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REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 02A743 (2016)

# Status of ECR ion sources for the Facility for Rare Isotope Beams (FRIB) (invited)

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Ahead of the commissioning schedule, installation of the first Electron Cyclotron Resonance (ECR) ion source in the front end area of the Facility for Rare Isotope Beam (FRIB) is planned for the end of 2015. Operating at 14 GHz, this first ECR will be used for the commissioning and initial operation of the facility. In parallel, a superconducting magnet structure compatible with operation at 28 GHz for a new ECR ion source is in development at Lawrence Berkeley National Laboratory. The paper reviews the overall work in progress and development done with ECR ion sources for FRIB. © *2016 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4939643]

## I. INTRODUCTION

The Facility for Rare Isotope Beam (FRIB) built on the campus of Michigan State University (MSU) is a new national user facility targeted for completion by 2022. Once operational this unique facility will provide a large range of research opportunity for the nuclear physics community from studying the properties of atomic nuclei far from stability to improving the understanding of nuclear process in the cosmos as well as developing applications of isotopes for society ranging from materials science, nuclear medicine, or national security. The facility is based on a superconducting-RF driver linear accelerator that will provide a maximum beam power of 400 kW for all beams ranging from uranium accelerated to 200 MeV/u to lighter ions accelerated to higher energy. The high beam power on the target, combined with the high acceptance of the fragment separator, will enable FRIB to reach yield of short lived isotopes several orders of magnitude higher than what is available today. The accelerator consists of a front end section that includes two Electron Cyclotron Resonance (ECR) ion sources, followed by an 80.5 MHz, four vanes Radio Frequency Quadrupole (RFQ), and then, followed by three linac segments arranged into a folded configuration. A stripper section is included after the first linac segment to help reach higher beam energy.[1] The ECR ion sources are located at ground-level, for safe access during operation, while the RFQ and superconducting linac are in a tunnel located about 40 ft underground.

## II. BEAM REQUIREMENTS

Table I summarizes the beam parameters for a few specific elements corresponding to the final beam power of 400 kW on the production target. The requirement on the initial ion beam intensity can be met using an ECR ion source operating at 28 GHz—such as VENUS (Versatile ECR ion source for NUclear Science) developed at Lawrence Berkeley National Laboratory (LBNL).[2]

To run the ion source within acceptable operational margins and maximize beam availability to the users, the driver linac was designed for the simultaneous acceleration of two charge states for elements heavier than xenon. VENUS recently demonstrated very high beam intensity for uranium[3] and recent results obtained with the Superconducting ECR with Advanced design in Lanzhou (SECRAL) in China,[4] for heavy elements such as bismuth, show that the limits of performance for ECR ion sources at 24 or 28 GHz have not yet been reached—indicating that the beam intensity requirement for FRIB, although high, is feasible for existing ECR sources. Improvement of the beam intensity has also been reported for lighter elements such as calcium from VENUS[5] which is very important due to the fact that acceleration for lighter elements than xenon will only be from a single charge state. The beam energy required for injection into the RFQ is 12 keV/U which can be accomplished by positioning the ion source on a high voltage (HV) platform. Platform voltages are indicated in Table I for various elements assuming an extraction voltage of 25 kV from the ion source and a Q/A = 1/7. The layout of the ion sources on the HV platform is shown in Figure 1. To provide operational flexibility and mitigate downtime risks, all equipment and utilities supporting the operation for each ion source are independent from one another.

## III. 28 GHz ECR ION SOURCE

A high intensity ECR ion source, based on the VENUS design, is in development for FRIB. Because of the high magnetic field needed for operation at 28 GHz, the magnet is using superconducting coils (SCs). A collaboration has been

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TABLE I. FRIB linac beam parameters for oxygen, krypton, xenon, and uranium from ion source to target. Ion source charge state reflects minimum charge compatible for injection into linac.

