The Status of a MARS Closed-loop Prototype Coil and Possible Optimizations to the Existing Magnet Structures for the Next G ECRISs

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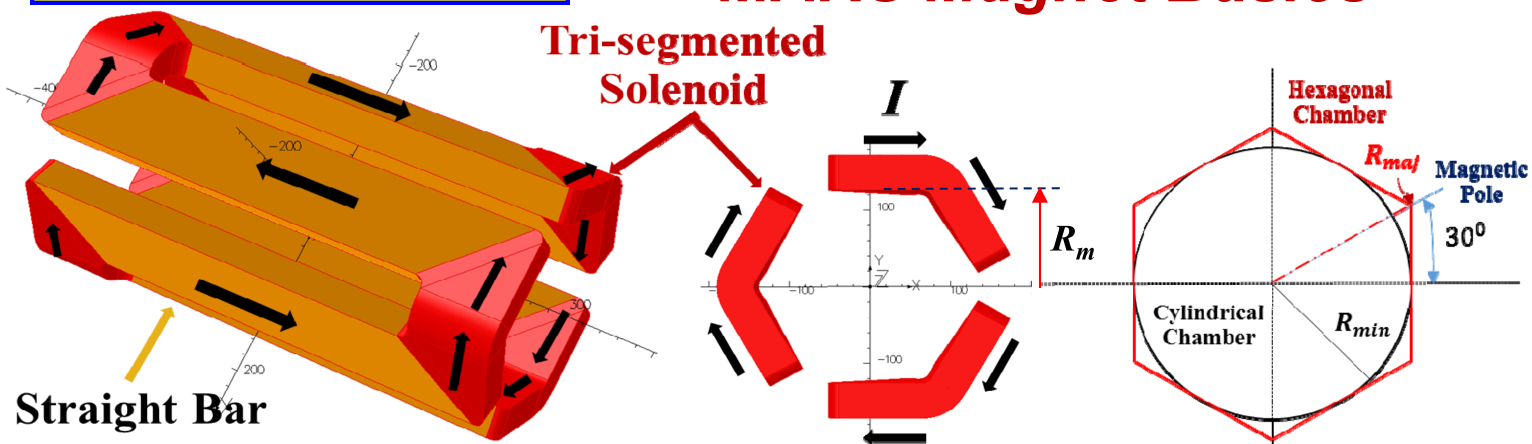
1. MARS (Mixed Axial and Radial field System) Basics
2. Status of MARS coil prototyping
3. Possible optimizations to the existing magnet systems
4. Summary

MARS Magnet Basics

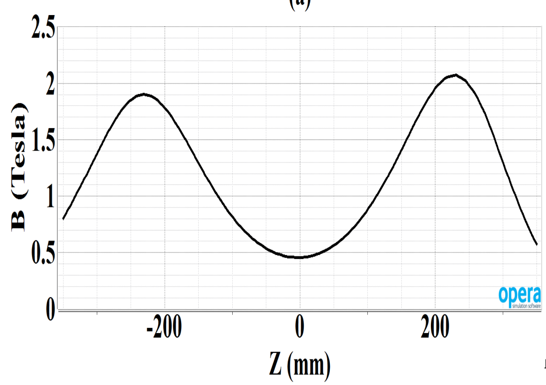
A closed-loop hexagon coil



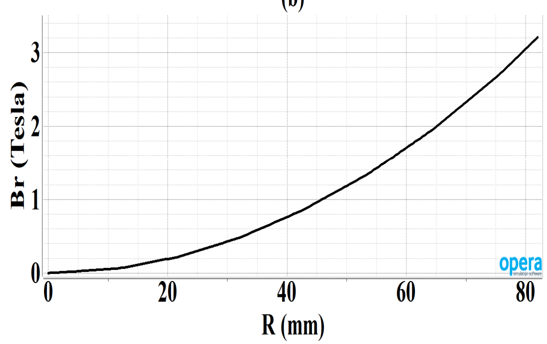
$B_r/B_m = (R_{maj}/R_m)^2 \sim 67\%$

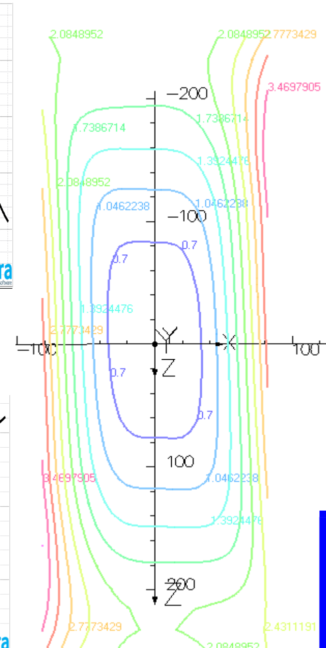
$B_r/B_m = (R_{min}/R_m)^2 \sim 50\%$

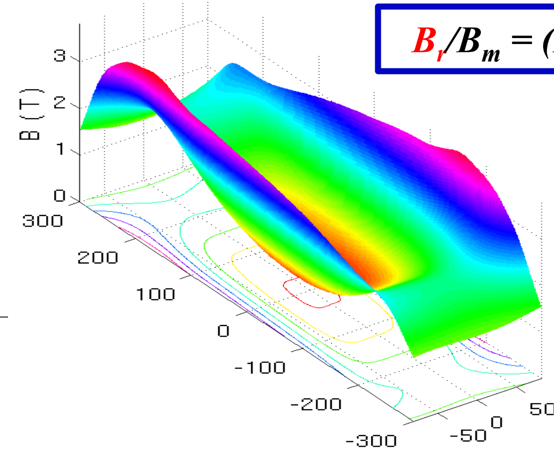
(a)



(b)

