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DESIGN STUDY OF AN AIR CORE THIN SOLENOID FOR THE SDC DETECTOR

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DESIGN STUDY OF AN

AIR CORE THIN SOLENOID FOR THE SDC DETECTOR

A. Yamamoto, Y. Doi, T. Kondo, Y. Makida and S. Terada

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Design study of an air core thin supercondcuting solenoid for the SDC detector has been made. The solenoid may provide a central magnetic field of 2 T and bending power of 3.6 - 2.7 Tesla meters within a tracking volume of 3.6 m in diameter and 9 m in length. The transparency of 1.16 (Xo) radiation thickness and 0.25 (λo) interaction lengths may be achieved under adequate safety boundary condition. This report describes the design aproach and status of the design study.. The reliability and safety is also discussed.. .

1. INTRODUCTION

An air core thin superconducting solenoid (Type-S) is being discussed as a possible magnet configuration in the central part of the SDC detector [1,2]. It has following advantages in the magnet and detector design:

1) possible more harmetic calorimeter design because of iron-free space available around the end of the coil,
2) negligible axial and radial decentering forces because of the lage distance to the iron returen yoke and
3) possible full excitation test and evaluation before its installation into the detector because of its basic iron free characteristics.

On the other hand, it is enevitable to have the following disadvantages:

1) less uniform magnetic field in the central tracking volume and large fringe fields extending into the volume occupied by calorimetry and other external detectors, and
2) large axial compressibe force on the winding due to radial magnetic field component

around the coil end.

The trade off study is under progress in detail between the air core colsnoid (Type-S) and a solenoid with iron (Type-I, L) [3]. In the following sections, the design process and status will be described and the reliability and saftey will be also discussed.

1. DESIGN CONCEPT

1.1. Requirements

The requirements and boundary conditions on the SDC solenoid magnet design are summarized as follows,

Magnet size:	
Cryostat Inner radius:	1.85 m
Outer radius:	2.2 m
Cryostat half length:	4.5 m
Tracking volume:	
Outer radius:	1.8 m
Half length	4.5 m
Nominal magnetic field:	2 Tesla
Transperency(η = 0):	<1.2 Xo

As shown in Fig. 1, the tracking volume of 1.8 m in radius and 4.5 m in half length is a guide line for the solenoid design in the EoI of the SDC detector [1]. The field of 2 tesla seems to be close to the limit to realize the thin superconducting solenid. The radiation tihckness of the solenoid should be less than 1.2 at $\eta = 0$ in order to keep the transperency of less than 3 Xo ($X = Xo/\sin\theta$) at η ($= -\ln(\tan\theta/2) = 1.5$.

1.2. Design Aproach

To design the air core thin solenoid the following design aproach has been taken:

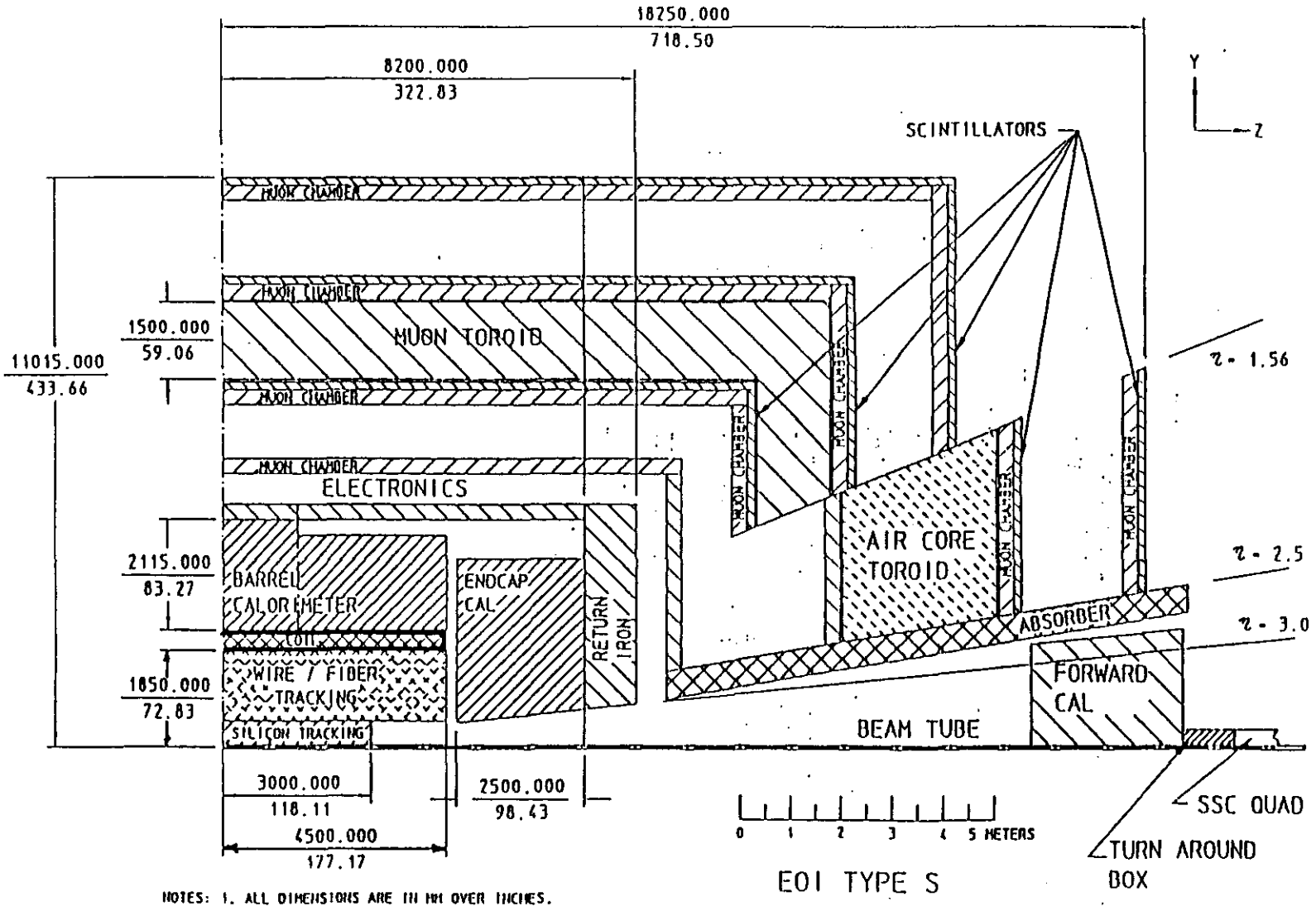


Fig. 1. Cross section of the SDC detector (Type-S).

