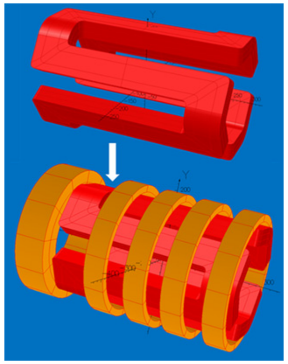
STATUS OF THE 45 GHZ MARS-D ECRIS

D. Z. Xie, J. Y. Benitez, M. Kireeff Covo, A. Hodgkinson, M. Juchno, L. Phair, D. Todd, L. Wang

LBNL, Berkeley, CA 94720, USA



Outline

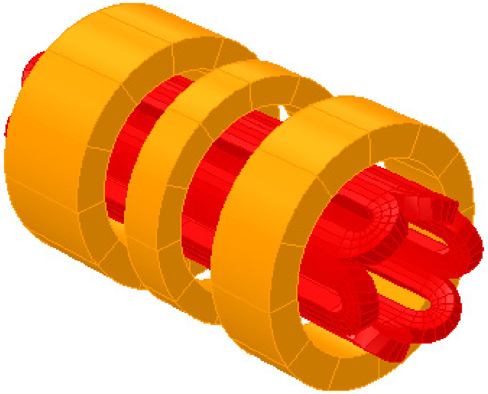
- MARS magnet geometry and advantages
- A NbTi MARS-magnet in 2015 and present for the 45 GHz MARS-D ECRIS
- MARS-D source components
- Multiple-frequency plasma heating
- Conventional source components
- Summary

PATHWAY TO THE NEXT GENERATION OF ECRIS

Next generation of ECRIS will operate at substantially higher magnetic fields and microwave frequencies, and source development will require addressing a number of challenges.

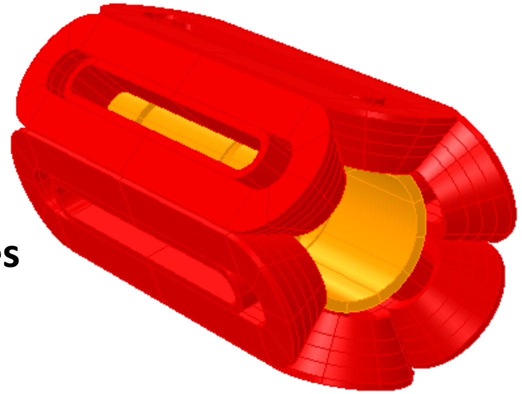
The most critical challenge is constructing a superconducting magnet system capable of producing the needed high-magnetic fields.

Sext-In-Sol (VENUS)



Existing magnet geometries

Sol-In-Sext (SECRAL)

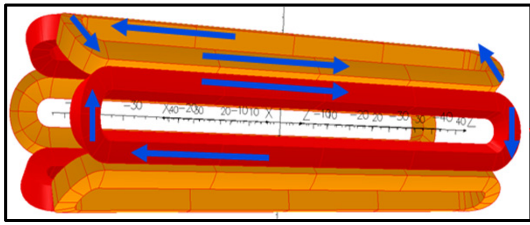


NbTi magnets have been reliably operating at their constraints in the 3rd generation of ECRIS for about two decades

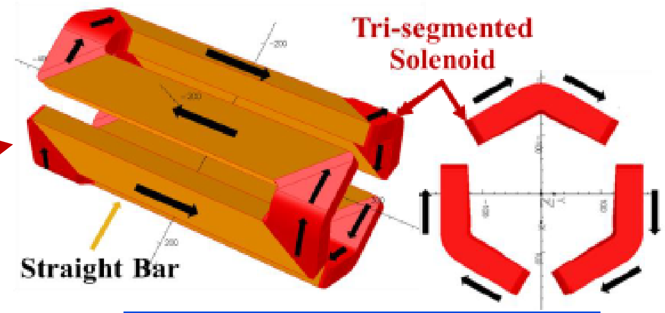
However, neither one can extend the NbTi magnet for ECRIS to optimally operate at 45 GHz

A Mixed Axial and Radial field System (MARS)

