Superconducting ECR ion sources: where things stand and how to move forward

Damon Todd

15 March 2022

Outline

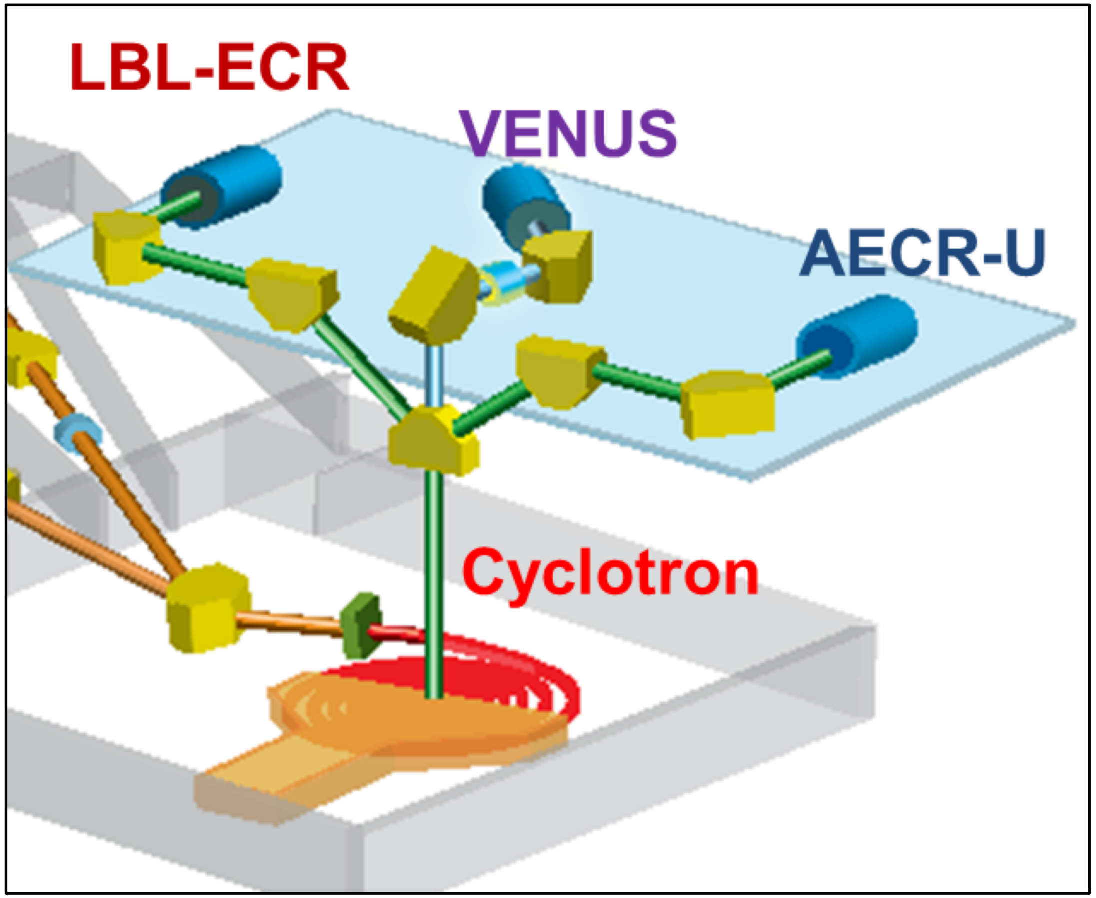
- Why electron cyclotron resonance (ECR) ion sources are important
- Where things stand
- Where to go from here

Why LBNL demonstrates the impact of ECR ion sources

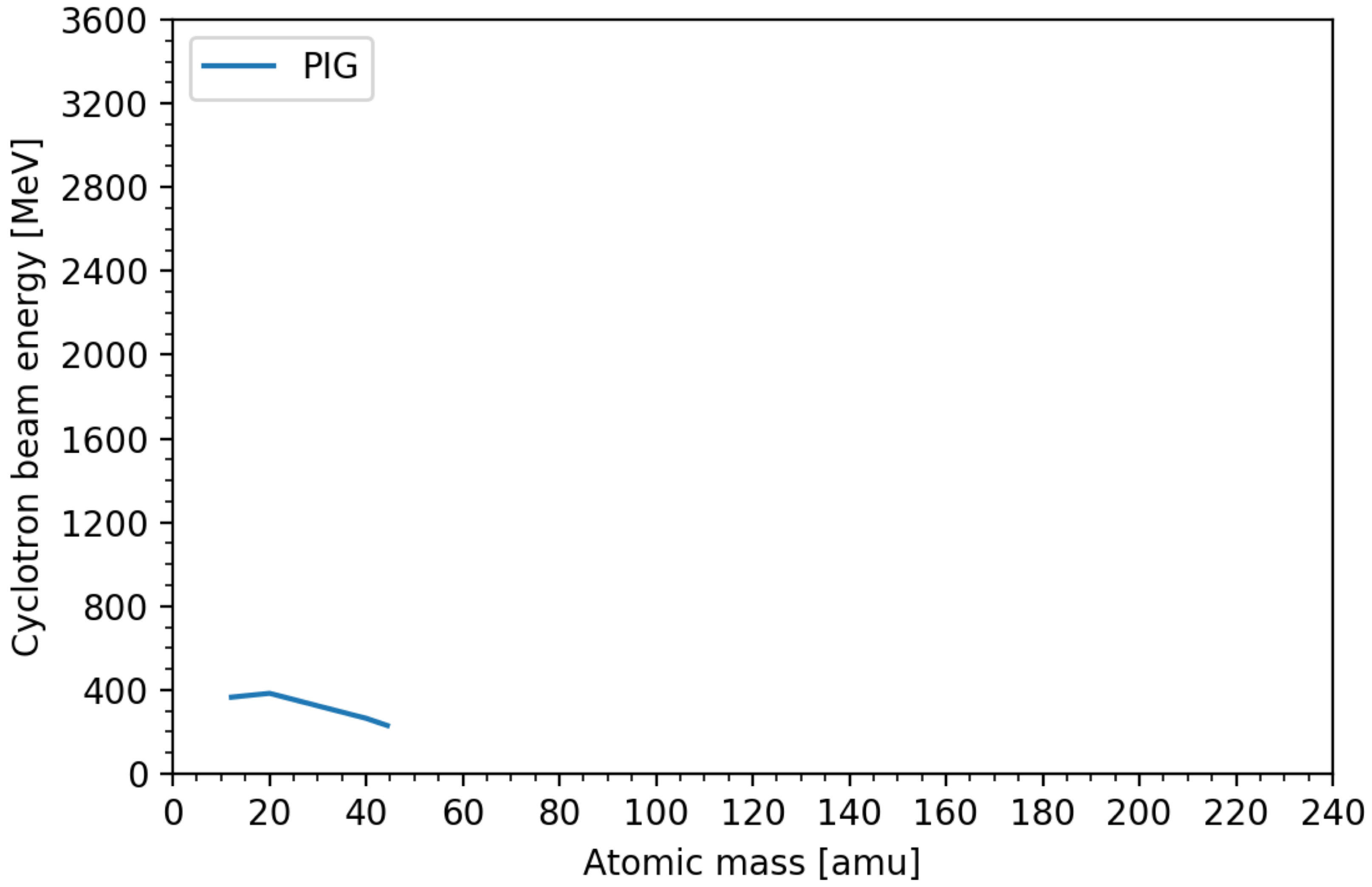
1. The 88” Cyclotron operated for over two decades before its first ECRIS

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



Impacts of ECR ion sources at the 88” Cyclotron

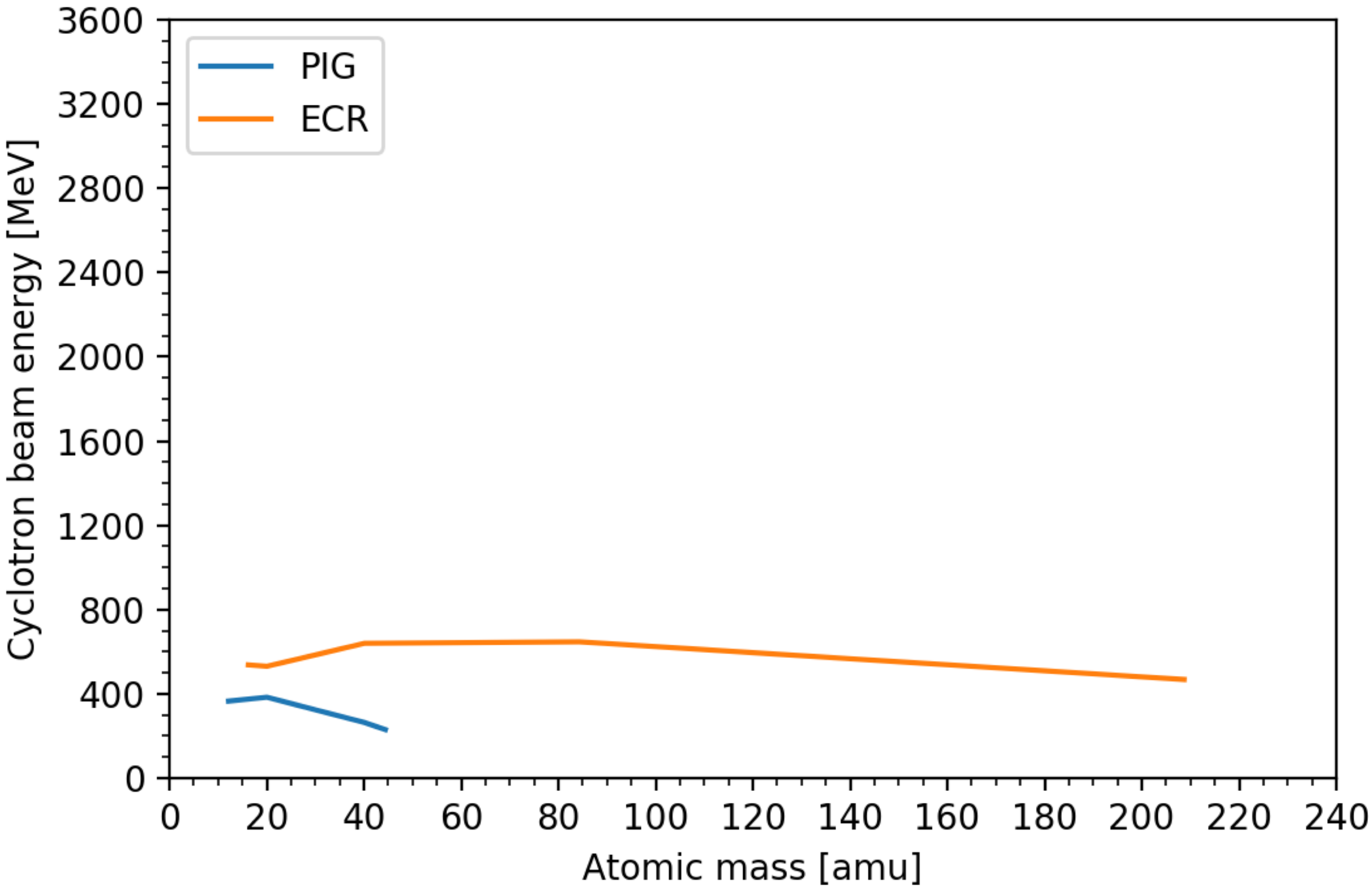


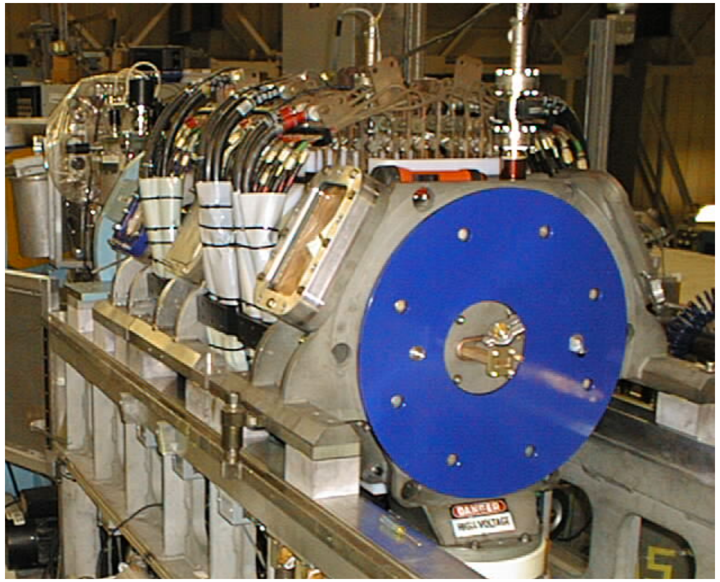
For the first 20+ years of operation, the 88” Cyclotron at LBNL used internal Penning or “PIG” sources

Shortcomings:

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

Impacts of ECR ion sources at the 88" Cyclotron

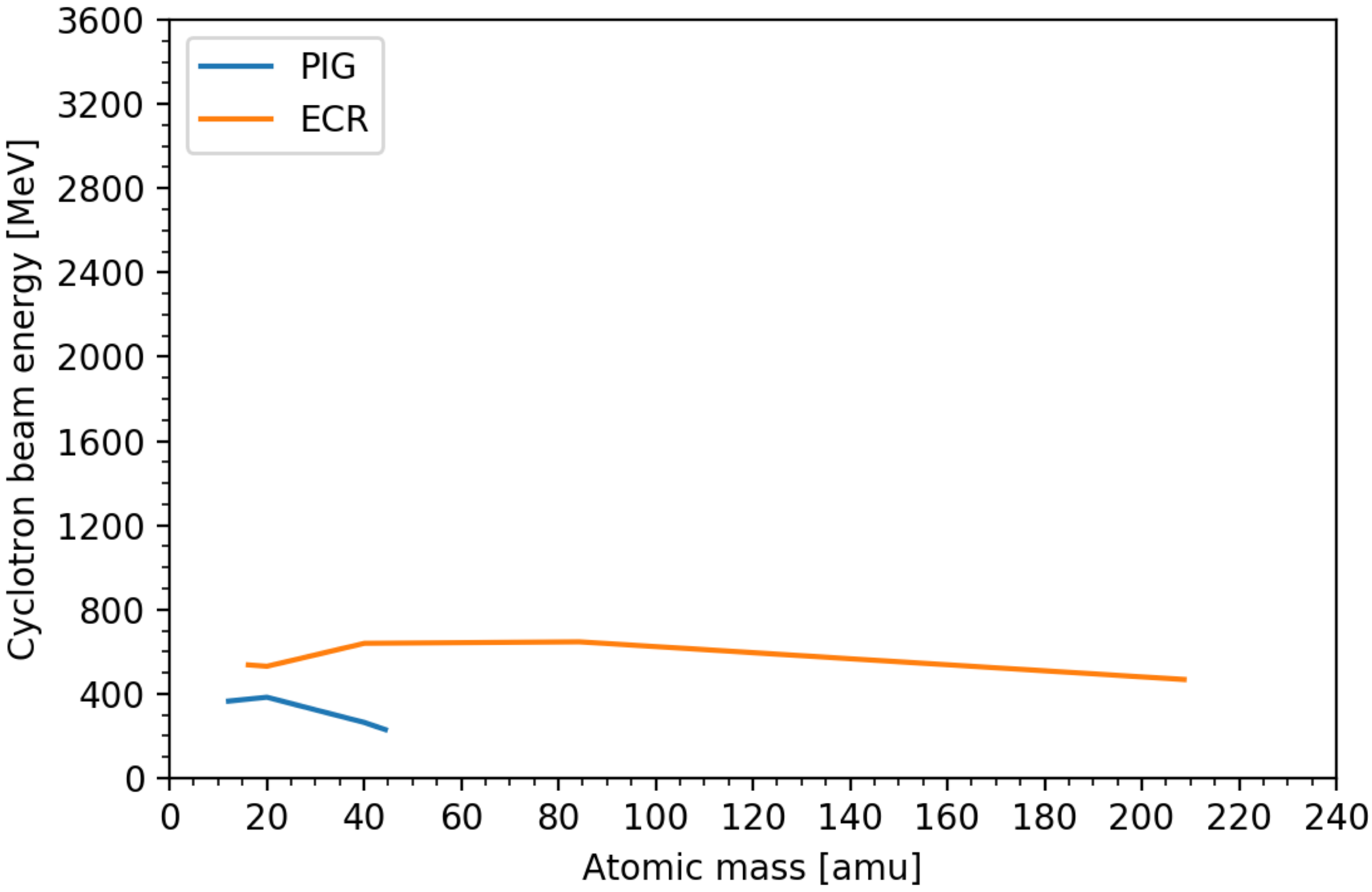




"LBL-ECR" ion source

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

Impacts of ECR ion sources at the 88” Cyclotron



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

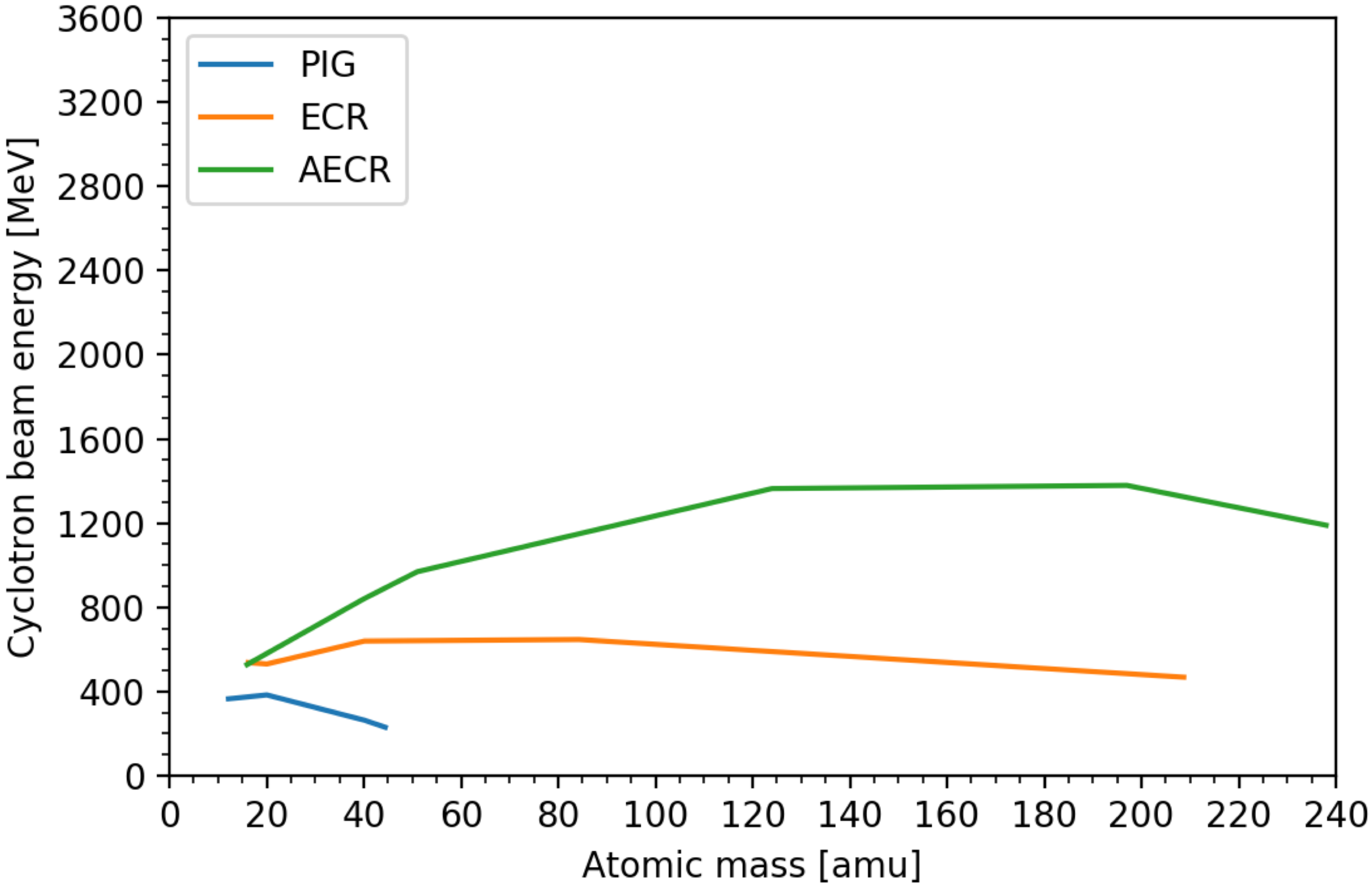
- Cyclotron accelerates a limited range of mass-to-charge ratios, so heavy ions must be more highly-charged to be accelerated

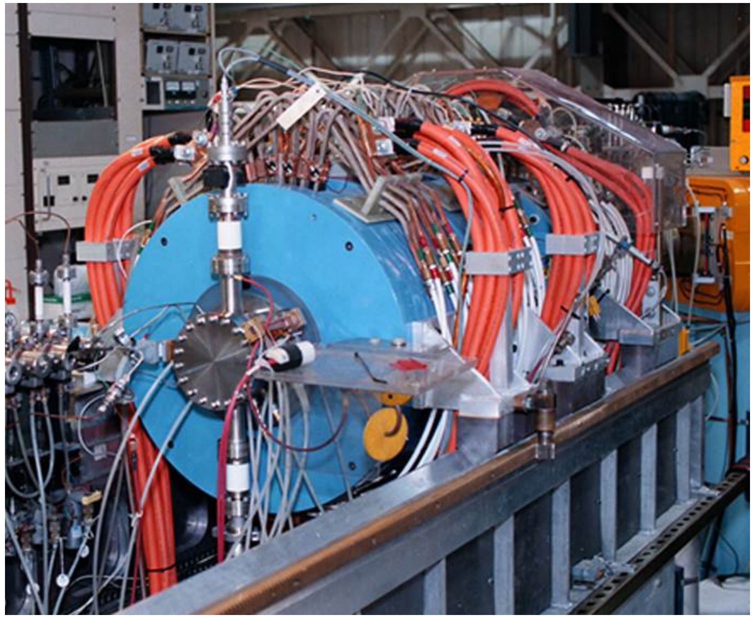
- Beam kinetic energies increase with Q for cyclotrons:

$$KE \propto Q^2$$

Missing from graph:
- ECRIS has no cathode, so continuous running for weeks

Impacts of ECR ion sources at the 88” Cyclotron

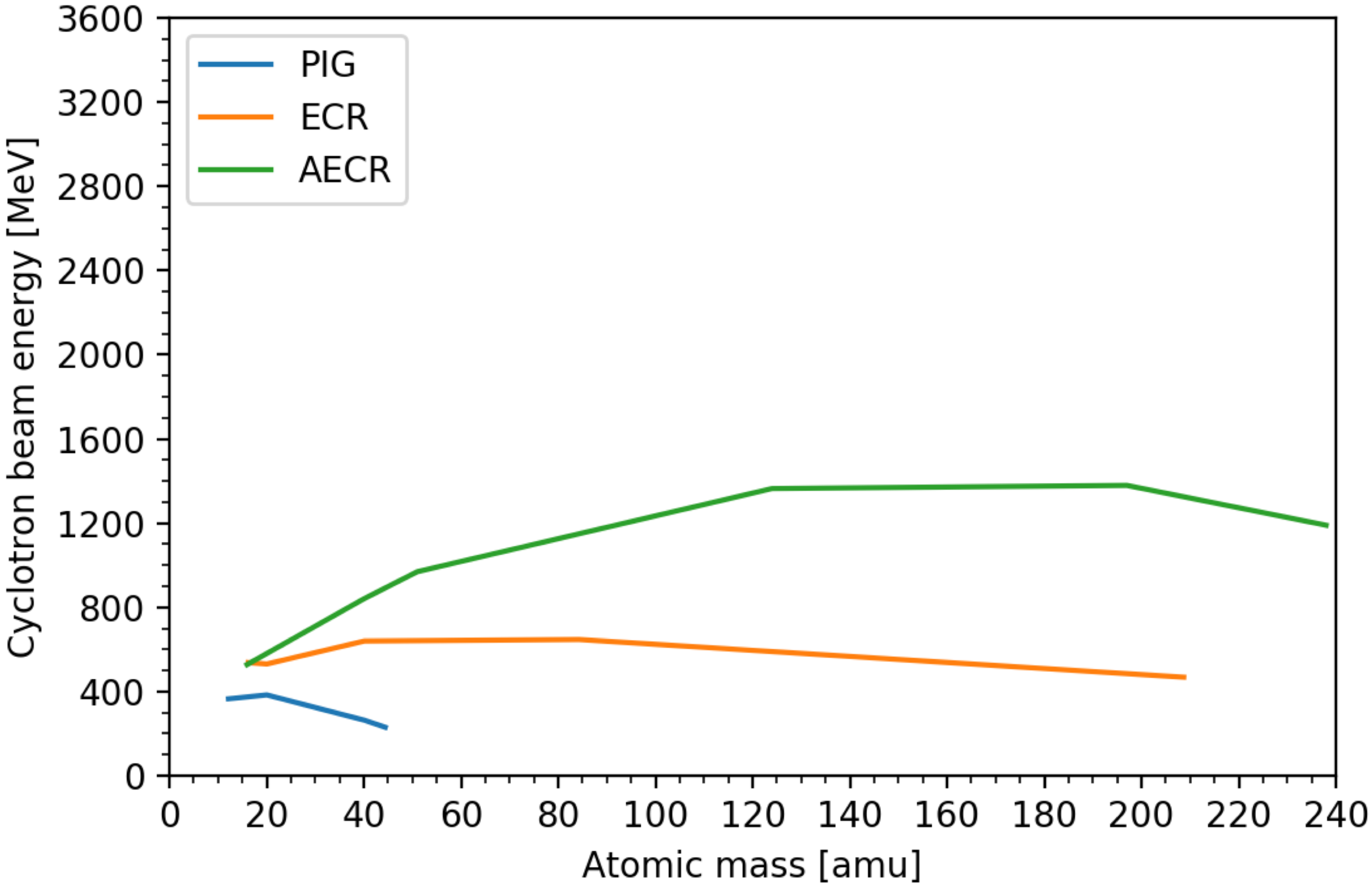


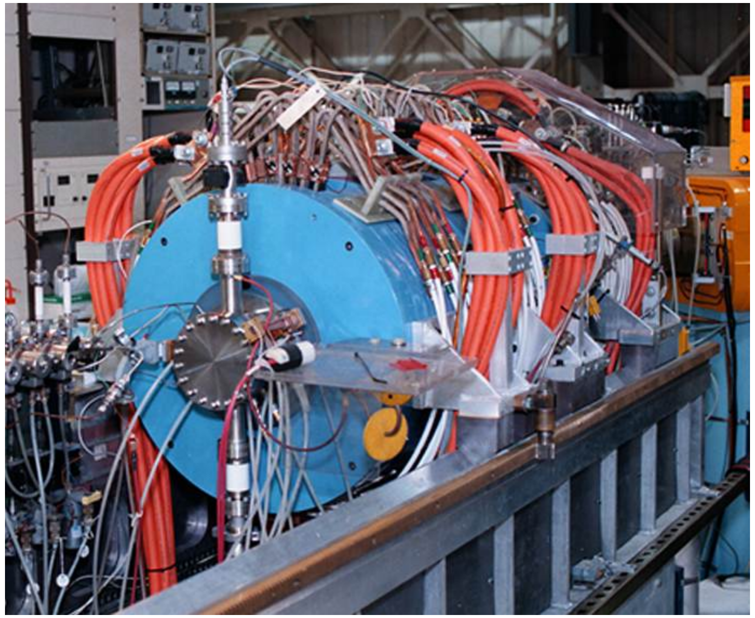


“AECR-U” ion source

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

Impacts of ECR ion sources at the 88" Cyclotron

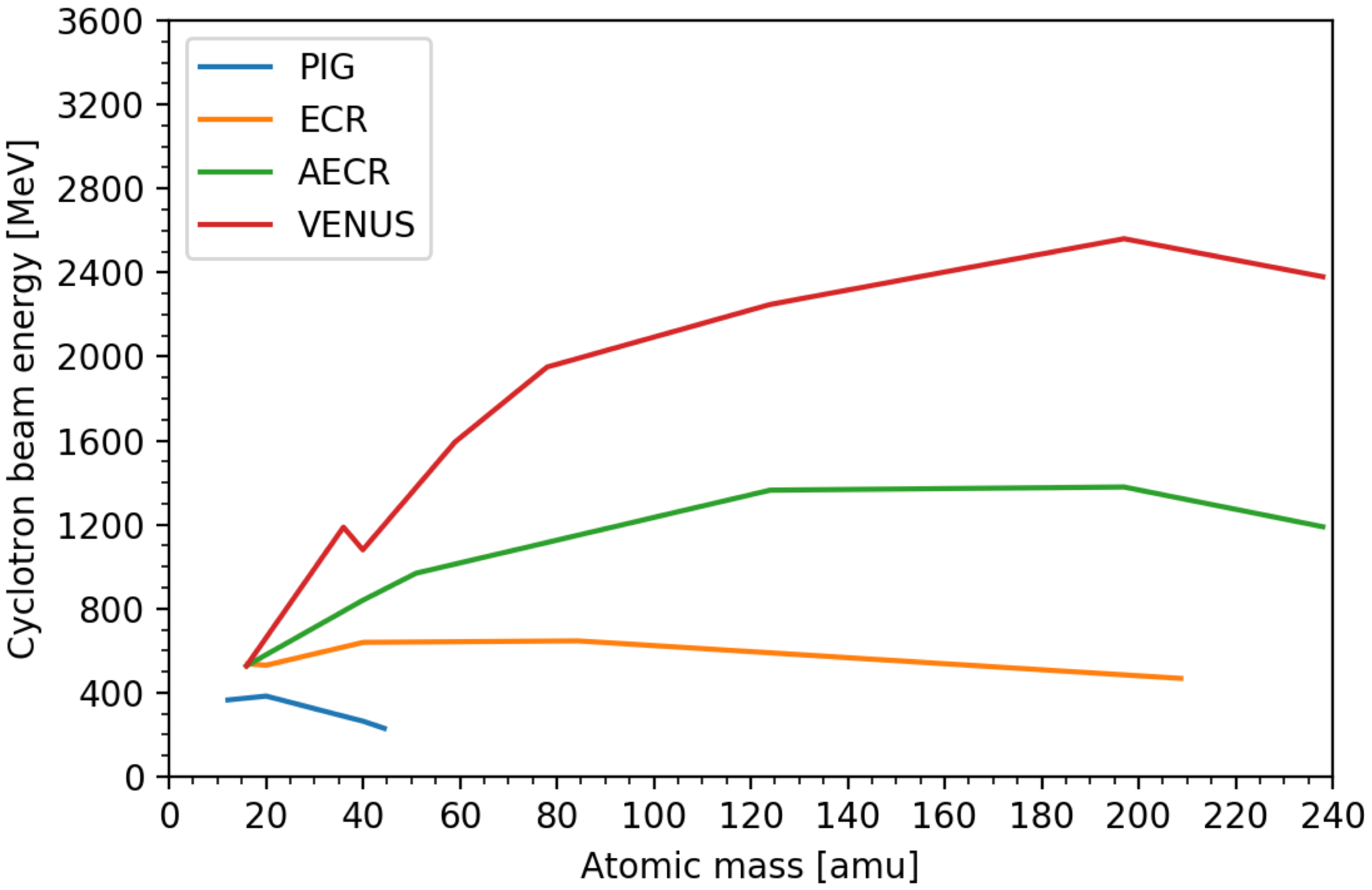


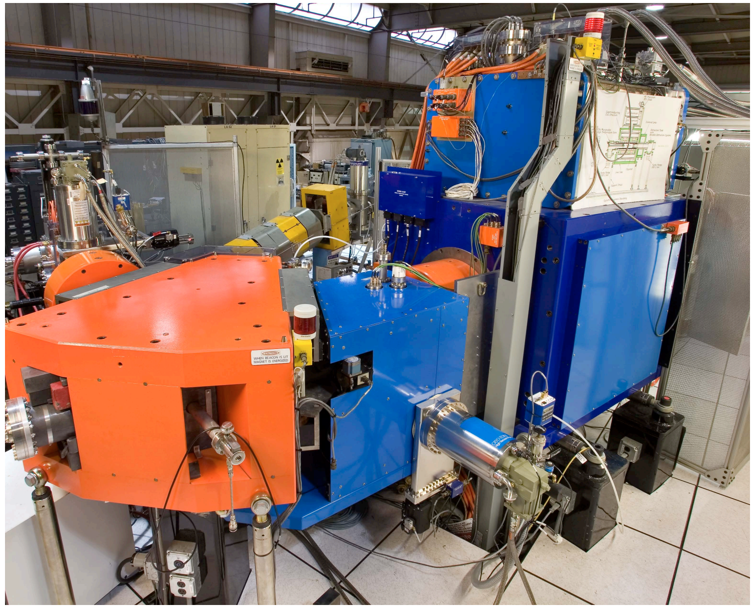


Success led to duplication around the world:

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

Impacts of ECR ion sources at the 88” Cyclotron

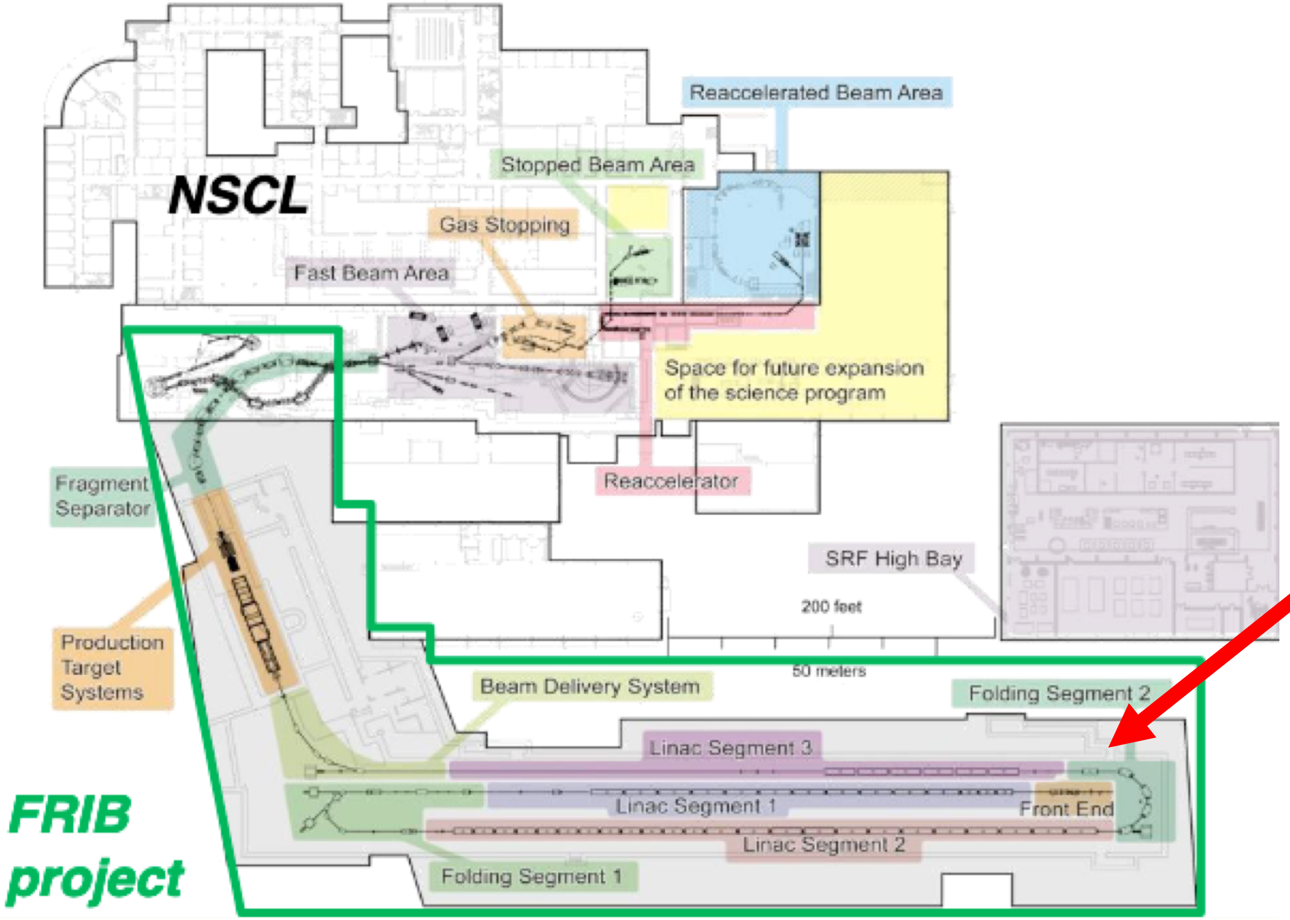


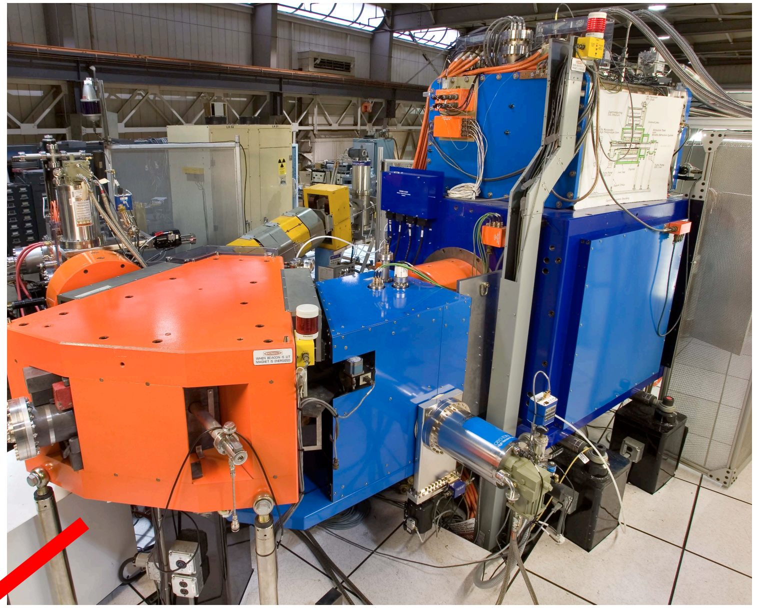


“VENUS” ion source

- World’s first third-generation ECR ion source
- Fully-superconducting (NbTi)

VENUS outside LBNL: Facility for Rare Isotope Beams (FRIB)

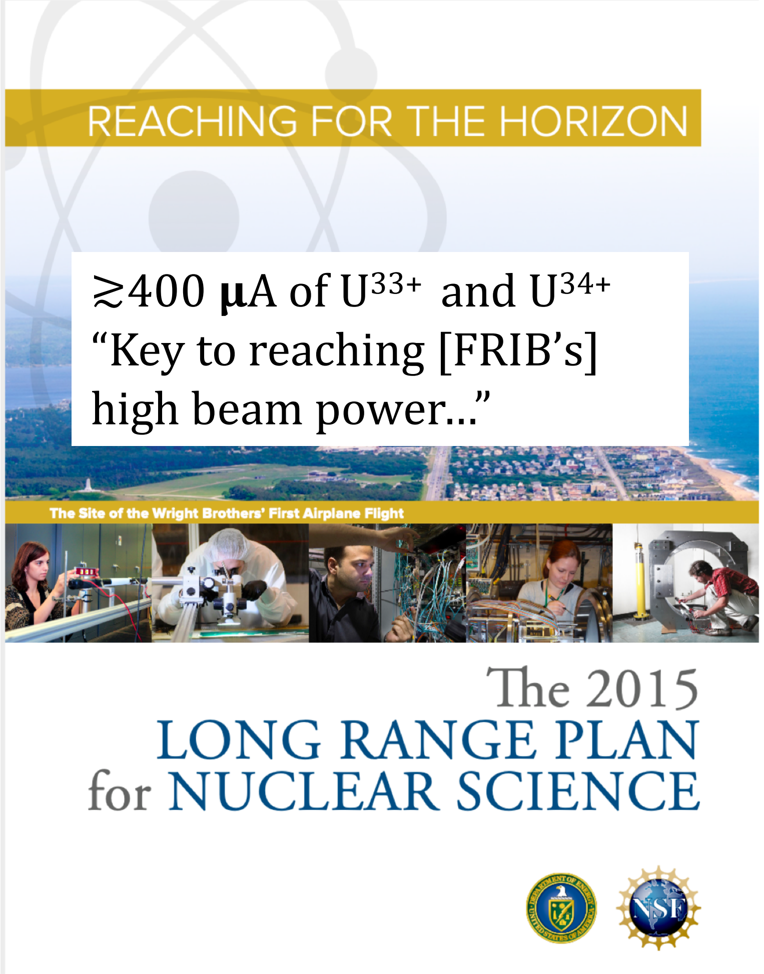




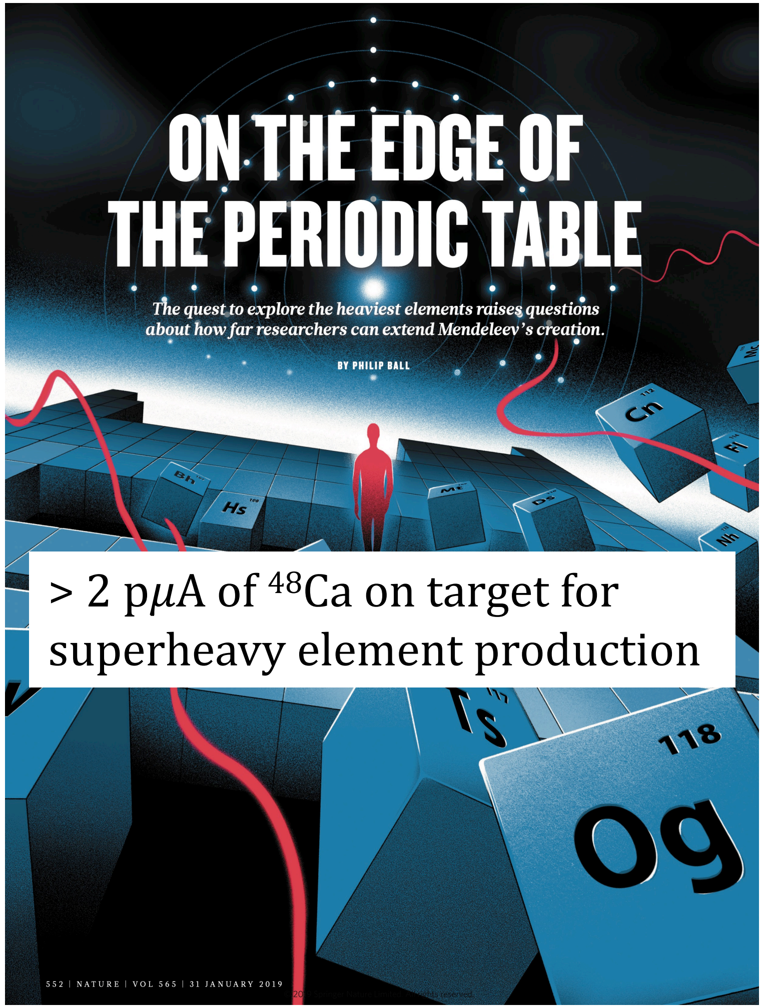
- VENUS copy being installed at FRIB
- A yet-more-advanced source is a cost-effective means of a future upgrade

Linear accelerators: KE ∝ Q

VENUS is a flexible and impressive source



≳400 μA of U^{33+} and U^{34+}
"Key to reaching [FRIB's] high beam power…"



> 2 pμA of ^{48}Ca on target for superheavy element production

BASE
Berkeley Accelerator Space Effects Facility

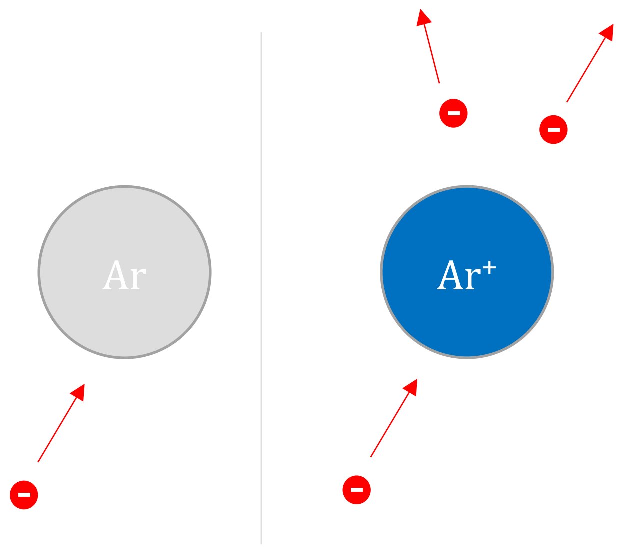
Space-X began testing at LBNL in 2016

$^{197}Au^{61+}$ through cyclotron

The heart of ion sources for accelerators

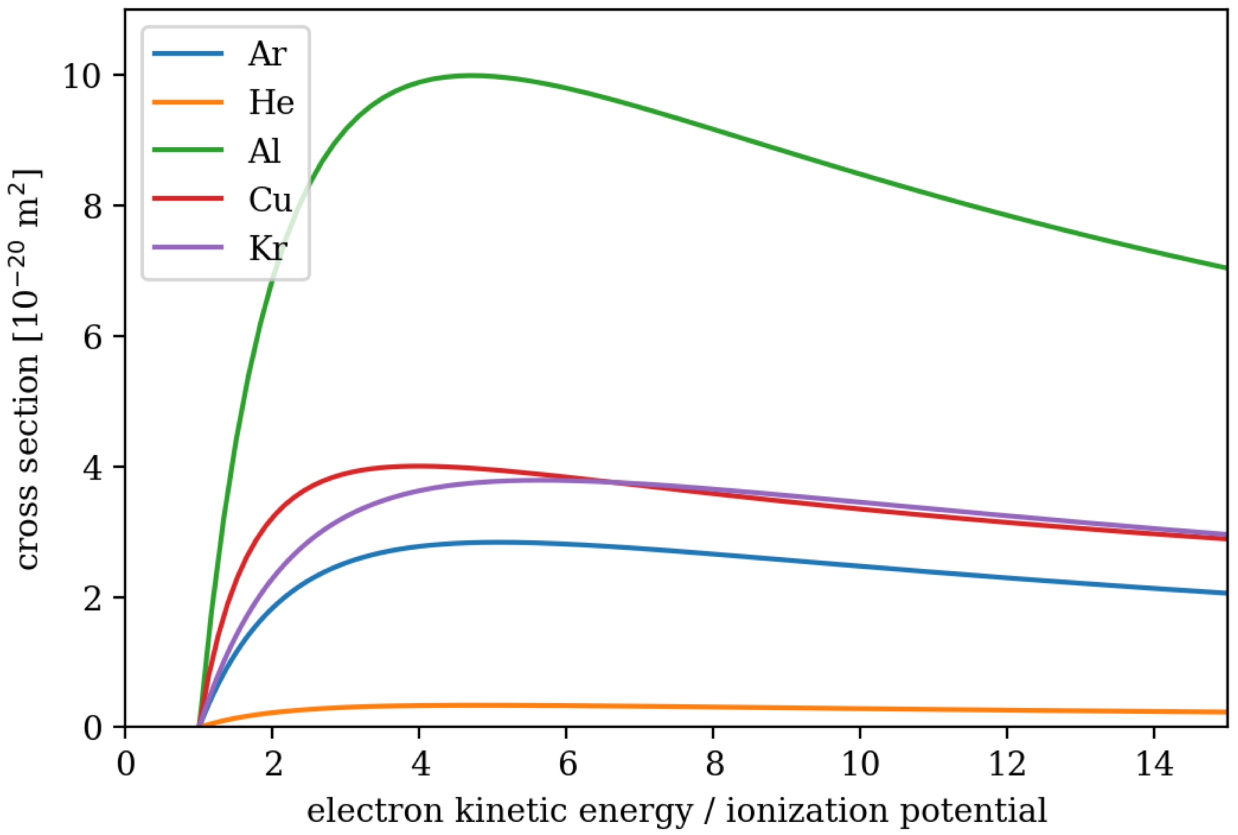
Plasma: mixture of ions,
electrons, and neutrals

Ionization

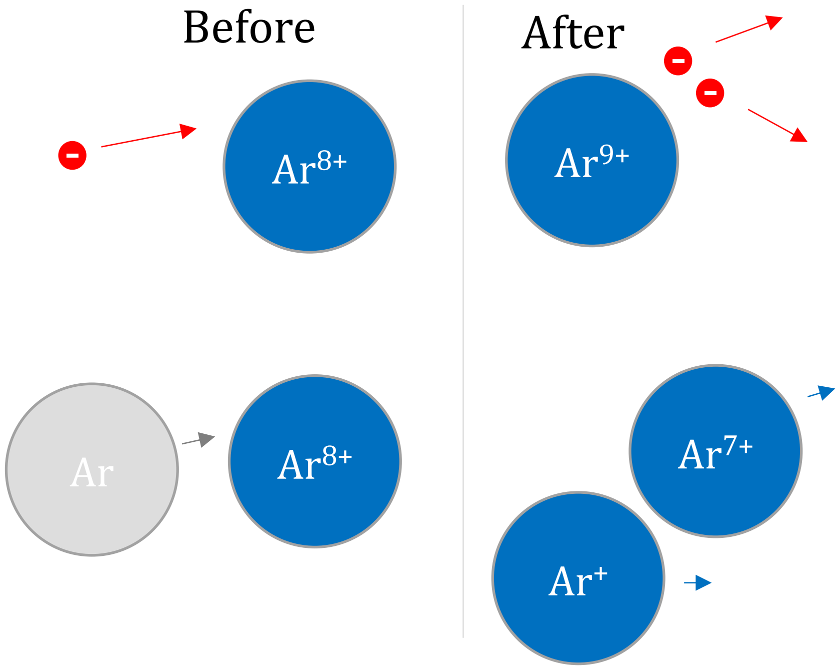


Initial charge state, Q: 0

Ionization energy [eV]: 15.8



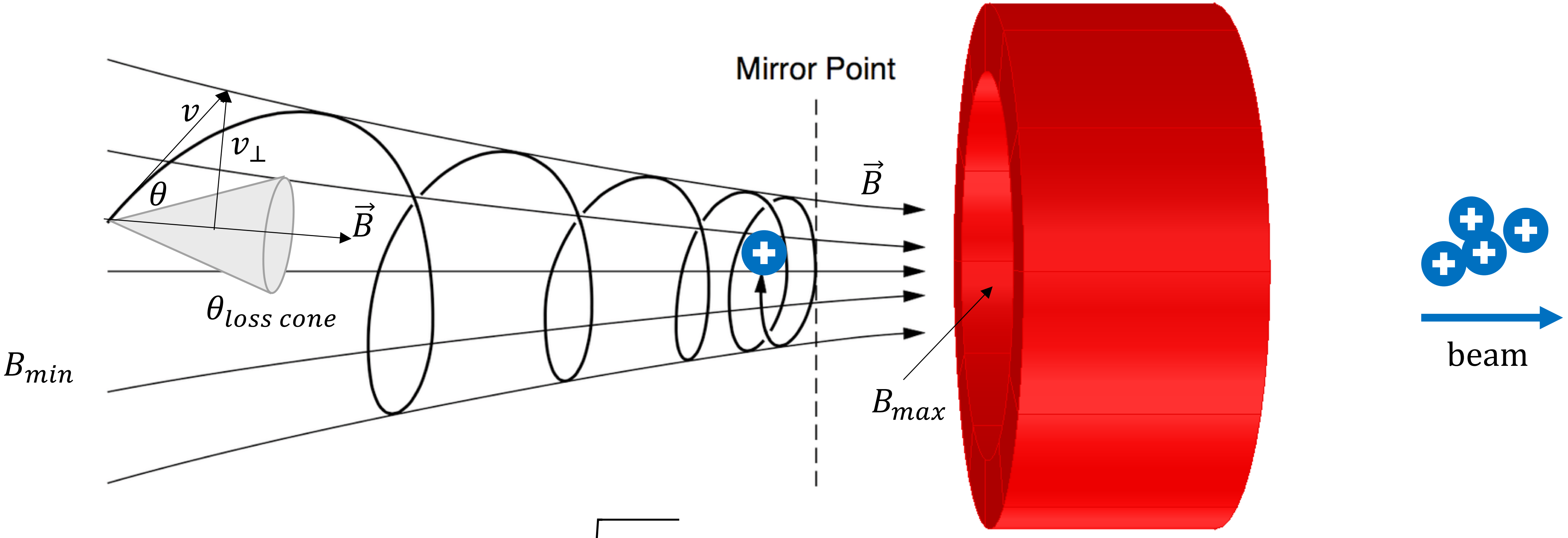
Ionization



Typical vacuum for medium-to-high charge state production in VENUS:
$8 \cdot 10^{-8}$ torr $\lesssim$ plasma chamber pressure $\lesssim 2 \cdot 10^{-7}$ torr

