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Metallic beam development for the Facility for Rare Isotope Beam[a)]

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The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) will accelerate a primary ion beam to energies beyond 200 MeV/u using a superconducting RF linac and will reach a maximum beam power of 400 kW on the fragmentation target. The beam intensity needed from the ECR ion source is expected to be between 0.4 and 0.5 emA for most medium mass to heavy mass elements. Adding to the challenge of reaching the required intensity, an expanded list of primary beams of interest has been established based on the production rate and the number of isotope beams that could be produced with FRIB. We report here on the development done for some of the beam in the list including mercury (natural), molybdenum (^{98}Mo), and selenium (^{82}Ser). © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4858095]

I. INTRODUCTION

The new rare isotope beams that will be available with the Facility for Rare Ion Beam (FRIB) will enable the nuclear physics community to make major advances in understanding the structure of nuclei, in nuclear astrophysics and will help test fundamental symmetries. To do so, a superconducting, heavy-ion, driver linac will accelerate a stable ion beam to an energy above 200 MeV/u at beam powers up to 400 kW on a production target. A large number of elements will be used for the primary beam ranging from oxygen to uranium.

During the commissioning of the accelerator, the Advanced Room TEMperature Ion Source (ARTEMIS) will be used to provide beam to the superconducting linac. ARTEMIS is a 14 GHz ion source based on the AECR-U from LBNL.[1] However, the capability of ARTEMIS to deliver high intensity beams is limited and the design of a high power ECR ion source operating at 28 GHz for use in FRIB is progressing.[2] After commissioning of the FRIB facility, the beam power delivered by the accelerator to the target will be gradually increased over the first five year of operation to 400 kW. During that time, the number of available stable beams will be increased from those available in the first year.

A list of key primary beams has been developed for FRIB based on the priorities defined by the nuclear physics community and some of the elements included in that list are shown in Table I. The elements present in the table are ranked using the number of secondary beams that can be generated at the target. The intensities required from the ECR ion source to reach the final beam power are also reported in the table along with the charge state selected from the ion source.

A significant effort to develop uranium beams has been done in recent years. Using uranium oxide (UO_2) heated with a resistive oven, VENUS (Versatile ECR ion source for NUclear Science) from LBNL was able to demonstrate over 440 eμA of U^{33+} and 400 eμA of U^{34+} which is sufficient to reach the required beam power of 400 kW even when considering single charge state acceleration.[2]

Published results for 40Ca and 48Ca beams from VENUS[3] and for 58Ni beams from SuSI[4] have demonstrated the capability of an ECR ion source to reach very high intensity for these elements. However, Table I also shows that many other beams are considered for the primary beam at FRIB for which very few results have been reported.

II. MERCURY BEAMS

The production of mercury beams for FRIB is particularly interesting for the nuclear physics community as it will provide access to a region of the nuclear chart that is so far largely unexplored especially on the neutron rich side. Surprisingly there has been very few reports on the development of mercury beams using ECR ion sources.[5] The production of mercury beams presents several challenges. First, mercury presents a health hazard due essentially to the risk of exposure to mercury vapor. Because of its high vapor pressure at room temperature (0.17 Pa[6]), mercury will evaporate, although very slowly, if left in an open container. At T = 323 K, the vapor pressure has increased by an order of magnitude, and would result in a corresponding increased evaporation rate. Therefore, precautions must be taken when handling mercury whether it is for storage, loading, or operation of the ion source as exposure to quantities as low as 0.1 mg/m^3 are considered harmful. Because of the high vapor pressure, mercury presents also a challenge to keep a good control on the amount of vapor fed to the ECR plasma. Finally, it is also important to limit the amount of mercury which can deposit in the plasma chamber because mercury reacts strongly with aluminum to form an amalgam which can alter the aluminum of the chamber.

