Development of a TPC for the Future Linear Collider

Proposal PRC R&D-01/03 to the DESY Project Review Committee
Status Report for the Desy Physics Review Committee Meeting of 7 May 2003

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Abstract

A Time Projection Chamber is foreseen as central tracker for a detector at the linear collider TESLA, and is being studied also for the other options of linear e^+e^- colliders. The LC TPC has to face significantly more complicated event topologies and higher backgrounds than at previous e^+e^- machines: this puts stringent requirements on the overall system design. In the present document the design issues and R&D plans are presented for developing such a high-performance TPC. Particular emphasis is put on the R&D for new types of gas-amplification systems, based on micro-pattern gas chambers.

It is an update of the LC Note LC-DET-2002-008 in which all issues discussed there are retained for completeness, and the revised arguments are put in italics to highlight the differences. This is necessary and useful since the thinking has been evolving and the specifications are being improved. An overview of the ongoing R&D by the collaborating groups is also given, including a listing of related work outside this PRC collaboration. A selection of quantitative results of the testing is included as Appendix to the present LC note.

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[2]The members from DESY, Hamburg University and NIKHEF would like to acknowledge the support of INTAS, grant number 00-00679.

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1 Introduction

While the R&D for a Time Projection Chamber (TPC) for the linear collider described below refers to the TDR detector [1], the TPC is equally viable for both warm or cold machines [2, 3].

The detector for TESLA outlined in Part III of the TDR [1] has a TPC central tracker. In the our proposal PRC R&D-01/03 the steps for developing this TPC are discussed, and a programme of research is outlined to solve the open questions. The goal of the proposal is to demonstrate within approximately three years the feasibility of a TPC for TESLA via a realistic prototype module, and to be ready to start the final engineering design, should a TPC be chosen as the central tracker for a linear collider of the next generation.

Some general arguments for a TPC as main tracker are repeated here to set the stage for the R&D issues.

- The tracks can be measured with a large number of ($r\phi$,z) space points, so that the tracking is continuous and the efficiency remains close to 100% for high multiplicity jets and in presence of high backgrounds.
- It presents a minimum of material to particles crossing it. This is important for getting the best possible performance from the electromagnetic calorimeter, and to minimise the effects from the $\sim 10^3$ beamstrahlung photons per bunch crossing which traverse the detector.
- The comparatively moderate σ_{point} and double-hit resolution are compensated by *the continurous tracking in* and the large volume which can be filled with fine granularity.
- *The timing is precise to about 2 ns (corresponding to 50 μm/ns drift speed of tracks hooked up to the Si detector with 25 μm strips or pixels), so that tracks from different bunch crossings can readily be distinguished.*
- It is well suited for a large magnetic field since the electrons drift parallel to $\vec{B}$, which in turn improves the two-hit resolution by compressing the transverse diffusion of the drifting electrons ($\mathrm{FWHM}_T \leq 2$ mm for Ar-10%CH_4 gas and a 4 T magnetic field).
- Non-pointing tracks, e.g. for V^0 detection, are an important addition to the energy flow measurement and help in the reconstruction of physics signatures in many scenarios beyond the standard model.
- The TPC gives good particle identification via the specific energy loss, dE/dx, which is important for many physics analyses *as shown at LEP and improves the $e-\pi$ separation for electron-identification and energy-flow applications.*
- A TPC is easy to maintain since, when designed appropriately, an endplate readout chamber can readily be accessed or exchanged if it is having problems.

To obtain good momentum resolution and to surpress backgrounds near the vertex, the TPC has to operate in a strong magnetic field. For the TESLA detector a 4 T solenoidal field is foreseen. The magnetic field has to be mapped to better than 10^{-3} in order to minimise corrections for the distortion of drifting electrons.

There are two features of a TPC which must be compensated by proper design work following our ensuing R&D programme. First, the readout endplanes and electronics present a fair amount of material to the interaction products in the forward direction. The goal is to keep this below 30% X_0. Second, its $\sim$ 50 μs memory time integrates over background and signal events from 160 TESLA bunch crossings at 500 GeV and twice as many at 800 GeV. This is being compensated by designing for the finest possible granularity: the sensitive volume will consist of at least $\sim 1.5 \times 10^6$ pads $\times$ 10^3 time buckets per pad, giving more than 10^9 3D-electronic readout pixels (voxels). Assuming roughly 15 electronic voxels are hit per ionisation deposit, then the chamber will have an effective granularity of 10^8 voxels (two orders of magnitude better than at LEP). This would then result in an occupancy of the TPC of less than $\sim$ 0.3% from beam backgrounds and gamma-gamma interactions[4]. Simulations have shown that efficient pattern recognition is possible even if the machine background calculations are underestimated by a large factor.

2 Overall Design

The design is presented in the TESLA TDR [1] and is an improved version of that in the CDR [2]. The main requirements are to develop a system which can achieve an overall performance which is significantly better than at LEP and in other current experiments – both in resolution and in granularity, which represents as little dead material as possible, and which is capable of operating continuously throughout one TESLA bunch train of $\sim$ 1 ms length. To achieve the performance systematic effects in the TPC track reconstruction must be kept to less than 10 μm to guarantee the momentum precision $\delta p_t/{p_t}^2 \sim 1.5 \cdot 10^{-4}$/GeV/c, (TPC only), $\delta p_t/{p_t}^2 \sim 7 \cdot 10^{-5}/GeV/c$ *(TPC+interaction vertex)* and $\delta p_t/{p_t}^2 \sim 5 \cdot 10^{-5}$/GeV/c (overall).

To ensure good solid angle coverage, good track resolution and simultaneously good determination of the specific energy loss, $\delta(\mathrm{dE/dx})/(\mathrm{dE/dx}) \leq 5\%$, a large number of points should be measured along each track. This dictates that the chamber should be rather large, both radially and longitudinally. At TESLA the main parameters for the TPC are listed in Table 1. The inner radius of the TPC is given by the size of the mask system, which extends to inside the TPC bore and which in turn is given by the dimensions of the final focus quadrupoles. The outer radius is determined by the dimensions of the calorimetry and the size needed to achieve both the desired momentum resolution and the measurement of around 200 space points along a track for the dE/dx resolution.

