Recap of the MARS-D review (June 9-11, 2020)

Damon Todd

July 14, 2020

Goal of review

1. Communicate why MARS-D (a fourth-generation, 45 GHz, fully-superconducting electron cyclotron resonance ion source) should be built

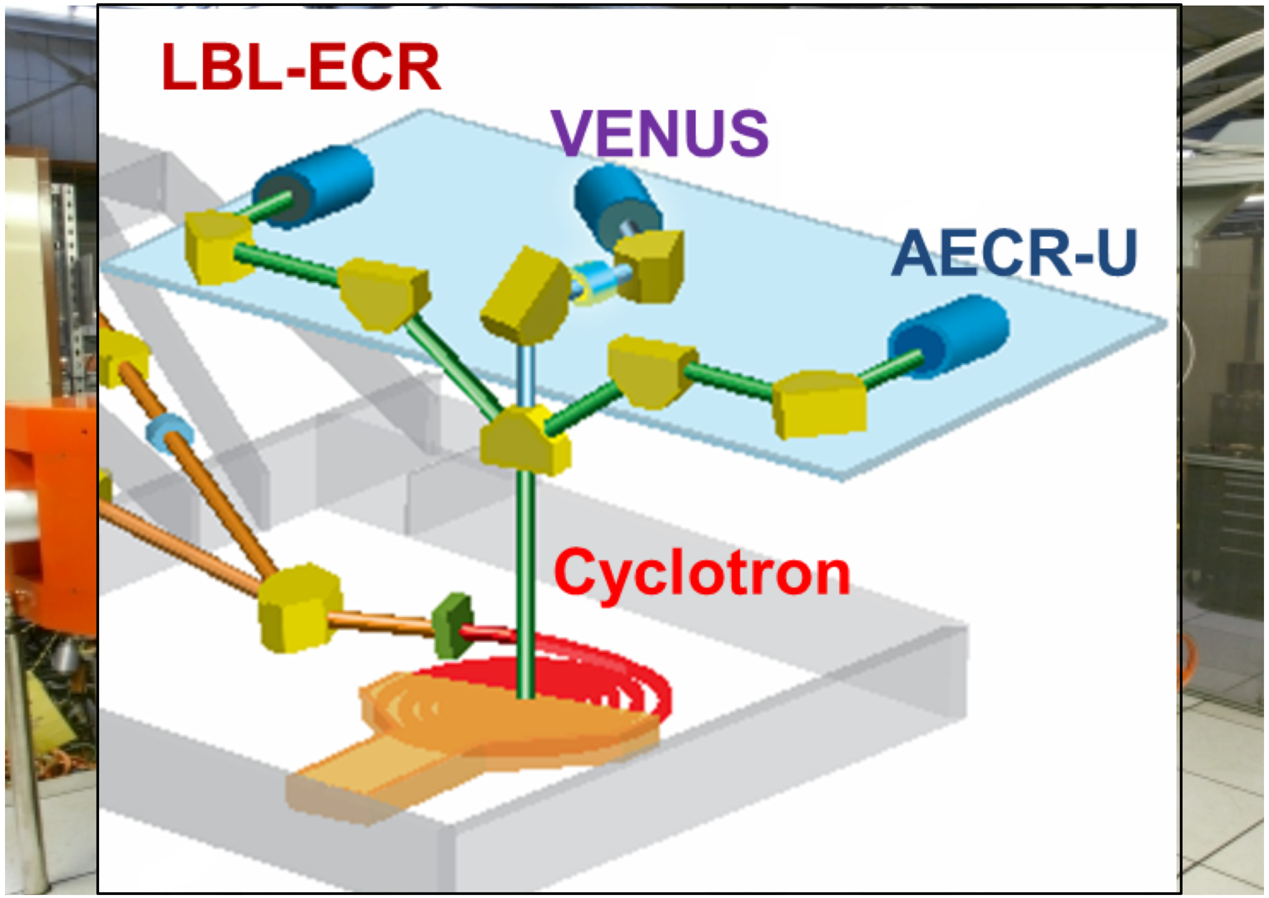
2. Communicate why MARS-D should be built at LBNL
   - Project Manager: Janilee Benitez
   - Chief Scientist: Dan Xie
     - With Jeff Bramble, Tom Gallant, Adrian Hodgkinson, Mariusz Juchno, Larry Phair, Damon Todd, and Li Wang

BCMT BERKELEY CENTER FOR MAGNET TECHNOLOGY

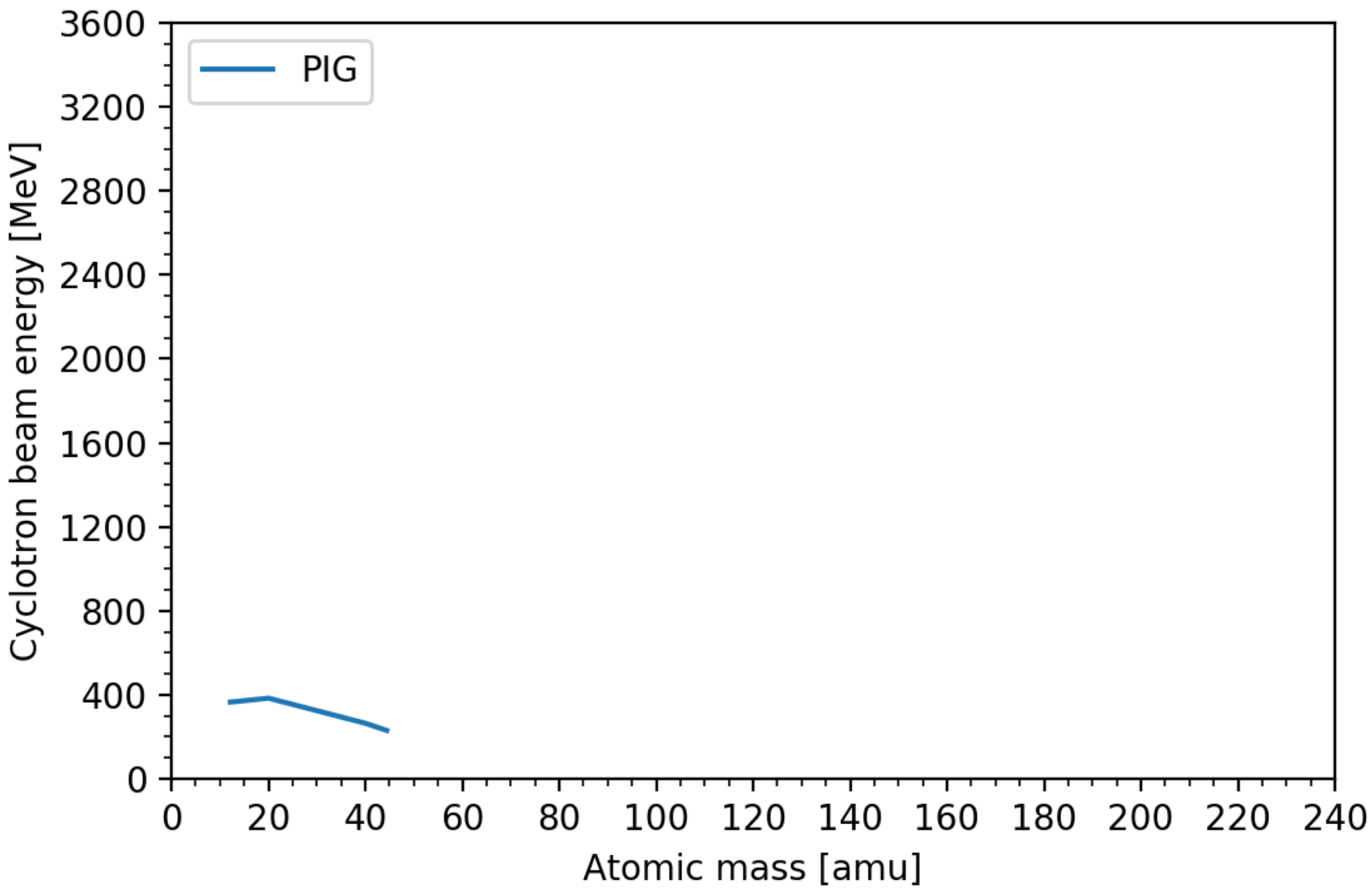
ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

LBNL as case study of the impact of ECR ion sources on accelerators

1. The 88” Cyclotron operated for over two decades before adding its first ECRIS (Electron Cyclotron Resonance Ion Source)
2. There are currently three ECR ion sources attached to the 88” Cyclotron: one of each generation
3. The newest source, VENUS, remains one of the two highest-performing ECRs in the world



Significance and impact of ECR ion sources at LBNL

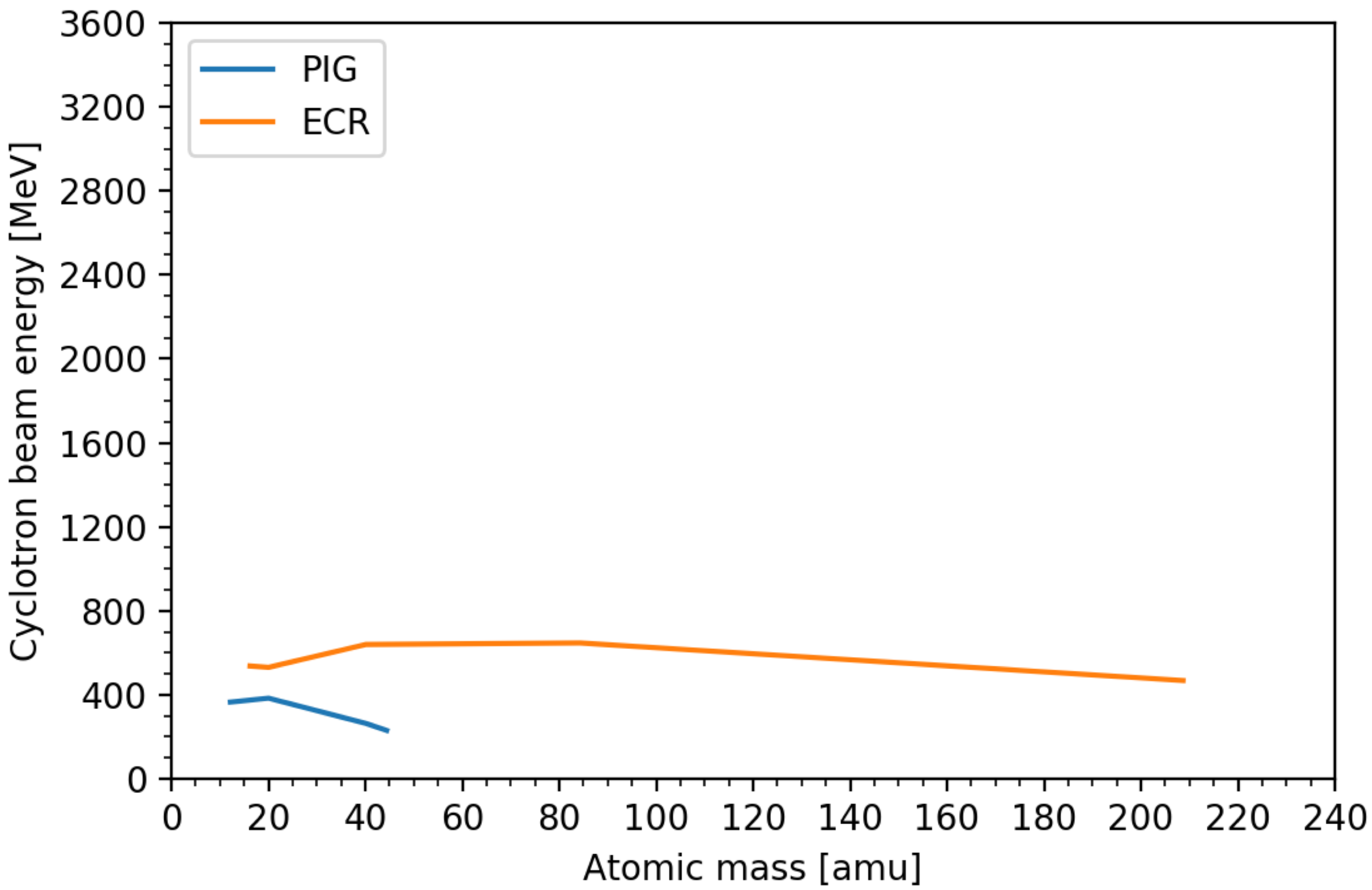


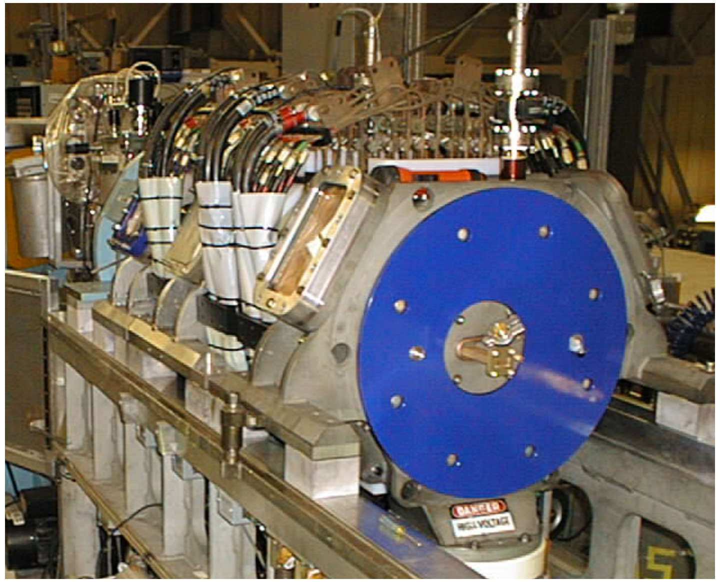
For the first 20+ years of operation, the 88” Cyclotron at LBNL used internal Penning or “PIG” sources

Shortcomings:

- $Q \lesssim 5+$
- Cathodes with lifetimes less than a day

Significance and impact of ECR ion sources at LBNL

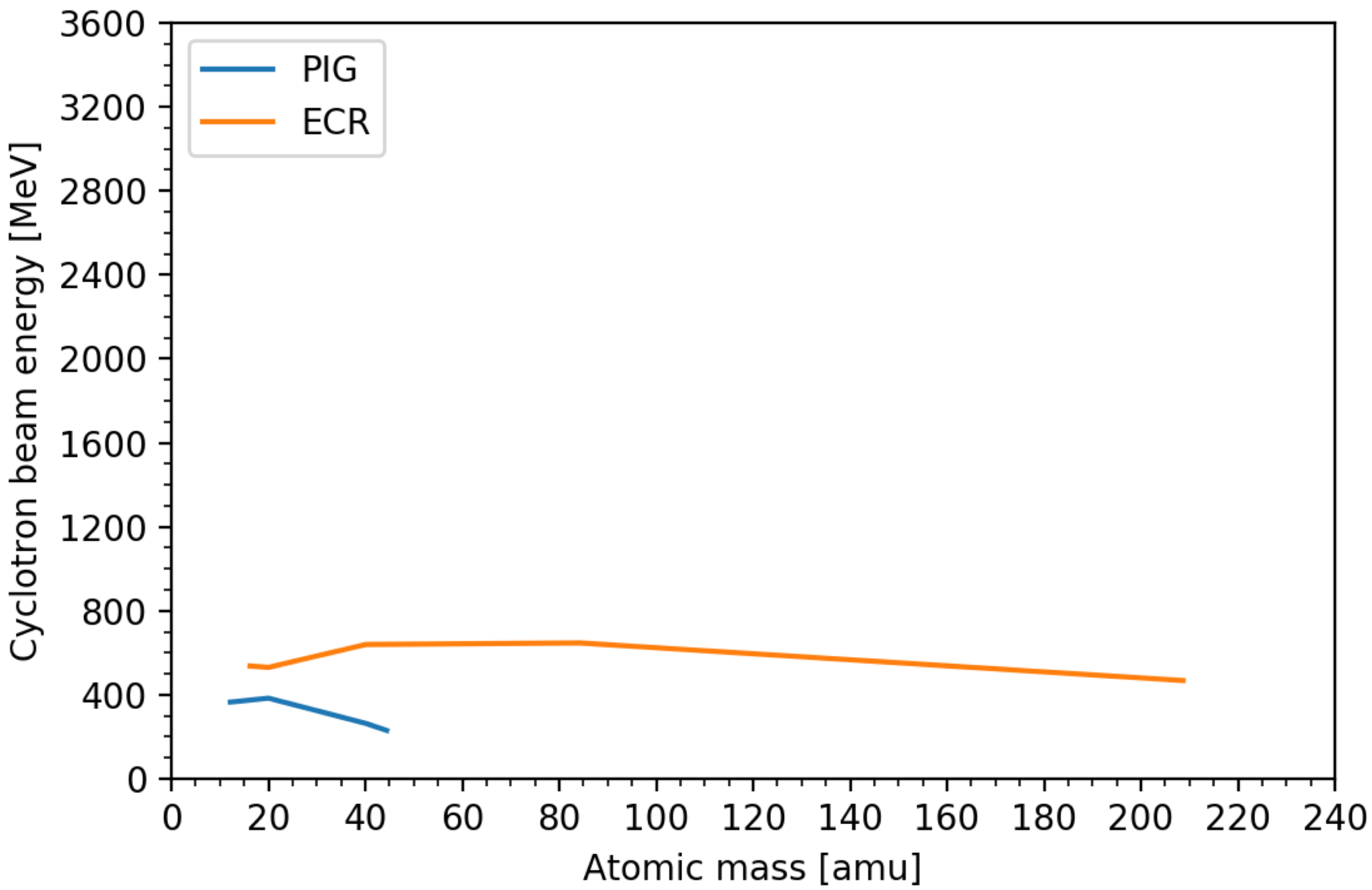




"LBL-ECR" ion source

- First-generation ECR ion source
- Delivered first beams: 1983

Significance and impact of ECR ion sources at LBNL



Increase in Cyclotron capabilities directly related to ECRIS' ability to produce more ions of higher charge state

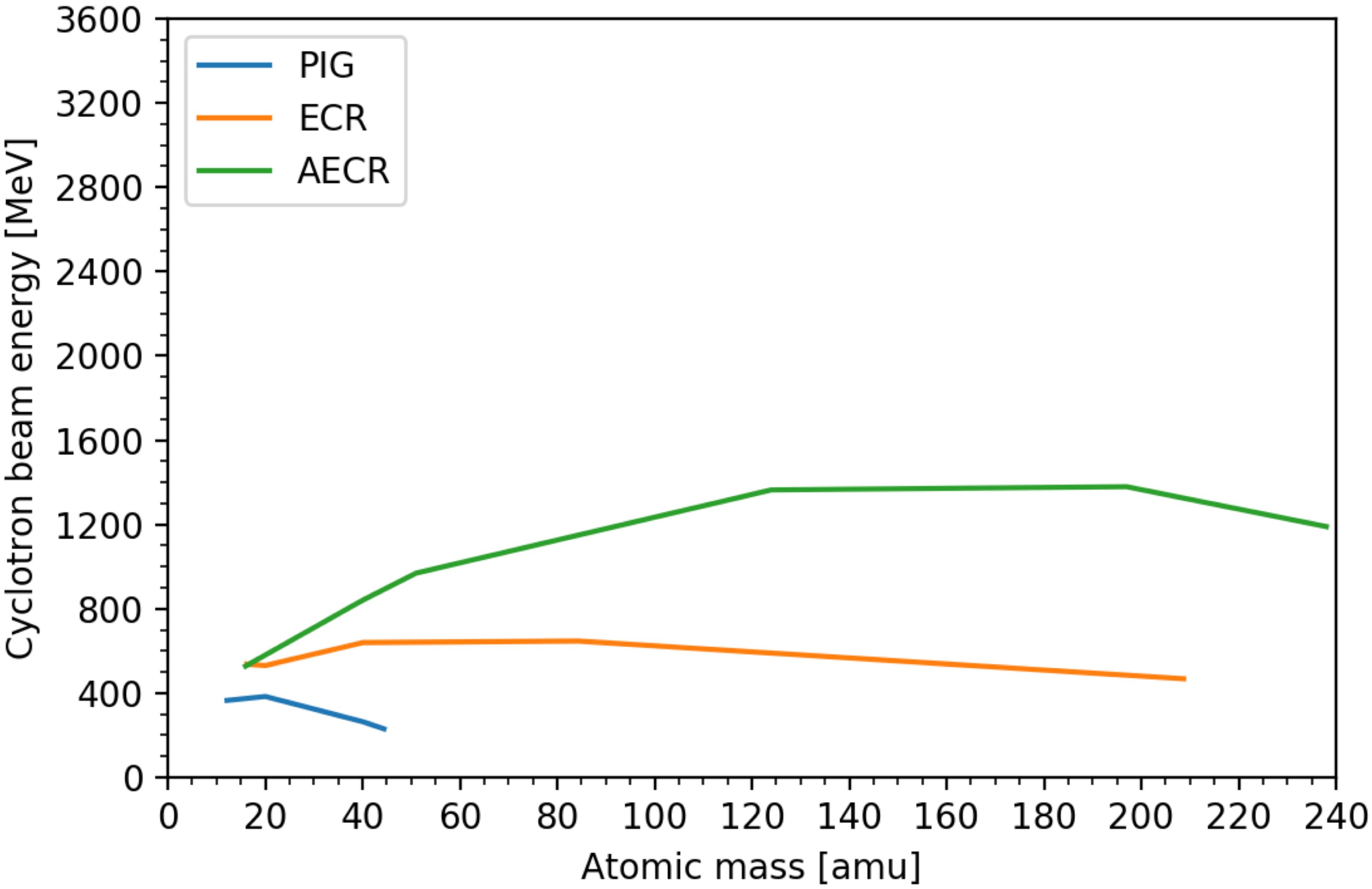
- Cyclotron accelerates a limited range of mass-to-charge ratios, so heavy ions must be more highly-charged to be accelerated
- Beam kinetic energies increase with Q for cyclotrons:

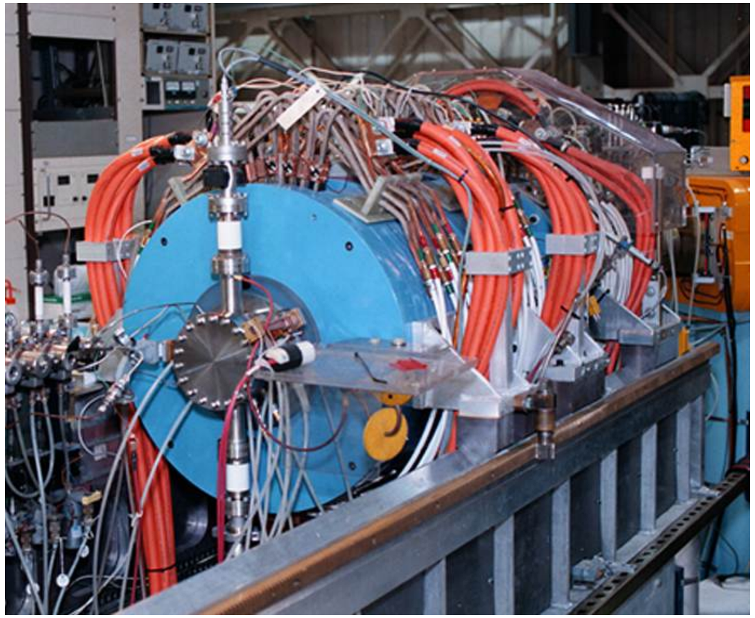
$$KE \propto Q^2$$

Missing from graph:

- ECRIS has no cathode, so continuous running for weeks

Significance and impact of ECR ion sources at LBNL





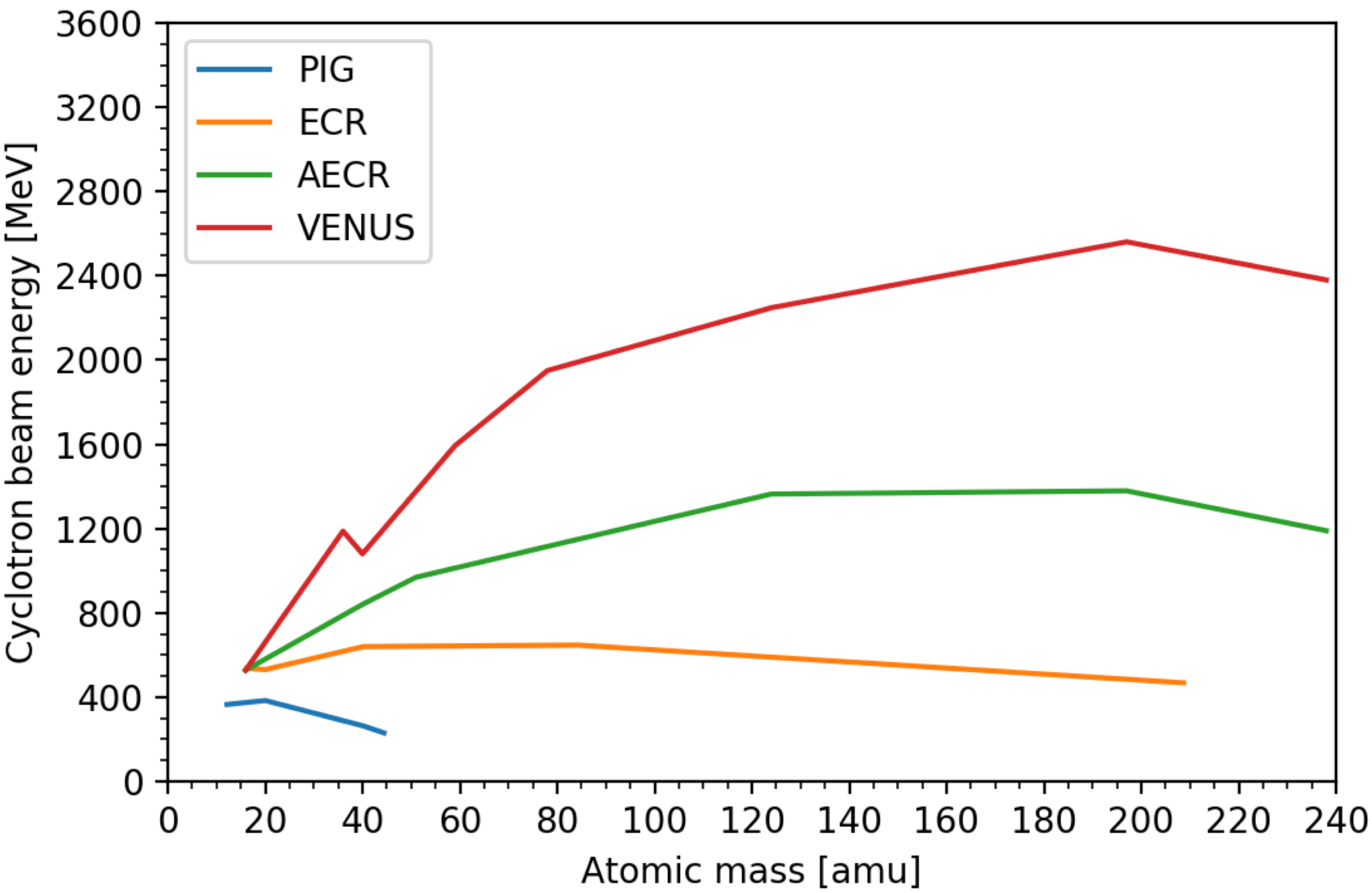
"AECR-U" ion source

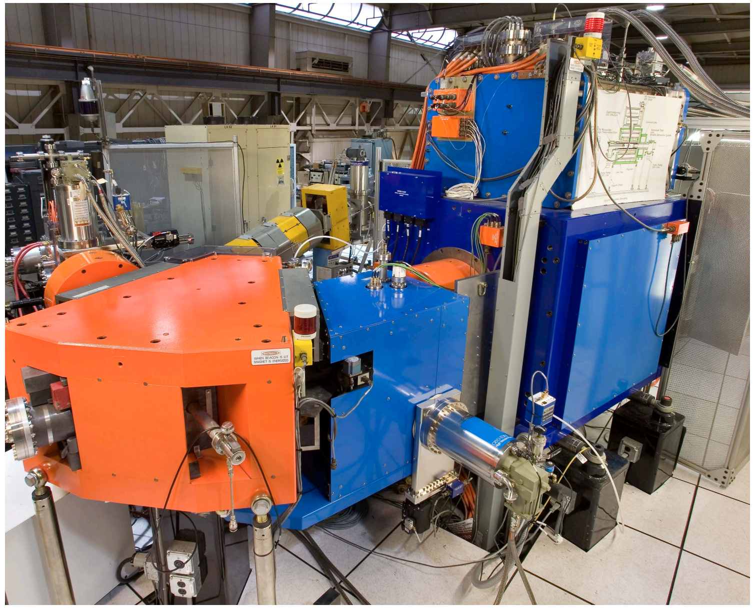
- Second-generation ECRIS
- Beams with higher currents and of higher charge state than LBL-ECR

Success led to duplication around the world:

- ATLAS/ANL
- NSCL/MSU
- U of Jyvaskyla, Finland
- KVI, Netherlands

Significance and impact of ECR ion sources at LBNL

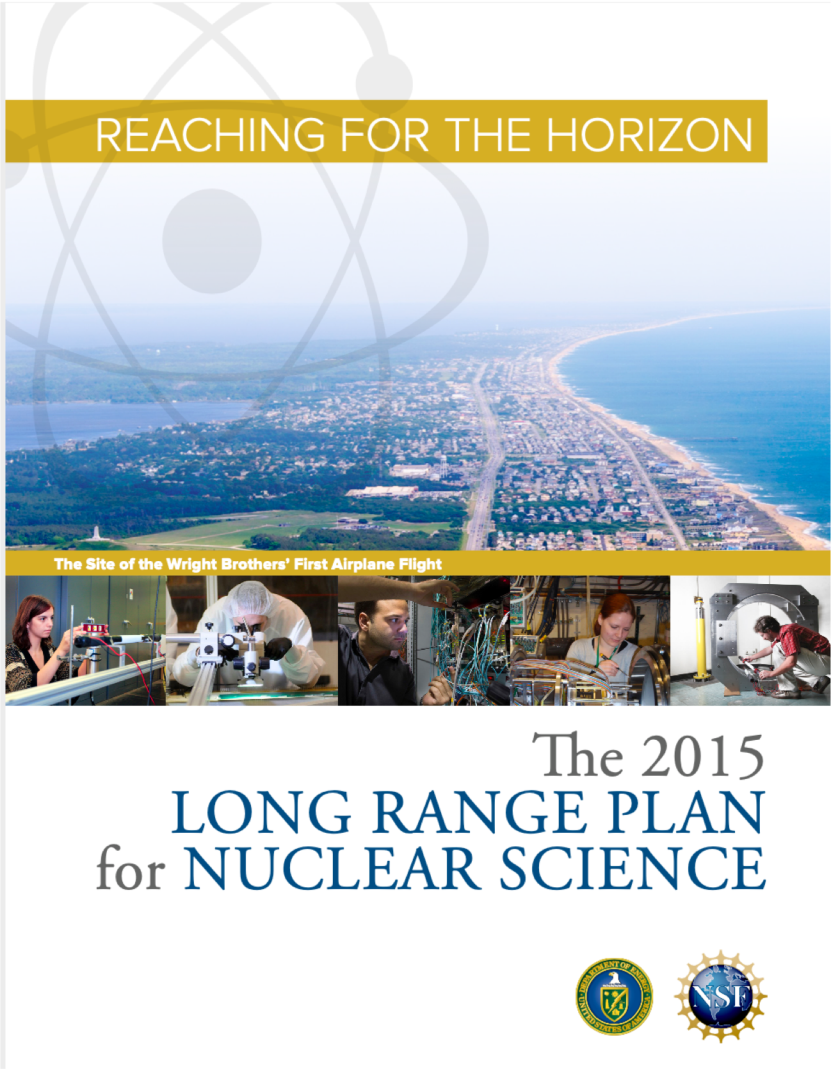




"VENUS" ion source

- World's first third-generation ECR ion source
- Fully-superconducting

VENUS impact outside of LBNL



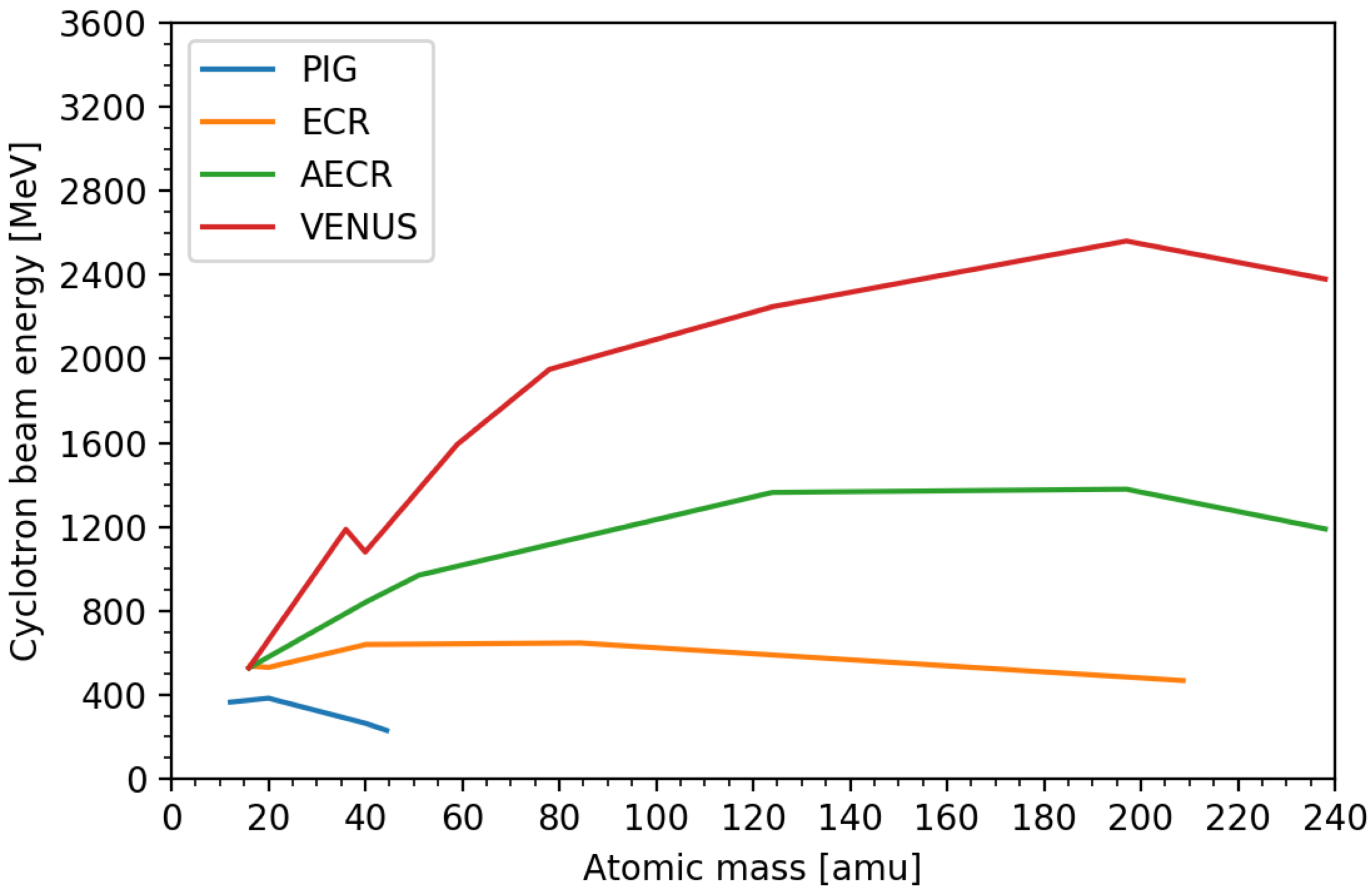
- VENUS' demonstrated ability to produce high currents of highly-charged uranium ($\gtrsim$400 μA of U^{33+} and U^{34+}) was essential for FRIB to have potential to reach such high power on target

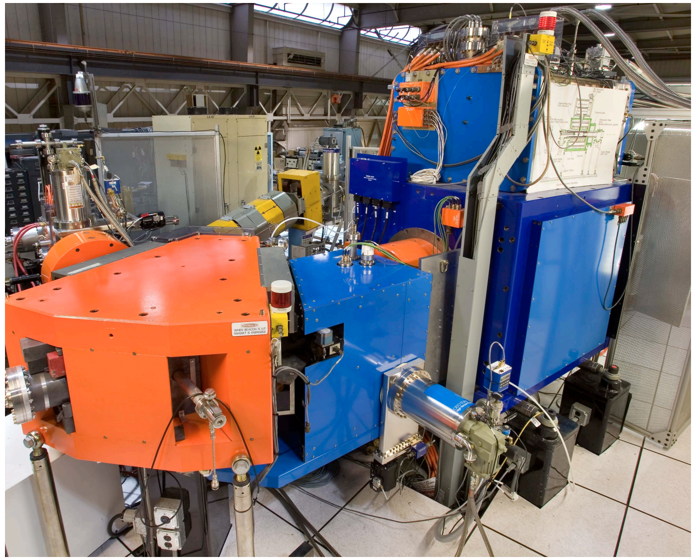
- VENUS' exceeding of earlier RIA requirements also allowed FRIB to be designed for lower cost since for linear accelerators:

$$KE \propto Q$$

- A duplicate of VENUS is currently being constructed for FRIB

Significance and impact of ECR ion sources at LBNL



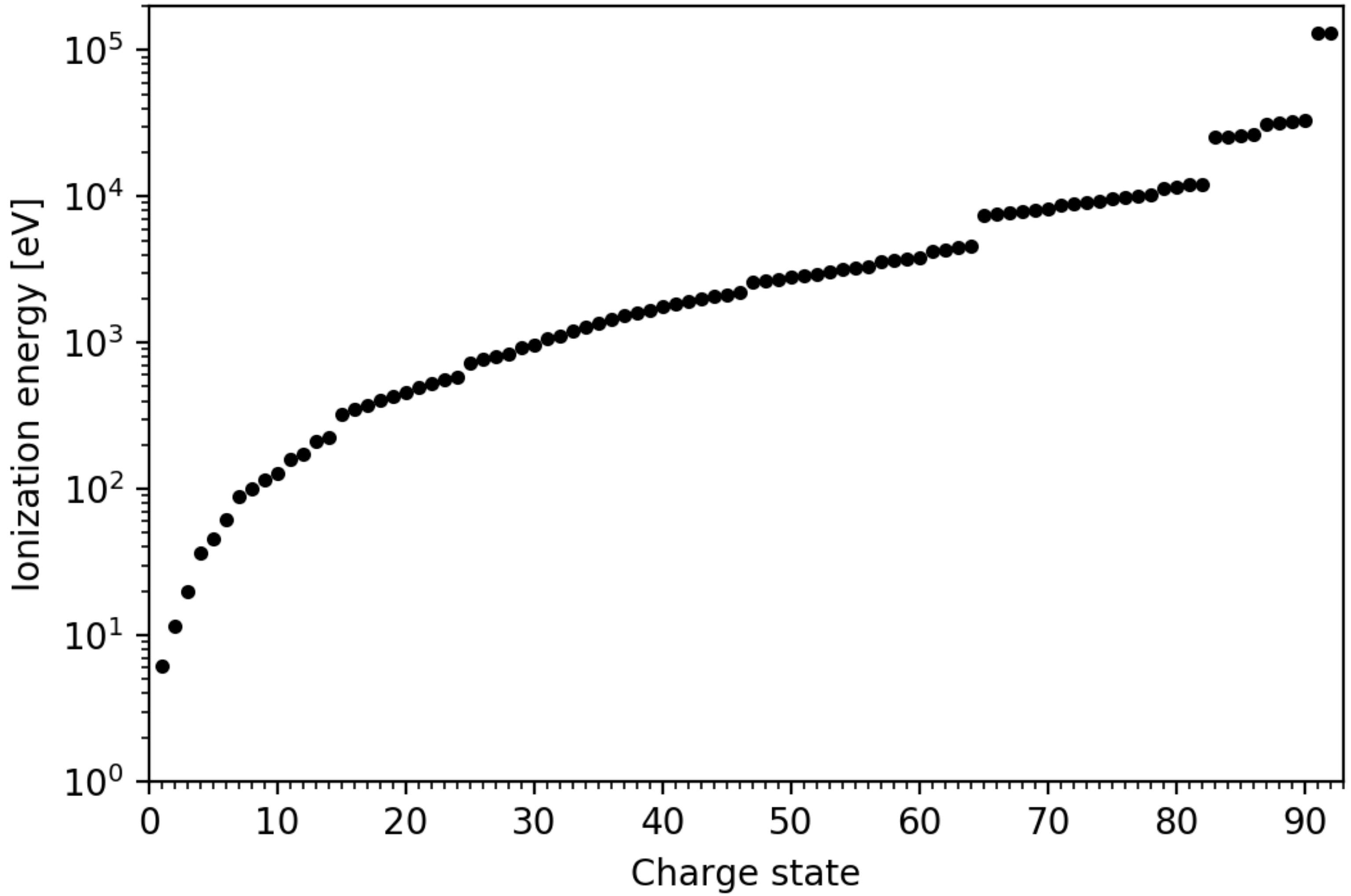


"VENUS" ion source

- World's first third-generation ECR ion source
- Fully-superconducting

What one is trying to do with a high-charge-state ECR ion source

Uranium ionization potential vs. charge state



Use energetic electrons to remove shell electrons from atoms

- Ionization potential rises significantly with charge state
- Ionization cross-section peaks for electrons with energies about 5x the ionization potential

How a modern ECR ion source works

Needs:

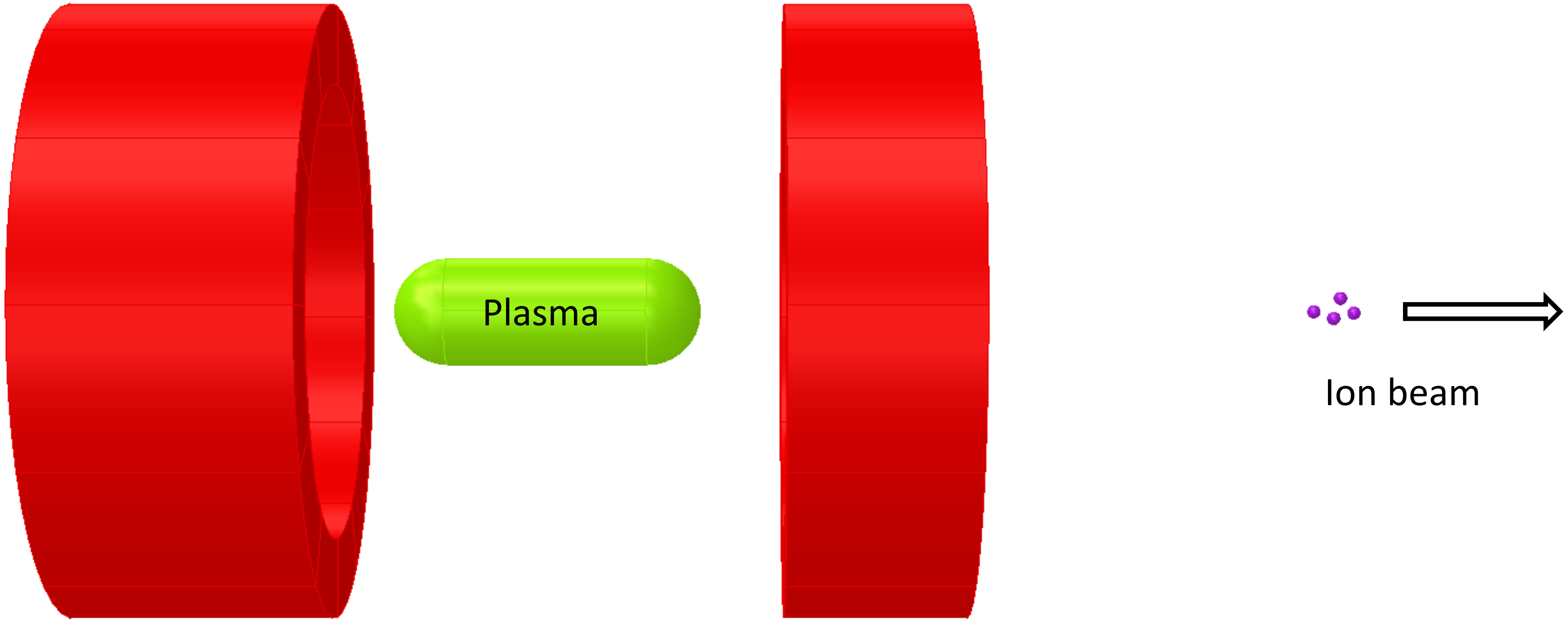
1. Confine plasma
2. Maintain plasma
3. Extract ions from plasma

