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SSC DETECTOR SOLENOID DESIGN NOTE #108

TITLE: Correspondence and Suggestions

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ABSTRACT: This Design Note consists of a letter from Peter Clee, RAL, in which he answers some questions put to him by Ron Fast and of a copy of a paper describing the DELPHI and H1 magnets built at RAL for LEP and HERA.

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December 21, 1989

P.T.M. Clee
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Dear Peter,

I regret that our paths have not crossed for some years now. I was planning to go to Japan for MT-11, but the trip did not work out. Actually I was prompted to write you after seeing your paper in the abstract booklet.

Several of us here at Fermilab have been involved with conceptual designs of a superconducting solenoid that might be part of a magnetic detector at the SSC. We at first worked on a 9 m ϕ x 16 m version which, because the calorimetry would be inside the cryostat, could be thick, cryostable, bath-cooled, etc. It became apparent, both to the physicists and to us, that even if feasible this 1.7 GJ magnet would be expensive and would take a long time to engineer, design and build.

It is now generally agreed that the calorimetry should be out of the central field region and so we are now working on a thin solenoid with a diameter of 3.4-4.0 m, between 8 and 16 m long.

It would be helpful if you could send us copies of RAL papers on Delphi and the H1 magnet for HERA. I have those papers which appeared in the proceedings of ASC-84 and MT-9, but we would appreciate the MT-11 paper and any RAL reports about conductor, coil and cryostat design and the LHe pump.

Our thoughts, and those of our colleagues at KEK, are leading us into "new" areas with regard to two or three items. We are seriously thinking about an aluminum honey comb with 1.5 mm aluminum skins for the outer vacuum shell and a flat annular vacuum head which is machined in a sort of waffle pattern (there is interest in maintaining the thinness down to small angles). We have essentially adopted an operating current of 10 kA, which for a given temperature rise gives a thinner coil than the usual 5 kA. Do you have any comments about these issues? I would appreciate hearing both your "knee-jerk" and more considered opinions.

Thanks for your help! Have a good Christmas holiday.

Warmest regards,

Ron Fast

Ron Fast

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8 January 1990

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Dear Ron

Thank you for your letter and Christmas greetings, and a Happy New Year to you.

With regards to your questions on large solenoids, you may be interested to know that I am planning to attend the detector workshop at Tuscon so I hope to see you there and discuss the problems in more detail. Meanwhile, as requested, our comments on your points raised in your letter are:-

1. Particle Transparency

a) General Comments

It is very important to adopt an integrated design concept from the beginning of the project. When choosing the construction material and actual thicknesses to improve the transparency, great care must be taken not to build in new problems. Continuous assessment of actual total savings in material thickness should be made throughout the design period and be weighted against overall reliability and safety.

We found with DELPHI that we were brought in too late to contribute to the design concept for the overall detector. In consequence we found many detail design problems that were difficult to resolve. As you know space at the ends of the cryostat is very limited for supports, cooling pipes and current leads etc, and therefore need to be considered at an early stage in the design.

b) Honeycomb Construction

The main problems with a honeycomb type design are not with the basic shell structure but with termination of the honeycomb structure at flanges and access ports, reaction of loads eg overall coil weight supported through the vessel to the main support and out-of-balance loads due to coil/iron asymmetries.

I would not advise a honeycomb structure without carefully considering what can be achieved with a more 'conventional' structure.

We considered the use of honeycomb for the initial design of ELECTRA - precursor of DELPHI.

In all these considerations the demands for high dimensional tolerances must be borne in mind. Both DELPHI and H1 solenoids were required to be extremely accurate both in coil and vacuum vessel, ie a few mms in 5-6 metres. This was difficult to achieve even though we used conventional welding and machining techniques with stainless steel for the vacuum vessel.

In addition to material thickness actual geometric radial space is at a premium and in the case of H1 we used the radial space between stiffening rings to locate the radiation shields and cooling pipes. This would not be possible in a honeycomb structure.

c) Operating Current

Some reduction in coil winding thickness achieved by operating at a higher current is clearly available in principle since for a fixed stored energy, quench voltage and peak quench temperature the coil thickness is given by:-

$$t \propto \left(\frac{1}{I}\right)^{1/2}$$

The reduction in coil winding thickness should be weighted carefully in terms of the overall thickness of coil and cryostat and other materials and in terms of the effect the higher current might have in ohmic heating at joints, junctions to current leads, current lead heat loads on refrigeration etc.

