# DESIGN STATUS OF ECR ION SOURCE AND LEBT FOR FRIB*

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*Abstract*

The Facility for Rare Isotope Beams (FRIB) at Michigan State University will provide intense beams of rare isotopes for research in nuclear physics, nuclear astrophysics and study of fundamental interactions. A Superconducting linac will accelerate the primary beam to energies beyond 200 Mev/u and is designed to reach a maximum beam power close to 400kW on the fragmentation target. In the case of Uranium about 13.3 pμA of U33+ are needed from the ion source to reach this maximum beam power on target. An ECR ion source operating at 28 GHz and based on the VENUS ion source developed at Lawrence Berkeley National Laboratory (LBNL) is currently being designed to meet the project intensity requirement and is presented in this paper. Although the intensity requirement from the ion source are very high for the FRIB project, new results have been obtained recently with VENUS that demonstrate that this ion source can actually produce close to 13pμA of U33+ within the emittance required by the accelerator. In addition an achromatic Low Energy Beam Line (LEBT) capable of transporting concurrently two charge states will be used to transport and accelerate the ion beam coming from the ion source.

## INTRODUCTION

Michigan State University has been selected to build the Facility for Rare Isotope Beams (FRIB) in 2008 by the US Department of Energy (DOE). The FRIB driver accelerator consists of two Electron Cyclotron Resonance (ECR) ion sources located on a high voltage platform that will provide a large range of elements from Oxygen to Uranium at an initial energy of 12 keV/u, an achromatic low energy beam transport, a Radiofrequency Quadrupole (RFQ), a first linac segment with Quarter-wave Resonators (QWR) of β=0.041 and 0.085 accelerating the beam up to 20 MeV/u, a liquid lithium based stripper to reach higher charge states followed by two other linac segments with Half-wave Resonators (HWR) of β=0.29 and 0.53 accelerating the beam above 200 MeV/u. The third linac segment could be used for a future energy upgrade of the facility to 400MeV/u. The linac will be located about 10 meters underground and following the different linac segments a beam delivery system will transport the accelerated beam to the target. This latter is followed by a fragment separator that merges with the existing nuclear experimental areas of the NSCL laboratory. The facility is also designed to allow for the future implementation of an ISOL option. Figure 1 below show a section view of the driver linac with the different segments. The FRIB driver accelerator is described in more details in other publications [1]

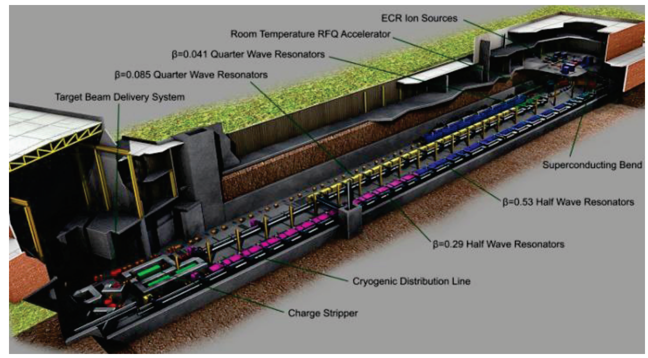


Figure 1: Layout of the FRIB driver linac. Ground level is shown in green at the top.

## FRIB ECR ION SOURCES

To limit machine downtime during ion source development or possible breakdown, two ECR ion sources will be implemented for FRIB. Each source is located above ground primarily for radiation safety reasons. FRIB won't operate at full power initially but instead the accelerator will be first commissioned at low beam power and later followed by an operational phase where the beam power will be gradually ramped up to the maximum design value. Intensity required from the ion source during the commissioning will be much lower and a simpler source can be used during that phase. ARTEMIS-B developed in 2005 for offline development [2] and based on the design of the AECR-U of LBNL is available and will be sufficient for the commissioning need of the accelerator. Although, ARTEMIS-B was originally built to be operated vertically, the design has been recently modified to position the ion source horizontally. A temporary deck has been built as well as a new stand to support the ion source. Over the next year, the source will be reassembled and tested in this new orientation. Because, the ion source will be operated on a high voltage platform, the power supplies used for the solenoid coils have to be replaced with ones that are more efficient in order to be compatible with operation on the high voltage platform. The NdFeB based hexapole magnet of ARTEMIS-B will be also upgraded with a materials grade that has a higher energy product to increase the radial field.

