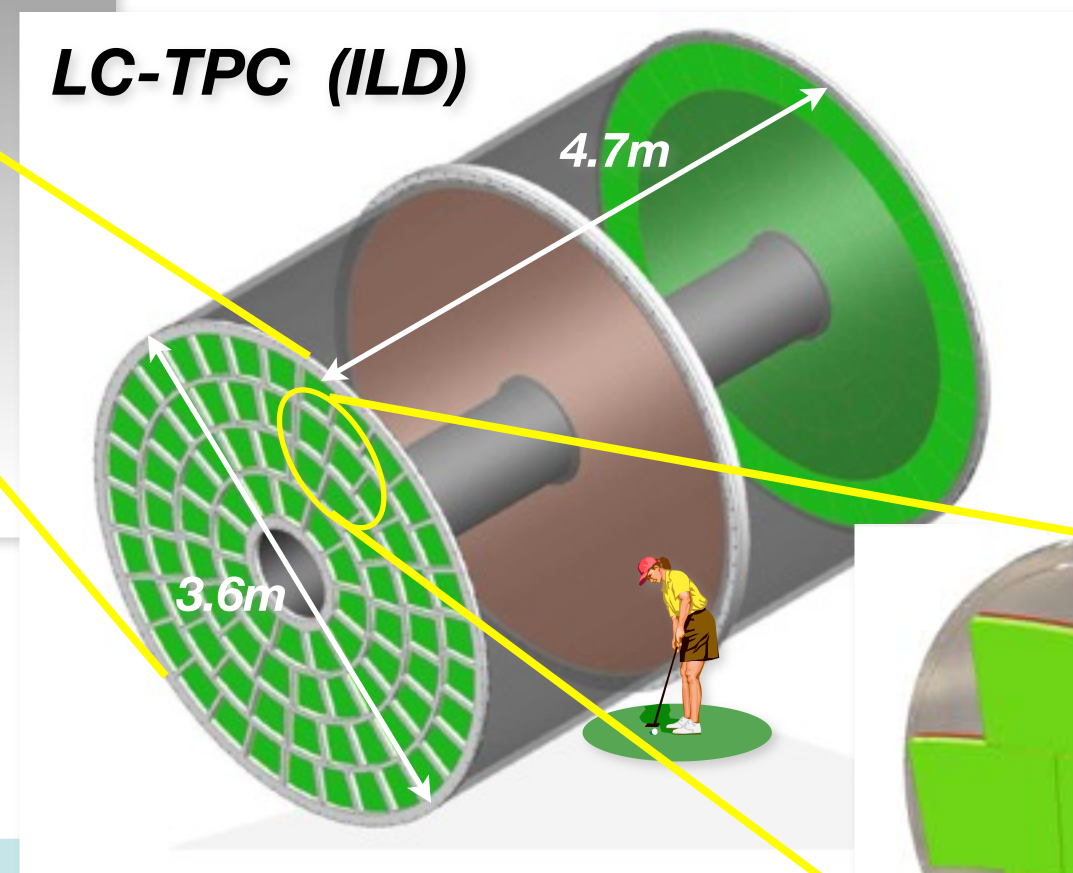
Toward the Final Design of a TPC for the ILD Detector

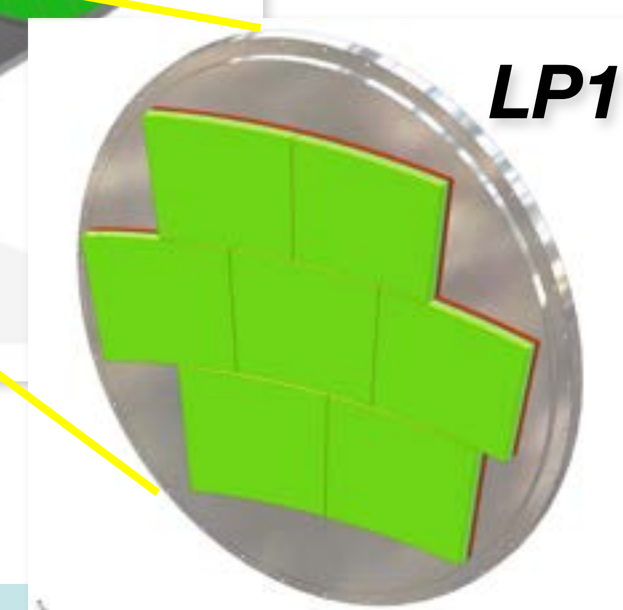
Keisuke Fujii, KEK
on behalf of the D_RD_9 team

LC-TPC

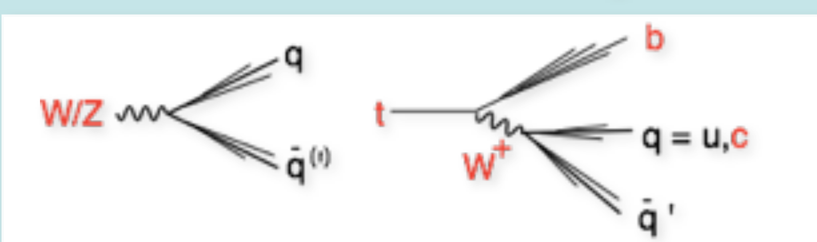
Performance Goals as compared to LHC detectors

Vertex resolution	2-7 times better
Momentum resolution	10 times better
Jet energy resolution	2 times better





ILD : optimized for Particle Flow Analysis



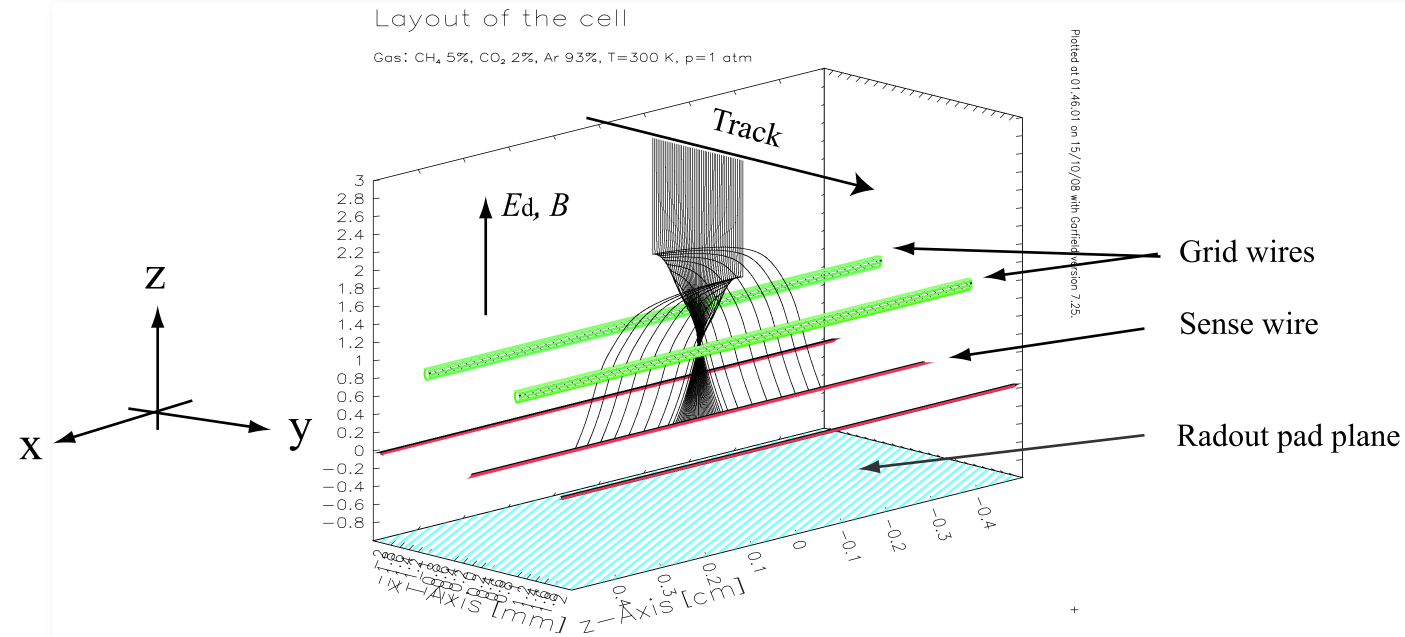
Highly efficient tracking in a jetty environment is an essential ingredient for PFA

Micro Pattern Gas Detector readout TPC provides pictorial 3D tracking by ~200 space points with $\sigma_{r\phi}$~100 μm and two-hit separation of ~2mm

Large Prototype
being tested at DESY

Why MPGD Readout?

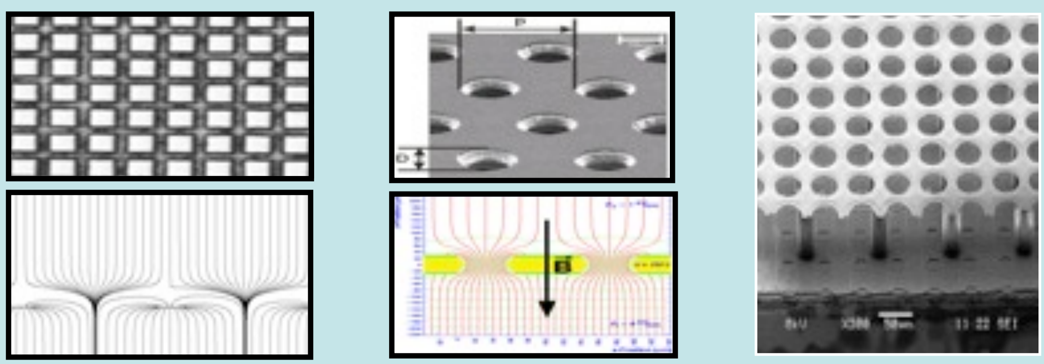
- We need high (>3 T) B field to confine e^+e^- pair BG from beam-beam interactions, then ExB is too big for conventional MWPC readout
- 2mm 2-track separation is difficult with MWPC readout
- Thick frames are unavoidable for MWPC readout

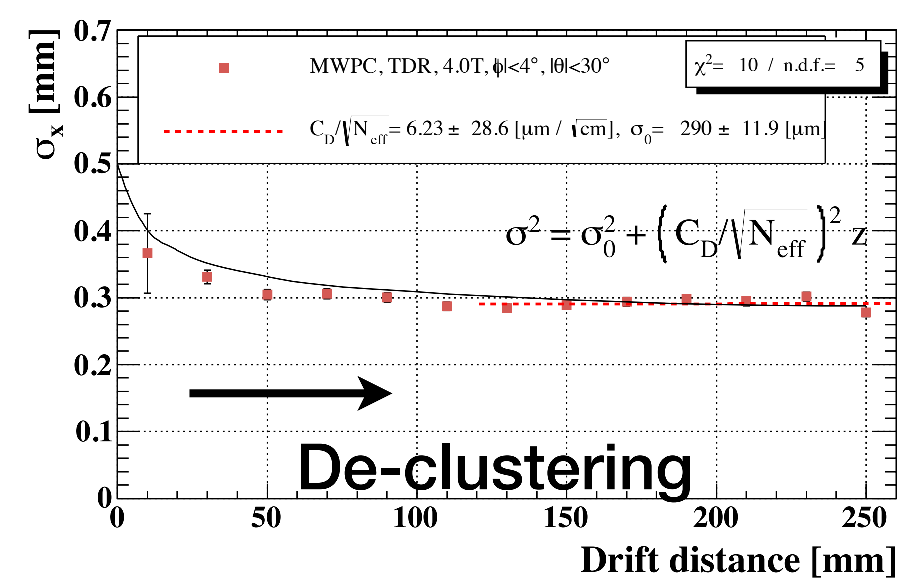


ExB spreads seed electrons along the sense wires, then avalanche fluctuation limits the spatial resolution!

Micro-Pattern Gas Detectors

Micromegas | *GEM* | *InGrid TimePix*





Pre-LCTPC group incl. the FJ team, together, excluded MWPC option with a small protoypte TPC!

