Reimagining FEBIAD Ion Sources

From Design Innovation to Performance Optimization

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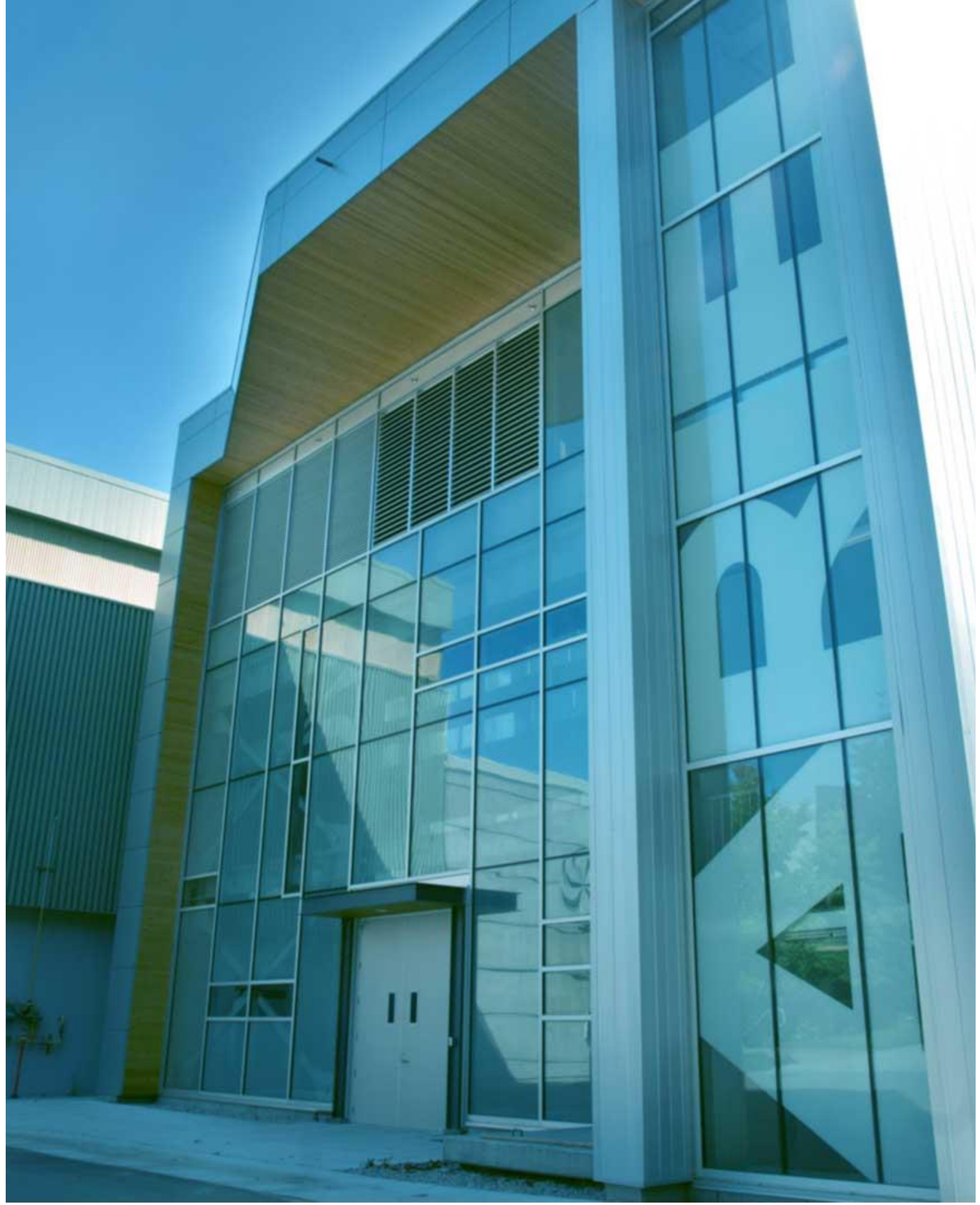


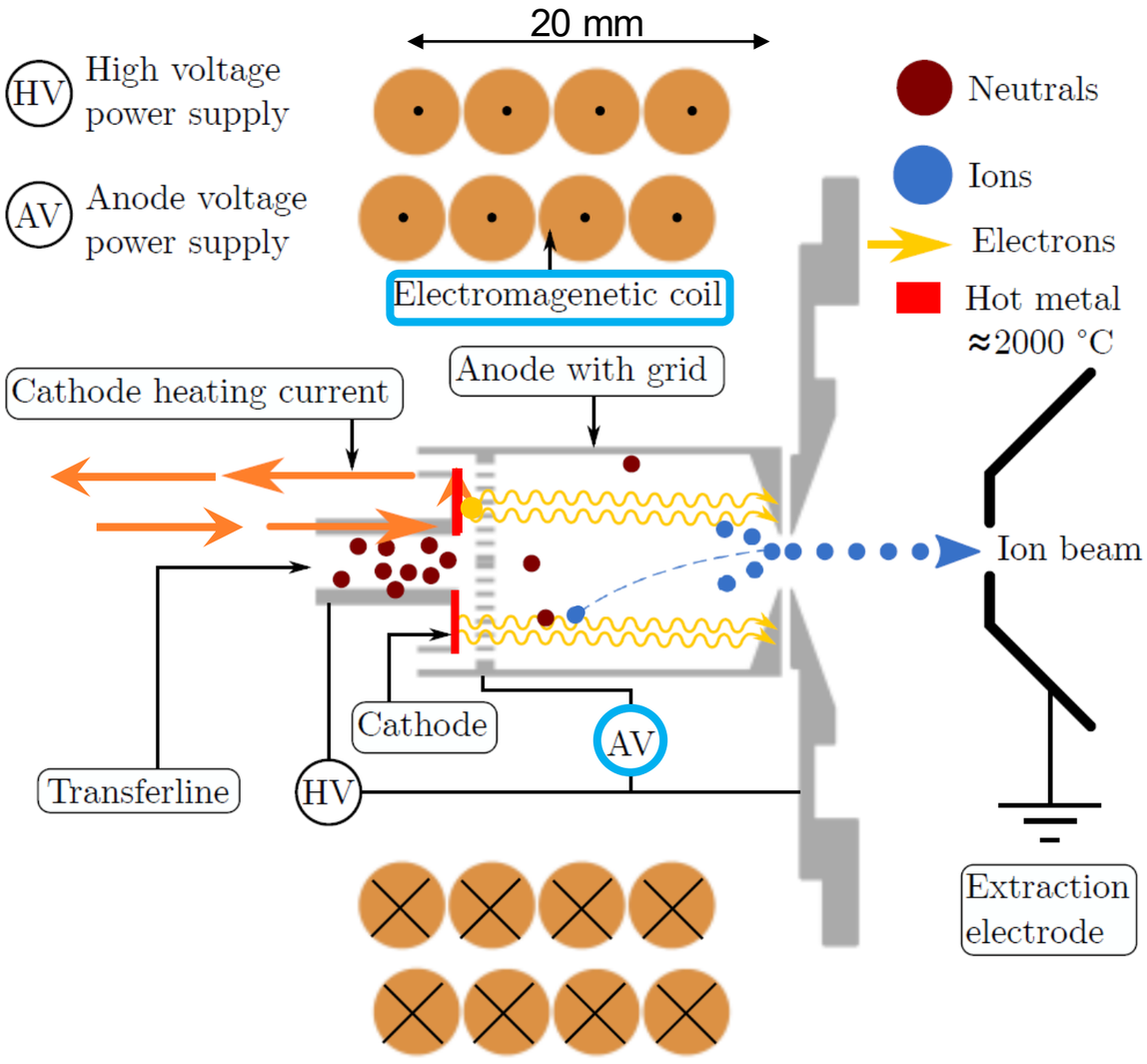
Discovery, accelerated

Outline

- Introduction
- Part I: Numerical Ionization Model and Validation
- Part II: Experimental Results
- Part III: Outlook for Radioactive Ion Source at TRIUMF
- Conclusions

Introduction

The Forced Electron Beam Induced *Arc Discharge* ion source



The FEBIAD ion source is typically used for noble gases*, halogens, and molecules.

- Hot cathode emits electrons.
- Electrons pulled into the anode volume.
- Magnetic field confines the electrons.
- Electron impact ionization.

