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Chapter 5

The Superconducting Solenoid

5.1 Introduction

Momentum analysis in GLUEX will be provided by a nominal 2 Tesla superconducting solenoid magnet. This solenoid was built at SLAC ca. 1970 for the LASS spectrometer and subsequently moved to LAMPF in 1985 for inclusion in the MEGA spectrometer. The MEGA Experiment and the solenoid were decommissioned in place in 1995. The MEGA experiment has since been removed from the solenoid and arrangements are underway to ship the solenoid from LANL to the Indiana University Cyclotron Facility (IUCF) for refurbishment and testing. This magnet was designed and built using standards that today would be considered ultra-conservative. The magnet employs a cryostat-ically stable design and uses cryostats that were designed to be easily opened for service with hand tools. A recent inspection of the magnet at LANL concluded that it is still in excellent condition and worthy of the use, time and cost involved in relocation and refurbishment. Nevertheless, the magnet support systems are now 30 years out of date so even though the magnet is in excellent condition it requires some maintenance, updating, and modifications for use as part of the GLUEX experiment.

5.2 Present Condition

The LASS/MEGA solenoid was inspected in April 2000 by a team from the GLUEX collaboration, JLab staff and two of the original designers of the magnet. This team met at Los Alamos with the MEGA staff and inspected the MEGA magnet installation and the fourth coil. Except for two small mechanical vacuum pumps the system was completely intact. The fourth coil was

found sealed in its original shipping crate. The fourth coil iron yoke ring, yoke stand and coil insertion tool were all found in storage. Several transportainers were found filled with magnet documentation including original drawings and micro film copies, log books, operating data, magnetic data, photo albums documenting all phases of the magnets life, manuals, calculations, and spare parts.

The committee concluded that “the condition of the magnet is excellent and if cooled down in place would in all likelihood work!” Subsequently Jefferson Lab formally transferred the solenoid system from Los Alamos to JLab as of October 2001, except for two items that are to be retained by Los Alamos, neither of which are required at JLab. A Memorandum-of-Understanding (MOU) was negotiated with LANL to cover all aspects of the MEGA experiment dismantling. This work, performed by a JLab crew, was begun in November 2001 and was completed in February 2002. All work was governed by a detailed Hazard Control Plan written to meet LANL safety standards. The solenoid is now bare and awaiting arrival of a heavy rigging contract crew for the final disassembly and shipment to IUCF. A detailed MOU was negotiated between JLab and IUCF to receive the solenoid, perform all the upgrade and maintenance work, and perform a full scale cryogenic system test of the solenoid.

5.3 Dismantling and Relocation

Our initial inspection showed that the MEGA setup was substantially unchanged since completion of the experiment years ago. The magnet still contained all the physics equipment for the MEGA experiment and was still connected to various utilities and piped services. The magnet was still connected to its power source. Further, there were small quantities of activated materials and hazardous materials within the MEGA installation. Each of these conditions had to be addressed by a comprehensive Hazard Control Plan (HCP) for the deactivation and disassembly of the MEGA experiment installation, and many items and materials may only be handled by certified personnel. The use of Los Alamos cranes and lift vehicles is similarly restricted.

JLab staff, including personnel from the JLab Radiation Control Group, were appropriately trained to perform all non-trade work. Small items were dismantled by JLab staff following the thorough deactivation of energized systems by LANL certified staff. The removal of hazardous and activated materials was performed by JLab staff under LANL supervision, and all removed materials were certified radiologically by JLab staff for free release. A large quantity of materials were removed from the MEGA installation, sorted and

recycled by JLab staff. The entire process was completed in February 2002, ahead of schedule and under cost.

The actual solenoid dismantling, removal and shipping will be performed by a private rigging contractor under contract from JLab with some on site LANL coordination and JLab supervision. JLab has bid to three rigging companies the work of dismantling, loading and shipment to Indiana. We estimate that two weeks will be required at LANL for dismantling and loading. This work will require special equipment consisting of a hydraulic lifting frame and a large (LANL owned and operated) 35-ton fork truck. Shipment to IUCF will consist of 14 truck loads by common carrier. This contract award is expected by September, and the work completed by the end of October 2002. Offloading at IUCF into storage can be performed using IUCF's crane and contract rigging staff.

