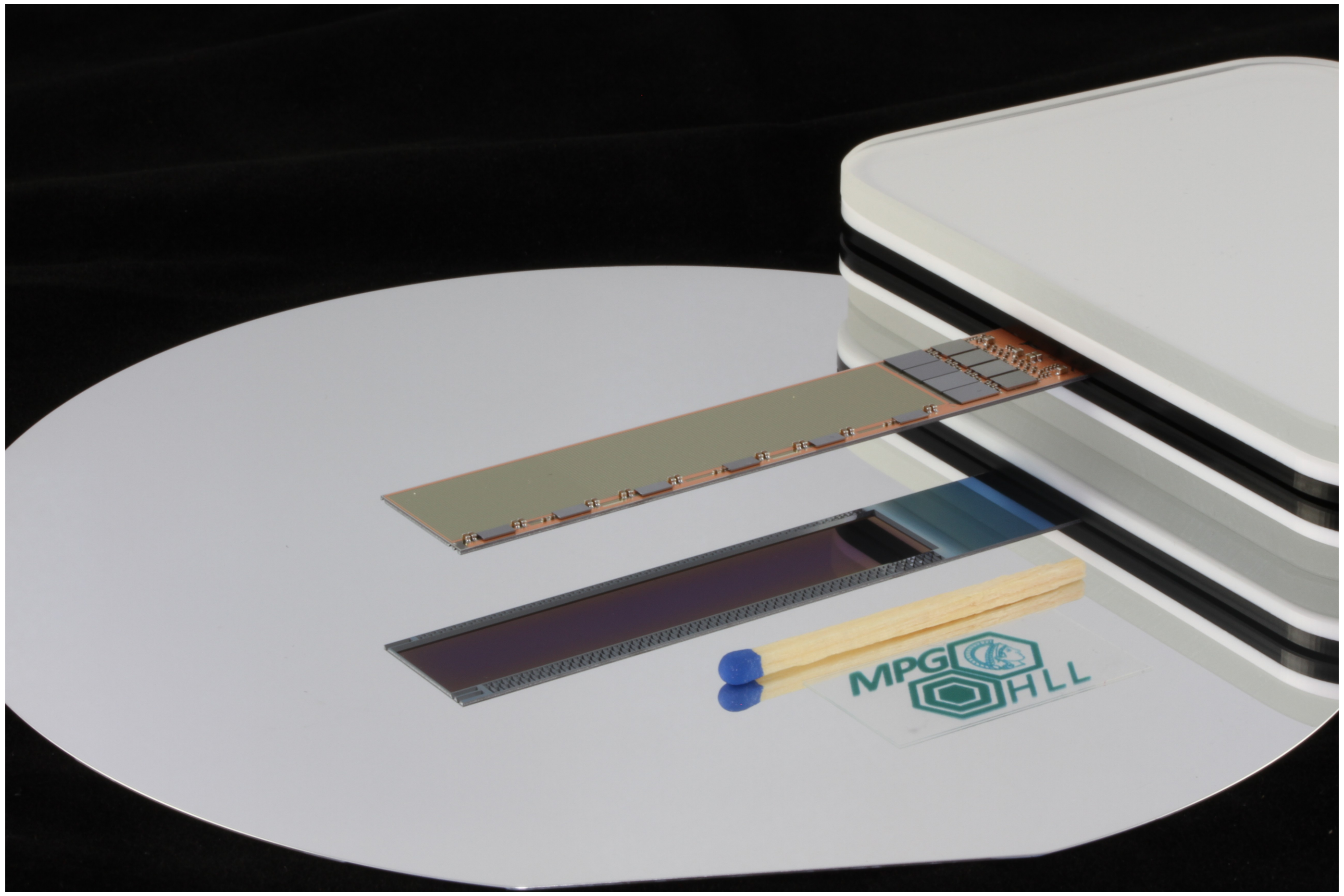
DEPFET vertex detector

LCWS15

Tracker & vertex detector R&D

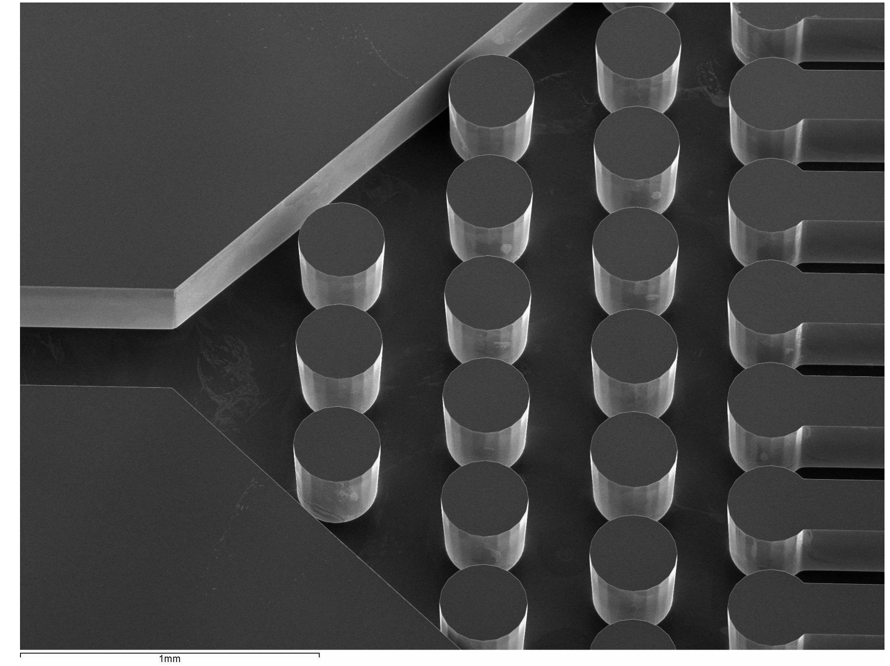
Whistler, Canada

Marcel Vos (IFIC Valencia),
for the DEPFET collaboration

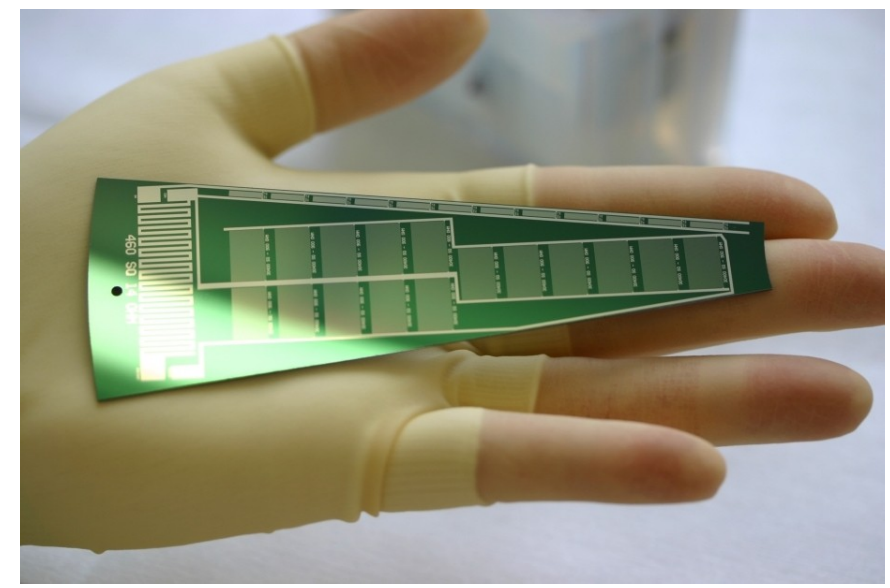


DEPFET
Active Pixel Detector

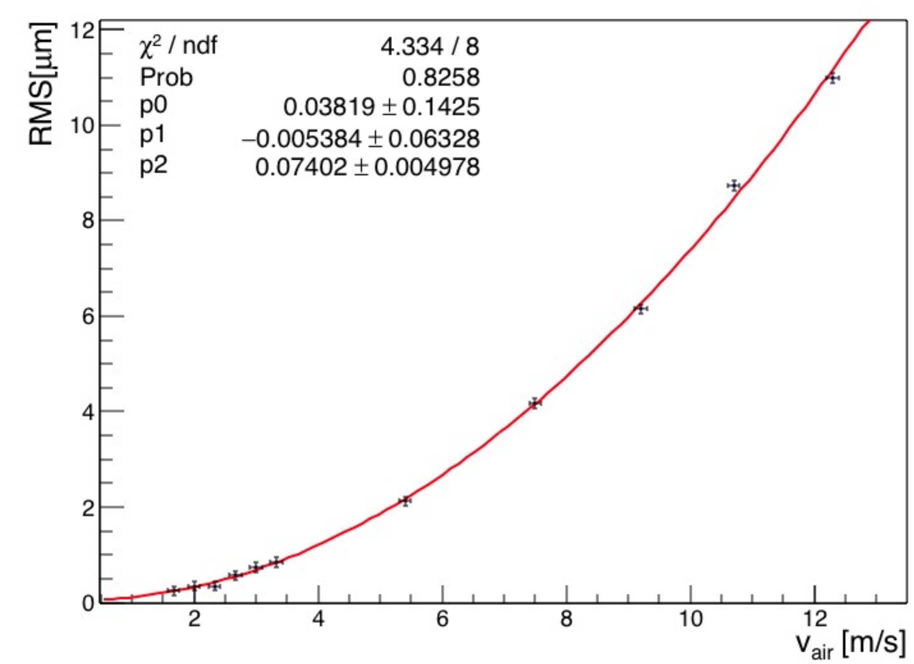
Not covered in this talk



Micro-channel cooling



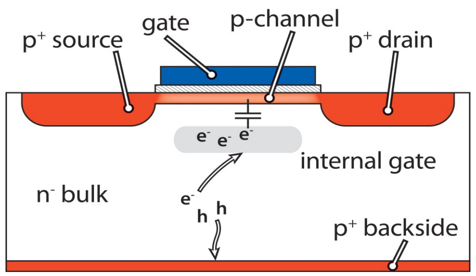
Solution for forward disks



Thermo-mechanical performance of ultra-thin sensors in LC environment

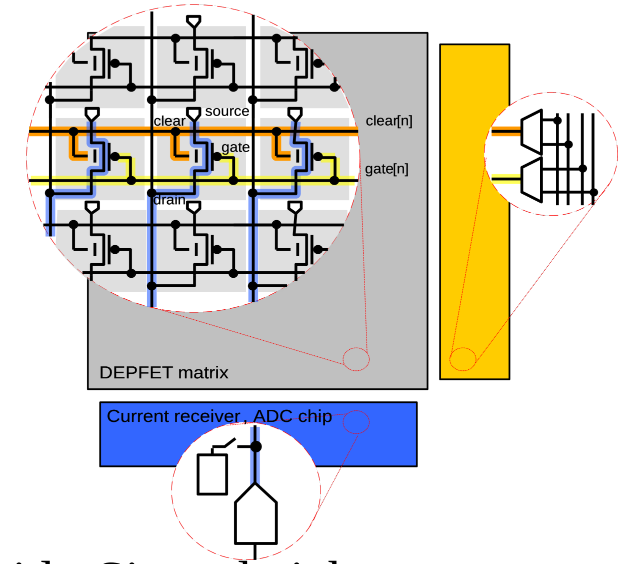
See talk by I. Garcia/M.A. Villarrejo in TRK/VTX session

