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Anomalous ionization regime for singly charged ^{40}Ar in a Radioactive Ion Source

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Motivation

TRIUMF utilizes the Isotope Separation On-Line (ISOL) [1] method to produce Radioactive Ion Beams (RIBs) at the Isotope Separation and Accelerator (ISAC) facility [2] (fig. 1).
The Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source [3] is typically used for noble gases, molecular beams and halogens, and is a baseline ion source for TRIUMF's new ISOL facility ARIEL (Advanced Rare IsotopE Laboratory) [4].
The ISAC-FEBIAD [5] (fig. 2) shows offline ionization efficiencies<1% for ^{40}Ar+, but up to 25% could be reached [6,7].
Towards increased efficiency, a combined numerical and experimental campaign takes place to identify the processes that improve the FEBIAD performance.

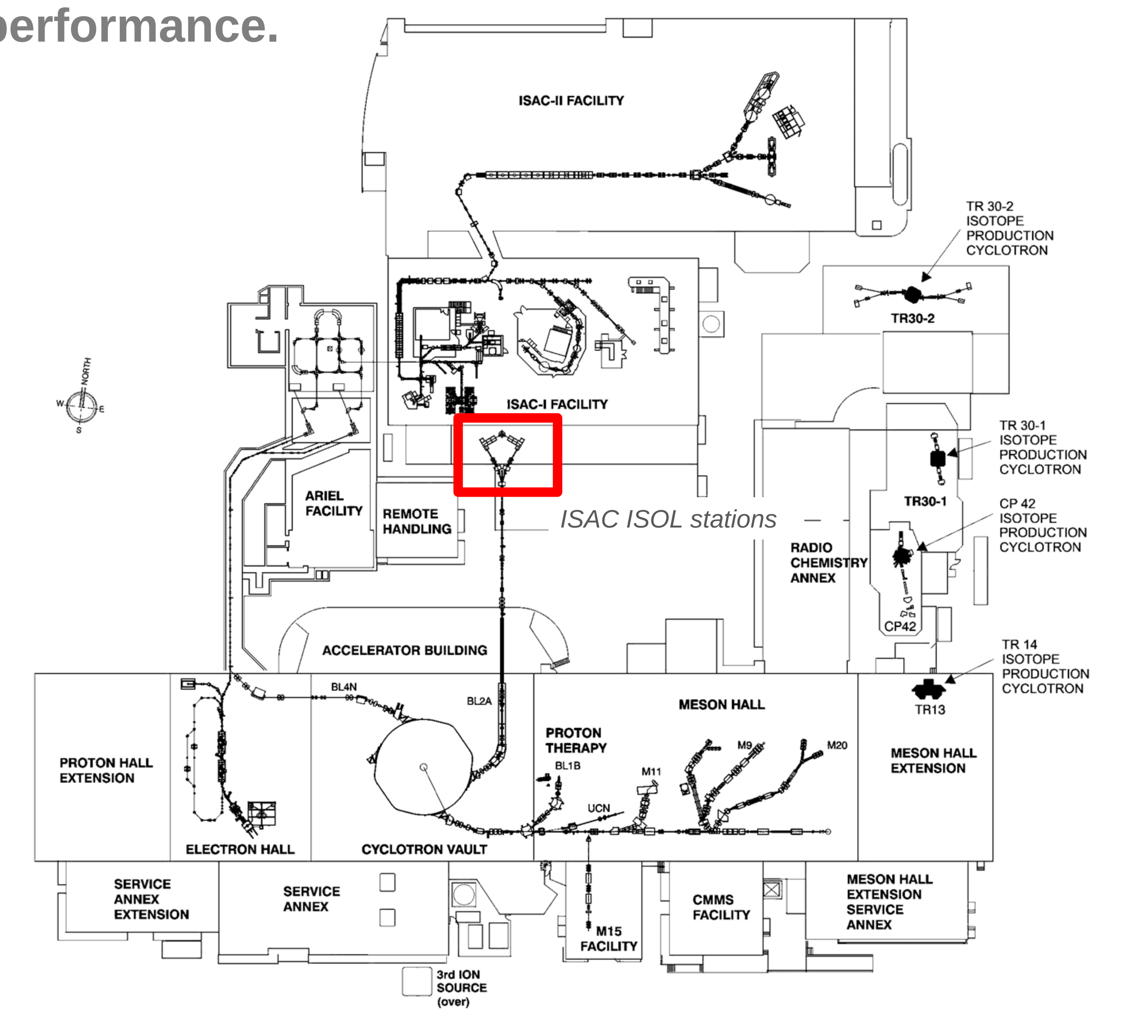

Fig 1. TRIUMF accelerator network. The highlighted region shows the current ISOL complex where the RIBs are produced with a driver beam impinging on a thick target to create nuclear reaction products that are ionized and extracted by a high voltage difference and sent to the experimental halls.

