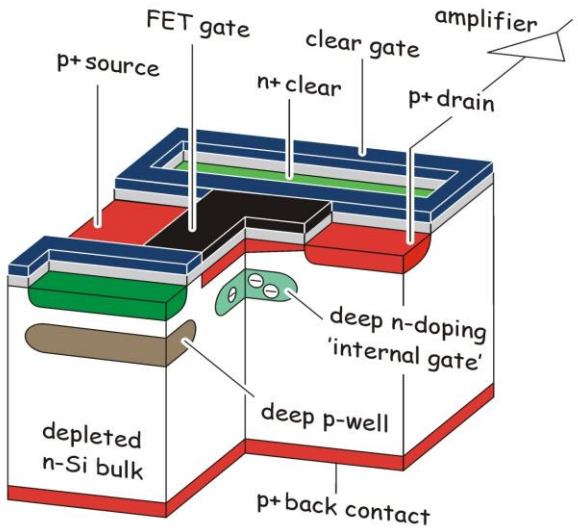
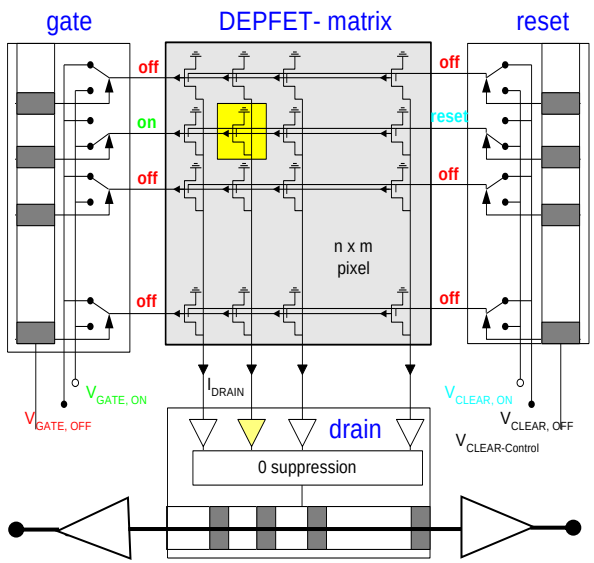
The DEPFET Active Pixel Sensor High Precision Vertex Detector for Belle-II and Future e+e- Colliders

