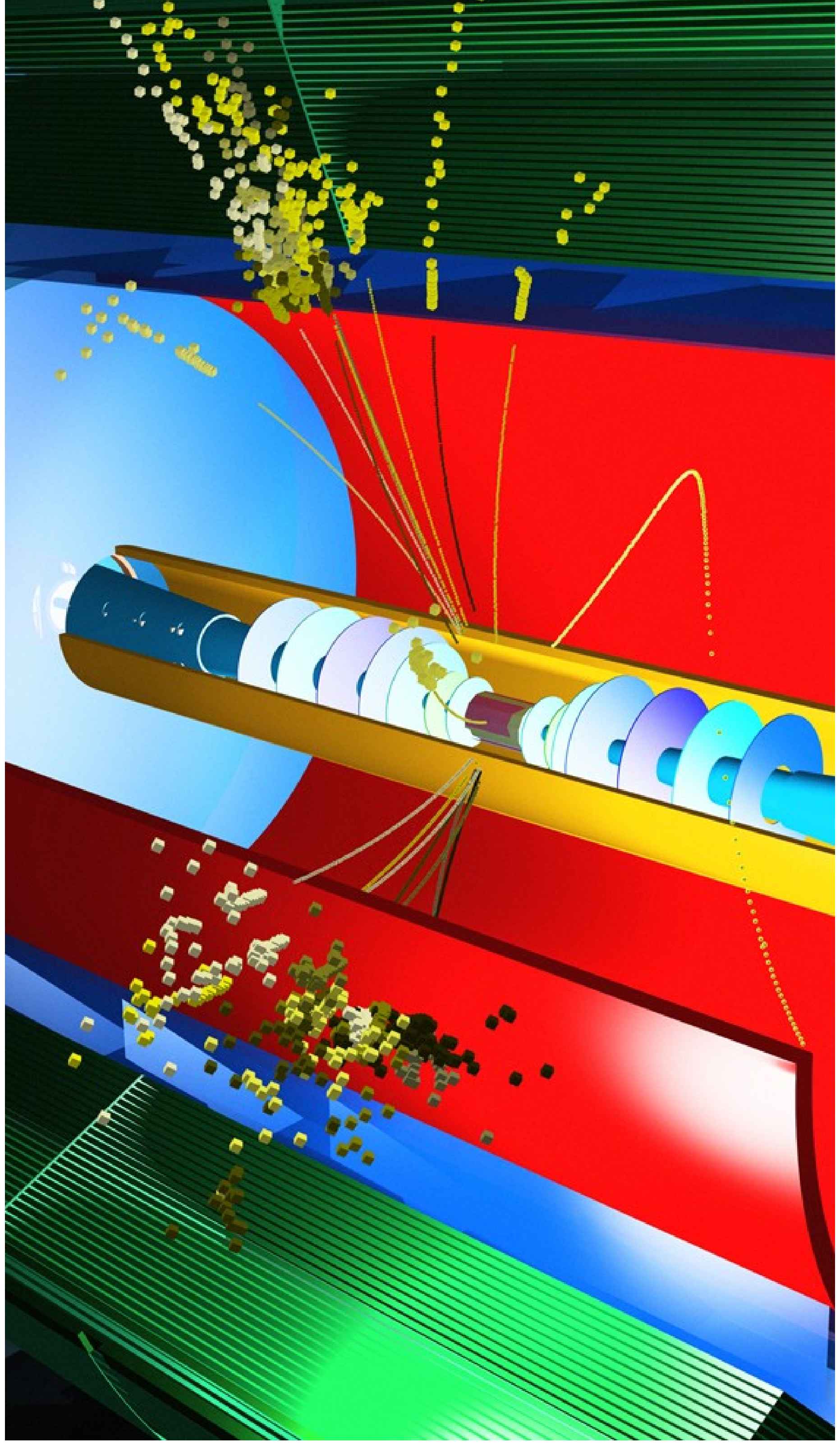
A DEPFET vertex detector for a future linear collider;

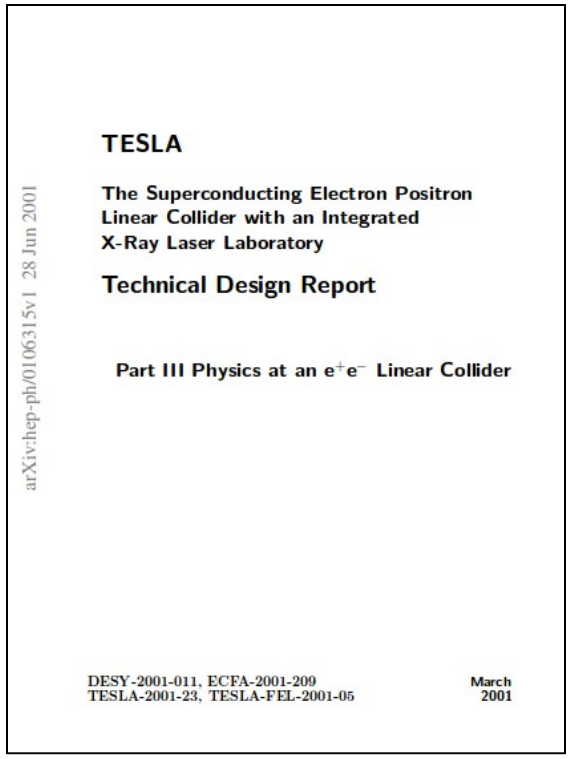


Vertex 2013
Lake Starnberg, Germany,
16-20 September 2013

Marcel Vos
IFIC (U. Valencia/CSIC), Spain

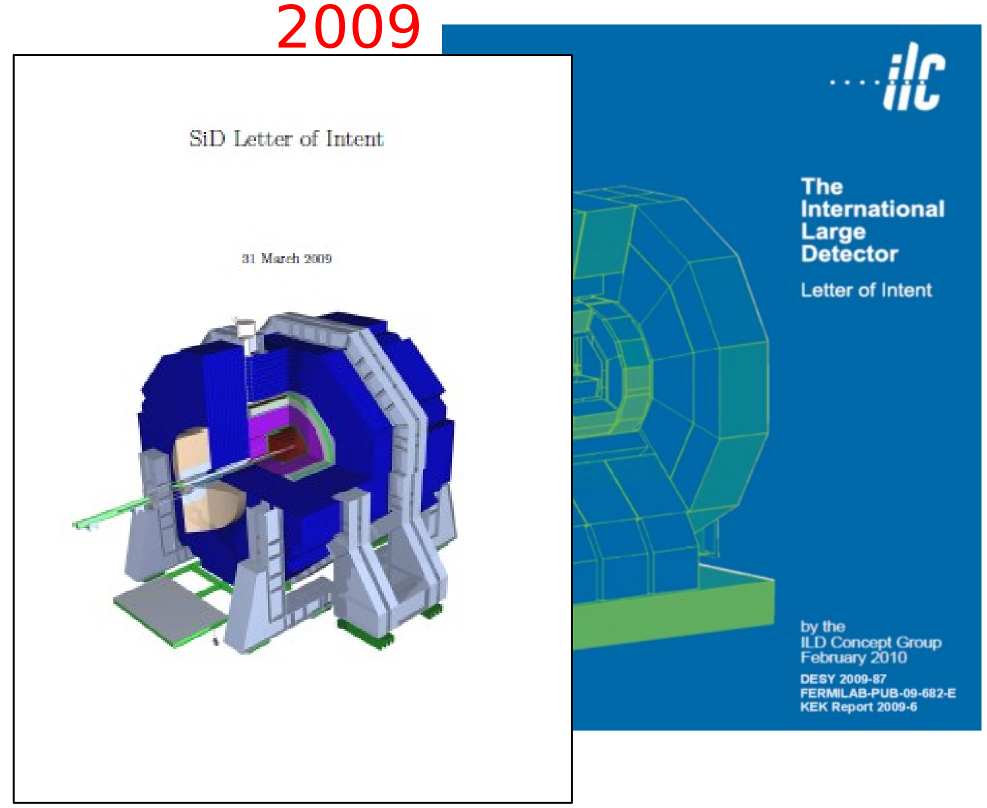
Linear Collider history

2001

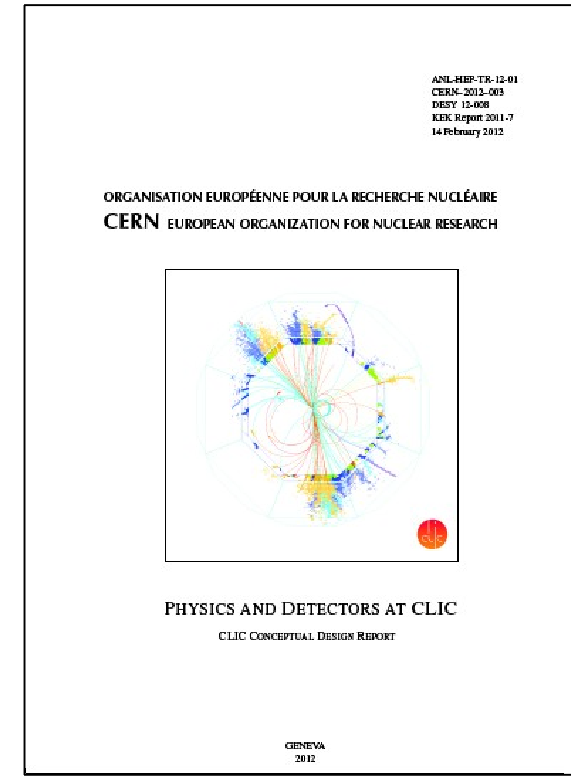


...

2009



2012

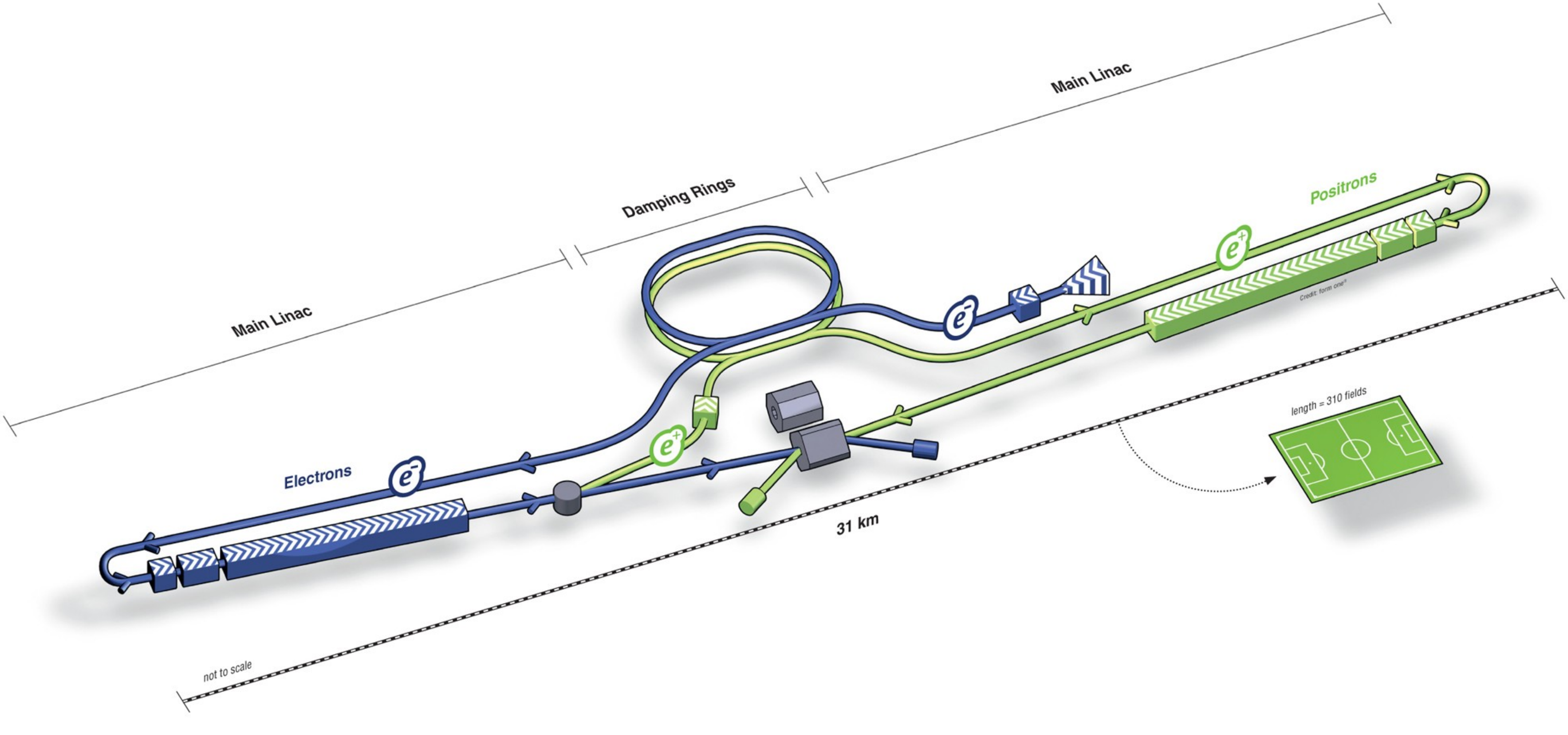


Reference documents prepared by the LC community:

- Tesla TDR (2001) part III on physics
- 2004 Report on the complementarity of LC and LHC
- CLIC physics report
- ILC Reference Design Report (2007): physics and detectors
- Letter Of Intent of the ILC experiments (2009) SiD and ILD
- Conceptual Design Report (2012) of the CLIC detectors
- This summer (june 2013): ILC TDR
- Includes: Detailed Baseline Design for the ILC experiments

DEPFET Active Pixel Detector

Future linear e^+e^- colliders



Accelerator R&D around the globe. Non-exhaustive list of test facilities:

ATF@KEK, nm size, low emittance beams

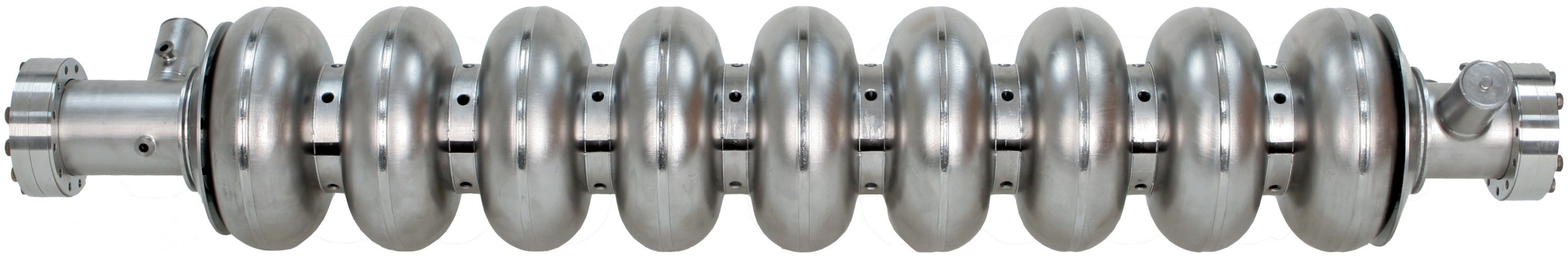
CESR/IT@Cornell (electron cloud)

CTF3@CERN, drive beam

XFEL@DESY

Future linear e^+e^- colliders

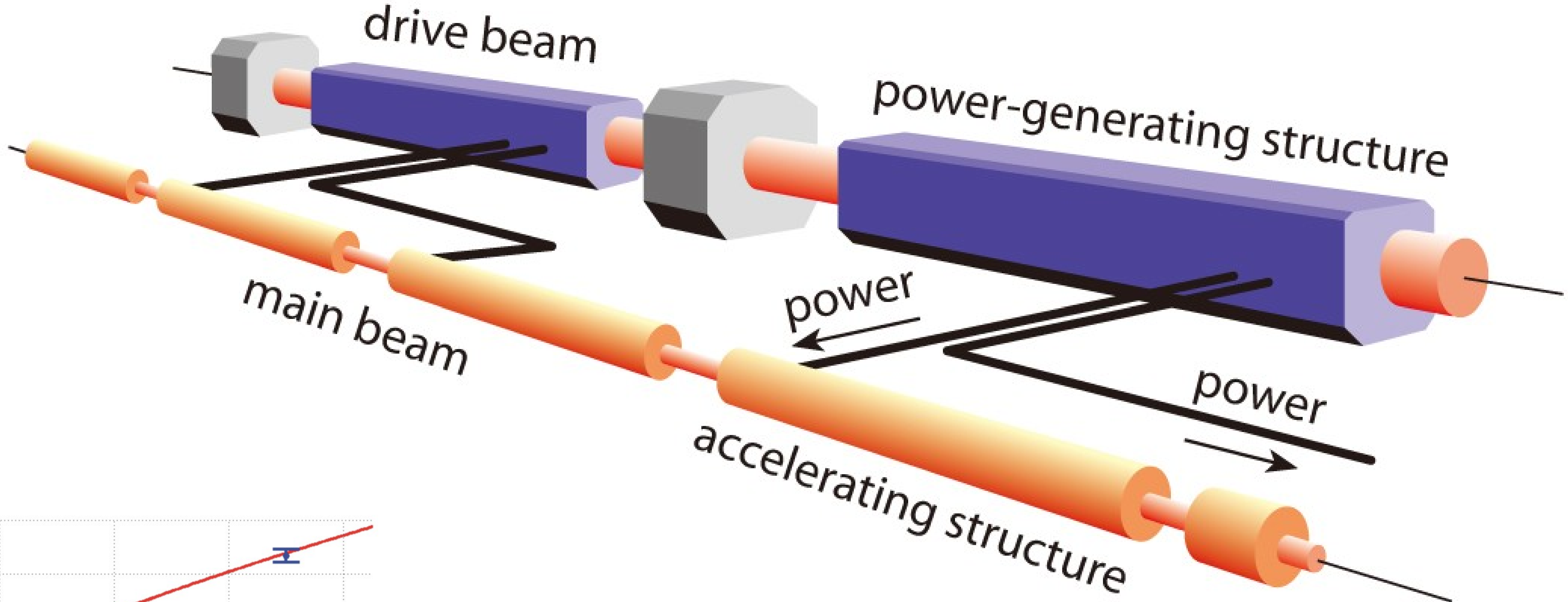
Superconducting RF cavities are in the industrialization phase and routinely reach gradients well over 30 MV/m.

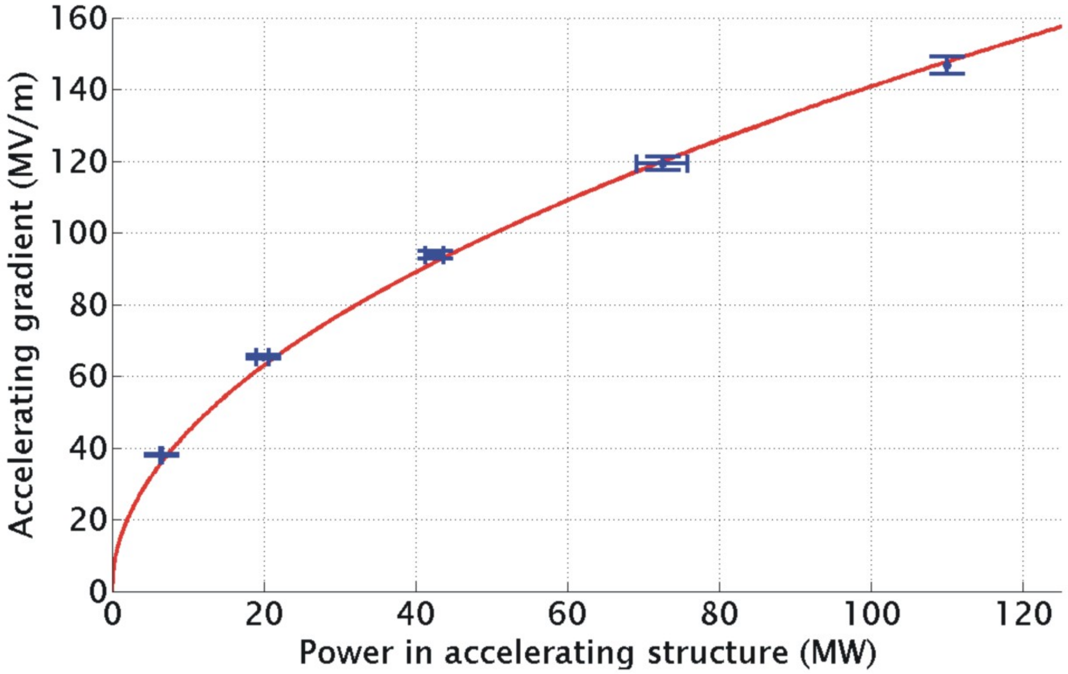


RF technology exists for a low-energy machine ($\sqrt{s}$ ~ 250-500 GeV)

ILC is shovel-ready!

Future linear e⁺e⁻ colliders





Higher gradient (~100 MV/m) can be achieved using drive beam concept.

R&D for $\sqrt{s}$ ~ 1-3 TeV → CLIC to open up the multi-TeV regime.

DEPFET
Active Pixel Detector

The e^+e^- precision physics programme

The physics programme of the LC (ILC and/or CLIC) envisages runs at several center-of-mass energies:

91 GeV *GigaZ* (*optional*) high-lumi run at the Z-pole

– ultra-precise measurements of electroweak observables

250/350 GeV *Higgs factory* study of $e^+e^- \rightarrow ZH$ process using recoil method

– Higgs couplings to Z and W, g, c, b, τ

345-355 GeV *top threshold scan*

– Precise top quark mass (width, α_s and top Yukawa coupling)

500 GeV *(nominal ILC energy)*

– Precise electroweak top couplings

For a detailed physics case, see Frank Simon's presentation

1 TeV *(ILC energy upgrade)*

– *Higgs self-coupling*

1.5 - 3 TeV *(CLIC high-energy programme)*

Leptons vs. hadrons

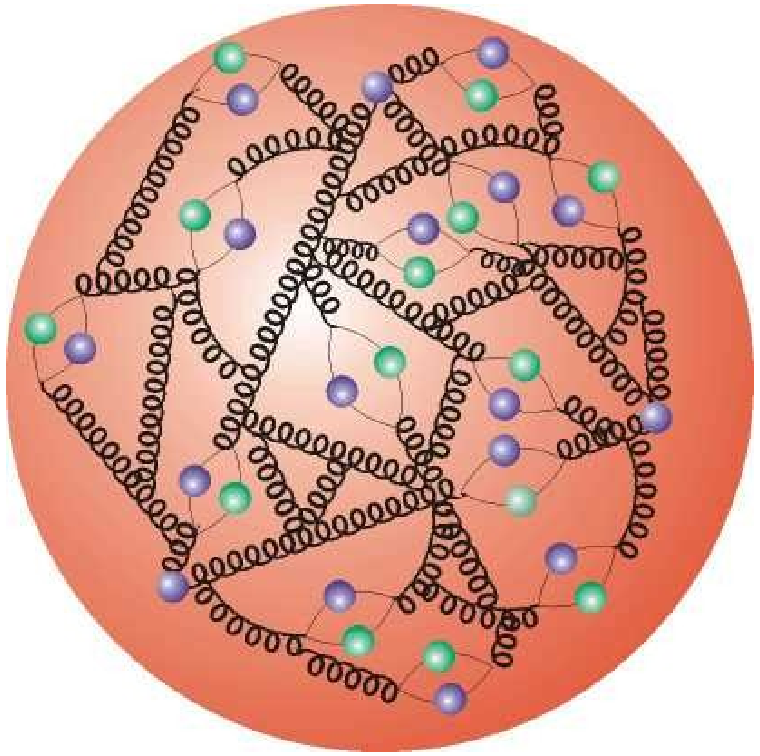
Colliding (composite) hadrons is different from colliding (elementary) leptons in several important ways

At lepton colliders:

- **Production rates are precisely calculable:**
  - *5% uncertainty on $t\bar{t}$ cross-section at LHC is a milestone, per mil level is feasible at ILC → precise calibration of luminosity*
- **Every GeV delivered to the projectile is used**:

  - a 2 TeV hadron collider may not be enough to find a 126 GeV particle, a 250 GeV lepton collider certainly is!
- **The initial state is precisely controlled:**
  - *total energy sums of to $2\ E_b$ → recoil mass analysis, energy scales polarization can be controlled (at linear collider)*
- **Production rates are democratic**:

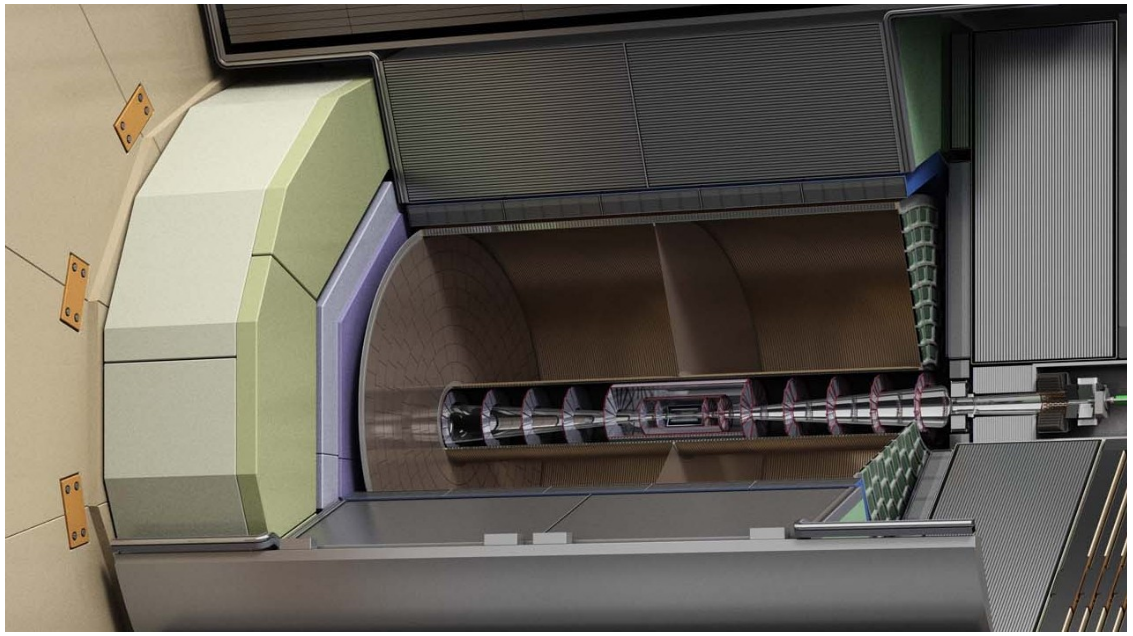
  - events *producing Higgs, top and major backgrounds are ~ equally likely. At hadron colliders we have to work through many orders of magnitude of QCD to reach rare processes*
- **Non-collision events are approximately empty:**
  - *no pile-up, relaxed read-out times, less radiation damage*

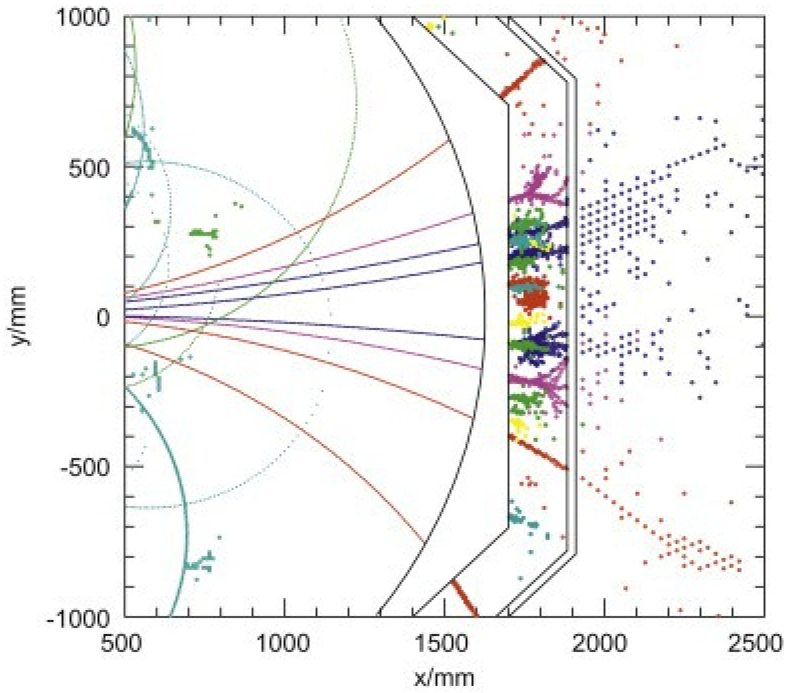


LC detectors

LC environment and detector R&D allow for a big leap in performance

- Well-defined initial state (CM energy, polarization)
- Signal and bkg x-sections of similar magnitude
- Triggerless read-out
- Background confined to innermost detectors





Particle Flow: highly granular calorimetry inside a large 3.5-5 Tesla solenoid allows to follow every single visible particle produced in the collisions from the cradle to the grave → best possible estimate of the jet energy: $\Delta E/E \sim 3\text{-}5\%$

Transparent and precise tracking/vertexing:

$\Delta(1/p_T) \sim 10^{-5}\ \text{GeV}^{-1}$

$\Delta(d_0) \sim 5 \oplus 10\text{-}20 / (p \sin^{3/2}\theta)$

Detailed Geant4 model and sophisticated reconstruction software allow realistic estimates of performance

Vertex detector

	a (μm)	b (μm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
ILC	5	10

Vertex detector

Reconstruct primary and secondary vertices,

flavour tagging, bottom/charm separation

Large polar angle coverage

Unprecedented performance:

$\sigma(d_0) < 5 \oplus 10/(p \sin^{3/2}\theta)$

Strongly reduce the multiple Coulomb scattering term

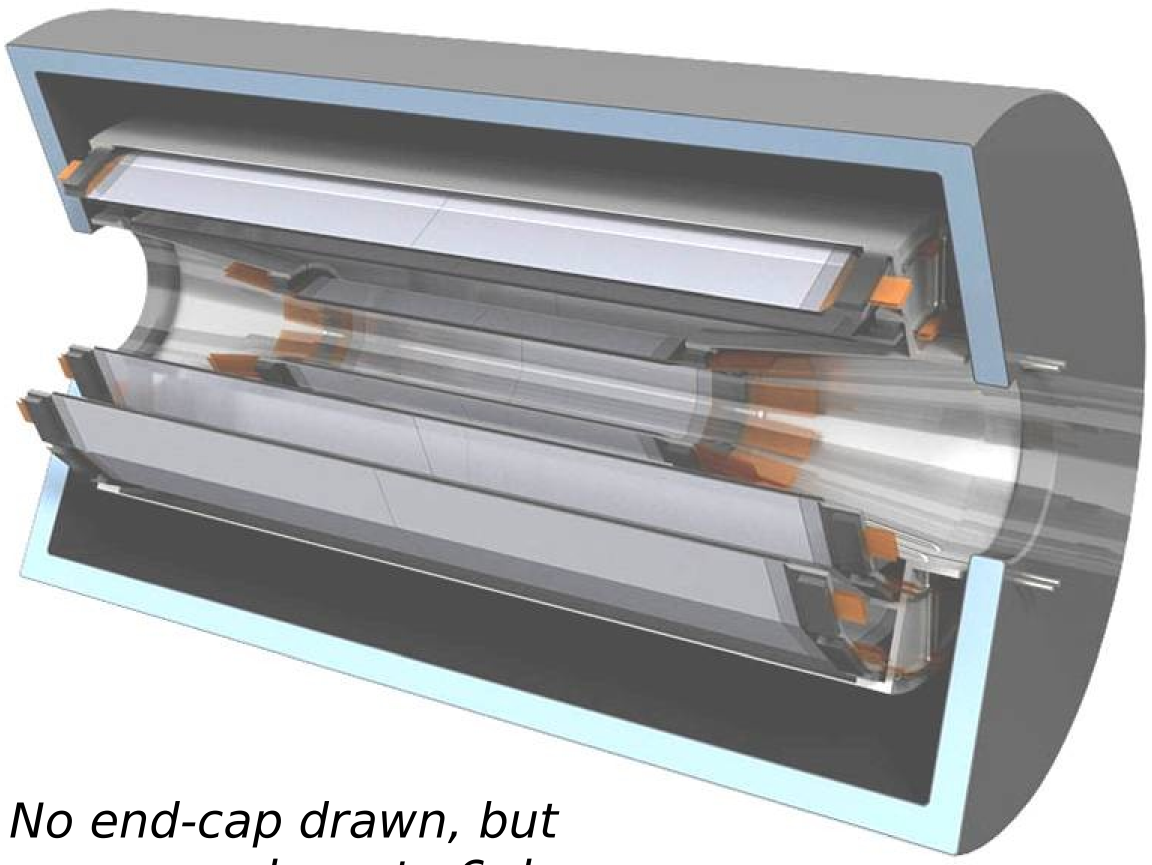
(0.1 % X_0 / layer ~ 100 μm Si)

Stringent requirements

Precision (20 x 20 μm^2)

Read-out speed (25/100 μs)