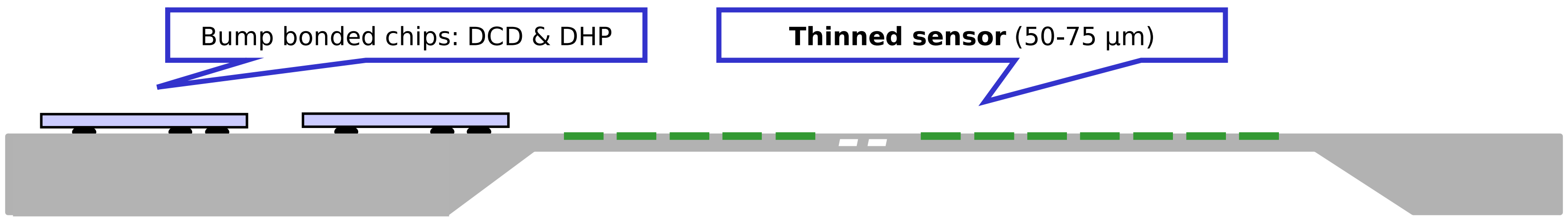
A DEPFET-based (all-silicon) vertex detector ladder



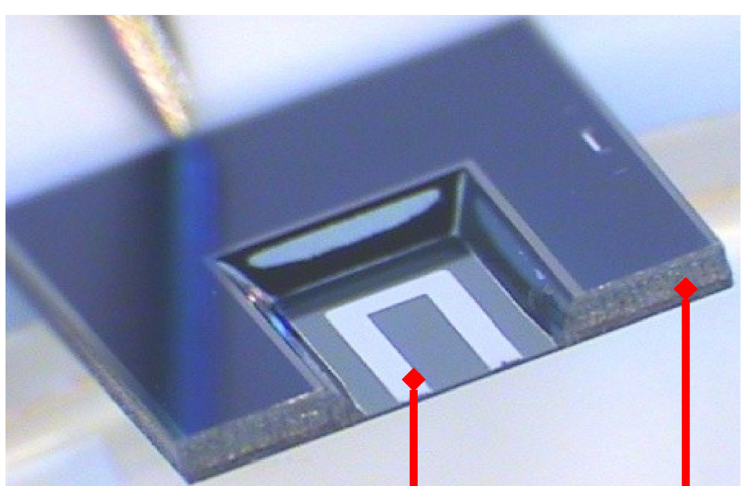
(1) Amplify signal in elementary DEPFET cell (pixel) with FET integrated in detector-grade Si. Drain current is modulated by charged collected on internal gate.

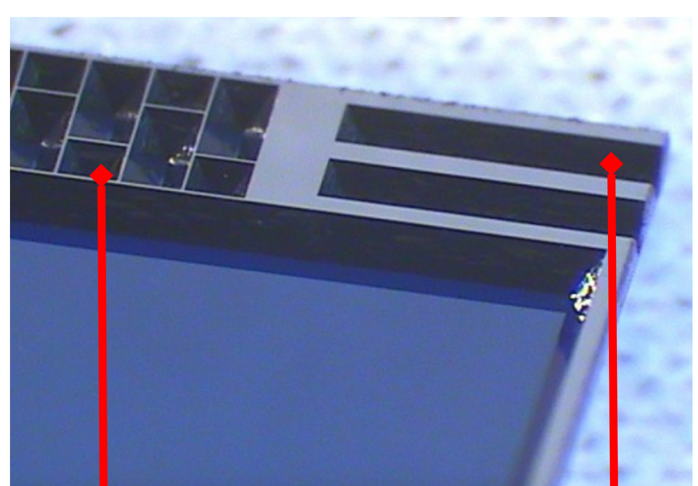
(2) Read out a column of DEPFET pixels with a FE ASIC. Rows are addressed in turn for rolling shutter operation.



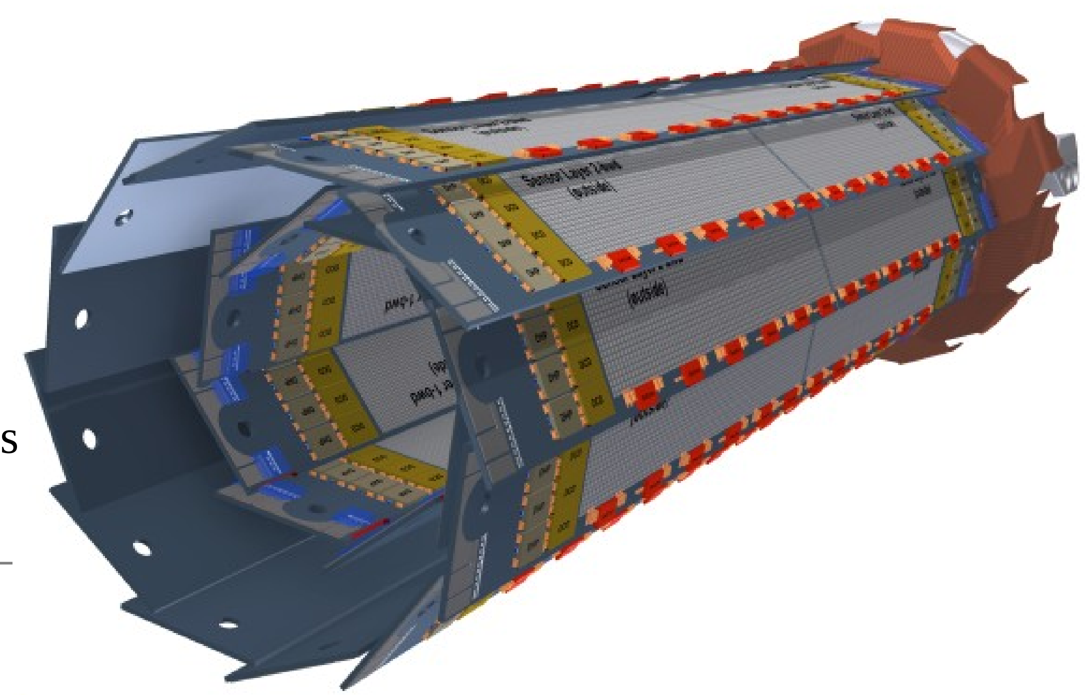


(3) Create an ultra-thin self-supporting Silicon sensor, starting with the ~1 mm thick Si-Oxide-Si sandwich formed by sensor and handle wafer, sculpt away superfluous material by grinding and lithography. Integrate signal and power lines in metal layers on Silicon, bump-bond ASICs directly on top.





(4) Assemble the ladders in a cylindrical structure to form the barrel vertex detector.



Thin sensor (50-75 um)

Thicker rim (500 um)

Structure to glue two half-ladders

Remove every gram that you can get rid off

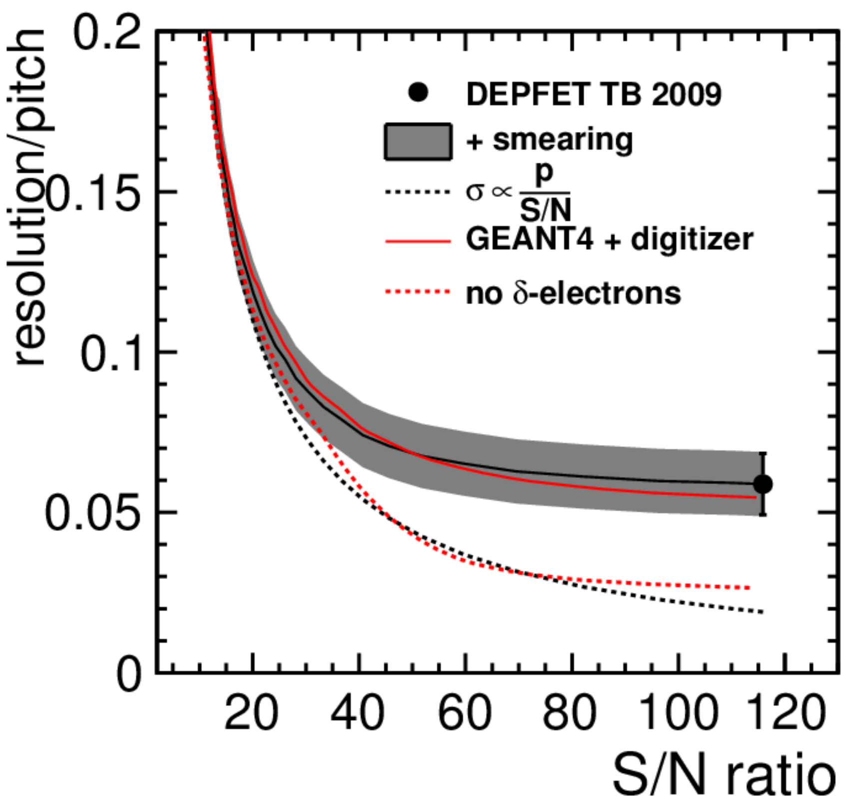
Spatial resolution – the limit

Thick DEPFET sensors have registered a resolution (for 120 GeV pions) of approximately **1 μm**

