# A PATHWAY TO ACCELERATE ION BEAMS TO 3 GEV WITH A K140 CYCLOTRON

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Outline:

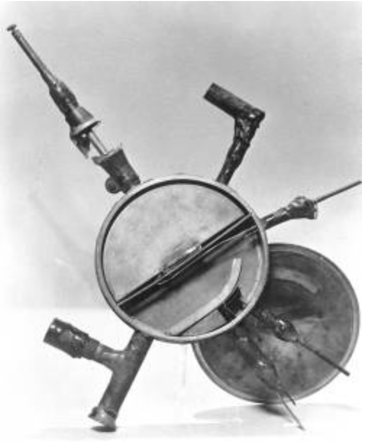
- Introduction to the 88-Inch Cyclotron Facility at LBNL
- How the ECR enhanced the 88-Inch Cyclotron's capabilities
- A future ECR ion source to allow the 88-Inch Cyclotron to produce beams with kinetic energy in excess of 3 Gev

# Berkeley Cyclotron History

**First cyclotron in January 1931 on UC Berkeley Campus:**

4.5″ (0.11 m) -> protons to 80 keV

| | | | | |
|---|---|---|---|---|
| 1931 | 1931 | 1932 | 1937 | 1939 |
| 9″ | 11″ | 27″ | 37″ | 60″ |
| 0.23 m | 0.28 m | 0.69 m | 0.94 m | 1.52 m |



1946: 184″(4.67 m) requires moving away from campus.
Birth of LBNL

May 1962: First external beam from 88-Inch Cyclotron---Last of the R&D cyclotrons at Berkeley