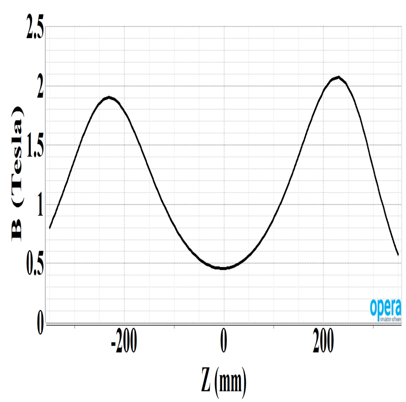
Optimization 1

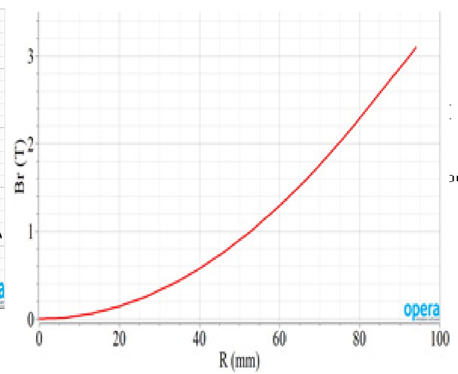


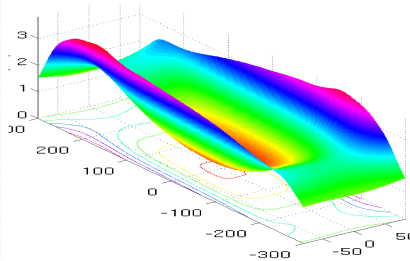
Convert 6 racetrack coils into a single closed-loop-coil



1. *A hexagonal closed-loop-coil*



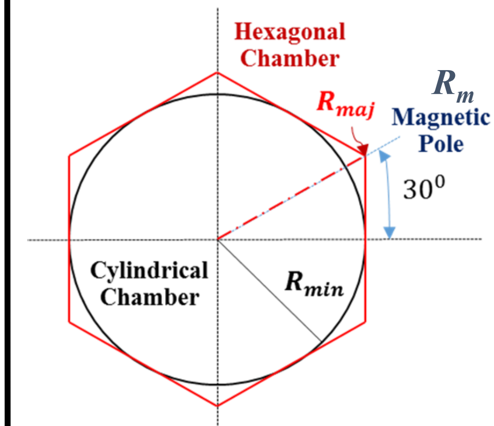




Optimization 2

A hexagonal plasma chamber

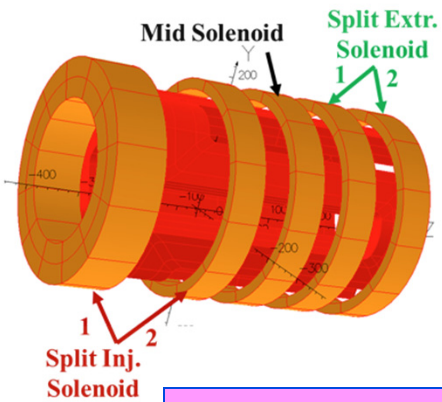
$B_r/B_m = (R_{maj}/R_m)^2 \sim 66\%$

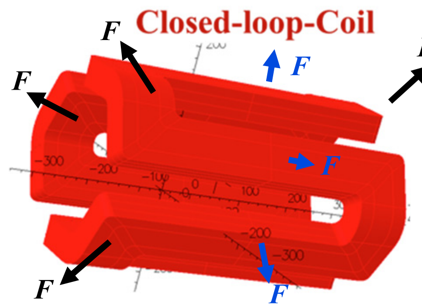


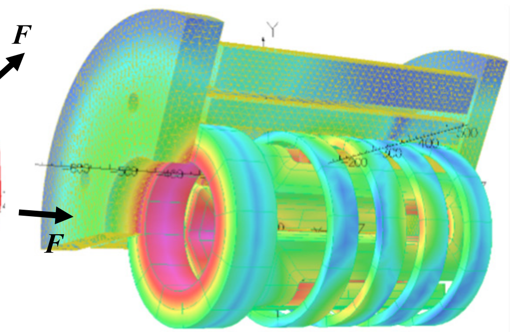
$B_r/B_m = (R_{min}/R_m)^2 \sim 50\%$

A cylindrical plasma chamber

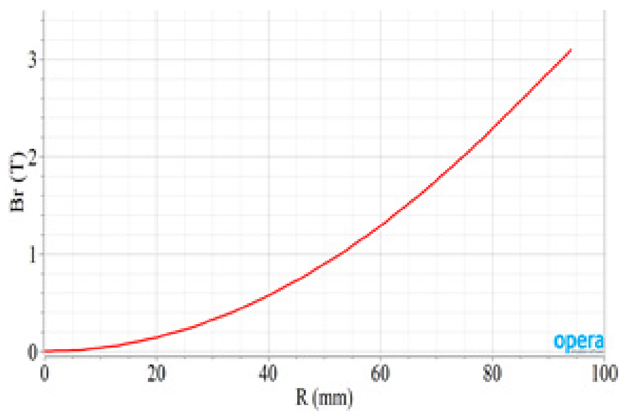
A NEXT G ECRIS BASED ON A NbTi MARS-MAGNET

