

# Addendum 2021 to the LCTPC MoA:

## Preparing for the LC

### Overview

The LCTPC Memorandum of Agreement (MoA), the groups which have signed it and the yearly Addenda are available at <http://www.lctpc.org/e9/e56939/>. The MoA was revised in 2016 and can be found at the above link. Updates in the collaboration are documented in the yearly Addenda.

## 1 2021 Activities

As described in the MoA, the R&D preparation of the LCTPC is proceeding in three phases: **1**-Small Prototypes, **2**-Large Prototypes and **3**-Design. Presently the work is mainly in phase **2**, and will pass to phase **3** during the 'ILC Pre-Lab' preparations (see Sec.1.3 below).

### 1.1 The ILD LOI, the DBD and the IDR

The International Large Detector (ILD) Letter of Intent (LOI) was validated in 2009 and was followed by the Detailed Baseline Design (DBD) of the detector in 2013. The latter was the result of more understanding being put into the detector and its engineering. The Technical Design Report (TDR) of the International Linear Collider (ILC) accelerator, also completed in 2013, and the DBD were combined into one document: <https://arxiv.org/abs/1306.6327>.

The ILD Interim Design Report (IDR), <https://arXiv.org/abs/2003.01116> [physics.ins-det] 2 Mar 2020, was produced in order to compile the latest information about the physics potential, the subdetector R&D, the machine-detector interface and the costing.

### 1.2 The LC

The LCTPC properties were originally developed for the Tesla linear collider and after that for the ILC, both with superconducting cavities and for energies  $\sqrt{s} \simeq 0.09$ -1.0 TeV. Other projects are also studying the possibility of employing a TPC as one of their subdetectors are welcome to profit from the information accumulated by the LCTPC collaboration.<sup>1</sup>

The ILC preparations for construction in Japan are underway. ILC is envisaged to be staged: The first stage, at  $\sim 250$  GeV (precision measurements of the Higgs and related quantities to find indications of Beyond-the-Standard-Model (BSM) physics, is expected to last about a decade. With additional funding, the machine could be upgraded to stages at  $\sim 350$  GeV to  $\sim 1000$  GeV for further precision measurements of the top quark, gauge-boson couplings, Higgs self-coupling, and search for BSM. In addition, the 'Giga-Z' measurement, in which  $10^9$  Z-bosons are produced at the Z-peak with polarized beams, is under serious study by machine and detector physicists. Progress is regularly reported in the 'LC Newline' <http://newsline.linearcollider.org>.

The collaboration and leadership, the international 'Linear Collider Collaboration' (LCC) with oversight committee 'Linear Collider Board' (LCB), were established to guide the efforts of the ILC, an arrangement that was approved by ICFA (International Committee for Future Accelerators).

### 1.3 The ILC International Development Team (IDT)

On August 2, 2020, ICFA announced the replacement of the LCC and LCB by the IDT as the first step towards the preparatory phase of the ILC project, with a mandate to make preparations for the ILC Pre-Lab in Japan. See ICFA\_Statement\_August\_2020.pdf at <https://icfa.fnal.gov/> for the ICFA statement.

In June the IDT submitted its report to ICFA describing the organization of the Pre-Lab: see <https://arxiv.org/abs/2106.00602>. The IDT is now under study by the Japanese government.

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<sup>1</sup>e.g., <http://cepc.ihep.ac.cn>

## 2 Responsibilities 2020

Present groups and Collaboration Board members are:

### 2.1 Collaboration Board (CB) – Table 1

–Americas–	
Carleton/Triumf:	<b>Madhu Dixit</b> msd@physics.carleton.ca
Carleton U:	<b>Alain Bellerive</b> alainb@physics.carleton.ca
Victoria:	<b>Dean Karlen</b> karlen@uvic.ca
BNL:	<b>Alexei Lebedev</b> alebedev@bnl.gov
–Asia———	
Tsinghua:	<b>Zhi Deng</b> dengz@mail.tsinghua.edu.cn
IHEP:	<b>Huirong Qi</b> qihr@ihep.ac.cn
Saha Kolkata:	<b>Supratik Mukhopadhyay</b> supratik.mukhopadhyay@saha.ac.in
Hiroshima:	<b>Tohru Takahashi</b> tohru-takahashi@hiroshima-u.ac.jp
Iwate:	<b>Shinya Narita</b> narita@iwate-u.ac.jp
KEK:	<b>Keisuke Fujii</b> keisuke.fujii@kek.jp
Kindai:	<b>Yukihiro Kato</b> katoy@phys.kindai.ac.jp
Saga:	<b>Akira Sugiyama</b> sugiyama@cc.saga-u.ac.jp
Kogakuin:	<b>Takashi Watanabe</b> takashi.watanabe@map.kogakuin.ac.jp
Nagasaki Inst AS:	<b>Ken Oyama</b> oyama_ken@nias.as.jp
–Europe———	
Inter U Inst for HEP(ULB-VUB):	<b>Gilles De Lentdecker</b> gilles.de.lentdecker@ulb.ac.be
CEA Saclay:	<b>Paul Colas</b> paul.colas@cea.fr
Bonn:	<b>Jochen Kaminski/Klaus Desch</b> kaminski@physik.uni-bonn.de/desch@physik.uni-bonn.de
DESY/HH:	<b>Ties Behnke</b> ties.behnke@desy.de
Kiev:	<b>Oleg Bezshyyko</b> obezsh@gmail.com
MPI-Munich:	<b>Ron Settles</b> settles@mpp.mpg.de
Siegen:	<b>Ivor Fleck</b> fleck@hep.physik.uni-siegen.de
Nikhef:	<b>Peter Kluit</b> p.kluit@nikhef.nl
Lund:	<b>Leif Jönsson</b> leif.jonsson@hep.lu.se

### 2.2 Observers

‘Observers’ are groups or persons that could not sign the MoA but are being informed as to the progress, thus are included in the lctpc mailing list. **Change of status** from ‘collaboration member’ to ‘observer’ is possible and has taken place several times.

Observer groups (collaboration members which changed status in bold):

Americas: **Cornell, Indiana**, LBNL, Louisiana Tech, **Montreal**, MIT, Purdue, Stony Brook, Yale.

Asia: Mindanao, U Tokyo, **Tokyo U A & T**.

Europe: **Aachen**, Bucharest, **CERN**, Freiburg, Karlsruhe, UMM Krakow, **LAL Orsay/IPN Orsay**, **Novosibirsk**, **Rostock**, St.Petersburg, TU Munich.

### 2.3 New groups

The LCTPC collaboration (<http://www.lctpc.org>) is open to all, and a group wishing to join (or rejoin after **change of status**) should contact us.

## 3 Further LCTPC Collaboration Information

### 3.1 Regional Coordinators (RC)

The RCs for 2007-2021 after selection of candidates in each region were elected by the CB members of the respective region. Previous RCs were

–Americas: **Dean Karlen** in 2007-10,

**Alain Bellerive** in 2011 to present.

–Asia: **Takeshi Matsuda** in 2007-09,

**Akira Sugiyama** in 2010 to 2021,

**Shinya Narita** in 2021 to present.

–Europe: **Ron Settles** in 2007,

**Jan Timmermans** in 2008-11,

**Jochen Kaminski** in 2012 to present.

Spokesperson selection: The RCs do not to have a predetermined rotation of RCs as their chairperson and spokesperson for the collaboration; he/she will be chosen by the RCs. Ron Settles had this function in 2007, and Jan Timmermans was elected as Chairperson/Spokesperson for 2008-11. Jochen Kaminski was chosen by the RCs as the Spokesperson for the following years up to present.

#### 3.1.1 CB Chair

In 2009, the Collaboration Board decided that each year it will appoint one member to chair its meetings for a period of two years. Leif Jönsson agreed to chair the CB meetings in 2012-15, and was reappointed for this task in 2016-2018. Ivor Fleck replaced him in 2018.