5.4 Summary of Proposed Modifications

IUCF was chosen to perform the solenoid modifications due to availability of a skilled technical work force and facilities at an attractive cost on a favorable timescale. There are numerous modernization, compatibility and maintenance tasks that must be performed to insure continued reliability of the solenoid. Most of the tasks listed below are straightforward, and involve changes needed for basic compatibility with existing JLab systems and codes, or to replace items that are obsolete and no longer serviceable. However, substantial design effort is still required for many of the solenoid improvements, and further analysis is needed to calculate and understand the solenoid magnetic performance. A description of the magnetic simulation effort can be found in Section 5.5.

1. Experiment related modifications

- Inclusion of "fourth coil"
- Closing of yoke gaps
- Thickening of fourth gap iron insert
- Thickening of downstream "pole cap"
- symmetric opening in upstream pole cap to match downstream
- Stands to increase the solenoid centerline height to 3.5 meters

2. JLab compatibility

- Cryogenic interface

- New JLab standard u-tube bayonet sockets
- New JLab standard JT type valves and actuators
- Cool down heat exchanger and controls
- Relocated Helium reservoir
- Burnout proof current leads
- Replacement of LN2 reservoir
- Replacement of LN2 and LHe level sensors
- JLab standard U-Tubes
- Transfer line to JLab CHL (not strictly part of magnet)
- Controls interface
 - Modern PLC and software
 - EPICS compatible controls and interface
- DC systems
 - NEC compatible energy dump and dump switch
 - New DC Power supply to match GLUEX required performance
 - DC bus compatible with power supply relocation

3. Serviceability items

- Controls and instrumentation
 - Data Logger
 - * Upgrade to instrumentation and signal processing electronics
 - * Remote control power supply link
 - * Replacement for interlock PLC retained by LANL
 - * Upgrade to quench voltage and current lead voltage detection
 - * Magnetic field monitoring probe(s) and readout
 - * Data cables as needed to allow relocation of controls
- Vacuum systems
 - Replacement of oil diffusion pump system with a modern turbo pump system.
 - Replacement of vacuum instrumentation as needed.

4. Maintenance items

- Replacement of cryostat vacuum system o-rings
- Replacement of LN2 shields to eliminate 30 year old leaks
- Leak testing and repair of Helium space leaks as needed if found
- Maintenance or replacement of thermal insulation systems as needed
- Test and maintenance of High Voltage insulation systems as needed
- Maintenance of vacuum valves and gauges
- Maintenance or replacement of internal instrumentation and wiring
- Replacement of internal strain gauges known to be faulty
- Replacement of 30 year old existing electronics and signal conditioners
- Replacement of existing data and instrumentation cabling
- Replacement of existing instrumentation vacuum feed-throughs

5.5 Magnetic Modifications Needed

The original SLAC configuration of the solenoid allowed for gaps in the return yoke so that wire chambers could be inserted from the outside. Further, in the LASS and MEGA installations the Cerenkov detector had to be located at large radius due to the presence of high magnetic fields near the downstream end of the solenoid. The source of these high fields has been investigated using a 3D TOSCA model of the yoke and coil and various methods to reduce these “stray” fields have been explored.

The solenoid was designed with a segmented yoke and four cryostats with sub-coils inside. There are a total of thirteen sub-coils located within the four cryostats, with the current density distributed by varying the number of turns. This was done to produce a more uniform internal field and to compensate for the gaps in the yoke and most prominently, for the asymmetric enlarged opening in the downstream pole cap. The thirteenth coil is very large, approximately four times the size of its neighbors. The other 12 coils vary by some few percent from each other. The thirteenth coil is needed to compensate for the large “Z” gradient in the field which, a consequence of the large opening in the yoke.

The coils further had to be operated at higher currents to drive the extra gap caused by the spaces in the yoke. The downstream pole cap was highly saturated due to the proximity of the thirteenth coil to the pole cap and the higher currents.

