SRF Photo-injector Kickoff Meeting

HTS Magnetic Design and Analysis

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Overview of the Presentation

- Brief review of various design options examined
  - ➢ How and why we got to this design
- Detailed magnetic analysis of the current design
- Latest test results
  - ➢ Fast, low cost tests (one of several benefits of HTS)
- Next step

Why HTS?

• Initially HTS solenoid was proposed because HTS magnet can be placed in cold to warm transition region (4K to room temp). This allowed solenoid to be placed close to cavity.

• Another advantage of HTS (over conventional superconductor) is the significant saving in test costs. Cost of HTS is smaller than the difference between the cost of normal 4 K liquid helium tests and 77 K HTS tests. Moreover, HTS cost is only a small portion of over solenoid cost.

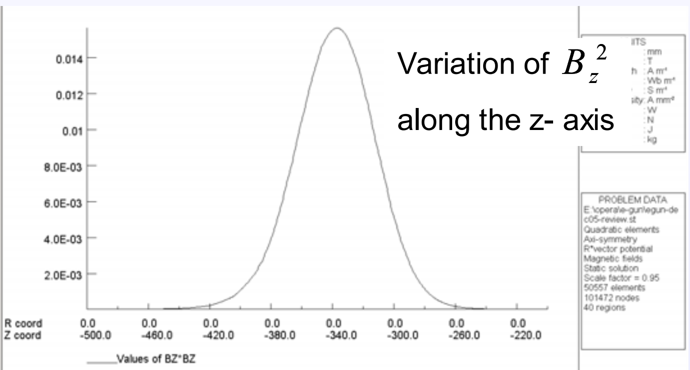
• Leads (HTS leads) become very attractive.

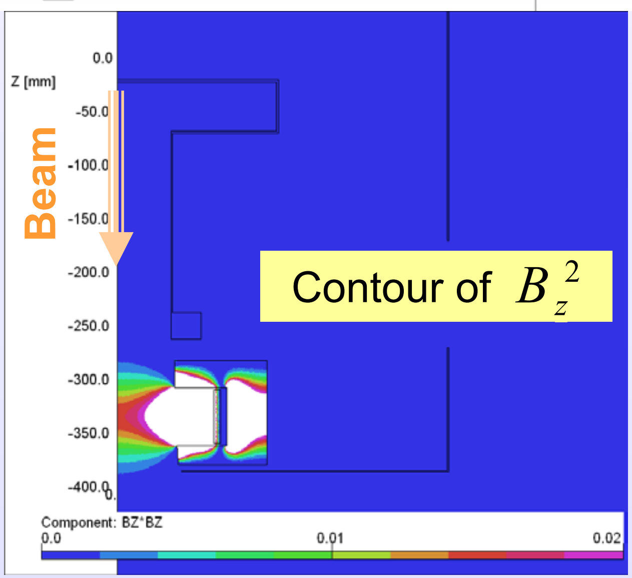
• Because the solenoid reaches the design field at ~80 K, one can go through the demagnetization cycle while cavity is still cooling down and has not yet reached the superconducting state.

Solenoid Design Requirements

Focusing Requirement :

$$\int B_z^2 dz \approx 1\ T^2\ .\ mm$$





Fringe Field Requirements:

1. Should be less than ~10 mG on the cavity when the it is turning to superconducting state (solenoid is OFF at this time).

2. Should be less than 1.5 kG (0.15 T) on the superconductor when the solenoid is ON.

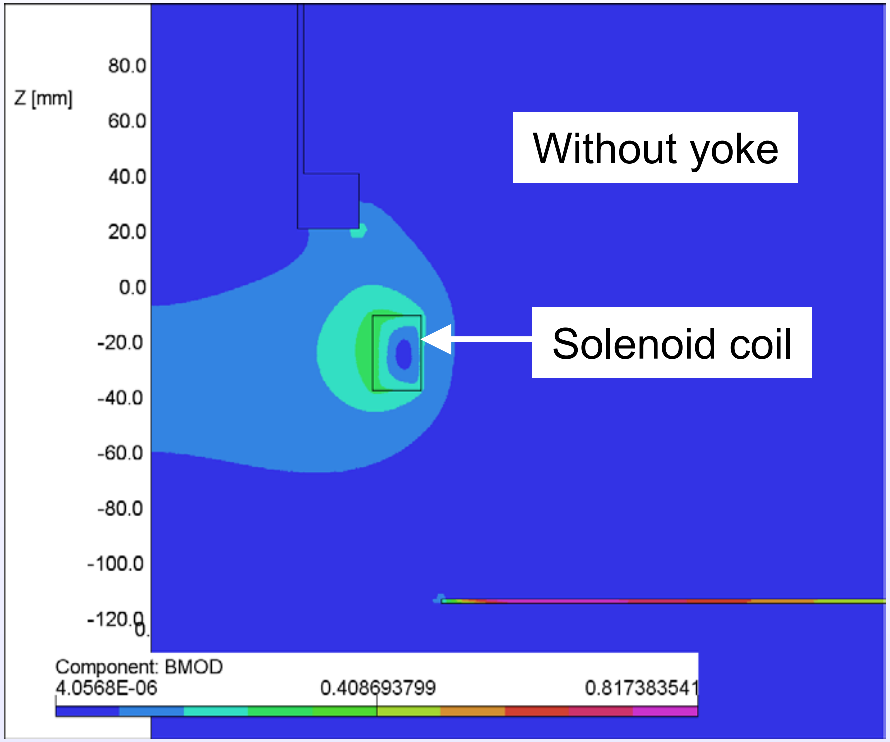
3. Trap field is a concern. The field on superconducting cavity should be less than ~10 mG, when the solenoid is excited.

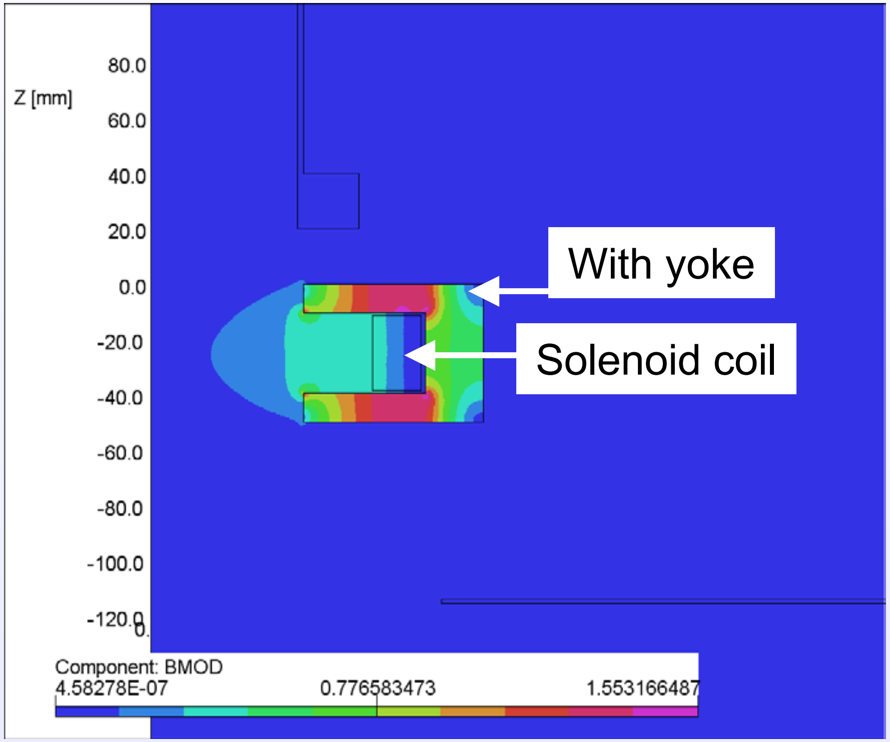
4. Field calculations (for beam focussing, etc.) must include the influence of shielding from superconductor and from mu-metal

Solenoid Design Development

- **"Yoke" Vs. "No Yoke" over Solenoid Coil**
  - **Fringe field Vs. residual field of magnetized iron**
- **Solenoid over Bellow**
  - **Significantly reduces overall space requirements**
- **Introduction of Bucking Coil**
  - **Significantly reduces field inside the cavity**
- **Interior Shield Moved Between Cavity and Solenoid**
  - **Significantly reduces field in and on the cavity**

Models Without and With Iron Yoke Over Solenoid





Significant fringe field from solenoid.

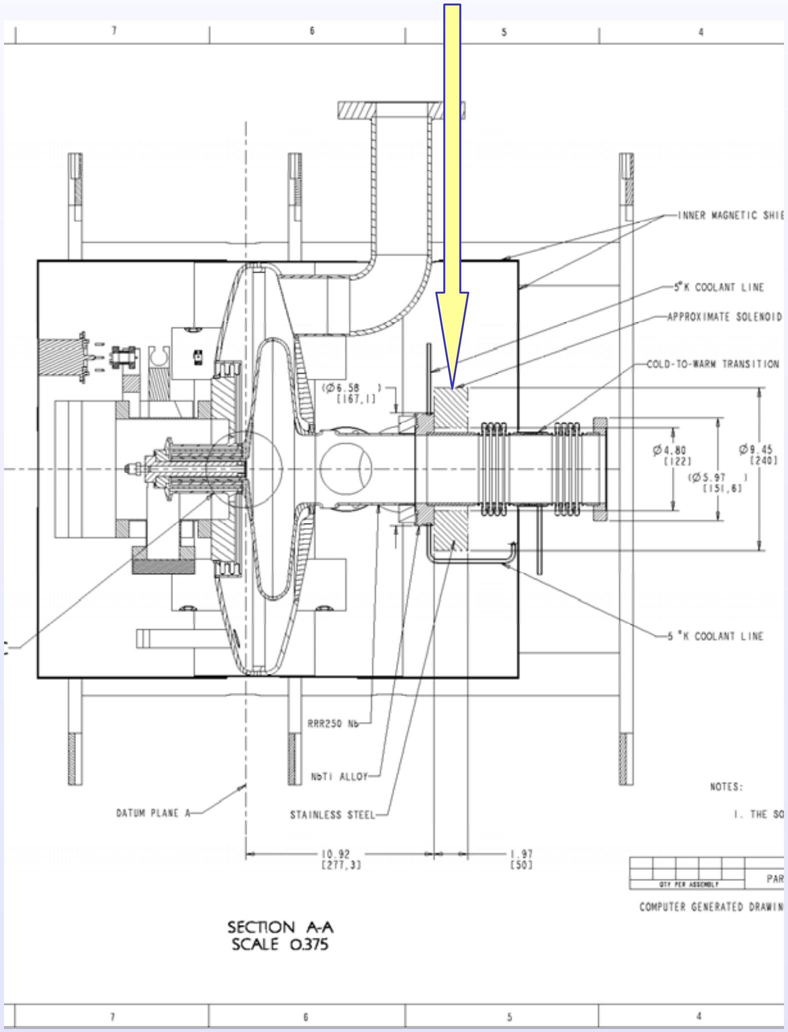
Maximum field on mu-metal is over 0.8 T. Also significant field on the superconducting cavity.

Small fringe field from solenoid on mu-metal shield and on cavity.

