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FEBIAD ION SOURCE DEVELOPMENT AT TRIUMF-ISAC

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Abstract

The ISOL facility TRIUMF-ISAC utilizes a number of different ion sources to produce rare isotope beams. Most isotopes are ionized using surface or resonant laser ionization, but these techniques are prohibitively inefficient for species with high ionization energies, such as noble gases and molecules. For these cases, the forced electron beam induced arc discharge (FEBIAD) ion source can be used. The FEBIAD uses a hot cathode to produce electrons, which are accelerated through a potential (< 200 V) into the anode. Isotopes entering the resulting plasma undergo impact ionization and are extracted. Efforts are underway to better understand the physics and operation of the FEBIAD, using both theory and experiment. Recent measurements and simulations on the ISAC FEBIAD will be reported here.

INTRODUCTION

The Isotope Separator and Accelerator (ISAC) facility [1] is located at TRIUMF in Vancouver, Canada. ISAC utilizes the isotope separation online (ISOL) technique to deliver rare isotope beams (RIB) to low- and high-energy experiments. A variety of ion sources are required to facilitate this process [2]: the surface ion source (SIS), the resonant ionization laser ion source (RILIS) [3], the ion guide laser ion source (IG-LIS) [4], and the FEBIAD. The large majority of RIB delivered at ISAC use the SIS/RILIS sources, while the IG-LIS and FEBIAD are utilized for more specific cases. In particular, the FEBIAD is used for species with large (> 8 eV) ionization potentials.

While the SIS and its laser-related variants are well understood, there is considerable effort underway to better understand the physics and operation of the FEBIAD (see for example [5], this conference). A series of simulations have been performed to determine how the various ion source parameters impact the ionization and extraction of the ion beam. At the same time, measurements are being performed to benchmark these theoretical results. This proceeding will discuss some recent experiments done using the FEBIAD source at ISAC, including measurements of the source efficiency and extracted beam emittance, which will be compared to simulation results. In addition, the commissioning results of a FEBIAD variant with a cold transfer line will be discussed and compared to the typical FEBIAD geometry.

FEBIAD OPERATION

Figure 1 shows a cross-sectional view of the ISAC FEBIAD. During normal operation, 480 MeV protons (with a current up to 100 μA) impinge on the target (a), which is typically comprised of refractory metals (e.g. Ta) or carbides (e.g. SiC). Nuclides produced in the target diffuse into the transfer line (b) and into the plasma chamber (i.e. anode) (d), which forms the ionization volume. At the same time, the transfer line is heated to produce electrons, which are accelerated into the anode using a potential of 100 – 200 V. Neutral species are ionized via electron impact, and are then extracted out of the source through the plasma (e) and extraction (f) electrodes. A coil (c) is used to generate a magnetic field (≈ 100 G) to provide confinement for the electrons.

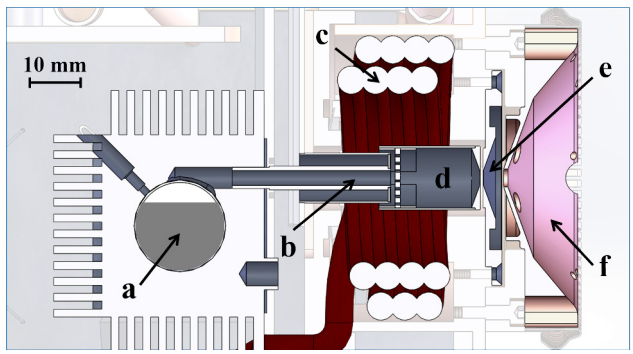

Figure 1: Cross-sectional view of the ISAC FEBIAD. (a) Target, (b) transfer line, (c) coil, (d) plasma chamber (i.e. anode), (e) plasma electrode, (f) extraction electrode.