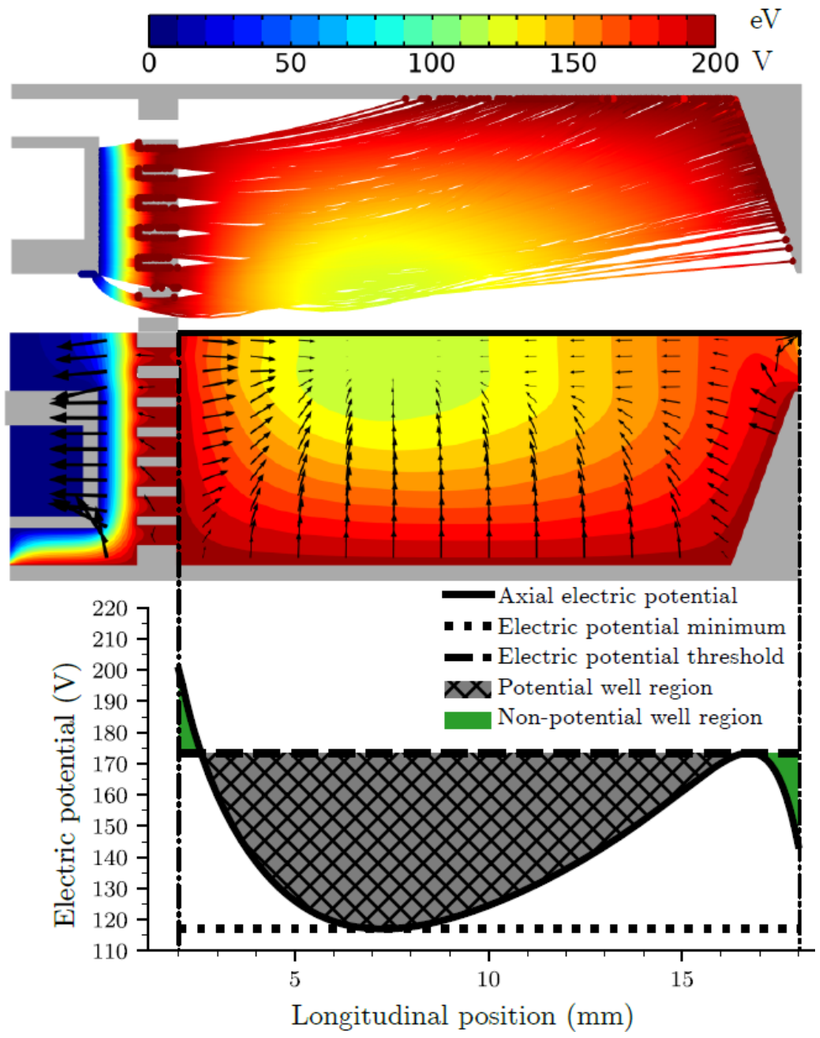
Multidimensional parameter space available for operation.

*Only source available for the high ionization potentials

Part I: Numerical Ionization Model and Validation for the FEBIAD Ion Source

With COMSOL Multiphysics ©

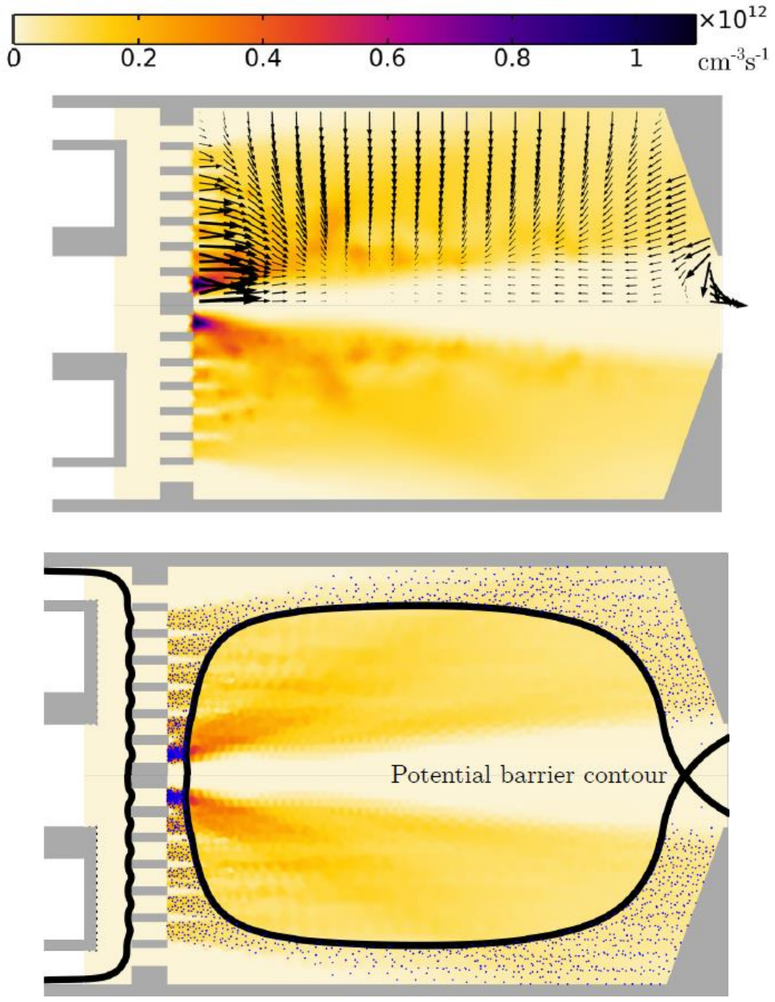
Electron transport simulations set the stage for the ionization model



- The electric field magnitude is proportional to the size of the black arrows which indicate that the highest electric field occurs close to both sides of the grid.
- The lower line plot shows the axial electric potential. For an applied voltage of 200 V, coil current of 30 A and electron current of 150 mA.

10.1016/j.nimb.2019.04.078

Ionization map: Convoluting molecular flow simulations, electron trajectories and electron impact ionization cross section

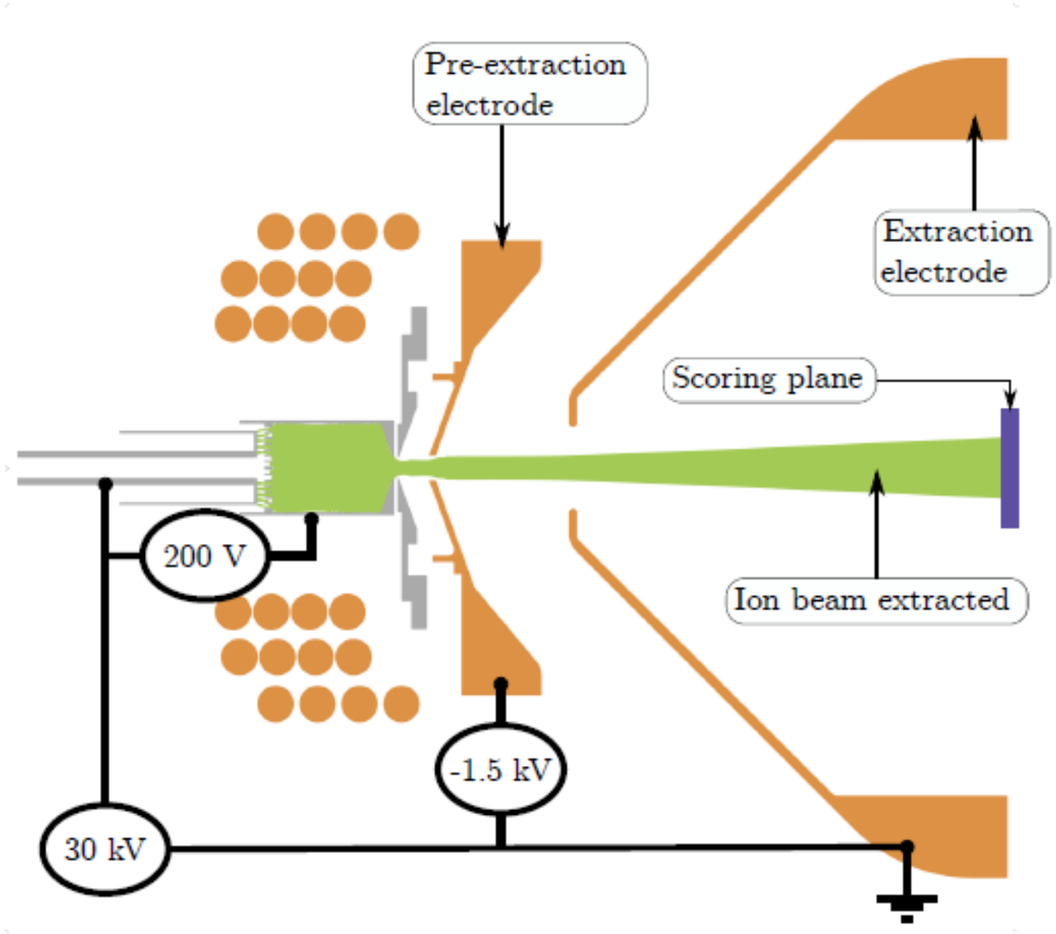


- Ionization rate per unit volume inside the anode volume for an applied voltage of 200 V, coil current of 30 A, and electron current of 150 mA.
- The ionization is higher near the grid as the electron density is higher at this location. This region also matches the place with the highest longitudinal electric field as depicted by the size of the black arrows.
- The equipotential line defines the potential barrier, and the blue dots corresponds to the ion initialization as computed from the ionization rate per unit volume