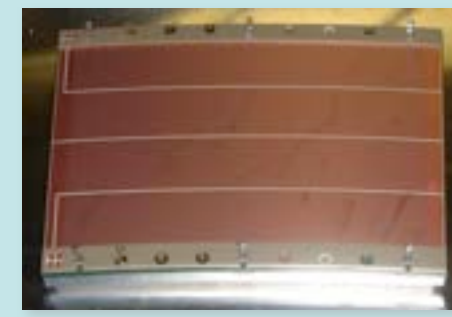
MPGD Options

After the initial stage of R&D with many small TPC prototypes, we are left with three options of MPGD TPC readout technologies for ILC, being tested at the Large prototype (LP) TPC at DESY.

I. Analog (Pad) TPC: Subject to the gas gain fluctuation in the gas amplification. Need to spread the avalanche charge for charge centroid.

(1) Multi layer GEM with the standard pad (~1x5mm^2) readout : (charge spread by diffusion)
Asian (KEK-Saga-Tsinghua) Module, DESY module

Asian GEM module



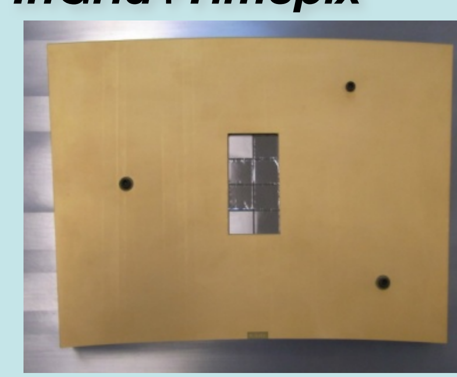
(2) Micromrgas with the resistive-anode (pad: ~3x7mm^2) readout :
Saclay-Carleton Module

MM (resistive anode)

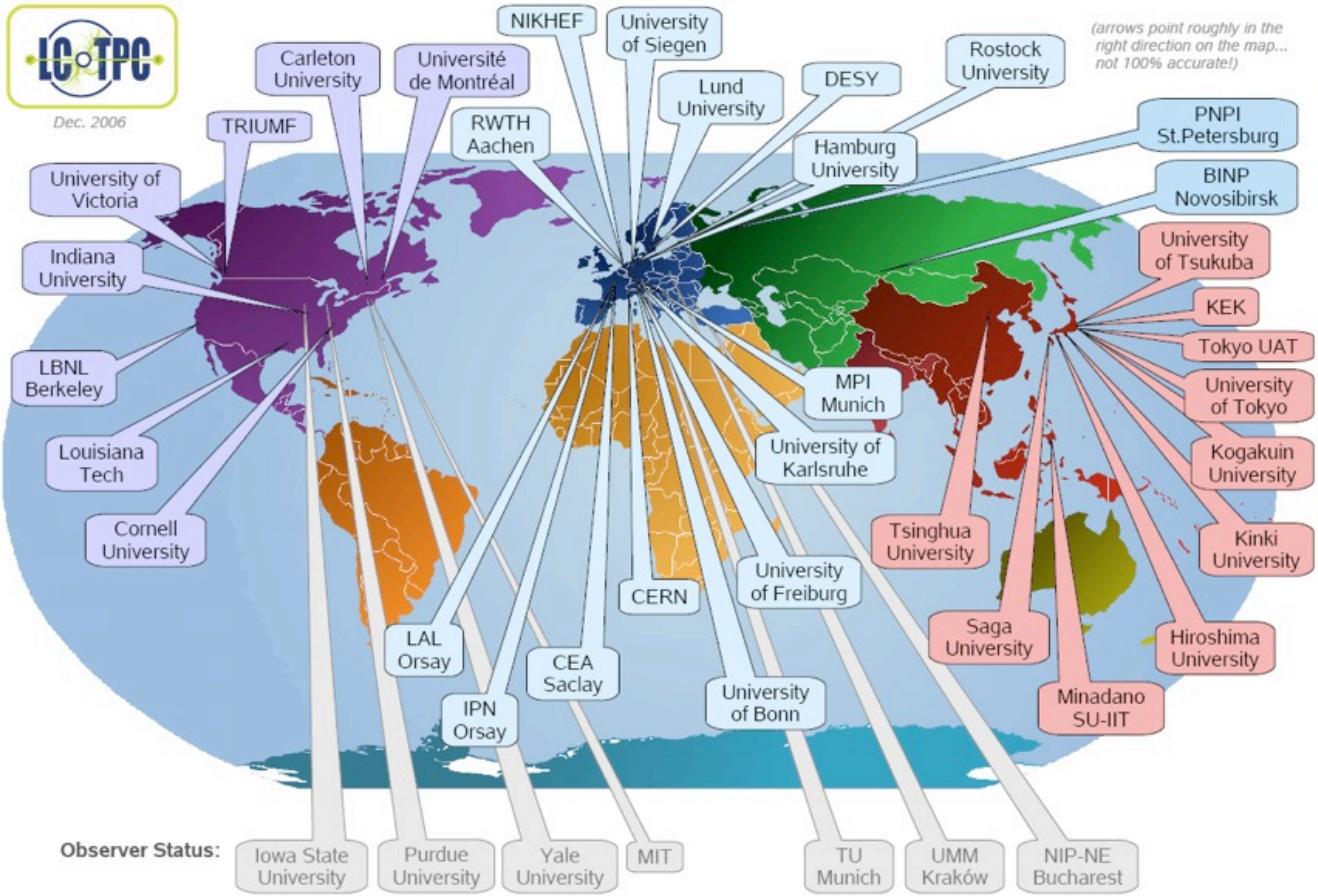
II. Digital (Pixel) TPC: Free from the gas gain fluctuation. Expect 20-30% improvement of position resolution in the case of digital readout.
No angular pad effect.
Theoretically the best but not yet ready for full implementation of a module.

(3) InGrid Micromegas mesh on Timepix chips (pixel: ~50x50μm^2)
NIKHEF-Saclay Module, Bonn-module

InGrid+Timepix



→ being tested in ***Large Prototype*** at DESY


LC TPC
Dec. 2006
(arrows point roughly in the right direction on the map... not 100% accurate!)
NIKHEF
University of Siegen
Carleton University
Université de Montréal
TRIUMF
RWTH Aachen
Lund University
DESY
Rostock University
Hamburg University
PNPI St.Petersburg
BINP Novosibirsk
University of Victoria
Indiana University
LBNL Berkeley
Louisiana Tech
Cornell University
University of Tsukuba
KEK
Tokyo UAT
University of Tokyo
MPI Munich
University of Karlsruhe
Kogakuin University
Tsinghua University
Kinki University
CERN
University of Freiburg
Saga University
LAL Orsay
CEA Saclay
Hiroshima University
Minadano SU-IIT
IPN Orsay
University of Bonn
Observer Status:
Iowa State University
Purdue University
Yale University
MIT
TU Munich
UMM Kraków
NIP-NE Bucharest

Large Prototype Test Beam Facility at DESY

LC TPC Collaboration

Si strip detector
(EUDET/SiLC/DESY)

Magnet: PCMAG and its upgrade
(KEK, EUDET/AIDA/DESY, CERN)

Field cage & Mechanics, Gas system
(EUDET/DESY)

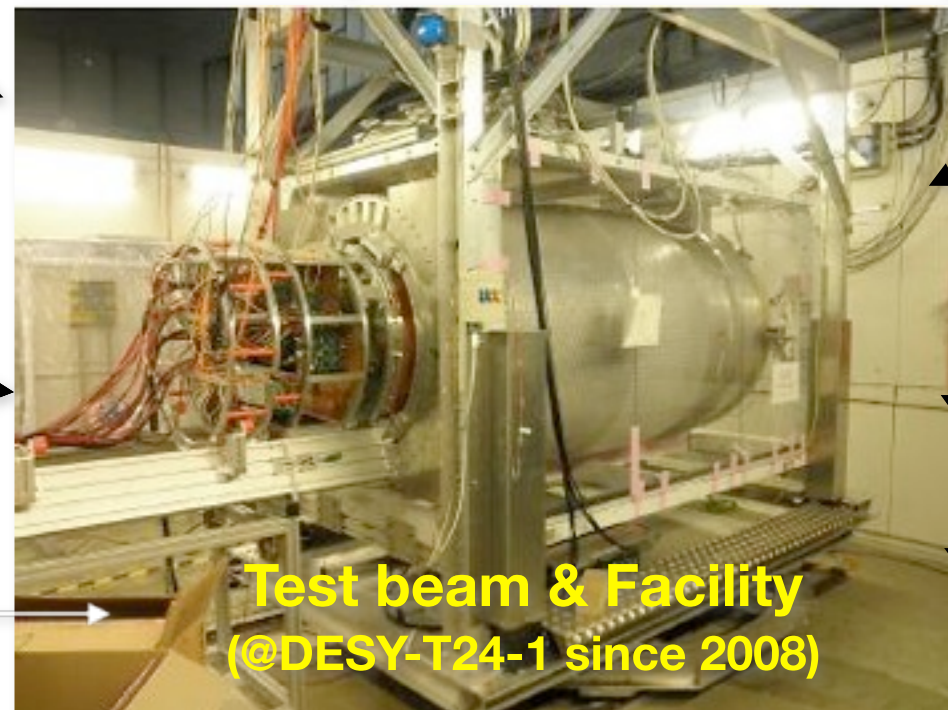
Endplate
(Cornell)

Cathode Laser Calib.
(Victoria)

DAQ & Monitoring
(EUDET/DESY)

Beam Trigger
(NIKEFH)

2PCO2 cooling system
(KEK, DESY)



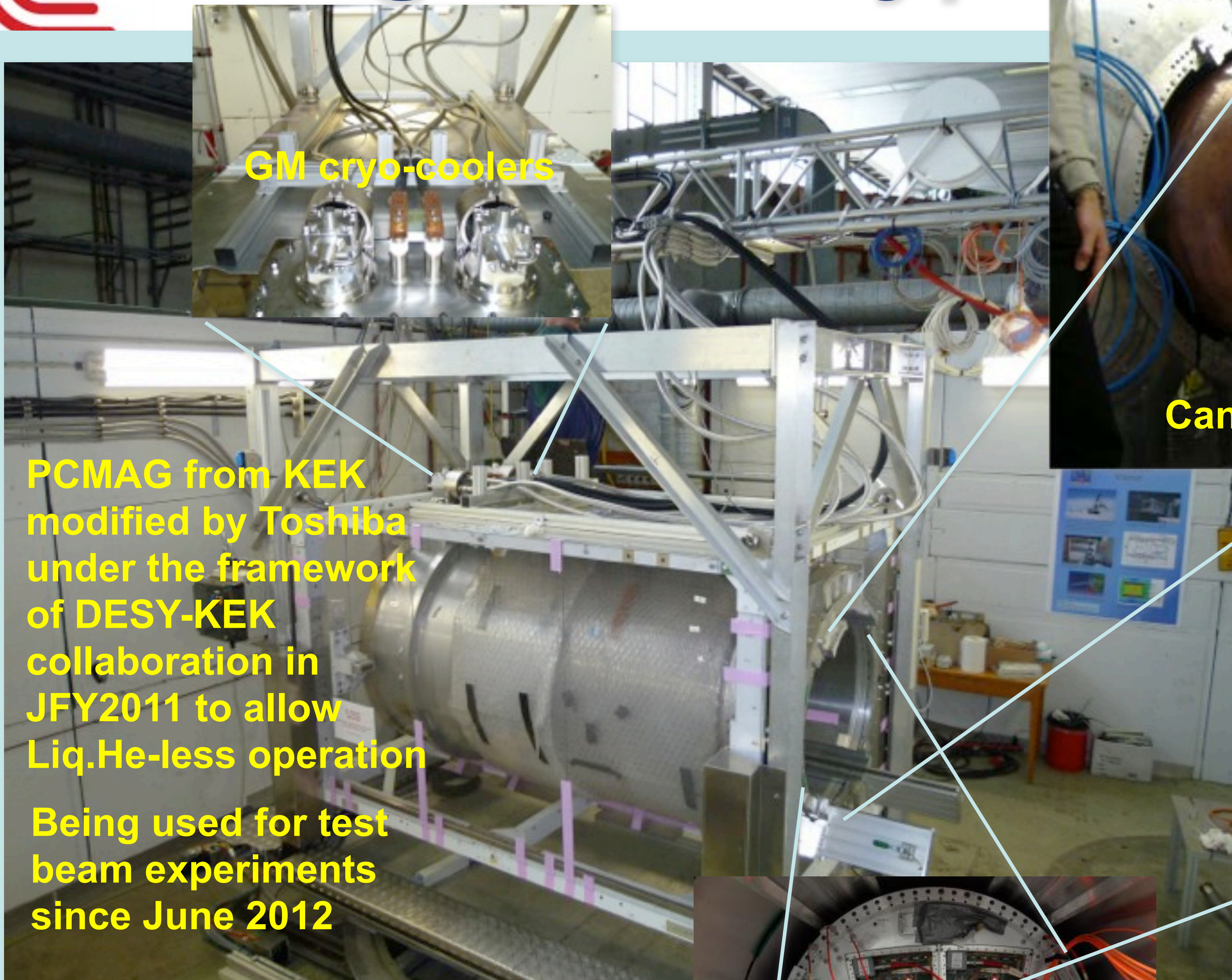
Cosmic trigger
(Saclay,KEK)

