Superconducting ECR ion sources: an untapped application of artificial intelligence and its superhuman patience

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Why Nuclear Physics should care about high performance Electron Cyclotron Resonance (ECR) ion sources

Example from LBNL:

- 88-Inch Cyclotron was constructed around 1960 as an accelerator of light ions to kinetic energies of low hundreds of MeV
- Today, using the superconducting ECR ion source VENUS, it accelerates ions from protons to uranium with maximum kinetic energies in excess of 2.6 GeV

Example for Nuclear Physics field:

- VENUS' demonstration of over 200 μA $^{238}U^{33+}$ and $^{238}U^{34+}$ in 2008 allowed FRIB to be designed to reach on-target power at half the cost by doubling the source-delivered current

(source cost: < \$20M, reduction in design cost: \$1B $\Longrightarrow$ \$500M)

- Since that time VENUS has doubled the extracted currents in both of these charge states

ECR ion sources are a cost-effective way to improve the performance of accelerators used for Nuclear Physics

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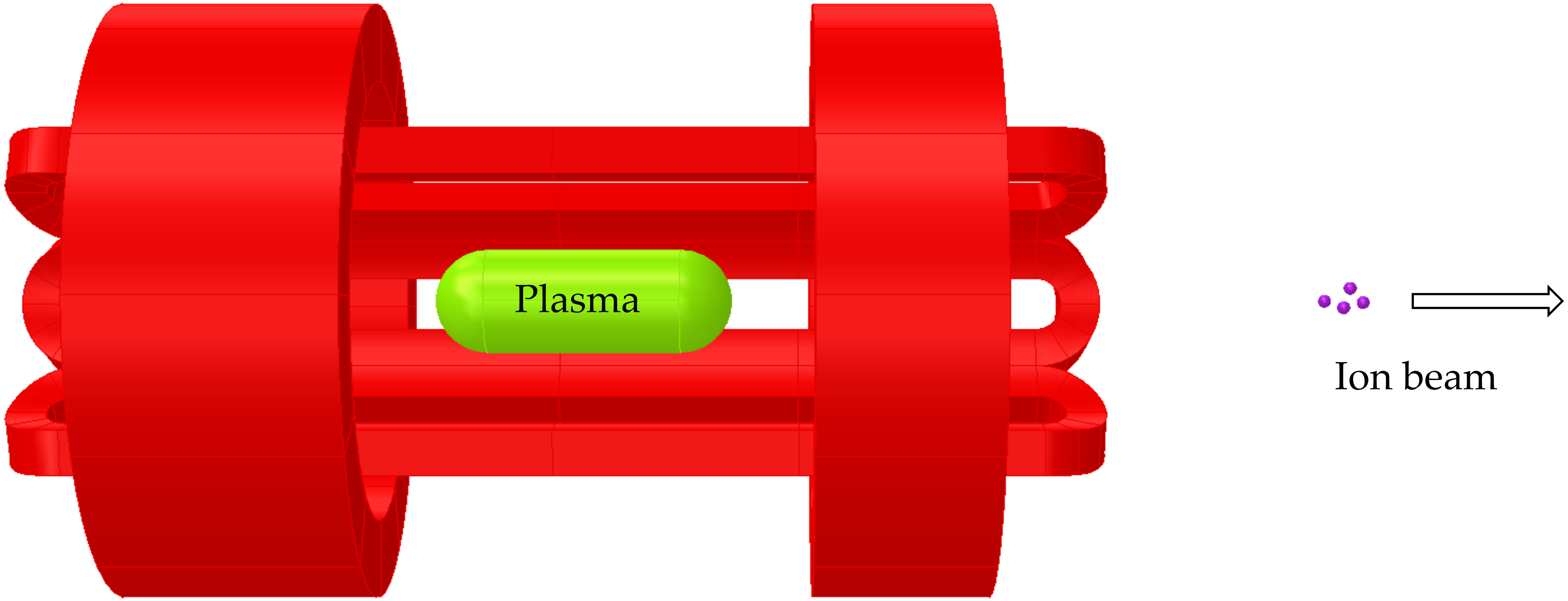
ECR ion source basics

Goal: extract high current, highly-charged ion beams from a stable plasma and send to accelerator

Needs:

1. Confine plasma
2. Maintain plasma
3. Extract ions from plasma

ECR ion source basics



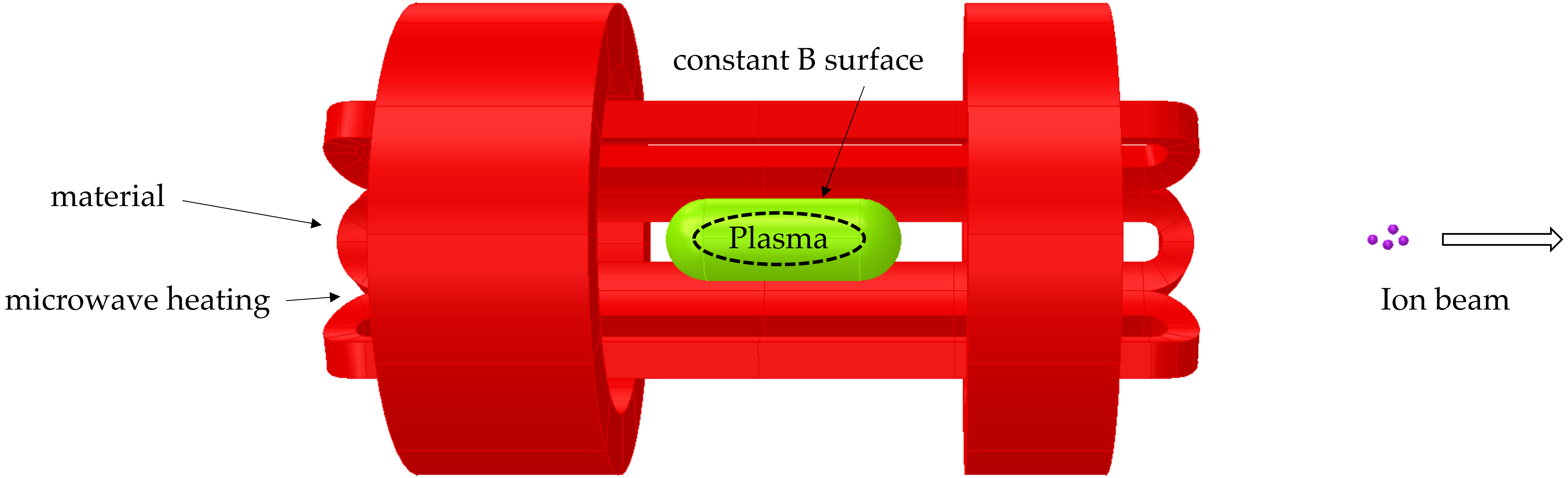
Needs:

1. **Confine plasma**
2. Maintain plasma
3. Extract ions from plasma

Use magnetic mirroring to confine plasma

- Magnetic field increases axially via solenoids
- Magnetic field increases radially via sextupoles
- Use superconductors for better confinement

