High Temperature Superconductor (HTS) Solenoid Status

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Overview of the Presentation

- High Temperature Superconductor (HTS) Solenoid
  - Unique properties of HTS that makes the system more efficient and simple
  - Relevant SMD/BNL experience with HTS technology
- Design Requirements
  - Beam dynamics
  - Fringe fields
- Magnetic Design Studies
  - Brief review of a number of designs/options examined
- Issues - examined & remaining (*please add, if something is missing*)
- Scope of HTS Solenoid Work at SMD/BNL
- Summary

Unique Advantage of HTS

- Solenoid made with HTS can satisfy the design requirements with a sufficient margin at 55 K or less temperature.

- This means this magnet can be placed close to the electron gun in a region where the temperature is 10 K or more.

- This is a better solution as compared to either a room temperature solenoid (which must be outside the cryostat and hence far away) or a conventional superconductor solenoid (which will at least increase the length of 4 K system).

- It appears that this is an ideal application of HTS.

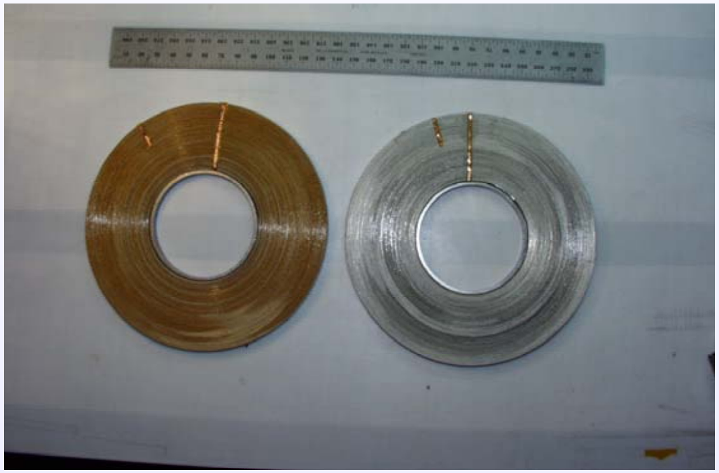
SMD@BNL and HTS

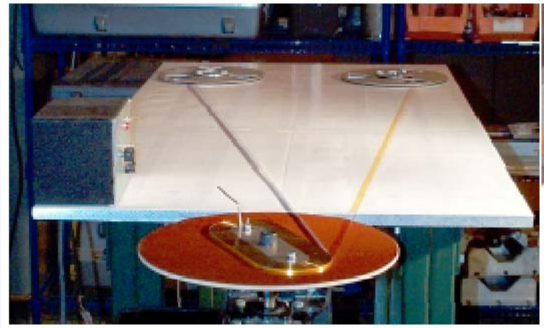
Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL) has been involved in the following HTS activities during the last decade:

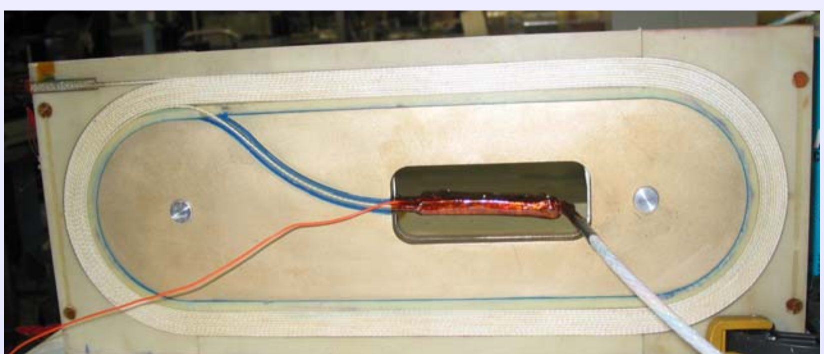
- Test HTS tapes, wires and cables
- Develop special magnet design that can take advantage of unique HTS properties and can use this (HTS) brittle material
- Build a variety of HTS coils and magnets
- Test HTS magnets

BNL is the only national laboratory with such an extensive experience with HTS technology.

A Few HTS Coils Made At BNL







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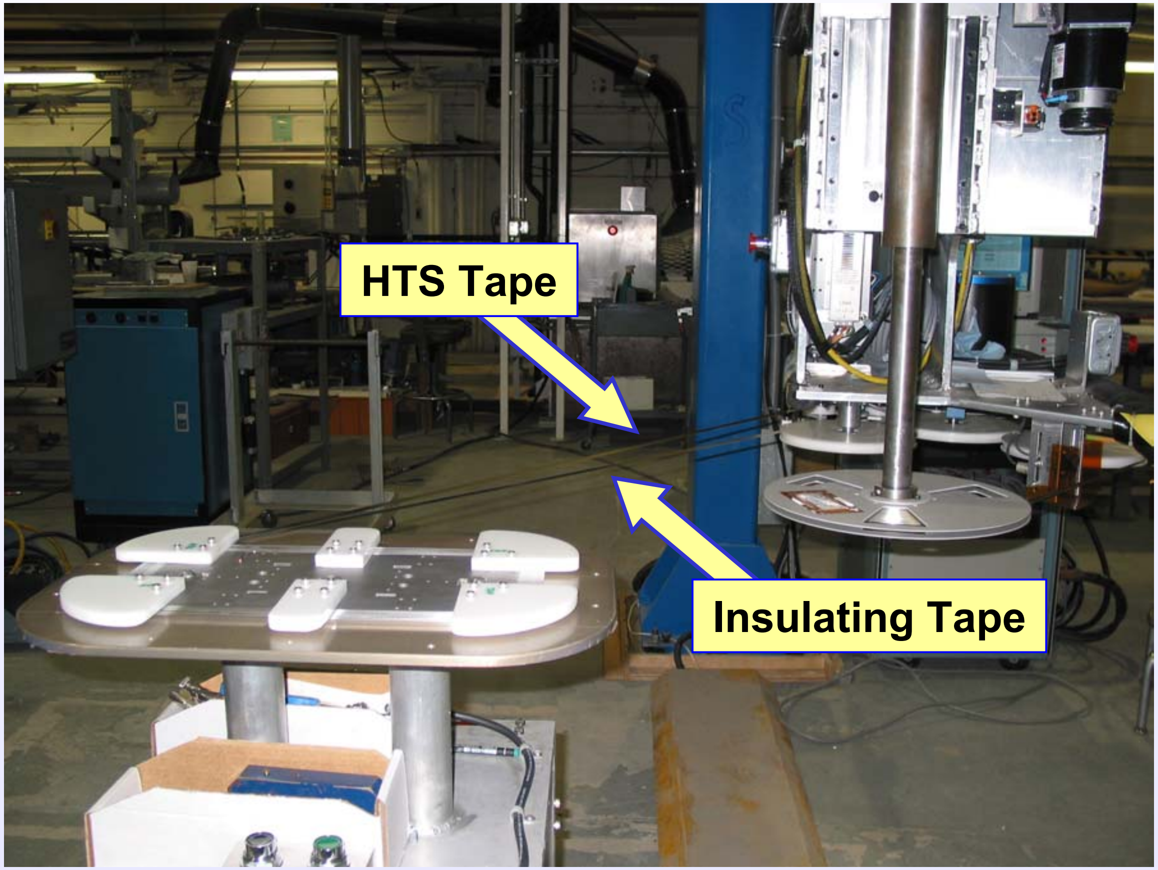
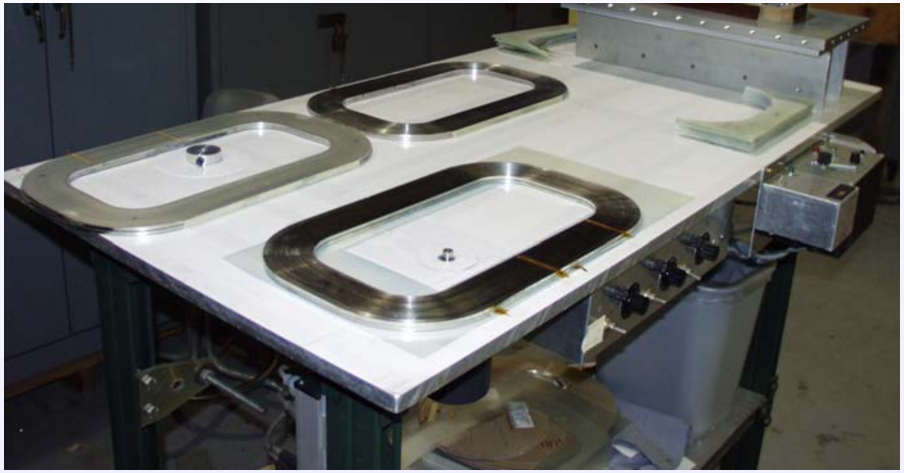
More Recent Coil Winding for Rare Isotope Accelerator (RIA)

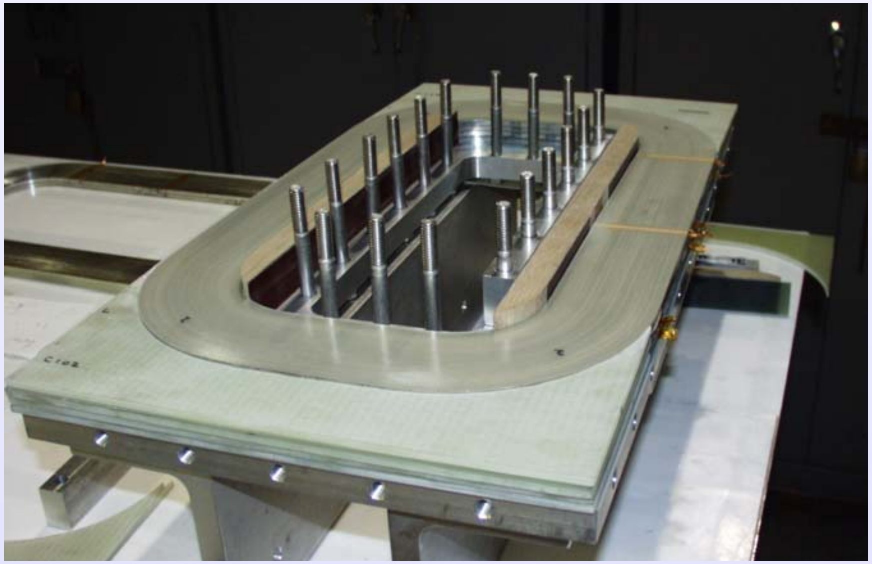


A coil being wound in a new computer controlled winding machine.

HTS Coils for RIA

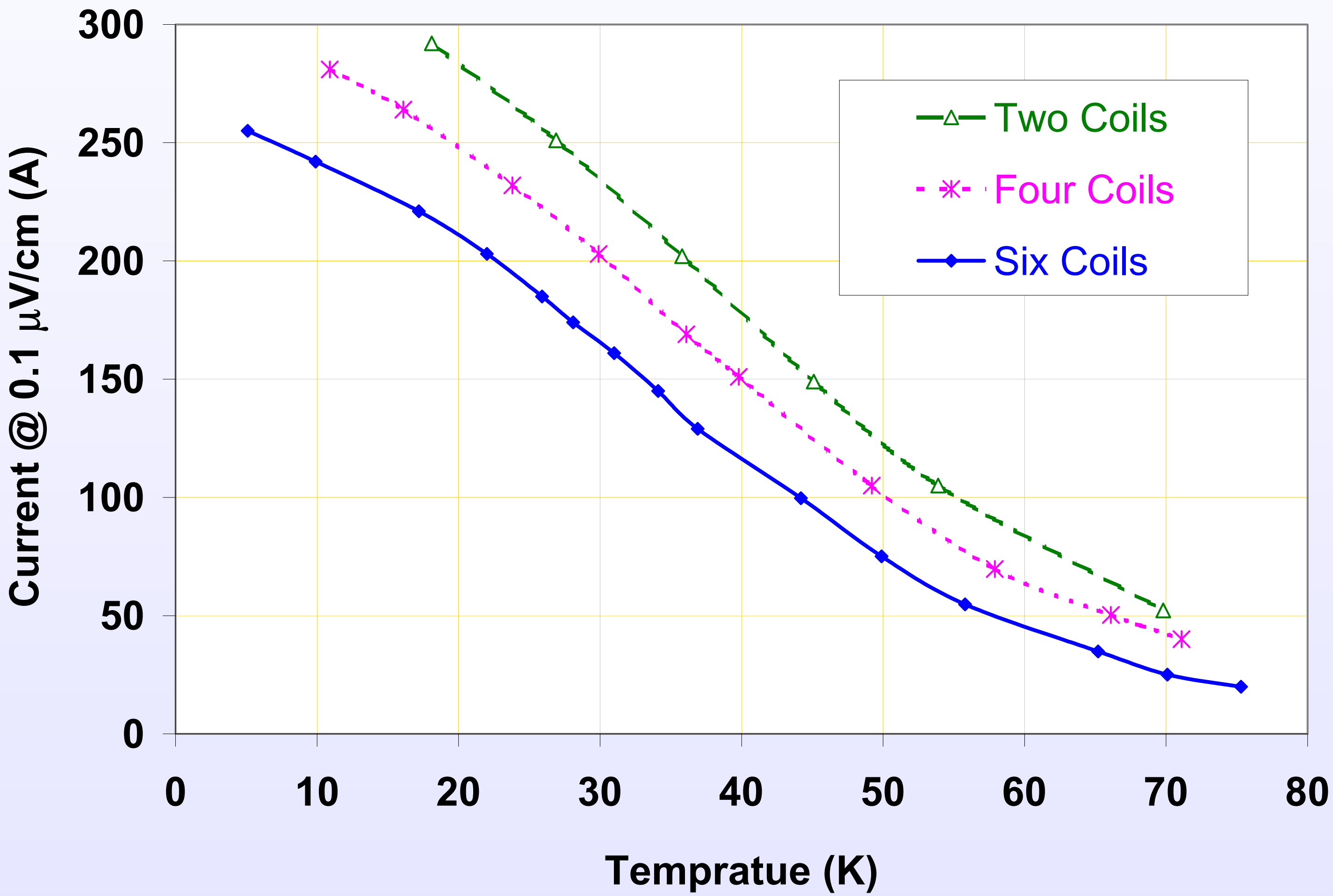


Three pairs of coils (six coils). These coils are made with HTS tape and insulating stainless steel tape.



