ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF141

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 augment 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 will be to provide CW 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 provide 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.

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 isotope, and fragment separator to purify the beam to be delivered to three large experimental areas for rare isotope nuclear physics research. The fast beam experimental area where the shortest-lived rare isotope beams (RIB) at energies >100 MeV/u are sent, and a stopped beam experimental area where RIBs are thermalized either in a gas cell or a cyclotron gas stopper before being transported to the trap and laser spectroscopy area or re-accelerated for low energy nuclear physics experiments with ReA [2]. Utilizing the modularity of the superconducting RF cyromodules, ReA currently re-accelerate thermal 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. ^{4}He).

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.

* Work supported by MSU and NSF PHYS-1102511
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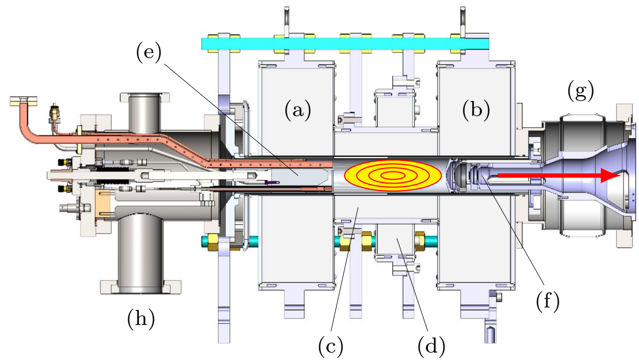

Figure 1: Cross-sectional diagram of the ECR ion source with (a) injection magnet, (b) extraction magnet, (c) hexapole magnet, (d) central magnet, (e) injection system, (f) extraction system, (g) high-voltage break, (h) injection vacuum port, ECR region, and direction of incident beam depicted.

Table 1: Requirements of the ECR Ion Source Injector

Parameter	Value
ReA Injection Energy	12 keV/u ± 5%
Q/A Range	0.2–0.5
Beam Current	~ 1–3 $e\mu$A
Optical Matching	$\alpha_x = 0.7$, $\beta_x = 8.4$ m/rad
Conditions	$\alpha_y = -1.1$, $\beta_y = 0.9$ m/rad

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 and SOLAIRE [3]. The design 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 is shown in Fig. 1 and Table 1 summarizes the injector requirements. The ECR ion source comprises of the injection, magnetic confinement, and extraction system to confine ions long

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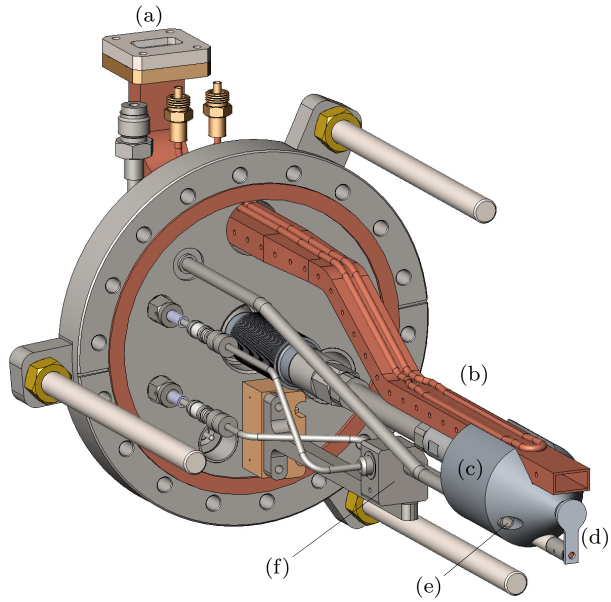

Figure 2: Diagram of the injection system where (a) is the RF window, (b) tapered and perforated water-cooled RF waveguide, (c) iron plug, (d) water-cooled bias disc, (e) gas feed inlet, (f) coolant distribution block.

enough to produce high charge state ions through the process of step-by-step electron impact ionization.

Injection System

The ECR ion source injection system includes an iron plug, gas feed inlet, RF waveguide, and bias disc shown in Fig. 2. The iron plug is axially adjustable to concentrate the magnetic field in the injection region. It is 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 WR-62 to minimize material subtracted from the iron plug. In addition, it 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 with frequency related to the ECR magnetic field into the plasma chamber for electron heating. Electrons spiraling near the injection region are repelled back into the ECR region by a disc that is negatively biased to enhance source performance. The disc is water-cooled to mitigate heating during operations. All components of the injection system are mounted on a custom 6.75″ CF zero length reducer coupled with a 4-way cross for ease of routine maintenance.

