2.6 The ILD Yoke and Coil System

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2.6.1 Physics Requirements

_ Magnetic Field

The basic layout of the ILD detector has always followed the strategy of tracking in a magnetic field. The large detector version (lower field in a larger volume) was found to have a better overall performance than the smaller one (higher field in a lower volume). So, the ILD detector design asks for a 4 T central field in a warm aperture of 6.88 m in diameter and 7.35 m long. Because of the presence of an anti DiD (Dipole in Detector) to clean the beam around the IP, no special field homogeneity is requested despite the presence of the TPC. Only an accurate field mapping will be requested. Some constraints have also been put on the fringing field, partly because of the push-pull operation: less than 50 G @ R = 15 m from the IP in the radial direction, and less than 100 G @ z = 10 m from the IP in the longitudinal direction.

The iron yoke, besides shielding the magnetic field, will be instrumented to be used as a high muon identifier (muon tagging and tail catcher). Consequently, the total segmented iron thickness is around 3 m.

2.6.2 Magnet Design

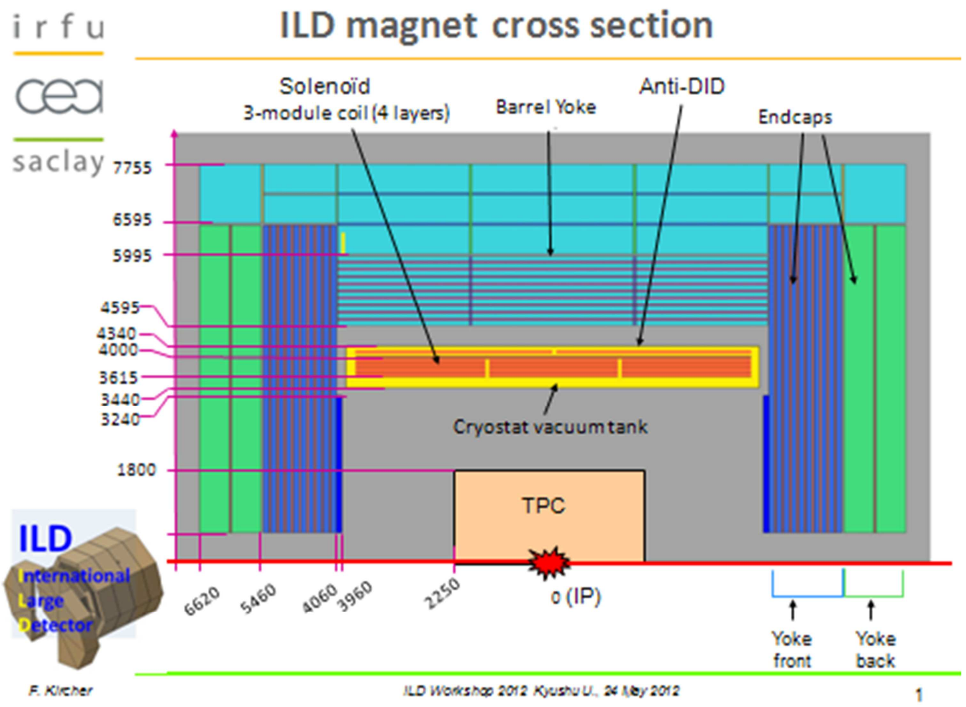
2.6.2.1 Generalities

The ILD magnet design is very similar to the CMS's one, except for its geometrical dimensions, and consequently, many technical solutions successfully used for CMS are proposed for ILD

The magnet consists of three parts:

- the superconducting solenoid coil, made of 3 modules, mechanically and electrically connected. With its thermal shields, it makes up the cold mass within the vacuum tank
- the anti DiD, a Dipole in Detector, located on the outer radius of the main solenoid, the dipolar magnetic field of which enables to clean the beam around the IP. This anti DID is presently designed to generate a dipolar field of 0.025 T @ z = 2 m from the IP (value to be confirmed)
- the iron yoke, consisting of the barrel yoke and the two end-cap yokes, all of them laminated to house muon detectors

A general cross section of the magnet is given on Fig. 2.6.1



ILD magnet cross section

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ILD Workshop 2012 Kyushu U., 24 May 2012

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Fig 6.2.1: ILD magnet cross section (just keep figure + dimensions)

2.6.2.2 Magnet main parameters

The main geometrical, magnetic and electrical parameters of the ILD magnet are summarized in Tab 6.2.1