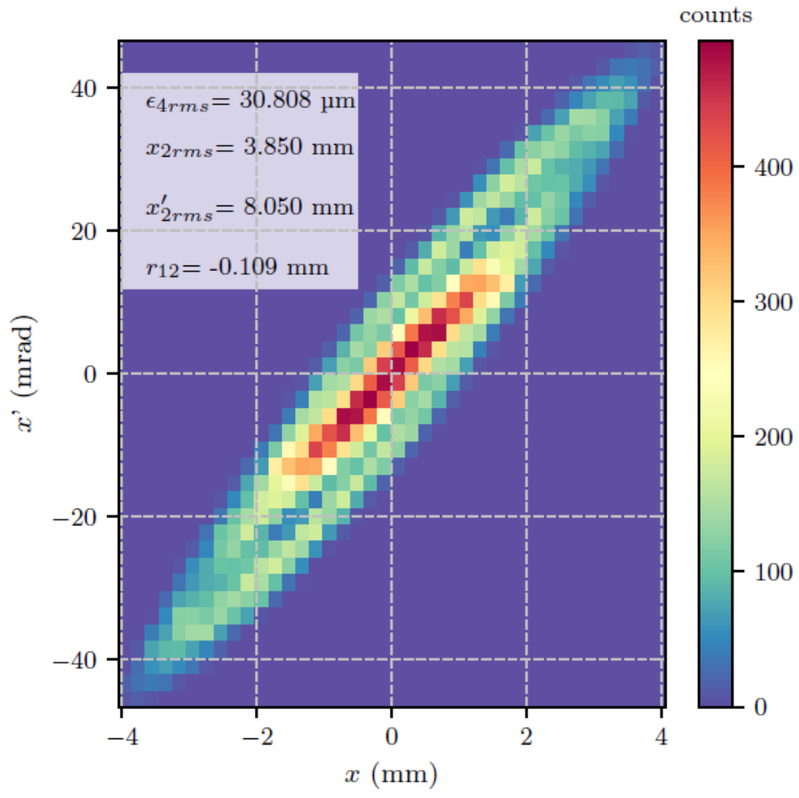
$$I_{n_i}(E_k, T, V, I_{coil}) = \int_{\Omega} n_i \, d\Omega,$$

$$I_{ion} = I_{n_i} \cdot (\text{ion extraction fraction})$$

Ion beam formation and transport simulation results

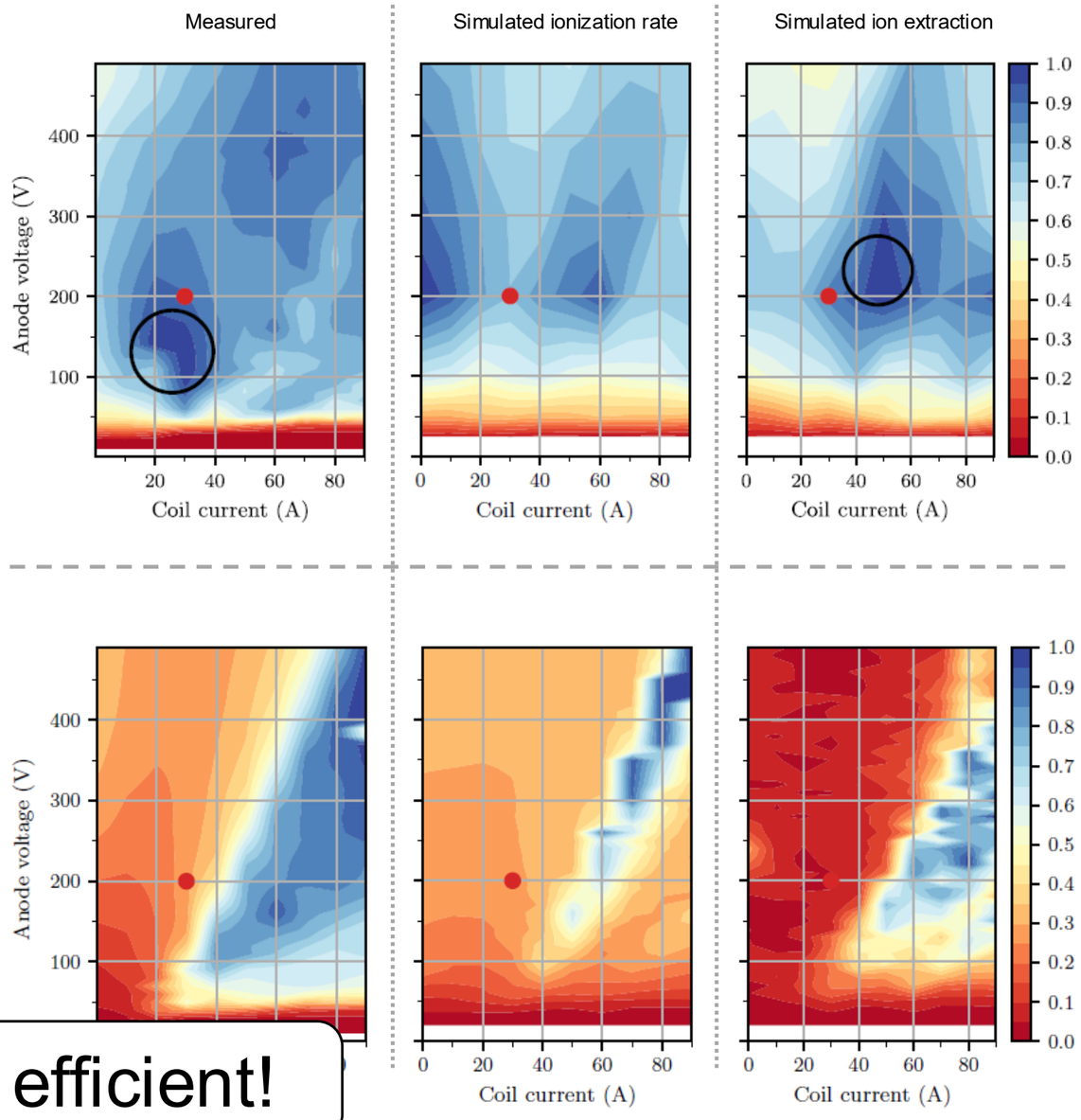


Parameter combination	Gaussian FWHM (eV)	2-RMS (eV)
(200 V, 30 A)	17.24	16.84



Simulated ion extraction reflects the parameters imposed and allow experimental comparison

Normalized ionization efficiency as a function of anode voltage and electromagnet current