Material: 0.1...% / layer

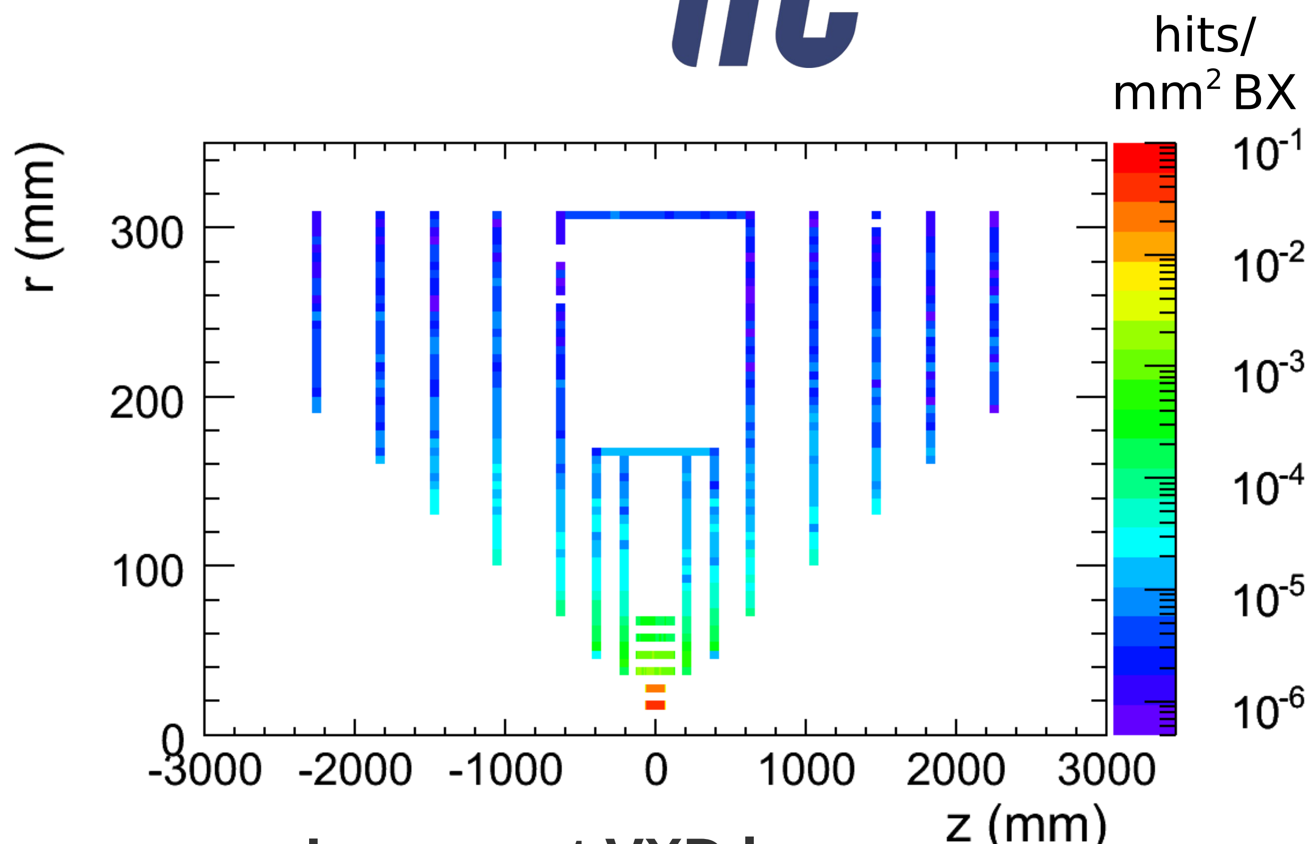


No end-cap drawn, but coverage down to 6 degrees

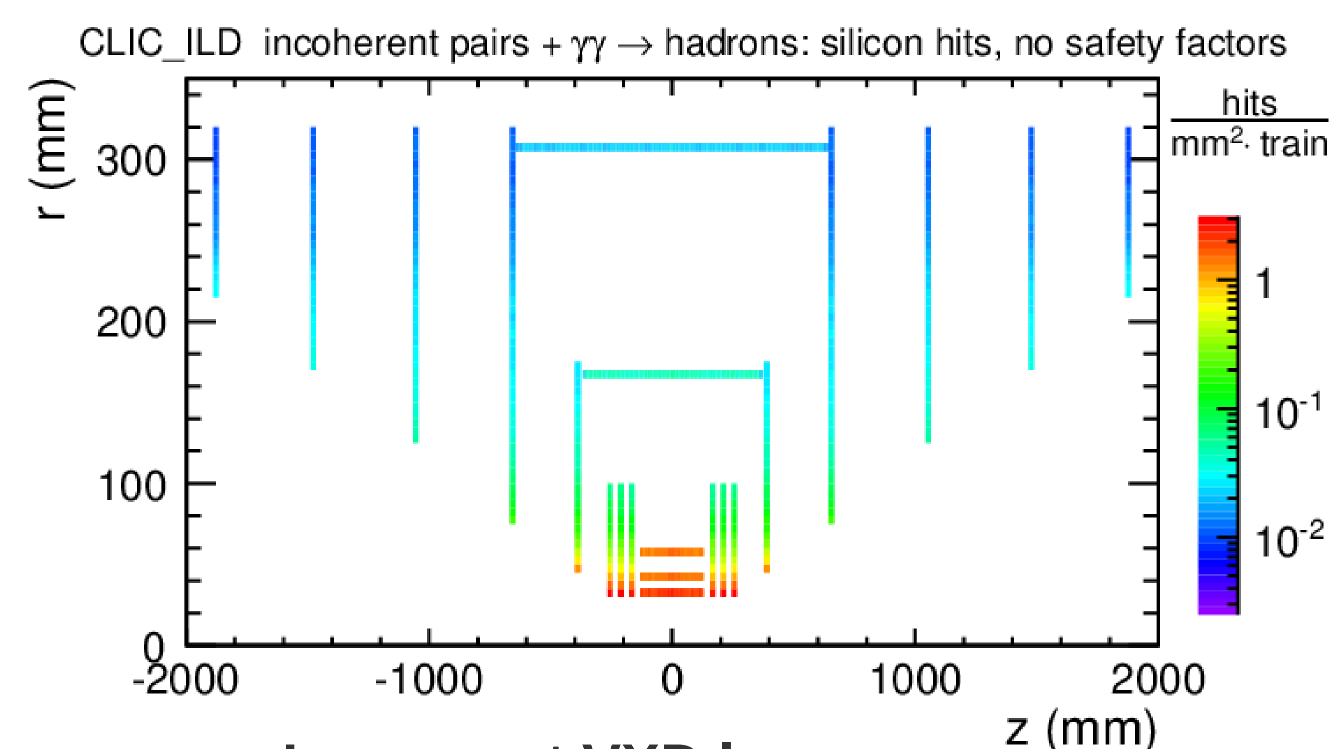
See Frank Simon's talk

Environment

Background levels in innermost detectors drives read-out speed requirement.
→ large uncertainties and strong dependence on the machine design
Rates are much reduced during initial low-energy phase
CLIC has ultra-fast bunch train structure: 312 BX in 150 ns
→ requires 10 ns time stamping for all sub-systems



Innermost VXD layer
R = 1.5 cm



Innermost VXD layer
R = 3 cm

Detector concepts

ILD (see DBD)

Candidate technologies:

(mature & pursued in ILD)

- CMOS MAPs (Strasbourg)
- FPCCD (KEK)
- DEPFET

One-page description in DBD

Several alternatives

A number of alternative technologies are under study which could feature the required high granularity and low material budget. Developments undertaken for the high energy run of the ILC, in particular high-resistivity substrate CMOS sensors and to multi-tier 3D pixel sensors.

SiD (see DBD)

Pushes for 3D integration

single BX time stamping

Fall-back scenario:

DEPFET, MAPs, FPCCDs

CLIC (see CDR)

Pushes hybrid solution (TimePix)

10 ns time stamping
Prohibitive for most

(alternative with timing fast timing layers interleaved with precise layers that integrate 150 ns bunch train – 20 ms to process frame)

Belle II synergy

	ILC	*Belle-II*
occupancy	0.13 hits/μm^2/s	0.4 hits/μm^2/s
radiation	< 100 krad/year	> 1Mrad/year
	10^{11} 1 MeV n_{eq}/year	2 10^{12} 1 MeV n_{eq}/year
Duty cycle	1/200	1
Frame time	25-100 μs (10 ns @ CLIC)	20 μs
Momentum range	All momenta	Low momentum (< 1 GeV)
Acceptance	6°-174°	17°-150°
Resolution	Excellent 3-5 μm (pixel size = 20 x 20 μm^2)	Moderate (pixel size = 50 x 75 μm^2)
Material budget	0.12 % X_0/layer	0.15 % X_0/layer

Belle-II presents a more severe challenge than the ILC in several aspects!

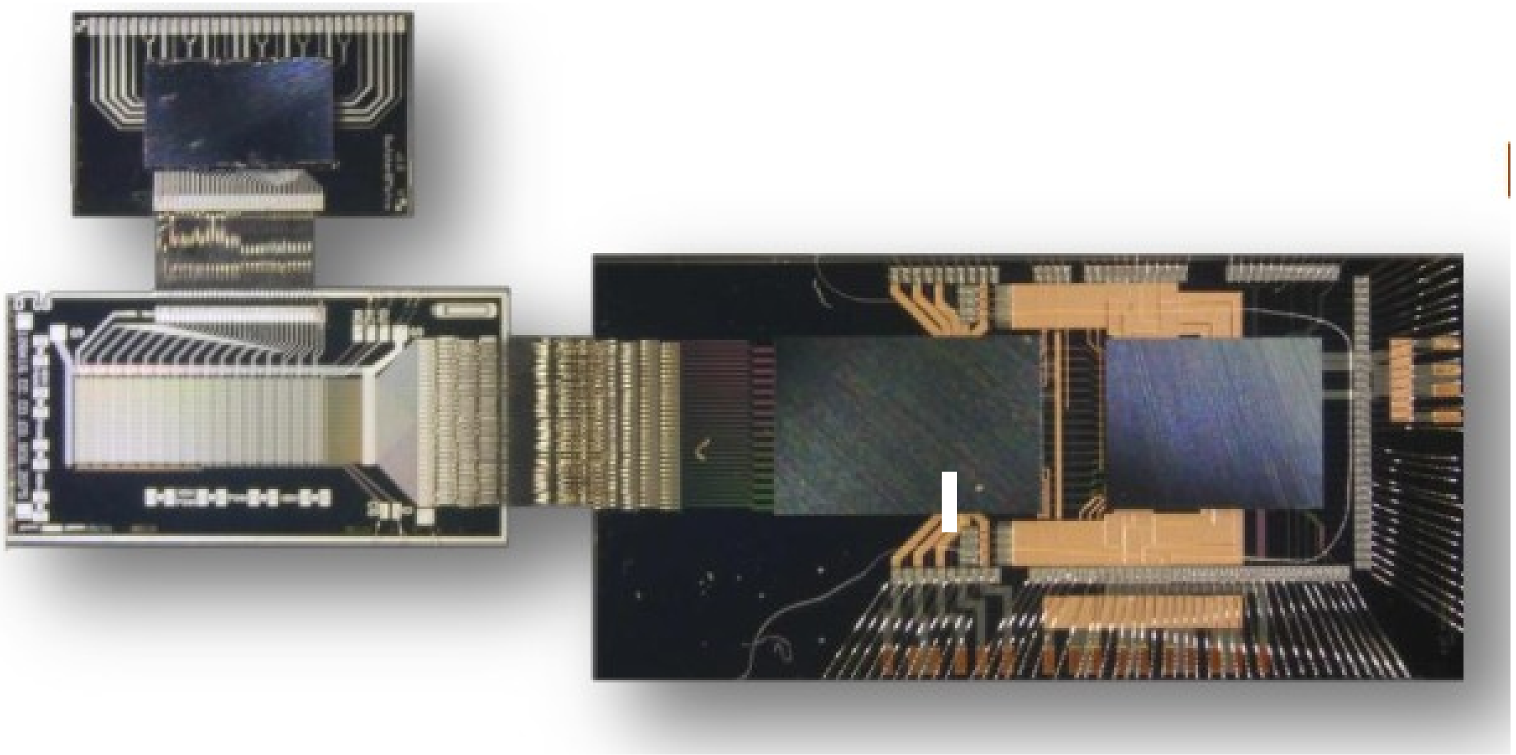
DEPFET Active Pixel Detector

Belle II synergy

For a status report of the DEPFET project for Belle II see Carlos Lacasta's talk

From concept to system, from prototypes to complete detector

- design and produce every component
- hands-on experience with mechanical properties of thin sensors
- study (air) cooling



Progress in read-out and steering ASICs

Operating the complete chain

DEPFET Active Pixel Detector

DEPFET LC prospects

TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 6, NO. 1, SEPTEMBER 2010 1

DEPFET active pixel detectors for a future linear e^+e^- collider

The DEPFET collaboration
(www.depfet.org)
O. Alonso, R. Casanova, A. Dieguez, J. Dingfelder, T. Hemperek, T. Kishishita, T. Kleinohl, M. Koch, H. Krüger, M. Lemarenko, F. Lütticke, C. Marinas, M. Schnell, N. Wermes, A. Campbell, T. Ferber, C. Kleinwort, C. Niebuhr, Y. Soloviev, M. Steder, R. Volkenborn, S. Yaschenko, P. Fischer, C. Kreidl, I. Peric, J. Knopf, M. Ritzert, E. Curras, A. Lopez-Virto, D. Moya, I. Vila, M. Boronat, D. Esperante, J. Fuster, I. Garcia Garcia, C. Lacasta, A. Oyanguren, P. Ruiz, G. Timon, M. Vos*, T. Gessler, W. Kühn, S. Lange, D. Münchow, B. Spruck, A. Frey, C. Geisler, B. Schwenker, F. Wilk, T. Barvich, M. Heck, S. Heindl, O. Lutz, Th. Müller, C. Pulvermacher, H.J. Simonis, T. Weiler, T. Krausser, O. Lipsky, S. Rummel, J. Schieck, T. Schlüter, K. Ackermann, L. Andricek, V. Chekelian, V. Chobanova, J. Dalseno, C. Kiesling, C. Koffmane, L. Li Gioi, A. Moll, H. G. Moser, F. Müller, E. Nedelkovska, J. Ninkovic, S. Petrovics, K. Prothmann, R. Richter, A. Ritter, M. Ritter, F. Simon, P. Vanhoefer, A. Wassatsch, Z. Dolezal, Z. Drasal, P. Kodys, P. Kvasnicka, J. Scheirich

supporting paper
in IEEE TNS

ILC newsline
December 2012

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LC NEWSLINE
THE NEWSLETTER OF THE LINEAR COLLIDER COMMUNITY

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Hiking like an electron
Impressions from Hamburg
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CALENDAR

AROUND THE WORLD

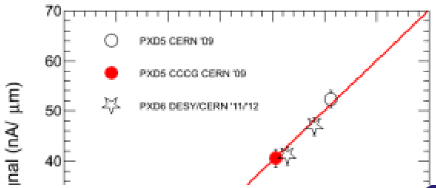
DEPFET active pixel detectors for the linear collider