For the results presented here, the ECR ion source ARTEMIS was used to produce the mercury beam and the setup used for the production of the mercury vapor is shown in Figure 1. The mercury was introduced axially through the

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TABLE I. Key FRIB beams ranked by the number of secondary beams generated at the target. Intensity requirements shown for the ion source are for a 400 kW beam on target. Charge states indicated with the symbol mean that the intensity will be met by accelerating two charge state through the linac.

Beam	Abundance (%)	Number of beams	Intensity from ECR (pμA/eμA)	Q
238U	99.30	1750	12.4/415	33 and 34
204Hg	6.90	308	16.4/484	29 and 30
82Se	8.70	156	34.3/412	>12
144Sm	3.10	139	17/416	24 and 25
58Ni	68.10	130	57.6/634	>11
176Yb	12.80	129	22.9/584	26 and 27
198Pt	7.20	122	17.6/519	29 and 30
48Ca	0.19	104	40.6/325	>8
106Cd	1.25	101	19.2/307	>16
92Mo	14.80	98	20.4/306	>15

injection flange and the flow of the vapor into the plasma chamber was precisely controlled using a variable leak valve. About 1 g of natural mercury was loaded into a small stainless steel chamber with a diameter of 6 mm. The connection between the leak valve and the chamber was made using stainless steel tubing and was made vacuum tight using compression fittings. A cartridge heater was installed close the mercury chamber to provide a way to increase the amount of vapor that flows to the ion source plasma chamber. The temperature of the chamber could be read using a thermocouple mounted on the side of the stainless steel chamber. A manifold, consisting of two bellows valves, with one to pump down the residual gas after loading and a second one to isolate the mercury chamber from the variable leak valve was added. Before pumping down and during any handling of the set-up, the mercury chamber was cooled down using liquid nitrogen to a temperature of $-60\,^{\circ}$C to $-80\,^{\circ}$C to ensure that mercury was solid. The ion source drain current throughout the measurements reported here was about 1 emA. A strong pumping effect was observed when the mercury was introduced in the chamber and oxygen was added as support gas to stabilize the plasma.

For the initial tuning the charge state distribution was optimized for Q = 22+/23+. About 20 eμA microamperes were obtained for the 22+ as shown in the charge state distribution (CSD) spectra shown in Figure 2 (top) and about 4 eμA for Q = 30+ (bottom). For Q = 27+, the maximum current obtained was about 12 eμA. The current read was the sum of all mercury isotopes present in the beam. During these measurements, the transmission to the faraday cup was low (between 10% and 20%). This low transmission was caused by both the focusing element installed after the extraction of ARTEMIS and also the use of a small aperture before the faraday cup to improve the resolution of the CSD.

Tuning of the mercury beam was very straightforward (similar to a gas) and the distribution could be shifted easily from low to high charge states using the variable leak valve. Overall mercury was run with ARTEMIS over 150 h. Once the leak valve was closed, the level of mercury dropped within minutes from about 8 eμA for Hg^{27+} to a couple of

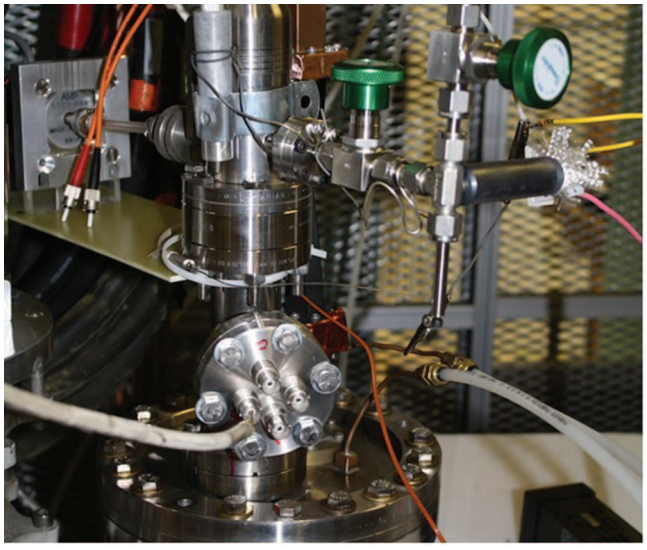

FIG. 1. Setup used for development of mercury beams. The stainless steel chamber used to hold the mercury is shown (center right) as well as the variable leak valve (center left).