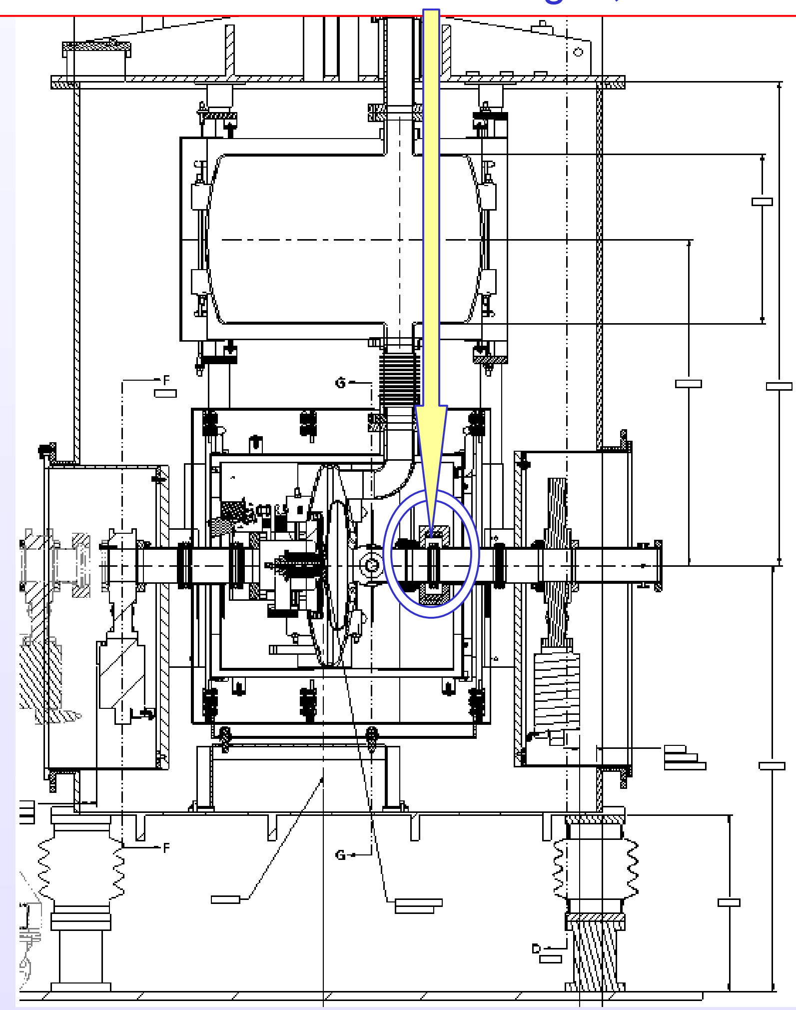
However, yoke magnetization must be reduced for remnant field. Adjust size and introduce de-magnetization cycles.

HTS Solenoid Over the Bellow

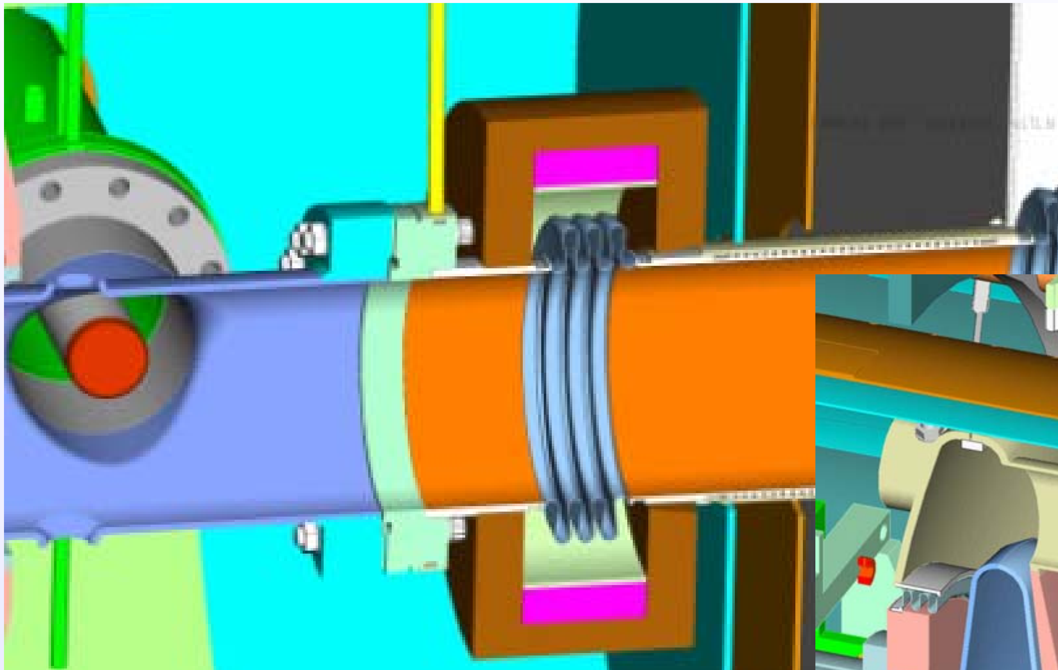
HTS solenoid before the bellow

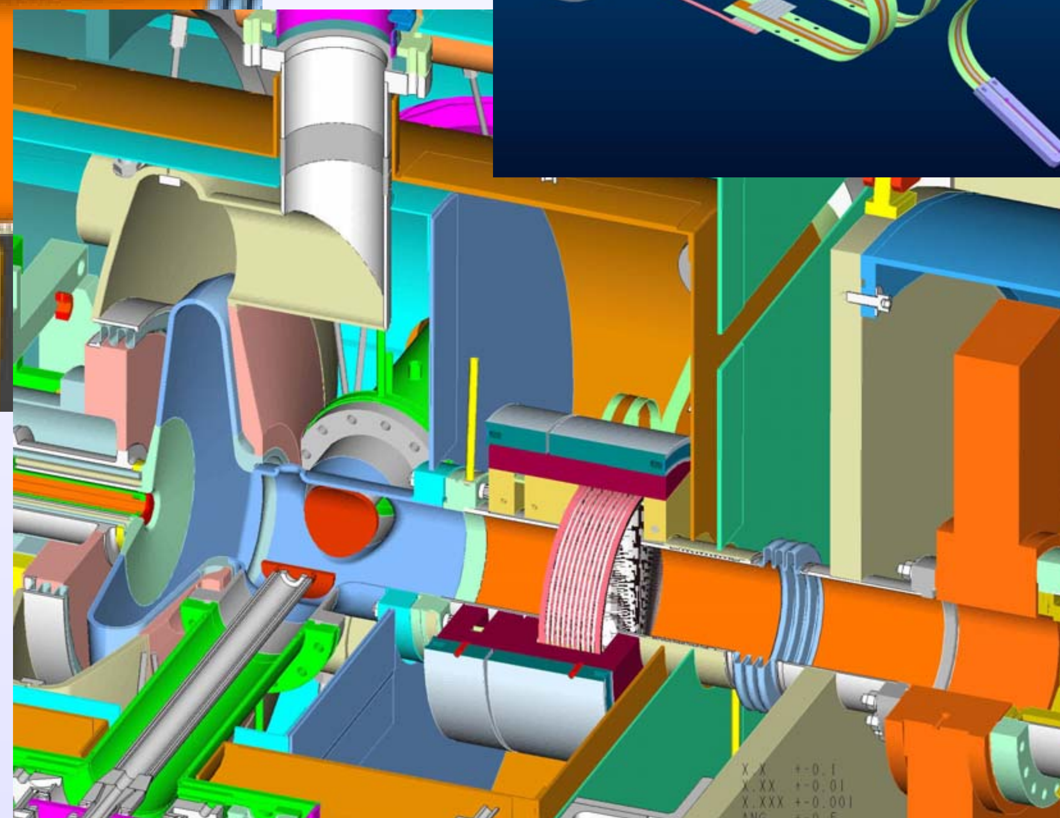


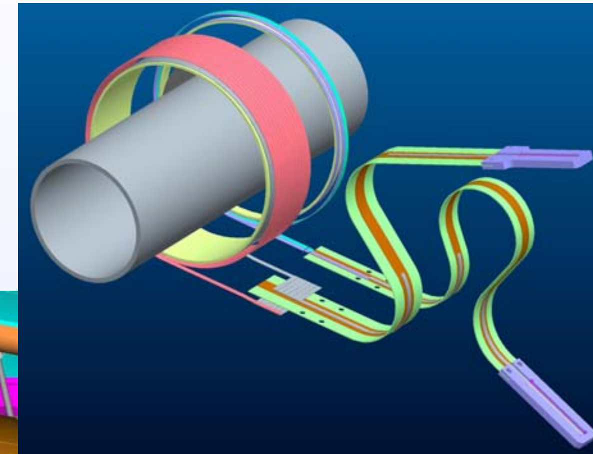
HTS Solenoid over the bellow. This reduces overall size. Coil clears all flanges, etc.



Introduction of Bucking Coil







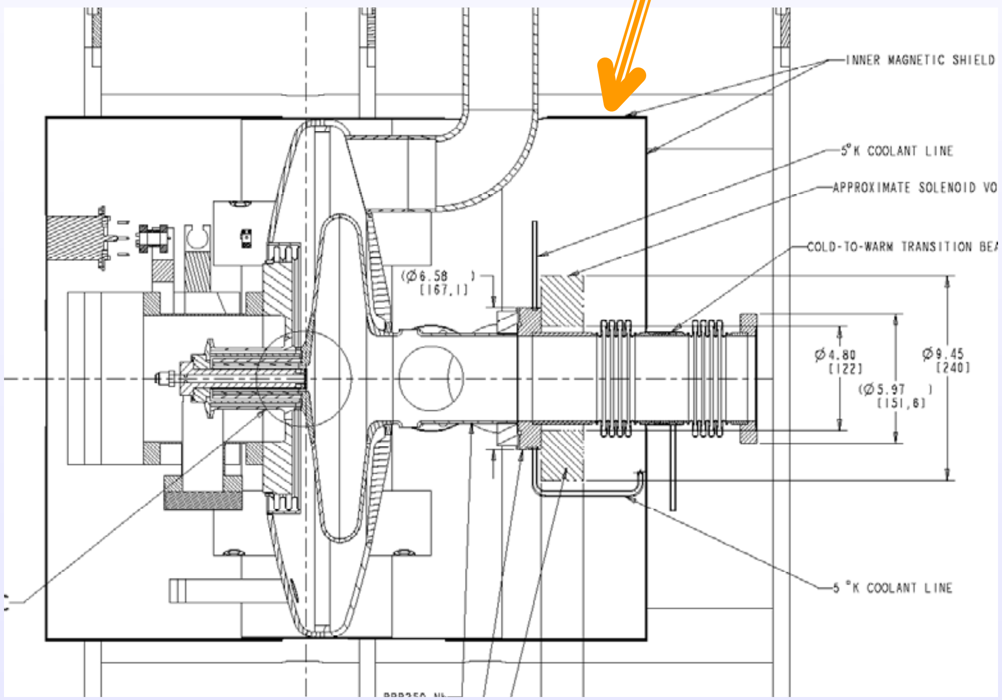
Bucking coil significantly reduces fringe field on the cavity side.