- As thin as possible and higher E/M required

$1 < X < 1.2$ (at $\eta = 0$)
E/M = 7.5 - 10 kJ/kg

- Must stable and safe against quench and full energy dump into the coil

J / Jc = 50 % on the load line.
T max < 100 K (after quench.)
Vmax < 1000 V
Fast Quench propagator with pure Al strip

- Optional current grading (20 %) at the coil end to improve field uniformity in the tracking volume.

Int. B x dl = 3.6 - 3.0 T.m (@ $0 < \eta < 1.5$)

The E/M ratio defined by [magnetic stored energy] / [cold mass] of the solenoid has been introduced as a simplified parameter to know the lightness and transparency of the solenid. It enable us to know the averaged temperature rise after quench according to the following relation:

$$R = E/M = H(T1) - H(To)$$

where H = INTEGRAL Cp dT is the enthalpy as a function of the temperature. As shown in Fig. 2, the enthalpy of aluminum of 10 kJ/kg corresponds to T1= 80 K and it is a reasonable value to keep the average temperature rise up to T=80 K and to keep the thermal stress still negligible after a quench and full energy dump in the worst case. Figure 3 shows E/M plots as a function of the stored energy in various magnets being operated in high energy physics experiments. Main parameters of the air core solenoid (Type-S)which we have designed with the above concepts are summarized in Table 1. A schematic cross section of the solenoid at the coil end is shown in Fig. 4.

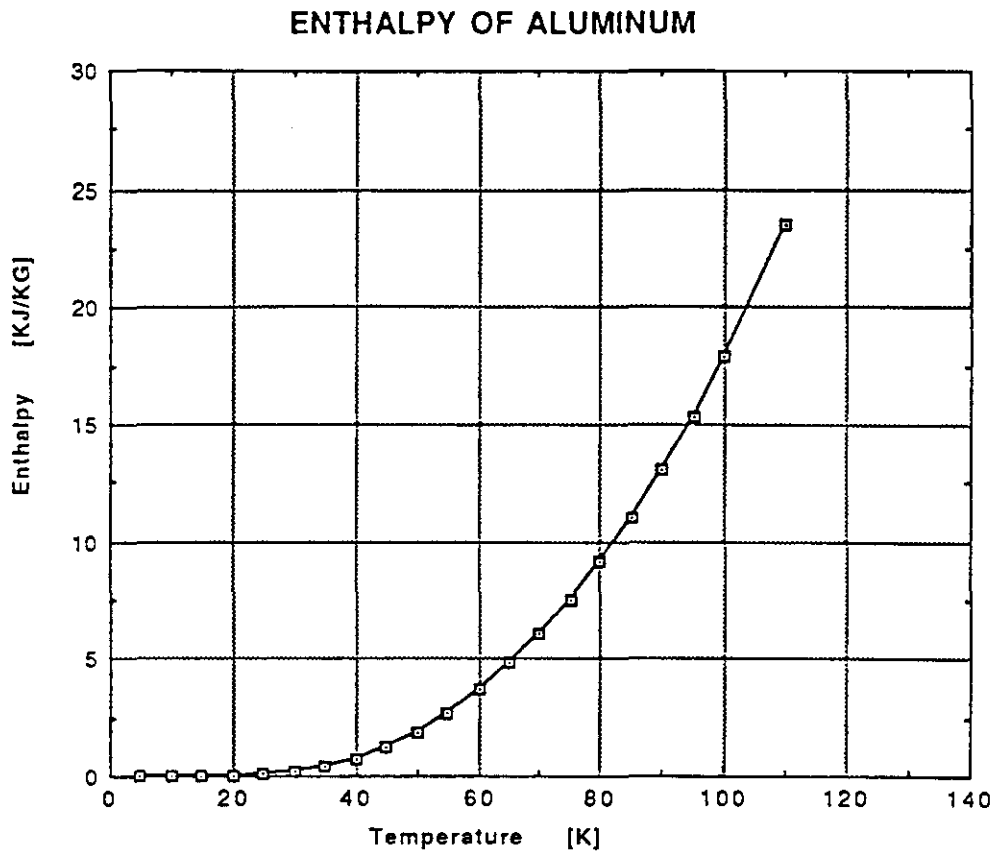


Fig. 2. Enthalpy of aluminum as a function of temperatue.

