DEPFET active pixel detectors

Marcel Vos – IFIC Valencia

The DEPleted Field Effect Transistor

Fully depleted sensor with in-pixel amplification

Fast signal collection

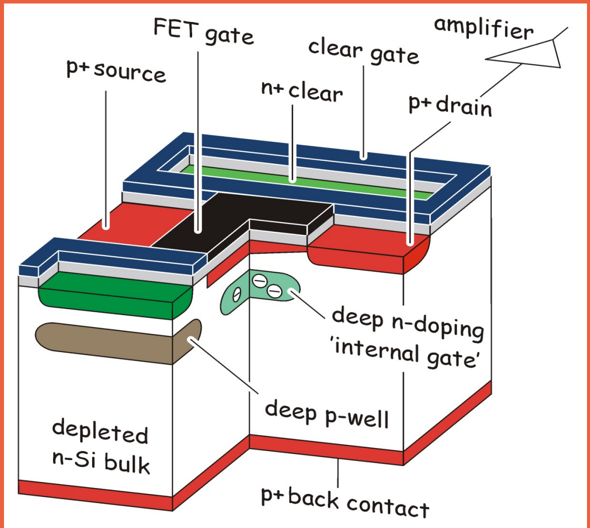
Excellent noise performance

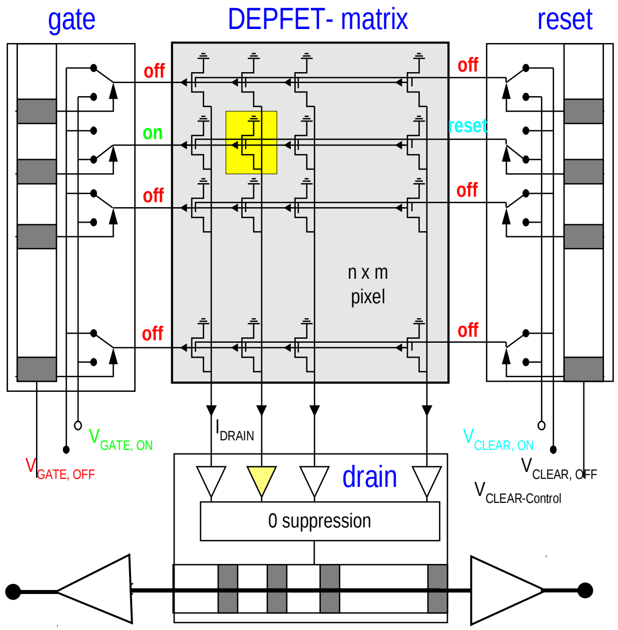
→ thin sensors!

Signal collected when pixel is "off"

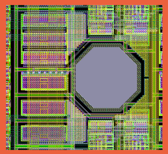
Low power consumption!

Clear the signal



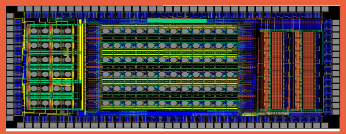


Switcher-4

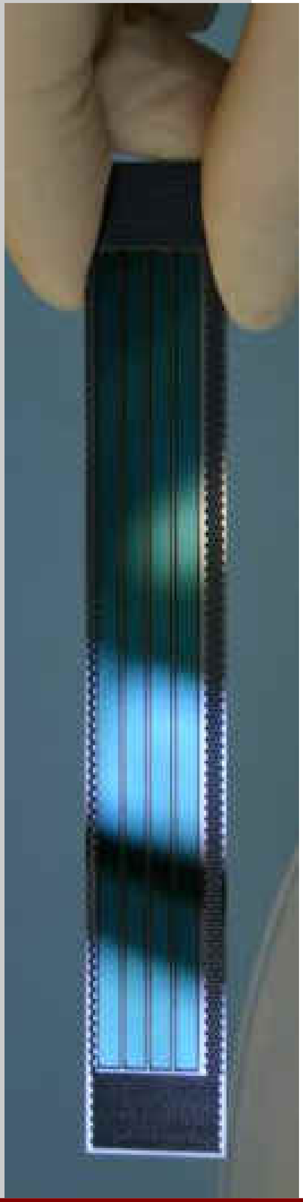


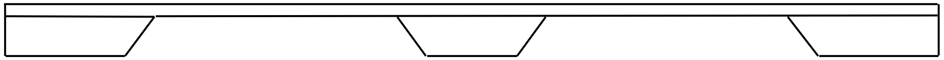
DCD

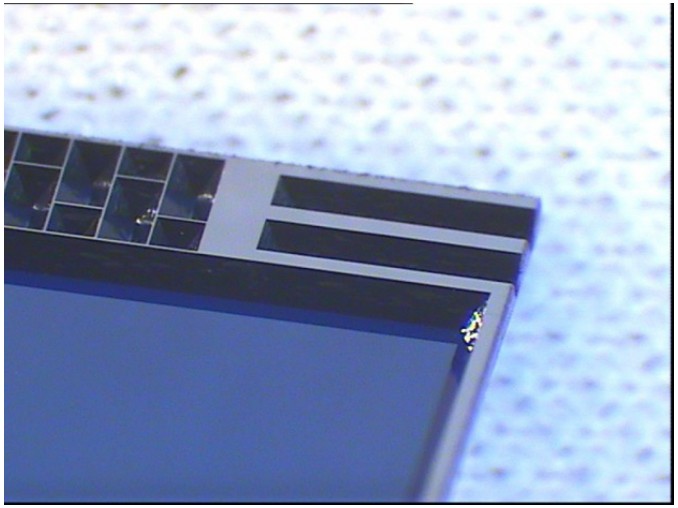
Drain Current Digitizer



The all-silicon module







The all-silicon module

- Use anisotropic etching on bonded wafers to create a thin, self-supporting sensor
- Auxiliary electronics located on the sensors, signals routed in metal layer
- One material – uniform (and small) thermal expansion

