0.1 The ILD TPC System (draft20121122)

The central tracker of ILD is a Time Projection Chamber with performance goals superior to those achieved in the past [1]. A TPC tracker in a linear collider experiment offers several advantages. Tracks can be measured with a large number of three-dimensional $r\phi$,z space points. The point resolution, σ_{point}, and double-hit resolution, which are moderate when compared to silicon detectors, are compensated by continuous tracking. The TPC presents a minimum amount of material X_0 as required for the best calorimeter and PFA performance. A low material budget also minimizes the effects due to the $\simeq 10^3$ beamstrahlung photons per bunch-crossing which traverse the barrel region [2]. Topological time-stamping in conjunction with inner silicon detectors is an important tool that is explained below in Sec. 0.1.1. To obtain good momentum resolution and to suppress backgrounds, the detector will be situated in a strong magnetic field of 3.5 Tesla, for which the TPC is well suited since the electrons drift parallel to $\vec{\mathrm{B}}$. The strong B-field improves the point resolution σ_{point} to better than 100μm and the two-hit resolution to better than $\mathcal{O}(1\text{ mm})$ by limiting the transverse diffusion of the drifting electrons.

Continuous tracking facilitates reconstruction of non-pointing tracks, significant for the particle-flow measurement and for the reconstruction of physics signatures in many standard-model-and-beyond scenarios, e.g. V^0s or new sources. The TPC gives good particle identification via the specific energy loss dE/dx which is valuable for many physics analyses and for electron-identification. The TPC will be designed to be robust while easy to maintain. Over the past years significant R&D work has been done to develop and optimise a design for a TPC at a linear collider detector in the context of the LCTPC collaboration [3].

0.1.1 Design of the TPC

The main parameters for the TPC are summarised in Table 0.1.1. The system has been optimised to the overall dimensions of the ILD detector. The design goal has been to maintain a very low material budget while at the same time delivering the required single and double-point resolution. The mechanical structure of the TPC will include a field cage made from advanced composite materials and an endplate where the readout of the amplified signals takes place via custom-designed electronics. Two main options for the gas amplification systems are Micromegas [4] and GEM [5]. At present either option would use pads of size $\approx 1 \times 6\,\text{mm}^2$, resulting in about 10^6 pads per endplate. An alternative technology of a pixelated readout with much smaller pitch is being investigated [6].

Table 0.1.1: Goals for performance and design parameters for the TPC with standard electronics and pads.

Performance/Design Goals	
Momentum resolution[a] at B=3.5T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c TPC only
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05\,\mathrm{X}_0$ including the outer field cage in r $< 0.25\,\mathrm{X}_0$ for readout endcaps in z
Number of pads/timebuckets	$\simeq$ 1-2$\times 10^6$/1000 per endcap
Pad pitch/no.padrows	$\simeq 1\,\mathrm{mm}\times 4\text{-}10\,\mathrm{mm}/\simeq 200$
σ_{point} in $r\phi$	$< 100\mu$m (avg for straight-radial tracks)
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)
2-hit resolution in $r\phi$	$\simeq$ 2 mm (for straight-radial tracks)
2-hit resolution in rz	$\simeq$ 6 mm (for straight-radial tracks)
dE/dx resolution	$\simeq$ 5 %
Performance	$>$ 97% efficiency for TPC only ($\mathrm{p_t} >$ 1GeV/c) $>$ 99% all tracking ($\mathrm{p_t} >$ 1GeV/c)
Background robustness	Full efficiency with 1% occupancy,
Background safety factor	Chamber prepared for $\sim$ 30% occupancy, at the linear collider start-up, for example.

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[a] The momentum resolution for the combined central tracker is $\delta(1/p_t) \simeq 2 \times 10^{-5}$/GeV/c

The design is the result of a systematic R&D program to develop and prove the concept of the high resolution TPC for a linear collider. In the beginning the basic properties were established with studies performed with a number of small prototypes(e.g. [7] [8] [9]). This was followed by a joint effort [3] [10] [11] to design, build and operate a "large prototype" (LP) ($\simeq$ 1 m diameter). Using the LP in a 1 T magnet mounted on a movable stage and the infrastructure of electron beams at DESY, the system performance for the technological options has been confirmed.

