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Chapter 5

The Superconducting Solenoid

5.1 Introduction

Momentum analysis in GlueX will be provided by a 2.24 T superconducting solenoid magnet. This solenoid was built at SLAC ca. 1970 for the LASS spectrometer and was 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 experimental equipment was dismantled and preparations for shipment started in the spring and summer of 2002. The solenoid was shipped from LANL to the Indiana University Cyclotron Facility (IUCF) for coil refurbishment and testing in October 2002. Currently all four coils have been extensively tested and coils one and two have been completely refurbished. Refurbishment efforts on coils three and four will start in the fall of 2004.

The magnet employs a cryostatically stable design and uses cryostats that were designed to be easily opened for service with hand tools. The inspection of the magnet performed at LANL in 2000 concluded that the solenoid was still in excellent condition and worthy the time and cost involved in relocation and refurbishment. Nevertheless, the magnet support systems are now 30 years old. Even though the magnet is in good condition, it still requires repairs, maintenance, updating, and modifications for use as part of the GlueX experiment.

5.2 Brief Description

The magnet is described in a technical note [1] and some relevant portions of that description are quoted below. Table 5.1 summarizes important magnet parameters. The refrigeration units are not currently available and new ones are required.

Inside winding diameter of SC coils	80 *inches*
Clear bore diameter	73 *inches*
Overall length (iron)	195 *inches*
Inside iron diameter	116 *inches*
Outside iron diameter	148 *inches*
Coil-to-coil separation	11 *inches*
Total iron weight	232 *tons*
Central field	22 kG
Conductor current	1800 A
Total stored energy	36 MJ
Inductance	22 H
Total helium volume (including reservoir)	5000 $liters$
Operating heat load (liquid He)	30 $liters/hour$
Operating heat load (liquid nitrogen)	30 $liters/hour$
Cool-down time	2 *weeks*
Copper to superconductor ratio	$20:1$ (grade A) $28:1$ (grade B)
Total conductor length	$117,600$ $feet$
Total conductor weight	$29,000$ lbs
Turn on time	20 $minutes$
Turn off time (normal)	20 $minutes$
Axial load per coil due to magnetic forces	280 *tons*

Table 5.1: Summary of characteristics of the solenoid as used in the LASS configuration.

The LASS solenoid magnet provides a 22.4 kG magnetic field parallel to the beam direction. The clear bore inside diameter of the magnet is 73 *inches* and its final - as modified overall length - is 195 *inches*. Within the clear bore region the field homogeneity is $\pm 3\%$. Along the beam axis the field homogeneity improves to ± 1 %. The solenoid is constructed of four separate superconducting solenoidal coil-cryostat units [2] and uses a segmented 232 *ton* iron flux return path that surrounds and supports the coil assemblies. A common liquid helium reservoir is located on top of the solenoid providing the gravity feed of the liquid to the coils.

The liquid helium vessel is surrounded by a liquid nitrogen cooled radiation shield and this assembly is centered in the vacuum tank by a circumferential series of tie bolts designed for minimum conductive heat flux to the helium bath. Radial centering and support are achieved by four low conductance hangers arranged in a spiral pattern. Various tie rods and hangers are instrumented with stress bolts to measure the tremendous forces on the assembly caused by the magnetic fields.

The inductance of the coil is 22 *Henries* , and the magnet is run at 1800 *Amperes*. The liquid helium volume is $\approx$ 5000 *liters* and the heat load is $\approx$ 50 *watts*. Refrigeration at Hall D will be supplied by a small local refrigerator of 200 watt capacity. This over-engineered nature of the design of the magnet, cryostat and the superconductor itself, has produced a stable, reliable and safe superconducting magnet.

5.3 Solenoid Refurbishment Activities

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. 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. Magnet documentation and spare parts were also found. Jefferson Lab subsequently entered into negotiation with Los Alamos and the DOE to transfer ownership of the magnet to Jefferson Lab. The solenoid was next dismantled by a heavy rigging contract crew and shipped to IUCF in October 2002.

Currently, two coils have been refurbished and the other two are expected to be completed in early 2005. The first two are expected to be moved to JLab in early 2005. After the all coils are completely refurbished at IUCF, the remainder of the solenoid will be moved to JLab for addition of new support systems including the DC system, control system and cryogenic interface. Testing of individual coils at 4.5 Kelvin and a full solenoid recommissioning test are planned prior to installation in HALL D.

