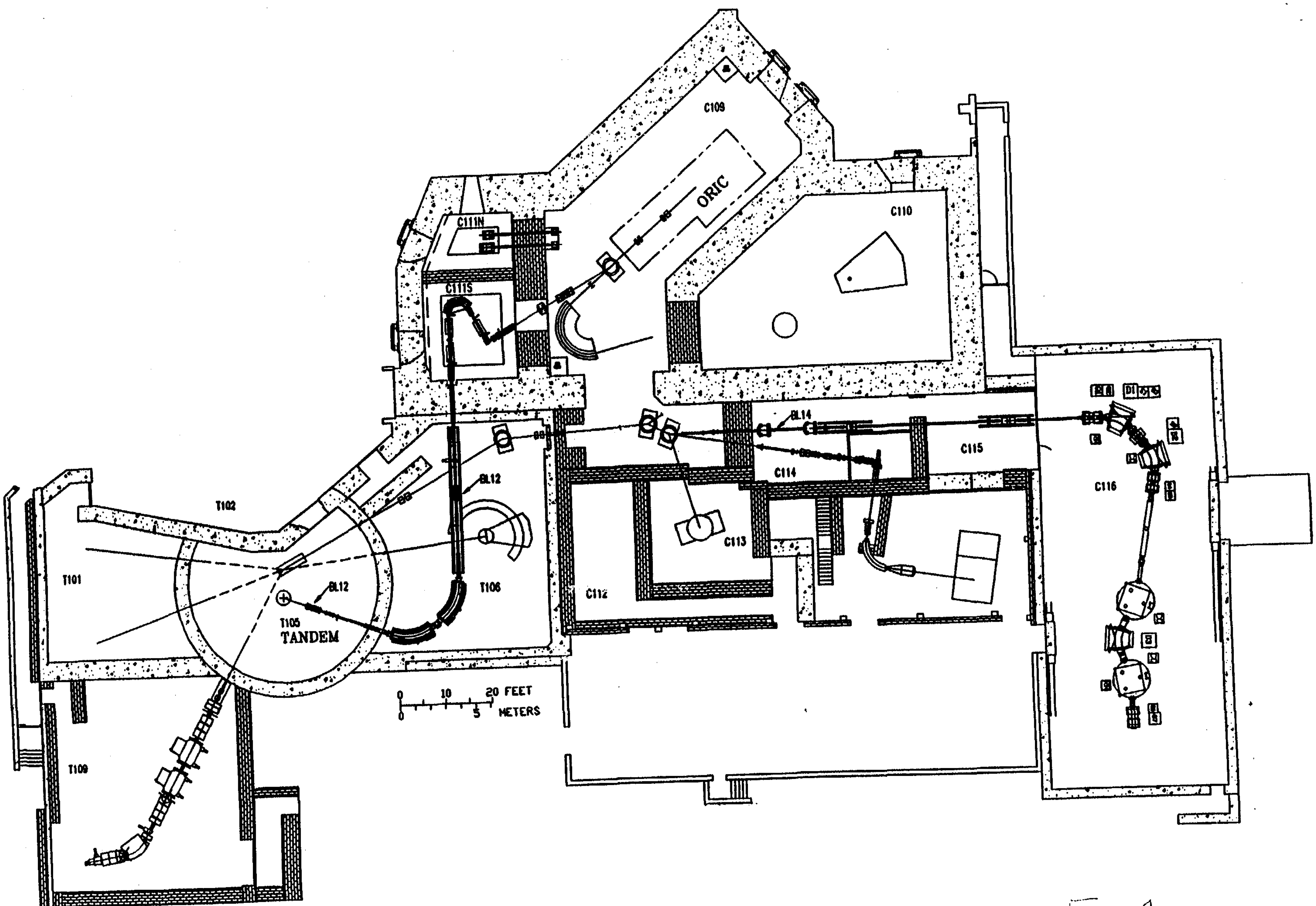
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Fig 1

"GOOD CASE" BEAM FROM THE HRIBF