(see more in the detailed magnetic analysis – soon to follow)

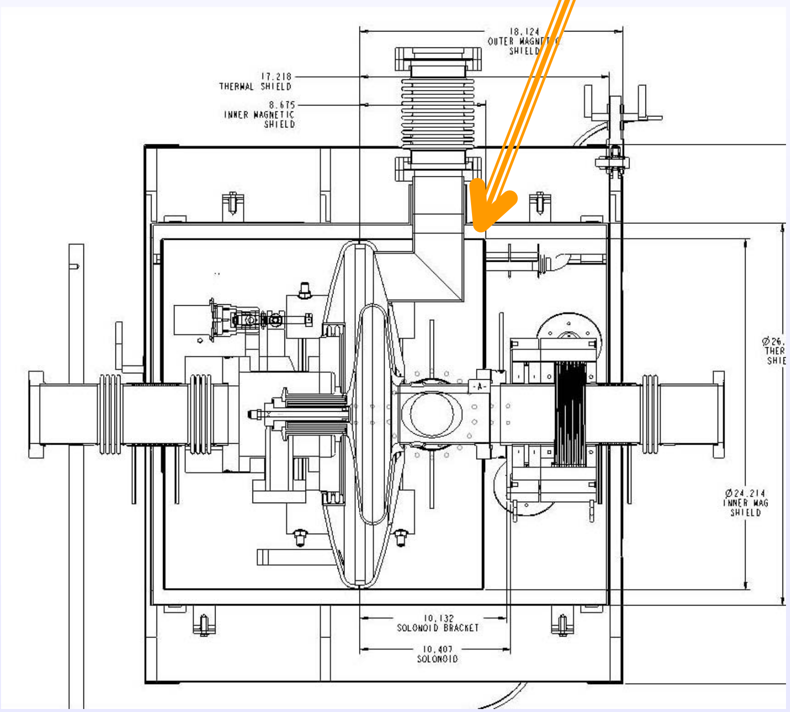
Location of Inner Magnetic Shield

Current design

Inner Magnetic shield



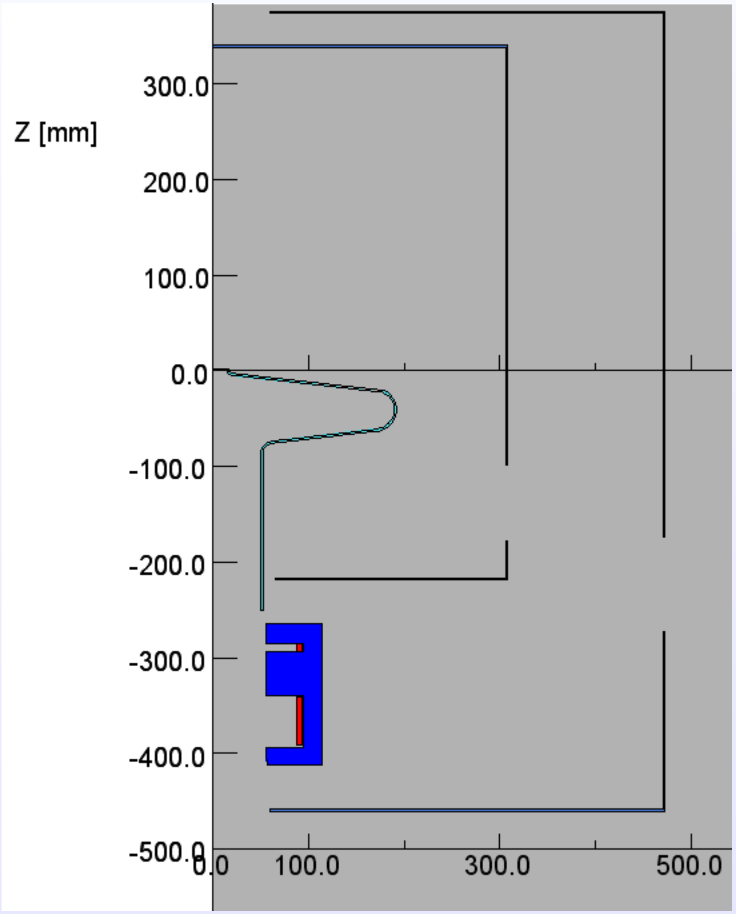
Inner Magnetic shield



Moving inner magnetic shield inside significantly reduces the field on superconducting cavity.

Magnetic analysis follows

The Current Design



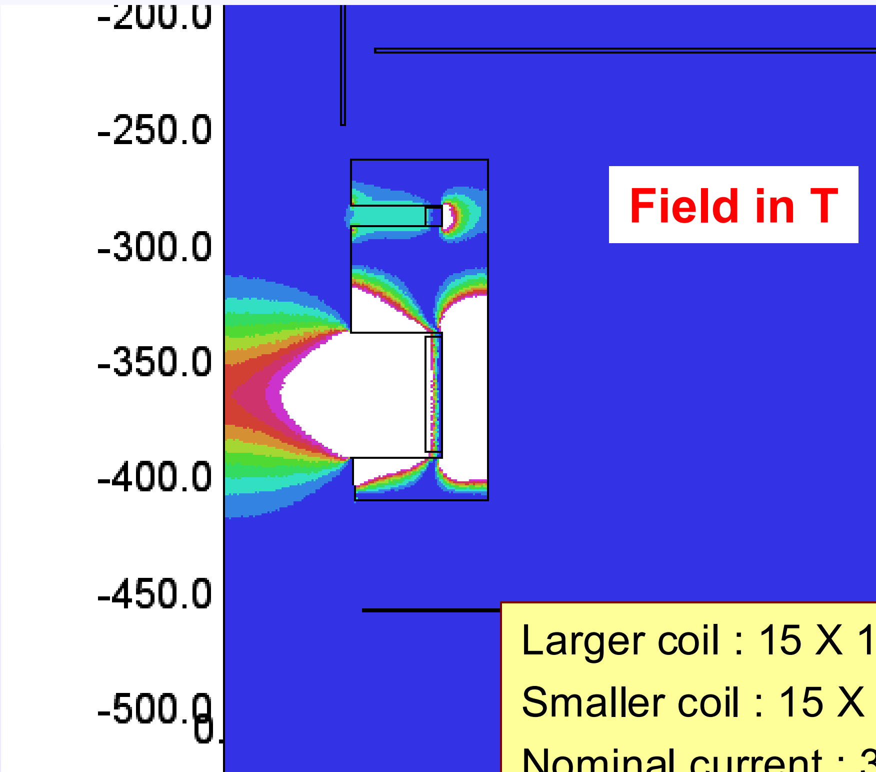
- There are two coils – main coil and bucking coil. Both coils have 15 layers. The main coil has 12 turns and bucking coil has 2 turns.
- Two coils are independently powered to obtain best cancellation of the field inside the cavity.
- Inner magnetic shield shield has been moved from outside the solenoid to inside (in between cavity and solenoid).

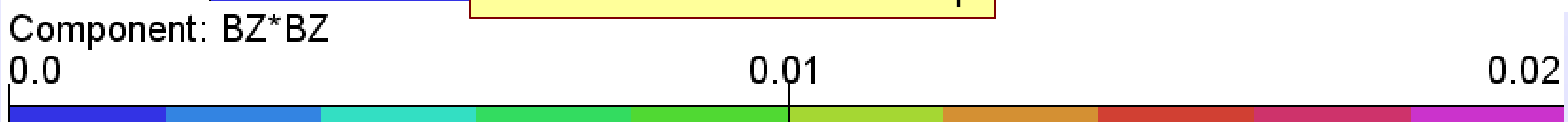
The influence of shielding and bucking coil has been analyzed.

Focusing in the Current Solenoid Design (Bucking coil to minimize field in cavity)

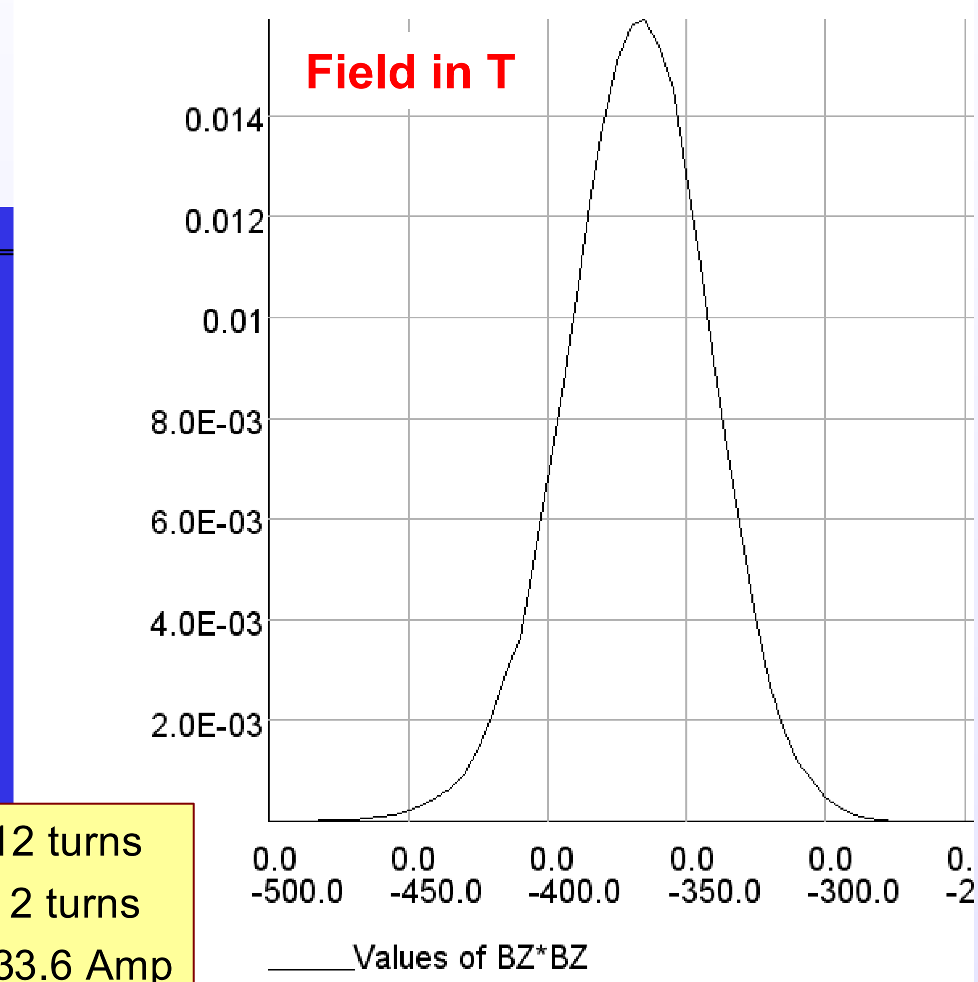
Basic Requirement :

$$\int B_z^2 dz \approx 1\ T^2 \ .\ mm$$



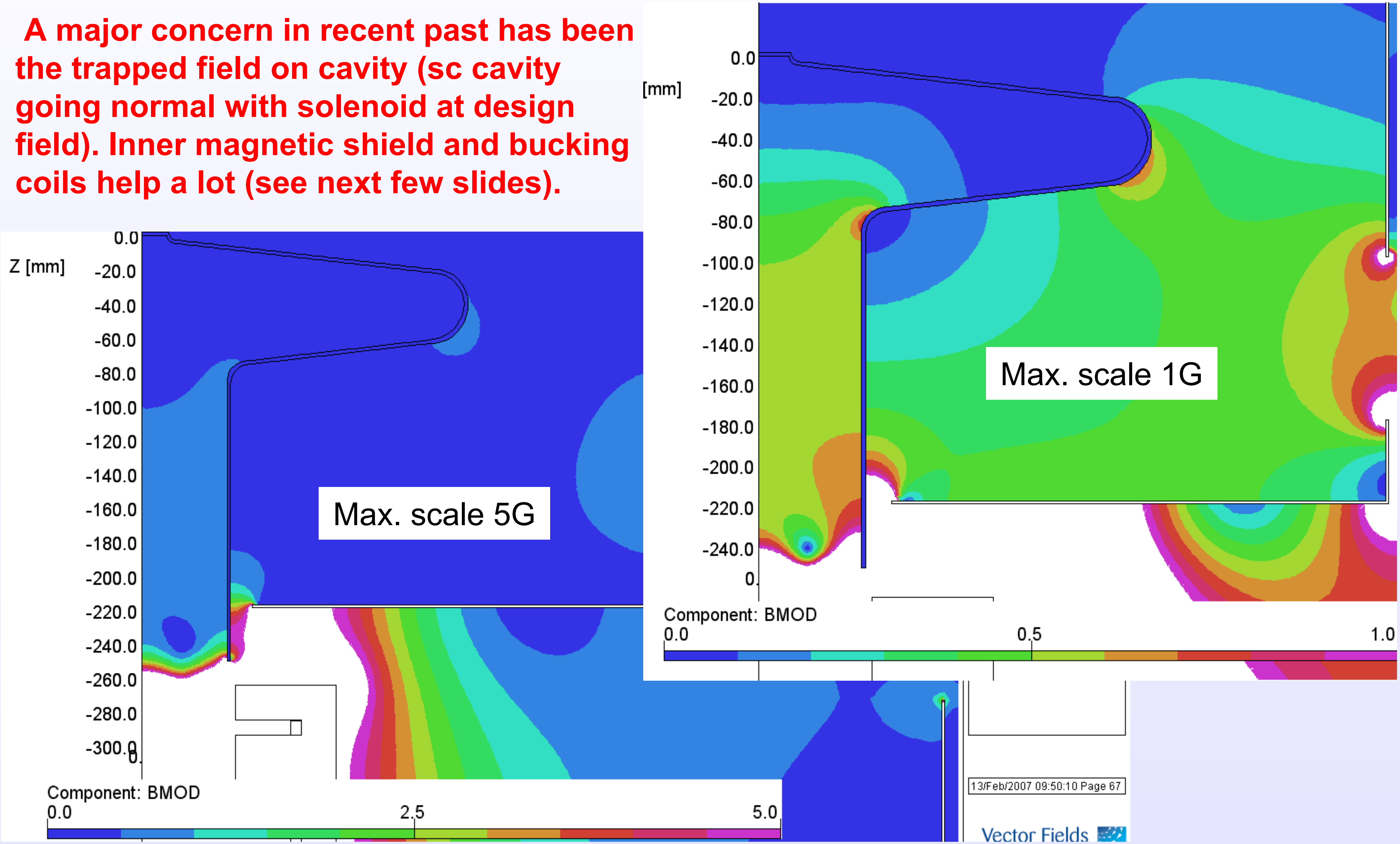


Larger coil : 15 X 12 turns
Smaller coil : 15 X 2 turns
Nominal current : 33.6 Amp