Marcel Vos reports on behalf of the collaboration

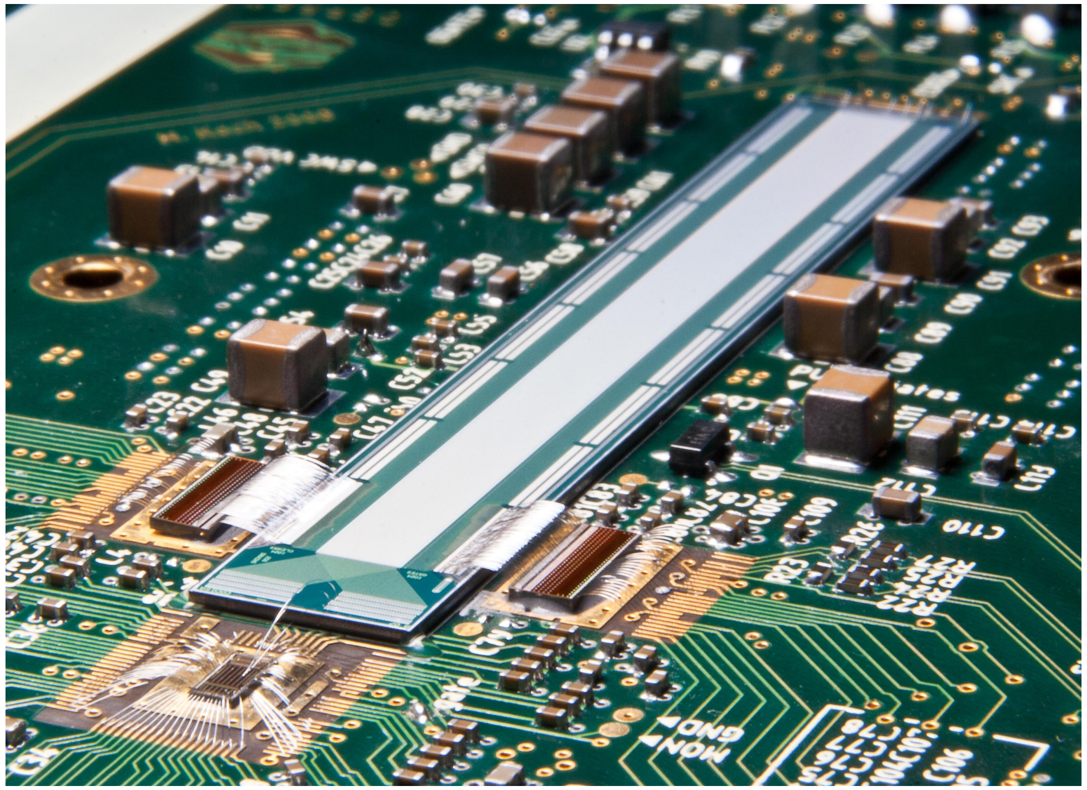
Share |

24 January 2013

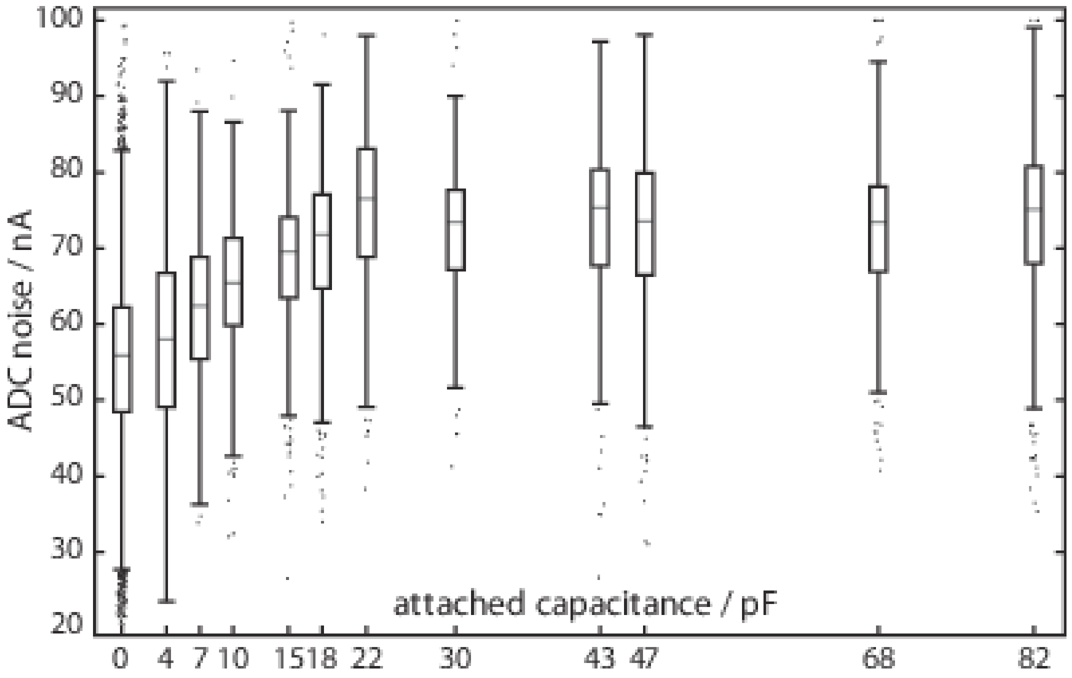
Solid-state devices for charged particle tracking proved their value in high energy physics in the most internal layers of the experiments of the Large Electron Positron Collider LEP at CERN, where they provided precise information on the production vertex of charged particles. These silicon micro-strip detectors consisted of a thin reverse-biased *pn*-junction segmented in narrow strips, each of which was read-out by an amplifier and analog-to-digital converter on a read-out ASIC. After a rapid evolution fueled



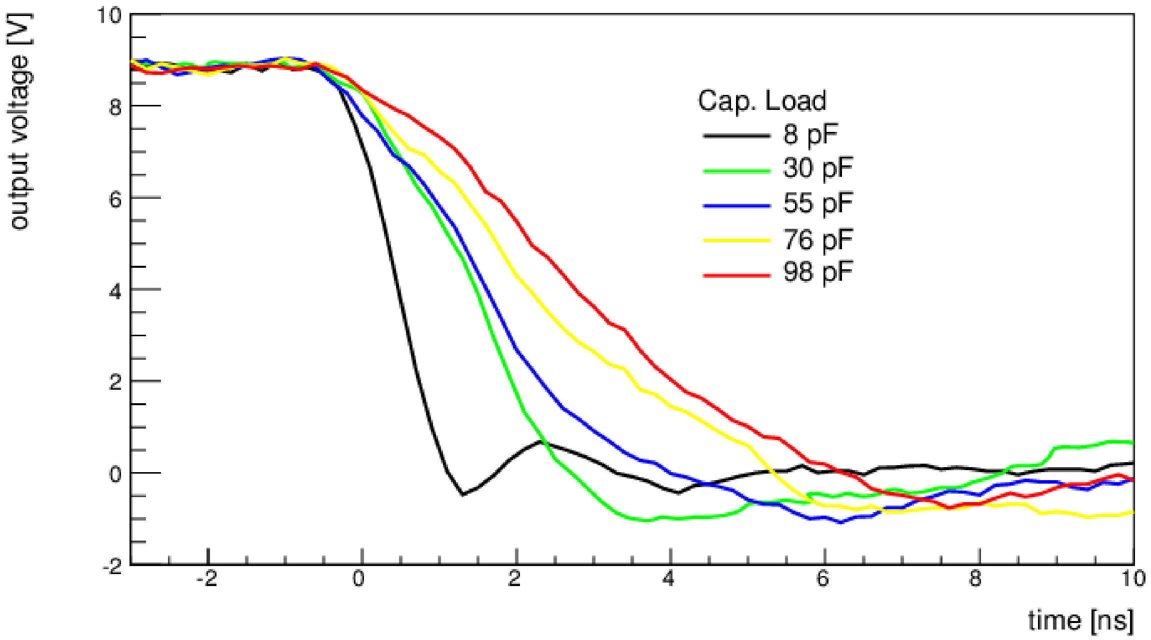
ASIC performance



Can now base LC prospects
on measurements

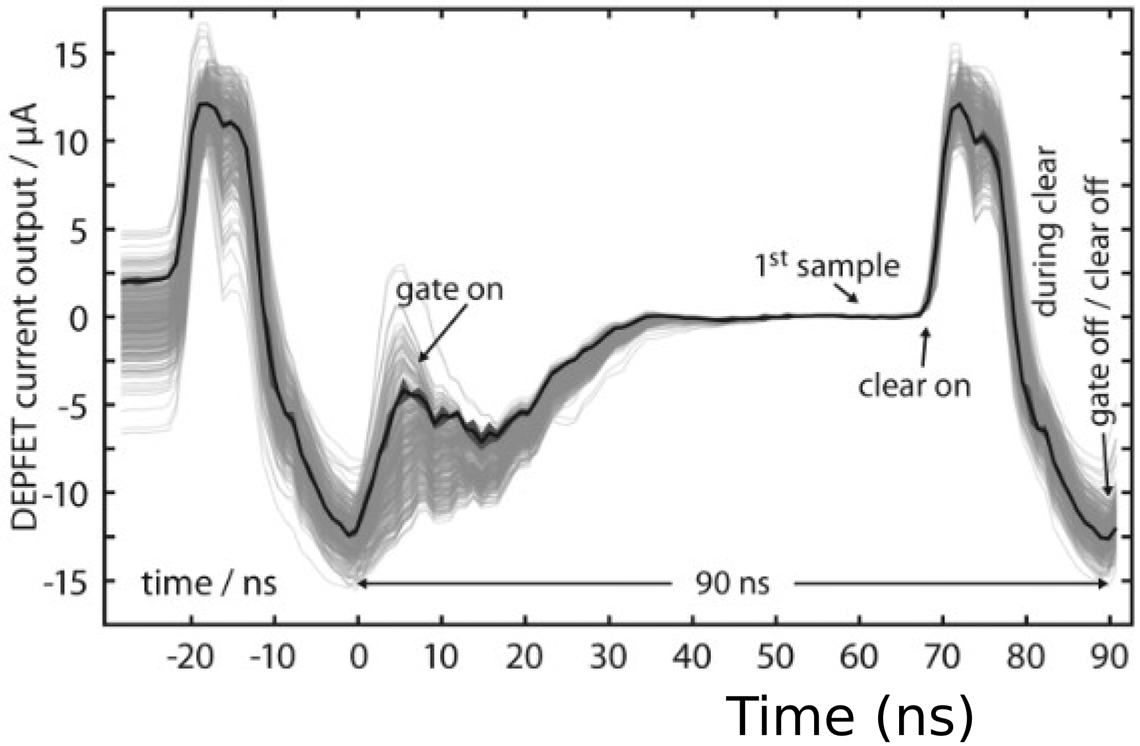


Noise of the FE chip (DCD) versus capacitative load



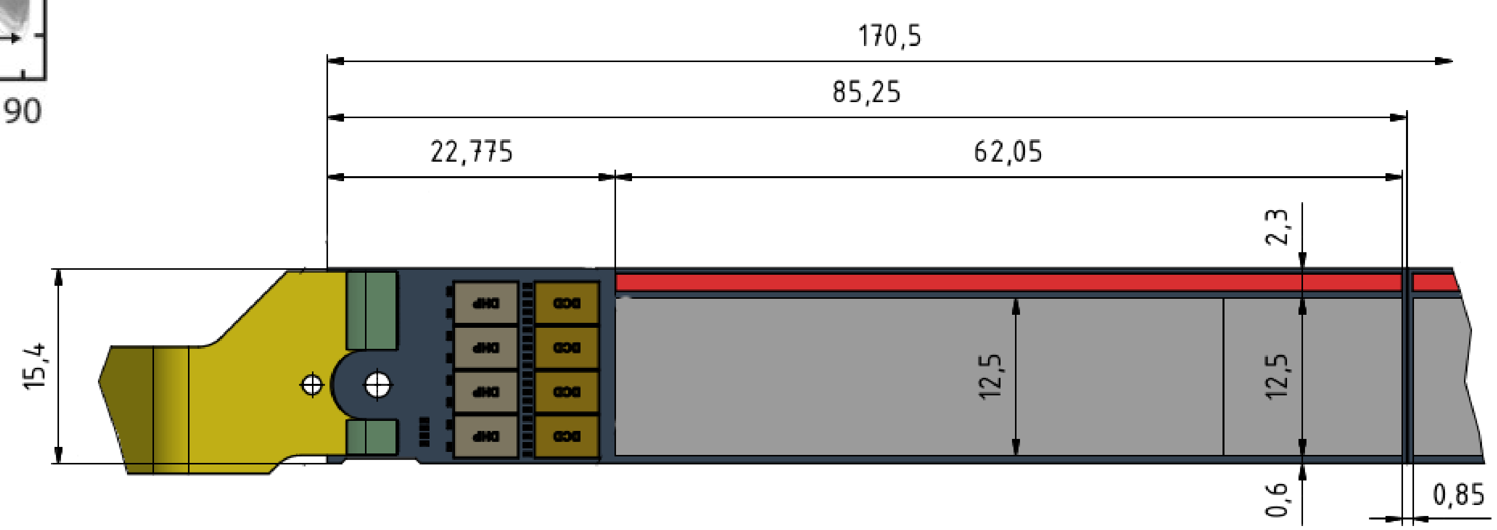
Clear pulse from Switcher

DEPFET @ LC - barrel



Read-out speed: current state-of-the-art allows for a row rate of 1/100 ns. Room for improvement.

VXD0 → 12.5cm long barrel layer with read-out ASICs on both ends.



Pixel size:

Center (|z|<1) → 25 x 25 μm^2

1 <|z|< 2 cm → 25 x 50 μm^2

|z| > 2 cm → 25 x 100 μm^2

Column depth: *1025 pixels/half-ladder*

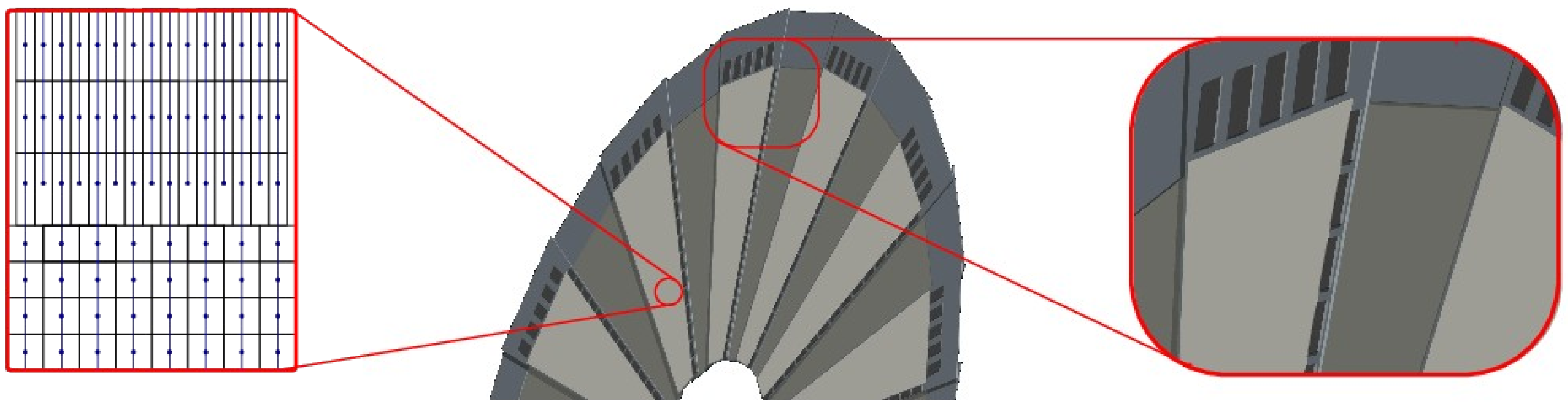
Multiplexing: *2 (4) rows sampled in //*