Topological Time-stamping

This technique utilizes the properties of both silicon and TPC detectors (described in the previous and present chapters), and will be reviewed first before delving into details of the TPC work.

Since the TPC drifts the tracks while the silicon pixels are fixed in space, the silicon can act as an external z detector (T0 device). Drifting TPC tracks are well-measured in $r\phi$ and angle; extrapolating a TPC track to match related silicon hits establishes where the track was in the z direction. An interesting description of this technique for a TPC and a similar one for a standard drift chamber is found in [12]. The time-stamping in ILD is precise to $\simeq 2$ ns (to be compared to $\simeq 300$ ns between BXs at the ILC) so that the bunch crossing which produced the track (the T0) can be identified. Cosmic background tracks can be eliminated with this tool (which also is viable in the CLIC environment [13]).

0.1.2 The ILD TPC Implementation

The main features of TPC implementation are lightweight endcaps mounted on a fieldcage, the endcaps being read out by a system of micropattern gas detectors with either traditional pad-based readout or a novel highly granular pixelated system. A design of the overall layout of the system has been developed, depicted in Fig. 0.1.1. The idea is to have concentric rows of modules, which are integrated with amplification and readout and mounted as a unit on the endplate [14]. Most of the implementation decisions result from a series of tests carried out either in the LP or in smaller prototypes.

Gas Amplification System

The gas amplification system for a pad-based TPC (Table 0.1.1) will be either GEM or Micromegas. The use of wires has been ruled out [8], since they do not meet the ambitious performance goals. Two or three GEMs are stacked together to achieve sufficient charge amplification Micromegas have enough amplification in a single structure, but the signals are very narrow on the readout plane. In order to spread the charge signal out over several pads, Micromegas use a resistive coating on the anode [15]. It has been demonstrated that both amplification technologies combined with pad readout can be built as modules which cover large areas with little dead space.

Gas

If the pads are narrow enough (e.g. 1 mm wide), the transverse diffusion has a major influences on the space point resolution. Thus a gas will be chosen which has a small value of transverse diffusion in the high magnetic field. A promising candidate is the so-called T2K gas (Ar-CF4(3%)-isobutane(2%) [16]), which has the appropriate properties in a 3.5 T field. Figure 0.1.2 shows the single point resolution versus the