| | Name | O | Kr | Xe | U |
|---|---|---|---|---|---|
| | Z | 8 | 36 | 54 | 92 |
| | A | 16 | 86 | 124 | 238 |
| Target | E (MeV/u) | 320 | 257 | 252 | 200 |
| | I (puA) | 78.1 | 18.1 | 12.8 | 8.4 |
| | P (kW) | 400 | 400 | 400 | 400 |
| Stripper | E (MeV/u) | 20 | 19.3 | 17.3 | 16.5 |
| | Q_out | 8 | 35 | 49,50, 51 | 76,77,78,79,80 |
| ECR | Q_ECR | >3 | >14 | >20 | >33,34 |
| | I (puA) | 122 | 49.4 | 23.4 | 15.6 |
| | E (keV/u) | 12 | 12 | 12 | 12 |
| | Platform HV (kV) | <39 | <49 | <57 | <62 |

established with the Superconducting Magnet Group at LBNL who is responsible for the design, fabrication, and testing of the FRIB SC-ECR magnet cold mass. The main magnetic parameters are very close to the original magnet parameters used with VENUS and are shown in Table II. Unlike the original VENUS sextupole, the poles of the sextupole coils for FRIB are almost entirely made of iron except for the very end which is made of aluminum. As a result, the radial field stays within 1% of the maximum field requirement of 2 T at the plasma chamber wall over a longitudinal length 8 cm longer than the original VENUS as shown in Figure 2 which also results in the last closed iso-B surface at about 1.86 T for FRIB SCECR versus 1.75 T for VENUS. Another difference with the original VENUS sextupole also shown on Figure 2 is the length of the sextupole coil which has been shortened on the extraction side for FRIB to accommodate the coil end support.

Because of the Lorentz forces between solenoids and sextupole, when the coils are energized, a mechanical structure that prevents movement of the SC coils and, in particular, the sextupole is required. Although the original VENUS cold mass was fabricated using a support structure that included

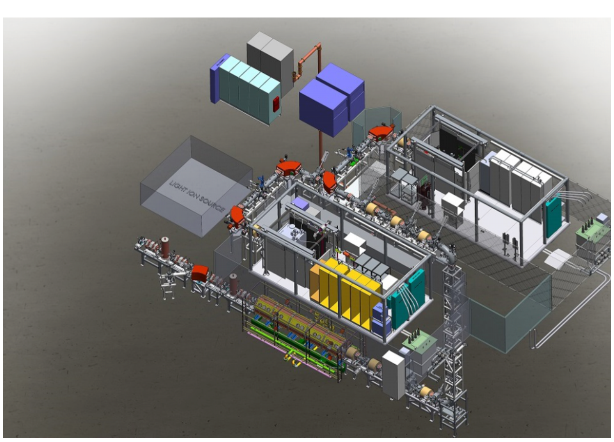

FIG. 1. Layout of FRIB ECR ion sources on HV platforms. The 28 GHz source is shown at the forefront while the 14 GHz ECR ion source used for commissioning is shown at the back. Supporting systems such as isolation transformer, radiation shielding, and microwave generators are also shown in the layout. LEBT line with the vertical chase and RFQ is also visible.

TABLE II. FRIB SCECR magnetic parameters.

| Parameters | FRIB SCECR |
|---|---|
| Sextupole | |
| Nominal current (A) | 450 |
| Peak field on conductor (T) | 6.6 |
| Peak field at plasma chamber wall (T) | 2.03 |
| Temperature margin (K) | 0.9 |
| Inductance (H) | 1.7 |
| Length (coil) (cm) | 84.6 |
| Injection/mid/extraction solenoid | |
| Nominal current (A) | 233/-155/152 |
| Peak field on conductor (T) | 6.15/3.4/4.1 |
| Peak field on axis (T) (nominal) | 4/0.6/2 |
| Temperature margin (K) | 1.47/3.97/2.76 |
| Inductance (H) | 13.96/2.4/8.05 |
| Inner/outer diameter (mm) | 170/229.46/170/220.98/170/229.46 |
| Last closed ISO-B surface | |
| Field value (T) | 1.86 |
| Length (mm) | 316 |
| ECR zone length (mm) | 170 |

metal-filled bladders,[6] this approach was not selected for the construction of the FRIB SCECR in part because of the difficulty to properly define and provide the right amount of preload needed to the sextupole coils during assembly, cool-down (CD), and operation. Instead, a shell-based support structure was developed that incorporates the use of bladders and keys[7] which not only provide a tool for precisely setting the sextupole preload but also allow for the reversibility of the magnet assembly. This can be very useful to apply adjustments by varying the size of the keys. This approach is based on the bladder and key technology developed by the LBNL Superconducting Magnet Group for high magnetic field $Nb_3Sn$ magnets fabricated through the LHC Advanced Research Program (LARP) collaboration[8] but also on the conceptual work done for the development of a fourth generation ECR ion source.[9] Inherent to this approach is a 2D and 3D finite element analysis that evaluates both contact pressure and stresses in the coils at all the phases of the magnet assembly—including room temperature pre-loading (bladder operation), after cool down (where the final coil preload stresses are attained), and finally, at full excitation of the coils. Peak stresses in the coils