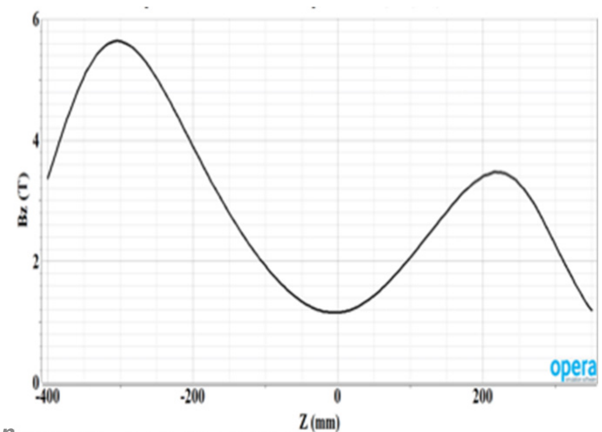






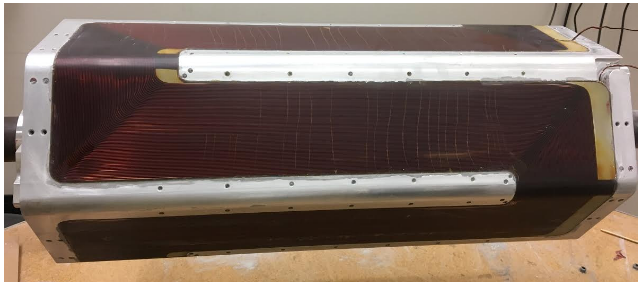
Add a set of smaller solenoids to increase the mirror fields for ECRIS applications.



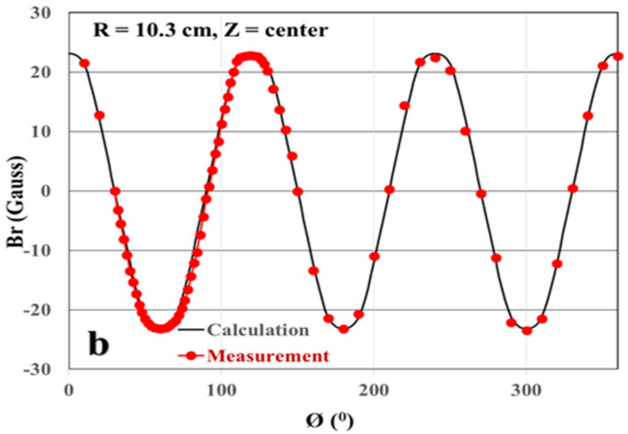


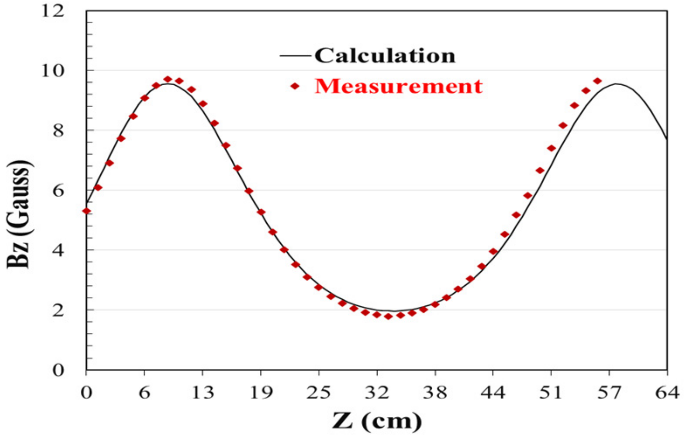
Addressing the Most Critical Challenge of a NbTi MARS-Magnet

The prototype copper coil has been wound and vacuum epoxy impregnated



~ 90% insulated wire packing achieved.