# 88-Inch Cyclotron at LBL

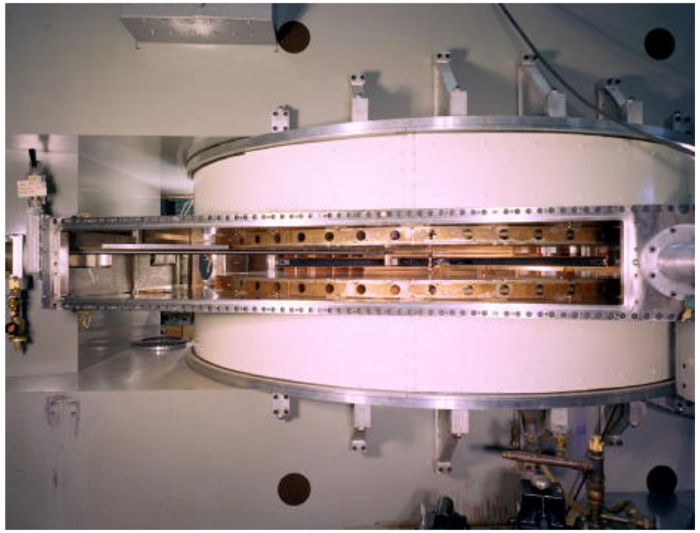
Sector-focused, K140 cyclotron

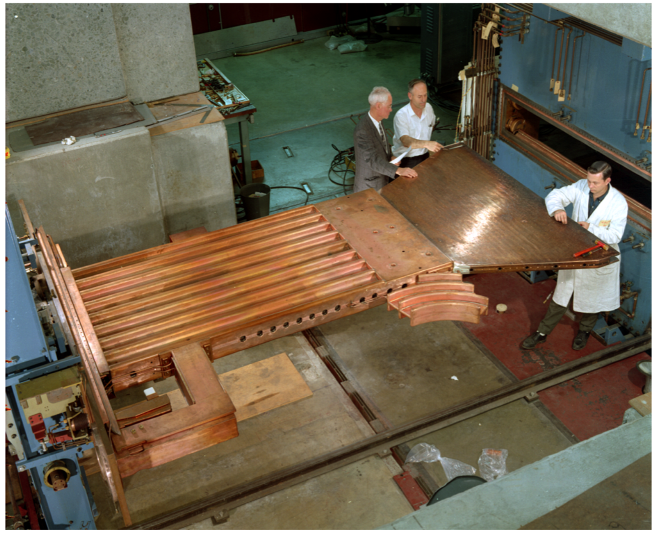
88 inch (2.24 m) diameter pole

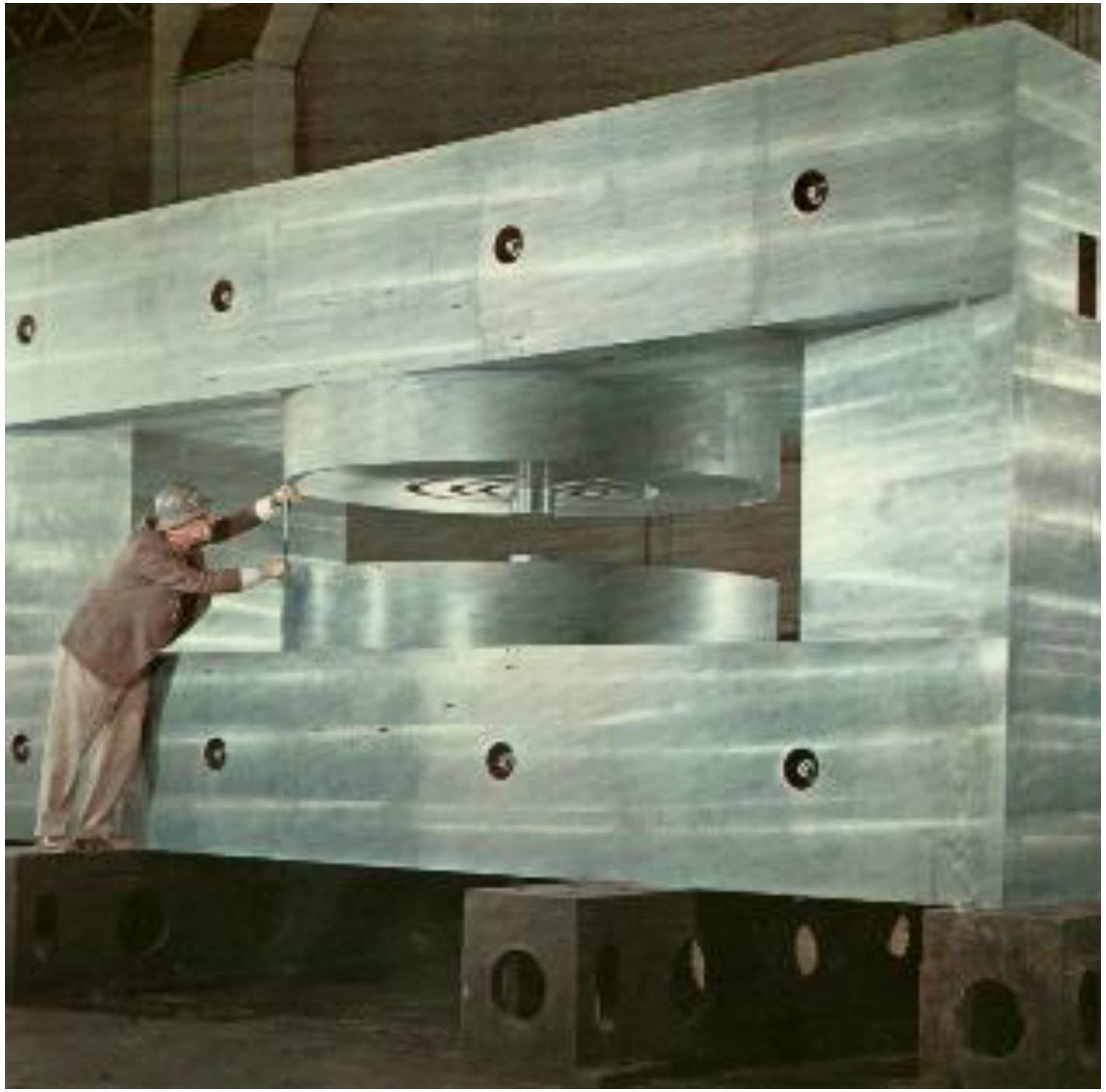
RF: 5.6 to 16.5 MHz, up to 70 kV

Designed as light ion accelerator
- 50 MeV protons, 65 MeV deuterons

Originally used internal PIG source to produce ions



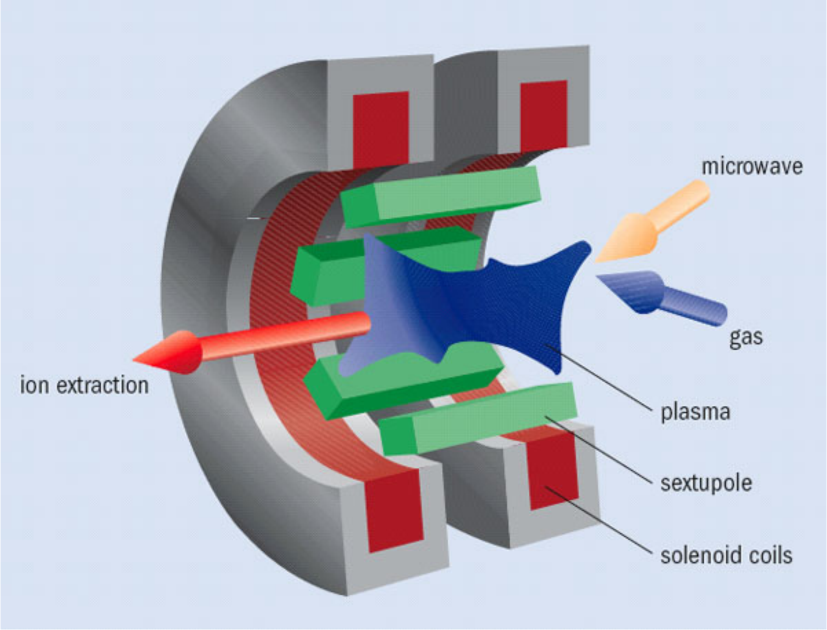




# ECR ion sources

- Electron cyclotron resonance ion source invented by Geller in late 1950s/early 1960s
- Plasma confined axially by solenoids and radially by multipole magnet (usually sextupole)

  → results in "Minimum-B" magnetic field structure
- Resonant electron heating via microwave on closed constant B surfaces leads to step-wise ionization




Increase plasma electrons' lifetime and you get:

- higher energy electrons -> higher charge state ions (remove high ionization potential electrons)
- more beam current

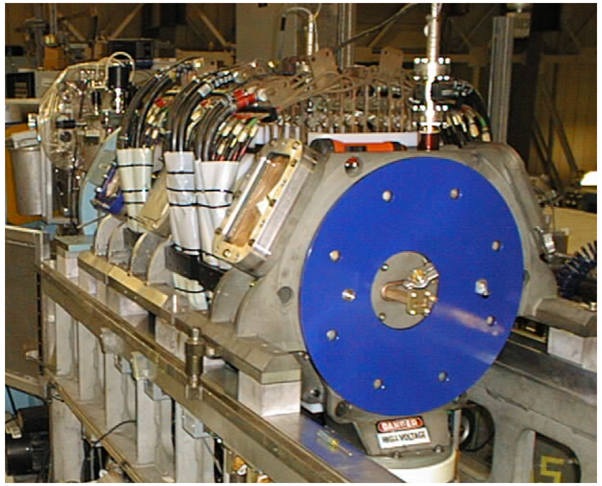
Geller gave semi-empirical scaling law: $I_q \propto f^2 \propto B^2$

- has held true for three generations of ion sources with no end in sight

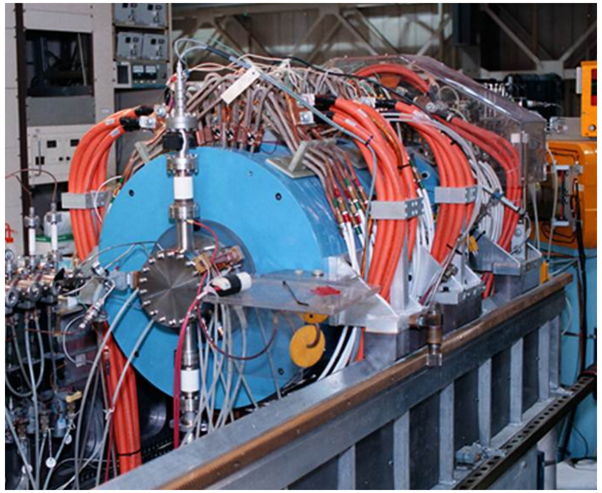
For cyclotrons: beam energy $KE \propto Q^2$
Higher field ECR ion sources
-> higher-current, highly charged ion beams
-> significantly higher energy cyclotron beams

# ECR ion sources at the 88-Inch Cyclotron

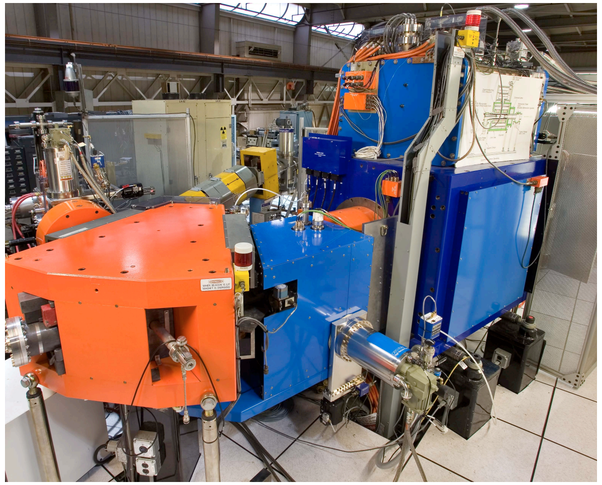
LBL-ECR (1983)
0.4 tesla
6.4 GHz (0.6 kW)