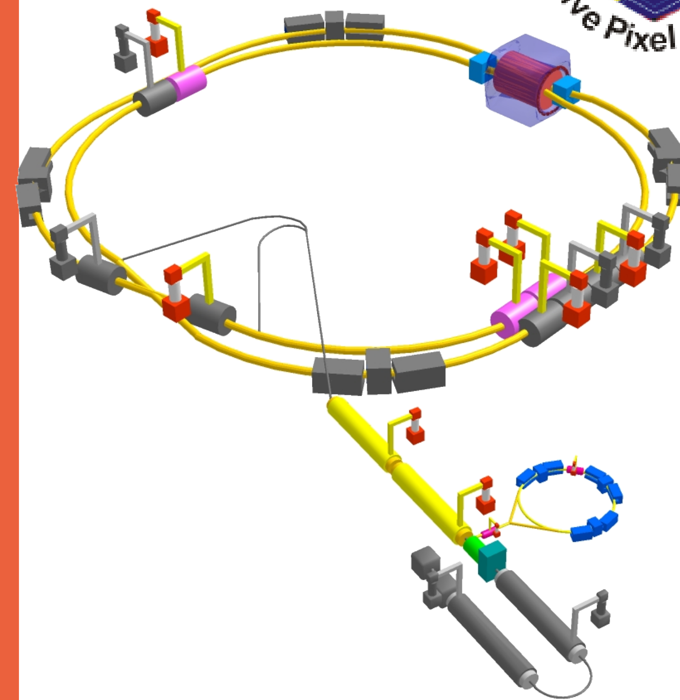
Future colliders – ILC vs. Belle-II

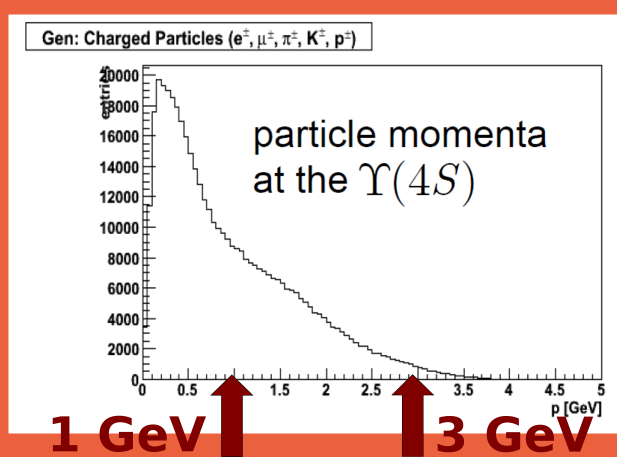
Belle-II detector upgrade

4 layer DSSD →
2 layer pixels + 4 DSSD

challenges for the detector
Watch your material budget!!
0.19 $\%X_0$ in total (0.15 % Si)

Building a complete system





Super KEKB
Quest for BSM

DEPFET Active Pixel Detector

ILC vs Belle-II

	ILC	*Belle-II*
occupancy	0.13 hits/μm^2/s	0.4 hits/μm^2/s
radiation	< 100 krad/year	> 1Mrad/year
Duty cycle	1/200	1
Frame time	25-100 μs	10 μs
Momentum range	All momenta	Low momentum (< 1 GeV)
Acceptance	6°-174°	17°-150°
	Excellent spatial resolution (3-5 μm) AND material budget (0.12 % X_0/layer)	Lowest possible material budget (0.15 % X_0/layer) Moderate pixel size (50 x 75 μm^2)

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

Future collider - ILC

VXD: impact parameter resolution 5 – 10 μm.

This precision is required to achieve excellent heavy flavour tagging, particularly for couplings of the Higgs boson to charm (cτ ~150 μm) and bottom (cτ ~ 450 μm)

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

Unprecedented precision
(small pixels, 20x20 μm^2)

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

To meet the resolution requirement ILC DEPFETs need small pixels (order 25x25 μm^2 pixels, Belle-II pixels are 50x75 μm^2).

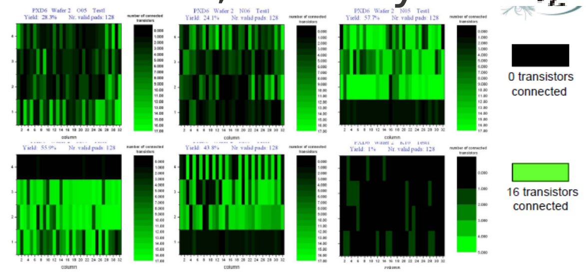
The feasibility and performance of small pixels have been demonstrated long ago, but long columns put pressure on the read-out speed

The sensor: PXD6 production

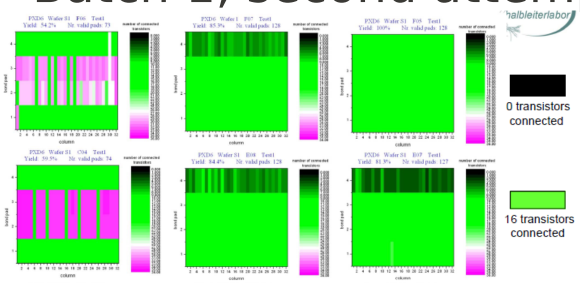
50 µm thin DEPFETs!