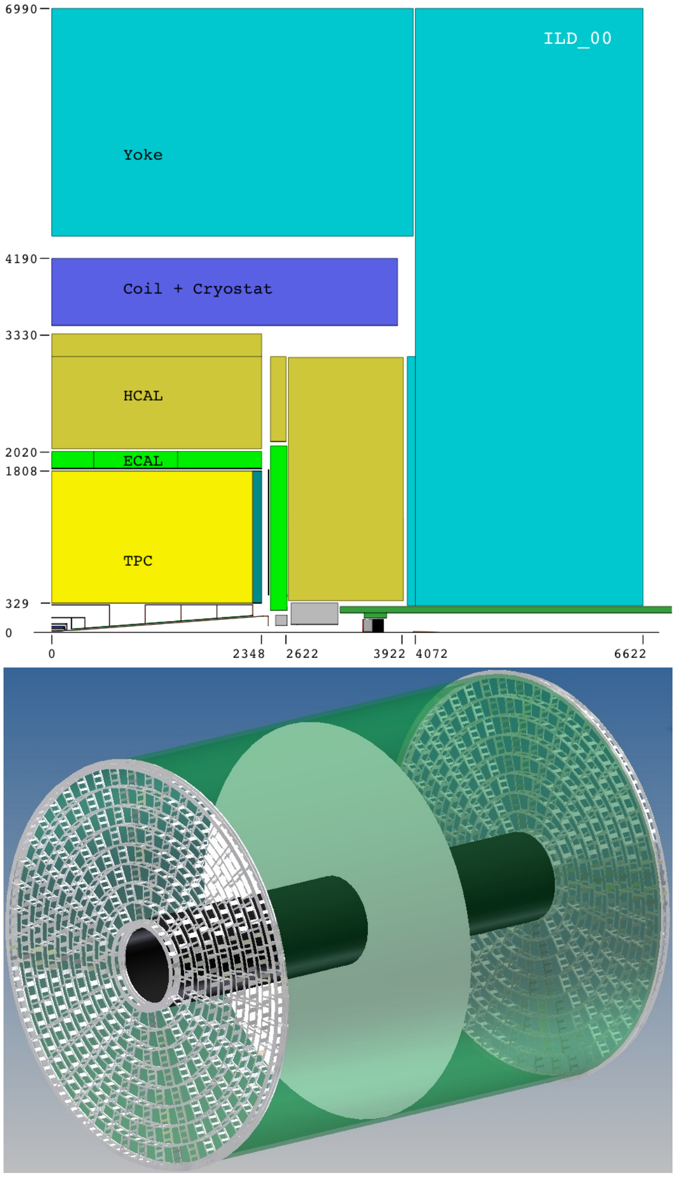

Figure 0.1.1: Upper: The ILD detector components. Lower: Sketch of the TPC assembly.

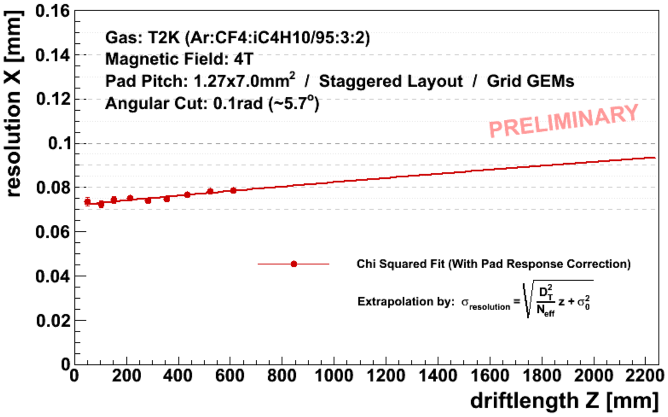

Figure 0.1.2: The resolution of data taken with a triple GEM stack at a magnetic field of 4 T, recorded in a small TPC prototype filled with T2K gas.

drift length of data taken in a 4 T magnetic field with a small prototype [17]; the chamber was limited to 66 cm drift length, and the extrapolation indicates single point resolution for the ILD TPC.

Endplate

An important task for the TPC system will be the design and construction of the low-mass endplate [14]. The material of the endplate introduced in front of the calorimeter can potentially disturb the particle flow performance. In recent simulation studies [9] [18] [19] the particle flow performance was evaluated using the pandora PFA program and the full ILD simulation for a range of endplate thicknesses. Increasing from 15% to 60% X_0 degrades the jet energy resolution from 4.2% to 4.8% for 45 GeV jets and 3.2% to 3.3% for 100 GeV jets (and about the same for 250 GeV jets). The very ambitious goal of 15%X_0 as stated in the LOI [1] therefore has been relaxed to 25%X_0, which is more realistic to achieve.

For the LP a new low-mass endplate has been designed and built, and will meet the relevant requirements for the ILD TPC [14]. It is based on a thinned aluminum structure stabilized by a system of adjustable struts (Fig. 0.1.3). Measurements confirmed finite element studies that this system provides adequate stability and

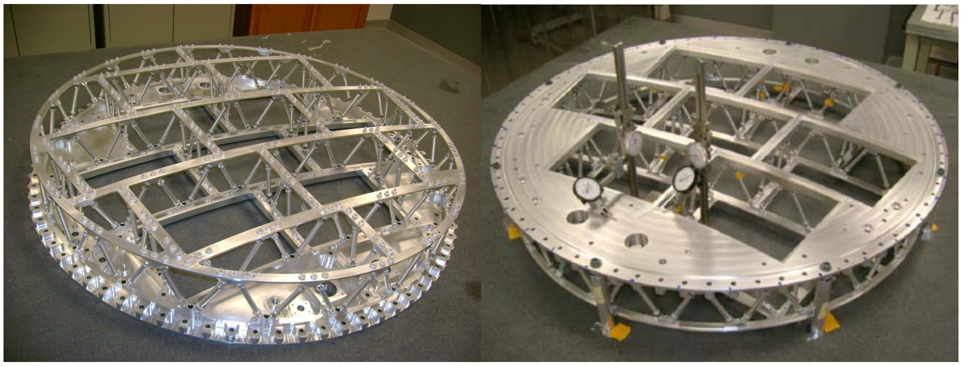

Figure 0.1.3: Left: Outside surface of low mass endplate for the LP. Right: Study of adjusting struts to achieve the required flatness of the inside surface.