Magnetic Confinement System

The design utilizes a minimum-B axial magnetic field configuration for the confinement of ionizing electrons and plasma. The minimum-B field profile are formed by four magnet assemblies, each composed of high remanence Nd-FeB alloy configured in various Halbach arrays [4], with the injection and extraction magnets providing axial confinement, hexapole magnet for radial confinement, and central magnet for enhancement of magnetic field in the ECR region. The superposition of axial magnetic field contributions of each magnet array was calculated with PANDIRA Poisson-SUPERFISH [5]. The results are summarized in Fig. 3 for various iron plug displacements. The iron plug is used to adjust the magnetic field in the injection region to optimize ECR ion source performance.

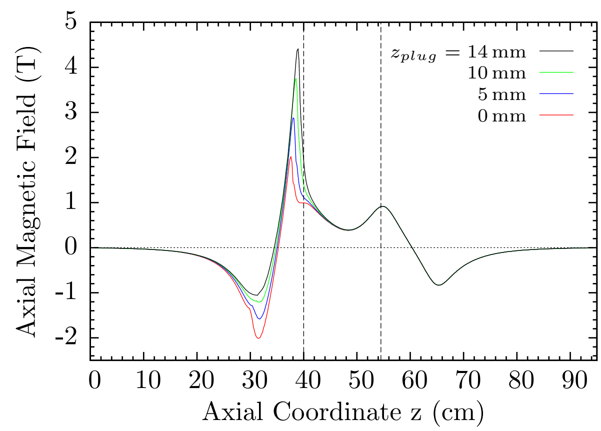

Figure 3: Axial magnetic field profile as a function of iron plug displacement relative to the injector magnet assembly where z_{plug} = 0 mm, 5 mm, 10 mm, and 14 mm. The region between the dashed-line depicts the boundaries of the plasma chamber where the ECR plasma reside.

Table 2: Specification of ECR Ion Source Extraction System

Parameter	**Potential**	**Aperture ⌀**
Plasma Electrode	0–30 kV	6 mm
Intermediate Electrode	20–30 kV	8 mm
Screening Electrode	−5–0 kV	10 mm
High-Voltage Ground	0–40 kV	12 mm

Extraction System

The tetrode extraction system, composed of four circular aperture electrodes, has been designed to minimize emittance growth due to aberrations for efficient beam transport [6]. The extraction system specifications are shown in Table 2. Simulation of the extraction system with IGUN [7] predict a RMS emittance of 20 mm·mrad for a 1.1 mA beam composed of $^{4}He^{1+}$, $^{4}He^{2+}$, $^{16}O^{2+}$, $^{16}O^{3+}$, $^{16}O^{4+}$, $^{16}O^{5+}$, and $^{16}O^{6+}$ when z_{plug} = 14 mm, V_{IE} = 22.5 kV, V_{SE} = −2 kV.

LOW ENERGY BEAM TRANSPORT LINE

The ECR ion source injector, shown in Fig. 4, is mounted on a two-stage high-voltage platform where the first stage (HV1) is adjustable up to 40 kV, referenced to ground, and the second stage (HV2) up to 30 kV, referenced to the HV1. The ECR ion source is mounted to HV2. The LEBT will focus, accelerate, and provide optical matching of ion beams into the ReA RFQ with an energy acceptance of 12 keV/u [8].

