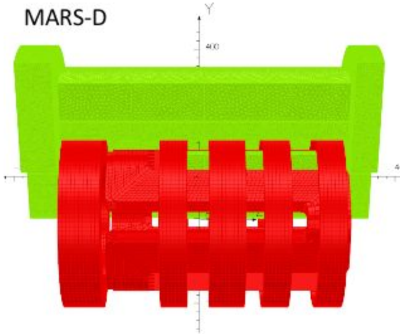
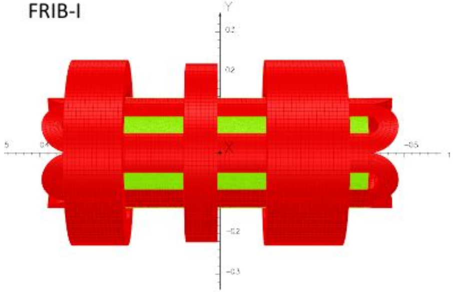
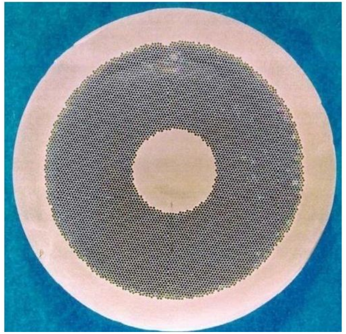
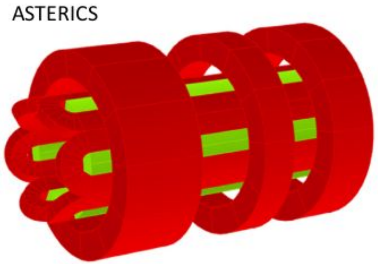
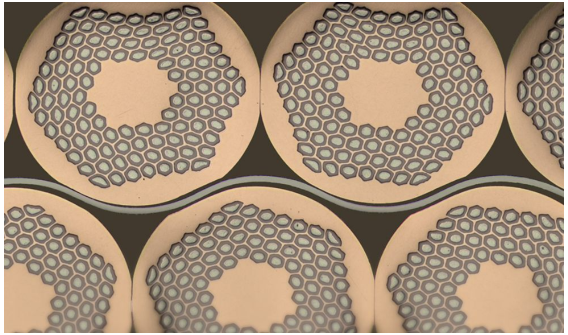




Session:
Magnetic Systems for Future ECRIS







Session Agenda

	Topic	Speaker	Talk (minutes)
2:30 PM - 2:35 PM	**Introduction**	Janilee Benitez	5
2:35 PM - 2:50 PM	**FECR - Update**	Lianting Sun	15
2:50 PM - 3:05 PM	**45 GHz MARS - Update**	Janilee Benitez	15
3:05 PM - 3:30 PM	**Beyond 45 GHz**	Paolo Ferracin	25
3:30 PM	**Discussion - Lessons Learned**	All	60

MARS-D

Janilee Benitez

Production of Intense Beams and Highly Charged Ions
April 8, 2025

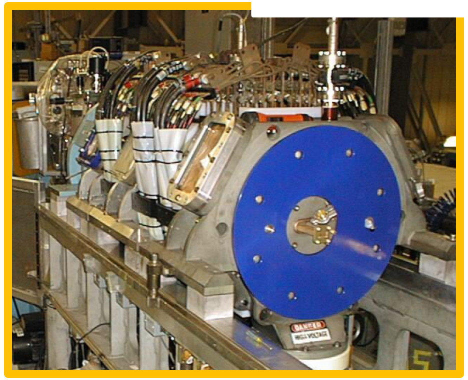
ECR Development at the 88

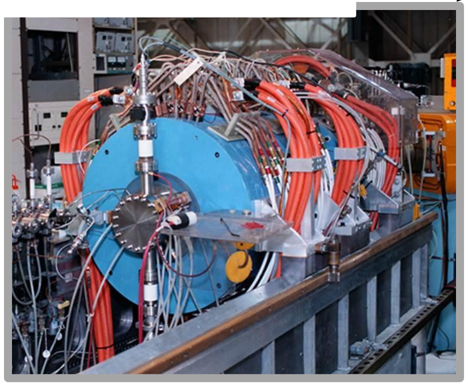
88-Inch Cyclotron

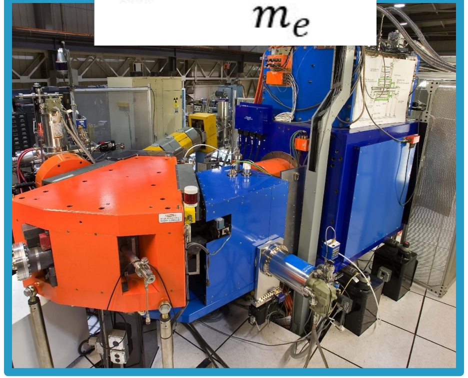
1st Generation ECR	2nd Generation AECR-U	3rd Generation VENUS	4th Generation MARS-D
1983	1996	2004, 2008 for operations	
Max B-Field: 0.4T	Max B-Field: 1.7T	Max B-Field: 4.0T	Max B-Field ~ 6T
Frequencies: 6.4GHz	Frequencies: 10, 14GHz	Frequencies: 18, 28GHz	Max Frequency: 45GHz
Max Power: 0.6kW	Max Power: 2.6kW	Max Power: 12kW	