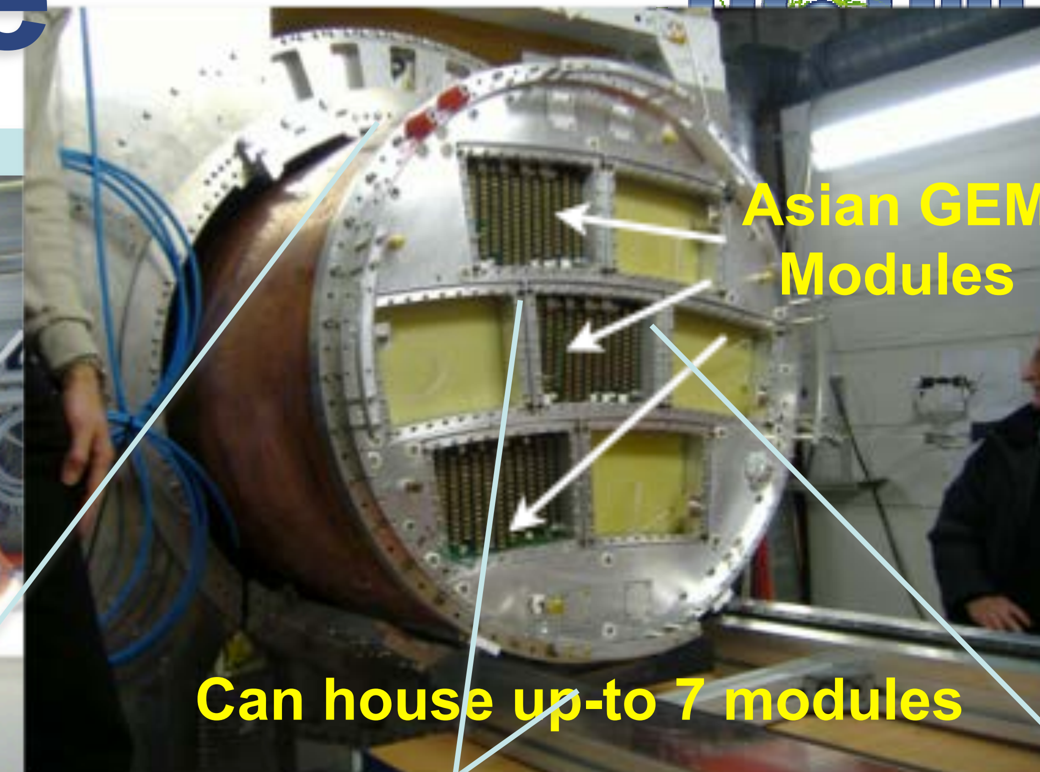
Two types of *Readout Electronics*
(EUDET/AIDA /Lund/DESY, KEK, Saclay)

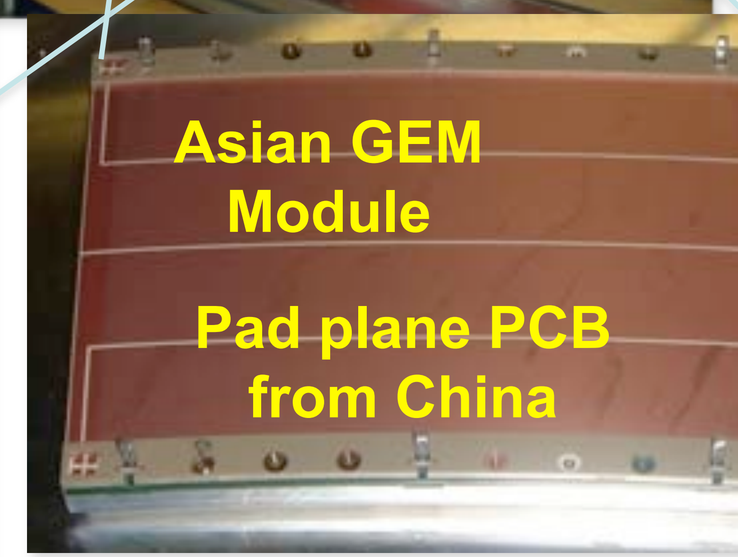
MPGD Detector Modules
(DESY, KEK/Tsinghua, Saclay/NIKHEF, Bonn)

Common Software Tools
(EUDET/AIDA , DESY, KEK, etc)