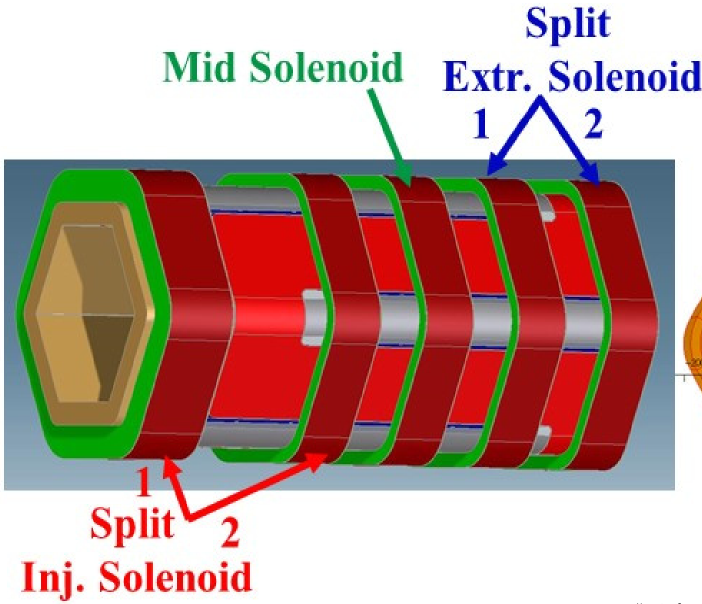


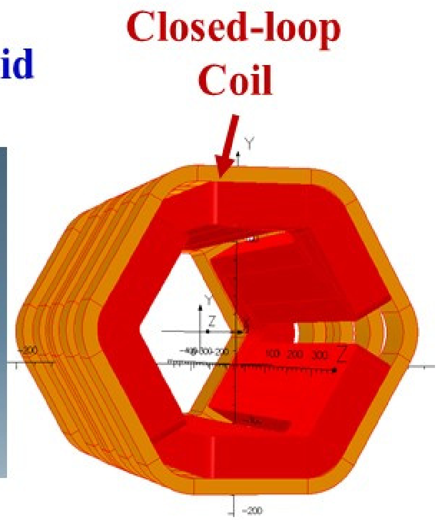




The Closed-loop Coil (ClC) generates a minimum-B configuration by itself, except the axial mirrors are not high enough for applications in ECRIS.

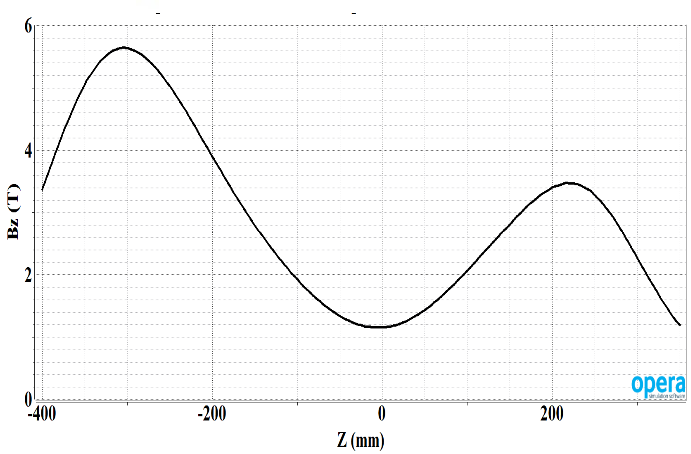
MARS Magnet Basics

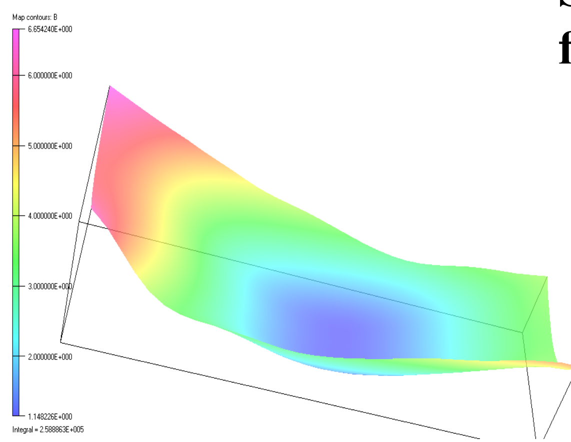




The merits of MARS;

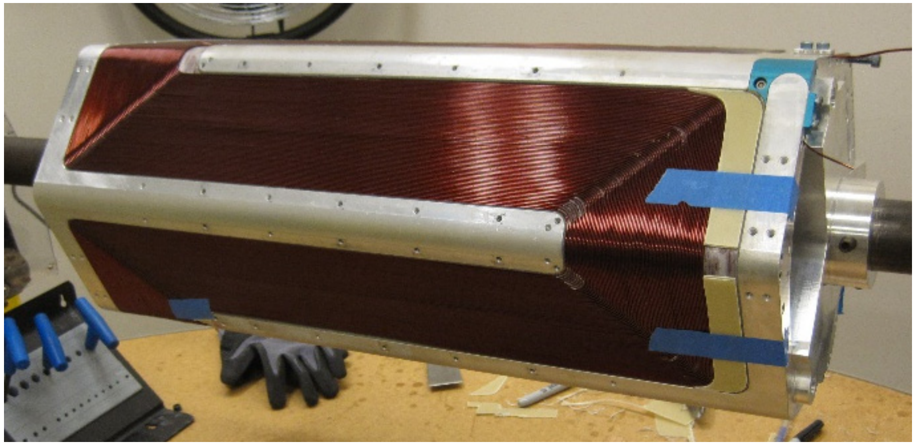
- **Better geometric form factor.**
- **Simpler interaction force patterns.**
- **≤ 50% as much conductor usage results in lower wire cost.**
- **Smaller system footprint**



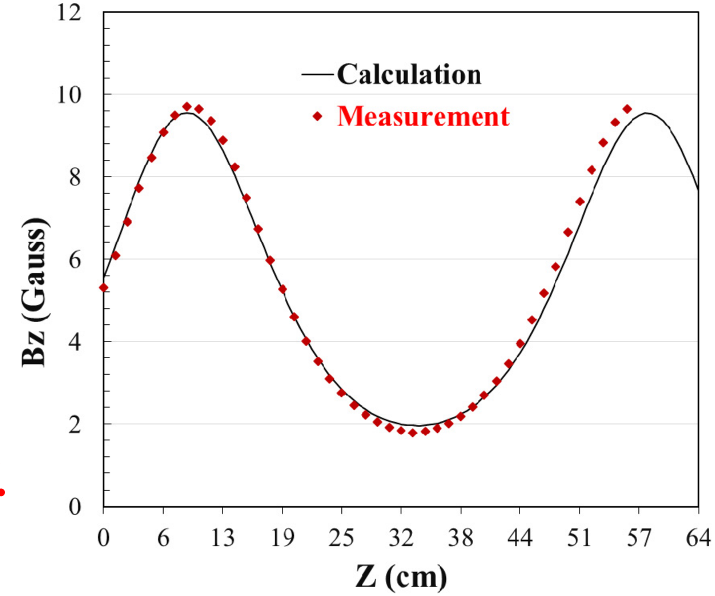


Challenge: Fabrication of a closed-loop coil!