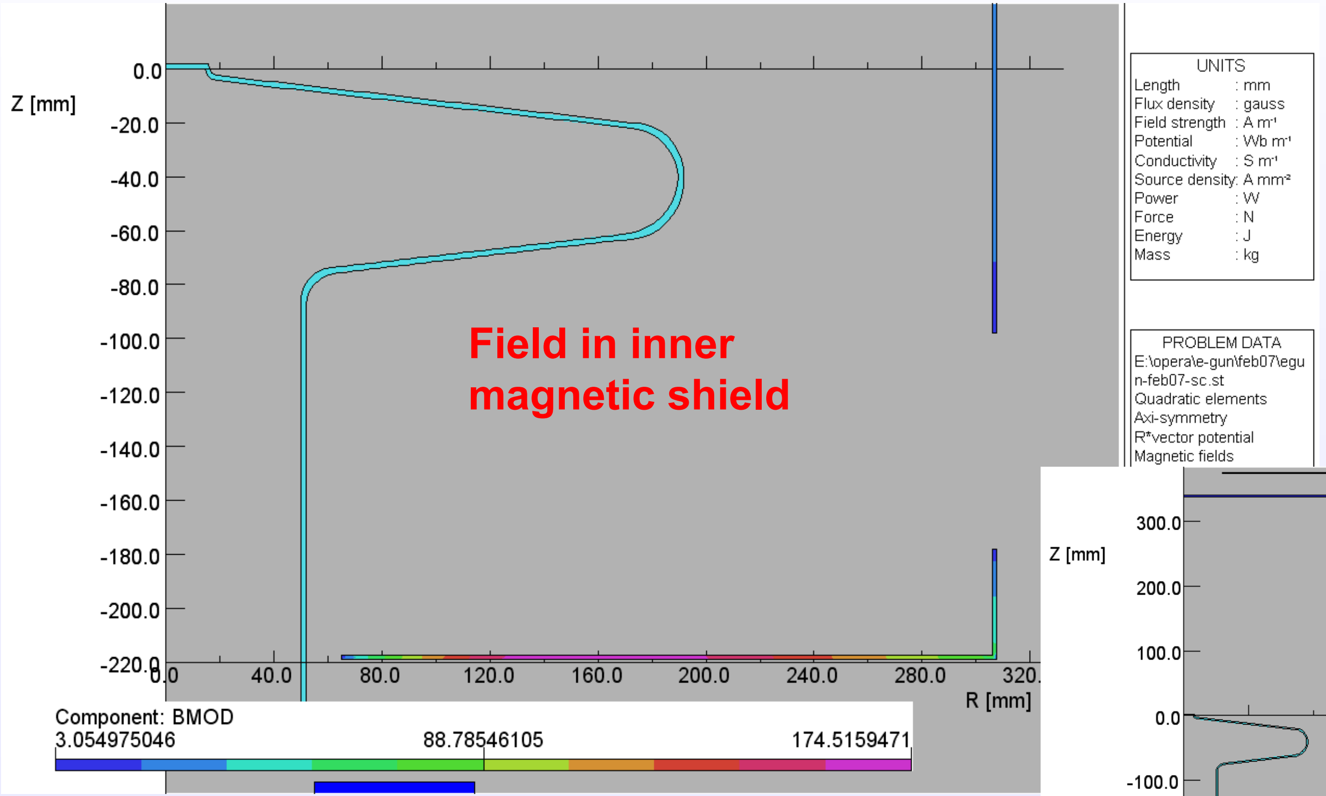


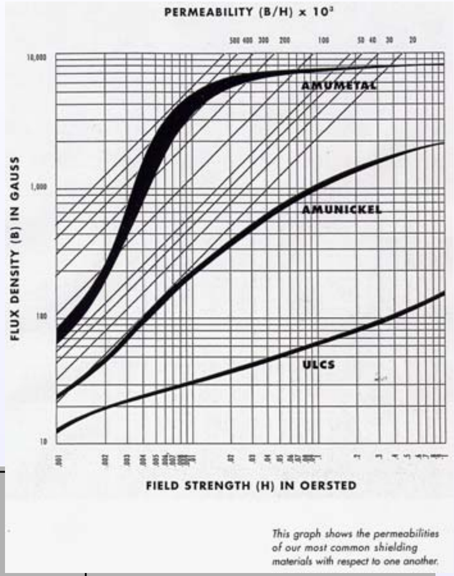
Fringe Field in Gauss With Inner Magnetic Shield

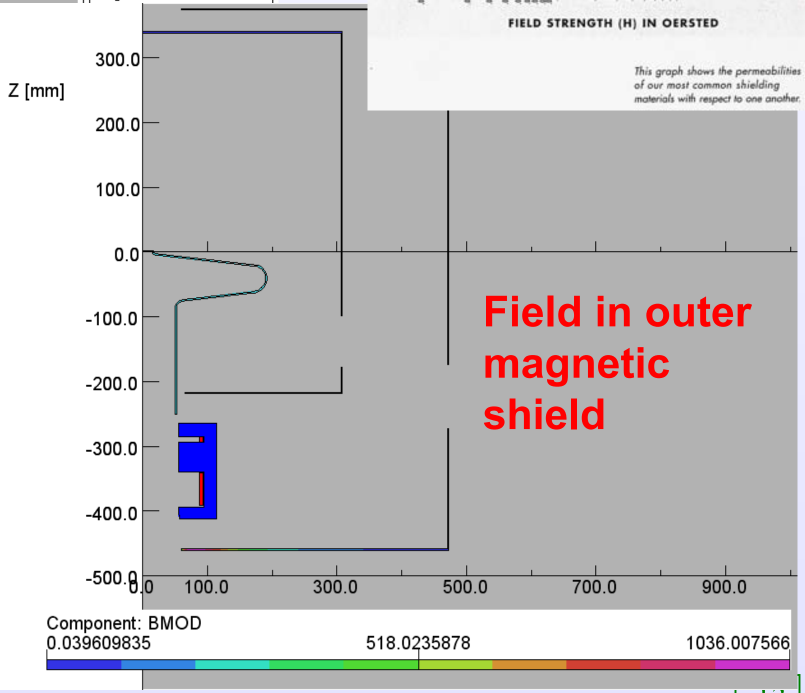
A major concern in recent past has been the trapped field on cavity (sc cavity going normal with solenoid at design field). Inner magnetic shield and bucking coils help a lot (see next few slides).