The second ion source will be a high performance superconducting ECR ion source capable to operate at 28 GHz and based on the ion source VENUS developed at LBNL. The magnet system follows the conventional design of the sextupole inside the solenoids. The VENUS

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magnet has been described extensively in previous publications [3],[4]. Calculations have been done with the commercial software LORENTZ regarding the magnetic field and match very closely the previous results obtained with VENUS. Table 1 summarizes the main parameters for the coils that are used to design the FRIB SC-ECR and the calculated magnetic field.

Table 1: FRIB SC-ECR Coil Parameters

| | Solenoid Injection | Solenoid Middle | Solenoid Extraction | Sextupole |
|---|---|---|---|---|
| Turn # | 6272 | 2208 | 4480 | 648 |
| ID(mm) | 340 | 340 | 340 | 200 |
| OD(mm) | 458 | 441 | 458 | 270 |
| Max B (T) on conductor | 6.14 | 4.22 | 5.47 | 7.3 |
| Field(T) on axis | 3.95 | 0.36 | 2.98 | - |
| Field (T) Chamber wall | - | - | - | 2.2 |
| Operating I (A) | 225 | -240 | 225 | 450 |

## PRELIMINARY DESIGN OF FRIB SCECR

Magnets for Superconducting ECR ion source are challenging because of the interaction forces between the solenoids and the sextupole coils. The design of the Superconducting Source for Ions (SuSI) built at MSU was also based on the VENUS ion source but has not been able to reach the field necessary for operation at 28 GHz and is instead limited to work at a maximum frequency of 22-24 GHz due to quenches in the sextupole coil when the solenoid are energized. Several differences were introduced in the design of SuSI that may explain the limitation of the magnet performance [5]. First, the NbTi conductor used with SuSI had different properties than the one used for VENUS and is discussed below. Second, the structural banding used to keep the sextupole tightly against the bore tube was not extended to the end regions of the coil for SuSI and the gap existing at this location was filled with soft material such as Kapton. Finally, the small gaps created between the coils and the bore tube after inflation of the bladders was not filled as it was for VENUS by vacuum impregnation. The approach for the VENUS project of using an aluminium structure around the sextupole coil (consisting of an aluminium sleeve followed by the thick solenoid bobbin) is necessary to ensure that the coils will be pre-stress in the radial direction during cool down before they are energized. This pre-stress has to be confirmed by measuring the contraction of the wire-epoxy composite during cool down to ensure that the aluminium contracts more. The bladders provide an elegant solution for the loss of stress in the azimuthal direction during cool down and will be used again for FRIB. More advanced techniques using water bladders and Keys have been developed at LBNL since the VENUS project and would certainly provide a better and more controlled clamping of the coil structure [6] which would especially be useful to reach magnetic field higher than required for operation at 28 GHz but would require substantial engineering and go beyond the scope of a project such as FRIB. The Bladders will be filled with indalloy which has a low melting point at 117F and does not change volume significantly after solidification. Calculations have been done with ANSYS to analyze the hoops stress and radial pressure resulting from the bladder inflation. Using an inflation pressure of 1500PSI for the bladders create a radial pressure of about 550PSI which is sufficient for the banding to yield and push the coils against the Aluminium sleeve.

The next step on the analysis of the pre-stress is to simulate the cool down and verify that the radial stress on the sextupole will increase. These calculations will be done using data available regarding the thermal contraction of the coils that was measured for VENUS [3] as well as the elastic modulus also measured for this type of conductor [7]. The last step of the analysis will be to include the impact of the Lorentz force when all coils are energized. The radial field experienced by the sextupole in the regions where the axial field profile is rapidly changing ($B_r$ proportional to $dB_z/dz$) can be very significant. Depending on the polarity of the current in the sextupole coil, this field either reinforce or weaken the self field of the sextupole. This is illustrated in figure 2 where the top picture shows the sextupole self field only and the bottom picture the contribution of both the sextupole and solenoids on one of the sextupole coil. The field is oriented perpendicular to the plan shown.

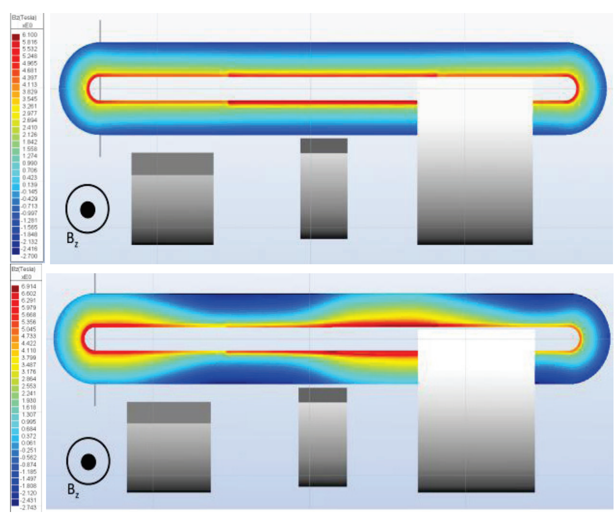

Figure 2: Magnetic field intensity along the radial direction. Top: self field of sextupole only. Bottom: Contribution from the solenoids is added. A section of the solenoids are shown in gray with the injection coil located to the right.