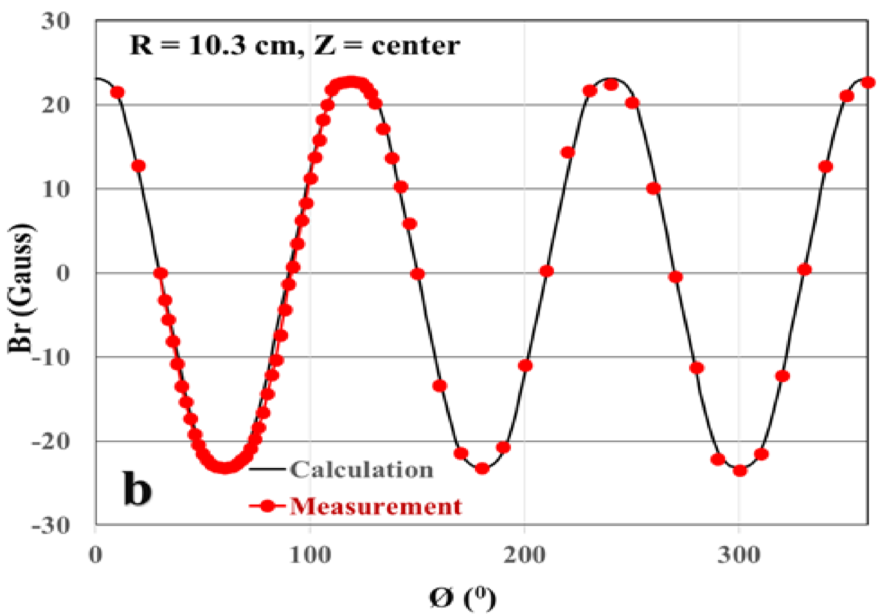
The Status of MARS Prototype Copper Coil



Winding of the prototype copper coil is completed.



Measured axial field profile ***I = 1 .00 A***



Measured radial field profile ***I = 1 .00 A***

The discrepancy of the average measured Br peak field is ≤ 1.0 % for the radial field profile.

The maximum discrepancy for the axial profile is ~ 3-4% due to the calculation is not able to completely simulate the coil-end winding.

Milestone

Excellent agreement of field mapping with the design and the completion of the copper closed-loop-coil winding have further demonstrated the feasibilitiy of a MARS magnet system for ECRISs.

The winding of a NbTi closed-loop coil will start soon for a demonstration ECR ion source: MARS-D

If validated, MARS magnet will be the best choice of magnet for future ECRIS.

If a Nb_3Sn magnet to be built with the existing magnet structures for future ECRISs

Question: *Can the existing magnets be optimized?*

Optimization: Generating the same fields inside the plasma chamber with the least Coil Excitation (CE)

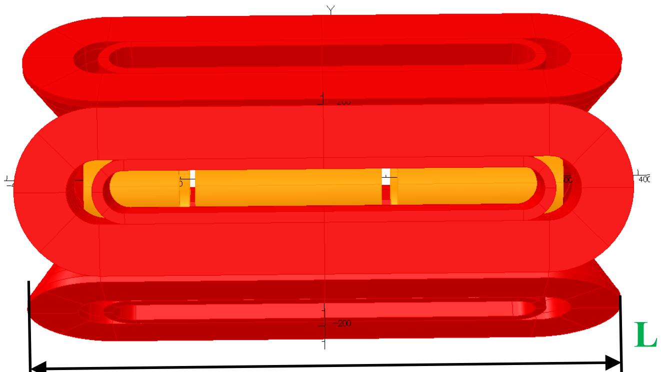
CE = LI (conductor wire length L current I)*

The goal of the optimization is to lower:

- *Maximum fields on the conductors thus the loading;*
- *Interaction forces;*
- *Complexity of clamping;*
- *Conductor usage;*
- *System stored energy.*

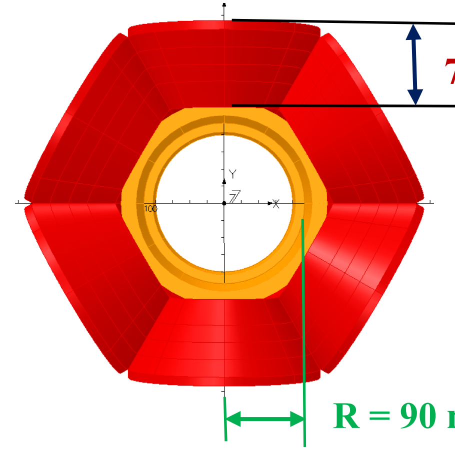
Any of these features is very preferable for constructing a superconducting magnet.

