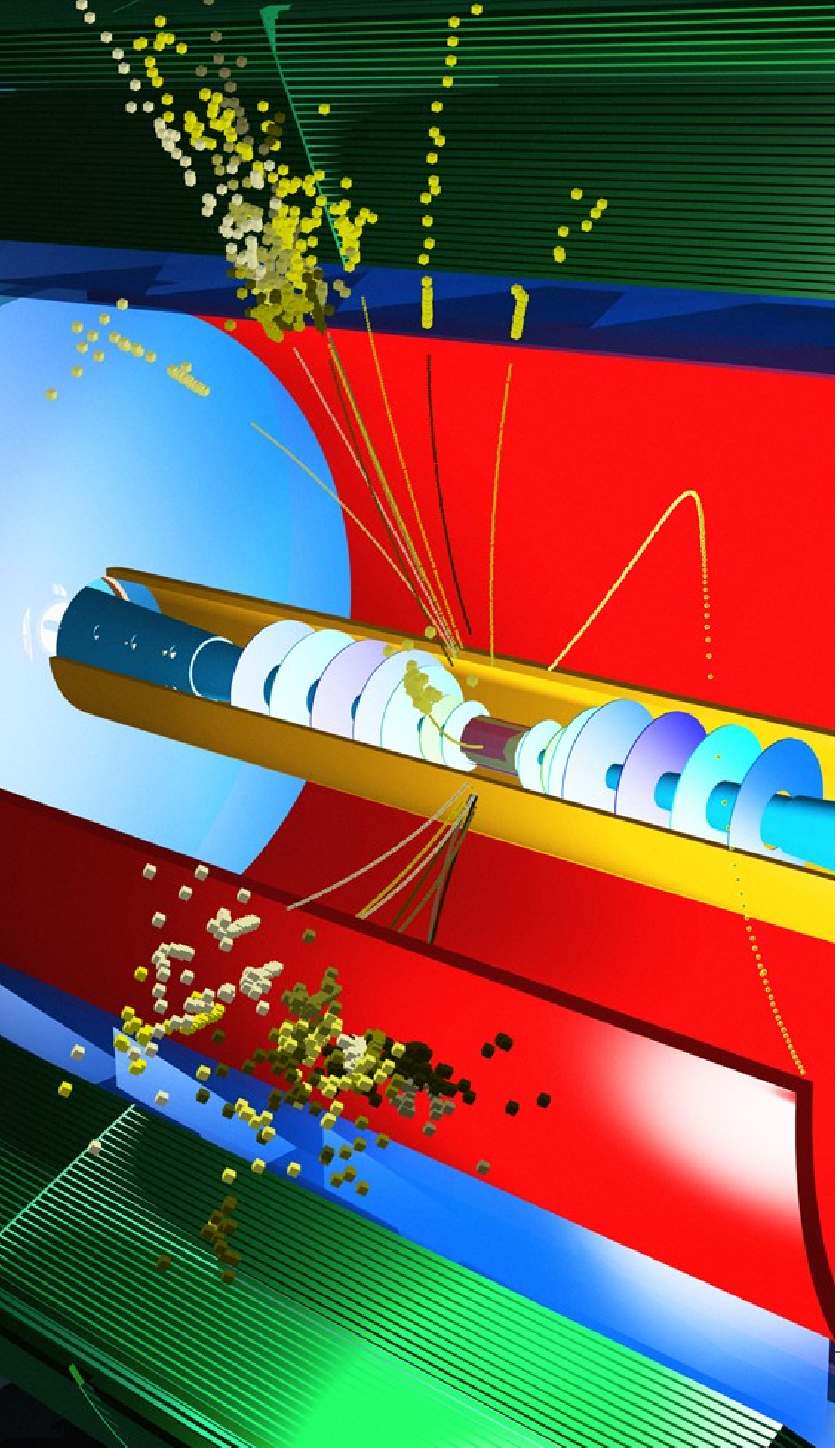


# DEPFET for energy-frontier electron-positron colliders;

***status of the $e^+e^-$ projects,***
***specific DEPFET LC activities***

**19th International workshop**
**on DEPFET detectors and applications**
**Kloster Seeon, May 2015**

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

# The $e^+e^-$ precision physics programme

**A complete $e^+e^-$ physics programme 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, $\tau$

**345-355 GeV *top threshold scan***

– Precise top quark mass (width, $\alpha_s$ and top Yukawa coupling)

**500 GeV *(nominal ILC energy)***

– Precise electroweak top couplings

**1 TeV *(ILC energy upgrade)***

– *Higgs self-coupling*

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

# The energy-frontier landscape

A lot of projects for electron-positron colliders that can probe Higgs and top

ILC – Japan
31 km – 500 GeV – 1 TeV
TDR 2012: shovel-ready
Physics by 2027

CLIC – CERN
31 km – 2-3 TeV
CDR 2014

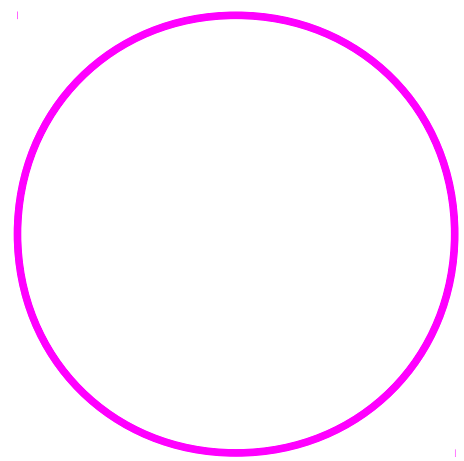
*CLIC two-beam scheme, with a gradient of 100 MV/m, allows greater energy reach with similar footprint*

CEPC – China

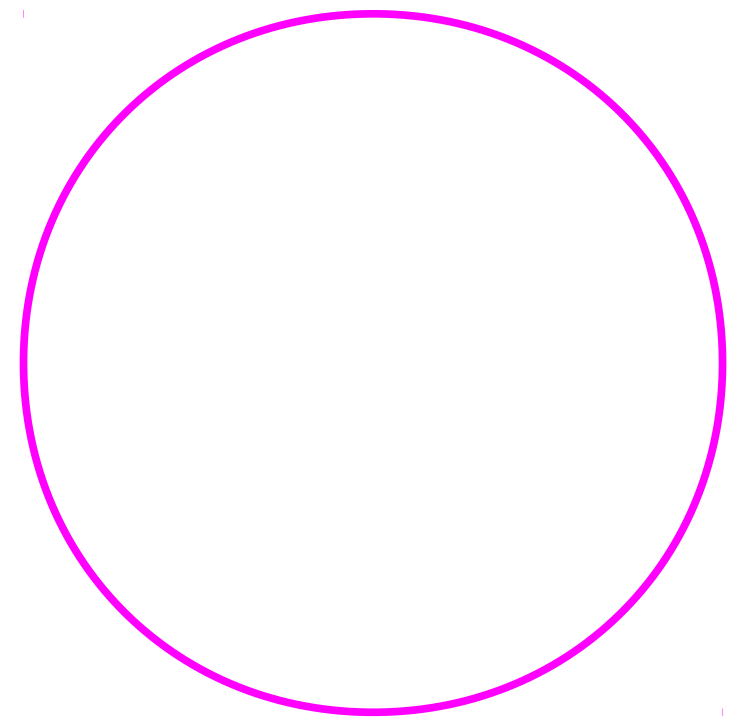
50 km – 250 GeV

Pre-CDR 2015

Physics by 2027?

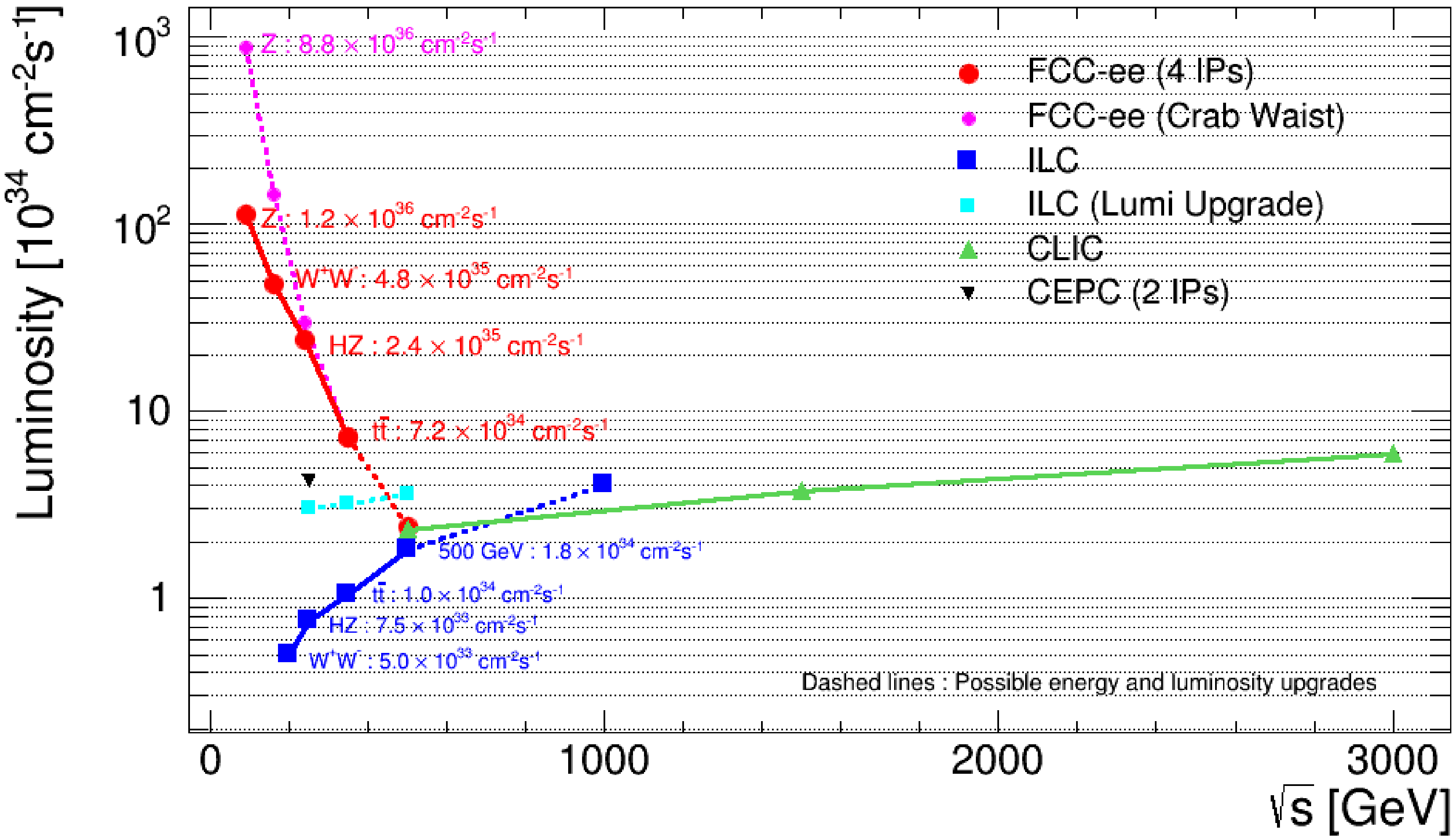


FCC-ee – CERN
80-100 km – 365 GeV
No estimate for a date



*Both circular tunnels to be used also for a hadron collider machine*
*China has indicated it will start with electron-positron collisions*

# Lepton collider complementarity




*Trust the slopes as indicative of "typical" machines, don't trust the normalization at all*

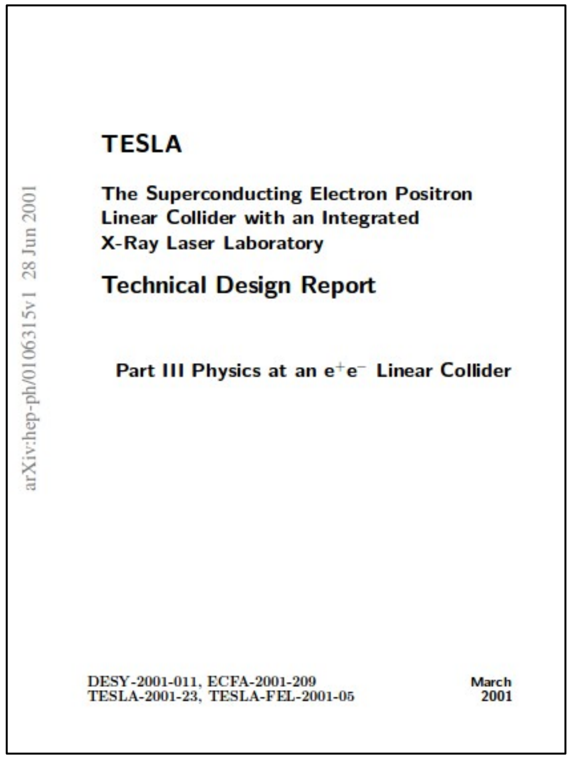
*Machines live on different time lines*

## Circular vs. linear

- **Circular colliders:** high luminosity at not-too-far-above LEP energies is great for Higgs-strahlung production (~250 GeV), but synchrotron radiation limits energy reach (365 GeV for FCC-ee, ~250 GeV for CEPC)
- **Linear colliders:** running at 350 GeV – 1 TeV allows to access vector boson fusion Higgs production, and to measure the top Yukawa and Higgs self-couplings. Multi-TeV operation in case of new discoveries.