The additional contributions from the solenoids results in added azimuthal forces for the straight sections of the sextupole. They also modify the force in the longitudinal direction for the end sections where depending on the

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polarity the coil can be either stretched or compressed. In the end region, the field has also a significant component in the longitudinal direction (not shown here) resulting in radial force that tend to flex the ends either inward toward the bore tube or outward to the aluminium sleeve around the sextupole. In the case of SuSI, these forces in the end region may have been responsible for the movement of the coils due to the lack of banding and epoxy.

The design of the FRIB cryostat is progressing. The cryostat has been modified from the original VENUS cryostat to increase the cooling capacity at 4.2 K using a GM-JT cryocooler that has a cooling capacity of 5W. This cryocooler is also capable to condensate liquid helium. The design leaves open the possibility to add another one later on. In addition to the GM-JT cryocooler, two pulse tubes PT415 with a capacity of 1.5W of 4.2 K have been added. Pulse tubes require much less maintenance than a GM type cryocooler and several other projects at NSCL already use this type of cryocooler. Finally a single stage cryocooler AL330 with a large cooling capacity at 40K will be used to cool the cryostat shield and will be located close to the warm ends of the HTC leads. Heat load calculations have been done and demonstrate that this arrangement of cooler would be sufficient for the FRIB SC-ECR. The thermal shield in the lower part of the cryostat will be made of copper instead of Aluminum to improve the thermal conduction in this section which is far from the cryocoolers. To avoid that eddy currents generated during a quench along the copper surface would strain the shield, this latter will be made out of 2 sections separated by a small gap.

## SELECTION OF NBTI CONDUCTOR

Because of the success of the VENUS project it was natural to select the NbTi conductor based on the conductor originally used for the construction of the magnet. However the sextupole conductor of VENUS was made in 1998 and was a special order from the Finnish manufacturer OUTOKUMPO. Custom orders are nowadays difficult from manufacturer of superconducting wire and it was not possible to order a conductor identical to the one used in VENUS sextupole. Extensive discussions let to prioritize the most important properties of the Superconducting wire for an ECR ion source. Beside the consideration of the critical current, the Copper to Superconducting ratio is a very important parameter in the selection of the conductor for an ECR magnet. Although many projects such as SuSI or MS-ECRIS or RIKEN SC-ECR have chosen conductor with a small Cu:Sc ratio (~1.3-1.6), VENUS sextupole used Cu:Sc ratio of 3 and for the solenoids a ratio of 4. NbTi conductors with a low Copper content are normally preferred due to the higher margin they offer to the critical current by lowering the current density. However it is known that larger copper content helps improve the stability of the coils by taking the excess heat away during micro-movements of the coils caused by magnetic force. Similarly larger Residual Resistivity Ratio (RRR) is an indicator of the quality of the stabilizer and smaller filament size also improves the stability of the conductor by better distributing the heat generated within a filament.

Table 2 below summarizes the characteristics of the conductor selected for FRIB ECR.

Table 2: NbTi Conductor Properties Selected for FRIB SC-ECR

| | Solenoid | Sextupole |
|---|---|---|
| Solenoid Cu:Sc | 4:1 | 3:1 |
| RRR | 60-70 | >140 |
| Filament Size (um) | <100 | <50 |
| Cross section | Rectangular | Rectangular |
| Filament size | 1.57mm x 0.88mm | 0.9mm x 1.8mm |
| Critical Current (A) | 600 @6T | 680 @7T |

The sextupole for FRIB SC-ECR will operate nominally at about 75 % of the critical current.