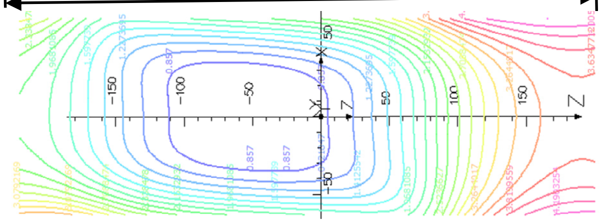
SECRAL-24 magnet built with NbTi wire



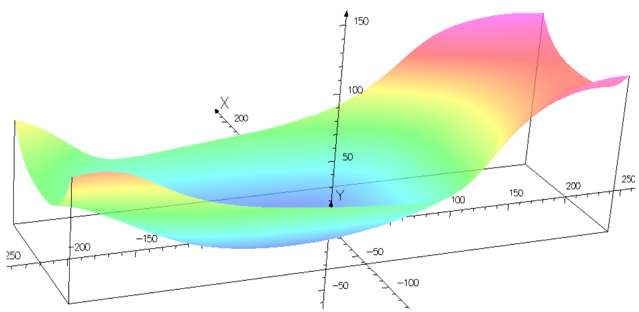
L = 725 mm

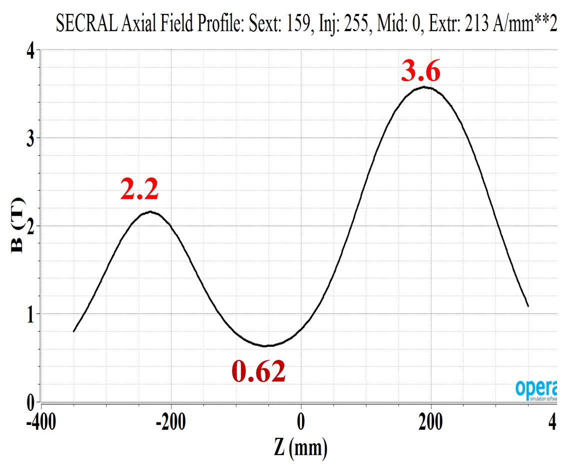
Solenoid-In-Sextupole Magnet Structure

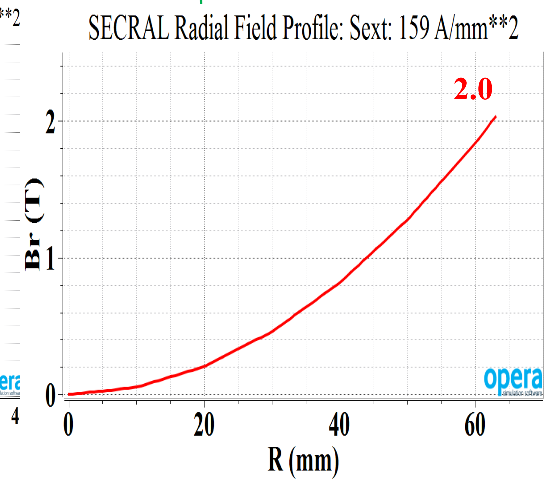




B_{last} = 1.86 T @ Bmin ~ 0.75*Becr





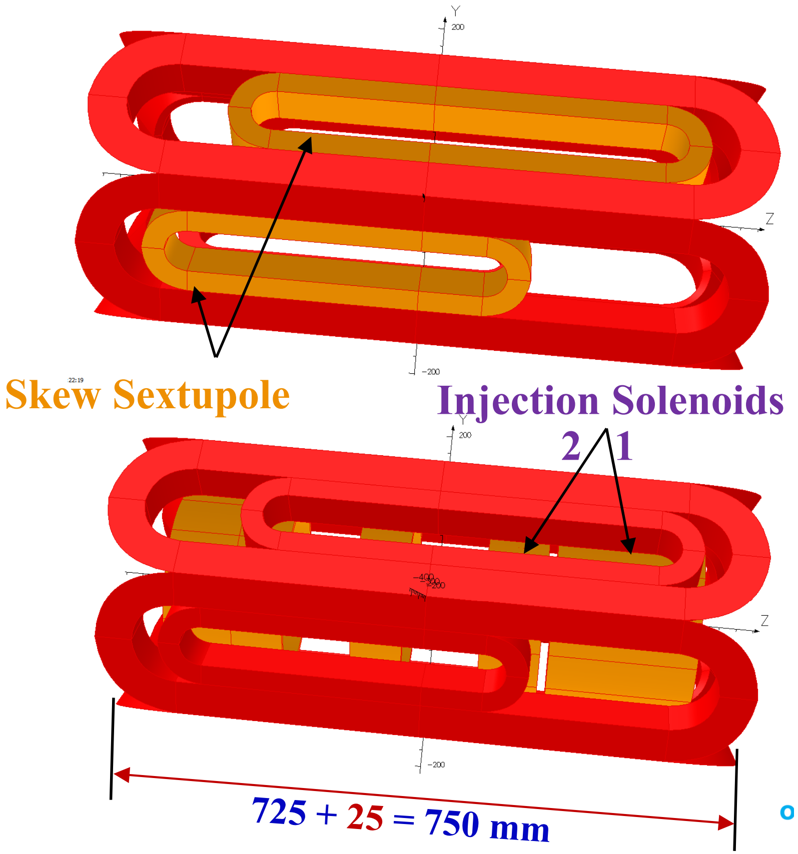


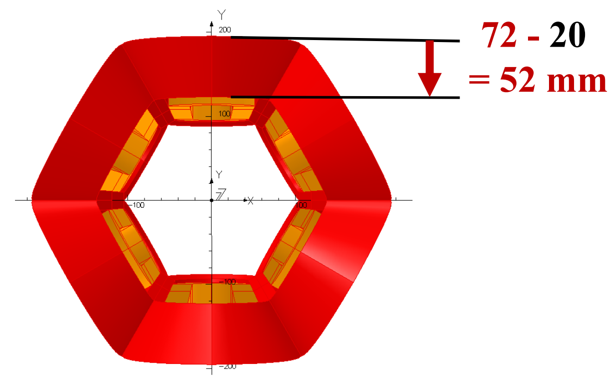
Plasma chamber R = 63 mm, B_{last} = 1.86 T

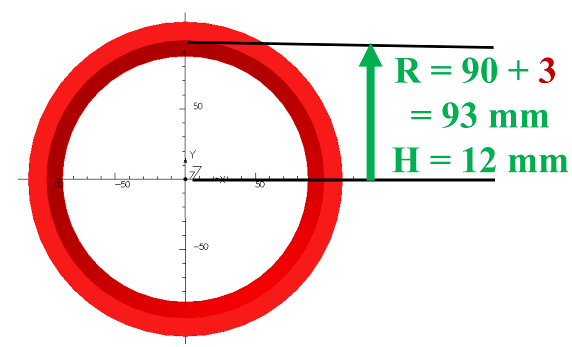
SECRAL has been reliably operating at 18 and 24 GHz since 2005 at IMP and has produced a good number ECR record beams.

Changes to be made:

- **Center section of the sextuple magnet skewed to lower the maximum field on the solenoids;**
- **Length of the magnet increased 25 mm, from 725 to 750 mm;**
- **Injection solenoid divided into two coils to lower the loading;**
- **Thickness of the sextupole reduced by 20 mm from 72 to 52 mm;**
- **IR of the injection and extraction solenoids increased by 3 mm, from 90 – 93 mm;**
- ***Plasma chamber radius R increased from 63 to 68 mm by slightly optimizing the cryostat;***
- ***Sext and Injection operate at higher current densities.***







- ***Plasma chamber R = 63 + 5 = 68 mm***

Note: Additional 2 mm can be obtained by optimizing the cryostat.

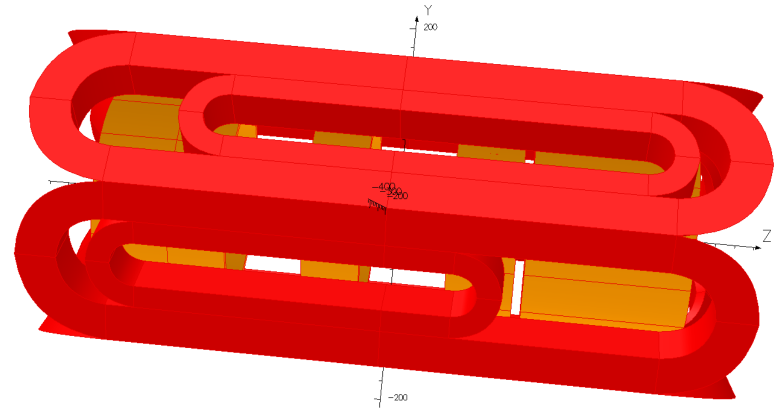
@ designed engineering current densities

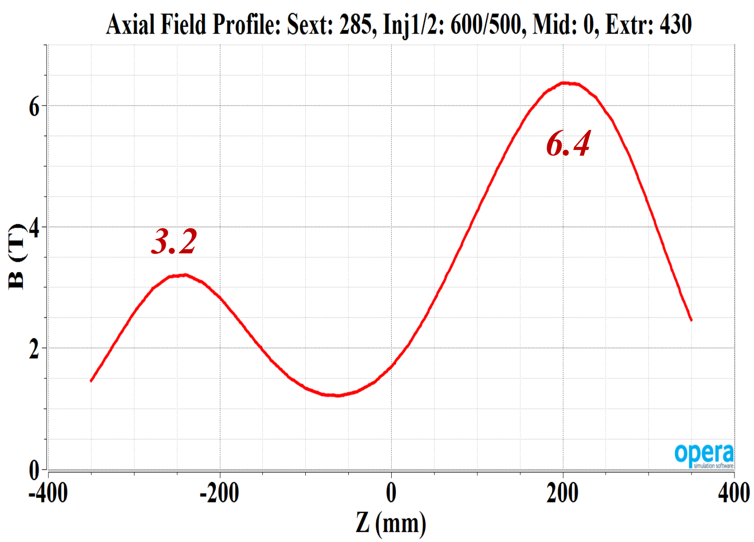
***J_e* (A/mm²):** Sext: 285, Inj-1: 600 , Inj-2: 500, Mid: 0, Extr: 430,

