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Engineering Challenges for detectors at the ILC

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Abstract

Over the last years two proposals for experiments at the ILC have been developed, ILD and SID. Extensive R&D has been carried out around the world to develop the needed technologies. Furthermore a first round of engineering studies was made as part of the ILC TDR to understand the integration of these different sub-systems into coherent and integrated detector concepts. Among the key challenges for the sub detectors are the extreme low mass/ low power requirements or the extreme channel densities needed in particle flow based detectors. Throughout these studies special care was taken to ensure that the engineering models and the simulation models, used in studies of the physics capabilities of the detectors, stay synchronized. In the near future, the models will need to be evolved to take the special requirements of the potential ILC site in Japan into account. The state of the integration of the detectors, and the future directions, will be discussed

Keywords: Engineering, R&D, Detectors, Assembly, Integration

1. Introduction

The ILC detectors face new challenges that require significant advances in collider detector performance [1], [2]. The machine environment is benign by LHC standards, enabling designs and technologies that are unthinkable at the LHC. Calorimetry must advance beyond current state of the art and an R&D program has been developing high field magnet and low mass trackers. The demand of fast readouts, requiring extra power set a significant challenge. However, the low duty cycle of the ILC permits power pulsing, which reduces the heat load and the need for cooling. For the first time two large detectors will be operating in the same experimental hall sharing a single IP with unprecedented engineering challenges to address.

2. Engineering requirements

The detector requirements are defined by the physic performances, the machine parameters and the operation mode. The strategy of the ILC Detectors [3] is based on the assumption that Particle Flow Calorimetry will be important. This leads directly to a reasonably large value of BR^2 and to an electromagnetic calorimeter (EMCal) design with a small Moliere radius and small pixel size. Silicon/Tungsten is the best approach. Such a calorimeter is expensive, and its cost is moderated by keeping the scale of the inner detectors down. This has many implications:

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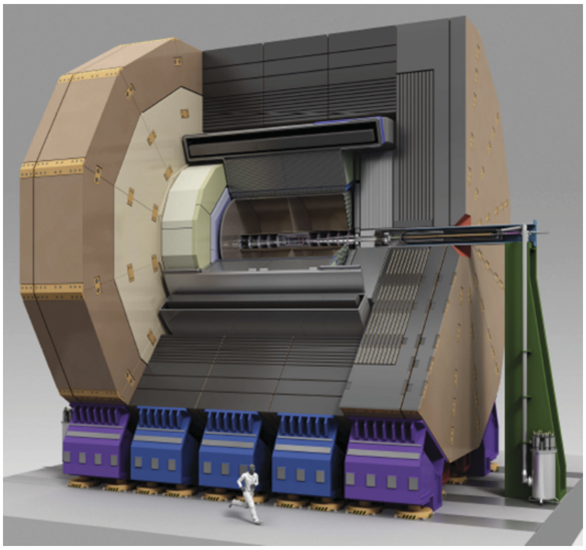
- Maintain BR^2 by pushing the central field B (~5T for SID and 3.5T for ILD). Large B field is also desirable to contain electron-positron pairs in beamline
- Excellent tracking and momentum resolution required in smaller volume with a low mass Silicon tracker for SID and Silicon+TPC for ILD.
- Detector R&D critically needed coupled with synergistic design of the Vertex detector, the Tracker and the Calorimeters integrated for optimal jet reconstruction.

The ILC time structure with its fraction of a per cent duty cycle makes power pulsing a possible and desirable feature. The short L* coupled with the nanometric size beams require the Final Focus System strongly integrated with the detector with a controlled vibrations environment.

The Interaction Region of the International Linear Collider is made of two detectors working in a push-pull mode. A time efficient implementation of this model sets specific requirements and challenges for many detector and machine systems, in particular the IR magnets, the cryogenics, the alignment system, the beamline shielding, the detector design and the overall integration. A strong coordination Machine-Detectors is even more required.