Beam Intensity ∝ ω^2

$$\omega = \frac{e \cdot B_{ECR}}{m_e}$$



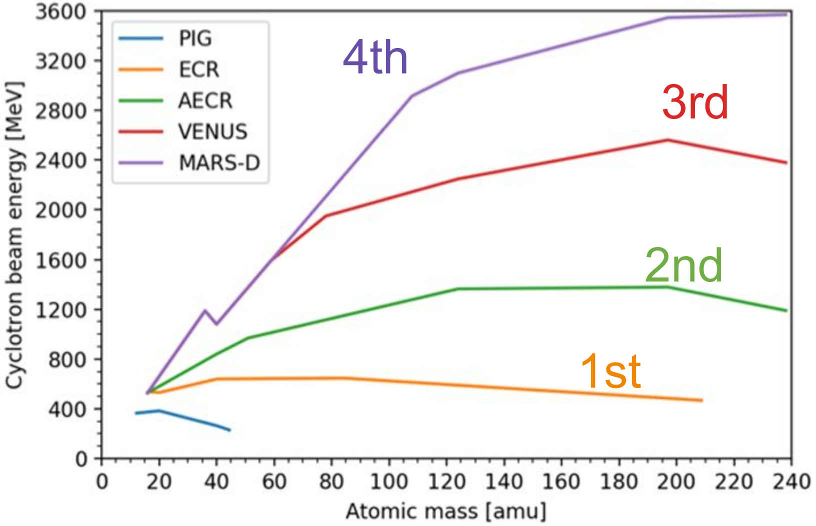




MARS

MARS-D

4th Generation 45 GHz MARS-D will produce higher intensities and higher charge states, leading to higher energy beam



$$E = K\frac{q^2}{m}$$

MARS-D

- DOE funded winding of the coldmass (sextupole + solenoids) & cryostat design through an FOAs
  Largest risk for 4th Generation MARS

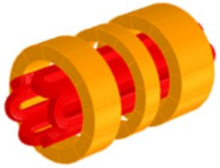
- MARS-D R&D Project
  - 1.1 Project Management
  - 1.2 Project Design Documentation
  - 1.4 Magnet Coldmass Design & Fabrication
    - 1.4.1 Conductor Procurement (NSD 88)
    - 1.4.2 Mechanical Analysis (ATAP)
    - 1.4.3 Engineering Design of Sext/Sol (NSD 88)
    - 1.4.4 Engineering Design of Support Structure (ATAP)
    - 1.4.5 Support Structure Procurement (ATAP)
    - 1.4.6 Coil Parts Procurement (NSD 88)
    - 1.4.7 Coil Fabrication (NSD 88)
    - 1.4.8 Impregnation (ATAP)
    - 1.4.9 Assembly (ATAP)
    - 1.4.10 Test (ATAP)
  - 1.6 Cryostat & Magnet in Cryostat Procurement
  - 1.8 Ion Source Design & Fabrication
  - 1.10 Beamline System Design & Fabrication
  - 1.12 RF System Design & Integration
  - 1.14 PLC System Design & Fabrication
  - 1.16 Installation and Commission Prep.
  - 1.17 MARS ECR Ion Source Installation
  - 1.19 Test & Commission Final System

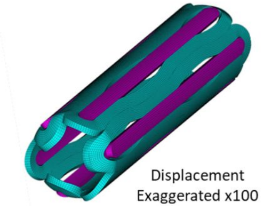
(ATAP)

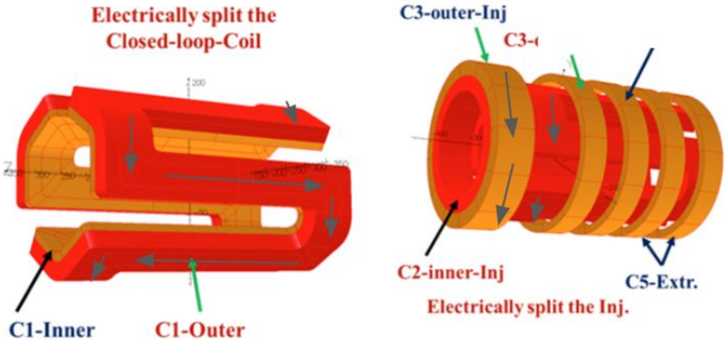
(NSD 88)

Coils

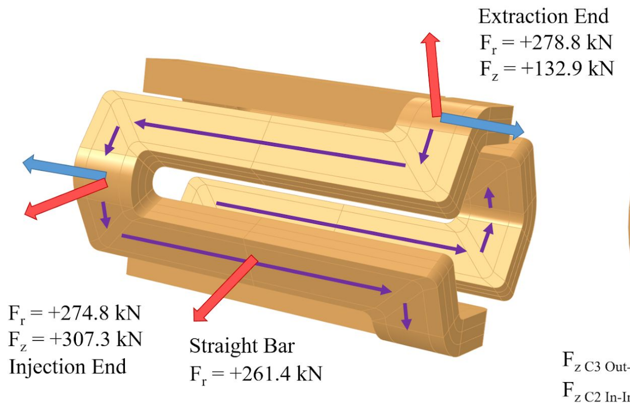
- 3rd generation VENUS uses NbTi in conventional structure
- 4th generation Nb_3Sn in conventional structure difficult to clamp
- 4th generation MARS-D allows continued use of NbTi
    - Optimized geometry provides 50% greater fields