Large Prototype





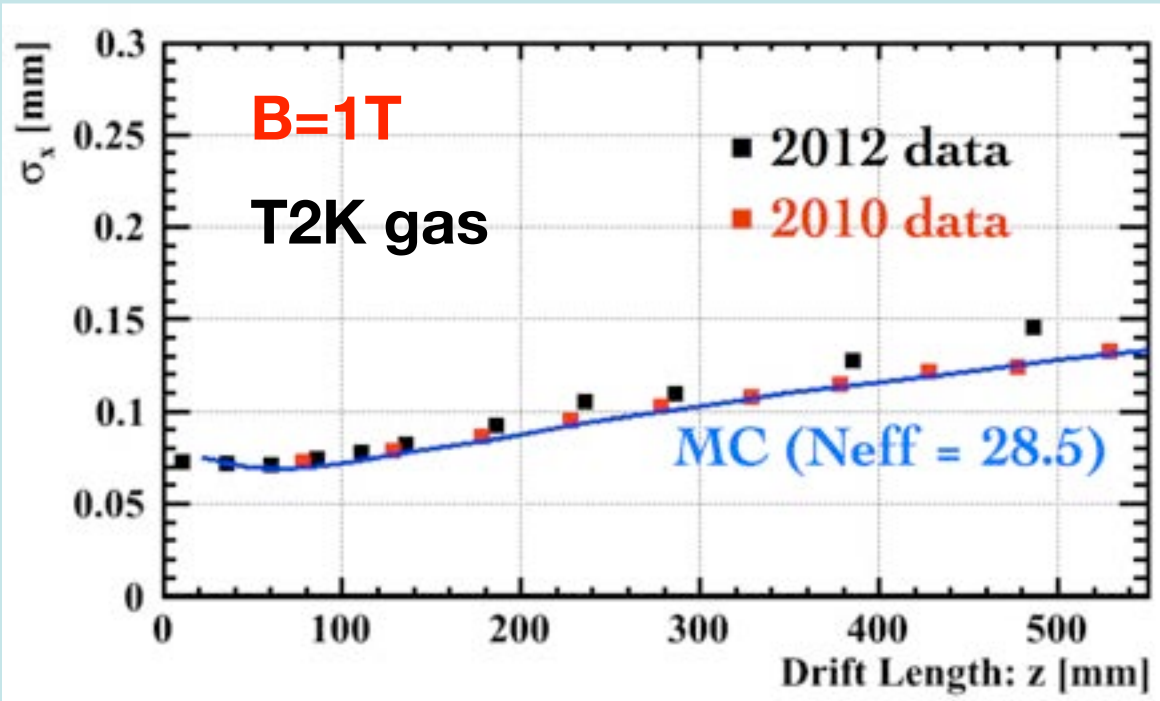


5GeV electron beam

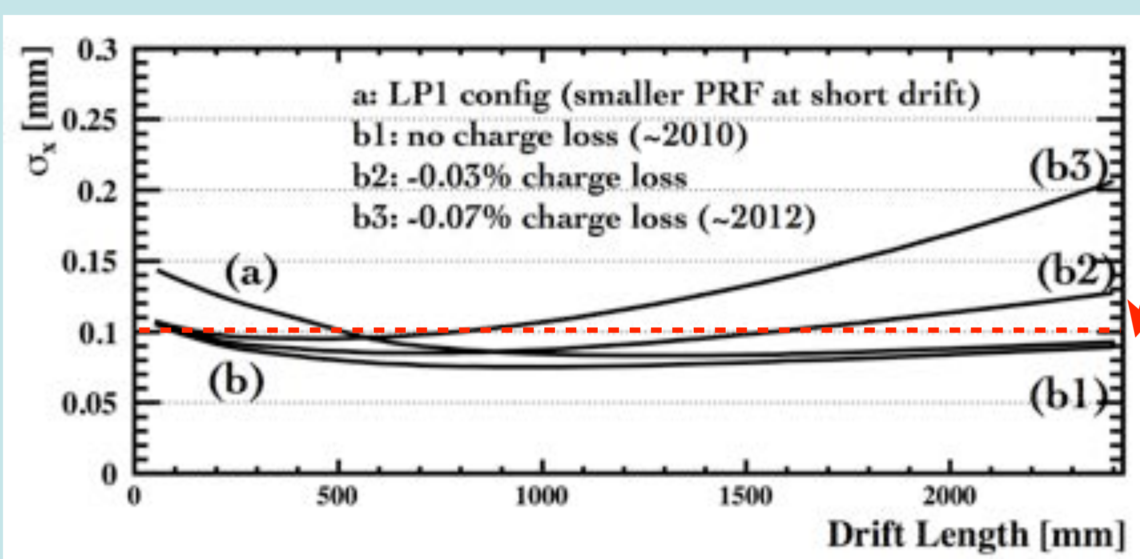
Large Prototype test beam

Spatial Resolution

Asian GEM Module

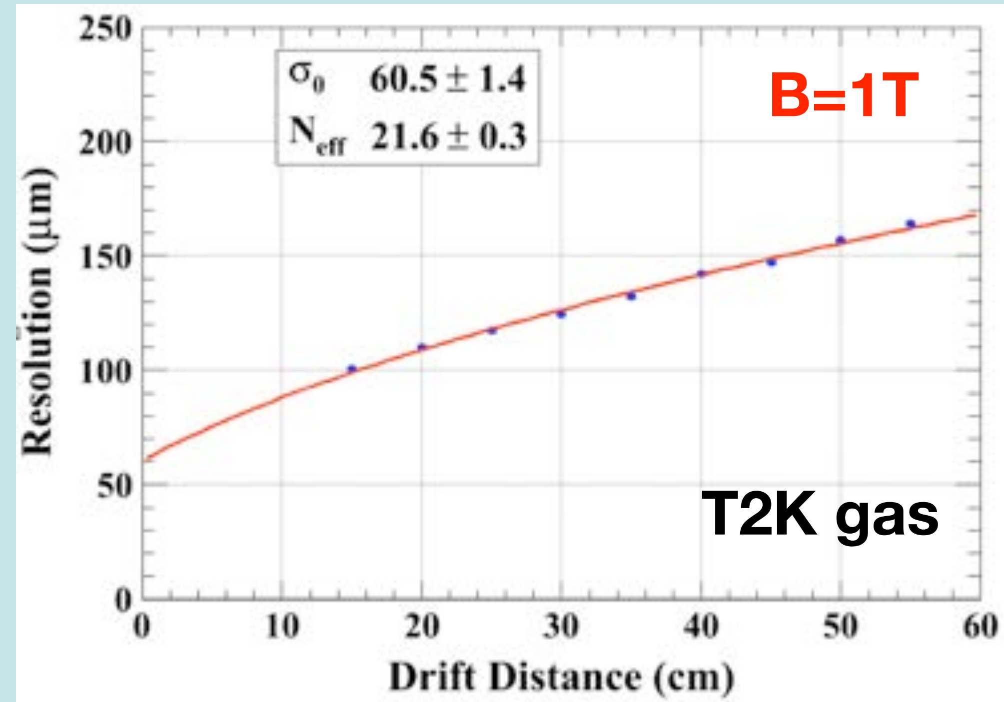


Extrapolation to B=3.5T

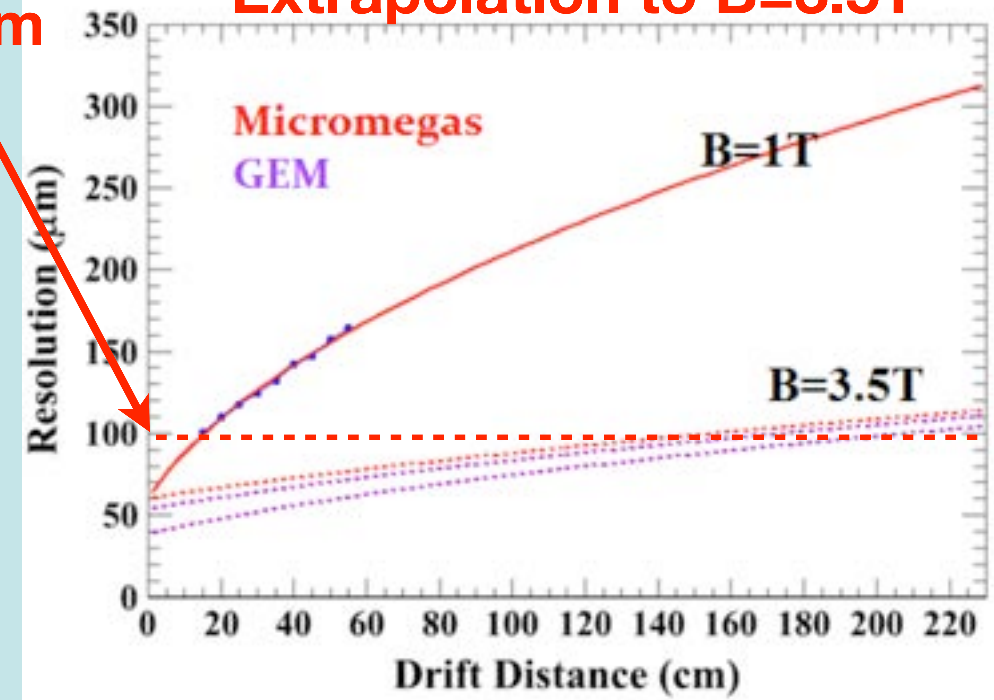


$\sigma_{r\phi}$=100 μm

Saclay-Carleton MM Module



Extrapolation to B=3.5T



Both options seem to satisfy the $\sigma_{r\phi}$=100μm requirement!

Resolution Formula

Since TPC operates on the nice and old "gas physics"; ionization, diffusion, gas amplification and fluctuation, etc., it is possible for the GEM TPC (option (1)) to formulate a fully analytic expression of its spatial resolution to understand the LP TPC results, to optimize parameters of the GEM TPC, and to extrapolate them to the ILD TPC (R. Yonamine / KF)

$$\sigma_x^2(z; w, L\tan\phi, C_d, N_{eff}, \hat{N}_{eff}, [f]) = [A] + \frac{1}{N_{eff}}[B] + [C] + \frac{1}{\hat{N}_{eff}}[D]$$

[A]: Hodoscope effect/S-shape at the short drift distances

$$[A] := \int_{-1/2}^{+1/2} d\left(\frac{\tilde{x}}{w}\right) \left(\sum_a (aw) \left\langle \langle F_a(\tilde{x} + y\tan\phi + \Delta x) \rangle_{\Delta x} \right\rangle_y - \tilde{x} \right)^2$$

diffusion-averaged & cluster position average charge centroid

systematics

asymptotic formula ([B] term)

$$\sigma_x^2 = \frac{1}{N_{eff}}(\sigma_0'^2 + C_d^2 z)$$

The constant term also scales as $1/N_{eff}$!

[B]: Diffusion + finite pad size term

$$[B] := \int_{-1/2}^{+1/2} d\left(\frac{\tilde{x}}{w}\right) \left\langle \left(\sum_a (aw) F_a(\tilde{x} + \Delta x) - \sum_a (aw) \langle F_a(\tilde{x} + \Delta x) \rangle_{\Delta x} \right)^2 \right\rangle_{\Delta x}$$

$$\approx [A]_{z=0} + \sigma_d^2$$

diffusion-averaged charge centroid

displacement due to diffusion for a single electron

$$N_{eff} := \left[\left\langle \sum_{i=1}^{N} k_i \left\langle \left(\frac{G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right)^2 \right\rangle_G^{\sum_{i=1}^{N} k_i} \right\rangle_{N,k} \right]^{-1}$$

: effective # electrons

[C]: Electronics noise

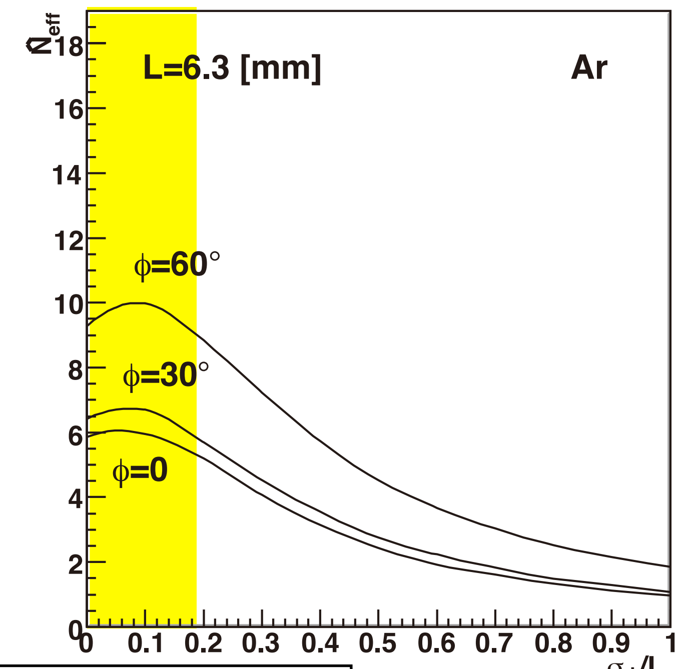
$$[C] := \left(\frac{\sigma_G}{\bar{G}}\right)^2 \left\langle \frac{1}{N^2} \right\rangle_N \sum_a (aw)^2$$

[D]: Angular pad effect

$$[D] := \frac{L^2 \tan^2\phi}{12}$$

$$\hat{N}_{eff} \simeq \left[\left\langle \sum_{i=1}^{N} \left\langle \left(\frac{\sum_{j=1}^{k_i} G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right)^2 \right\rangle_G^{k_i, \sum_{i=1}^{N} k_i} \right\rangle_{N,k} \right]^{-1}$$

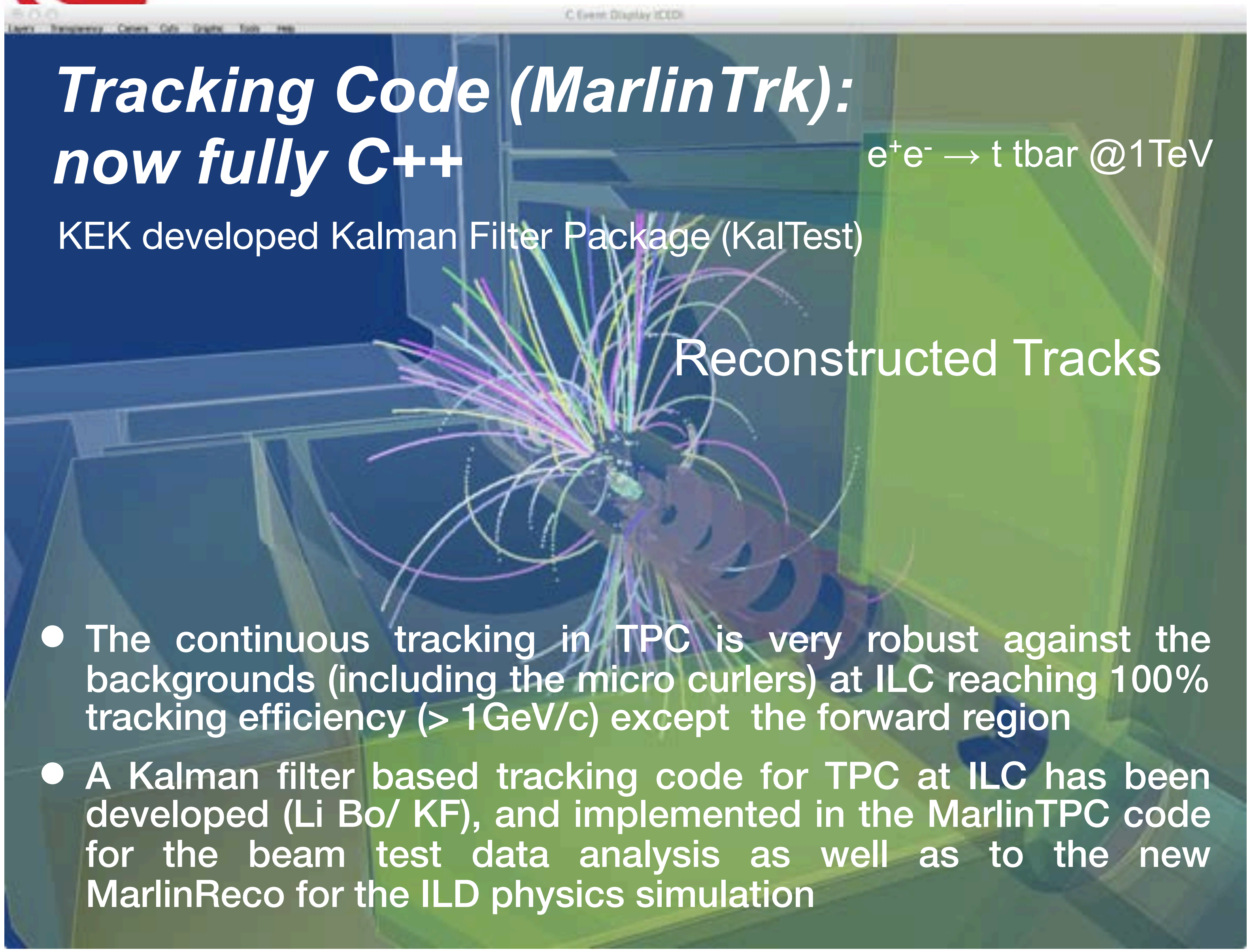
: effective # clusters



$$\hat{N}_{eff} \ll N_{eff}$$

$\sigma_{r\phi}$ quickly deteriorates with ϕ!