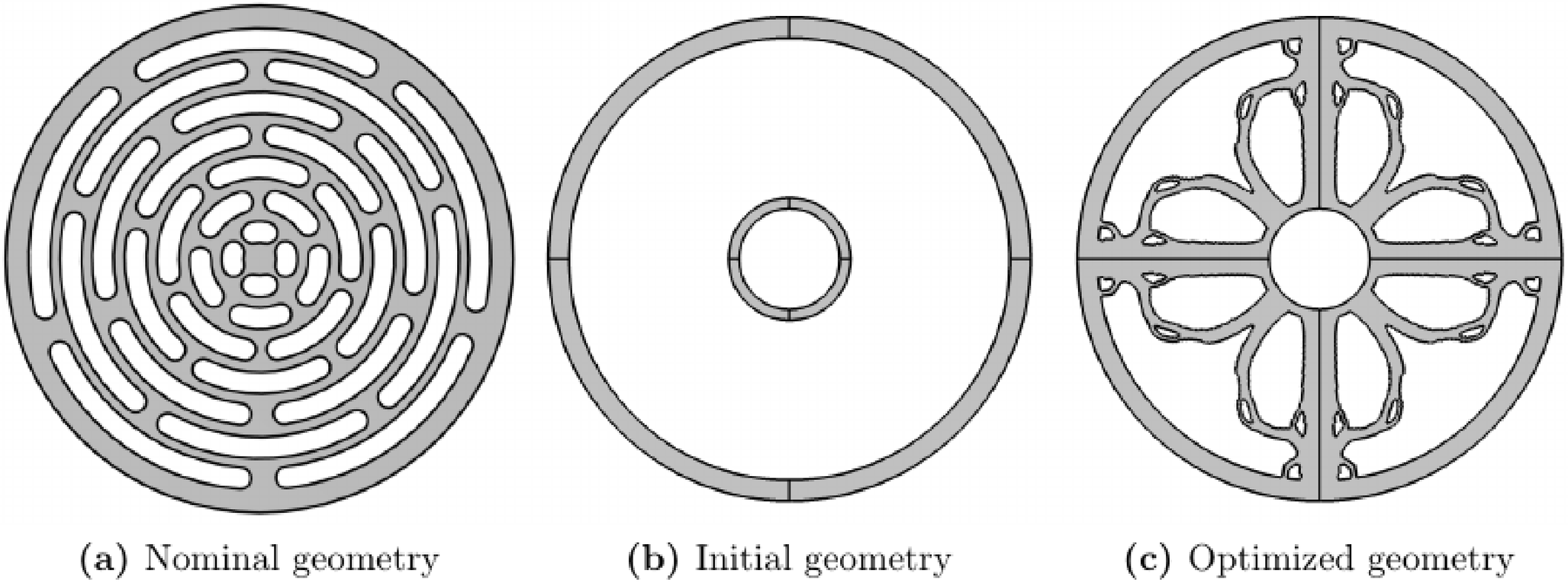


- No dominant effect with electromagnet current
- Blue hue in most of the map (> 0.6)
- Higher efficiency island near operation point
- Simulated ion extraction qualitatively agrees

2x more efficient!

- Dominant effect with electromagnet current
- Red hue in most of the map (< 0.4)
- Simultaneous increase with voltage and current
- Simulated ion extraction qualitatively agrees

From experimental benchmarking to novel geometries via generative design



(a) Nominal geometry (b) Initial geometry (c) Optimized geometry

Thermal and structural optimization to extract more electrons.

10.1016/j.nimb.2023.05.056

Part II: Experiments

Manufacturing Novel Grid Geometry:

The target-ion source system for the SPES facility commissioning: design, development and online testing

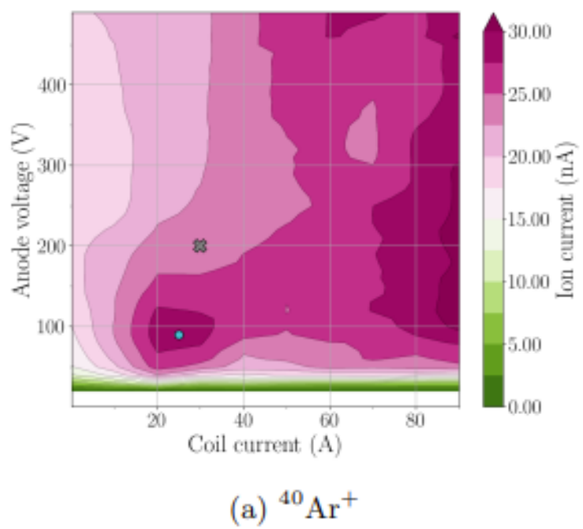
Author: Michele Ballan[1] Poster yesterday

- Additive manufacturing of Ta
  - A standard geometry tested at ISOLDE in 2023 as part of a collaboration with SPES.
- Monolith geometry for ARIEL manufactured including anode body
  - To be tested next year at ISOLDE

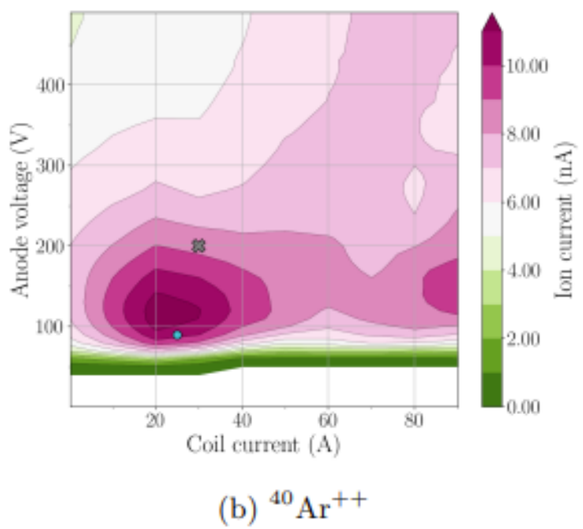
Courtesy of Sebastian Rothe

Parameter optimization for molecular beam delivery

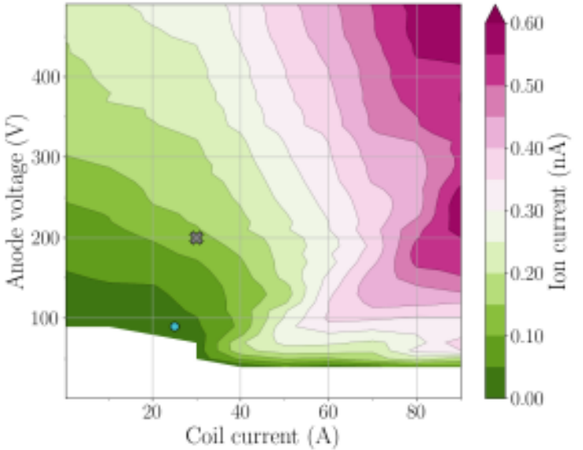
Characterization of ~~un~~wanted species for the ISAC FEBIAD