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

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

Empirical answer: sensor with S/N > 100, smear signal to mimic worse S/N



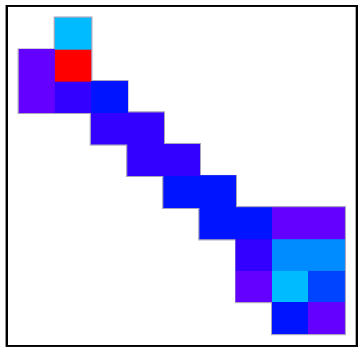
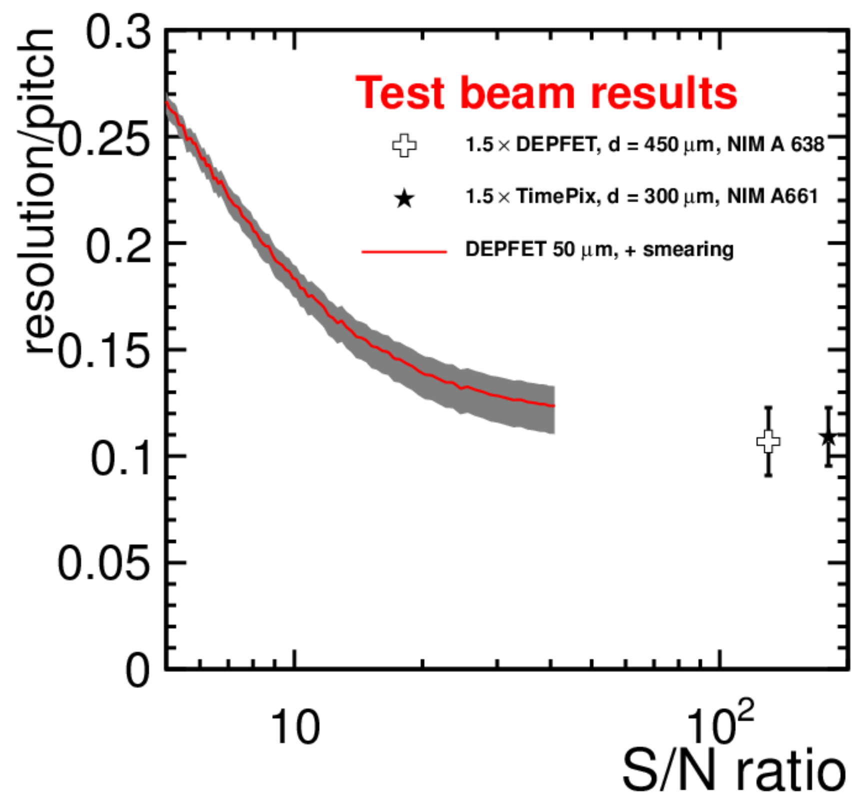


Image of a δ electron captured in a DEPFET beam test



Incidence angle such that projection = pixel size
Landau fluctuations start to play a role
Asymptotic resolution depends on thickness
σ/p ~ 0.12 for d=50 μm

Perp. Incidence: the spatial resolution “saturates” at σ/p ~ 0.07 (approx. 1 μm for state-of-the-art devices). Further progress is checked by δ-electrons

IEEE TNS 62 (2015) 1

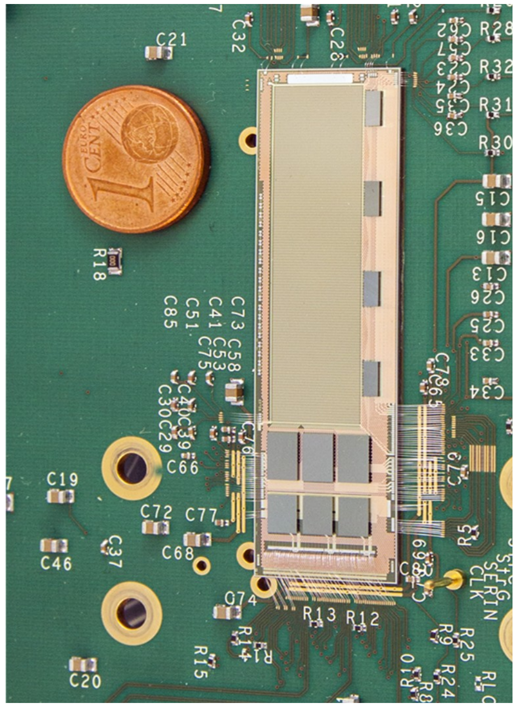
DEPFET Active Pixel Detector

DEPFET time-line

"Early days"

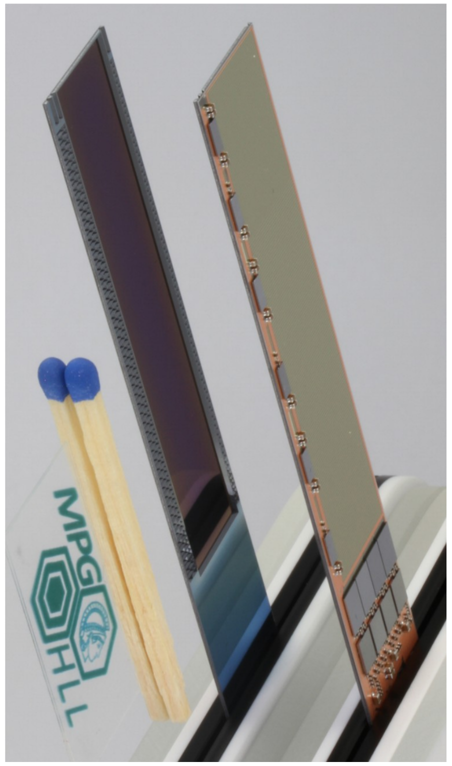
2007-2011 prototypes with $O(10^3$-$10^4)$ pixels

"The most complex piece of silicon in the world", our ECFA reviewer



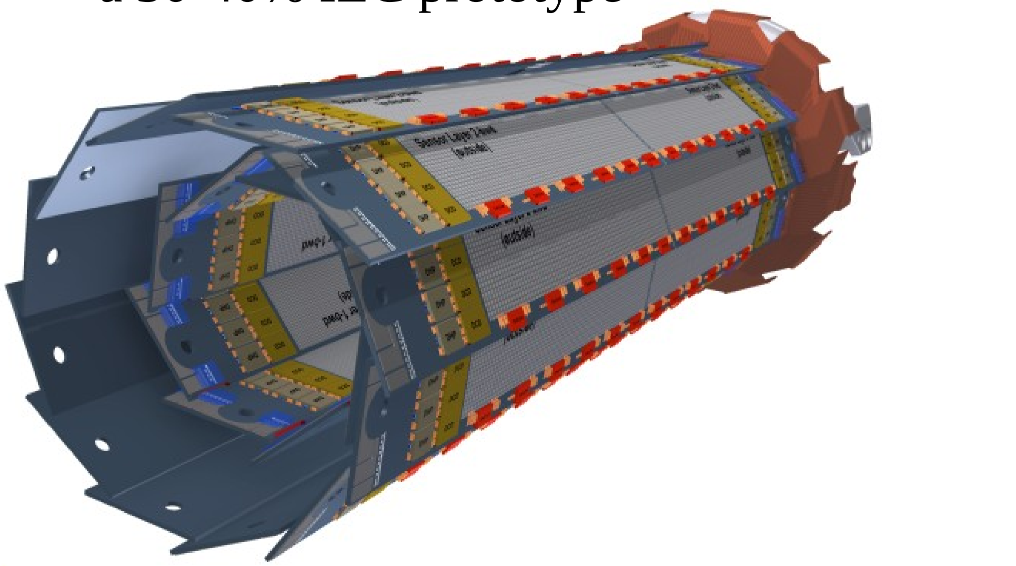
January 2014, first large-scale, multi-ASIC ladder at DESY TB

"The real thing!"



October 2015, first complete & operational Belle II ladder

The Belle II VXD
"a 30-40% ILC prototype"



Assembly Belle II VXD

DEPFET
Active Pixel Detector

Belle II upgrade

Proof-of-principle | Complete demonstrator | A real detector | Physics

2002.... | 2007.... | 2013 | 2014 | 2015 | 2016 | 2018

LC-specific detector R&D

a vertex detector for TESLA

Small-pixel prototype with 1.5 µm resolution

DEPFET for ILC, IEEE TNS 60, 2, 2

ECFA review: http://ific.uv.es/~vos/ECFA_DEPFET.pdf

ILC candidacy benefits from developments for Belle-II and X-rays

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 for ILC TDR/DBD
in IEEE TNS 60, 2, 2 (2013)

ILC newsline
December 2012

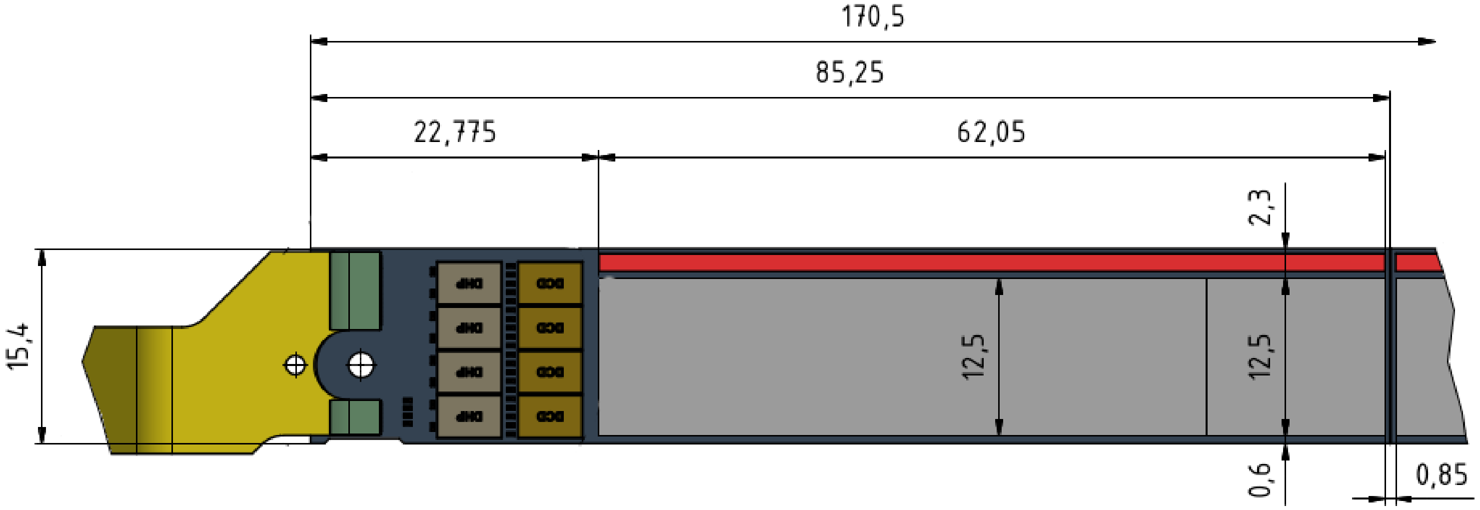
DEPFET active pixel detectors for a future linear e^+e^- collider - Report for the ECFA Detector R&D review, DESY, June 2014