The following yoke modifications will reduce the saturation in the pole cap and lower the stray field in the region where the GLUEX Cerenkov will be located:

1. Replace the air gaps with iron rings. This lowers the required operating current to achieve the same central field. The lowering of the local fields especially around coil thirteen helps reduce pole cap saturation.
2. Increase the distance in “Z” between the thirteenth coil and the downstream pole cap. This lowers the local field near the pole cap and thus lowers the saturation.
3. Increase the thickness of the pole cap by adding an iron disk to dilute the pole cap field and reduce saturation.

These yoke modifications will reduce the stray field levels in the Cerenkov region from ~ 700 gauss down to ~ 50 gauss, low enough to be shielded by thin iron and Mu-metal shields.

5.6 TOSCA Simulations

5.6.1 Introduction

The original solenoid magnet was designed without the benefit of modern 3D magnetic modeling, yet the magnet has worked long and well in two experiments. But there has been a persistent difficulty with downstream stray fields, as noted above. Thus we have created a 3D TOSCA model of the solenoids fields to study the problem in detail and design a remedy.

5.6.2 TOSCA Model

The yoke has been modeled such that the effect of closing the yoke gaps or creating new gaps, or opening or closing the ends can be studied by simply changing materials definitions.

The coils were approximated as follows. The 13th (last) coil was modeled exactly because of its expected large effect on yoke end saturation and external downstream fields. The other 12 closely spaced coils were approximated by a single uniform solenoid since the 12 coils are all nearly the same size, are uniformly spaced, and each has near equal current compared to coil 13 (which is 4 times the average size of the other 12). Furthermore, the 12 smaller coils

are in a region where the yoke is continuous and thus the external effects of this current distribution should be very small.

The internal fields are expected to be affected by the exact distribution of current and the yoke details. The current distribution of the solenoid is not easily modified in any case and thus must be taken as a given. The modifications to the yoke are a mix of requirements from physics, need to lower external fields, and modifications to provide new access for the GLUEX detectors. The model is designed to evaluate the yoke modifications needed to lower the external fields. The effect on internal fields will be the subject of a more detailed study.

The volume modeled is a 45 degree slice of cylindrical geometry that contains a yoke segment and the surrounding air. The space modeled extends from -40 inches to + 600 inches along the z axis and out to a radius of 240 inches. This space is subdivided into regions that contain air or iron, or reduced potential regions that contain currents. The volume modeled has 334,000 linear elements. With the high subdivision already present, we obtain adequate accuracy without the extra computational time required using quadratic elements. A full nonlinear computation is used in the iron based on the properties of generic 1006 steel, which is similar to the actual 1010 steel. The coils are modeled as full 3D coils superimposed on the 45 degree iron and air geometry. TOSCA uses symmetry to compute the fields in all space. The 45 degree segment of yoke is subdivided according to actual SLAC dimensions and all iron features and details are modeled. Additional geometry has been included to simulate the extra gap on the upstream end that has been suggested for allowing cables to exit the yoke.

Also, by simply changing the iron to air on the upstream pole cap one can calculate the effect of a symmetric magnet, i.e. one with both ends open. The effect of extending the yoke geometry by adding extra iron to the downstream end was studied by simply extending the existing geometry.

5.7 Preliminary Results

Four GLUEX models were investigated. The original and last configurations are shown in Figure 5.1. All four models use identical coil models and identical current densities. The integral field increases by 2.6 % as a result of filling the gaps. The other modifications have no significant effect on the total field. This effect can be easily understood since most of the flux must return through the original gaps. Thus filling them with iron must have a large effect on the field integral while only some of the flux is effected by the other changes, and thus