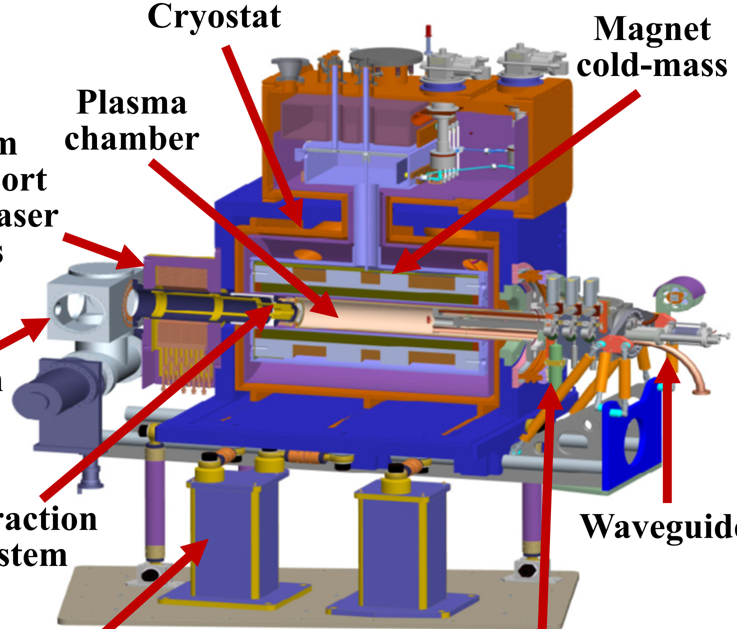


❖ Field mapping has confirmed the design concept and this copper coil prototyping has demonstrated the fabrication feasibility of a NbTi MARS closed-loop-coil

ADVANTAGES OF A NbTi MARS-MAGNET

- Continue the advantage of the well proven NbTi magnet reliability
- Better form factor for more efficient utilization of the generated fields thus the NbTi magnets can be extended to 45 GHz operations
- Simplified interaction force pattern with zero repulsions between the solenoids and the closed-loop-coil ends
- Less demanding coil clamping
- A smaller cold mass with lower conductor usage (uses about one half of the same conductor compared to a Sext-In-Sol geometry for the same fields)
- ....

Components of a Superconducting ECRIS



Microwave systems, beam line components and control console are not shown here.

Three Categories

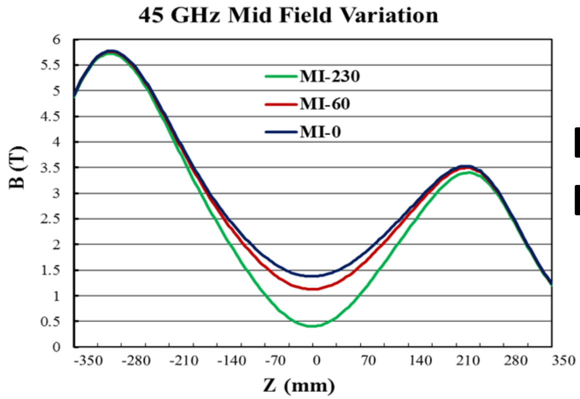
1. Minim-B Field

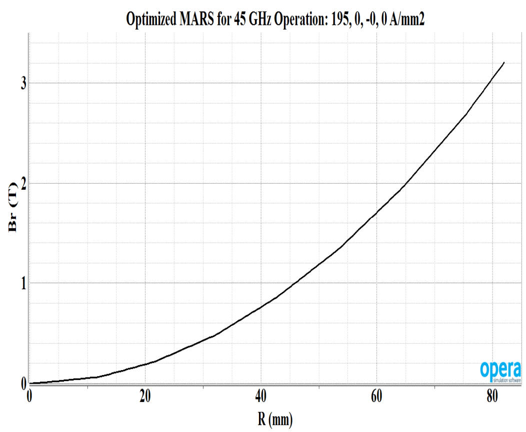
   The key component

2. Microwave Generators

3. Conventional Components

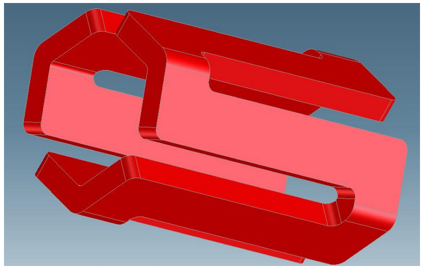
A NbTi MARS-MAGNET FOR A 45 GHZ ECRIS: MARS-D