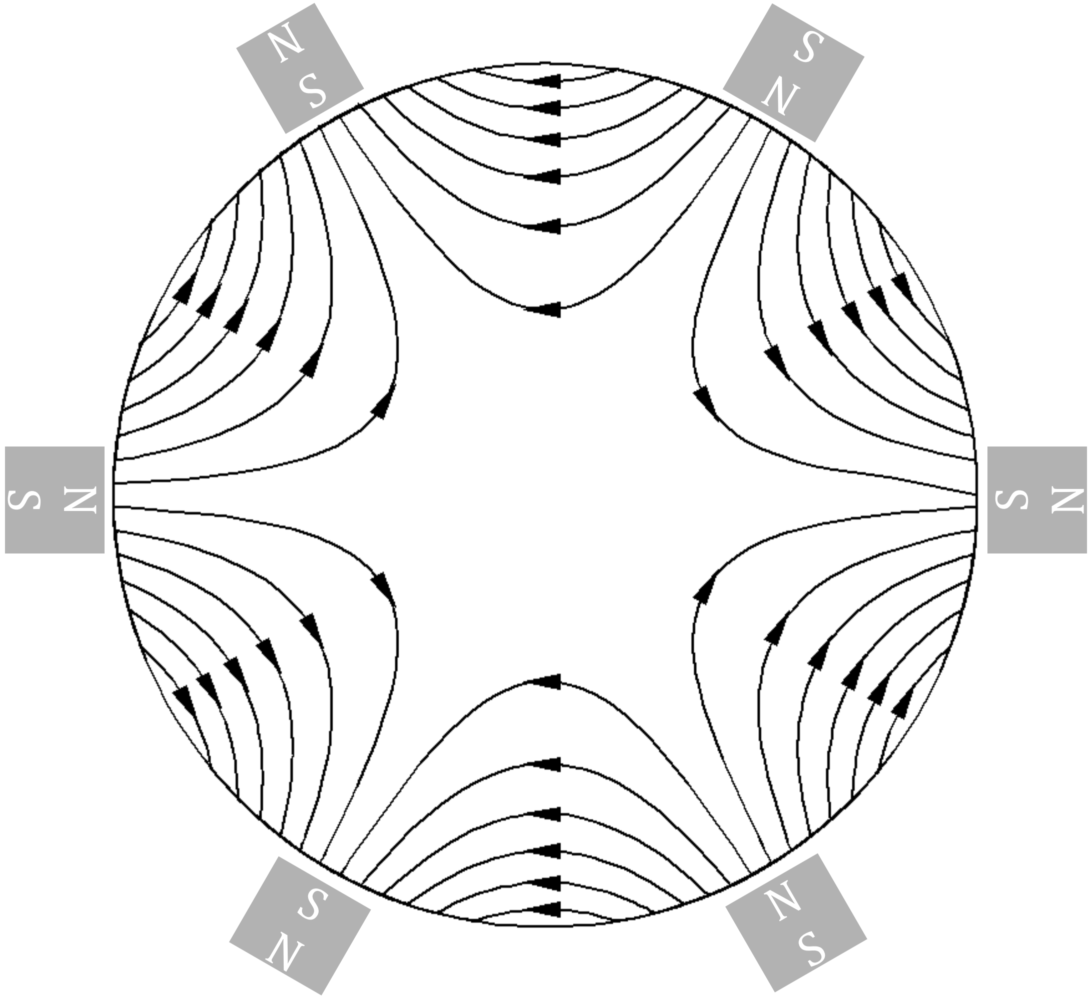
Initial charge state, Q:	0	1	8
Ionization energy [eV]:	15.8	38.5	422.6
Cross-section [10^{-20} m^2]			
• Ionization ($Q^+ \rightarrow (Q+1)^+$):	2.8	0.9	.002

Magnetic confinement

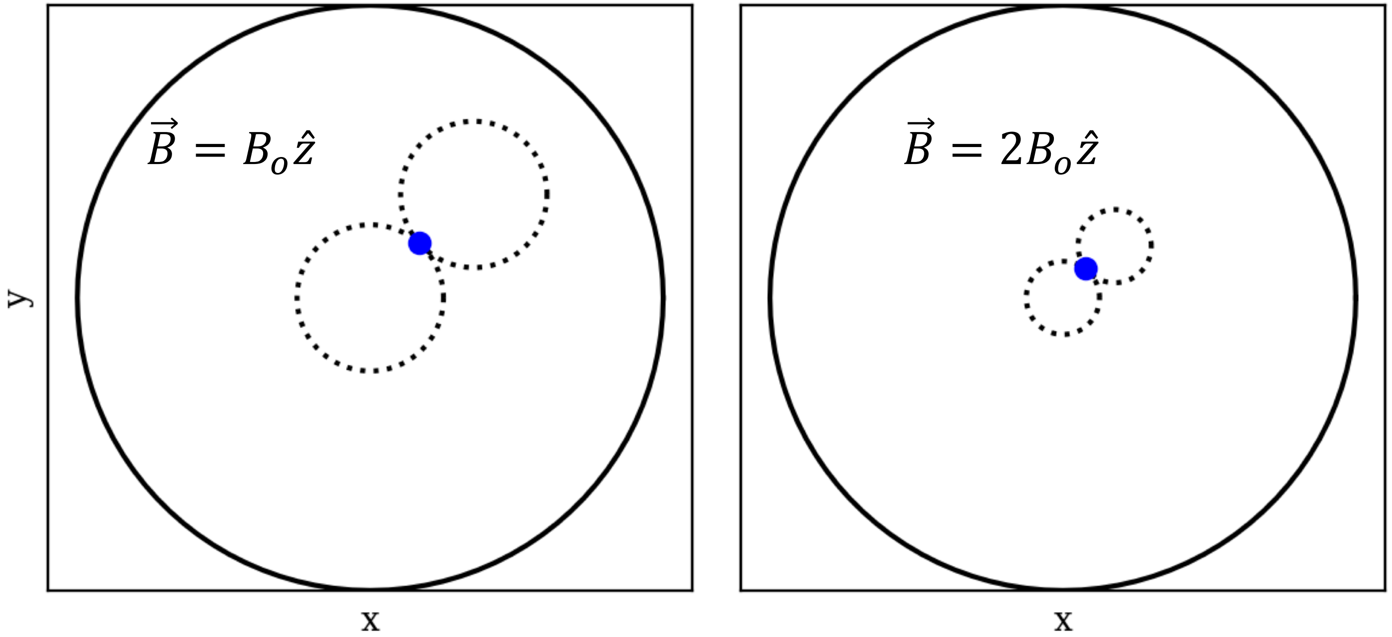


$$\theta_{loss\ cone} = \sin^{-1}\sqrt{\frac{B_{min}}{B_{max}}}$$

Sextupole (or other multipoles) also provide confinement



A note about field strength



- Same ion and initial velocity
- 2x B-field → 2x rotation frequency and half the rotation radius

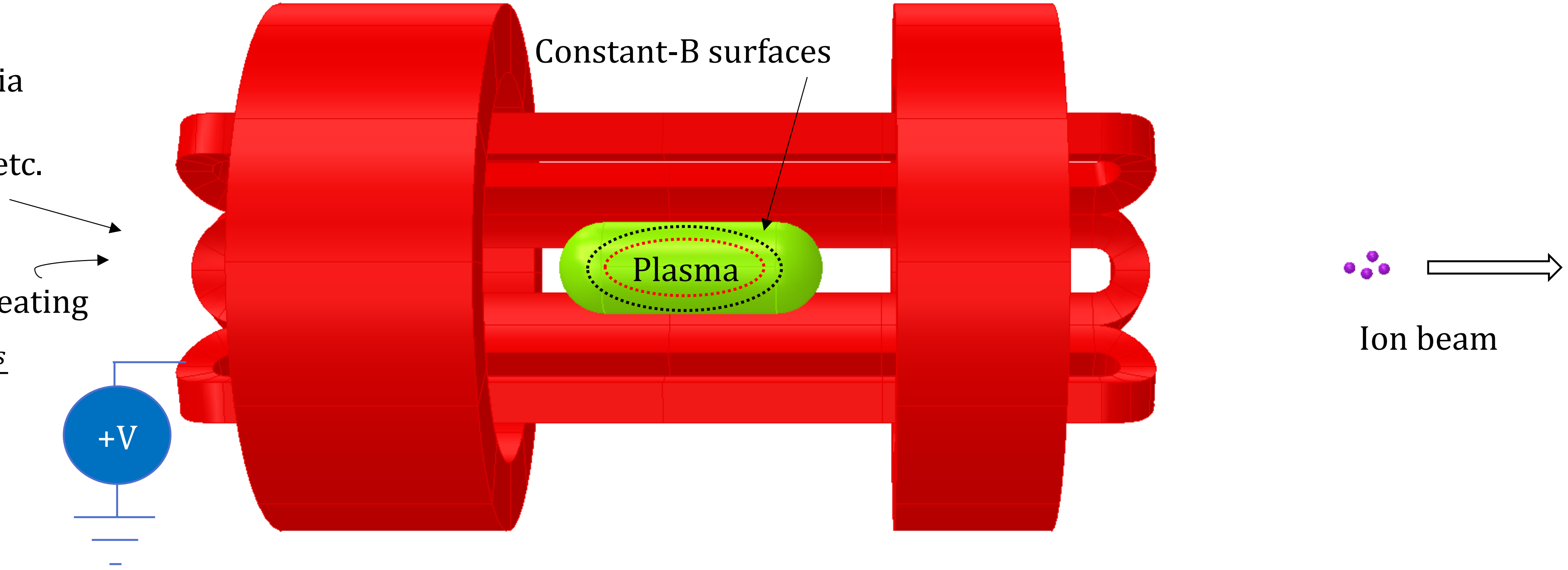
Notes:
- Higher fields slow radial losses
- Ions primarily lost radially, electrons at field line ends

The essentials of an ECR ion source

atoms or molecules via gas, ovens, sputtering, etc.

microwave heating

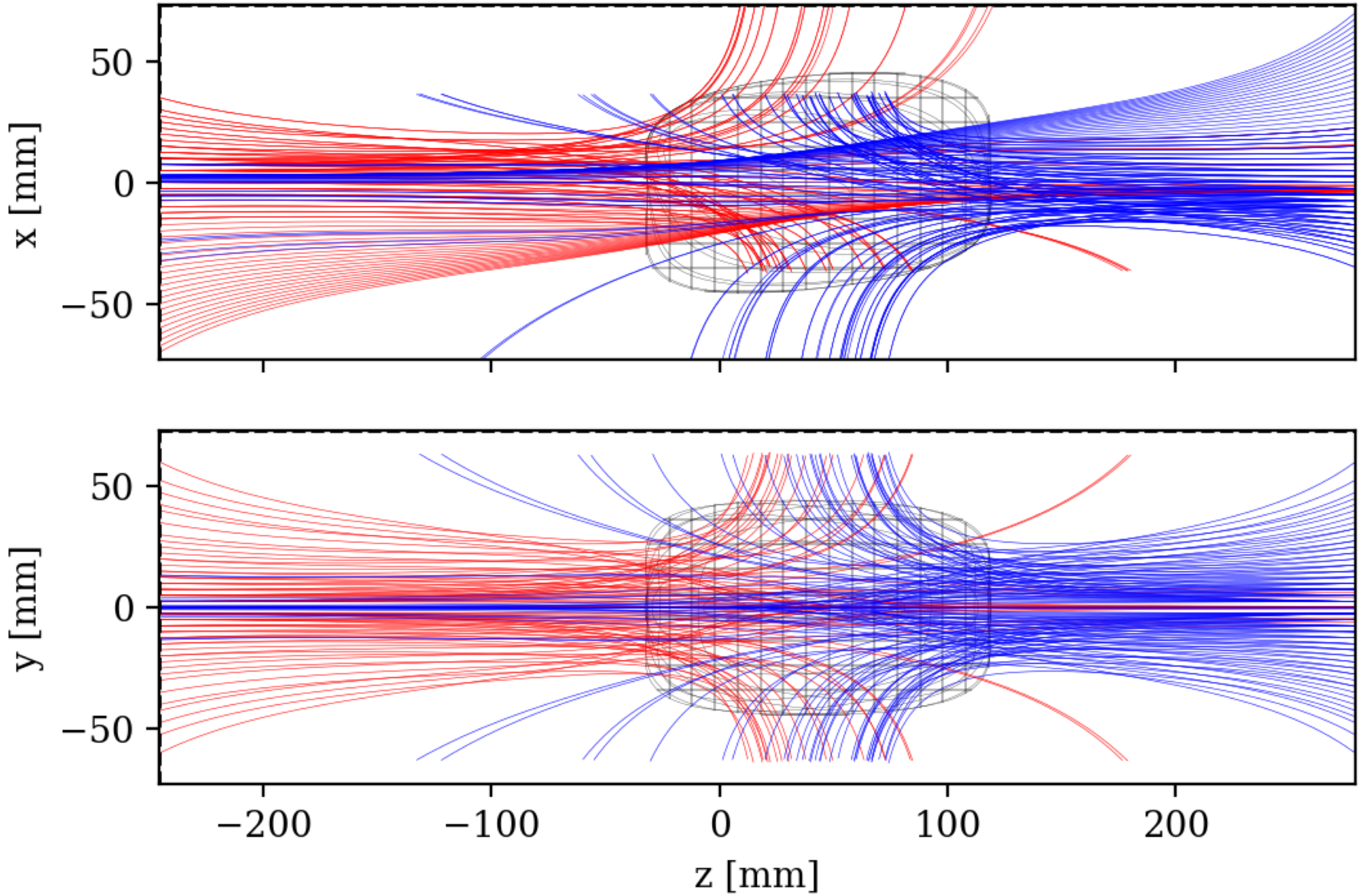
$$\omega_{rf} = \frac{eB_{res}}{m_e}$$

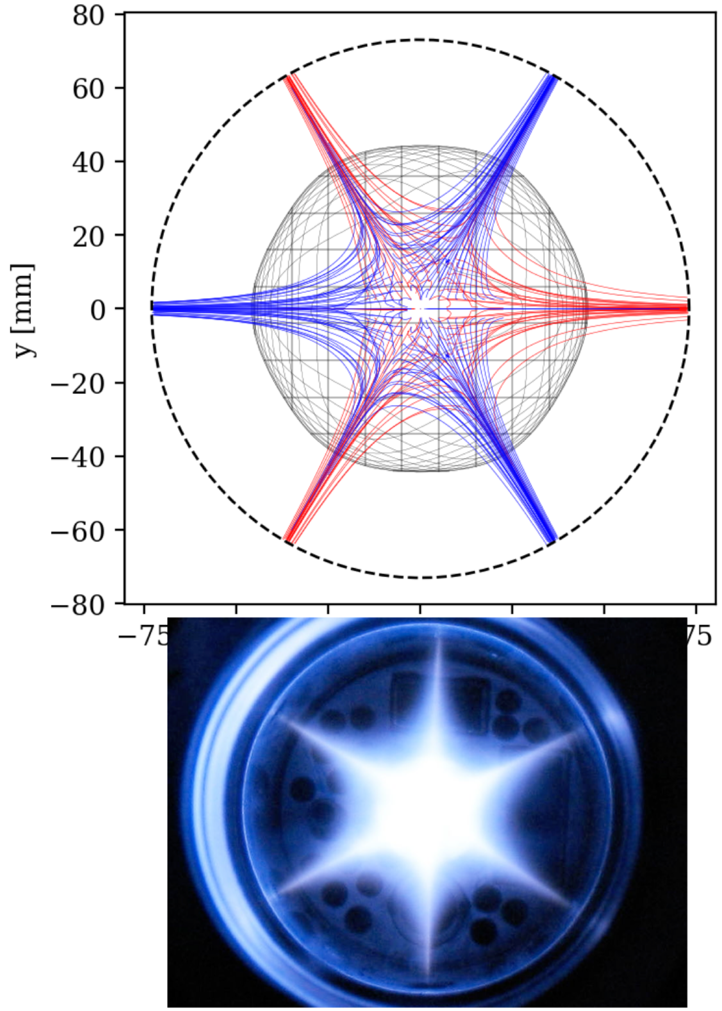


Needs:

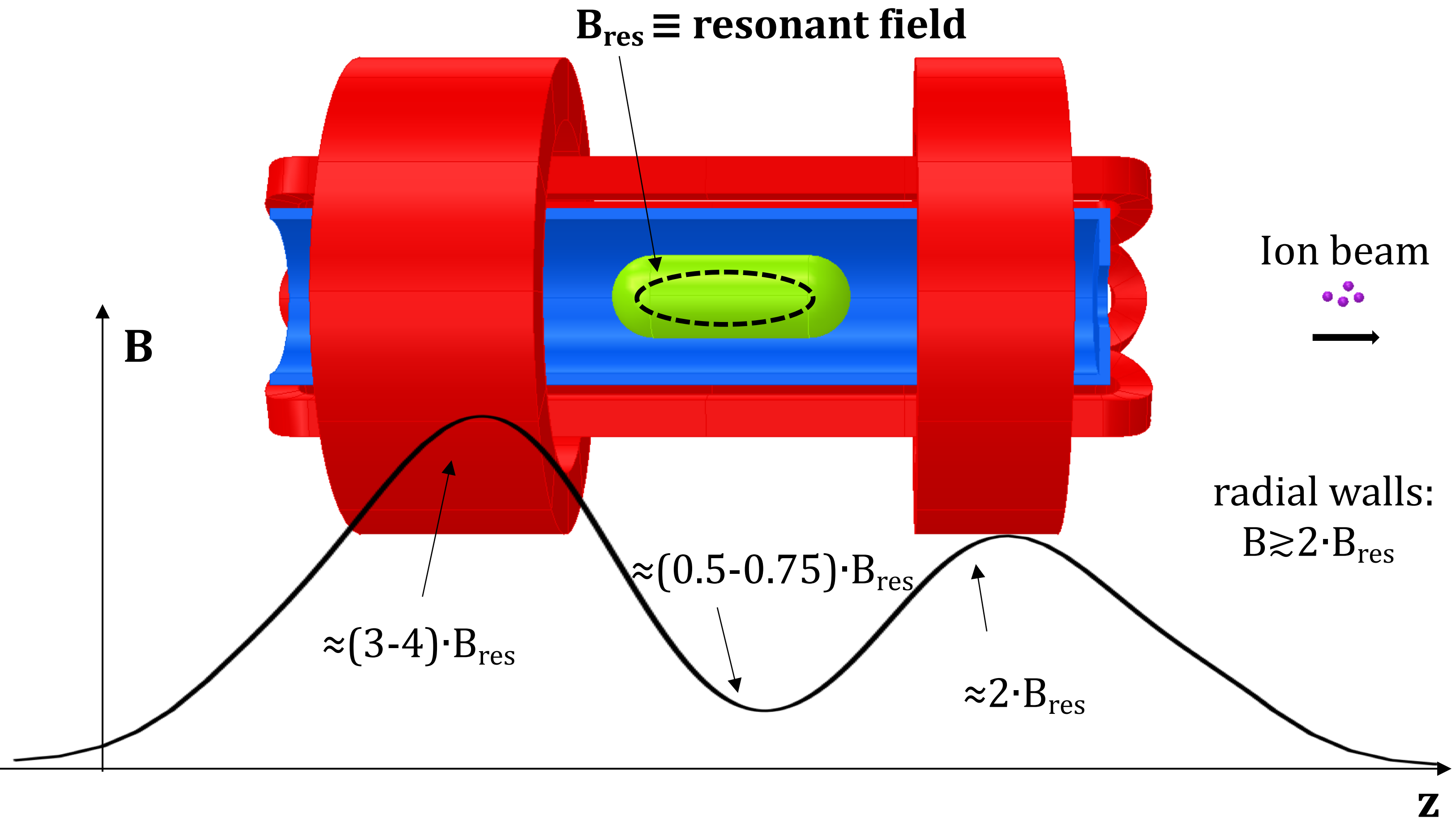
- Material
- Confinement
- Electron heating
- Ion extraction

An aside---what things really look like in VENUS





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



Plus Richard Geller's semi-empirical scaling law:

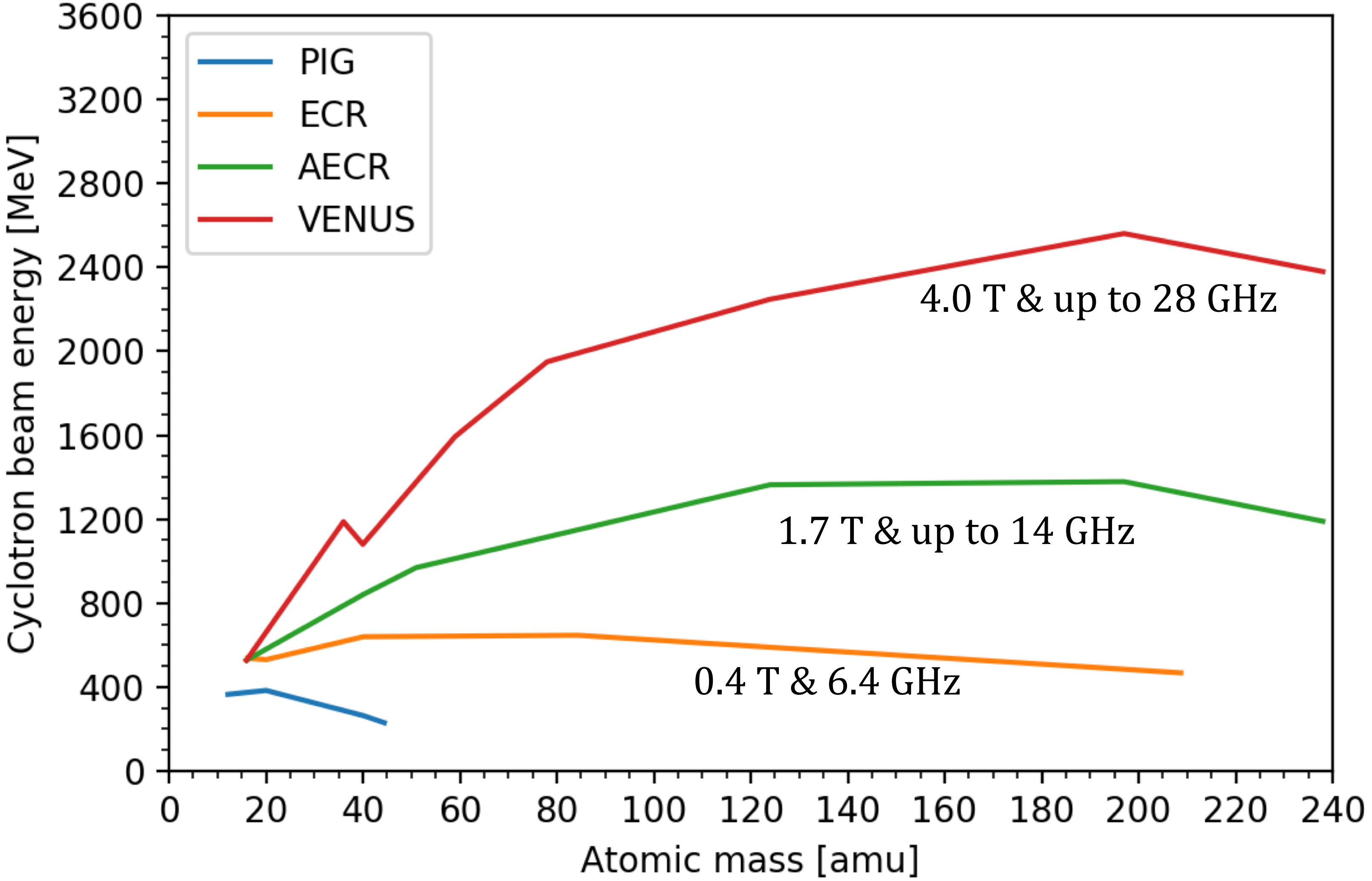
$$I_q \propto n_e \propto B_{res}^2 \propto \omega_{rf}^2$$

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**

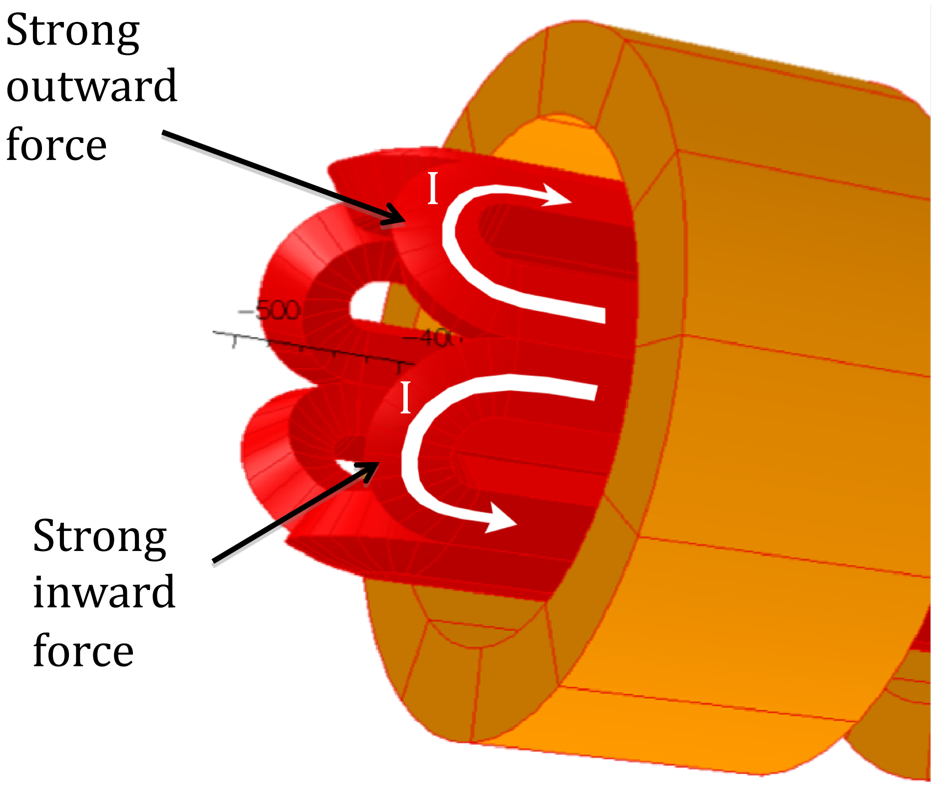


$$I_q \propto n_e \propto B_{res}^2 \propto \omega_{rf}^2$$

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

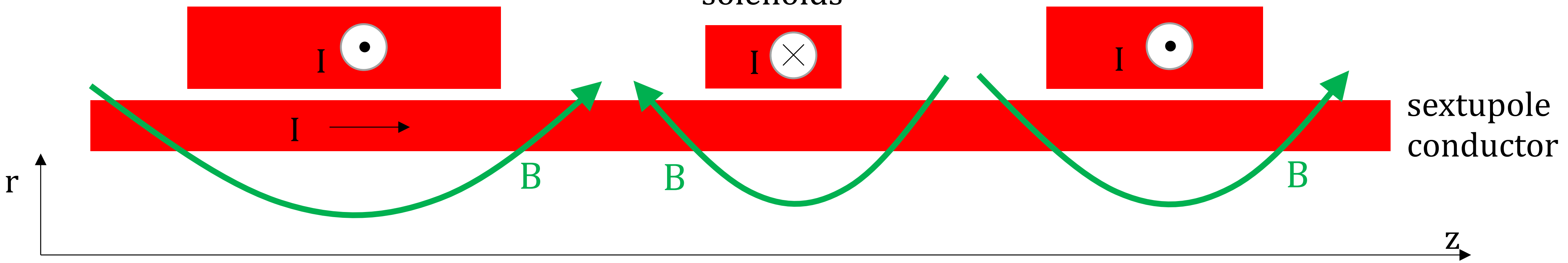
Complicated forces on conductors, take 1

- Energized superconducting coils must not move
- ECR coils strongly interact

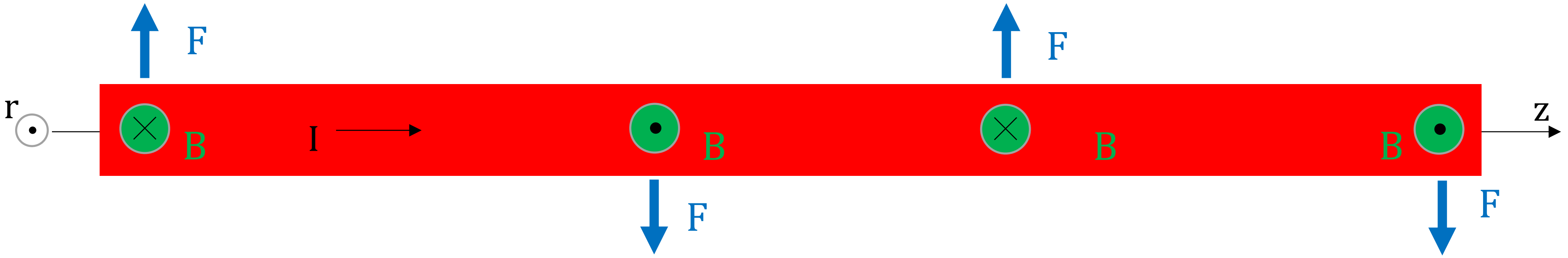


Complicated forces on conductors, take 2

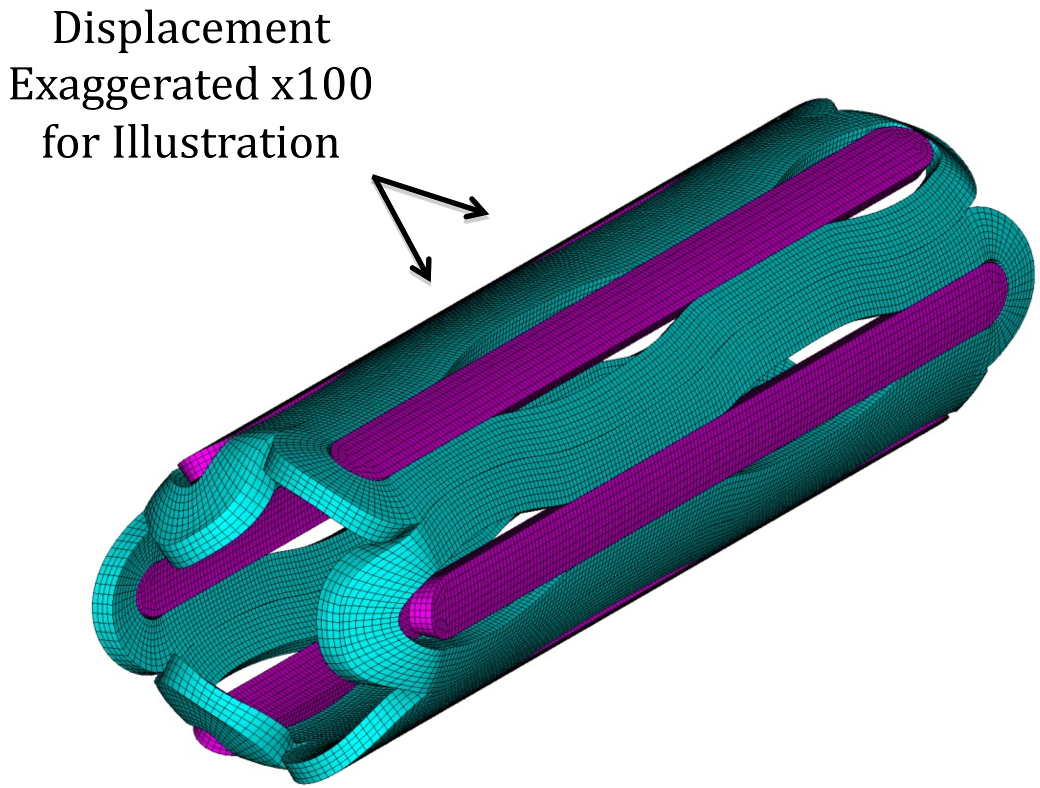
Cross-section view



Sextupole conductor viewed from outer radius



Finite element analysis



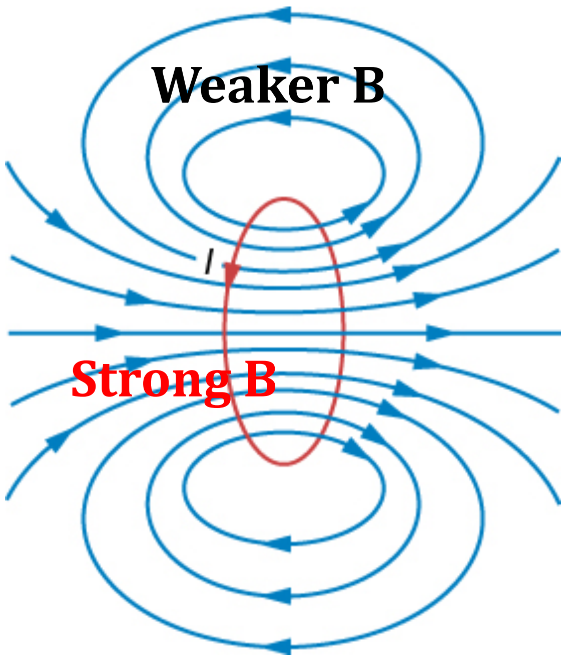
Overall solutions for VENUS:

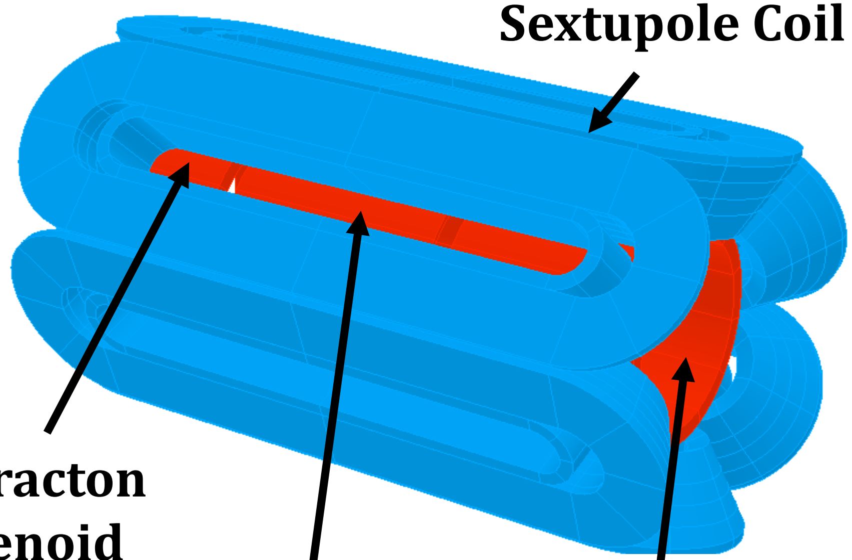
- Make longer sextupoles to reduce forces on ends
- Use liquid-metal bladders to prevent motion

Another solution to deal with forces on conductors

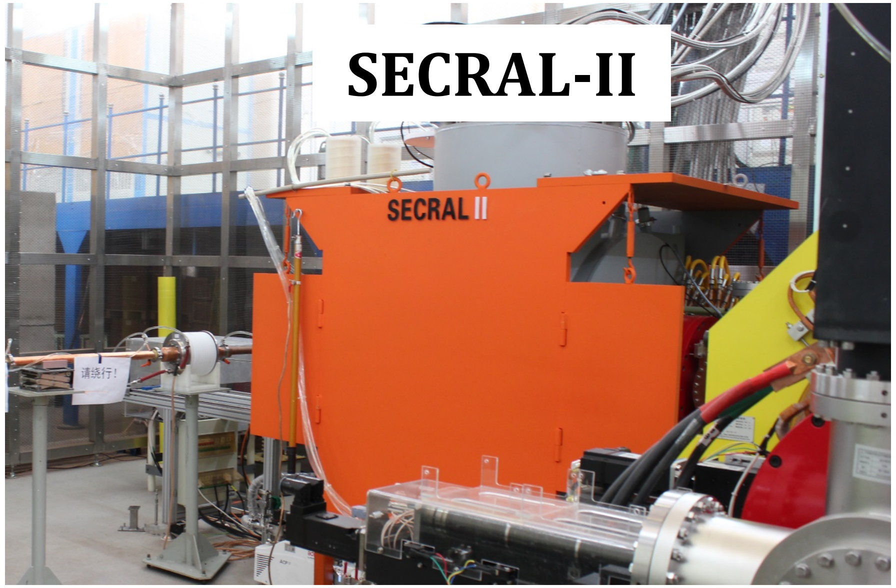
Dan Xie came up with the idea of inverting traditional design.

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





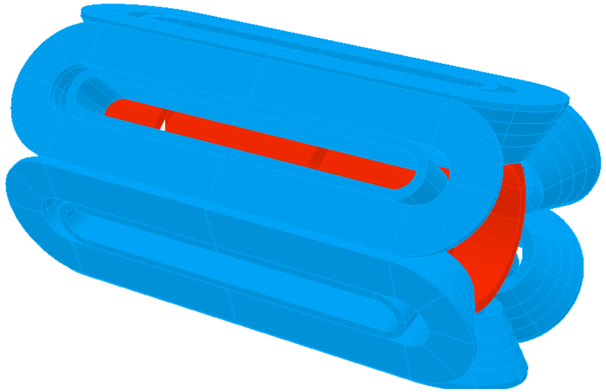
Inverted design successfully implemented at IMP in Lanzhou, China



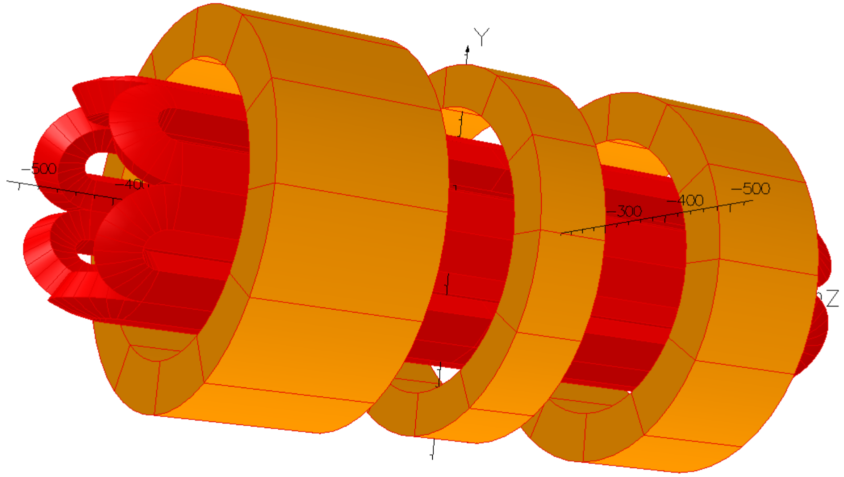
- 3.7 T, 24-28 GHz (+45 GHz at times. Not optimized)

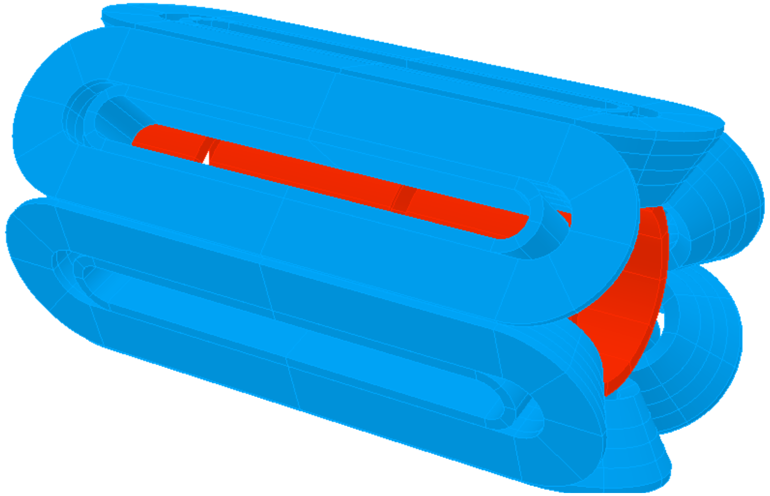
Performance of SECRAL-II nearly identical to VENUS

- Plasma doesn't care how field is made!



Limits of conventional source design with NbTi





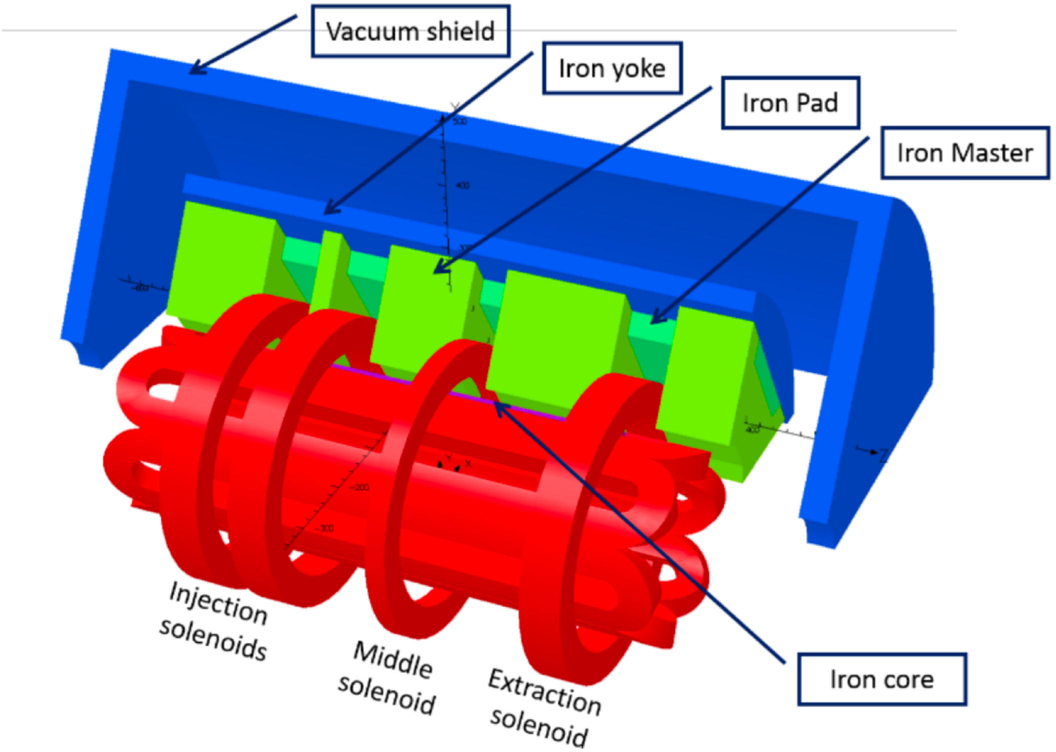
VENUS and SECRAL-II have reached limits of NbTi superconductor in these two coil configurations

Options to move to next-generation:

1. Build a source with a superconductor capable of higher field operation

2. Be creative with NbTi

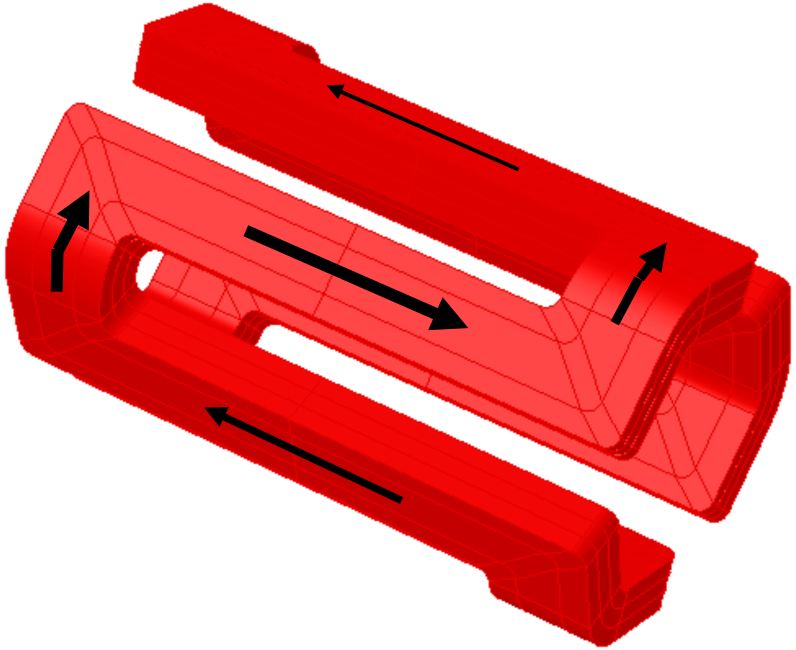
Option 1: different superconductor

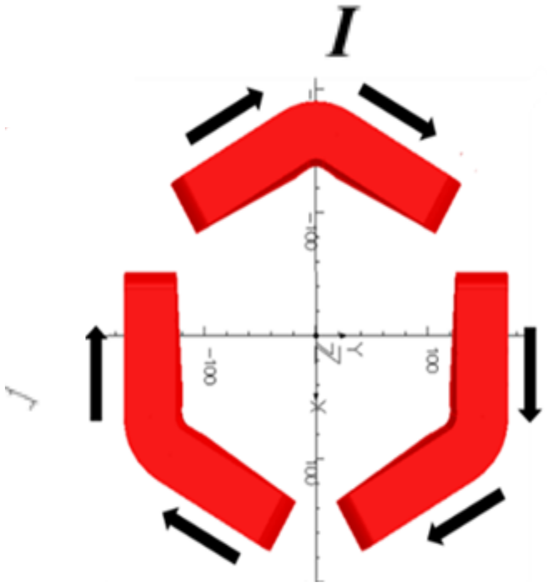


IMP (Lanzhou, China) is the only laboratory currently pursuing a fourth-generation ECRIS

- VENUS-like structure with Nb_3Sn coils, an unproven material for such a complicated magnet
- Have so far encountered great difficulty in coil clamping; even test coil has failed

Option 2: get more out of NbTi

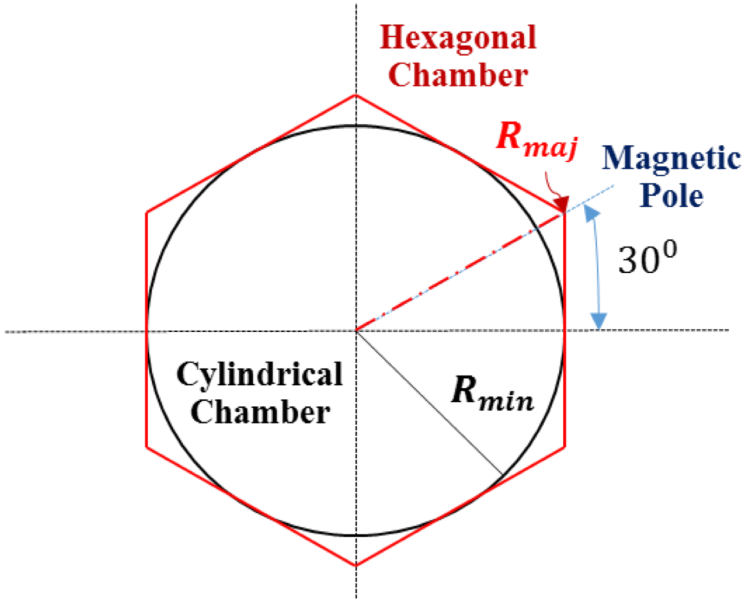




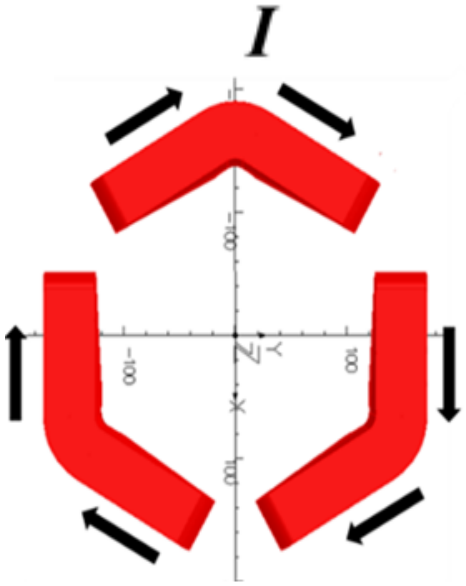
Dan Xie's MARS coil:

- Sextupole coil also produces solenoid moment
- Can use smaller, augmenting solenoids
- Clamping is easier
- Winding is trickier
- Capable of reaching fields for 45 GHz operation with NbTi

Option 2: get more out of NbTi



$$\frac{B_r(r = R_{maj})}{B_r(r = R_{min})} = \frac{R_{maj}^2}{R_{min}^2} \sim 1.33$$



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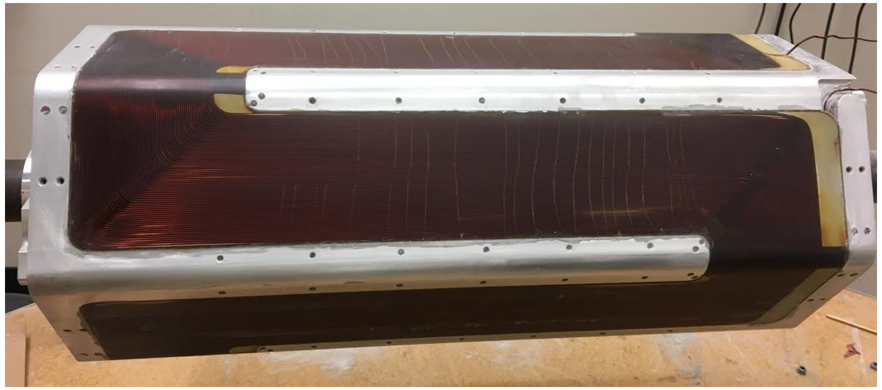
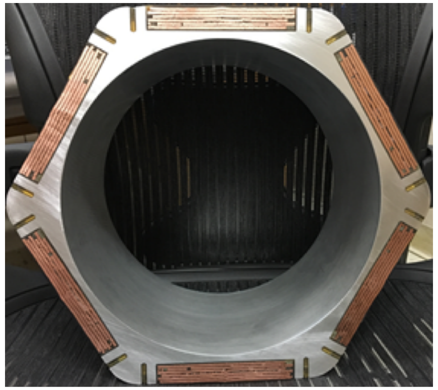
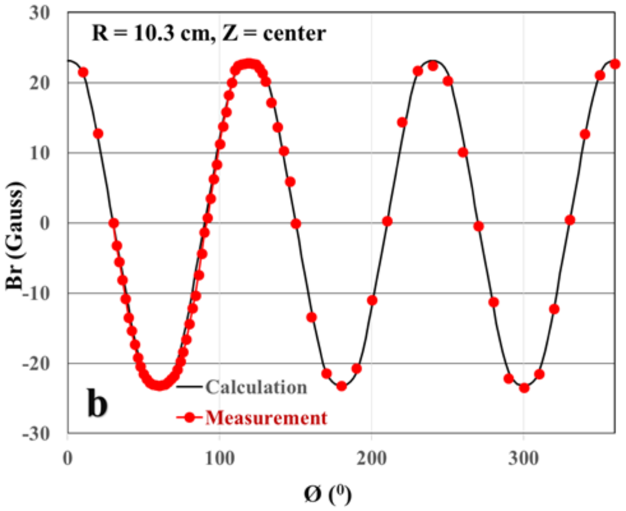
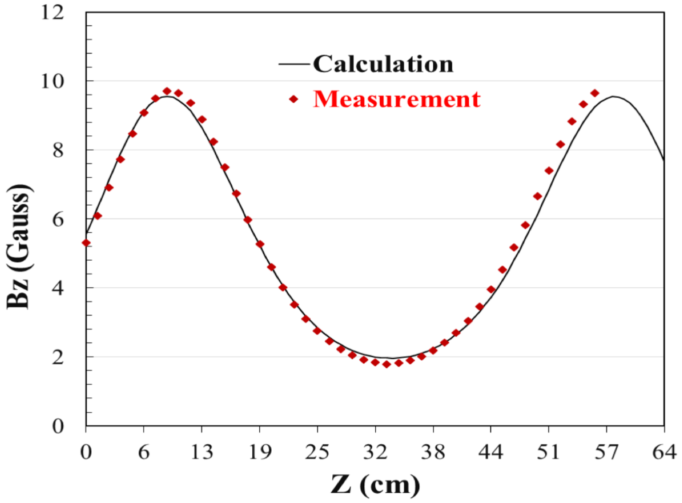
Successfully wound a test coil