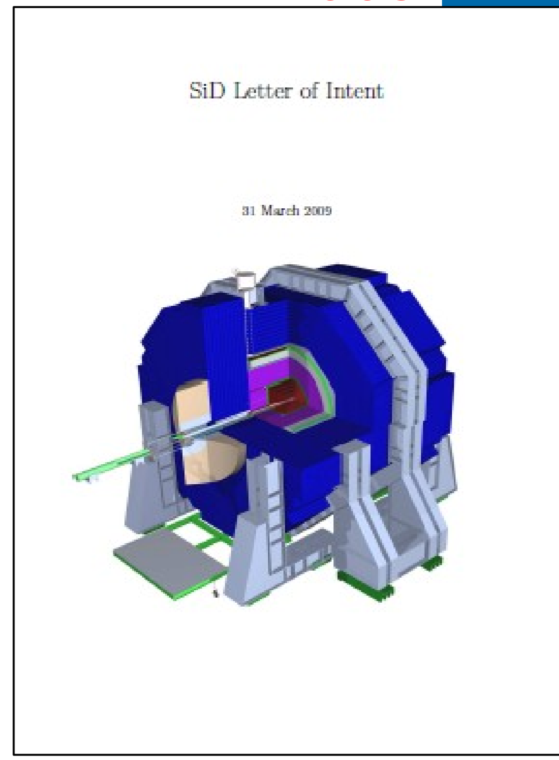
# LC history

2001

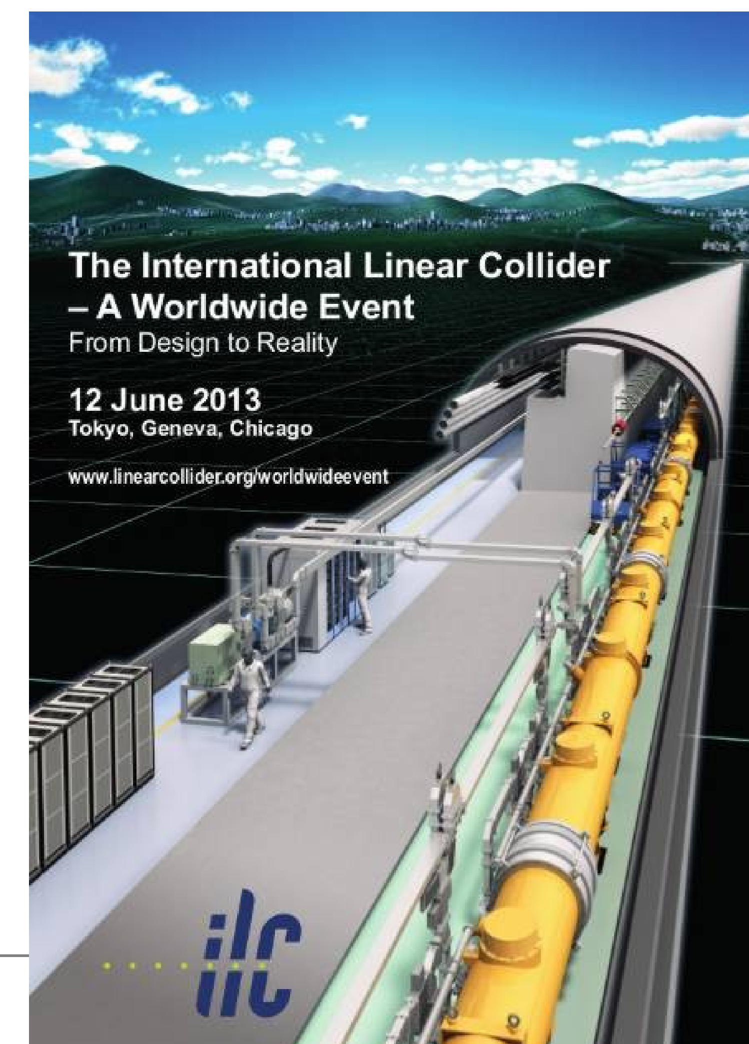



...

2009







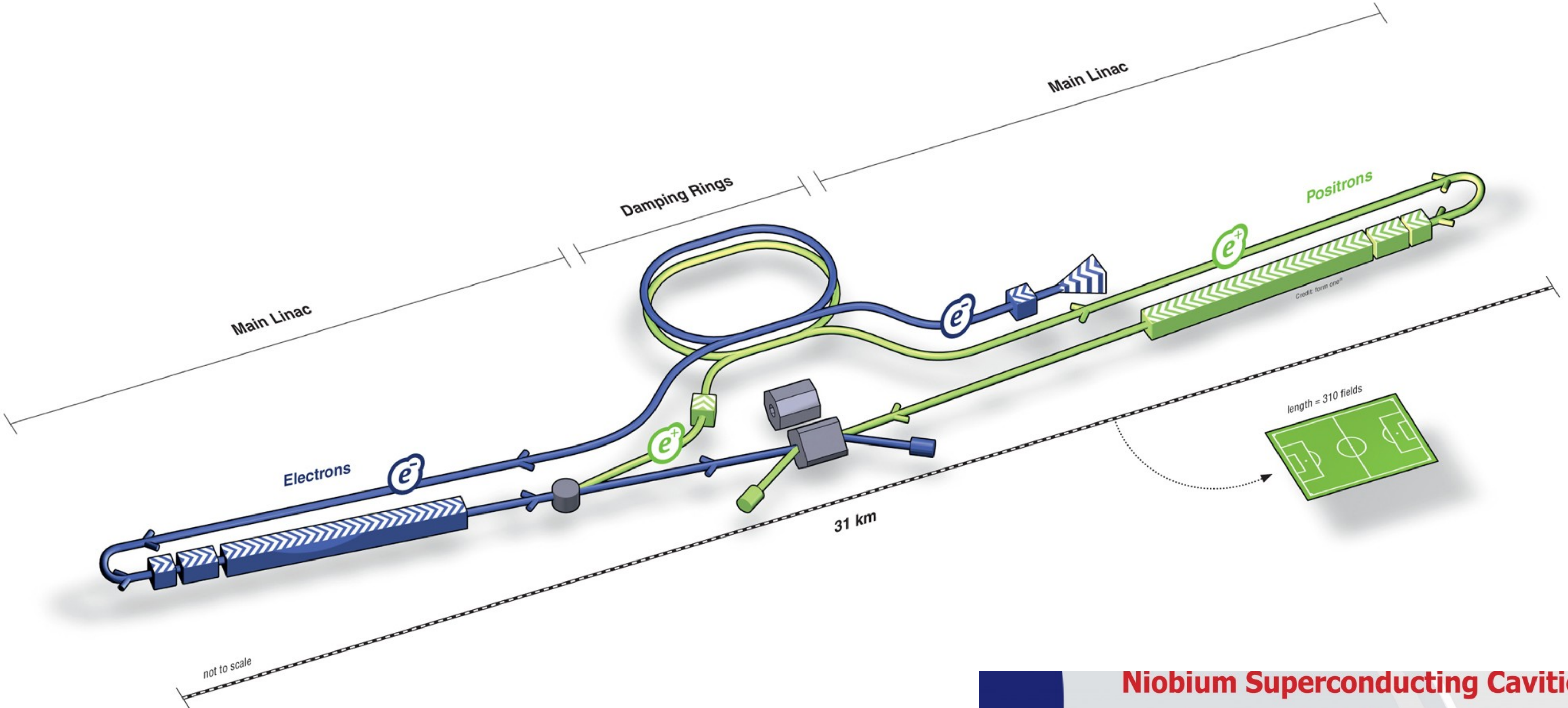

## Reference documents:

- 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
- June 2013: ILC TDR
- Includes: Detailed Baseline Design for the ILC experiments

**TDR marks milestone for R&D on ILC machine.**

*“The ILC design is much more mature than the LHC was when it was approved”, Lyn Evans*

# The International Linear Collider

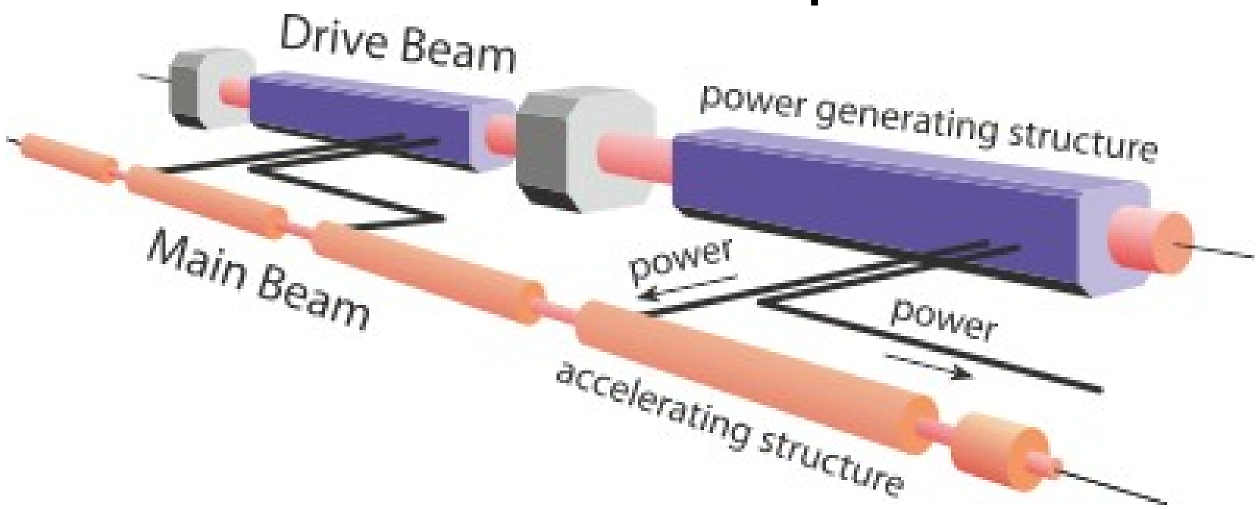



Superconducting RF cavity with required 30 MV/m gradient
Complete cryomodules have been built in several places
Production deployed in industry (Germany, US, Japan, China)
ATF2@KEK Has demonstrated nm size, low emittance beams

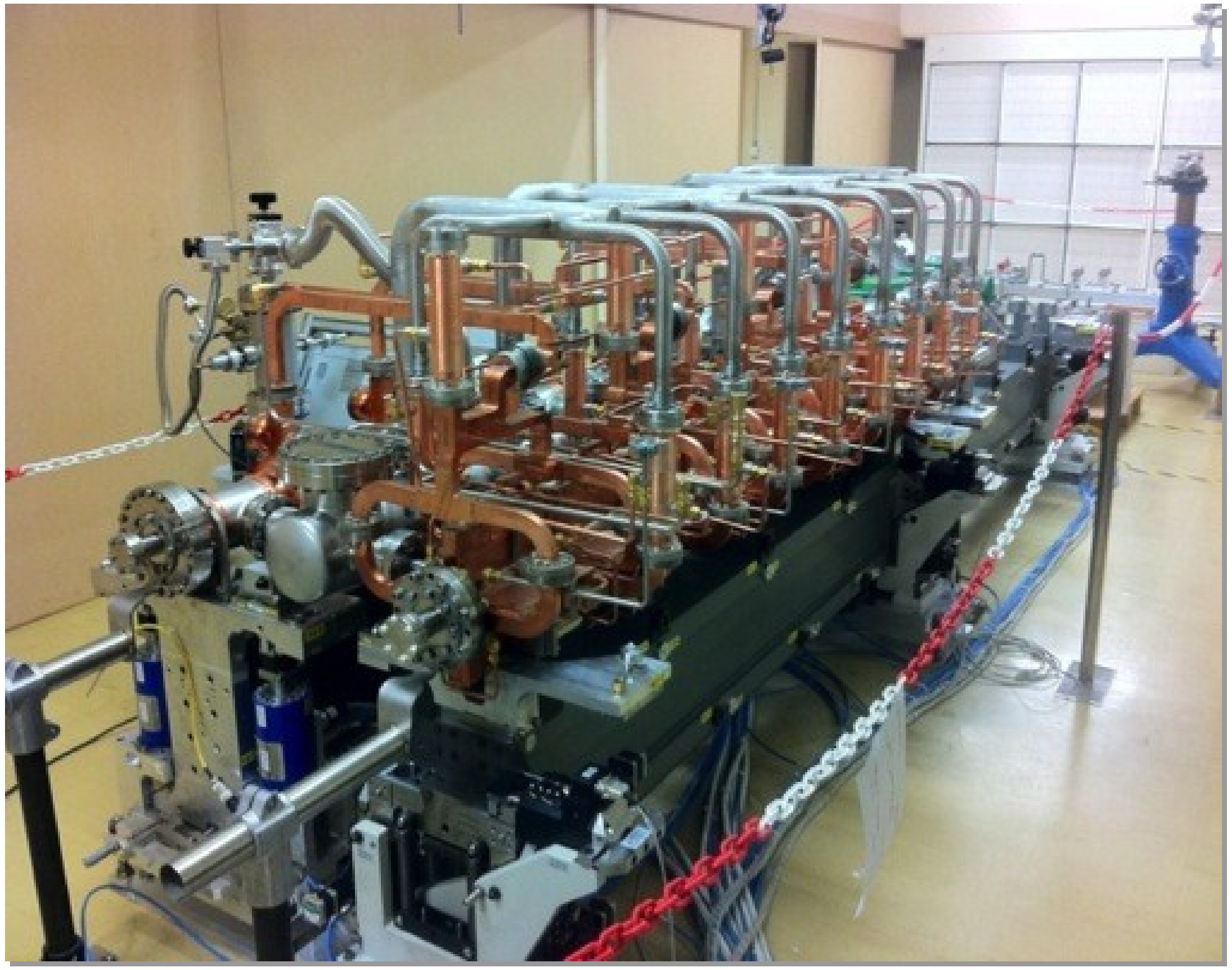

XFEL@DESY: a 10% prototype
ILC is shovel-ready!