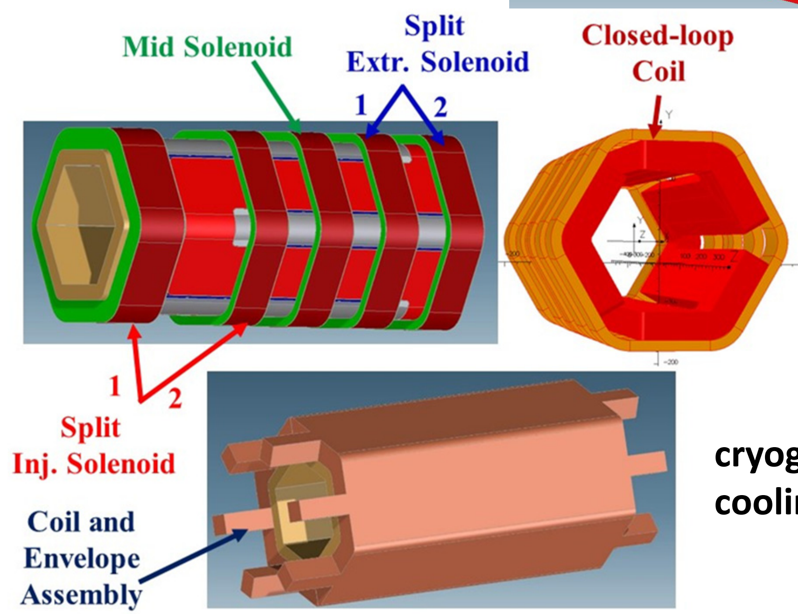




2015

$B_{inj} \sim 5.7$, $B_{ext} \sim 3.2$, $B_{rad} \sim 3.2$, $B_{min} \sim 0.4 - 1.2$ T