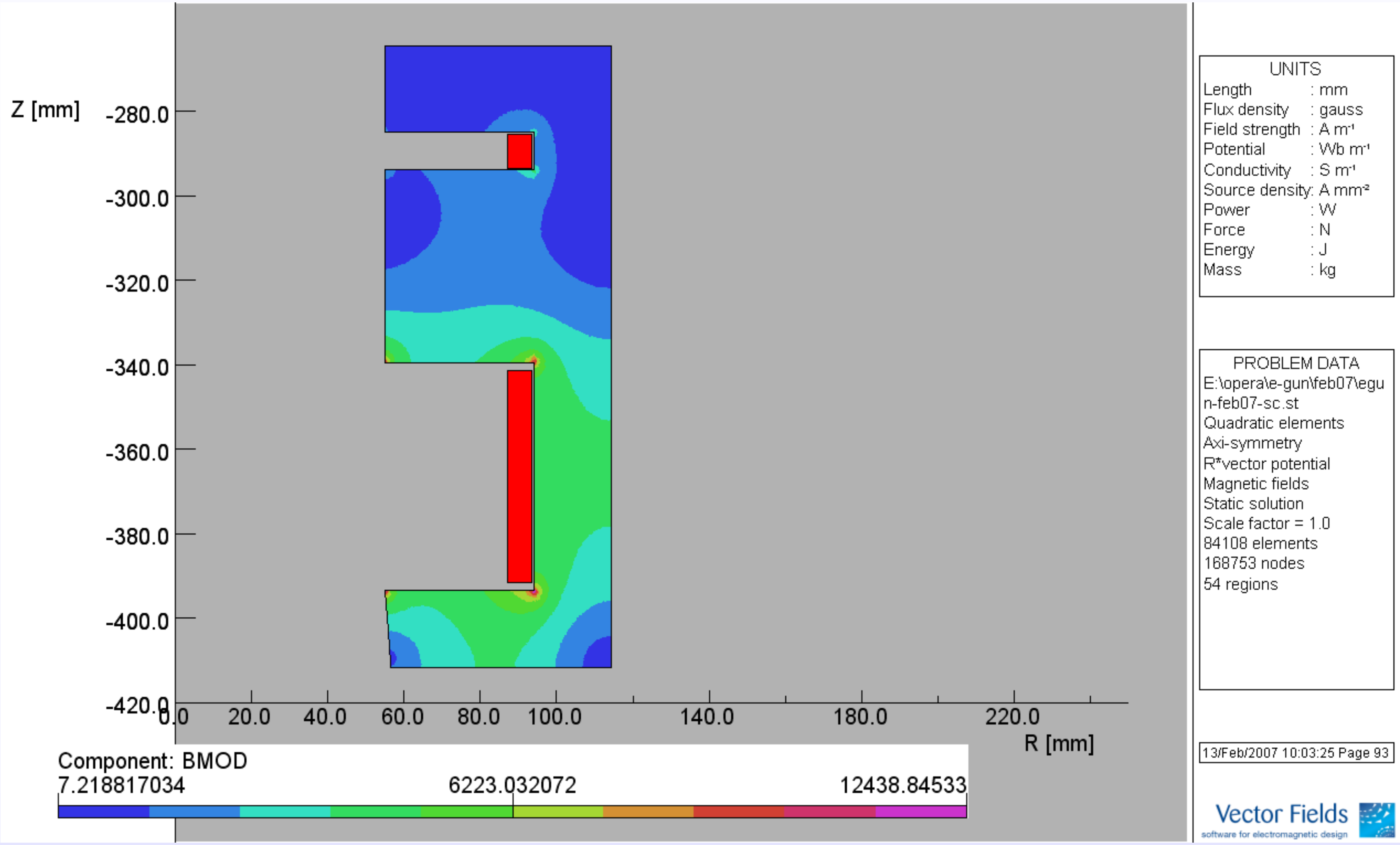
Field (G) on Magnetic Shields







Field (G) in Solenoid Yoke



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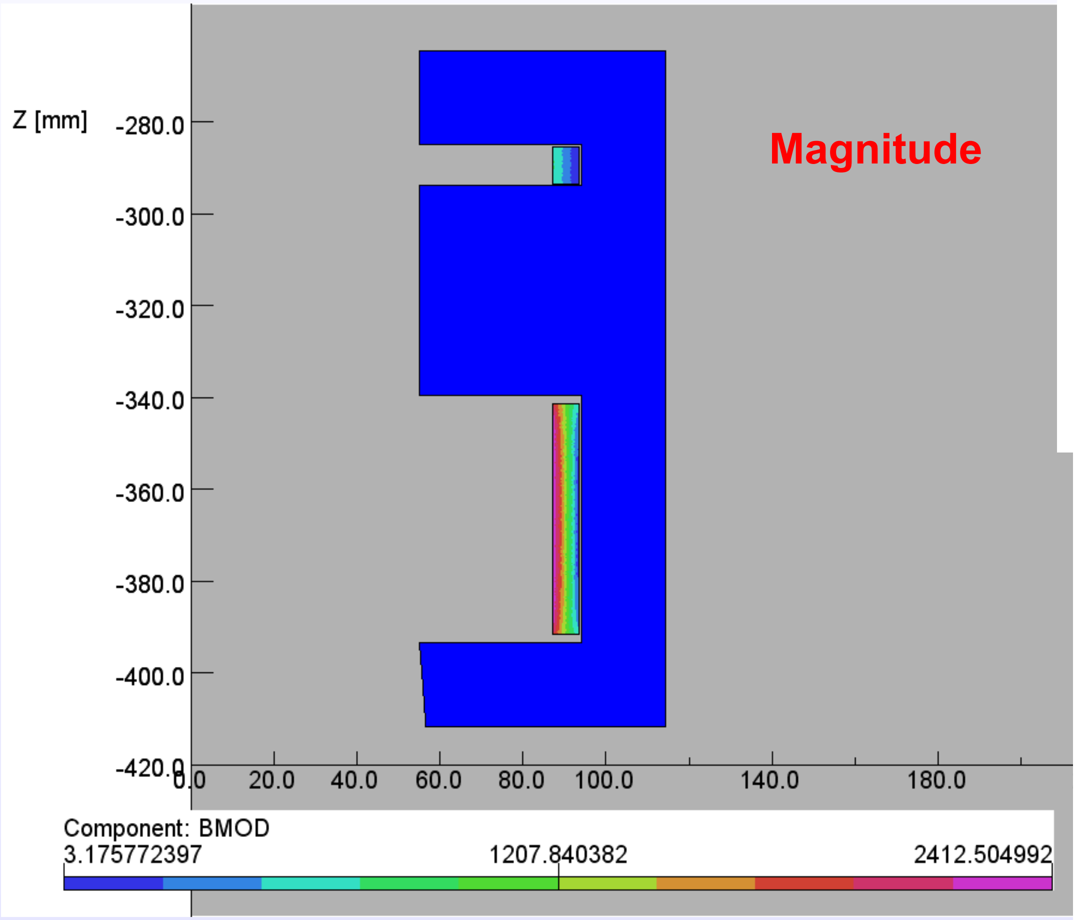
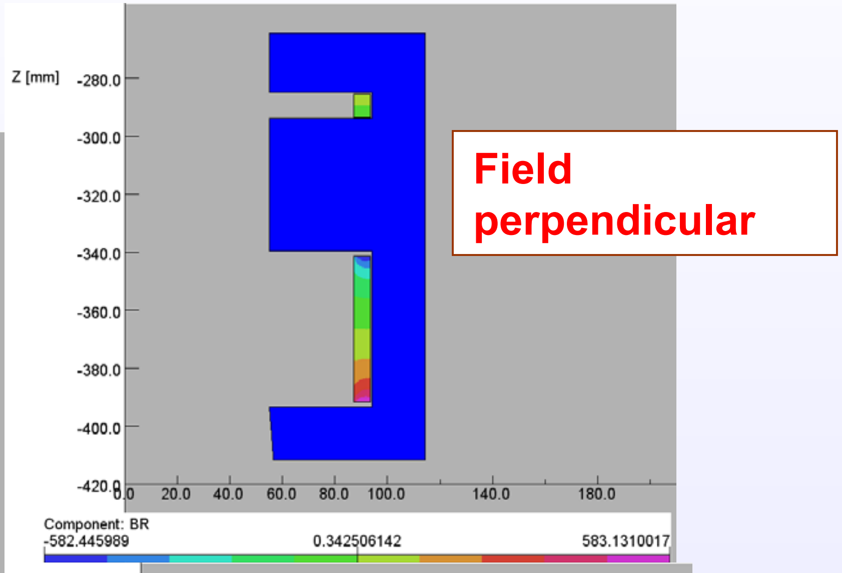
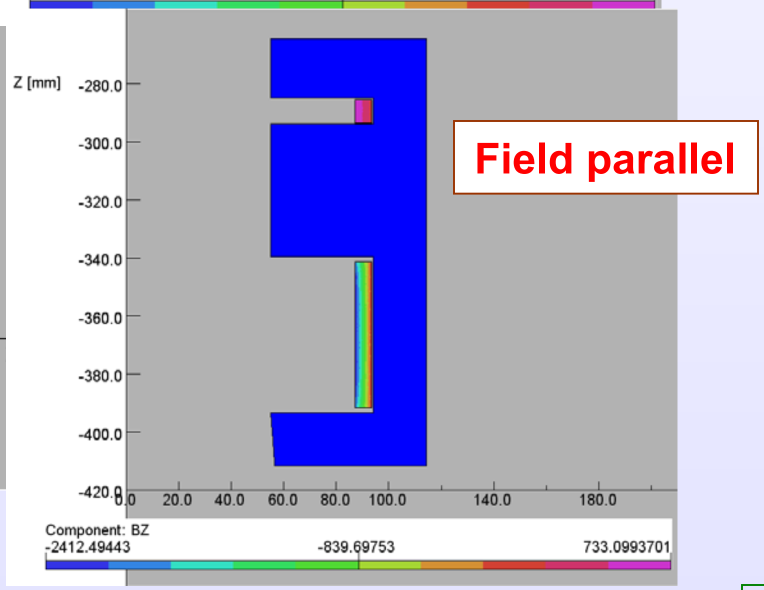
Field on HTS Coil (magnitude and field components)

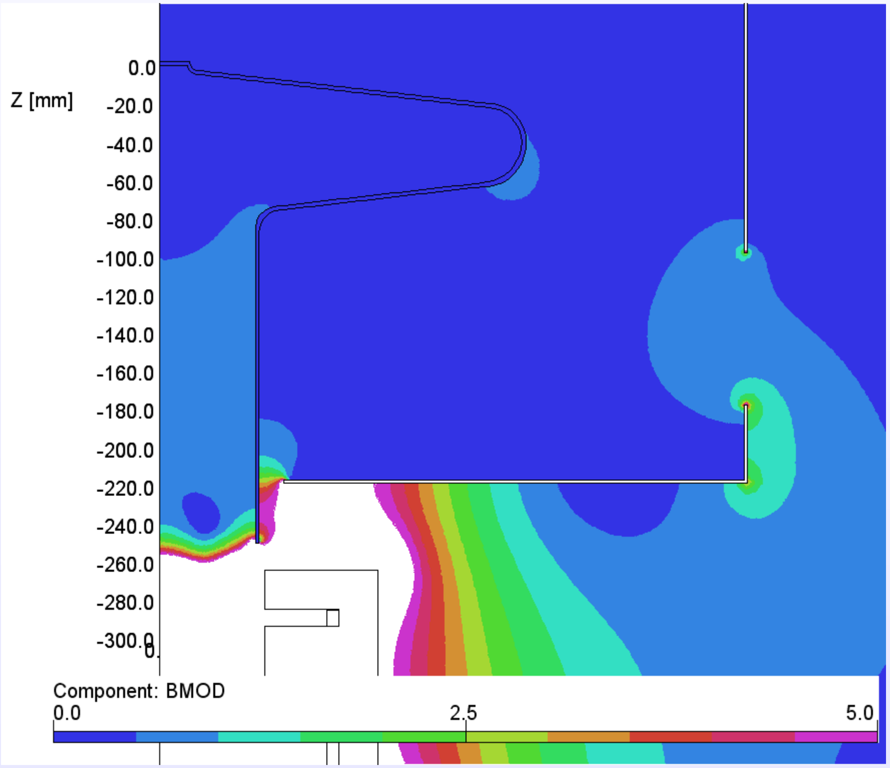




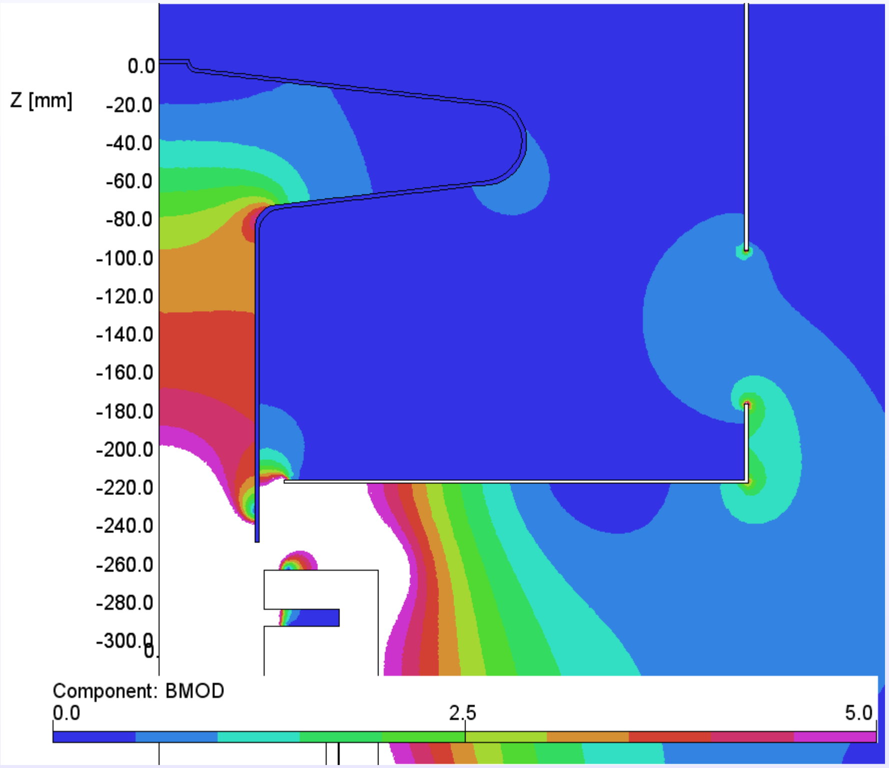


Field (G) Inside Cavity Region

Field inside cavity with bucking coil excited (current in bucking coil 5/16 of main coil)