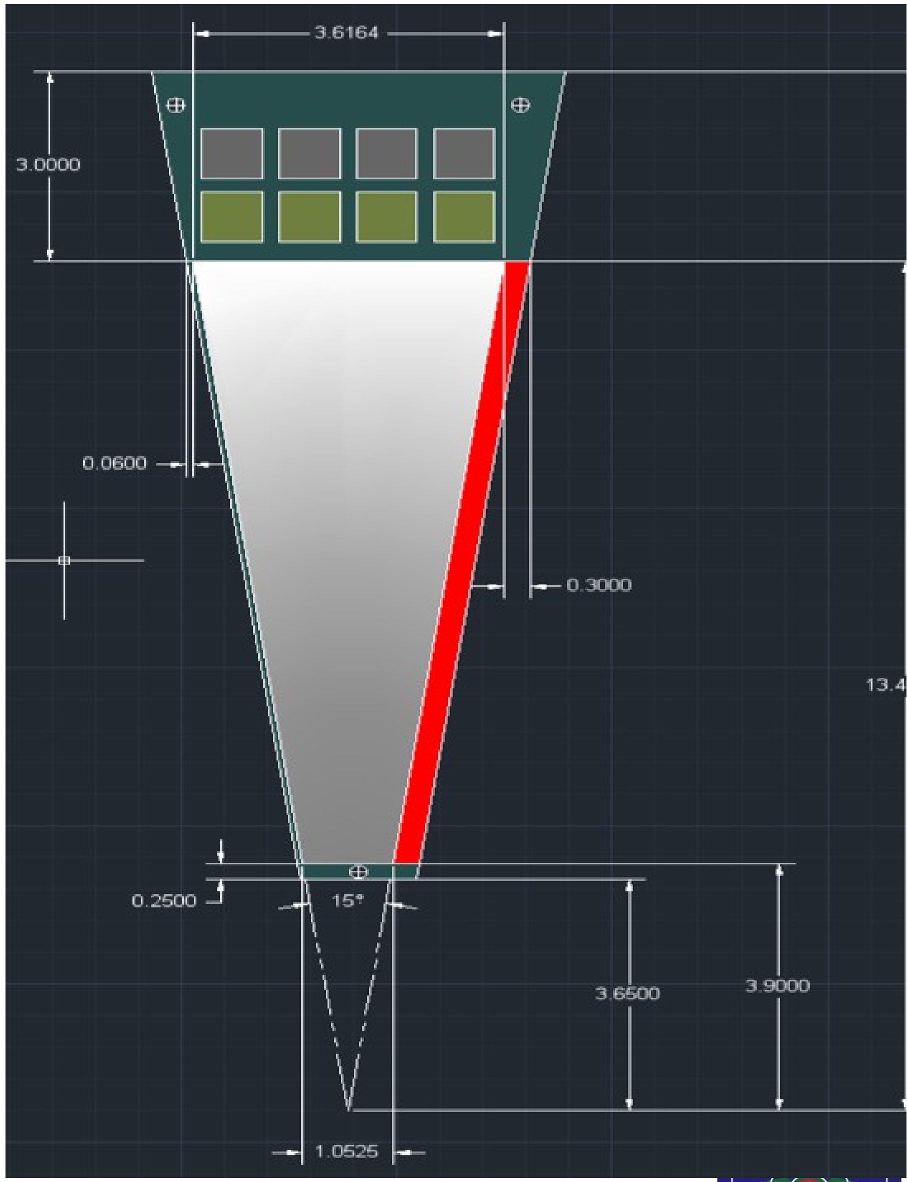
Row rate: *1/80 ns*

Frame time: *40 μs (20 μs)*

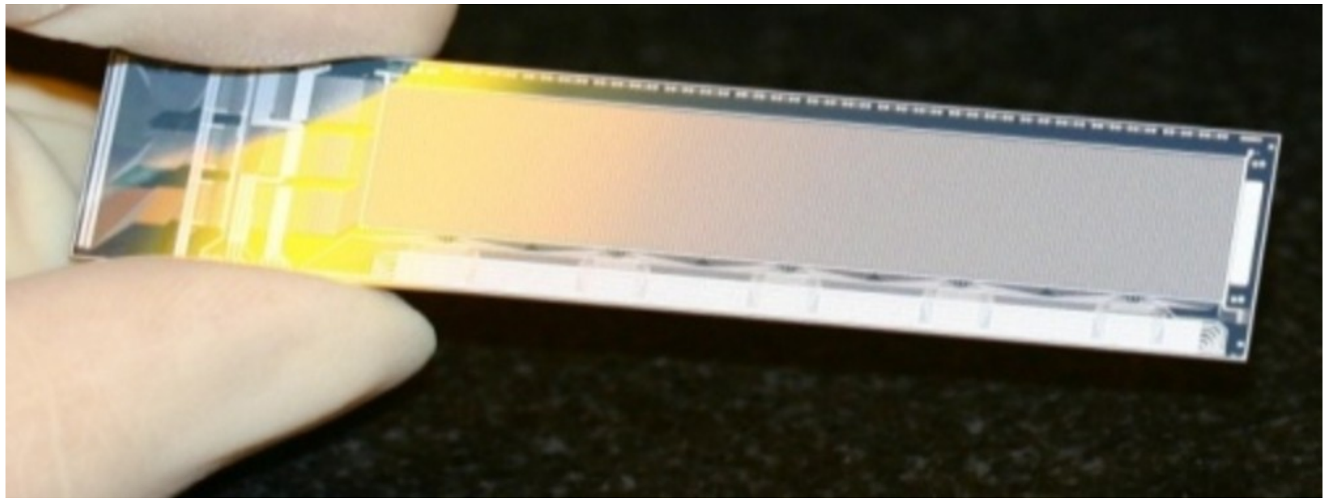
DEPFET @ LC disks

- LC detector concepts require pixelated disks
  - → vertex detector end-cap in SiD, Forward Tracking Disks in ILD
  - → adapt DEPFET all-Si “ladder” design to “petal” geometry





- Woking on fully engineered design + mock-up
- Hoping to learn:
  - *Sensor: feasibility of layout with variable pitch & length*
  - *Ancillary: length of switcher lines, load on DCD...*
  - *Mechanics: self-supporting frame*
  - *Cooling: air flow through disks*
  - *Physics: assess performance of this design*

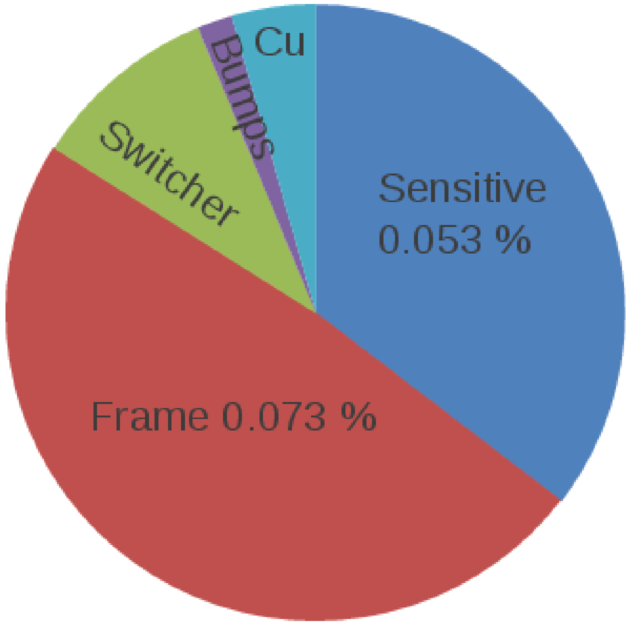


Material budget

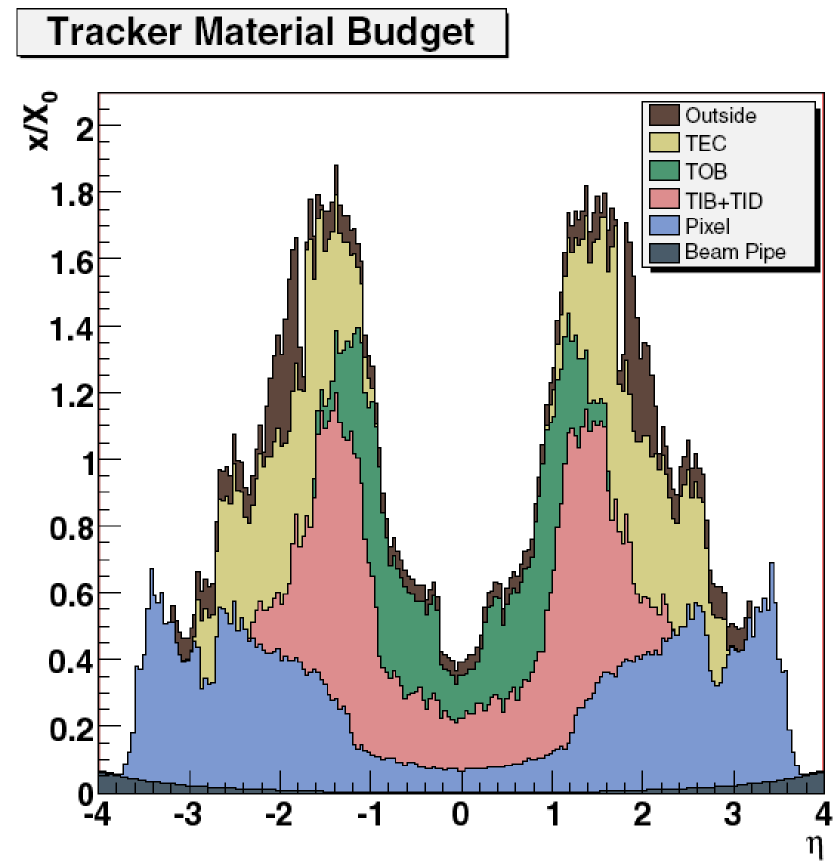
Integrate!

- *Amplification stage in sensor*
- *Support structure in sensor*
- *Signal and power lines on sensor*
- *Electronics on sensors*

Material budget close to LC goal!!!



Sensitive	0.053 % X_0
Frame	0.073 % X_0
Switcher	0.015 % X_0
Cu layer	0.007 % X_0
Bumps	0.003 % X_0
Total ladder	0.15 % X_0

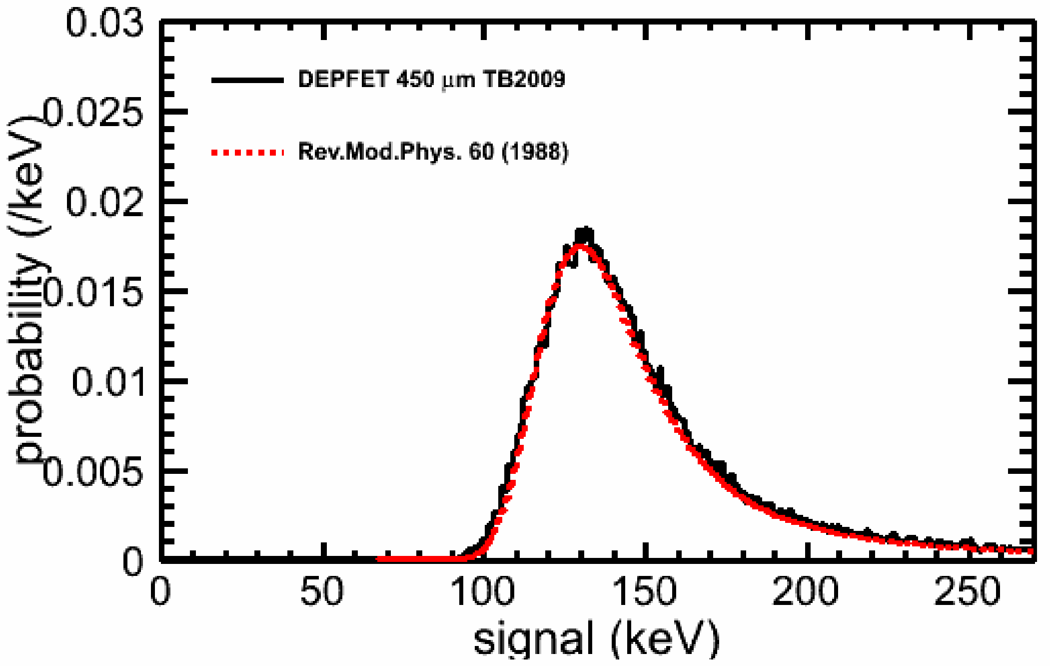


Big leap wrt to LHC...