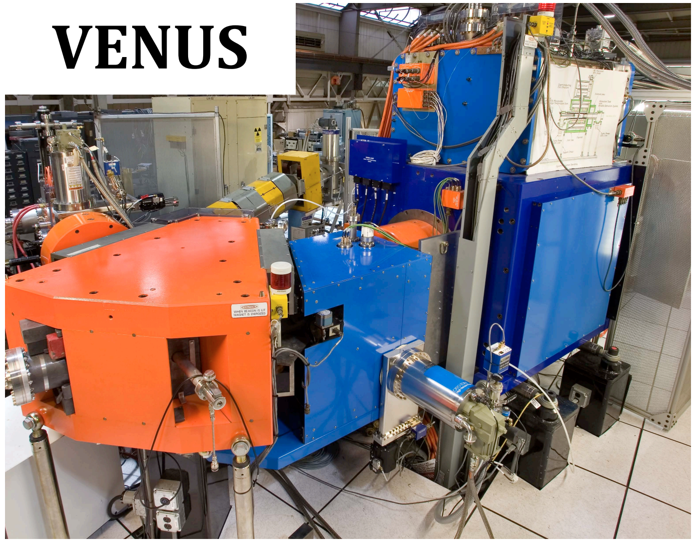
The closed-loop-coil is difficult to wind. To address this:

- Tooling and a winding stand were designed and constructed at LBNL
- A radial 1/3-thickness prototype was wound from copper with similar dimensions to NbTi wire
- Coil field mapping showed it matched predicted fields and profiles
- Sectioning of coil showed necessary packing factors were reached

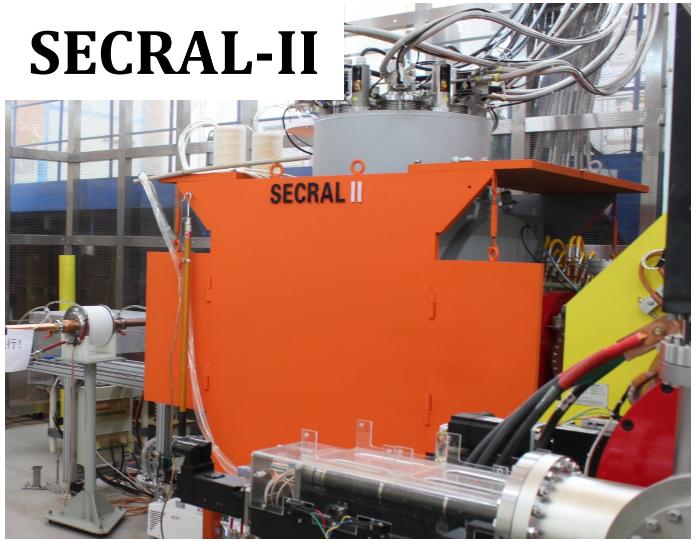
Where ECR ion sources stand

The state of the art

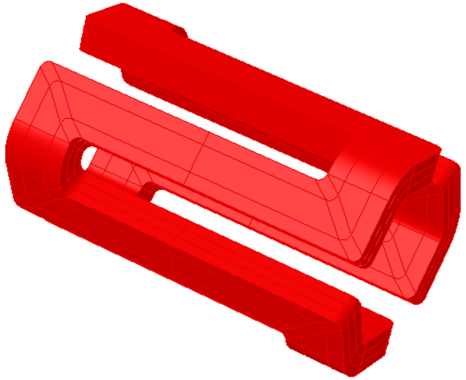
VENUS



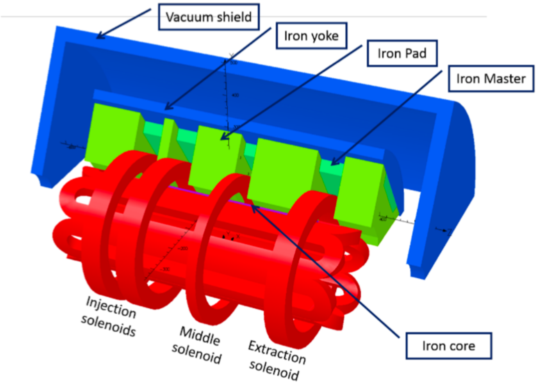
SECRAL-II



Moving forward



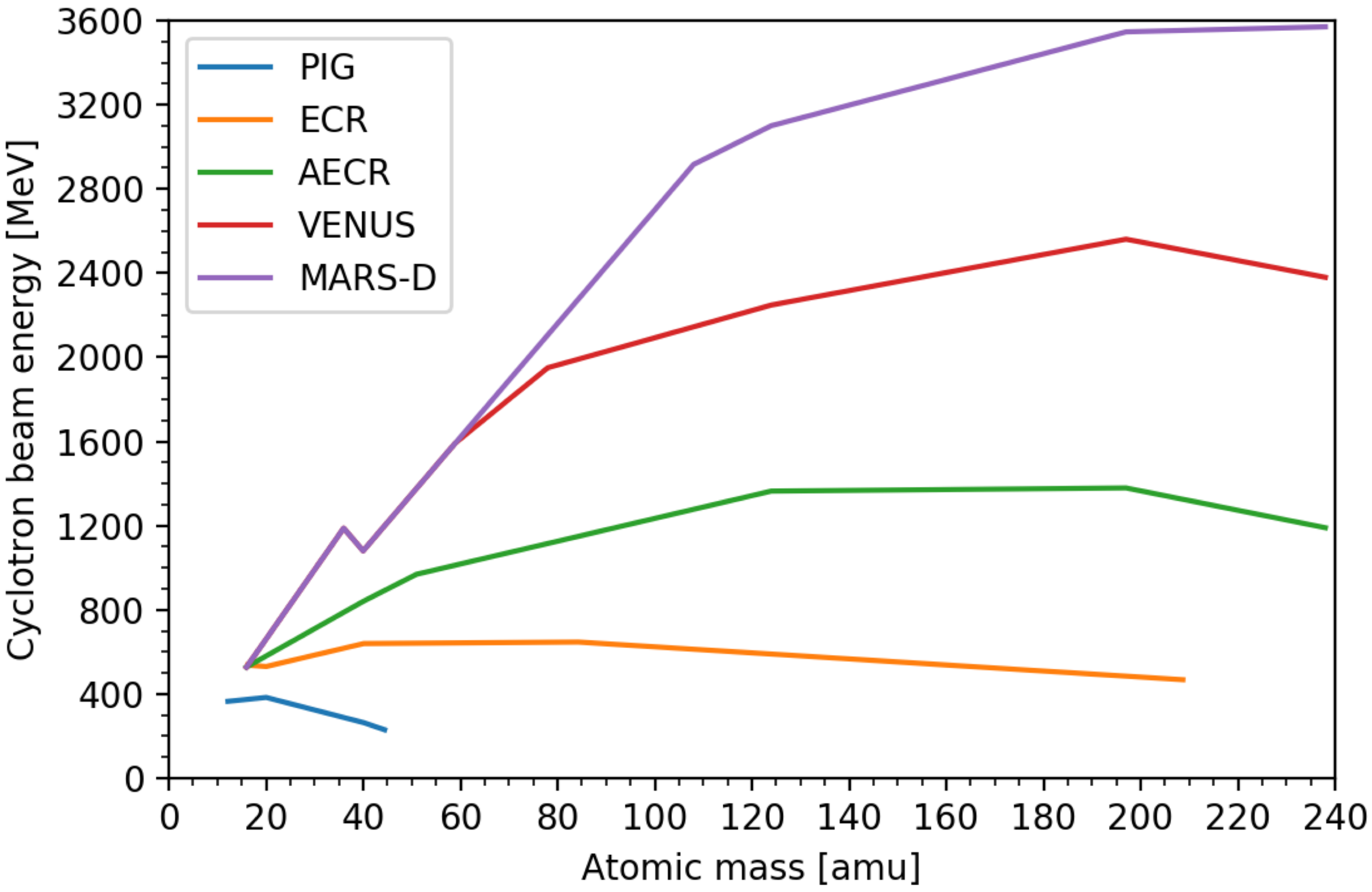
New ideas



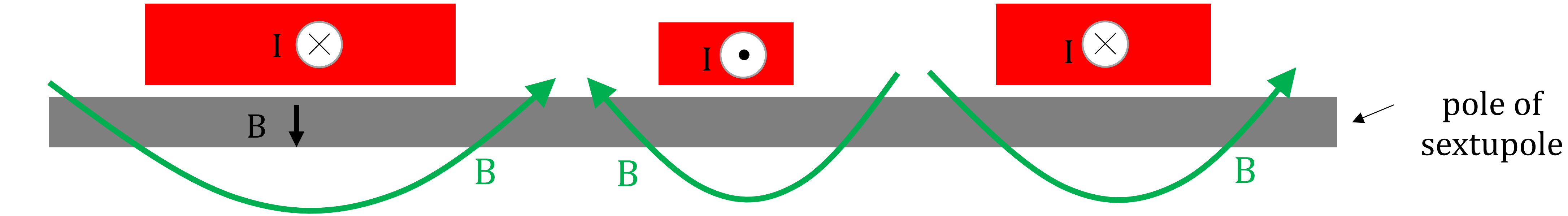
New materials

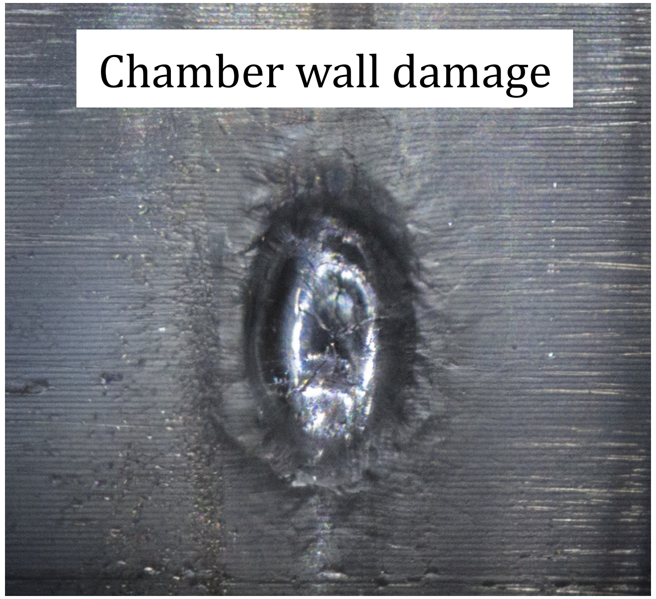
Expected performance increase moving to 45 GHz

Ion	Current [μA] VENUS 28+18 GHz ≤12 kW	Current [μA] 4th gen. 45 GHz 15 kW
Ar^{14+}	840	≥ 1000
Kr^{18+}	770	≥ 1000
Xe^{30+}	325	≥ 400
Bi^{36+}	90	≥ 300
U^{41+}	19	≥ 200



Electron losses




Chamber wall damage

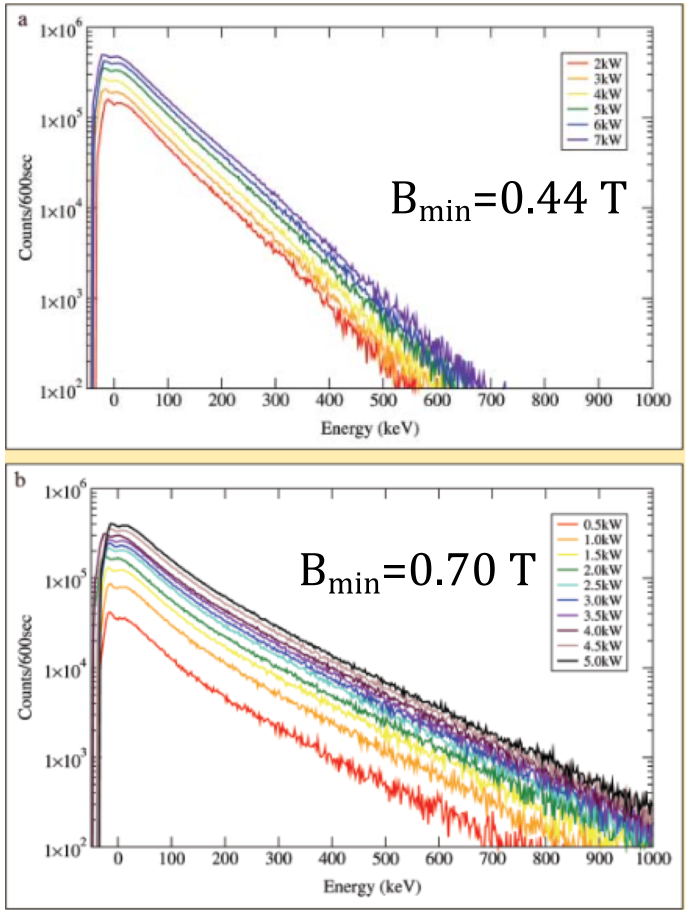
Insulation damage from heat/bremsstrahlung

Spectral temperature dependence on B_{min}

ANALYSIS OF X-RAY SPECTRA EMITTED FROM THE VENUS ECR ION SOURCE

JANILEE BENITEZ, DANIELA LEITNER

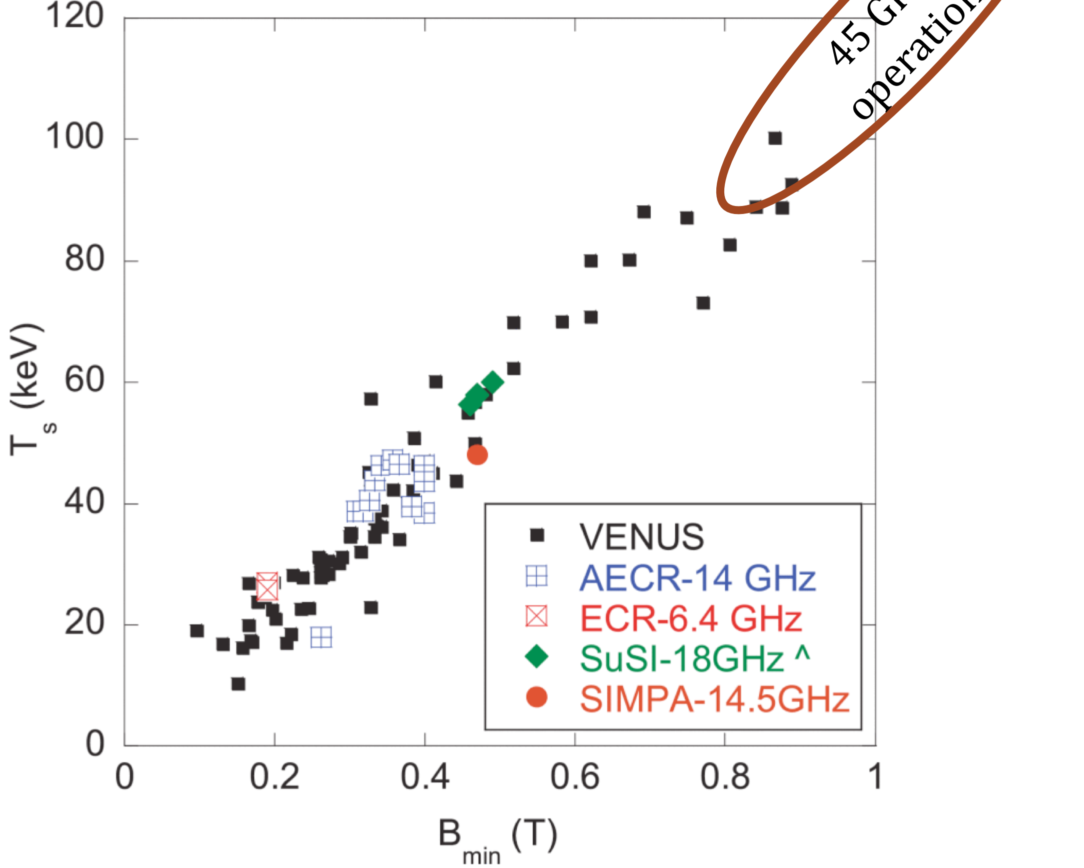
U.S. Department of Energy Journal of Undergraduate Research (v.8 2008)