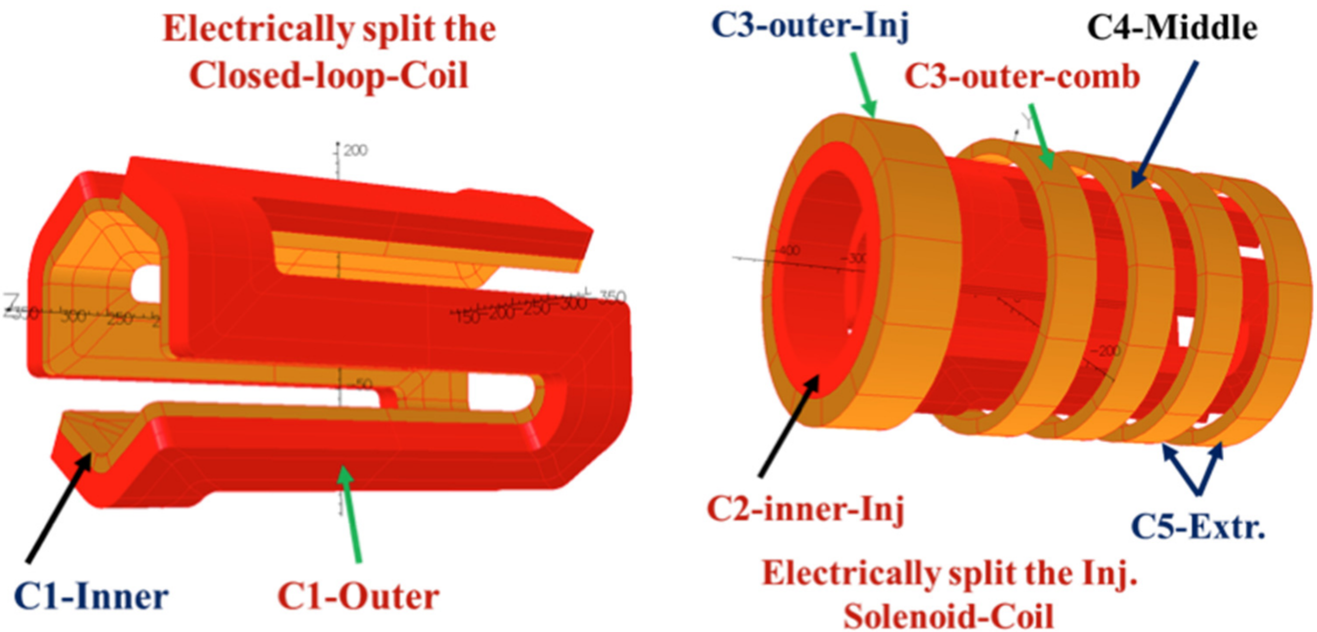




cryogen-free cooling

A NbTi MARS-MAGNET FOR A 45 GHZ ECRIS: MARS-D

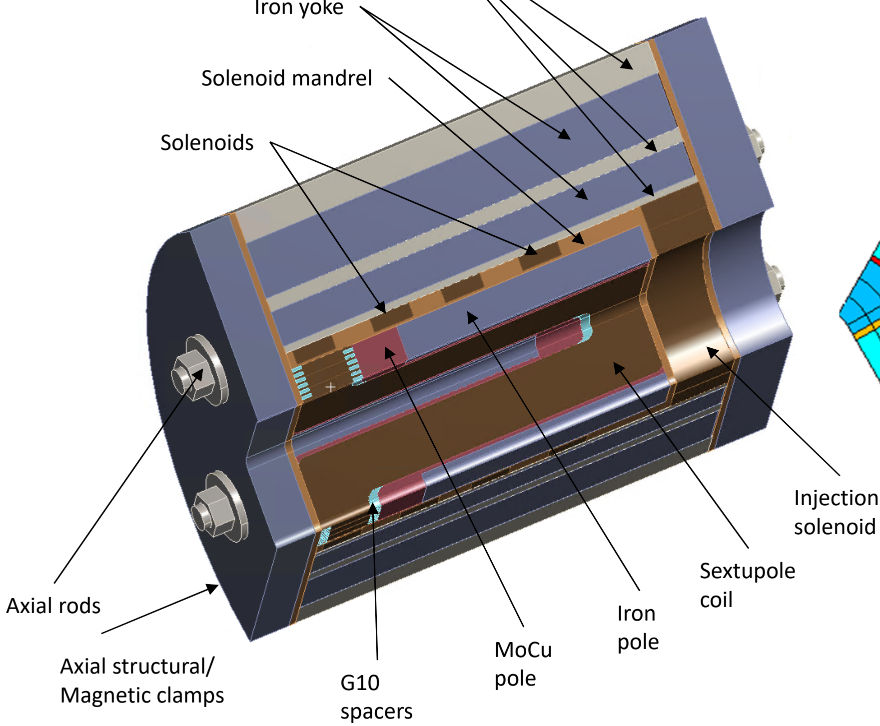
2020

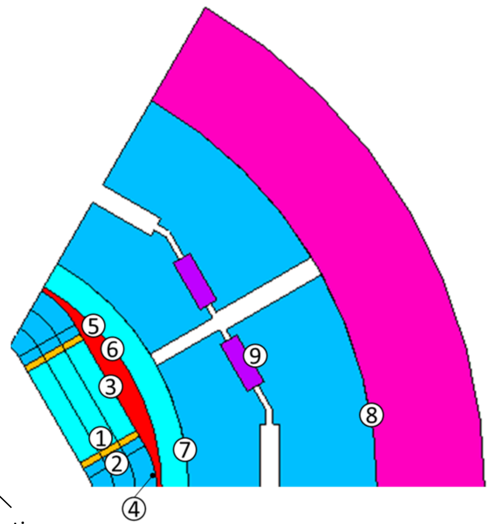


The NbTi MARS-magnet coils are electrically split in various ways, as indicated by the labels, to reduce the maximum field in the coils. In addition, the injection and closed-loop-coil are electrically divided into two to three sub-divisions to achieve higher temperature margins for reliable magnet operation, at a price of 2 more power supplies and HTS leads.

Plan for the MARS-D Cold Mass

A BCMT shell-based bladder-and-key to radially clamp down the coils.



