PRC R&D-01/03
Update for DESY PRC Meeting of 1-2 April 2008
Version No. 2.4, 31.03.2008

TPC R&D for a Linear Collider Detector

Status Report from the LCTPC Collaboration [1]

LCTPC groups

AMERICAS
Canada: Carleton U & TRIUMF, U Montreal, U Victoria & TRIUMF
United States: BNL, Cornell U, Indiana U, LBNL, Louisiana Tech U
ASIA
China: Tsinghua U
Japan: Hiroshima U, KEK Tsukuba, Kinki U, Nagasaki Inst AS, Kogakuin U Tokyo, Saga U, Tokyo UAT, U Tokyo
Philippines: Minadano SU-IIT
EUROPE
Belgium: IIHE ULB-VUB Bruxelles
France: LAL Orsay, IPN Orsay, CEA Saclay
Germany: RWTH Aachen, U Bonn, DESY/U Hamburg, U Freiburg, MPI-Munich, U Karlsruhe, U Rostock, U Siegen
Netherlands: NIKHEF
Russian Federation: BINP Novosibirsk, PNPI St.Petersburg
Sweden: U Lund
Switzerland: CERN
Groups with Oberserver status:
Iowa State U, Purdue U, MIT, Yale U, TU Munich, UMM Kraków, NIP-NE Bucharest

See
https://wiki.lepp.cornell.edu/ilc/bin/view/Public/WWS/TrackLCTPCcollabCollaborators
for the list of collaborators.

Abstract

This report gives a summary of TPC studies and an update since the PRC review in May 2006. The R&D issues are related to the the LCTPC design criteria which are covered in some detail. Some representative results for the various issues are presented and plans for the future described. The formation of an LCTPC collaboration to address the R&D is in progress; it is open to all and continually evolving. The LCTPC Memorandum of Agreement is presented in this report.

[1]Original proposal PRC R&D-01/03 for the DESY Physics Review Committee.

1 Introduction

A detector at a the International Linear Collider will have a high-precision tracking system inside a calorimeter system, and both systems will have very high granularity. These will be contained in the detector solenoid which will produce the high magnetic field ($\sim$ 4T) needed to reduce backgrounds at the vertex and to enable very good momentum resolution.

There are two important aspects for tracking at the ILC. The first is, as required by precision-physics measurements at the linear collider, that the detector must determine the momentum of charged tracks an order of magnitude more precisely than in previous experiments. The second aspect is that the detector must be optimized for the reconstruction of multi-jet final states. The jet-energy resolution using the particle-flow technique is best when the reconstruction of individual particles in jets is as complete as possible, which means that efficiency in reconstructing charged tracks should be as high as possible.

A typical design of a "large" detector is the LDC– Large Detector Concept[1] – and the GLD - Global Large Detector[2] – which have tracking systems consisting of a large TPC as the central tracker[3] combined with other detectors for vertexing, barrel and forward tracking. The current designs with a TPC are similar to an earlier design proposed in the TESLA Technical Design Report[4]. Meanwhile the LDC and GLD concepts have decided to merge into one with the name ILD [5].

A Time Projection Chamber (TPC) is a candidate for the central tracker because of its very good performance in past collider experiments. In order to obtain the order-of-magnitude improvement in momentum resolution and the highest possible track-recognition efficiency, the LCTPC groups [10] are pursuing R&D to find the best state-of-the-art technology for the TPC.

This TPC R&D has been reviewed regularly by the DESY PRC. The orginal proposal[6] was approved by the DESY PRC in 2001. Subsequent reviews were held in April 2003[7], October 2004[8] and May 2006[9].

This document is an update to the report compiled for the WWSOC R&D Tracking Review in Beijing, 6-7 February 2007[10]. The latter forms part of this PRC review in April 2008. This update consists of short progress reports from the different global regions participating in the LCTPC collaboration in Sections 2.1, 2.2 and 2.3. Section 3 presents the Memorandum of Agreement (MOA) of the collaboration and contains an overview of the goals, R&D phases and institutes joining this effort. Finally, Section 4 describes the next steps in the work ahead and a scenario for the next few years, and conclusions are drawn in Section 5.

2 Progress reports since the Beijing 2007 review

In the following sections recent results from each of the three regions, the Americas, Asia and Europe are reviewed. An executive summary to help guide the reading is as follows:

- America.
  · Carleton and collaborators have measured very good point-resolution values using Micromegas plus resistive-anode technique.
  · Victoria made such measurements using GEM plus normal anode in the past and is now actively pursing correction techniques for E- and B-field distortions for the large prototype (LP) being built for the Eudet facility at Desy.

· Cornell is a key player in designing and fabricating the endplate components for the LP; Cornell and collaborators are also measuring point resolution using their small prototype with GEM and Micromegas endplates.
· BNL has joined the LP effort and is providing a system of laser mirrors for it.

- Asia.
  · The Asian groups and other collaborators led by the KEK and Saga CDC groups are (1) measuring point-resolution for different gas-amplification technologies and testing gas mixtures using the MP-TPC and Tsinghua TPC prototypes, (2) simulating and testing of GEM gating and (3) preparing GEM detector modules for the TPC at the LP at the DESY test beam.
  · KEK provided the magnet for the Eudet facility at Desy.
  · The Minadano group has been active in analyzing the test-beam data taken with the MP-TPC.

- Europe.
  · All European groups have been, in addition to other work below, actively involved in getting the hardware built and software written for the LP work which is to start this year at the Desy test beam:
  · Bonn/Freiburg – GEM pixel module and software,
  · Desy and other German groups – fieldcage, infrastructure and coordination,
  · MPI-Munich – LCTPC coordination and the MP-TPC prototype with different endplate technologies,
  · Saclay/Orsay – Micromegas pixel and resistive-anode modules and the LP trigger,
  · Lund/Brussels/CERN – LP and LCTPC electronics, and
  · Nikhef – CMOS pixel TPC and Timepix development, to be tested in the LP.

A detailed description now follows.

2.1 Americas

Since the last PRC report, the Canadian groups have been active in evaluating the charge dispersion MPGD-TPC performance in magnetic fields, in developing concepts for TPC readout electronics, building simulation and track reconstruction software, and developing a concept for the calibration system for the large prototype TPC.

In 2006, two charge dispersion TPCs were tested in the 1T superconducting magnet in a 4 GeV/c test beam at KEK, a collaboration of groups from Carleton, Montreal, MPI, Saclay, Orsay, KEK, and several university groups from Japan (Saga University, TUAT Tokyo, Tsukuba University, KEK/IPNS, Kogakuin University, Kinnki University, and Hiroshima University). Excellent resolution was obtained with both TPCs, reaching the limit of 50 microns per 6 mm sample for the shortest drift distances. The 15 cm drift TPC was also operated in the 5T magnet at DESY (a collaboration of Carleton, Montreal, Saclay and Orsay) and 50 micron resolution was observed over the full drift length, since the diffusion effects are much smaller in such strong fields. The performance was measured also with the micromegas operating at the relatively low gain of 2300, and no loss in performance was observed.

At the ILC, the TPC will need to be long, resulting in rather long rise times for the charge signals, due to longitudinal diffusion. The Montreal/Carleton group has paid special attention to the treatment of the charge signals in order not to compromise resolution (should short shaping be used) or two track separation power (should long shaping be used). The group is proposing that no shaping be use, and instead digitize the preamplifier charge signal directly. These ideas have been validated, and have been incorporated as an option for the new ALTRO PASA design, produced for the upcoming tests of the LCTPC large prototype.