If a cabled superconductor insert is used in an aluminium substrate there would seem to be no real problem in terms of conductor manufacture. The manufacture and operation of conductors with cable inserts is well established from DELPHI, H1 and ALEPH.

Again the increase in operating current and its effect on coil thickness should be viewed as an overall concept rather than in isolation.

2. Helium Pumps

The helium pumps used on DELPHI and H1 are of the CERN design - infact the DELPHI pumps were procured and installed by CERN. For H1 the pumps were manufactured through RAL to CERN specification and assembled at CERN under their technical supervision. The pumps allow large mass flows of two phase helium approximately 50g/sec to be circulated.

The pumps require an intermediate dewar system helium reservoir to act as a buffer between the solenoid and the refrigeration system. This buffer volume allows the solenoid to be run down in a controlled fashion to zero current in the event of a refrigeration supply failure. I am not certain as to whether or not a paper has been produced on these pumps but I will check when next at CERN.

I will also look out other information that may be of use to you.

I am afraid my comments are not very supportive to your problem and I expect you have considered most of these points already. However I look forward to further discussions at Tuscon.

Kind regards

Peter

Peter Clee

TOWARDS THE REALIZATION OF TWO 1.2 TESLA SUPERCONDUCTING SOLENOIDS FOR PARTICLE PHYSICS EXPERIMENTS,

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ABSTRACT

Superconducting solenoids are required to produce a magnetic field of 1.2 Tesla in a room temperature volume of 145m^3 for the DELPHI particle physics experiment on LEP at CERN and for the H1 experiment on HERA at DESY.

The large solenoids which are in the region of 5-6m diameter and 5-7m long, were constructed with aluminium clad Nb-Ti conductor, wound on the inside of a liquid helium cooled support cylinder.

The coils are indirectly cooled with 2 phase liquid helium and suspended within an 80K gas cooled radiation shield inside a stainless steel vacuum vessel.

The coils have a stored energy > 100 MJ when powered at 5000A.

The paper covers aspects of the construction, installation and test of the two solenoids.

INTRODUCTION

The Rutherford Appleton Laboratory (RAL) has designed, built, installed and tested two superconducting solenoids providing very large volumes of magnetic field for High Energy Particle Physics experiments. The first was for DELPHI, one of four experiments operating on the Large Electron Positron (LEP) Collider at CERN, Geneva. The second was part of the UKs contribution to the H1 Experiment on the Hadron Electron Ring Accelerator (HERA) at Deutsches Elektronen Synchrotron (DESY), Hamburg.

The basic design concept used for DELPHI Solenoid (described in a previous paper)[1] was also adopted for H1. The overall parameters for the Solenoids are given in Table 1.

The DELPHI Solenoid has been fully installed and commissioned. H1 has passed the preliminary tests at RAL, been installed at DESY, and is at the stage of final commissioning and test.

TABLE 1
Parameters

		DELPHI	H1
Central Field	T	1.2	1.2
Peak Field	T	1.6	2.2
Current			
Main Coil	A	5kA	5.5kA
Trim Coil	A	±1kA	–
Ampere Turns	At	7.45×10^6	7.0×10^6
Run Up Time	Min	60	60
Run Down Time	Min	95	120
Inductance	H	8.75	7.8
Stored Energy	MJ	109.4	120
Discharge Volt.	V	750	750
Discharge Time	Sec	60	60
Inner Clear Dia	mm	5200	5205
Outer Clear Dia	mm	6200	6075
Radial Width	mm	500	435
Length Overall	mm	7400	5751
Weight Total	Tonnes	84	73

GENERAL DESIGN CONCEPTS

The overall design and development carried out for the DELPHI Solenoid produced a design and construction techniques which in practice proved to be sound and economic.

The main design concept adopted for the coils in both Solenoids is illustrated in Figure 1. The conductor, made up with Nb-Ti Rutherford cable and clad with aluminium for stabilisation, is wound on the inside of a support cylinder. Conductor joints within the coil were made by welding of parallel conductors over one complete turn of the coil (>15m); originally developed in Japan for CDF and Topaz Solenoids. Very low resistance joints were made - extrapolation from short joint tests indicate $<10^{-10}$ per joint.