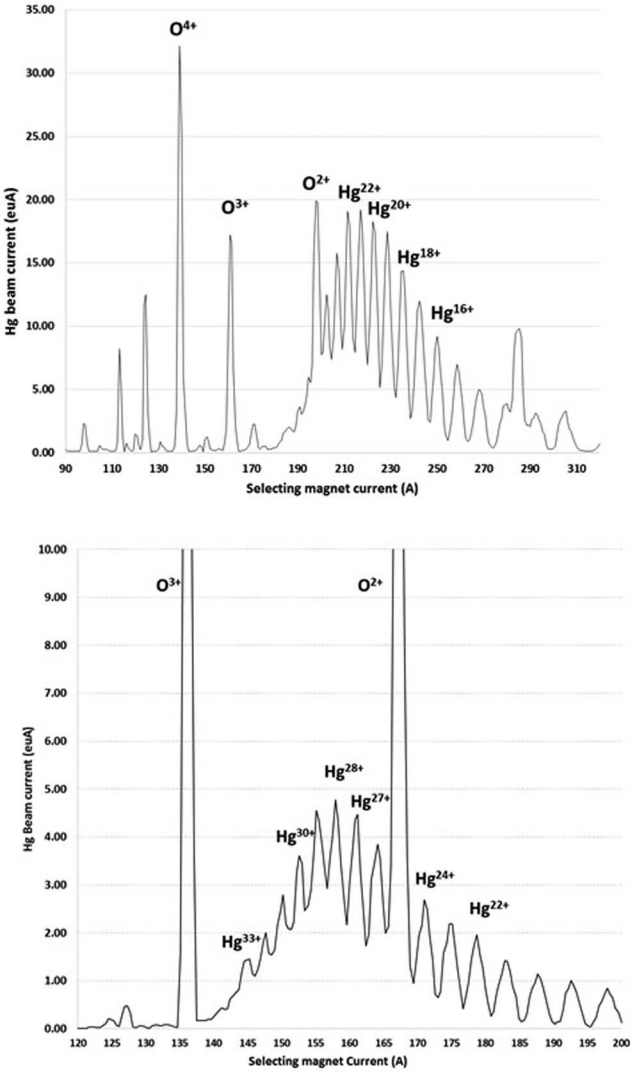

FIG. 2. Charge state distribution of mercury beams optimized for Q = 22+ (top) and Q = 30+ (bottom).

hundreds of nano-amperes and within hours to a few tens of nano-amperes which would indicate a limited contamination of the chamber.

III. MOLYBDENUM DEVELOPMENT

Molybdenum is among the beam of interest for FRIB. Experiments using ^{92}Mo are also planned for the Coupled Cyclotron Facility (CCF). Beams for refractory elements are in general very difficult to produce due to the high temperature required to produce a significant amount of vapor. However, molybdenum trioxide (MoO_3) has a characteristic vapor pressure in the desired range of 1 mTorr to 10 mTorr between the temperatures of 850 K and 890 K. For the measurements presented here, ^{98}Mo was used to lower the cost and loaded into SuSI resistive oven. The oven was positioned axially in the SUSI ion source. The distribution was optimized for Mo^{15+} and Mo^{16+} and then later on Mo^{20+}. SuSI operates at 18 GHz and up to 2.2 kW of microwave power was injected into the ion source. A spectrum obtained for Mo^{16+} is shown in Figure 3. Oxygen was used as support gas.

