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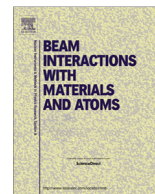
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Design of a compact all-permanent magnet ECR ion source injector for ReA at the MSU NSCL[☆]

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ABSTRACT

The design of a compact all-permanent magnet electron cyclotron resonance (ECR) ion source injector for the ReAccelerator Facility (ReA) at the Michigan State University (MSU) National Superconducting Cyclotron Laboratory (NSCL) is currently being carried out. The ECR ion source injector will complement the electron beam ion trap (EBIT) charge breeder as an off-line stable ion beam injector for the ReA linac. The objective of the ECR ion source injector is to provide continuous-wave beams of heavy ions from hydrogen to masses up to ^{136}Xe within the ReA charge-to-mass ratio (Q/A) operational range from 0.2 to 0.5. The ECR ion source will be mounted on a high-voltage platform that can be adjusted to obtain the required 12 keV/u injection energy into a room temperature radio-frequency quadrupole (RFQ) for further acceleration. The beam line consists of a 30 kV tetrode extraction system, mass analyzing section, and optical matching section for injection into the existing ReA low energy beam transport (LEBT) line. The design of the ECR ion source and the associated beam line are discussed.

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1. Introduction

The Facility for Rare Isotope Beams (FRIB) is currently under construction at MSU [1]. FRIB consists of a heavy ion driver linac, target station to produce rare isotopes, and fragment separator to purify the beam to be delivered to three large experimental areas for rare isotope nuclear physics research. Until FRIB is fully-operational, scheduled for 2022, the rare isotope beam experimental areas are currently receiving beams from the Coupled Cyclotron Facility (CCF) which is operated by the NSCL at MSU and funded by the NSF [2]. In the fast-beam experimental area, the shortest-lived rare isotope beams (RIB) of energies >150 MeV/u are delivered. In the stopped-beam experimental area, RIBs are thermalized either in a gas cell or a cyclotron gas stopper before being transported to the trap and laser spectroscopy area. Thermalized RIBs may alternatively be delivered to ReA [3], shown in Fig. 1, to be re-accelerated for low energy nuclear physics experiments. Utilizing the modularity of the superconducting RF cyromodules, ReA is capable of re-accelerating thermalized heavy ion beams from the gas stopper to 0.3–3 MeV/u for Q/A of 0.25 and up to 6 MeV/u for

Q/A of 0.5. In its final configuration, ReA will reach kinetic energies of up to 12 MeV/u for the heaviest ions (e.g. ^{238}U) and 24 MeV/u for light ions (e.g. ^4He). ReA3 has been commissioned with rare isotopes in 2013 and added to the suite of rare isotope delivered to experiments at the NSCL.

In addition to the EBIT charge breeder, the user program at ReA requires a variety of continuous-wave heavy ion beams to commission new experimental systems on one of three end stations. The current off-line ion source is a simple Colutron-type ion source that can only produce singly-charged ions. With the addition of an all-permanent magnet off-line ECR ion source, the existing beam delivery capabilities at ReA will be significantly expanded by providing a source of continuous-wave stable heavy ion beams for commissioning, beam preparation, detector testing, and stable beams experiments. The robust ECR ion source will be integrated with existing facility capabilities to allow for independent tuning of the linac with stable beams while optimizing the EBIT charge breeder during radioactive ion beam development for experiments.

2. ECR ion source design

The design of the all-permanent magnet ECR ion source presented is based on a reference design developed at CEA-Grenoble, and later built for Oak Ridge National Laboratory [4]. The design

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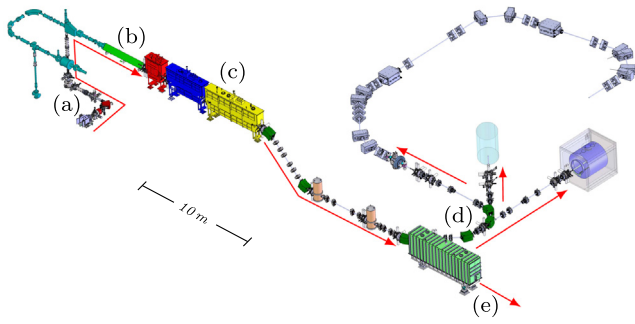


Fig. 1. Layout of ReA showing (a) the ECR ion source injector, (b) RFQ, (c) cryomodules housing the superconducting RF cavities that accelerate heavy ions up to 3 MeV/u, (d) current experimental hall under construction, and (e) additional cryomodule upgrade to deliver heavy ions up to 12 MeV/u to future experimental areas.

allows for a compact, cost-effective ECR ion source with low power consumption that is optimized for the production of multiply charged heavy ions. A cross-sectional diagram of the ECR ion source, with plasma chamber diameter of 49 mm and overall length of 145 mm, is shown in Fig. 2. Table 1 summarizes the injector requirements. The ECR ion source comprises of the injection, magnetic confinement, and extraction system to provide adequate confinement times to produce high charge state ions through the process of step-by-step electron impact ionization.