MEASUREMENTS AND DISCUSSION

Cold Transfer Line Commissioning

The presence of isobaric contaminants is a significant issue for RIB delivery. The ISAC mass separator resolution ($m/\Delta m \approx 2000$) is insufficient to resolve most isobars. This is particularly problematic in the mass ranges corresponding to alkali contaminants such as Na, Rb, and Cs, for which the yields can be many orders of magnitude greater than the isotope of interest. For the SIS and RILIS there is little that can be done to mitigate this. In cases where the nuclide of interest has a laser ionization scheme, the IG-LIS can be used to greatly reduce the contaminant level. An electrode inside the source is biased to repel surface-ionized species, and neutral atoms that diffuse through are then laser ionized. The IG-LIS has been used to reduce Na isobars by up to six orders of magnitude [4].

As this technique can not be implemented in the FEBIAD, a cold transfer line (CTL) can be used instead. In the standard FEBIAD (Fig. 1) the transfer line is a straight tube connecting the target to the anode, which is heated to $T \approx 2000\,^{\circ}$C. In the FEBIAD-CTL, part of the transfer line is in thermal contact with the target heat shield. This cooler region ($T \approx 200\,^{\circ}$C) acts as a condenser for non-volatile species, while the diffusion of more volatile species should remain relatively unaffected.

A revised prototype FEBIAD-CTL was tested in 2013, and then commissioned online in 2017. The geometry is

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similar to the source utilized at ISOLDE, where both cold- and warm-temperature transfer line variants have been employed [6]. The results of FEBIAD-CTL yield measurements are plotted in Fig. 2, as well as results measured previously using the standard FEBIAD. There was a significant decrease in the yield of F and CO (i.e. $^{12}C^{14}O$) by up to two orders of magnitude. At the same time, the yields of He and Ne isotopes were unaffected, within the uncertainty of target-to-target fluctuations (and factoring in proton current). The only exception is ^{25}Ne, where the FEBIAD-CTL yield was two orders of magnitude larger. However, this measurement is clearly an anomaly, as the other values fit much better with the general trend. There was no previous FEBIAD measurement for ^{26}Ne.

The $A = 24$ isobars can be used to estimate CTL suppression. For example, the ISAC mass separator cannot resolve ^{24}Ne and ^{24}Na, so both are delivered simultaneously. For the target from which the ^{24}Ne yield was measured (using the standard FEBIAD), the ^{24}Na yield was 2–3 orders of magnitude larger than that of the Ne. However, for the FEBIAD-CTL target there was no sign of the ^{24}Na, within the statistics of the measurement. This indicates a suppression of Na by several orders of magnitude.

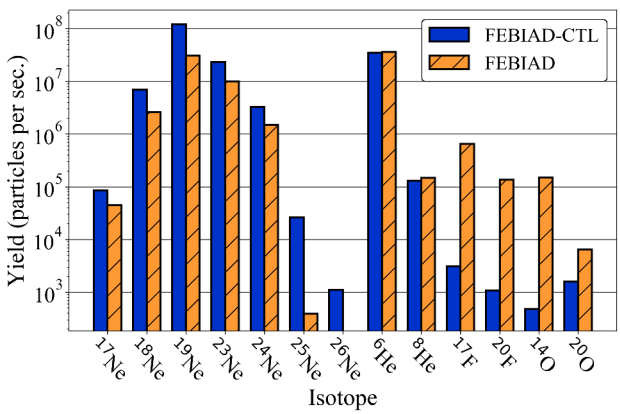

Figure 2: Yield comparison for FEBIAD (SiC target, proton current = 50–75 μA) and FEBIAD-CTL (SiC target, proton current = 65 μA) sources.

The total efficiency combines the efficiency of diffusion out of the target and through the transfer line, as well as the ionization, extraction, and beam transport efficiencies. In the following discussion, the last three will be collectively referred to as the source efficiency. The total efficiency can be estimated by taking the ratio of the measured yield to the simulated in-target production yield. (The simulations were performed using the Geant4-INCL++ code.) The total efficiency for the FEBIAD and FEBIAD-CTL are plotted in Fig. 3 as a function of the Ne isotope half-life $t_{1/2}$. For both sources, the efficiency increases slowly up to $t_{1/2} \sim 10$ s, before increasing sharply. This confirms that the release of the volatile Ne isotopes from the source was unaffected by the increased length and complexity of the CTL. However, it is not clear why the efficiency was so low at relatively long half-lives, where the release from the target should not be diffusion-limited. These effects will be further investigated in an upcoming FEBIAD-CTL run.