precision. With the size of the modules chosen as for the LP, the ILD TPC endplate would be equipped with about 240 readout modules per side. Alternative approaches (for example with larger readout modules) are also under consideration. The design can be finalized after choice of the gas amplification technology has been made.

Readout Module

Each module consists of the gas amplification system (GEM or Micromegas), the pad plane, and the readout electronics. The readout module also contains all necessary high voltage and low voltage supply lines to operate the system, and a cooling system to dissipate the heat from the electronics.

A challenge for the multi-GEM systems is the provision of a support system that keeps the GEM surfaces both flat and parallel without introducing dead space or adding too much material to the detector. Several options have been developed and successfully operated [9]. The Micromegas system with one stage amplification has a fine wire mesh mounted in front of the readout pad plane. A system of small pillars maintains a constant distance between the mesh and the pad plane.

The charge from either amplification system is collected on a pad board. For the traditional readout scheme the size of the pads is chosen to be about 1 mm×6 mm to collect enough charge for a good signal-to-noise ratio. For a GEM readout the transverse diffusion within the GEM stack itself is enough to spread the charge over several 1 mm wide pads, which allows a good point reconstruction. The diffusion in the amplification region is much less for the Micromegas, the solution being the resistive anode described above in Sec. 0.1.2.

Readout Electronics

For test beam purposes, electronics based on the ALICE TPC readout (ALTRO) [20] has been used successfully several times with different GEM modules in the LP. The next version is the S-ALTRO16 [21] [22], a fully-integrated analog-digital chip more compact than the original ALTRO, which allows for power pulsing. It is expected that a complete prototype system based on this development will be available within the next one or two years. The next step will be the GdSP (gaseous detector signal processor) chip, the successor to S-ALTRO16. It has a higher channel density (64-128ch/chip), lower power consumption and a programmable DSP instead of hard-wired digital processor. This work is a joint effort with CMS (muon detector upgrade), aiming to be ready by 2014-15.

The power management relies critically on the ability of the system to use power pulsing. Power pulsing has been demonstrated for the S-ALTRO16, but more must be done for the GdSP and the whole electronics chain.

Two-phase CO_2 cooling is planned; test setups are foreseen for KEK and DESY. Since both the cooling and the powering are areas where progress is being made for the LHC upgrade project, the ILD detector will profit from this work.

For Micromegas LP tests, a version based on the AFTER electronics (used by the T2K experiment [23]) was developed. This design underwent severe modification and miniaturization: front-end cards with wire-bonded naked chips are placed flat on the PCB, and an additional mezzanine card is on top with analog to digital conversion, zero suppression and multiplexing of the signal sent through an optical fibre. A picture of these modules mounted on the LP is given in Fig. 0.1.4, alongside an event display from the data acquisition.

For the optional technology of pixel readout the Timepix3 chip is a further development of the Timepix system, valid for both GEM and Micromegas options. Timepix3 has better final resolution, both time and charge measurement per pixel, possible power pulsing, and through-Si vias. An important issue is the supply of low voltage to the system. A number of different approaches are under study, with the goal to minimise the material.

Fieldcage

The inner and the outer fieldcages will be built using composite materials [24]. A core made of honey-comb 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,