## URANIUM BEAM DEVELOPMENT

Transport and acceleration of heavier beams such as Uranium represents one of the most difficult challenges for an accelerator such as FRIB. To reach the nominal beam power of 400 kW on target requires an initial beam current of more than 13 puA from the ion source coming in a charge state of at least U33+. Uranium beam measurements with the ECR ion source VENUS at LBNL had shown that about only half of the current required for FRIB could be achieved for the charge state U33+ and U34+ [8]. This situation was resolved early on in FRIB by designing the LEBT and the linac to transport and accelerate two charge states. For the beam measurements done with VENUS, a compound of URe2 was used in a resistive Ta oven which provided U vapour at temperature between 1800C to 2000C. Beyond 2000C a phase transition in the compound would separate the Uranium from the Rhenium and would make the crucible unusable which ultimately limited the amount of Uranium vapour available during these measurements. After the measurements, it was also observed that the crucible stems were damaged by the action of the Lorentz forces. Recently, new measurements with VENUS have been done using Uranium oxide (U02) loaded respectively into a W and Re crucible. Uranium Oxide is very stable even at temperature well above 2000C (melts around 2700C) but require a temperature above 2000C to reach a sufficient vapour pressure (therefore somewhat higher than URe2). The initial measurements using the tungsten oven weren't very successful and only provided at best about 100euA of U33+.The production of the vapour was also quite instable. Although one cannot rule out that chemical reaction between the tungsten and the sample may have hinder the production of the Uranium vapour,



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an important difference of the Tungsten and Rhenium is the relatively lower resistivity of Tungsten compare to Rhenium which led to couple significantly more power on the Tungsten crucible (up to 700W) to reach the production temperature.

With such power, the voltage of the power supply feeding the oven was fluctuating which may have been caused by poor contact between the crucible stems and the oven at high temperature. In the case of the Rhenium crucible, the production was very stable and responded very well to increase in the oven current. Figure 3 below shows the measured ion beam current for U33+ and U34+ function of the current in the oven with the Rhenium crucible.

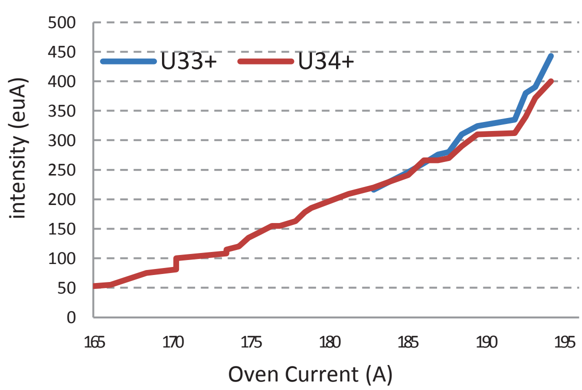

Figure 3: Uranium beam currents for the Rhenium crucible function of oven current

An important result for the FRIB project is that the maximum current reach for U33+ and U34+ exceeded 400euA. The charge state distribution obtained for Uranium is shown below in figure 4

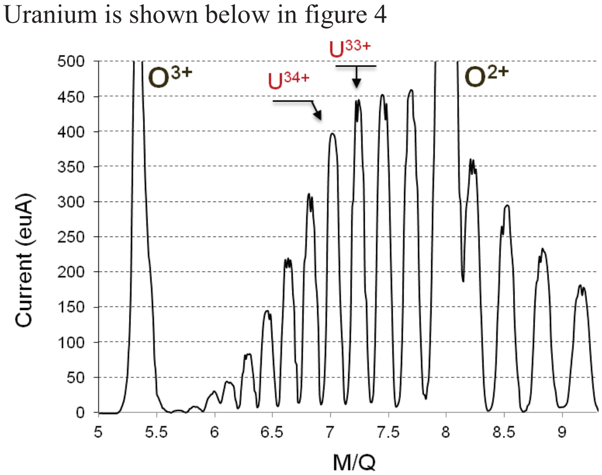

Figure 4: CSD of Uranium optimized for U33+ and U34+. Close to 450euA of U33+ was obtained. Power :1.8kW (18GHz) + 6.5kW (28 GHz). Drain current~9emA. Pext=4.8E-8 mbar.

The total injected power reached 8.3kW with 6.5kW coming from the 28 GHz gyrotron and the total extracted current was above 9emA. The VENUS LEBT line is not optimized to transport such a high current and the transmission measured by summing up the peaks of the CSD only reached about 55% of the drain current. One factor that limited the transmission of the beam was the extraction voltage of VENUS which was limited to 22kV. The high intensity (consistently above ~300euA) beam was maintained overall for about 10 hours. The power was not increased further by fear of damaging the ion source but the CSD was still very responsive to increase in microwave power or increase in the oven current when the CSD shown in figure 4 was obtained. It is likely that still better performance can be obtained be extraction at higher voltage and by coupling additional power.