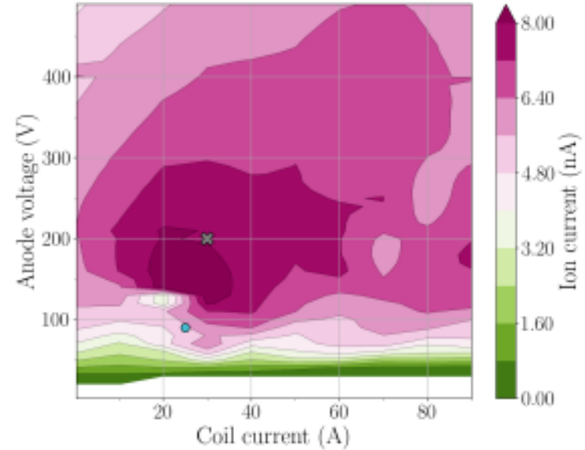
(a) $^{40}Ar^{+}$



(b) $^{40}Ar^{++}$



(c) $^{16}O_2^{+}$

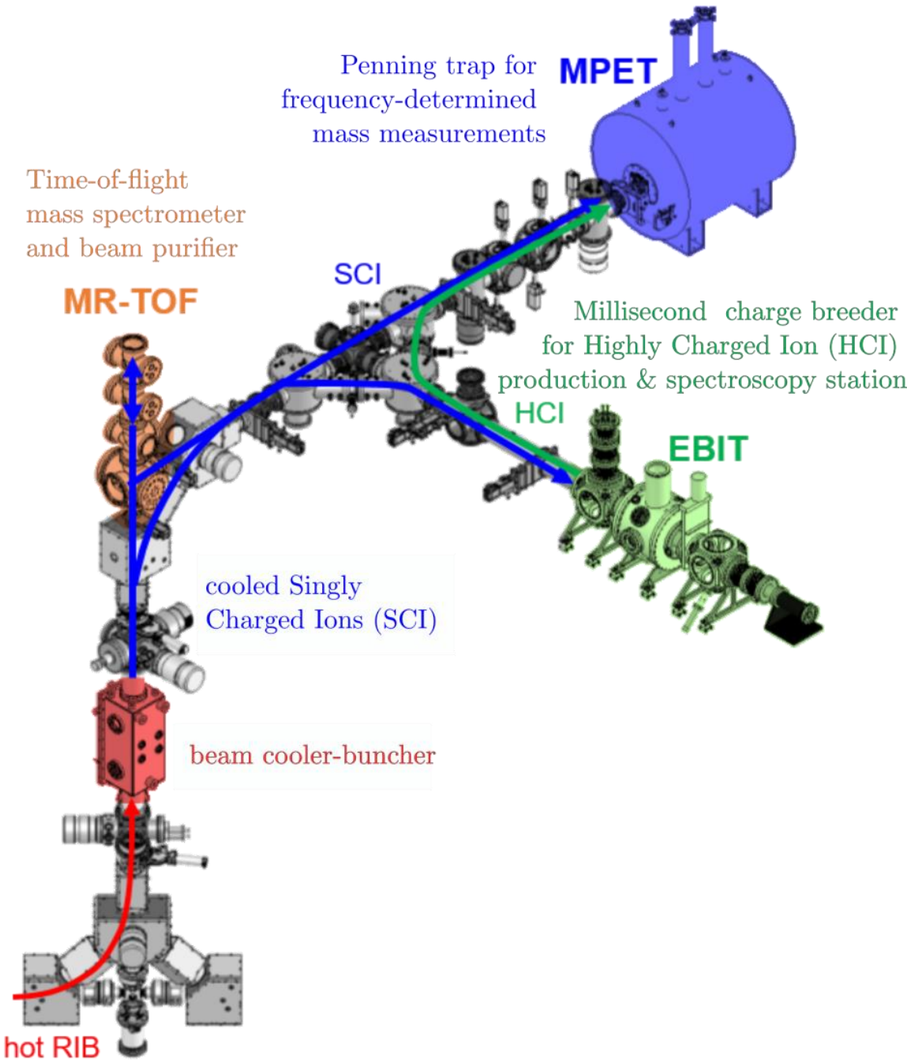


(d) $^{16}OH^{+}$

- At the same ion source settings, the molecules and doubly charged ions behave differently.

10.1088/1742-6596/2743/1/012069

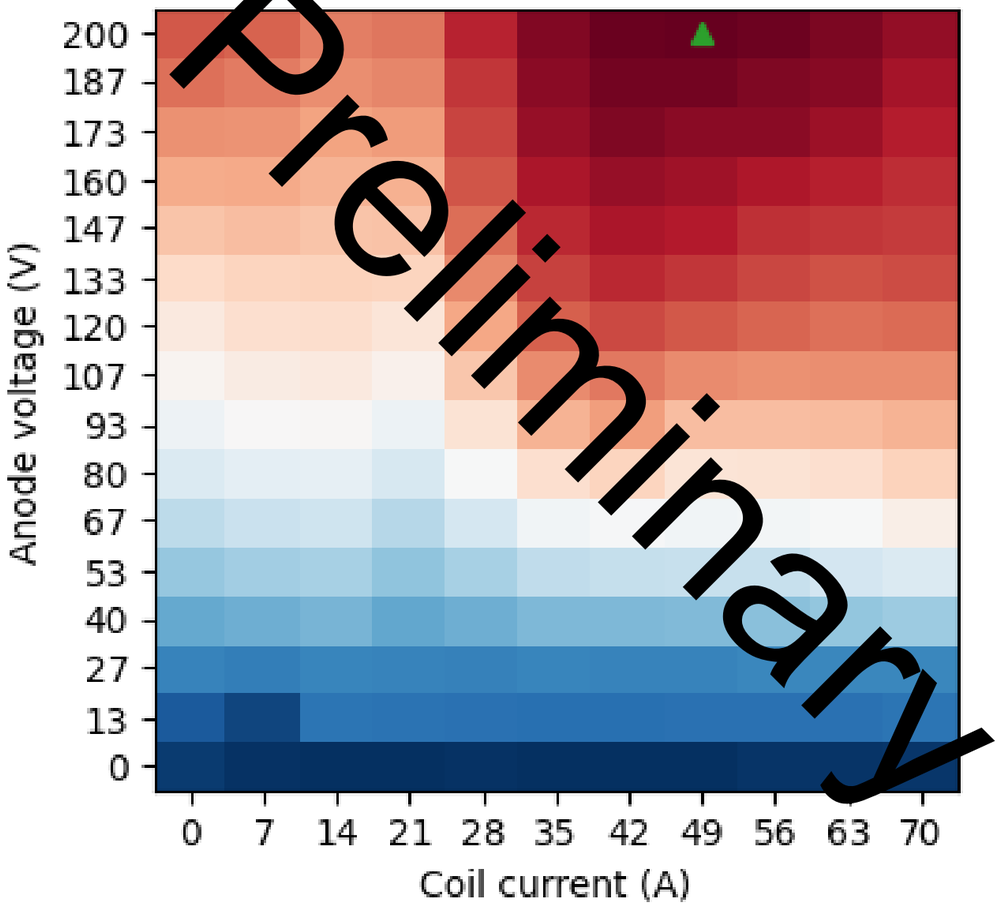
Beam development for $^{238}U^{19}F^{+}$ at TRIUMF's Ion Trap for Atomic And Nuclear science (TITAN)



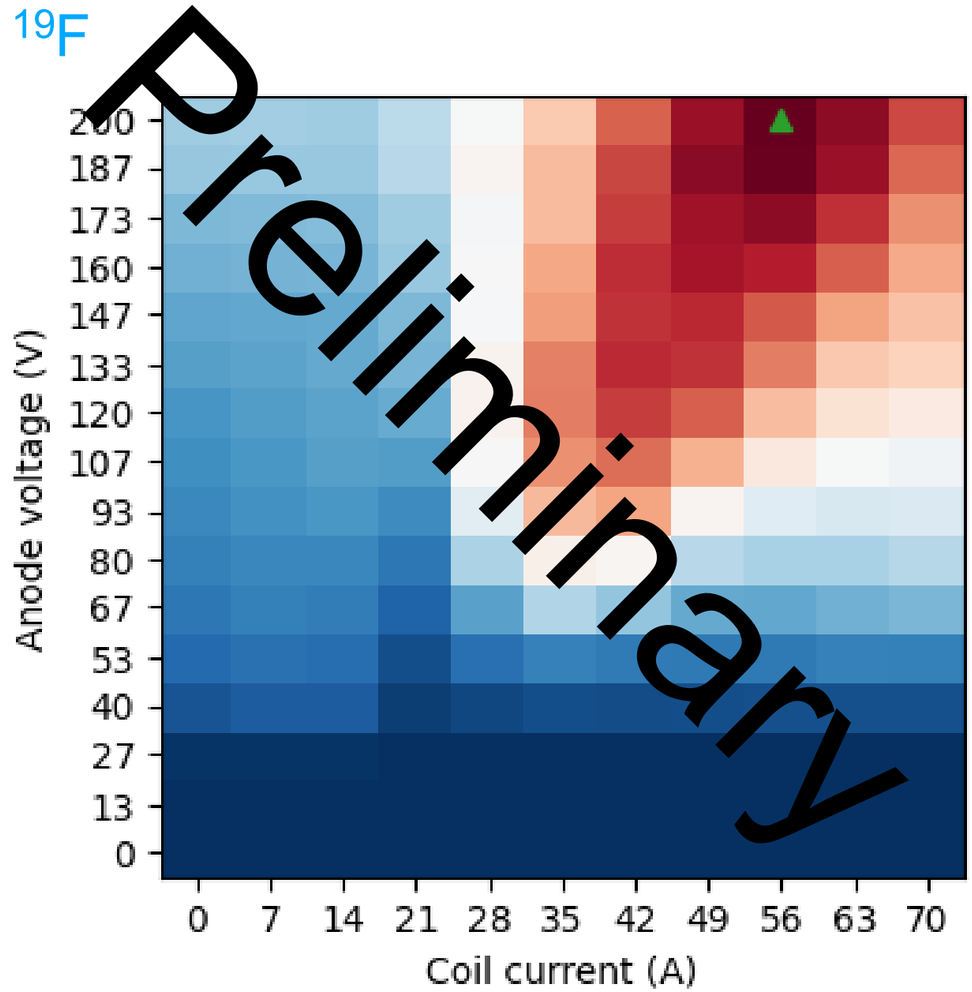
- Unirradiated Uranium Carbide with a FEBIAD ion source
- CF_4 injection
- Proof-of-principle to prove in-target molecular formation
- Less than 2 hours for Ion Source development