Three pairs of coils with internal splice during their assembly in a support structure.

RIA HTS Model Magnet Test Results for Various Configurations



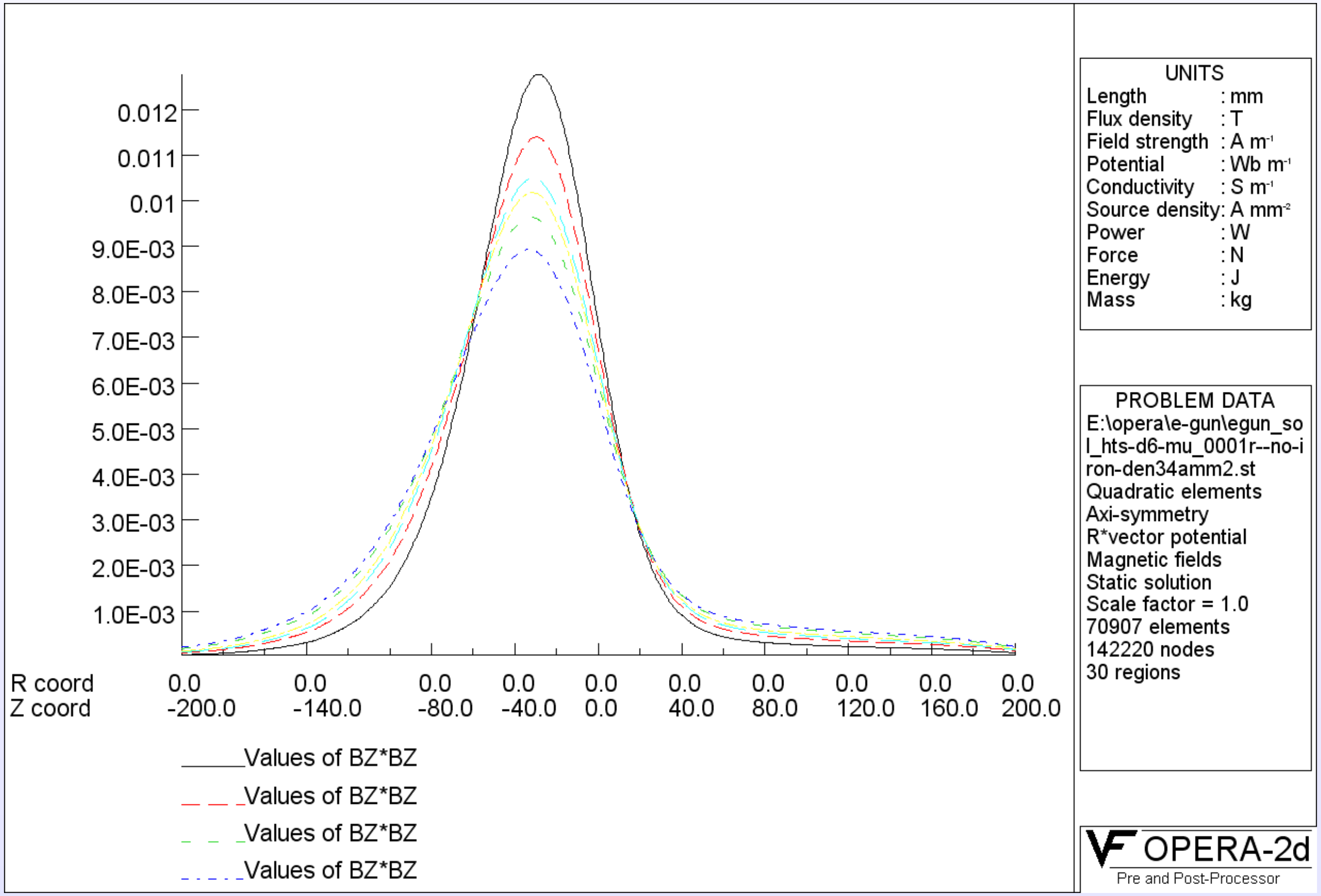
More coils create more field and hence would have lower current carrying capacity

High Temperature Superconductor (HTS) Solenoid Design Studies

Beam Dynamics Requirements

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

Variation of $B_z^{\,2}$ along the axis (all have integral field of ~$1\ T^2\ .\ mm$)



Certain variations in design change the field profile along the z-axis.

Beam dynamic studies will determine if these differences are significant.

If all do the job well, then we should not bring unnecessary complications in the magnet design and construction.

Fringe Field Requirements

1. Should be less than 1.5 kG on the superconductor when the solenoid is ON.
2. Should be less than a few mG on the cavity when the cavity is turning to superconducting state (solenoid is OFF at this time).

- Iron around solenoid reduces the field on superconductor when solenoid is ON.
- But the iron gets magnetized during the powering. In that case we must make sure that the residual field of iron is below a few mG when the cavity is becoming superconducting.
- A few mG is a very low field! Consider yoke degaussing cycles and/or some sort of shield. Write proper procedures and make sure that these procedures are followed during operation.
- A solenoid "without iron" (hence no residual field from magnetized iron) that keeps field on superconductor below ~1.5 kG (when it is fully powered), would significantly simplify operation.
- Note: If solenoid was left on before the cavity is brought into superconducting state then one should also consider the residual field caused by persistent currents in coils even if solenoid has zero current at that time. If this is one of the possible "operational scenario" then put heaters around solenoid coil to bring it to a normal state before cavity is cooled. This is not a major thing but needs to be incorporated, if required.

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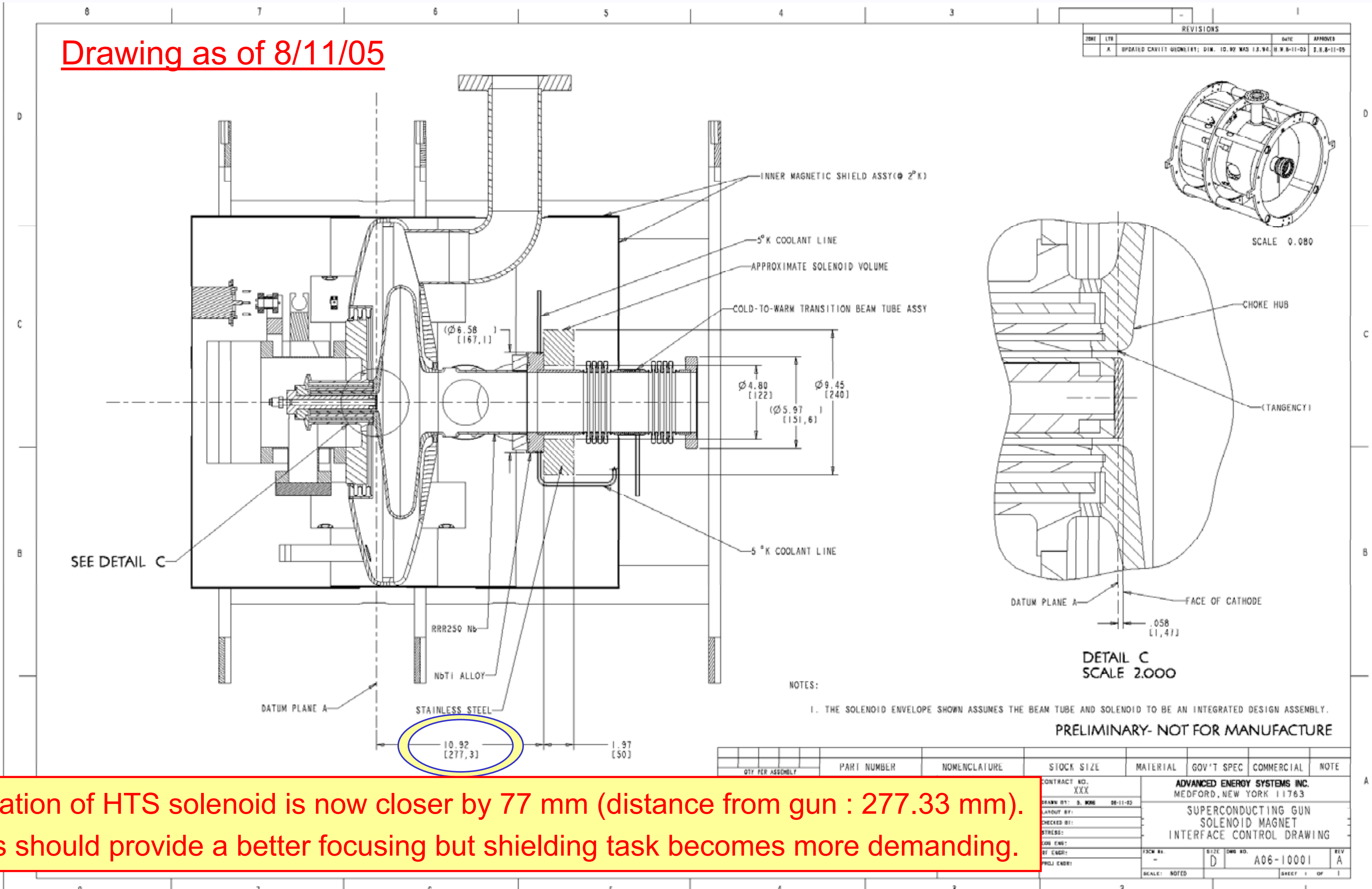
Location of HTS Solenoid

Drawing as of 8/11/05

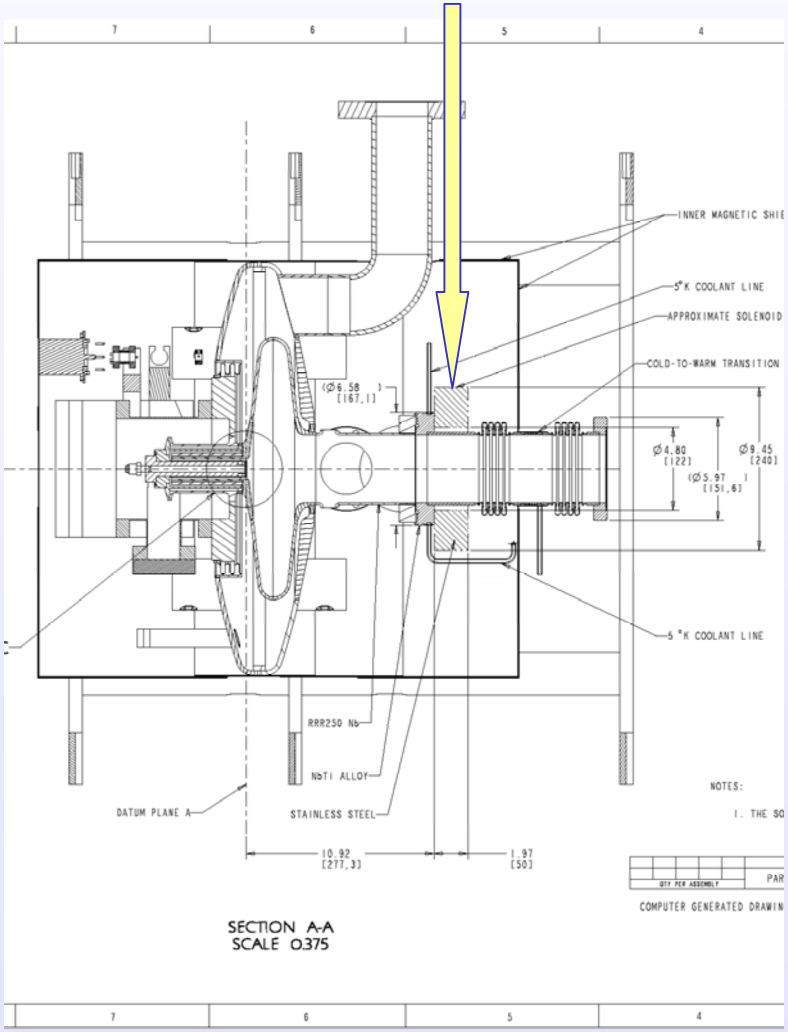


Location of HTS solenoid is now closer by 77 mm (distance from gun : 277.33 mm).
This should provide a better focusing but shielding task becomes more demanding.