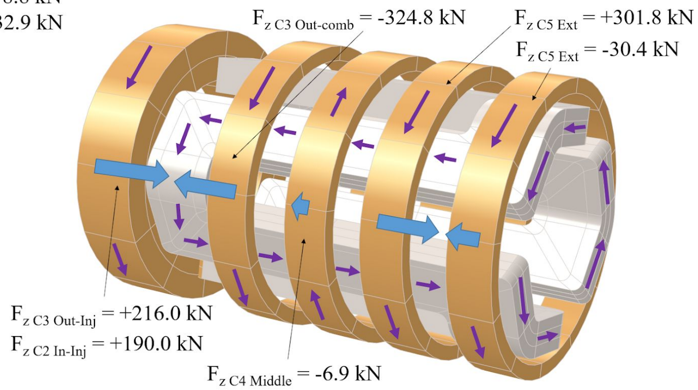






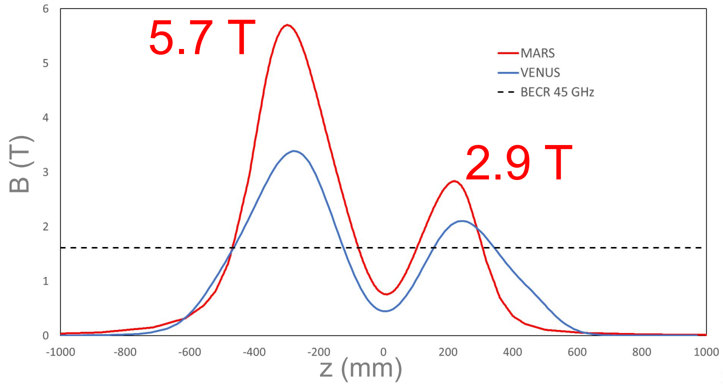
Coils

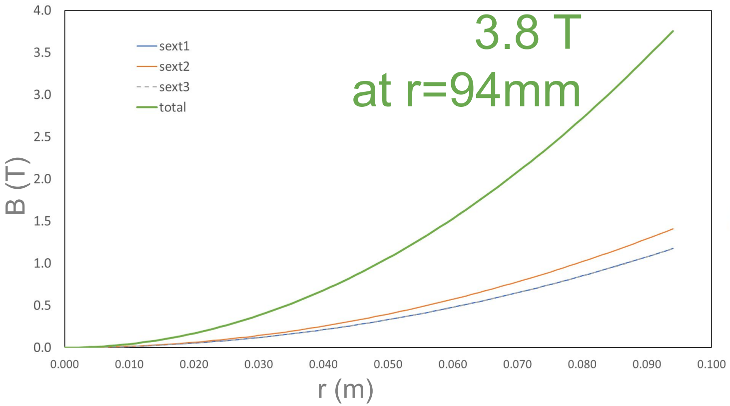


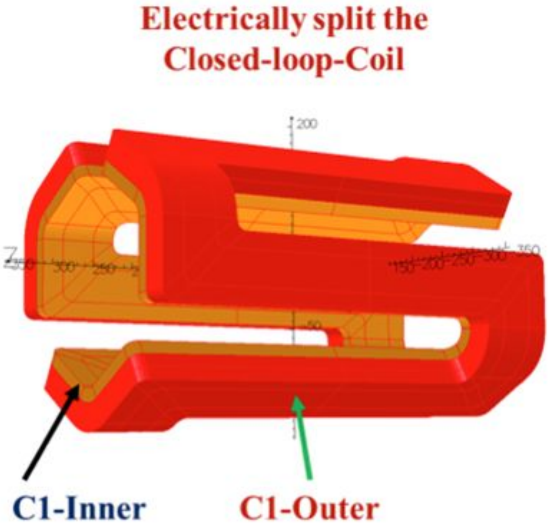


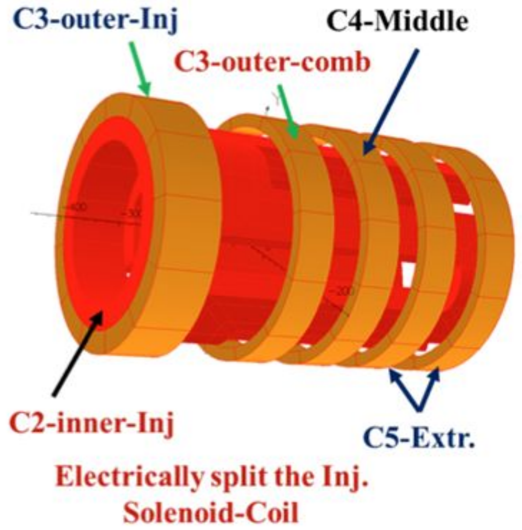
- Close-loop coil provides radial + solenoid field
- Simpler Lorentz force distribution
- Higher field in hexagon “Corners”
- Complex and labor-intensive winding

Coils


5.7 T
2.9 T
MARS
VENUS
BECR 45 GHz
B (T)
z (mm)
6
5
4
3
2
1
0
-1000
-800
-600
-400
-200
0
200
400
600
800
1000


3.8 T
at r=94mm
sext1
sext2
sext3
total
B (T)
r (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100


Electrically split the Closed-loop-Coil
C1-Inner
C1-Outer

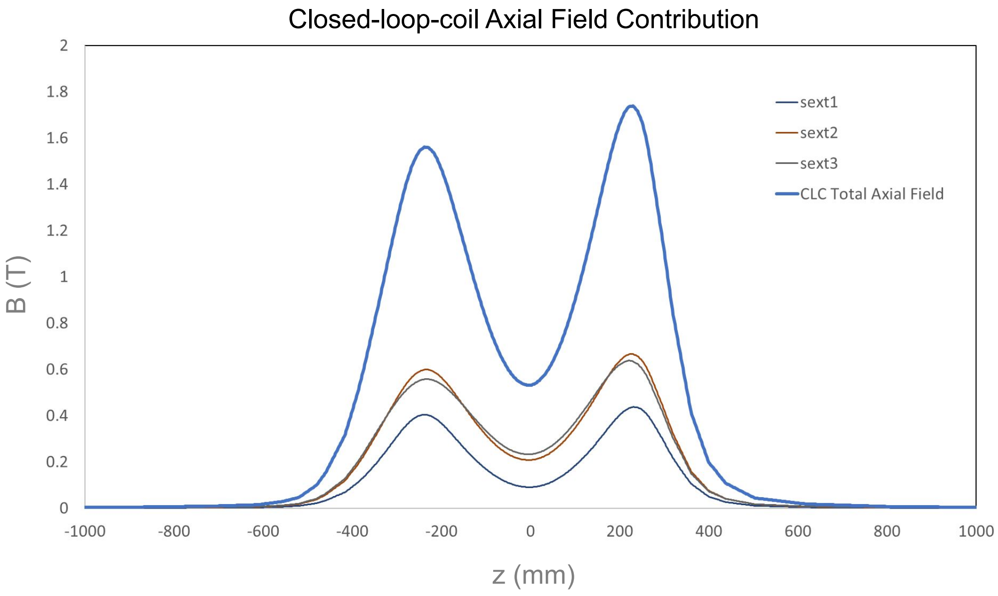

C3-outer-Inj
C4-Middle
C3-outer-comb
C2-inner-Inj
C5-Extr.
Electrically split the Inj. Solenoid-Coil