Tab 6.2.1: ILD magnet main parameters

Cryostat inner radius (mm)	3440	Design solenoid central field (T°)	4.0
Coil inner radius (mm)	3615	Maximum field on conductor (T)	4.5 (TBC)
Coil outer radius (mm)	4000	Field integral (T*m)	32.65
Cryostat outer radius (mm)	4340	Stored energy (GJ)	2.2
Barrel yoke inner radius (mm)	4595	Stored energy per unit of cold mass (kJ/kg)	11.7
Barrel yoke outer radius (mm)	7755	Nominal current (A)	21.7
Coil length (mm)	7350	Total ampere-turns solenoid (MAt)	27.35
Cryostat length (mm)	7810	Stored energy (GJ)	2.2
Yoke overall length (mm)	13240	Inductance (H)	9.26

The weight of the different parts are respectively XXX t for the cold mass, YYY t for the barrel yoke, ZZZ t for the end cap yokes, giving a total magnet mass of TTT t.

2.6.3 Solenoid design

The total length of the ILD coil enables to make it in 3 modules, each 2.45 m long. The reasons of this choice of 3 modules, rather than 2 or 1, are multiple as easiness and risks are concerned: fabrication of the external support, winding and impregnation, transport and handling. Moreover, this enables to have shorter unit lengths of conductor of about XXXkm and to join them in known position, and in low field regions, on the outer radius of the main solenoid.

Each module has 4 layers, with 105 turns per layer. The nominal current is 21.7 kA for the design central field of 4 T.

2.6.3.1 Superconducting conductor

The conductor design is similar to the CMS one. It consists of a superconducting cable, electrically stabilized and mechanically reinforced. Two solutions are possible for the reinforcement: micro-alloyed material such as the ATLAS central solenoid [ref] (R&D on Al-Ni underway with large cross section) or 'à la CMS' [ref] (Al-alloy + high purity Al). Compared with CMS, the number of strands in the cable has been slightly increased to take into account the larger nominal current (36 strands instead of 32), and the conductor width has also been slightly increased to take into account the larger hoop stress. The overall bare dimension of the conductor is 73*22.3 mm^2. The conductor load line is given on Fig. 6.2.2, showing that the temperature margin is around 1.93K, assuming a maximum operation temperature in the coil of 4.5 K.

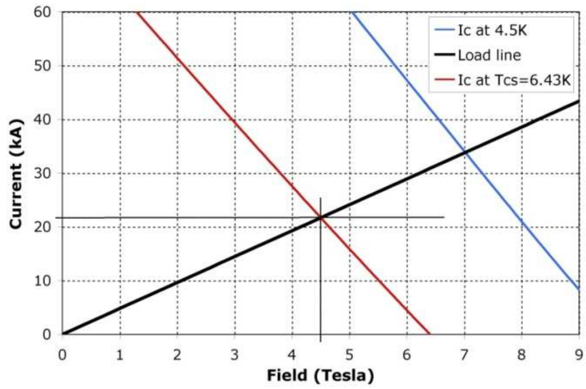


Fig. 6.2.2: conductor load line (from CMS strand data Ic = 3000A/mm^2 at 4.2 K and 5 T)

2.6.3.2 Coil structure and winding technical aspects

The winding will be done inside the coil mandrel, similarly to CMS, with the inner winding technique. This Al-alloy mandrel, about 50 mm thick, has several important other roles, as it will also be used as a mechanical support, a path for the indirect cooling of the coil (done with cooling tubes where liquid helium circulates welded on the outer radius of the mandrel), and a quench back tube (induced currents in this mandrel in case of quench or fast discharge enable an uniform quench of the coil and a limited radial temperature gradient). Both the anti-DiD and the tie rods supporting the whole cold mass will be attached to the mandrel.

The electromagnetic forces will be contained both by the local reinforcement of the conductor and by the outer mandrel. The design has been done to have the same maximum stress and strain than in CMS (respectively 145 MPa and 0.15 %).

The cold mass will be indirectly cooled by saturated liquid helium at 4.5 K, circulating in a thermosiphon mode. This mode, already successfully used for Aleph and CMS, has the advantage of being passive. The expected cryogenics loads are given in § 2.6.6.3.

2.6.3.3 Coil protection

In a classical way, the coil protection in case of quench uses an external dump circuit. With a dump voltage of 500 V, about half of the stored energy is discharged outside the magnet, and the maximum temperature within the coil does not exceed XXX K. Although a large redundancy will be used for the quench detection and dump actuators, this temperature reaches YYY K if the external dump process is not activated.

2.6.4 Anti DiD design

2.6.4.1 Main parameters and characteristics

The anti-DiD will provide a magnetic field of 0.025T at Z=2m from IP on detector axis.