Initial design of HTS Solenoid

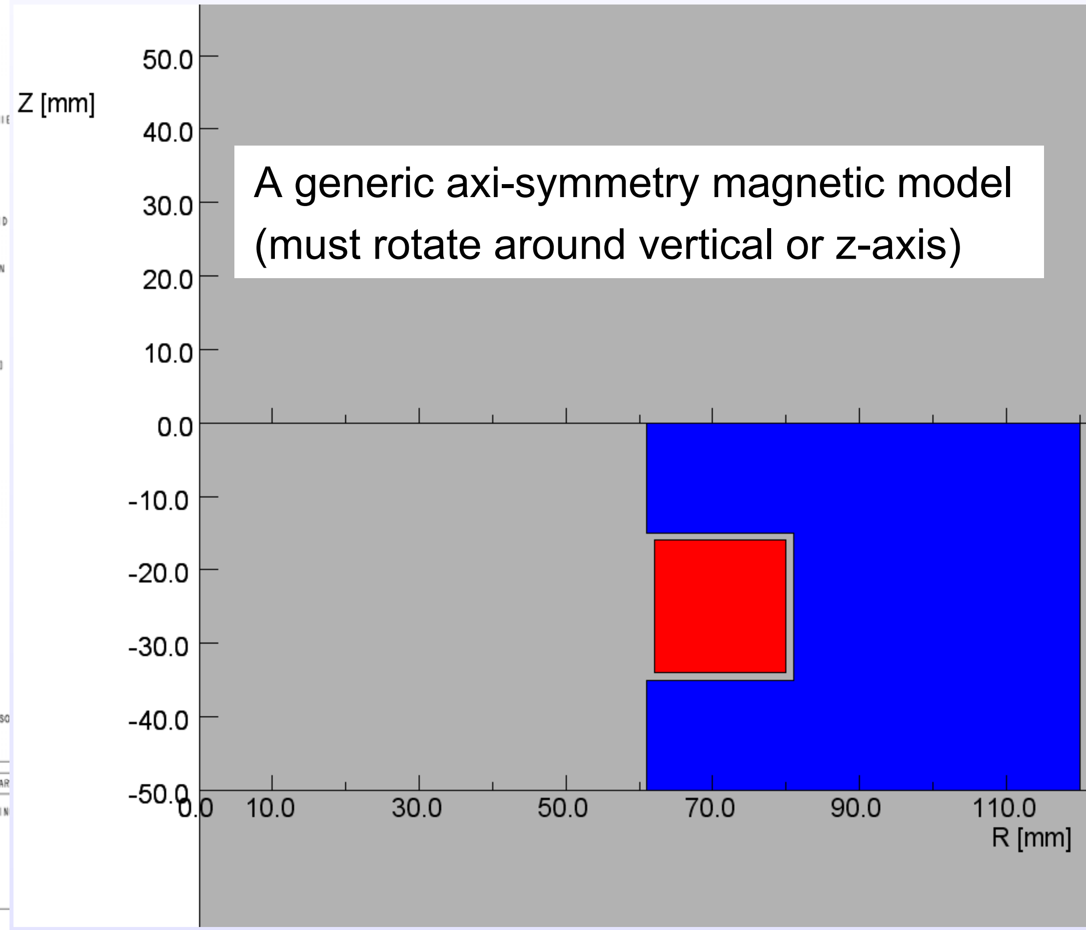
Cross-section

HTS solenoid



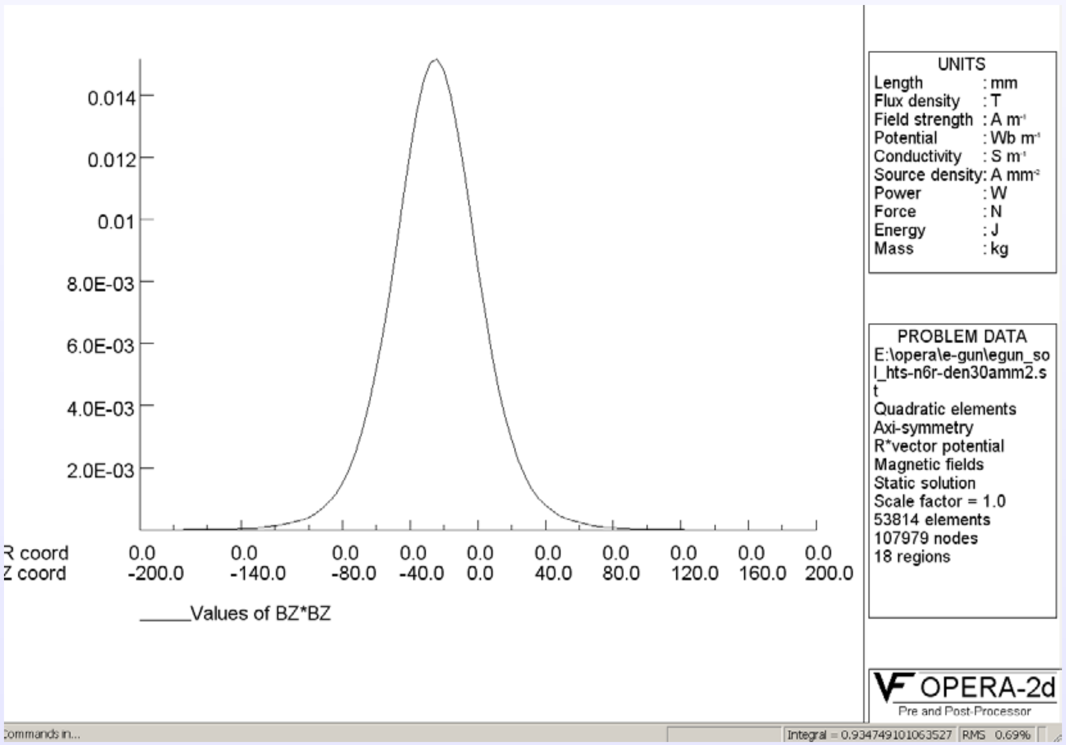
Allowed axial space for HTS 50 mm;