PXD6 production was split before the 1st metal layer:
- batch 1 (4 wafers, 3 SOI) finished, 3 wafers cut, one wafer repaired with many shorts
- batch 2 (4 wafers, 3 SOI) finished, 2 wafers repaired & cut, matrix characterization ongoing
- batch 3 (2 SOI wafers with DHP footprint), partially processed

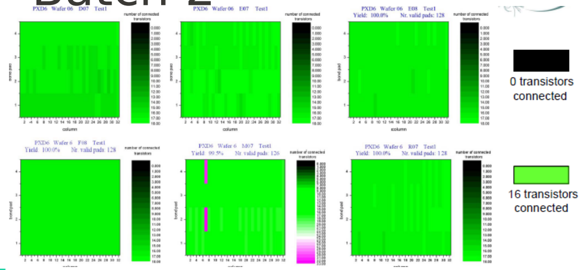
Batch 1, initially



Batch 1, second attempt



Batch 2

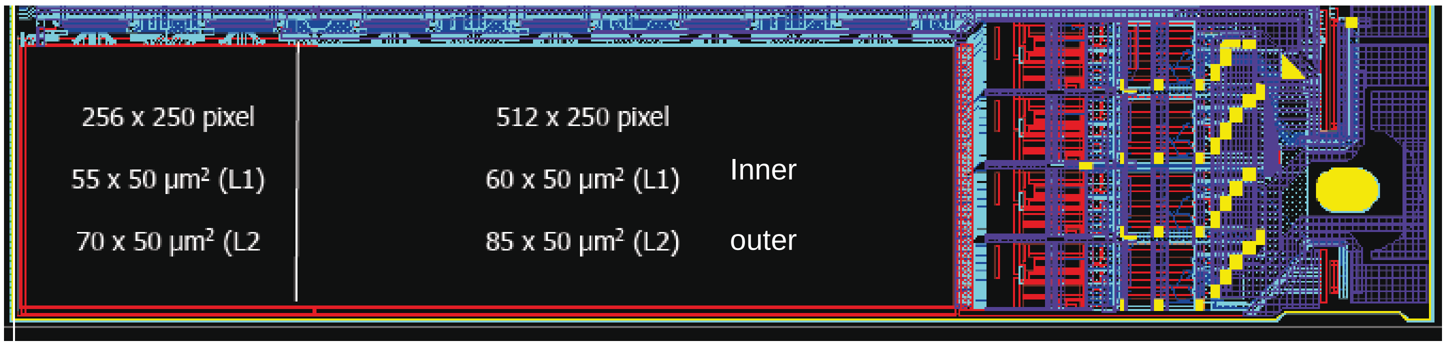


Yield	Batch I	Batch II (after repair)	Batch III
Small matrices	30%	99%	98%
Half ladders	~6% (1/16) (after Al1 6.25% - 1/16)	25% (4/16) (after Al1 100% - 16/16)	50% (4/8) (after Al1 100% - 8/8)

Measuremtents of full size matrices started

The sensor: PXD9 production

Original Plan (Nagoya, July 2012): Production with 2x6 wafers for Fast Prototype run, to be followed by main production

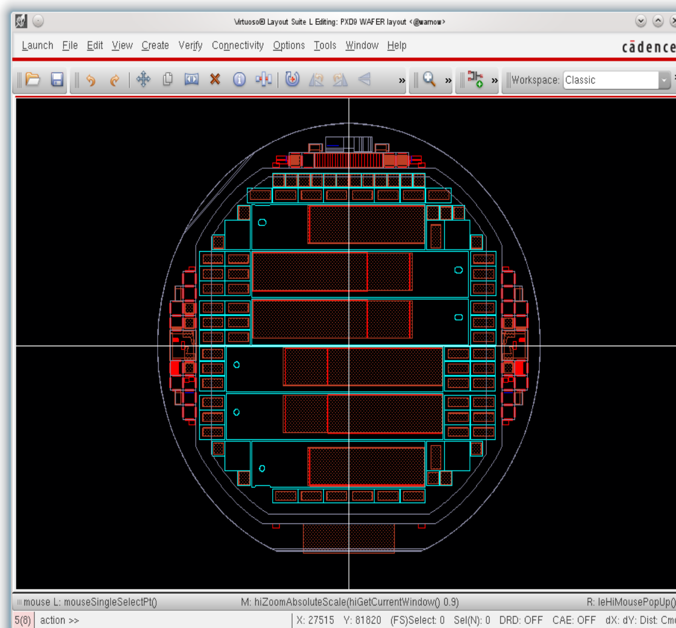


2 inner modules
4 outer modules

⇒1 inner ladder
⇒2 outer ladders

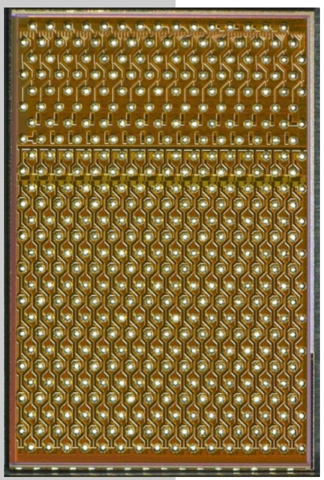
	built	needed	min yield
Inner. x24	24	8	33%
Outer x24	48	12	25%

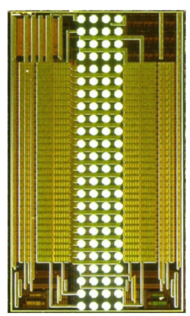
Last PXD6 batch: ~ 50%

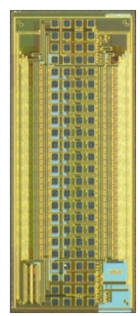


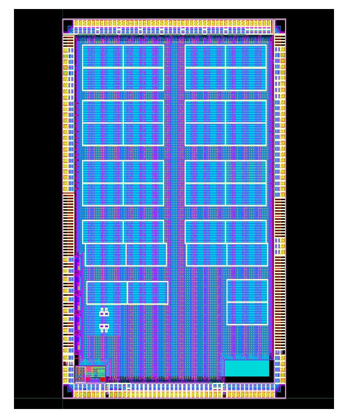
The ASICs are ready!

The full-size close to final versions of the ASICs are designed, produced and found to work.
DCDBv2 (some excess noise is to be understood, but still better than v1)
SWITCHERBv1 and SWITCHERB18
DHP02 (in 90nm IBM technology) NEW (but needs to be redesigned for TSMC 65nm). The layout of the module periphery has been done as well









Milestone!