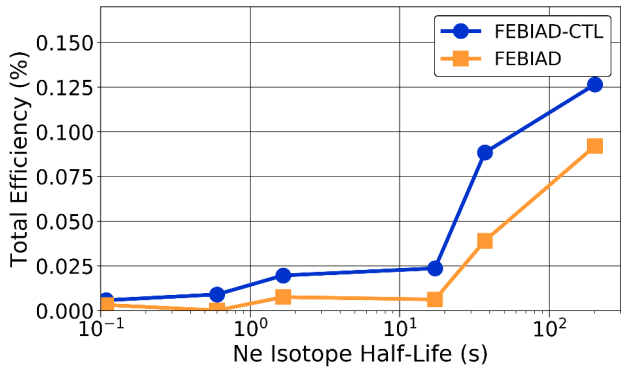

Figure 3: Total efficiency as a function of Ne isotope half-life for FEBIAD and FEBIAD-CTL sources.

Source Efficiency

The source efficiency has a direct impact on the yield of extracted nuclides. However, it can be a difficult quantity to estimate, as it has to be separated from efficiencies related to the diffusion of nuclides out of the target and through the transfer line. For the FEBIAD, this can be accomplished by injecting gas directly into the source, bypassing the target altogether. The source efficiency is then a function of source parameters, including the electron current density, electron energy (which factors into the electron impact ionization cross sections), and magnetic field. It also depends on the extraction electrode potential, which impacts both the ion extraction from the plasma, as well as beam transport (in the form of the beam emittance).

The ISAC target stations are fitted with calibrated leak sources, which can be used to inject gaseous species such as Ne, Ar, Kr, and CF_4. For a given isotope, the difference in beam intensity with the gas valve open and closed can be measured. The ratio of this difference with the total injected beam current gives the source efficiency. Table 1 lists preliminary measurements of the source efficiencies for stable Ne and Ar (from a FEBIAD-CTL). Although the efficiencies are both low, the Ne efficiency is comparable to the value obtained at ISOLDE [7] using the MK7 FEBIAD variant (which also employs a cold transfer line), while the Ar value is a factor of three smaller.

To calculate the efficiency, it was assumed that all of the gas leaving the leak arrived at the source. This is likely not valid, as the interconnecting gas line is long ($\approx$ 20 m) and contains possible leak points where the line enters the target/source region. In addition, the injected beam current was calculated using the quoted leak rate; however, the actual rate will decrease over time. It is difficult to quantify the effect of these assumptions, but since both will lead to an overestimate of the injected current (and therefore an underestimate of the conversion efficiency), the numbers quoted in the table can be considered lower limits.

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Table 1: Measured FEBIAD source efficiencies. See text for discussion.

Isotope	Source Efficiency (%)	
	ISAC	ISOLDE MK7 [7]
^{20}Ne	0.3	0.36
^{40}Ar	0.6	2.0

Beam Emittance

The emittance of ion beams at ISAC is measured using an Allison-style rig [8] located at the image plane of the mass separator. The device can be rotated to measure the horizontal or vertical emittance. Figure 4 shows a typical horizontal emittance plot from the FEBIAD source (beam energy = 30.0 keV, extraction electrode = 1.6 kV). The ellipse representing the 4rms emittance is also shown, with $4\epsilon_{\mathrm{rms}} = 33.5\ \mu$m. The scan was performed with all beamline slits fully open to permit the full beam to be transported. Normally, the object and image slits are set to a width of 0.8 mm; in this case, the measured emittance was 14.8 μm. For comparison, the typical beam emittance from the SIS is 5–10 μm. It is not yet clear why the FEBIAD emittance is so much larger than that from the SIS, but the properties of the plasma will certainly impact the extraction of ions, as well as the emittance of the resulting beam.