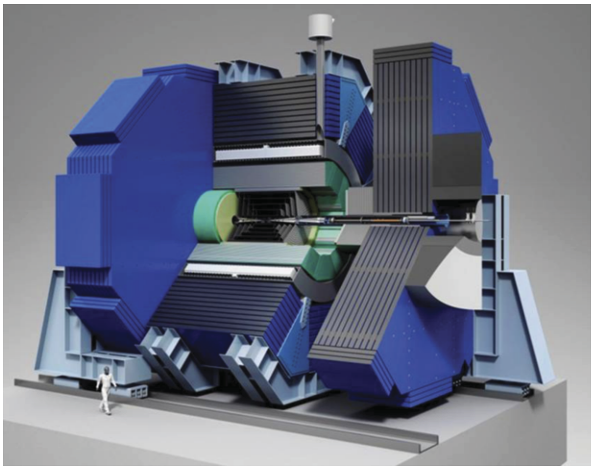


Fig. 1, SID Dector (top), ILD Detector (bottom)

3. Subdetectors

3.1. Power Pulsing Electronics

The millisecond bunch trains at 5 Hz time structure1 enable power pulsing, a possible and desirable feature for many of the detector subsystems, significantly reducing heat load. Nevertheless, powering the readout electronics of each subsystem, such as the front-end readout chip of the silicon tracker, is a challenge. The readout chips require high current at low voltage with large conductor mass. In order to reduce this mass, power delivery based on serial power or capacitive DC-DC conversion is being studied. In addition, the pulsed power system must deliver quiescent currents. SID developed the KPiX, a 1024 channels “System on Chip” for the Si strip Tracker and the EMCal. The CALICE collaboration has developed a family of chips for imaging calorimetry like SPIROC (Analog HCAL for SiPM), HARDROC (Digital HCAL for RPC, μmegas or GEMs), SKIROC (ECAL Si PIN diode). The power pulsing was used at SLC at 120Hz and it has been demonstrated by CALICE within the Hardrock family of chips.

3.2. Vertex and Tracker

Vertex detectors at ILC should comply with the following specifications:

- A spatial resolution near the IP better than 3 μm ;
- A material budget below 0.15% $X0$/layer;
- A first layer located at a radius of ≥ 1.6 cm;

The power consumption should be low enough to minimise the material budget of the cooling system inside the detector sensitive volume. The required radiation tolerance follows entirely from the beam related backgroun which is expected to affect predominantly the innermost layer. The requirements for the total ionising dose and the fluence amount respectively to about 1 kGy and 1011 n*eq*/cm2 per annum.

The baseline design of the ILD vertex detector consists of three, nearly cylindrical, concentric layers of double-sided ladders. Each ladder is equipped with pixel sensors on both sides, ≥ 2 mm apart, resulting in six measured impact positions for each charged particle traversing the detector. The radii covered by the detector range from 16 mm to 60 mm.

The vertex detector ladders must comply with a particularly tight material budget reflecting the ambitious impact parameter resolution goals. Excellent mechanical properties are required, in particular when power pulsing is foreseen.

The ladders have a structure of a rigid foam core sandwiched by thin (≥ 50 μm) silicon pixel sensors. Low density silicon carbide (SiC) and carbon foams (RVC) are considered for the core material.

Two different cooling options are considered, depending on the sensor technology. Those may be air flow cooling similar to the one used for the STAR-PXL [205] or two-phase CO2 cooling may be used.

The SID detector has a full Si strip tracker while ILD has in addition a TPC tracking volume. The silicon tracking system poses several challenges as the development of lightweight but stiff structures. It should introduce a low amount of dead material, be fairly simple and modular, but at the same time stable also during external manipulations of the detector. During detector push-pull operations it should maintain its position so that a new calibration can be done quickly and efficiently. Progress in materials will also be utilised to arrive at optimized structures. The baseline design uses relatively conventional technologies to achieve the performance goals with low risk and minimal cost. The barrel and disk supports, as well as the module supports, are composites of carbon fibre and low-density Rohacell foam. Low-mass hardware is fabricated in polyether ether ketone (PEEK).