5.3.1 Detailed Tests of The Coils

The detailed examination of the solenoid's four coils began in May 2003. The goal of this detailed testing was to accurately determine the leak rates, verify pressure ratings and verify operation of all internal instrumentation. The solenoid has had a 30 year history of large internal leaks which complicated operations and raised the cryogenic heat load. The internal instrumentation

Coil	N2 shield 10^{-5}torr-liter/s	He Vessel 10^{-5}torr-liter/s	External Vessel	Over Pressure
1	5	ok	12in bellows	ok
2	ok	0.2	12in bellows	ok
3	4	ok	12in bellows	ok
4	0.4	ok	12in bellows	ok

Table 5.2: Status of leak and pressure testing. To date, coils one and two have been tested and show no leaks. The status of "ok" indicates a leak rate of less than10^{-9}torr-liter/s

was known to have deteriorated and accurate checks of coil electrical properties needed to be confirmed.

Coil	Resistance Across coil (Ω)	Resistance LH Lead-Ground (Ω)	Resistance RH Lead-Ground (Ω)	Inductance (mH)
1	4.9	2.2	6.4	372
2	3.2	open	open	244
3	2.7	2.6	0.2	172
4	5.2	open	open	763

Table 5.3: Measured electrical properties of the four coils.

One of the goals of this effort was to carefully perform calibrated leak rate measurements of the four coils' helium spaces, nitrogen spaces and vacuum spaces. This was necessary to quantify the leaks to guide the decision to repair. A decision was reached early on - when good leak detection sensitivity could not be achieved - to install 8 conflats on each of the four coils. This resulted in achieving leak detection sensitivity of 1×10^{-9} torr-liter per second. At this sensitivity the leaks were quickly identified and quantified. The complication due to 18 inch bellows failure was corrected by replacing the bellows. Coil four, which was not part of the MEGA experiment at LANL, had a non-standard vacuum pump-out flange that required replacing. The coil electrical properties and internal instrumentation were measured during this time also. The instrumentation operability was confirmed and the wiring was verified and documented. The results of the testing are summarized in Tables 5.2, 5.3 and 5.4.

The work at IUCF to test the four coils in detail and to perform such repairs as to permit the testing was concluded in February 2004. At the conclusion of this work all four coils had been extensively tested, and the leak position had been determined in coils one and two.

Coil	Voltage Taps	Carbon Resistance Thermometer (4 to 300K)	Thermocouple (80 to 300K)	Platinum Resistance (40 to 300K)	Strain Gauge (new)
1	ok	7 of 8 ok	removed	30 new	6 new
2	ok	ok	removed	30 new	6 new
3	ok	ok	TBD	TBD	TBD
4	ok	4 of 7 ok	TBD	TBD	TBD

Table 5.4: Table of internal instrumentation and voltage taps. Each coil has voltage taps (VT) and Carbon Resistance Thermometers (CRT) in the Helium vessel and Thermocouples (TC) on the N2 shield and strain gauges (SG) on the support posts.

5.3.2 Refurbishment of Coils One and Two

Following the conclusion of the initial investigations, a contract was negotiated with IUCF to perform all repairs and proof testing on coils one and two. The scope of work of this effort included localizing and repairing all leaks. Replacement of all strain gauges as most had failed. To replace the thermal couples shield thermometers with Platinum resistance thermometers (PT100). The replacement of all wiring, and finally to replace the aluminized mylar multi layer insulation(MLI). A decision was made to retain the original Liquid Nitrogen shields due to their good state of repairs and functionality. The new PT100 thermometers were installed in small copper blocks soldered to the copper shield panels for good thermal contact and reliable mounting. The new strain gauges were installed on the outermost of the three nested cylinders of the cold to warm supports.

Coil one was previously determined to have a shield leak only. The most difficult part of completing coils one and two was reconnecting the shields and plumbing due to the out of sequence reassembly. This necessitated replacing the simple joints with more complex junctions that had only forward facing welds. This technique was used extensively on a magnet in JLabs Hall C namely the HMS Dipole. Both coils were cooled to approximately 120 Kelvin and no leaks were found. A side benefit of this testing was the confirmation of proper operation of the new shield PT100 thermometers and the wiring correctness. Both coils were pressure tested to 100 psi successfully. This concluded the testing and internal repair phase of coils one and two. The next step was to replace all the shield MLI insulation and perform a final evacuation as preparation for placing the coils in storage. Both coils one and two achieved vacuum in the range of 1×10^{-5} , passed a final leak check and were subsequently backfilled with N2 gas, sealed and moved to an inside storage location at IUCF.