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

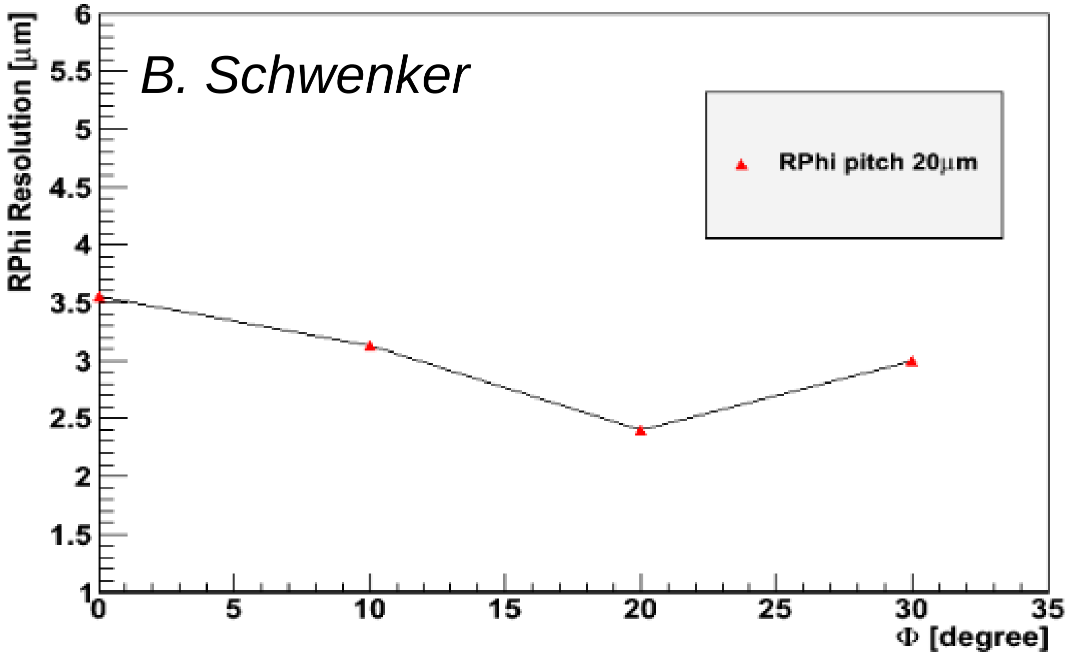
ABSTRACT: The DEPFET collaboration develops highly granular, ultra-transparent active pixel detectors for high-performance vertex reconstruction at e^+e^- collider experiments, such as Belle II and a future e^+e^- collider at the energy frontier. In this report, we review measurements on prototypes that 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.

Report for ECFA review, June 2014
http://ific.uv.es/~vos/ECFA_DEPFET.pdf

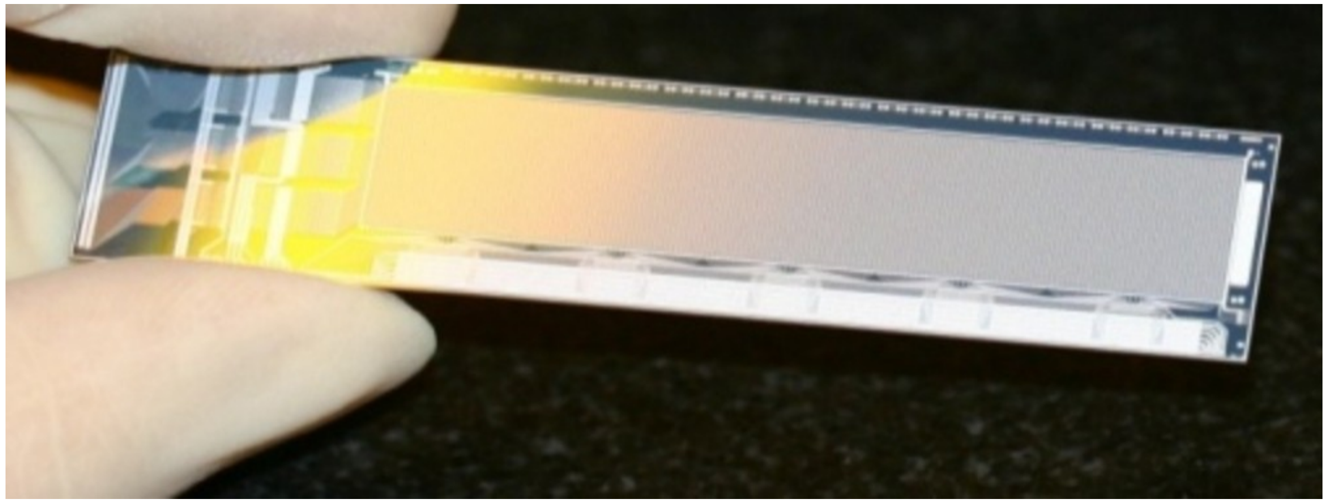
LC performance estimates



IEEE TNS 60,2,2, ECFA review report

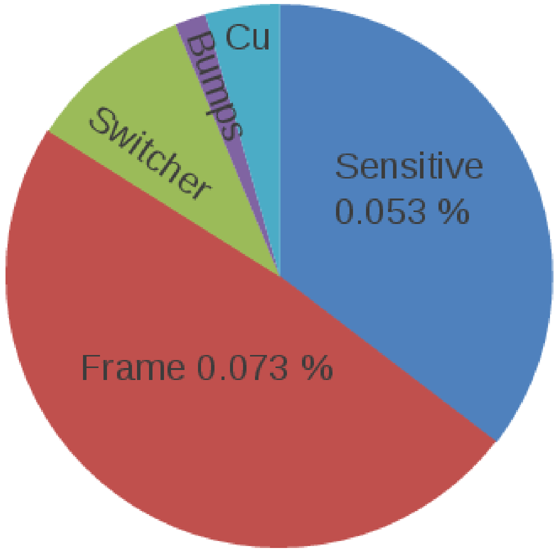


Spatial resolution in LC environment:
2.3 - 3.5 μm



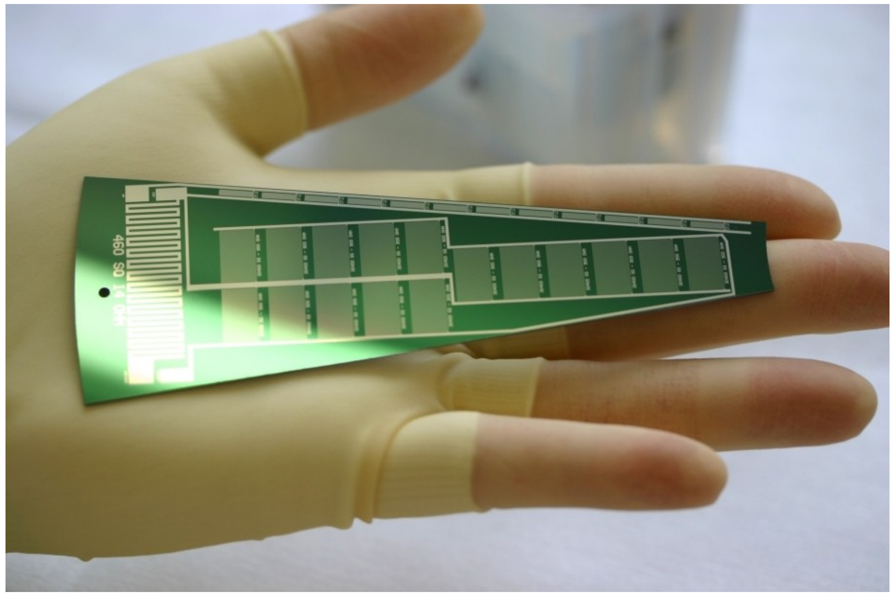
Frame time (barrel layer1/2):
40 μs (20 μs)

Material budget:
0.15% X_0



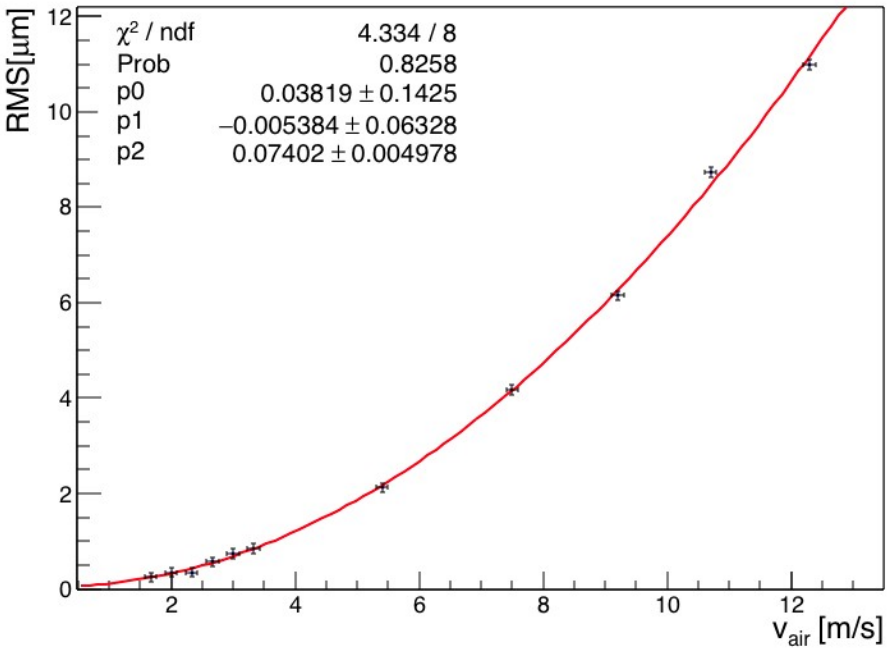
Sensitive	0.053 % X_0
Frame	0.073 % X_0
Switcher	0.015 % X_0
Cu layer	0.007 % X_0
Bumps	0.003 % X_0
Total ladder	0.15 % X_0

LC thermo-mechanics



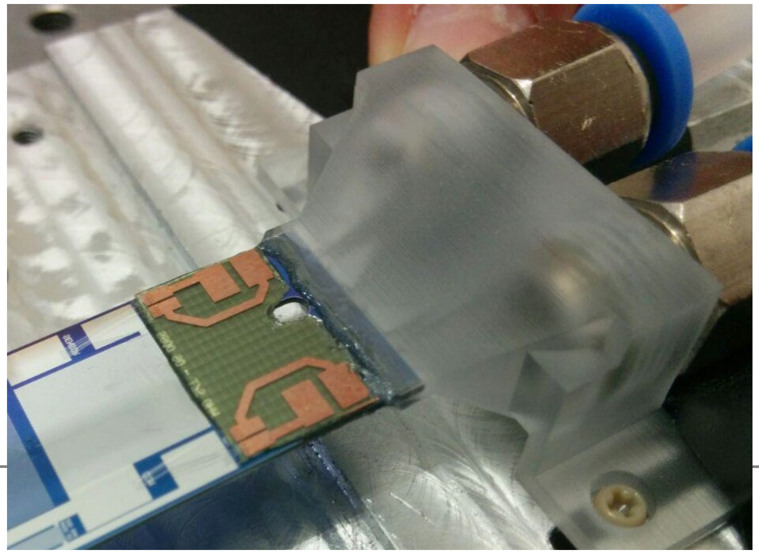
DEPFET solution for forward disks

Adapted ladder design → all-silicon petal
Mock-up for ILD FTD1-2 under construction