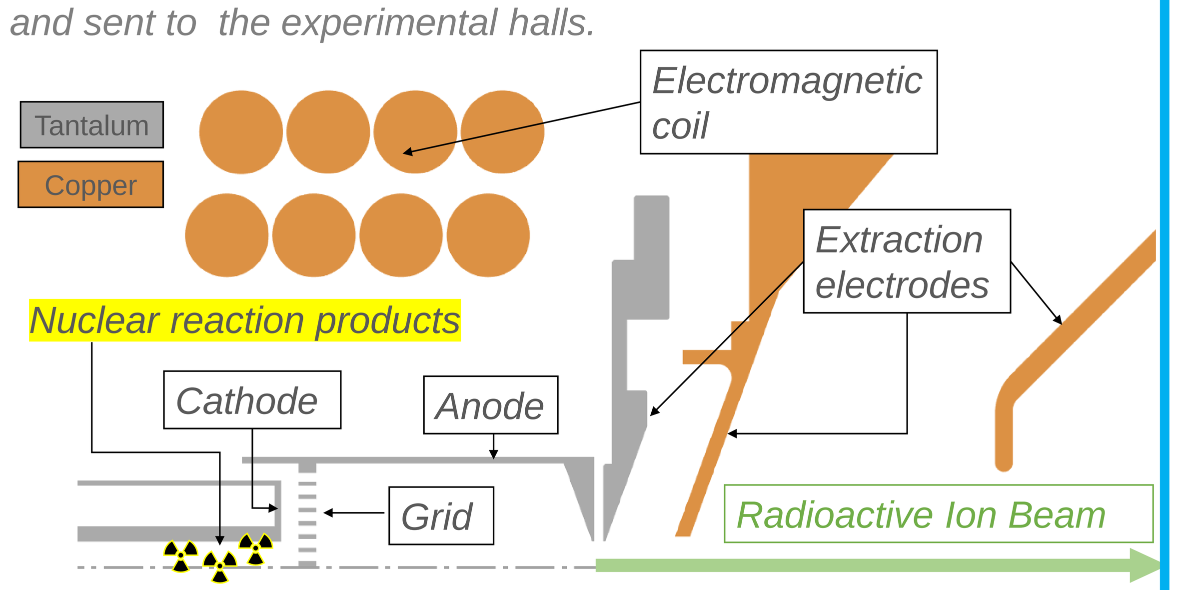

Fig 2. Axially-symmetric cross-section of the ISAC-FEBIAD ion source to produce RIBs with the ISOL method. A hot hollow cathode [8] generates electrons that are accelerated via a grid into an anode volume to cause electron impact ionization. A tunable electromagnetic coil provides electron confinement.

Methods

A multiparameter scanning algorithm was developed to automatically vary cathode heating current , coil current, and anode voltage. The algorithm recorded simultaneously the ion current on a faraday cup (fig. 3) and the electron current sunk into the anode power supply.
To determine the ionization efficiency a known argon calibrated leak was installed on the ion source unit and the efficiency was computed as the ratio between ions extracted over the neutrals entering the system.
Vertical emittance for selected cases were measured with an Allison type meter [9] from which the 90% intensity emittance was computed.
Complementary to the experiments, a comprehensive simulation package was developed [10] with COMSOL Multiphysics [11] to gain insight on the FEBIAD performance.

