Ion Source R/D at the 88-Inch Cyclotron

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Ongoing ion source R/D at the 88-Inch Cyclotron

- **MARS-D, a next generation 45 GHz ECR ion source**
- **Intense Ti ion beams with new HTOs**
- **Intense 1+/1- ion source**
- **VENUS with a chamber insert**

VENUS: One of the present state of the art ECRISs

The first superconducting ECRIS designed to operate at 28 GHz

- **Max. Bz field on axis: 4.0 T and Br field at chamber wall: 2.2 T** (at the NbTi conductor constraints)
- **Max. microwave power (28+18 GHz): 12 kW**

VENUS

Prototype source for FRIB

Milestone: $^{238}U^{33+}$: **0.45 emA ~ 13.6 pμA**

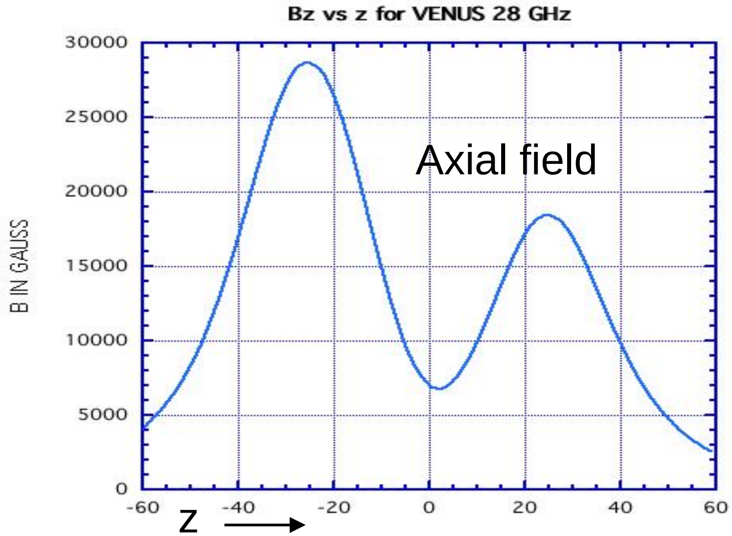
	VENUS (28+18 GHz) (≤2015, 8 kW)	VENUS (28+18 GHz) (> 2015, 10 kW)	VENUS Improv't Present/2015
$^{16}O^{6+}$	2.85	**4.75**	**1.67**
O^{7+}	0.85	**1.90**	**2.23**
$^{40}Ar^{12+}$	0.86	**1.06**	**1.23**
Ar^{16+}	0.27	**0.525**	**1.94**
Ar^{18+}	0.001	**0.004**	**4.0**
$^{78}Kr^{18+}$		**0.77**	
Kr^{23+}	0.088	**0.42**	**4.77**
Kr^{32+}		**0.007**	∝
$^{129}Xe^{38+}$	0.007	**0.026**	**3.71**
Xe^{42+}		**0.006**	∝
Xe^{45+}		**0.0008**	∝
$^{197}Au^{52+}$	0.0008	**0.0047**	**5.87**
Au^{57+}		**0.0013**	∝
Au^{59+}		**0.0003**	∝
$^{209}Bi^{51+}$	0.0033	**0.022**	6.67
Bi^{57+}		**0.0023**	∝
Bi^{61+}		**0.0001**	∝

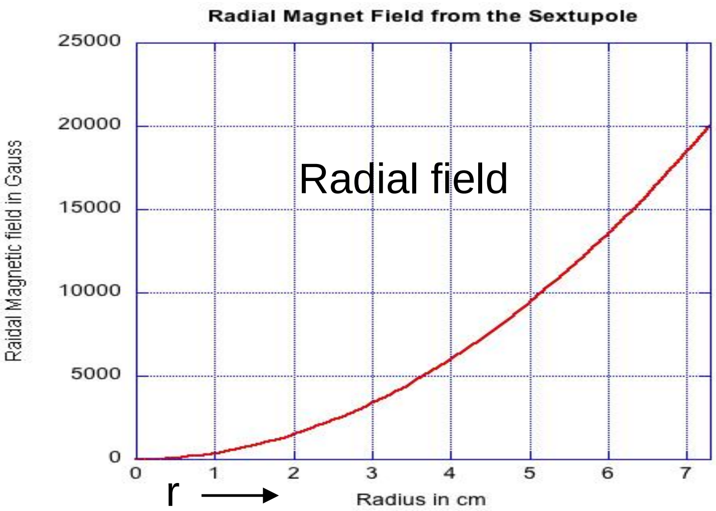
***: All currents are in unit of emAs**

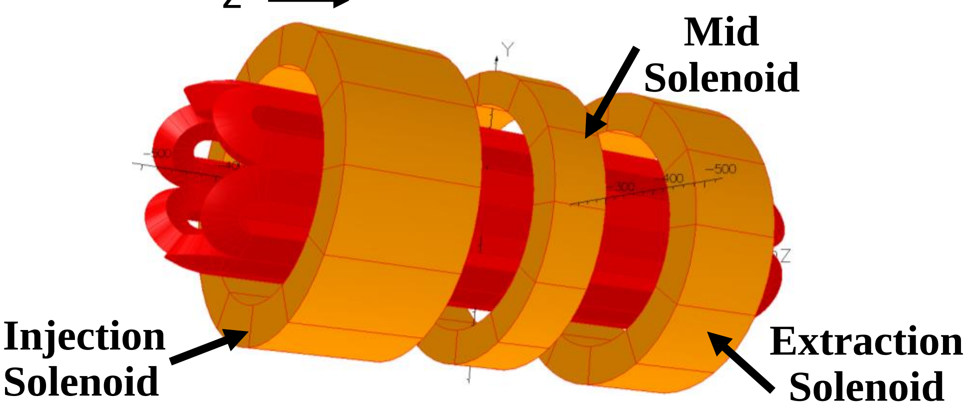
Recently added 20 MeV/u cocktail beams up to Xe for BASE