The Victoria group has contributed to the Marlin/Mokka software for simulating and reconstructing tracks in the TPC that has been developed for the LDC (now ILD) detector concept. Carleton is also developing software to contribute in this area. This work aims to tackle the problem of simulating non-uniform magnetic fields and developing algorithms to correct for such effects.

The Victoria group has developed the concept for using photoelectrons produced at the central cathode in order to detect and correct distortions in the TPC. Aluminum features are placed and precisely surveyed on the predominately copper surface of the central cathode. A fibre through the readout endplate illuminates the cathode with a diffuse pulse of UV light at the wavelength of 266 nm, producing photoelectrons only from the aluminum features. By comparing the imaged locations of the aluminum elements with their true locations, transverse displacements in the drift paths of the photoelectrons can be detected directly and can be used as a first correction for magnetic and electric field distortions. The concept was proven to work in a prototype TPC built for the T2K project, and plans are underway to incorporate this in the LCTPC large prototype.

Since the PRC meeting, the Cornell group has been active in designing the LCTPC large prototype endplates and, in collaboration with the Purdue group, evaluating GEM and Micromegas gas amplification devices in a TPC at Cornell.

The large prototype endplate will mate with the field cage being produced by the DESY group and will support and locate the detector readout modules being produced by Saga, Saclay and Bonn. The Cornell design provides mounting for seven modules in a pattern that is a circular subsection of a possible final TPC for the ILC (see Fig. 1). The scope of the Cornell work includes the endplate, the mechanical parts of the readout modules that mate to the endplate (back-frames) , as well as the field cage termination plates that will provide potential in those areas of the endplate that are not instrumented with modules.

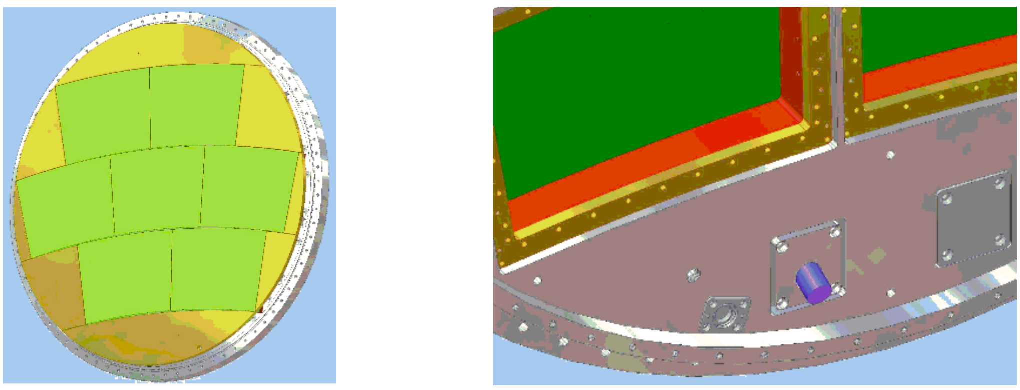

Figure 1: *Left: Design of the large prototype endplate. Right: Detailed view of the endplate with some auxiliary connections and mountings for calibration system.*

A major design goal for this endplate is to position the readout modules to an accuracy of better than 50 microns, thus allowing a track-based calibration of the magnetic field distortions to be decoupled from distortions of readout module alignment. Study of possible manufacturing processes, using preliminary mechanical structures, has resulted in adopting a process that includes three iterative machining steps and two cold-shock steps to achieve the goal.

Other design considerations include the need to provide a rigid mounting surface for the modules in the presence of the slight chamber over-pressure and providing an interface to the field cage that meets the mechanical requirements of the field cage. The endplate also provides mountings for the light source required for the Victoria photoelectron-based calibration.

As of 17-March-2008, the design was complete. A preliminary production of module back-frames has been delivered to module-producing groups at Saga, Saclay, and Bonn. Bid have been requested for the endplates, final production of back-frames, and the field cage termination plates.

In 2006 and 2007, the Cornell group, in collaboration with the Purdue group, have used the Cornell small prototype TPC to measure characteristics of triple-GEM and Micromegas gas-amplification devices using a common TPC. In addition, the TPC was used to measure electron and ion transmission though a GEM. To date, measurements have been made only in zero magnetic field. There are plans to repeat these measurements in the CLEO 1.5 Tesla magnet in August 2008.

Laser calibration beams have been a useful tool to measure drift velocity and investigate track distortions in TPCs. BNL joined the LCTPC large prototype project at the end of 2007. The first goal is to install two bundles with micromirrors and thus produce 10-14 laser beams 1 mm diameter to simulate straight charge particles. This approach was used in STAR and ALICE TPCs. To date, hardware that will be used for this project has been defined and mountings for the device has been design in coordination with those responsible for the cathode and endplate. In the future, BNL will explore new approaches to produce laser beams with much smaller diameters and divergences to meet the stringent requirements for the ILC tracking performance.

2.2 Asia

In 2004-2006, the CDC group, the only Asian group of the LC TPC collaboration at the time, carried out the series of beam tests at KEK-PS, under the collaboration with groups from Carleton University, DESY, MPI, Orsay and Saclay, to study the point resolutions of TPCs with MWPC and MPGDs using the MP-TPC prototype [11]. A new analytic formula [11, 12] derived from the first principles of the TPC operation fit nicely the results. One of the features of the formula is that it predicts the point resolution of LC TPC provided with a diffusion constant of TPC gas mixture, the width of readout pads and the electronics noise by assuming the effective number of primary electrons N_{eff}.

Since the time of the Beijing tracker review at the beginning of 2007, the Asian groups, now also include a group from Tsinghua University, Beijing, have focused their R&D activities on the following three areas:

- (1) Test of gas mixtures for LC TPC using MP-TPC prototype and Tsinghua TPC prototype,
- (2) Simulation and test of GEM gating,

- (3) Preparation of GEM detector modules for the TPC Large Prototype (LP) test at the DESY test beam.

The R&D studies (1) and (2) are remaining and important issues to realize the LC TPC. Some details of the TPC LP test (3) may be found elsewhere in this report.

2.2.1 Test of gas mixtures for LC TPC

Three MPGD TPCs described in the ILC Reference Design Report [13] have the dimension of 2.8 - 4 m in diameter and 3 - 4.6 m in length. They are to provide 200 space points along a particle track with the Rϕ spatial resolution of 100 μm or better. The momentum resolution of $\delta(1/p_t) \leq 0.5 \cdot 10^{-4}(GeV/c)^{-1}$ is envisaged in the magnetic field of 3-4 T.

To realize the excellent space resolution of 100 μm, a TPC with MPGD readout instead of the MWPC readout is needed. Also the best gas mixture with small transverse diffusion, or with a large $\omega\tau$ in the high magnetic field, must be chosen. Beside this requirement, the TPC gas mixture has to meet the following conditions: (a) sufficient number of the primary electrons and small electron attachment, (b) sufficiently fast drift velocities of electron and ions at an acceptable drift field, (c) gating conditions in the case of the GEM gating, (d) minimum amount of hydrogen molecule to avoid the neutron induced background [13], and, (e) conditions to guarantee stable operation of MPGD TPC in the long term. Since some of the conditions are rather specific to the LC TPC and thus new for us, systematic R&D studies to find the best gas mixture must be performed.