ECR ion source basics

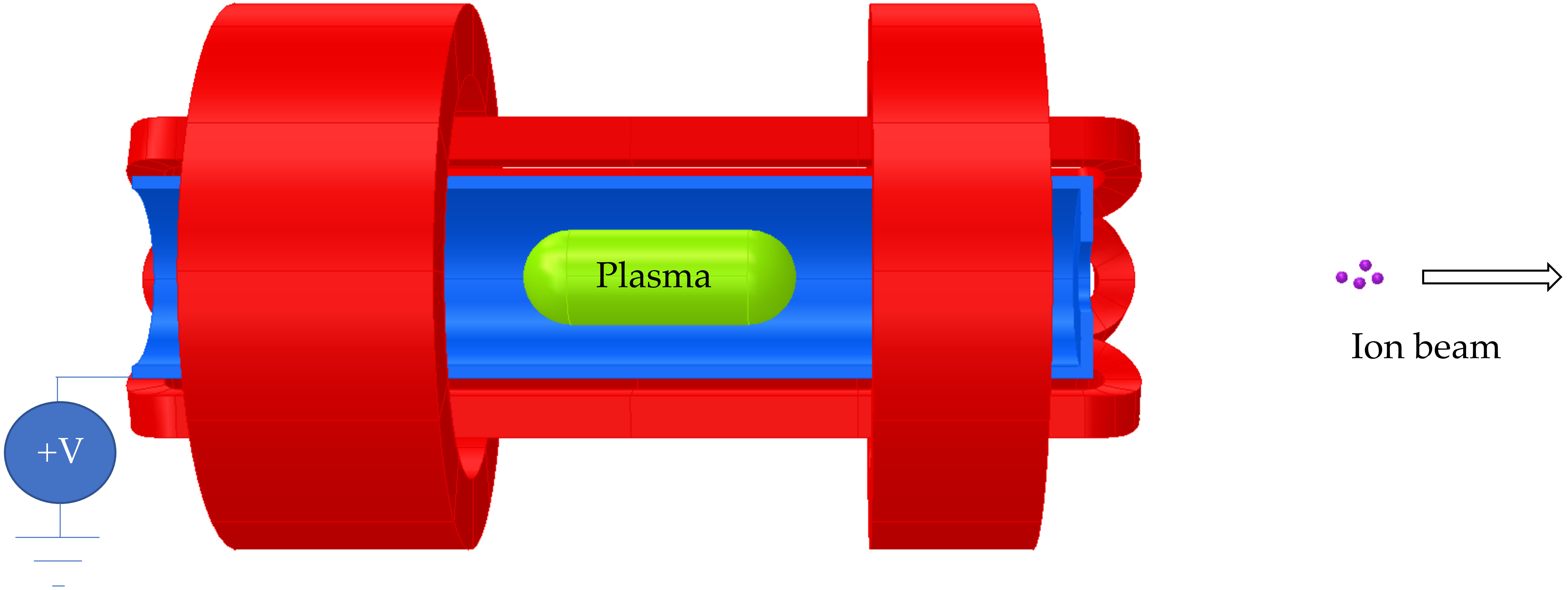


Needs:
1. Confine plasma
2. **Maintain plasma**
3. Extract ions from plasma

Magnetic field magnitude increases from source center
- Resonantly heat electrons on closed surface to provide energy
- Add plasma material via gas, sputtering, ovens, etc.

Note: higher frequency RF heating (again, higher magnetic fields) leads to higher currents and higher charge states

ECR ion source basics

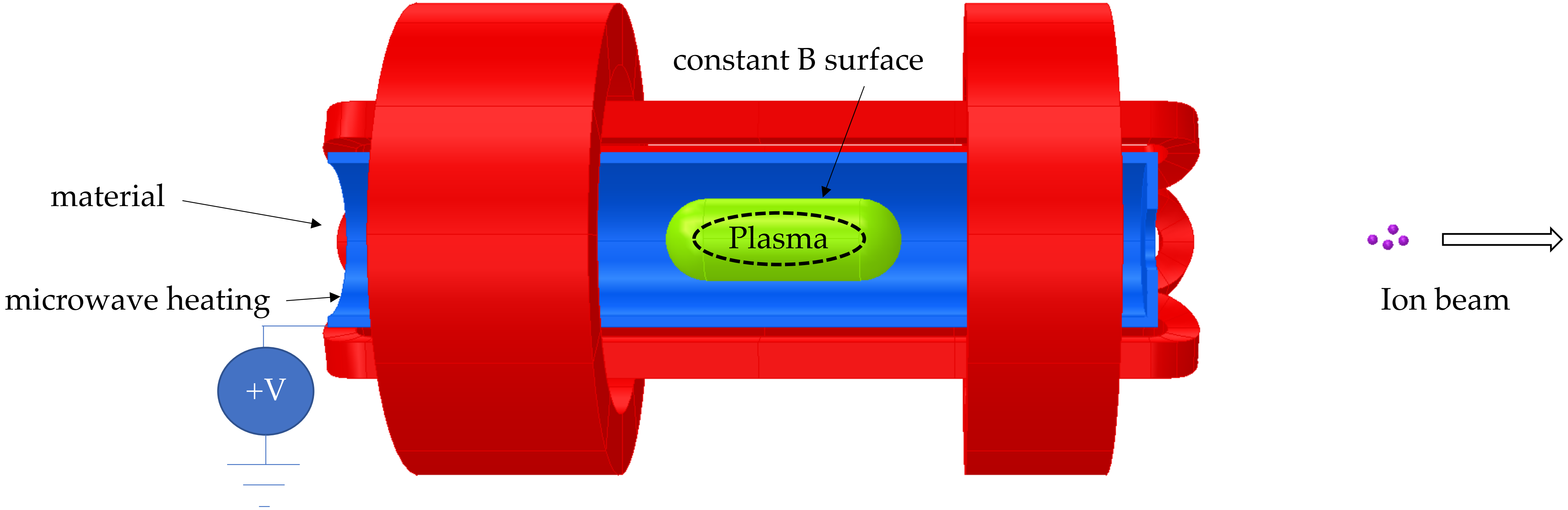


Needs:

1. Confine plasma
2. Maintain plasma
3. **Extract ions from plasma**

Positively bias a plasma chamber relative to beam line to encourage ions to come out.