# The Compact Linear Collider

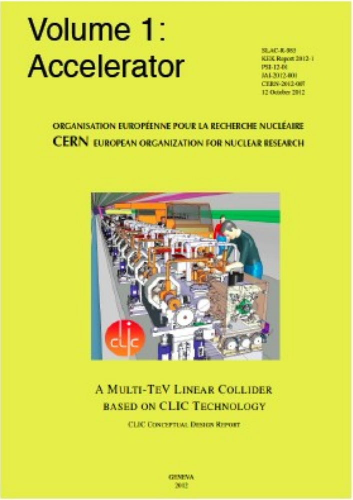
CLIC two-beam acceleration is currently the only mature scheme to build a multi-TeV lepton collider...



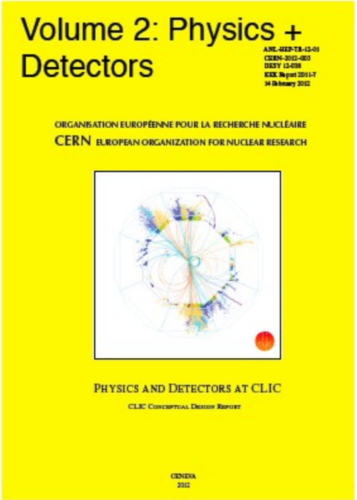

... unique role in the lepton collider landscape



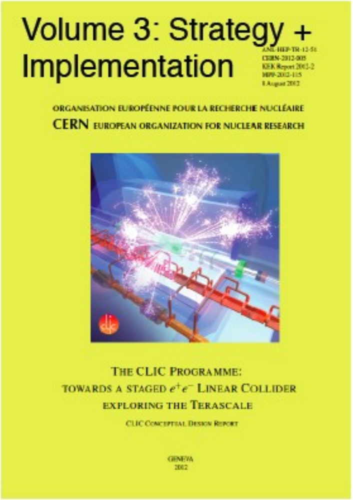
Proof of concept in Conceptual Design Report in 2012




CERN-2012-007




CERN-2012-003




CERN-2012-005

# World-wide strategy

**Japan**
"*We will call for inter-governmental negotiations with European and American governments in the first half of 2013*", Minister Shimomura (MEXT)
*Kitakami site in Tohoku, North Japan selected in August 2013*

**AsiaHEP/ACFA (September 2013) Asia ≠ Japan**
*"AsiaHEP/ACFA believes that the ILC is the most promising electron positron collider to achieve next generation physics objectives […] AsiaHEP/ACFA welcomes the proposal by the Japanese HEP community [...and] looks forward to a proposal from the Japanese Government to initiate the ILC project [...]"*

**European Strategy (Cracow 2012, approved by CERN council)**
*"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. […] The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation."*

**American Strategy (Snowmass 2013)**
P5 (particle physics project priorization panel)
*"The interest expressed in Japan in hosting the International Linear Collider (ILC) is an exciting development. Participation by the U.S. in project construction depends on a number of important factors, some of which are beyond the scope of P5 and some of which depend on budget Scenarios. As the physics case is extremely strong, all Scenarios include ILC support at some level through a decision point within the next 5 years."*

**Scientists have defined our roadmap. Now move over to political level:**

Japanese science ministry (MEXT) has created a committee to evaluate impact of the project (social, economic and scientific) on Japan – interim report this summer

High-level negotiations with US are ongoing (at a less advanced stage in Europe)

Some level of discussion between China and Japan

# ILC progress – the Tokyo statement


At the ILC Tokyo Symposium, held on 22 April 2015 at the Ito International Hall, Tokyo, Japan, the Linear Collider Collaboration (LCC) and the participants around the world at the Asian Linear Collider Workshop (ALCW) 2015 decided to issue a statement confirming their conviction of the scientific justification for a prompt realisation of the International Linear Collider (ILC).

1) The ILC's role in particle physics is to explore with exquisite detail the time just after the beginning of the Universe. This research is unique and indispensable for adeep understanding of how our Universe began, how it evolved, and how it works today. We are eager to build and work at the facility.

2) The technical feasibility of the ILC has been demonstrated in the Technical Design Report. The ILC is ready to be built following the completion of an engineering-design phase. The project is now in a phase where government involvement should lead to a decision to realize the project. In this context we express our appreciation of the ongoing project assessment being undertaken by the Japanese government.

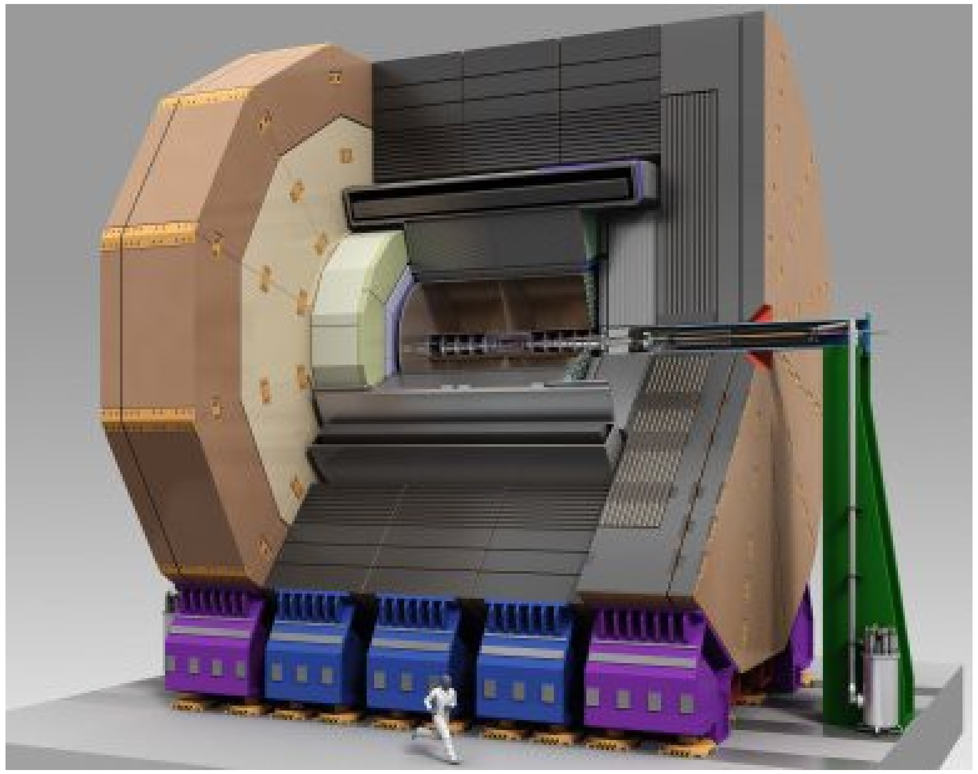
3) The ILC is one of the largest scientific projects ever proposed, on a similar scale to the Large Hadron Collider project and that its realisation as an international project requires the establishment of an international framework for sharing the cost and expertise among countries. We therefore intend to facilitate discussions between governments and funding authorities to achieve this goal as soon as possible.
*Lyn Evans, Director of the LCC, on behalf of the LCC and scientists at the ALCW 2015.*

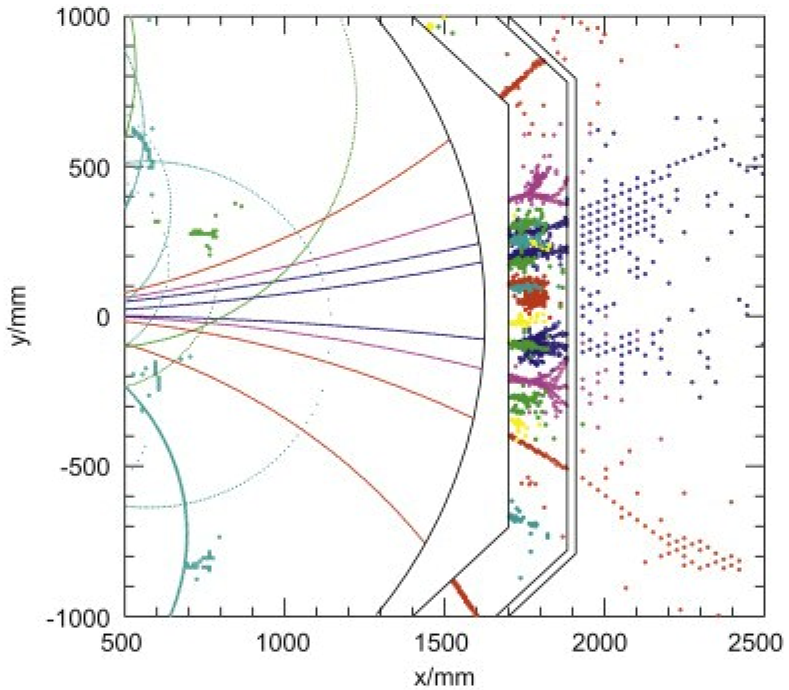
Some pressure on Japanese and international politics to come to a decision soon

# LC detectors

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

- Signal and bkg x-sections of similar magnitude
- Well-defined initial state (CM energy, polarization)
- Background in innermost layers up to 0.1 hits/mm$^2$/BX
- Radiation levels $10^{11}$ - $10^{12}$ n/cm$^2$






**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: ΔE/E~3-5%

**Transparent and precise tracking/vertexing:**

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

# ILC vertex detector

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

**Strongly reduce the multiple Coulomb scattering term**
(0.1 % $X_0$ / layer ~ 100 μm Si)

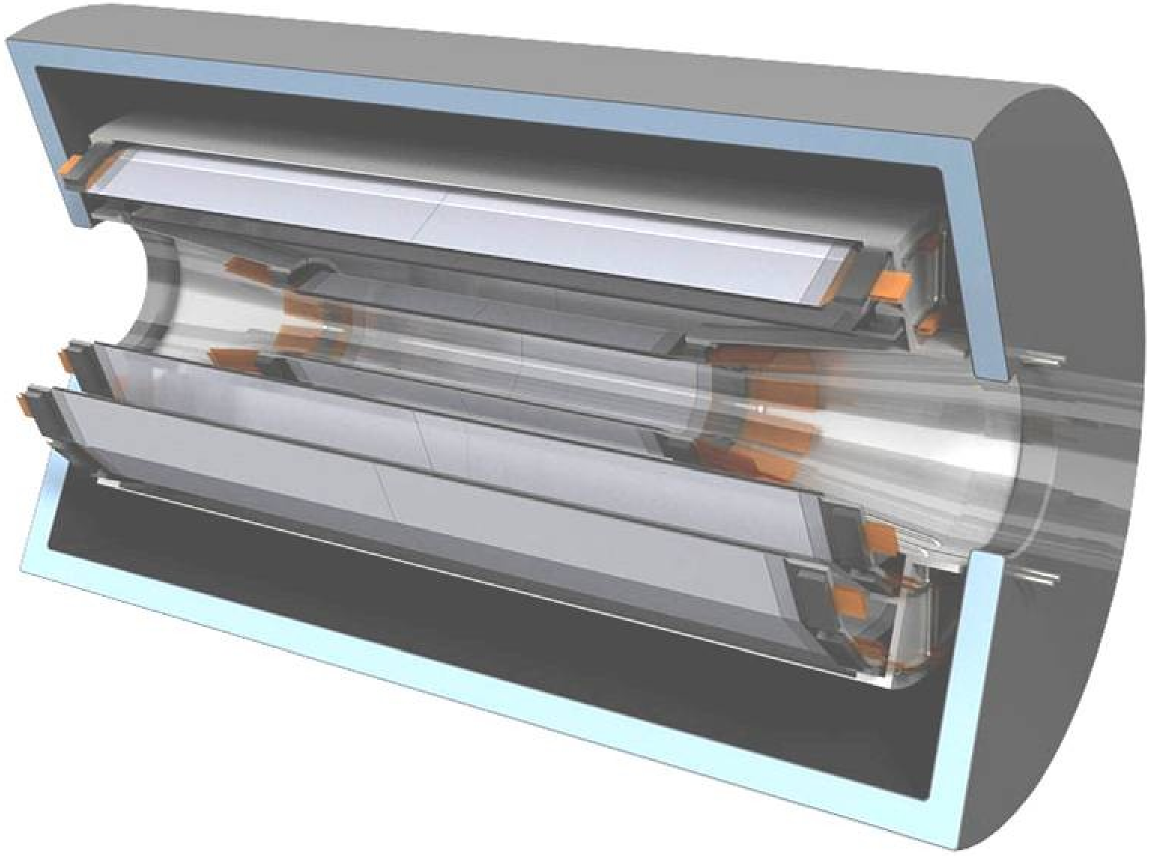
## Vertex detector

Reconstruct primary and secondary vertices,
flavour tagging, bottom/charm separation

Large polar angle coverage

Unprecedented performance:

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



## Stringent requirements

Resolution: 20 x 20 $\mu m^2$

Read-out speed: < 25/100 μs

(down to 500 or even 0.5 ns)

Material: 0.1...% / layer

# Technology options

## ILD (see DBD)

Candidate technologies:

(mature & pursued in ILD)

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

Several alternatives

high-resistivity substrate CMOS sensors

multi-tier 3D pixel sensors.

## SiD (see DBD)

Pushes for 3D integration

single BX (~500 ns) time stamping

Fall-back scenario:

DEPFET, MAPs, FPCCDs

## CLIC (see CDR)

Pushes hybrid solution (TimePix)

10 ns time stamping

## CEPC (see pre-CDR)

fine pitch, low power consumption and fast readout
DC machine, no power-pulsing!!!