Mechanical radii	320 mm inner, 1700 mm outer
Overall length	2 $\times$ 2730 mm
Radii of sensitive volume	386 mm inner, 1626 mm outer
Length of sensitive volume	2 $\times$ 2500mm
Weight	$\sim$ 4 t
Gas volume	38 m^3
TPC material goals	0.03 X_0 to outer field cage (in r)
	0.30 X_0 for readout endcaps (in z)
No. of pads "partout"	$\sim$ 10^6 *per endcap*
Pad size/no.padrows/σ_{point}	*$\sim$2mm$\times$6mm/200/<140μm*

Table 1: TPC parameters in the TESLA TDR.

3 The R&D Issues

The main challenge of this TPC is to design and build a system with the finest possible granularity, which is robust in operation and performance in high backgrounds, has a minimum of material in front of the calorimeters and is constructed in such a way that systematic distortions can be controlled to better than 10 μm over the whole volume. Development work is needed on all aspects of the TPC, in particular on the amplification and ion-suppression schemes and on the integration of frontend electronics.

3.1 Readout System

TPC gas-amplification readout systems up to now have been realised using proportional wire chambers. The signal produced in the wire chamber is read out via pads which detect the induced signals from the wires. These systems worked extremely well and provided robust and reliable solutions. However they have a number of drawbacks: wires are one-dimensional, and $\vec{E} \times \vec{B}$ wire effects in strong magnetic fields can be significant *(but might be acceptable for small pad–wire distances as will be tested)*. The induced signal on the pads is broader than the arriving electron cloud and thus compromises the two-hit resolution as well as the overall granularity of the TPC. In addition the fact that many wires need to be supported means that more material may be present in the endplates.

With the advent of micropattern gas detectors such as the Gas Electron Multiplier [5] or Micromegas [6] attractive candidates exist for the readout planes which solve some of the drawbacks of the wire technology. These devices are intrinsically two-dimensional, they have hole or grid spacing similar to the point resolution of around 100μm so that $\vec{E} \times \vec{B}$, and they may possibly be built with less material present in the end plates.

Before a TPC based on one of these new technologies can be safely proposed, several questions need to be answered. For this reason the wire chamber version[1] will be further developed as a back-up in this R&D project. For the new technologies, the issues are covered in the following subsection 3.1.1.

3.1.1 Chamber Development

The properties of the micropattern gas detector (MPGD) such as gain, stability, and granularity are related in part to mechanical properties of the MPGD. For GEMs most studies so far used foils supplied by CERN with similar hole shape and hole spacing. A systematic optimisation of the shape of the GEM holes, of their arrangements and of the density of holes is needed. This should go hand-in-hand with a comparison of GEMs supplied from different manufacturers. Particular emphasis should go into the development of GEM structures which are more stable and uniform than currently available. Similar studies are needed for the Micromegas: for example, understanding Micromegas detectors with different mesh pitches is important in terms of reducing positive ion feedback, and metallic meshes of various materials from different sources should also be compared.

MPGD operation

MPGDs are still comparatively new devices, with little experience in operation and long term behaviour. Valuable information is available from experiments like Hera-B, NA48, Cast and Compass where GEMs and Micromegas have been used for the first time on a large scale. Nevertheless it is desirable to complement this by dedicated exploration of the parameter space available for stable MPGD operation via small-scale laboratory tests. Important for the application in the TPC are the long term stability of the MPGD and the homogeneity of the device. This has consequences for the capability of the final TPC to contribute to the identification of particle types via the measurement of the specific energy loss dE/dx. This work also includes a comprehensive study of systematic effects which might affect the behaviour of a MPGD TPC.

Signal pickup

The ionisation originating in the drift volume of the TPC is amplified inside the MPGD and transferred onto a set of pads which are read out via charge sensitive preamplifiers. The charge is measured directly, as opposed to wire chambers where the signal generated at the wires is induced on the pads. This direct charge provides for large signals, but has the drawback that no or only very small induced signals are usable on neighbouring pads. Thus if the charge is picked up by a single pad only, that point will be measured with worse resolution than for the case where several pads are hit. The former can happen for drift distances that are too short to allow sufficient charge-spreading by diffusion. The solution for example to fully use the resolution given by the size of the electron cloud would be to have pad sizes matched to the minimum drifted electron cluster size (several tens of μm), but this would result in a number of pads which is much too large (unless silicon techniques would prove feasible).

A number of ideas are being discussed how the resolution can be improved:

- Specially shaped pads can be used which maximise the charge sharing between neighbouring pads, without actually spreading the charge.[8]
- During the gas amplification in a GEM a small signal is induced on the pads, before the full electron signal arrives. It has been shown that these signals can be used to improve the resolution via very fast sampling with the ATWD chip[9], albeit at the cost of a significantly more complicated electronics and hit reconstruction.
- Different techniques are being discussed to physically spread the charge on the pads. This can be done by inserting a resistive layer on top of the pads. Significant R&D is needed to demonstrate this technique.
- Similar to the technique used in Si detectors the density of pads can be increased, with only every second, third or similar pad being read out. Capacitive coupling between the pads can be used to improve the resolution. Such an approach has never been used in a TPC.
- *Diffusion between GEM foils may be a solution to the problem.*

This question has many consequences for the design of the endplate, the number of channels, and therefore ultimately also the cost. It is one of the central questions to be addressed in this R&D.

MPGD ageing

Although radiation damage to detectors is not expected to be a major concern at a linear collider, nevertheless care has to be taken to ensure that all components survive for the estimated lifetime of the experiments. In particular a significant neutron flux is expected at the location of the MPGDs. Therefore dedicated neutron irradiations and ageing studies should be carried out to measure the dose up to which a MPGD TPC can operate reliably.

Apart from influencing the materials used in the construction of the chamber this can also dictate the choice of gas and have consequences on the type and operation of the MPGD.

MPGD towers

Currently typical MPGD sizes are $< 40 \times 40$ cm^2, though larger detectors might become available in the future. Since the TPC endplate is much larger, ways have to be found to combine individual MPGDs into larger active areas, with as small as possible dead zones and distortions between neighouring MPGDs. In the TDR the concept of a MPGD tower was introduced. The MPGD, together with the readout pads, possibly a gating plane, and the readout electronics for the pads form one self-contained unit. The idea is that spacers maintain the MPGDs at the proper distance without external frames, thus minimising dead zones between the MPGDs. Significant work is needed to further develop this idea and to understand how to build these MPGD towers and the interface between neighbouring MPGD towers.