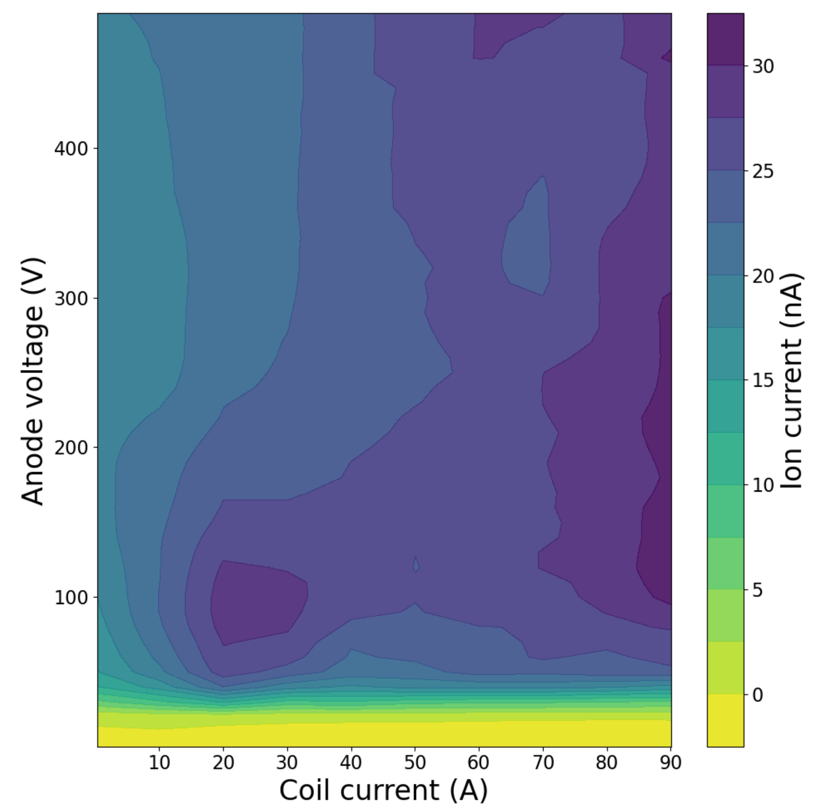

Fig 3. Ion current contour plot as a function of coil current and anode voltage at a fixed cathode heating current.

Results II

In a second FEBIAD unit, the onset of the anomalous regime matches with a geometry deformation of the grid.
Given the identical deformation in both sources it is believed that sharp points and a reduced cathode-anode distance causes increased localized electric fields.
The results suggest that a thermally robust grid with features that enhance the electric field at the center could improve the ionization efficiency.