DEPFET is mentioned prominently

**Current effort**

Adequate presence in ILD
Essentially no effort in SiD
Some involvement in CLIC
Some interest from CEPC

# DEPFET@ILC publications

Document by LCC detector R&D liaisons will contain ~two pages on DEPFET

DEPFET active pixel detectors for a future linear $e^+e^-$ collider - Report for the ECFA Detector R&D review, DESY, June 2014

The DEPFET collaboration (www.depfet.org)
*E-mail:* marcel.vos@ific.uv.es, cmarinas@uni-bonn.de, chk@hll.mpg.de, lca@hll.mpg.de

ABSTRACT: The DEPFET collaboration develops highly granular, ultra-transparent active pixel detectors for high-performance vertex reconstruction at $e^+e^-$ collider experiments, such as Belle II and a future $e^+e^-$ collider at the energy frontier. In this report, we review measurements on prototypes that prove the potential of the DEPFET operation principle and provide a status report for the development of a complete detector concept, including solutions for mechanical support, cooling, and services. An overview is also given of LC-specific R&D. Based on this experience we revisit the expected performance of a DEPFET-based vertex detector and show that DEPFET can meet the stringent requirements of the detector concepts for a future linear $e^+e^-$ collider.

*ECFA detector R&D panel*
*June 2014*


*ILC newsline*
*December 2012*

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 for ILC TDR*

in IEEE TNS 60, 2 (2012),

still the official source

# ECFA detector R&D review

**Recommendations:**

The DEPFET collaboration has developed a detector ladder that already now meet many ILC requirements.

For the ILC the main challenge is to engineer the forward tracking disk region. We recommend that the work on forward petal continues to demonstrate that petals that meet ILC requirements can be made... that more effort is made on the transition and forward regions to find a credible engineering solution taking into account mechanics, cooling and services.

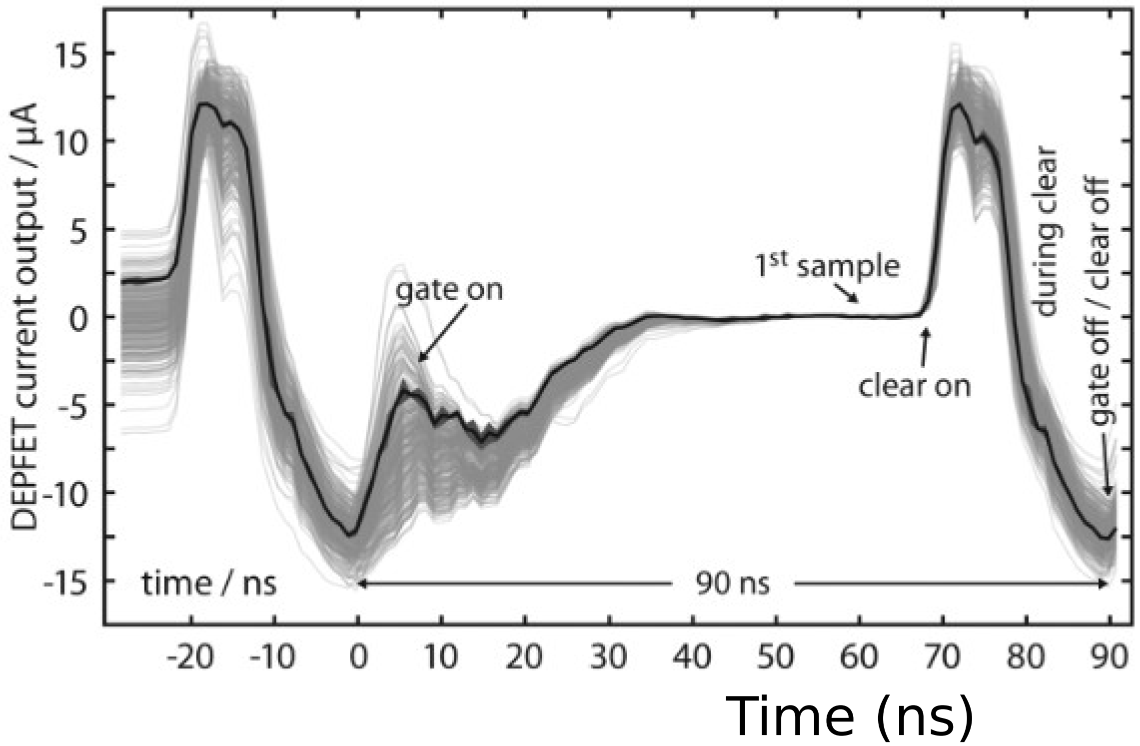
The work on micro-channel cooling can profit from collaboration with other groups doing the same development. → AIDA2020 WP9

The ILC tracker is significantly larger than the Belle II vertex detector and the all-silicon ladder requires a very sophisticated fabrication process with many processing steps. → yield for Belle II

Not all issues for ILC will be addressed in the Belle II development hence additional support will be needed for developing the DEPFET technology for use in an ILC tracker.

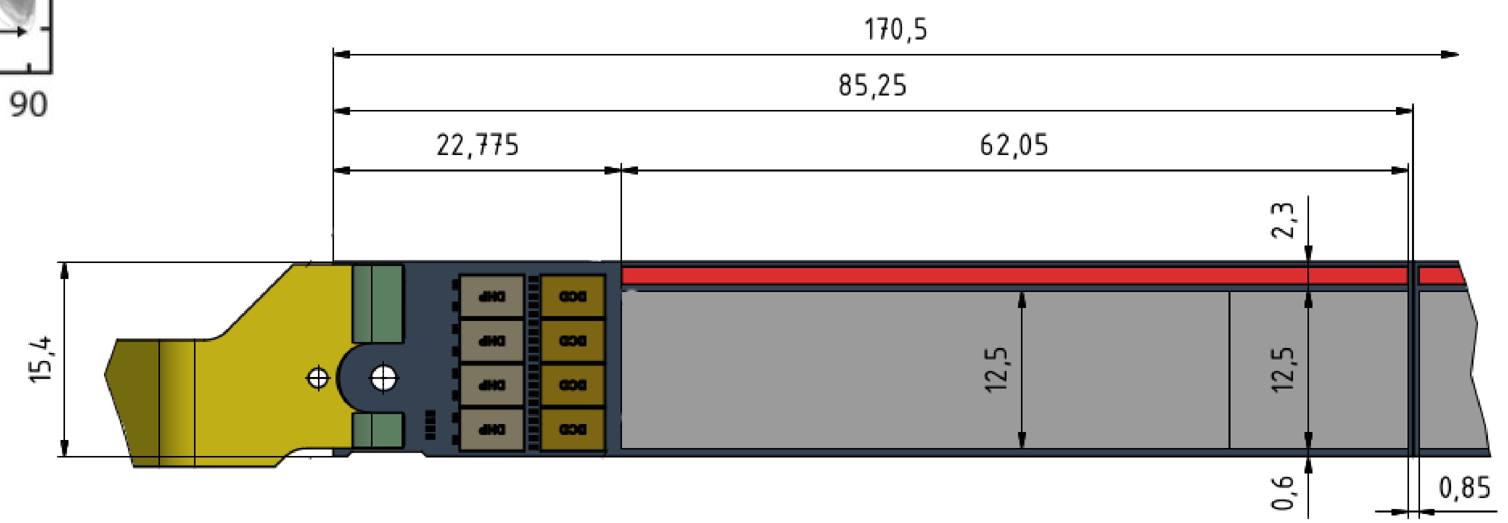
cf. “One of the main limitations of state of the art CMOS sensors comes from a rather low readout speed.”

# 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 $\mu m^2$

1 <|z|< 2 cm → 25 x 50 $\mu m^2$

|z| > 2 cm → 25 x 100 $\mu m^2$

**Column depth:** *1025 pixels/half-ladder*

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

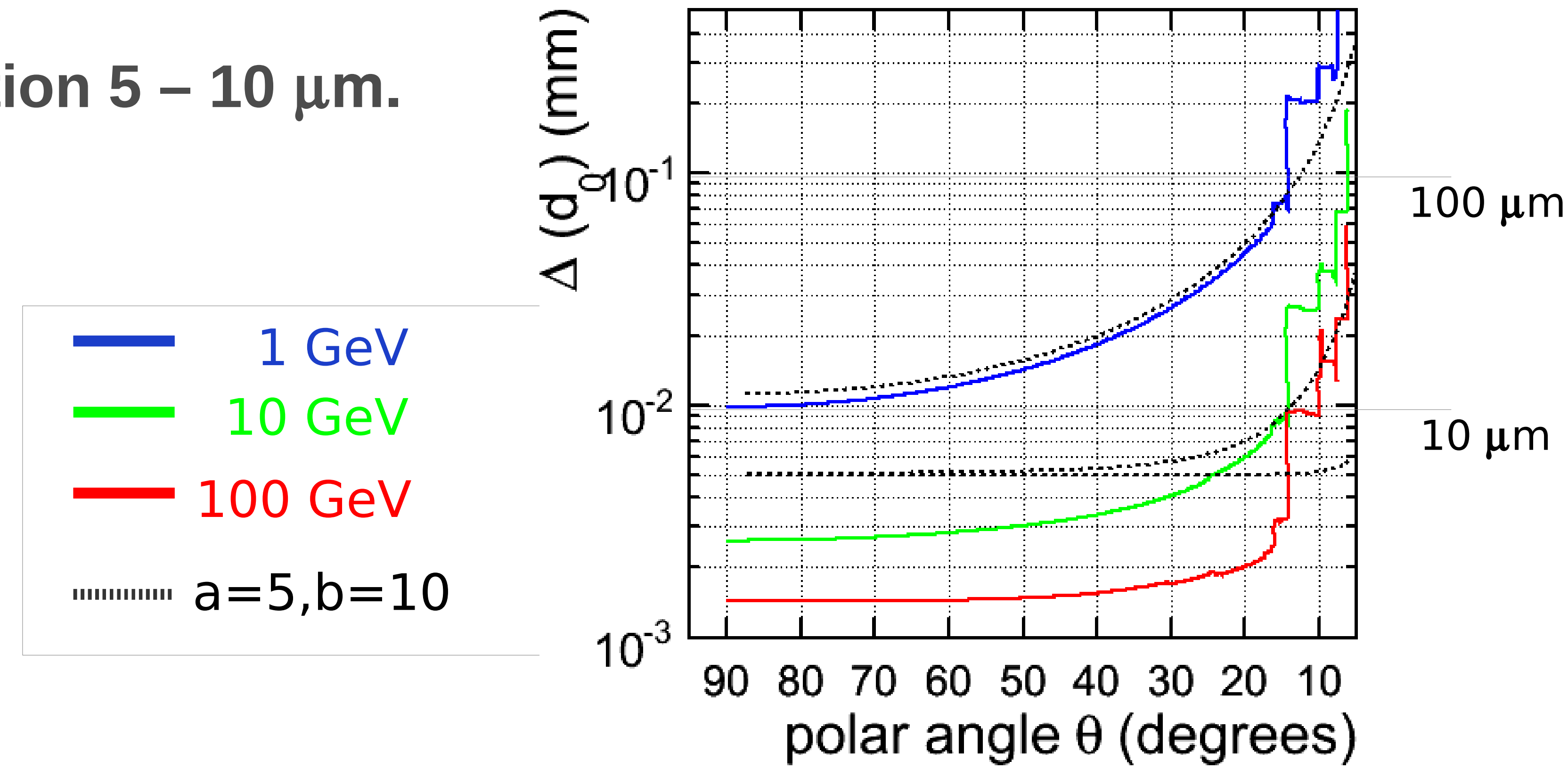
**Row rate:** *1/80 ns*

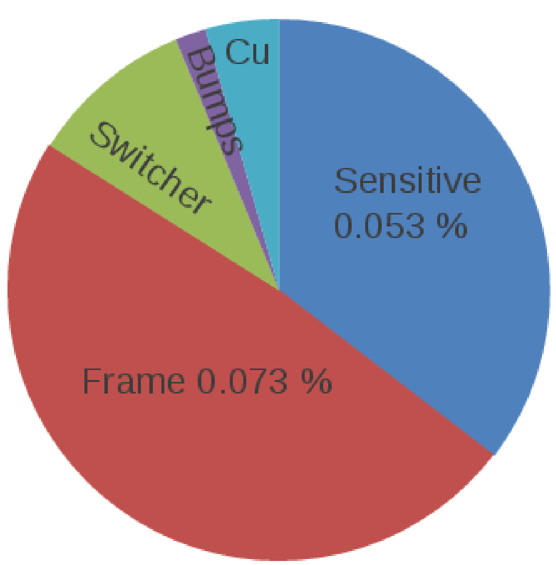
**Frame time:** *40 $\mu s$ (20 $\mu s$)*