DCDBv2
180nm UMC
(Heidelberg)

SWITCHERB
350nm HV AMS

SWITCHERB18
180nm HV AMS
(Heidelberg)

DHP0.2
90nm IBM
(Bonn with help from Barcelona)

Drain Current Digitizer – DCD

- 0.18 µm technology
- regulated cascode
- current memory cells
- two 8-bit algorithmic ADCs
- 6:1 multiplexed LVDS outputs
- bump bond IOs + wire bonds for testing

Measured performance

Fully functional at 600 MHz clock-speed

Noise at 12.5 MHz:

0.6 – 1 LSB (w/o cap. input load)

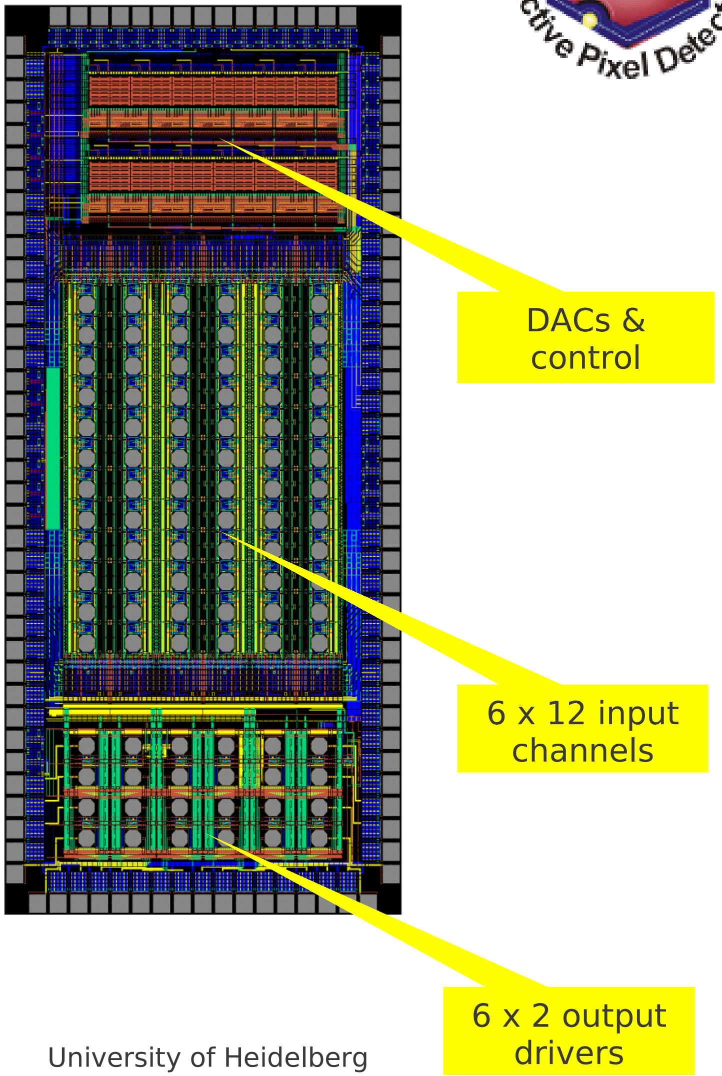
< 2 LSB with up to 82 pF load

Input range: [**0..24µA**] (19 MIPs @ 50 µm)

LSB: 100 nA (higher than designed)

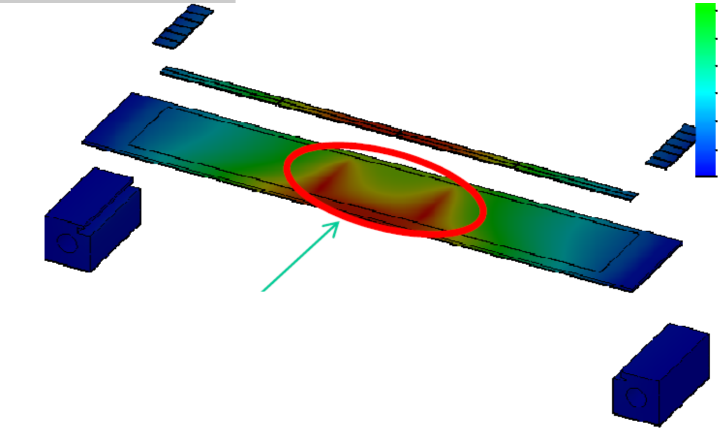
Gain: 10 ± 0.1 LSB / µA

Power: 6 mW/channel



University of Heidelberg

Thermal issues



Carlos Mariñas, thesis U. Valencia, CERN-THESIS-2011-101

System issues

Cooling/mechanics are being addressed for Belle-II by a combination of measurements on a mock-up and simulations.