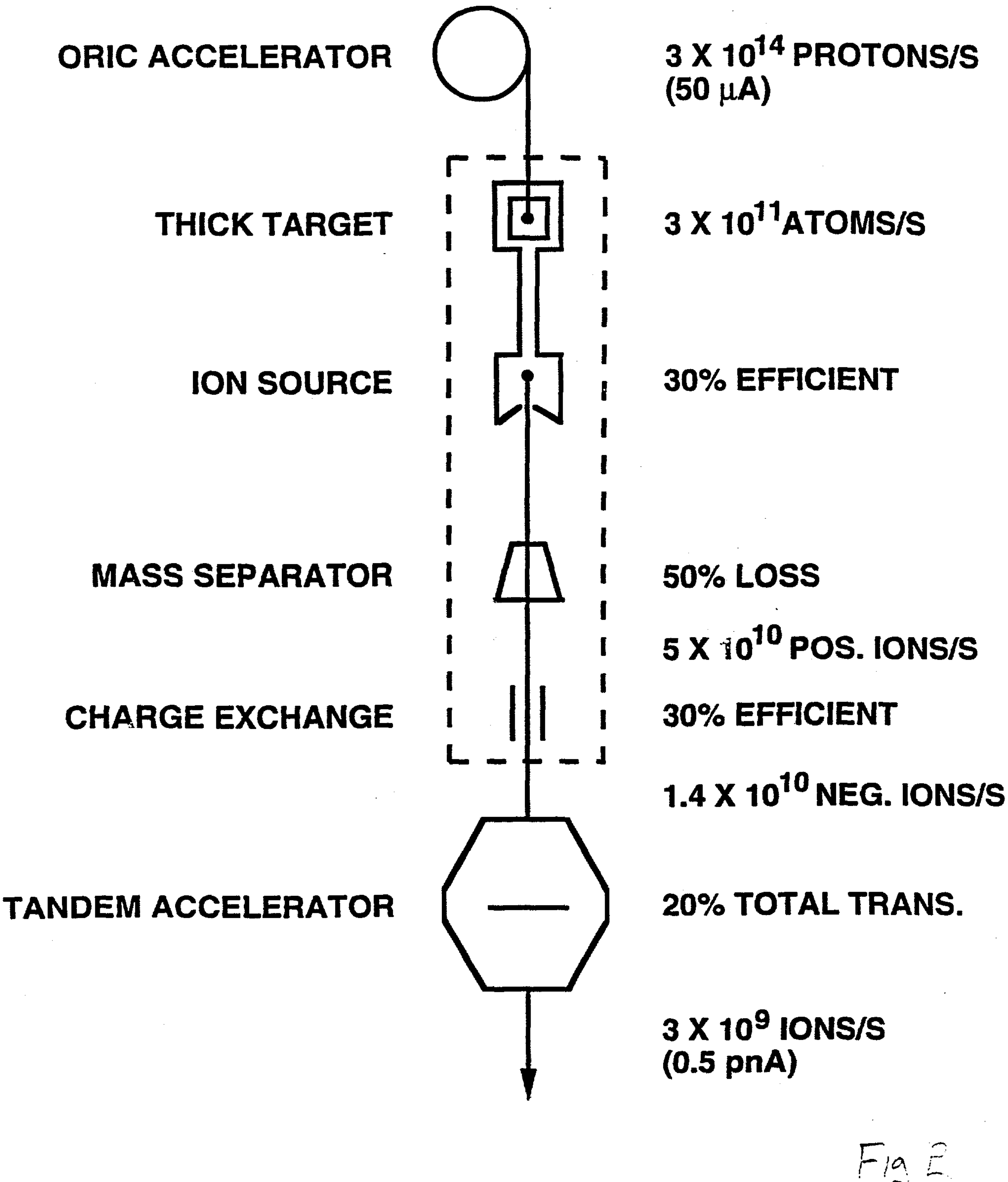
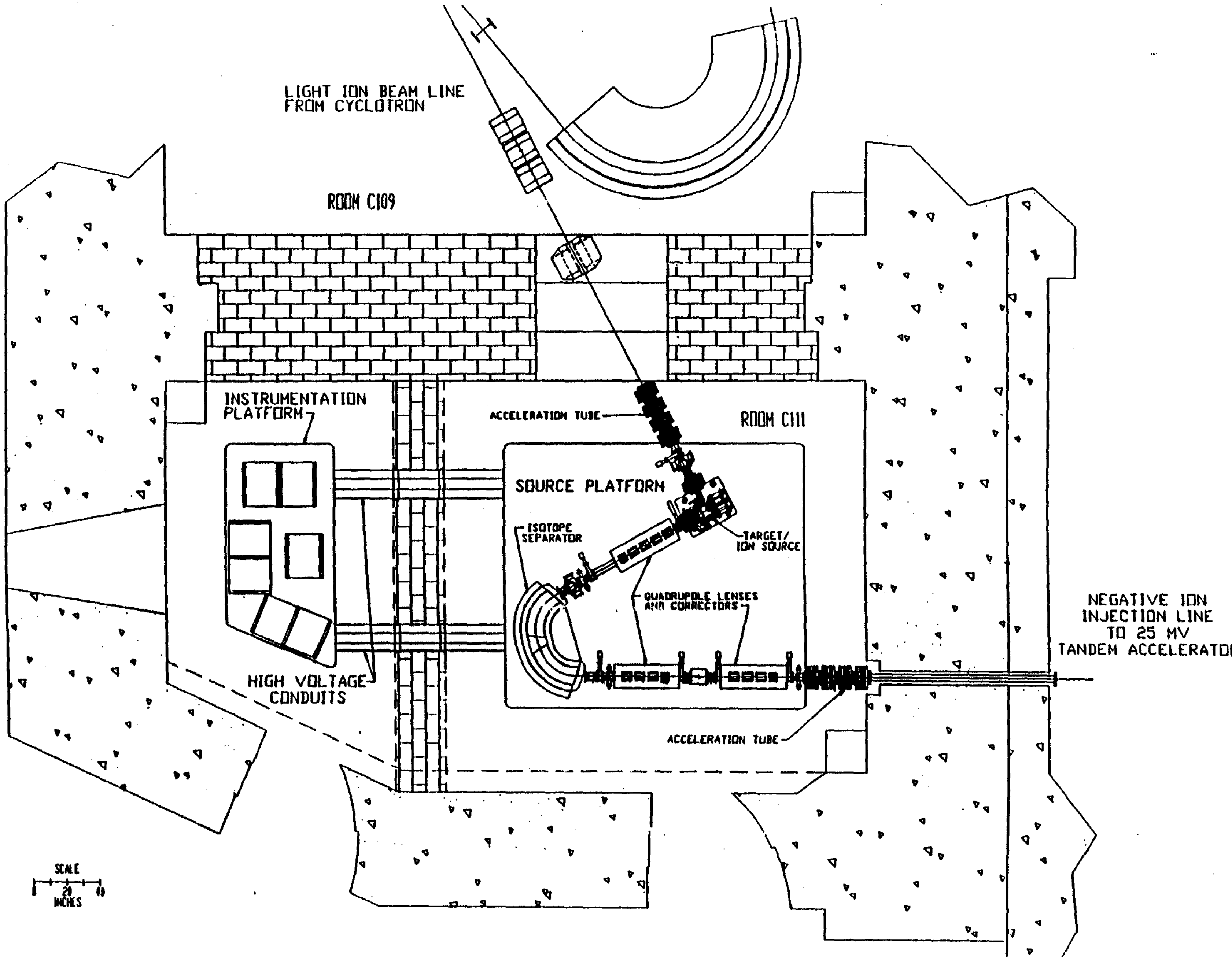


Fig E


LIGHT ION BEAM LINE
FROM CYCLOTRON