# Impact parameter resolution

**VXD: impact parameter resolution 5 – 10 μm.**

Forward vertexing in ILD:
http://arxiv.org/pdf/1303.3187.pdf

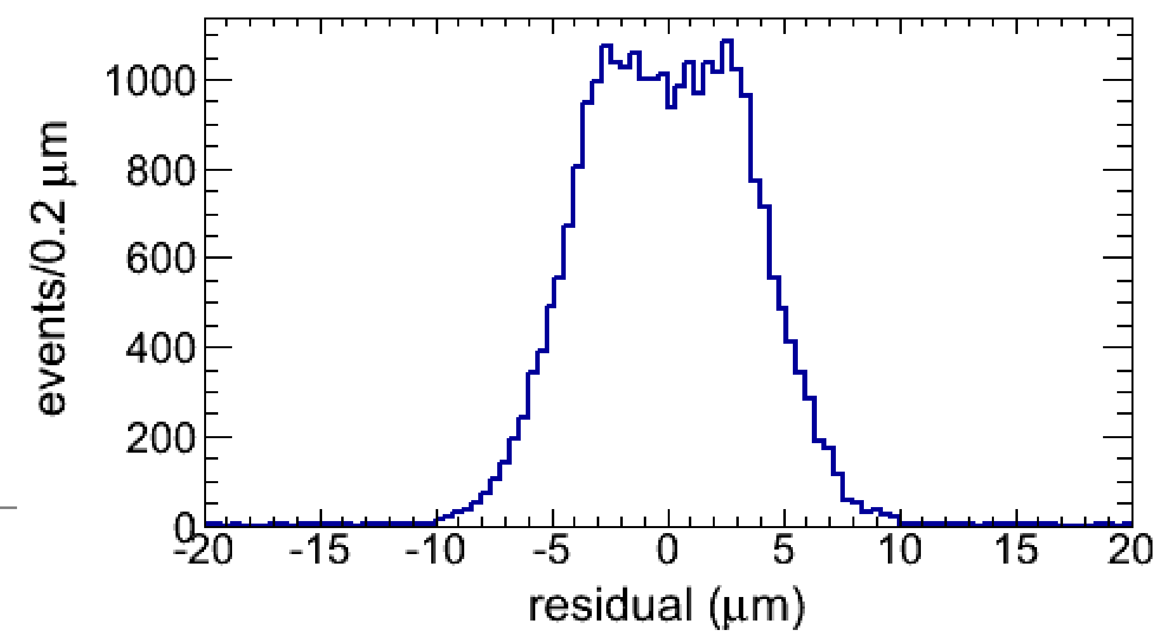



| | |
|---|---|
| Sensitive | 0.053 % $X_0$ |
| Frame | 0.073 % $X_0$ |
| Switcher | 0.015 % $X_0$ |
| Cu layer | 0.007 % $X_0$ |
| Bumps | 0.003 % $X_0$ |
| Total ladder | 0.15 % $X_0$ |

← **Material budget**
(averaging over ladder active area)

**Spatial resolution** →
(simulation, perp. Incidence)

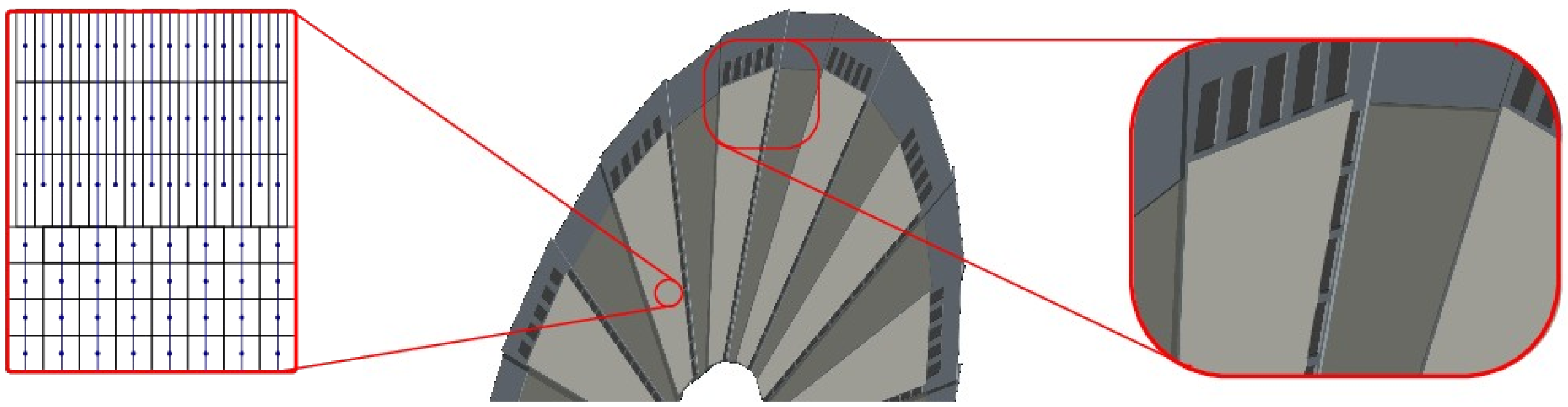


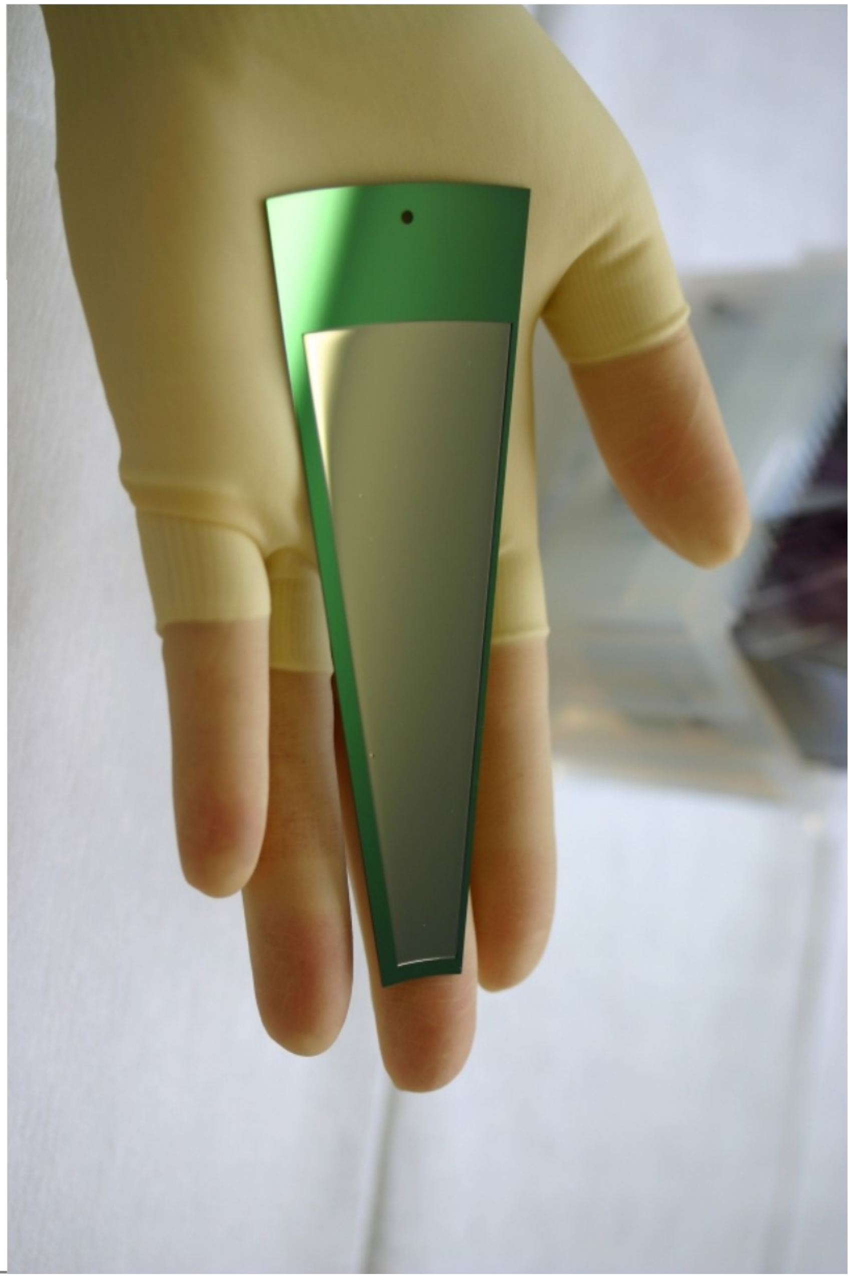
# Disk design

**One major difference between Belle II and LC is the polar angle coverage**

- Implications for support, cooling and services of the barrel detector
- Requires “end-cap” with pixelated disks

→ adapt “ladder” design to “petal” geometry

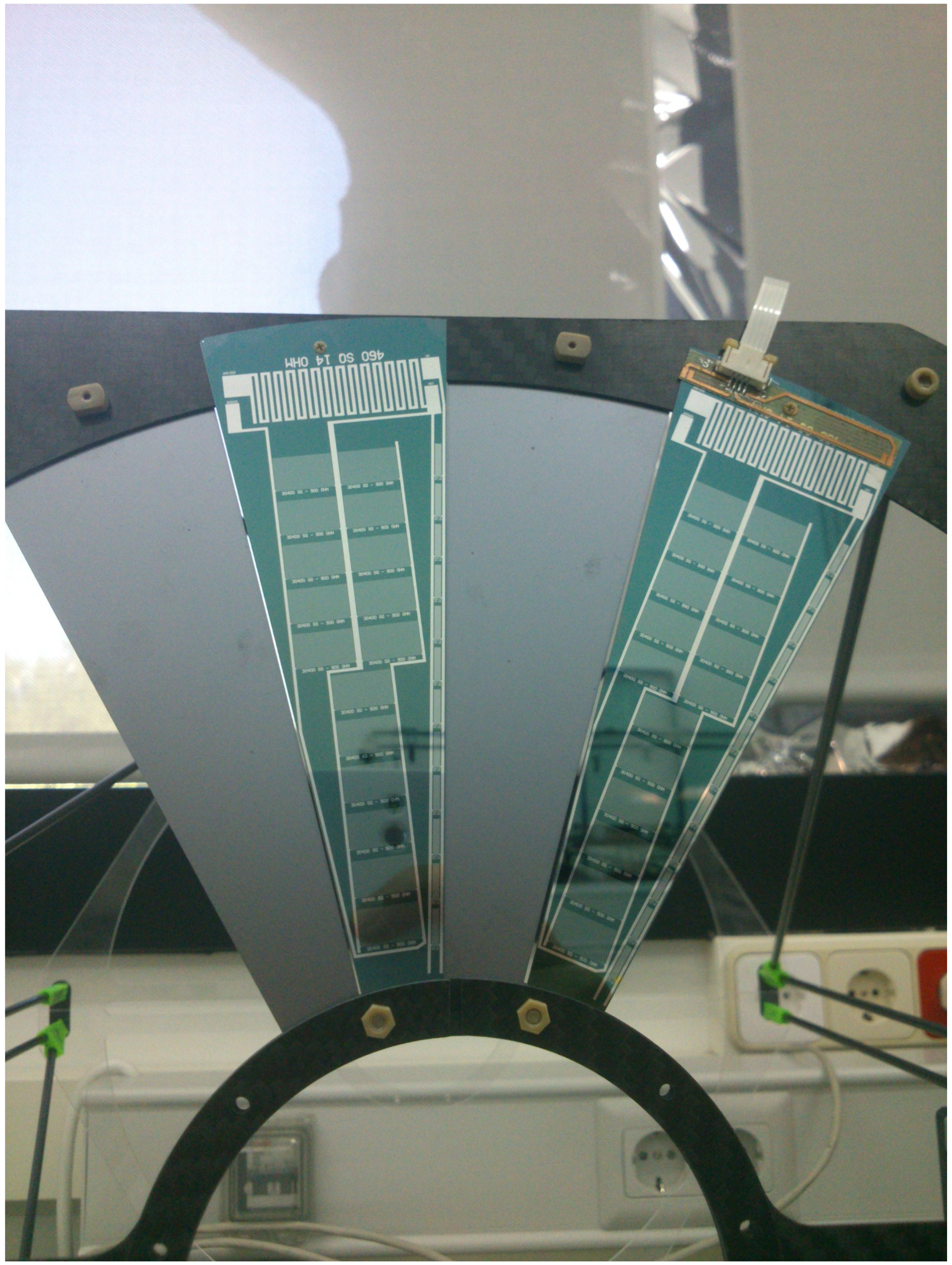




## DEPFET solution for end-cap developed

concept → CAD → mechanical dummy → active petal

# Full mock-up



**Subject thinned petals to ILC environment:**

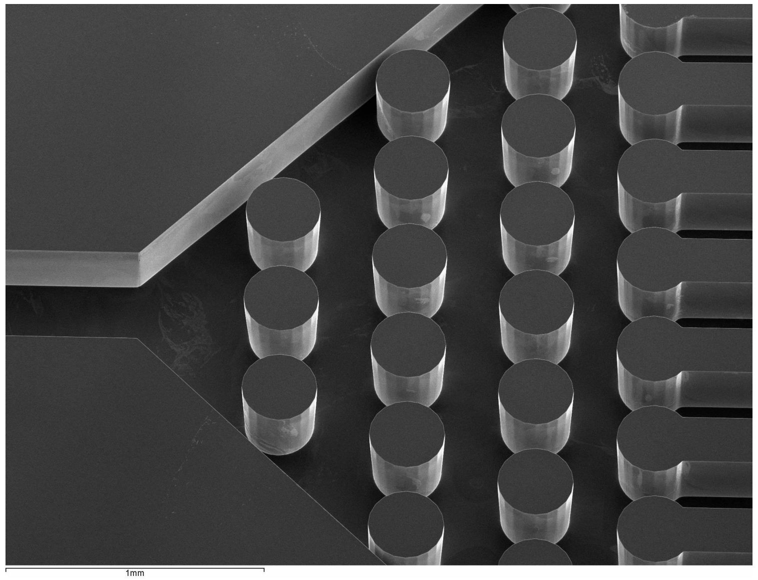
- ILD/FTD geometry
- low-mass CF support structure
- pulsed power in heater circuits
- forced air flow for cooling (no liquid!)