2.1. Injection system

The ECR ion source injection system includes an iron plug, gas feed inlet, RF waveguide, and bias disc shown in Fig. 3. The iron plug is axially adjustable to provide variability of the magnetic field in the injection region and designed with three ports that allow for gas injection, RF power coupling, and the possibility for a high-temperature oven for metallic beams in the future. The water-cooled RF waveguide is tapered from WR-75 to a modified WR-62 (15.8 mm $\times$ 6 mm) to enhance electric fields in the injection region. The waveguide is perforated to allow for pumping between the vacuum window and plasma chamber. A 12.75–14.5 GHz, 650 W helix traveling-wave tube (TWT) microwave source couples RF power into the chamber to sustain the ECR plasma. Electrons spiraling near the injection region are repelled back into the ECR region by a negatively biased disc that is water-cooled to mitigate heating for stability during operation. This disc is located at the point of injection where $z = 0$ cm as

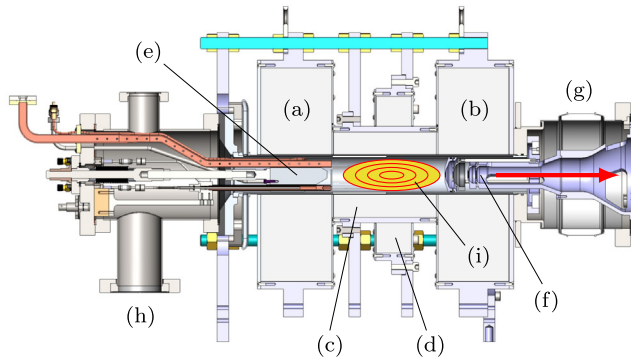


Fig. 2. Cross-sectional diagram of the ECR ion source showing (a) the injection magnet, (b) extraction magnet, (c) hexapole magnet, (d) central magnet, (e) injection system, (f) extraction system, (g) high-voltage break, (h) injection vacuum port, (i) ECR plasma within the plasma chamber, and direction of the extracted beam.

Table 1
Requirements of the ECR ion source injector.

Parameter	Value
ReA injection energy	12 keV/u $\pm$ 5%
Q/A range	0.2–0.5
Beam current	$\sim$ 1–5 eμA
Optical matching	$\alpha_x = 0.7$, $\beta_x = 8.4$ m/rad
Conditions	$\alpha_y = -1.1$, $\beta_y = 0.9$ m/rad

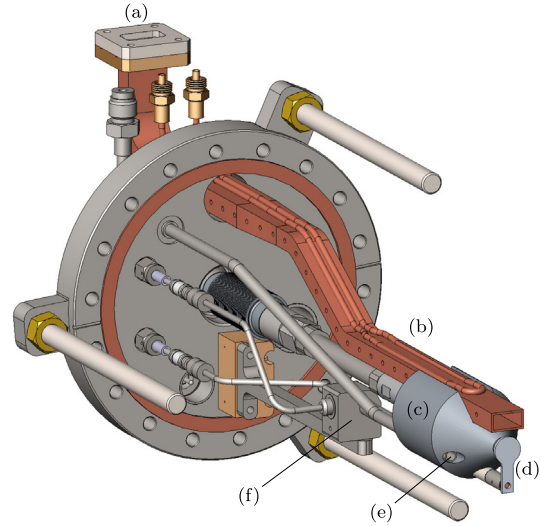


Fig. 3. Diagram of the injection system showing (a) the RF window, (b) tapered and perforated water-cooled RF waveguide, (c) adjustable iron plug, (d) water-cooled bias disc, (e) gas feed inlet, and (f) coolant distribution block.

shown in Fig. 4. All components of the injection system are mounted on a custom 6.75" CF zero length reducer coupled to a 4-way cross for ease of routine maintenance.