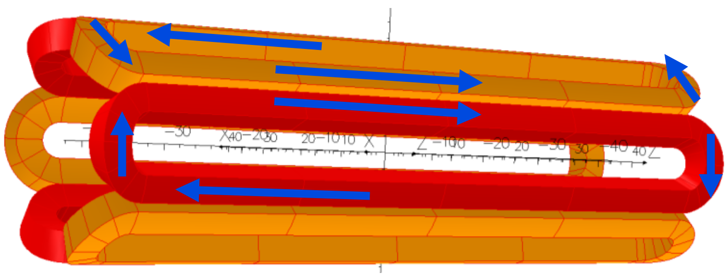
Critical component of a high charge state Electron Cyclotron Resonance Ion Source (ECRIS)

The most critical component of a high charge state ECRIS is a min-B magnetic configuration, typically a superposition of axial mirrors (solenoids) and radial fields (pure sextupoles without axial fields)









Sextupole
6 racetrack coils, no axial fields

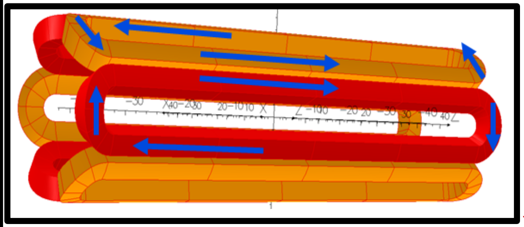
Ion Source R&D – MARS magnet for next generation of ECRIS

❖ Two pathways for a next generation ECRIS operating at ~ 45 GHz:

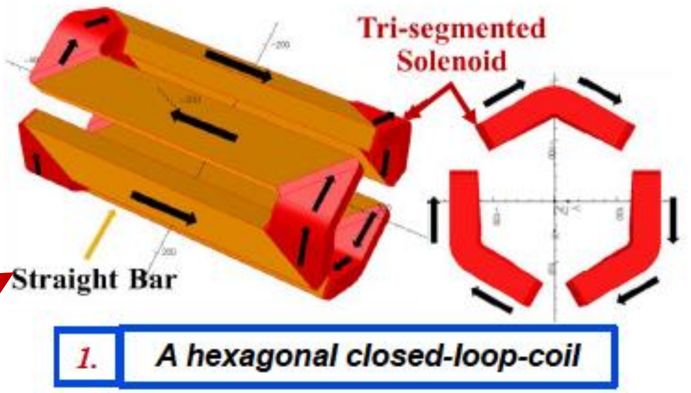
1. Replace the sc conductors used in the existing coil geometry with higher current versions, (e.g., Nb_3Sn conductor).

- Unproven magnet reliability
- Condutor heat-react and brittleness result in much more complex coil fabrication
- Conductor's poor quench propagation requires very demanding quench protection system
- ....

2. Optimized geometry, MARS (Mixed Axial and Radial field System).



Sextupole
6 racetrack coils



MARS leads to:

- **Well proven NbTi magnet reliability**
- **Lower cost for the cold mass**
- **Better form factor for field utilization**
- **Simplified interaction patterns and lower forces**

Critical challenge is winding a closed-loop-coil but **coil fabrication has already been demonstrated** (2017)

❖ **MARS is the better pathway toward a next generation ECR ion source.**

Comparison of the max. Stress (Von Mises) on coils in different magnet geometries

	FRIB VENUS[1] (28 GHz)	IMP FECR[2] (45 GHz)	MARS-D[3] (45 GHz)
Sextupole Coil	~ 140	~ 144	**~ 80**
Sextupole coil deformation	Waiting for info	166 um	**TBD**
Solenoid coils	~ 90	~ 100	**~ 70**
Notes	**NbTi** magnet. At designed fields using an existing magnet geometry	**Nb_3Sn** magnet. At designed fields using an existing magnet geometry	**NbTi magnet. At designed fields using a MARS magnet geometry**

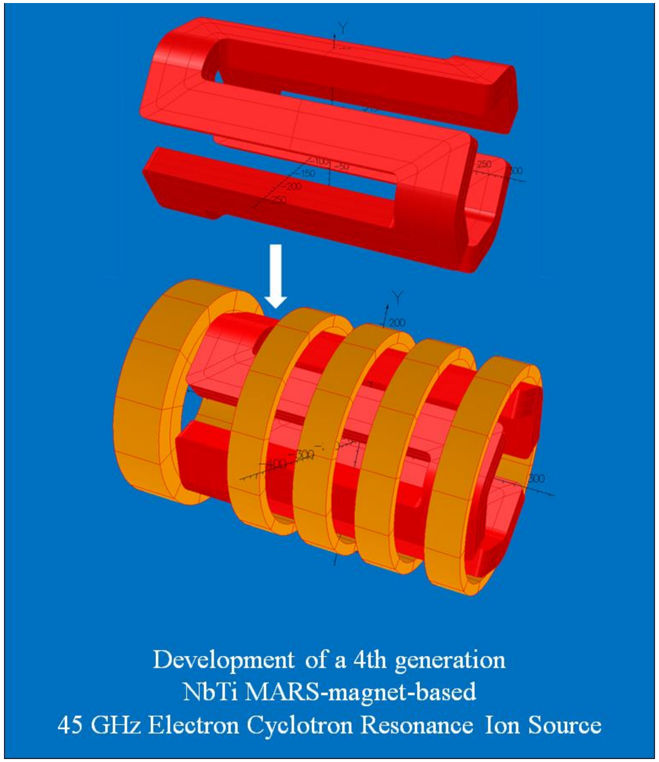
[1]: H. Felice, Report on the FRIB VENUS NbTi magnet (Oct 2013) and Intermediate Design Review (Sept 2014).