ECR ion source basics

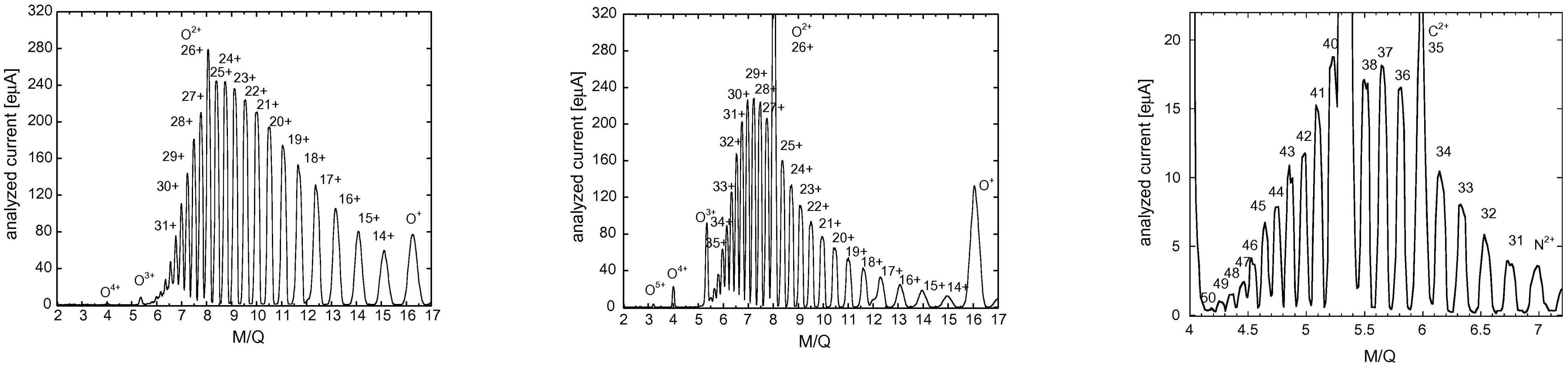


Source optimization (current, charge state, and stability) requires adjusting multiple knobs:

- Coil currents
- Gas pressures
- Heating power
- Extraction voltages
- Oven temperatures
- Sputtering voltages
- etc.

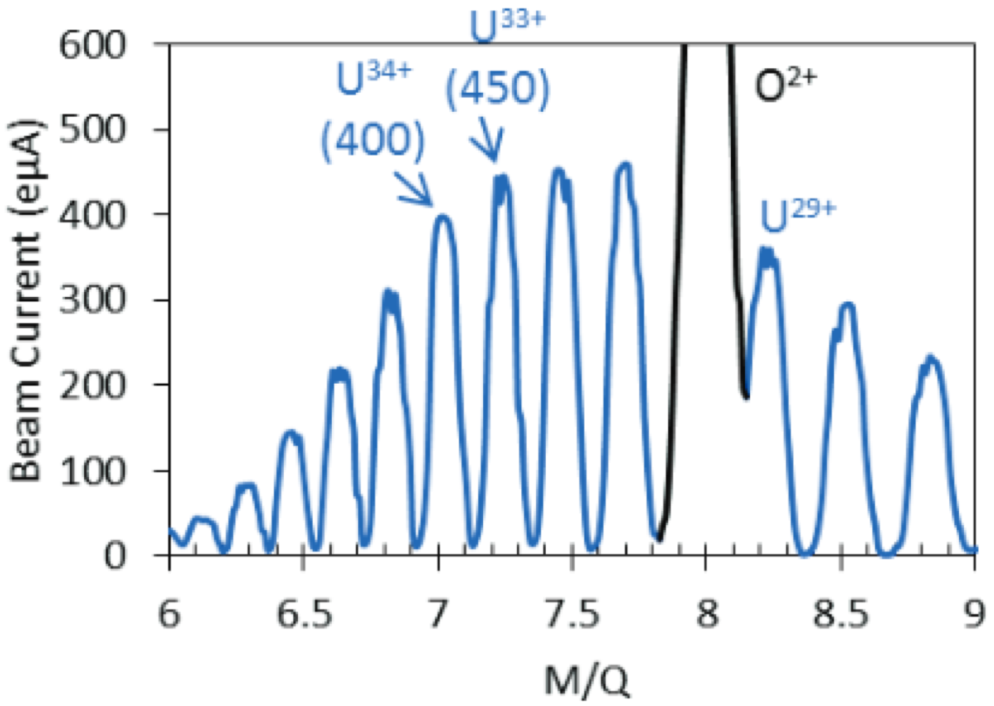
Ion source tuning produces very different results

Example: bismuth production



- Adjusting source parameters (fields, RF power, pressure, etc.) shifts charge state distribution toward higher charge states
- This tuning is a slow and tedious multiple-parameter search of the operational phase space
- Typically the goals are relatively simple:
  - Increase charge state and/or increase current
  - Maintain long-term (~weeks) plasma stability

Improved performance comes from tuning



- VENUS production of U^{33+} and U^{34+} doubled between 2008 and 2012 with much of the increase due to finding better performance configurations (i.e. significant dedicated time spent tuning)

- Record beam production of different species bounces back and forth between Lanzhou, China and LBNL based largely on who has put more time in tuning

Where does AI come in?