#### 3.1.2 Editorial Board (EB)

The purpose of the EB is to approve publications of the collaboration.

The EB is presently made up of: Alain Bellerive, Ties Behnke, Madhu Dixit, Takahiro Fusayasu, Keisuke Fujii, Leif Jönsson, Jochen Kaminski, Takeshi Matsuda, Ron Settles, Akira Sugiyama and Jan Timmermans. Takahiro Fusayasu has agreed to chair the EB in 2016 to present.

#### 3.1.3 Speakers Bureau

The speakers bureau, installed in 2009 by the CB to monitor the LCTPC presentations at major conferences, is made up of the the three regional coordinators and one additional person per region. The RCs in 2009 were Jan Timmermans, Takeshi Matsuda and Dean Karlen; the persons per region were Paul Colas as chair up to December 2010, Yuanning Gao and Dan Peterson. The RCs that followed were Jochen Kaminski, Akira Sugiyama and Alain Bellerive and the regional persons were Jan Timmermans, Yulan Li and Dan Peterson in 2011-13; David Attie replaced Jan Timmermans in 2014. Dan Peterson chaired the meetings in 2012, Alain Bellerive for one year starting mid-2013, followed by David Attie mid-2014. Serguei Ganjour was chair in 2018-2019. Maxim Titov ([maxim.titov@cea.fr](mailto:maxim.titov@cea.fr)) took over the chair in 2020. Huirong Qi agreed to be the regional person for Asia in 2021.

## 3.2 Technical Board (TB)

There were four original workpackages in the MoA (WP(1) Mechanics, WP(2) Electronics, WP(3) Software, WP(4) Calibration) which were supplemented by a fifth workpackage (WP(5) Coordination) in 2010 to prepare for the DBD; with the DBD finished, WP(5) will now oversee the R&D.

The WP(1)-WP(4) structure was utilized at the beginning of the LCTPC collaboration, with individual workpackages meetings to discuss their issues. The structure is out-of-date now and is repeated here for historical completeness. Therefore the ‘conveners’ will be referred to as ‘contacts’.

There are bi-weekly meetings which include all workpackages convened by the collaboration spokesperson Jochen Kaminski. There are also regular meetings of the Asian groups and of the pixel groups.

The **TB members**, the ‘contacts’ for the workpackages and their email addresses, and the groups involved:

Table 2	
Workpackage	→ Groups involved Contact
Workpackage(0) TPC R&D Program	LCTPC collaboration
Workpackage(1) Mechanics	
a) LP endplate design and Fieldcage development	→ Cornell,Bonn, Desy/HH,Japan/China,MPI,Saclay up to 2017 <b>Dan Peterson</b> daniel.peterson@cornell.edu →BNL,Desy/HH <b>Ties Behnke</b> ties.behnke@desy.de
b) GEM panels for endplate	→Bonn,Desy/HH,Japan/China <b>Akira Sugiyama</b> sugiyama@cc.saga-u.ac.jp
c) MicroMegas panels for endplate	→Carleton,IHEP,SahaKolkata,Saclay <b>Paul Colas</b> paul.colas@cea.fr
d) Pixel panels for endplate	→Bonn,Nikhef,Saclay <b>Jan Timmermans</b> jan.timmermans@nikhef.nl
e) Resistive anode for endplate	→Carleton,SahaKolkata,Saclay <b>Madhu Dixit</b> msd@physics.carleton.ca
Workpackage(2) Electronics	
a) Standard RO for the LP	→ Brussels,Cern,Desy/HH,Lund <b>Leif Jönsson</b> leif.jonsson@hep.lu.se
b) CMOS RO electronics	→ Bonn,Nikhef,Saclay <b>Harry van der Graaf</b> vdgraaf@nikhef.nl
c) Standard electronics for LCTPC	→ Brussels,Desy/HH,Lund, up to 2010 <b>Luciano Musa</b> luciano.musa@cern.ch
Workpackage(3) Software	
a) LP software/simulation/reconstruction	→ Bonn,Cern,Desy/HH,Victoria up to 2014 <b>Astrid Muennich</b> astrid.muennich@desy.de
b) LP DAQ	→Brussels,Lund <b>Gilles De Lentdecker</b> gilles.de.lentdecker@ulb.ac.be
c) LCTPC performance/backgrounds	→ Bonn,Carleton,Cern,Desy/HH,Japan/China <b>Keisuke Fujii</b> keisuke.fujii@kek.jp
Workpackage(4) Calibration	
a) Field map for the LP	→ Cern,Desy/HH <b>Lucie Linsen</b> lucie.linsen@cern.ch
b) Alignment	→ Cern,Desy/HH,Nikhef,JapaneseGroups <b>Takeshi Matsuda</b> takeshi.matsuda@kek.jp
c) Distortion correction	→ Desy/HH,MPI,JapenseGroups,Nikhef,Victoria <b>Dean Karlen</b> karlen@uvic.ca
d) Gas/HV/Infrastructure for the LP	→ Desy/HH,Saclay <b>Ralf Diener</b> ralf.diener@desy.de