**And monitor thermo-mechanical properties:**

- thin petals are very rigid when subject to perp. force
  - Deformations are 3x larger than solid 450 μm thick petal
  - Deformations are 23x smaller than solid 113 μm thick petal (same material)
- pulsed power with ILC duty cycle (1 ms on, 200 ms off)
  - No sign of fast temperature excursions ($\tau$~3 s)
  - No sign of vibrations induced by power pulsing (for B=0)
- small temperature increase for nom. power and 1/25 duty cycle
  - $\Delta T$ ~ 3 degrees for single petal
- cooled very effectively by air flow of 1 m/s
  - $\Delta T$ ~ 3 degrees even for ¼ duty cycle
- air flow induces measurable vibrations
  - Frequency varies with clamping: 60 Hz (1-point support) to 300 Hz (3-point)
  - Amplitude controlled to few microns if correctly clamped

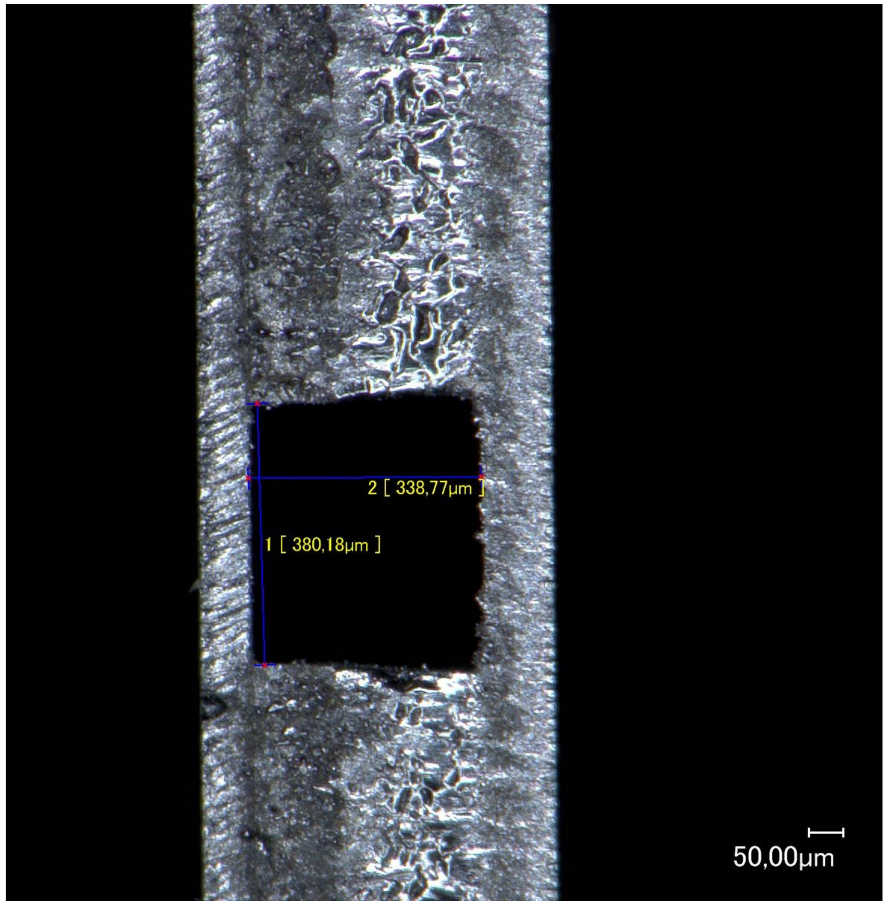
**Thin petal thermo-mechanical performance reproduced by Finite Element simulation**

# Micro-channel cooling



DEPFET generates > 80% of heat on the end-of-ladder area
Micro-channel cooling is very effective to remove this heat

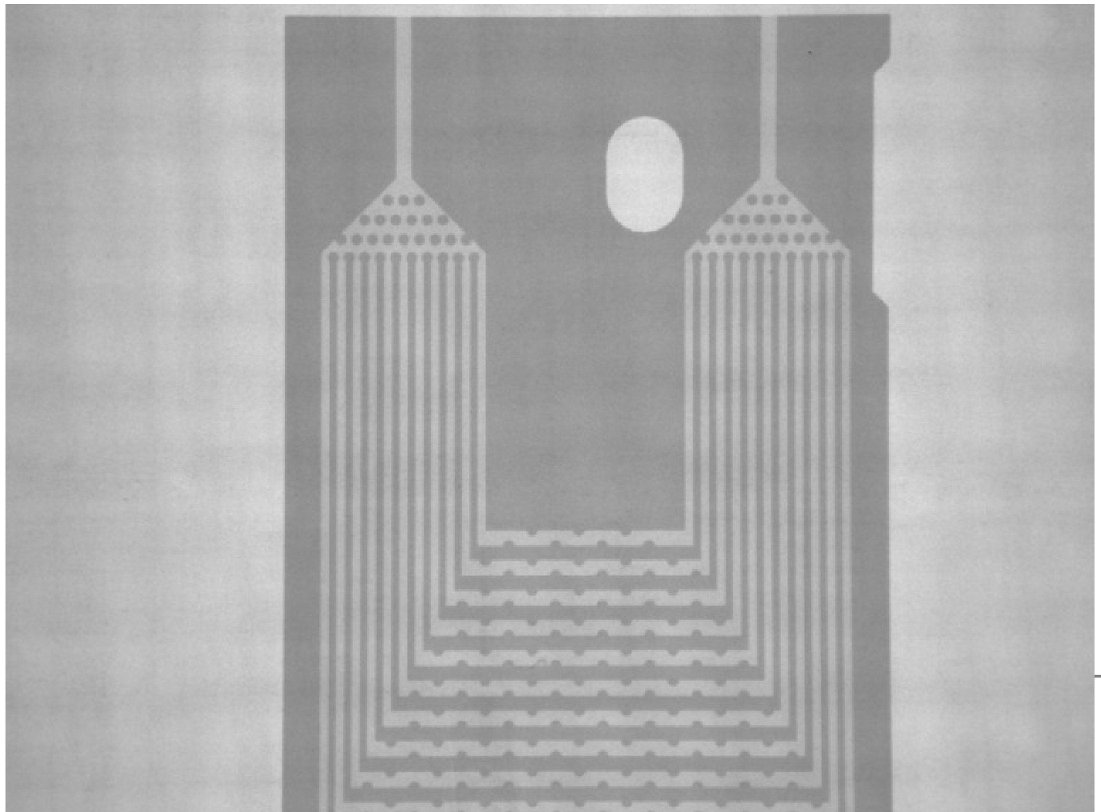
*Zoom of inlet*




*Detail of manifold before wafer bonding*

Integrate in DEPFET all-silicon ladder concept; micro-manifold etched in handle wafer, sealed when active wafer is bonded on top

Inlet and outlet (340 x 380 $\mu m^2$) accessible in-plane

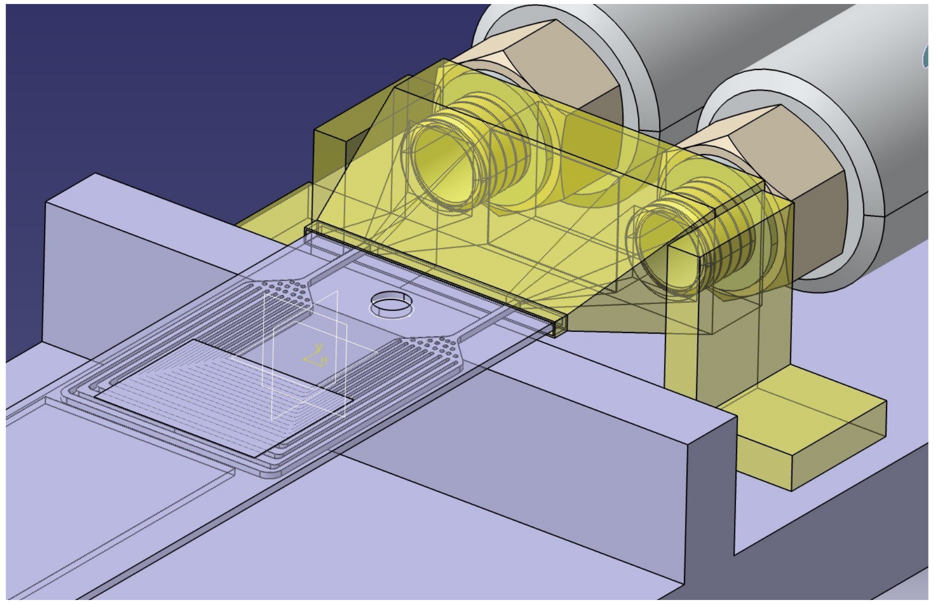


Several samples produced at HLL
Heater circuits in Al metal layer to mimic heat loads

*X-ray image of end-of-ladder with integrated micro-manifold*

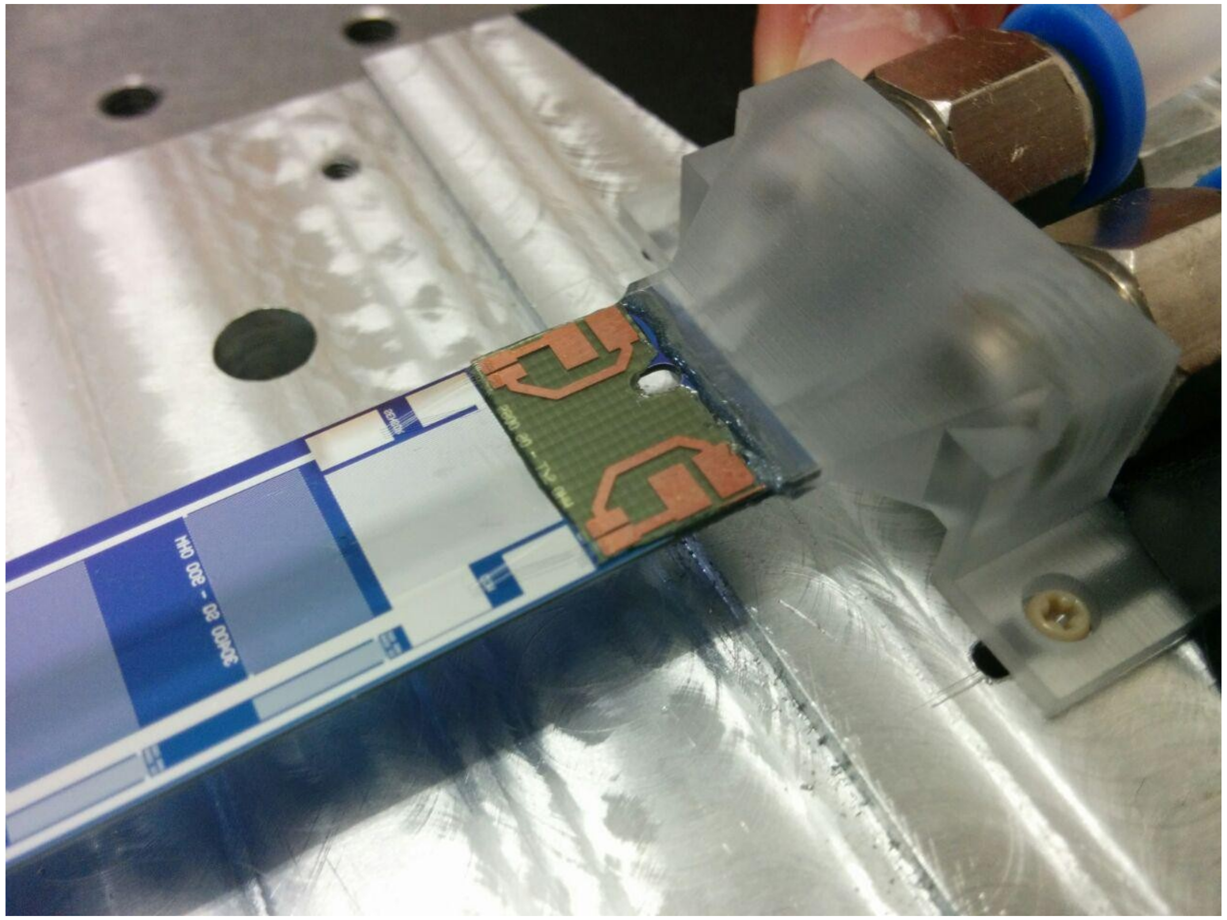
# Micro-channel cooling

Proof-of-principle tests at U. Bonn are very promising



## Cooling setup for characterization

"swagelok" world: pumps, flow-, thermo-, manometers



## Plastic interconnect

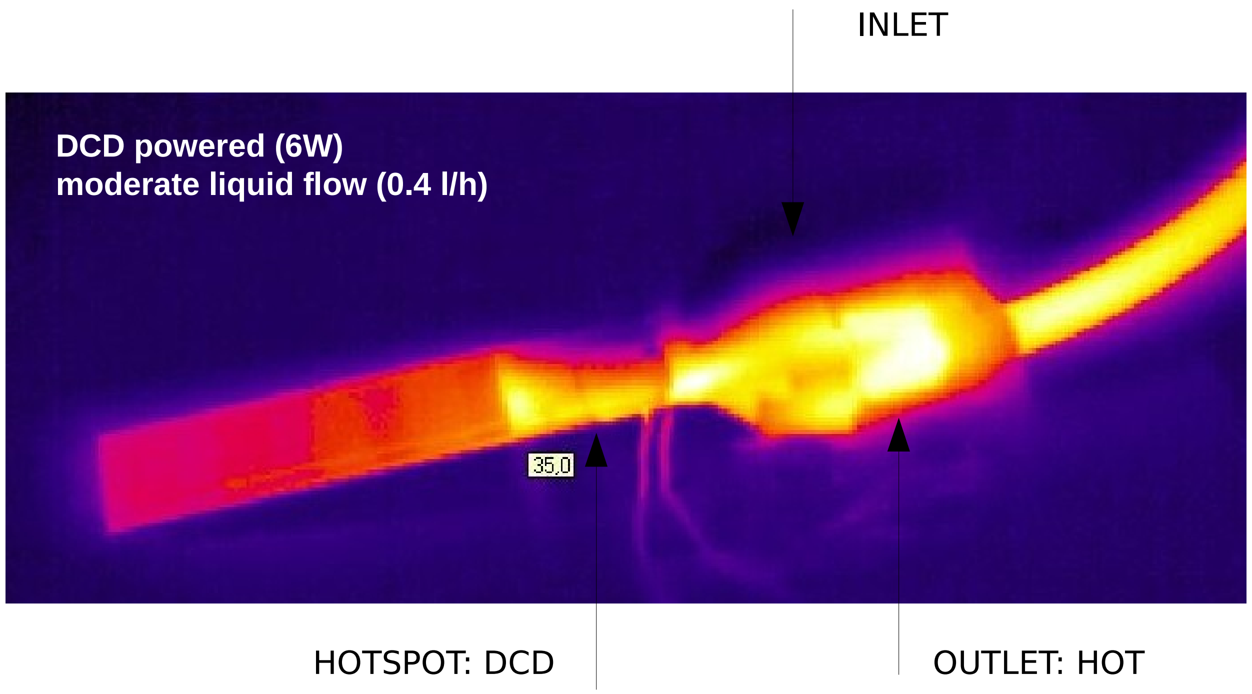
3D printed to 15 $\mu$m precision
Self-aligning: bottleneck is Si inlet/outlet
Sealed with glue
Success rate: 2/2