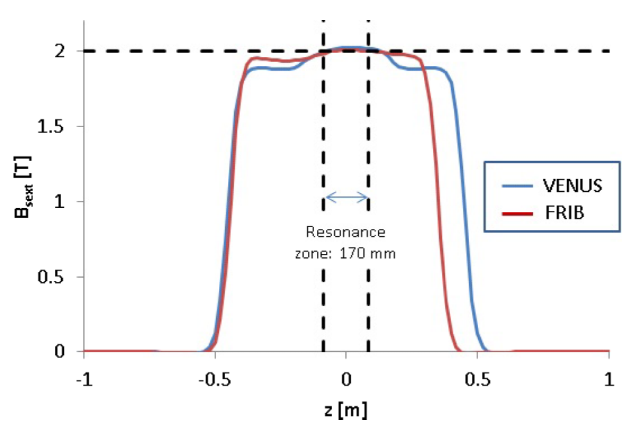


FIG. 2. Comparison of the longitudinal profile of the radial magnetic field along the plasma chamber wall between VENUS and FRIB SCECR.

have to stay low compared to yield stresses while contact pressures must stay positive at all steps to maintain the coils in compression. Particular attention was paid during analysis of the FRIB SCECR to the contact pressure between the straight section of the sextupole coil and the iron pole as well as to the support needed for the sextupole coils end. Assembly of the cold mass starts with the winding of the three solenoids on an aluminum mandrel. A winding tension of 60 MPa was found adequate to maintain compression of the solenoids against the mandrel. In parallel, the sextupole coils (wound and epoxy impregnated) are assembled together in six stainless steel load pads bolted together as a coil pack. The sextupole coil pack subassembly is then inserted into the aluminum mandrel. Following this step, bladders are inserted between the pads and the mandrel and inflated using pressurized water. The gap created by inflating the bladders is filled with a key and shims of suitable thickness (nominal 200 $\mu$m) to reach a defined level of azimuthal stress into the sextupole coil and aluminum mandrel. Bladders are then deflated and removed while keys are locked in the assembly. The level of azimuthal stress in the sextupole during the bladder-key operations can be directly measured and monitored by installed strain gauges in the pads and compared against the calculated target stresses in the 3D model. As an example,[10] the calculated contact pressure of the sextupole coil against the pole at various stages of assembly is shown in Figure 3.

Note that although the contact pressure is inhomogeneous along the mandrel length, it stays positive during all assembly steps and, in particular, after Cool Down (CD) and full excitation of Lorentz Forces (LF). The reason for the inhomogeneous profile is due to the radial compression of the mandrel during winding of the solenoids which lead to a stronger contact with the keys under the solenoids and, therefore, higher preload at those locations at room temperature. It is somewhat offset during cool down due to the larger differential contraction of the aluminum mandrel in areas that are between solenoids. In order to attain a uniform surface contact between the coil and the load pads and to also improve the coil packing factor, the sextupole coils are dry wound followed by application of epoxy using vacuum impregnation. A practice coil, using a rectangular wire close to the production conductor size, was completed

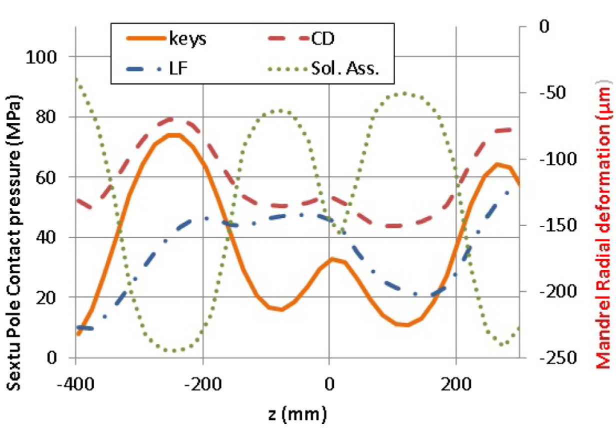


FIG. 3. Predicted radial deformation of the aluminum mandrel during solenoid winding and sextupole straight section contact pressure against pole is shown for all steps of assembly.