For GEMs to obtain large enough gains (*at the moment the goal is to be able to work with a gain of about a 1000*) it might be necessary to cascade at least two GEMs. Further studies should clarify whether two or even more GEM planes are needed, what the implications of such multi-GEM detectors are and how robust is the operational experience with them.

Ion feedback

There are two aspects related to ions produced during gas amplification: the amount of charge buildup around the MPGD (or wire) plane during a bunch train and the fraction of that charge which feeds back into the TPC sensitve volume. These may affect the signal formation or produce distortions. The gas gain and the amount of positive charge escaping the MPGD should clearly be as small as possible, and, to achieve the best possible momentum resolution the sensitive volume should be kept as clear as possible of positive ions. In conventional wire TPCs to now, a gating plane was installed which blocked positive ions except after a trigger (e.g. PEP) or bunch crossing (e.g. LEP). At a linear collider like TESLA no explicit fast trigger is foreseen, thus excluding the possibility of triggered gating, and the bunch-crossing time is so short that only train-to-train gating is feasible. The MPGDs promise to significantly reduce the ion feedback into the amplification region. Thus the measurement and minimization of ion production is an important part of the R&D studies.

The degree of ion feedback depends on the choice of operational parameters and the MPGD used. At the moment suppressions to the level of $< 10^{-2}$ *have been demonstrated. However, lower levels may be needed since these ions would drift as a few-mm thick sheet through the sensitive region during subsequent bunch trains. How this sheet would affect the track reconstruction must be studied, but a level of* $<< 10^{-3}$ *may well be desirable to ensure that the positive-ion effect on the momentum measurement is at an acceptable level.*

To guarantee a stable and robust chamber operation, it may be prudent to insert a gating plane, which would be closed between bunch trains and remain open throughout one full train. In principle this would eliminate ion feedback into the drift volume completely, as long as the ion components and their drift velocities are well understood.

In summary the R&D requires the measurement of the amount ion feedback in order to achieve the smallest possible ion buildup, and similarly the v_{ion} for all possible gas components must be measured to *confirm ideas about* minimizing the ion leakage into the sensitive volume.

Magnetic field behaviour

MPGDs have been shown to operate reliably in strong magnetic fields, as they are planned for the TESLA detector. One of the advantages of the MPGD in fact is that when operating in a magnetic field a significant reduction of systematic effects close to the MPGD due to $\vec{E} \times \vec{B}$ distortions is expected, when compared to a TPC equipped with wire chambers. Dedicated studies are needed to prove and quantify this effect, and to understand the level of remaining systematic effects, as a function of the type of the MPGD used. For this study the operation of a MPGD TPC in a strong magnetic field under realistic conditions is essential.

Double track resolution

While first results on the spatial resolution obtainable with a MPGD TPC look very promising and were documented in the TDR, no experimental results exist yet on the achievable double track resolution. It is expected that significant improvements can be made compared to a wire TPC, but experimental proof is lacking. This measurement requires extensive test beam studies.

3.1.2 Gas Studies

The choice of gas influences strongly the design of the fieldcage, the two-hit resolution and the sensitivity to backgrounds. In the TDR gases considered were Argon with quenchers of CH_4 or a mixture of CO_2+CH_4. Quenchers containing no hydrogen are much less sensitive to neutron backgrounds, which can be high at the LC, so that other quenchers like CF_4 (mentioned in the CDR) are also being studied and require understanding of their properties. Finally the operating pressure of the TPC, which influences also the mechanical design, must be decided.

3.1.3 Electronics

A TPC for the linear collider will pose new challenges on the design of the readout electronics. In the TDR the number of channels considered was of order 10^6 per side. Due to this large number, very compact and cheap electronics are needed which simultaneously fully utilise the potential of the TPC. Development work is expected to happen in the area of the preamplifier and the digitisation technique used. Highly integrated solutions must be found, where e.g. the pre-amplifier and the digitisation electronics are combined into one chip.

Several options are under investigation for the digitisation. In the past modules based on CCD/ADCs or FADCs have been used to read out the timing and charge information from the pads. Alternatively the use of advanced multi-hit-TDC/ADC boards will be investigated. In addition to more integration, higher sampling speed is also wanted, as already mentioned.

The most modern system for the readout of a TPC is that developed for the Star experiment at Brookhaven[7] based on the switched-capacitor-array/ADC technique. The packing density however is still an order of magnitude smaller than that required for the TESLA TPC. For the next generation of prototype chambers a solution similar to that of the Star experiment will possibly be used.

3.2 Endplate Design

For the conceptual layout as given in the TDR, the endplate is subdivided into 8 individual modules. Each can be removed without disturbing the neighouring ones, so that a maintainance and repair of modules is possible. Further development work is required to translate the conceptual design into a real one. Many technical questions have to be solved, both mechanically and electrically.

3.2.1 Cooling

Cooling of the on-detector electronics is always a major design task. At the linear collider the design can profit from the long idle times between bunch trains. It is expected that a properly designed electronics can be switched off between trains, thus significantly reducing the average power and therefore the cooling power needed.

3.2.2 Mechanics

The goal as spelled out in the TDR is that the fieldcages together should not present more that 3% of a radiation length of material, and that the endplate should not be thicker than 30% of a radiation length. It will be particularly challenging to fit the large number of electronic channels onto the endplates without introducing too much material. Another issue is the plan to roll out the TPC in order to service the inner detectors. These aspects will be demanding on the engineering and must be studied on a timely basis.

3.3 Fieldcage Design

Of central importance for the reliable and stable operation of the TPC is a proper design of the fieldcage. The system proposed in the TDR is based on HV-experience gained with the Aleph, Star and D0 experiments. Further work is needed to detail the design and to test it comprehensively. It is planned that the next generation of prototypes should be equipped with a development version of the proposed fieldcage. The main questions to be addressed are:

- high voltage stability of the structure
- mechanical stability of the structure
- optimisation of the field strip pattern
- development of compact voltage dividers
- integration of the cathode into the field cage.