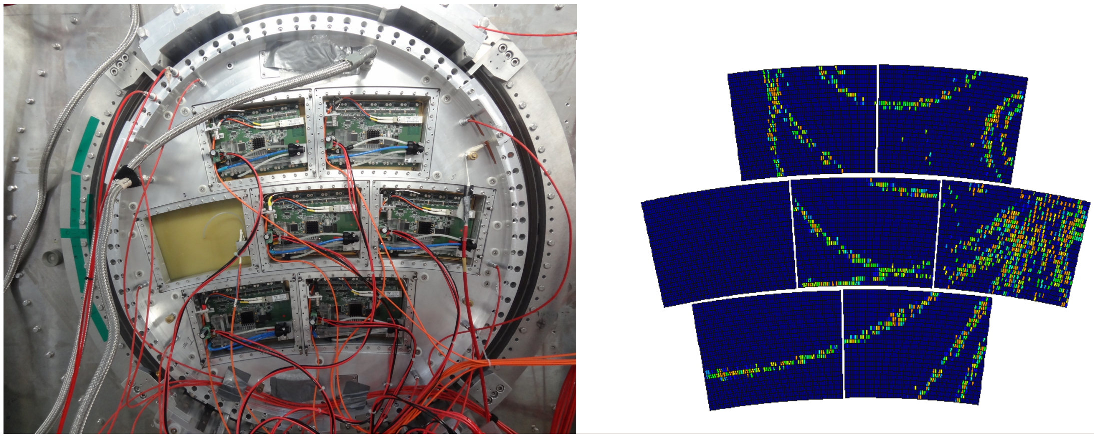

Figure 0.1.4: Left: Six Micromegas modules (with resistive anode) mounted on the LP endplate,equipped with highly integrated electronics. Right: A trigger during running: a cosmic muon shower.

Kapton sheets with 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 inside and outside of the system. On the outside of the TPC, each cylinder will be covered with grounding sheets.

The conceptual design of the fieldcage has been tested and demonstrated with the LP [24]. It is a prototype for the ILD TPC electrical, mechanical and operational aspects. Estimating from this experience a material budget of 1% X_0 for the inner and 3% X_0 for the outer fieldcage seem to be feasible. Designs exist for the transition from the fieldcage to the endcap, which will add only minimal material in the corner region. Tests for the manufacture of a second fieldcage version for the LP have started.

Less well developed is the design of the central cathode membrane. At the moment the design foresees a thin membrane stretched between a light-weight inner and an outer ring, at $z = 0$; discussions have begun with experts who built the ALICE-TPC [20], in which a thin, stretched mylar foil coated with aluminum is used.

Mechanical Design

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 in particular the z direction, 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 weight of the TPC estimated to be around 2 tons, the weight is not a problem. The main challenge will be to provide a mechanism which does not allow the TPC to move in the longitudinal direction to ensure that the system is not damaged in case of earthquakes or similar events. This will simplify the recovery of the alignment of the TPC after a push-pull cycle. At the moment supports using double-T beams made of lightweight carbon, ceramic fibre reinforced composite (CFRP) or by a system of flat CFRP ribbons are being studied. The ribbon system needs less space in the endcap-barrel transition region, but requires an additional fixation of the TPC in longitudinal direction.

The TPC fieldcage will support the inner and outer Silicon trackers. While there are no conceptual problems, this additional load on the field cage might require a stiffer system and somewhat more material than anticipated.

Ion Backdrift

The high precision goals require a careful control of the accumulated charge in the TPC drift volume. Studies and detailed simulations have been performed to understand the impact on detector performance of ions which were produced during the primary ionisation and during the amplification phase. The requirement of continuous operation during an ILC bunch train implies that no gating of positive ions will be possible during a bunch train.

Recent calculations [25] of distortions due to positive ions at a 500 GeV ILC have shown that the effects of primary ions are manageable and that effects from ions between a possible gate and the amplification region are negligible. Distortions arising from the so-called 'ion sheets' due to the secondary-ion backflow into the drift region from MPGD gas amplification can result in up to 60 μm of transverse displacement of the drifting electrons, as seen in Fig. 0.1.5. The ion sheets arise because the TPC is active during the 1 ms bunch train followed by a 199ms pause, while the backflow ions from the amplification region take about 1 s to drift out of the TPC. An ion gate can eliminate a sheet by gating before the ions can enter the drift region. Therefore an ion gate will be designed for all MPGD options.