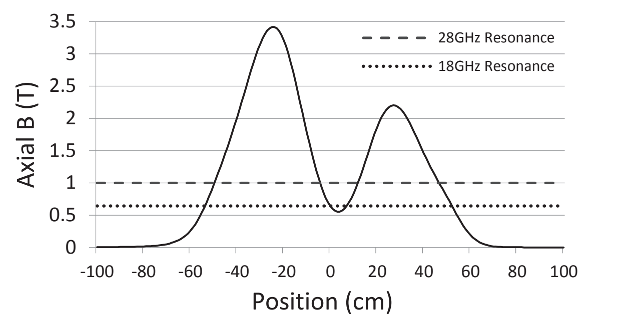

Figure 5: Axial magnetic field profile of VENUS used for the production of high intensity uranium beam.

The material consumption measured after the measurement was estimated to be over 9mg/hr. Finally the axial magnetic field profile used during the production of high intensity uranium is shown in figure 5 above.
The beam emittance of the uranium beam was measured for U 33+ and U 34+ and the result are summarized in table 3 below. In this case, the total extracted current was about 7.5emA.

Table 3: Measured Beam Emittance for U33+ and U34+ with VENUS

| Beam | Plan | Current (euA) | ε emittance - 1rms normalized | % of beam within 0.6 mm.mrad | % of beam within 0.9 mm.mrad |
|---|---|---|---|---|---|
| U33+ | H | 365 | 0.156 | 86 | 95 |
| U33+ | V | 365 | 0.112 | 95 | 99 |
| U34+ | H | 311 | 0.141 | 90 | 95 |
| U34+ | V | 311 | 0.112 | 95 | 99 |

Emittance requirement for beam injected into FRIB linac are set to 0.6 pi.mm.mrad for the transport of two charge states and 0.9 pi.mm.mrad for single charge state acceleration. For this last case, the table shows that close to 95 % of the beam fall inside the emittance requirement for acceleration of a single charge state and therefore at least for U33+ these new results show that almost enough intensity is available from VENUS in one charge state for U33+ to reach FRIB goal of 400kW on the production target. However such conclusion would not be exactly correct as other parameters have to be considered in general to define the level of beam available for the accelerator such as time spent tuning the ion source, or higher losses than expected or stability of the beam. More experience is needed to operate high frequency ECR ion

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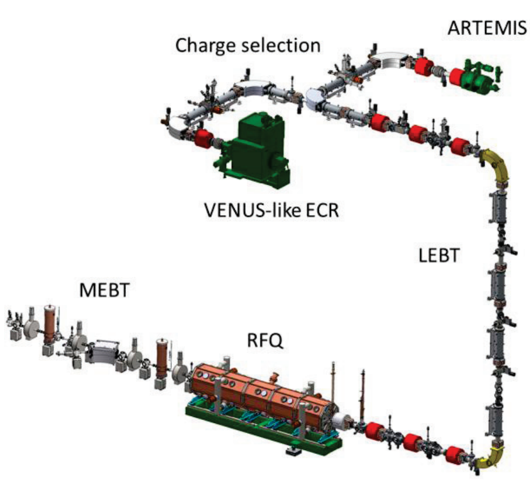
sources at high power to know what can be routinely achieved.

## LEBT DESIGN

As mentioned previously, the LEBT was designed to be achromatic to transport two charge states simultaneously. To reduce cost, most of the focusing in the LEBT is done through electrostatic elements including quadrupoles and two 90° dipoles for the vertical line transporting the beam into the tunnel. The beam halo is collimated by several apertures in the LEBT in a process similar to the collimation channel developed for SuSI. A chopper is used to vary the duty cycle to control the pulse length from several hundreds of ns to CW and the pulse frequency from 0 to 30 kHz. The machine protection system is implemented in the LEBT by switching off very fast the voltage of one of the 90° dipoles. Due to the length of the LEBT, the vacuum requirement is very low (5E-9 Torr) throughout the LEBT to minimize losses through charge exchange especially for heavy elements. At the ion source extraction as well as in the charge selecting section, it is expected that the vacuum will be much higher however. Finally, The FRIB RFQ is a 4-vane structure to accelerate single and two-charge state beams from 12 to 500 keV/u with an estimated transmission efficiency above 80%. A layout of the FRIB front end beamline is shown in figure 6 below. More details on the LEBT and RFQ can be found in [9]




## CONCLUSION

The design of the FRIB SC-ECR cold mass and cryostat are well advanced. The procurement of the NbTi conductor is being finalized and the conductor should be delivered at MSU in the spring 2013. Winding of the coils for the ion source will be done through an external vendor but the assembly and testing of the cold mass including the inflation of the bladders will take place at MSU and should be completed in 2014. The ion source with the cryostat is expected to be completed in 2016 and available for commissioning of FRIB in 2017. ARTEMIS-B will be first used for the accelerator in 2016.

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