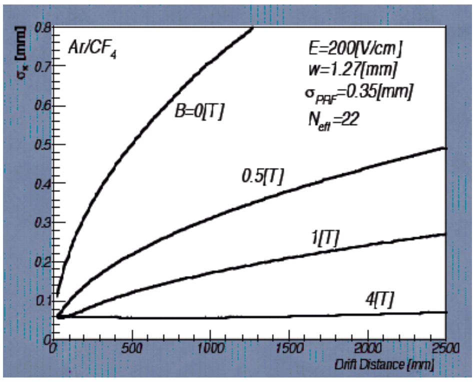

Figure 2: *The Rϕ spatial resolution of GEM TPC calculated by the analytic formula for Ar(97%)-CF_4(3%) gas mixture in the magnetic field up to 4T.*

Ar-CF_4 gas mixtures are known to have a large $\omega\tau$ up to around 20 at 4T. Figure 2 shows the expected spatial resolutions of LC TPC with GEM for the Ar(97%)-CF_4(3%) gas mixture. The point resolutions are calculated by the analytic formula [12]. Although the Ar-CF_4 gas mixture is known to have high electron attachment at the high electric field above 1 kV/cm [14], studies in the LC TPC collaboration have shown that both the MicroMEGAS TPC and the 3 layers GEM TPC could be operated stably for this gas mixture when a few % of Isobutane was added. The test of the MicroMEGAS readout by a resistive anode provided the excellent spatial resolutions of around 50 μm in the 5T magnetic field at a low gain for Ar(95%)-CF_4(3%)$-iC_4H_{10}$(2%) gas mixture [15].

The CDC group is carrying out a systematic test of Ar-CF_4 (3%)-Isobutane gas mixtures using the MP-TPC prototype with a three layers GEM in a super conducting MRI solenoid (1T) at the KEK Cryogenic Center. Also Tsinghua group has been testing their TU TPC prototype with the same gas mixtures. The group performed a measurement in the MRI magnet at KEK at the end of last year (Fig. 3).

Figure 3: *TU-TPC prototype and people from Tsinghua University and KEK in front of the MRI magnet (left), and the same MRI magnet with MP-TPC prototype in the KEK Cryogenic Center.*

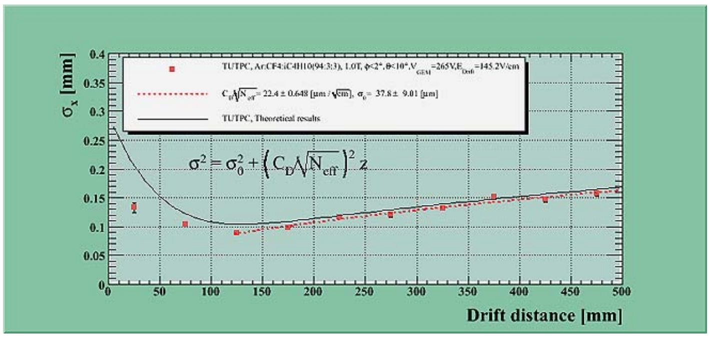

Figure 4: *The resolution σ_x as a function of the drift distance measured for TU-TPC prototype in 1T magnetic field. The pad pitch of TU-TPC is 1.6 mm and the length 10 mm. The gas was Ar(94%)-CF_4(3%)$-iC_4H_{10}$(3%). The drift field was 145.2 V/cm. The solid curve is the prediction of the analytic formula where N_{eff} is 36. The measured diffusion constant C_d was about 139 $\mu m/cm^{1/2}$ while the Garfield simulation predicts 80.3 $\mu m/cm^{1/2}$.*

One of the point resolution measurements by the Tsinghua TPC prototype is shown in Fig. 4. The measured resolutions agree very well with the prediction of the analytic formula (the solid curve in the figure) with the effective number of electrons N_{eff} of around 38. This N_{eff} agrees well with ones measured with the MP-TPC when one considers the ratio of the lengths of their readout pads (10 mm for Tsinghua TPC and 6.3 mm for MP-TPC). However, the preliminary results of the diffusion constants obtained from the drift-length dependence of the pad response (the spread of the signal on the pad plane) do not agree with the predictions of the Garfield simulation [16] as shown in Fig. 5. The measured diffusion constants are significantly higher than those from the simulation in particular in the higher drift fields, degrading the advantage of this gas mixture for the LC TPC. The results are still preliminary and the groups will investigate if the Garfield simulation might need some tuning for these gas mixtures, or if the measurements might have some problems. The groups continue the measurements by changing the isobutane condensation and the drift field, and also moving toward higher magnetic fields. The other gas mixtures are also in their sight.

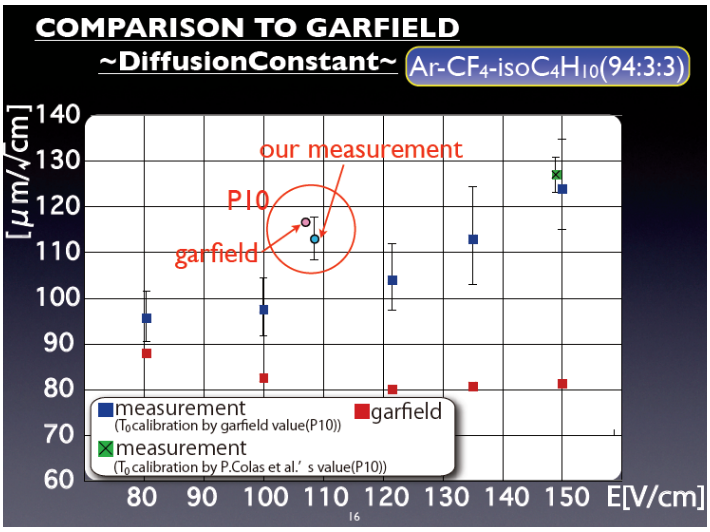

Figure 5: *Comparison of C_d measured by the MP-TPC (blue) in 1T field to the predictions by the Garfield simulation (red) for Ar(94%)-CF_4(3%)$-iC_4H_{10}$(3%) with a calibration point for P10 gas (green). The results are still preliminary.*

2.2.2 Simulation and test of GEM gating

Another remaining issue of the LC TPC is the feedback ions form the gas amplification region [17]. The feedback ions may create a few (3-4) thin ions disks of about 4 mm thick equally spaced in the TPC drift space. The disks drift very slowly toward the central membrane (the cathode) of TPC in around 600 ms. These disks introduce distortion of tracks when the ion density inside the disk might be high. The ion feedback ratios measured for the MicroMEGAS or with three layers GEM are both around $(2-3)\cdot 10^{-3}$. With the gas gain of 1,000, the ion density in the disk becomes around 100 times larger than the average density of the primary ions in the TPC drift space. To evaluate the effects of the disks to tracking, corrections and the TPC momentum resolution, a study with a full TPC simulator such as the Marlin TPC will be needed.