3.4 Calibration, Alignment

The LEP experience shows that tracks from e^+e^- events and in particular Z-peak running are the best source for correcting distortions, that Si layers inside the TPC inner field cage and that a measured point outside the TPC are likewise valuable tools for mapping and monitoring the corrections. The inner Si layers are already the TDR design, while an outer point (along the lines of the Opal z-chamber but two-dimensional) is not yet. Aleph could correct the effects to the 30 μm level but did not have a measured point outside the TPC, and it should be studied to see if an outside point would improve the reduction of distortions to below 10 μm. Recently a group from the University of Paris[10] has been looking at the use of Si layers to provide such a point, *and the Calice collboration[11] has shown that a additional layer in the ECAL could also fulfill this function.*

A laser system was included in the TDR design as a tool to help monitor the distortions. The implications and the usefulness of such a system have to be studied. *Experience to date is that calibration with laser is inadequate, this however is not finally decided, as is the case with all components of the LC TPC. Final decisions can only be made after the R&D phase is more advanced.*

3.5 Software Developments

The software effort needed to accompany the research and development work for the TPC has two components.

First some development work is necessary to provide software tools which can simulate the behaviour and properties of MPGDs in more detail in order to understand better the results from prototype work on a MPGD TPC. In particular the detailed modelling of the charge collection properties of a MPGD, of the ion feedback and the signal generation is still unsatisfactory.

Second the MPGD TPC needs to be fully modelled and included in the GEANT based detector simulation for the TESLA detector. Although significant studies were done in the preparation for the TDR, more work on the detailed simulation of the different TPC parts and on their interaction with the pulse and track reconstruction should be done.

4 Participating Institutes

In this section a brief, telegram-style description of activities at each of the participating groups is given. Also TPC-related work by groups outside our proposal PRC R&D-01/03 is listed since this work is highly relevant and good contact must be maintained.

General — *It can be seen from the descriptions below that quite a lot of task sharing is occurring between the institutes. A few examples are: LBNL is providing Star electronics for Canadians, French and German groups; similarly MPI is providing Aleph electronics; the 5T magnet in Desy will be used by at least five groups in Germany and Canada; French, US and Canadian groups have common Micromegas projects; GEM work is being pursued by US, Canadian, German and Russian groups; fieldcage studies are going on in Russia and Germany; electronics development is starting in several places.*

Aachen — *Three test GEM TPCs running: A small chamber for current measurements (e^- transparency, ion feedback) in as function of B field; measurements made in 2T (Jülich) and 5T (Desy) solenoids. Another small one for pulse width and shape studies. A larger one (1.4 m^3) (Aleph electronics) for tracking/readout studies. Detailed electric/magnetic-field simulations of GEM detectors.*

Berkeley — *Star electronics test-stands with $\sim 10^3$ channels for prototype testing provided to Carleton/Montreal/Victoria, Saclay/Orsay and Karlsruhe/Munich. Several simulations of TPC for the LC environment. TPC symposium October 2003.*

Carleton/Montreal/Victoria	*Double-GEM TPC (Aleph electronics) for diffusion/resolution studies as function of pad-width and gas. New GEM TPC (Star electronics) for studies in 1T (Triumph) and 5T (Desy) magnets. Testing of resistive foils for charge spreading. Simulations of* σ_{point} *accuracy for rectangular and chevron pads and diffusion charge-spreading.* σ_{point} *measurements in GEM and Micromegas together with Saclay/Orsay. New electronics (Montreal) for TPC prototyping studies along with small test TPC being built.*
DESY/Hamburg	*Larger prototype with double-GEM TPC (Aleph electronics) for performance studies with cosmics (B=0); measurement and simulation of signal width for chevron and rectangular pads. Two solenoids commissioned, 1T for test beam, 5T for cosmics. First 5T measurements made together with Aachen. New TPC prototype for 5T magnet ready. Fieldcage studies started. Laser system under preparation.*
Karlsruhe/CERN	*Star electronics commissioned with LBNL. Prototype GEM TPC built; first measurements in Cern test beam (B=0). Further work for 5T magnet (Desy) in preparation.*
Krakow	*Continuing study of gas-mixture parameter space to find the optimum for a TPC with MPDG readout. In particular characteristic parameters of gas mixtures based on Argon with inorganic admixtures (CH4, CF4, etc) have been measured.*
MIT	*Simulation/measurement of drift velocity, Lorentz angle for different gas mixtures, study of 1, 2 and 3-fold GEMs using laser tracks or cosmics. Study of GEM-foil manufacturing techniques and test productions thereof.*
MPI-Munich	*Prototype TPC (Star electronics) for the 5T magnet (Desy) almost completed to allow testing of the different technologies (wires, GEMs and MicroMegas); first version* $\rightarrow$ *wire chamber. Star electronics teststand commissioned together with Karlsruhe and LBNL*
NIKHEF	*A prototype TPC set-up which combines GEM foils with a Si pixel (Medipix) readout constructed and being commissioned.*
Novosibirsk	*Measurements of electron transparency, ion feedback, ion drift velocity and gating using different GEM configurations and gas mixtures in triple-GEM detector prototypes. Measurements of signal width at the readout electrode in different GEM structures. Manufacturing techniques of GEM foils together with a local company under study.*
Orsay/Saclay	*One small, one large test Micromegas TPC in operation for establishing Micromegas-mesh parameters via current measurements and ion feedback. Measurement of induced signals on nearby strips via a resistive foil together with Carleton. Star teststand together with LBNL running. 2T solenoid commissioned; new larger Micromegas TPC prototype for it ready for testing with cosmics. Ion feedback and* Fe^{55} *measured as function of B field. Many measurements of* CF_4 *quencher and much simulation work in general. Further studies include capacitive coupling between adjacent pads via a mesh.*

Rostock	*Development work of a TDC-based readout for the TPC, together with Desy and Hamburg.*
St. Petersburg	*Plan to do extensive optimization on fieldcage: simulations started.*
Other studies outside PRC R&D-01/03	*Below the acronyms LCRD and UCRD stand for "Linear Collider R&D" and "University Consortium for Linear Collider R&D", the groupings of proposals being funded by the DOE and NSF, respectively. More details about this work can be found on the web[12].* *·BNL–* *Phoenix and Star development of GEM chamber with pure CF_4 for measurements at RHIC.* *·Chicago/Purdue/3M–* *Mass prodution of GEM foils; Fe^{55} measurements.* *·Chicago/Purdue–* *Large-scale GEM detectors for low-background physics.* *·Cornell (UCLC)–* *Simulation studies of the LC TPC.* *·MIT (LCRD)–* *Develop in-house GEM manufacture.* *·Temple/Wayne State (UCLC)–* *Feasibility studies for a negative-ion TPC.* *·Yale–* *TPC plus double-GEM detector response simulation.* *·Asia–* *EOI to start R&D on the option of a TPC.*

5 Road Map

5.1 Priorities

The goals of the R&D work detailed above can be structured into three parts: short term, medium term and long term goals.