5.3.3 Plans To Complete Coils Three and Four

As of September 2004, coils three and four have been moved into the working area at IUCF and contract negotiations for their refurbishment are underway. This work is expected to begin in the fall of 2004 and be completed before summer 2005.

5.3.4 Plans To Complete The Solenoid at JLab

The remaining work to upgrade and re-assemble and test the solenoid is planned to occur at JLab. Activities during 2005 include securing a test and assembly space in the Test Lab at JLab, moving coils one and two to the space in the test lab and preparing the coils for cool-down to 4.5 Kelvin. This testing effort requires equipping and staffing the solenoid test area in the test lab and designing and fabricating a new single coil test interface. The original SLAC-designed test interface was never found so a replacement is required to support testing. The replacement will have connections matching JLab standards. A set of temporary cryogenic connection lines for use in the Test Lab will also need to be designed and fabricated. These two design and fabricate items will become the highest priority of the JLab HALL D design and engineering staff in FY 2005. This is to support the cool-down and test of one single coil by the end of FY 2005. This test would consist of cool down and fill at 4.5 Kelvin with helium, LN2 shield cool down and fill and only limited low current operation of the coil.

The solenoid also requires an entirely new control system. The original solenoid had only manual controls and instrument data were recorded in paper log books. The cryogenic control of the solenoid was completely absent and all cooling was achieved by manipulating a small Helium refrigerator. The replacement of the controls on the HMS SC magnets at JLAB at this time and the similarity of many systems and identical nature of others leads to common solutions. The prototype for the solenoid new controls is being tested as this is written. A full system of the prototype is planned for January and February 2005. Following debugging and commissioning of the HMS Dipole prototype system a clone will be prepared for the Hall D solenoid. The current plan calls for a more complete test of coil two using the new solenoid controls, new power supply (already on site) and would operate a single coil at full current. Test and re-assembly of the entire solenoid are pending and depend significantly on the year of availability of HALL D.

5.4 The Magnetic Field of The Solenoid

5.4.1 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 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 seventeen helps reduce pole cap saturation.
2. Increase the distance in "Z" between the seventeenth 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 $\sim$700 gauss down to $\sim$50 gauss, low enough to be shielded by thin iron and Mu-metal shields.

5.4.2 TOSCA Simulations

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.

TOSCA Model

The yoke and coils have been modeled using the TOSCA 3D magnetic analysis software. This model was prepared with geometry that allowed simulating the effect of closing the yoke gaps or creating new gaps, or opening or closing the ends by simply changing materials definitions.

The solenoid magnetic field as currently modeled is based on the actual distribution of current within the four coil cryostats and the actual details of the yoke construction. The yoke modifications for the benefit of the GlueX experiment have also been included. The current distribution of the solenoid can not be modified and therefore the details must be included to accurately model the magnetic fields for experiment simulation taken and to test the effect of various modifications. The TOSCA model also provides valuable design information about the magnetic environment as seen by each detector system. The modifications to the yoke are a mix of requirements from GlueX physics, the need to lower external fields, and modifications to provide better access for the GlueX detectors. The TOSCA model is designed to evaluate the yoke modifications needed to lower the external fields. The TOSCA modeled internal fields have already been valuable as the source of magnetic fields for the Geant simulations. Further magnetic simulation work will be performed to study more carefully the effect of all the above changes on the exact B vs I excitation curve, the inductance and stored energy and the forces on the coils. Generally filling in the yoke gaps will lower all of these quantities but the exact values remain to be confirmed.

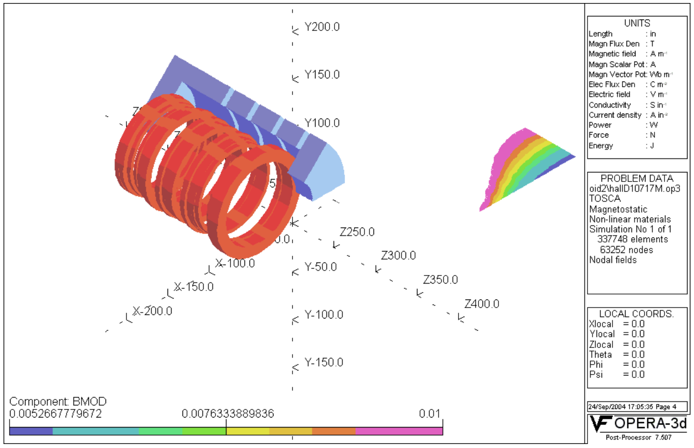
Preliminary Results

Four GlueX models were investigated. The original and last configurations are shown in Figure5.1. 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 a minimal effect on field integral is seen.