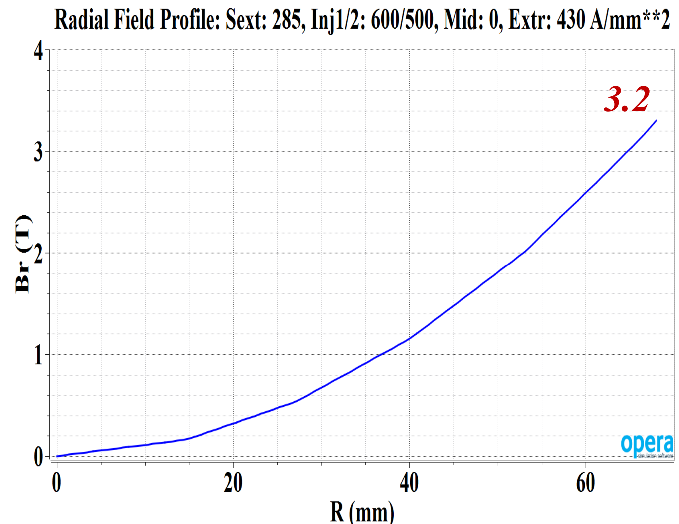
Lecr = 12.0 cm

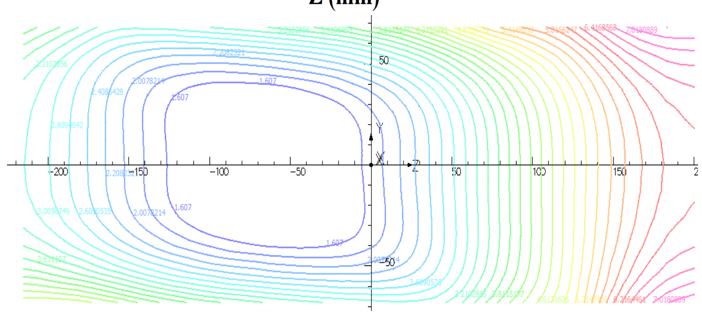
Bm(T) on coil: Sext: <u>11.8, Inj-1: 9.2, Inj-2: 10.0</u>, Mid: 8.1, Extr: 9.6

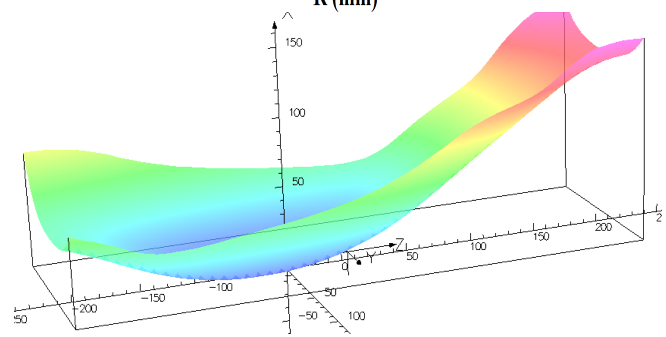
At R = 68 mm, Blast = 3.03 T







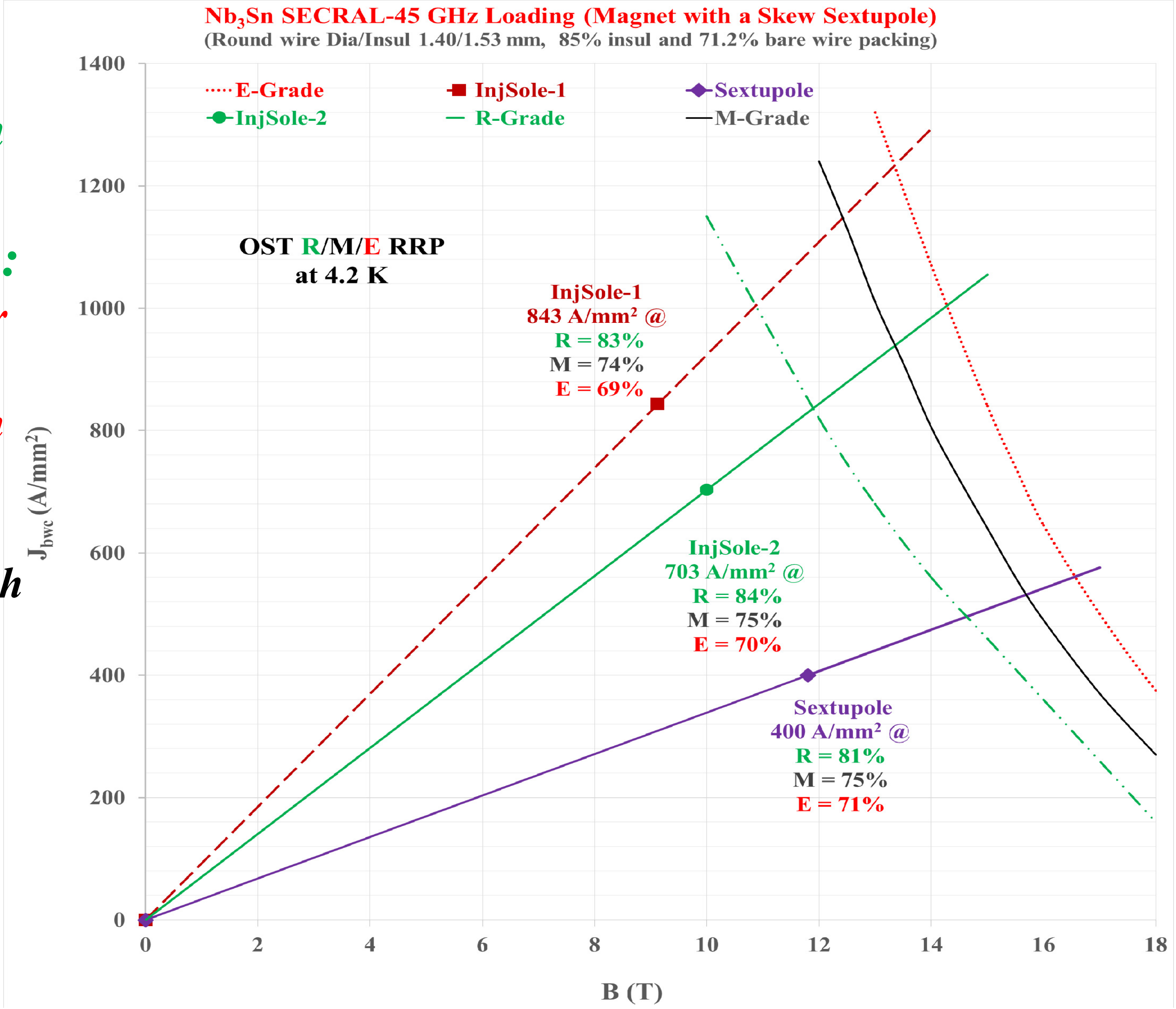




Nb_3Sn Skew Solenoid-In-Sextupole

Comparison to no modification:

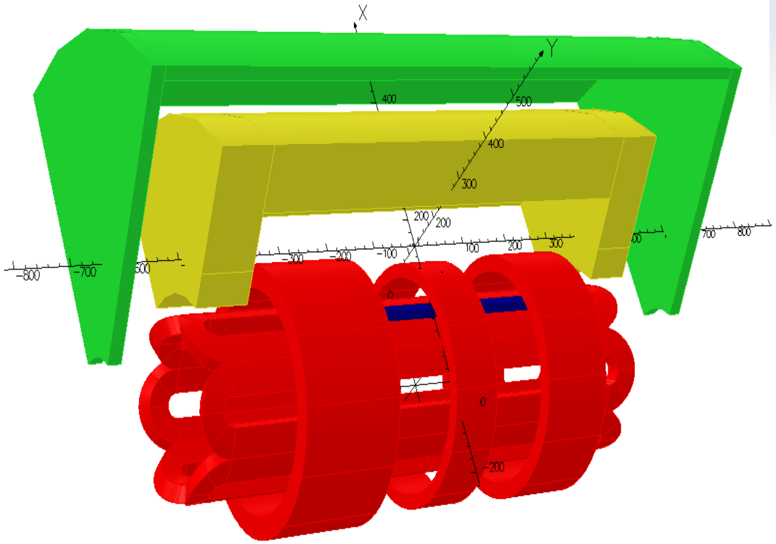
- *~ 10% lower loading on the injection solenoids*
- *Use only 60% as much Nb_3Sn conductor*

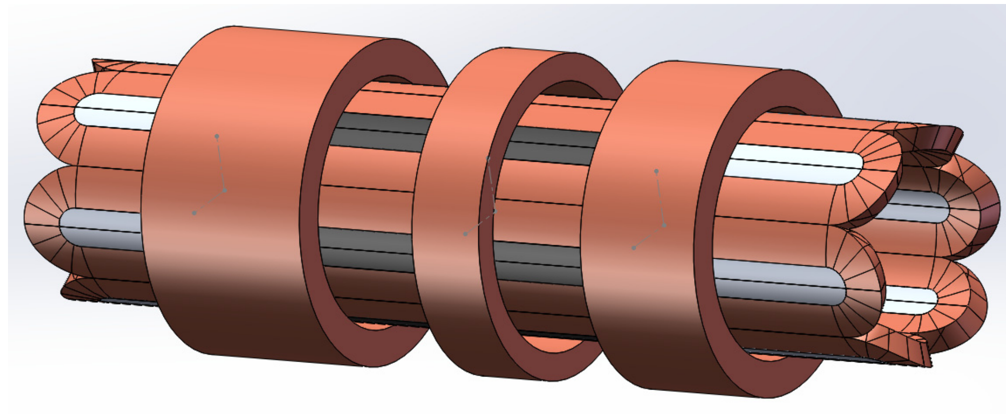


Proposed FECRAL with an Arc-Sext Magnet

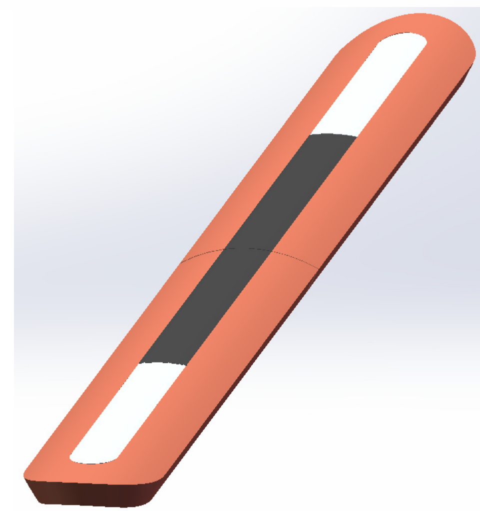
for 45 GHz operations

Require $B_{inj} \geq 6.4$, $B_{ext} \geq 3.5$, $B_r \geq 3.6$ T with a plasma chamber of R ~ 75 mm





Sextupole-In-Solenoid Magnet Structure



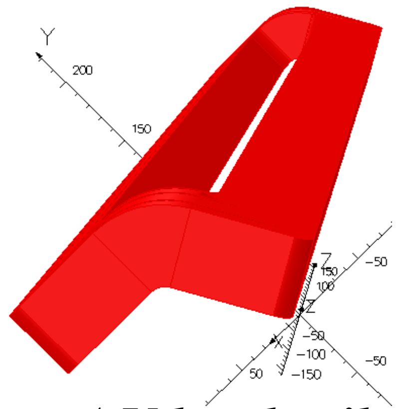
@ designed engineering current densities J_e (A/mm^2):

Sext: 440, Inj: 320 , Mid: -135, Extr: 300, Lecr = 12.6 cm

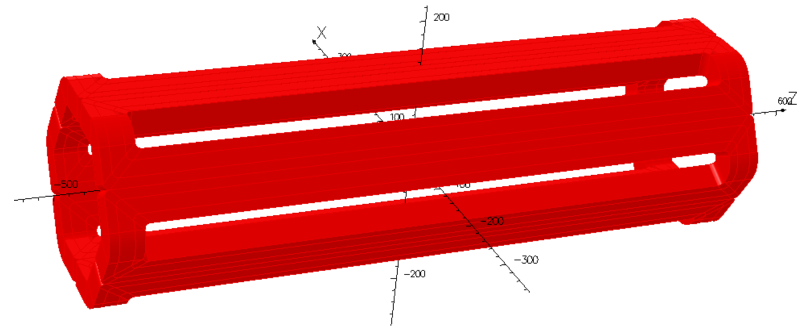
Bm(T) on coil: Sext: 10.8, Inj: 9.5, Mid: 4.3, Extr: 6.9