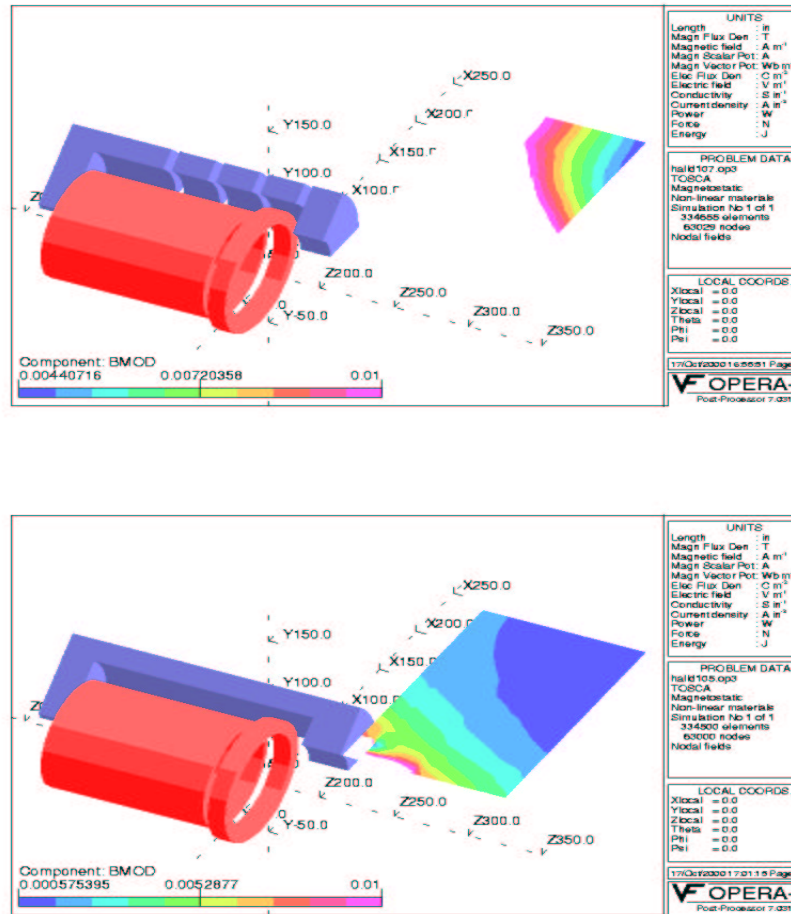


Figure 5.1: TOSCA models for upper) the original magnet configuration and lower) configuration that fills the gaps with iron, extends the fourth gap and thickens the pole. Both figures show the model for the coils (solenoid and 13th coil ring) and a 45 degree pie slice of the yoke iron. Also shown is a contour plot of fields which are less than 100 G in the region of 50 to 240 in radially and 190 to 300 in along the axis. This is a region that could be considered acceptable for placing photomultiplier tubes. Note that in the bottom configuration the region of low field begins at the iron, allowing detectors to be mounted near the solenoid. The magnetic field scale is in Tesla.

a minimal effect on field integral is seen.

Model Number	Max Field (G)	Min Field (G)	Low-Field Area (%)	$\int B \cdot dl$ (T·Inches)
Hall D 107	1067	523.0	none	302.8
Hall D 106	351	82.5	none	311.0
Hall D 103	241	56.7	17	311.3
Hall D 105	158	45.7	50	310.8

Table 5.1: Field parameters for the region between 50 and 80 in radially, where Cerenkov photomultiplier tubes might be placed. The entries correspond to the maximum and minimum B fields, and fractional area with field below 75 Gauss. Also given is the on-axis field integral for each TOSCA model.

We briefly describe each configuration:

Hall D 107 has the iron yoke and coil configuration of the original LASS solenoid as it was used at SLAC. This model is to provide a baseline for comparison and to compare with historical calculations and measurements. The model has the original segmented yoke with the four original 6 inch air gaps. *This model should be used to measure the effectiveness of the yoke changes which are the subject of the other three models.*

Hall D 106 has the SLAC yoke but with the four 6 inch gaps filled with the same iron as the rest of the yoke. This was a requested change and it has the effect of lowering the external fields. You can clearly see that the external fields are in general lower, especially in the regions where it would be desirable to locate photo tubes.

Hall D 103 has the four gaps filled with steel and gap four extended from 6 inches to 12 inches. This modification was selected because of the extreme saturation in the yoke that was observed around the 13th coil. Fields as high as 3 Tesla are observed near the 13th coil. Moving the yoke further away from the 13th coil will lower the yoke saturation and thus make the yoke more effective in collecting external flux and channeling it back within the yoke iron.

Hall D 105 has the down stream “pole cap” thickened from 20 inches to 26 inches. This is in addition to filling the gaps and extending the fourth

gap. This modification was selected to further reduce saturation levels in the yoke and thus reduce further the external fields.