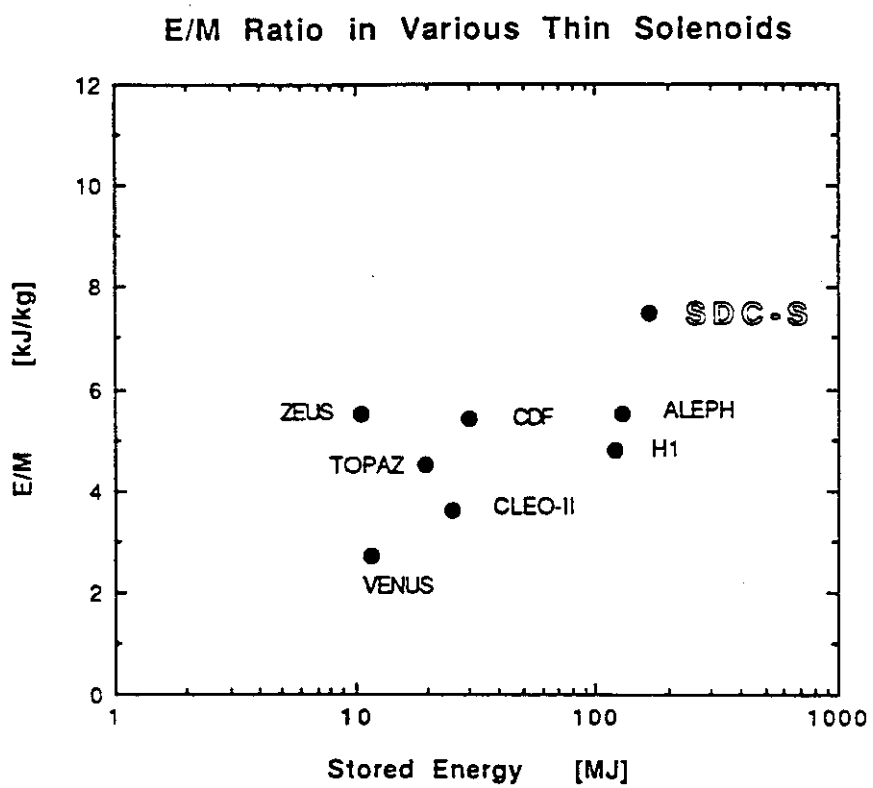


Fig. 3. E/M ratio in thin supercondcuting solenoid used in high energy physics experiments.

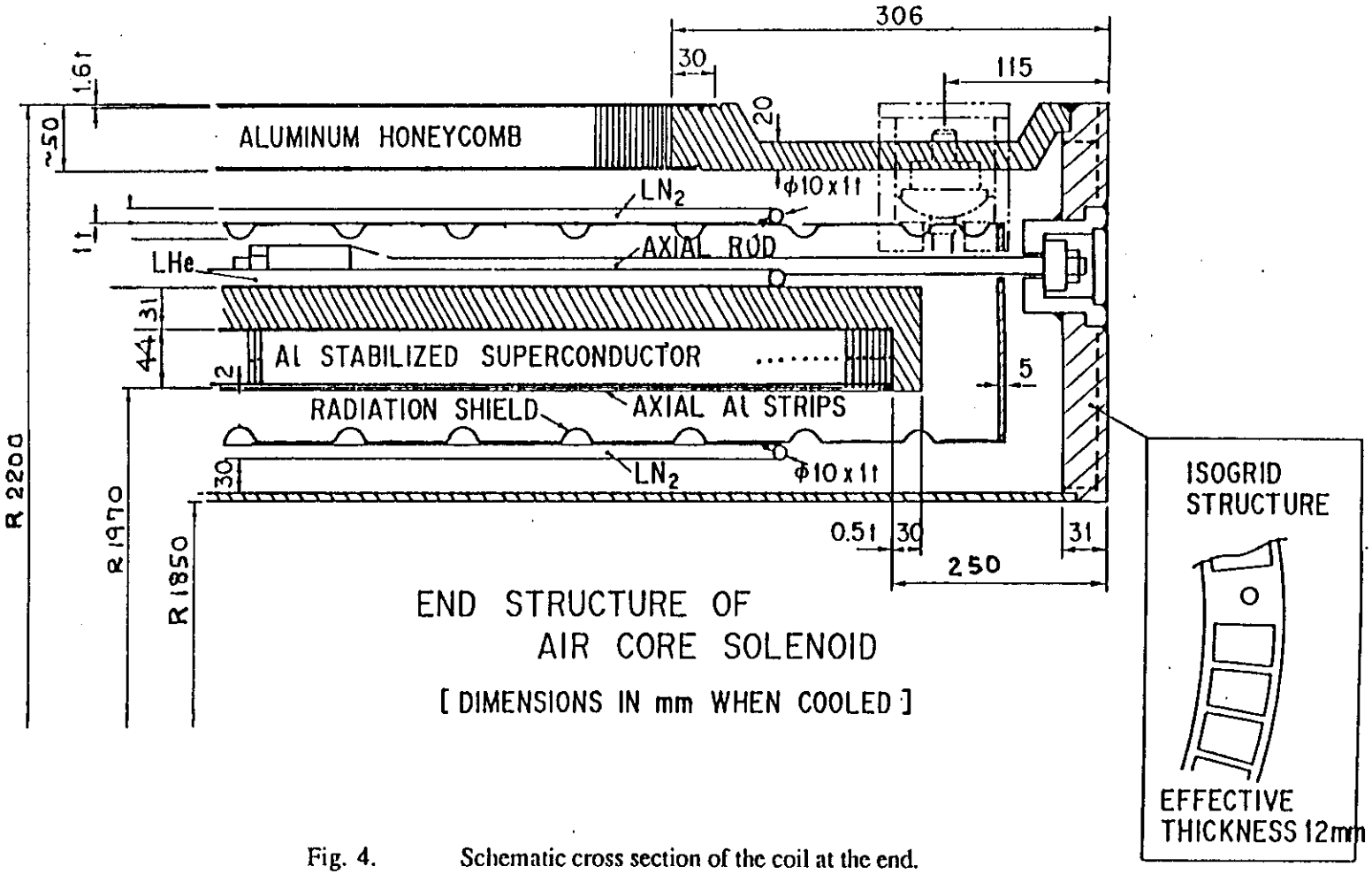


Fig. 4. Schematic cross section of the coil at the end.