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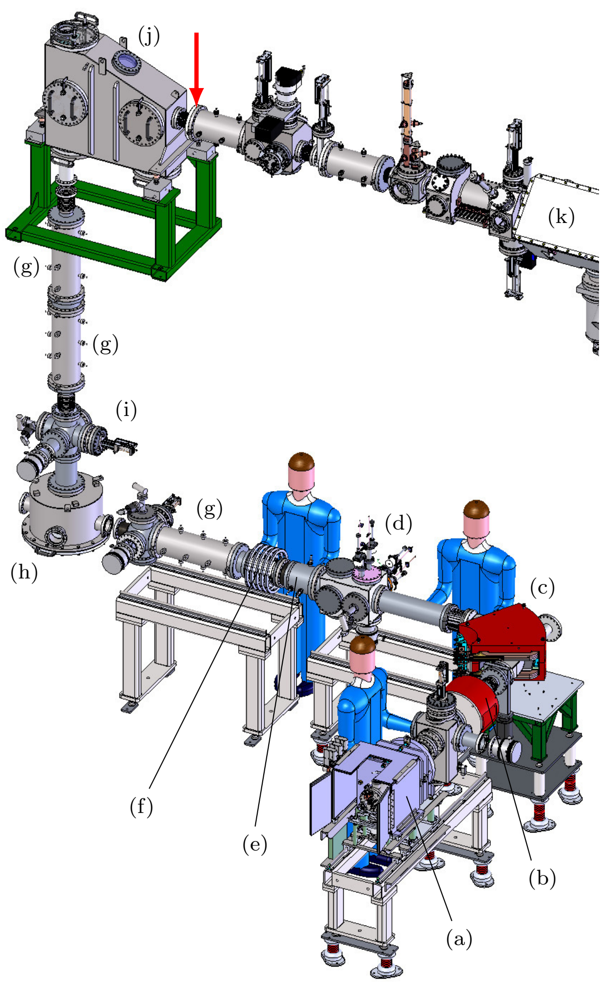

Figure 4: Diagram of the ECR ion source injector where (a) is the ion source, (b) solenoid, (c) analyzer magnet, (d) 4-jaw separator slits, (e) split-cylinder Einzel-Sikler lens, (f) acceleration gap, (g) electrostatic quadrupole triplet, (h) spherical 90° electrostatic bender (i) separator slit, (j) spherical 75° electrostatic bender and 15° parallel-plate deflector, (k) ReA RFQ, and matching point indicated with a red arrow.

Low energy beam transport simulations were carried out using the COSY Infinity [9].

Q/A Spectrometer

Ion beams emanating from the ECR ion source will undergo Q/A separation while traversing a focusing solenoid, 90° double-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 both edge angles at 28.5°, was designed with large aperture and to minimize field aberrations. The first-order mass resolving power of the Q/A spectrometer was calculated to be $R \propto (x,\delta)/(x,x) = 974.5$ for horizontal separator slit width of 1 mm.

Optical Matching and Acceleration

After the Q/A separation, the ion beam is focused by a 100 mm aperture cylindrical electrostatic lens into the acceleration gap where the beam is accelerated to the final energy of 12 keV/u. The electrostatic lens used will be a split-cylinder Einzel-Sikler lens [10] that will allow for beam steering in both transverse directions in addition to focusing with low aberrations. The beam is optically matched into the spherical 90° electrostatic bender (e-bender) using a 100 mm aperture electrostatic quadrupole (e-quad) triplet. An optional secondary spectrometer system is currently being explored as an alternative to the 90° electrostatic bender for better mass resolution. Two pairs of electrostatic quadrupole triplets will be used to provide optical matching through the spherical 75° electrostatic bender and 15° parallel-plate deflector to a matching point that is ~30 cm from the electrostatic bender housing.

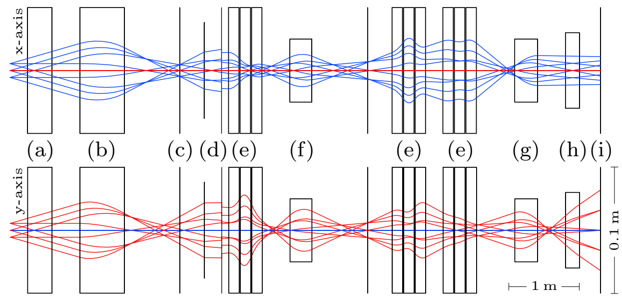

Figure 5: Beam envelope from COSY where (a) is the solenoid, (b) analyzer magnet, (c) separator slits, (d) Einzel-Sikler lens and acceleration gap, (e) e-quad triplet, (f) spherical 90° e-bender, (g) spherical 75° e-bender, (h) 15° deflector, (i) matching point, and overall length of 8.2 m.

ACKNOWLEDGMENTS

We would like to thank D. Hitz from CEA Grenoble who provided the reference design, A. Lapierre, S. Nash, S. Krause, M. Syphers, D. Cole, L. Tobos, W. Wittmer, and J. Stetson for their help and insightful discussions.

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