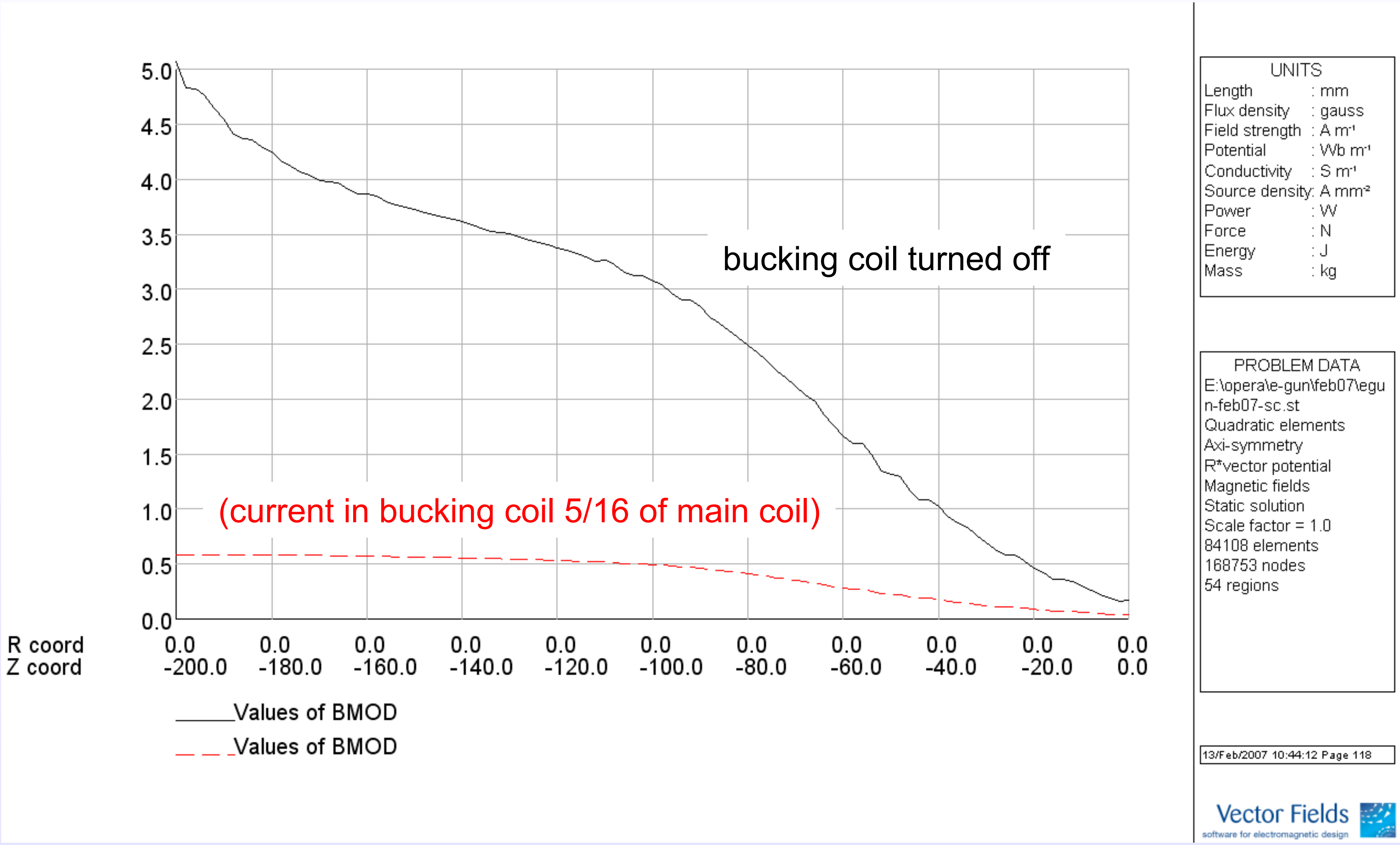


Field inside cavity with bucking coil turned off

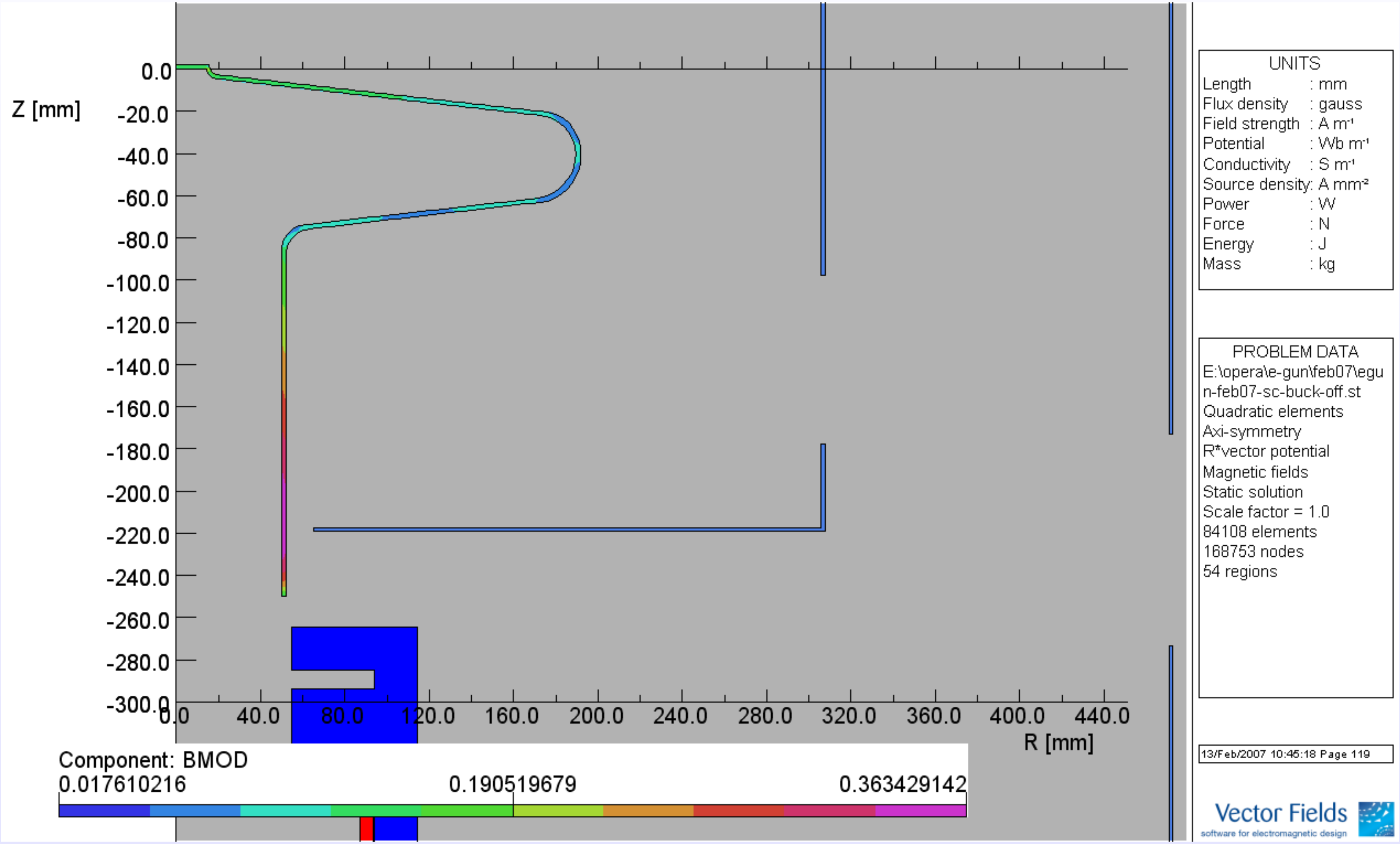


Note: Bucking coil significantly reduces the field inside the cavity region. (Field on superconducting cavity is low in either case).

Impact of Bucking Coil on Field (G) on the Axis of Solenoid



Field (G) on SC Cavity With No Bucking Coil



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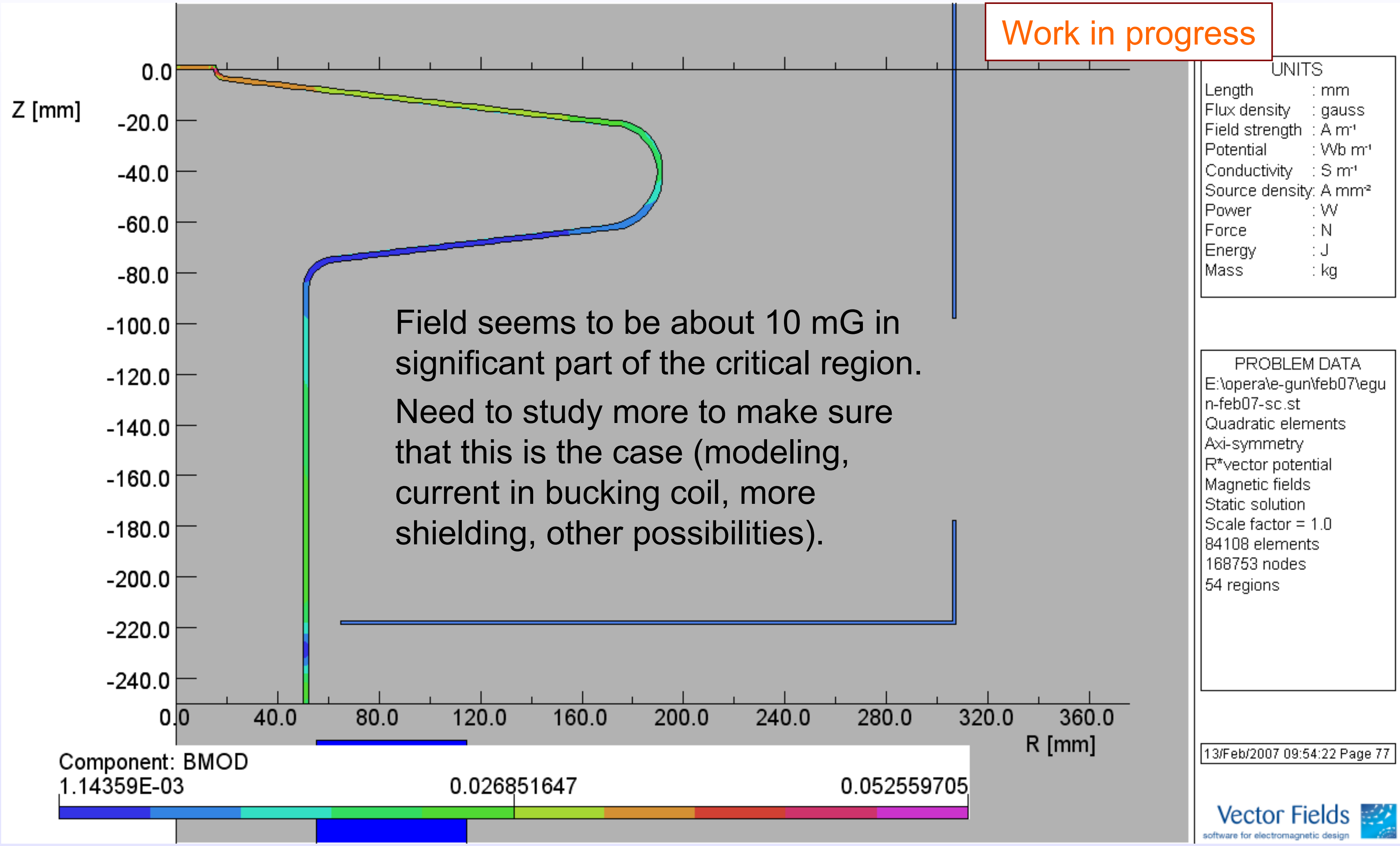
Field (G) on Superconducting Cavity (bucking coil at 5/16 of main coil)



Field seems to be about 10 mG in significant part of the critical region.

Need to study more to make sure that this is the case (modeling, current in bucking coil, more shielding, other possibilities).

Present Test Vs. Real Situation

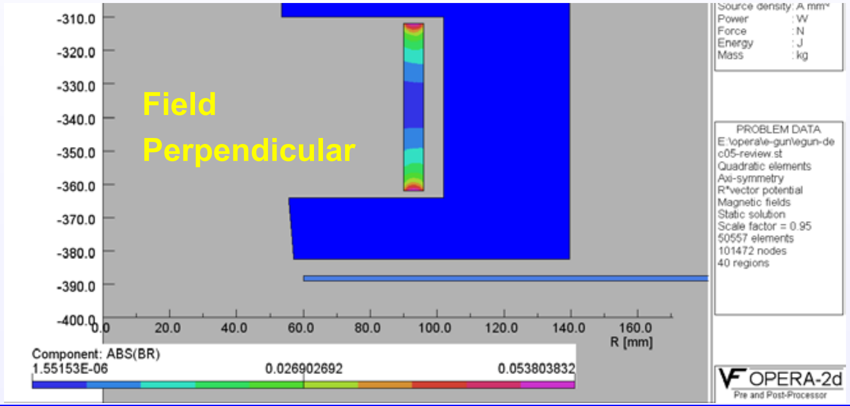
• We have tested solenoid coils in standalone mode at 77 K.