## Electrical connections

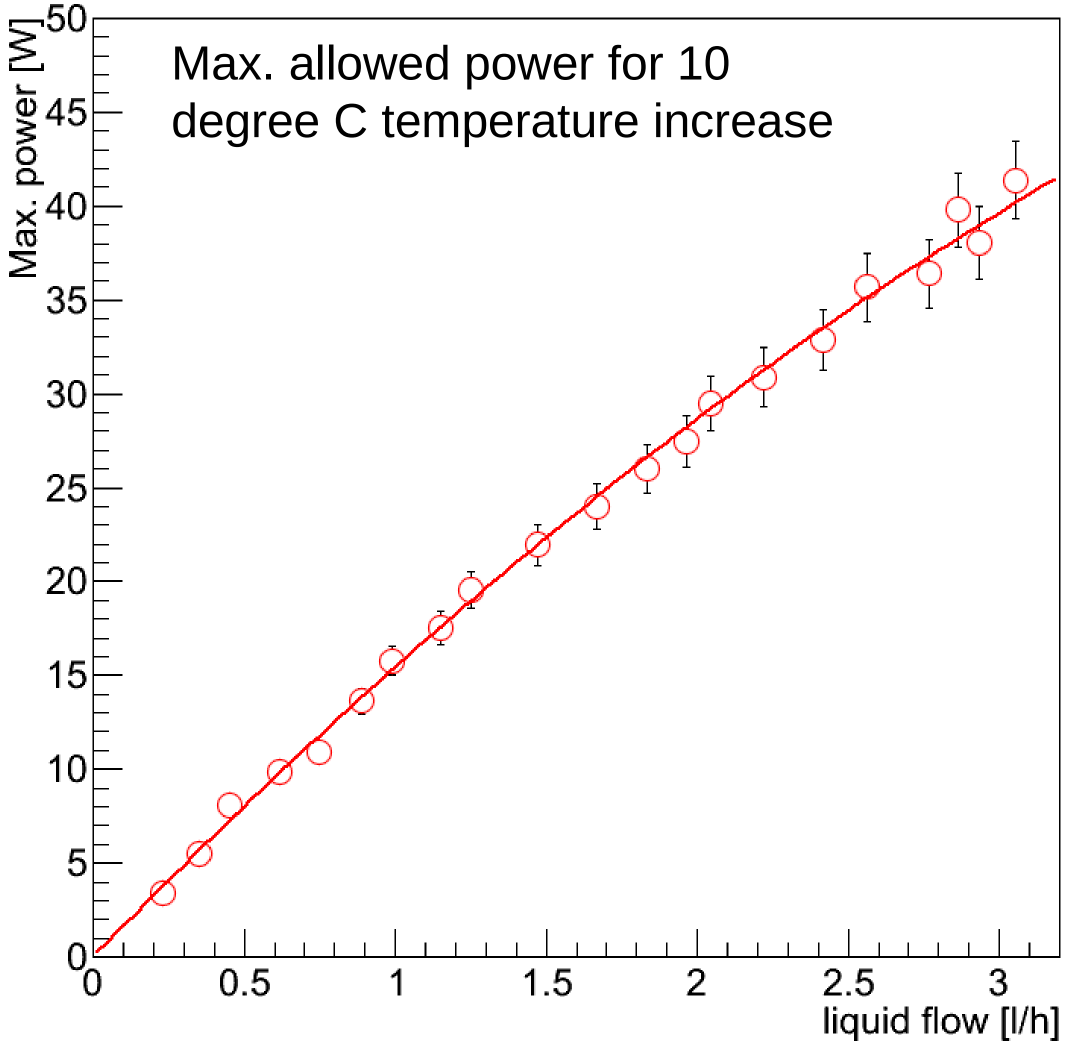
Mini-PCB with wirebonds and soldered wire connects heater circuits

For detectors operating above 0° C, prefer mono-phase (water) cooling
Controlled environment to quantify cooling performance
Operated non-stop for a week; no leaks, no clogging...
Stress test: over 100 W on end-of-ladder, up to 3 l/h (but less than 10 bar)

# MCC results




The micro-circuit is an amazing heat exchanger; $T_{liquid} \sim T_{si}$ up to (at least) 3 l/h flow




**Cooling power for local (DCD) heat dissipation is great:**

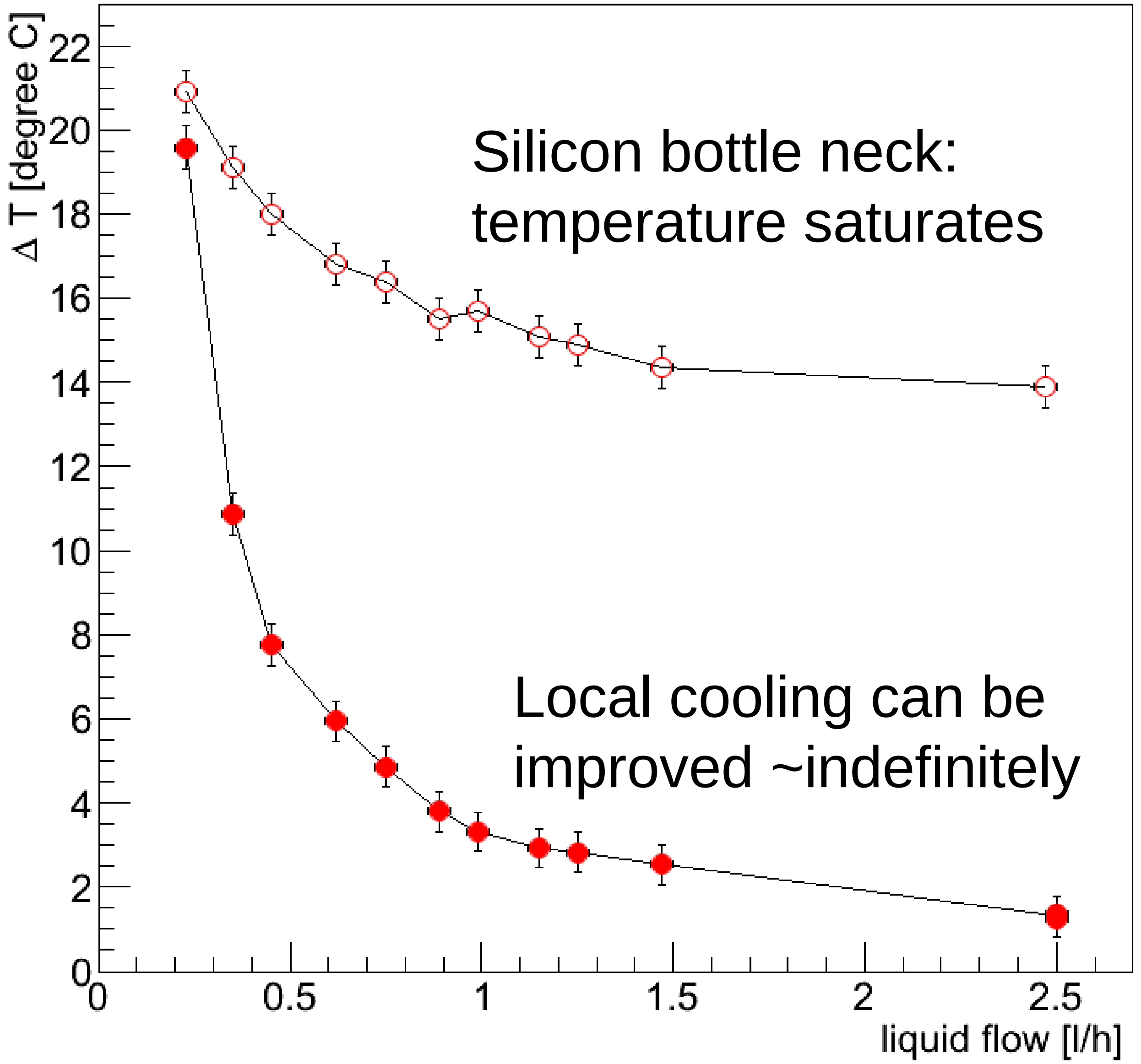
Cool away over 40 W on cm$^2$
with $\Delta T \sim 10$ degree C

**And the limit is not in sight**
$\Delta T/P \sim c$ up to max. pump power

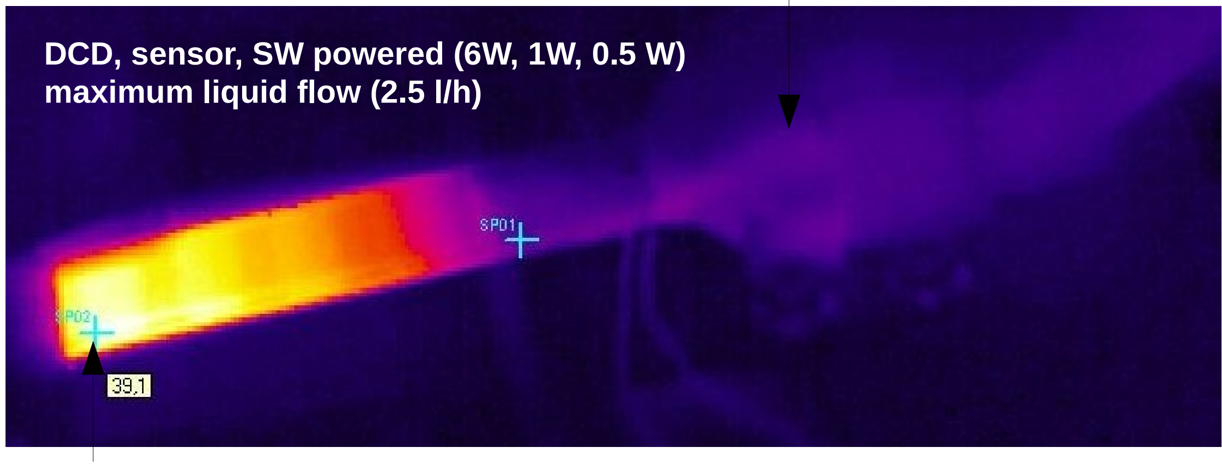
**Low-pressure solution**
All this at less than 10 bar

# MCC results

*Note: thick ladder, heat transfer for thinned sensor expected to be worse*




INLET, DCD, OUTLET: COLD




HOTSPOT: TIP OF SENSOR

○ Nominal power on ladder
DCD (6 W) + sensor (1W) + SW (0.5 W)

● Nominal power on DCD

**Silicon heat transfer limits performance when power is dissipated far from the MCC**

MCC is excellent solution for localized heat dissipation
For long DEPFET ladders, add gentle air flow (or extend MCC to sensor/balcony)

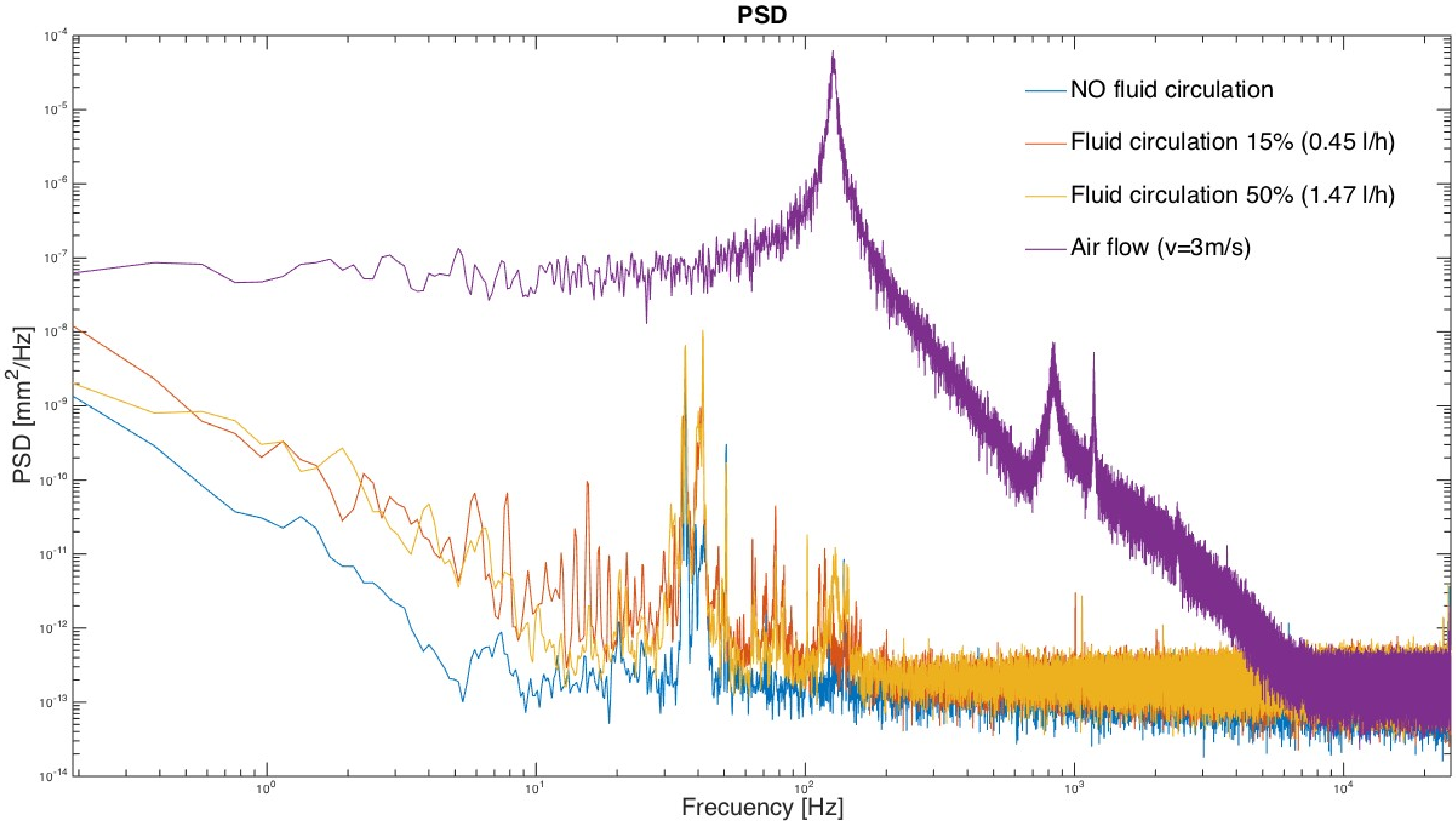
# Impact on mechanics

Sensor clamped on end-of-ladder side only

FFT of the position of the tip the sensor

Fluid circulation through the micro-channel circuit does not induce vibrations

Temperature variations do induce slow variations (stability under study)