One obvious approach is to implement a gating device to stop all the feed back ions as done in all the previous TPCs. Since the wire gating method, although it is known to work perfectly at least in the lower magnetic field of O(1T), does not match well mechanically the endplate structure of the modern MPGD TPC, the idea of GEM gating has been pursued [18]. Since any gating GEM with a reversed bias at the level of about 10V or larger stop the feedback ions down to 10^{-4} or better, the major issue of the GEM gating is the electron transmission of the gating GEM. If the electron transmission is small, the effective numbers of the primary electrons which contribute to the position measurement reduces and the position resolution is degraded accordingly. The CDC group, in particular its subgroup at Saga University, has been investigating this problem by a simulation using MAXWELL 3D and Garfield simulation. The best electron transmission obtained by the simulation for the gas mixture of Ar (96%)-CF_4 (5%)-Isobutane (1%) at 3T magnetic field is around 70% for a thin GEM

(12.5 μm thick) with wide holes (100 μm in diameter). To validate the simulation the group measured the transmission with (1T) and without magnetic field for a gating GEM of 25 μm thick with wider holes (90 μm in diameter). The gas mixture was Ar (90%)-Isobutane (10%). The measured transmissions at 1T are well reproduced by the simulation, but those at 0T are not, as shown in Fig. 6. The group has not understood the discrepancy yet. The group plans the measurement with a thinner gating GEM of 12.5 μm for realistic gases in higher magnetic fields, possibly under wider collaboration in the LC TPC collaboration.

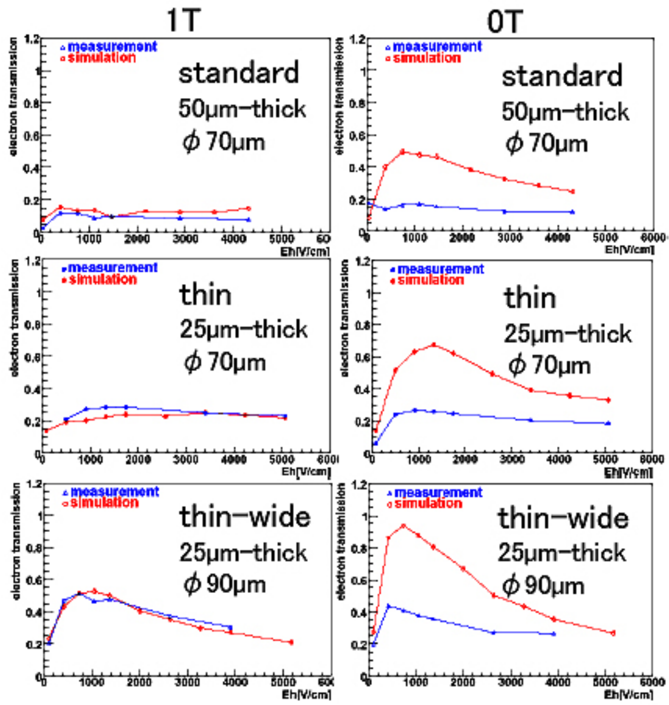

Figure 6: *The electron transmissions measured for gating GEMs of different GEM thickness and the hole size (blue) compared to the Garfield simulation (red). They agree well at 1T magnetic field but not for 0T. The maximum transmission found was around 55% for the thin GEM with the large hole size. The measurement was made by varying the voltage across the GEM. The horizontal axis is the electric field at the hole center calculated by Maxwell 3D for the fixed drift field of 50V/cm and the fixed electric field of 300V/cm in the transfer region below the gating GEM. The gas mixture in this specific case was Ar(90%)-Isobutane(10%).*

2.2.3 Preparation of GEM detector panels for the TPC Large prototype test at the DESY test beam

As is described elsewhere in this report, the LC TPC collaboration plans to perform the TPC large Prototype (LP) tests at DESY. The Asian groups plan to fabricate GEM detector panels for this common effort of the LC TPC collaboration. The sketch of the GEM detector panel is given in Fig. 7. The GEM detector consists of two layers of thick (100 μm) GEM and a gating GEM (not shown in the Fig. 7) mounted on a pad plane. The GEMs are fabricated in Japan. The width of the pads is around 1 mm and the length between 5 and 6 mm providing a good position resolution of better than 100 μm. The pad plane, which is an 8 layer PCB board, routs the signals from the pads to the mini connectors behind the pad plane. The front-end cards mounting a new general purpose preamplifier chips and an ALTRO chip are to be connected via short flexible cables to the detector module.

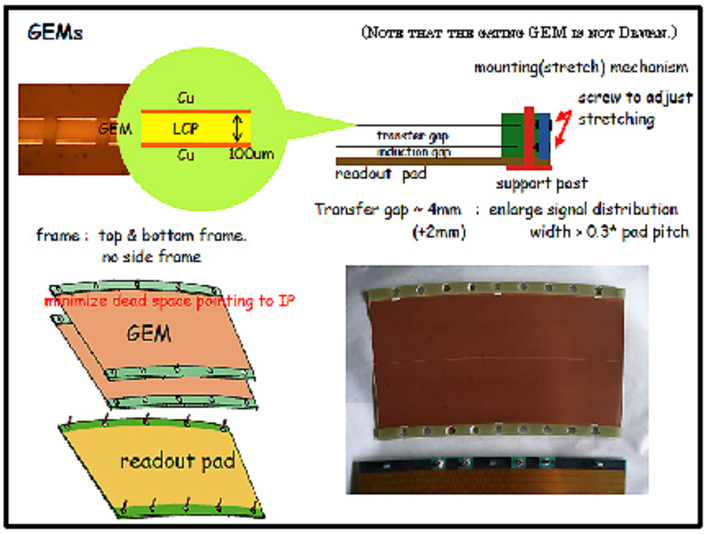

Figure 7: *A sketch of the GEM detector module for the TPC Large Prototype test at DESY. The gating GEM on the top of the two 100 μm GEMs for gas amplification is not drawn. The GEMs are supported at the top and bottom frames to minimize the dead area in $R\phi$. The GEM voltages are supplied through pins at the frames.*

The groups plan to produce 4 GEM detector modules and necessary dummy modules in 2008. Most of the components and tools for laboratory test are now ready except the PCB board, the final gating GEM and the ALTRO readout electronics. The design of the PCB boards, which will be fabricated by Tsinghua group, is now in the final stage. The group expects to receive and test the thin gating GEM of 12.5 μm thick soon. If every goes fine, the first GEM detector module will be ready for laboratory test in May-June 2008.

2.3 Europe

Many details on the progress in the framework of the EUDET project can be found in a series of writups of presentations at the 2006/2007 Annual Meetings [19]- [28].

2.3.1 The TPC development facility at DESY testbeam (Large Prototype LP TPC)

The TPC development facility consists of the design and construction of a large field cage, designed to fit into the superconducting magnet (PCMAG) made available within the EUDET program by KEK, and prototype readout electronics. The field cage for the Large Prototype of a Time Projection Chamber (TPC) at the ILC is a large and low mass device, which provides a highly homogeneous electric field throughout its volume. DESY and University of Hamburg are contributing to the design and construction of the field cage. During 2007 the design of the field cage structure has been finished. Extensive tests have been made evaluating the mechanical and electrical performance of the chosen structure (see Fig. 8). In close communication with the partners within the EUDET project and in consultation with anticipated users of this device the parameters have been defined.