2.2. Magnetic confinement system

The design utilizes a minimum-B axial magnetic field configuration for the confinement of the heated plasma. The minimum-B field profile is formed by four magnet assemblies, each composed of high remanence NdFeB alloy magnets configured in Halbach

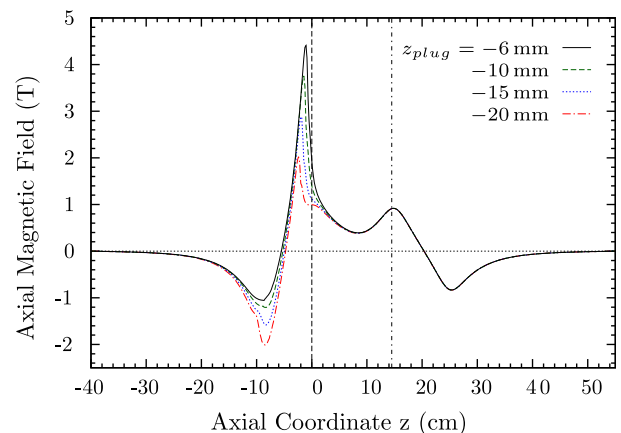


Fig. 4. Axial magnetic field profile for various iron plug displacements z_{plug} referenced to the injection bias disc location at $z = 0$ cm. At the ends of the plasma chamber, the dashed line denote the location of the injection bias disc and dash-dotted line the location of beam extraction.

arrays [5], with the injection and extraction magnets providing axial confinement, a hexapole magnet for radial confinement, and a central magnet for enhancement of magnetic field in the ECR region. The superposition of axial magnetic field contributions of each magnet array were calculated with PANDIRA, a package in the Poisson-SUPERFISH software suite [6]. The resulting axial magnetic field profiles for various iron plug displacements z_{plug} , referenced to the injection bias disc, are summarized in Fig. 4 and presented in previous works [7]. Table 2 gives the numerical values for the axial magnetic field at the location of the injection bias disc ($z = 0$ cm), extraction ($z = 14.5$ cm), and minimum ($z = 8.4$ cm) with varying iron plug displacements. These axial magnetic field calculations were made assuming that the central magnet was placed at a nominal distant of 7 cm axially from the location of injection bias disc. It is to be noted that the displacement of the iron plug does not significantly alter the axial magnetic field at the location of the minimum and extraction. The performance of an ECR ion source can be optimized by adjusting the magnetic fields to improve the confinement of the plasma. It was found that an iron plug displacement of $z_{\text{plug}} = -6$ mm should be optimal for the system according to ECR ion source scaling laws [8].

2.3. Extraction system

Composed of four nested circular aperture electrodes that are electrically isolated, the plasma electrode (PE), intermediate electrode (IE), screening electrode (SE), and extraction electrode (EE) make up the tetrode extraction system that is shown in Fig. 5. The extraction system has been designed to minimize emittance growth due to aberrations for efficient beam transport. The electric field gradient between the PE and IE will be adjusted to establish the shape of the plasma meniscus independent of the acceleration–deceleration electric field regions formed by the IE, SE, and EE. The specifications of the extraction system are shown in Table 3. Simulation of the extraction system was carried out using IGUN [9] and results converted to x – x' and y – y' phase space with skewed beam dynamics considered [10]. Fig. 6 summarizes RMS emittance for various ℓ_2 , separation distances between IE and SE. The separation distance ℓ_1 , between PE and IE, and ℓ_3 , between SE and EE, are held fixed

Table 2

Axial magnetic field at the point of injection, extraction, and minimum for various iron plug displacements z_{plug} that are referenced to the injection bias disc.

z_{plug} (mm)	B_{inj} (T)	B_{ext} (T)	B_{min} (T)
–6	1.936	0.913	0.393
–10	1.402	0.912	0.389
–15	1.118	0.911	0.386
–20	0.995	0.910	0.383

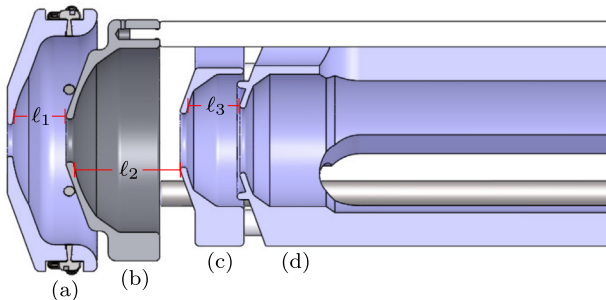


Fig. 5. Cross-sectional diagram of the tetrode extraction system showing (a) the plasma electrode (PE), (b) intermediate electrode (IE), (c) screening electrode (SE), and (d) extraction electrode (EE).