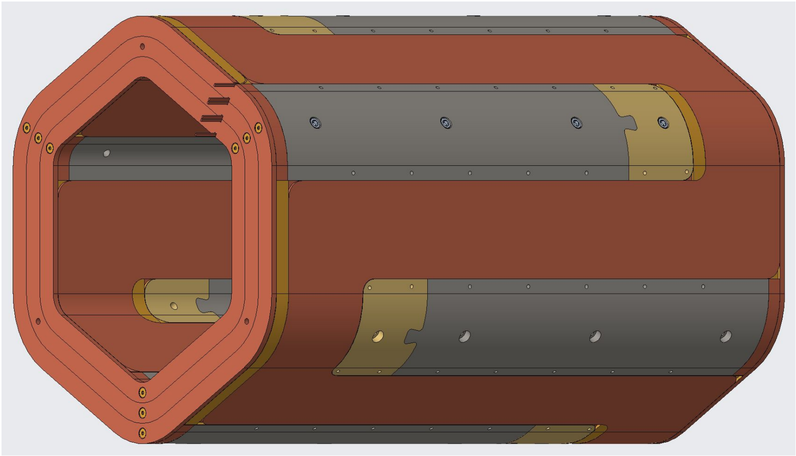
Coil Parameters

MARS-D Specifications*		
	Closed-loop coil	Solenoid
Conductor size (mm2)	1.45 x 0.71	1.91 x 1.23
Copper ratio	1.3	1.4
Conductor length (km)	5.6	10.9
Load line (%)	88.6	83.3
Stored energy (kJ)	560	

* Y. Yang *et al*., "Design Margin Comparison of a Sextupole-in-Solenoid and a Closed-Loop-Coil Type Nb-Ti Superconducting ECR Magnets," in *IEEE Transactions on Applied Superconductivity*, vol. 35, no. 5, pp. 1-5, Aug. 2025, Art no. 4100605, doi: 10.1109/TASC.2025.3527961.

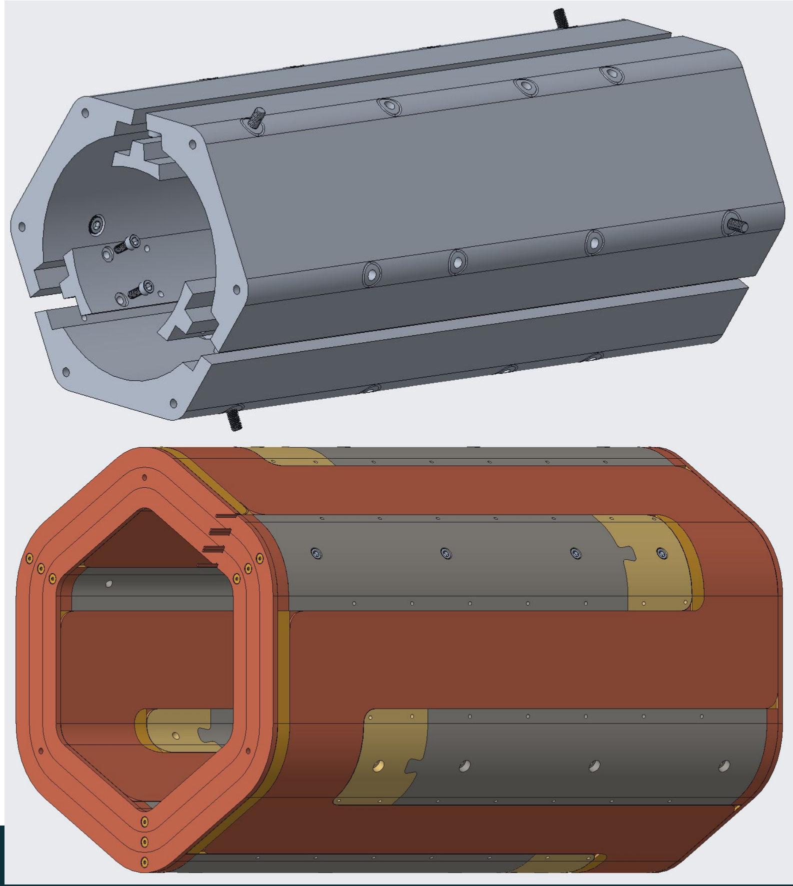
Closed-loop-Coil Structure



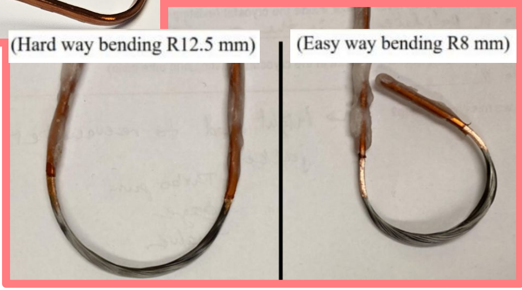


Coil Structure

- The coil is wound on a removable mandrel (to maximize the use of the magnetic field)
- Divide the sextupole coil into 3 coil layers. (optimized field with different currents)
- Each coil layer has 8 wire-layers. (24 total layers)
- Each wire-layer has maximum 64 turns of SC wire.