Tracking Codes for LP TPC and ILD TPC

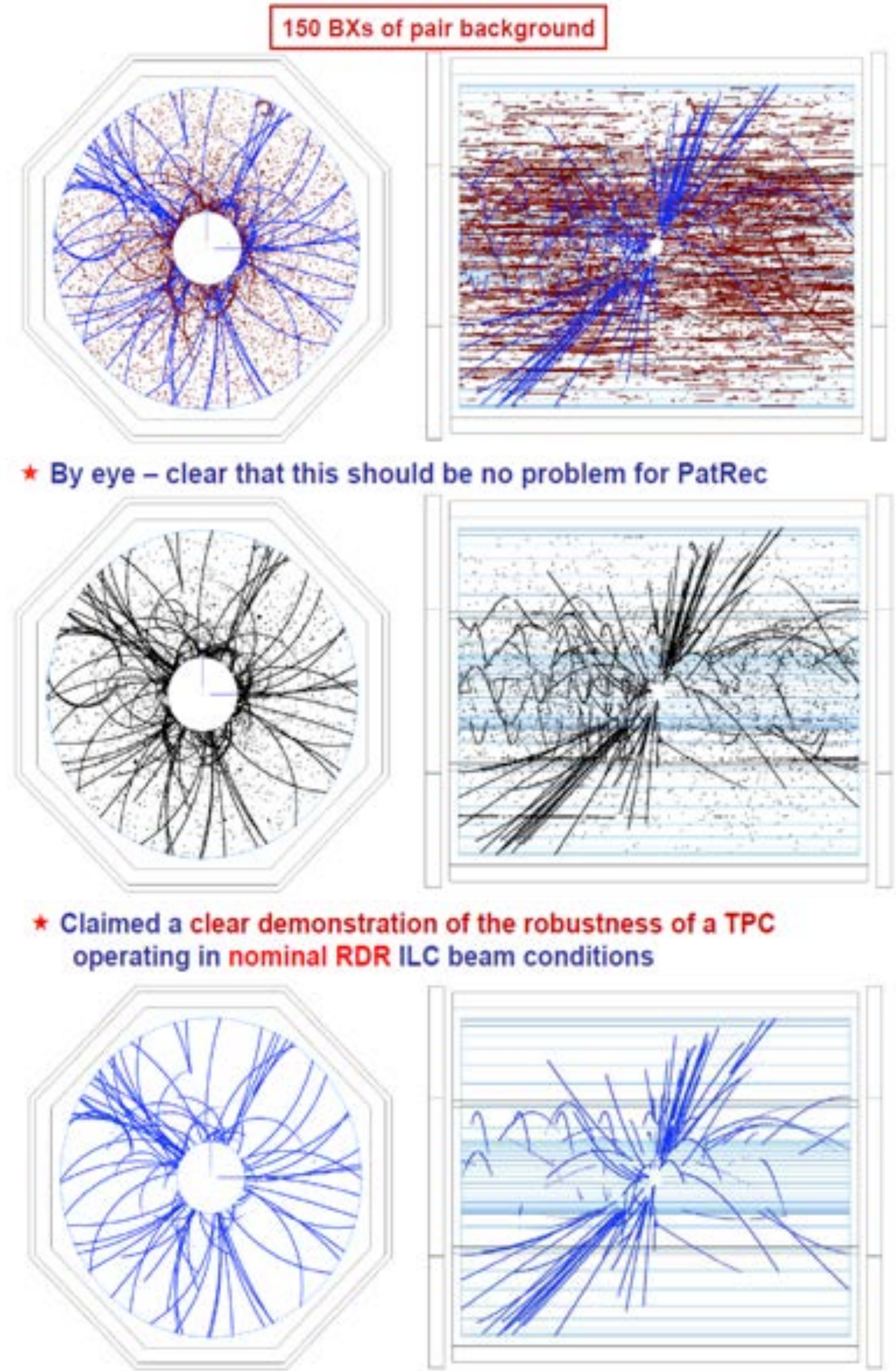


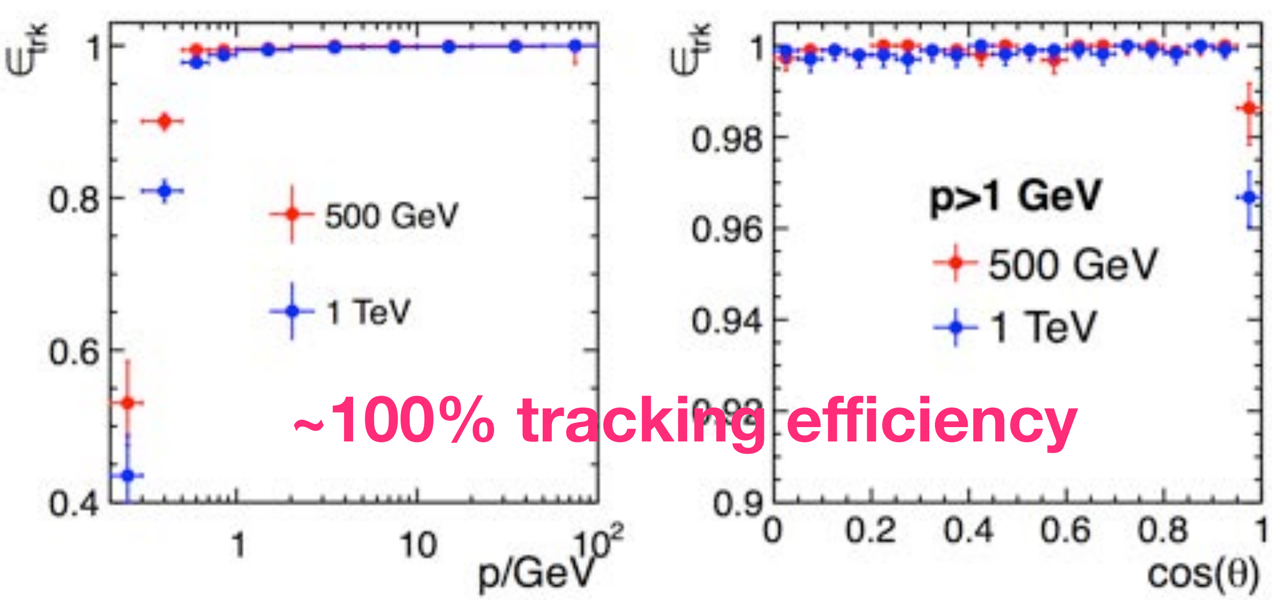
Tracking Code (MarlinTrk): now fully C++

$e^+e^- \rightarrow$ t tbar @1TeV

KEK developed Kalman Filter Package (KalTest)

- The continuous tracking in TPC is very robust against the backgrounds (including the micro curlers) at ILC reaching 100% tracking efficiency (> 1GeV/c) except the forward region
- A Kalman filter based tracking code for TPC at ILC has been developed (Li Bo/ KF), and implemented in the MarlinTPC code for the beam test data analysis as well as to the new MarlinReco for the ILD physics simulation



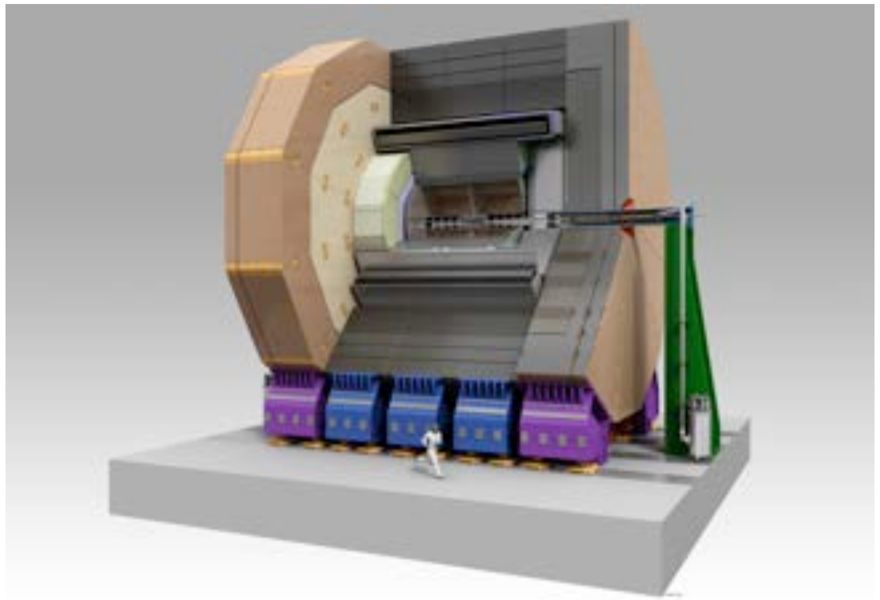


~100% tracking efficiency

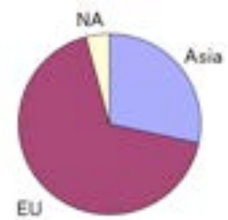
Despite the more realism (cracks, support structures, and service materials) brought in to the simulator,

PFA performance is now better than that of LoI!

ILD Detailed Baseline Design



Letter of Intent (2009)
~700 signatories
~120 from Japan



ILD DBD now completed in March 2013!
We are now entering the phase for the Final Engineering Design!

Contents iii

Entering New Phase
D_RD_9

ILD Detailed Baseline Design now completed!

We are now entering the phase for the Final Engineering Design!

In addition to further R&D towards engineering design of the GEM or MM module on each side, we need to work together on the following:

- Common tracking and analysis software R&D
- Gating Device
- 2-Phase CO2 Cooling
- Readout Electronics: Analog-Digital mixed chip for (semi-)surface mounting

Common Tracking and Analysis Software

to compare different technologies on the equal footing for eventual technology choice

Kalman Filter Based Track Fitting in Non-uniform B Field

arXiv: physics.ins-det/1305.7300

Basic idea of the algorithm

To use the helical track model of KalTest in the non-uniform magnetic field, we have to:

- assume the magnetic field between two nearby layers is uniform;
- transform the frame to make the z axis point to the direction of magnetic field.

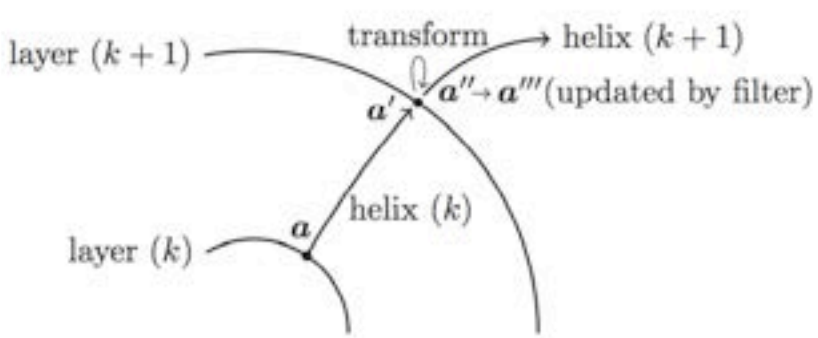
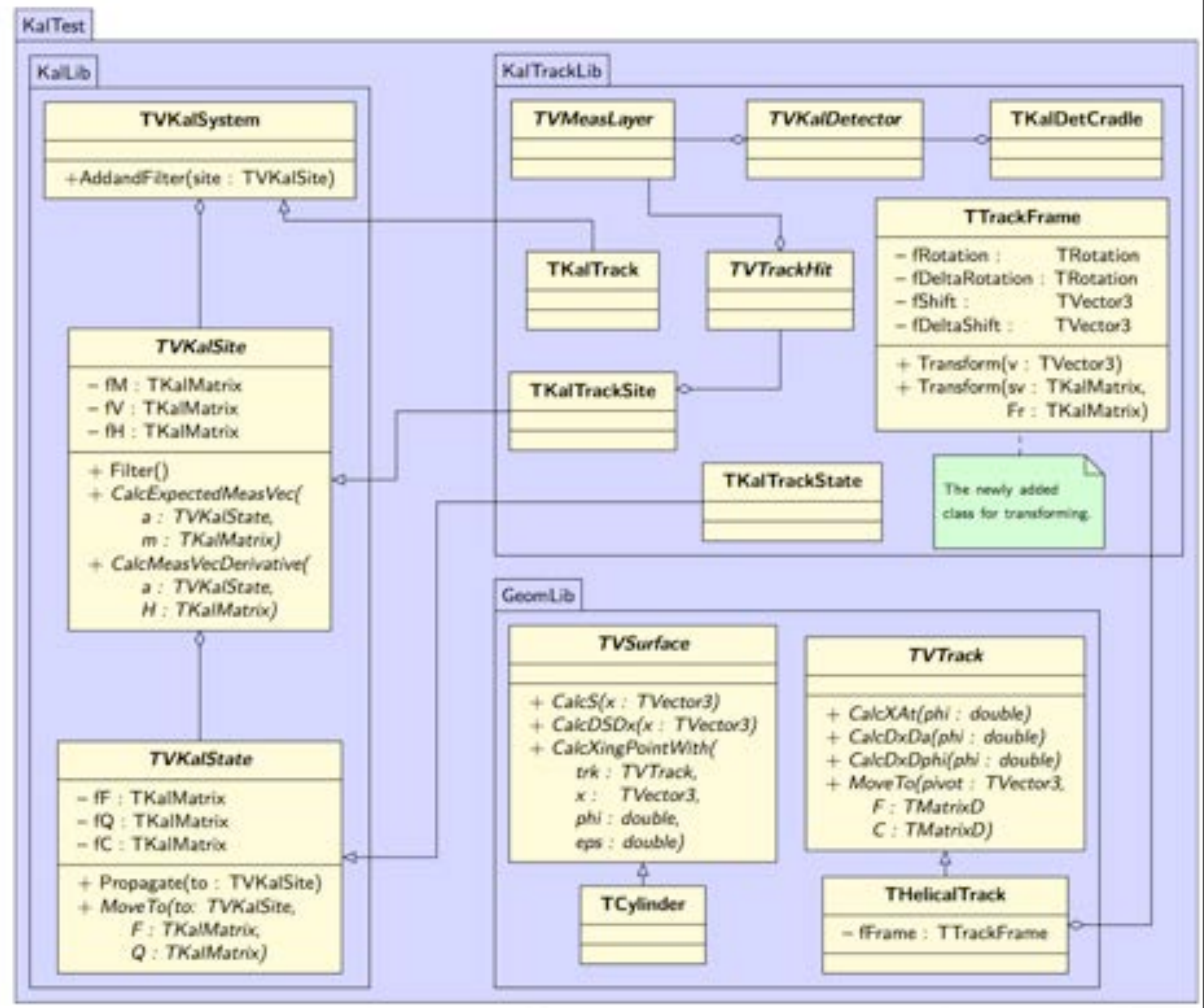
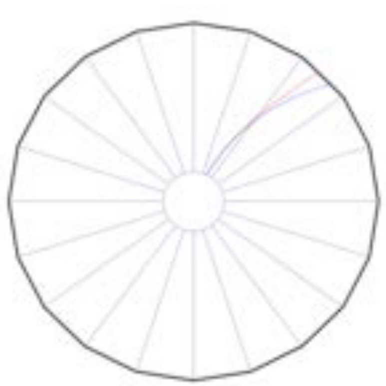