The most important development work to be done is on the gas amplification system. The main question to be solved is which amplification scheme is best suited for a TPC at a linear collider.

With slightly lower priority and on a somewhat longer time scale, progress has to be made on a more detailed technical design of the different parts of the TPC, in particular of the electronics and of the fieldcage. Significant engineering is necessary in these areas.

For the long term solutions for the integration of the TPC into the overall mechanical detector concept have to be found. The currently proposed solutions as presented in the TDR will have to evolve further as the concept is refined.

The work on the first two issues will include a combination of tests at the different labs and small scale beam tests. It is expected to lead up to the construction of a large prototype for the LC TPC and start of significant beam testing in approximately three years.

5.2 Milestones

As pointed out the investigation of the amplification system is the most pressing question to be answered by the proposed R&D program. While it is most likely that a final decision on the technology to be used can only be taken once a real detector collaboration for the linear collider has formed, important information should be available earlier. It is expected that many of the questions outlined above can be answered within approximately two years.

The major goal of this proposal is the construction of a TPC prototype module optimised for the linear collider environment. This TPC module should reflect the main results from the R&D work on gas-amplification system, endplate and fieldcage, and use the best prototype electronic scheme available at that time. Such a prototype can be designed and built within approximately one year after the two-year development phase mentioned above, assuming that no major difficilties are found during that phase. The prototype TPC module will then be tested at DESY in an electron test beam to determine its basic operation characteristics. Tests in hadron test beams at other labs might be necessary at a later date.

It should be pointed out that basic development work on the gas-amplification scheme will likely continue also beyond the two-to-three years, since it will include the construction and operation of a number of small test systems, each with of order a few hundred channels, which will be undergoing extensive testing.

6 Summary

The present proposal by a global group of institutes has goal of coordinating important R&D work needed to make the Time Projection Chamber a viable technology for the central tracker of the linear collider detector. The main challenge is to design a continuous-tracking, high-performance TPC with the finest possible granularity, which is robust in high backgrounds, has a minimum of material and can keep residual distortions below 10 μm. Development work is required on all aspects of the TPC, in particular on the amplification, the ion-suppression scheme and the large-scale integration of electronics. The aim is to make technical decisions based on the present R&D within three years, to design and build a realistic prototype within the following year and to then start extensive testing.

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http://alephwww.mppmu.mpg.de/ settles/tracking/amsterdamtracking/talkswelcome.html

7 APPENDIX

Foils of Selected LC TPC R&D Results

for the DESY RPC Meeting 2003 May 07

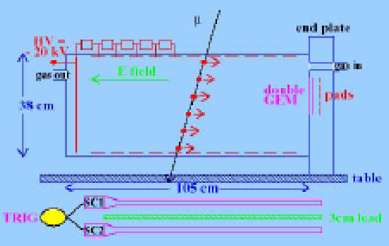
The LC TPC R&D Groups of the PRC R&D-01/03 Proposal

Carleton, Montreal, Victoria,
Orsay, Saclay,
Aachen, DESY, Hamburg, Karlsruhe, MPI-Munich, Rostock,
NIKHEF,
Cracow,
Novosibirsk, St. Petersburg,
Berkeley, MIT

Abstract

Examples of the results from TPC R&D studies are collected here. They were part of the full PRC presentation (alephwww.mppmu.mpg.de/~settles/tpc/tpcstatus070503.ppt). In the following a more detailed description has been added to selected results which supplement the note submitted to the PRC (alephwww.mppmu.mpg.de/~settles/tpc/tpcprcstatus070503.ps). Recent tests in high magnetic field have been emphasized since this was encouraged in the original PRC recommendations of 2001 October 26

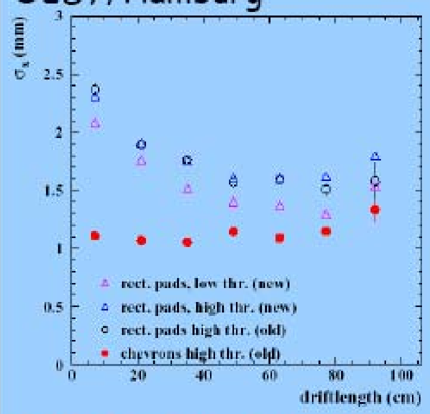
DESY/Hamburg large Gem prototype (B=0)



- gas: Ar-CH_4-CO_2 (93-5-2)
- double GEM structure
- cosmic muons
- trigger: 2 scintillators
- readout: ALEPH preamps + TPD + MAC II + Labview

Several TPC prototypes, large and small, are now in operation. Shown here is the large one in DESY/Hamburg which uses cosmic rays to study the tracking characteristics using GEM gas-amplification. Obviously these studies are with no magnetic field. The size of the chamber is suitable for studies of gas properties and of the impact of readout geometry on the coordinate resolution.

DESY/Hamburg



- Old data were taken with pads on HV, bad signal/noise ratio
- New data were taken with grounded pads, good signal/noise ratio
  $\Rightarrow$ Reduced threshold value possible
- New measurement for chevrons soon to come

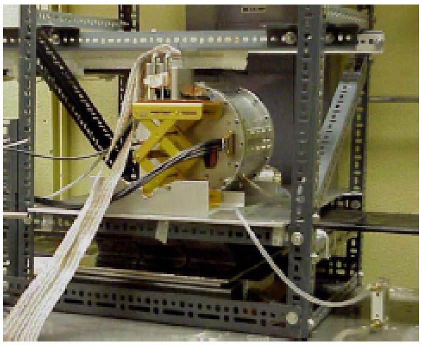
For the first time the diffusion limit is visible from the measurements (rise at long drift distances)

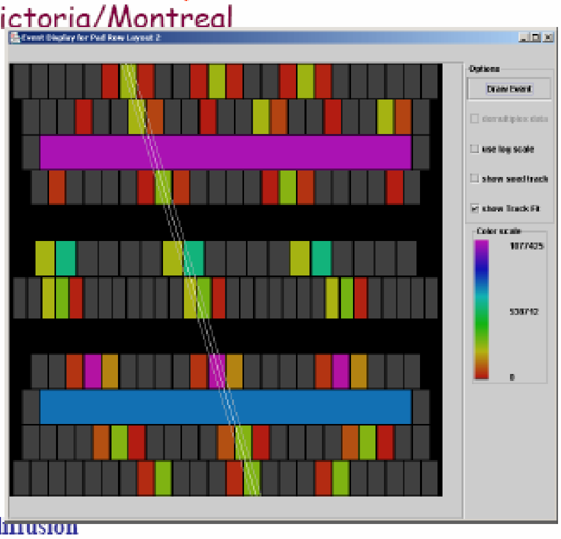
An example of the results from the DESY/Hamburg test chamber (Foil 2). The wide resolution reflects the large readout pad size, which was scaled to match the larger diffusion in the absence of a magnetic field. In the early version of the set-up, the first GEM foil was at ground potential for the drift volume, which meant that the pads were at ca. 2 kV. This turned out to be somewhat delicate and was changed in order to run the pads at ground which enabled lower thresholds..