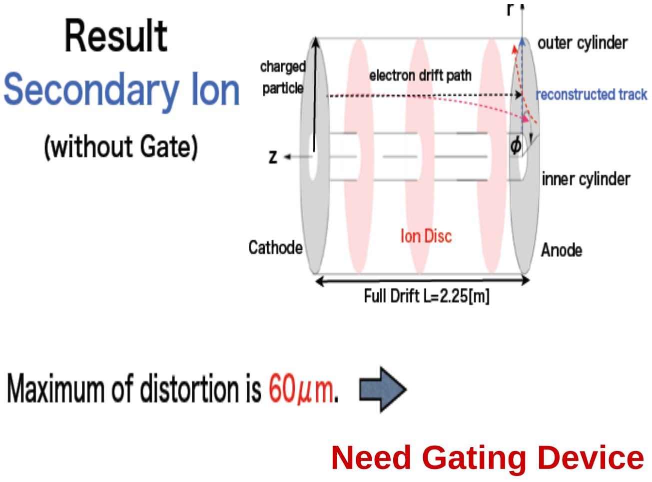

Figure 0.1.5: The ion discs can result in a distortion of around 60 μm which must removed by a gate.

A number of different options are under study for the inclusion of a gating device in the amplification structure [26]. The simplest solution will be to add a wire-based gate at an appropriate distance away from the amplification structure. This would be able to remove all positive ions in a sheet accumulated during a bunch train. Other solutions e.g. based on special GEM foils are under study, but have not delivered the anticipated performance up to now.

0.1.3 Calibration and Internal Alignment of the TPC

As described in the LOI [1], achieving a momentum resolution an order of magnitude better than any of the collider detectors to date will be a challenge. The systematics of the internal alignment of the TPC must be well understood to guarantee its performance. Redundant tools [27] [28] for solving this issue are Z peak running (used at LEP), laser system (described below), a good B-field map, a matrix of Hall-plates/NMR-probes outside the TPC, and Si-layers inside the inner field cage and outside the outer field cage. In general based on experience at LEP, about 10 pb^{-1} of data at the Z peak during commissioning could be sufficient for the alignment of the different subdetectors, and typically 1 pb^{-1} during the year may be needed depending on the background and operation of the linear collider machine (e.g., after push-pull). For detector calibration, the machine should deliver about $10^{32}/\mathrm{cm}^2/\mathrm{s}$ at the Z peak.

For alignment purposes a laser system is foreseen and may be integrated into the field cage [20, 29]. Another possible solution is to illuminate calibration spots on the cathode. Electrons will be released from these spots via the photo effect. These electrons then drift into the drift volume at well defined places and at well defined times, under the influence of all field components along its path. Such a system is being tested at the LP [9], and is being used at the T2K experiment [23] [30].

The non-uniformities of the electric field due to the fieldcage design and fabrication can be minimized as in past TPCs. Extensive simulations have been undertaken [31, 32] to eliminate such problems.

An important future task of the R&D program will be to demonstrate experimentally using the LP that the distortions can be corrected. The setup of the LP has a superconducting magnet without a return yoke so that measurements are made in an inhomogeneous magnetic field and will require correcting.

0.1.4 Status of R&D and future work for the LCTPC

Up to date at the LP, the GEM and Micromegas-based readout systems have been tested, both equipped with either pad-based or pixelated readout. Recently data with six Micromegas-based modules were taken (Fig. 0.1.4). GEM equipped endplates have been tested with two and three modules. For both technologies the basic system goals have been reached.

The pixel-based readout scheme has also been demonstrated at the LP [6], but so far only with small systems with up to eight readout chips. It has been shown to work with both GEM-based and Micromegas-based systems. Missing is the proof that large area readouts can be realised in this technology.

In addition to the issues described above, the following tasks are important:
- continue electron beam tests to perfect correction and alignment procedures;
- future tests in hadron beam for momentum resolution and for performance in a jet environment;
- further reduction of the pad size is a topic for the far future: for example 1 mm × 1 mm for the standard readout or pixel readout would require substantial progress in the electronics, power pulsing, and cooling.

0.1.5 Conclusions

The concept of a TPC based on MPGD readout has been successfully demonstrated, and the spatial resolution established. Several groups are testing different readout schemes based on Micromegas, GEMs or pixelated integrated readout techniques. The main tasks ahead will be to develop a convincing overall design, to demonstrate its system performance, and in particular to verify the momentum resolution and the two-track resolution.

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