Coils were fabricated in modular form of lengths up to 1.5m for both double and single layers, and were wound on a custom built machine using the 'inside winding' technique developed at RAL. This enabled a production line to be set up to manufacture all the modules and included - support cylinder cleaning - lining with glass/resin insulation - bonding and curing - electrical insulation test - conductor cleaning - winding of modules with continuous double half lap tape insulating and inline joint welding - bonding and curing - then final electrical test.

The earlier paper [1] indicated that 'B' stage glass/resin was to be used as the insulating and bonding medium. This material only carries a small amount of resin which is partially cured and requires large pressures between mating surfaces during the curing process to achieve high bond strengths.

Since that statement a similar but much improved system has been developed and used for both Solenoids. This consists of mixing solid and liquid epoxy resin to produce a thixotropic consistency. The glass cloth and tape, are vacuum impregnated with this mixture but unlike 'B' stage, the resin is not partially cured. The system enables a large amount of resin to be taken up by the glass. When finally vacuum bagged and/or pressure bonded with a 120°C cure, the final coils are indiscernible from a vacuum potted coil and very high insulation resistances are achieved.

H1 DEVIATIONS FROM DELPHI

There were many small changes to the DELPHI design and layout of components to meet the H1 requirements, but two major changes in concept were introduced. These were the reduction in the radial width of the Solenoid and the introduction of compression rather than tension supports for the coil within the vacuum vessel.

To meet the 435mm radial dimension, it was necessary to put the vacuum vessel stiffening rings inside the vessel and use the space between the rings to locate the circumferential radiation shields (see Figure 1). By designing the shields as simple aluminium sheets with He gas cooled pipes welded to the outer surface,

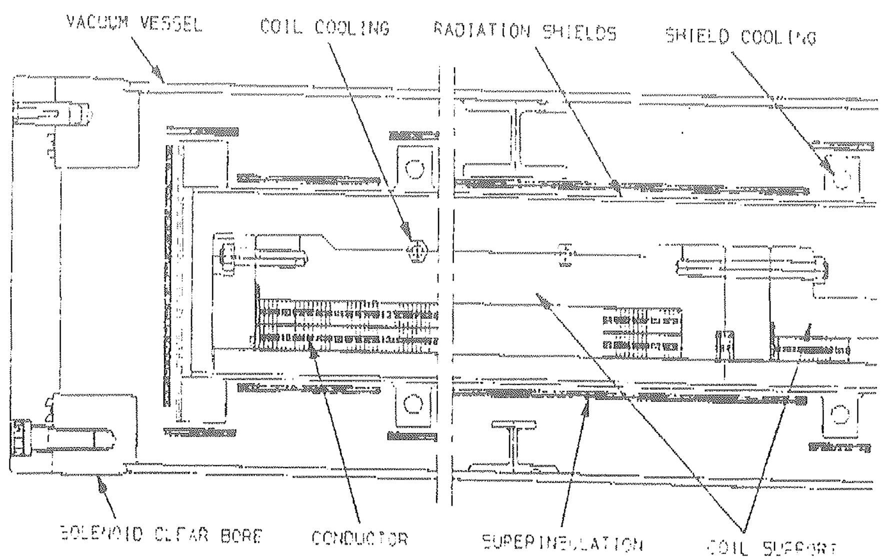

FIGURE 1 Cross Section of H1 Solenoid

it was possible to highly polish the surface facing the coil, thereby avoiding the need for any superinsulating blankets between the coil and shields.

The DELPHI coil was suspended at the ends from the vacuum vessel, on thin stainless steel rods and additional tie rods provided lateral stability. In the finished state this principle was perfectly acceptable, in practice however, during the assembly stage with the vacuum vessel end plates removed, the unsupported inner and outer shells moved a few millimetres. This made the setting up operation of centring the coil and then fitting the end plates very difficult.

For this reason, the support system for H1 was changed to two glass fibre support pillars located at each end on the horizontal axis. Linear bearings were built into the supports to accommodate the contraction of the coil during cooldown to 4.5K.

CRYOGENIC SYSTEMS

The cryogenic systems are required to cooldown and maintain the coil at 4.5K, the radiation shields at 80K and provide 4.5K gas and liquid to cool the current leads. Additional cooling is required during the current change in the coils to remove inductive heat generated in the support cylinder and a reserve of coolant is required for the coil and current leads when the coil is run down in the case of a power outage.

Cryogens for H1 are supplied from a large central refrigerator feeding a ring main, whereas for DELPHI a local refrigerator is provided by CERN.