## WP(5) Coordination of LCTPC R&D

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a) Advanced endcap and fieldcage	→ Desy/HH,Japan/China,MPI,Saclay <b>Ties Behnke</b> ties.behnke@desy.de
b) Advanced endcap/Electronics development	→Cern,Japan/China,Lund,Nikhef,Saclay <b>Anders Oskarsson</b> anders.oskarsson@hep.lu.se <b>Leif Jönsson</b> leif.jonsson@hep.lu.se up to 2010 <b>Luciano Musa</b> luciano.musa@cern.ch 2011 <b>Eric Delagnes</b> eric.delagnes@cea.fr
Advanced endcap/power pulsing/cooling	→Desy,Japan/China,Lund,Nikhef,Saclay <b>Takahiro Fusayasu</b> fusayasu@cc.saga-u.ac.jp
c) Gating device	→ JapeneseGroups <b>Akira Sugiyama</b> sugiyama@cc.saga-u.ac.jp
d) ILD TPC Integration/Mach-Det Interface	→ Desy/HH,MPI,Saclay <b>Volker Prahl</b> volker.prahl@desy.de <b>Ron Settles</b> settles@mpp.mpg.de
e) ILD Contacts	<b>Paul Colas</b> paul.colas@cea.fr up to 2021 <b>Akira Sugiyama</b> sugiyama@cc.saga-u.ac.jp <b>Shinya Narita</b> narita@iwate-u.ac.jp
f) LCTPC Software/Correction methods	→Bonn,Carleton,Desy/HH,JapaneseGroups up to 2014 <b>Astrid Muennich</b> astrid.muennich@desy.de from 2018 analysis coordinators: <b>Paul Colas</b> paul.colas@cea.fr and <b>Peter Kluit</b> p.kluit@nikhef.nl from 2018 MarlinTPC coordinator <b>Oliver Schaefer</b> oliver.schaefer@desy.de
g) Pixel-Module Development	→Bonn,Carleton,Nikhef,Saclay up to 2015 <b>Michael Lupberger</b> michael.lupberger@cern.ch <b>Jochen Kaminski</b> kaminski@physik.uni-bonn.de from 2018 <b>Peter Kluit</b> p.kluit@nikhef.nl
h) Testbeam	→ all groups <b>Ralf Diener</b> ralf.diener@desy.de
Lykoris	→ Desy/HH <b>Uwe Krämer</b> uwe.kraemer@desy.de <b>Mengqing Wu</b> mengqing.wu@desy.de

## 4 Future R&D, the LP and SPs

### 4.1 What has been learned

As written in Section 1, the R&D is proceeding in three phases: (1) Small Prototypes–SP, (2) Large Prototypes–LP and (3) Design.