[2]: M. Juchno, Report on the IMP 45 GHz ECRIS magnet preliminary design review (Dec 2016).

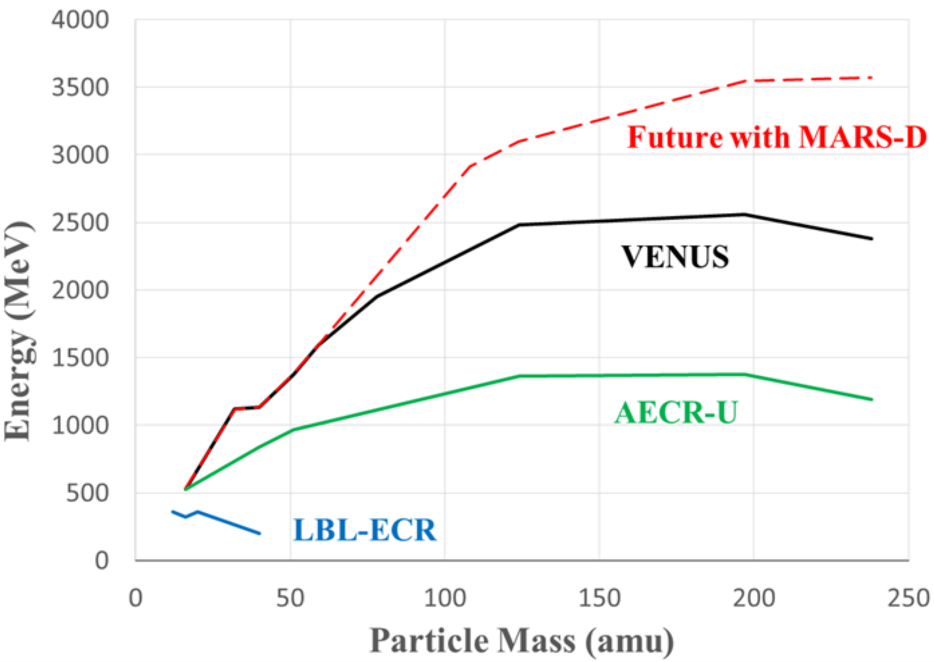
[3]: M. Juchno, Preliminary stress analyses on the MARS-based NbTi magnet for a 45 GHz ECRIS. (Nov 2019).

Ion Source R&D – A 45 GHz ECRIS: MARS-D

MARS-Demonstrator: MARS-D, a 4th Generation 45 GHz ECR source



A proposal for the development of a 45 GHz ECR ion source: MARS-D submitted to DOE in 2019.
Requested Funding
$12.5 M (including $3.5 M Contingency)
FY20-FY24



- Production of milliamps of CW ion beams up to U of charge state 30+ to 40+
- At intensity of eμAs, U charge state 50+ to 65+

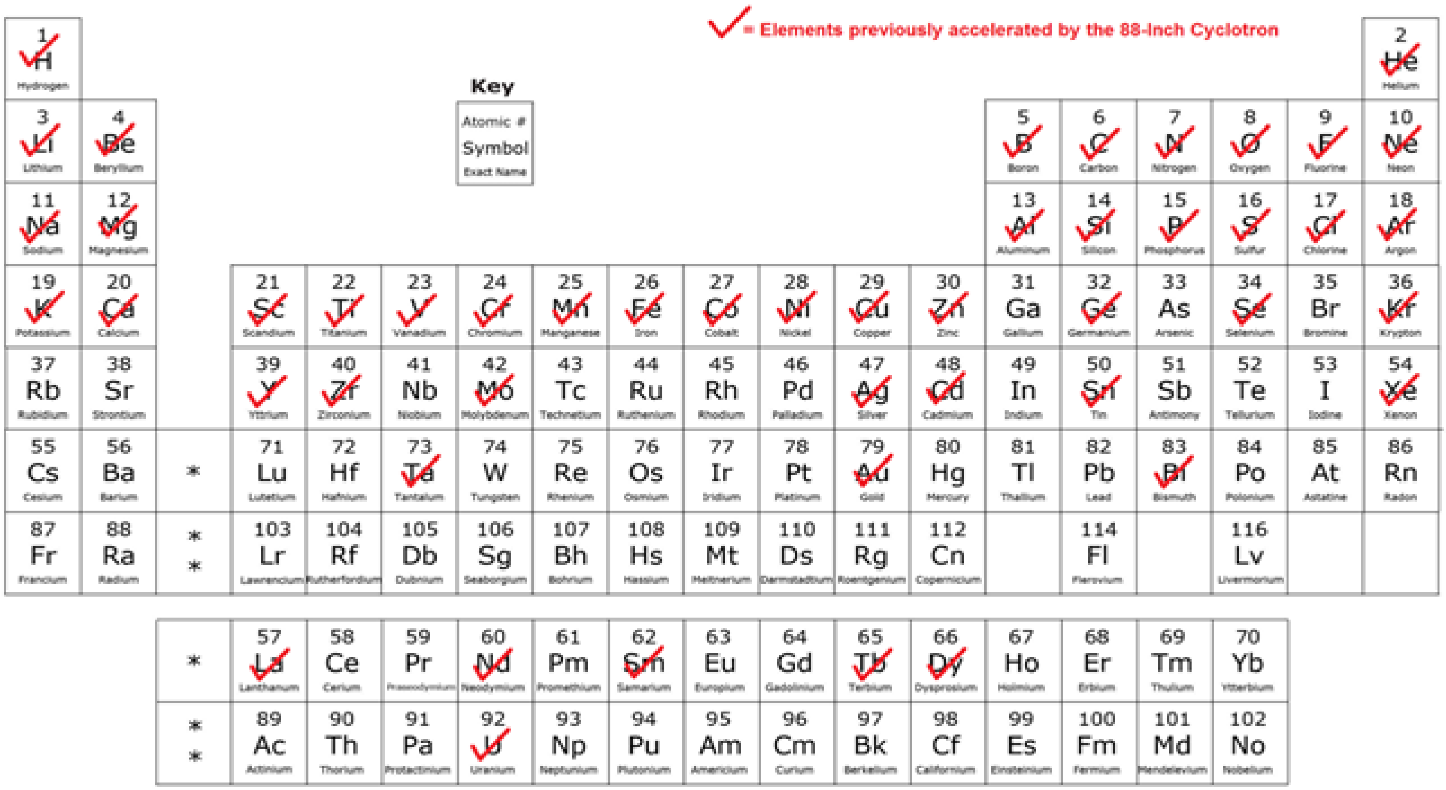
Potential impacts: FRIB, ATLAS, TAMU.....