For the Barrel, a set of cylindrical layers provides tracking coverage in the central portion of the detector. Each cylinder is formed from a sandwich of carbon fibre and Rohacell cured as a single unit, similar to those used in the DØ and the ATLAS. A similar design will be used for the Disks.

3.3. TPC

The central tracker of ILD is a Time Projection Chamber (TPC), which in a linear collider experiment offers several advantages. The design goal has been to maintain a very low material budget and to achieve the required single and double-point resolution. The mechanical structure of the TPC consists of an endplate, where the readout of the amplified signals takes place using custom-designed electronics, and a fieldcage, made from advanced composite materials.

The inner and the outer fieldcages will be built using composite materials. A core made of honeycomb is covered on the inside and outside with a layer of glass-fibre reinforced epoxy. On the drift-volume side of the inner and outer cylinders, Kapton sheets with metallised potential strips provide insulation and field-shaping electrodes. The potential of the strips is defined by a resistive divider mounted inside the gas volume. Mirror strips on the back of the Kapton sheets shield the field against the grounds on the outside of the TPC, where each cylinder will be covered with grounding sheets. The fieldcage will provide a homogeneous electric field. Simulations show that field distortions due to the electrical properties of the field cage alone should stay below 50 μm.

The TPC support structure will be non-magnetic, have a low thermal expansion coefficient, be robust in all directions (x,y,z), maintain accuracy and stability over long time periods, absorb vibrations, and provide a position accuracy of 100 μm or better.

In the present design the TPC endplates are suspended from the solenoid. A number of spokes run radially along the faces of the calorimeter to the TPC endplates. With the total mass of the TPC estimated to be around 2 t, the weight is not a problem. A mechanism must be developed which prevents the TPC to move in the longitudinal direction to ensure that the system is not damaged in case of earthquakes and simplifies the recovery of the alignment of the TPC after a push-pull cycle.

3.4. Electromagnetic calorimeter

Particle Flow Algorithm (PFA) approach in Calorimetry implies that the readout needs to be finely segmented transversely and longitudinally. The calorimeters need to be inside the solenoid to be able to do track to cluster association and the gap between the tracker and the ECAL should be minimised.

Because of its small radiation length and Moliere radius, as well as its mechanical suitability, tungsten absorbers/radiators have been chosen. Due to practical considerations for ease of production of large plates and machining, the tungsten will be a (non-magnetic) alloy. This currently chosen alloy includes 93% W with radiation length 3.9 mm and Moliere radius 9.7 mm. An additional benefit of tungsten is that it has a relatively large interaction length, which helps to ameliorate confusion between electromagnetic and hadron showers in the ECAL. The longitudinal structure has 30 total layers with variable thickness. which is a compromise between cost, shower radius, sampling frequency, and shower containment. The cost is roughly proportional to the silicon area, hence the total number of layers.

For SID [4], the construction of a barrel "wedge" module is carried out by interconnecting the plates with a screw-and-insert network, which transfers the load from the bottom of the stack to the rail. The design is self-supporting and it does not require additional material to provide the required stiffness. The assembly procedure for a single wedge is sequential with the sensors permanently captured in the gap between tungsten plates, which are specified to have high planarity, achieved at the vendor site by grinding. Because of the trapezoidal cross-section of the wedge, the assembly sequence is bottom up, with the wider plate at the base. The first layer of tungsten will be laid down on a jig tool to set the basic tolerances of the stack. Spacing inserts are placed at the locations of the cutouts at the sensor edges followed by the sensors with flex cables.

The assembly of the sensors on the flex-cable will be done on a precision jig, which will guarantee the repeatability of the assigned tolerances. Prior to insertion, each individual wedge will be equipped with a cold plate for thermal management, running along z on one side of the wedge. The boxes on the two opposite sides at $\pm z$ contain the data concentrator electronics, which completes the assembly.