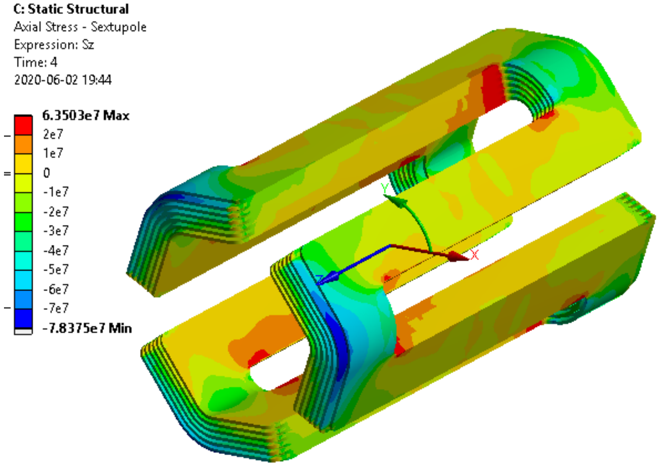


1. Coil to MoCu pole – BONDED
2. MoCu to Iron pole – SLIDING
3. Coil/MoCu pole to Mandrel – SLIDING
4. Iron pole to Mandrel – SLIDING with GAP
5. Mandrel to Solenoid – STANDARD
6. Mandrel to Mandrel rib (behind Solenoid) – BONDED
7. Mandrel rib/Solenoid to Pad – STANDARD
8. Shell to Yoke – STANDARD
9. Yoke/pad to Key – SLIDING with INTERFERENCE

Comparison of the max. coil stress (Von Mises) for three magnets

Maximum magnet coil stress of three magnet systems for MARS-D, FRIB VENUS and IMP FECR.

	FRIB VENUS[1]	IMP FECR[2]	MARS-D[3]
Frequency	28 GHz	45 GHz	45 GHz
Sextupole	140 MPa	144 MPa	80 MPa
Solenoids	90 MPa	100 MPa	55 MPa
Sys. stored Energy	720 kJ	1600 kJ	560 kJ
Geometry	Sext-In-Sol	Sext-In-Sol	MARS
Conductor	NbTi	Nb_3Sn	NbTi



With magnetic forces
Coil **coil-ends** remain
compressed (30-80 MPa)

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

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

[3] M. Juchno, P**reliminary stress analyses on the NbTi MARS-magnet for a 45 GHz** ECRIS (June 2020)

Four-frequency Plasma Heating in MARS-D

MARS-D is designed with a good dynamic field range (B_{min} ~ 0.4-1.2 T) that allows us to further explore the detailed effects of multiple-frequency plasma heating in ECRIS.

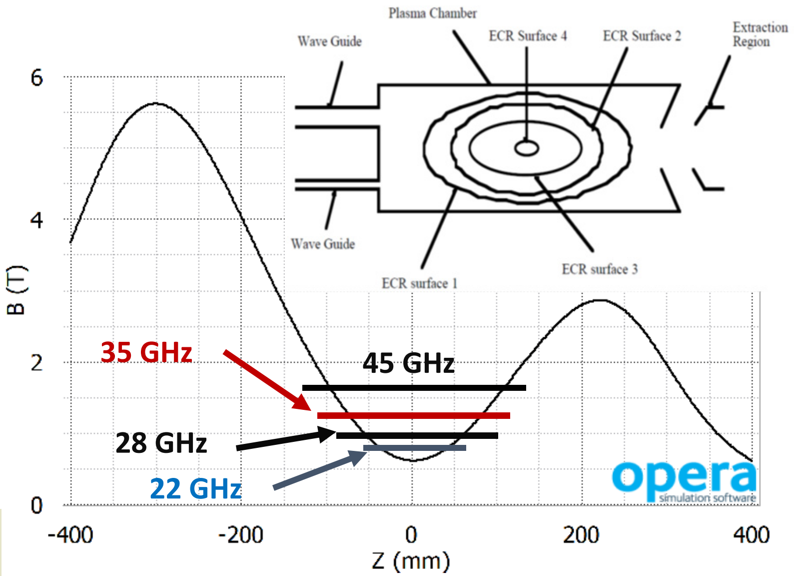
Based on Geller's scaling laws: q_{opt} the optimum charge state is proportional to the angular frequency ϖ, power dependence on q_{opt} and ϖ: $q_{opt} \sim \log(\varpi^{3.5})$ and $P_\mu / V_{ECRH} \sim \varpi^{1/2} q^3$

MARS-D minimum-B field

B_{inj} ~ 5.7, B_{min} ~ 0.4-1.2, B_{ext} ~ 3.2, B_{rad} ~ 3.2 T

F (GHz)	B_{ecr} (T)	V_{ECRH} (L)	M. Power (kW)
22	0.79	0-0.4	1.5
28	1.00	0.5-0.9	1.0
35	1.25	1.1-1.5	1.0
45	1.61	2.3-2.5	0.5