Table 3

Specification of ion source tetrode extraction system where the * denotes electrodes referenced to the extraction electrode with the extraction electrode on HV1 referenced to earth-ground.

Parameter	Potential	Aperture $\varnothing$
Plasma electrode*	0–30 kV	6 mm
Intermediate electrode*	20–30 kV	8 mm
Screening electrode*	–5–0 kV	10 mm
Extraction electrode	0–40 kV	12 mm

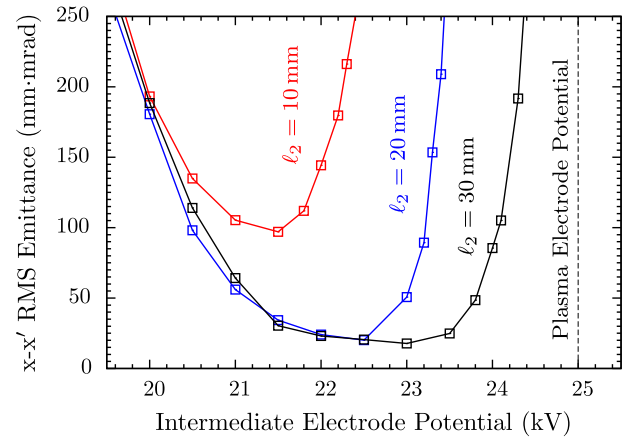


Fig. 6. x – x' RMS emittance as a function of intermediate electrode potential obtained from IGUN where the distance between the SE and IE are $\ell_2 = 10$ mm, 20 mm, and 30 mm for the case where $V_{\text{PE}} = +25$ kV, $V_{\text{SE}} = -2$ kV, and $V_{\text{EE}} = 0$ kV.

and chosen to be $\ell_1 = \ell_3 = 10$ mm in the extraction system design. The surface of the PE was inclined 20.3° with respect the plane of the plasma meniscus to satisfy the requirements for space-charge-limited flow and uniform ion flux [11]. A total extracted beam current of 1.1 mA, composed of $^4\text{He}^{1+}$, $^4\text{He}^{2+}$, $^{16}\text{O}^{2+}$, $^{16}\text{O}^{3+}$, $^{16}\text{O}^{4+}$, $^{16}\text{O}^{5+}$, and $^{16}\text{O}^{6+}$ was used in the simulation. The results show that a RMS emittance < 20 mm mrad can be attained for electrode configuration where $\ell_2 = 30$ mm, $V_{\text{PE}} = 25$ kV, $V_{\text{IE}} \sim 23$ kV, $V_{\text{SE}} = -2$ kV, and $V_{\text{EE}} = 0$ kV. Furthermore, the extraction system configuration where $\ell_2 = 30$ mm exhibits a relative insensitivity of the transverse RMS emittance to the applied IE electrostatic potential which will become an advantage while tuning and optimizing the source performance during operation.

3. Low energy beam transport line

The ECR ion source injector, shown in Fig. 7, will be mounted on a two-stage high-voltage platform where the first stage (HV1) is adjustable up to 40 kV, referenced to earth-ground, and the second stage (HV2) up to 30 kV, referenced to the HV1. The ECR ion source will be mounted to HV2, and thus the PE will be equipotential to HV2. The potential difference between HV2 and HV1 (up to 30 kV) will form the net acceleration–deceleration electrostatic fields that makes up the extraction system. While the potential difference between HV1 and earth-ground can be adjusted to match the energy of the ion beam to the 12 keV/u energy acceptance of the ReA RFQ [12]. The ECR ion source LEBT line will provide focusing and optical matching of ion beams to be injected into the ReA LEBT line. The low energy beam transport simulations were carried out using COSY Infinity [13].

3.1. Q/A spectrometer

Ion beams extracted from the ECR ion source will undergo Q/A separation while traversing a focusing solenoid, 90° double-