Beam development for $^{238}U^{19}F^{+}$

Total source current

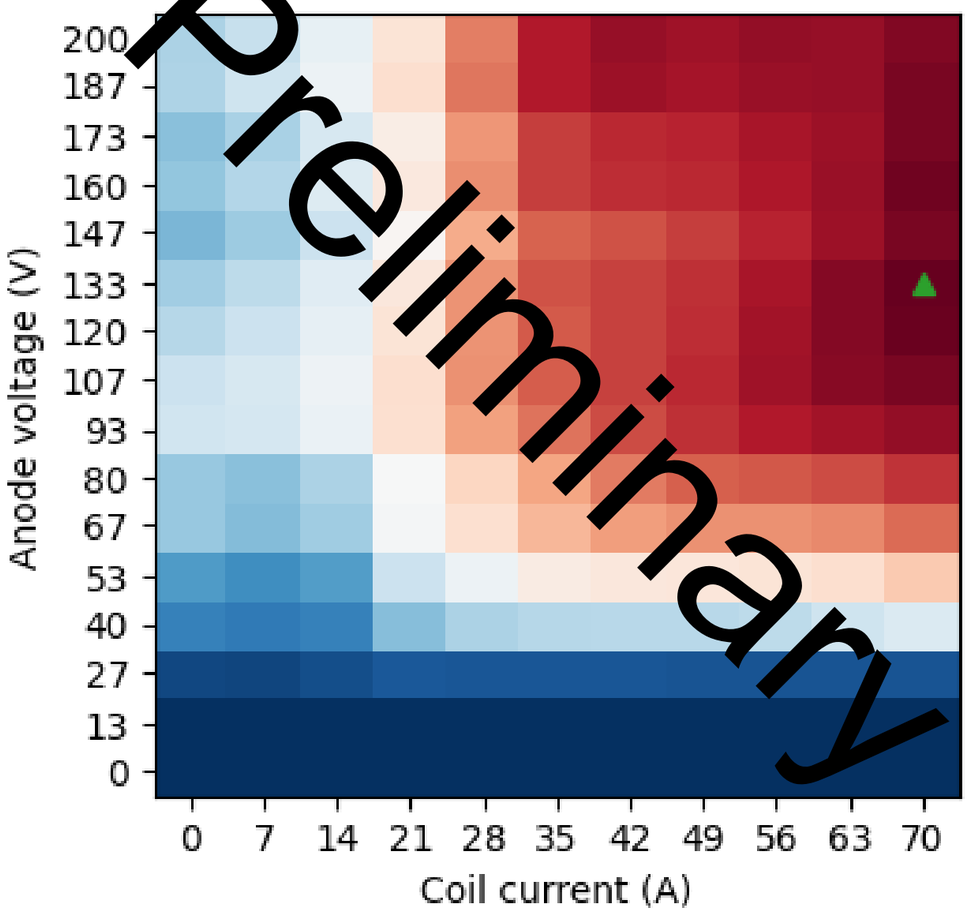


^{19}F

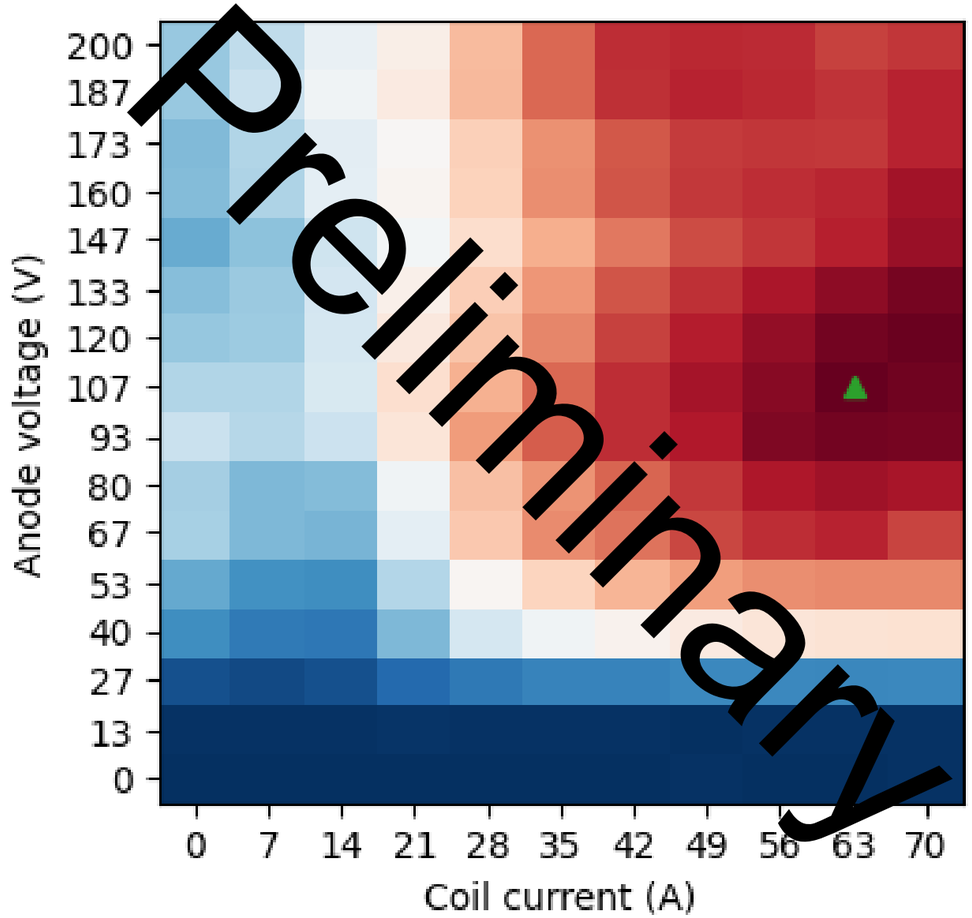


Investigating fragments and reaction products

$^{12}C^{19}F_3^+$

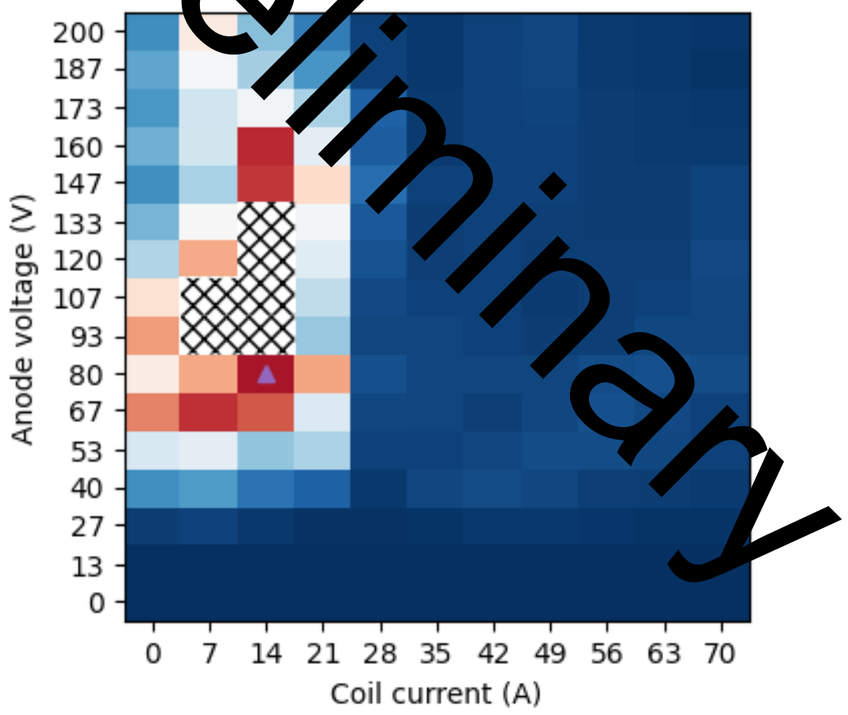


$^{238}U^+$



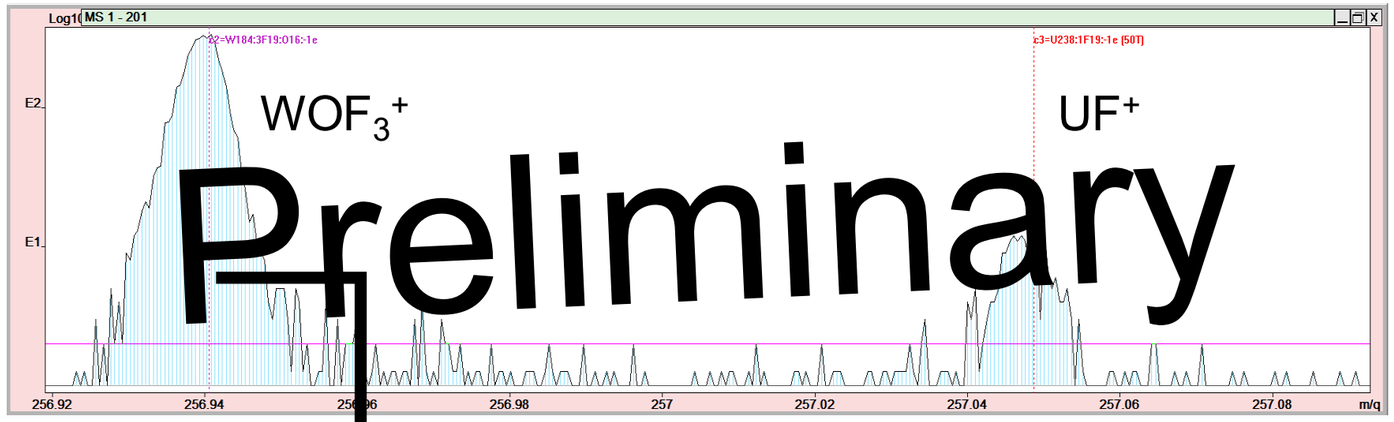
Investigating fragments and reaction products

$^{238}U+^{19}F$

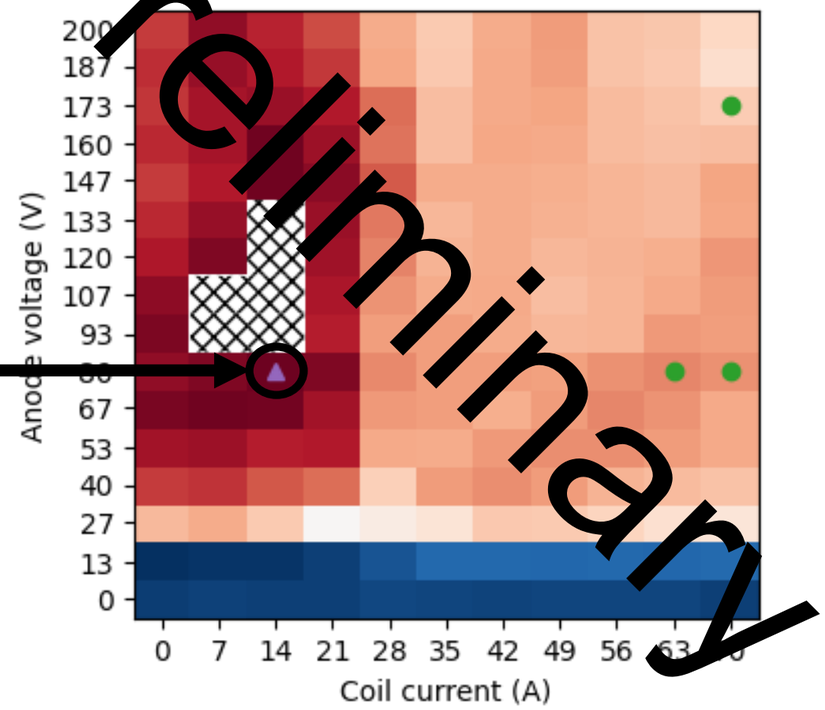


Map in linear scale. *Hatch indicates readback error*

UF^+ at A/q=257 shows strong contaminant



Ratio=4%

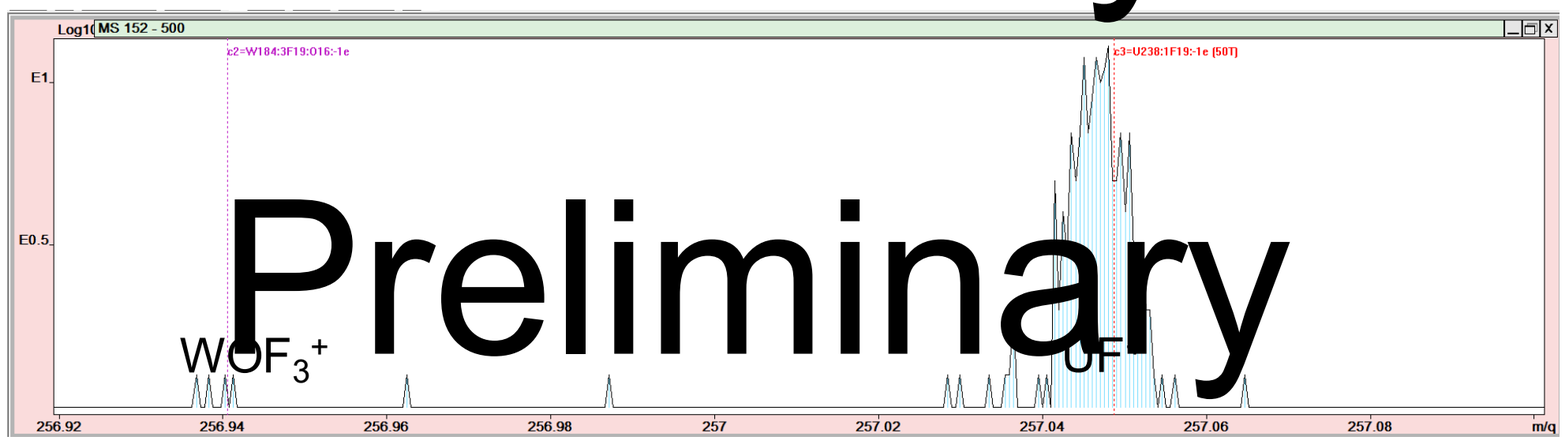


Map in log scale. *Hatch indicates readback error*

- Closing slits and tapping the magnet did not mitigate the isobaric contamination