DEPFET thermo-mechanical performance in LC environment

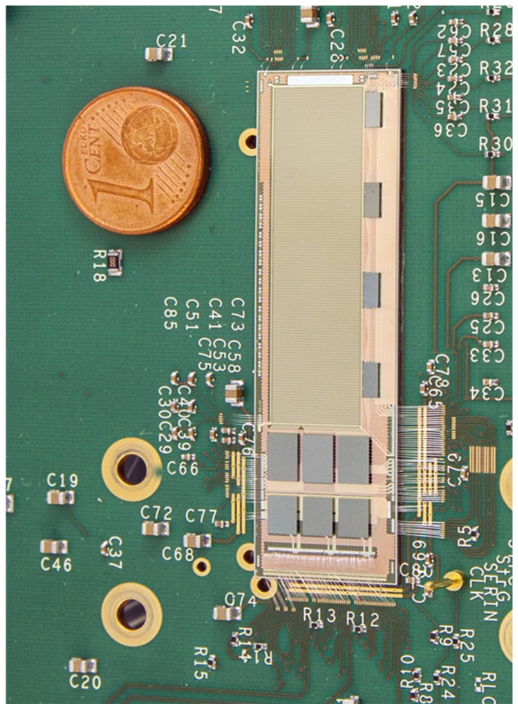
Power pulsing very effective: ΔT = 3 K, without cooling!
No impact on mechanical stability
Gentle air flow is enough to remove heat;
induced vibrations are small



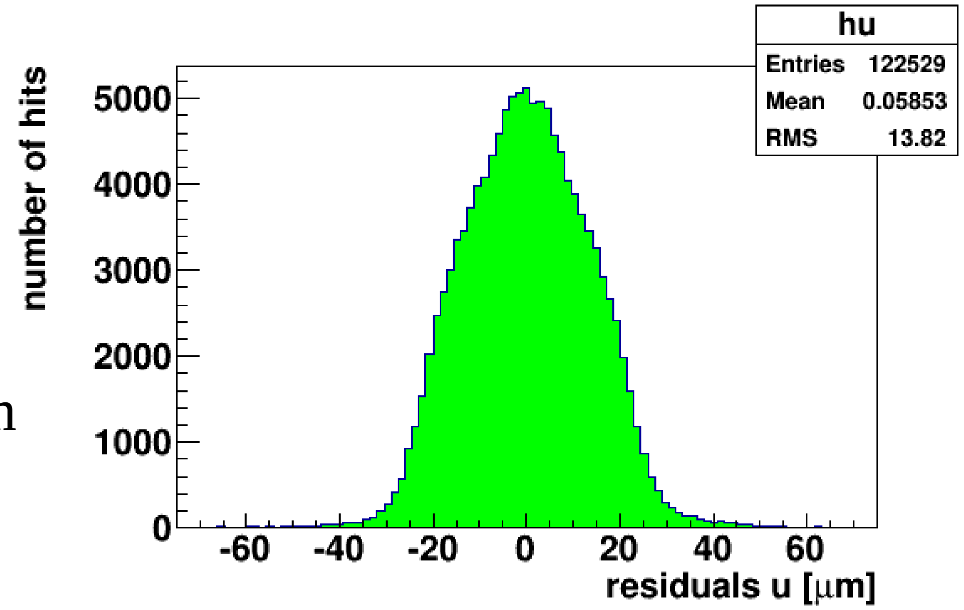
micro-channel cooling DEPFET ladders

Results in a dedicated talk (M.A. Villarejo, this session)

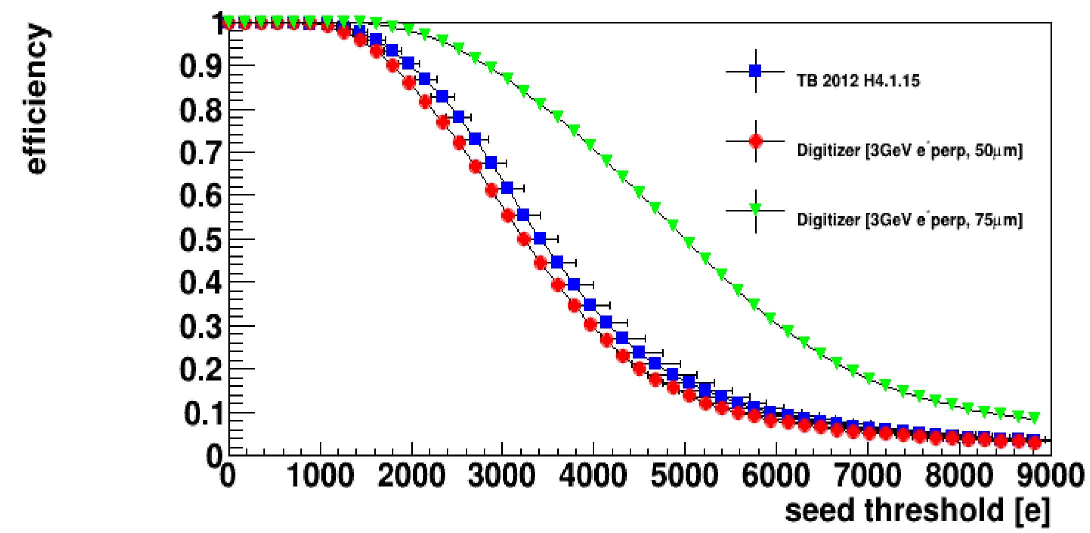
Belle II prototypes & performance: PXD6



PXD6 – the first multi-chip module
Sensor thinned to 50 micron
(Belle II → 75 micron)
3 read-out chip pairs + 4 steering ASICs bump-bonded on metal
(Belle II → 2x4 DCD+DHP, 2x6 SW)
First TB at DESY in January 2014

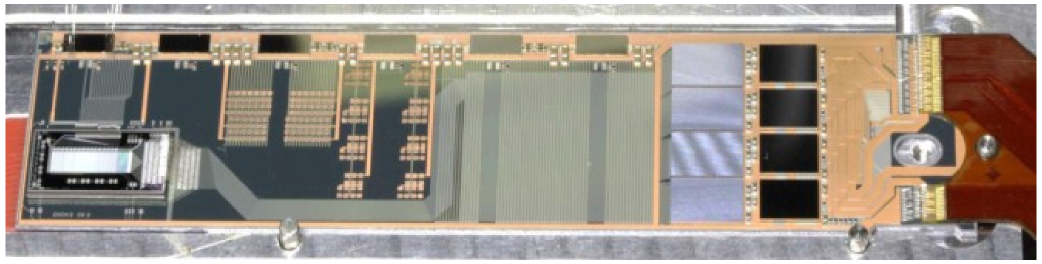


Resolution as expected for 50 µm pitch on 50 µm thick substrate

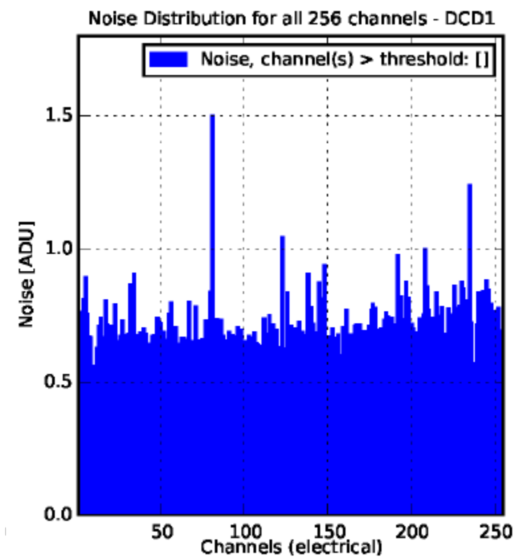


Efficiency vs. (seed) threshold: for 75 mm thick sensor and perpendicular incidence 2000 electrons is still 99% efficient

Belle II prototypes & performance: PXD6



EMCM – final metal layout + ASIC integration
(just lacking the implants that turn the silicon into a detector)



0.7 ADU noise ~ 115 electrons
For full (305 MHz) speed operation!

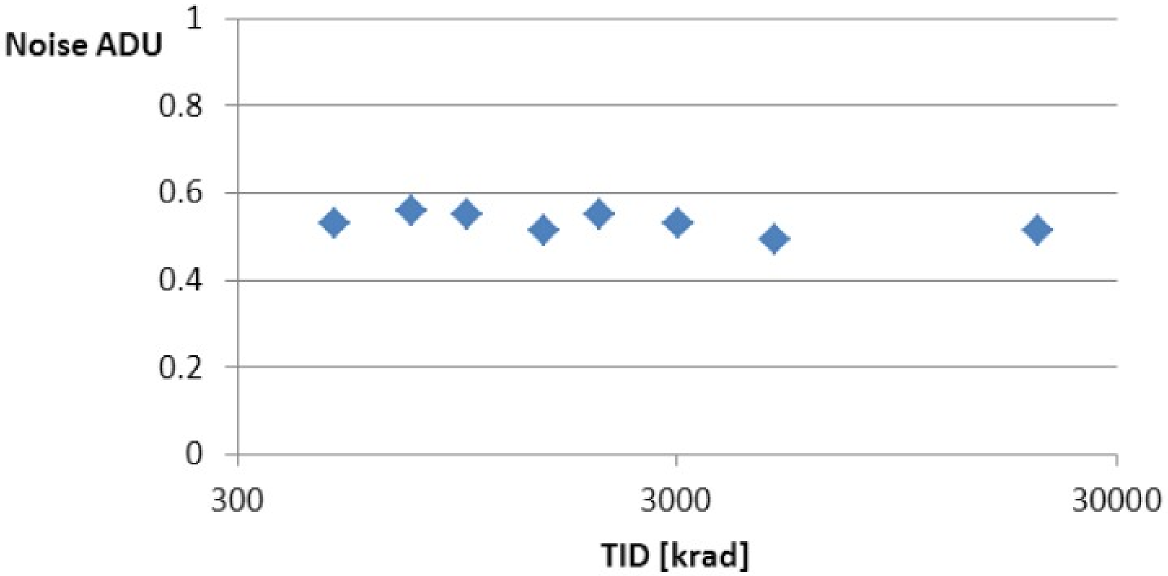


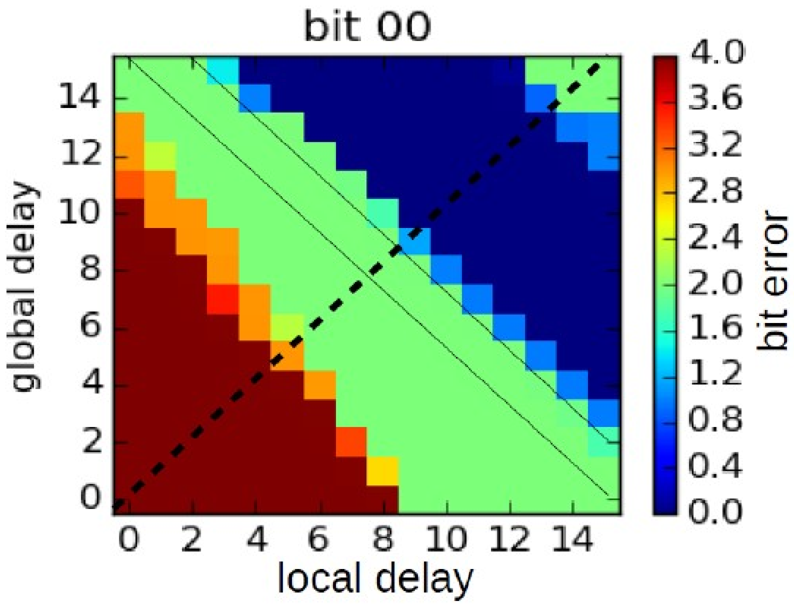
Fig. 3-20 Evolution of noise with higher TID