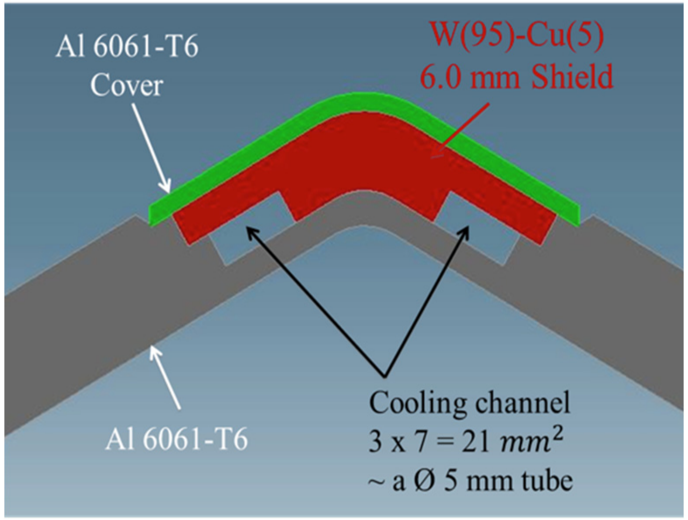
Total commissioning wave power: 4 kW

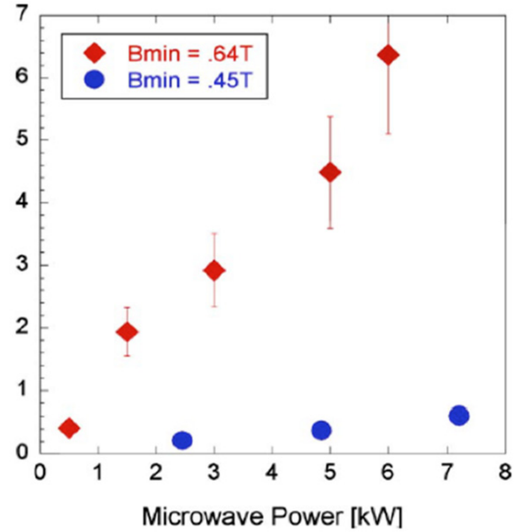


Conceptual Design of the MARS-D Plasma Chamber

Requirements:

- **Sustain ≥ 20 kW microwave power** (Sufficient water flow)
- **Mitigate the hot electron heating** (Take care of the localized hot electrons and x-rays)
- **Attenuate the energetic x-ray, T_s Ջ B_{min}** (As low B_{min} as possible, but may run at 0.8-1.0 T)



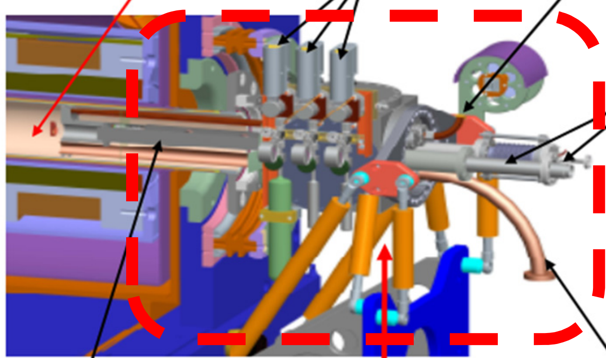


X-ray E(keV)	6.0 mm W(95)+Cu(5)	6.0 mm Ta(100)	2.0 mm Ta(100)
200	~100%	~100%	92%
300	97%	95%	65%
400	88%	85%	46%
500	78%	74%	36%
800	59%	55%	23%
1000	52%	42%	20%
	MARS-D		VENUS

Set up a baseline for future higher power operations up to 20 kW.

Preliminary Plan for MARS-D Injection Assembly

VENUS
Injection Assembly



Simplify and shorten the injection assembly by exposing all the outer surfaces of the insertions to air.

Sub Components	QTY
WR62 waveguide & DC break	4 sets (22+28+35+45 GHz)
Circular waveguide & DC break	1 set (45 GHz)
Oven mounting port	2
Gas system	1 set of six valves
Pumping port	1 (~ 100 l/s TMP)

MARS-D plasma chamber cross-section is about 220 cm^2, ~ 40% larger than the VENUS chamber.

Summary

The most critical challenge in fabricating a NbTi MARS magnet has been addressed.
Ready for cold-mass fabrication.

Plan has been set for plasma heating with a quard-frequency heating (~ 4 kW) for source commissioning and future operations with a high power upgrade to 20-30 kW.

Conventional source components to be duplicated from VENUS with some minor revisions.

Funding is likely available next fiscal year (2021).

Thank You!