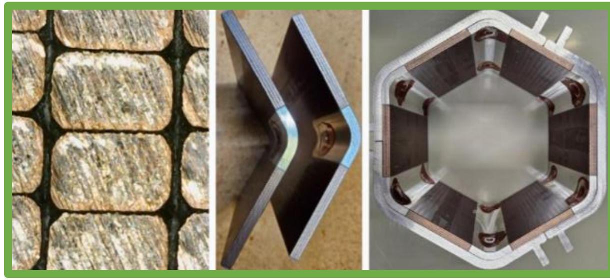


Test Wind

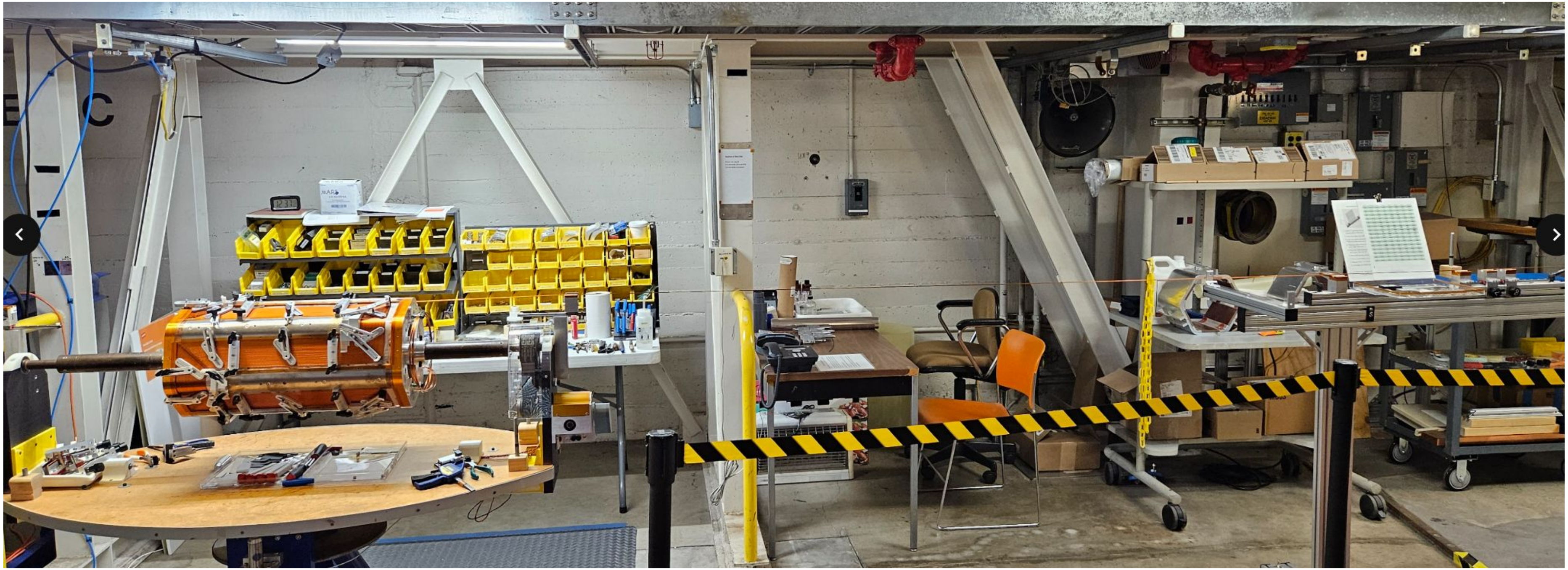


4 layer NbTi Test Coil:

1. **Pre-overbending**
    a. bend tests showed no broken wires
        i. R12.5 mm 90° bend at the easy way
        ii. R20.0 mm 120° bend the hard way
2. Winding Procedures
3. **Impregnation**
    a. CTD-101K epoxy in vacuum at 135 °C
    b. Cold test 2 cycles to 77K
        i. Found changes in superglue, minimize
        ii. Epoxy ok
4. **Removable Mandrel**
    a. Mold release to facilitate demolding