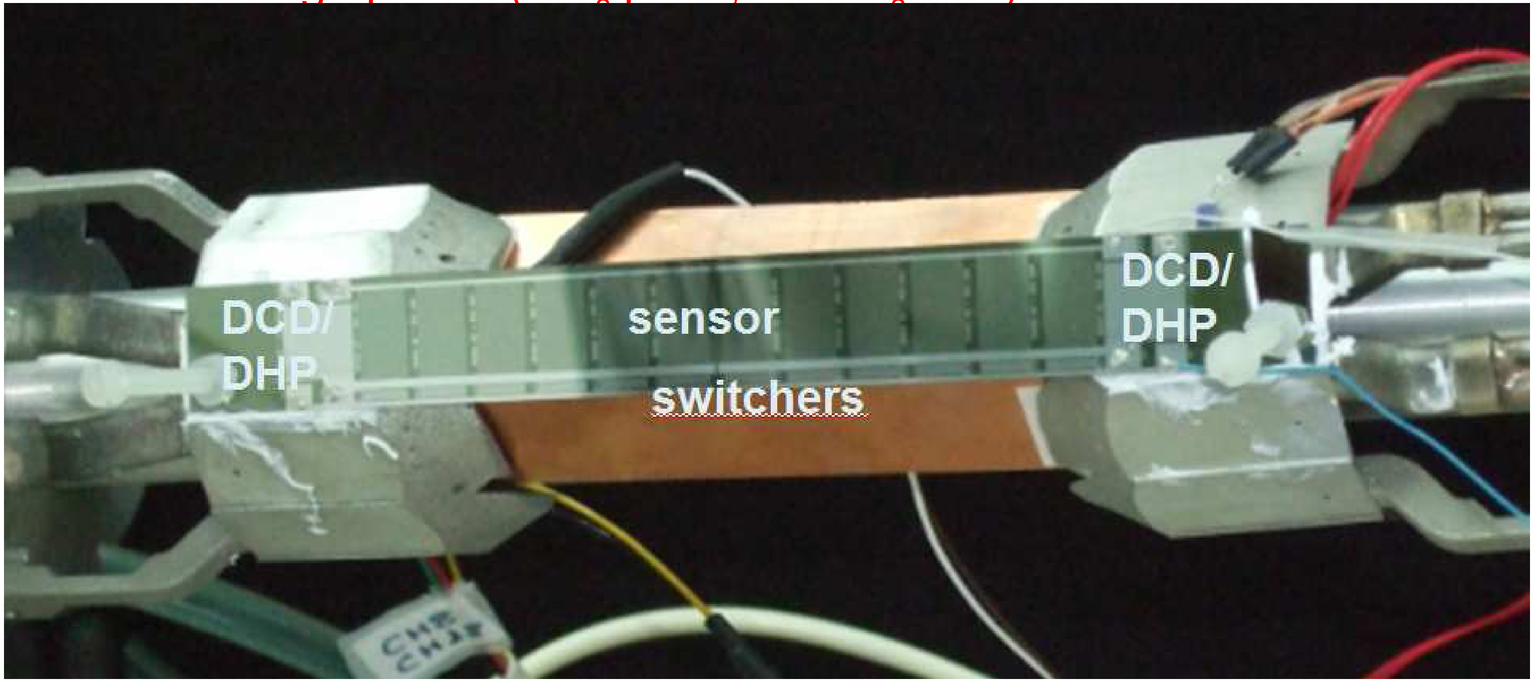
Belle-II; combination of liquid and air cooling required to remove power dissipated by DCDs, switchers and sensor

ILC; only air cooling to remove much-reduced heat load

Thermal performance

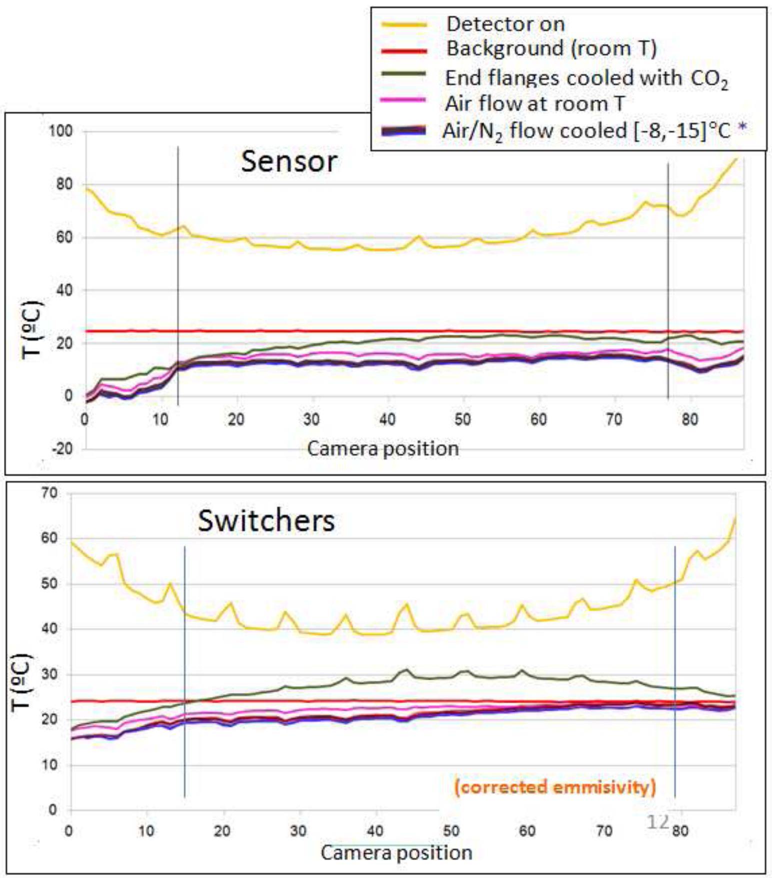
The key element: mechanical "dummy" sensor: mechanically identical to the real thing, but with circuits designed as "heaters" in the metal layer

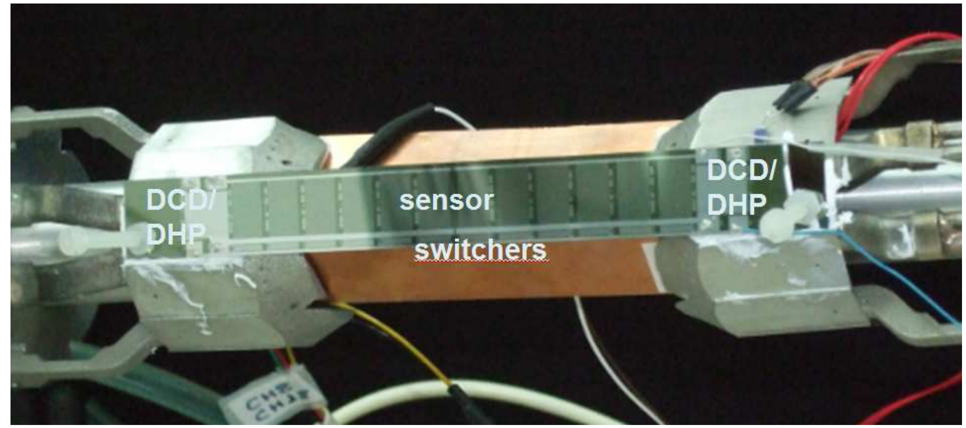
Integrate into Belle-II detector mock-up at IFIC Valencia with realistic supports and complete set of cooling options (CO_2 plant, cold N_2 flow)