How a modern ECR ion source works

Needs:

1. **Confine plasma** → **Use magnetic mirroring**
2. Maintain plasma
3. Extract ions from plasma

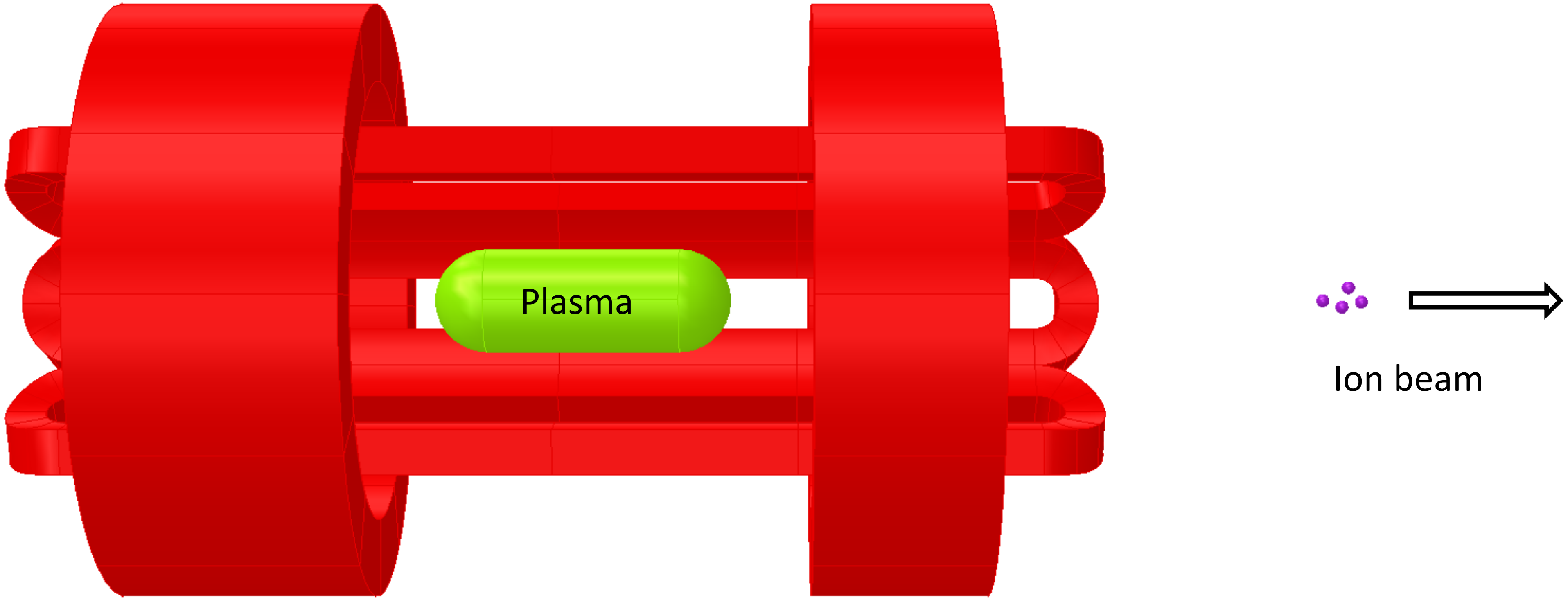
How a modern ECR ion source works



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

Use magnetic mirroring
- **Magnetic field increases axially via solenoids**

How a modern ECR ion source works



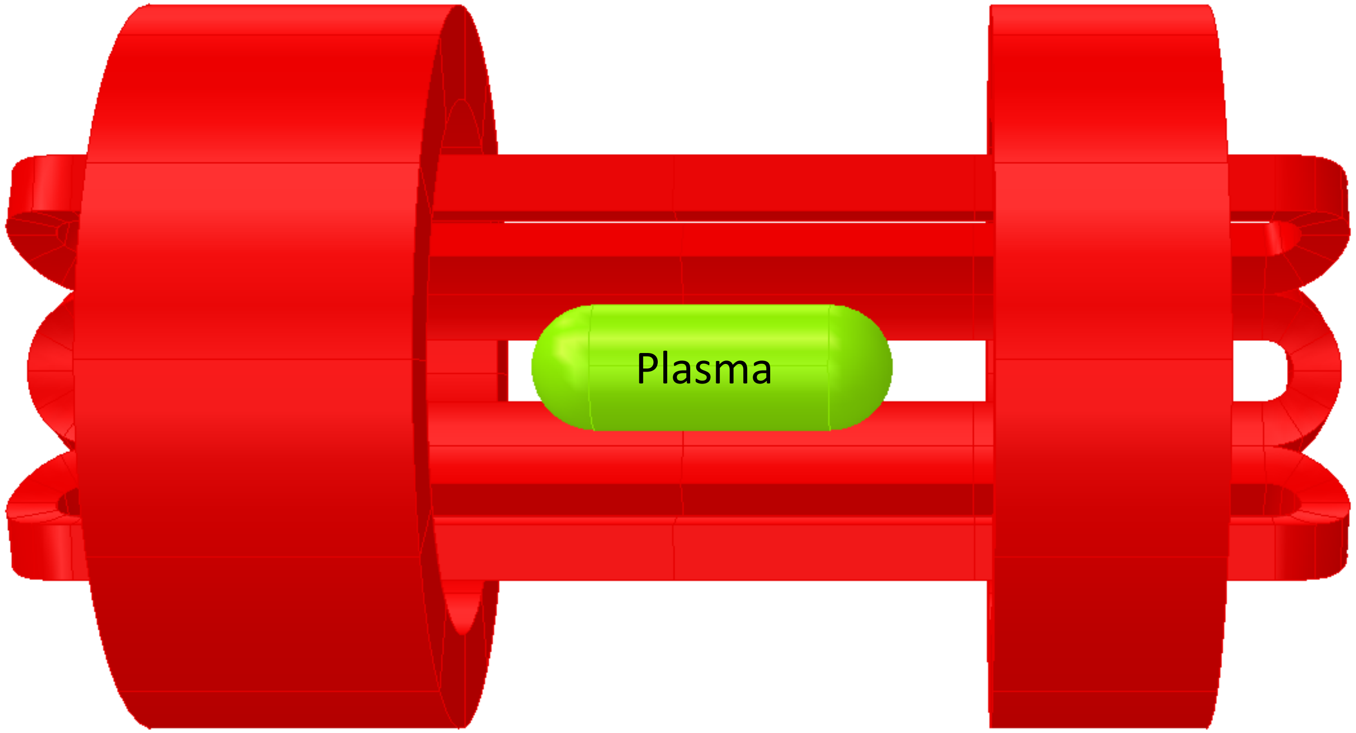
Needs:

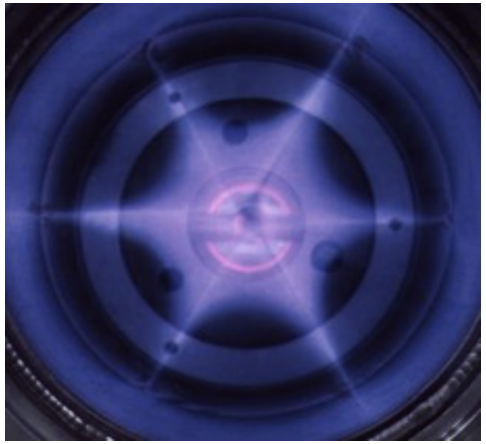
1. **Confine plasma**
2. Maintain plasma
3. Extract ions from plasma

Use magnetic mirroring

- Magnetic field increases axially via solenoids
- **Magnetic field increases radially via sextupoles**

How a modern ECR ion source works



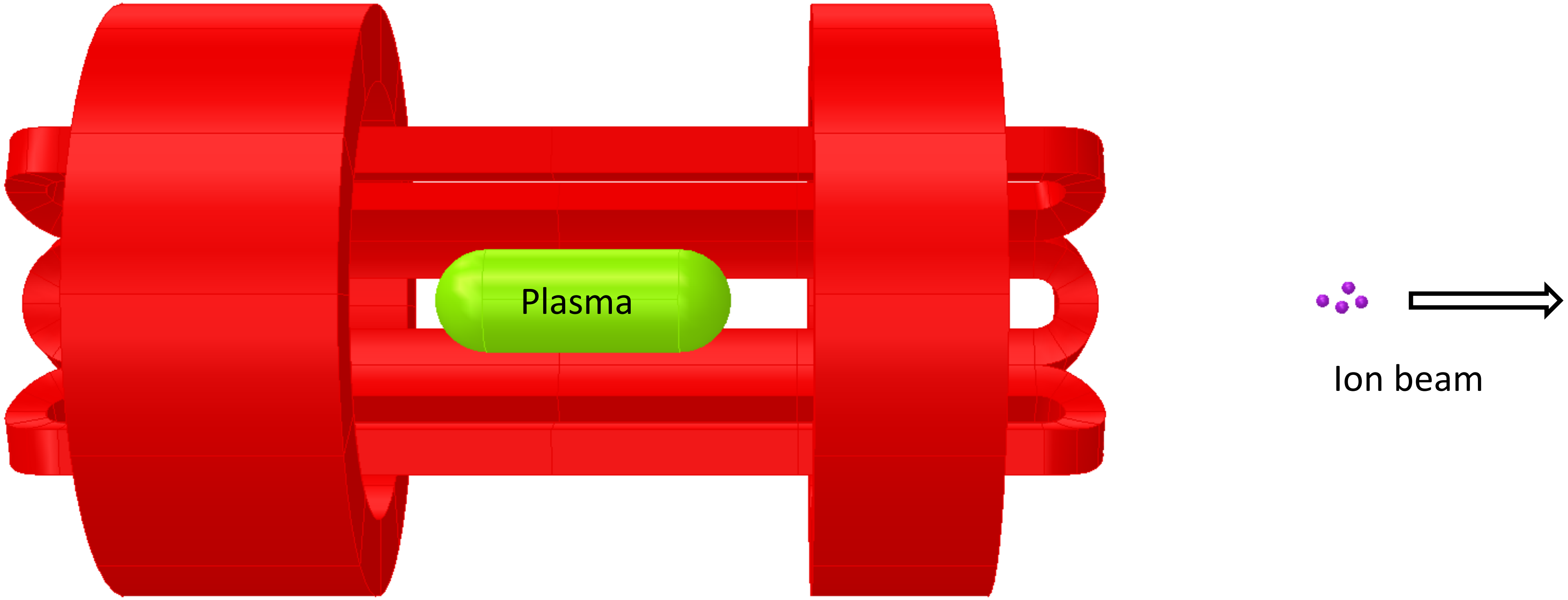


Real plasma shape

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

How a modern ECR ion source works

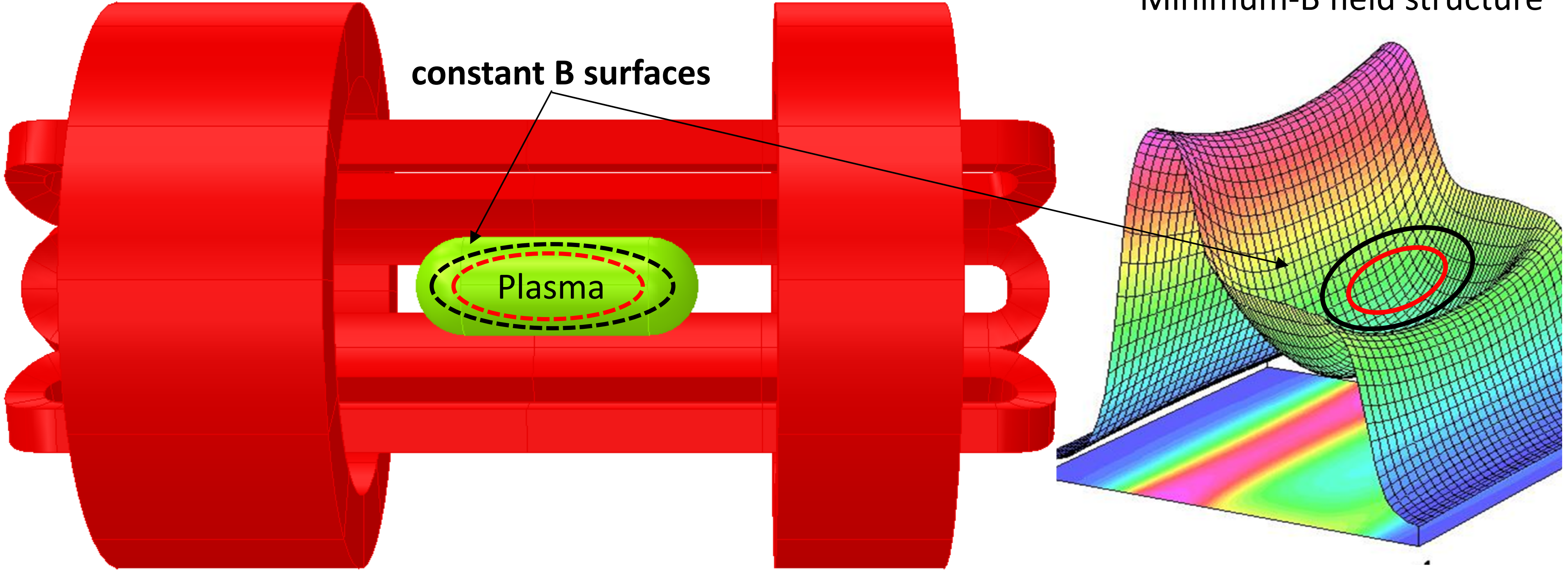


Needs:

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

How a modern ECR ion source works

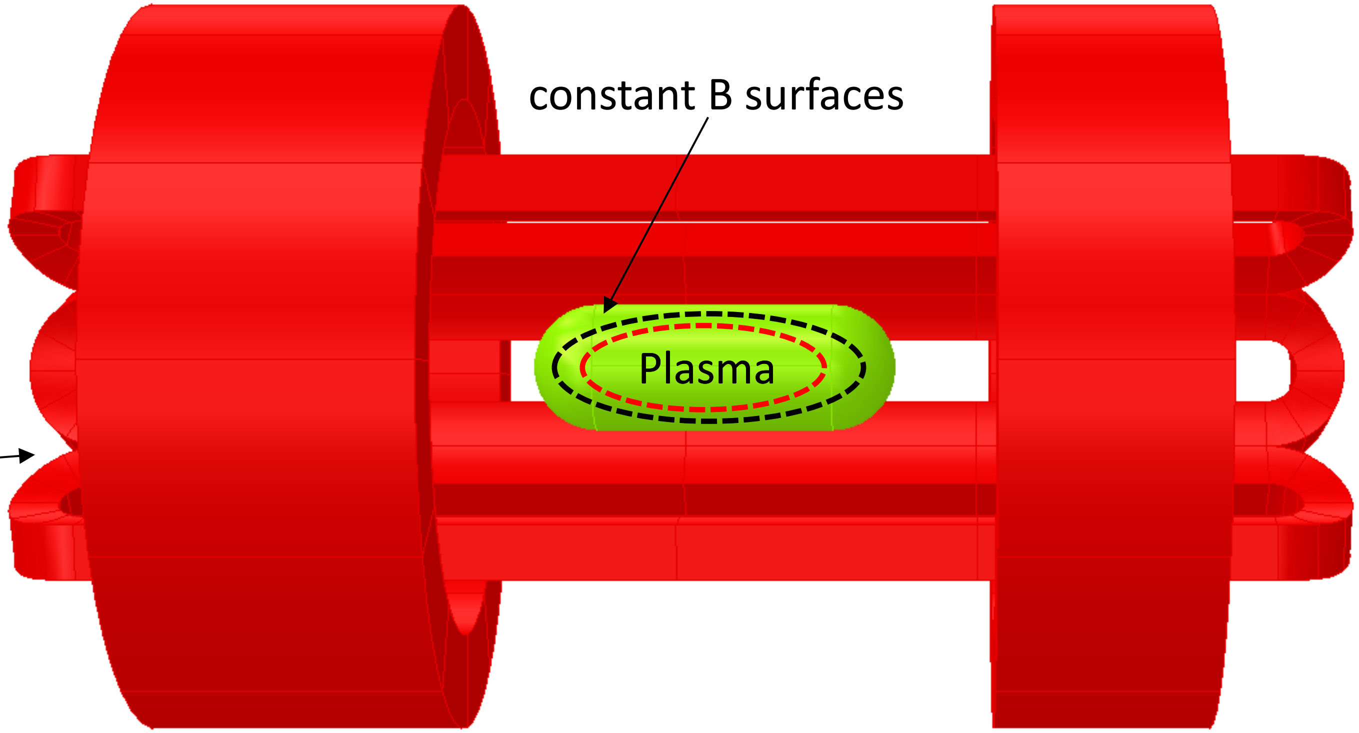
Minimum-B field structure



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

Magnetic field magnitude increases from source center

How a modern ECR ion source works



microwave heating

$$\omega_{rf} = \frac{eB_{res}}{m_e}$$

Ion beam

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

Magnetic field magnitude increases from source center

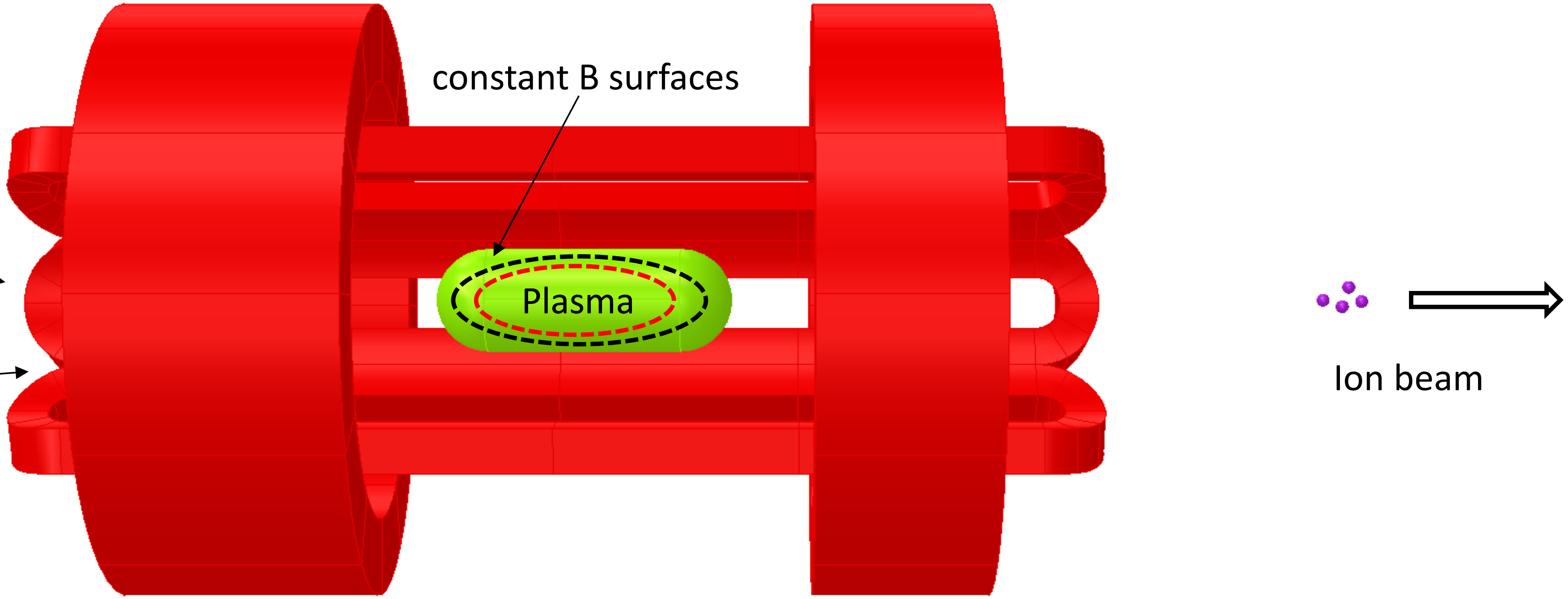
- **Resonantly heat electrons on closed surface to provide energy**

How a modern ECR ion source works

material

microwave heating

$$\omega_{rf} = \frac{eB_{res}}{m_e}$$



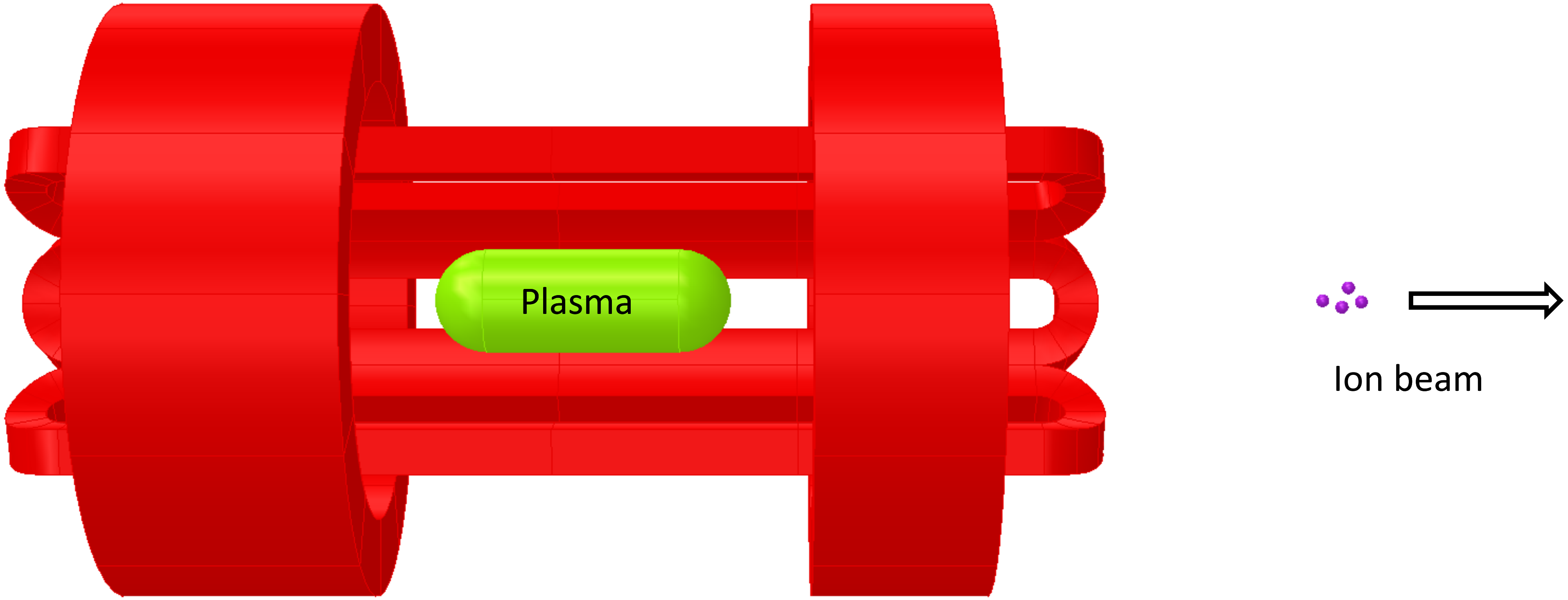
Needs:

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**.

How a modern ECR ion source works



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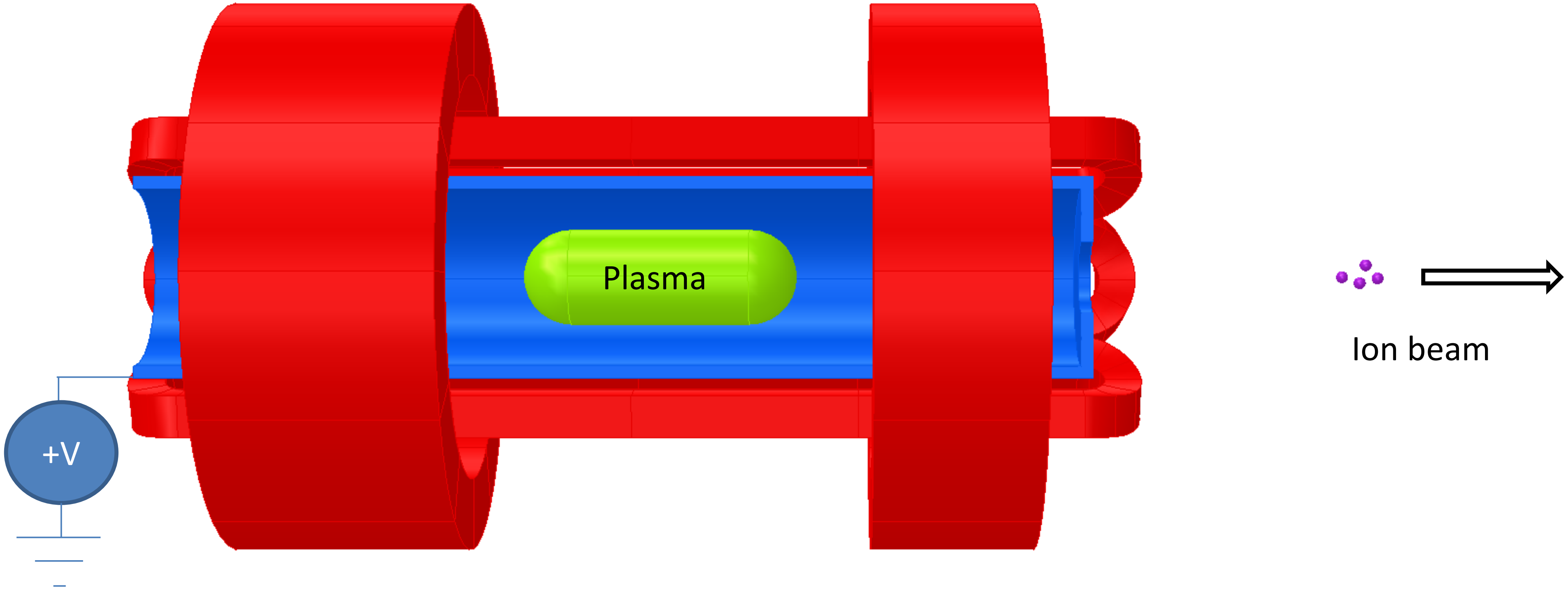
How a modern ECR ion source works

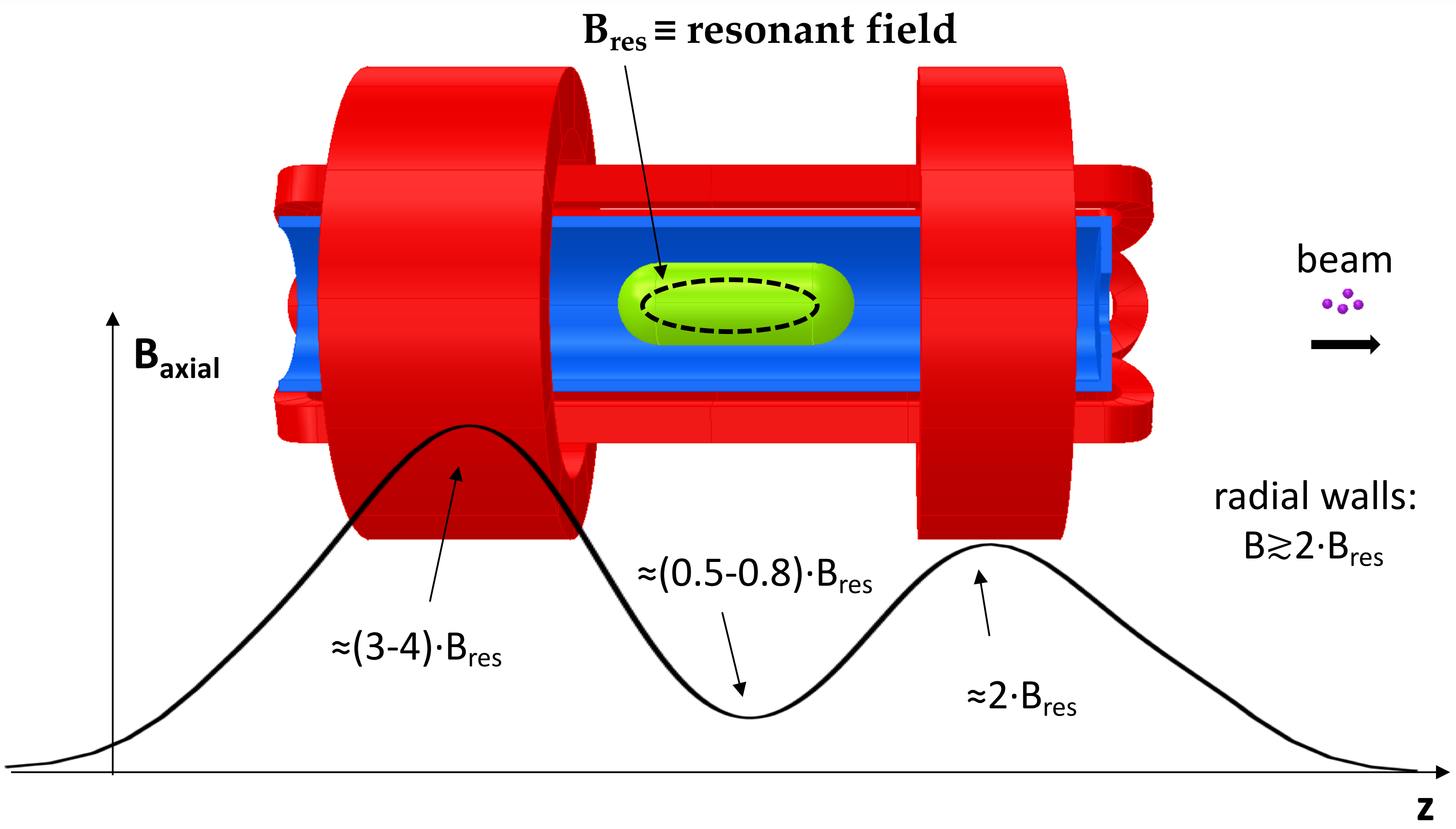


Needs:

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.