- Likely, uranium vapor was depleted as well. Increasing the target temperature increased both peaks
- Proceeded to run F-scans with almost closed slits
- Magnet tapping while watching live the counts in the MR-TOF

After the iterative process. Unwanted species was suppressed

Ratio=4%



Ratio=97%

Very promising results. A collaboration with TITAN will benefit us both. We get FEBIAD developments, and they get radioactive molecules or new radioactive noble gases beams

Corollary from radioactive molecule development

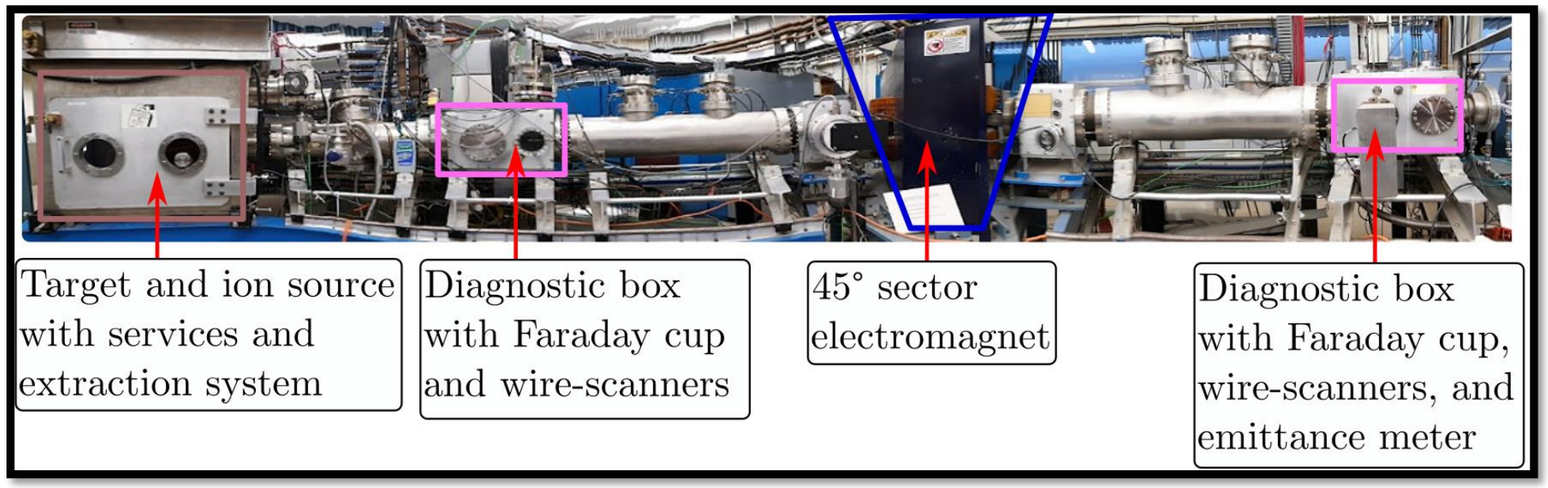
- The FEBIAD can be selective
  - At least can unfavored unwanted isobaric molecules
- Methodology needs refinement if/when we want to produce in-target radioactive lantanum fluorides.