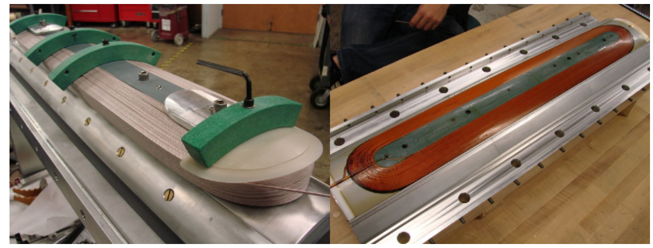

FIG. 4. FRIB 28 GHz SCECR sextupole practice coil.

successfully and showed a very good turn to turn positioning as well as a good quality of insulation. Figure 4 shows result of the practice coil during winding and after impregnation.

The tooling for the production coil winding and impregnation has been designed and is being fabricated. Winding of the sextupole will start in the next few months. Completion of the cold mass is expected by the end of 2016.

## IV. FACILITY STATUS AND COMMISSIONING

One of the initial commissioning goals of the FRIB linac is to accelerate a beam of $^{36}$Ar beyond 200 MeV/u. A second goal is to detect $^{84}$Se as a secondary beam in the new fragment separator using $^{86}$Kr as primary beam. Beam intensity requirements from the ion source during commissioning of the facility are much lower than what will be needed to reach 400 kW on the target and have been set to 50 euA[11] after stripping to provide enough accuracy and resolution to test beam diagnostics. Also during commissioning, only one charge state will be selected and accelerated. Because of the lower beam intensity requirement, a 28 GHz ECR ion source is not needed during this phase but instead will rely on a 14 GHz ECR ion source already available from the National Superconducting Cyclotron Laboratory (NSCL).

This ion source ARTEMIS magnet is based on the AECR-U[12] that was developed at LBNL and features room temperature coils for the solenoids and N42H NdFeB permanent magnet for the sextupole to provide direct pumping into the plasma chamber. The ion source was built in 2005[13] in a vertical configuration and operated until 2010 for optic and diagnostic development at NSCL. Over the past year, ARTEMIS has been modified for horizontal operation for FRIB and is shown reassembled in Figure 5. The ion source was tested in July

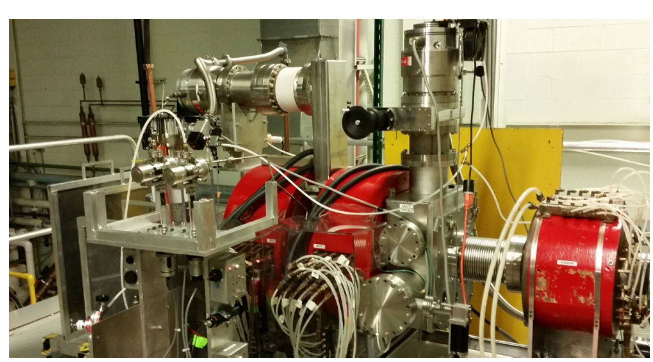

FIG. 5. 14 GHz ECR ion source ARTEMIS is shown. The ion source was reconfigured for FRIB to operate with the main ion source axis horizontal. Ion source was operated in July 2015.

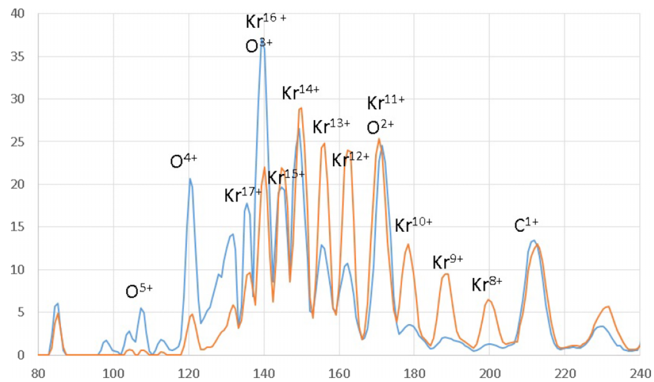


FIG. 6. Charge state distribution obtained for 86-Kr with ARTEMIS-B ion source in July 2015. The distribution in orange was optimized for Kr14+ and was obtained with an injected power of 350 W while the blue distribution was optimized for krypton 17+ and obtained at a higher power of 470 W.

2015 and produced a beam of 86 Kr as shown in Figure 6. Beam intensity obtained for krypton is close to what will be needed during FRIB commissioning.