The FEBIAD emittance was simulated using the IGUN [9] software. The IGUN code calculates the trajectories of extracted ions in a self-consistent fashion, by modeling the position and shape of the emission surface (i.e. plasma meniscus). A series of extraction electrode (EE) voltages were input and the resulting $4\epsilon_{\mathrm{rms}}$ (for the horizontal direction) is plotted in Fig. 5. The measured emittance over the same voltage range is plotted for comparison. For the experimental data, the uncertainty is analysis-based, accounting for possible removal of beam data during the background subtraction. The uncertainty in the simulated values was estimated from the convergence of the source current while varying the number of orbit iterations. While the simulated curve shows some dependence on the EE voltage (particularly when $V_{\mathrm{EE}} < 2$ kV), the measured values are comparatively constant over the entire voltage range. The measured emittance is also systematically larger than the simulated values, by a factor of 2–3. The difference between experiment and simulation is likely due to a discrepancy between the plasma parameters input into IGUN (including the plasma density and the electron/ion temperatures) and the actual conditions inside the source. The plasma properties cannot be directly measured; values were estimated from the electron current entering the anode, which itself is only measured approximately. Computational efforts are underway to try and reconcile these differences.

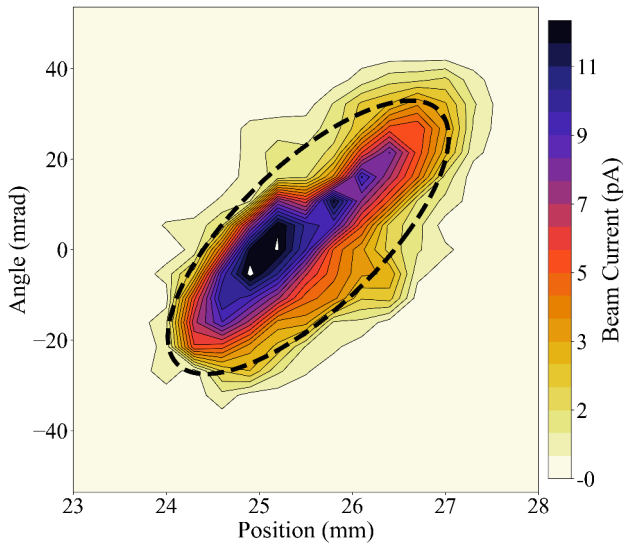

Figure 4: Horizontal emittance scan (beam energy = 30.0 keV, extraction electrode = 1.6 kV). Ellipse represents 4rms emittance: $4\epsilon_{\mathrm{rms}} = 33.5\ \mu$m, $2x_{\mathrm{rms}} = 1.5$ mm, $2x'_{\mathrm{rms}} = 30.2$ mrad.

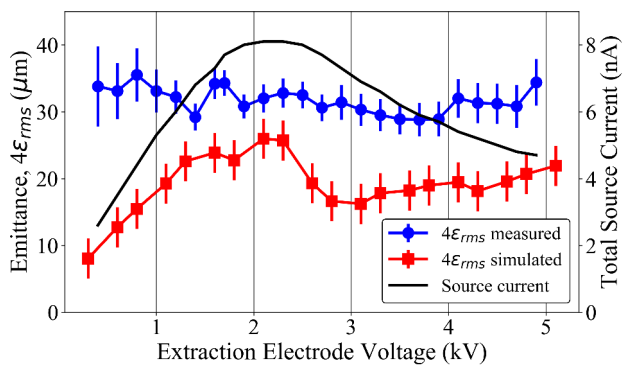

Figure 5: Measured and simulated 4rms emittance of beam extracted from the FEBIAD for different extraction electrode voltages. The total measured extracted ion current is also shown.

CONCLUSION

A series of measurements and simulations have been performed to investigate and characterize the performance of FEBIAD ion sources at TRIUMF-ISAC. The source efficiency was measured, and while the values are low, they are comparable to the numbers obtained from a similar FEBIAD source used at ISOLDE. In addition, the beam emittance has been measured for a range of extraction electrode values and compared to simulations. The discrepancy in the results requires further investigation, both experimental and computational. Finally, a cold transfer line FEBIAD, used for contaminant suppression, has been successfully commissioned and is performing as expected.

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