Up to now during Phase(1), a summary of what has been learned:

- the MWPC option was ruled out,
- the resistive-anode charge-dispersion technique was demonstrated,
- the MicroMegas option without resistive anode was ruled out,
- gas properties have been well measured and the best drift-gas selected,
- the best possible point resolution achieved,
- reliable assemblies of GEM-modules and MicroMegas-modules have been developed,
- CMOS pixel RO technology has been demonstrated and is being developed,
- the dE/dx resolution has been confirmed,
- design of the gating device has been successful.

Therefore the baseline options are MicroMegas with resistive anode with standard electronics, or GEM with standard electronics, or the pixel TPC (= MicroMegas integrated on a pixel chip).

The Phase(2) LP and SP tests are expected to continue and will be followed by Phase(3), the design of the LCTPC. A scenario for Phase(2) options is presented below in Table 3 which will be readjusted as the situation progresses.

## 4.2 Review of the ILD TPC R&D

The TPC R&D program and status has been reviewed several times, most recently by the ECFA Panel at Desy on Nov.4, 2013, at which the TPC gave a complete update of the situation. The Review Report is available as LC Note LC-DET-2014-001 at <http://www-f1c.desy.de/lcnotes>.

### 4.2.1 2014 - 2021

Scenarios for the preliminary, improved and ‘final’ stages of R&D at the LP are summarized in the Table 3. Supplemental testing with SPs, which have been used extensively to date by the LCTPC collaboration (Section 4.1), may continue since there are still many issues which can be explored more efficiently using small, specialized set-ups.

<b>Table 3</b>		Scenarios, updated June 2021
Device	Lab(years)	Large Prototype R&D Configuration
Preliminary	Desy(2013-15)	Fieldcage⊕first endplates: GEM, MicroMegas, or pixel <i>Purpose: Test construction techniques using ~10000 pad read-out channels to demonstrate measurement of the Desy test-beam or cosmics over 70cm tracklength, including development of correction procedures.</i>
Improved	Desy(2016-20)	Fieldcage⊕thinned endplate: GEM, MicroMegas, or pixel <i>Purpose: Continue tests using 10000 pad read-out channels to demonstrate measurement of the Desy test-beam or cosmics 70cm tracklength using LP1 thinned endplate and external detector. If possible, simulate a jet-like environment. Pixels tested the ‘100-chip’ LP-module.</i>
Final	Desy(after 2021)	Fieldcage⊕advanced-endcap prototype: GEM, MicroMegas, or pixel <i>Purpose: Prototype for LCTPC design based on R&amp;D results for items that are ready: mechanics, electronics, cooling, power pulsing, gating, and fieldcage</i>

Review of the TPC design, performance and engineering issues result in a constant reassessment of the R&D priorities. This Table 4 gives a short overview:

#### **Table 4**

- Continue tests in the Desy test-beam or cosmics to perfect calibration procedures and to improve point resolution, two-point separation, dE/dx resolutions
- Continue to design/test gating device
- Endplate/module/fieldcage studies with a maximum of 25% X0 in the endplate including electronics/cooling
- Software development for simulation and reconstruction
- Electronics development: the design of a new readout chip
- Power pulsing/cooling tests using both LP and SP

More discussions on the tasks ahead were held at workpackage meetings 176/185/222/258 where more details can be found. The links for these meetings are

176–<http://agenda.linearcollider.org/event/6097/>  
 185–<http://agenda.linearcollider.org/event/6251/>  
 222–<http://agenda.linearcollider.org/event/6786/>  
 258–<http://agenda.linearcollider.org/event/7510/>

The latest update took place at the collaboration meeting on January 14, 2020. The detailed list of issues can be found in the document 22\_planlist\_new.pdf at <https://agenda.linearcollider.org/event/8362/contributions/45066/>.