Table 1. Design parameters for the SDC solenoid (Type-s)

Design parameters		Ordinal	(Aggressive)
Dimensions:			
Cryostat	Inner radius	1.85 m	
	Outer radius	2.2 m	
	Half length	4.5 m	
Coil	Effect. radius	1.97 m	
	Half length	4.25 m	
	Coil + OSC thick.	44 + 31 mm	
Tracking	Apert. radius	1.8 m	
	Apert Half length	4.5 m	
Transperency	Rad. thickness	1.16 Xo	
	Int. lengths	0.25 λo	
Electrical Parameters			(w/ Grading)
Central Field		2.0 T	
Int. B.dl	(h=0.)	3.6 T.m	(3.6 T.m)
	(h=1.0)	3.4 T.m	(3.6 T.m)
	(h=1.5.)	2.7 T.m	(3.0 T.m)
Nominal Current		10,000 A	
Inductance		3.31 H	(3.64 H)
Stored Energy		166 MJ	(182 MJ)
E/M		7.5 kJ/kg	(8.3 kJ/kg)
Mechanical Parameters			
Effective cold mass		22 tons	(22 tons)
Total weight		32 tons	
Mag. radial pressure(@z=0)		1.6 MN/m^2	
Axial total compressive. force		20 MN	
Superconductor			
Nb.Ti/Cu/Al ratio		0.5/0.5/29	
Overall conductor size		5.5 x 44	(4.6 x 44)
Nb.Ti/Cu cable size		1.6 x 5	
Load line ratio (@2,2 T, 4.2 K)		50 %	
RRR of Pure Al (@B=0 T)		750	
Yield strength of pure Al		>4 kgf/mm^2	

3. FIELD QUALITY

The field distribution of the air core thin solenoid has been evaluated with program ANSYS and an analytical calculation. Figure 5 shows the flux lines and contour plots with ANSYS in cylindrical symmetry coordinates. Figure 6 (a) shows field integral of (Integral B x dl) as a function of pseudorapidity, η . The field uniformity is improved by current grading with 20 %

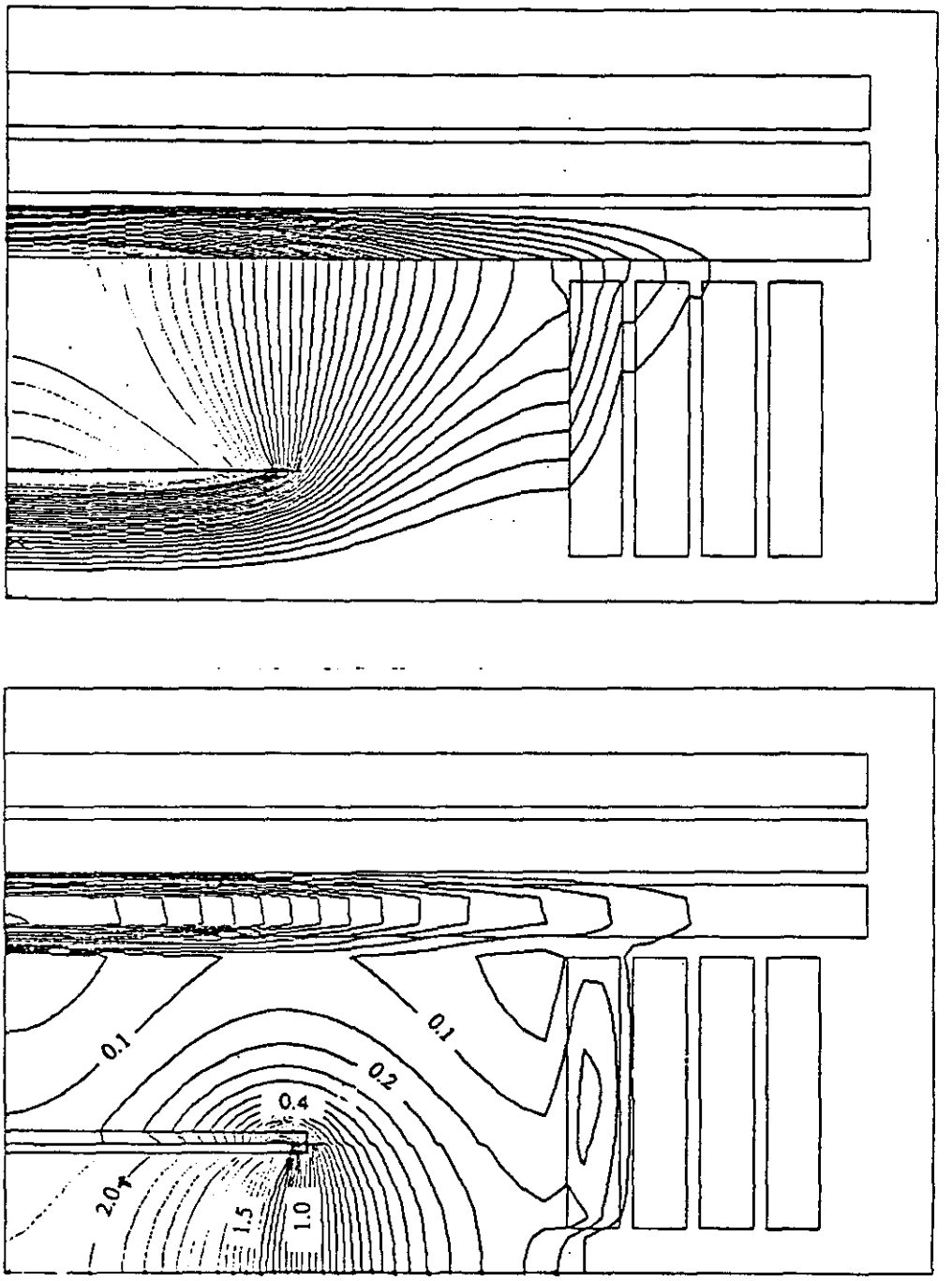


Fig. 5. Magnetic field distribution in the Type-S thin solenoid: flux lines (top) and field contour lines (bottom)