We studied the external fields in the region where Cerenkov photomultiplier tubes may be located. The region extends in z for 20 inches and in R from 50 to 80 inches. This 20 inch by 30 inch space is kept a constant 10 inches from the down stream yoke end for the four models discussed above. Models Hall D 107 and Hall D 106 have the patch of space located at from 199 to 219 inches in Z . Model Hall D 103 has the patch located at 205 to 225 in Z because the yoke has been lengthened by 6 inches overall. Model Hall D 105 has the patch located at 211 to 231 in Z due to the extended gap and the extra pole cap thickness adding 12 inches overall to the yoke length. Thus the four patches are a constant distance from the yoke end and clearly show the substantial improvements that are possible. The model Hall D 105 has a substantial volume ($\sim 50\%$) with fields between 46 and 74 gauss (see Table 5.1). These fields can be shielded by a combination of soft iron and Mu-Metal tubes. As this region extends from 65 to 80 inches in radius, the photomultiplier tubes for the Cerenkov could be located much close to the detection volume. A maximum distance of about 2 meters (~ 80 inches) is certainly possible. Figure 5.2 plots the computed fields for the four models as a function of radial distance in the area where we expect to place sensitive detectors, and Table 5.1 summarizes the characteristics for each case. Clearly there are large regions close to the detection volume where tubes could be located. It is also obvious that simply moving further out can have the same effect. Indeed the original solution chosen at SLAC was to locate the tubes at 4 meters where the fields are ~ 75 gauss for the original SLAC /LASS geometry. The modifications computed above can achieve these field levels in a much more efficient manner.

5.8 Compensation for The Upstream Plug

The collaboration desires a matching full aperture hole (73 inch diameter) in the upstream yoke to provide access to the detector volume for service, installation and support, and also to provide a route for cables to exit the upstream end of the magnetic volume. This upstream hole has the same effect on the internal field quality as the downstream hole and thus must be studied carefully. The downstream hole in the yoke is the same diameter as the cryostat inner diameter, 73 inches. This opening is equivalent in magnetic effect to boring a large hole in the center of the pole of a dipole magnet because

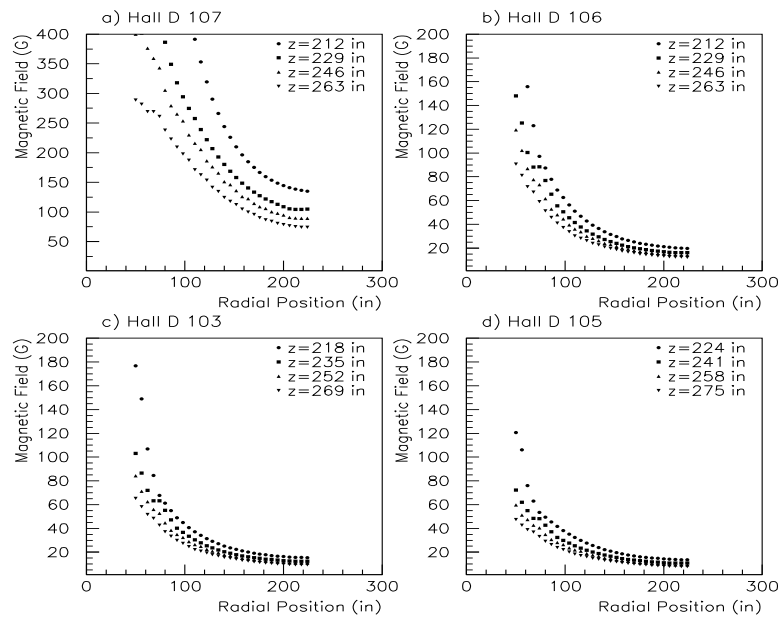


Figure 5.2: Magnetic field as a function of radial distance at constant distance along the z axis for the four different configurations of the solenoid. Note the scale change for plot a).

the end yoke pieces for the solenoid are in fact the poles. The designers of the solenoid compensated for this large hole by increasing the current density in coil # 4, which has four times the average number of Amp-turns of the other 16 coils. This compensates for the missing iron and also contributes to the nearby yoke saturation and stray fields that we dealt with in the previous sections.