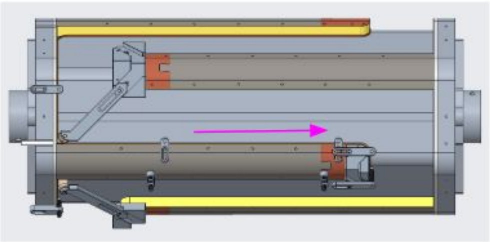


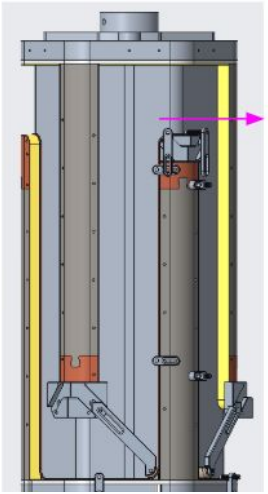
Winding Procedure

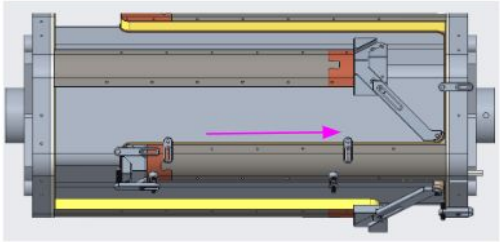


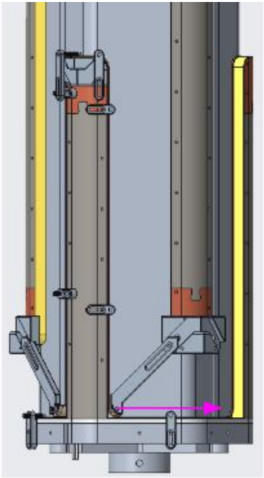
Winding Procedure

Starting









Maximum wire tension 5 kg

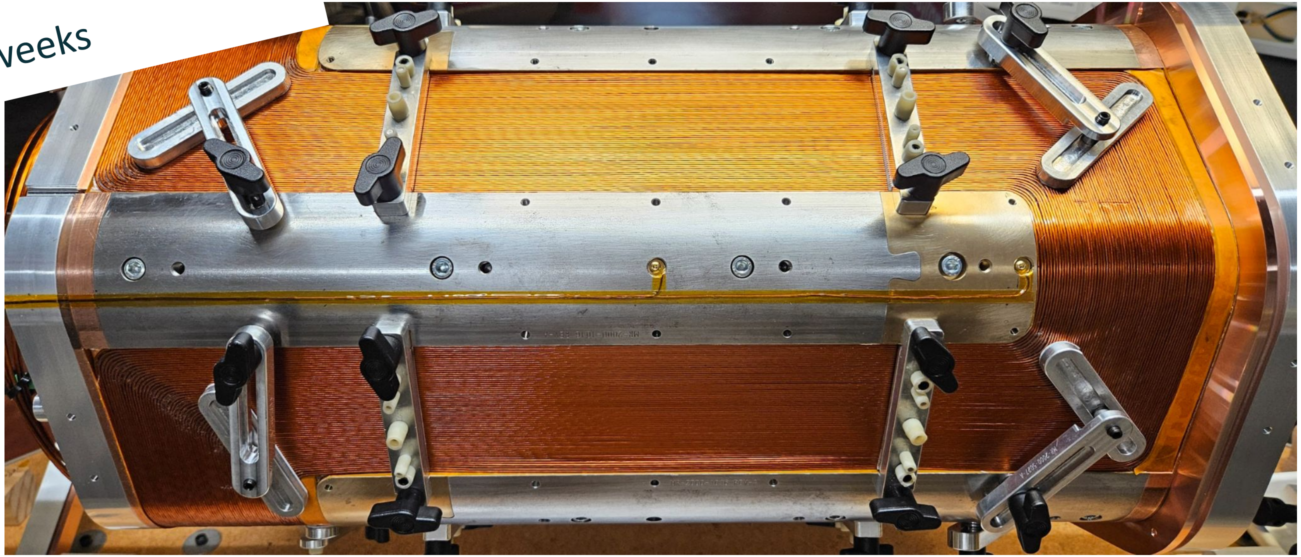
Current & Next Steps

Closed-loop coil is ⅔ complete

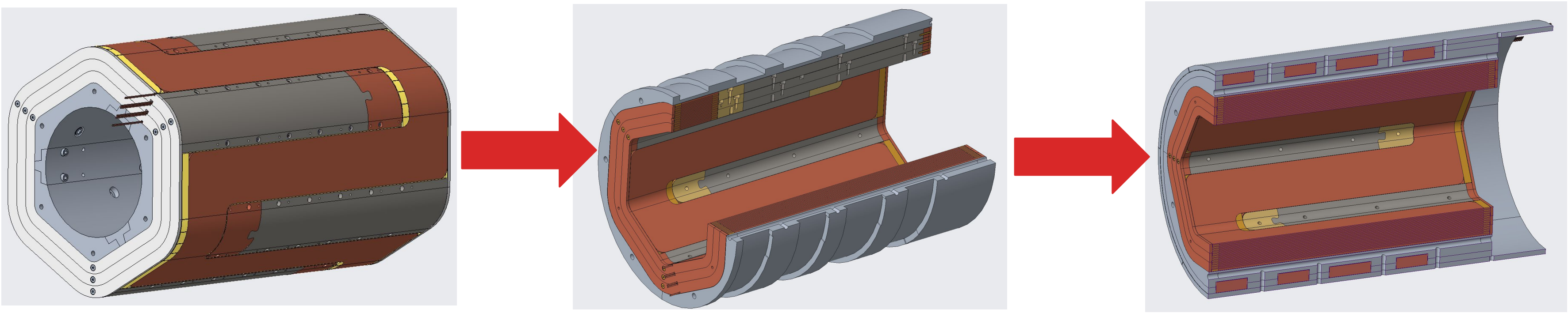
100% this summer

Each turn ~ 45 minutes to 1 hour

Each layer ~2.5 weeks

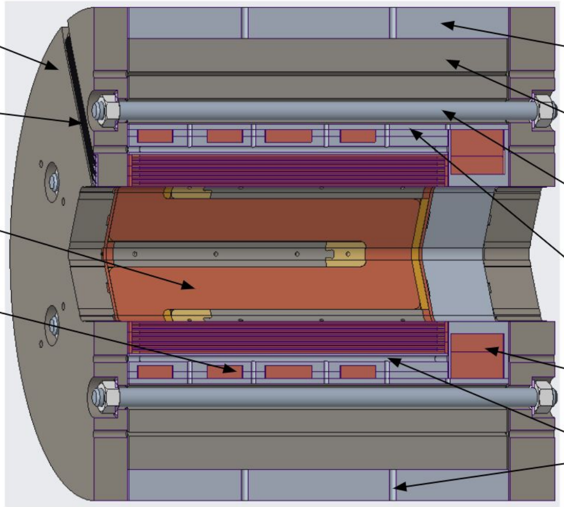


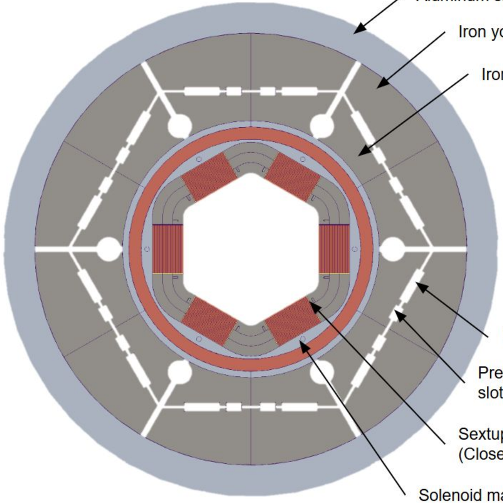
Solenoids



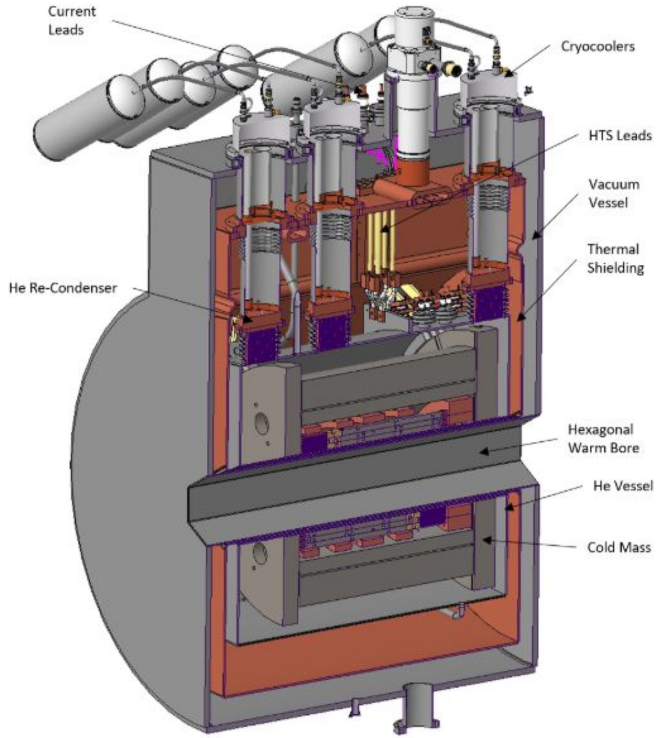
- Divide the solenoid mandrel into **3 sections**, alignment and assembly using **pins** and **shrink-fit reinforcement rings**
- **No gap** between the sextupole coil and the solenoid mandrels, CNC machine enclosures
- one-time impregnation
- After cool down from RT to 4.2K, the solenoid mandrel will shrink more than the sextupole coil, ~0.46 mm.

Cold Mass Structure