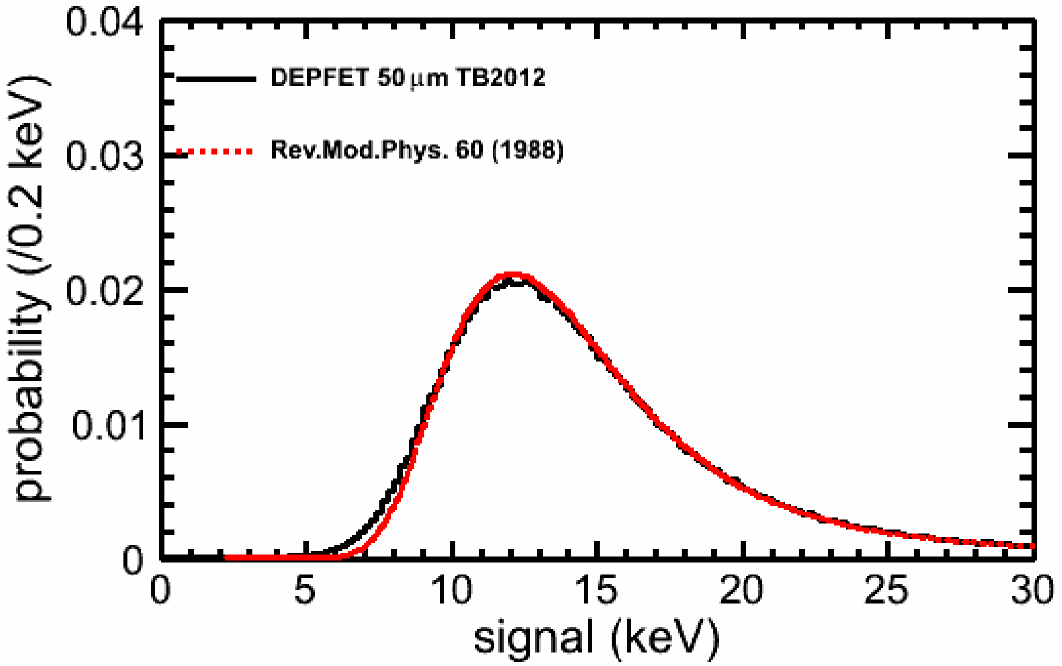
Admittedly not a fair comparison

DEPFET
Active Pixel Detector

Test beam measurements



450 μm thick prototype
with 20x20 μm2 pixels
Slow (CURO) read-out
S/N ratio = 130-200



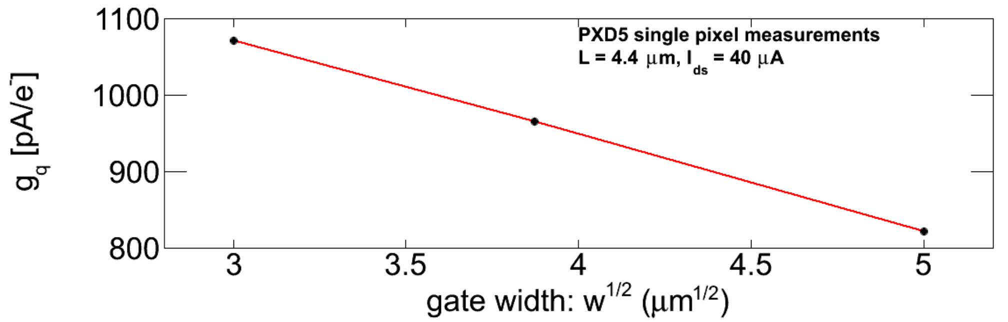
50 μm thick prototype
With 50x75 μm2 pitch
Close to final (DCDB) read-out
S/N ratio = 20-40

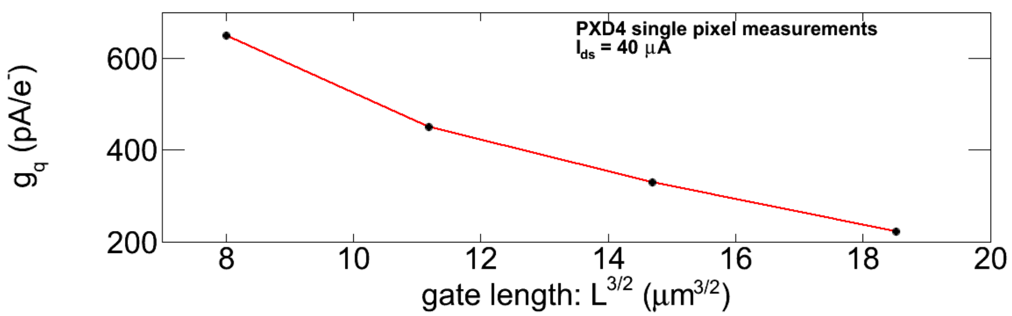
A major milestone for the Belle II and LC projects

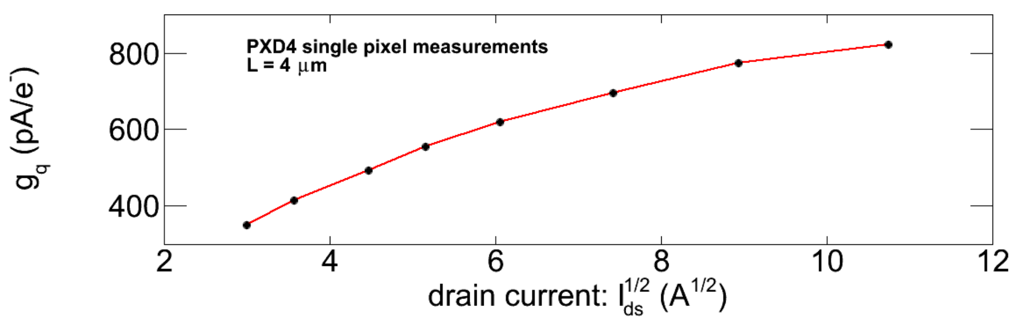
Excellent agreement with straggling model by H. Bichsel
up to several times the Most Probable Signal
Width of distribution due to “Landau” fluctuations
correctly predicted

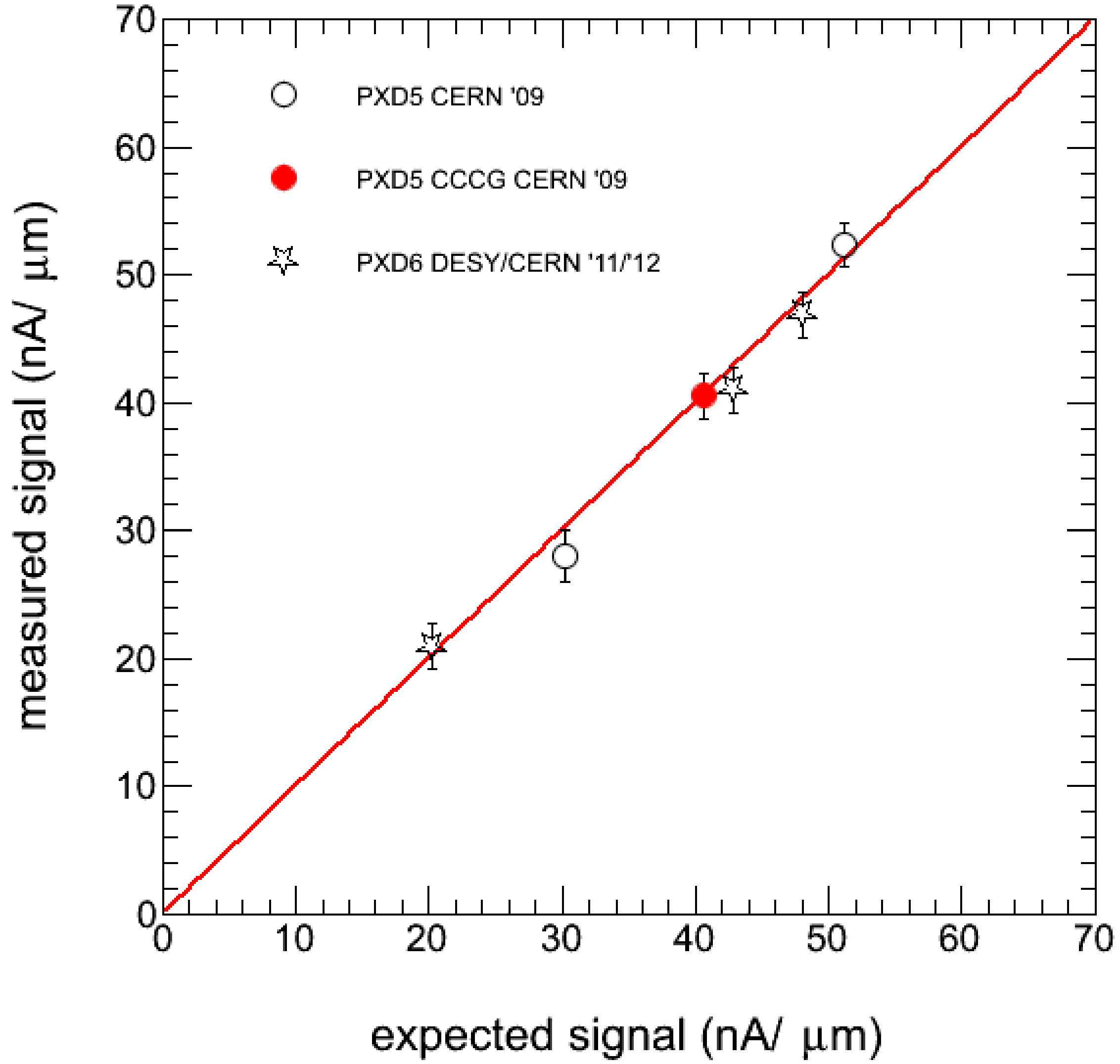
Internal amplification

A key DEPFET parameter:
Larger g_q → higher S/N
→ thinner sensor









4 years of gain measurements on many different sensor designs

Spatial resolution – perp. incidence

450 μm thick DEPFET sensors have registered a resolution for perpendicularly incident minimum ionizing particles (120 GeV pions) of approximately **1 μm**

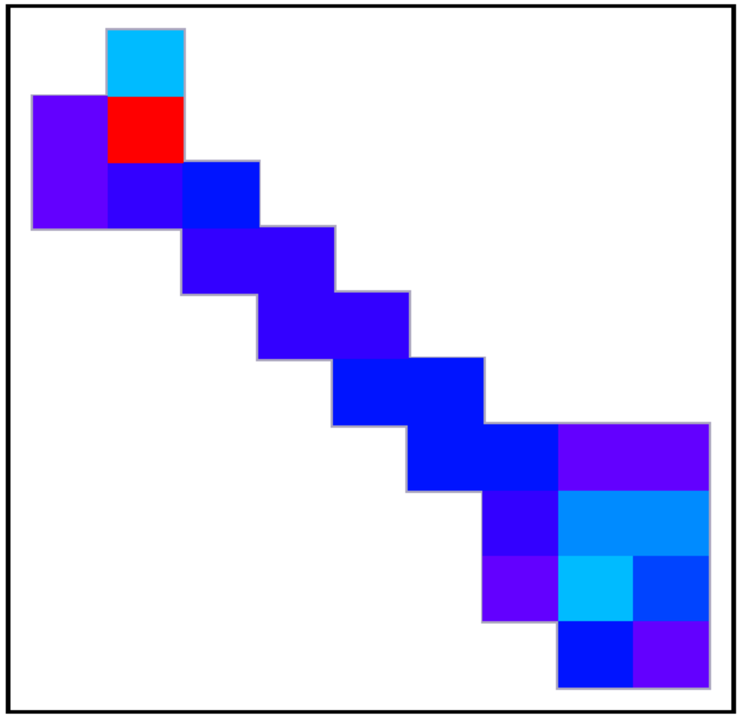
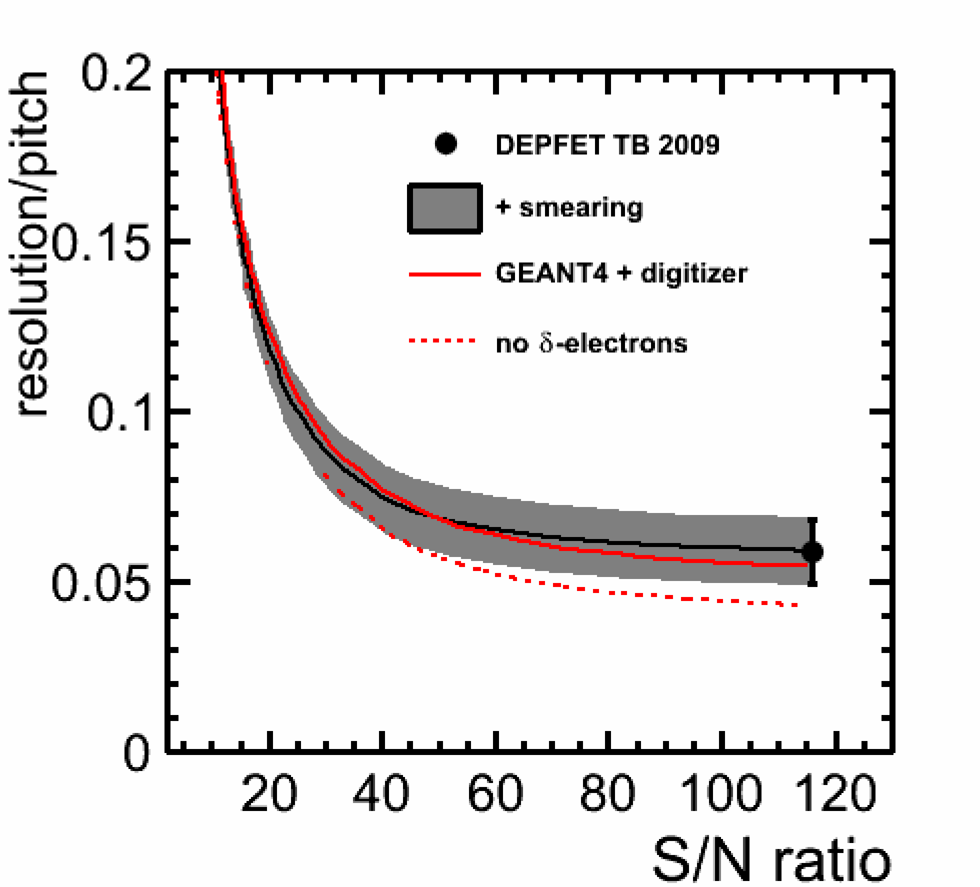


Image of a δ electron captured in a DEPFET beam test

Questions: *Is that what we would expect?*
What should we do to do better still?