At R = 75 mm, Blast = 3.3 T

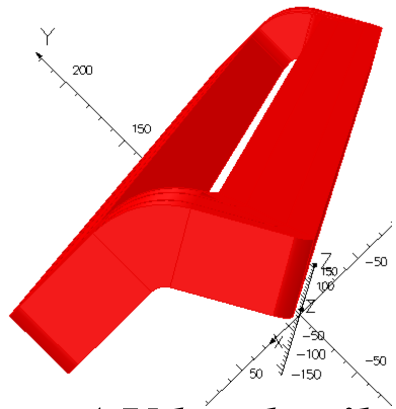
A V_bend_Sextupole-In-Solenoids magnet



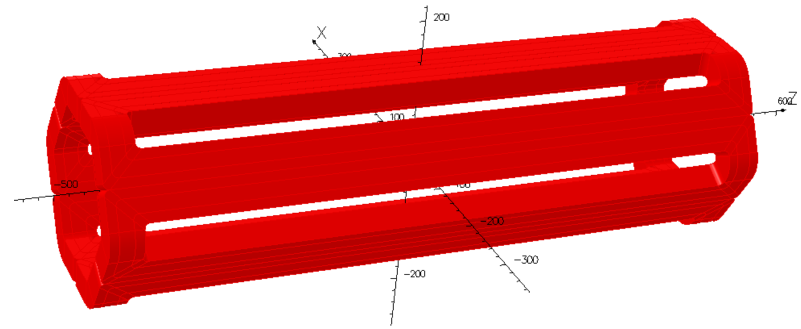
A V-bend coil

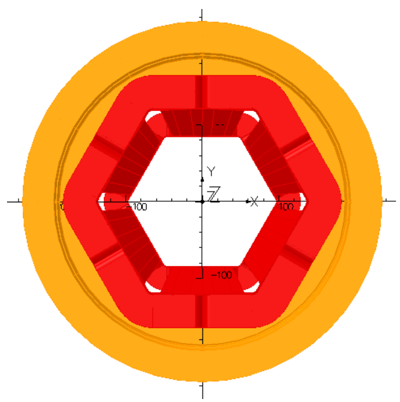


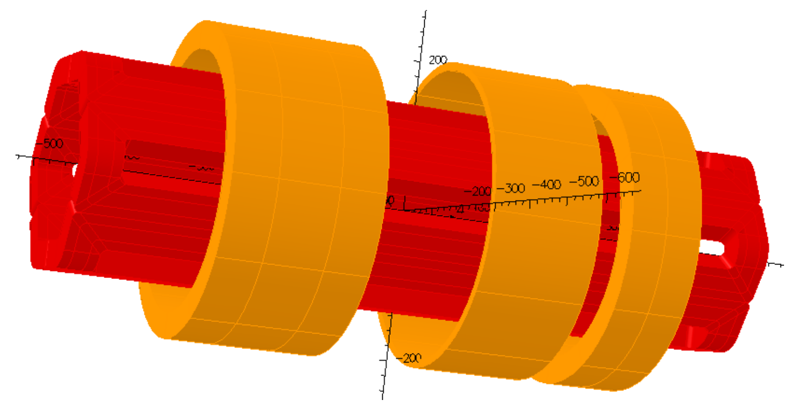
A V_bend_Sextupole-In-Solenoids magnet



A V-bend coil

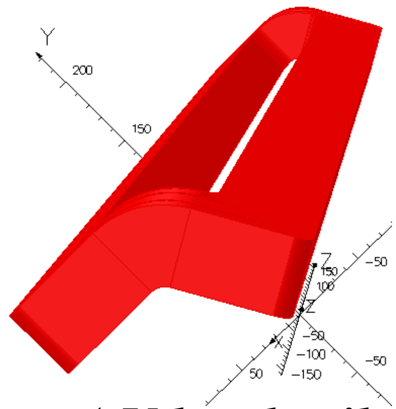




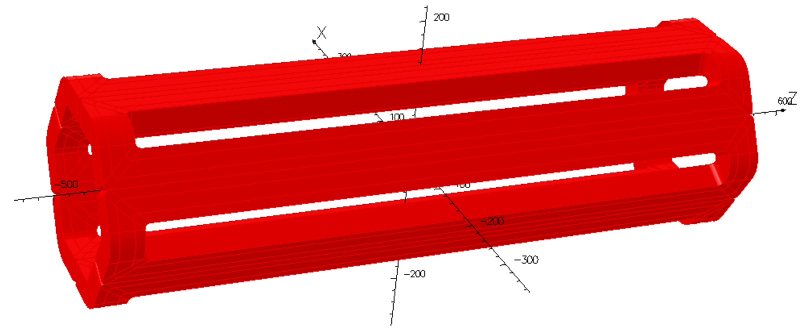


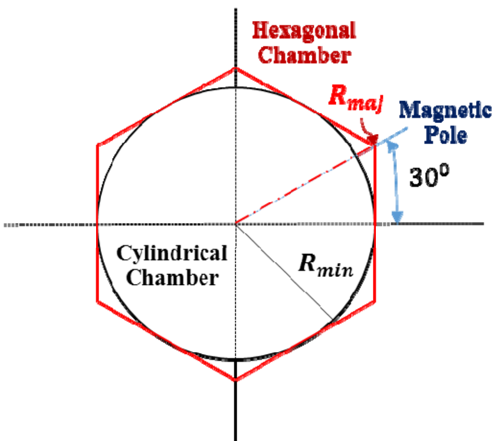
A V_bend_Sextupole-In-Solenoids magnet

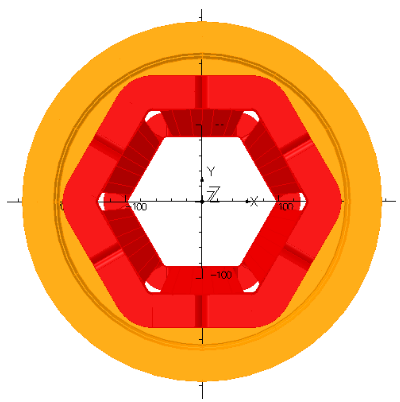
About the same over all dimensions as those proposed for FECRAL but with a major chamber radius of ~ 82 mm