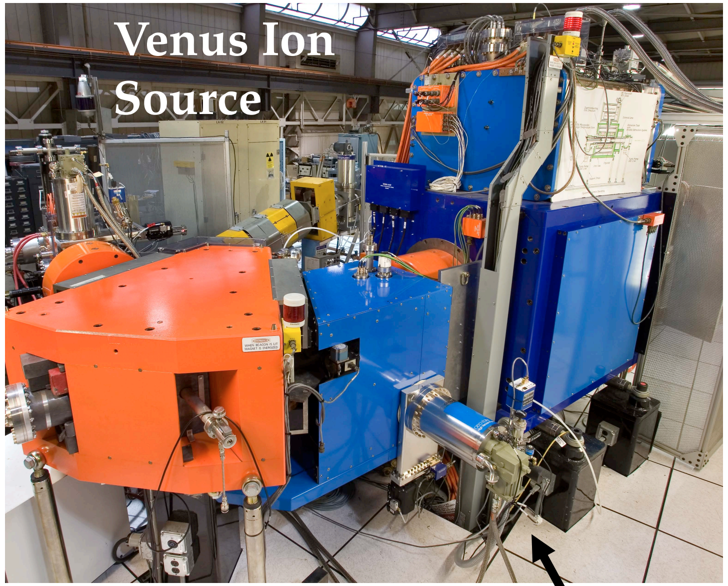
- Tuning a plasma is a slow, often tedious, job that requires incredible patience. The computer has infinite patience.

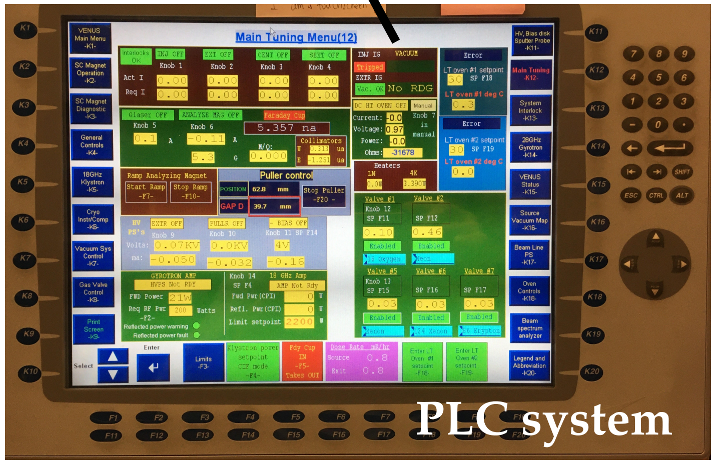
- Human operators most often perform a two-parameter probing of operation space. Computers can perform more complicated searches turning multiple knobs at once

- Computer run multiple-parameter searches would be expected to find operation points with higher beam production, better stability, and reduced consumption rates of expensive consumables (^{48}Ca, ^{50}Ti, etc.)

- AI could be used to constantly monitor source and make small changes to maintain long-term stability or catch first signs of failure

Why we should implement AI with VENUS at LBNL





Superconducting ECR ion source VENUS is fully PLC-driven, so it is ready to be run via computer

The PLC system is robust safety-wise. Limits have been engineered to prevent operators running the source in an unsafe manner

The performance criteria are relatively simple: beam stability, beam current, charge state distribution, emittance. Determining "better" performance is straightforward

This would immediately benefit FRIB as well. Their new ion source is a near-replica of the VENUS ion source and that new source will not have the luxury of extended R&D tuning to improve performance

Conclusions

- LBNL's superconducting ECR ion source, VENUS, is a shovel-ready project in the implementation of artificial intelligence and eventually machine learning
- The performance and our understanding of superconducting ECR ion sources could benefit greatly from a computer-driven investigation of their operational space
- A near-identical source will come online at FRIB. Improved source operation will make reaching and maintaining target beam power easier

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