HTS coil 18 mm X 18 mm

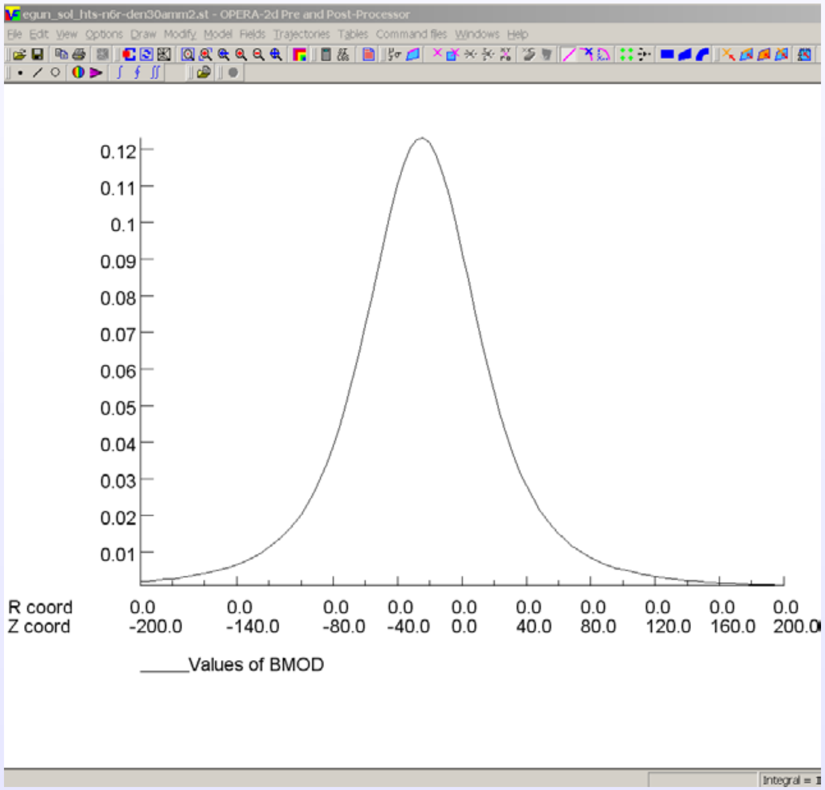


Field Profile on the Axis

$B_z^{\,2}$ *along the axis*



Magnitude of the field

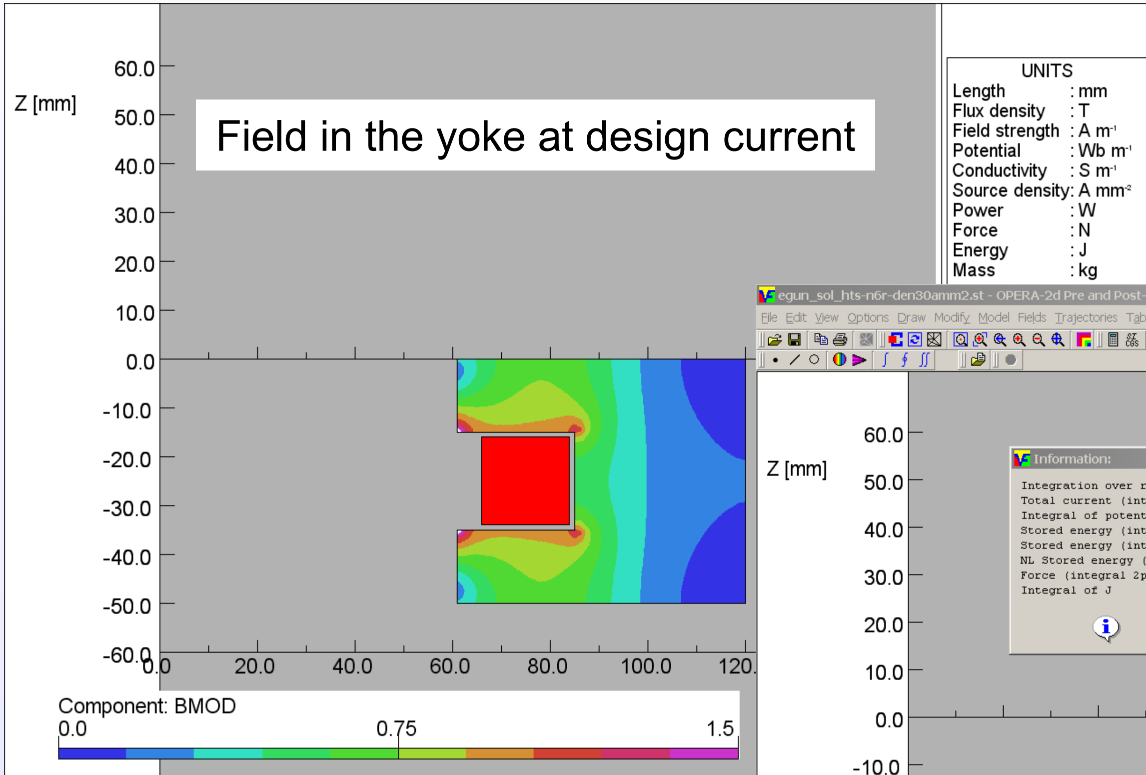


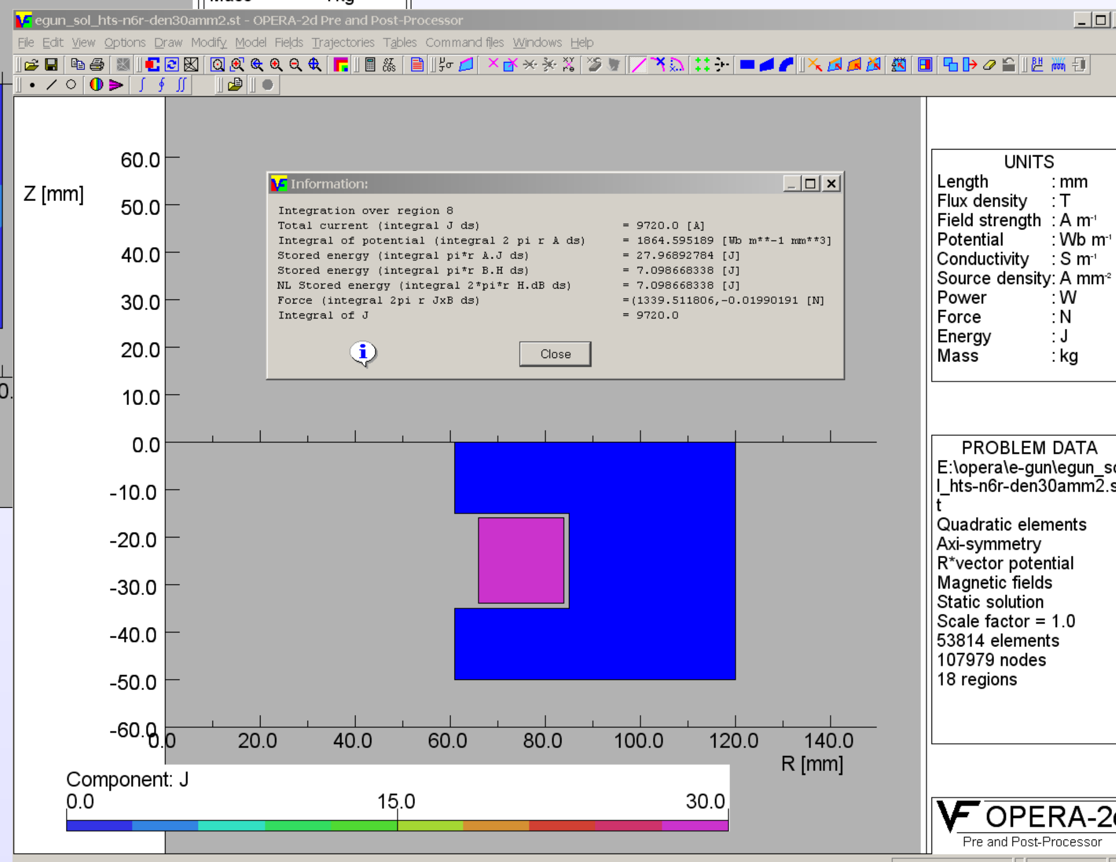
Integral focusing is about right

Meets the design requirement

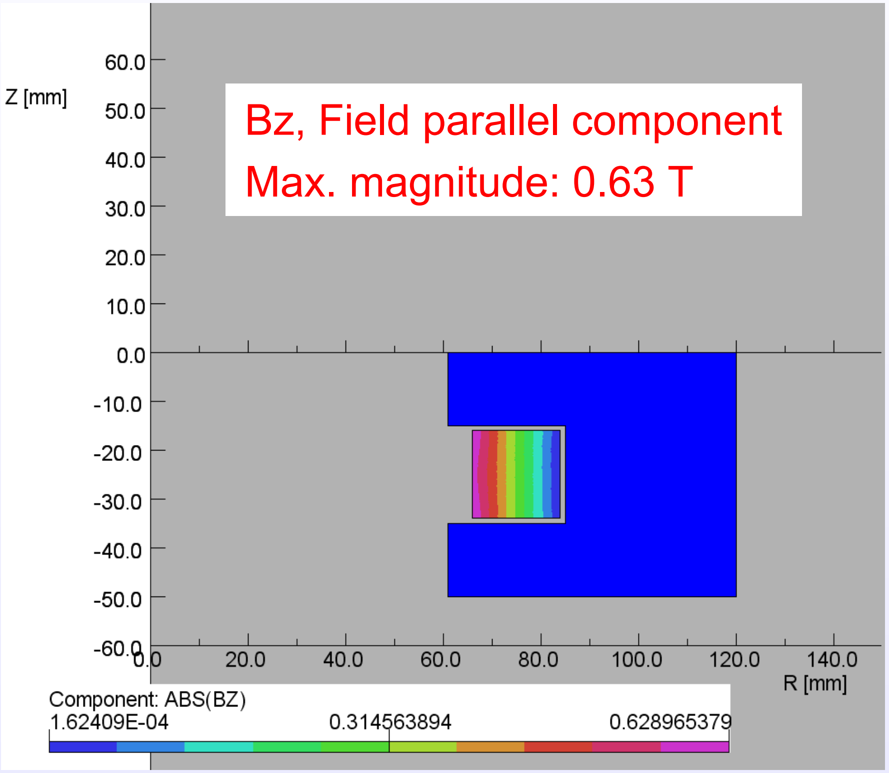
Computer Model of the First Design

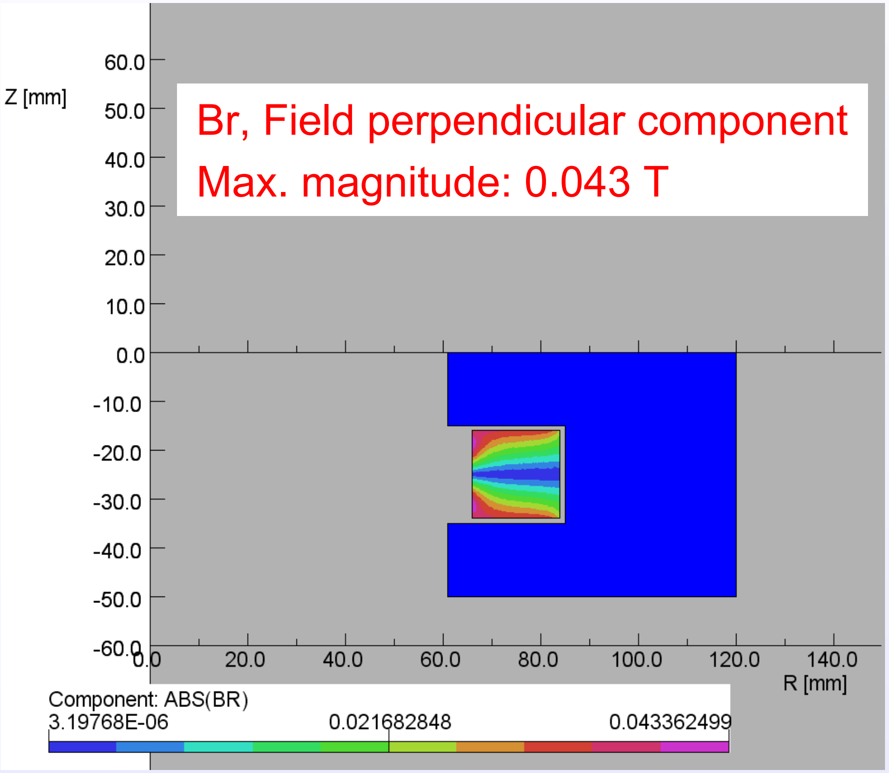
Stored Energy, Forces, etc.





Component of Field On the HTS Coil





Note: Field perpendicular component is very small.

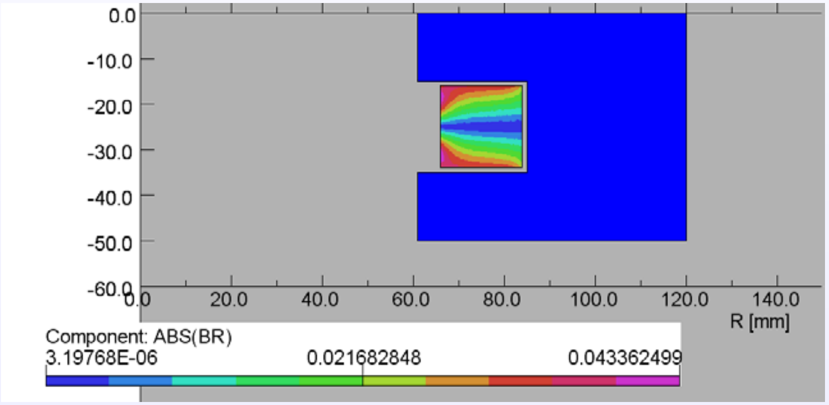
It brings a major saving in the cost of testing as all testing can be done with nitrogen (NO Helium).

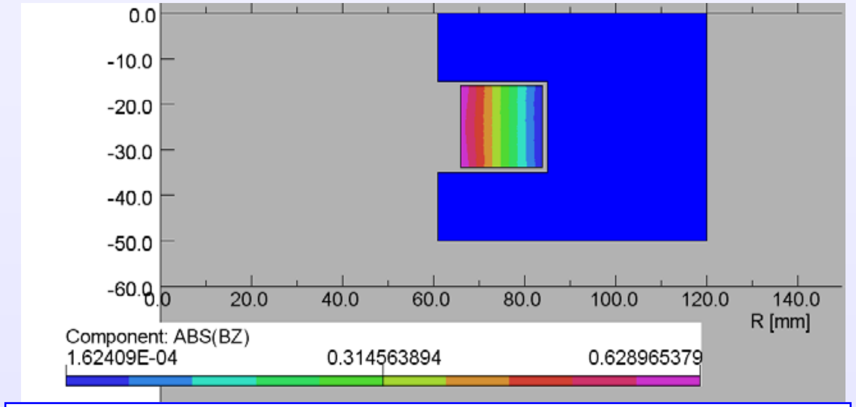
Another significant aspect of the design:

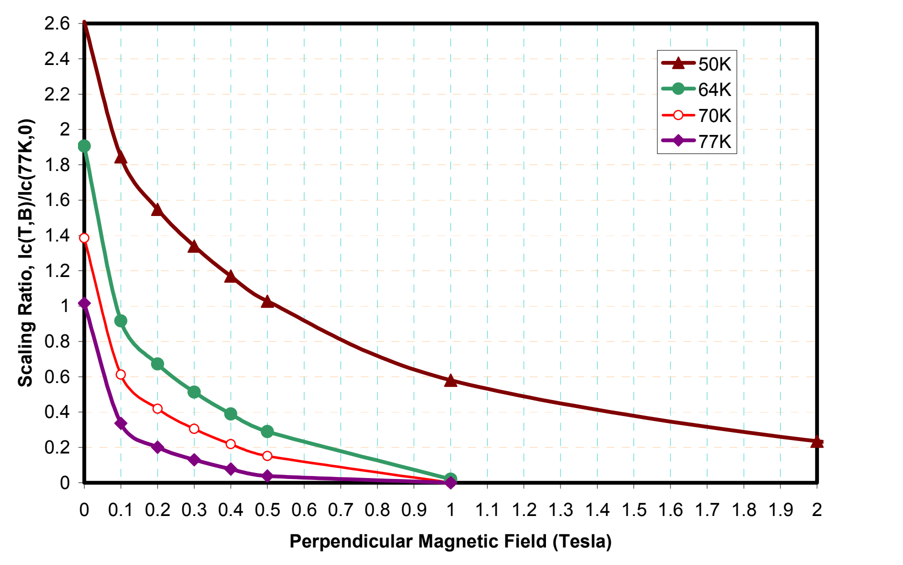
Operating current is 50 Ampere or less. This reduces cost of leads (feed thru), power supply, etc.

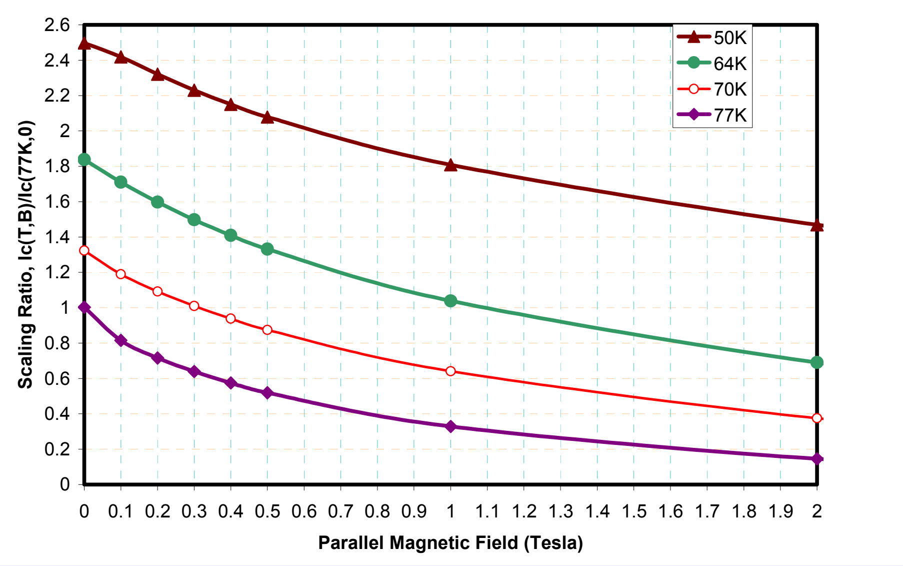
Current Carrying Capacity As A Function of Field and Temperature (Scaling Factor)