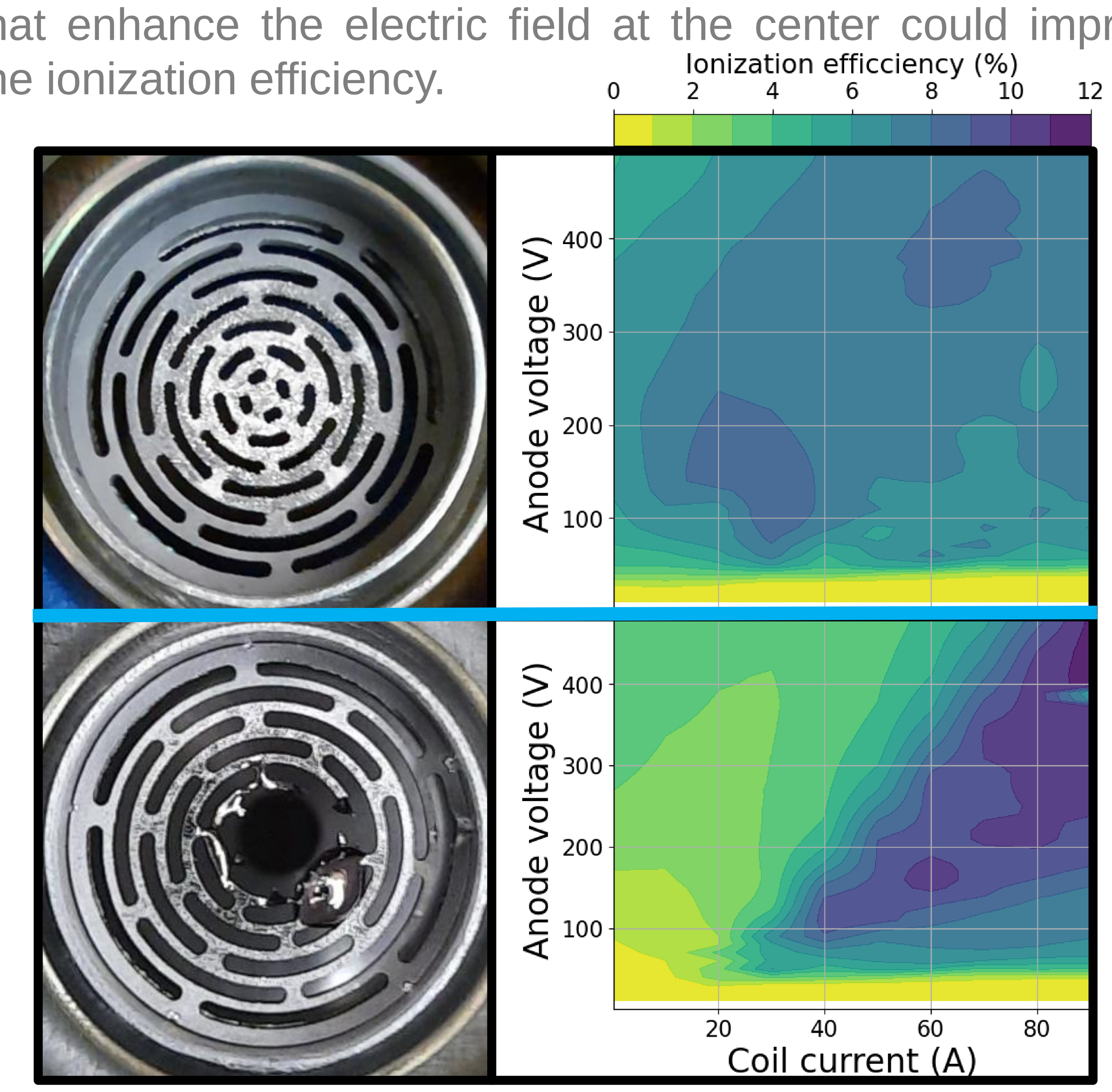

Fig 5. Top: Anode grid geometry and efficiency contour plot with a maximum efficiency centered at ≈30 A and ≈150 V. Bottom: Deformed grid and contour plot. The grid geometry clearly affects the ionization efficiency and the overall effect of the electromagnet coil.

Simulations

The measured electron current is used for particle tracking and power deposition simulations. The power is coupled to thermal simulations and indicate that at least half of the electron current must come from the inner hot hollow cathode.
Under this condition, the simulations show that the center of the grid rises above 3000 °C (fig. 6).

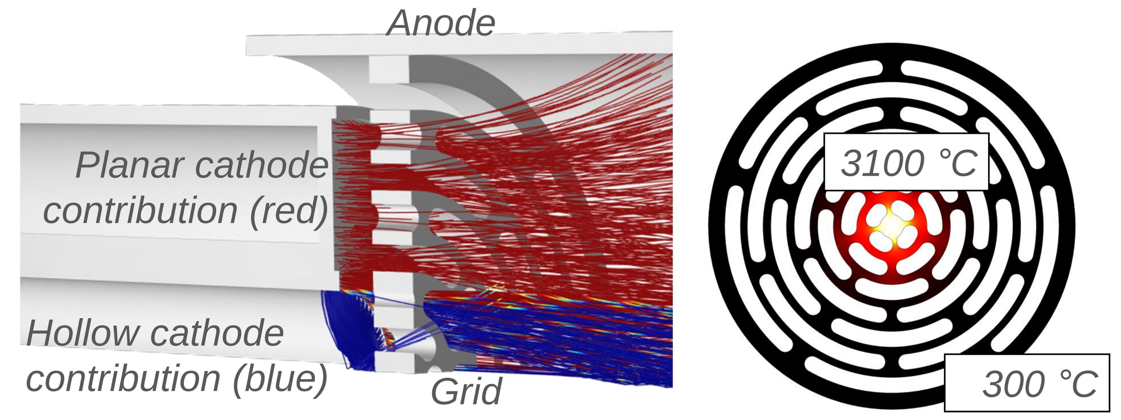

Fig 6. Left: Electron particle tracking simulation to compute power deposition with a two-part contribution, namely from planar cathode and from hollow cathode. Right: Anode grid temperature profile obtained from simulations showing a maximum temperature of 3100°C that explains the thermal failure observed.

Outlook

The electron particle tracking is not only used to account for the grid reliability but also to estimate the ionization rate inside the anode volume [10].
By combining the increased data obtained and the advance simulation package, TRIUMF is paving the way for more reliable and efficient radioactive ion sources.