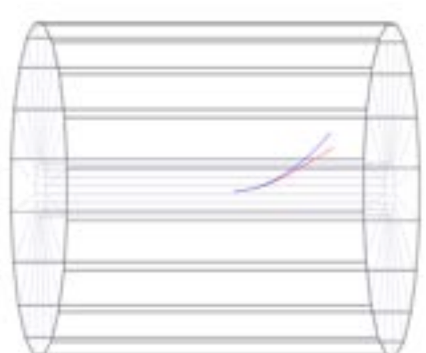
Figure 1 : The updated track propagation procedure.

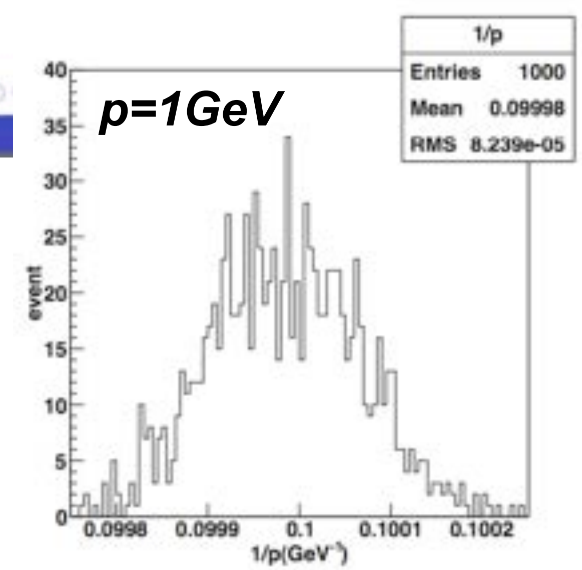
Therefore we now have a **segment-wise helical track model**.

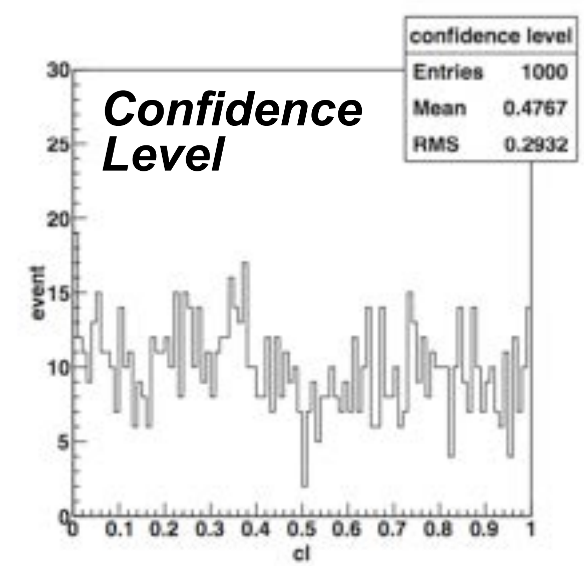
Track fitting in non-uniform magnetic field June 1, 2013 2 / 10











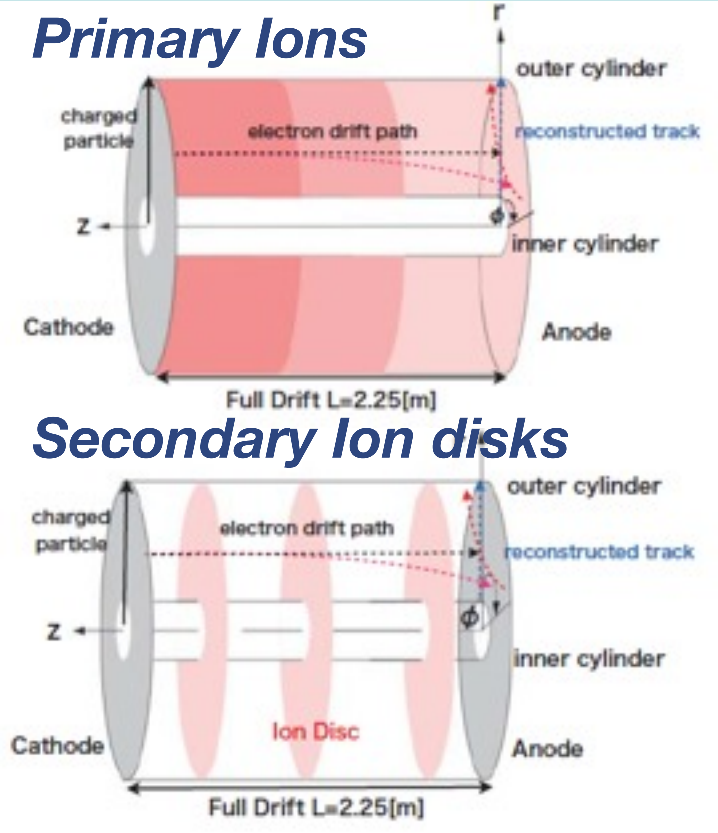
Works in B field with >40% non-uniformity !

Ion Gate

Effects of Positive Ions and Ion Gating at ILC

Solved the Poisson equation for the simulated ion density distribution with proper boundary conditions and then estimated the distortion of drift electron trajectory by the Langevin equation (D. Arai and KF)

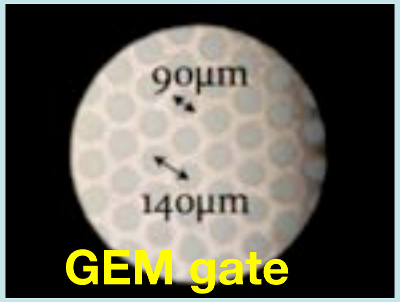
	without Gating Device	with Gating Device	
Primary Ion	8.5 μm	8.5 μm	OK
Secondary Ion	60 μm	0.01 μm	Not OK
sum	70 μm	8.5 μm	

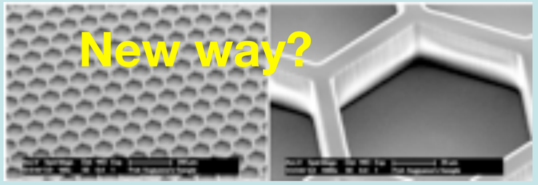


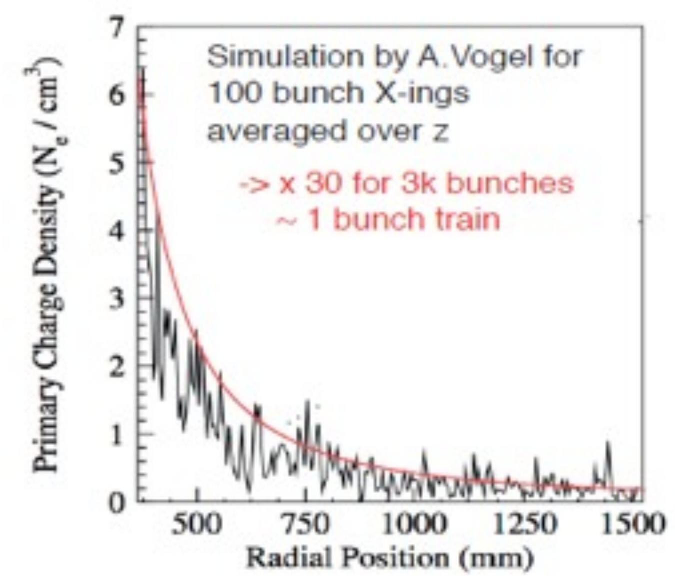
For the secondary ions from the amplification, we need an ion gate device for the ion feed back ratio of >10^{-3} (measured both for the triple GEM and Micromegas) at the gas gain of 1,000.

The current options of the ion gate are limited:

- **The traditional wire gate is expected to work, but introduces mechanical complications to the MPGD modules. We also need to check ExB effect.**
- **Thin GEM gate offers the electron transmission of only 50%@ 1T → 30% loss in the point resolution (Japanese LC TPC group).**
- **Try a larger geometric aperture with new fabrication method?**