Recipe for an ECR ion source capable of making highly charged ions



Plus Richard Geller's semi-empirical scaling law:

$$I_q \propto n_e \propto B_{res}^2 \sim \omega_{rf}^2$$

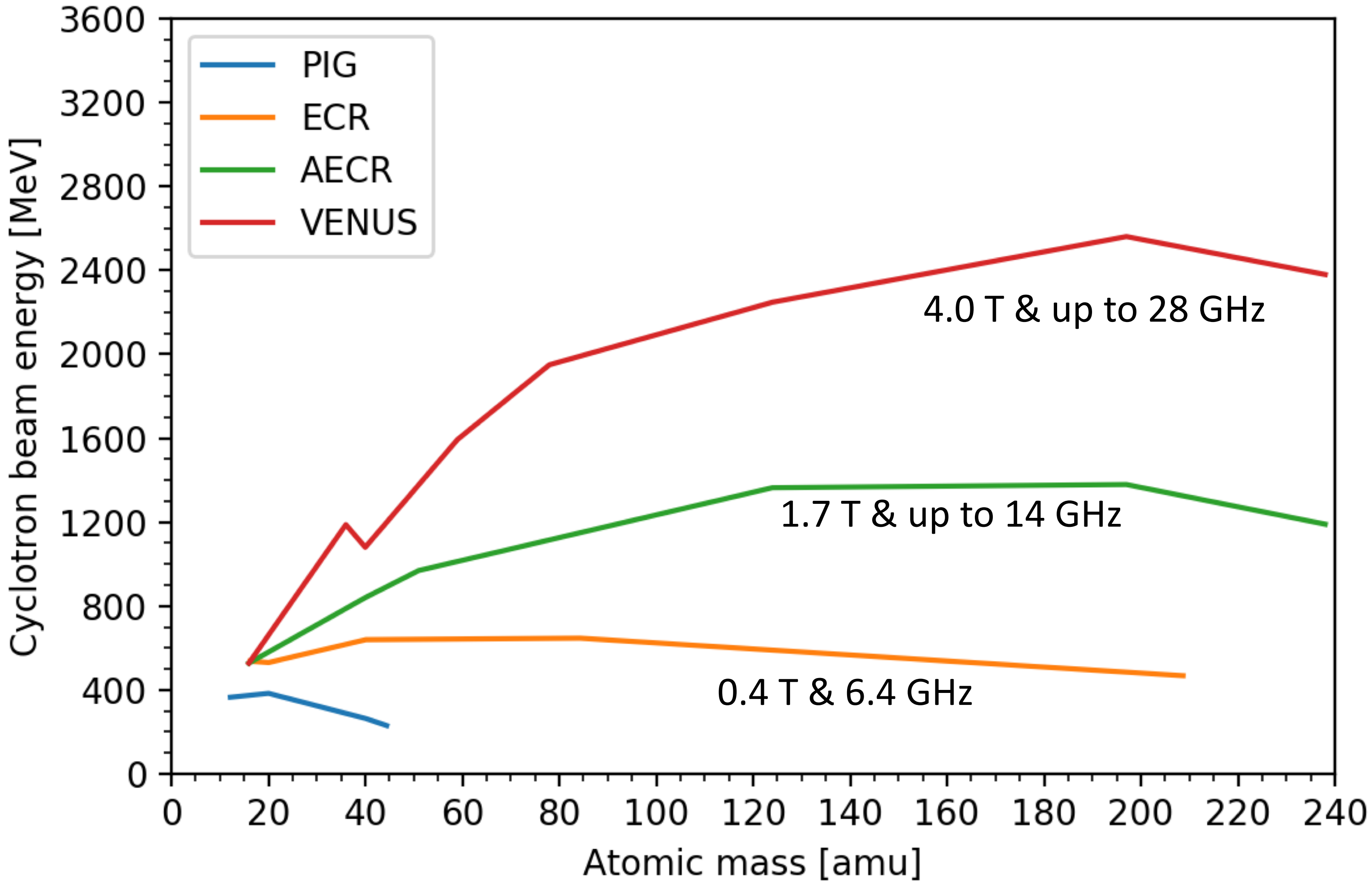
Increase resonance field/heating frequency

Get higher electron density

Which creates more high-charge-state ions

∴ Make the highest-field source you can having the properties on the left

Source improvement largely due to field/RF increases



$I_q \propto n_e \propto B_{res}^2 \sim \omega_{rf}^2$

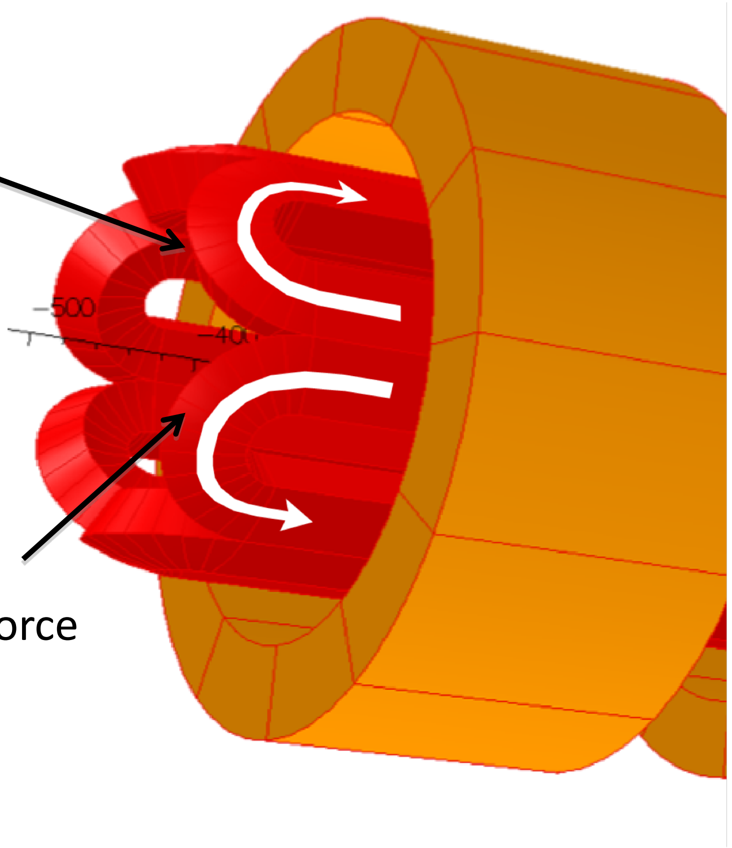
Why has VENUS remained atop the list of high-performing ECRs for 15+ years?

VENUS construction was not simple

Superconducting coils must not move:

ECR coils strongly interact

Strong outward force



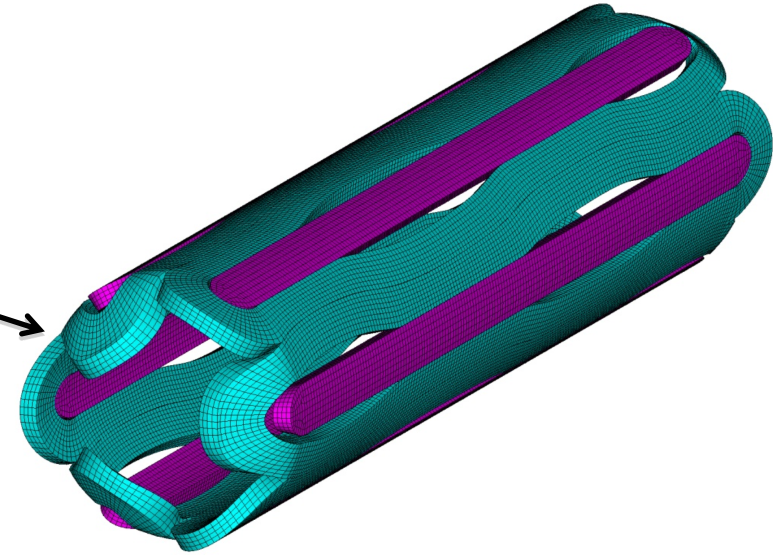
Strong inward force

Solution:

Make longer sextupoles to reduce forces.

New problem: “wavy” forces along sextupole straight sections

Displacement Exaggerated x100 for Illustration



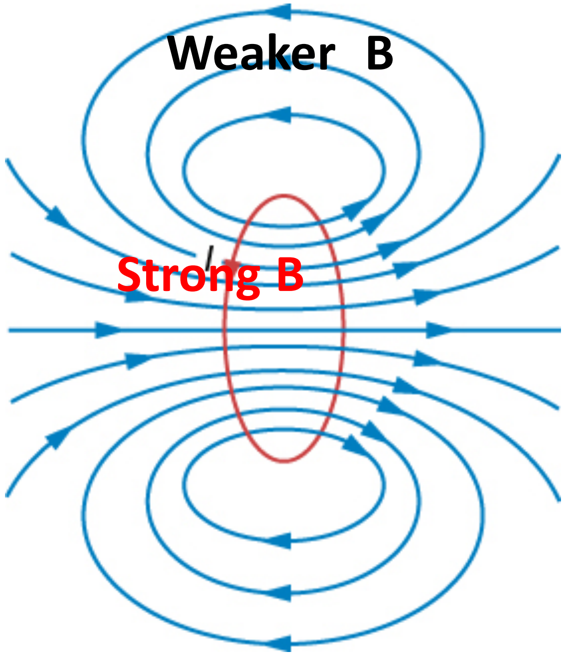
Ultimate solution for VENUS:

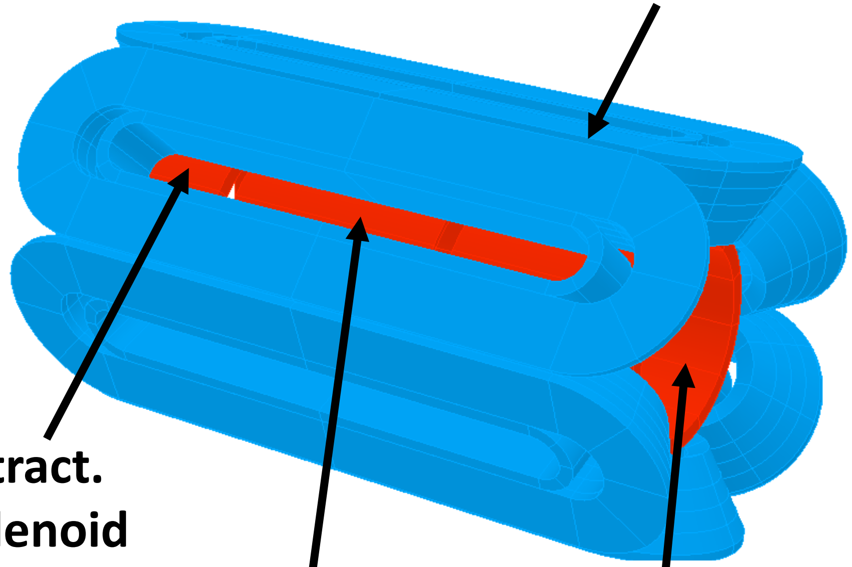
Longer sextupoles with liquid-metal filled bladders to prevent motion

Minimizing forces on sextupole

Dan Xie came up with the idea of inverting traditional design.

- Sextupole outside of solenoid where fields are weaker
- Solenoid clamping is more straightforward than sextupoles
- No liquid-metal bladders needed!!



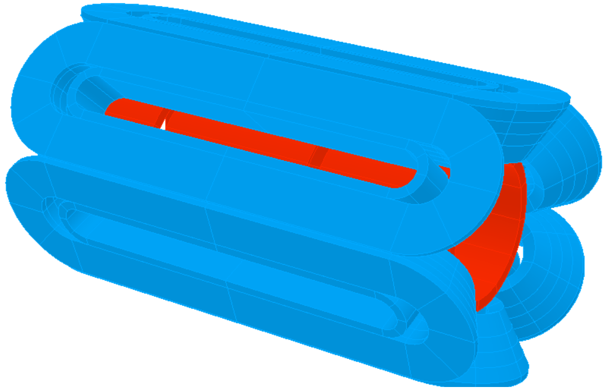


SECRAL ion sources at IMP in Lanzhou, China

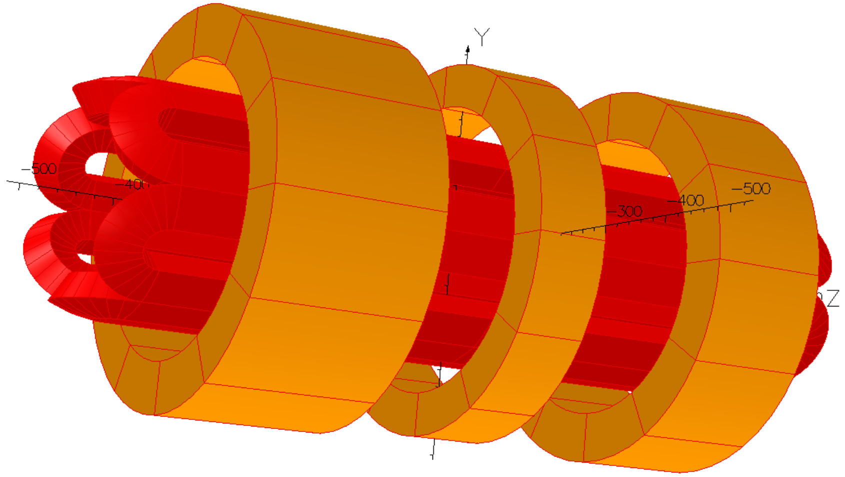
- 3.7 T, 24-28 GHz

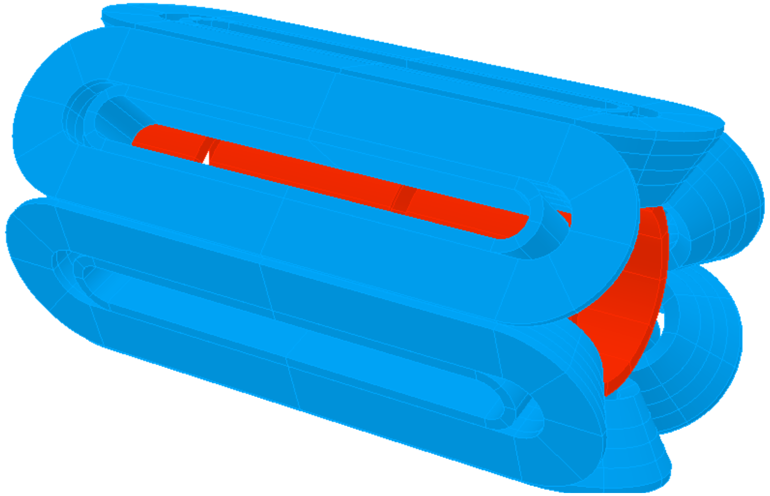
Performance of SECRAL-II nearly identical to VENUS