We briefly describe each configuration:

Hall D 107 has the iron yoke and coil configuration of the original LASS

a) Hall D 107



b) Hall D 105

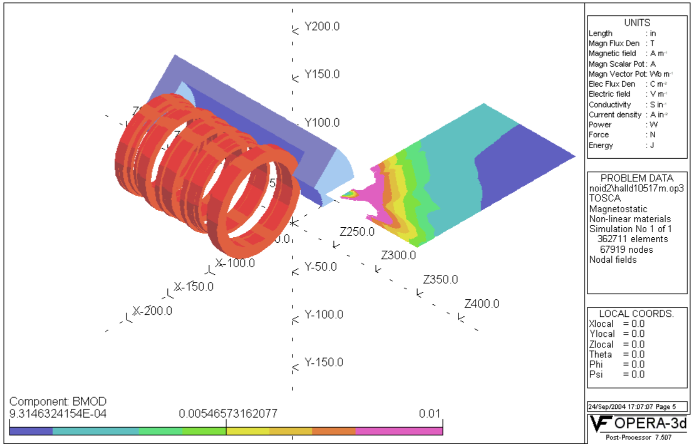


Figure 5.1: TOSCA models for a) the original magnet configuration and b) configuration that fills the gaps with iron, extends the fourth gap and thickens the pole. Both figures show the model for the coils (solenoid and 13th coil ring) and a 45 degree pie slice of the yoke iron. Also shown is a contour 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.

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 5.5: 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.

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 a 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. The model Hall D 105 has a substantial volume ($\sim$ 50 %) with fields between 46 and 74 gauss (see Table 5.5). 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 closer to the detection volume. A maximum distance of about 2 meters ($\sim$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 5.5 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 $\sim$75 gauss for the original SLAC /LASS geometry. The modifications computed above can achieve these field levels in a much more efficient manner.

5.4.3 Compensation of 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 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 and c) increasing the current by 15% in all the coils of cryostat # 1 Figure 5.3 and show the on-axis magnitude of the field through the solenoid for the various options discussed above. The first is the nominal configuration with the upstream plug in place and the second 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.

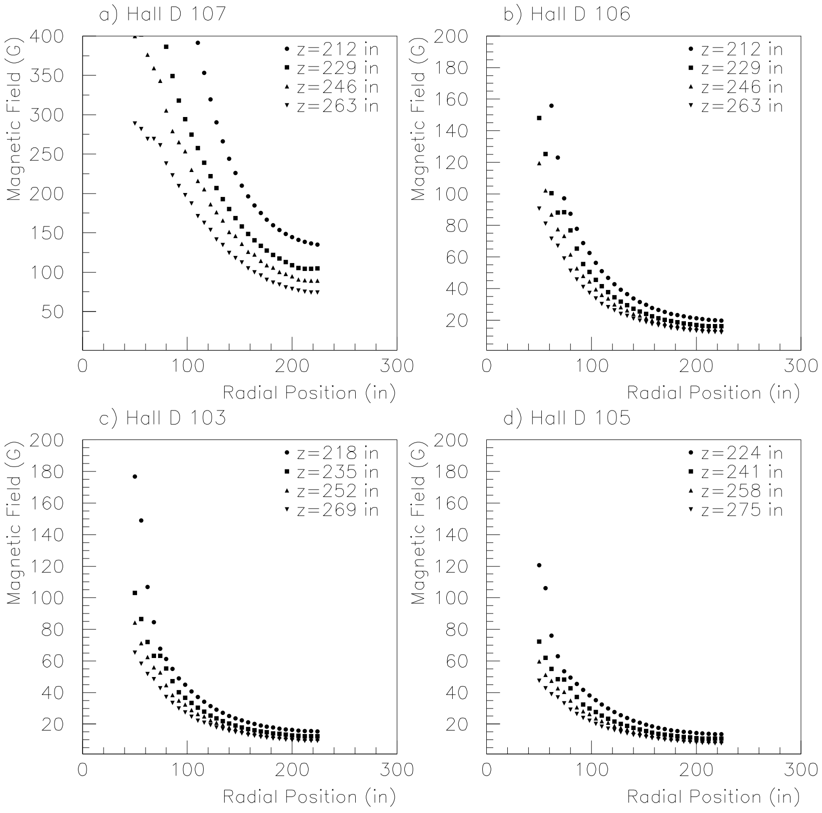


Figure 5.2: Magnetic field as a function of radial distance at constant distance along the z axis for the four different configurations of the solenoid. Note the scale change for plot a).