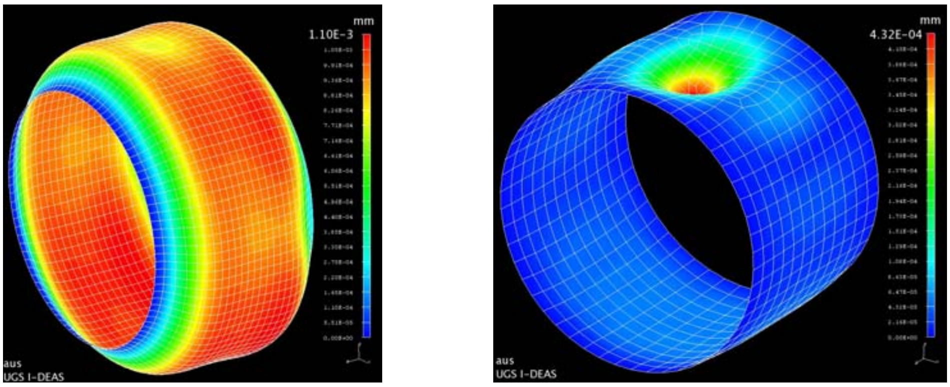

Figure 8: *Left: Result of the simulation of the behaviour of the field cage under an overpressure of 100 mbar. Right: Expected deformation of the field cage under a point-like force of 5 kg at the top.*

A major stumbling block was the design and fabrication of the field strip foil. This foil is responsible for the homogeneity of the electric field inside the chamber. A detailed computer model of the field has been developed, and the strip design has been optimised based upon this. The finalised design has been handed over to a specialised vendor. Unfortunately the first vendor defaulted on the project, and a new source had to be found well into the project. The field strip foil was delivered in February 2008. The completion of the field cage construction at DESY is foreseen for end April 2008, about 7 months behind the implementation plan. While this shortens the time available for finishing and commissioning the field cage, one is confident that the goal of a fully functional chamber in the beam by summer 2008 can still be met.

In parallel to the design and construction of the field cage, the infrastructure needed to operate the field cage is being assembled. A first version of a slow control system is now available, which can monitor crucial gas and environmental parameters. It is expected that the system will be extended over the next few months, to be more automated, and more reliable. Discussions on the design and the control of the high voltage are ongoing.

The readout system for the large prototype is based on the read-out electronics developed for the ALICE experiment at the LHC. In the EUDET consortium CERN and the University of LUND collaborate to develop and construct the prototype electronics. The main part of this system is a fast analogue-to-digital converter. This ALTRO chip will digitize the TPC signals with a sampling frequency of 25 MHz or 40 MHz. Presently 125 ALTRO chips (corresponding to 2000 channels) with 40 MHz readout are available and another 1600 chips with 25 MHz sampling. In order to adopt this chip to the specifics of a TPC readout with micro-pattern gas detectors, a new charge sensitive pre-amplifier has been developed. The so-called PCA16 chip is a programmable charge sensitive device, which integrates 16 channels into one package, which has a programmable peaking time between 30 and 120 ns, and a programmable gain in four steps between 12 and 27 mC/fC. A first non-progammable version of this chip has been developed and produced, to test the basic layout. After passing the tests 1000 PCA16 chips have been produced which is sufficient to satisfy the needs of the EUDET project (Large Prototype). A schematic picture of the complete readout chain is shown in Fig. 9.

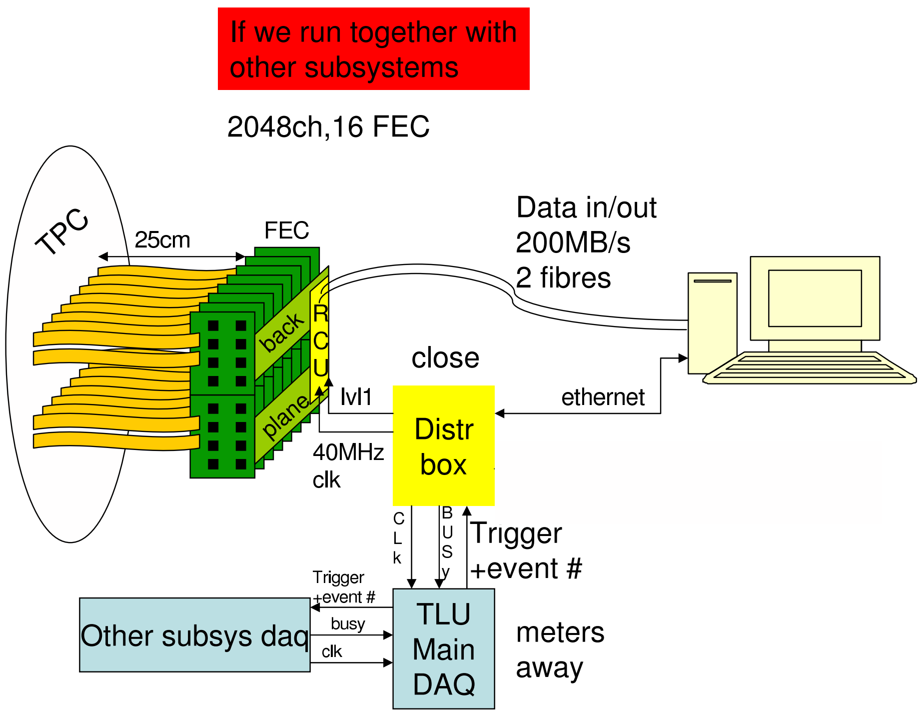

Figure 9: *Layout of the TPC electronics, including hardware and DAQ components.*

The endplate proposed for the TPC will have small pads, typically 1x5 mm^2. This results in a large number of channels to be read out. For the prototype developments it has been decided to build two independent sets of boards: the pad-plane, and the readout electronics, which are connected through a high density cable. Special high density connectors are going to be used, to connect both within the available area. The readout software will be based as well on the ALICE system, extended and modified to comply with the EUDET standards. The control software however is newly developed for this TPC application. A special trigger logic unit has been developed based again on the EUDET developments. A first version of the control and DAQ software is available. Discussions with the DAQ task in EUDET on the integration of the TPC system into the overall EUDET system have started.

The realisation of the preamp chips has taken longer than anticipated. The additional time for producing and testing the front-end electronics is about three months and should thus not delay the completion of the overall project. The front end prototype board will be complete and ready by the end of March'08.

Development of an alternative TPC readout electronics based on time-to-digital converters is being carried out by the University of Rostock. Time of arrival and charge of signals from TPC pads are measured with help of a time-to-digital converter. The charge is measured indirectly, with help of charge-to-time converters. In 2007 most of the necessary elements, including front-end electronics, pitch adapter and pad-planes, have been designed and components have been purchhased. The TDC specific components of the data acquisition have been developed and successfully tested. Procurement problems with special connectors for the front-end electronics delayed the completion of the system which is now expected to be available in spring 2008.

2.3.2 CMOS pixel readout of TPC

The goal of the SiTPC task within EUDET is to provide a precision endplate structure (or module) for the highly pixelised readout of a TPC consisting of either Gas Electron Multipliers (GEMs) or Micromegas as gas multiplication devices and integrated CMOS amplifiers and digitization ASICs as a replacement of the conventional pad readout. The Universities of Freiburg and Bonn, CEA-Saclay, CERN and NIKHEF contribute to this task.

The TimePix readout chip, developed in 2006 within this project, was first used in small gas-filled drift detectors already at the end of 2006 and minimum ionising particles were detected, both in a beam test by the Freiburg/Bonn groups (combining the TimePix with a triple-GEM stack) and from cosmics in a NIKHEF test chamber combining the TimePix with a single Micromegas for the gas multiplication. From a first “engineering run” of 12 Timepix wafers the average yield of good quality chips is 70%. A second production of 48 wafers is under way.

During 2007 several single-chip systems have been tested in detail by all groups and preparations have started to build small multi-chip systems with between 4-8 chips per detector plane.