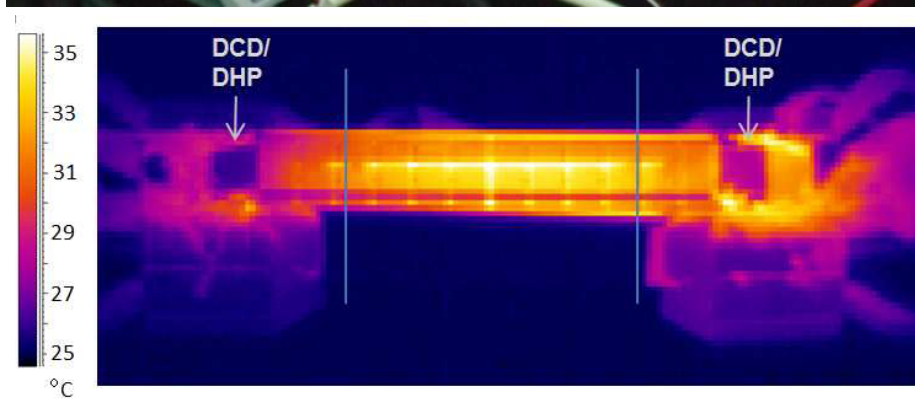


Thermal performance

Look at the detector at a different wave length

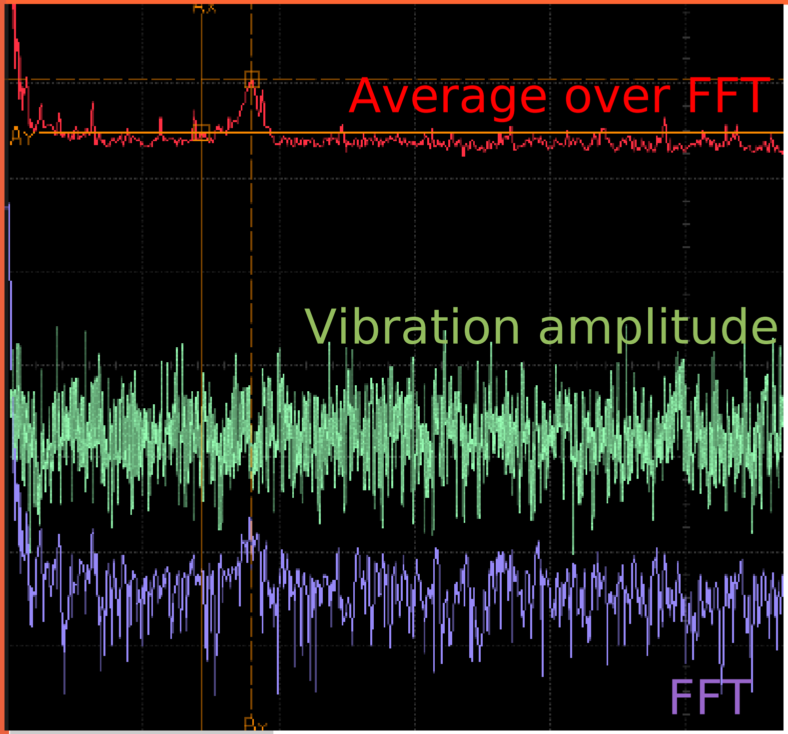






Confirm Finite Element studies:
Modest (1 m/s) air flow needed and sufficient to cool sensor center
A. Oyanguren, LCWS11

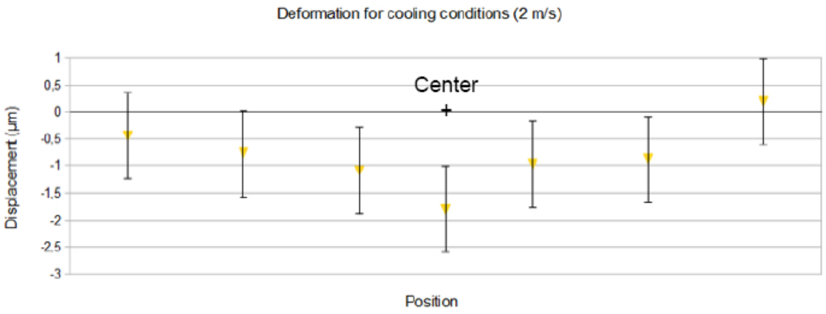
Mechanical impact of air cooling



Capacitive sensor (Micro-epsilon Capa NCDT 6100) and piezo-electric accelerometer (3PCB Piezotronics model 352A24)
A peak at ~400 Hz (depending slightly on position, orientation) appears for gas flow with a pressure greater than 4 bar

Deformation:
2 μm for nominal gas flow of 2 m/s,
up to 8 μm for max. pressure (10 bar)

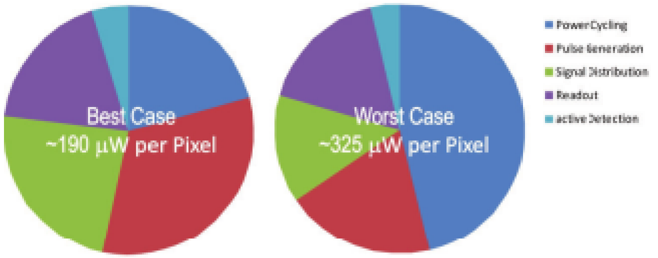
Vibration @ 400 Hz:
Amplitude = 0.7 μm (nominal)
Amplitude = 1.2 μm (max.)