AECR-U (1996)
1.7 tesla
10 + 14 GHz (2.6 kW)



VENUS (2001)
4.0 tesla
18 + 28 GHz (12 kW)



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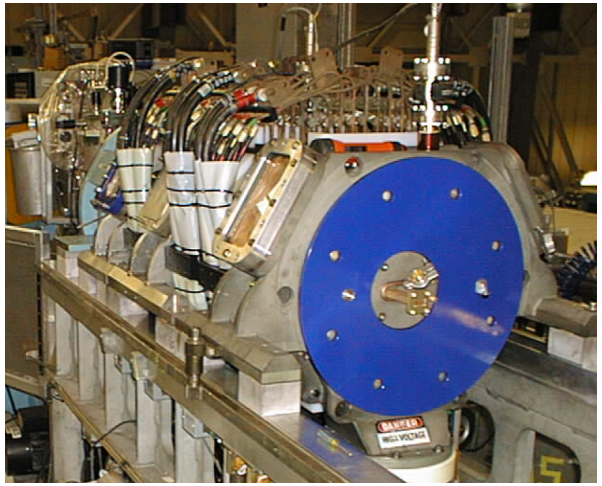

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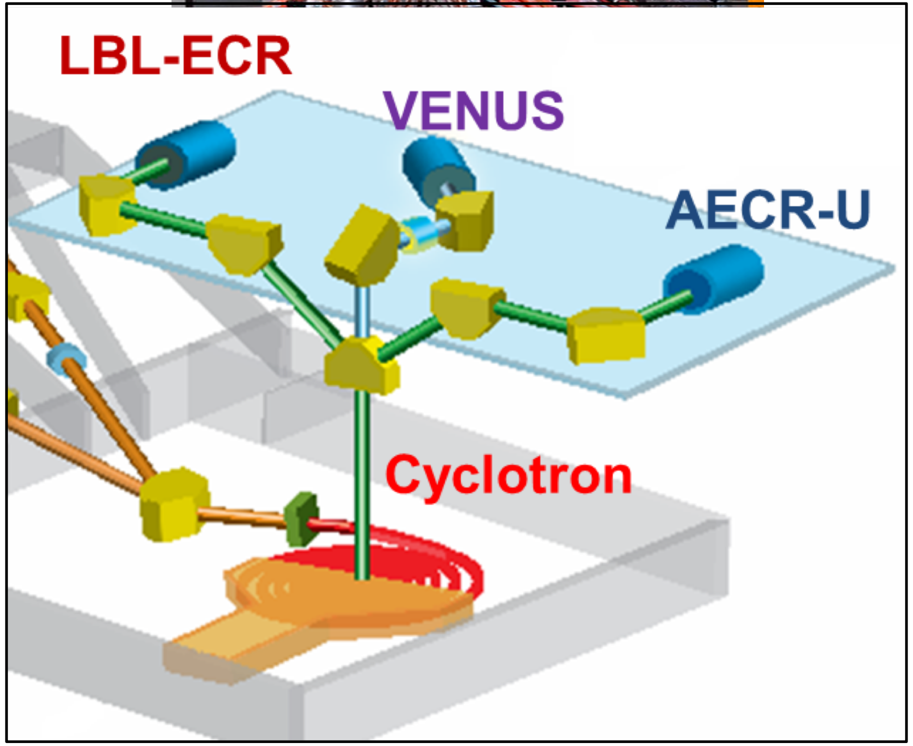