For ILD [5], where the Moliere Radius s 9 mm, the mechanical structure consists of a carbon reinforced epoxy (CRP) composite structure, which supports every second tungsten absorber plate. The carbon fibre structure ensures that the tungsten plates are at a well-defined distance, and provide the overall mechanical integrity of the system (the so-called alveolar structure). Into the space between two tungsten plates another tungsten plate is inserted, which supports on both sides the active elements, the readout structure and necessary services. This results in a very compact structure with minimal dead space. The mechanical structure is equally well suited for both proposed technologies. For the end-cap region alveolar layers of up to 2.5m length have been fabricated. While in the barrel the shape of all alveolar structures is the same, three different shapes of alveolar structures are needed in the end-caps. Recent studies revealed that in the end-caps considerable forces are exerted onto the thin carbon fibre walls, which enclose the alveolar structure.

3.5. Solenoid

The superconducting solenoid is an expensive and technically challenging component. Its design is based on the successful 4 T CERN CMS superconducting solenoid. High purity aluminium superconductor stabilisation with indirect LHe cooling will be used. The CMS individual self supporting winding turn design philosophy is used, becoming even more important due to the higher 5 T field of SID and the increased radial softness of six layers versus four layers. The maximum stored energy per unit of cold mass of 12 kJ/kg, which is close to the upper bound at which such a large aluminium dominated magnet can be operated in a fail safe manner, in case the quench detection or energy extraction circuit were to fail. Upon such a failure, the average magnet temperature would reach 130 K. A superconductor stability margin similar to CMS will be used requiring that the Rutherford cable be increased in size from 32 to 40 strands. In comparison to CMS, operating current as a % of critical current based on magnet peak field and temperature, improves from 33% to 32% for SiD.

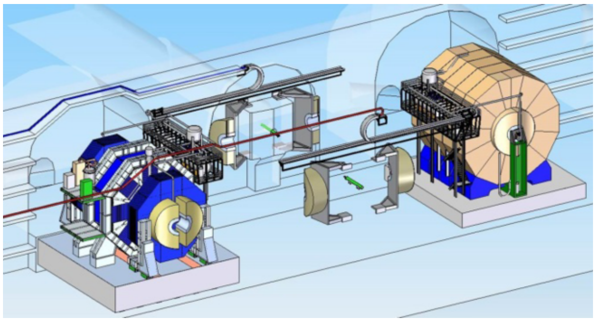
Many other conductor designs are possible. One possibility is replacement of the high purity aluminium with an Al-0.1%Ni alloy that is stronger but still has good conductivity. Many other dilute aluminium alloys (e.g. scandium or binary elements) that form small intermetallic precipitates are possible but largely unexplored. Replacement of the structural aluminium with internal stainless steel rope would simplify conductor manufacture if a different method of coextrusion such as the ConKlad process could be industrialised for this size. A Detector Integrated Dipole (DID) is required to compensate the effect of the solenoid due to crossing angle. The DID is mounted directly on top of the solenoid cooling tubes and made of four separate 600 kA turn winding packages sandwiched between a lower 3 mm Al sheet and an upper 5 mm Al sheet. Each package consists of five coils all electrically connected in series creating either a DID or anti-DID field. The coil packages are mounted directly on top of the solenoid LHe cooling loops by metal screws attached to the solenoid winding mandrel. The stored energy for an independently powered DID is in the range of 240 kJ. When coupled to the solenoidal field, the stored energy increases by ~ 8 MJ. Because the stored energy is so small, the volume fraction of high purity aluminium to superconductor needed for safe energy extraction during a quench has been reduced from the CMS 12.4 to a ratio of 2.5. Forces on each of the four coils are rather large in sum but spread somewhat uniformly and are manageable (4100 kN radial and 7800 kN axial).

4. Machine-Detectors Interface

4.1. Push-Pull

With a single interaction point the two detectors move in and out of the beam to share the luminosity [6]. The sequence of the push-pull operation should allow a fast detector interchange to minimise the interruption of the machine to deliver luminosity. Realistically it should not take more than a few days to realise the swap, a little bit longer at the beginning of the project life. Defining as t = 0 the time when the beams have been dumped and the interlocks are released to allow the access of the technical personnel, the key steps are the opening of the Pacman shielding, the breaking of the vacuum between the QD0 and the QF1, a reasonably fast horizontal movement from the IP to the garage position with an easy and reliable alignment system. The cryogenic system will stay on during the push-pull, with the umbilical able to accommodate the ~30 m movement requested.