We examined four options to deal with the loss of field integral and flatness caused by the new opening: a) no action, b) creating a gap in the upstream yoke, c) increasing the current by 15% in all the coils of cryostat # 1, and d) filling the hole with the proposed upstream iron-scintillator calorimeter veto and making gaps elsewhere in the yoke to provide cable access. Figures 5.3a and 5.3b show the on-axis magnitude of the field through the solenoid for the various options discussed above. Fig. 5.3a is the nominal configuration with the upstream plug in place and Fig. 5.3b is with the new upstream hole. All other modifications mentioned earlier are included. The loss of field integral in the backward direction is not a significant problem, but the reduction of flatness has the effect of increasing the computation requirements for analysis. Clearly, an improvement in the upstream field flatness is desirable. We detail the three options considered:

New upstream yoke gap

Creating a new upstream yoke gap was examined in the first round of magnetic simulations and the conclusion was that this creates more of a problem than it solves. The new gaps make a lot of exterior field that can get into phototubes and it adds the complication to the assembly that cables, the yoke and detectors are now linked. The new gaps do not cause a loss of good field region but it does reduce the integral on axis.

Increase current in cryostat # 1

Increasing the current in the 7 coils inside cryostat # 1 by approximately 15% has the effect of increasing the local Amp-turns to boost the field back up and replace the flux lost by enlarging the upstream yoke hole. This can easily be accomplished by stacking a floating DC power supply across cryostat # 1 to enhance the current relative to the main current. The main current power supply provides 1800 A to all 4 cryostats in series. In this way all 17 internal coils are in series and have the same charging and discharging. The small biasing DC power supply that floats across cryostat # 1 permits a local current increase and is adjustable. This method if selected requires that a low amperage (≈ 300 A) current

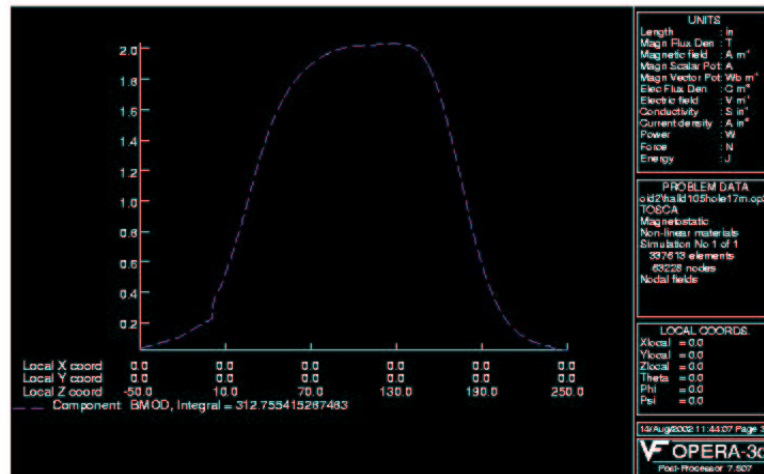
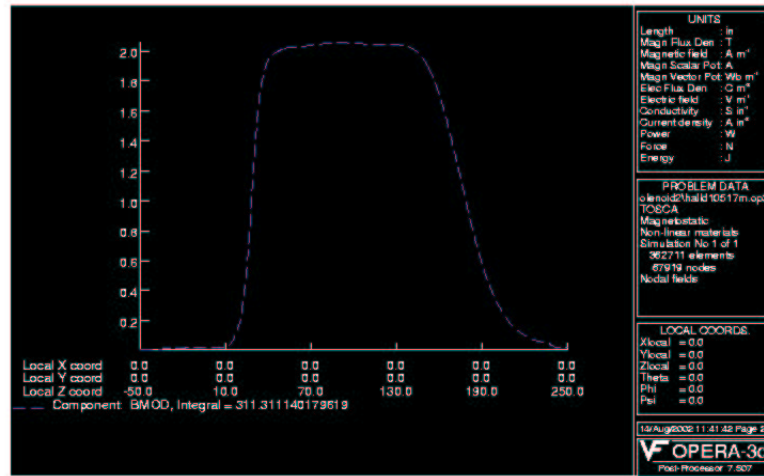


Figure 5.3: upper) Standard configuration. lower) Standard configuration without upstream plug.