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QUADRUPOLE LENSES
AND CORRECTORS
NEGATIVE ION
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Fig 3

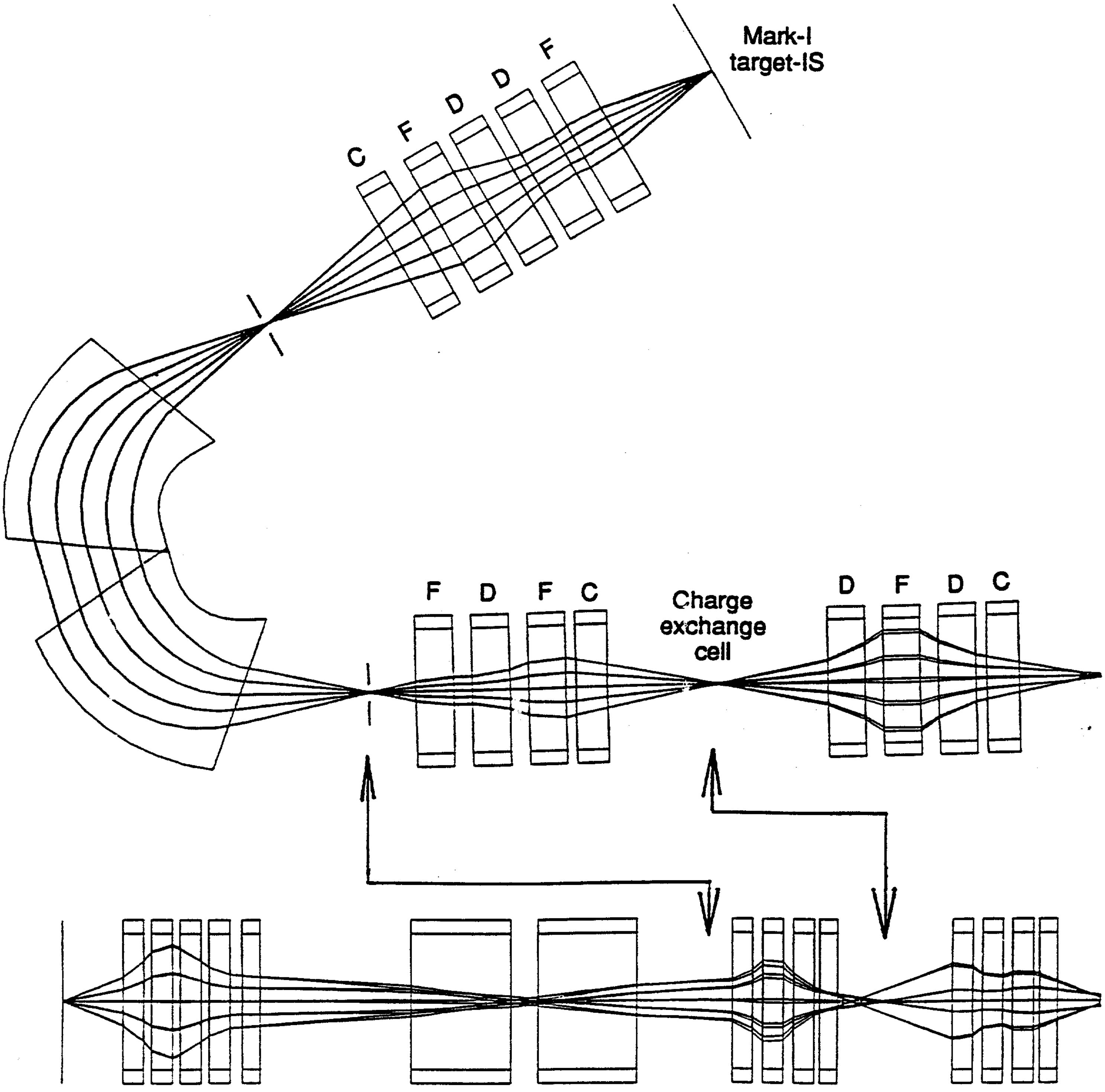

Fig 4

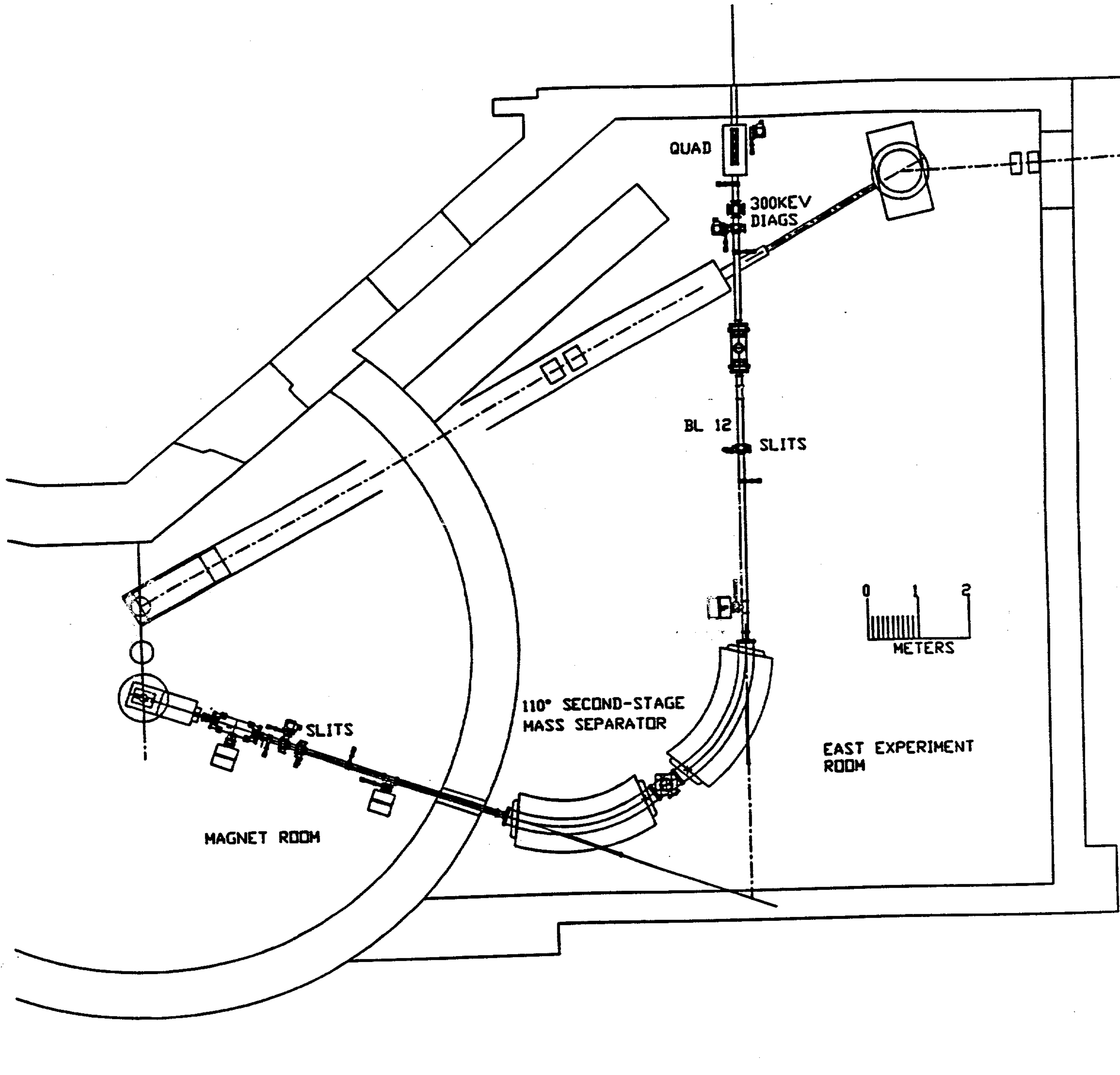