88-Inch Cyclotron: ~ 30 MeV/u Kr, ~ 25 MeV/u Xe and ~ 15 MeV/u Au for BASE

Intense Ti ion beams with New HTOs

Up to date the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory has accelerated 49 elements (indicated with the red checks), which is more than one half of the natural elements.

Periodic Table of the Elements

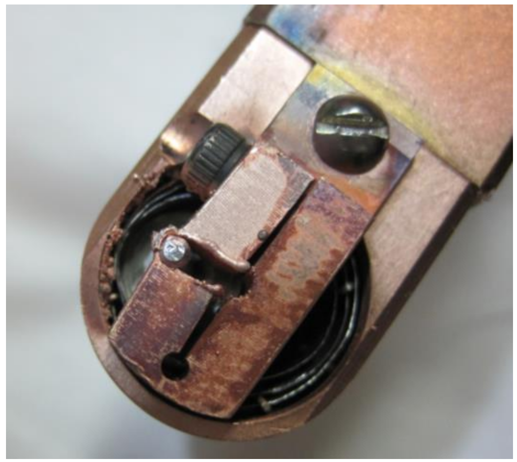


A great variety of ions has been accelerated by the 88-Inch Cyclotron,
thanks a lot to the high temperature ovens for the ECRISs!

Intense Ti ion beams with New HTOs

ECRIS group at LBNL has a long history of developing resistively heated custom-made HTOs that work fine for up to 14 GHz ECRISs.

VENUS, B_{inj} ~ 3 T, I ~ 450 A and l ~ 3 cm, *F ~ 40 N with a complex pattern.*

The VENUS' much higher magnetic fields damage the expensive custom-made HTOs (Ta, W and Re, of a small loading volume of V ~ 0.3 cm^3, ~ 5 k$/set).

The ovens lasted hours to a few days at elevated temperature ≥ 1600 ^{0}C for the production of mainly ~ 10s eμA ion beams

- ❖ **Durable and large-loading-volume HTOs are needed, especially now to meet the new demands for intense metal ion beams of 100s eμA to provide ~ 1.5 to 2 pμA for the BGS runs.**

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Intense Ti ion beams with New HTOs

Strategy: Use as many commercially available heaters as possible to lower the cost and as low heating currents as possible.

W or Ta folded boat (0.010”-0.015” thick, ~ $30/boat)

Loading Volume: 2 cm^3, a factor of ~ 6 larger

Tests have shown these boat ovens be able to against the VENUS’ strong magnetic fields for days without severe damage and can be reused.

Consumption of Ti	Max. I of Ti^{11+}	Injected into 88”	Total Extracted	Flux (pμA)	MeV/u
30 - 50 mgs/h	120 eμA	68 eμA	6.5 eμA	~ 0.6	~ 5

- **Issues: Poor long-term stability and high consumption (a factor of ~ 10 - 20 higher than the custom made cylindrical HTOs).**
- **Remedies to be carried out: Guide the vapor right into the plasma through optimizing the oven location and vapor exit aperture.**

Ion Source R&D – Intense (1+/1-) Ion Source

A Cascade ion source for intense (1+,1-) ion beams

- Cascade arc plasma source can operate at atmospheric pressure Reported plasma flux of 1-10's of amperes per cm^2

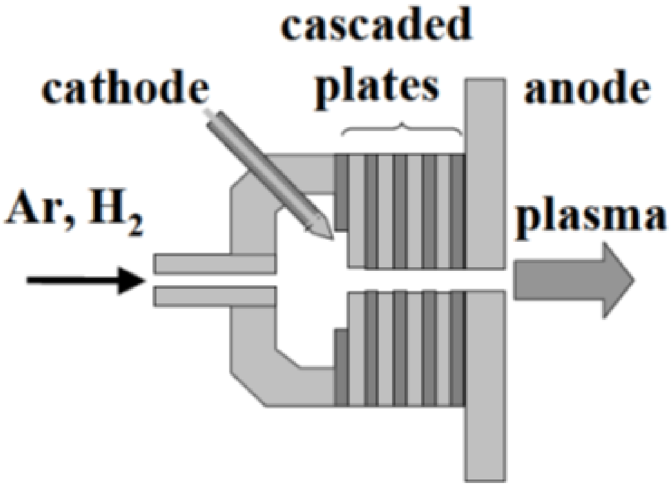
- Is used for many applications but not yet as ion sources, likely due to beam formation and extraction issues.