- Lesson 1: Plasma doesn’t care how field is made
- Lesson 2: Two sources means more time tuning



Limits of conventional source design with NbTi



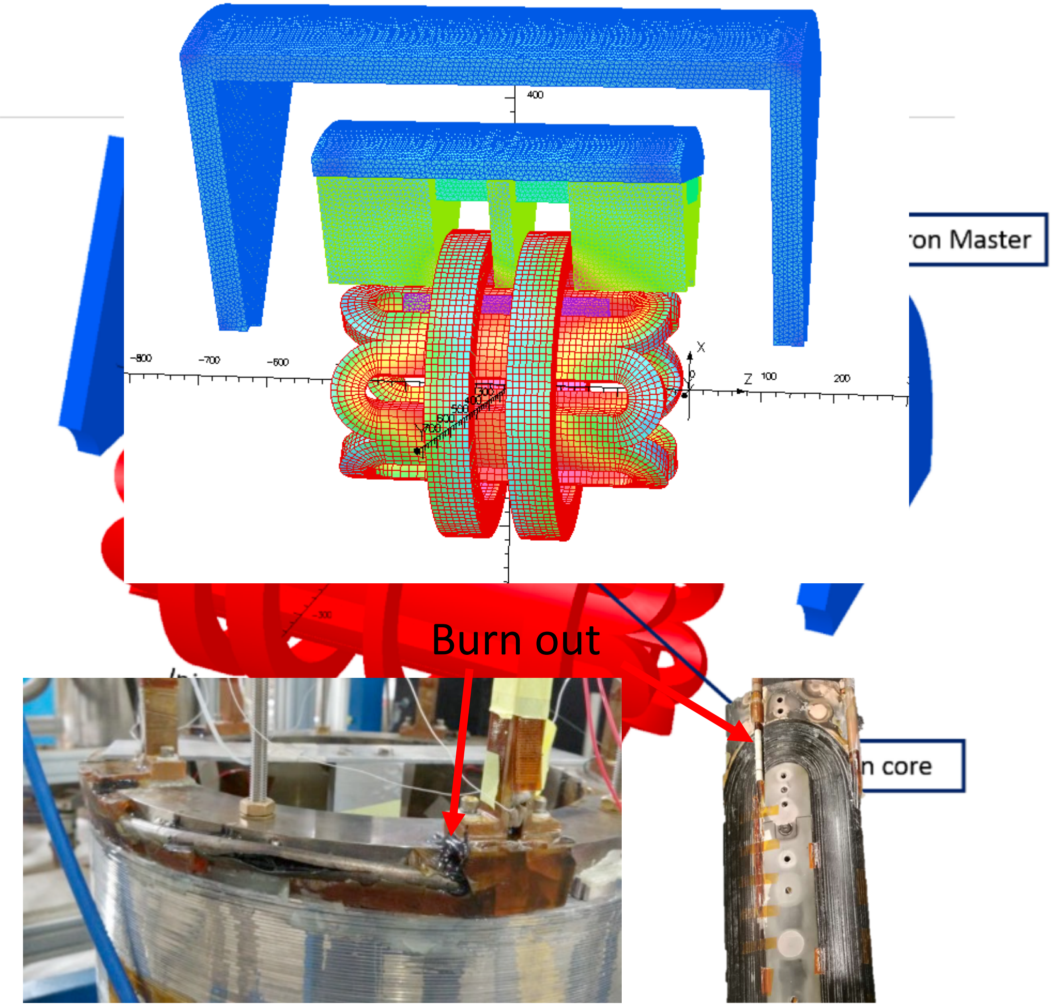


VENUS and SECRAL-II have reached limits of NbTi superconductor in these two coil configurations

Options to move to next-generation:

1. Build a source with a superconductor capable of higher field operation
2. Be creative with NbTi

Option 1: different superconductor



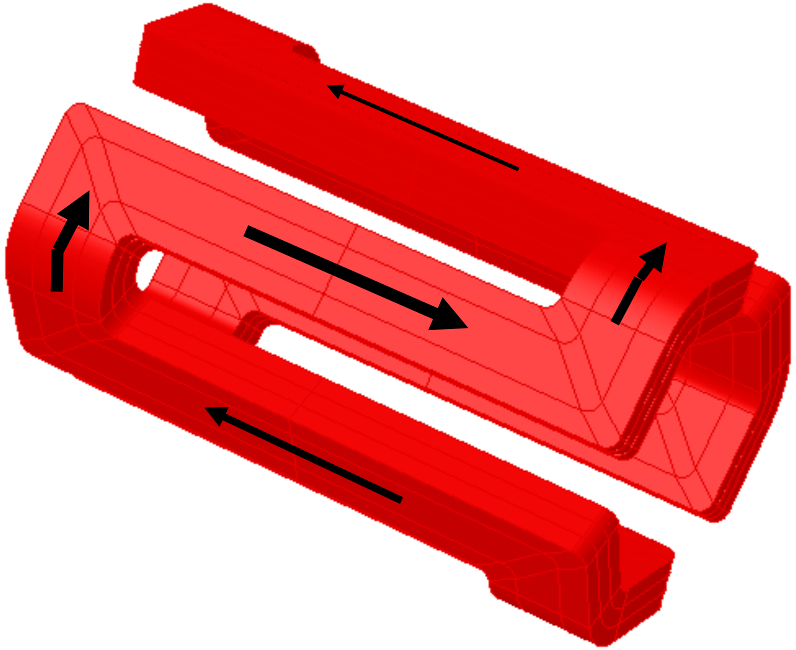
Solenoid

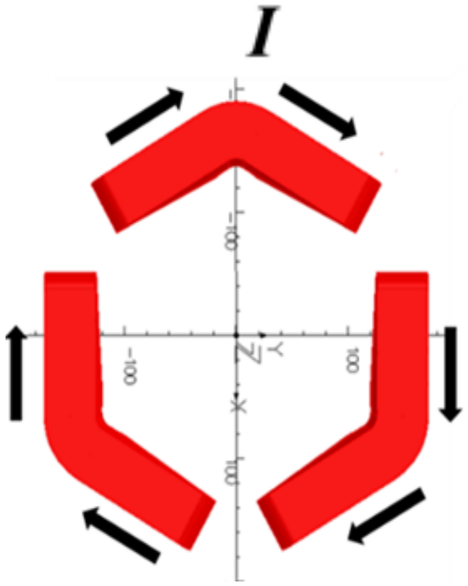
Sextupole

IMP (Lanzhou, China) is the only laboratory currently pursuing a fourth-generation ECRIS

- VENUS-like structure with Nb_3Sn coils, an unproven material for such a complicated magnet
- IMP is working to wind and energize a smaller test magnet…
- …but has encountered great difficulty in coil clamping leading to coil failures

Option 2: get more out of NbTi

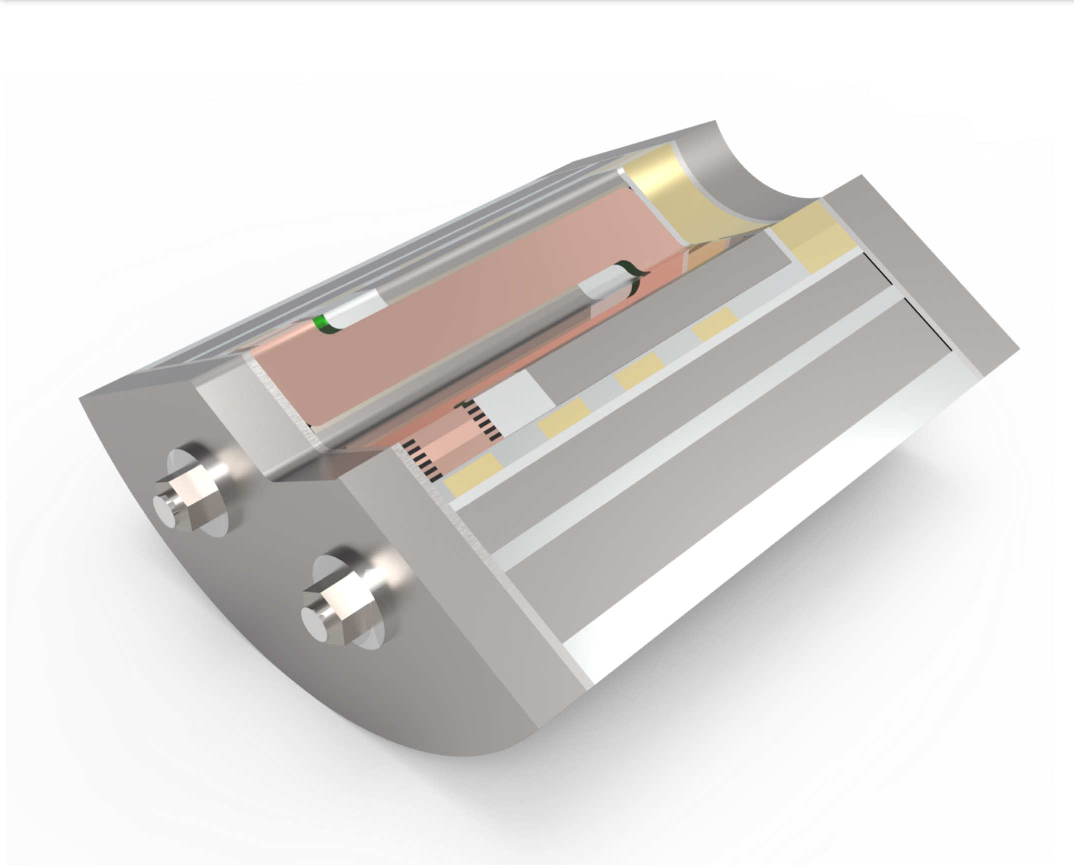




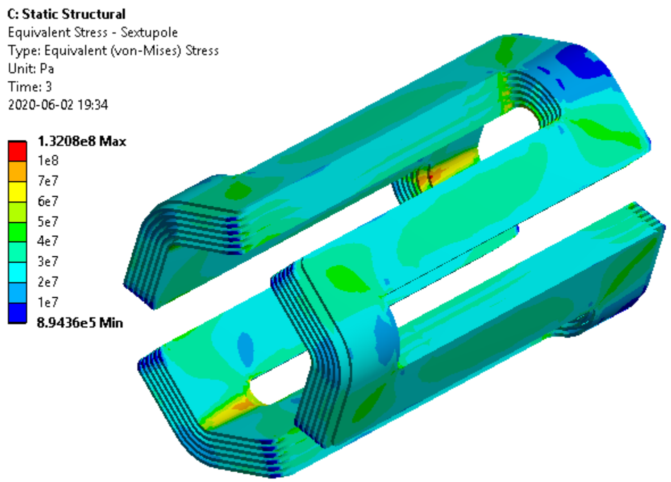
Dan Xie's MARS (Mixed Axial and Radial System) coil:

- Sextupole coil produces solenoid moment
- Capable of reaching fields for 45 GHz operation with NbTi
- Clamping is easier
- Winding is trickier

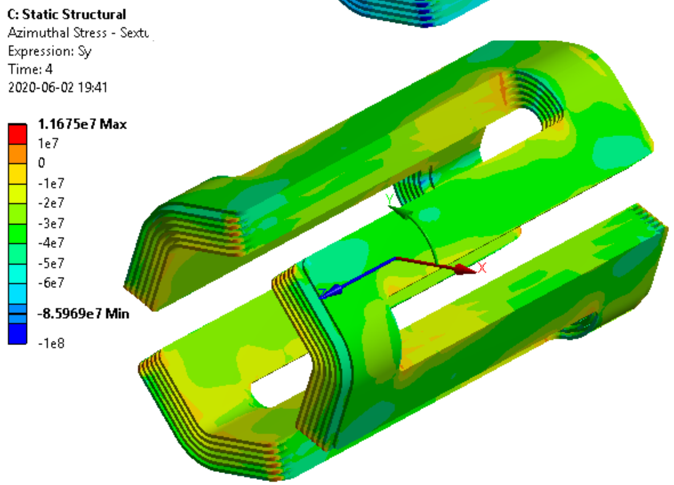
Engineering and stress analysis effort

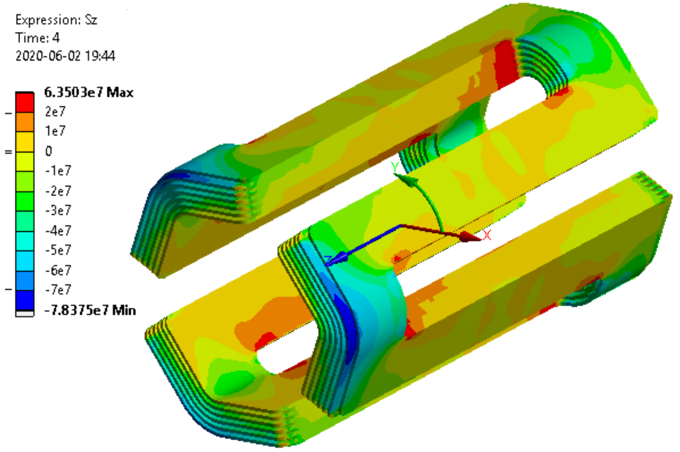


3D CAD model



Von Mises stress after cool-down < 132 MPa

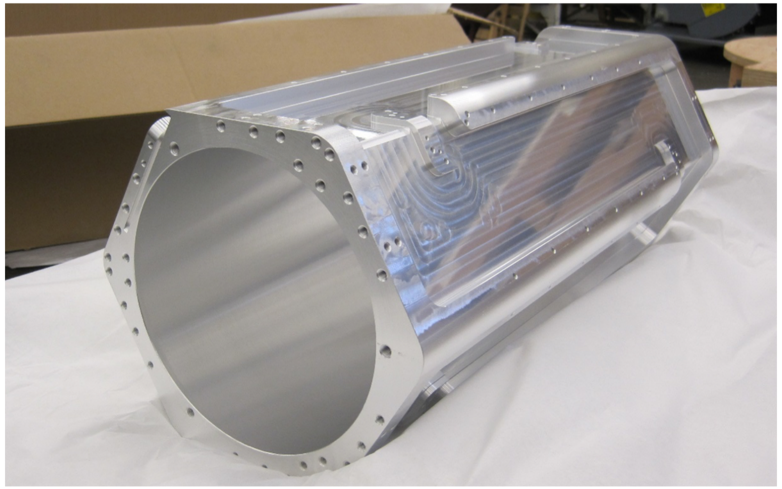




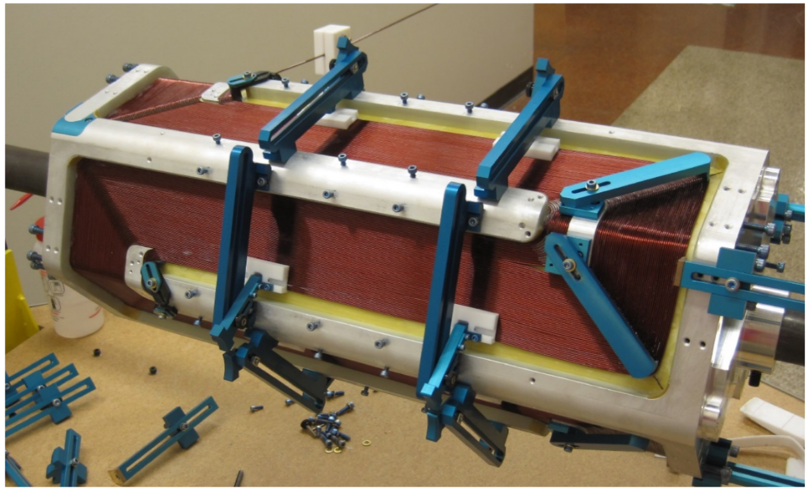
Azimuthal stress with magnetic forces
Coil **straight section** remain compressed (10-50 MPa)