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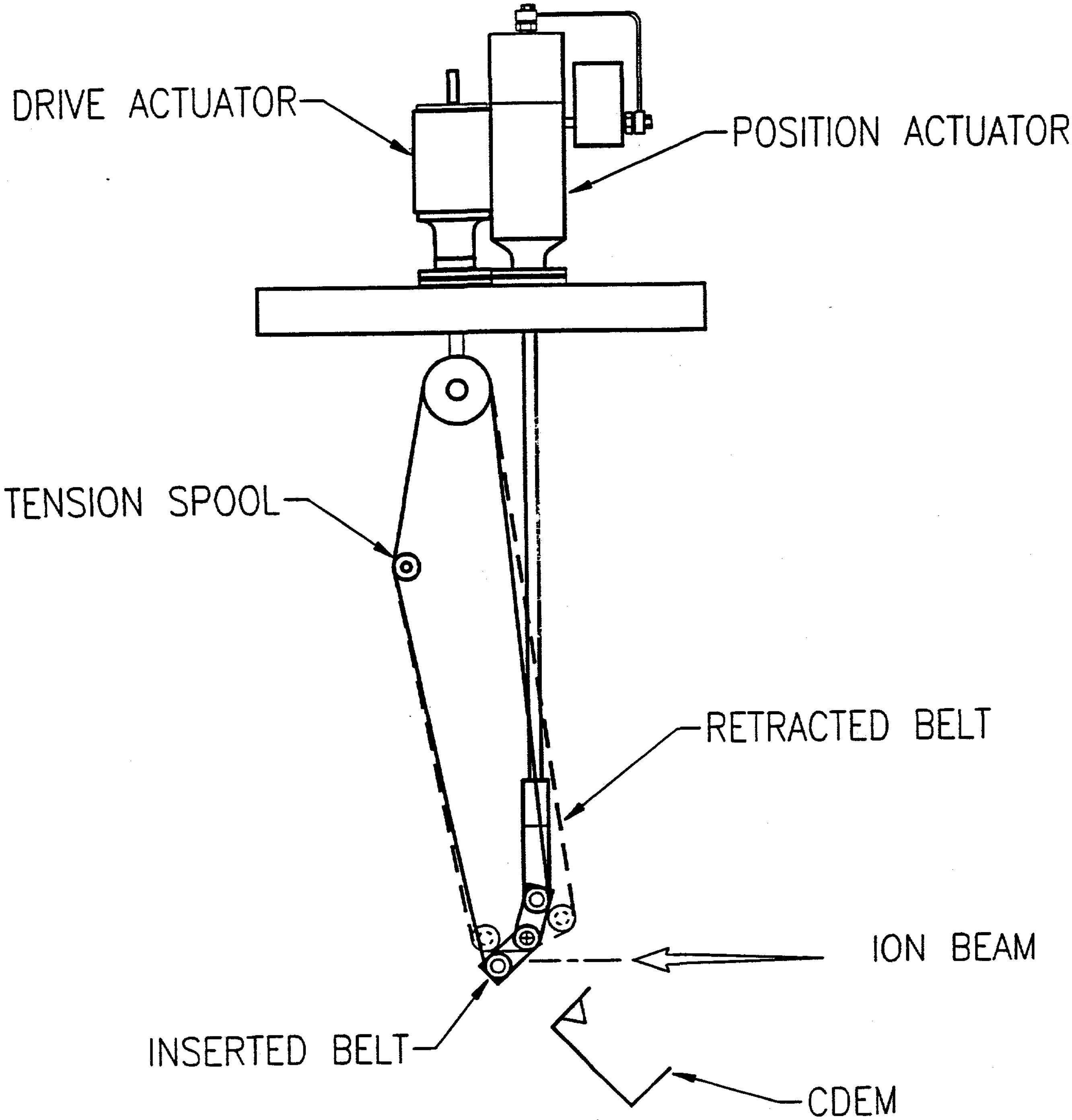
Fig 5

Fig 6