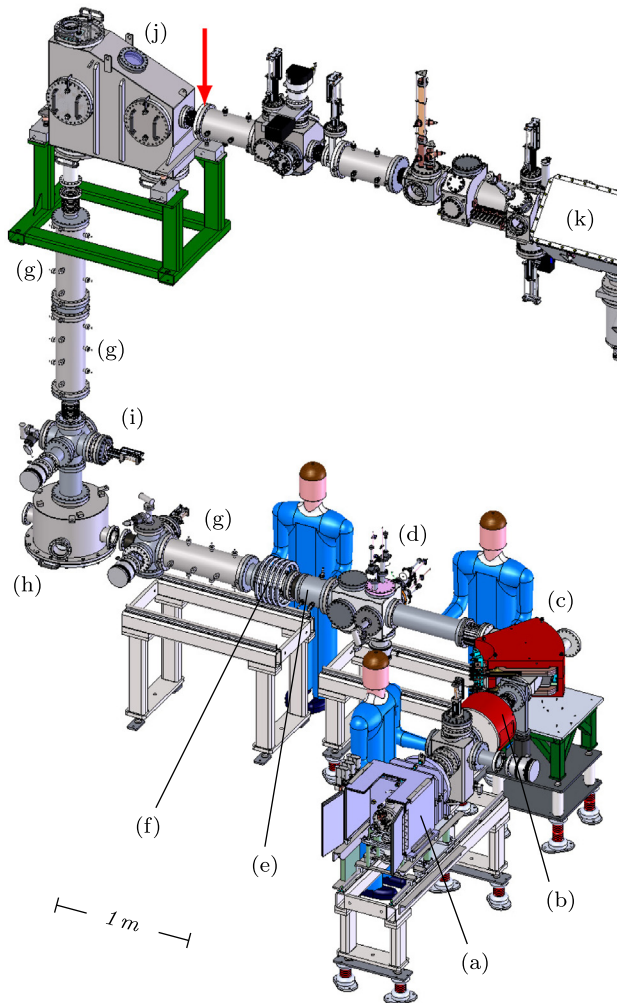


Fig. 7. Diagram of the ECR ion source injector showing (a) the ion source, (b) solenoid, (c) analyzer magnet, (d) 4-jaw separator slits, (e) split-cylinder Einzel-Sikler lens, (f) acceleration gap, (g) electrostatic quadrupole triplet, (h) spherical 90° electrostatic bender (i) separator slit, (j) spherical 75° electrostatic bender and 15° parallel-plate deflector, (k) ReA RFQ, and optical matching location indicated with a red arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

focusing analyzer dipole magnet, and 4-jaw separator slit that is located ~ 0.8 m from the exit of the analyzer magnet. The analyzer magnet, with entrance and exit edge angles of 28.5° , was designed with large aperture, small field aberrations, and balanced focusing in the two transverse planes. The focusing solenoid will ensure that the beam focal point will be located at the slits after the analyzer magnet. The first-order mass resolving power of the Q/A spectrometer system was calculated to be $R \propto (x, \delta)/(x, x) = 974.5$ for horizontal separator slit width set at 1 mm.

3.2. Optical matching and acceleration

After the Q/A separation, ion beams are focused by a 100 mm aperture cylindrical electrostatic lens into the high-voltage break (acceleration gap) where beams are accelerated to the final energy of 12 keV/u. The electrostatic lens was chosen to be a split-cylinder Einzel-Sikler lens [14] that will allow for beam steering in both transverse directions simultaneously with low aberration focusing. The beam is optically matched into the spherical 90° electrostatic

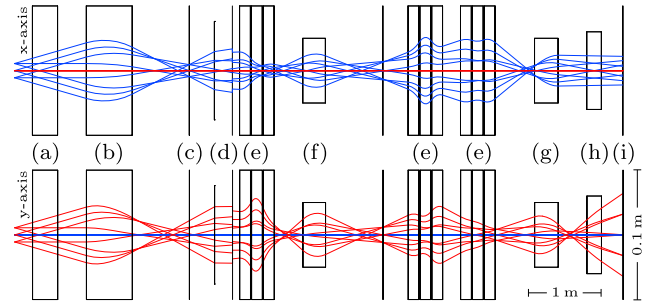


Fig. 8. Beam envelope obtained from COSY Infinity showing (a) the solenoid, (b) analyzer magnet, (c) separator slits, (d) Einzel-Sikler lens and acceleration gap, (e) e-quad triplet, (f) spherical 90° e-bender, (g) spherical 75° e-bender, (h) 15° deflector, (i) optical matching location, and overall beam line length of 8.2 m.

bender (e-bender) using a 100 mm aperture electrostatic quadrupole (e-quad) triplet. An optional secondary analyzer magnet spectrometer system is currently being explored as an alternative to the 90° e-bender to further improve the mass resolution. Two pairs of e-quad triplets will be used to provide optical matching through the spherical 75° e-bender and 15° parallel-plate deflector to a matching point that is ~ 30 cm from the e-bender housing. The optical matching conditions at this location are given in Table 1. These matching conditions were obtained from known optical tunes for beam line elements that provides matching into the ReA RFQ during operation. Fig. 8 shows the optimal transverse beam envelopes obtained from COSY Infinity for all optical elements in the ECR ion source injector system.

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