Magnetic model has been optimized to reduce perpendicular field







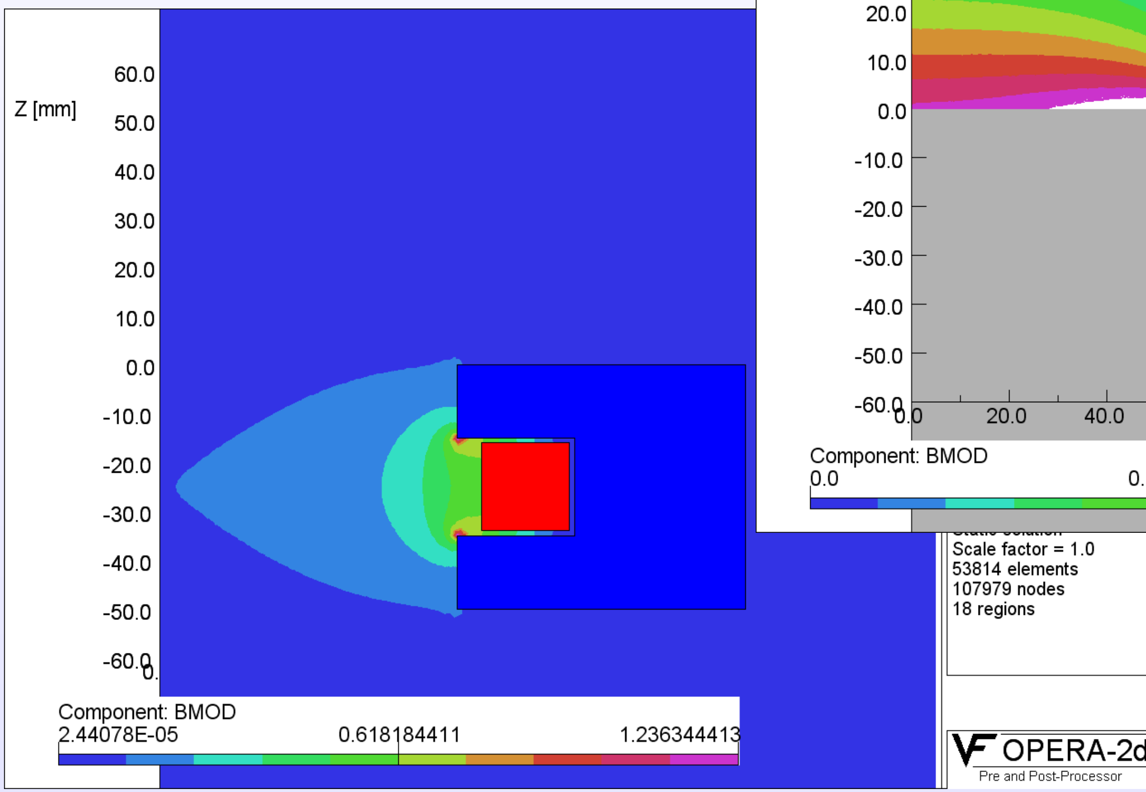


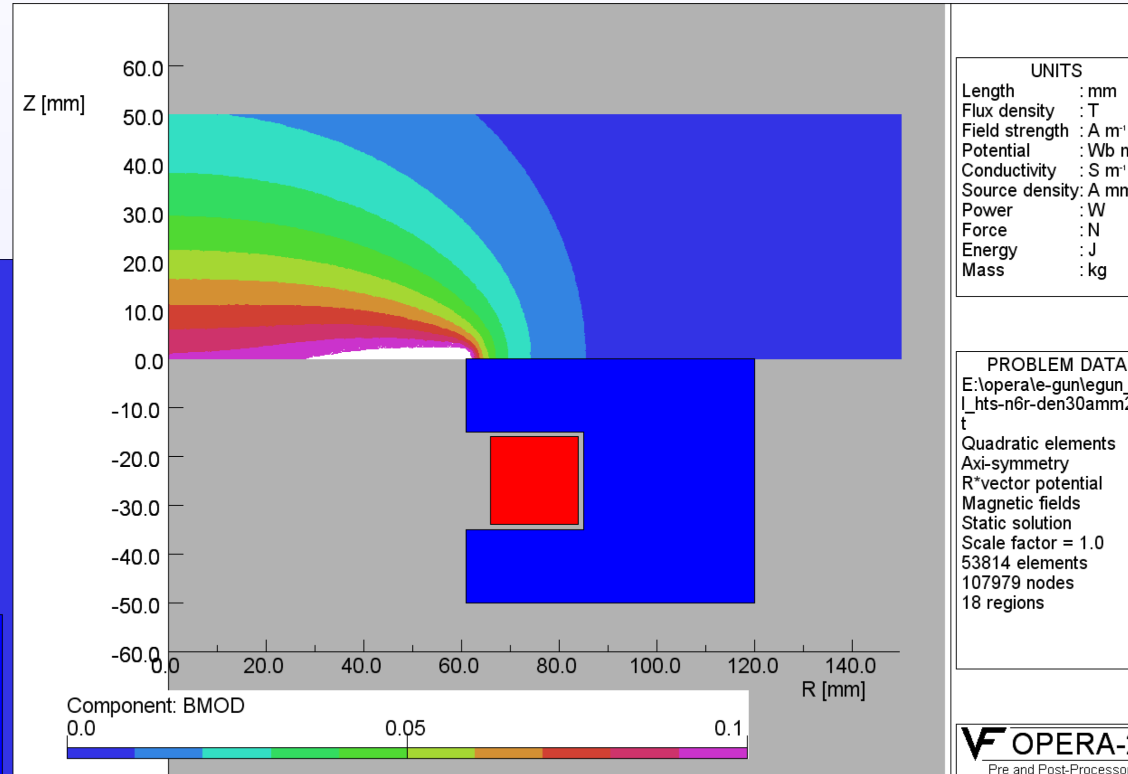
We can test solenoid at the design current with nitrogen only (significant cost saving).

Lower temperature gives extra margin.

Field Contours (Magnitude of Field)

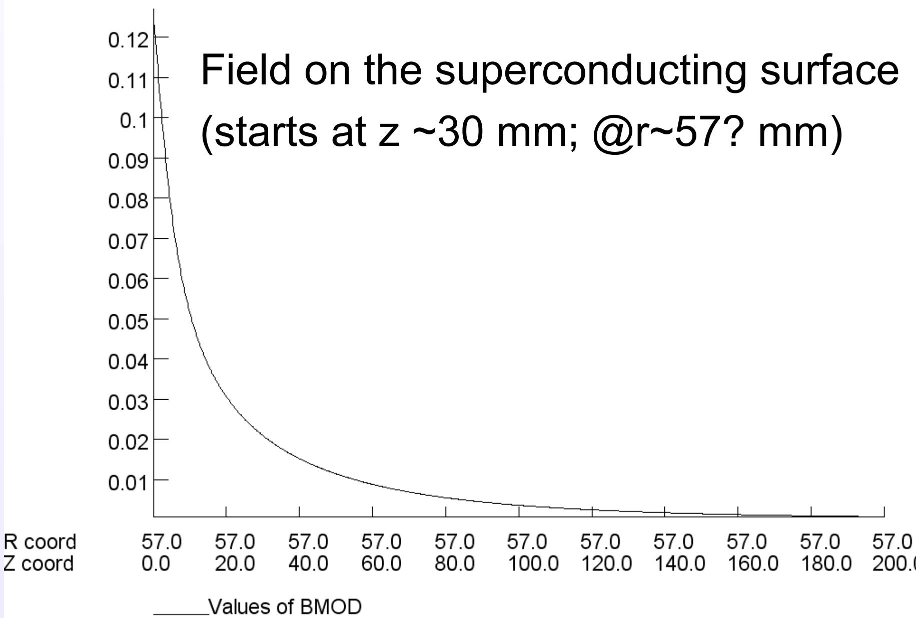
Magnitude of the field

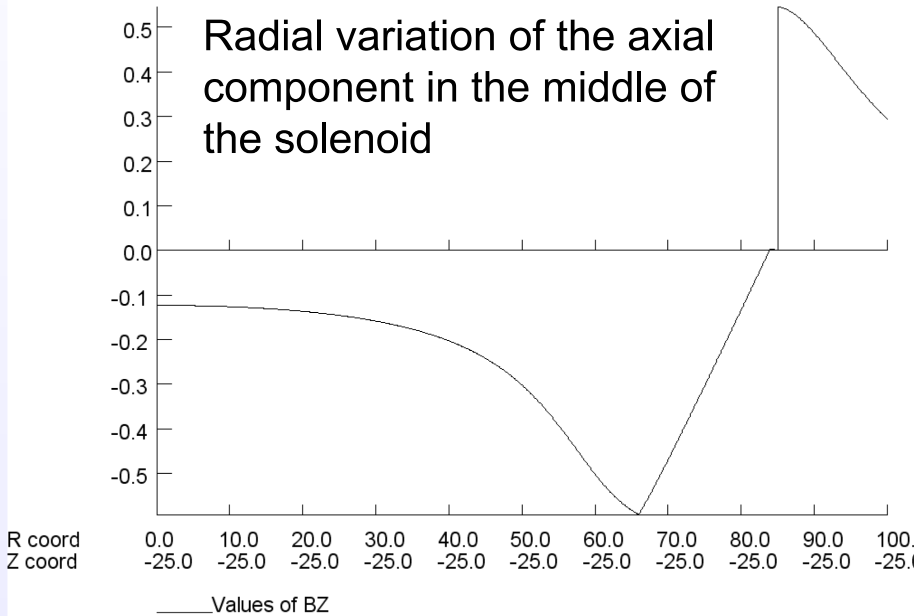




Magnitude of the fringe field

Field Variation



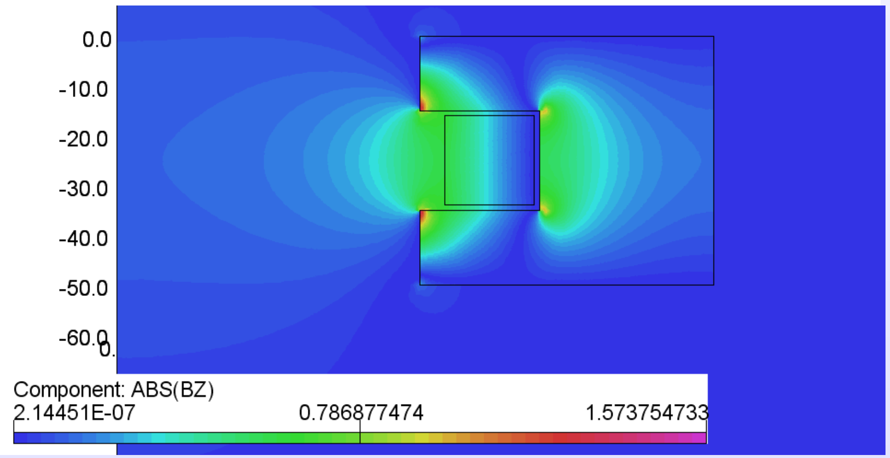


Field is much smaller than 1.5 kG (0.15 T)

Field at the cavity is ~10 mT

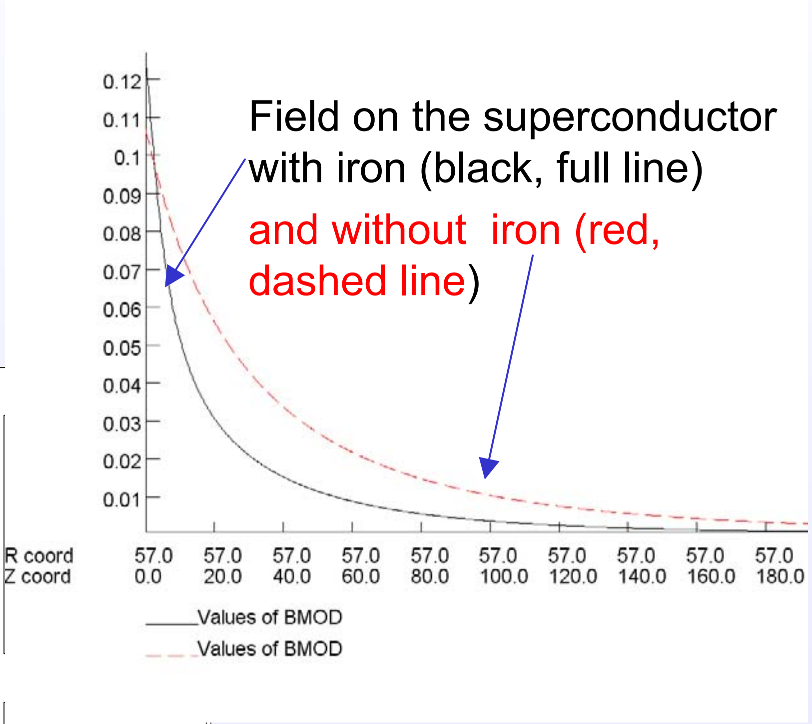
Question: What will be the residual field?

- Depends on the property of iron
- Demagnetization cycle

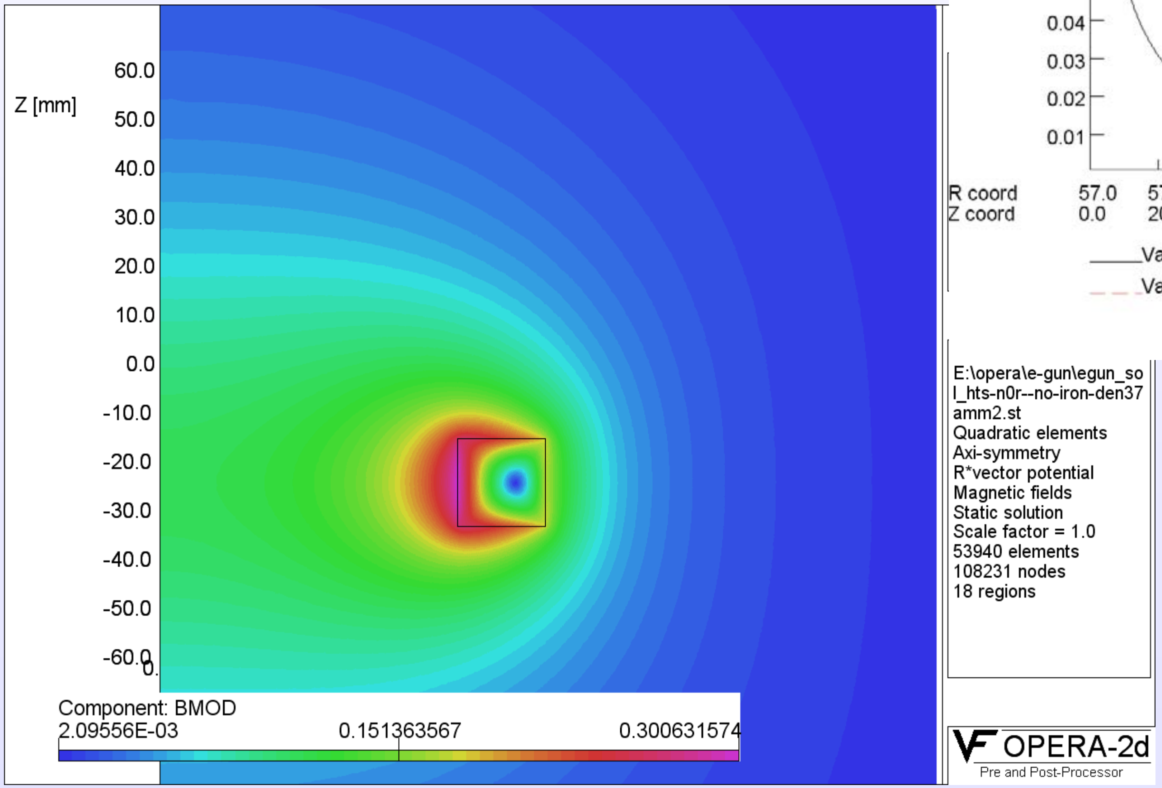


Dealing with Residual Field

Can we get rid of the culprit? The Iron?