The collaboration decided that it was not yet necessary to choose between options, because the performance of the LCTPC for the ILD is guaranteed by Tables 5 and 6 in Sec. 4.3, showing the performance expected based on the R&D efforts. However these technical choices will have to be made in order to design the LCTPC, as described in the following Sec. 4.2.2.

#### 4.2.2 After 2021

After a positive decision in Japan, during the ILC Pre-Lab phase (Sec.1.3) a selection must be made from the different technological options – GEM, MicroMegas, resistive anode, pixel, electronics, gating device, endcap structure, cooling, mechanics, integration – to establish a working model for the design of the LCTPC. The R&D can continue on other options.

### 4.3 Performance Goals

Understanding the properties and achieving the best possible point resolution have been the object of R&D studies of Micro-Pattern Gas Detectors – GEM, MicroMegas, and pixel; results from this work used to define the parameters in Tables 5 and 6.

These studies will continue in order to improve on the performance. Upgrades to the preliminary design will be implemented where improvements have been established by R&D results and are compatible with the LC timeline.

Also noted is the study by the ILD collaboration of a “large” version with 1808 mm TPC outer radius and 3.5T B-field (the standard used up to now) and a new “small” version with 1460 mm TPC outer radius and 4T B-field. The Table 5 below is for the “large” version, Table 6 for the “small” version. The values in the two tables are approximations only and are presented for the purpose of comparison. <sup>2 3 4 5 6</sup>

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<sup>2</sup>The point resolution, 0.1 mm, for this year’s tables was assumed to be the same for GEM and MicroMegas. The value for the pixel option was assumed to be 0.055mm/ $\sqrt{12}$  for zero drift and 0.4mm for maximum drift: the talk at the ILCX2021 workshop [https://agenda.linearcollider.org/event/9211/contributions/58794/attachments/37527/58794/ILCX\\_pixelTPC\\_2021.pdf](https://agenda.linearcollider.org/event/9211/contributions/58794/attachments/37527/58794/ILCX_pixelTPC_2021.pdf) and references therein give resolutions for both pad and pixel versions which are used for the comparisons shown here in Tables 5 and 6.

<sup>3</sup>For the effective track length in both cases, small and large, 100mm has been added to the inner radius and 100mm subtracted from the outer radius, in order to account for fieldcages, mechanics and services.

<sup>4</sup>The overall tracking resolution (including silicon tracking) would be roughly  $\simeq 2 \times 10^{-5}$  for the large version and  $\simeq 3 \times 10^{-5}$  for the small version. Physics simulations using both versions have shown similar performance for the two: the large is better in several studies; however, the small is better in a few cases.

<sup>5</sup>For physics analyses, the interaction point (IP) will be included in the track fit; the position of the IP will be known to a couple of microns. According to the Gluckstern formula, this constraint will decrease the momentum error by  $\sqrt{320/720}$ . (see: *R. L. Gluckstern, Uncertainties in track momentum and direction due to multiple scattering and measurement errors, NIMA 24 (1963) 381-389, or, e.g. Review of Particle Physics 2020, Particle Data Group, https://doi.org/10.1093/ptep/ptaa104, Section 35.12*) The TPC tracking resolution including the IP will be particularly useful for events in which the vertex detector information is missing for some reason.

<sup>6</sup>For this dE/dx simple calculation, the assumption for the pixel TPC is that a track travels from the inner radius at the middle of the TPC ( $r, \phi, z \simeq 429mm, \phi = K(constant), 0mm$ ) to the outer radius near the endcap ( $r, \phi, z \simeq 1700mm(large), \phi = K, 2200mm$ ), ( $r, \phi, z \simeq 1300mm(small), \phi = K, 2200mm$ ), that three-fourths to one-half of the track length ( $ld \equiv$  long drift) uses the standard dE/dx (truncated mean) estimation with a resolution of  $\sigma_{ld} \simeq 5\%$  and that one-fourth to one-half ( $sd \equiv$  short drift) uses cluster counting with a resolution of  $\sigma_{sd} \simeq 3\%$ . The weighted mean is calculated with weights  $\frac{1}{\sigma_{ld}^2}$  and  $\frac{1}{\sigma_{sd}^2}$  for the  $ld$  and  $sd$ , respectively. The two errors are combined in the standard way:

$$\frac{1}{\sigma_{hypotheticaltrack}^2} = \frac{1}{\sigma_{ld}^2} + \frac{1}{\sigma_{sd}^2}.$$