In both cases a pumped two phase helium system has been adopted, using mechanical pumps developed by CERN[2] which are located in an intermediate dewar (ID) which also contains the reservoir of LHe. Two LHe pumps are installed, one operates under normal conditions with the second as a spare. During the current run up and down modes both pumps are operated.

The items most likely to cause problems during the lifetime of the Solenoid are the current leads, the superconducting/resistive transition joints, the electrically insulated joints in the current lead cooling circuits and the cryogenic interface connections. In the case of DELPHI these items are housed in special turrets located on top of the iron yoke at each end of the magnet and for H1 inside a valve/current lead box located on the floor outside the iron yoke.

The current lead system is based on a horizontal fin heat exchanger design developed by CERN[3]. For coils with stored energy > 100MJ, current lead reliability under fault conditions is of greater importance than minimising refrigeration heat loads at 4.5K. The fin type design allows extremely good safety in the event of gas flow failure with acceptable 4.5K heat loads for normal operation. Under test conditions lead temperatures did not exceed 350K when the current was run down from 5kA over 2 hours with zero gas flow.

The fin heat exchanger section between 4.5K and 300K is cooled with 4.5 gas taken from the top of the intermediate dewar. The base of the current lead is separately connected by a heat exchanger to the two phase circuit of the coil. In this way the base of the current lead is held at 4.5K by the two phase flow which absorbs the main heat load from 300K.

POWER SUPPLIES AND PROTECTION SYSTEM

The H1 Solenoid is powered from a 20 volt, 6kA power supply connected to the coil through high voltage, high power circuit breakers. DELPHI has a similar main supply but in addition there are two trim correction circuits powered by supplies that can operate up to $\pm$ 1kA.

Under quench conditions the circuit breakers are opened and approximately 100 MJ of the stored energy is dumped into a large external resistor. This process takes about 2 minutes and the resistor is sized to limit the temperature rise to less than 300^{o}C. This is for safety reasons with the possibility of inflammable gases in the area.

A quench fault condition is detected by multiple bridge circuits across the coil which senses any out of balance voltage developed across a normal region in the superconductor. An added complication arises with the DELPHI trim circuits from induced out of balance voltages when the correction currents are changed. These voltages are compensated by a signal from mutual inductors located in the correction current busbar circuit.

For normal run down of the magnetic field the voltage and current decay are controlled by passive diode resistor assemblies. Due to the low inductance of the DELPHI trim coils the currents decay more rapidly than the main coil current. The voltage drop in the trim circuits is minimised to extend the decay time and avoid excessive eddy current heating in the coil support cylinder which could initiate a quench.

ASSEMBLY AND TRANSPORT

The available buildings at RAL were not ideal for constructing the Solenoids, therefore a horizontal assembly process was developed. Figure 2 shows the assembly area with the coil modules in the foreground and to the left, is the inner cylinder cantilevered from a large support frame. Successive cylinders, supported on a trolley, were slid over the cantilevered assembly.

On completion of assembly and tests, all connecting pipes and transfer lines were removed and additional supports to react high 'G' loads on the coil during transit were fitted. The Solenoids were rolled out of the building on a trolley and transferred to a multi wheel (all steerable) transport trailer by a mobile crane, for transit by road and roll-on, roll-off ship to the destinations at CERN and DESY.

H1 SOLENOID TEST

Final assembly and pre-shipment test of the H1 Solenoid was made at RAL during March/April 1989. See Figure 3. The test programme was designed to demonstrate correct cryogenic operation of the coil, radiation shields and cryogenic systems and to establish correct operation of all electrical and protection systems at excitation currents up to 2kA. The upper limit of test current was set at 2kA since the test was executed without the iron yoke structure.

Cooldown and Cryogenic Tests

(i) Cooldown of the Solenoid and Radiation Shields to 90K. In this phase helium gas at 15bar was circulated using a compressor/heat exchanger unit built by DESY. Cooling was provided by heat exchange between the closed circuit helium loops and liquid nitrogen from a storage dewar.

During cooldown the temperature differential across the Solenoid was limited to 40K in order to keep thermal stresses within the coil to a minimum.