Fringe field without iron

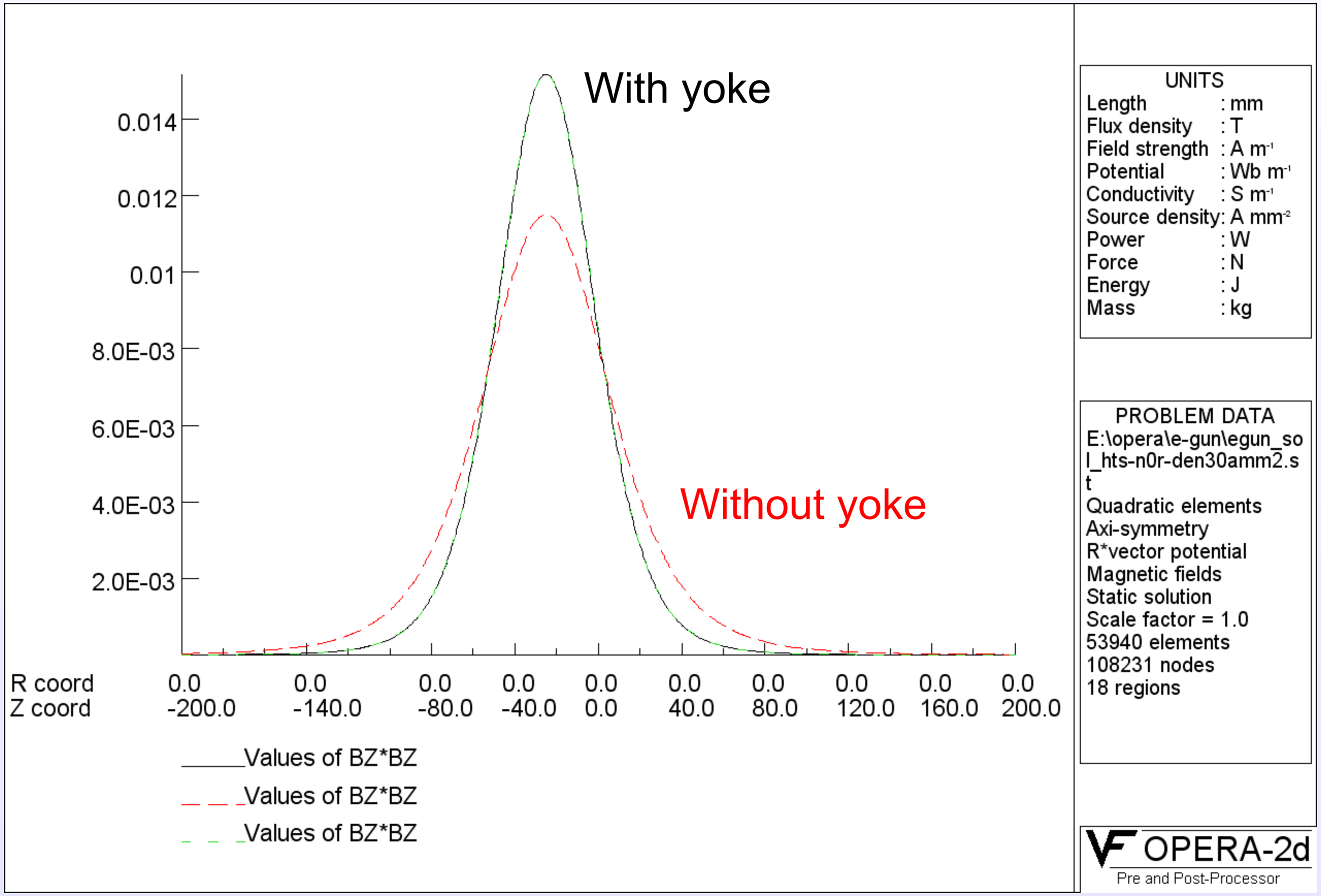


Since the field on SC surface is below the target of 0.15 T, we are fine there !!!

No iron, no residual field;
This particular issue resolved.

But what about to the focusing in NO yoke case?

B_z^2 *along the axis*



Dmitry Kayran is checking if this is acceptable.

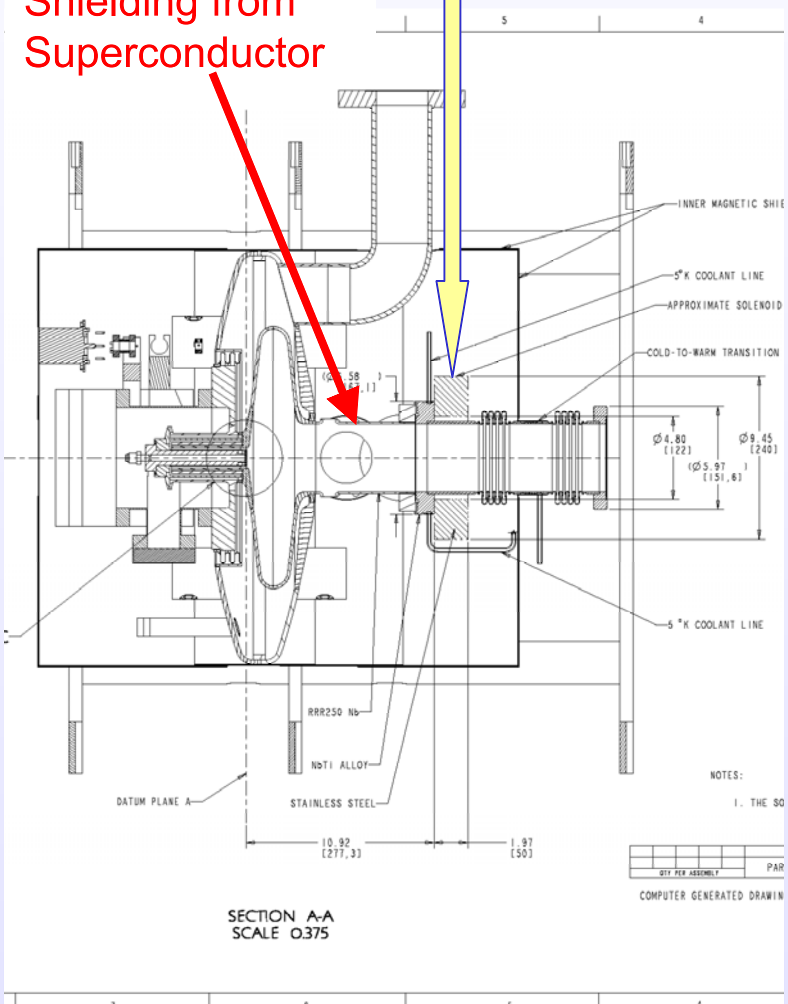
We got better focusing by bringing solenoid closer.

Can we use that credit here?

Field Profile with SC Shielding in Actual Configuration

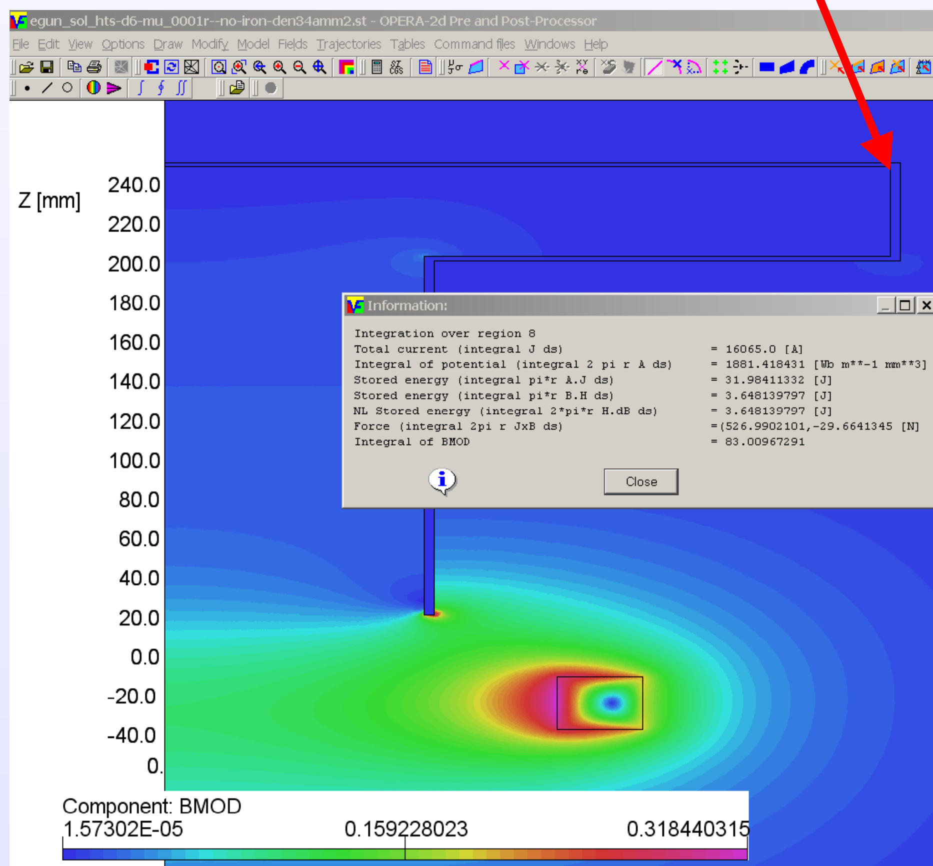
Magnetic Shielding from Superconductor

HTS solenoid



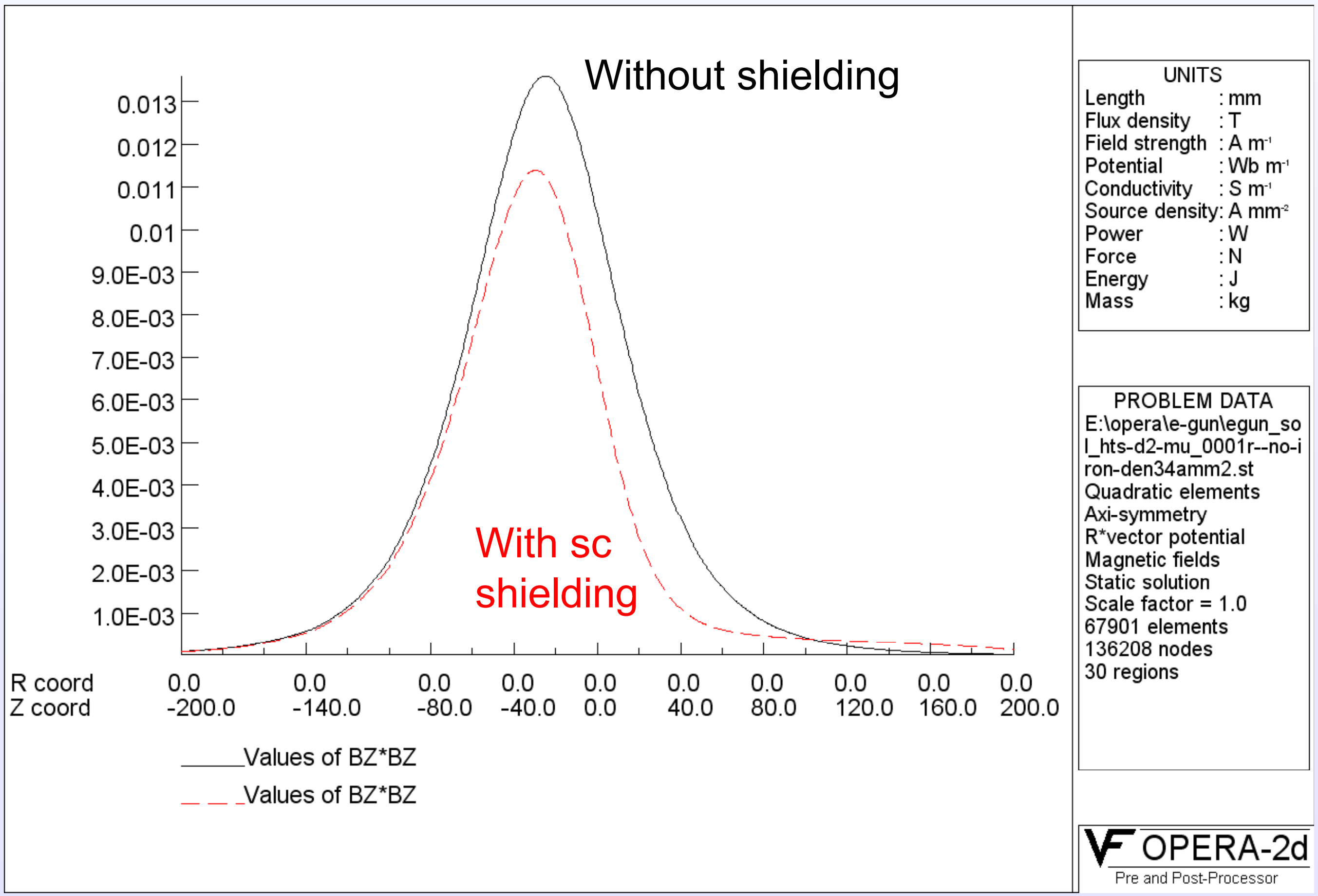
A rough model of superconducting shield (scale distorted)

Note: No magnetic flux goes through the superconductor



Focusing in Presence of Shielding (More Realistic Calculations)

B_z^2 *along the axis*



The actual focusing is smaller due to shielding from superconductor

(this means one needs higher operating current).

