# ECR ION SOURCES FOR THE FACILITY FOR RARE ISOTOPE BEAMS (FRIB) PROJECT AT MICHIGAN STATE UNIVERSITY*

G. Machicoane, M. Doleans, O. Kester, E. Pozdeyev, T. Ropponen, L. Sun, E. Tanke, X. Wu
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA.
D. Leitner, 88 inch cyclotron Lawrence Berkeley National Laboratory, Berkeley CA 94720

*Abstract*

Once operational, the Facility for Rare Isotope Beams (FRIB) will open the possibility to gain key understanding in nuclear science and in particular regarding the properties of nuclei far from the valley of stability or the nuclear processes in the universe. In addition it will also allow experimenters to test fundamental symmetries. The production of rare isotopes with FRIB will be achieved, using a heavy ion driver linac that will accelerate a stable isotope beam to 200 Mev/u and deliver it on a fragmentation target. FRIB aims to reach a primary beam power of 400 kW for light to heavy elements up to uranium. To meet the intensity requirement, two high performance ECR ion sources operating at 28 GHz will be used to produce high intensity of medium to high charge states ion beams. Plans regarding initial beam production with the ECR ion sources and beam transport through the front end will be discussed.

## INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) (formerly referred to as RIA - Rare Isotope Accelerator) will provide intense beams of rare isotopes for a wide variety of studies in nuclear science. In particular it will help to deepen the current understanding of nuclear structure and help develop a comprehensive model of nuclei. In nuclear astrophysics, it will allow astrophysicists to model and understand the origin and evolution of elements in the cosmos and will permit sensitive tests of the fundamental symmetries of nature. Finally it will provide the scientific community with a source of rare isotopes to develop new applications for medicine, stockpile stewardship and improve applications that benefit from the use of radioisotopes. The FRIB facility is based on a heavy-ion linac with a minimum energy of 200 MeV/u for all ions at a beam power of 400 kW. To minimize the cost of the conventional facility, the layout of the accelerator follows a double folded geometry. The linac has been designed to accelerate ions with a charge to mass ratio higher than 1/7. The first segment with superconducting $\lambda/4$ cavities will accelerates the ion beam to 17 MeV/u and will be followed by a folded section that includes a charge stripper and a 180º magnetic bend. A second section with superconducting $\lambda/2$ cavities will accelerate ions to 108 Mev/u and again will be followed by a 180º magnetic bend but without charge stripping. A final accelerating section will allow the ion beam to reach 200 Mev/u for all ions up to uranium. The facility will have a production target for in-flight production of rare isotopes. A three-stage fragment separator will be used to prepare fast rare isotope beams with high-purity that can be used at velocity for fast-beam experiments. A multiconcept beam stopping facility will provide thermalized ion beams for stopped beam experiments or for reacceleration at energies up to 3 MeV/u for uranium.

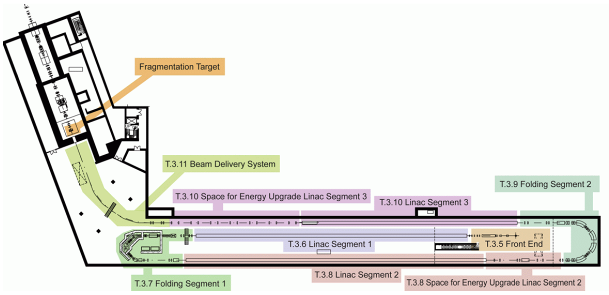

Figure1: Layout of the FRIB driver linac.

## FRIB FRONT END

The main functions of the FRIB front end will be on one hand to produce the ion beam using an ECR ion source and on the other hand to prepare the beam for injection into the superconducting linac by providing an initial beam acceleration to 0.3 MeV/u through a Radio Frequency Quadrupole (RFQ) and to ensure proper beam matching in the longitudinal and transverse directions. The front end includes the following segments: First heavy ion beams for FRIB will be produced from high performance ECR ion sources operating at 28 GHz. Two ion sources are necessary to ensure maximum beam availability through redundancy. The initial ion beam energy after extraction from the ion source will be 12 keV/u. This corresponds to an accelerating voltage around 90 kV for $U^{33+}$. Such a potential difference can not be achieved directly in one acceleration gap at the ECR extraction and a high voltage platform will be used to reach the initial required energy. Then, following the high voltage platform, an achromatic charge to mass selection system will be used to minimize transverse emittance growth in particular for heavy ion beams. The low energy beam transport section (LEBT) will include a transverse collimation system to ensure that the full normalized transverse beam emittance does not exceed the acceptance of the Superconducting linac.