Jelena Ninkovic *for the DEPFET Collaboration (www.depfet.org)*

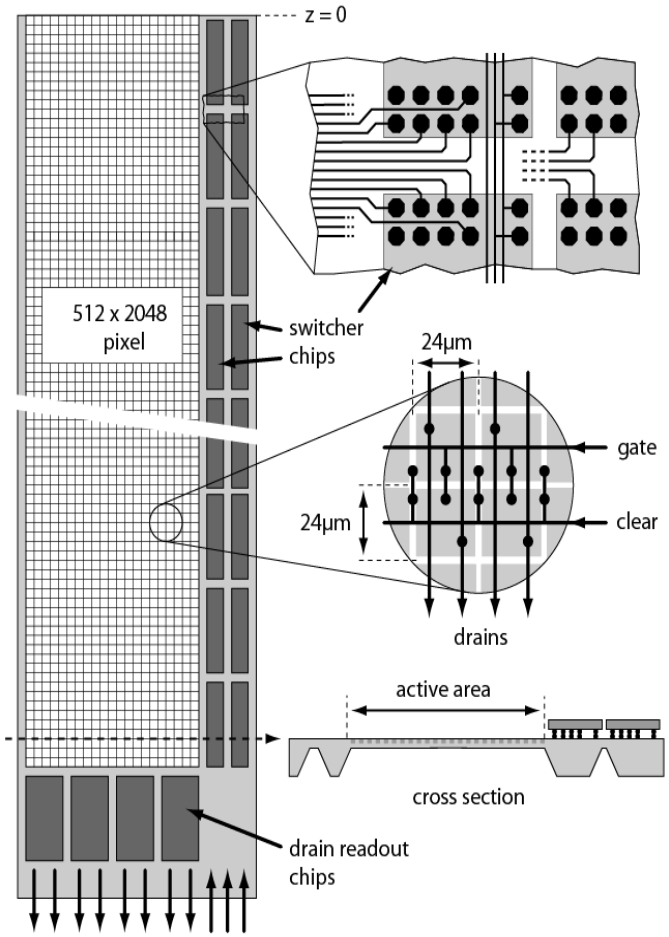
DEPFET basics





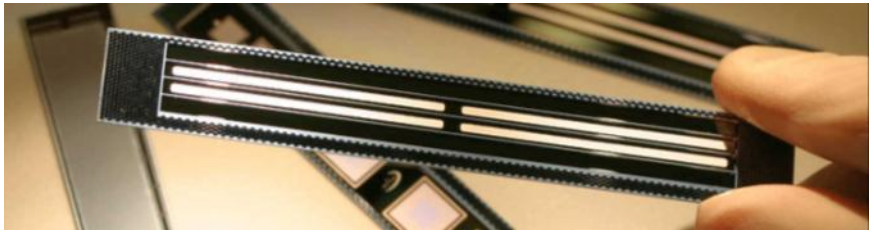
- fully depleted sensitive volume
  - fast signal rise time (~ns), small cluster size
- fabrication at MPI Semiconductor Lab (MPI HLL)
  - Wafer scale devices possible
  - no stitching, 100% fill factor
- no charge transfer needed
  - faster read out
  - better radiation tolerance
- charge collection in "off" state, read out on demand
  - potentially low power device
- internal amplification
  - charge-to-current conversion
  - large signal, even for thin devices
  - r/o cap. independent of sensor thickness
- Matrix read out in “Rolling shutter” mode
  - select row with external gate, read current, clear DEPFET
  - two different auxiliary ASICs needed, but no interconnect in sensitive area
  - only few rows active → low power consumption

Past…Present…Future



DEPFETs for the ILC VXD

- ✓ Many years of R&D → www.depfet.org and the "Backup Document"
- ✓ Prototype System with DEPFETs (450µm), CURO and Switcher
- ✓ Many beam tests at DESY and CERN
- ✓ Thinning technology established, thickness can be adjusted to the needs of the experiment (~20 µm … ~100 µm),
- ✓ radiation tolerance tested with single pixel structures up to 4 Mrad and ~10^{12} n_{eq}/cm^2