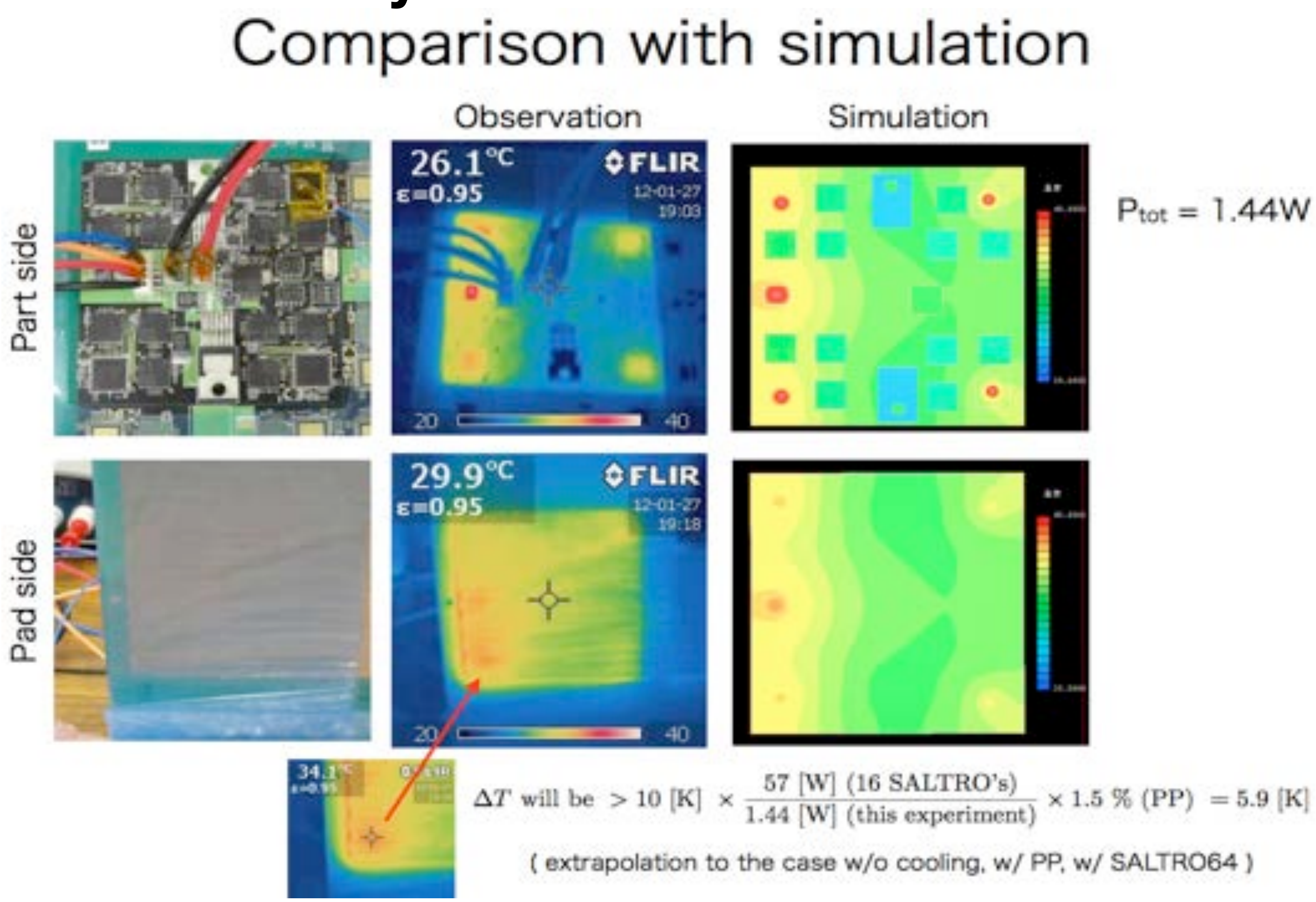


No two-photon hadron BG included.
-> underestimate

2P CO2 Cooling

R&D on Power Pulsing and Cooling

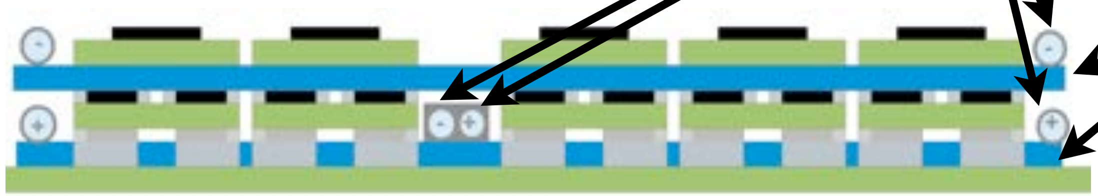
Test with Dummy Module

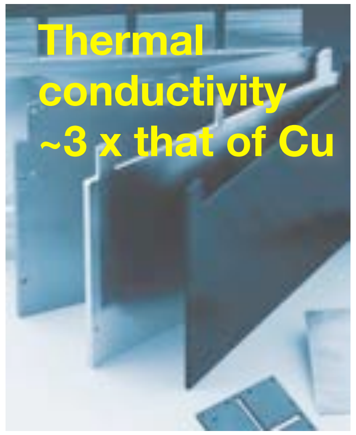


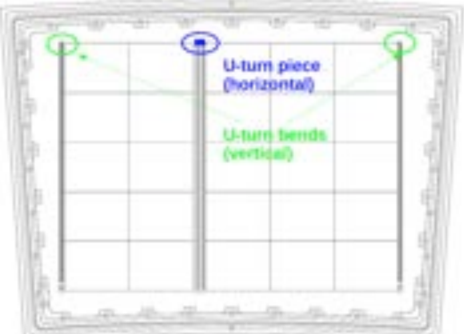
Cooling Channel R&D

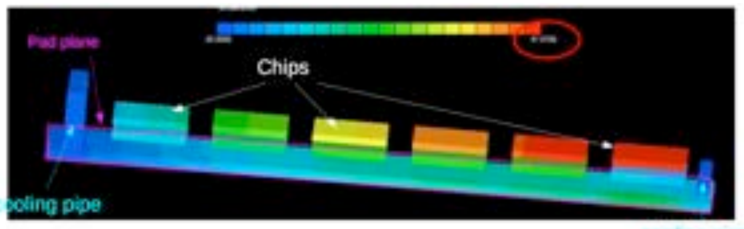
cooling pipes

TPG: Carbon
(Momentive)