- **Goal: To produce 300 – 1000 mA singly-charged (1+) or 100s mA of negative (1-) ion beams.**

Potential impacts:

❖ **Enhanced isotope production through Electric-Magnetic-Separation by providing more intense ion beams,**

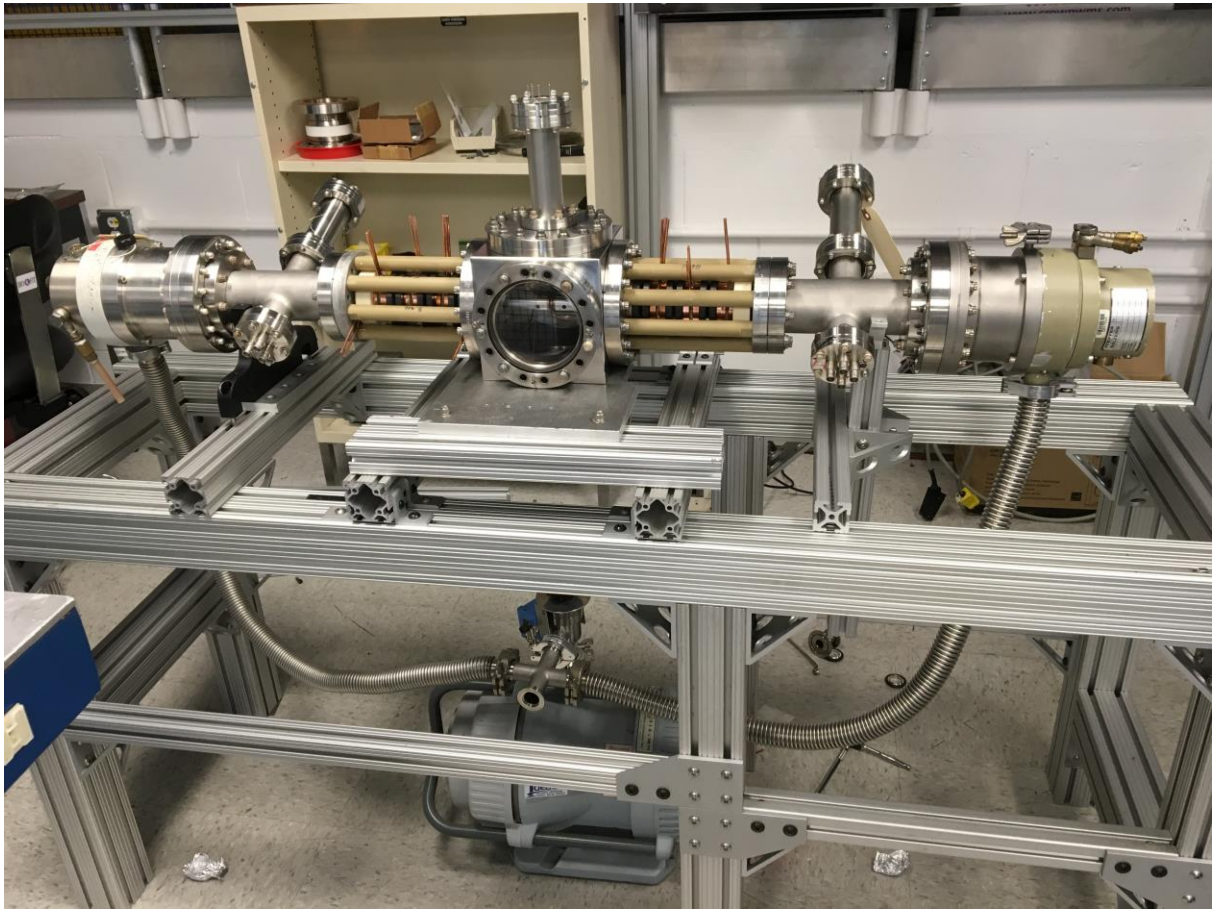
❖ **Applications in accelerators and academic and industry.**



A Cascaded arc plasma source

Ion Source R&D – Intense (1+/1-) Ion Source

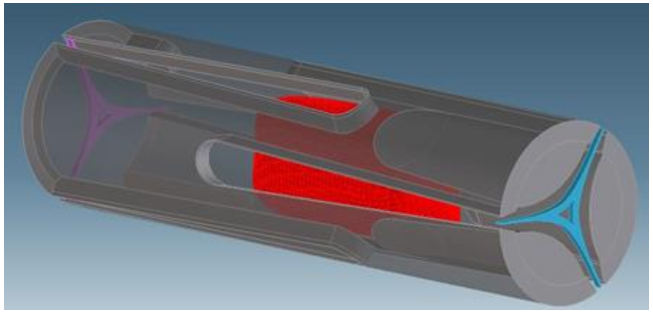
To carry out the development a test bench is needed. Construction of the test bench progresses is almost completed. Hopefully experiments could be carried out soon.