ILC-specific thermo-mechanics

Thermal load & cooling concept very different at the ILC

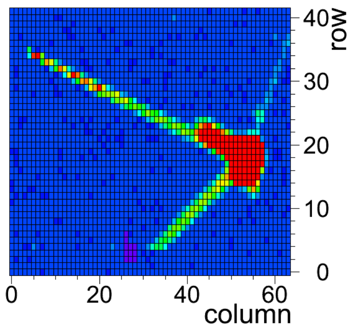
- ✔ Power pulsing; exercised at XFEL (MPI/Heidelberg)
  - ➔ derive realistic duty cycle
- ✔ Finite Element analysis set up (Bonn)
  - ➔ preliminary results look good
- ✔ Port Belle-II mockup to ILC (IFIC Valencia)
  - ➔ light supports/gas cooling
- ✔ Existing infrastructure for thermo-mechanical characterization will be extended within AIDA (DESY, Saclay, Oxford, IFIC, IFCA)
  - ➔ similar plans exist at CERN and elsewhere
  - ➔ Integrate IFIC Bragg fiber system



Hands-on power pulsing experience for DSSC at XFEL: completely shutting down the DEPFET and the analogue part of the electronics between bursts (~1ms burst, ~100ms gap). The total power consumption is reduced to 1/25.

By the DBD we want to have a full set of measurements & simulations

Beam tests



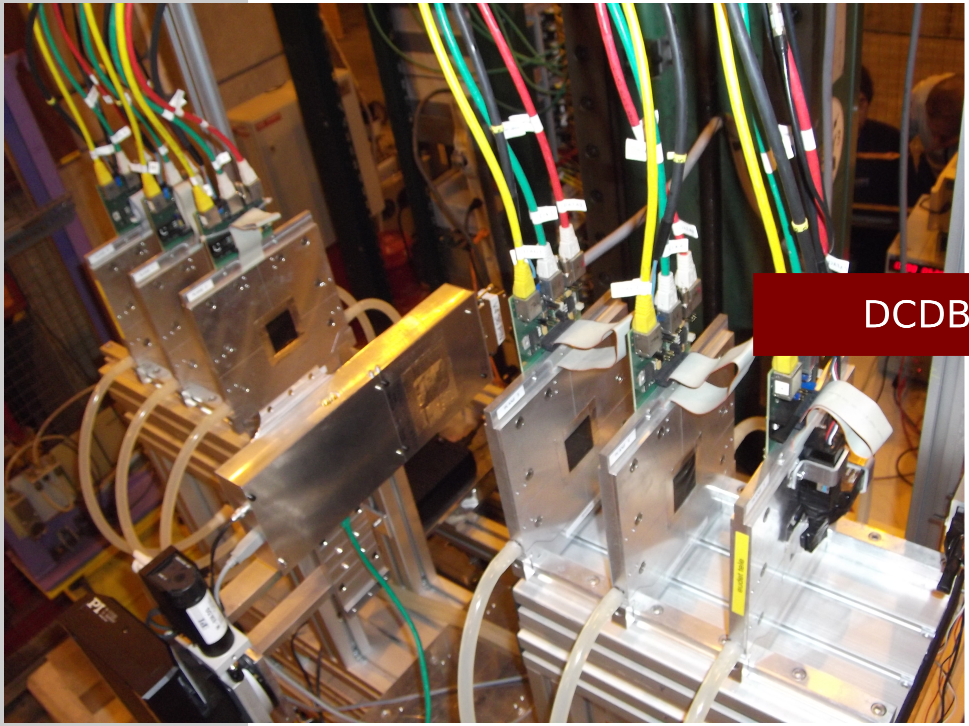
Devices Under Test:

ILC design

450 µm thick, small-pixel ILC design sensor

Three PXD6 devices

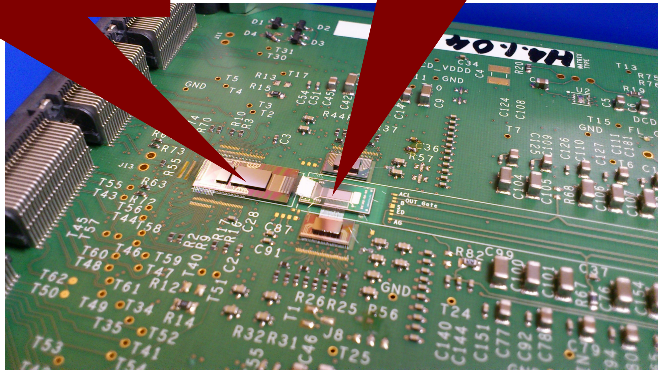
- Belle-II design (50 x 75 and 50 x 50 µm)
- Sensors thinned to 50 µm
- DCDB read-out 100 or 320 MHz



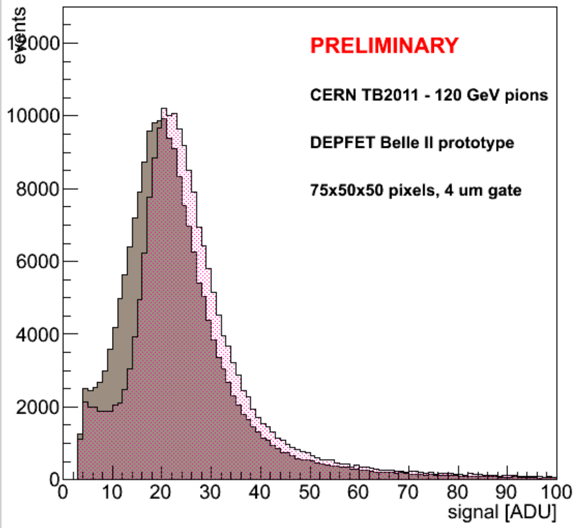
October 2011 (SPS)
April 2012 (DESY)
July/October 2012 (SPS)