RESULTS ON RESOLUTION AT LARGE DRIFT DISTANCE

Double GEM TPC Cosmic Ray Tests

Carleton/Victoria/Montreal





- Aleph TPC preamps + Montreal 200 MHz FADCs
- 15 cm drift (no **B** field)
- **Pads can share track charge due to transverse diffusion**
  - Ar CO_2(90:10), small σ_T ~ 200 μm / √cm
  - P10 Ar CH_4(90:10), large σ_T ~ 500 μm / √cm
- Compute pad centroids, measure resolution for different width pads

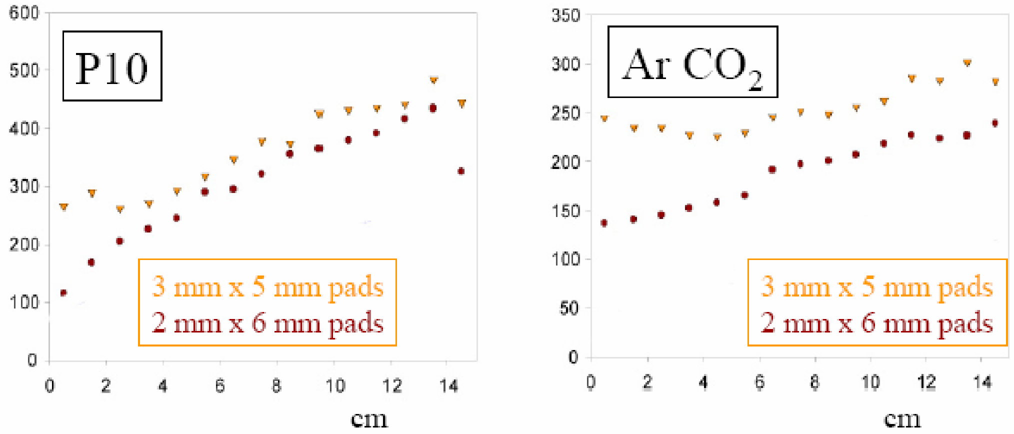
The photograph shows the Carleton test chamber using GEMs. Again there is no magnetic field, and the pad layout is with 3x multiplexed readout (thus the mirrored hits in the right diagram). Drift distances up to 15cm, two different gases (Argon with CO2 or CH4) and resolution with different pad widths (2mm and 3mm) have been studied; the pads were rectangular and charge sharing took place via transverse diffusion in the induction gap (between GEM and anode). The track was defined by outer rows (3 on each side) and the resolution measured on the middle rows (see Foil 5).

SET-UP FOR DIFFERENT PAD GEOMETRIES

Resolution vs Drift Distance for Different Pad Widths

$|\varphi| < 0.1$

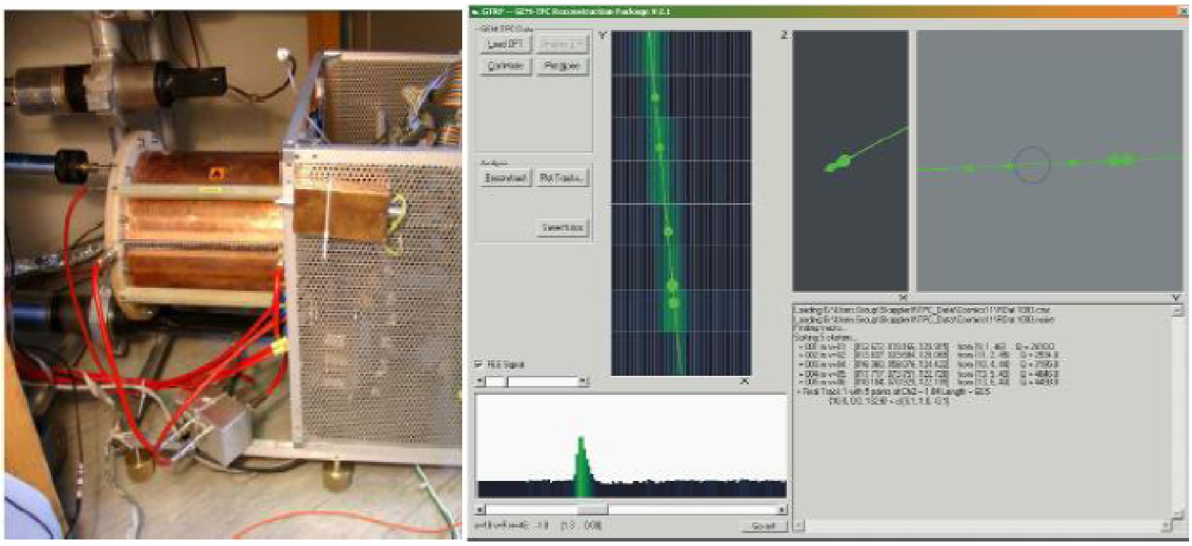
Carleton/Victoria/Montreal



Single pad row resolution measurements from the Carleton TPC (Foil 4). Tracks are formed from the outer 6 rows, and residuals calculated for each of the two inner rows with 2mm x 6mm (triangles) and 3mm x 5mm (circles) pads. The residuals are fit to Gaussians, and the standard deviations (in microns) is shown here for different drift distances.