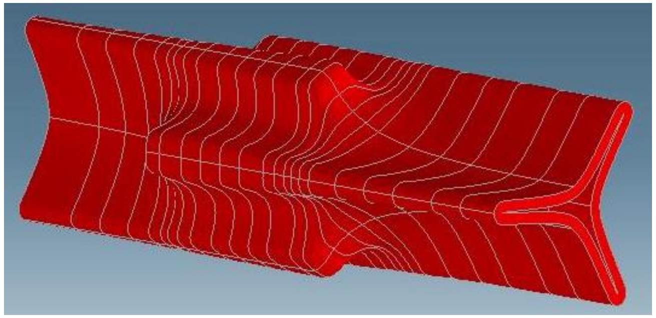


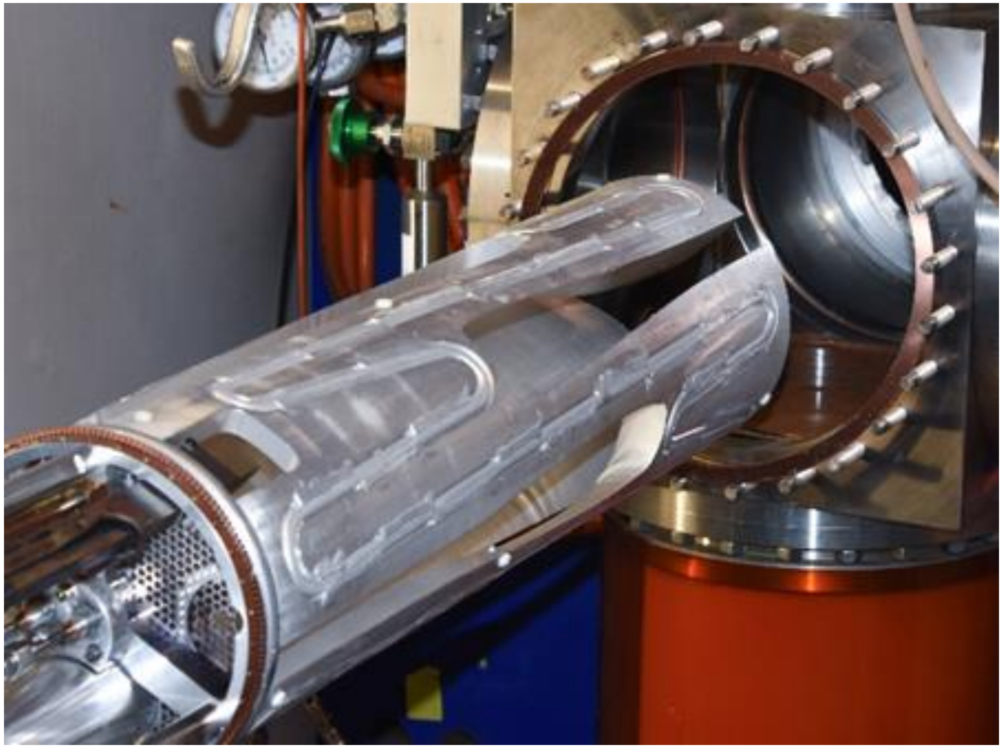
Ion Source R&D – A Chamber Insert in VENUS

ExB to improve the plasma stability needed for the production of the ultra-high-charge-state ion beams.

A chamber insert to provide spatial plasma biasing is being tested in VENUS

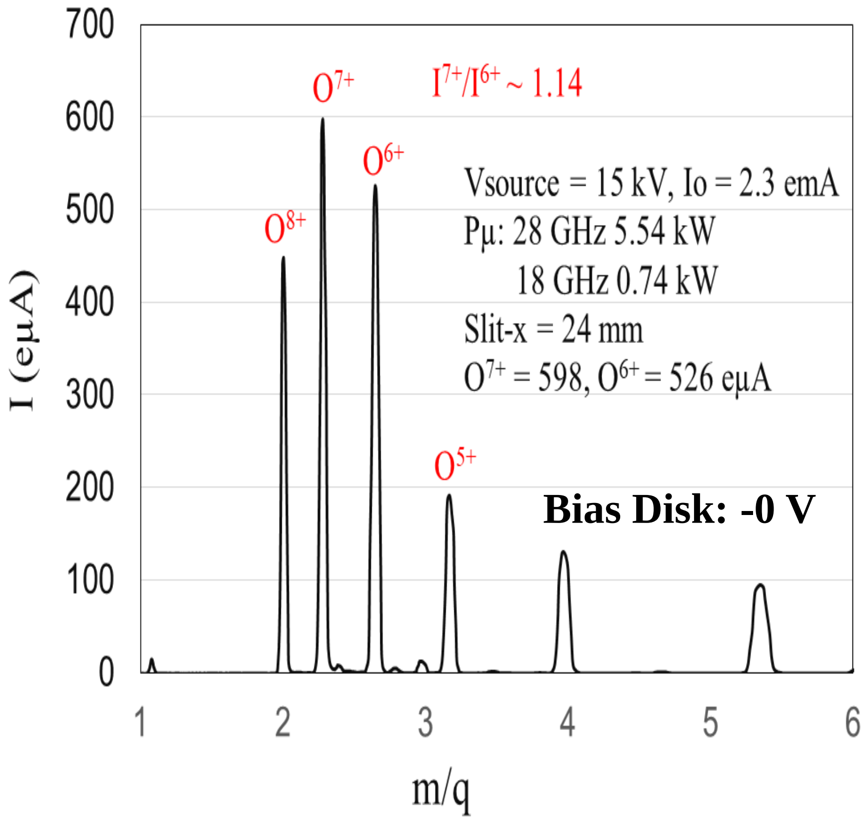






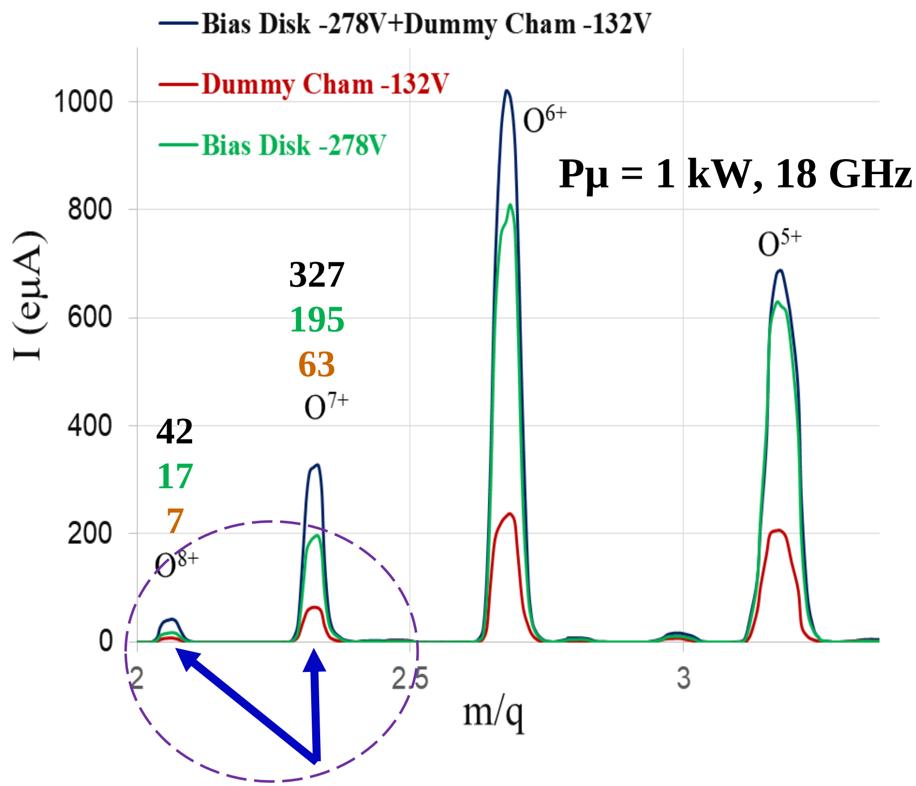
Ion Source R&D – A Chamber Insertion in VENUS