About 150 eμA of Mo^{16+} was obtained but resulted in a very high consumption rate of the material of approximately 11 mg/h. The rapid change of the molybdenum trioxide vapor pressure with temperature made it difficult to control the flow of vapor into the plasma. We also observed that the vapor of molybdenum trioxide condensates very easily as we found that the crucible was plugged with approximately 90 mg of MoO_3 after the run. At a more moderate current (50 eμA of $^{98}Mo^{15+}$) the oven did not plug up and stable operations were achieved until the crucible was empty (~18 h). The results are shown in Table II. Overall, the efficiencies were quite low. While these first results are promising, further optimization of the oven and oven geometry for injecting the vapor into the source will be necessary to achieve the required FRIB intensities.

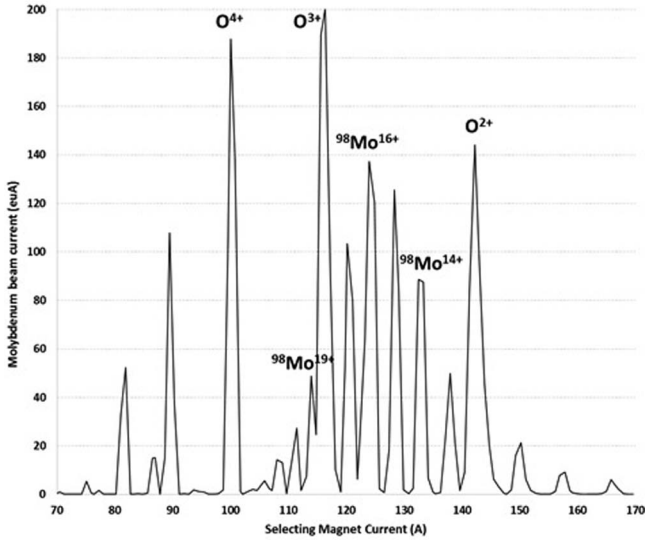

FIG. 3. Molybdenum beam optimized for Mo^{16+} produced using molybdenum trioxide.

TABLE II. Efficiencies for molybdenum 15+ and 20+.

Isotope	Q	Intensity (eμA)	Duration (h)	Consumption (mg/h)	Efficiency (%)
98Mo	16	150	<12	11	
98Mo	15	50	18	5.76	0.8
98Mo	20	63	18	5.17	0.15

IV. SELENIUM DEVELOPMENT

Selenium beams have been used extensively for CCF for the past three years with over 2500 h of running operation for this element. Typical current extracted from the ion source ranges from 5 to 10 eμA for $^{82}Se^{12+}$. Selenium is introduced radially into the ion source. The main oven body is positioned as far out as possible to decouple the oven from the plasma when producing the selenium vapor. This is done using a heated nozzle. However, because the operating temperature for producing the selenium vapor is relatively low (around 250 °C), it is very difficult to keep a good control on the vapor production. Operating selenium usually results in a large contamination of the plasma chamber and requires a thorough clean-up after completion of the run. Recent tests for Selenium done with SuSI achieved 50 eμA for Se^{14+} for only 300 W of injected power using the same oven technique. However, the output was irresponsive to both the microwave power and the oven indicating that the plasma chamber was already largely polluted by selenium. Although current intensity levels are sufficient for CCF, the development of high intensity selenium beams for FRIB will require a different approach to introduce the vapor into the plasma chamber.

V. OUTLOOK

Metallic beam development is ongoing at MSU for the need of the nuclear science program and also the future need of the FRIB project. Development of mercury beam reported here, worked very well and did not result in any significant contamination. The setup used to introduce the mercury vapor into the ion source could potentially be used for beams where the production of the vapor requires very low temperature such as cadmium, selenium, or sulfur. We also investigated the development of lanthanides beam (samarium, ytterbium, and dysprosium) which are also of interest for FRIB and CCF. However, we were unable to produce the vapor for any of the three elements mentioned above using our high temperature oven (up to 1700 °C) because the materials used were in an oxide form instead of metal. Reduction of rare earth elements is known[7] and we will perform such procedure in the near future to continue development for these beams.

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