Axial stress with magnetic forces
Coil **coil-ends** remain compressed (30-80 MPa)

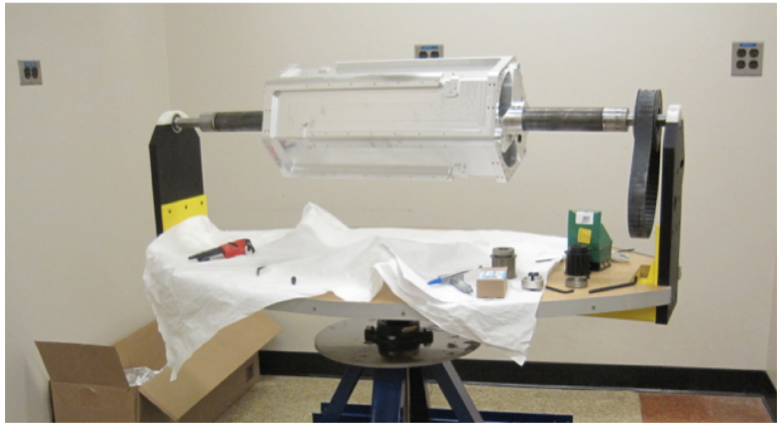
Test Winding



Winding Former - Manufactured



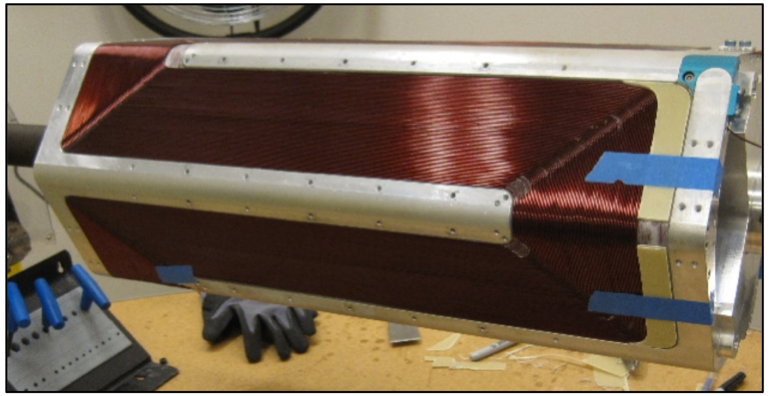
Winding in Progress



Winding Table & Tooling Assembled

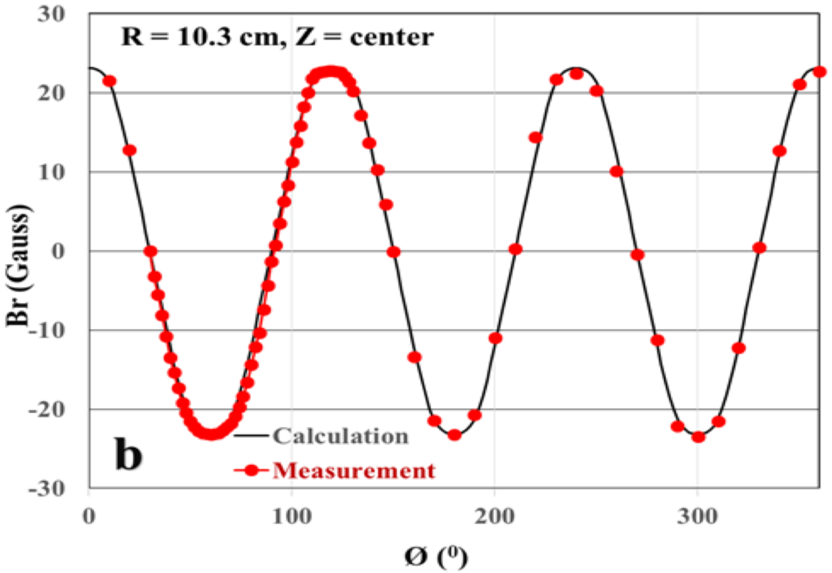
- Copper wire of same form factor as selected conductor
- Tooling refined during Test Winding
- Process refined during Test Winding

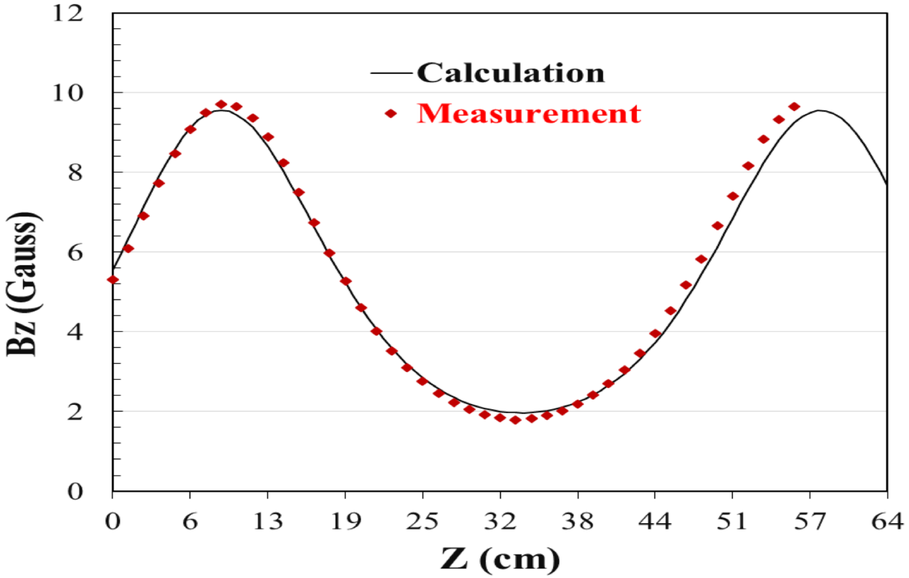
Test Winding

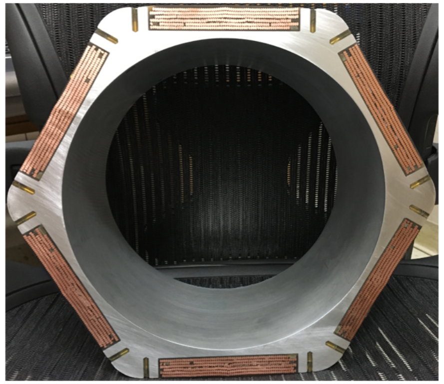


Completed Test Winding

- Completed, many lessons learned
- Windings potted with the use of a LBL-BCMT Vacuum Chamber
- Magnet measurements taken (Scaled to Magnetic Design)
- Coil cut up and examined:
  - Packing Factor
  - Vertical stacking / Keystoning
  - Conductor Straightness & Position







Cut & Polished Sections

MARS-D selected capabilities when heating increased to 15 kW

VENUS performance

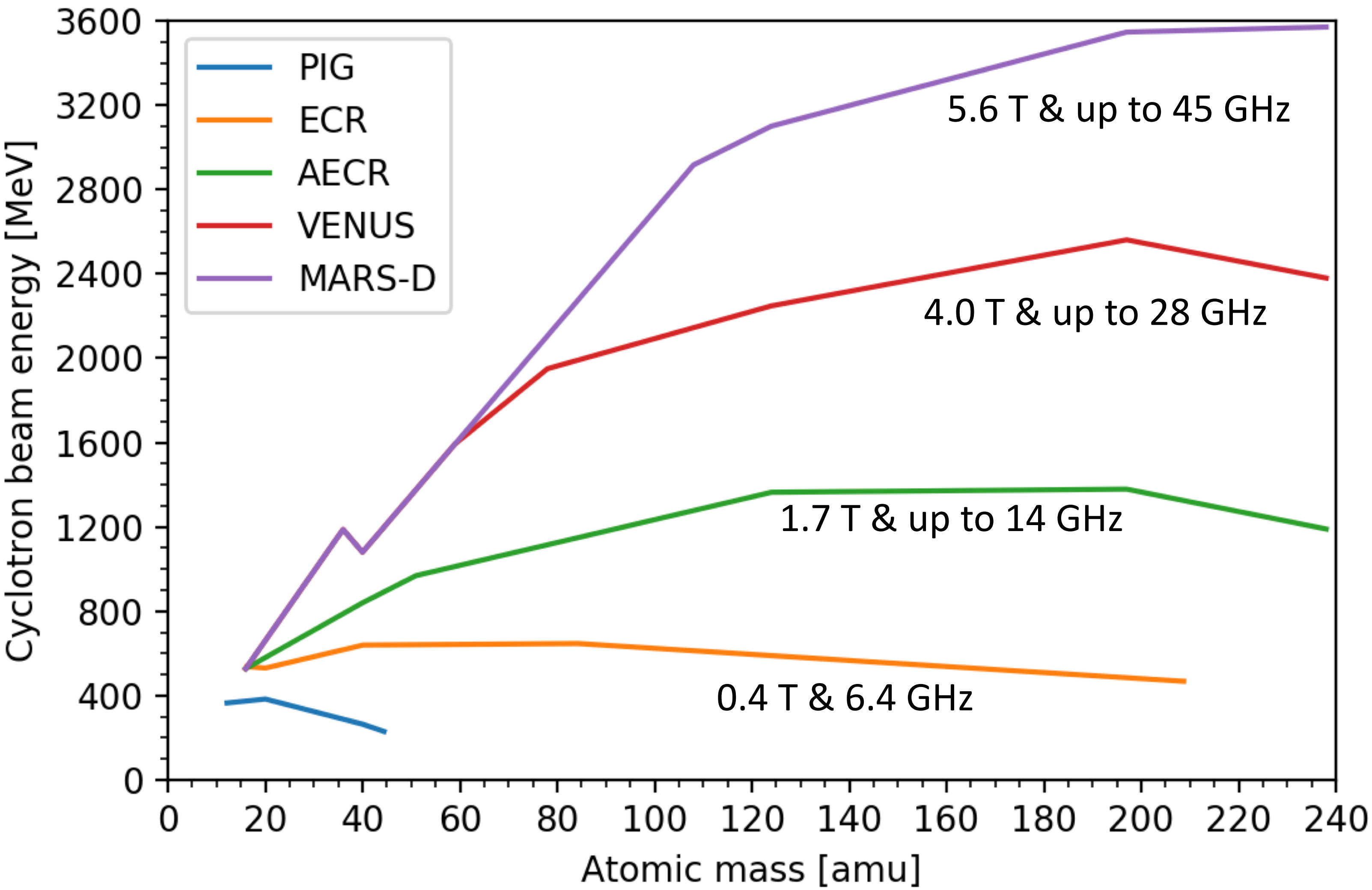
Ion	Ar^{14+}	Kr^{18+}	Xe^{30+}	Bi^{36+}	U^{41+}
I (eμA)	840	770	325	90	19

Expected MARS-D performance if 15 kW is coupled in

Ion	Ar^{14+}	Kr^{18+}	Xe^{30+}	Bi^{36+}	U^{41+}
I (eμA)	≥ 1000	≥ 1000	≥ 400	≥ 300	≥ 200

What does MARS-D provide for LBNL?

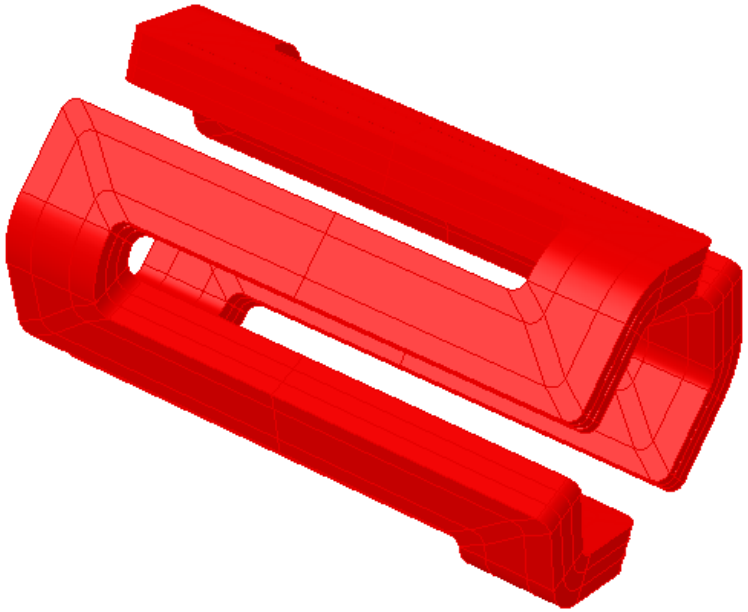
- Reestablishes LBNL as world leader in ECR ion source design and construction
- Higher current beams for super-heavy element research
- Higher energy beams for BASE facility (testing at air)
- Second source frees up time for high-performance ECRIS research



What does a 45 GHz MARS-D source provide outside LBNL?

- A means of significantly increasing the capabilities of existing heavy ion facilities
- An essential element for a future FRIB upgrade
- An ion source that will allow future heavy ion facilities to reach further in beam energy and power at a lower cost compared to simply building a bigger accelerator
- It provides path to 5^{th} generation (>60 GHz) ion source as high temperature superconductors become available

Conclusion



- A fourth-generation ECR ion source will significantly increase our ability to produce high-current, highly-charged ion beams
- MARS-D provides a sound path to a fourth-generation ECR ion source by utilizing well-tested materials while avoiding pitfalls one will encounter in a significant technology leap
- A completed MARS-D ion source will help achieve the mission of the DOE-NP program by increasing the capabilities of both current and future accelerators