Beyond commissioning of the linac, ARTEMIS will be able to support operation of the facility during the early stages of the power ramp up especially for light ion beams but will be limited in use for heavy ion beams that will require an ion source operating at a higher frequency. The high voltage platform has been designed to support close to 40 000 lbs of equipment required for the 28 GHz ion source including gyrotron, equipment racks, crycooler compressors, and the radiation shielding. The platforms will be standing on large ceramic insulators that have a high compressive strength. Two platforms have been fabricated by a local vendor and are ready to be moved to the front end area. Platforms and insulators are shown in Figure 7.

Cooling for the equipment on each, the high voltage platforms will be done with a dedicated water system each capable to provide 100 GPM of low conductivity water with a nominal resistivity of 6 MΩ/cm. A large isolation transformer, rated for up to 350 kVA and 125 kV DC of isolation, is also under procurement. To keep personnel exposure to X-ray radiation generated by the ECR plasma to less than 0.1 mrem/h, the ion source on the platform is enclosed within lead panels on all sides. Building construction has been moving ahead of schedule and installation of the high voltage platform and related equipment is planned before the end of 2015 in the front end area. The 14 GHz ECR ion source will be moved in early 2016 and installation of equipment and utilities will continue thereafter. First beam from the ion source is tentatively planned for the second half of 2016.

FIG. 7. High voltage platform shown after fabrication with insulator shown in bottom insert.

## V. ION SOURCE DEVELOPMENT

Aside from ECR ion sources design and preparation for FRIB, beam development is ongoing using the superconducting ECR ion source, SuSI—available from NSCL. SuSI has been used for development at 24 GHz with a 10 kW gyrotron. Commissioning of the gyrotron was completed in 2013 and the first results obtained in 2014. Up to 5 kW of power has been coupled to the ion source with extremely good results obtained for light elements such as oxygen and argon that are equivalent to performances obtained for similar elements with VENUS at LBNL.[14] In addition, the beam intensity extracted with the ion source is not saturating with the level of microwave power injected and better performances could be reached with additional conditioning of the ion source. In order to save on costs, the 24 GHz gyrotron will be transferred to FRIB for operation with the new high performance SCECR.

In parallel, reliable production of vapor plays a crucial role for facilities such as NSCL and FRIB. A new high temperature oven made is in development that could provide high intensity of uranium, germanium, or possibly zirconium beam. A thermal analysis was done to guide the mechanical design to obtain temperatures in excess of 2000 °C. Using tantalum for the heater element, the oven reached the design goal by circulating

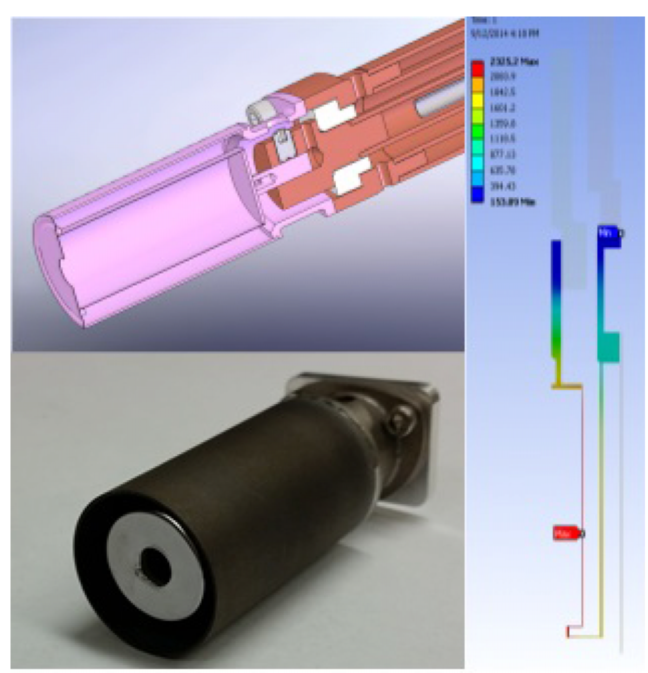

FIG. 8. High temperature tantalum oven developed for use at NSCL and FRIB. FEA analysis shows that temperatures beyond 2000 °C can be reached with about 200 A of current circulating in the heater element.

about 200 A of current which is reasonable and prevents having to dissipate too much power in water-cooled parts adjacent to the heater element. The geometry of the oven was optimized to keep current running as much as possible parallel with the axial magnetic field to minimize Lorentz forces on the unit. With an inner volume of almost 3 $cm^3$, the oven will be able to hold a large quantity of material. The oven is shown in Figure 8. The heater element was fabricated by an outside vendor and testing is planned during the coming year.

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