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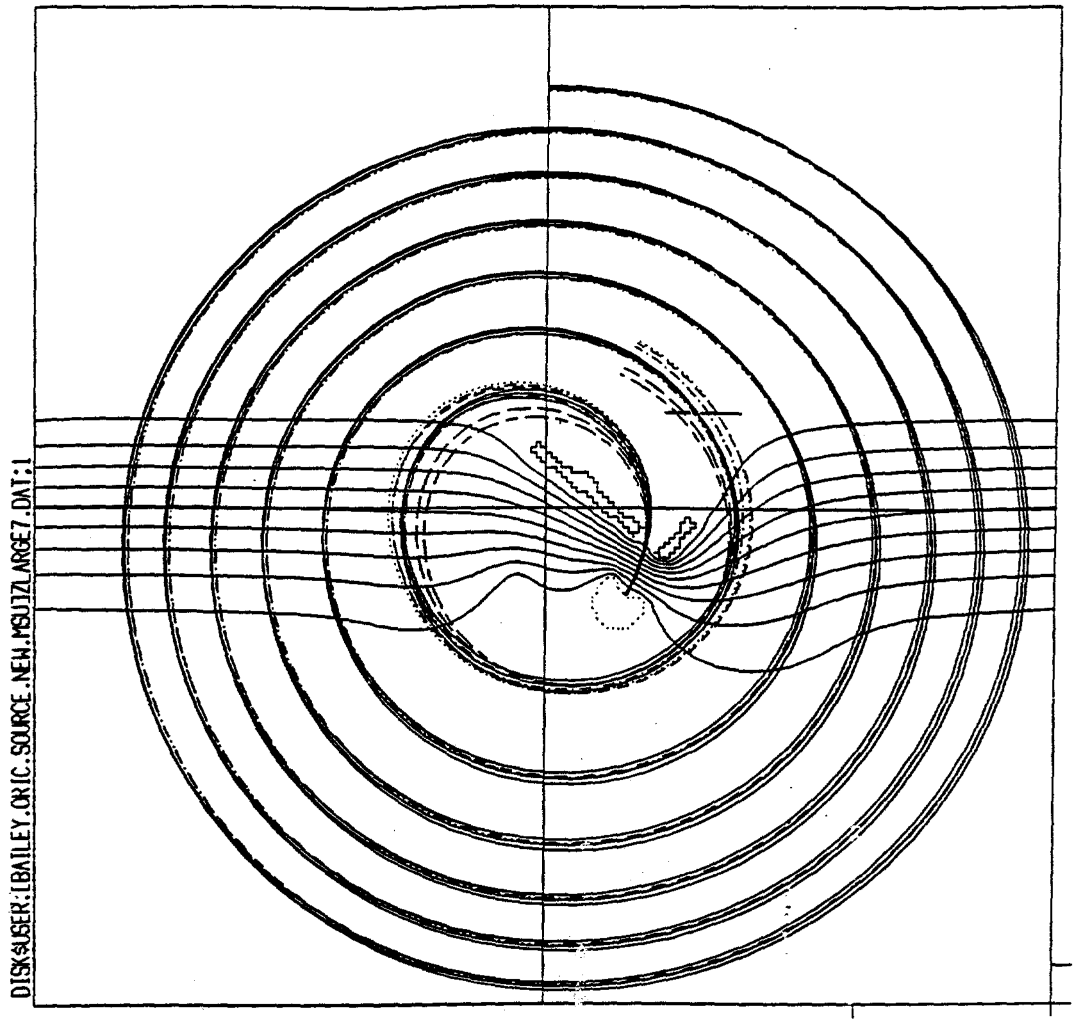

Fig 7

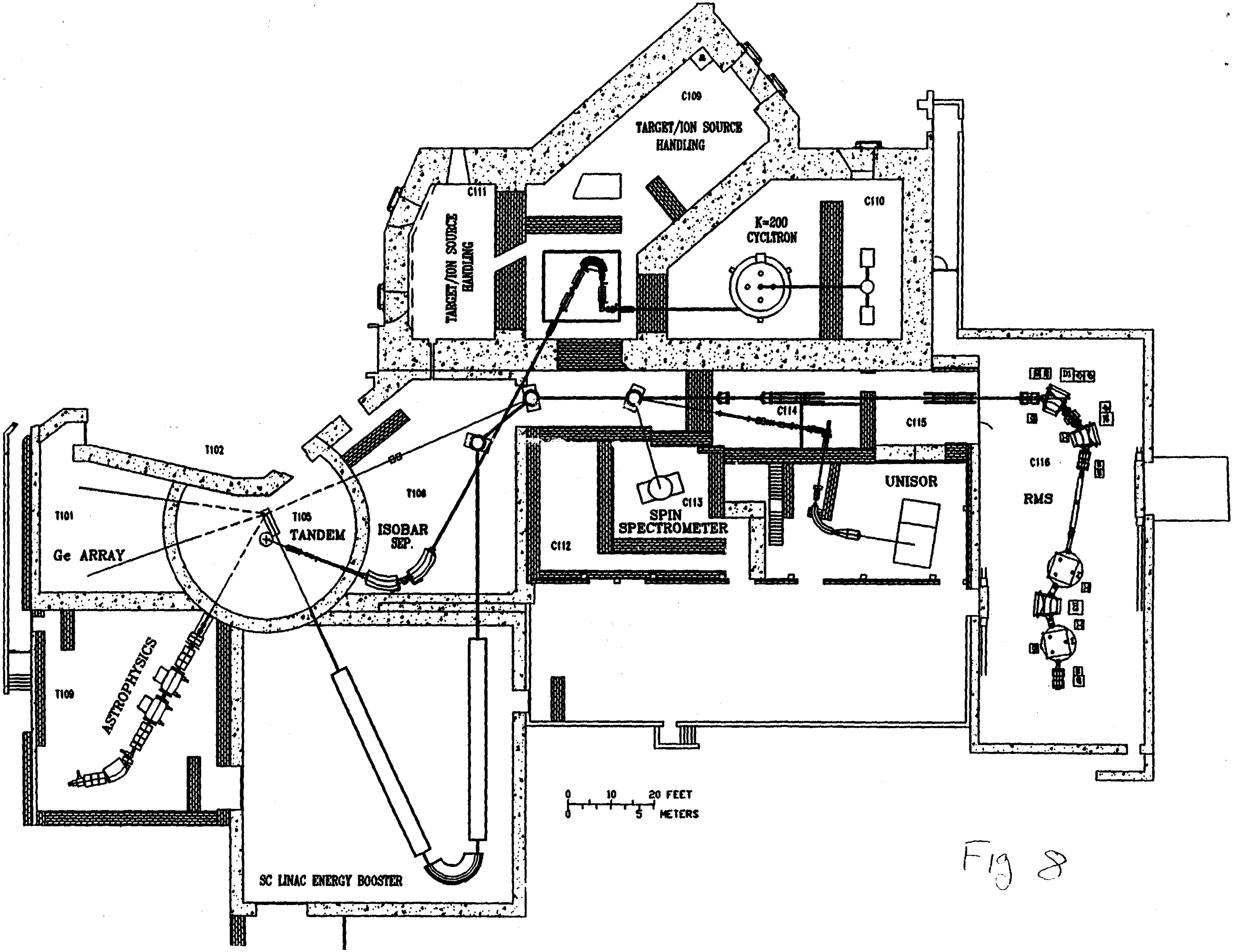
C109
TARGET/ION SOURCE HANDLING
C111
TARGET/ION SOURCE HANDLING
C110
K=200 CYCLTRON
T102
T101
Ge ARRAY
T105
TANDEM
T106
ISOBAR SEP.
C114
C115
C116
RMS
UNISOR
C113
SPIN SPECTROMETER
C112
T109
ASTROPHYSICS
SC LINAC ENERGY BOOSTER
0 10 20 FEET
0 5 METERS

Fig 8