An ion beam chopper is also included in this section to reduce the average beam intensity without impacting the nominal beam bunch intensity for safe tuning and

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operation of the machine. A multi-harmonic buncher operating at a fundamental frequency of 40.25 MHz will then change the DC beam produced by the ECR ion source to a pulsed beam for injection into the RFQ. Finally a Medium Energy Beam Transport (MEBT) section will match the beam coming out of the RFQ to the first segment of the superconducting linac and catch beam particles not accelerated by the RFQ.

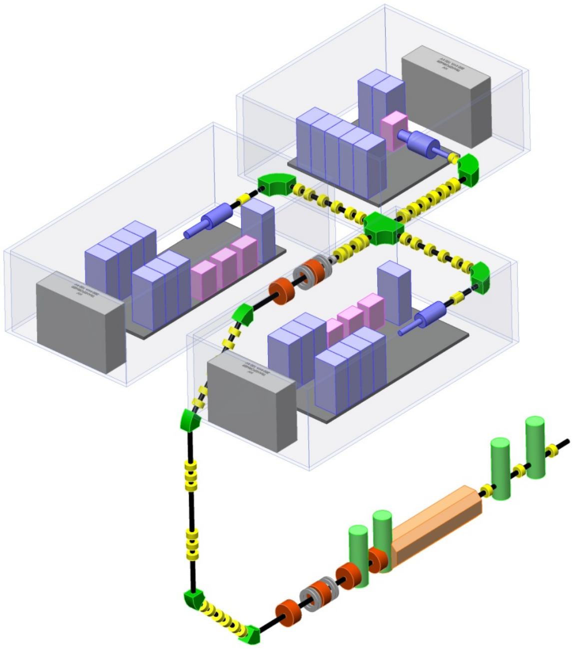

Figure 2: Front end for FRIB. Two ECR ion sources on high voltage platforms will provide the primary ion beam. Each ion source is followed by an achromatic charge selection system. Beam is then transported into the linac tunnel where the RFQ is located. A light ion source on a third platform is shown for future upgrade.

## REQUIREMENTS FOR FRIB ECR ION SOURCE

The most stringent requirement on the ECR ion sources is the beam intensity needed to reach 400 kW on the fragmentation target for heavy ions and in particular uranium. From the final beam power and the beam energy per nucleon, the particle beam current on target can be easily calculated and gives 8.1 pμA for $^{238}$U. Conservative estimates for beam losses through the LEBT and the charge stripping section provide a transmission of 64 % for uranium from the source to the target therefore raising the initial beam requirement from the ECR ion source to 12.7 pμA. The design of the superconducting linac imposes an initial charge state not lower than $U^{33+}$ which leads to an electrical current of 424 eμA. This current exceeds by approximately a factor two, the highest performance demonstrated for $U^{33+}$ with the ECR ion source VENUS [1]. Therefore, to reach the final beam power in the production target, the driver linac will accelerate concurrently two charges states for heavy ion beams. This approach has been selected for ions heavier than xenon. Table 1 summarizes intensity requirements and expected transmission for various elements. It is clear from the table that the FRIB project does not require the ECR ion source to produce very high charges states but rather medium charges state ion beams. Of course the possibility to produce higher charge states without diminishing too heavily the beam intensity could be a strong advantage if the accelerating gradient in the RF cavities are somewhat lower than projected.

Table 1: Projected intensity and charge state needed from the FRIB ECR ion source for various elements once the facility operates at full power (400 kW)

| | A | Z | Q-ECR | Transmission (%) | I-ECR (eμA) | I-ECR (pμA) |
|---|---|---|---|---|---|---|
| Argon | 40 | 18 | 8 | 0.8 | 378 | 47.3 |
| Calcium | 48 | 20 | 11 | 0.8 | 468 | 42.5 |
| Nickel | 58 | 28 | 12 | 0.8 | 365 | 30.4 |
| Krypton | 78 | 36 | 14 | 0.8 | 331 | 23.6 |
| Tin | 112 | 50 | 18 | 0.72 | 354 | 19.7 |
| Xenon | 124 | 54 | 20 | 0.72 | 334 | 18.5 |
| Lead | 208 | 82 | 27,28 | 0.64 | 392 | 14.3 |
| Bismuth | 209 | 83 | 28,29 | 0.64 | 404 | 14.2 |
| Uranium | 238 | 92 | 33,34 | 0.64 | 424 | 12.7 |

In addition, to the requirement on the beam intensity shown in table 1, the ion beam transverse phase space distribution has to be within the acceptance of the RFQ and superconducting linac. In particular, beam dynamic calculations show that the full normalized emittance for one charge state ion beam has to be within 0.9 pi.mm.mrad, while, for the acceleration of two charge states, each individual charge state should have a full normalized emittance smaller than 0.6 pi.mm.mrad.