Each detector will seat on reinforced concrete platform equipped with a movement system based on rollers or air pads able to position the detector on the beam within +1 mm. The total weight of one detector is ~15,000 tons. A Frequency Scanning Interferometry with a precision of O(5 um) will be used at this purpose.



4.2. Self Shielding

The Push-Pull operations require the two detectors to be self-shielded in term of radiation and magnetic fields in order to protect people and equipment in the garage position when the other detector is on the beam.

The requirements on the magnetic field outside of detector operating on the beamline will define the amount of iron in the detector or degree of compensation of an iron-free detector design. While regional authorities will ultimately dictate the upper limits for personal safety, a limiting field of 50 Gauss at the location where the off-beam detector will be maintained, will allow the use of iron-based tools. The limit. Radiation shielding is essential with two detectors occupying the same Interaction Region. The final radiation safety criteria will be developed in consultations with the relevant regional authorities and will include criteria for both normal operation and for protection in the event of the worst case beam loss accident.

4.3. Assembly

The main subcomponents are its central barrel and its two doors. The majority of the mass results from the flux return iron. The iron will be shipped to the ILC site from an industrial production facility in the form of sub-modules suitably sized (~60 tonne) for road transportation. The solenoid coil will likewise be wound industrially and transported in two sections.

The layout allows that the ~3 m thick push-pull platform be positioned directly under a 4,000 tons gantry. The service caverns allow for storage of the endcap doors and unimpeded access to the barrel region for the initial installation or replacement of detector subcomponents. The vertical access assembly presumes that the magnet, comprising the superconducting coil, iron barrel yoke and iron endcap doors, will be pre-assembled and tested in an assembly hall above ground. Any detector subcomponents, notably the HCAL and ECAL, that are ready in time can be installed and tested above ground.

Then main subcomponents, the barrels and two endcaps, will each be lowered as a unit through the 18 m diameter shaft onto the push-pull platform below.

The assembly hall above ground will be also equipped with two steel reinforced concrete slabs that can carry SiD and ILD parts from their construction area to a point over the 18 m access shaft; The current plan is to lower the doors first and to put them in their service caverns before returning to the main shaft to merge with the barrels. Once these assemblies have been lowered the main shaft and gantry are no longer needed. A 215 tonne bridge crane suffices for installation.

4.4. Vibrations

The L* for SiD has been set at 3.5 m locating the final focus system de-facto inside the detector. To facilitate the push-pull operations it has been decided to have the QD0 supported from the door, push-pulling together with detector, provided that only a short spool piece on the beampipe is physically connecting the Detector to the BDS. With this configuration one must verify that the beam jitter induced by the vibrations from the ground and the technical infrastructure is below the maximum budget allowed by the IP Luminosity feedback system to minimise the luminosity loss.

Another advantage of having the QD0 captured by the door is that, under the effect of the magnetic field, the iron of the detector will behave almost as a monolithic structure, ensuring the highest correlation between the respective movements of the two doublets.

A structural dynamic model of the QD0 supported from SiD, including the platform, has been developed to calculate the free modes as well as the transfer function between the ground and the doublet. Using different ground vibration models available in literature and corresponding at different accelerator sites in the world, a maximum r.m.s. displacement of 20 nm has been calculated, more than a factor two below the maximum allowed. A campaign of experimental measurements of vibrations has been carried out to validate some key features of the model: the simulation of the reinforced concrete platform and correlation measurements between distant locations in the detector hall of CMS at CERN and SLD at SLAC. The reinforced concrete slab of CMS has been instrumented with geophones in various locations and the data have been used to benchmark a finite element model of the platform. A good agreement between experimental data and simulation has been found with an internal damping ratio of 6.5%, somewhat higher than the values recommended in literature for similar materials. The difference can be explained by the soil deformation and the presence of wheels, which both were not included in the model. The set of correlation measurements done at CMS and SLD have shown a good correlation at low frequencies between points at the two extreme sides of the cavern, i.e. the location of the final focus system.

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