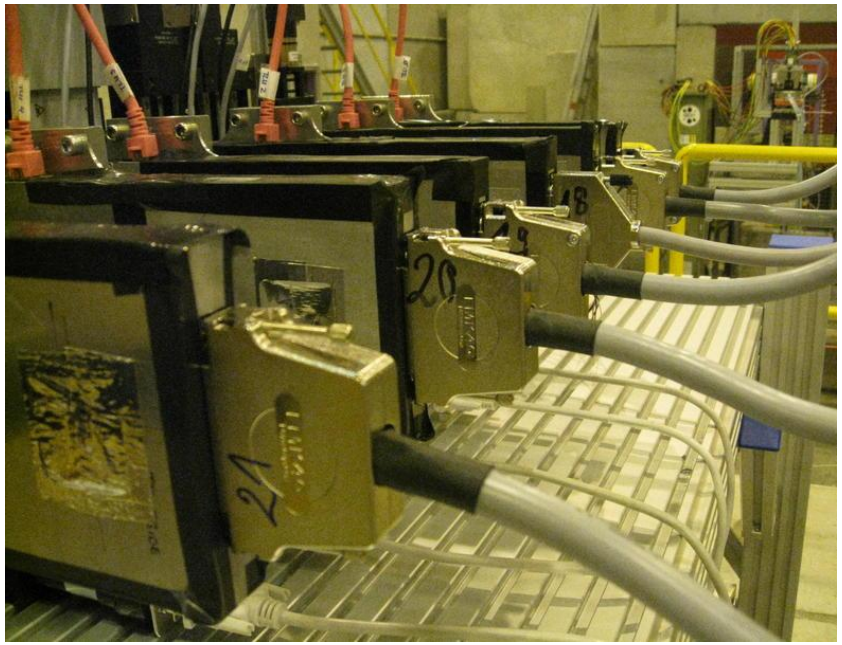


Test Beam Campaign 2008 and 2009

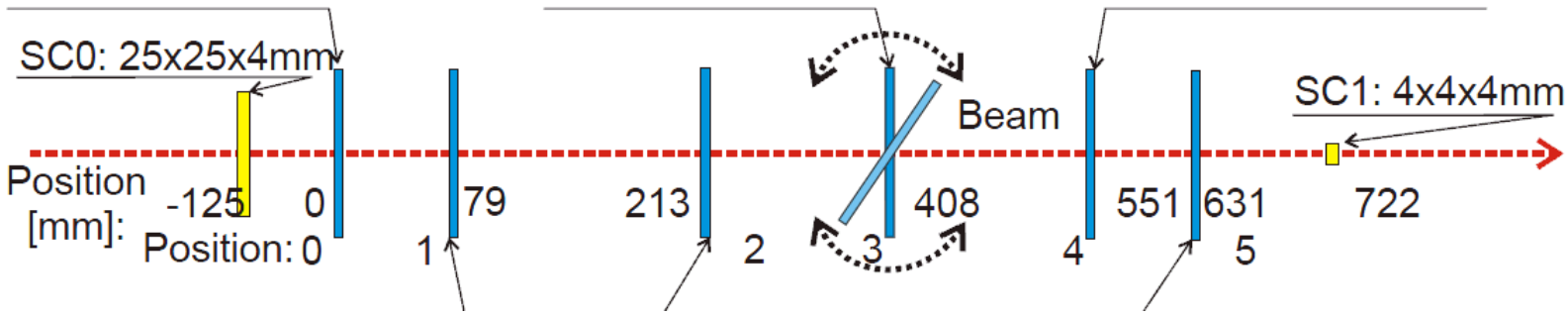
The goal was to:

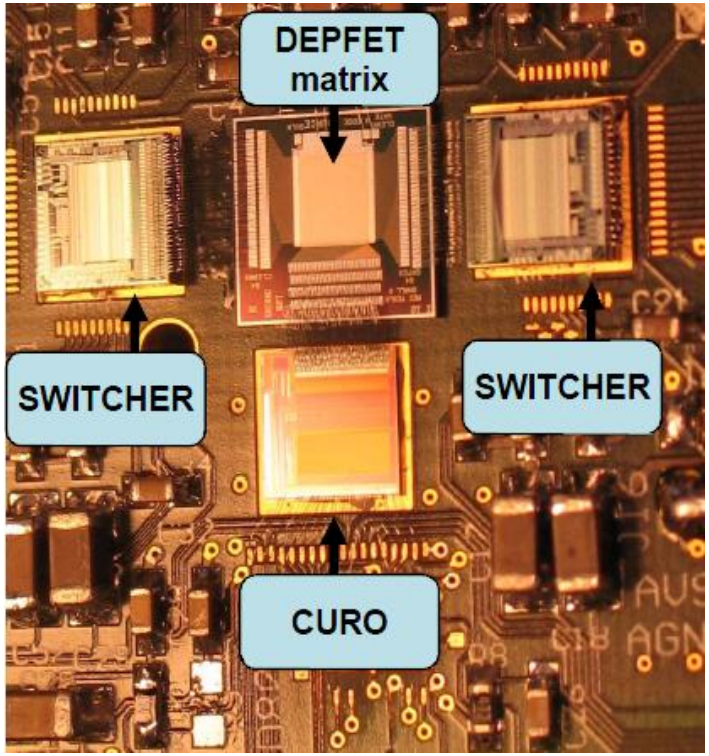
- prepare the necessary tools for a fast and efficient testing of the DEPFETs
  - construct a robust telescope with excellent resolution
- gain experience in running DEPFETs in a “real” environment
- test new and more ambitious DEPFET cells

- → CERN SPS H6 beam line 2008 and 2009
- stand alone DEPFET telescope and integration as a DUT in the EUDET telescope