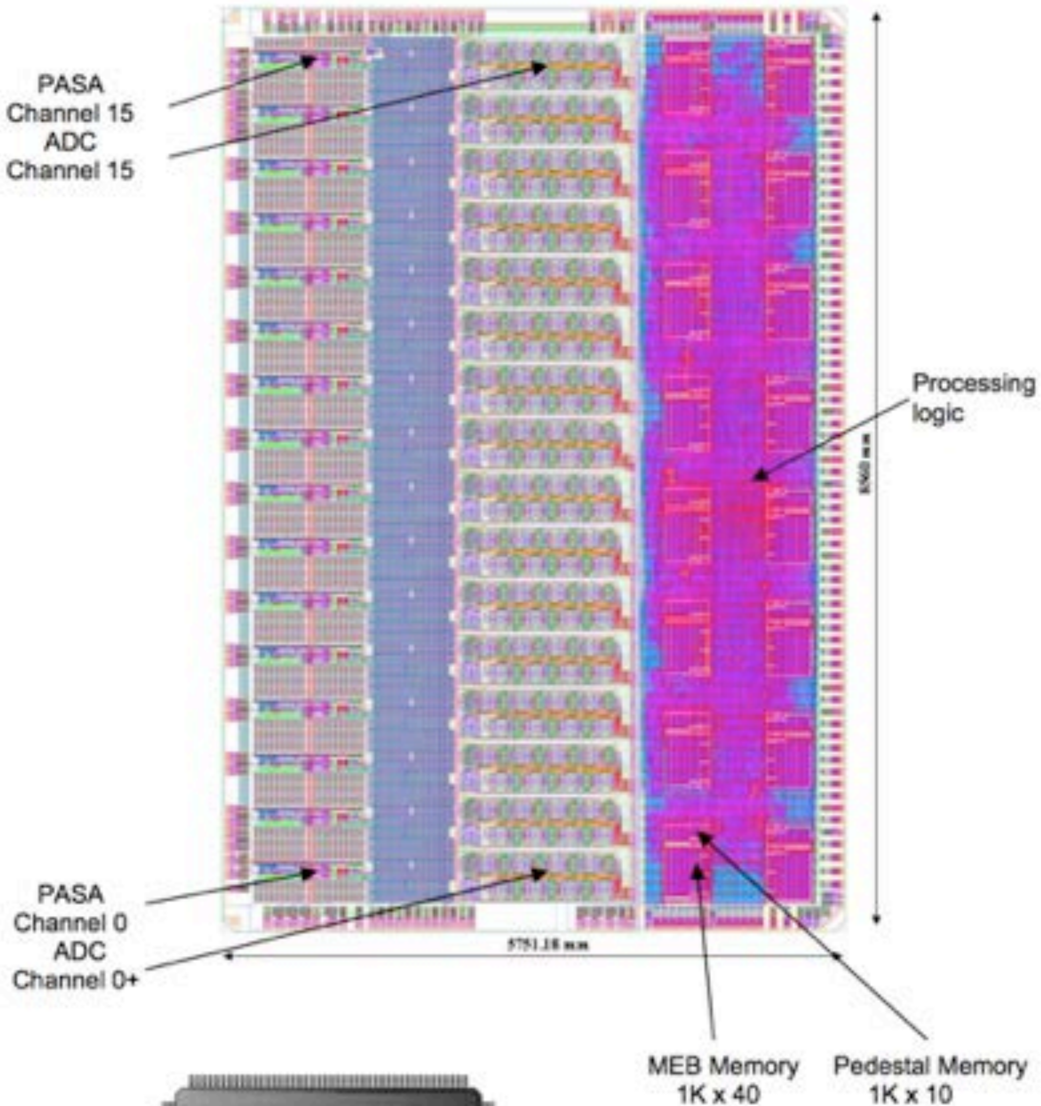


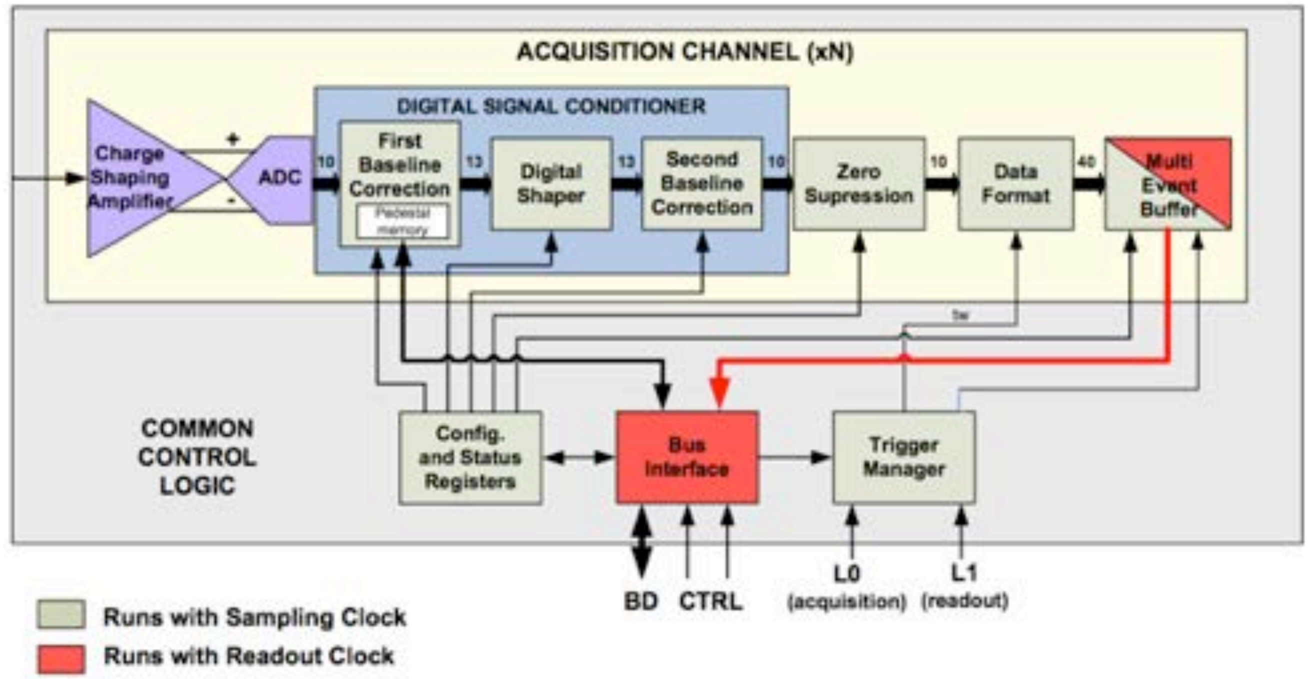
Thermal simulation

Readout Electronics

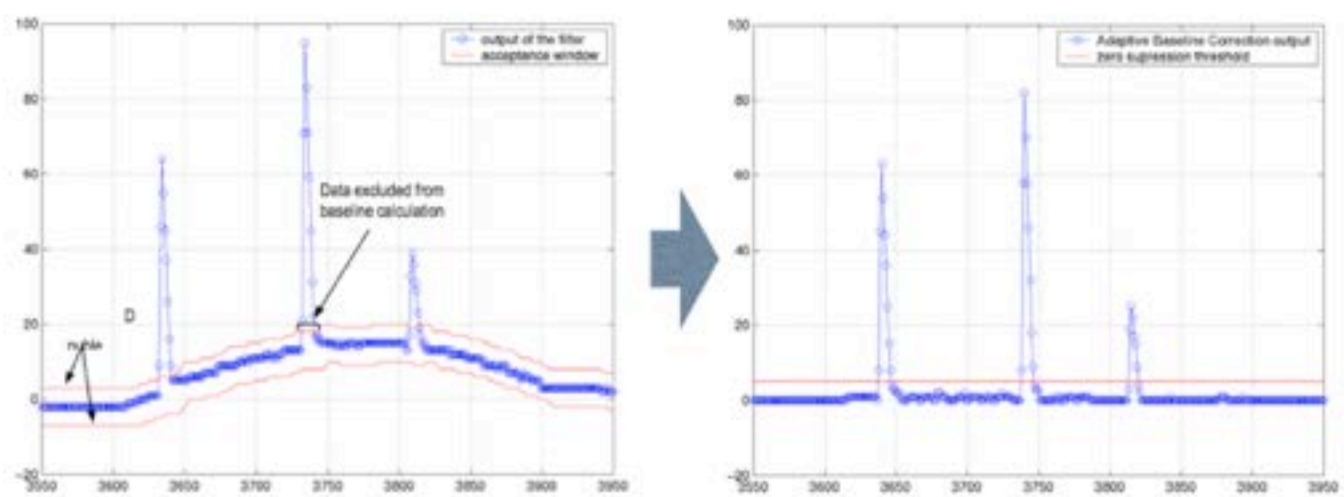
S-ALTRO 16 Development

as a Pre-advanced Stage





Wire bonding package
24mm x 24mm x 1.4mm



Example of baseline correction

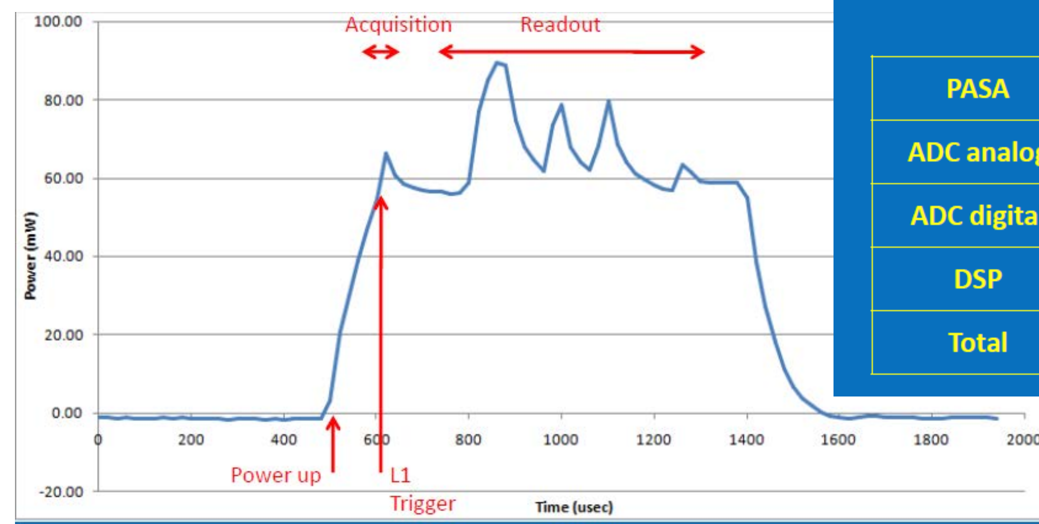
- Received back from foundry: Q1/2011.
- Characterization done

Reference:
"S-ALTRO prototype" 27.07.2010

Gas detector Signal Processor ?

Our path not yet totally clear (definitely need collaboration)

S-ALTRO 16 Power Pulsing Test



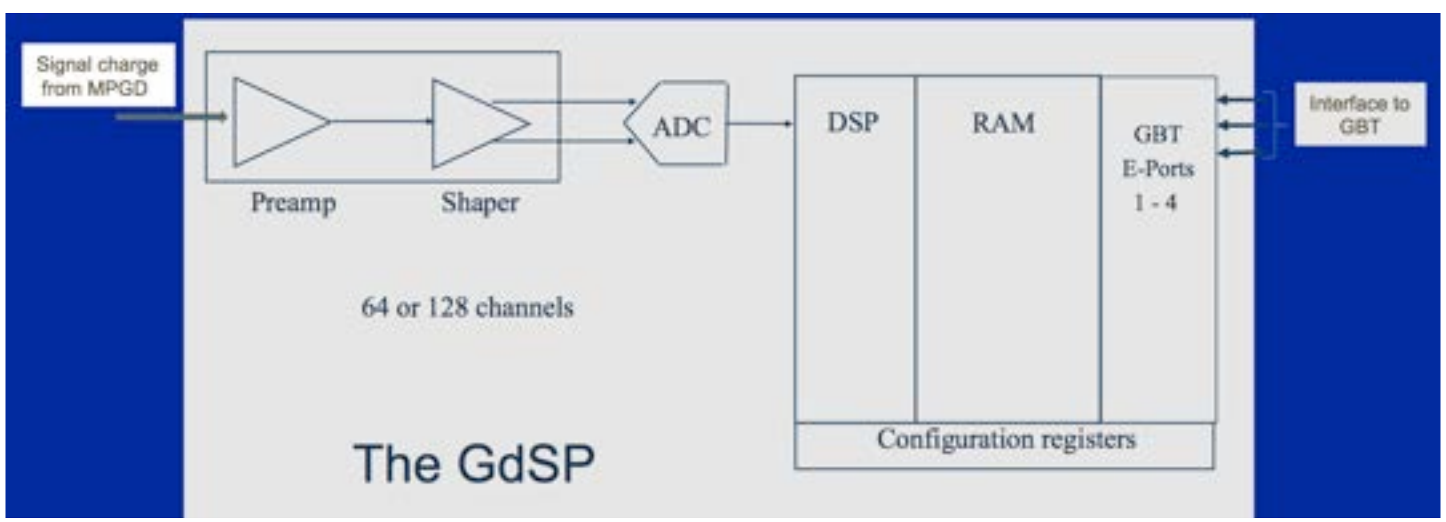
	Power (mW)
PASA	2.68
ADC analog	24.96
ADC digital	0.01
DSP	0.40
Total	28.1

S-ALTRO

- 756mW / chip if no power pulsing
- 28mW / chip if 5Hz power pulsing

Still too high!

Next Step



Natural successor of S-ALTRO chip

- Very low power ADC: 4mW/ch, complete revision of other sections, too, for low power consumption.
- S-ALTRO → GdSP 64 → 128ch / chip ?
- Optimized DSP
- Fully accommodates power pulsing
- Section-by-section power management
- Applications: CMS high-η, ILD-TPC, ...?

Summary

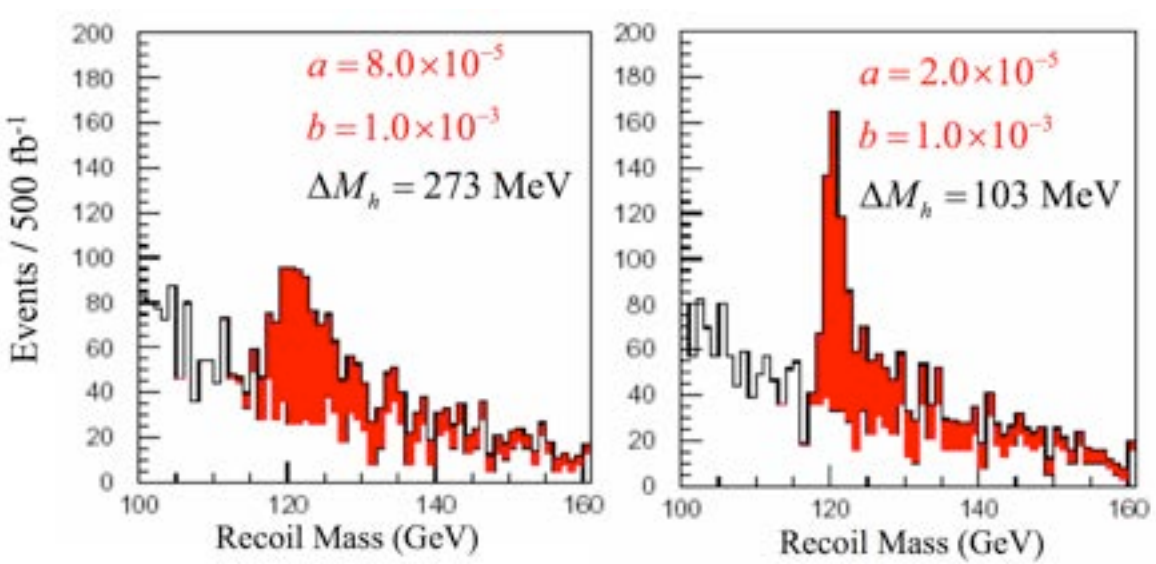
Now and Future

- The France-Japan collaboration on the LCTPC R&D has
  - clarified the basic principles to determine the spatial resolution through series of test beam experiments using a Large Prototype TPC and through development of an analytic resolution formula to understand their results, and
  - demonstrated that both the GEM and the restive anode readout Micromegas modules meet the ILC's $\sigma_{r\phi}$ requirement.
- In addition to further R&D for solving remaining issues towards the engineering design of the GEM or MM module on each side, we need to work together on the following common issues:
  - Tracking and analysis software R&D,
  - Gating Device,
  - 2-Phase CO2 Cooling, and
  - Readout Electronics: Analog-Digital mixed chip for (semi-)surface mounting.
- The France-Japan team has been the driving force of the LC-TPC collaboration. This tradition should continue towards the final design of the Linear Collider TPC.

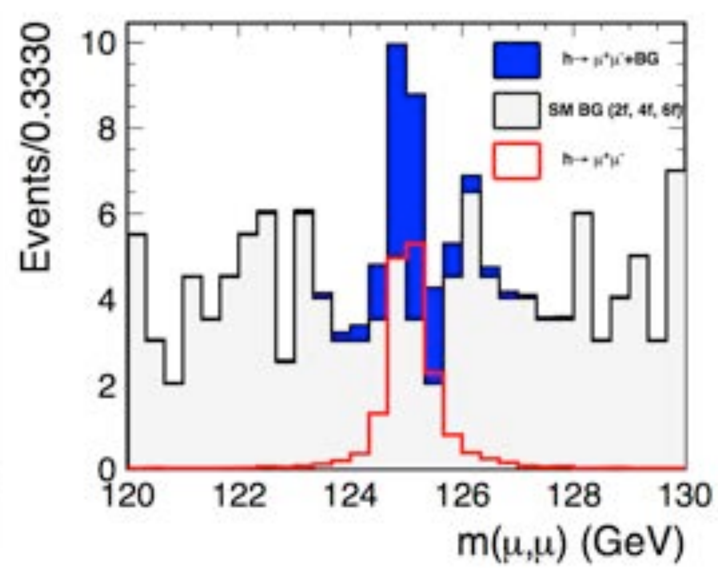
Backup

Performance Goals

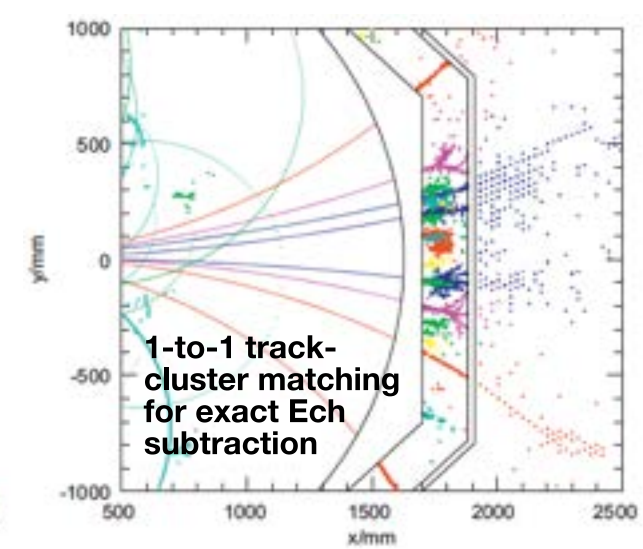
- **Momentum Resolution:** $\sigma(1/p_t) = 2\times10^{-5}$ (GeV^{-1})
  >200 sampling points along a track with a spatial resolution better than $\sigma_{r\phi}$~100 μm over the full drift length of >2m in B=3.5T (recoil mass, $H\rightarrow\mu^+\mu^-$).
- **High Efficiency:** 2-track separation better than ~2mm to assure essentially 100% tracking efficiency for PFA in jetty events.
  High tracking efficiency also requires minimization of dead spaces near the boundaries of readout modules.
- **Minimum material:** for PFA calorimeters behind, also to facilitate extrapolation to the inner Si tracker and the vertex detector



Recoil Mass Measurement



$H\rightarrow\mu^+\mu^-$



Particle Flow Analysis

25