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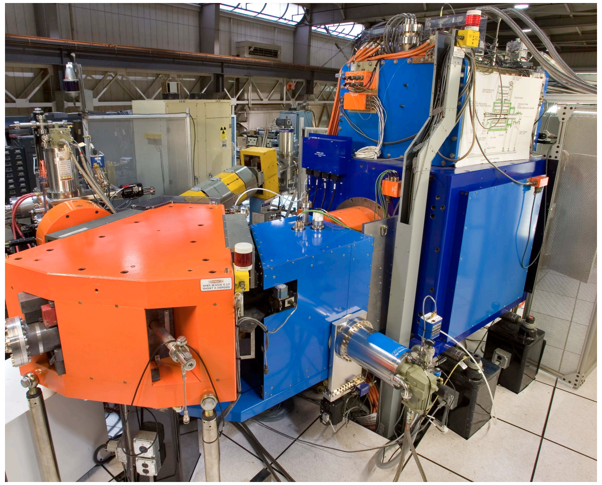
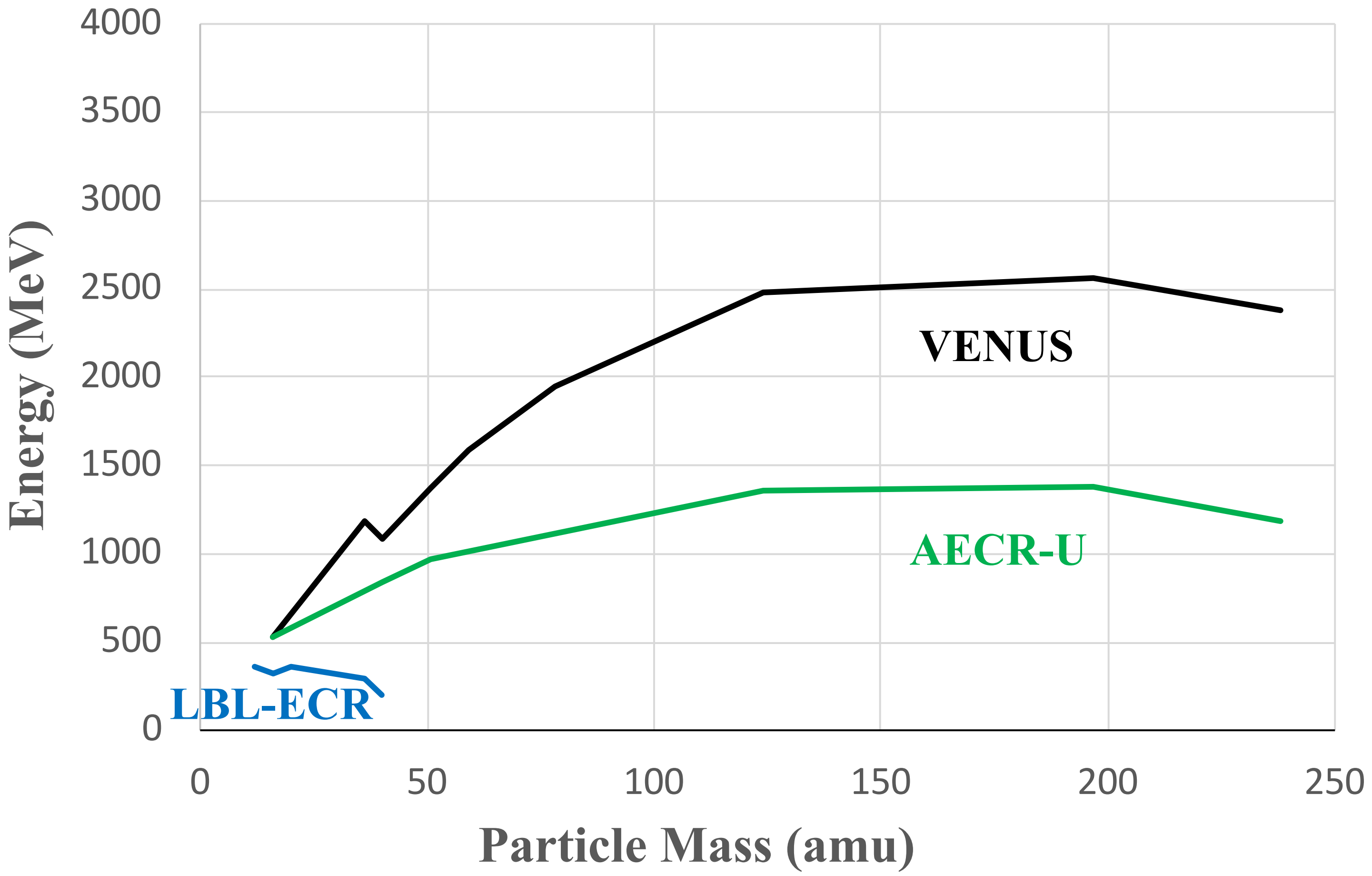
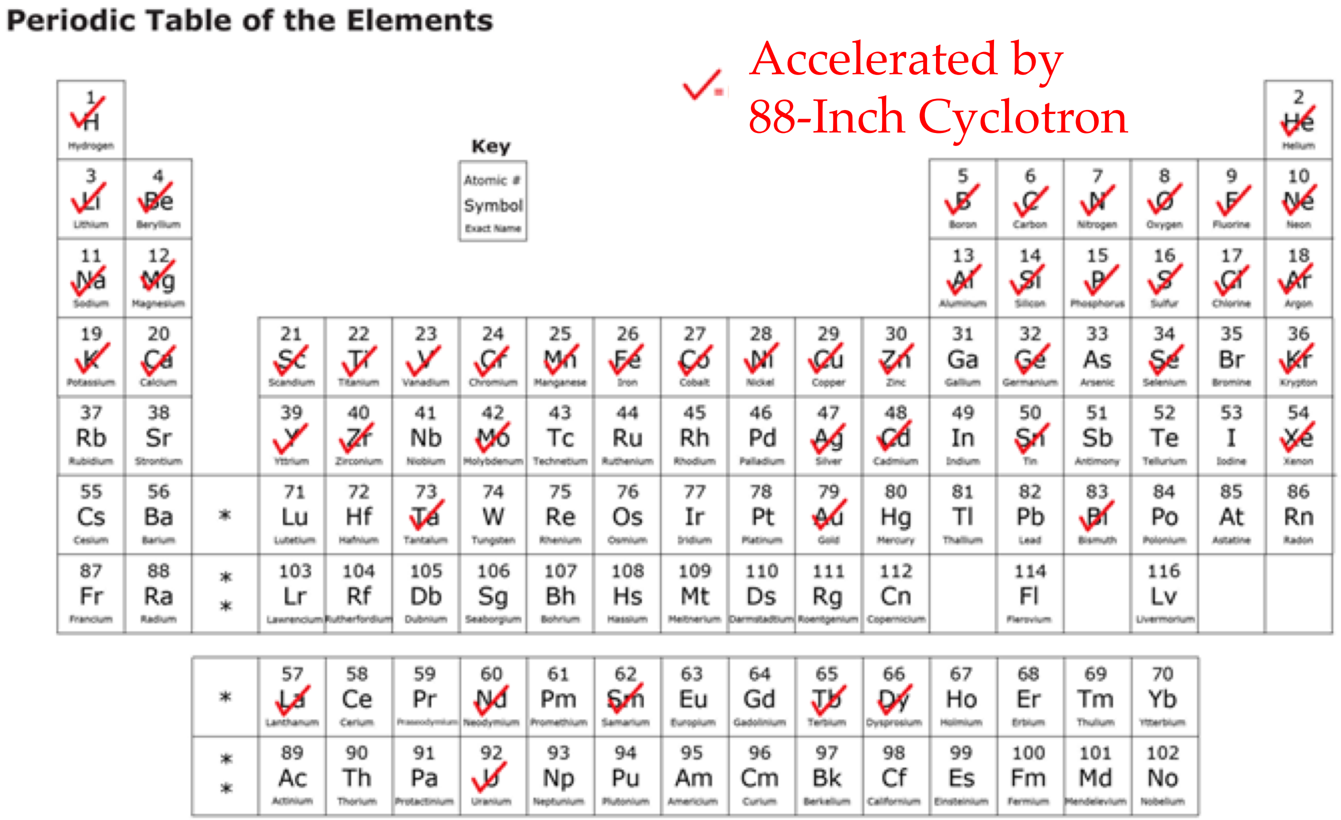