| | |
|---|---|
| No cooling | → RMS = 0.3 μm |
| Liquid circulation (1.5 l/h) | → RMS = 0.5 μm |
| Liquid cooling | → RMS ~ 1 μm |
| Air cooling (3 m/s) | → RMS = 57 μm |

Even in quite exposed situation, MCC has no significant impact on mechanical stability

# Conclusions

A global LC hosted in Japan...
It might just happen!
Be ready to react if it does.

**Small, but adequate, DEPFET presence in LC:**
- contributions to ILC TDR & liaison report, IEEE TNS paper, ECFA R&D report
- Regular reports in LC workshops (ALCW15, LCWS14, ….)

**DEPFET remains a solid candidate for the ILC VXD:**
The best argument for DEPFET is: **success of the Belle II PXD**

**LC-specific developments:**
- continue to improve system performance (S/N, speed)
- smaller pixels, deeper columns, larger #columns
- petal design + pulsed power + air-cooling → FTD mock-up
- micro-channel cooling seems very promising → AIDA2020 funding

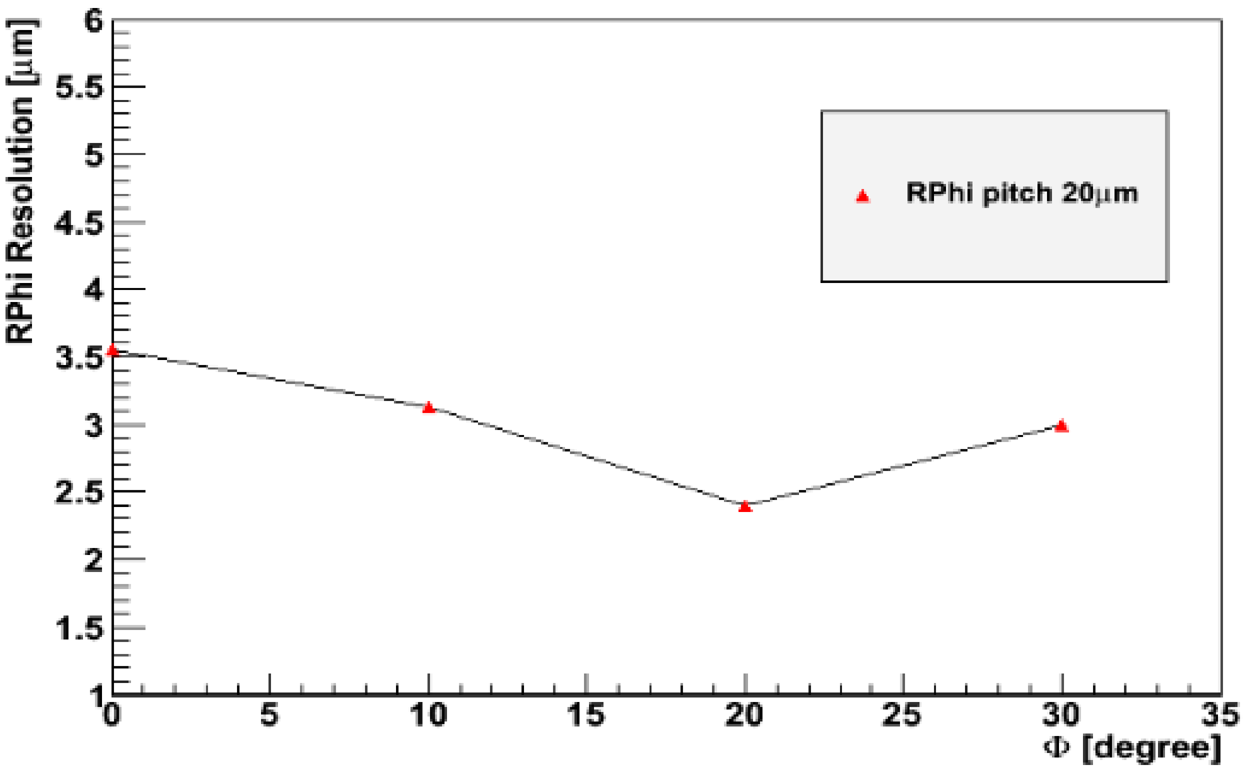
# Summary: LC vs Belle-II

| | *ILC* | *Belle-II* |
|---|---|---|
| occupancy | 0.13 hits/$\mu m^2$/s | 0.4 hits/$\mu m^2$/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 $\mu$s (10 ns @ CLIC) | 20 $\mu$s |
| Momentum range | All momenta | Low momentum (< 1 GeV) |
| Acceptance | 6°-174° | 17°-150° |
| Resolution | Excellent 3-5 $\mu$m (pixel size = 20 x 20 $\mu m^2$) | Moderate (pixel size = 50 x 75 $\mu m^2$) |
| Material budget | 0.12 % $X_0$/layer | 0.15 % $X_0$/layer |

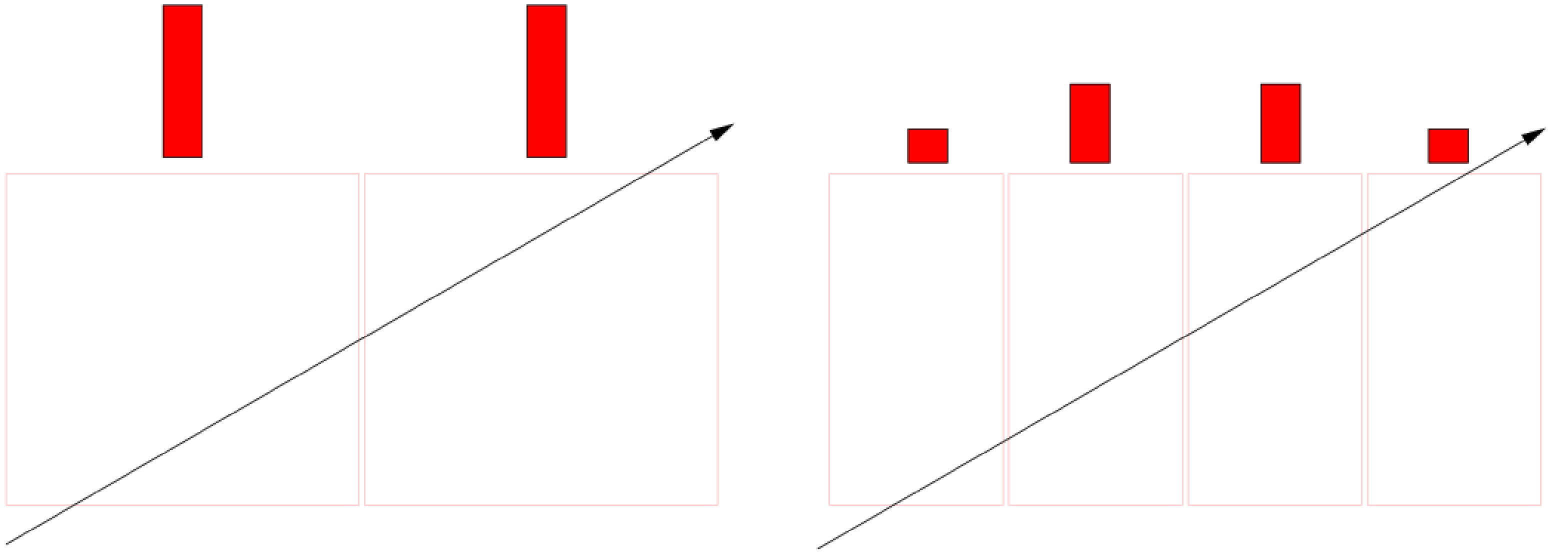
Belle-II presents a more severe challenge than the ILC in several aspects!

# Resolution vs. incidence angle

Spatial resolution of an ILC design DEFPET vertex detector predicted by digitizer




Charge sharing helps improve the resolution (up to a point)

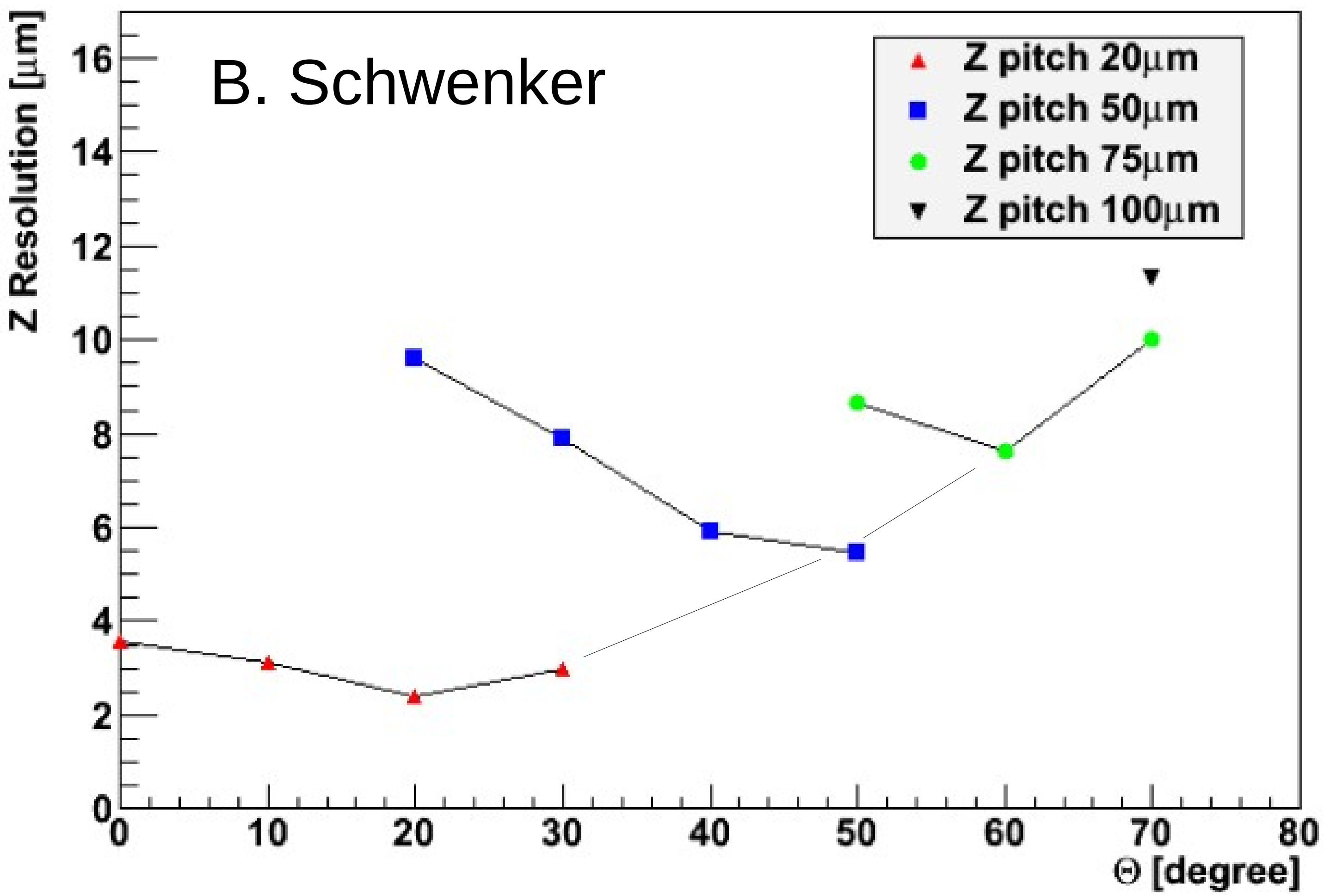


# Spatial resolution for shallow tracks

Some degradation of the resolution towards the end-of-ladder seems inevitable

S/N is still crucial:
- forces detector thickness
  (and consequently pitch)

Improve by increasing $g_q$



# European Strategy - old

*The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

*In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.*

*It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precisionfr ontier; thereshould be a strong well-coordinated Eur opean activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.*

# European Strategy - updated

*The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

*To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide. e.*

*There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.*