Preliminary Oxygen Results



(Chamber insert was not biased)

The first oxygen CSD peaked at O^{7+} produced by an ECR ion source



It demonstrated that the chamber insert benefitted the higher charge state oxygen ions more: O^{7+} was increased more than 50% at the same input power (1 kW).

Ion Source R&D – A Chamber Insertion in VENUS

Preliminary tests of oxygen with a chamber insert

- **The oxygen results are very promising as it enhanced the yields of high charge state $O^{7+, 8+}$ ions by > 50% at 1 kW 18 GHz. It should enhance yields of the ultra-high-charge-state ions as well.**
- **The complex shape of the chamber insert has upended the ECRIS community's conventional belief that a plasma chamber symmetry is a must in ECR ion sources, e.g., a non-cylindrical chamber can be used in ECRISs.**

❖ **We have plan to demonstrate the benefits of the chamber insertion on the ultra-high-charge-state ions (IP ≥ 3 keV) in the near future. If successful, it will further enhance the energy of the heavier ions from the 88-Inch Cyclotron for BASE.**

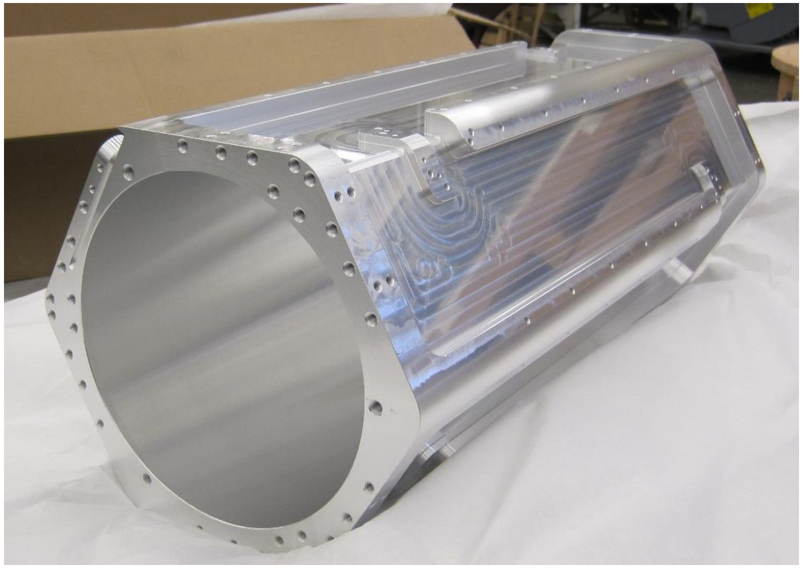

THANK
YOU

Addressing the Critical Challenge of a NbTi MARS Magnet

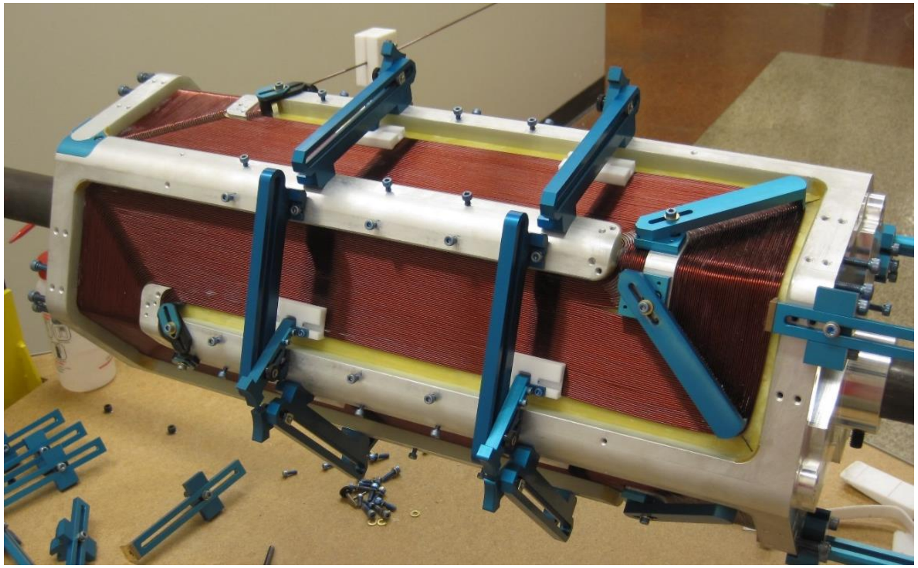
The critical challenge in construction of a MARS magnet is winding the closed-loop-coil.