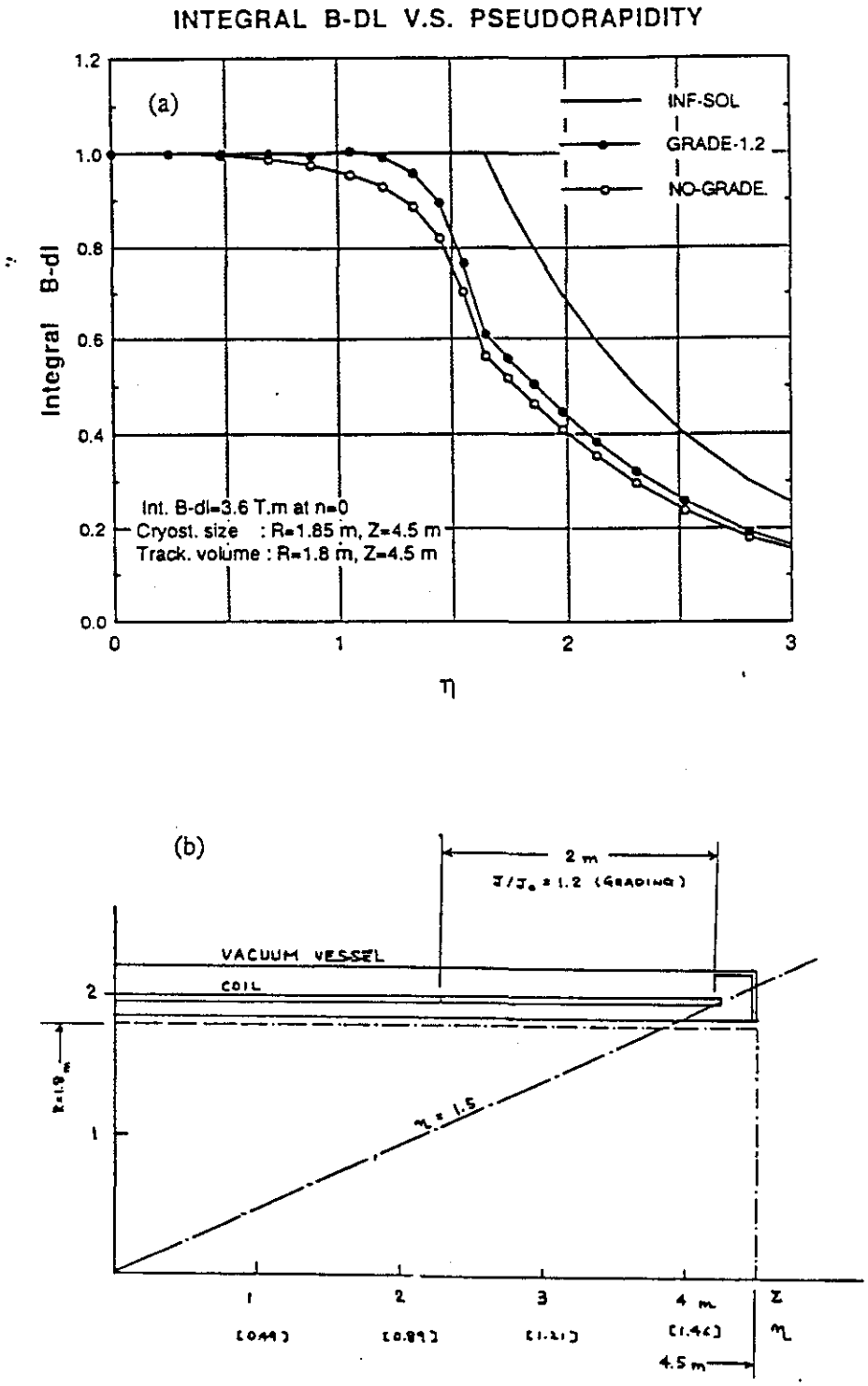


Fig. 6 (a) Field integral (B x dl) as function of pseudorapidity.
(b) Current configuration in the coil and field integrated volume.

higher current density at the coil end of 2 m as indicated in Fig.6 (b). The field integrals in each case are summarized in Table 2.

Table 2. . Integral **B x.dl.** as a function of pseudorapidity.

	Pseudorapidity	no-grading	w/ grading
Int. **B x.dl**	(η=0.)	3.6 T.m	3.6 T.m
	(η=1.0)	3.4 T.m	3.6 T.m
	(η=1.5)	2.7 T.m	3.0 T.m
	(η=2.0)	1.4 T.m	1.6 T.m

*Grading: 20 % high at the coil each end of 2 m in length.

4. TRANSPERENCY

The transparency of the solenoid wall was calculated as summarized in Table 3. The radiation thickness of 1.16 Xo and interaction length of 0.25 λo were obtained in this configuration. We assumed that the E/M ratio is 7.5 kJ/kg with no curent-grading at the coil end. In the case with current grading, the E/M ratio will be increased to 8.3 kJ/kg with the same physical design except for the current density at the coil end.. Figure 7 shows radiation thickness as a function of η.

Table 3. Transperency of the air core thin Solenoid (Type-S).

Element	t-eff	Xo	λo_
Outer vac. Vessel (Al-HNC)	8	0.090	0.0203
Outer rad. shield	2	0.025	0.0051
Outer support cylinder	31	0.348	0.0787
Superconductor			
(Al stab and strip)	42.5	0.478	0.1079
(Nb.Ti/Cu)	1.5	0.094	0.0086
(Ins)	2	0.011	0.0038
Inner radiation shield	2	0.025	0.0051
Inner vac. vessel	7	0.079	0.0178
Super-insulation	2	0.005	0.0023
Total		1.16	0.250