In June 2007 the Freiburg and Bonn groups performed a detailed study in the DESY 5 GeV electron beam using a TimePix + triple-GEM stack (hole pitch 140 μm). A spatial resolution in the plane of the TimePix of 20-30 μm and of about 10 ns in drifttime was achieved. Using a new GEM type with a hole pitch of only 50 μm improved the space resolution to $\approx$ 15 μm (see Fig. 10. The Freiburg group in collaboration with the Freiburger Material-Forschungszentrum (FMF) also prepared a wafer postprocessing step to enlarge the effective pixel size by a factor 2 in both dimensions, in order to operate the system at lower gas gain or higher single electron efficiency.

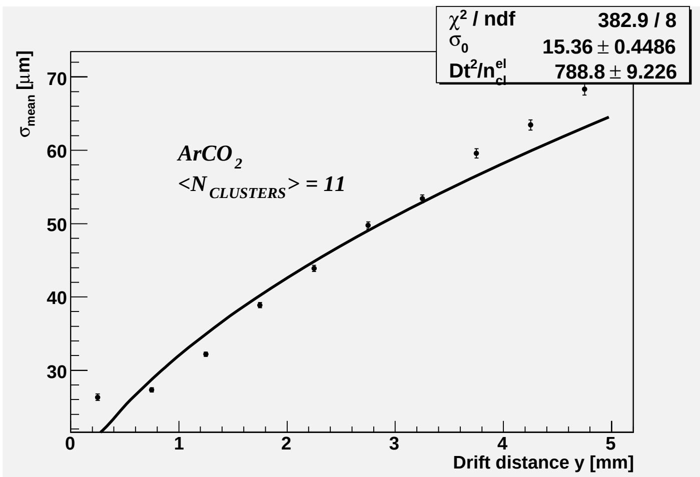

Figure 10: *The resolution σ_{meas} as function of the driftdistance in $ArCO_2$ for a small pitched GEM*

The University of Bonn group is developing prototype readout modules that combine conventional pickup pads and TimePix chips with a triple-GEM amplification structure. The TimePix chips will be arranged in two 4-chip arrangements using NIKHEF 4-chip carrying boards. First (prototype) detectors are operational. Reconstruction (and simulation) of TimePix data is being implemented in the Marlin/LCIO analysis framework.

The CEA-Saclay group constructed a small drift chamber with a drift space of 6 cm and first tests were done using TimePix readout + Micromegas using radioactive sources. The TimePix chip was protected against destructive sparks by a 20 μm thick high-resistive amorphous silicon layer (aSi:H, see below). A 2 x 4 matrix of TimePix chips on PCB that fits an endplate module of the TPC Large Prototype at the EUDET testbeam facility at DESY is under construction.

The NIKHEF group concentrated on the long-term stability of the TimePix readout with either Micromegas or Ingrid using cosmics. Ingrid is the integrated amplification grid developed in collaboration with the MESA+ institute of the University of Twente (NL). The application of a 3 μm thick aSi:H protection layer on top of the chip allowed continuous, stable operation in a He-Isobutane (77/23) gas mixture for more than three months. However, a first test with a Ar/Isobutane (80/20) mixture resulted in only a 24 hour lifetime. Following attempts with 20 μm thick protection layers were very successful. The performance of minimum ionising particle detection was only marginally affected, but the TimePix chips were no longer destroyed by discharges, even in Ar/Isobutane. Most spectacular were the recorded discharges triggered by α particles traversing the detectors after introducing a small amount of Radon in the gas flow. The combination of TimePix, protected with a thin layer of aSi:H and an integrated gas multiplication grid has now proven to be a viable candidate for readout of a TPC. Detailed studies were initiated on a large variety of geometries for the integrated grid structures (gap and hole dimensions and shapes) in order to optimise the single electron detection performance and at the same time limit the ion backflow. A nice example of two electron tracks from ^{90}Sr recorded in a 5 cm^3 TPC inside a 0.2T magnetic field is given in Fig. 11.

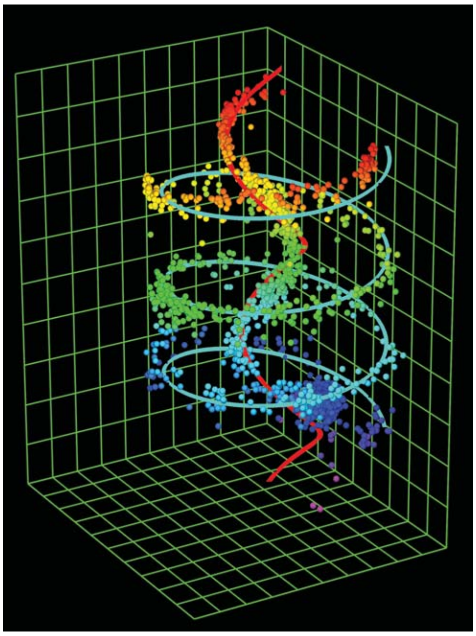

Figure 11: *Two electron tracks from ^{90}Sr source recorded with the Timepix chip as anode in a 5 cm^3 TPC inside a 0.2T magnetic field.*

3 The LCTPC MOA

The Memorandum of Agreement which outlines the overall program is presented here. The collecting of signatures from each the groups is almost completed.

Memorandum of Agreement
on the Formation of the LCTPC Collaboration

October 2007

3.1 Introduction

3.1.1 Preamble

Several detector concepts for the International Linear Collider (ILC) foresee a time projection chamber (TPC) as the central tracker in a tracking system of high precision and fine granularity combined with a calorimeter system of very fine granularity. The detector is being designed for precision measurements in the electroweak sector and of new HEP-phenomena which might be discovered. One aspect of precision experiments requires the measurement of charged tracks with an order of magnitude better accuracy than at previously built collider-detectors. Another aspect requires the detector to be optimized for the reconstruction of multi-jet final states. The jet energy resolution using the particle-flow technique is best when the reconstruction of individual particles in jets is as complete as possible, meaning efficiency in reconstructing charged tracks is more important than momentum precision. A TPC central tracker is being developed to meet these requirements in concert with the other subdetectors. The issues for the TPC performance within the ILC framework have been described many times, most recently in LC Note LC-DET-2007-005 at http://flcweb01.desy.de/lcnotes/. The formation of an R&D collaboration to address these issues is the purpose of this document.

3.1.2 Scope of the Collaboration

The groups signing this Memorandum of Agreement (MOA) express their interest to contribute to the development, prototyping and design of a TPC for an experiment at the ILC. This MOA describes the main goals and the structure of the LCTPC Collaboration. The MOA enters into effect upon signature by a majority of partners; it can be terminated with the formation of the ILC detector collaboration or with dissolvement by its members.

An overview of R&D strategy is given in Section 3.2.1, the structure of the LCTPC collaboration is explained in Section 3.2.2. General policies on new groups, finances and publications are covered in Sections 3.2.3, 3.2.4 and 3.2.5. The groups and the signatories of this MOA are listed in Section 3.2.7. The names of the responsible persons in the collaboration and a more detailed description of the R&D program are provided in an *Addendum* which will be updated regularly as the collaboration and tasks evolve.

3.2 The LCTPC collaboration

3.2.1 R&D Strategy

The R&D work is proceeding in three phases:

(1) Demonstration Phase: Finish the on-going exploratory work using "small" ($\phi \sim$30cm) prototypes (SP), built and tested by several of the LCTPC groups. This work provided a basic evaluation of the properties of a TPC with Micropattern Gas Detector (MPGD) gas amplification, demonstrating that the requirements for the ILC can be met.