Solenoid design calculations takes this in to account.

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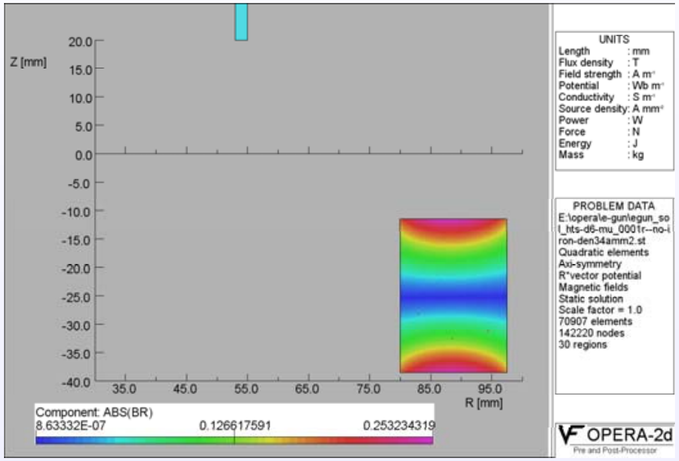
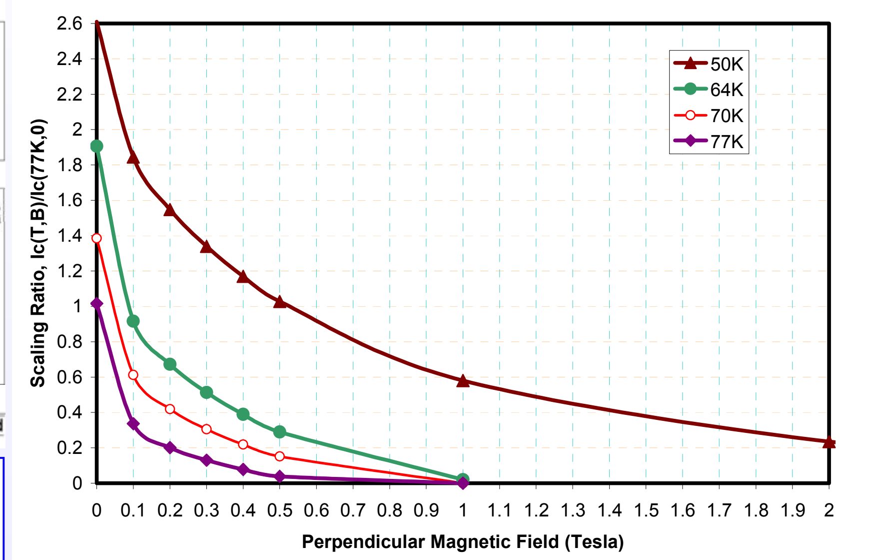
Field in the HTS Solenoid Coil in the Present Model (SC Shielding, No Yoke)

Field Perpendicular

Monitor 145 A (spec) divided by scaling factor

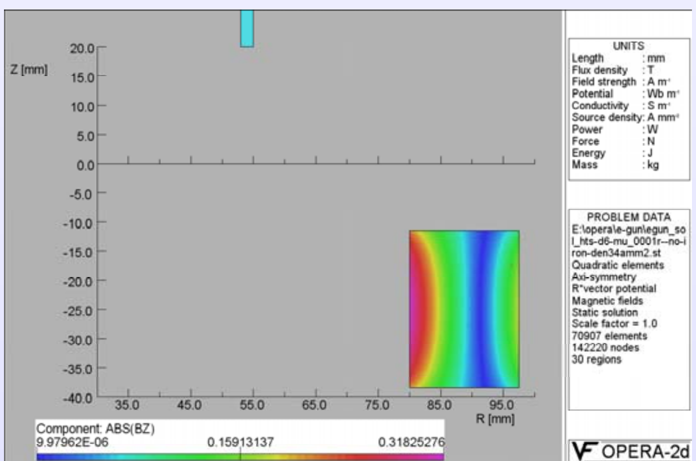


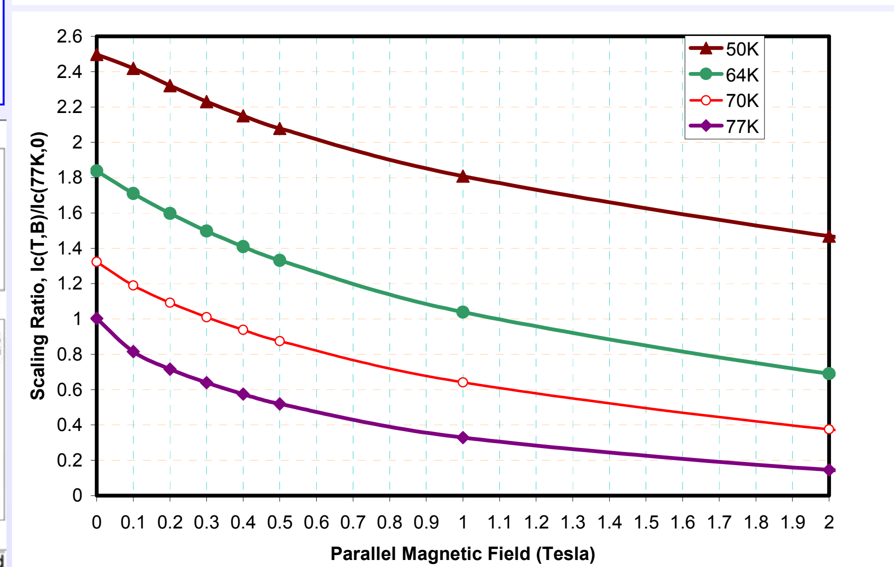


We can still test solenoid at the design current with nitrogen only, need sub-cool (~70 K) nitrogen (significant cost saving over helium testing).

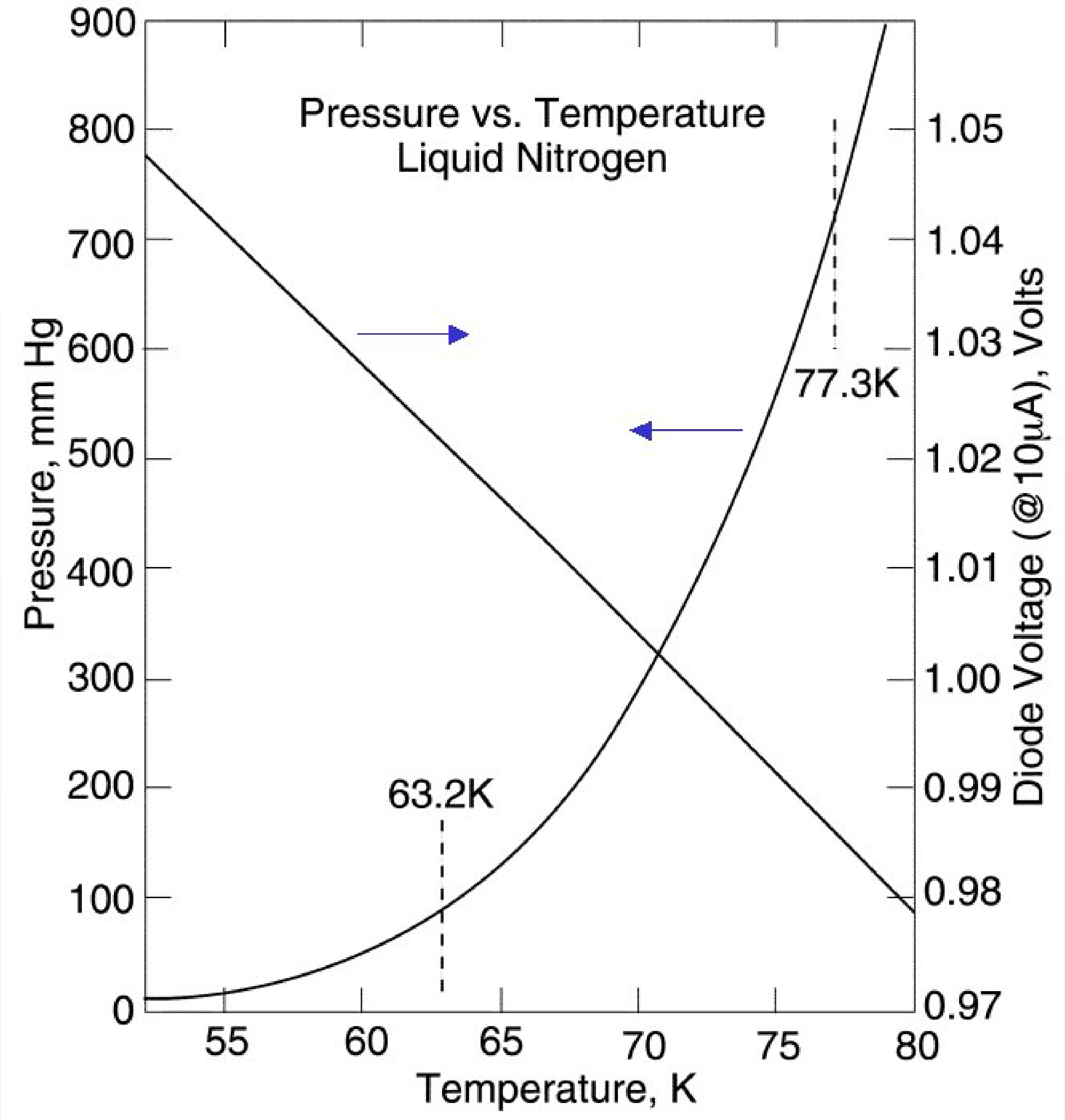
Lower temperature gives extra margin.

Field Parallel





Bath Temperature of Nitrogen can be Lowered by Pumping

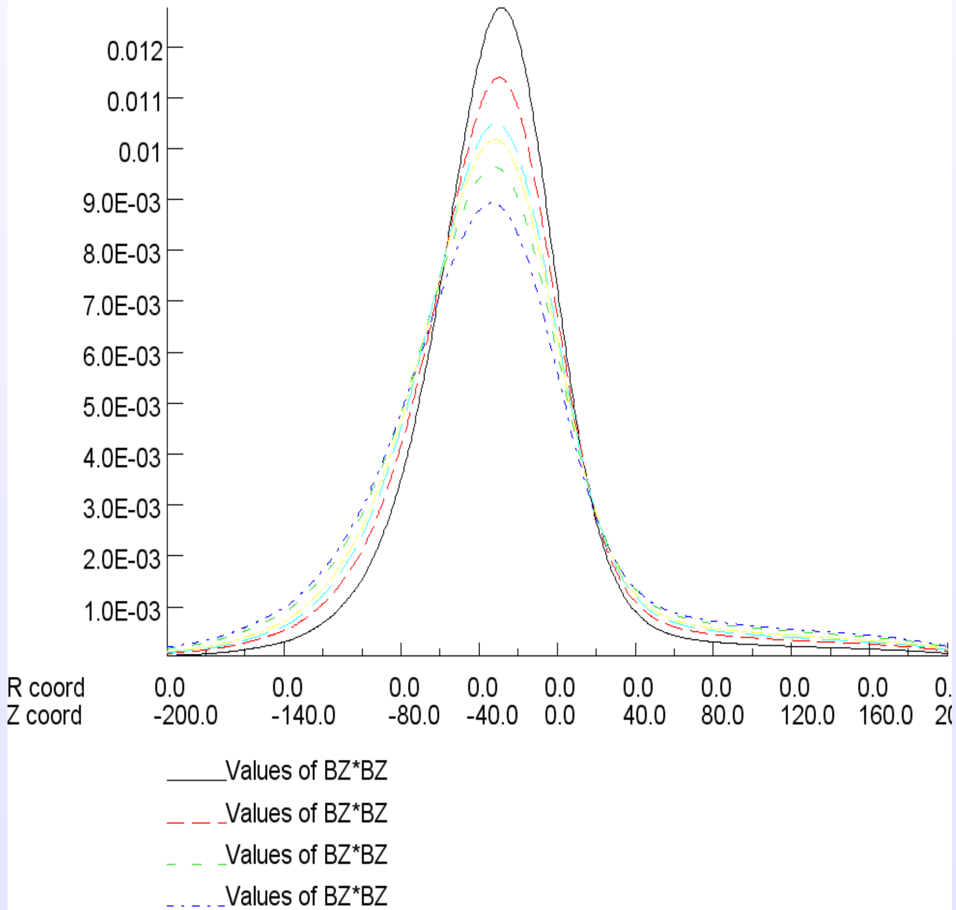


In this low field application, we can test HTS magnet to the design field with nitrogen only.