# Increased cyclotron capability with each new source



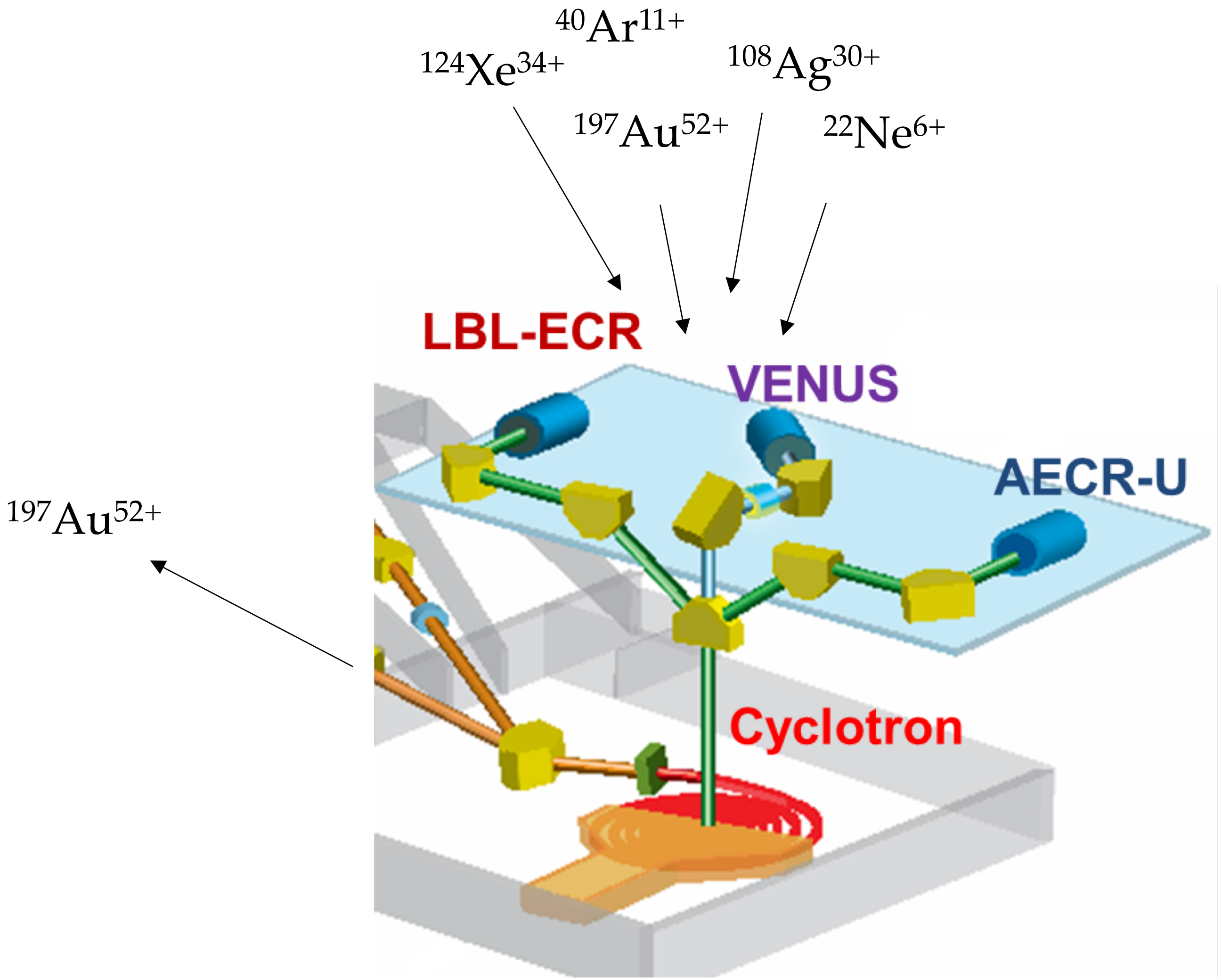

Each new ion source has increased the maximum achievable energy across mass spectrum

# ECR ion sources give 88-Inch Cyclotron flexibility




88-Inch Cyclotron has accelerated 49 of the 92 naturally occurring elements (53 %)

# Cocktail beams from 88-Inch Cyclotron




ECR ion sources allowed a new use for 88-Inch Cyclotron: Space Effects testing

- Cocktail beams: inject multiple ion species but only fully accelerate one by small RF changes
- Change beams in ~1-2 minutes
- Deposit energy into computer chips at different depths dependent on mass & energy

- Chip testers want higher energy beams to minimize part preparation, but only need low currents (~ $10^6$ ions/second)

# VENUS superconducting ECR ion source

- One of the most powerful ECR ion sources in the world

VENUS: selected ions and beam currents [μA]

| | |
|---|---|
| $^{16}O^{6+}$ | 4750 |
| $O^{7+}$ | 1900 |
| $^{40}Ar^{12+}$ | 1060 |
| $Ar^{14+}$ | 840 |
| $Ar^{16+}$ | 525 |
| $Ar^{17+}$ | 120 |
| $Ar^{18+}$ | 4 |
| $^{78}Kr^{28+}$ | 100 |
| $Kr^{31+}$ | 17 |
| $Kr^{32+}$ | 7 |
| $^{129}Xe^{38+}$ | 26 |
| $Xe^{42+}$ | 6 |
| $Xe^{44+}$ | 2 |
| $Xe^{45+}$ | 0.8 |
| $^{197}Au^{55+}$ | 2.2 |
| $Au^{57+}$ | 1.3 |
| $Au^{58+}$ | 0.6 |
| $Au^{59+}$ | 0.3 |

# VENUS superconducting ECR ion source

- One of the most powerful ECR ion sources in the world
- Has allowed 88-Inch Cyclotron to extract ions with KE > 2.6 GeV

Ultra-High Charge State Ion Beams
Accelerated by the 88-Inch Cyclotron

| Ion | E (MeV/n) | $E_{total}$ (GeV) | I (pA) |
|---|---|---|---|
| $^{124}Xe^{47+}$ | 19.2 | 2.38 | 62 |
| $^{124}Xe^{48+}$ | 20.0 | 2.48 | 10.5 |
| $^{124}Xe^{49+}$ | 20.8 | 2.58 | 2.1 |
| $^{179}Au^{63+}$ | 13.5 | 2.66 | ~1 |

# VENUS superconducting ECR ion source

- One of the most powerful ECR ion sources in the world
- Has allowed 88-Inch Cyclotron to extract ions with KE > 2.6 GeV
- Higher energies will require more current of high charge state ions

VENUS: selected ions and beam currents [µA]

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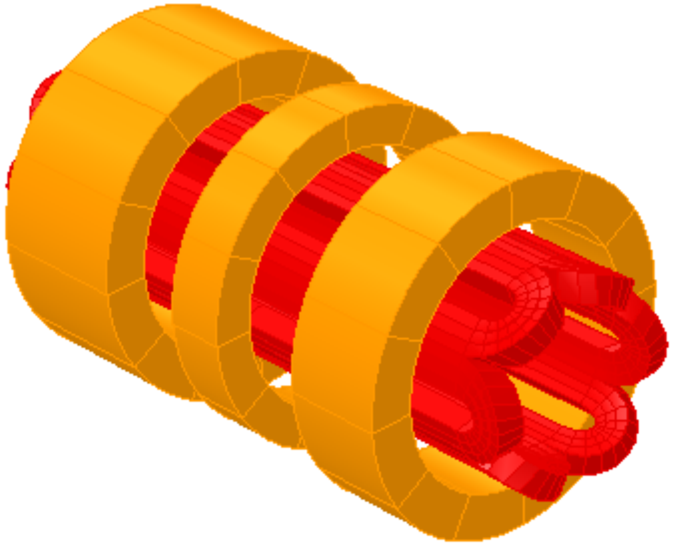
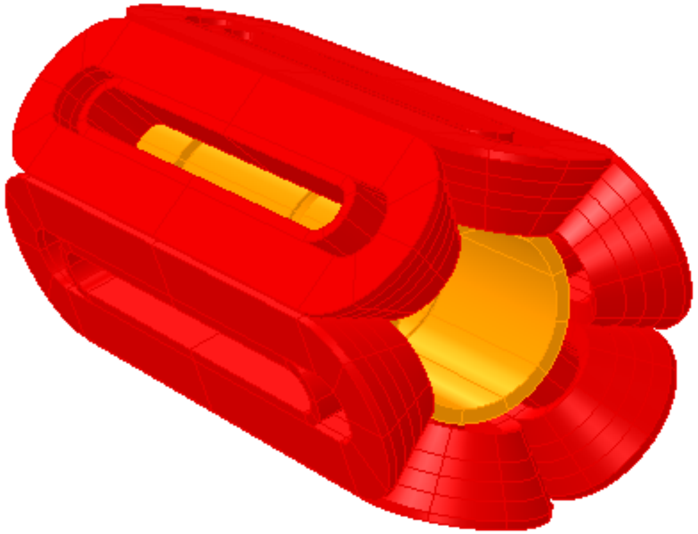
ECR ion source solution: higher magnetic field and 45 GHz operation!