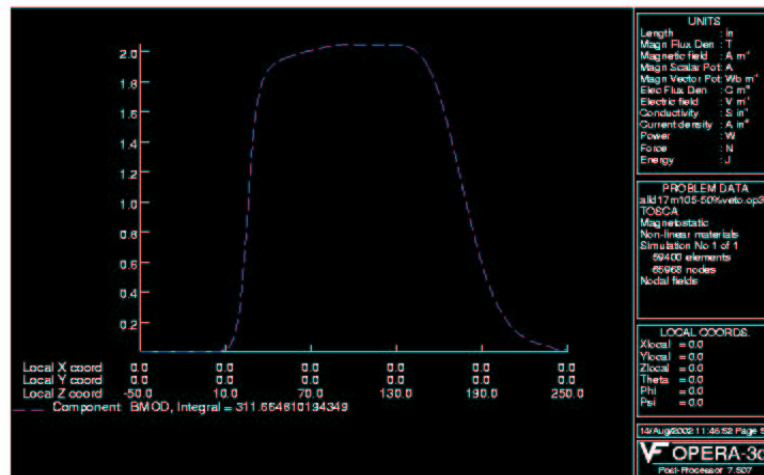
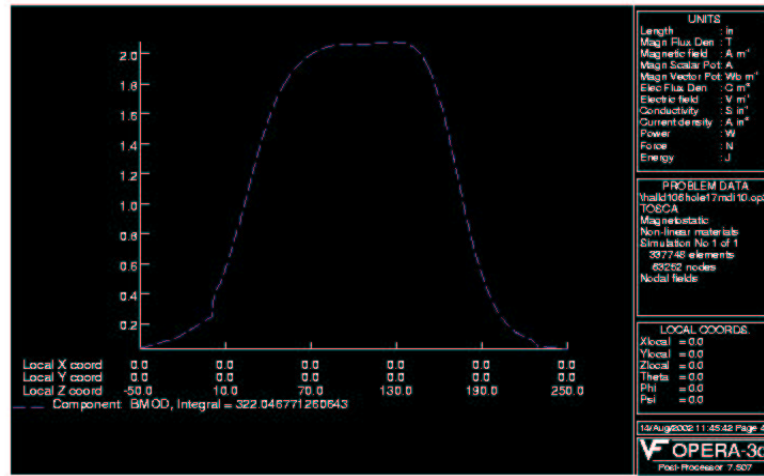


Figure 5.3 upper) No upstream plug, nominal current in coils 2-4 (14000 A/in²), but current in coils 2-4 increased by 10% (15400 A/in²). lower) No upstream plug, nominal current, and upstream iron-scintillator veto with a 50% packing fraction.

lead be added to the new cryo-reservoir during the solenoid refurbishment. The new DC biasing supply is simply connected between one of the main current leads and the low current biasing current lead. This is an adjustable, low cost, and reliable method to boost the field back up and is identical in principal to the method used to boost the downstream field. Instead of adding turns, which is difficult, one just adds some extra current to the existing turns. The magnet control and quench protection stems are marginally more complex as a result of this solution. Precautions must be taken to guarantee that there can never be a current path through the biasing lead and power supply that conducts the main 1800 A solenoid current. Figure 5.3c is a graph of the central field with extra current in the 7 coils of cryostat #1.

Upstream veto with iron radiator

The new upstream hole in the yoke provides the opportunity to use a veto calorimeter to reject events with a backward (in the lab) particle. This veto calorimeter, if made from an iron and scintillator sandwich, could significantly replace some of the missing iron. Figure 5.3d shows the central solenoid field assuming a 50% packing factor for the iron-scintillator sandwich in the upstream veto detector. The result is that most of the missing field is restored. This method has the benefit of being passive and providing a useful enhancement to the detector package. The extra benefit of keeping the external fields lower near the upstream end of the solenoid makes this the favored choice. Further simulations are required as the veto design progresses, and allowance must still be made for the gap in the pole so that cables can exit.

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