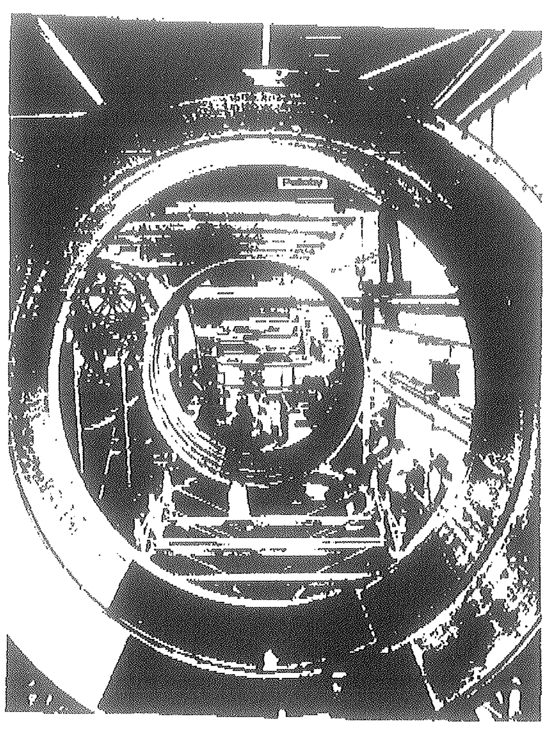

FIGURE 2 H1 Solenoid Assembly

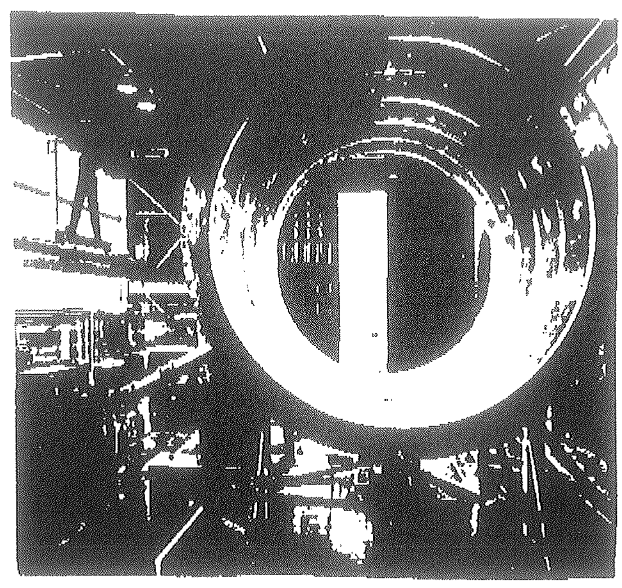

FIGURE 3 H1 Test at RAL

With a helium mass flow rate of ~ 30 g/sec the cooldown of the 25 tonne coil to 90K was achieved in approximately 10 days.

The mass flow through the radiation shields was controlled in order to maintain a temperature differential between coil and shields <10K.

With the system cooled to 90K flow was directed to maintain the shields at 90K under the radiation heat load.

(ii) Cooldown and Operation of the Solenoid coil at 5K. The cooldown of the Solenoid coil to 5K was made using 5K helium gas supplied from a large mobile 30000 litre tanker. In this operation the mass flow through the coil was carefully controlled in order to achieve maximum enthalpy exchange with the gas. Cooldown of the coil required approximately 9000 liquid litres against a perfect efficiency requirement of approximately 7000 litres. With the Solenoid at <10K the helium supply was switched to transfer liquid to the dewar. Circulation of two phase liquid through the coil was established

Cryogenic tests were carried out to confirm heat loads to the coil and radiation shields:-

(a) radiation shields ~600 watts radiation and conduction.

(b) coil static heat load ~100 watts with radiation shields at 90K.

These measurements showed heat loads within the design limits.

Electrical Tests

Electrical tests on the Solenoid coil showed correct performance of joints and superconductor up to 2kA. In addition the electrical test programme was designed to commission the main power supply and protection system.

Correct operation of both slow dump and fast dump protection systems were demonstrated at currents up to 2kA.

Coil temperature rise under fast dump was in line with computed predictions.

DELPHI SOLENOID TEST AND COMMISSIONING

Although a large amount of stage and partial tests were carried out, it was not possible to fully test the solenoid until the final installation in the Experimental Hall.

Pump Down of the Vacuum System

It took 14 days to reach a pressure of 10^{-5} mbar and the overall leak rate was measured as 2×10^{-5} L mbar sec^{-1}.

Cooldown and Cryogenic Tests

The cold box, intermediate dewar (ID) and Solenoid were cooled as one at an average rate of 1.7K/hour from room temperature to 4.5K in 7 days.