Preliminary Thoughts On Overall Structure

- Split cylindrical aluminum clamp over coil (Aluminum has good thermal conductivity, easy to machine and during cool-down provides better clamping due to shrinking.
- There is essentially no axial Lorentz force, there is only small outward radial force (hoop stress) which can be easily handled by aluminum. In addition, HTS tape has stainless steel on it.
- HTS coils may be wound on aluminum bobbin (details to be worked out).
- HTS coils can be consisted of one, two or three double-layer pancakes. Details to be worked out with respect to construction, field profile (beam dynamics), etc.
- Leads (low 50 Amp current) don't need any stabilization, as there is adequate margin.

Profiles depends on the details of solenoid design

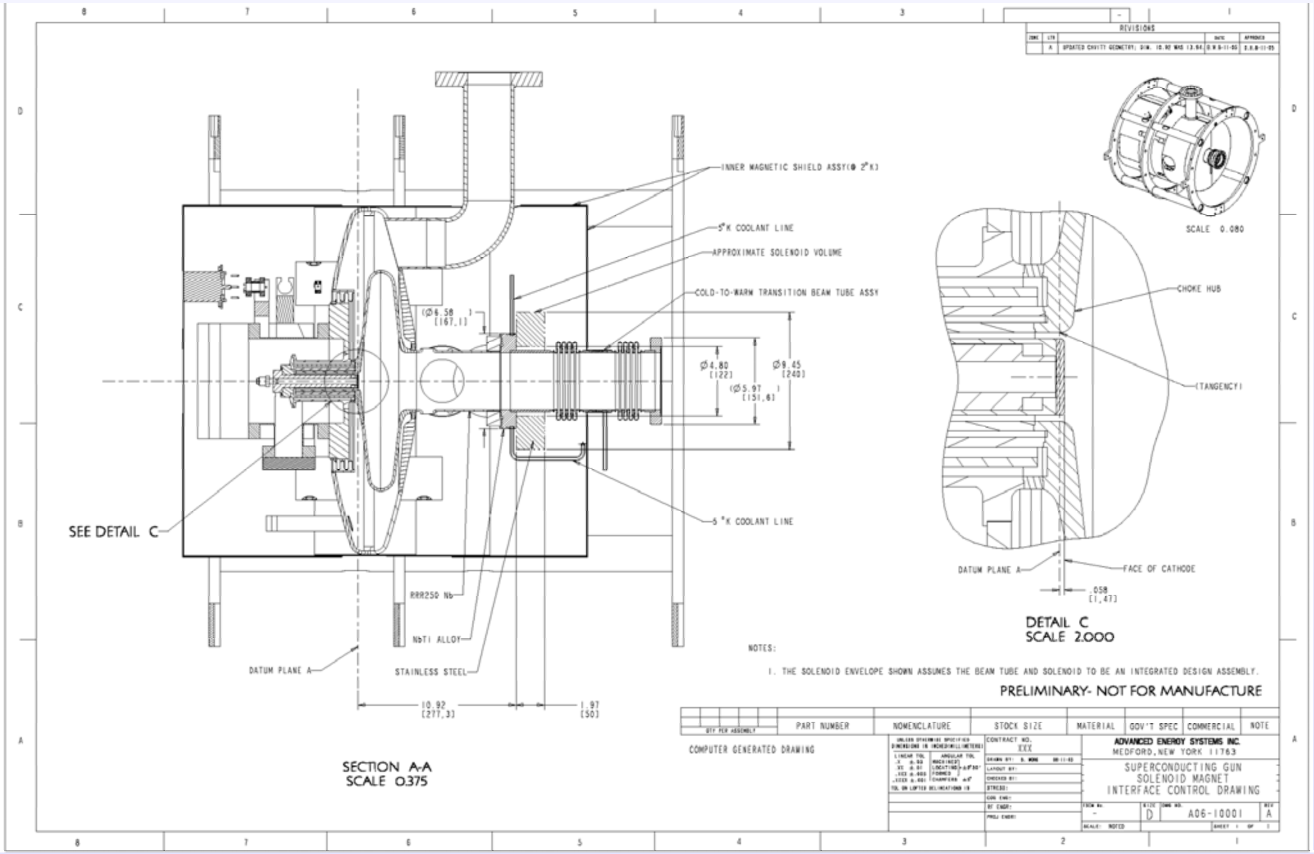


Location of HTS Solenoid (Revisited)

In the following drawing some extra space has been added (?) to insert solenoid.

Calculations show that the basic requirements can be met even if HTS solenoid is placed over the bellows (this implies that we have a focusing solution that does not need any extra space)

The temperature at solenoid can be practically any thing (55 K or lower for sufficient margin)



Information from Vendor for Radiation Issues on PTFE Insulation on HTS Tape

W. L. GORE & ASSOCIATES • ELECTRONIC PRODUCTS DIVISION

GORE™ HIGH STRENGTH TOUGHENED FLUOROPOLYMER WIRE INSULATION PROPERTIES

Summary

GORE™ High Strength Toughened Fluoropolymer dielectric provides the chemical, electrical and thermal resistance of PTFE with vastly improved mechanical performance. The extraordinary abrasion and cut-through resistance of GORE™ High Strength Toughened Fluoropolymer allows for ultra-thin and flexible insulation with no sacrifice in mechanical or electrical integrity. Additionally, GORE™ High Strength Toughened Fluoropolymer provides magnitudes higher creep resistance over typical fluoropolymers. This material can be used throughout a wide temperature range (cryogenic to 260° C) and is available in wall thickness starting at 0.0005" for wires from 50 to 20 AWG.

Physical and Thermal Properties

Property	Typical Value
Specific gravity	2.15
Tensile strength (psi)	50,000
Elongation (%)	50
Modulus of elasticity in tension (psi)	40×10^5
Thermal conductivity (cal sec^{-1} cm^{-1} °C^{-1})	
Specific heat (cal gm^{-1} °C^{-1})	0.25
Thermal expansion (°C^{-1})	10×10^5
Continuous use temperature (°C)	260
10-minute endurance temperature (°C)	325
Melt temperature (°C)	327
Low temperature limit (°C)	Near -273
Flammability	Non-flammable

Electrical Properties

Property	Typical Value
Dielectric constant	2.1
Dissipation factor	0.0002
Volume resisitivity (ohm-cm)	$>10^{18}$
Dielectric Strength (kV/mil)	>1
Corona resistance	Fair

Environmental Properties

Resistance to	Rating
Cold flow or cut-through	Excellent
Ultraviolet radiation	Excellent
Nuclear radiation	Poor
Electrical-mechanical stress cracking	Excellent
Chemical-mechanical stress cracking	Excellent

** In the absence of oxygen, radiation resistance is improved by a factor of more than 100.*

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Advanced Circuit Materials Division
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Chandler, AZ 85226
Tel: 480-961-1382, Fax: 480-961-4533
www.rogerscorporation.com

Properties
2.9.3

The Effect of Nuclear Radiation Exposure to RT/duroid® PTFE-Based Composites

The radiation resistance of RT/duroid® materials is of concern in space applications where microwave devices or antennas will be exposed to nuclear radiation.

RT/duroid materials are based on polytetrafluoroethylene (PTFE) combined with glass microfiber or ceramic filler. In either case, the component most susceptible to nuclear radiation damage is the PTFE. Because of the low cohesive forces between PTFE molecular chains, a polymer must be of very high molecular weight in order to realize the desired mechanical properties.

The primary effect of radiation on PTFE is the reduction of molecular weight by breaking the large polymer molecule into smaller parts. Oxygen is essential to some of the possible radiation induced reactions. Thus the damage due to radiation is minimized in an oxygen-free environment such as space.

The effect of molecular weight reduction is primarily on mechanical properties. There will be an increase in brittleness. Tensile strength, modulus and elongation are all reduced.

It has been reported that the mechanical changes in PTFE appear to depend on the total radiation dose and to be independent of dose rate. The dielectric properties are affected by electrical charge distributions in the resin which decay with time, and thus the dose rate is important.

During irradiation the dielectric constant and loss factor will be temporarily increased. The effect of radiation on these properties is less at elevated frequencies such as would be encountered in microwave applications.

The degree to which PTFE is affected is essentially a function of the amount of energy absorbed regardless of the identity of the radiation. That is, beta, gamma, X-ray, etc. have about equivalent effect. The radiation dose unit usually employed in radiation studies is the rad. One rad equals 100 ergs/grams.

The following is a summary of radiation doses in rads related to damage levels.

	In Air	In Vacuum
Threshold	$2\text{-}7\times10^4$	$2\text{-}7\times10^5$ or more
50% tensile strength	10^4	10^7 or more
40% tensile strength	10^7 or more	8×10^8 or more
Retain 100% elongation	$2\text{-}5\times10^5$	$2\text{-}5\times10^4$

Frequently the dose rate of 10 rads/hour is quoted for the Van Allen Radiation Belt. At this rate PTFE could operate for 5 to 50 years before a thresholds level of damage would be detectable mechanically.

Since the primary function of RT/duroid® microwave laminates is electrical, with mechanical support usually provided by metallic components, the exposures cited above can be expected to be well below the point where electrical performance would be impaired. The resistance of PTFE to radiation damage is generally better than that of solid state electronic devices such as transistors.

More on Radiation Issue on Insulation

Our material science expert say that Teflon should easily handle 1 Mrad.

Is this an issue in this application?

American Superconductor had advertised two options for insulation (PTFE and kapton). Since PTFE became standard, they lost contact with kapton vendor (a much more radiation resistant insulator). They are looking into reviving it.

PTFE vendor indicates (web info) that they have another product that is radiation resistant. We have asked American Superconductor to look into that.

We can easily wind coil with an additional kapton insulation between the turns. Space for this option has been allowed in magnetic design.

Two coils, previously made at BNL for another project, one is co-wound with kapton insulation and the other with stainless steel.

Initial Estimates Of SMD Task

1. Design

Task(s)	Estimates
Overall Task Management System Design Magnetic Design and Modeling o Create the desired integrated field o Compute fringe field and keep below superconductor limit o Field map with superconducting shield for beam tracking o Design iterations (assume that a few will be required)	Scientist: 0.3 FTE
Support Structure and Assembly	Engineer: 0.1 FTE
Design/Drafting (details only of HTS Solenoid)	Designer: 0.05 FTE

2. Construction

Task(s)	Estimates
Bobbin for coil winding Setting up of computer controlled machine for winding Coil Winding (test + actual) Epoxy painting on the surface Splice between coils Machining iron yoke + other support structure material Coldmass assembly Prepare magnet for 77 K Test	Technician: 0.5 FTE Engineer: 0.1 FTE Scientist: 0.1 FTE

3. Test (only 77 K tests)

Task(s)	Estimates
77 K tests in Liquid Nitrogen (LN2): Required for certification o Test wires (tapes) as received from the vendor o Test of individual coils after they are wound o Test completed solenoid (with all coils and iron yoke) Data analysis and preparation of report	Scientist: 0.2 FTE Technician: 0.1 FTE

Estimated time for the completion of this project: ~1 year after receiving go-ahead and delivery of conductor.

Not yet included in the estimates: Current leads and feed-through, heaters, instrumentation, etc.

Additional 4 K test, not included in this task, may not be needed.

Proposed Work in Near Future (next few months) and Remaining Issues

Determine the complete scope of the task

Are we (BNL) making current leads/feed through?
If yes, does SMD only design and delivers it or also install it?

Determine instrumentation and any other such needs (e.g., all of the following, a few or none)
Warm-up heaters, temperature sensors, hall probe, any other?

Make a decision on the insulation issue with regard to the radiation.

Complete magnetic design that is consistent with accelerator physics requirements and meets various physical constraints

Complete overall conceptual design

Wind double pancake practice coil with stainless steel tape (same dimension as conductor) and may be a few turn HTS coil with left over conductor we have from another project.

Decide if "sub-cool" nitrogen testing is sufficient (the solenoid will reach the design field)

Identify left out issues, etc.

SUMMARY

- **HTS solenoid offers a unique and efficient solution.**
- **Initial design has been developed.**
- **Task and issues have been identified.**
- **We are ready to move ahead.**