1746 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 45, NO. 7, JULY 2017

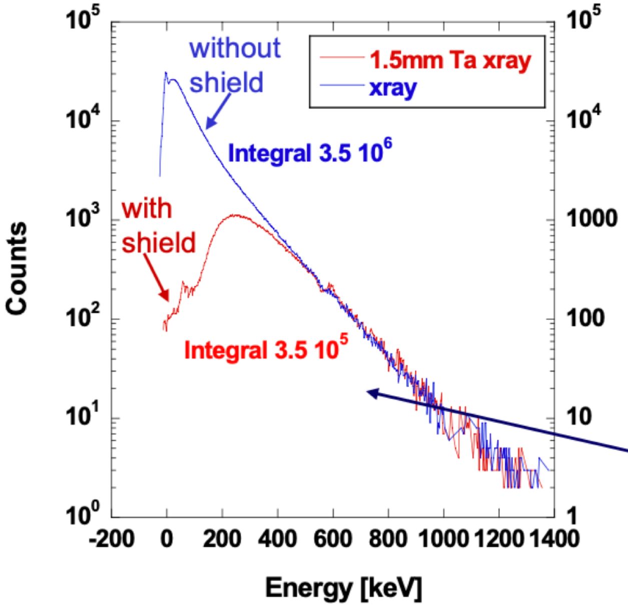
Dependence of the Bremsstrahlung Spectral Temperature in Minimum-B Electron Cyclotron Resonance Ion Sources

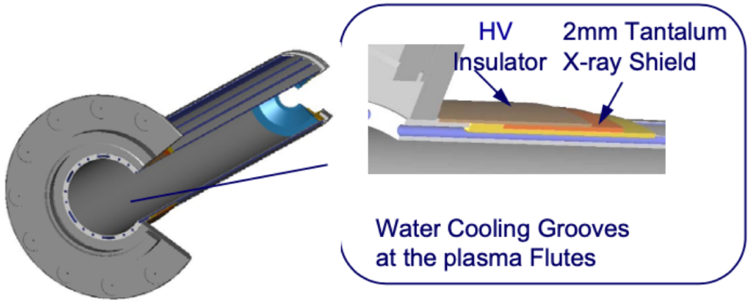
J. Benitez, C. Lyneis, L. Phair, D. Todd, and D. Xie



VENUS attenuation of xray load to cryostat

A major challenge for high field SC ECR ion sources is the heat load from bremsstrahlung absorbed in the cryostat



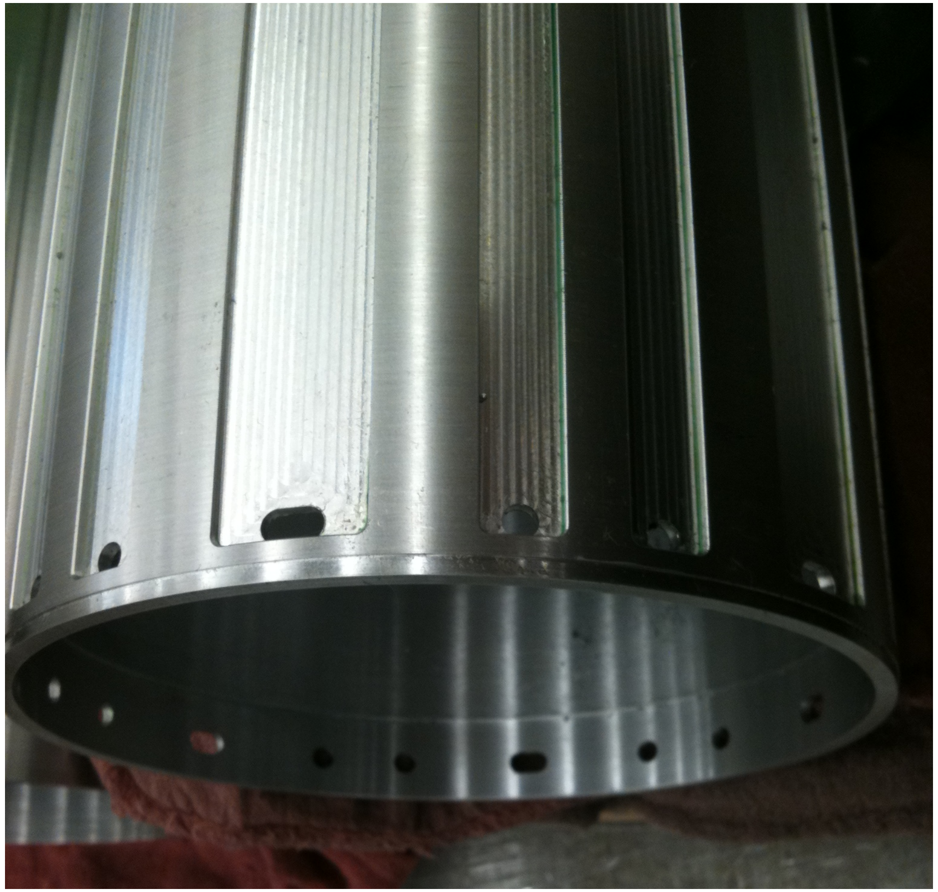


1.5 - 2 mm Ta shielding effectively attenuates the low energy bremsstrahlung, but becomes transparent for x-rays above 400keV

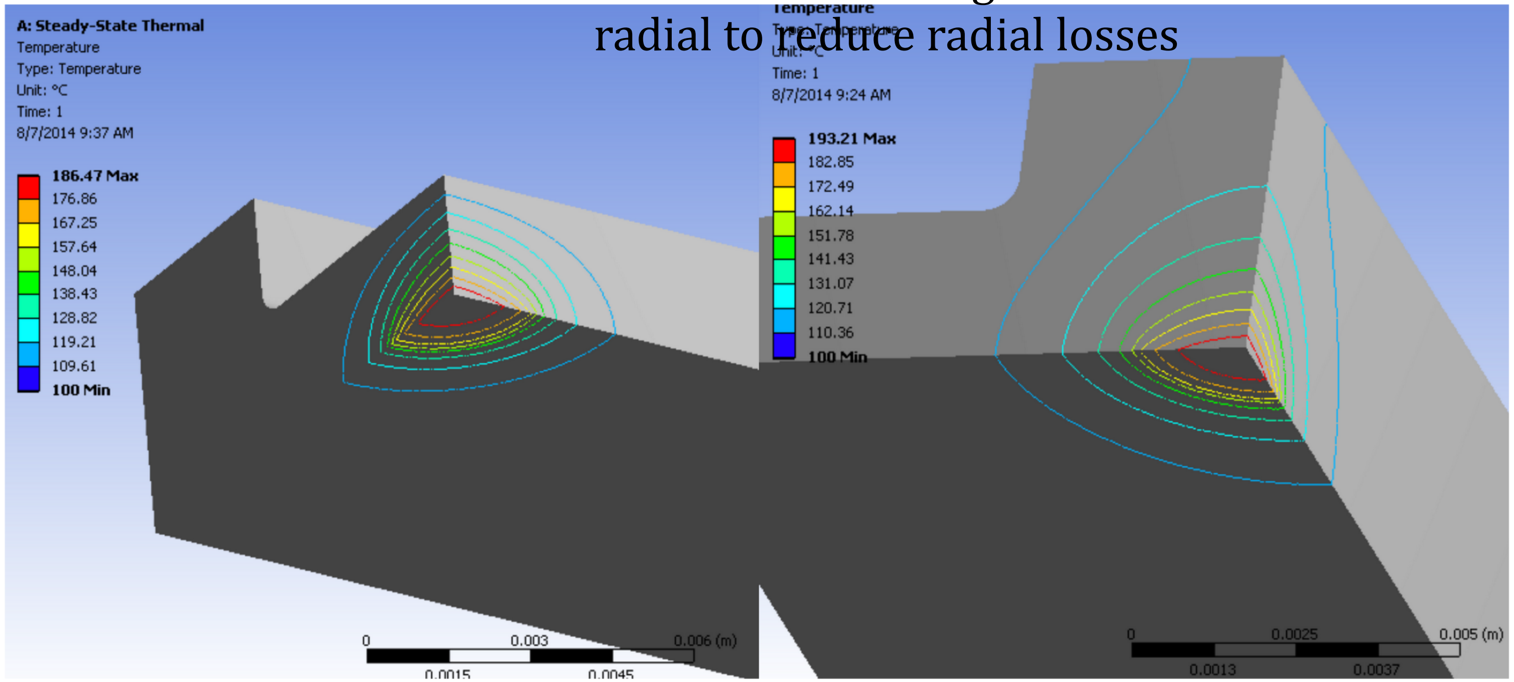
The high energy tail of the x-ray spectrum increases substantially at the higher microwave frequency
(10s of) watts of cooling power must be reserved for the cryostat.

Daniela Leitner
"Superconducting Ion Source Development in Berkeley"
HIAT 2009, Venice, Italy

Improving likelihood of VENUS chamber survival



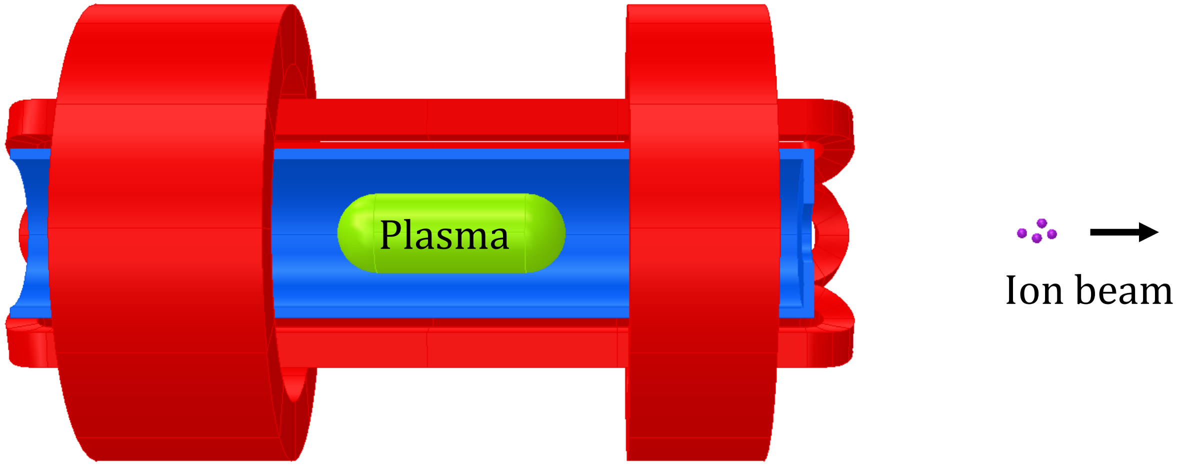
Additional: running axial field lower than radial to reduce radial losses



ECR ion source optimization problem

Control parameters include:
- Confining fields
- RF heating
- Plasma materials

~ 15-20 knobs

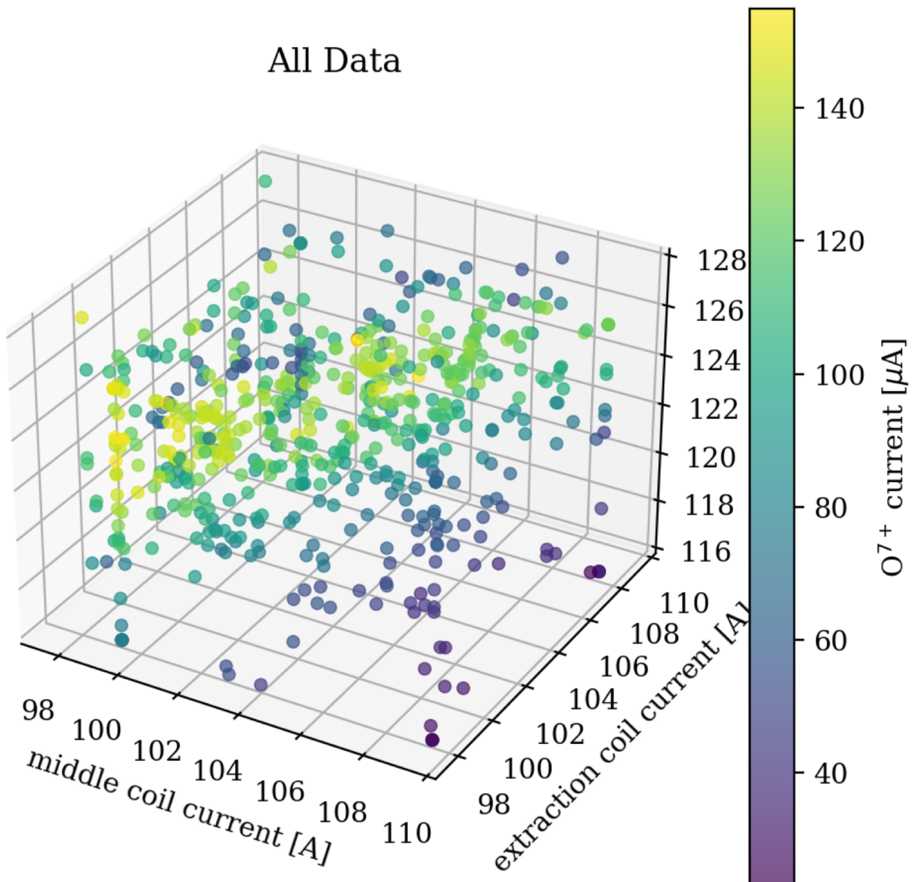


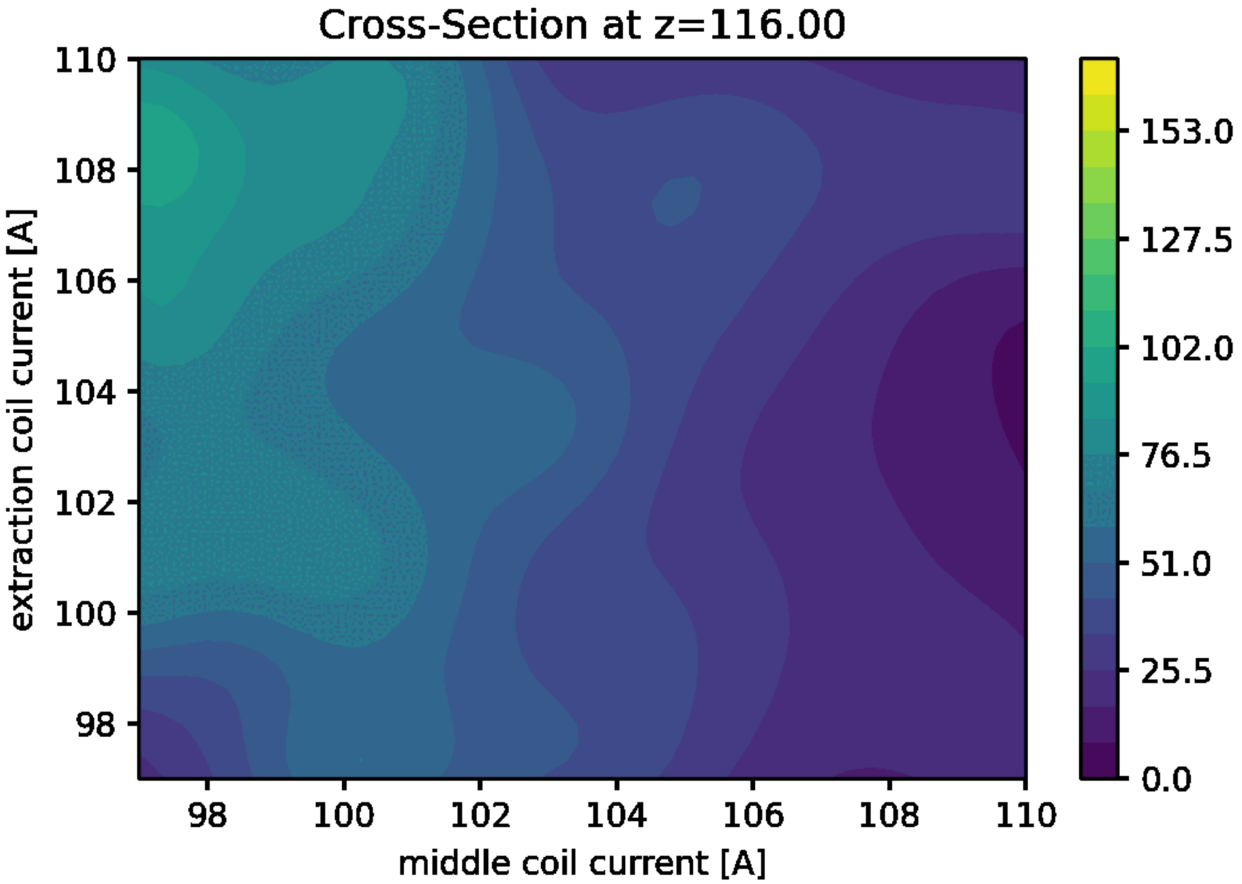
Diagnostics include:
- Beam current
- Charge state distribution
- Emittance
- Bremsstrahlung

What you really want to know:
- Plasma density distribution
- Electron energy distribution
- Particle lifetimes
- RF distribution

2021 $1M FOA award: “Machine Learning Optimization Upstream and Downstream of the Accelerator: The Cases of VENUS and GRETA”

First steps toward Machine Learning





Thank you!

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Machine Learning Collaborators:
Alex Kireef, Marco Salathe, Harvey Yu, Wenhan Sun, Brian Quiter, Ren Cooper, Chris Campbell, Heather Crawford