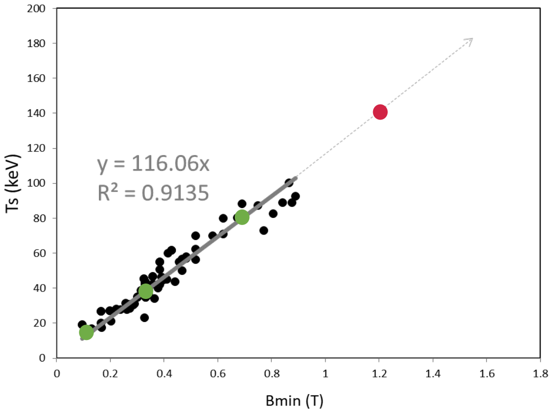
Cryostat Design



- 1 PT Cryocoolers. AL330
  - 135W at 40K
  - Thermal shielding
  - RT Leads
- 4 PT Cryocoolers. PT450
  - 60 W at 45K. First Stage
    - HTS
    - Thermal shielding
  - 5 W at 4.2K. Second Stage
    - Low temperature superconductors.
- Static load: ~2-3W

Credit: Li Wang & Lianrong Xu

MARS Challenges



We expect 4th Generation MARS to have much higher electron temperatures!

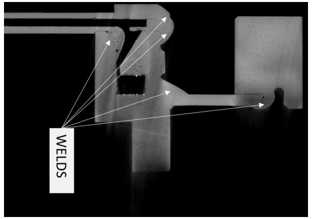
Scaling Law:

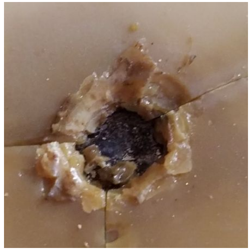
$$B_{min} = 0.5 - 0.8B_{ECR}$$

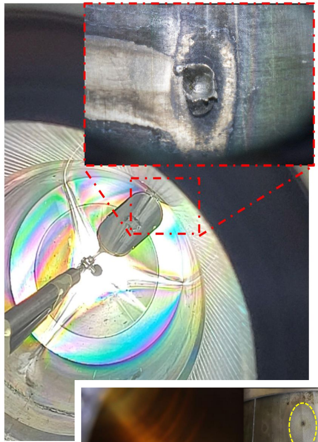
Generation	ω (GHz)	$^{16}O^{6+}$	B_{ECR} (T)	B_{min} (T)	T_s (keV)
1st (ECR)	6.4 GHz	45	0.23	0.1-0.18	20 keV
2nd (AECR)	14 GHz	800	0.50	0.2-0.4	35 keV
3rd (VENUS)	28 GHz	4,750	1.0	0.5-0.8	80 keV
4th (MARS)	45 GHz	-	1.6	0.5-1.2	140 keV

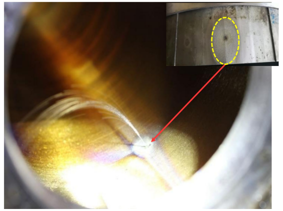
Impacts:
Personnel safety
Cryostat design
Plasma chamber design