FURTHER RESULTS VS DRIFT DISTANCE 5

TPC cosmic tests at Karlsruhe



Cosmic ray setup using STAR electronics
Measured resolution 124 µm, S/N = 18:1

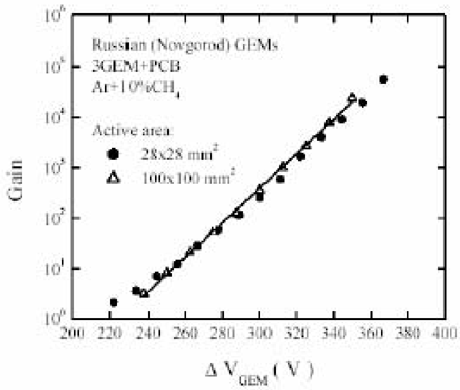
The Karlsruhe test chamber with GEMs (left) has recorded cosmics and was also exposed to a test beam in CERN. The figure on the right shows a measured track. The readout took place using the STAR electronics test-stand supplied by LBNL. The tests were with no magnetic field, but the chamber can fit into the 5T magnet at DESY.

TEST MEASUREMENT USING STAR ELECTRONICS 6

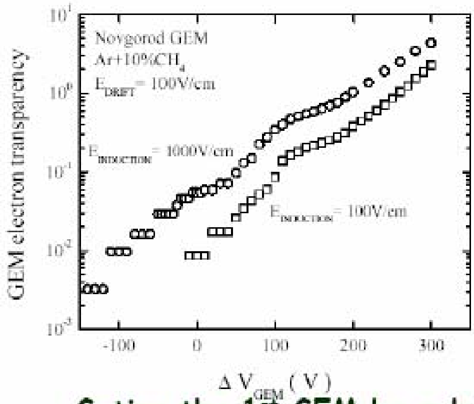
Novosibirsk

Russian GEM manufacturing company in Nijni Novgorod

(80 μm holes at a 140 μm pitch)



GEM electron transparency vs GEM voltage

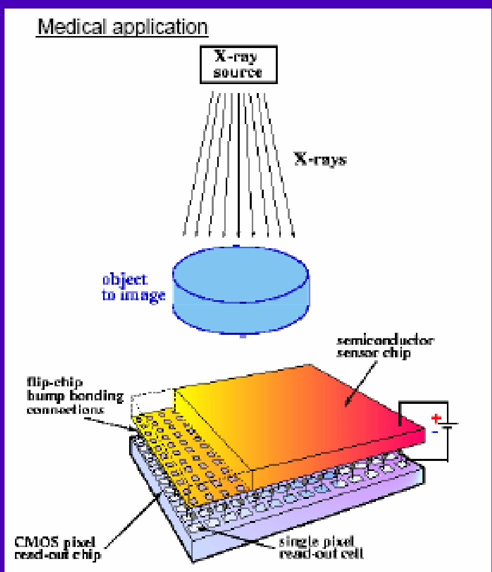


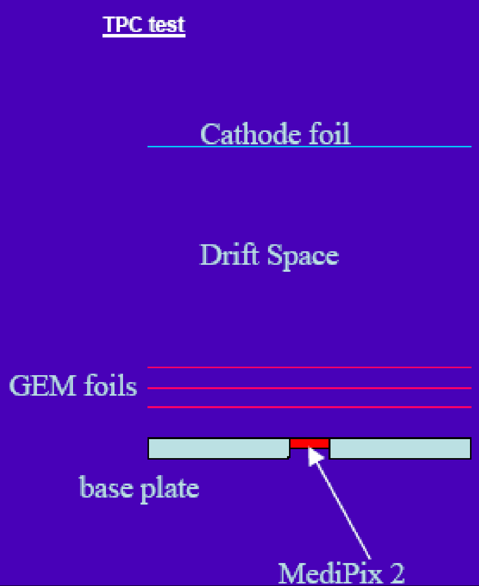
Gating the 1^{st} GEM by pulsing

Using a test chamber at Novosibirsk, GEM manufacturing and gating are under study, among other things. Left: Gain-voltage characteristics of the triple-GEM structures, produced by a local company at Nijni Novgorod with active areas of 28mm x 28mm and 100mm x 100mm. Gains as high as few tens of thousands can be reached. Right: Electron transparency of a GEM as a function of the GEM voltage, at the induction field of 100 and 1000 V/cm. At zero GEM voltage the GEM transparency to electrons and ions can be as low as 0.01, and the voltage needed to "open" the GEM, in a gating mode, is about 300 V.

NIKHEF

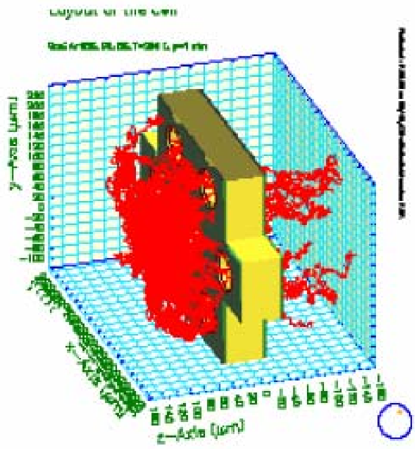
MediPix2 Si-pixel detector

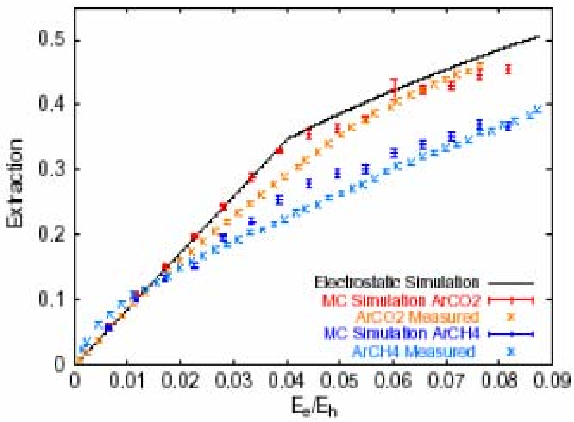




At NIKHEF a new idea is being tried out, namely to read out a TPC using a Si detector with pixels matching the GEM-hole pitch. Left: the MediPix2 chip has 256 x 256 pixels of 55 x 55 μm², low noise and a minimum threshold of about 1000 electrons. Right: schematic view of the one liter test TPC with a triple-GEM arrangement and an insert in the base plate for the MediPix2 chip.