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 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 down stream 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 5.3 is a graph of the central field with extra current in the 7 coils of cryostat #1.

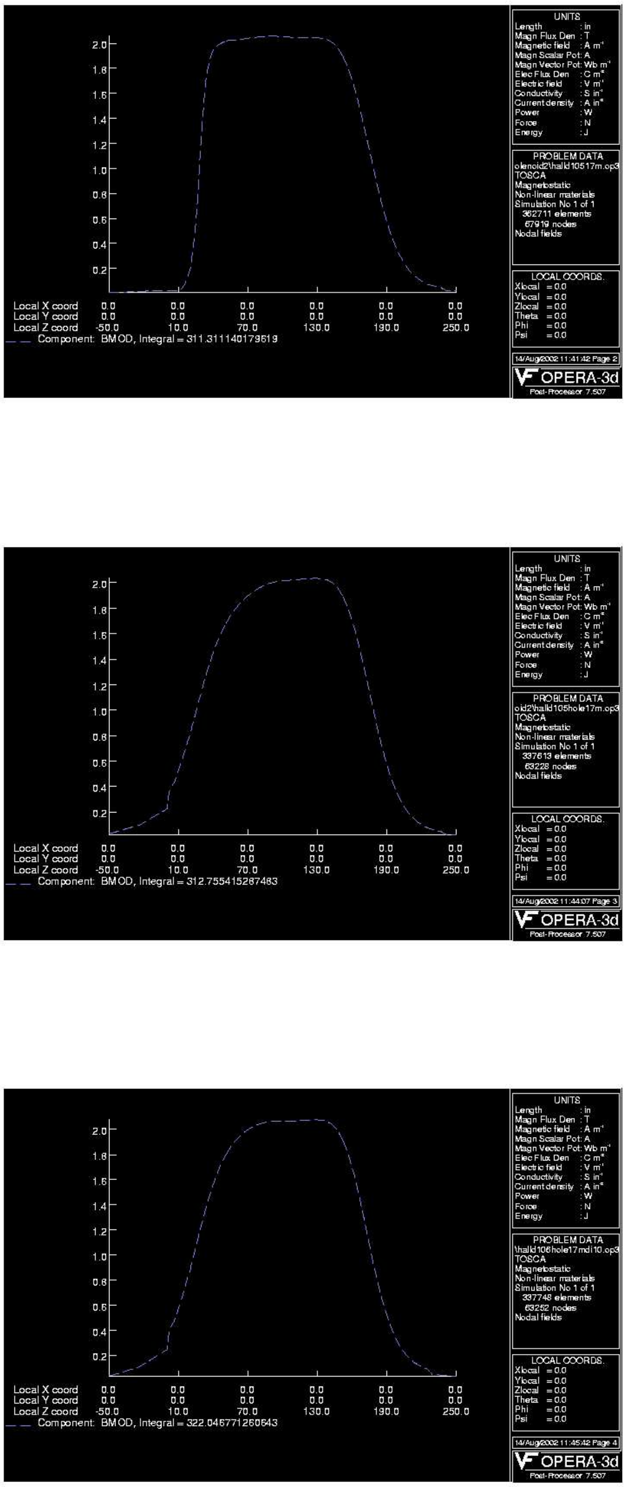


Figure 5.3: Upper) Standard configuration. Middle) Standard configuration without upstream plug. Lower) No upstream plug, nominal current in coils 2-4 (14000 A/in^2), but current in coils 2-4 i ncreased by 10% (15400 A/in^2).

List of Figures

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Bibliography

[1] D. Aston *et al.* The LASS spectrometer. Technical Report SLAC-Report-298, 1987. Copies available from the SLAC publications office, at `http://www.slac.stanford.edu/pubs/`.

[2] J. S. Alcorn, H.O. Peterson, and S. St. Lorent. In *Applied Superconductivity Conference*, page 273, 1972.