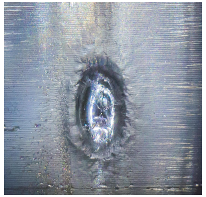
MARS Challenges

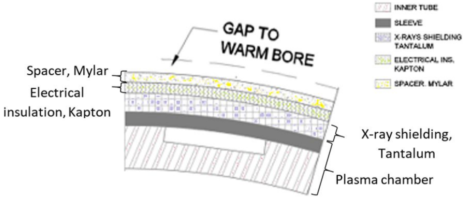


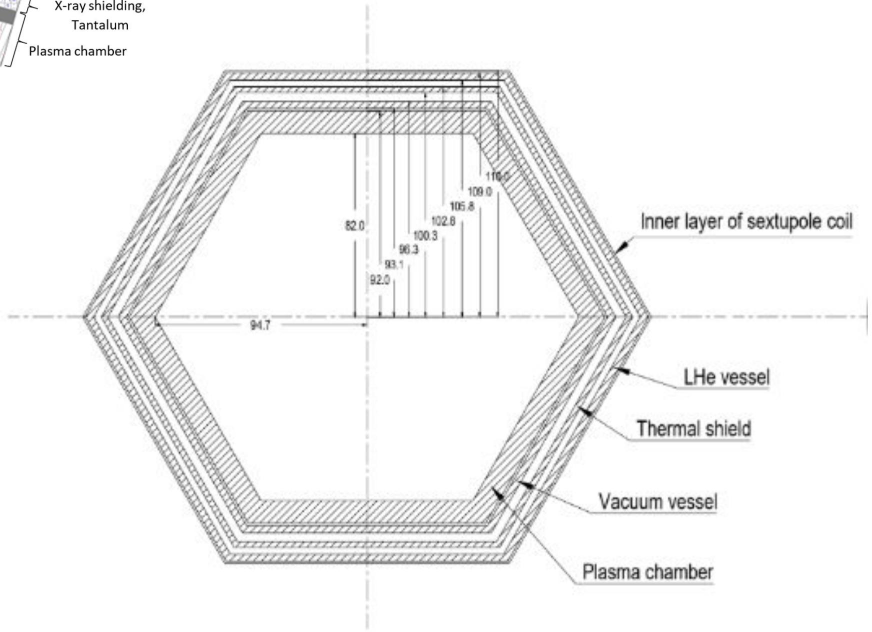






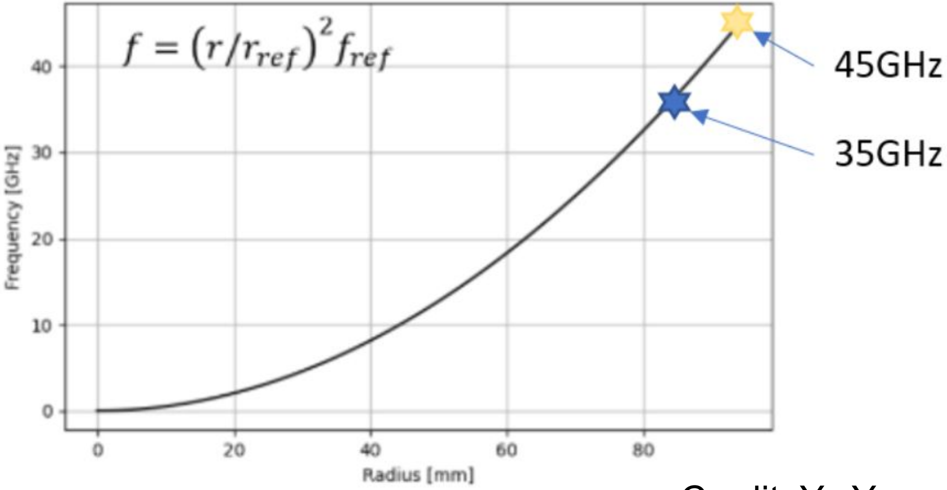




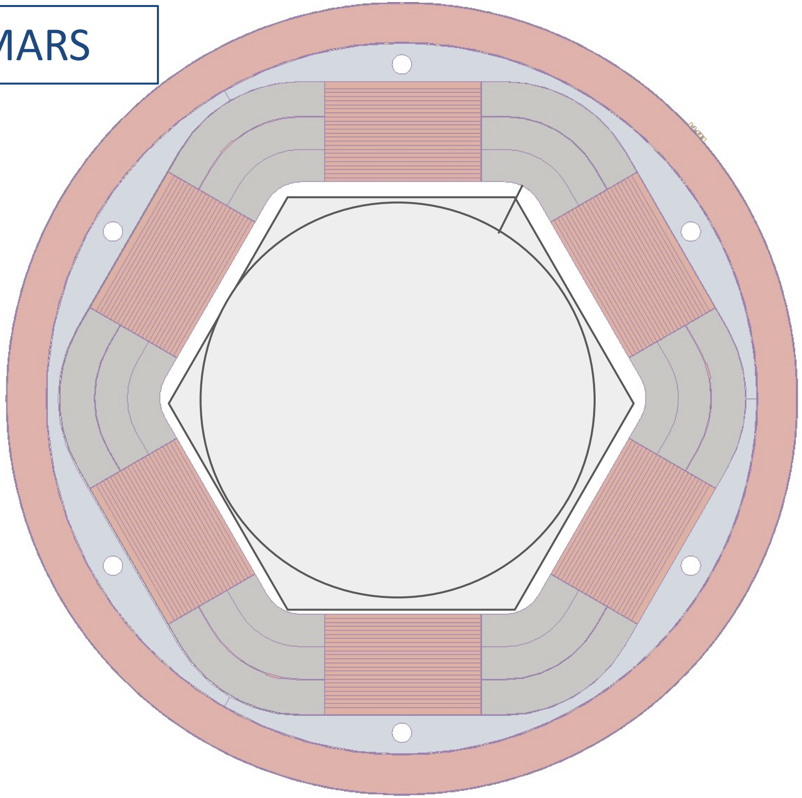


MARS Challenges

- Hexagonal chamber:
  - $B_r = 3.01$ T at 94 mm → 45 GHz
- Circular chamber:
  - $B_r = 2.34$ T at $r_{ref} = 82$ mm
  - Frequency: 35 GHz



MARS



Credit: Ye Yang

Thank you!

Discussion

Availability of high frequency, high power gyrotrons?

Safety considerations for in-air 45 GHz transport (no waveguides).

Scaling laws and expected heat load into cryostat?

Timeline for long enough cables for HTSC source. Can we use HTSC leads?

Other issues to consider?