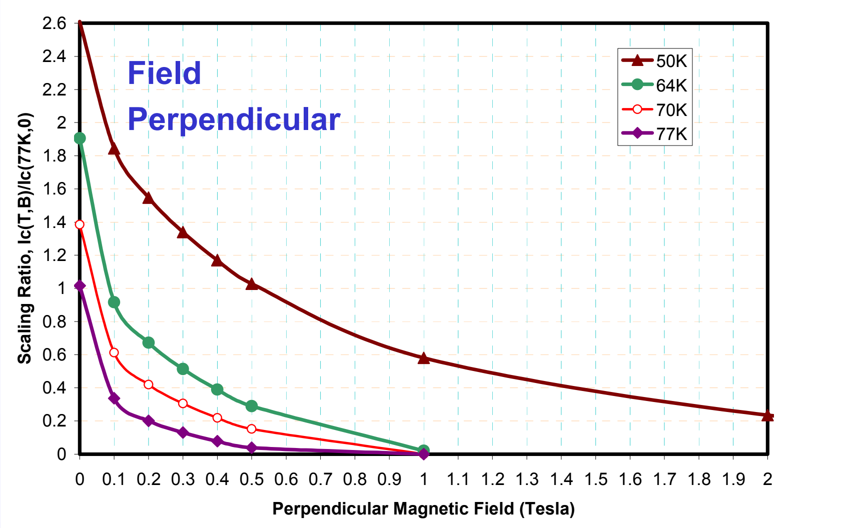
• In reality the coils will be in iron yoke and will be at 5-10 K.

• The performance in real condition will be several time better because of (a) lower temperature and (b) field component on HTS coil.

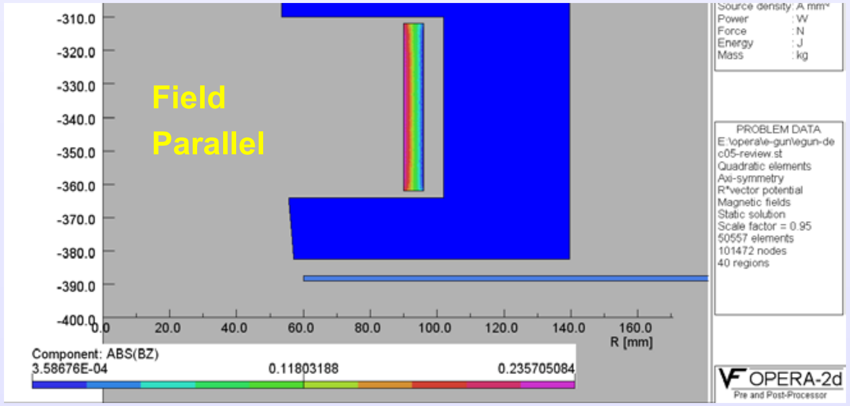
Testing In Liquid Nitrogen (77 K) Will Validate the Required Design Performance

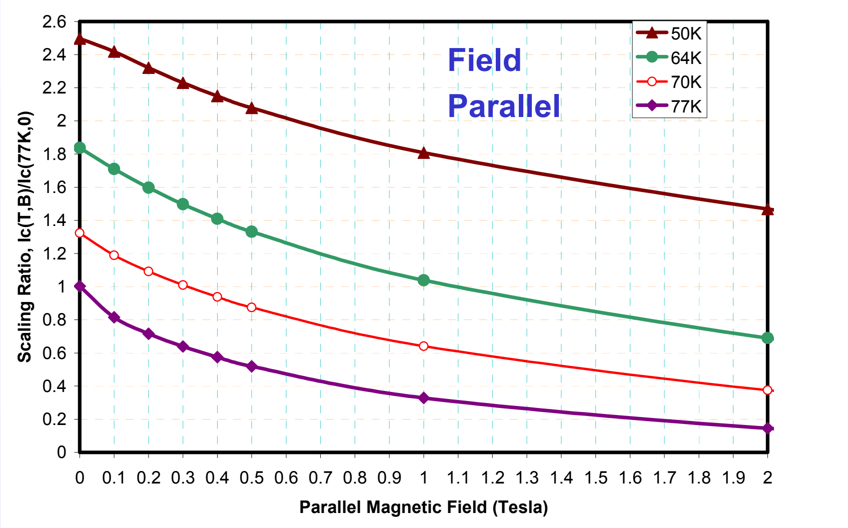
Magnetic model has also been optimized to reduce the perpendicular field in the superconductor



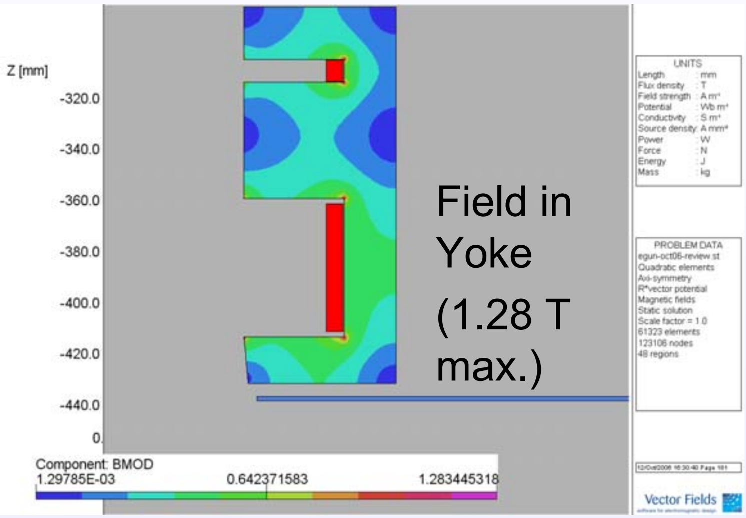


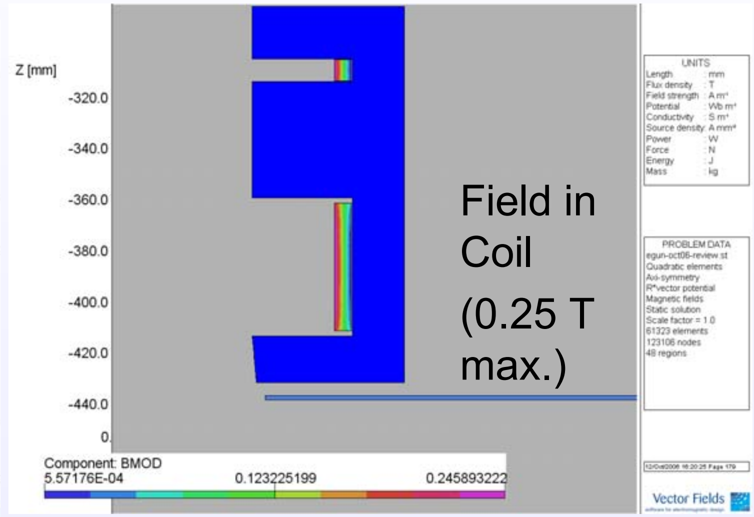
We will be able to test solenoid at a current greater than the design value @77 K itself with liquid nitrogen only. No need for the liquid helium or even sub-cool nitrogen testing (significant cost saving). Lower temperature operation gives extra margin.





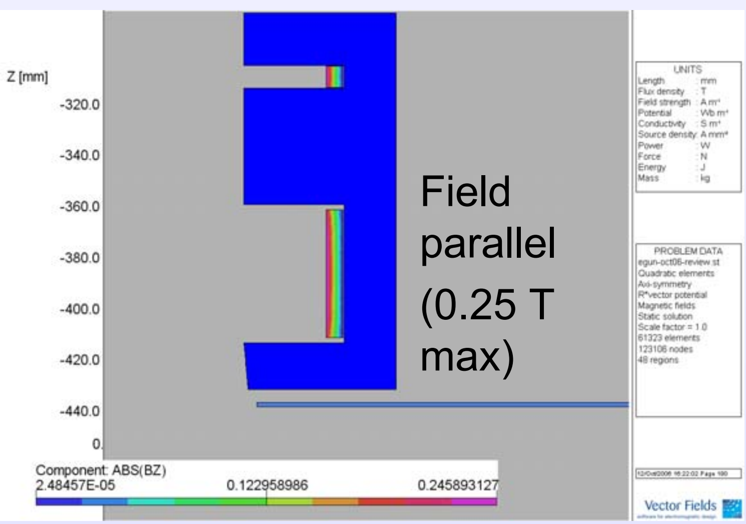
Field Components at Design Field (Important for 77 K testing at LN_2)

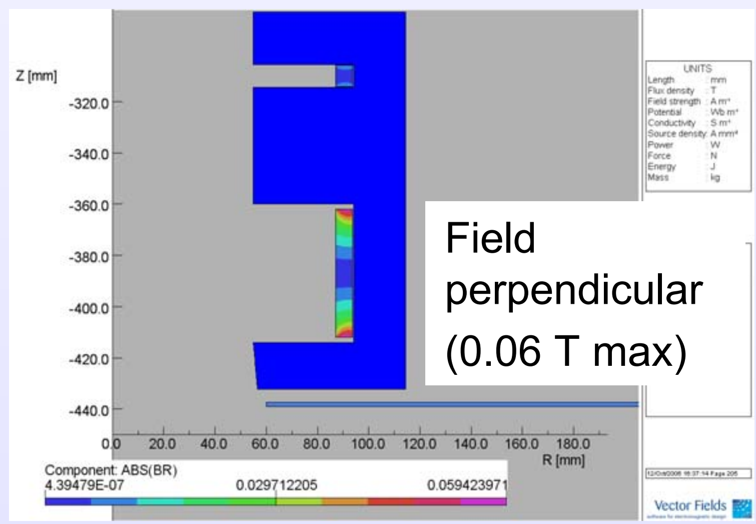




Nominal self-field performance of conductor: 145 A

(verified by measurement).





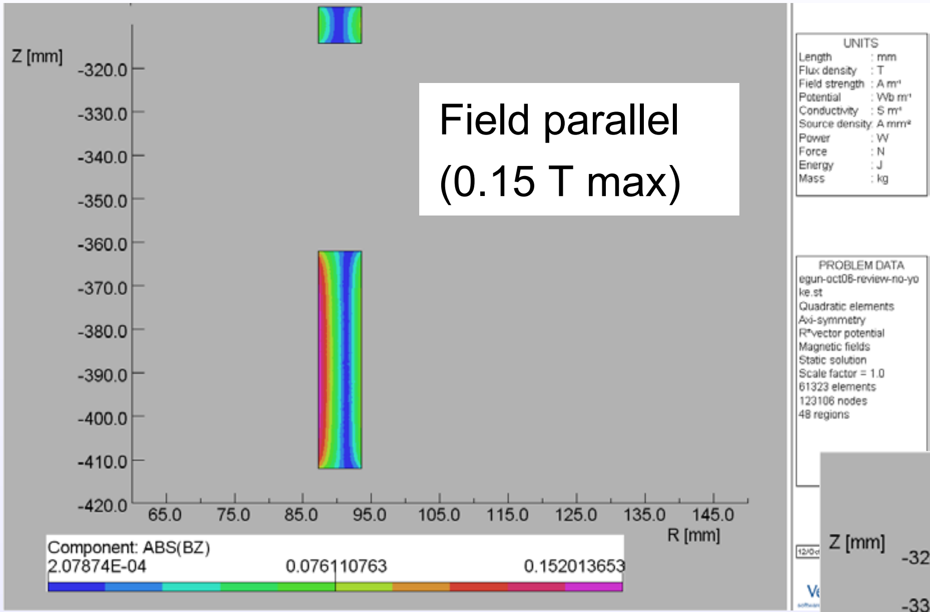
Scale factor at these field is : ~0.6 at 77 K.

Expected performance: 145*0.6= ~87 A.