Figure XX. Field B=F(z) on detector axis

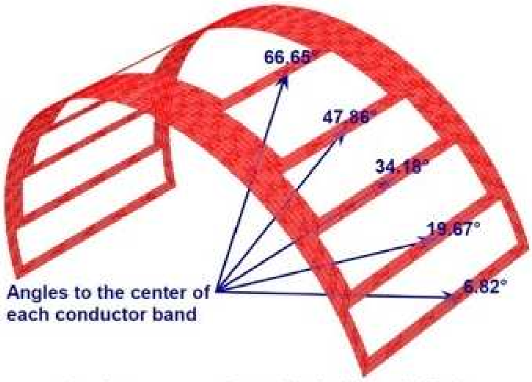
For integration reason, the anti-DiD is within the cryostat close to the main solenoid. It benefits from the cryogenics of the main coil. It is located in the low field region on the outside radius of the main solenoid, which is favorable for the temperature margin of the superconductor.

The superconductor shall be aluminum stabilized for protection against quench, as it will be indirectly cooled with the same cryogenics as the main coil and in thermosiphon mode. The protection of the superconductor against quench is achieved by activating heaters to trigger the fast dump of the current. This will bring the whole anti-DiD in resistive state to ensure a uniform temperature distribution to avoid a large thermal gradient around the hot spot and the associated stresses and distortions that could be destructive. The quench heaters shall also be triggered in case of fast dump of the main solenoid as the refrigeration is stopped in such a case, but inversely, the protection system shall avoid the fast dump of the main coil in case of fast dump of the anti-DiD.

The preferred superconductor is NbTi to tolerate some deformation of the winding pack with the cooling from 300K to 4.2K and the magnetic forces, but other superconductor (like Nb3Sn and MgB2) shall be re-evaluated at a more advance stage of the design according to the superconducting technology development.

2.6.4.2 Manufacturing of the anti DiD

The manufacturing of the 4 poles constituting the anti-DiD shall be independent from main coil. It shall be done in parallel with a specific tooling in common for each pole fabrication. The 4 poles will be made of a one-layer winding pack, with a distribution of the turns in phi as shown in fig. YY.



Conductors are reflected in the *XY* and *XZ* planes

Fig YY.

It is proposed a winding on a coil casing. The coil casing will be made from bent aluminum alloy profiles attached to a dedicated mechanical frame, on its outer radius. The casing will first be partially assembled in order to be able to wind the conductor, using an outer winding technique, then it will be completed at the end of the winding process to fully clamp the winding pack. To ensure the mechanical integrity of the coil casing, and the homogeneity of the winding pack, wedges with dummy conductor can be used. For the completion of the coil casing, bolted or welded solutions can be applied. Welding solutions with low energy deposit and low deformation will be used, such as the electron beam welding. The superconductor shall be wrapped with a fiber glass mat to reinforce the insulation between turns. Similarly to the ATLAS barrel toroids [ref], the conductor will be blocked against the casing walls by bladders inflated with pressurized epoxy resin. A vacuum impregnation shall be performed at this stage with epoxy type resin, together with the associated curing thermal heat treatment which can provide some stress relief.

The mechanical supporting frame will be used for coil casing assembly, conductor winding, vacuum impregnation, until the anti-DiD pole final assembly on the coil, when a complementary structure will be necessary to do the anti-DiD pole coupling on the outer mandrel of the main solenoid. These structures will allow a blank assembly at the manufacturer premises of the anti-DiD pole on a two-module stack of the main solenoid before the vacuum impregnation. If needed, machining or mechanical shimming shall be possible. The stress level in the bent profiles of the DiD shall be estimated and kept to a minimum to limit the pre-stress level. The winding procedure and toolings shall be validated with a winding test using a dummy conductor (aluminum profile without superconducting cable).

2.6.5 Assembly of the coils

The three modules of the main solenoid will be assembled on the ILC experimental site in a surface hall. The three modules will be stacked vertically for the mechanical coupling. The electrical joints and helium tubing will be connected before the assembly of the anti DiD. The anti DiD will be assembled with the main solenoid in the same vertical position. The final assembly of the anti-DiD poles will be done on the experimental site after the completion of the solenoid assembly. The mechanical coupling of the poles will be made on dedicated shoulders located on the external radius of the main solenoid mandrel. The mechanical support frame of each anti DiD poles will be removed after their fixing on the mandrel. This support system will be designed to allow the deformations due to both the thermal shrinkage during cool down from 300K to 4.2K, and the deformation of the main solenoid when it is energized. The electrical joints between the 4 poles shall done in a similar way as the joints between the layers and modules of the main solenoid. The helium tubing of the anti DiD will be connected to the helium feeding manifolds.