Part III: Outlook

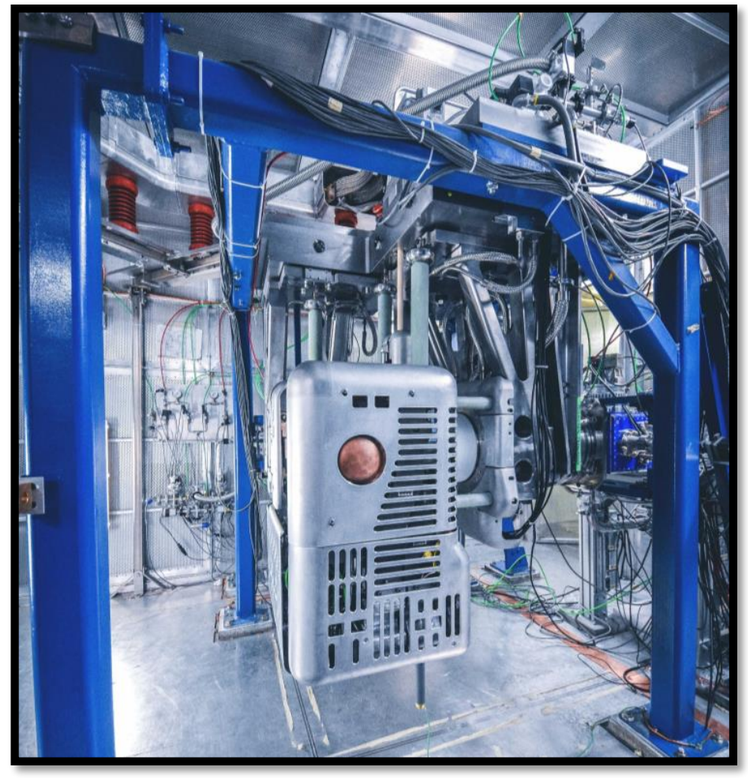
So is the FEBIAD an electron impact ion source or a plasma ion source?

- The right question is how to exploit either regime.
- For long lived isotopes a plasma regime might be more efficient, we need to study this at TRIUMF
- For fragile molecules a tunable electron beam regime might prove more useful, this avenue has already started at TRIUMF

- Two Offline test stands



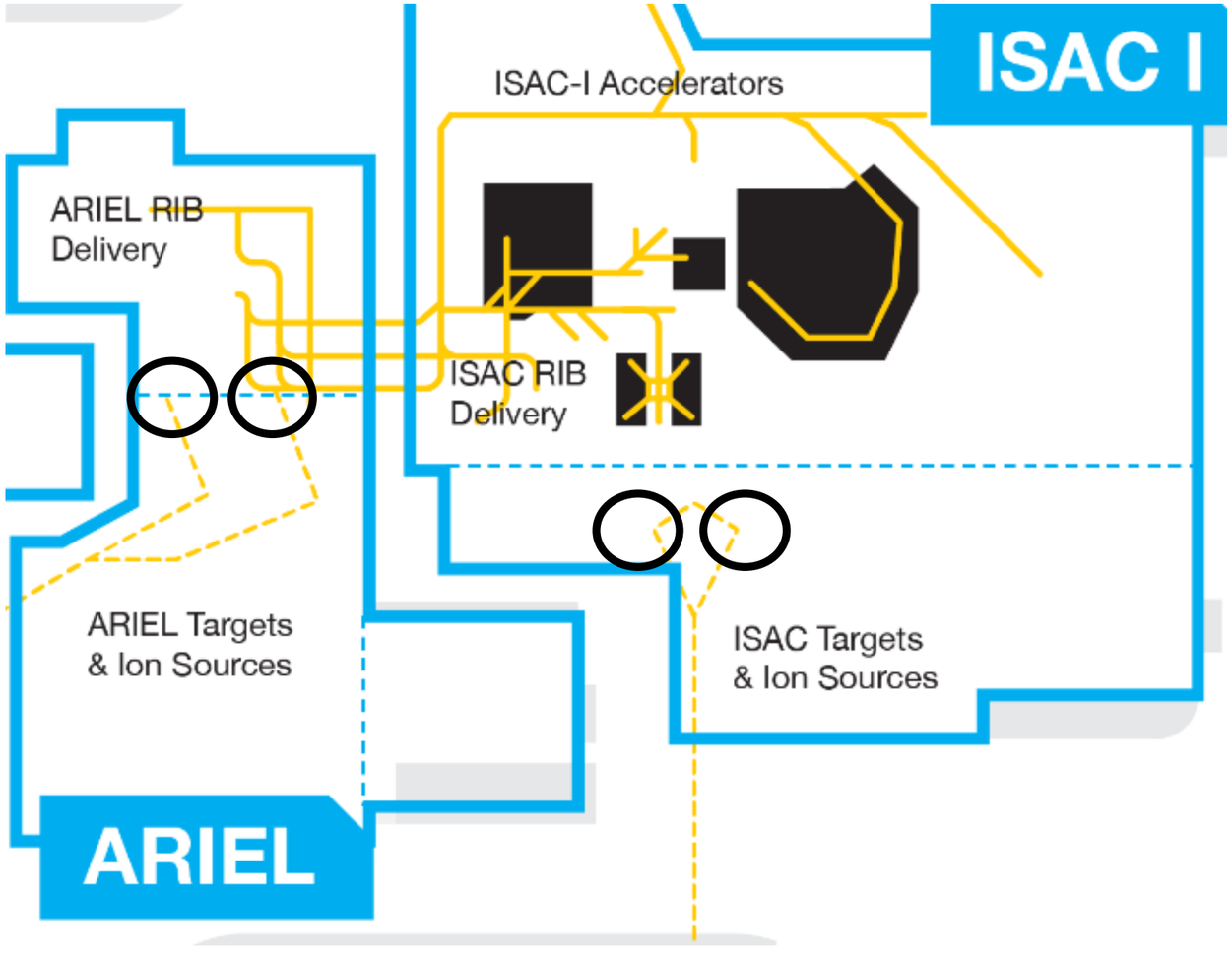
ISAC offline test stand



ARIEL offline test stand

ARIEL: new infrastructure, new opportunities

- Two Offline test stands
- Four target stations



- Two Offline test stands
- Four target stations

After ARIEL commissioning, a new era for R&D is foreseen:

- Standard radioactive ion sources implementation for ARIEL,
- Simulation framework to be exploited to its limit to start adding more complex physics as needed (students will be needed)
- Streamline novel ion source geometries prototyping and testing by strengthening collaboration with our R&D program

Summary

- A **numerical model has been developed** comprising the relevant operational parameters of the FEBIAD ion source and from fundamental principles.
- The ionization model allows **proposing geometrical and operational changes to increase the ionization efficiency while maintaining beam quality**.
- With all the simulation-based optimization results, the geometrical changes can potentially **increase the ionization efficiency ≥ ten-fold**.
- Tuning the FEBIAD, while using the appropriate diagnostics, **isobaric selection for molecules is possible**.

Thank you!

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