(2) Consolidation Phase: Design, build and operate a "Large Prototype" (LP) at the Eudet facility using low-energy (Desy) and high-energy (Cern, Fermilab) beams. By "Large" is meant $\sim$1m diameter, so that: first iterations of TPC-design details for the LCTPC can be tested, larger area readout systems can be operated and tracks with a large number of measured points are available for analysis and correction procedures. The tasks have been divided into workpackages listed in Section 3.2.2.

(3) Design Phase: Start work on an engineering design for the final detector. This work in part will overlap with the R&D for the LP, and the final design will start after the LP/SP results allow decisions on technical options.

3.2.2 Organizational Structure

The LCTPC structure consists of management and workpackage bodies.

The main governing body of the collaboration is the collaboration board (CB) in which each member institution is represented by one person and one vote. All major decisions are taken by the CB which meets at least twice per year. A quorum for a CB meeting exists if at least 50% of its members are present, and decisions are taken by simple majority. In urgent cases, the CB can take decisions also by phone/video conference or by e-mail vote. The CB can delegate decision power on certain issues to other boards. In particular to the Regional Coordinators, described next, will be charged with the day-to-day management of the collaboration.

Three regional coordinators (RC), one each from the Americas, Asia and Europe, are elected for two-year periods by the CB members of the corresponding region. The R&D planning and the collaboration meetings are organized by the RCs. They are responsible for tracking the progress of the collaboration, preparing decisions and reporting regularly to the CB. To expedite their work, the three RCs will choose one of their members to be the LCTPC Spokesperson who will organize/summarize workpackage meetings and chair the collaboration meetings.

For day-to-day running, the RCs will work closely with the technical board (TB). The TB consists of the leaders of the different workpackages defined below. They are charged with coordinating within their respective workpackages, and report on this regularly to the RC and the CB. At the time of writing this MOA the following workpackages were set up, and changes to the structure of the work packages can be decided by the CB at any time:

Workpackage (0) TPC R&D Program
Workpackage (1) Mechanics
a) LP endplate structure with panels
b) Fieldcage
c) GEM panels
d) Micromegas panels
e) Pixel panels
f) Panels with charge-dispersion-anode
Workpackage (2) Electronics
a) Standard RO/DAQ sytem for LP
b) CMOS RO electronics
c) Electronics for LCTPC
Workpackage (3) Software
a) LP software +simul./reconstr.framework
b) LCTPC simulation/perf./backgrounds
c) Full detector simulation/performance
Workpackage (4) Calibration
a) Field map for the LP
b) Alignment
c) Distortion correction
d) Radiation hardness of materials
e) Gas/HV/Infrastructure for the LP

3.2.3 New Groups

The LCTPC collaboration is open to new members. A new group should apply for membership to the CB and will be accepted into the collaboration by a vote of the CB.

3.2.4 Finances

The work of the LCTPC collaboration is funded through the individual budgets of its members. Items of common expense will be shared between the collaborators based on a case-by-case agreement. Collaborators agree to provide financial information to the RCs. The information will be treated confidentially if so requested.

3.2.5 Publications

All results obtained from the work within the LCTPC collaboration will be openly available to all members, and data obtained using common prototypes or common equipment will belong to all collaborators. The groups agree that they will not publish or make otherwise public any information belonging to LCTPC without obtaining prior agreement of the collaboration. Results from the collaboration will be published under the name “LCTPC Collaboration”. The CB will install a proper editorial process before releasing material to the public. In case of a conflict the collaborators agree to accept the decision of the CB as final.

3.2.6 Ownership of Equipment

All equipment purchased or fabricated using funds of a member institution remains the property of that member institution and shall be subject to the property management system of that institution. It is the intent of the members that all equipment purchased or fabricated by a member institution and incorporated into the LCTPC prototype or a test facility would remain with the prototype effort or test facility until it is determined by the LCTPC collaboration that such equipment is no longer needed. At that time the property would be returned to that member institution at its expense.

3.2.7 Institutes

Groups in the three regions which have signaled interest in participating in the LCTPC R&D are listed here. The signatories of the MOA are compiled in Section 3.2.8.

Americas

Carleton Univ & TRIUMF, Ottawa, ON K1S 5B6, Canada
Univ. de Montreal, Montreal, PQ H3C 3J7, Canada
Univ. of Victoria & TRIUMF, Victoria, BC V8W 3P6, Canada
Brookhaven National Laboratory, Upton, NY 11973-5000, USA
Cornell Univ., Ithaca, NY 14853-5002, USA
Indiana Univ., Bloomington, IN 47405, USA
Lawrence Berkeley National Lab., Berkeley, CA 94720-8153, USA
Louisiana Tech Univ., College of Eng.&Sience, Ruston, LA 71272, USA

Asia

Tsinghua Univ., Beijing 100084, China
Hiroshima Univ., Higashi-Hiroshima, Hiroshima 739-8526, Japan
KEK, Tsukuba, Ibaraki 305-0801, Japan
Inst. of Space&Astron.Science, Jap.Aerosp.Expl.Ag., Kanagawa 229-8510, Japan
Kinki Univ., Higashi-Osaka, Osaka 577-8502, Japan
Kogakuin Univ., Hachiohjii, Tokyo 192-0015, Japan
Nagasaki Inst. AS, Nagasaki, Japan
Saga Univ., Faculty of Science and Engineering, Honjo, Saga 840-8502, Japan
Tokyo Univ. Agriculture and Technology, Koganei, Tokyo 184-8588, Japan
Univ. of Tokyo, ICEPP, Tokyo 113-0033, Japan
Minadanao State Univ., Iligan City 9200, Philippines

Europe

IIHE (Inter-university Institute for High Energies) ULB-VUB, B-1050 Bruxelles
LAL, IN2P3 and Univ. de Paris-Sud, F-91898 Orsay, France
IPN, IN2P3 and Univ. de Paris-Sud, F-91405 Orsay, France
CEA Saclay, DAPNIA, F-91191 Gif-sur-Yvette, France
RWTH Aachen, D-52056 Aachen, Germany
Univ. Bonn, D-53115 Bonn, Germany
DESY Hamburg, D-22603 Hamburg, Germany
EUDET, D-22603 Hamburg, Germany
Albert-Ludwigs Univ., D-79104 Freiburg, Germany
Univ. Hamburg, D-22603 Hamburg, Germany
Univ. Karlsruhe, D-76128 Karlsruhe, Germany

Max-Plank-Inst. für Physik, D-80805 Munich, Germany
Univ. Rostock, D-18051 Rostock, Germany
Univ. Siegen, D-57068 Siegen, Germany
NIKHEF, NL-1009 DB Amsterdam, Netherlands
Budker Inst. of Nuclear Physics, RU-630090 Novosibirsk, Russia
Petersburg Nuclear Physics Inst., St. Petersburg, RU-188300 Gatchina, Russia
Lund University, Dept. of Physics, Box 118, S-221 00 Lund, Sweden
CERN, CH-1211 Geneva 23, Switzerland

3.2.8 Signatories

The following pages contain the MOA Forms signed by a responsible authority in each institute.

4 Next steps

The Phase(2) LP and SP work is expected to take about four years and will be followed by Phase(3), the design of the LCTPC. A scenario for the options in presented in Table 1 which will be updated in future as the planning progresses.