**Table 5, large TPC, for pad/pixel electronics**

Parameter	
B-field	3.5T
Geometrical parameters	$r_{in}$ $r_{out}$ $z$ 329 mm    1808 mm $\pm$ 2350 mm
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05 X_0$ including outer fieldcage in $r$ $< 0.25 X_0$ for readout endcaps in $z$
Number of pads/timebuckets	$\simeq 10^6/1000$ per endcap
<i>Number of pixels/timebuckets</i>	$\simeq 10^9/1000$ per endcap
Pad pitch/ no.padrows	$\simeq 1 \times 6 \text{ mm}^2 / 213$
$\sigma_{point}$ in $r\phi$	$\simeq 60 \mu\text{m}$ for zero drift, $< 100 \mu\text{m}$ overall
$\sigma_{point}$ in $r\phi$	$\simeq 0.055\text{mm}/\sqrt{12}$ for zero drift, $0.4\text{mm}$ for max drift
$\sigma_{point}$ in $rz$	$\simeq 0.4 - 1.4 \text{ mm}$ (for zero – full drift)
2-hit separation in $r\phi$	$\simeq 2 \text{ mm}$
2-hit separation in $rz$	$\simeq 6 \text{ mm}$
dE/dx resolution	$\simeq 5 \%$
<i>dE/dx resolution</i>	$\simeq 4 \%$
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}/\text{GeV}/c$ (TPC only)( $\times 0.7$ TPC+IP)
<i>Momentum resolution at B=3.5 T</i>	$\delta(1/p_t) \simeq 0.8 \times 10^{-4}/\text{GeV}/c$ (60% cov, TPC only)( $\times 0.7$ TPC+IP)

**Table 6, small TPC, for pad/pixel electronics**

Parameter	
B-field	4.0T
Geometrical parameters	$r_{in}$ $r_{out}$ $z$ 329 mm    1460 mm $\pm$ 2350 mm
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05 X_0$ including outer fieldcage in $r$ $< 0.25 X_0$ for readout endcaps in $z$
Number of pads/timebuckets	$\simeq 5 \times 10^5/1000$ per endcap
<i>Number of pixels/timebuckets</i>	$\simeq 5 \times 10^8/1000$ per endcap
Pad pitch/ no.padrows	$\simeq 1 \times 6 \text{ mm}^2 / 155$
$\sigma_{point}$ in $r\phi$	$\simeq 60 \mu\text{m}$ for zero drift, $< 100 \mu\text{m}$ overall
$\sigma_{point}$ in $r\phi$	$\simeq 0.055\text{mm}/\sqrt{12}$ for zero drift, $0.4\text{mm}$ for max drift
$\sigma_{point}$ in $rz$	$\simeq 0.4 - 1.4 \text{ mm}$ (for zero – full drift)
2-hit separation in $r\phi$	$\simeq 2 \text{ mm}$
2-hit separation in $rz$	$\simeq 6 \text{ mm}$
dE/dx resolution	$\simeq 6 \%$
<i>dE/dx resolution</i>	$\simeq 5 \%$
Momentum resolution at B=4 T	$\delta(1/p_t) \simeq 2 \times 10^{-4}/\text{GeV}/c$ (TPC only)( $\times 0.7$ TPC+IP)
<i>Momentum resolution at B=4 T</i>	$\delta(1/p_t) \simeq 1.6 \times 10^{-4}/\text{GeV}/c$ (60% cov, TPC only)( $\times 0.7$ TPC+IP)