Aachen





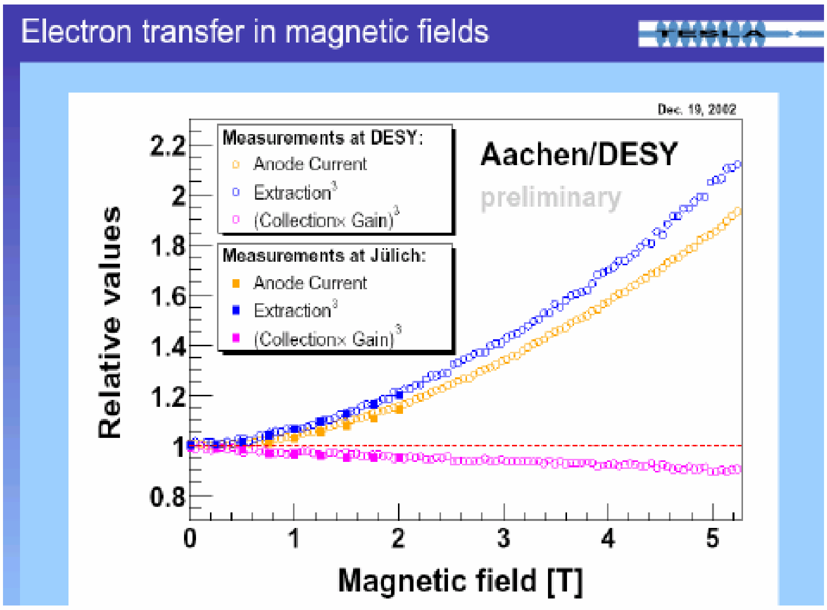
Three test chambers have been built in Aachen (see also below) and detailed simulations on GEM properties are also being carried out. On the left are the simulated electron-drift trajectories in a GEM using the programs MAXWELL and GARFIELD, and on the right is the calculated extraction efficiency compared with measurements. The black curve is a parameterization of results from simulation with MAXWELL only, which is adequate for gases with small diffusion. The data points labeled "MC simulation" are due to the combination of MAXWELL+GARFIELD so that diffusion is included. That simulation and results agree well will be important for the final optimization of a GEM TPC readout.

- Max. magnetic field > 5 T
- Diameter of opening 28 cm
- Total length 187 cm

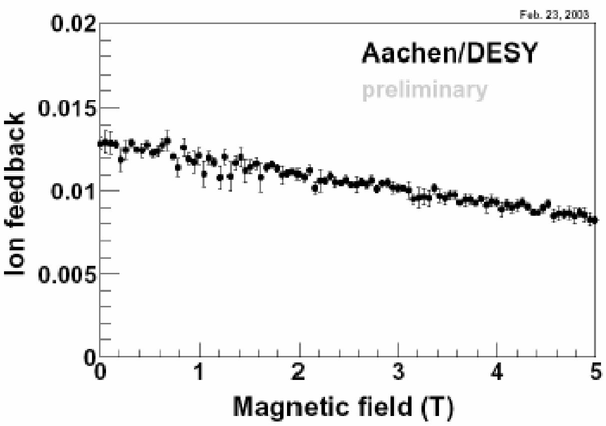
First TPC studies in the magnet on December 18, 2002

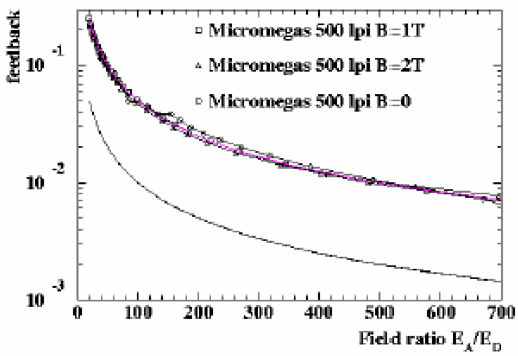
Left: The 5T superconducting solenoid at DESY which started operation at the end of last year. First tests (see below, Foil 11) were made using a small GEM device built at Aachen to allow measurement of all currents in order to derive the charge-transfer characteristics. Similar measurements had previously been carried out in a 2T magnet at Jülich.

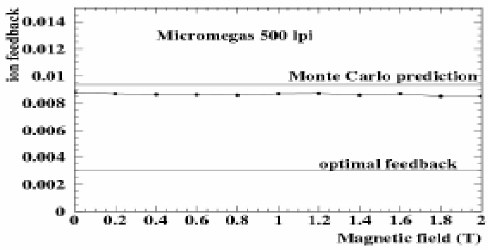
Right: The 2T superconducting solenoid magnet in operation in Saclay has a 53 cm bore diameter and a length of 150 cm. It has been used for testing two Micromegas TPCs and a wire TPC built by Saclay/Orsay using current measurements. It is now being equipped with a 1000-channel cosmic ray Micromegas prototype with a 50 cm drift length.



Here are the results mentioned above (Foil 10) which were obtained with the Aachen test chamber in the DESY magnet, and which confirm and extend previous measurements carried out at Julich. The various currents arise from an Fe55 source. The anode current (electrons arriving at pads) rises significantly with B-field. In order to understand this, the triple-GEM structure was operated with symmetric settings (GEM voltages at 330V and transfer fields at 1kV/cm) so that all GEMs have equal collection efficiency C, gain G and extraction efficiency X, and the anode current was the primary current times $C^3G^3X^3$. The collection times gain drops slightly while the extraction improves, meaning only few primary electrons are lost during collection at 5T while the net gain of the overall structure increases at higher B-fields.







Left: the ion-feedback improves at high magnetic field in GEMs, as seen from the Aachen/DESY measurements described on Foils 10-11.

Right: Positive ion feedback fraction as a function of magnetic field, as measured in the 15cm Orsay/Saclay Micromegas TPC.
No dependence on the magnetic field is observed, consistent with expectations, and it is about 3 times the optimal feedback due to the use of a relatively coarse micromesh (500 lines per inch). A finer mesh (1000 lpi) should allow reaching the optimal feedback with this gas (Ar10%CH4).

Orsay/Saclay

Summary ↔ Outlook

- Measurements in high B-field have started, with encouraging results for the charge-transfer coefficients for GEM and Micromegas
- Better understanding of amplification and resolution achieved
- Test-stand infrastructure now functioning for systematic optimization

- Resolution in high B-fields must be measured for all three technologies, GEM, Micromegas and wires
- Design and testing of large prototypes should follow promptly
- Mechanics, electronics and field cage design studies should start now

Milestone exercise TPC

The TPC group went through the exercise of seeing what steps are involved in producing a final detector and came up with the following realistic milestones (the first two are rather ambitious).

- 2005 - “Large” TPC prototype design/testing
- 2007 - Final design all components
- 2011 - Four years for construction
- 2012 - Commission TPC alone
- 2014 - Install and integrate