After the installation of the thermal screens and the multilayer insulation on the coil in vertical positions, the cold mass is ready for the final introduction in the cryostat. The cold mass is swiveled to the horizontal position on its supporting platform, and inserted into the outer cylinder of the vacuum tank which is fixed in cantilever to the central yoke barrel. The coil is then attached to the outer cylinder of the cryostat with several longitudinal and radial tie rods.

2.6.6 Ancillaries

2.6.6.1 Power circuit:

The power circuit must include a dump resistor always connected to the magnet to ensure the safe discharge of the magnetic energy by disconnecting the power supply.

The power supply will allow to ramp up the current with a control rate for a typical total ramp up duration of about 4 hours. A two quadrant converter will offer the possibility to ramp down the field at intermediate values for intervention. The nominal current will be delivered with a precision of a few ppm. The converter will be located in the underground service area, to limit the voltage drop on the powering lines.

The superconducting (SC) high critical temperature (Tc) is a preferred option for the flexible power lines. Such a line is cooled by the helium gas coming from the magnet back to the refrigerator, with a temperature between 5K and 20K. These flexible lines can be permanently connected to the magnet both for the on-beam and garage positions. The bending radius of the SC power lines has to be known to finalize the integration studies to allow the movement from the garage to the on-beam position. Compared to the conventional copper busbars, the SC high Tc line also brings less power dissipation, it is less heavy and massive to support and integrate.

The connection between the superconducting coils (main solenoid and anti-DiD) and the SC high Tc power lines will be made with a superconducting busbar made of copper stabilized Nb3Sn cable with gas helium cooling at 4.2K, located inside a specific chimney across the yoke thickness. The diameter of this chimney will therefore be minimized with comparison to the conventional copper current leads with one extremity at room temperature.

The current leads shall be built as well with high Tc superconductor. They will be located outside the yoke. In this configuration, their length can be reduced. Two pairs of current leads are needed: one pair to connect the dump resistor on top of the yoke, the other pair in the service area at the other extremity of the SC high Tc power lines to connect the power converter.

The dump resistor must be designed to dissipate either the full magnetic energy in case of slow dump (SD) with a time constant about=9300s and a peak power=480 kW, or about half of the magnetic energy in case of fast dump (FD) with a time constant=420 s and a peak power=11MW. The power lines connecting the current leads to the dump resistor must be sturdy enough against the SD and FD even in case of failure of their cooling system. The dump resistor has to be located on top of the magnet as the dump resistor cannot be connected to the magnet through high Tc flexible power lines for safety. The resistor design shall be compact, with two configurations for the SD and the FD, selected with locally installed power contactors.

The main switch breakers are doubled for safety. They are located in the service underground area near the power supply.

The anti-DiD will have its own power circuit with similar characteristics as the one described for the main coil (power supply, high Tc power lines, current leads, dump resistor). The same chimney will be used to connect the solenoid and the anti-DiD to the power lines.

2.6.6.2 Control and safety systems

- Magnet control system for all operation phases, plus a magnet safety system to safely discharge the energy of the magnet.
- Quench detector comparing voltage across the coil modules (2x3 QDs for redundancy) and the anti-DiD poles (2x4 QDs), plus QDs on SC busbars connecting to the high Tc power lines.
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2.6.6.3 Cryogenic plant

The same refrigerator will be used to cool the main solenoid and the anti did.. It shall also be able to extract the dynamic losses during the magnet ramps, during a SD of the main coil and a FD of the anti DiD.

- Compressors at the surface, with gas He tank storage, and LN2 tank for pre-cooling and compressed air back up for the pneumatic valves.
- Helium liquefier in underground service area, for both the liquid helium supply and the helium gas return from the magnet and the high Tc power lines and current leads.

On top of the magnet: proximity cryogenics

- Dewar with spare volume of LHe to keep the magnet at nominal field in case of temporary disruption of LHe supply.
- Valve box,
- Phase separator to feed the thermosyphon,
  Flexible vacuum line to connect the liquefier to the proximity cryogenics.

2.6.7 Final tests and Field mapping

Field map : precision of 10-4.

Final test of the magnet in the surface assembly hall before lowering in the experimental cavern.

2.6.8 Iron Yoke Design

2.6.4.1 Design Considerations

_ (modified) CMS style assembly
_ Segmentation
_ Forces
_ Stray _eld

2.6.4.2 Barrel Design

_ Design
_ Deformation and Stress

_ Support feet
_ Assembly
2.6.4.3 Endcap Design
_ Design
_ Deformation and Stress
_ Assembly
2.6.4.4 Support of Solenoid Cryostat