# How to increase B fields for 45 GHz operation?



Sextupole-in-solenoid (VENUS-like)



Solenoid-in-sextupole (SECRAL-like)

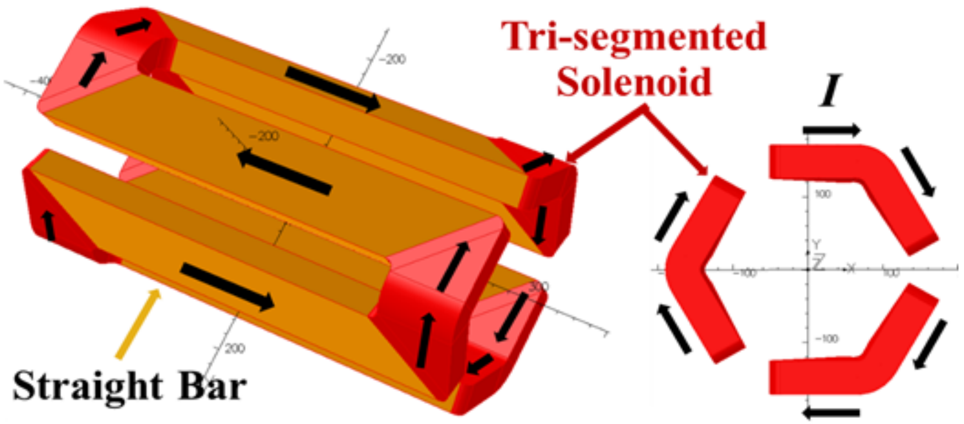
- Two highest performing ECR ion sources at 28 GHz use two different designs
- For both designs NbTi coils are running near their limit
- Could change materials (e.g. $Nb_3Sn$), but this is proving difficult

What if we rethink geometry while using well-proven NbTi?

# MARS coil design (Mixed Axial and Radial System)

Start with closed-loop-coil

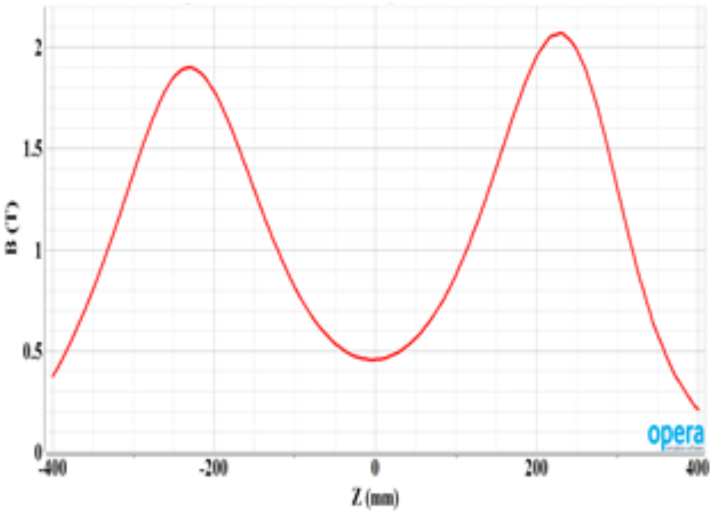
- Unlike racetrack sextupole whose end fields cancel, closed-loop-coil ends produce a solenoid fields
- This coil, alone, produces a minimum-B magnetic field

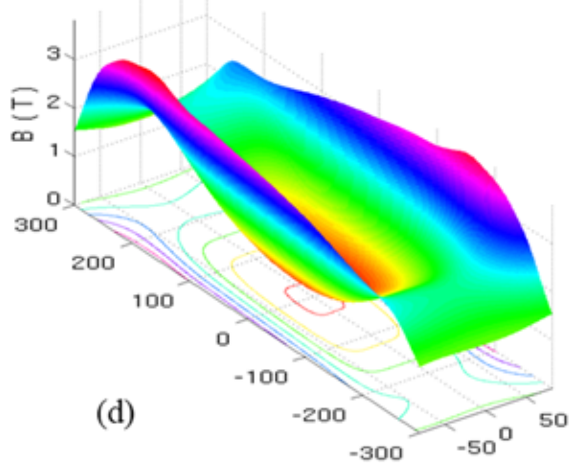



Advantages of starting with closed-loop-coil

- Smaller solenoids required
  → smaller overall source size
  → lower solenoid fields on sextupole

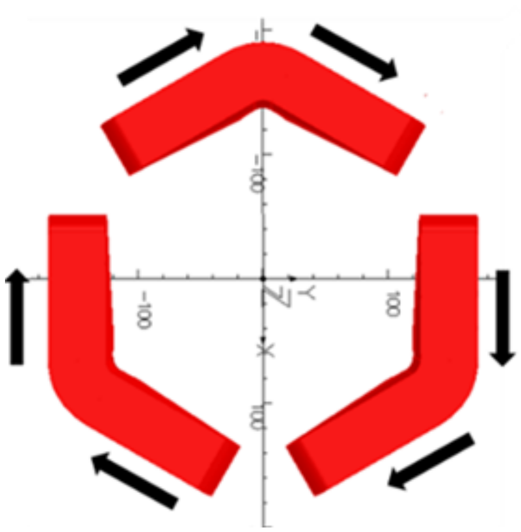
- Clamping easier as forces on sextupole ends are all outward (not true for racetracks)