To overcome the number one challenge

- **A closed-loop-coil prototyping has been successfully completed with rectangular copper wire of about the same size as the intended NbTi wire.**
- **Winding fixtures and techniques have been developed.**

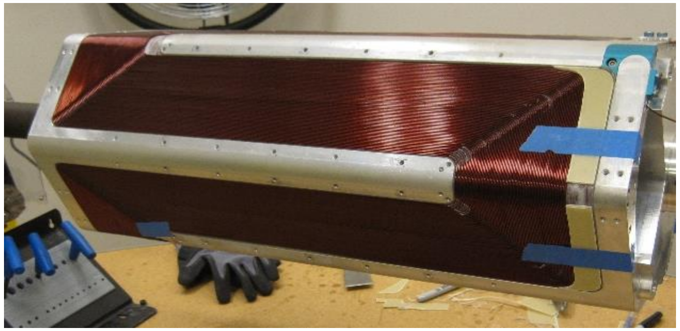


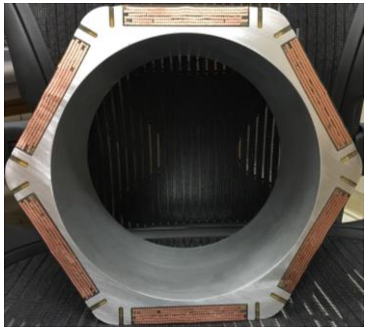
Aluminum mandrel

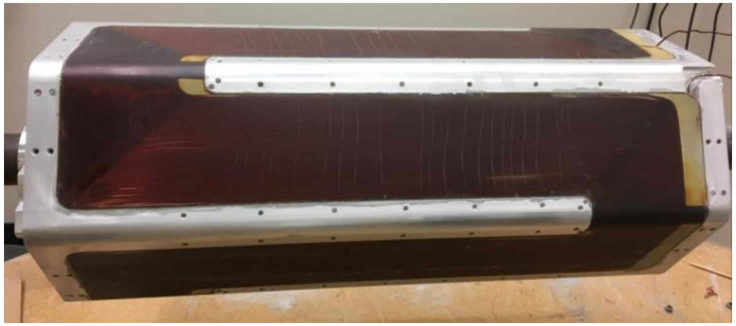


Winding fixtures hold the Cu wire to the mandrel

Addressing the Critical Challenge of a NbTi MARS Magnet

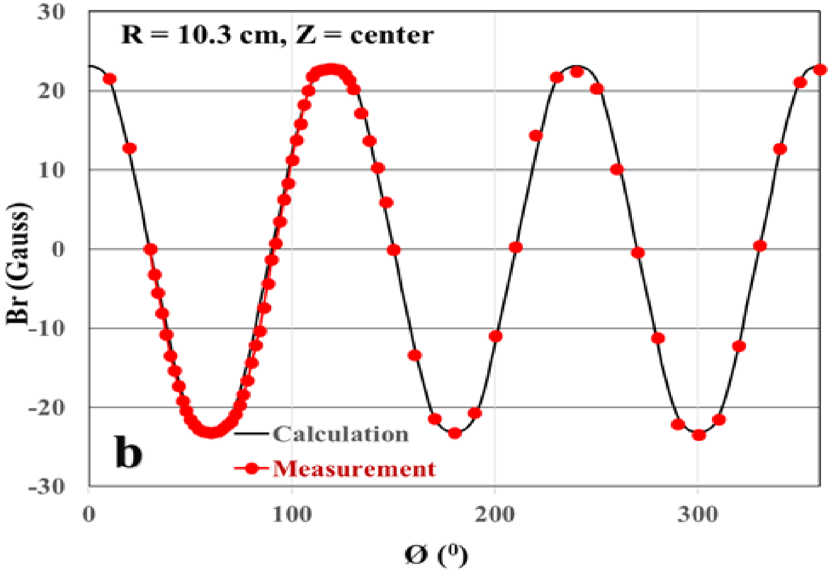


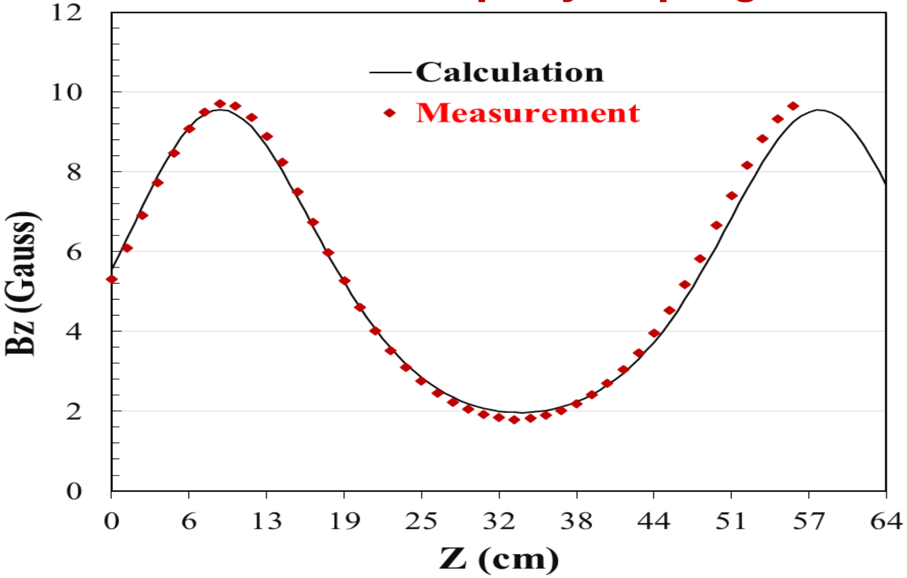




Milestone:

The prototype copper coil has been wound and vacuum epoxy impregnated.





Field mapping has confirmed the design concept and this copper coil prototyping has demonstrated the fabrication feasibility of a NbTi MARS closed-loop-coil