DEPFET Telescope and System



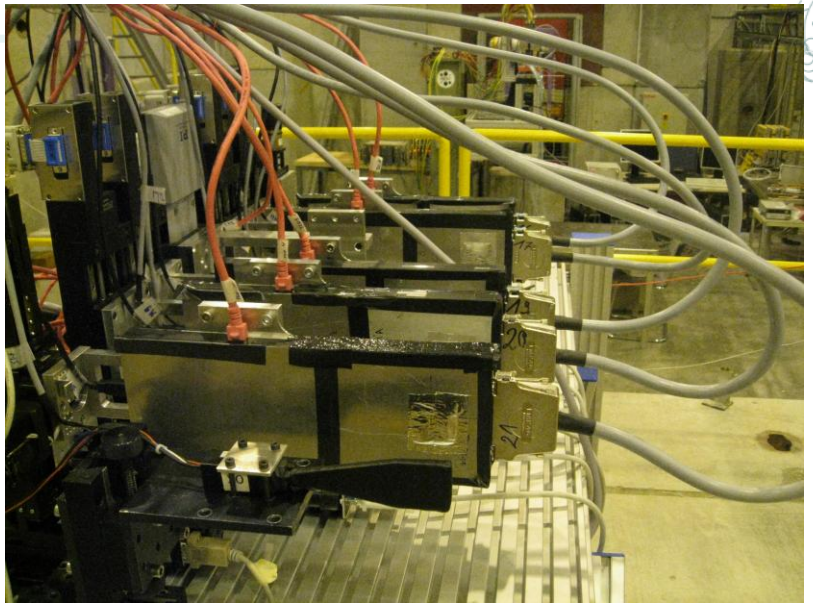


- 5 telescope planes with "standard" DEPFET matrices, 450 µm thick
  - 32x24 µm^2 pixel size
  - 2008: 64x128 pixels
  - 2009: new readout board for 64x256 matrices
- one device under test (DUT)
  - 2008: 64x128 pixels, 24x24 µm^2 - on the rotation stage
  - 2009: 64x256 pixels
    - 20x20 µm^2 with shorter gate length
    - capacitively coupled clear gate (…better clear)
- all devices characterized in the lab before test beam
- Test beam program:
  - high statistics run for in-pixel studies
  - angular scans
  - "clear" parameter and depletion voltage scans
  - Beam energy scan…

“a small technicality”

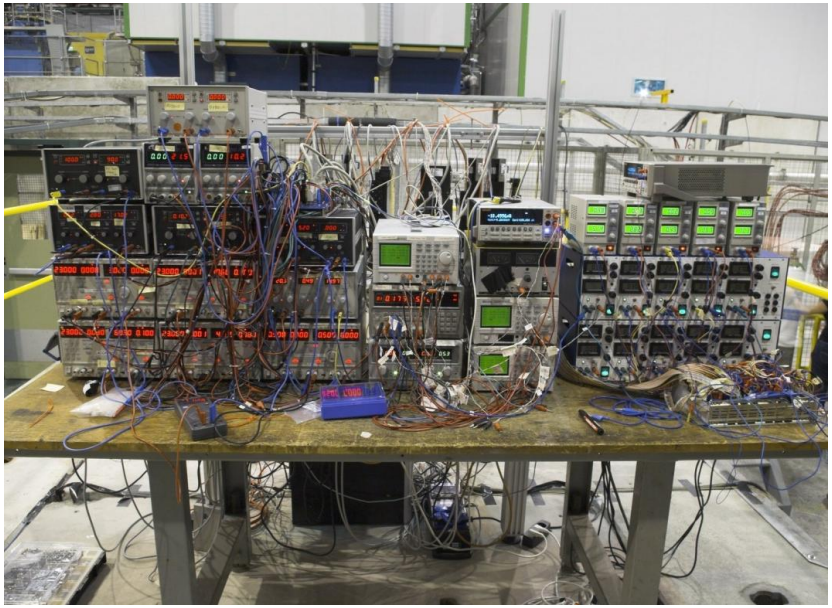
Since summer 2009:

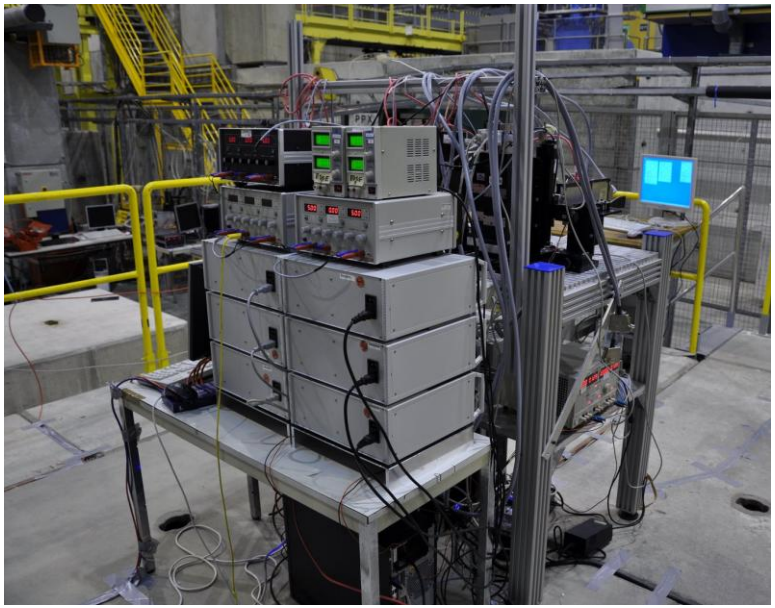
- Dedicated DEPFET power supply systems available, one per module
- “plug-and-play” DEPFET telescope