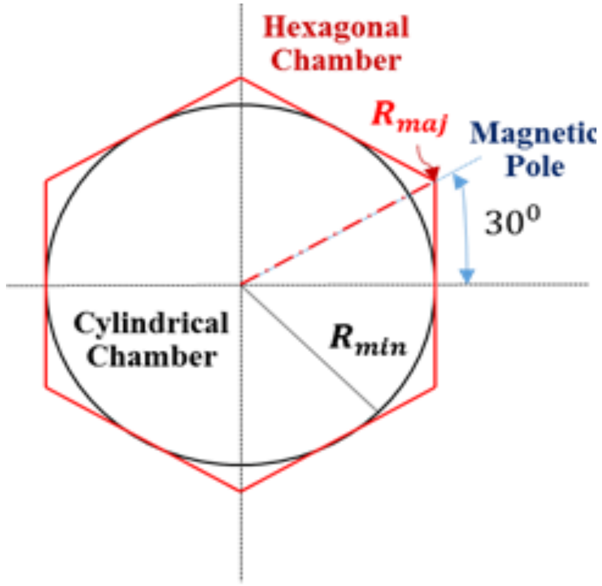


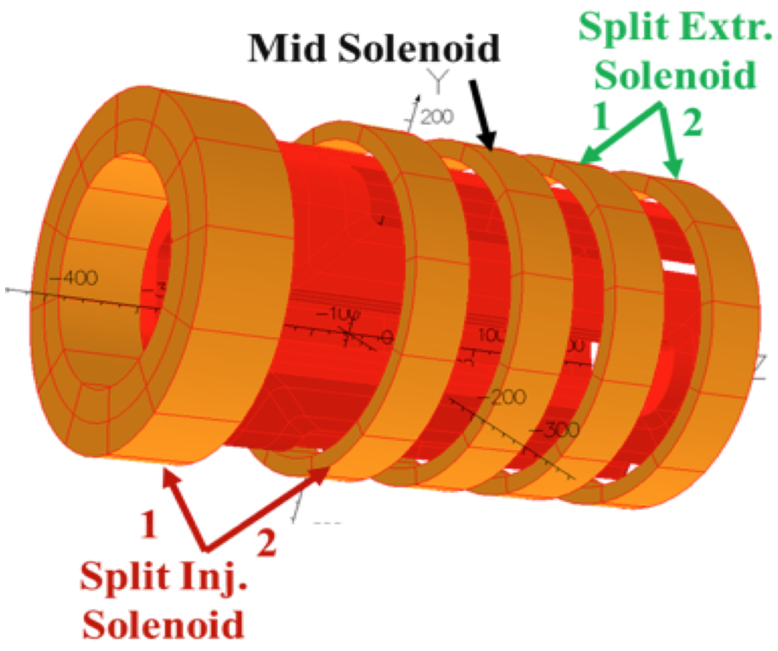



# MARS-D: a path to a 45 GHz ECR source using NbTi

MARS-D will better utilize sextupole field ($B \propto r^2$) by using hexagonal plasma chamber (30% increase over cylindrical)






**Nominal ECRIS Design Criterion**

$B_{inj}$ ~3-4 $B_{ecr}$ on axis

$B_{rad}$ ~ 2 $B_{ecr}$ at the chamber walls

$B_{ext}$ ~ 2 $B_{ecr}$ on axis

$B_{min}$ ~ 0.5-0.8 $B_{ecr}$ on axis

**MARS-D design fields**

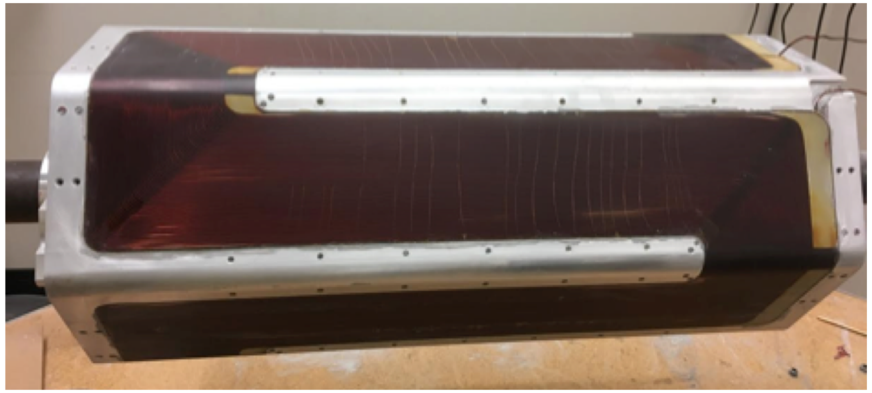
$B_{inj}$ = 5.8 T (3.6 · $B_{ecr}$)

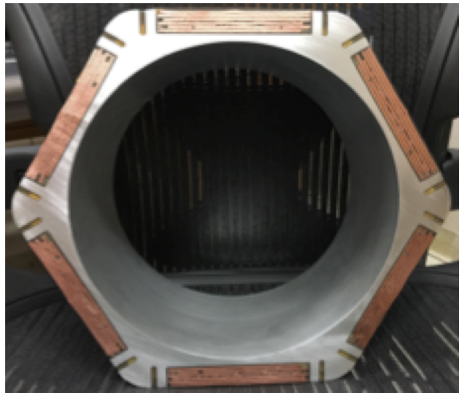
$B_{rad}$ = 3.2 T (2.0 · $B_{ecr}$)

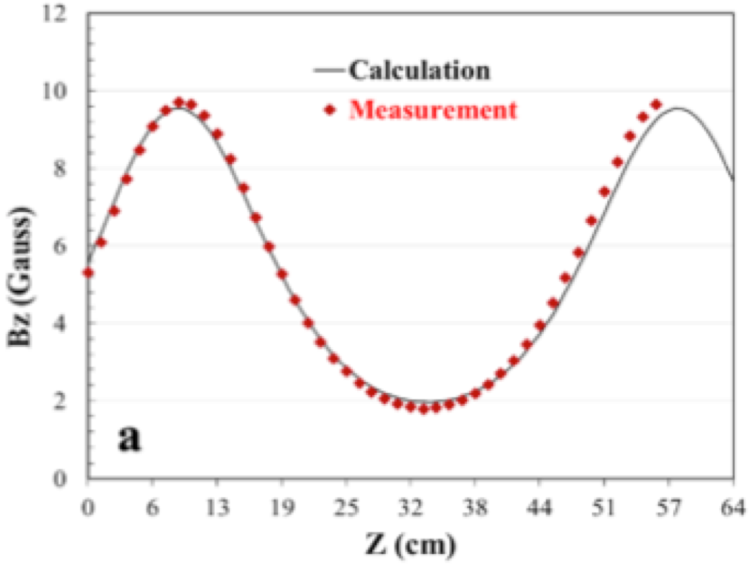
$B_{ext}$ = 3.4 T (2.1 · $B_{ecr}$)

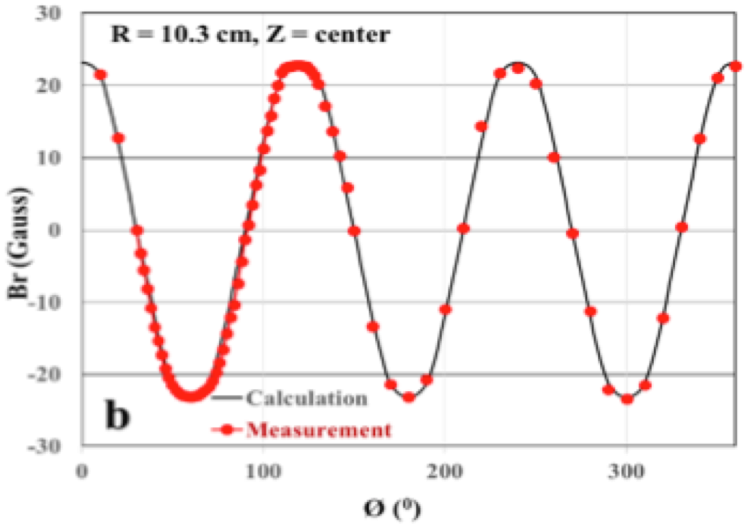
$B_{min}$ ~ 1.1 T (0.7 · $B_{ecr}$)