Theory Answer: $\sigma \propto \frac{p}{S/N}$ *(constant depends on charge sharing details)*

Assuming signal distribution is a good measure of particle position

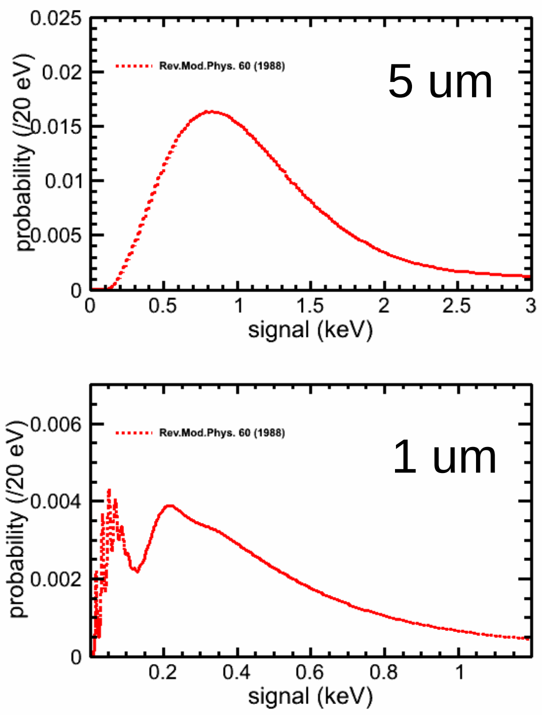


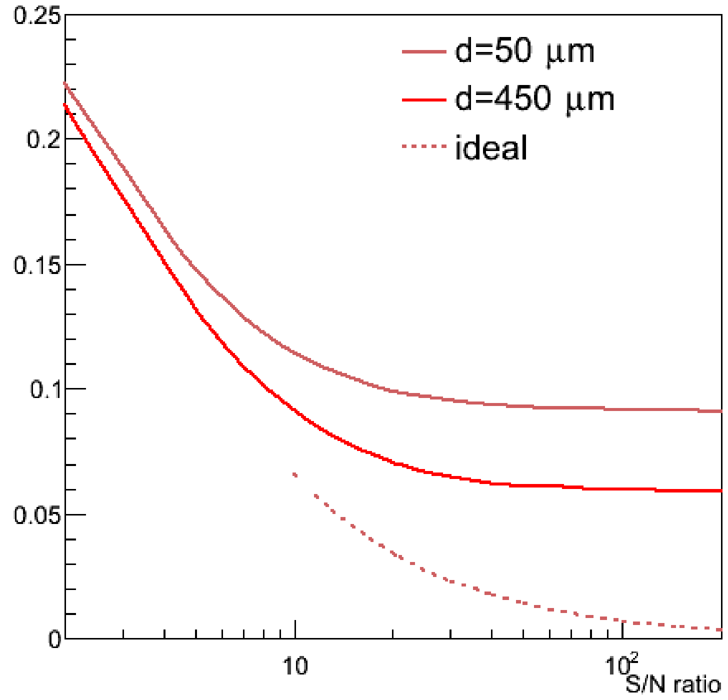
Artificially worsen the S/N ratio by smearing the signal

The spatial resolution "saturates" for very large S/N ratio, at least in part due to δ-electrons

DEPFET Active Pixel Detector

“Landau” fluctuations



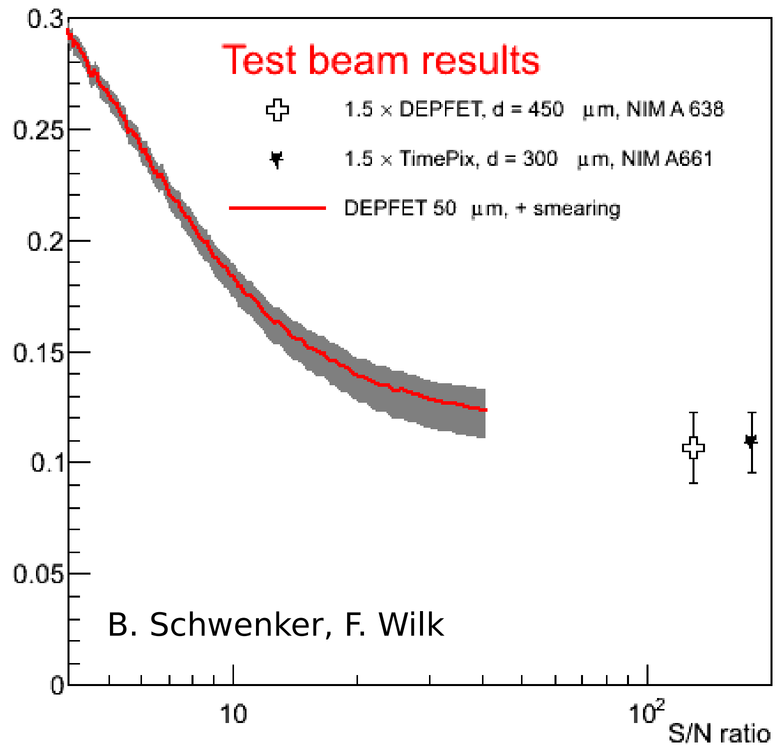


Toy model to propagate fluctuations
to position measurement
M. Boronat (Preliminary)

thin sensors (d=50 um) **σ/p ~ 10%**

thick sensors (d=300-500 um) **σ/p ~ 7%**

Ideal detector (S μ l)



Smearing TB data on 50 μm DEPFET

Fluctuations in signal deposition per unit length of the particle trajectory in silicon limit the resolution.

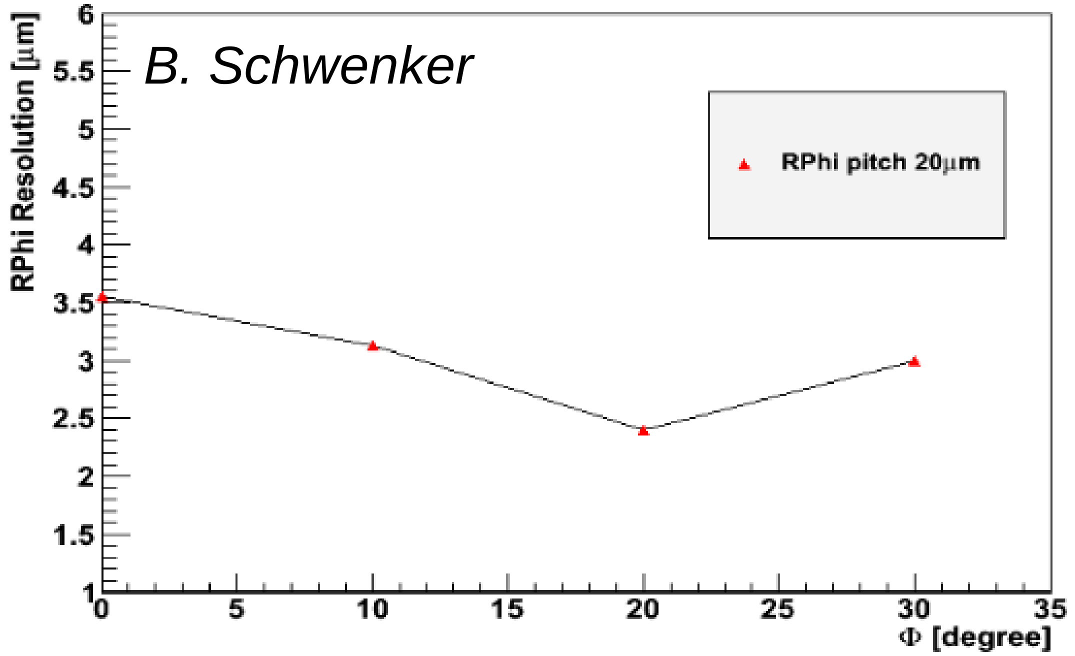
DEPFET
Active Pixel Detector

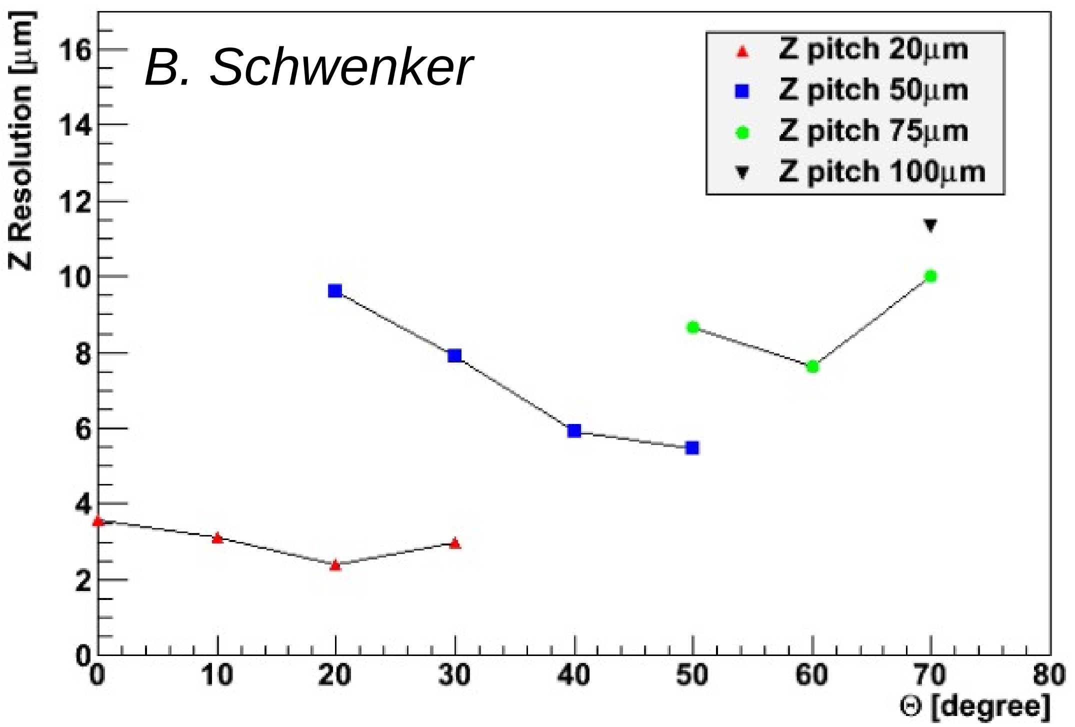
Spatial resolution

Digitizer predictions for LC DEPFET spatial resolution

rϕ-resolution varies between
2.3 - 3.5 μm
(ILD spec. 2.8 μm, SiD 5 μm)

z-resolution is similar for θ < 45°, but a degradation for shallow tracks seems inevitable





DEPFET @ LC: conclusions

The “next big machine” might become a reality in Japan

DEPFET remains a strong candidate for LC vertex detector

- benefit from progress building the Belle II **system**
  - → proof-of-principle for thin sensors
  - → development of complete read-out chain
  - → measurements validate cooling and mechanical concept
- LC prototypes can cope with requirements
  - → small-pixel: 20 x 20 μm^2
  - → 2-4 μm spatial resolution
  - → read-out speed: 40 μs/frame for ILD layer 1
  - → ladder material ~ 0.15% X_0, close to LC specification

- Learnt something about limitations of spatial resolution along the way

- next generation of LC prototypes expected soon
- petal design for disks underway

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