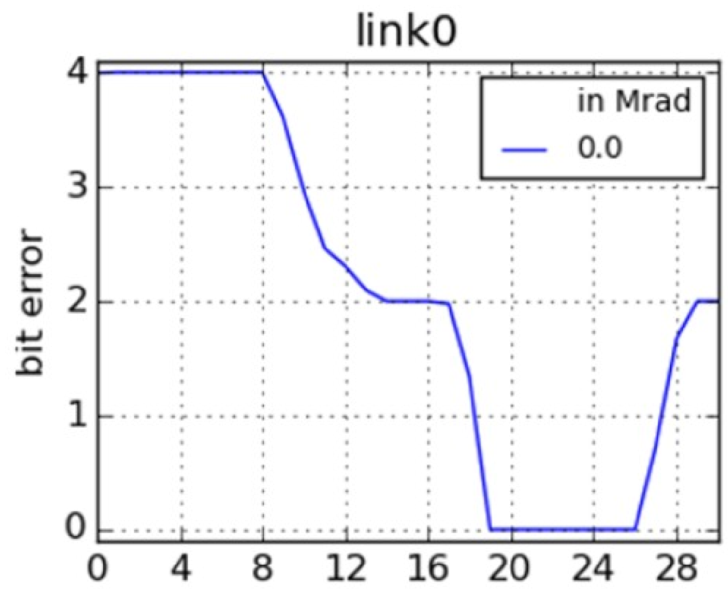
Noise unchanged after mounting on silicon-only ladder
Noise unchanged after irradiation with an ionizing dose of up to 30 Mrad

DCDB2, DCDB4, DHP0.2, DHPTv1.0, Switcher-B18 v1.0 & v2.0

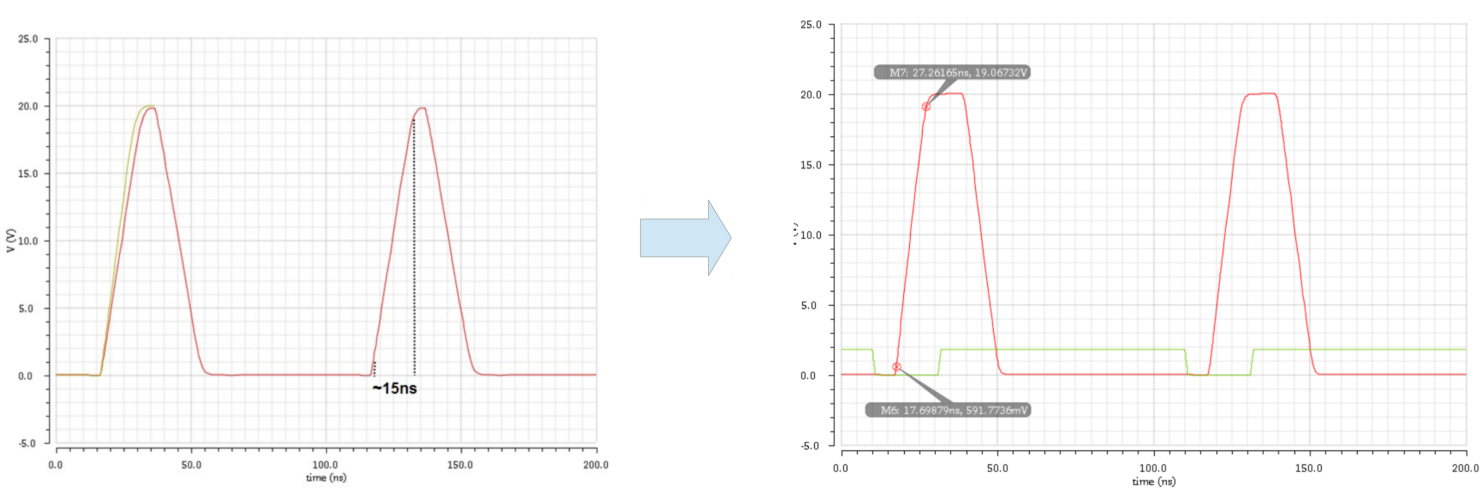
DEPFET
Active Pixel Detector

Prototypes & performance: PXD6





Problem in high speed data transfer between read-out chip DCDB4 and data handler DHPT1.0
Work-around: slight over-voltage
Solution: include stronger driver in DHPT1.1 (March)



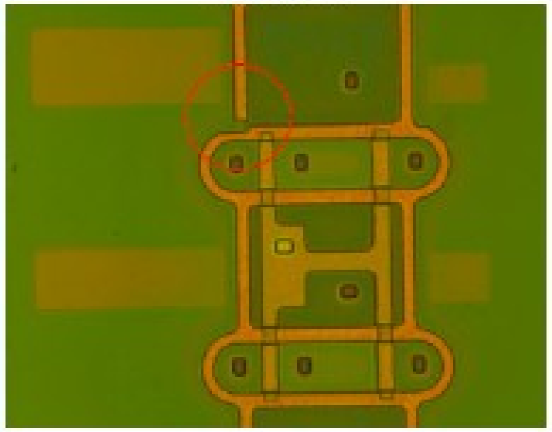
Current steering ASIC SwitcherB18 satisfies requirements
Rise time of clear signal under full load of CLEAR network (150 pF) to be improved in V2.1 (December)

DEPFET
Active Pixel Detector

Belle II production: sensors

PXD9-6: Belle II production pilot run
5 dummy + 3 real wafers

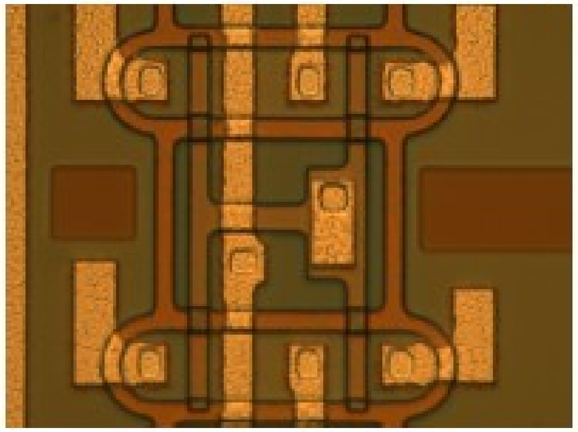
Phase I



→ only by optical inspection after each step

→ impact of defect not always obvious

Phase II

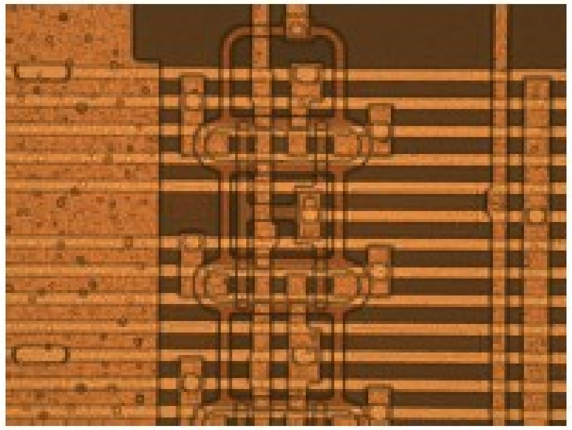


after 1st aluminum

→ 1st elec. Measurements

→ Global contacts

→ Diodes, single DEPFETs, test structures



after 2nd aluminum

→ Matrix testing with probe card on semi-automatic probe station

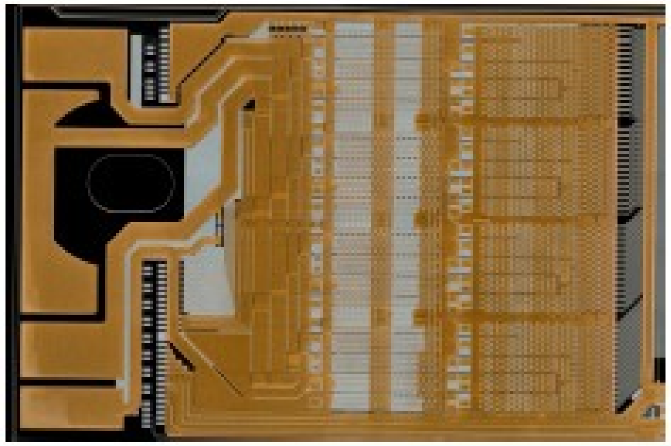
Phase III

After Cu process

→ EOS and periphery testing

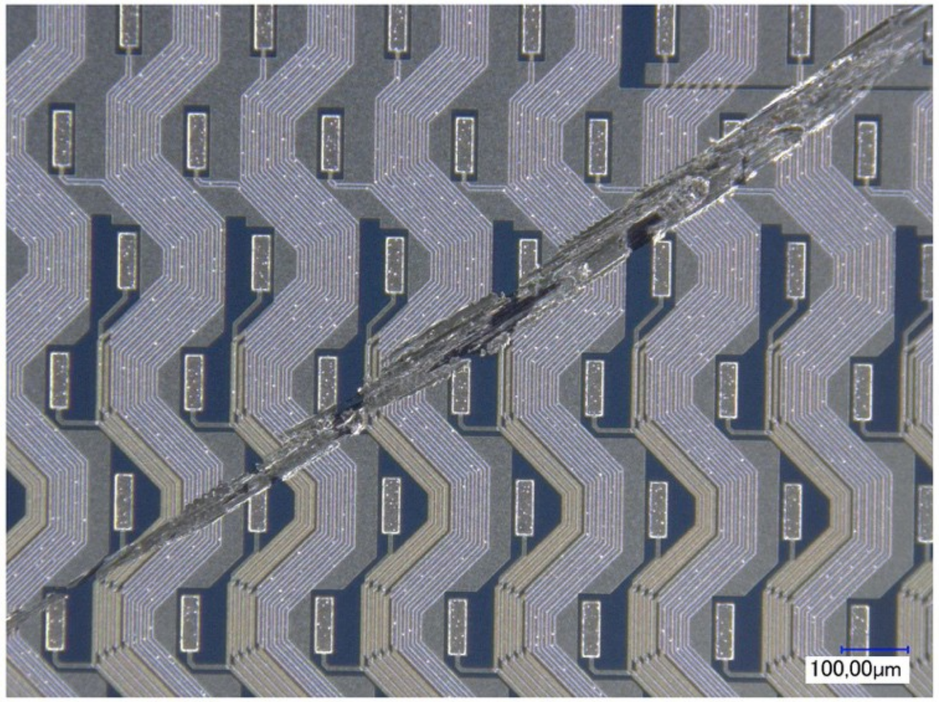
→ Flying prober testing

→ Final yield number



DEPFET
Active Pixel Detector

Sensor production: yield



Sensor was "suspicious" after phase I visual inspection
Accident during test after Aluminium 2 finished it off