DCDB read-out

DEPFET Matrix

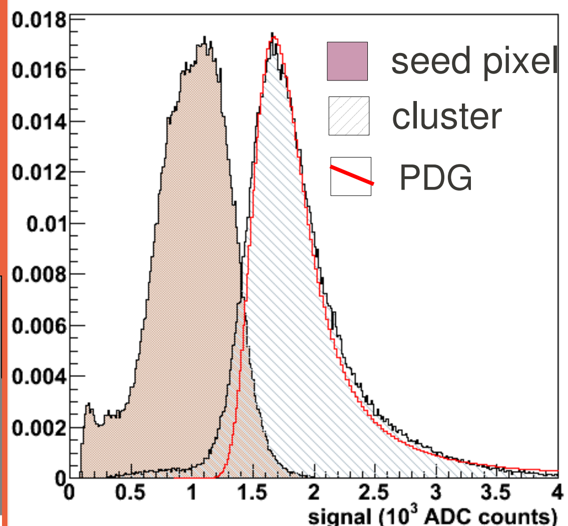


Result



Most Probable Signal:
S/N ratio ~ 20 - 40

TB2011 confirms the expected dependence on DEPFET parameters: gate length, oxide thickness
TB2012 → offset current subtraction from DCDBv2



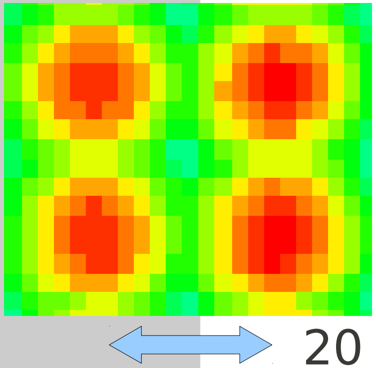
S/N on Belle-II design ~ 40

- S/N = 60 with 75 μm sensor
- Using conservative 5 μm gate length

Within errors of expected ratio

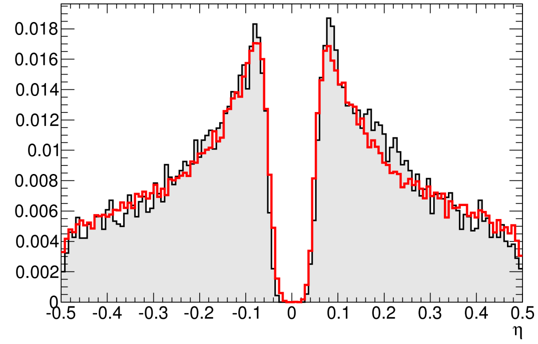
Charge collection

Charge collection from DEPFET is extensively studied in 7 years of beam tests, mostly on ILC design sensors

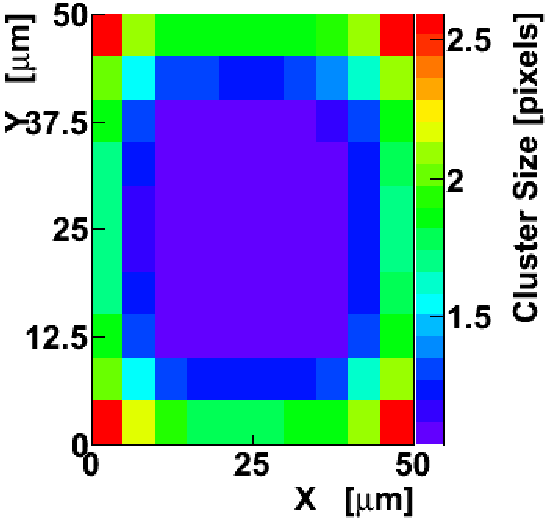


20 µm

"seed" pixel signal vs. position



η distribution in data
And digitizer

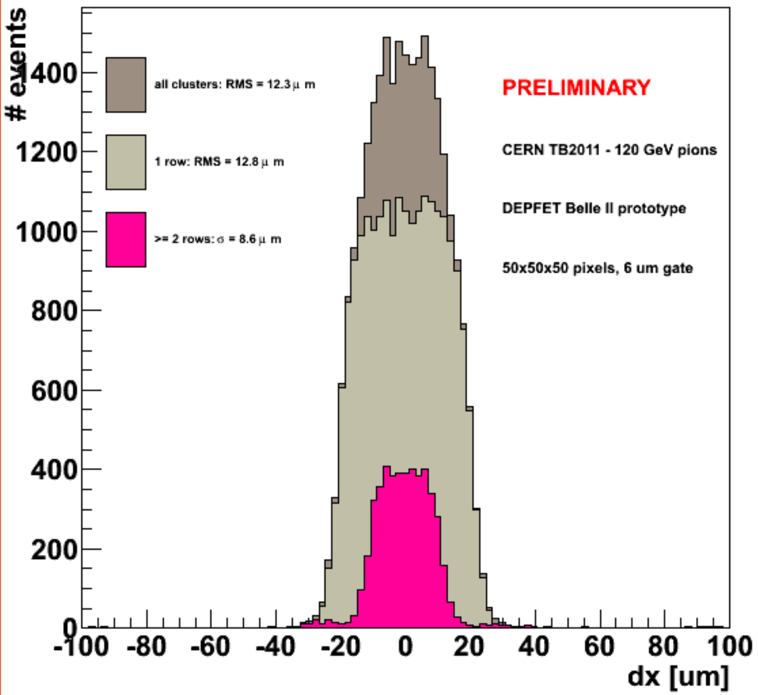


A detailed digitizer exists
- in ILC software
- validated using TB data

Increased realism in DBD: Evaluate technology-specific performance in ILC?

Cluster size vs. in-pixel position
for a Belle-II design sensor

Spatial resolution



Spatial resolution of module H4.1.04, Belle-II design

Single-pixel cluster show expected "box" distribution from -25 to +25 µm,

- smearing by telescope resolution ~ 2-3 µm
- binary RMS = 50 µm / $\sqrt{12}$ = 14.4 µm

Multiple-pixel clusters are relatively rare under perpendicular incidence

Spatial resolution depends on incidence angle, S/N, clustering (esp. 0-suppression), bias voltage (scan under analysis)

Summary

The DEPFET collaboration is developing pixel sensors with integrated amplification

- ✔ Performance in terms of spatial resolution, sensor material and power consumption well-established
- ✔ Applications: transparent and precise VXD for Belle-II and ILC
- ✔ Build a real system: auxiliary electronics development, cooling/mechanics
- ✔ Small, but steady effort to produce a backup document for the DBD with ILC-specific results