Variations in beam intensity from the ECR ion source beyond a few percent can lead to frequent retuning of the machine and should be minimized. Fast beam variations exceeding 10 kHz can lead to beam loading of the RF cavities and could increase beam losses in the linac. Recent measurements at MSU for low intensity uranium with the ECR ion source SuSI using a scope with a capability of Fourier analysis showed that the ion beam did not have oscillations of the beam intensity exceeding a few kHz. The amplitude of the AC variations however could reach between 5 to 10% of the DC value.

## CONCEPTUAL DESIGN

The selected approach for the conceptual design of the FRIB ECR ion source is to use the ECR ion source VENUS design developed at LBNL with added modifications that reflect the experience gained with the ion source construction and operation. This approach is based on the following considerations. First, the primary operating frequency for the FRIB ECR ion source should be 28 GHz in order to reach the highest electron density in the ECR plasma as demonstrated by the VENUS ion source. Choosing an operating frequency beyond 28 GHz, would require further development and progress of ECR ion source technology. Such developments are less likely to mature within the timeframe of the FRIB project. An additional microwave generator operating at a frequency between 18 GHz to 24 GHz should also be added. Operation of the ECR ion source at 18 GHz could be beneficial for lighter ion beams. Second, the VENUS coil package has demonstrated the unique capability to run independently the hexapole from the solenoid coil despite strong interaction forces between the two coil system. In particular, innovative techniques were developed to improve the clamping of the coils using expendables bladders. Another technical choice was to use a large copper to superconducting ratio for the hexapole coil wire to improve its stability [2]. However, experience with the VENUS ion source has shown that the heat load induced by the radiation generated by the ECR plasma can add up to one watt for each kilowatt of microwave power at 28 GHz operation. Therefore, in order to inject a maximum of 10 to 12 kW of microwave power into the ECR ion source from a Gyrotron amplifier, an overall cooling capacity of 13 to 15 W at 4.2 K is needed even if we are to consider a low static load (1 W). This will require modifying the VENUS cryostat. Two cryocoolers with each a cooling capacity of 5W (single stage Gifford-McMahon Joule-Thomson crycooler) will be needed as well as additionals two stage Gifford-McMahon cryocoolers (1.5W) to reach the desired cooling capacity. An additional cryocooler will be also needed for the precooling of the HTc leads. Another possibility that has not been fully explored is to use circulating liquid helium to cool the ion source cryostat through a cold box installed on the high voltage platform. Although this solution offers many advantages, it also poses the problem as to where the compressor can be located and overall, requires a larger footprint.

## CHALLENGES AND DEVELOPMENT

For medium mass ions to heavy ions the electrical currents shown in table 1 are close to the maximum performance reached by existing ECR ion sources. Therefore, to meet the requirement set by FRIB, most of the current extracted from the ECR ion source needs to be within the acceptance of the linac. Although several groups have measured beam emittance, this has often been at a relatively low intensity and full emittance at high extracted currents have seldom been reported. Two factors can contribute to emittance growth during beam formation. One is the angular momentum caused by the decreasing magnetic field in the extraction region. This contribution will in principle increase with higher operating magnetic field. The other is caused by space charge forces which can contribute significantly to emittance growth for drain currents exceeding several milliamperes. For higher charge states, the first effect could be mitigated by a smaller effective radius at extraction as evidenced by smaller measured emittance with higher charge states [3]. However more measurements are needed to fully characterize intense high charge states ion beams. For medium charge state ion beams it is unclear what fraction of the ion beam current can fit within the FRIB linac acceptance. Recent measurements at MSU with the ion source SuSI using an intense beam of $Kr^{14+}$ (~400 euA) indicates that at least a third of the beam exceeds the required FRIB emittance 0.9 pi.mm.mrad [4].

It is anticipated that, during the operation of the FRIB facility, users will run experiments for several weeks with minimum interruption. The stability of the beam extracted from the ECR ion source will therefore be critical to successfully operate the facility at full power. In particular, for metallic beams, the techniques used to produce the initial vapour have to be optimized. Several techniques such as resistive oven [3], inductive oven [4] and sputtering [5] have already produced significant amounts of uranium beam but need to be further optimized. Initial estimation indicates that the material consumption needed to run the ion source could reach up to 10 mg/h assuming a 10 % efficiency. In addition, several new primary beams will have to be developed for FRIB such as $^{204}Hg$ or $^{82}Se$. Some rare earth elements or refractory elements could also be added to the primary beam list.

## OUTLOOK

As of August 2010, a Conceptual Design Report (CDR) for the FRIB project has been proposed and reviewed by the U.S Deparment of Energy. It is anticipated that during the fiscal year 2011, a preliminary design of the FRIB front end will be completed. In particular, technical solutions for the cryostat and coil package will be selected. Completion of the project is expected at the earliest in 2018. However, at least one high performance ECR ion source needs to be constructed and tested by early 2016.

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