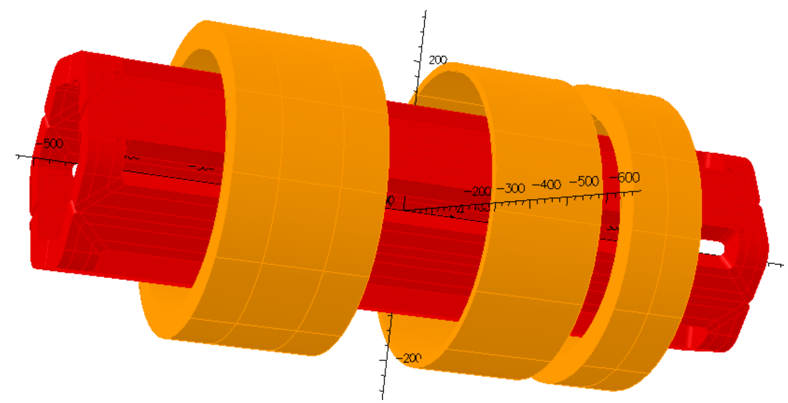


A V-bend coil









$B_r/B_m = (R_{maj}/R_m)^2 \sim 67\%$

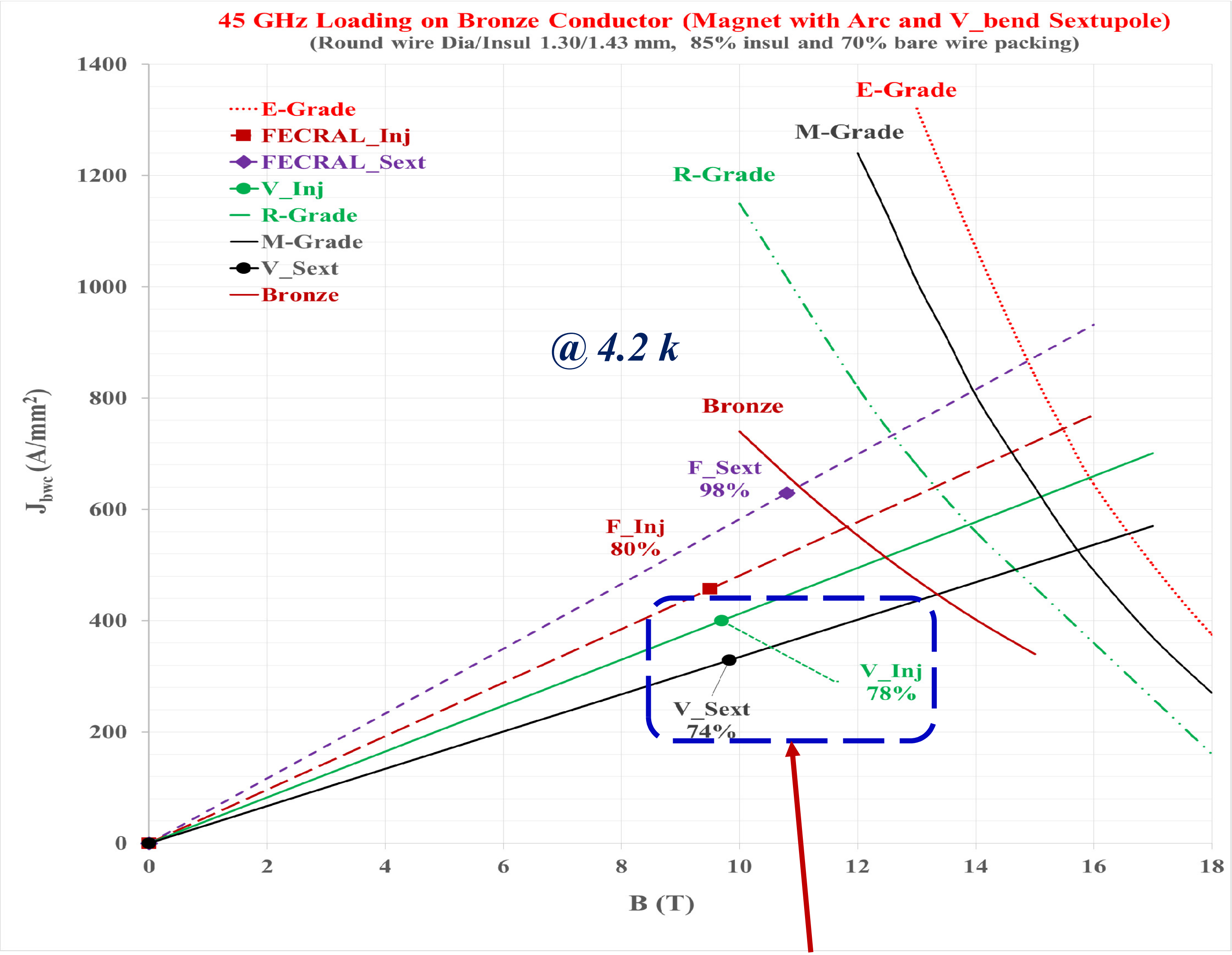
@ designed engineering current densities J_e (A/mm^2):

Sext: 230, Inj: 280 , Mid: -150, Extr: 275, Lecr = 10.3 cm

Bm(T) on coil: Sext: 9.8, Inj: 9.7, Mid: 4.3, Extr: 7.9

At major R = 82 mm, Blast = 2.9 T

Difficulty of winding a V-bend and an arc coil



Substantially lower wire loading!

The magnet with V-bend sextupole coils could use lower Jc Bronze wires at maximum loading of only 78% for 45 GHz operation!

Summary

- ***MARS magnet: A step closer to a MARS magnet for future ECRISs.***
- ***The above discussed magnet optimizations can be further refined for better efficiency but should be verified with thorough stress analyses.***

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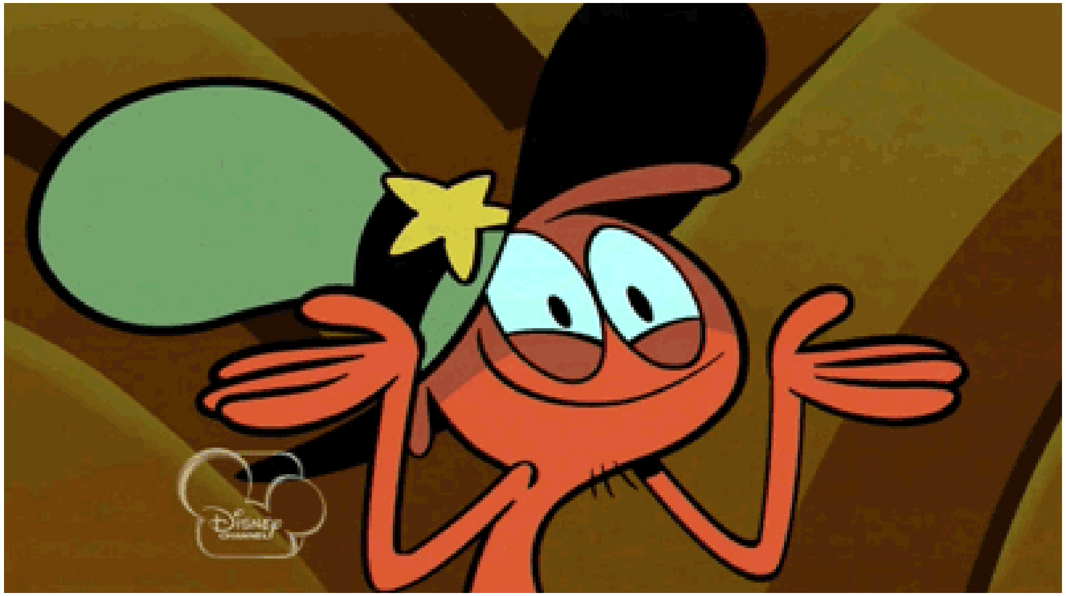

Thanks For Your Attention!