Design requires <34 A at ~5K

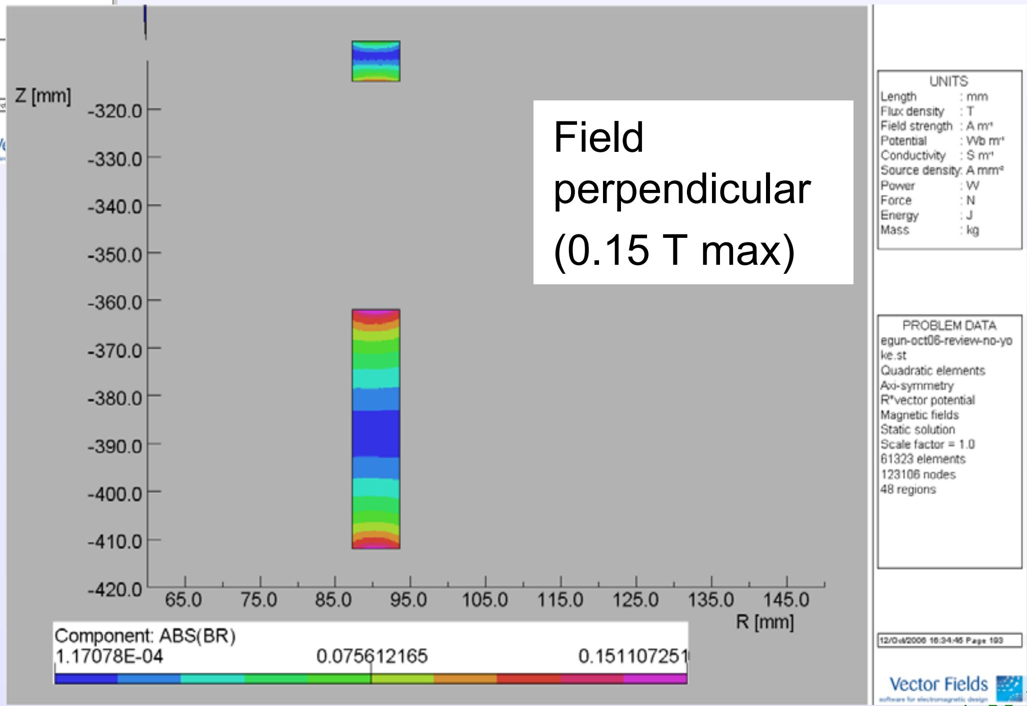
(huge margin even for 77 K test).

Field Component in Yoke Free Case at design current (LN_2 test)

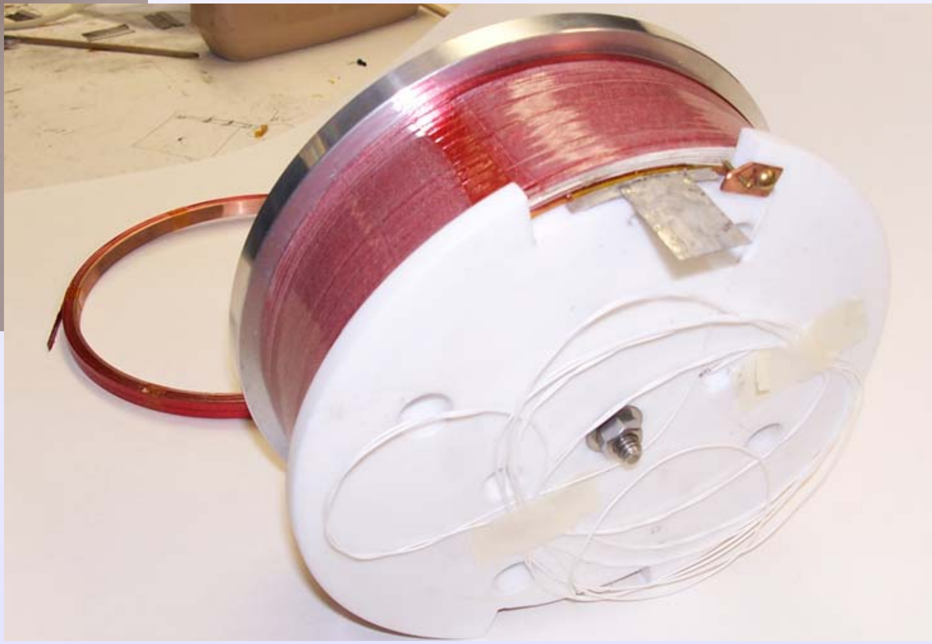


- The maximum value of both field parallel and field perpendicular is ~0.15 T.
- This is significantly different than 0.25 T and 0.06 T respectively in the case when these coils are in yoke.

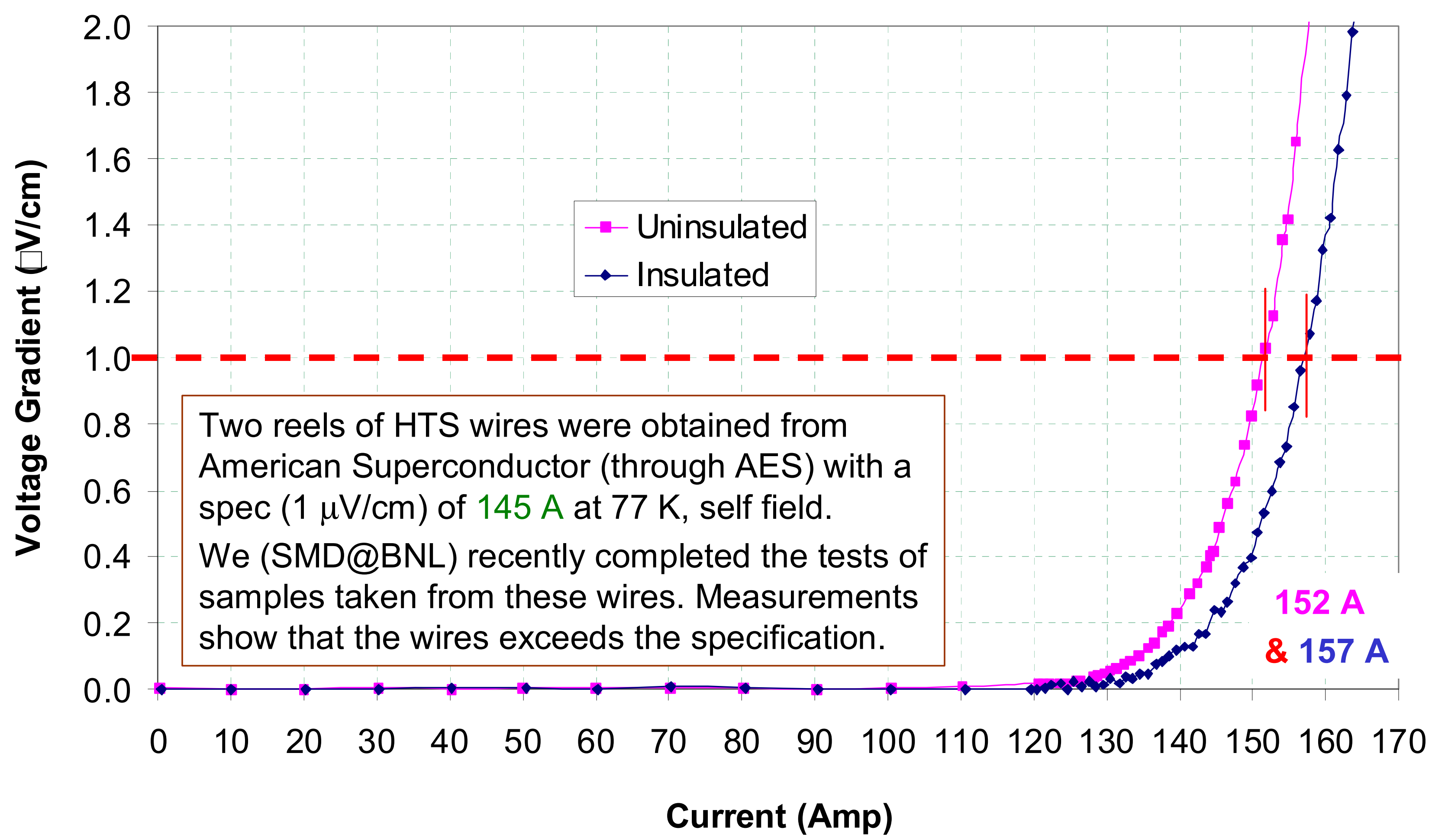
- Scale factor at 0.15 T is ~0.22.
- Expected current: 145*.22 =32A
- In reality we obtain much higher current (over the design current) because of the details of field distribution.
- However, Lorentz forces will be significantly lower and different.



HTS Solenoid Coils



Measurements of Two HTS Wire Samples at Superconducting Magnet Division (SMD)

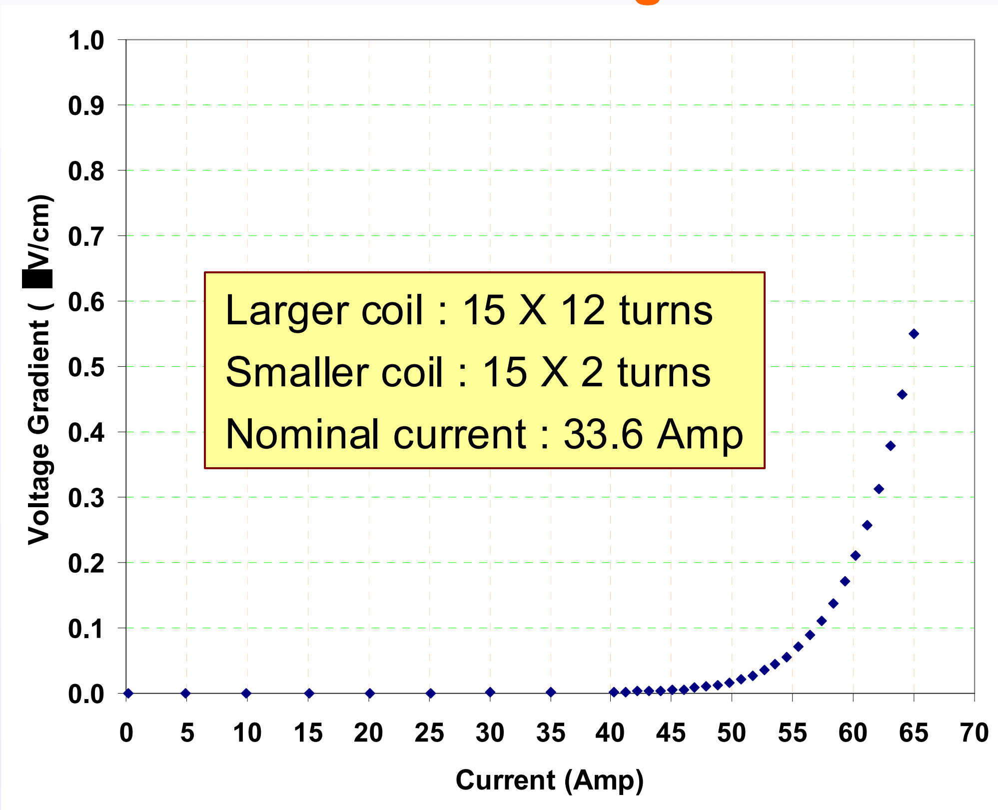


Two reels of HTS wires were obtained from American Superconductor (through AES) with a spec (1 μV/cm) of 145 A at 77 K, self field.

We (SMD@BNL) recently completed the tests of samples taken from these wires. Measurements show that the wires exceeds the specification.

Performance of Solenoid Coils (at 77 K in the absence of yoke)

Test results of larger coil



Design current ~34 A @ 0.1 μV/cm (industry spec more liberal: @ 1 μV/cm)

- **Larger coil was successfully operated well above the design current (~34 Amps) even at 77 K (higher value expected at 5-10 K), and without yoke (higher value expected with yoke).**
- **Smaller coil was also recently tested and it successfully operated at ~80 Amps in similar conditions.**
- **These test should be considered as certification of HTS solenoid for its ability to reach design current.**
- **These tests do not address the field issue (fringe field, etc.).**

Remaining Work

Make sure that we are <u>not</u> in a situation where the trap field is unacceptable - 10 mG ?

Coils are built and successfully tested.

Yoke and rest of the assembly remains - Steve Plate.

LN2 measurements of the complete solenoid, including magnetic measurements?