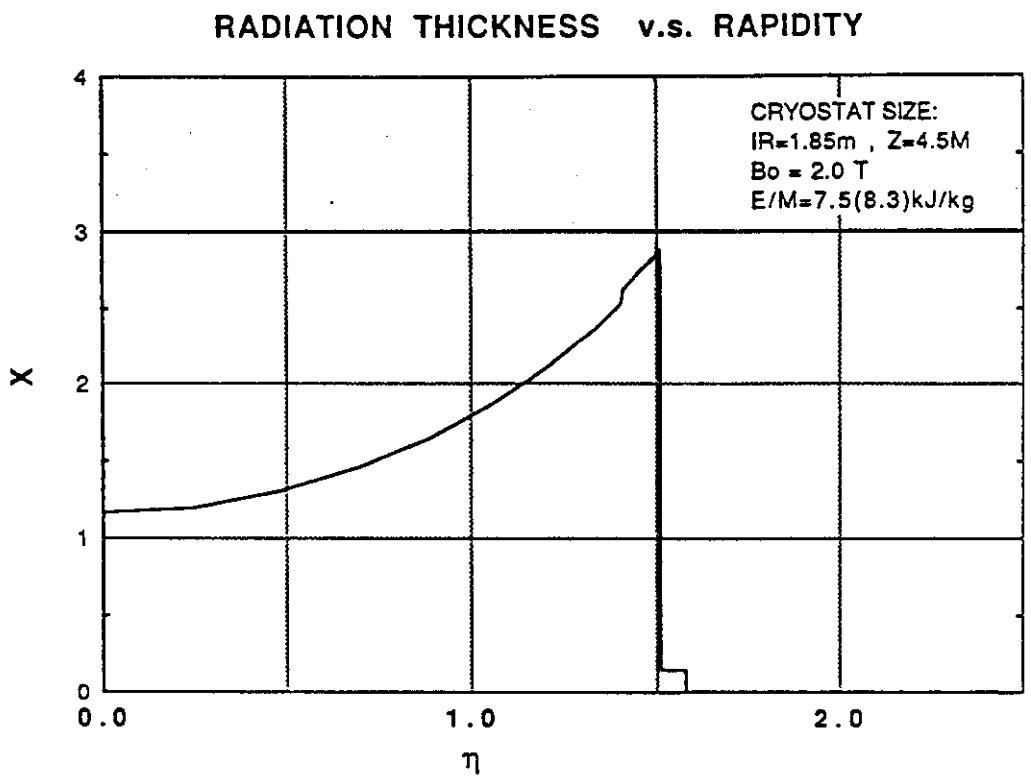


Fig. 7. Radiaton thickness of the coil as a function of pseudorapidity.

In the above table, the following basic parameters are assumed:

Material	Xo	λo
aluminum	89 mm	394 mm
copper	14.3 mm	151 mm
superconductor	16 mm	174 mm
GFRP	190 mm	530 mm
Mylar(SI)	287 mm	857 mm

5. MECHANICAL STABILITY

The mechanical stability in the coil and support structure was evaluated with the finite element analysis [4]. Main results are summarized in Table 4. The mechanical stress in each material is acceptable and the system should be mechanically stable enough.

As described below, it has been recently found that mechanical strength of pure aluminum can be improved by using cold-work technique in addition to control the purity of aluminum and heat treatment [5]. As a result, a yield (0.2 %) strength of 5.7 kgf/mm2 has been obtained at liquid nitrogen temperature, 77 K. This result enables us to consider mechanical design under fully elastic condition as simply described below.:

Radial magnetic pressure in a long solenoid is approximately given by

$$p_r = B_z^2 / 2\mu o = 1.6 \times 10E6 \ N/mm^2 = 0.16 \ kgf/mm^2$$

Therefore, hoop stress in the coil and support cylinder is

$$\sigma_\phi = R/t \times p_r = 2000/75 \times 0.16 = 4.3 \ kgf/mm^2 < 5.7 \ kgf/mm^2$$

On the other hand, the axial force into the coil in the long solenoids is approximately,

$$F_z = dE/dz = B^2 / 2\mu o \times V / z_{coil} = B_z^2 / 2\mu o \times S_{ap} = 2 \times 10^7 \ N = 2{,}000 \ tonf.$$

where E is the stored energy, z is the effective coil length, V is the magnetic volume, and Sap is the area of effective magnetic aperture. Therefore, the averaged axial stress in the coil and support cylinder is

$$\sigma_z = Fz / (2 \pi R t) = 2.1 \text{ kgf/mm}^2 << 5.7 \text{ kgf/mm}^2$$

Then, mechanical strain in the system should be less than 0.1 % as follows:

$$\varepsilon = \sigma / E < 5 / 7{,}000 = 0.07 \%.$$

We have seen, here, it is very helpful to improve the mechanical strength of pure aluminum in order to make sure the mechanical stability and reliability in the SDC thin slenoid, although it is also necessary to make a trade-off study between mechanical stability and quench behaviour.

Table. 4. Computed Mechanical stability of the SDC air core solenoid.

	Cylinder	Stabilizer	Insulator
Material	A5083-O	4N7 Al	GKG/Epoxy
RRR		810	
Young's modulus [kgf/mm2]	7500	7000	3450
Tension. Stress [kgf/mm2]			
Tensile strength (@LN2)	41.5		>20
0.2%Yield st.(@LN2)	16.9	>4	>10
Computed max. stress	9.3	3.8*	<4.2
Shearing Stresss			
Shearing strength(@LN2)			>1.5
Computed max. sh. stress			<0.4
Strain			
Computed max. strain	0.0012	0.0012	0.0012

* Yield strength of 4 kgf/mm^2 assumed

6. QUENCH PROTECTION AND SAFETY

The safety of the solenoid against quench was evaluated with the program "QUENCH". When the protection switch works correctly, the coil must be safe and the peak temperature in the coil is less than 60 K, because the main part of stored energy may be extracted and dumped into the protection resistor of about 0.1 ohms. When the protection switch is failed to work, whole the energy must be dumped into the coil. The peak temperature was computed to be below 100 K with the aid of pure aluminum strip quench propagator [6, 7]. In the worst case with no quench propagator and no quench-back action from the support cylinder, the peak temperature may reach close to 160 K. The calculated results are summarized in Table 5. We conclude this coil will be safe enough against quench.

Table. 5. Quench behaviour and safety condition.