PXD9 wafer number

Ladder type

	W30	W35	W36
IF	0	98.44	98.96
OF1	100.00	98.44	98.96
OF2	99.48	98.96	99.48
OB1	97.72	99.40	0
OB2	99.48	0	98.96
IB	97.92	0	99.48
Total	**83.3**	**66.6**	**83.3**

Shorts between n+ and p+ implant (lethal) detected after Aluminimum I

Executive yield summary:
14/18 (78%) sensors are working
10/18 (56%) are grade A (>99% of pixels)

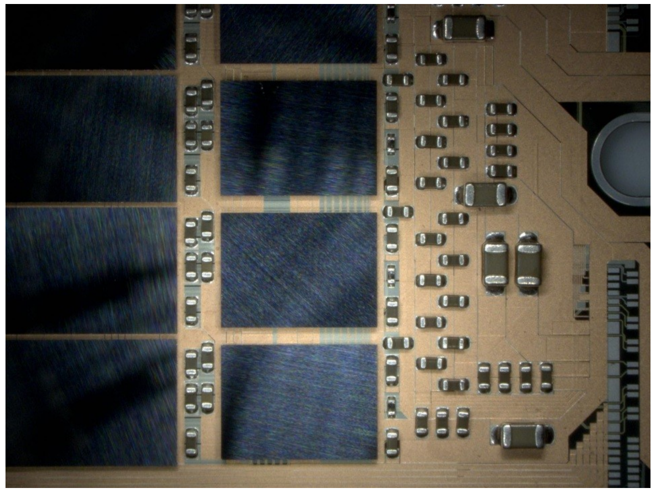
Better than we hoped after phase I!
Bulk sensor production starting

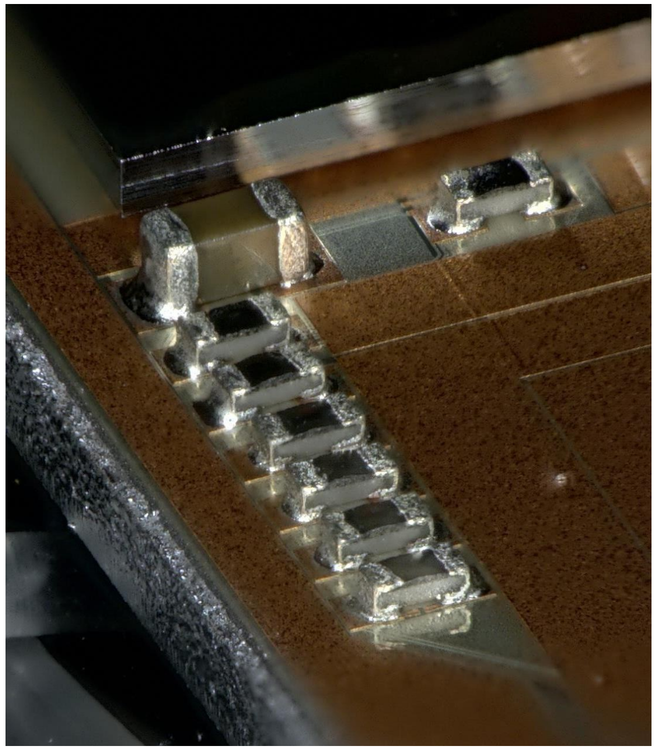
DEPFET
Active Pixel Detector

Ladder assembly

Flip Chip of ASICs (~240°C):

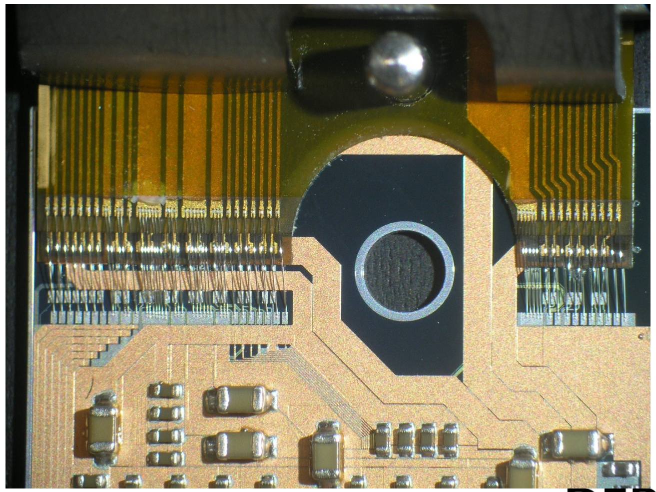
- ▷ Bumped ASICs have the same solder balls (SAC305)
  - DHP bumping at TSMC, DCD bumping organized via Europractice
  - SWBv2 bumping on chip level at PacTech
- ▷ **Flip Chip of PXD modules on custom made support plates**
- ▷ **Two PXD9 from W30 assembled**





SMD placement (~200°C):

- ▷ Passive components (termination resistors, decoupling caps)
- ▷ Dispense solder paste/jetting of solder balls, pick, place and reflow
  - PbSn 37/63 solder
- ▷ Process by Finetech in Berlin
  - **Install Finetech process at HLL**
  - **Backup at NTC in Valencia**

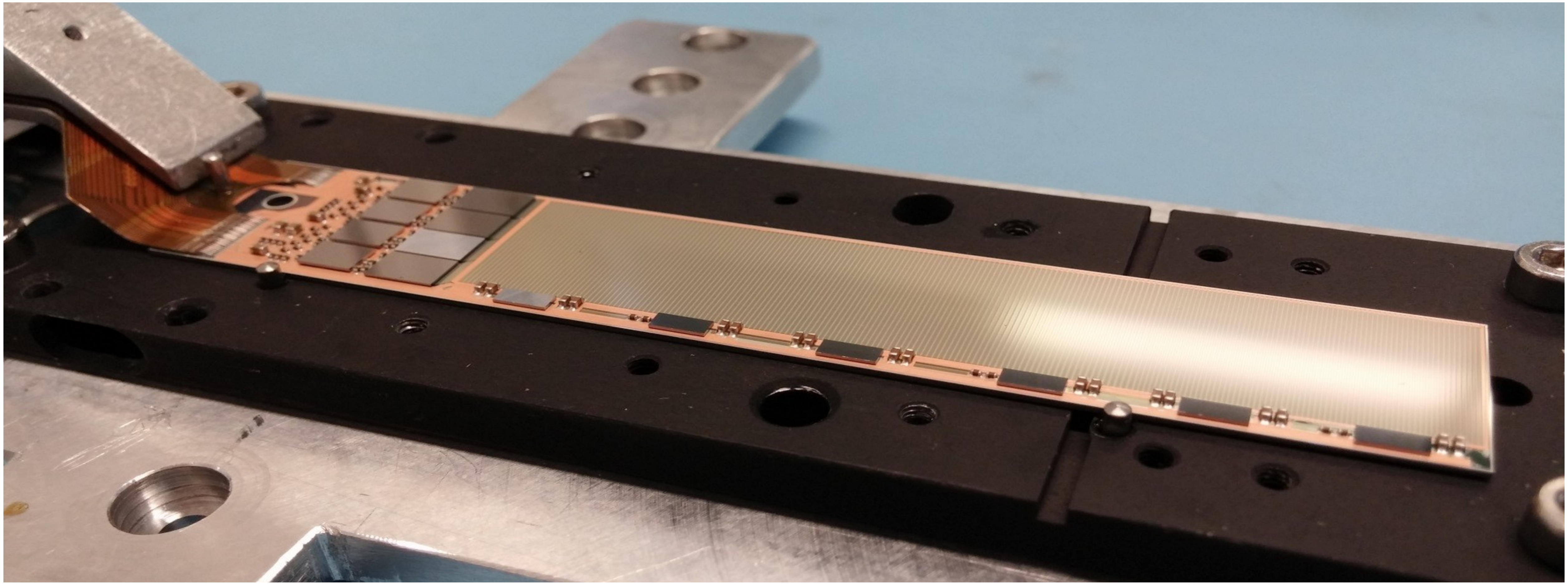


Kapton attachment (~170°C), wire bonding:

- ▷ Solder paste printing on kapton,
- ▷ Wire-bond, 32 μm Al wires kapton-substrate
- ▷ EMCM and production MPP Munich

Final half-ladder

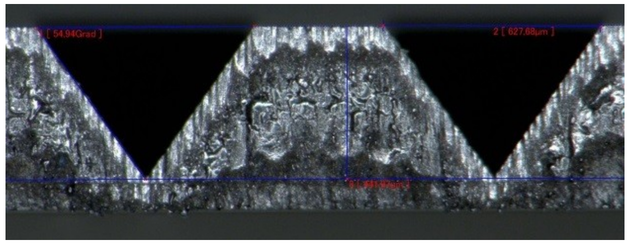
Fully functional.... major milestone for the Belle II project!