Regular bi-weekly WP phone meetings started in May 2006 where details for the LP design are being worked out as explained above and next R&D steps are being developed. The LP is underway, and the groups agree that over the next three years there will be an evolution of endplates towards a true prototype for the LCTPC. These stages are sympolized by LP1, LP1.5, LP2 in the table. Supplemental testing with the SPs, which have been used extensively to date, will continue, since there are still several issues to be explored which can be performed more efficiently using small, specialized set-ups. The small-prototype work is driven to a large extent by the needs of the individual labs, and certain issues can be studied; example as seen in the following Table 1.

Table 1: LCTPC R&D Scenarios for Large Prototype and Small Prototypes.

Large Prototype R&D		
Device	Lab(years)	Configuration
LP1	Desy/Eudet(2007-2009)	Fieldcage⊕2 endplates: GEM+pixel, Micromegas+pixel
Purpose: Test construction techniques using ∼10000 Alice/Eudet channels to demonstrate measurement of 6 GeV/c beam momentum over 70cm tracklength, including development of correction procedures.		
LP1.5	F.L.-Cern/Eudet(2010)	Fieldcage⊕2 endplates: GEM+pixel, Micromegas+pixel
Purpose: Continue tests using 10000 Alice/Eudet channels to demonstrate measurement of 100GeV beam momentum over 70cm tracklength, in a jet environment and with ILC beam structure using LP1.		
LP2	F.L.-Cern/Eudet(2011)	Fieldcage⊕endplate: GEM, Micromegas, or pixel
Purpose: Prototype for LCTPC including gating and other options, demonstrate measurement of 100GeV beam momentum over 70cm tracklength, and in jet evironment and ILC beam structure, test prototype LCTPC electronics.		

Small Prototype R&D		
Device	Lab(years)	Test
SP1	KEK(2007-2008)	Gas tests, gating configurations
SP2,SP3	F.L.-Cern(2008-2009)	Performance in jet environment
SPn	LCTPC groups(2007-2009)	Performance, gas tests, dE/dx measurements, continuation of measurements in progress by groups with small prototypes

5 Conclusion

The LCTPC groups after more than five years of concerted effort have accumulated a large body of data and experience with the operation of TPCs equipped with MPGDs. The basic feasibility of using MPGDs in a TPC could be demonstrated.

Currently the participating groups are in the process of finalizing first systematic investigations of the single-point and double-track resolutions. Several methods are under study to readout the large number of channels required, including a proposal to directly couple a CMOS pixel sensor to the readout plane of a TPC.

In future the work will concentrate on the design, building and operation of a series of larger prototype-endplates within the LCTPC/LP project at the EUDET facility, to test not only the basic feasibility but also many engineering questions. Detailed questions will often be more effeciently addressed using the existing small prototypes. All these should be answered before a real design of a TPC for the ILC detector can be started.

The LCTPC groups expect that this second phase of the work will take around four years and will require substantial funding in addition to what will be provided by the EUDET infrastructure.

References

[1] http://www.ilcldc.org/

[2] http://ilcphys.kek.jp/gld/

[3] The other concepts are the SiD, http://www-sid.slac.stanford.edu, which has silicon tracking, and the "4th" concept (http://www.4thconcept.org/) which has several options for the central tracker, one of which is a TPC.

[4] TESLA Technical Design Report, DESY 2001-011, ECFA 2001-209, March 2001.

[5] The world-wide 'ILc Detector concept'
http://www.ilcild.org

[6] Proposal PRC R&D-01/03 to the DESY Physics Review Committee and LC Note LC-DET-2002-008 (http://www-flc.desy.de/lcnotes). See also http://www.desy.de/f/prc/ and http://mppmu.mpg.de/∼settles/tpc/prc for developments since 2001.

[7] http://www.desy.de/f/prc/talks_open/meet_55/tpcstatus070503_open.pdf

[8] http://www.desy.de/f/prc/docs_rd/prc_rd_01_03_update_03_04.pdf

[9] http://www.desy.de/f/prc/docs_rd/prc_rd_01-03_update_04-06.pdf

[10] TPC R&D for an ILC Detector
(Status Report for the WWSOC R&D Tracking Review, Beijing, 6-7 February 2007)
LC-DET-2007-025, http://www-flc.desy.de/lcnotes

[11] D.C Arogancia et al., arXiv: 0705.2210v1 [hep-ex] 15 May 2007

[12] A talk by Keisuke Fujii at the ILC TPC School, Beijing, 7-11 Jan 2008: http://www.hep.tsinghua.edu.cn/talks/TPCSchool2008/Fujiii_Keisuke/TPCfundamentals-1.pdf

[13] ILC Global Design Effort and World Wide Study, ILC, Reference Design Report, August, 2007: http://www.linearcollider.org/cms/?pid=1000025

[14] S. Biaggi, Magboltz 2 version 7.1, (2004) CERN library.

[15] M. Dixit et. al., CARLETON-HP-732, Mar 2007.
K. Kuroiwa et al., "A Study of Spatial Resolution of GEM TPC with Ar-$CF_4 - iC_4H_{10}$ Gas Mixtures" to appeare in the proceedings of LCWS2007, Hamburg, May 2007.

[16] R. Veenhof, Nucl. Inst. and Meth. A419 726-730 (1998).

[17] For an example, see a talk by Vincent Lepeltier at TILC08, Sendai, 2-7 March 2008: http://ilcagenda.linearcollider.org/getFile.py/access?contribId=94&sessionId=12&resId=1&materialId=slides&confId=2432

[18] F. Sauli, Nucl. Inst. and Meth. A386 531-534 (1997).
F. Sauli et al., Nucl. Inst. and Meth. A560 269-277 (2006).
A. Sugiyama et.al., "Simulation Study of GEM Gating at ILC-TPC", to appear in the proceedings of LCWS2007, Hamburg, May 2007.
See also the slides: http://ilcagenda.linearcollider.org/getFile.py/access?contribId=323&sessionId=74&re

[19] K. Desch et al., "Progress on Pixel Readout of a TPC", http://www.eudet.org/e26/e28/e182/e289/eudet-memo-2007-005.pdf

[20] A. Bamberger et al., "Activities on Si-TPC with GEMs", http://www.eudet.org/e26/e28/e182/e601/eudet-memo-2007-30.pdf

[21] Y. Bilevych et al., "Recent results with discharge protected Timepix detectors", http://www.eudet.org/e26/e28/e182/e420/eudet-memo-2007-33.pdf

[22] A. Bamberger et al., "Status of the Bonn R&D Activities for a Pixel Based TPC", http://www.eudet.org/e26/e28/e182/e595/eudet-memo-2007-34.pdf

[23] A. Kaukher et al., "Status Report on TDC-based readout electronics for the LP TPC", http://www.eudet.org/e26/e28/e182/e612/eudet-memo-2007-38.pdf

[24] T. Behnke et al., "Integration Issues Around the TPC", http://www.eudet.org/e26/e28/e182/e435/EUDET-MEMO-2007-42.pdf

[25] D. Attie et al., "Status of the CEA Saclay R&D activities on pixelised readout of TPC", http://www.eudet.org/e26/e28/e182/e611/EUDET-Memo-2007-44_NEW.pdf

[26] L. Joensson et al., "Front-end electronics and data acquisition for the LCTPC", http://www.eudet.org/e26/e28/e182/e605/eudet-memo-2007-53.pdf

[27] J. Alozy et al., "First Version of the PCMAG Field Map", http://www.eudet.org/e26/e28/e182/e599/eudet-memo-2007-51.pdf

[28] S. Haensel et al., "SiLC Sensors for the Large Prototype TPC at DESY", http://www.eudet.org/e26/e28/e182/e599/eudet-memo-2007-51.pdf