	Switch active	Switch failed
Energy dump in coil / cylinder:	20 MJ	166 MJ
Eneregy dump ratio in coil/cyl.:	12 %	100 %
Averaged temp. rise in coil/cyl:	45 K	75 K
Peak temperature (Tp) in:		
coil with pure Al strips	<60 K	<100 K
coil w/o pure Al strips	<60 K	<160 K

* RRR=750 in Al stablizer and no current grading assumed.

7. STATUS OF R & D FOR THIN SOLENOIDS

7.1. R & D for Al stabilized superconductor

It is one of the most important R & D items to improve (or optimize) mechanical strength of aluminum stabilizer in the superconductor with keeping appropriate residual resistance ratio (RRR). Recently, this effort has been made in the R & D program for superconducting magnets in the particle astrophysics magnet facility project, ASTROMAG [8]. By using the

following process, we could control and improve mechanical strength of pure aluminum stabilizer.

Initial condition:		Purity...4N7 (99.997 %)
Process:	-	Co-Extrusion with Nb.Ti/Cu conductor,
	-	Drawing (Cold-work for Size Reduction),
	-	Heat treatment to simulate curing process of the coil.
Characteristics:		
RRR:		810 (R300 K / R 10 K)
Yield strength:		5.7 kgf/mm**2 (@LN2 temp.)
Ultimate Strength:		14.1 kgf/mm*2 (@LN2 temp.)

The cold work dependence of 4N7 pure aluminum on the mechanical strength is shown in Fig. 8. The above technique can be applied in the SDC solenoid and it may be possible to improve strength up to 6 kgf/mm^2.

The followings are further R and D work suggested to be done for the superconductor in the SDC solenoid.

- Optimization of conductor parameters, especially for RRR and Y.S.
- Co-extrusion with cabled superconductor,
- Large and high aspect ratio (aprox. 10) superconductor,
- Long conductor and superconducting joints,
- Electrical insulation: material, thinness and strength.

7.2 R & D for Honeycomb vaccum vessel

It is obvious that honeycomb structure in the outer vaccuum vessel much help to reduce material in the cryostat wall. The ordinal honeycomb structure, however, is not designed to have harmetic structure to use it in the cryostat. A R & D effort to develop completely harmetic honeycomb structure to guarantee the quality of metal sealing (10^{-9} Torr.l/sec) has been carried out at KEK [9]. A model honeycomb cryostat has been developed with the parameters given in Table 6. Figure 9 shows of pictures of the develped harmetic honeycomb

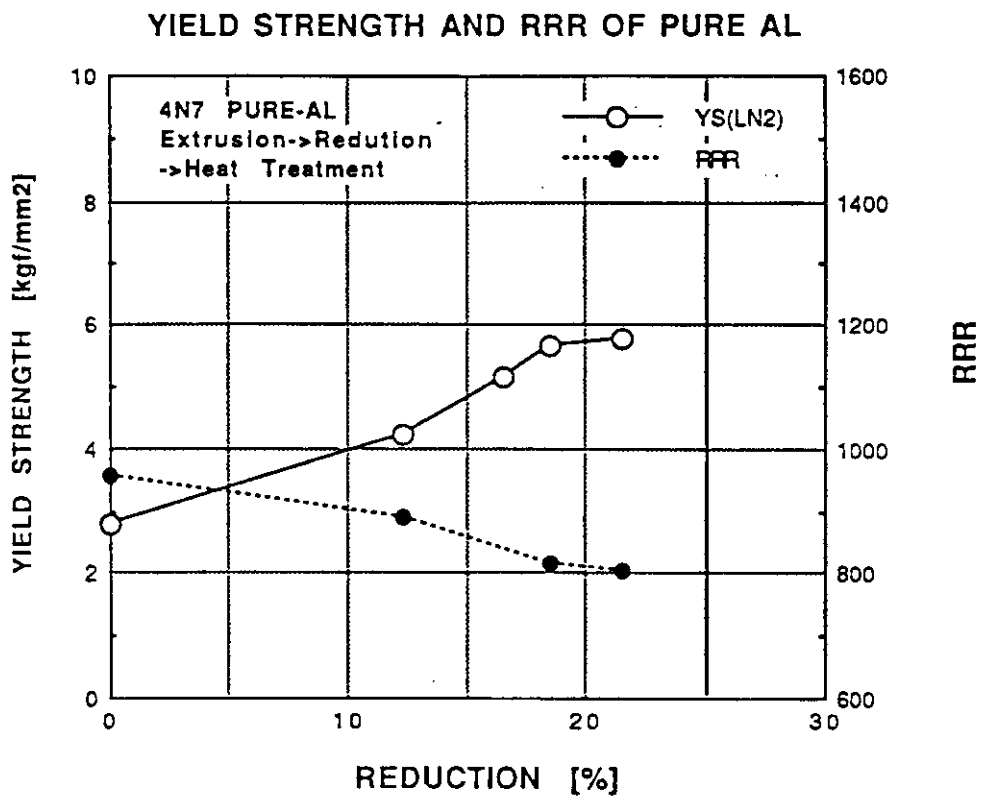
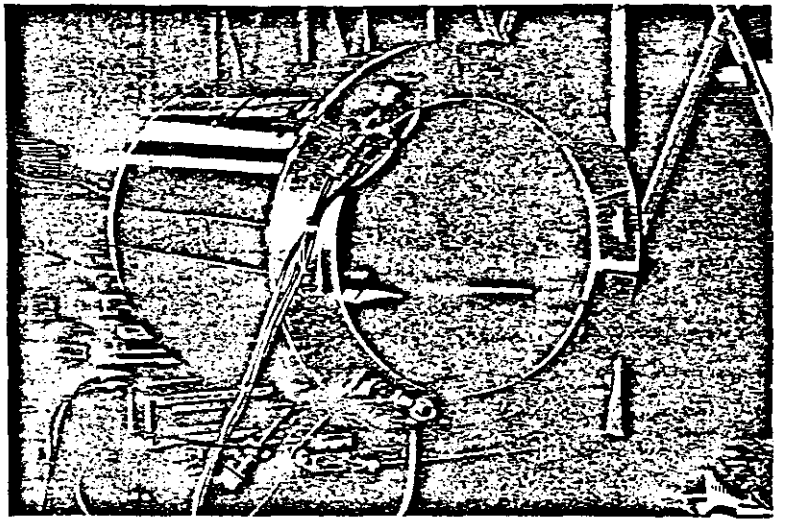


Fig. 8. RRR and yield strength of pure aluminum stabilizer as a function of size reduction ratio during cold work.