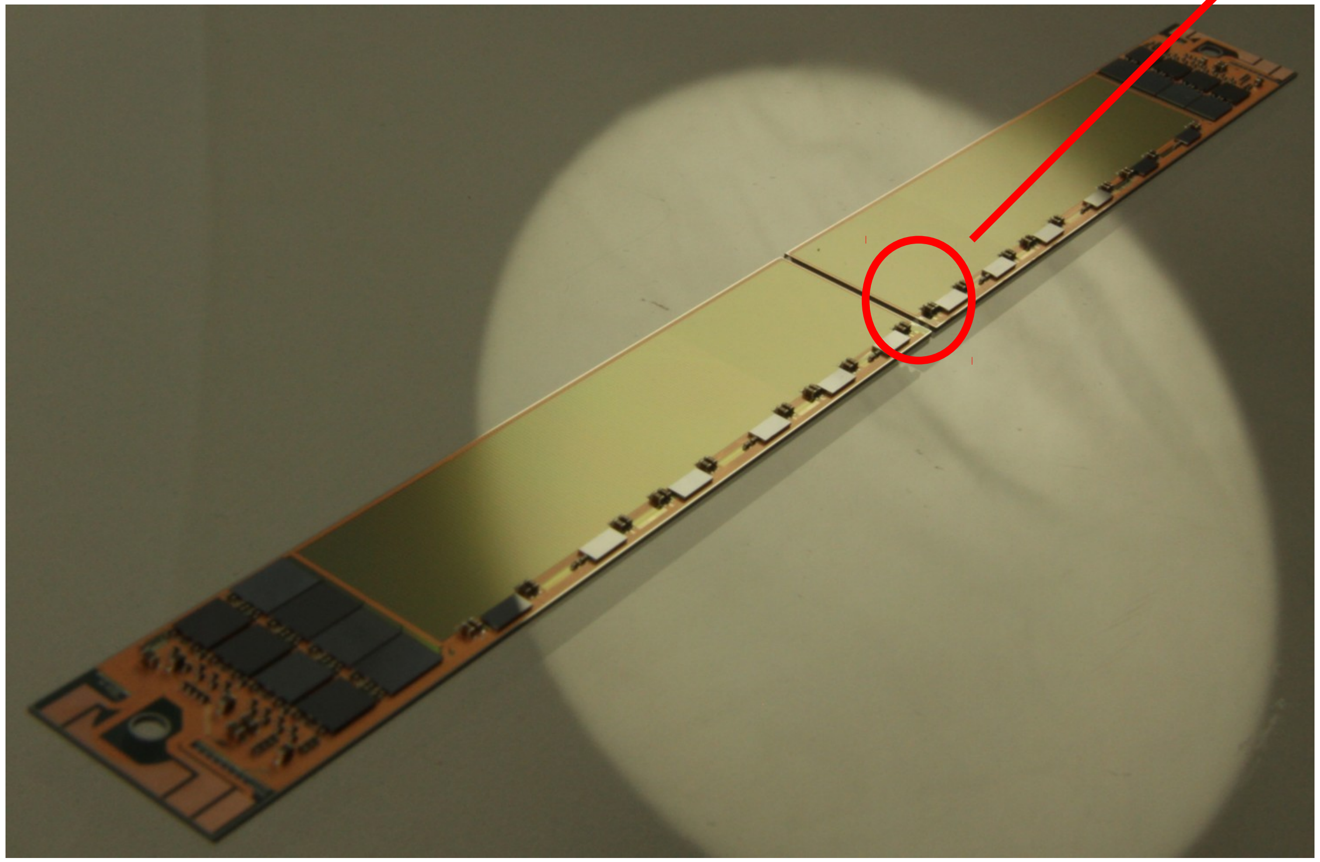


detailed electrical characterization ongoing

From half-ladder to a full-length ladder

Full-length ladder achieved by connecting two half-ladders





Exercised on mechanical samples.
Looking forward to the real thing.

Conclusions

The DEPFET collaboration has built the first complete all-silicon ladder with integrated support, read-out and steering

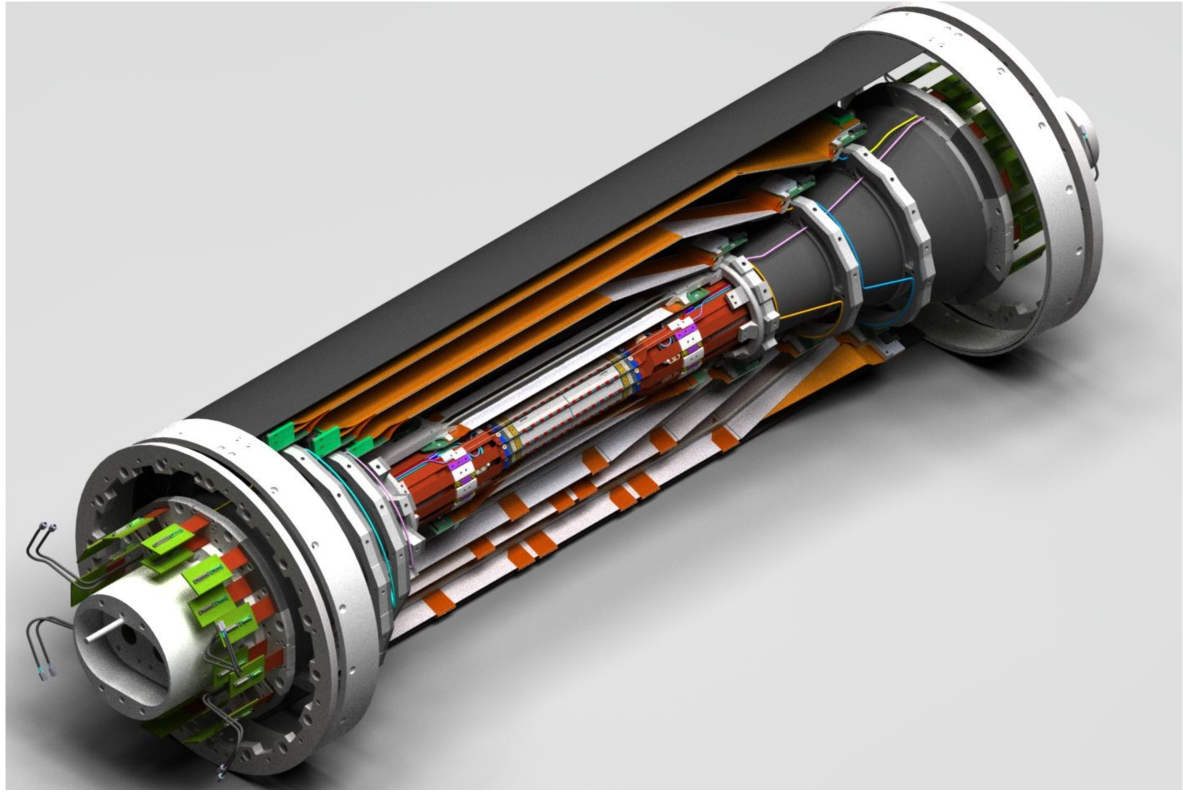
→ sensor production yield acceptable
→ ASIC and passive component placed successfully, performance as expected
→ full-length double-ladder assembled

DEPFET can meet the main LC vertex detector requirements

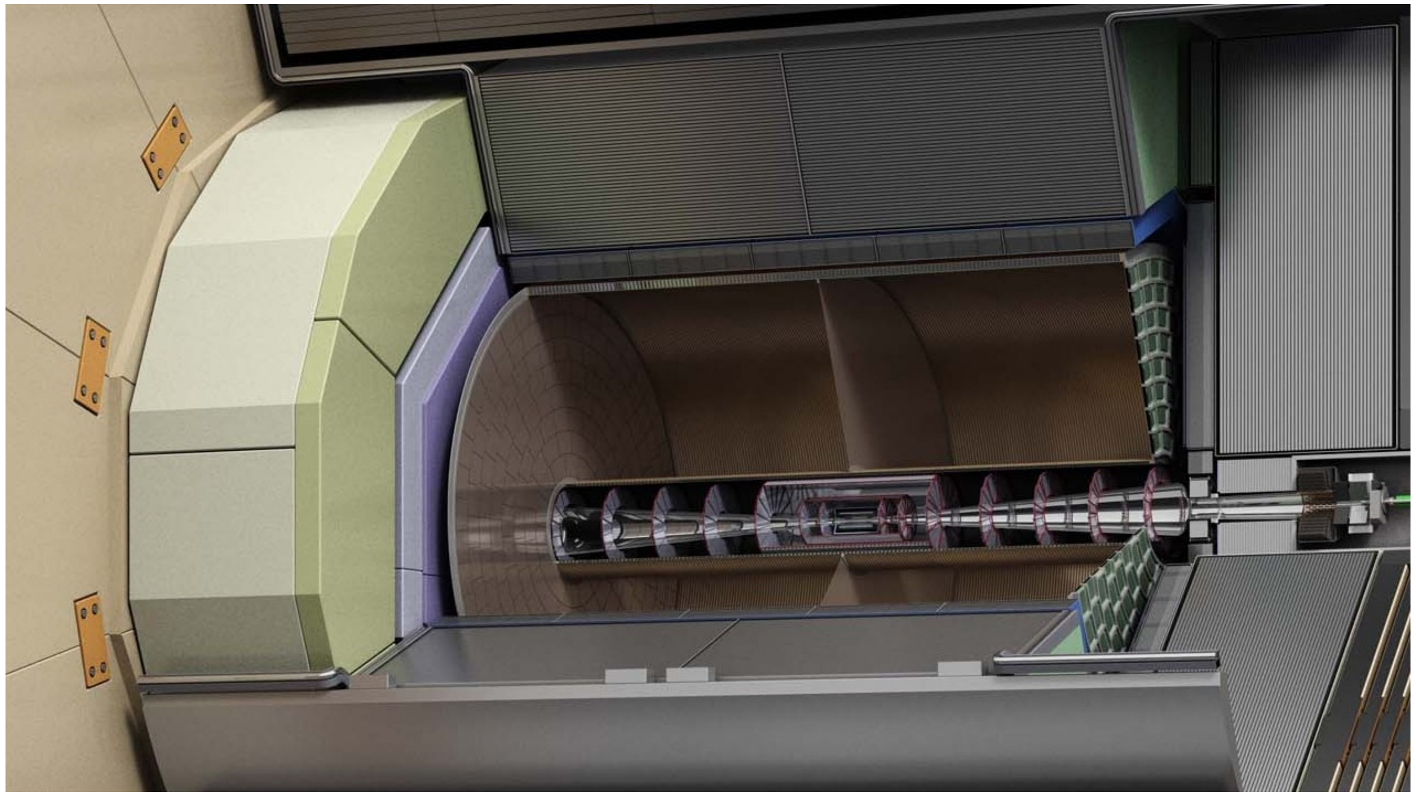
(IEEE TNS paper)

→ 2-4 μm spatial resolution (with small-pixel sensor, 20 x 20 μm^2)
→ read-out speed: 40 μs/frame for ILD layer 1 (with current read-out)
→ ladder material ~ 0.15% X_0, close to LC specification (0.21% X_0 in Belle-II)
→ solution for pixelated disks is being developed
→ thermo-mechanical properties OK (air cooling, power pulsing)

Belle II vs future LC



Belle II vertex detector (2016):
innermost two layers based on DEPFET active pixel sensors



ILD and SiD inner tracking systems (202X):
five- or six-layer barrel vertex detector and several pixelated disks

	ILC	*Belle-II*
occupancy	0.13 hits/μm^2/s	0.4 hits/μm^2/s
Radiation	< 100 krad/year, 10^{11} 1 MeV n_{eq}/year	> 1Mrad/year, 2 x 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	0.15 % X_0/layer	0.21 % X_0/layer