# Copper test winding



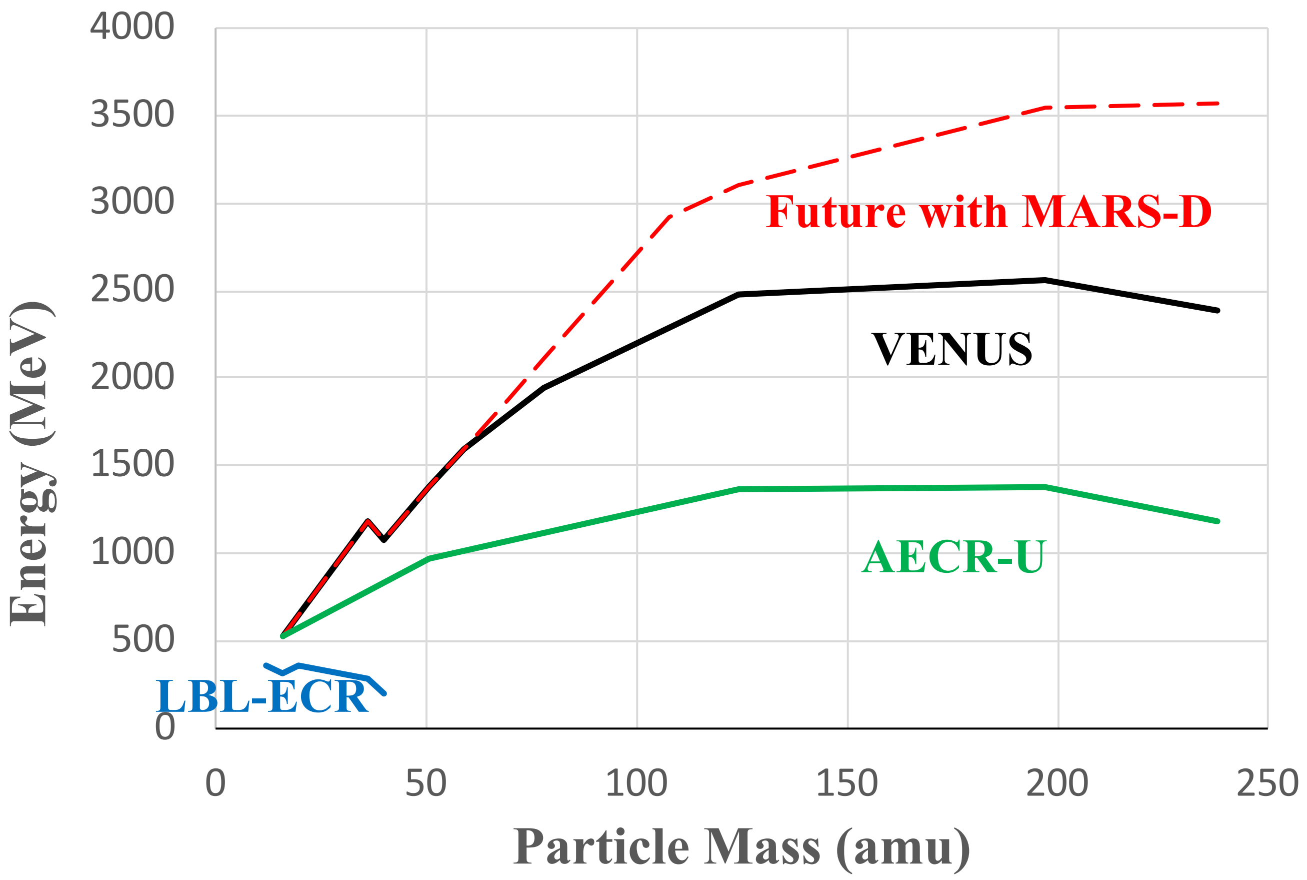


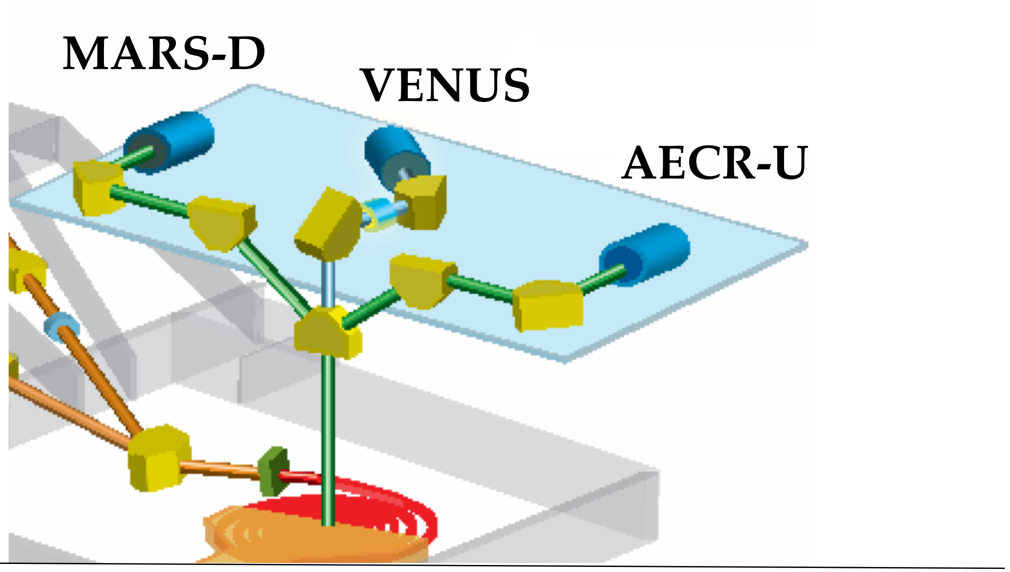



Based on this successful experience, we believe MARS-D could be constructed and producing beams for the 88-Inch Cyclotron in five years

# Expected performance increase based on scaling laws




**Predicted Cyclotron Performance with MARS-D**

| Ion | E (MeV/n) | $E_{total}$ (GeV) |
|---|---|---|
| $^{124}Xe^{52+}$ | 23.4 | **2.90** |
| $^{124}Xe^{53+}$ | 24.3 | **3.01** |
| $^{124}Xe^{54+}$ | 25.2 | **3.12** |
| $^{179}Au^{69+}$ | 16.2 | **3.19** |
| $^{179}Au^{70+}$ | 16.6 | **3.27** |
| $^{179}Au^{73+}$ | 18.0 | **3.55** |

# Conclusions

- ECR ion sources have transformed the nearly 60-year-old 88-Inch Cyclotron from a light ion accelerator to one that has accelerated over half the naturally occurring elements
- Superconducting ECR ion source, VENUS, has made it possible for the 88-Inch Cyclotron to accelerate ions to over 2.6 GeV
- Developing a 45 GHz ECR ion source is expected to allow the 88-Inch Cyclotron to accelerate beams in excess of 3 GeV
- The MARS-D ECR ion source provides a path to a 45 GHz source using the well-tested superconductor NbTi, avoiding the difficulties of other high-field materials