Static heat load into the Solenoid, measured by temperature rise of the known mass was:-

	Measured	Calculate Max
Thermal Shield at 77K	900W	2500W
4.5K System	40W	87W

The dynamic heat leak of the coil, transfer lines and ID was found to be higher than expected, namely 147W at 4.5K. This was measured by recording the fall in LHe level in the ID with the refrigerator closed off. The reason for this high heat load is not fully understood at present. The overall heat load on the total system however, is well within the capacity of the refrigerator.

The current leads operated to specification and the total liquification load at 4.5K was 0.823 g/s. This is less than the design figure of 1.1 g/s because the final operating currents through the main leads are 4.1kA and 4.3kA instead of the nominal 5kA.

Powering and Protection Tests

Powering of the Solenoid was carried out in steps of 500A up to 5kA to enable all the equipment to be checked out and to ensure that the protection system could handle the extraction of 110MJ of energy. During this test the temperature rise of the external dump resistor was 100°C compared with the 300°C restriction and the temperature rise of the coil was 34K compared to the computed temperature of 42K.

In commissioning the protection system the response of the quench detector to current changes in the main windings was as expected, but the response to changes in the end trim windings was more complex. This was probably due to the effect of eddy current transients in the coil support cylinder, which made it difficult to maintain a null output from the detector during the first few seconds of the slow run down. This problem was solved by filtering the signal from the mutual inductors.

As mentioned earlier, problems could develop from the rapid decay of the trim currents creating eddy current heating in the coil support cylinder which could initiate a quench. In practice this was the case and the problem was overcome by by-passing the flywheel diodes in the trim power supplies with a shorting contactor during the slow run down, this doubled the decay time.

Magnetic Measurements

In measuring the magnetic field [4] it was found that the properties of the iron yoke were better than expected and the extra ampere turns at the coil ends over compensated for the field fall off. This was corrected by running the trim current in the end turns in the reverse direction to the main coil current. The field measurements also indicated that the Solenoid was offset axially relative to the iron yoke by 6mm. This was also corrected by adjusting the trim currents. The final trim current settings were -700A and -900A.

At these current settings, the field was measured over a cylindrical volume of 202cm radius and 560cm length and out to a radius of 252cm at the ends. The Bz fields at three radii are shown in Figure 4 and are well within the required ± 0.01% over the volume of the TPC. Br was within specification and $B\theta$ was at most ± 1 Gauss within the volume of the TPC and ± 3 Gauss elsewhere. The stability of the field was 0.01% over a 12 hour period.

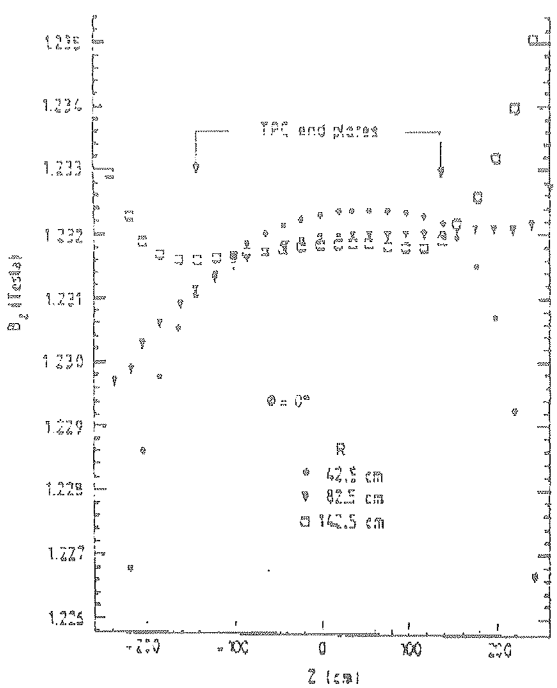

FIGURE 4 Bz Along Axis

CONCLUSIONS

It is now clear that large solenoids can be designed and built to specification by careful use of suitable computation models [1]. In arriving at an optimised design all the requirements for space, materials, heat load, supports, ancilliary equipment etc, had to be carefully examined by several iterations to ensure a practical, safe and economic solution was obtained.

ACKNOWLEDGEMENTS

The RAL H1 and DELPHI Project Teams are grateful to CERN, DELPHI Collaboration, DESY and H1 Collaboration for the opportunity to be involved in these two interesting and challenging projects.

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