Results I

A ^{40}Ar+ ionization efficiency of 10% is achieved by increasing the cathode heating current from the nominal 290 A to 330 A. The current difference corresponds to a cathode temperature change from ≈1700 °C to ≈1900 °C.
Below ≈1900 °C and 200 V, the electron current is described either by the Space Charge Limited (SCL) regime [12] or the Thermal Limited (TL) regime [13]. However, above 1900 °C a customized fitting routing using both SCL and TL cannot describe the electron current even if the material properties are widely varied (fig. 4).
The anomalously higher electron current above 1900 °C causes the ionization efficiency to triple at anode voltages > 350 V.
Finally, the 90% intensity emittance ranges between 8-12 µm and these values are compatible with the transport system.

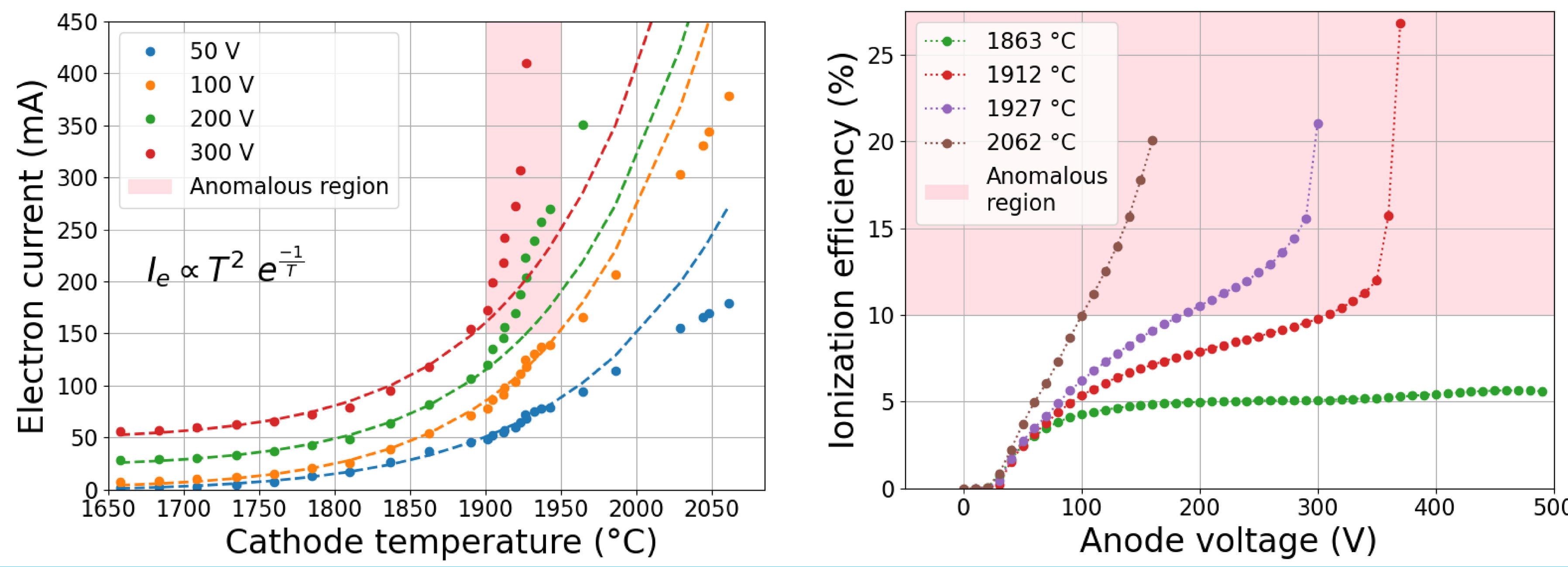

Fig 4. Left: Electron current measured as a function of temperature for various anode voltages. Dotted lines indicate the best fit by using the SCL and TL formulas. A sharp increase is observed and cannot be captured by the equations.
Right: Ionization efficiency as a function of voltage for some cathode temperatures. The anomalous regime corresponds to the sharp increase in efficiency.

Conclusion

- Increased localized electric fields in front of the hottest part of the cathode triggers the anomalous ionization regime.
- The grid geometry has a large impact on the optimum ion current, however it's prone to increased heating which ultimately leads to thermal failure.
- The simulations developed for the nominal geometry match the results observed and can be used to reliably predict the robustness and efficiency of new designs.

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