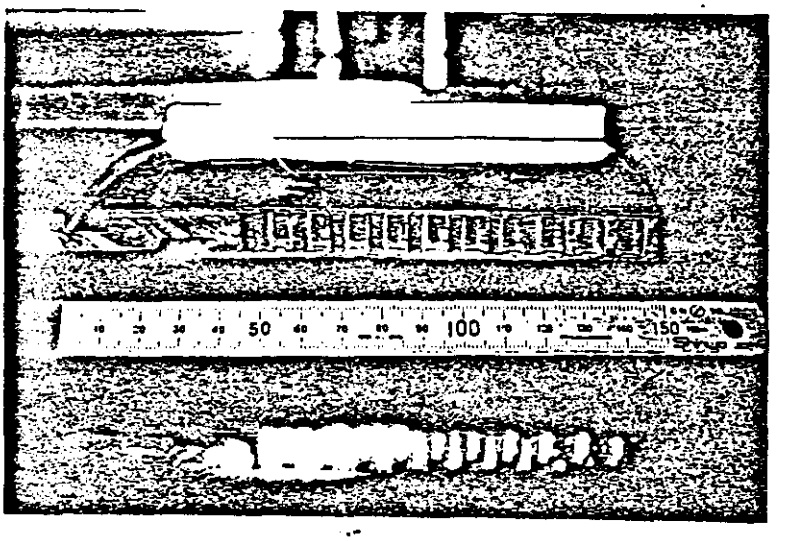


Fig. 9. A test cryostat fabricated with harmetic honeycom structure in outer wall.

Table 6. Main parameters of the model honeycomb vacuum vessel.

Vac. vessel:	1.2 m in diameter,
	1.5 m in length
Wall skin:	1 mm
core:	10 mm
End flange:	Isogrid configuration
	(t-min = 2 mm)
Buck. ext. pressure:	>5 atm (in design)
Weight reduction ratio:	1 / 3.6 (barrel wall)
	1 / 1.7 (end flange)
Performances:	
Pressure	5.4×10^{-6} Torr in 23 h
He Leak rate:	$<1 \times 10^{-9}$ Torr.l/sec
Build-up rate:	3.9×10^{-5} Torr.l/sec
Test pressure: difference	dP = 1 atm. external.

cryostat . A similar R and D work has been done by Toshiba Co. Ltd. to fabricate a superconducting magnet for cosmic ray balloon experiments, as mentioned below.

7.3. R & D for High E/M magnet.

An air core thin solenoid (PCMAG) has been developed for the balloon borne experiment, BESS, to search for cosmic- ray antimatter with the following parameters [6,7].

size	:	1 m ϕ x 1.3 m
Bo	:	1.2 T
E	:	815 kJ
E/M	:	7 kJ/kg
X	:	0.2 Xo

The development has been successfully carried out and this experience is being very useful to consider the SDC solenoid design with a high E/M ratio of 7.5 kJ/kg or more. The pure

aluminum strip technique [6] to homogenize the coil temperature and to enhace quench propagation velocity will be also applicable in the SDC solenoid.

The following items are suggested for further R & D work to be done for the SDC coil fabrication:

- Full size (4 m diameter) coil winding to establish widing technique and reliable bonding of the coil to the outer support cylinder by using epoxy resin.
- Development of one quater scaled model magnet to investigate the higher E/M ratio (for example, 10 kj/kg) and full energy dump in the coil.

8. SUMMARY AND CONCLUSION

1. The air core thin solenoid is feasible to be built for the SDC detector with the following parameters:

Half aperture size		1.85 m(R) x 4.5 m (Z)	
Central magnetic field		2 Tesla	
			(w/ grading)
Integral B.dl	(η =0.0)	3.6 T.m	(3.6 T.m)
	(=1.0)	3.4 T.m	(3.6 T.m)
	(=1.5)	2.7 T.m	(3.0 T.m)
E/M		7.5 kJ/kg	
Transparency (η =0.0)		1.16 Xo	
		0.25 λo	

2. Basic technologies to realize more tranparent solenoids are being established, i.e.:

   - E/M Ratio of 7 kJ/kg,
   - High strength pure Al stabilizer (Y.S= 5.7kgf/mm^2):
   - Honeycomb structure in outer vacuum wall

3. Further R and D efforts may be suggested to establish the technology to realize large scale air core thin solenoid for the SDC detector as follows:

- Higher mechanical strength in pure aluminum,
- Large and high aspect-ratio superconductor,
- Winding technique of the coil and reliable bonding techniq to the support cylinder

4. The air core solenoid (Type-S) has a disadvantage to support the axial magnetic force by itself due to no iron mirror boundary. On the other hand, it should be a big advantage that full excitation test can be completed without iron structure.

5. It is true that the iron dominated solenoid (Type-I and L) is free from the axial force in normal operation with iron structure. However, it is also true that the magnet must be tested in air before installation into the iron return yoke structure. It means that the iron dominated solenoid also will have to support large axial force in the performance test process in air, even if the full excitation is not intended.

6. We consider that the SDC solenoid magnet should be based on the concept of the air core solenoid design. The additional radiation thickness to take the air core solenoid design should be less than 10 %. Then, the solenoid can be fully tested in air in either case of the Type S or the Type I/L. It may be more conservative way to integrate the detector sytem reliably, and it is also important issue in the large scale detector construction.

ACKNOWLEDGEMENT

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