TB 2009

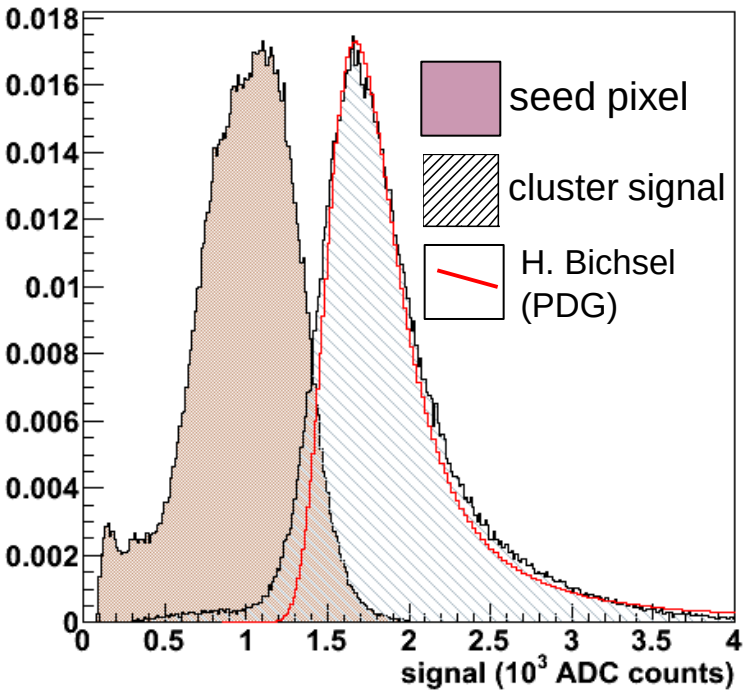
TB 2008



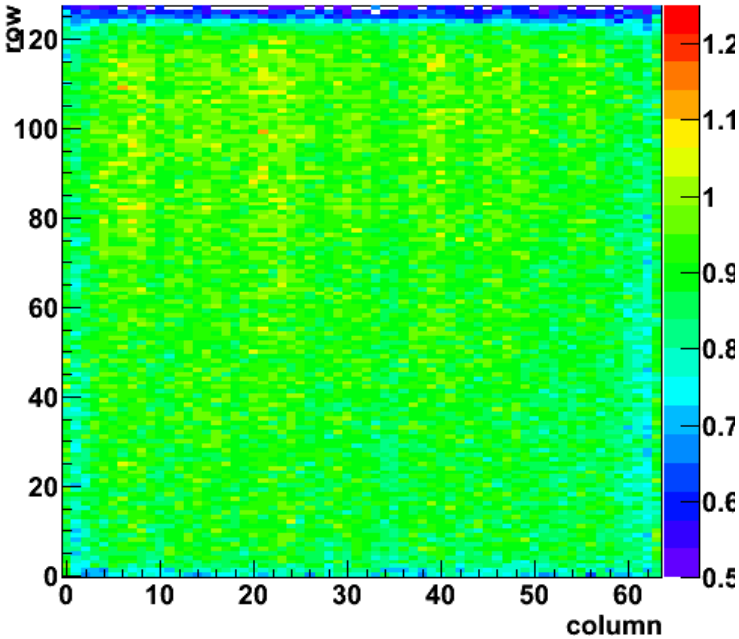


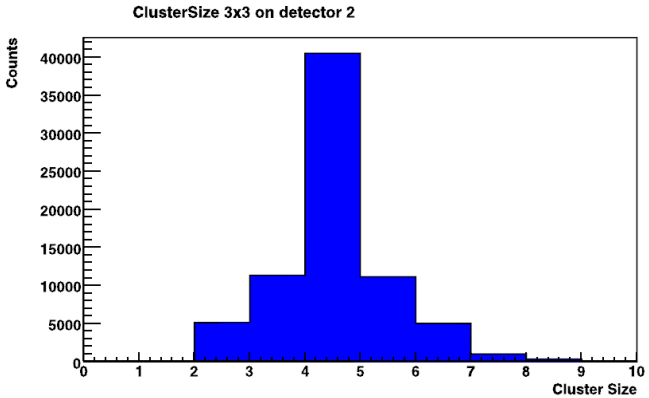
Typical clusters and signals

TB2008, 120 GeV pions, 90˚, 24 x 24 μm^2 pixel



Gain map: Deviation from average seed signal



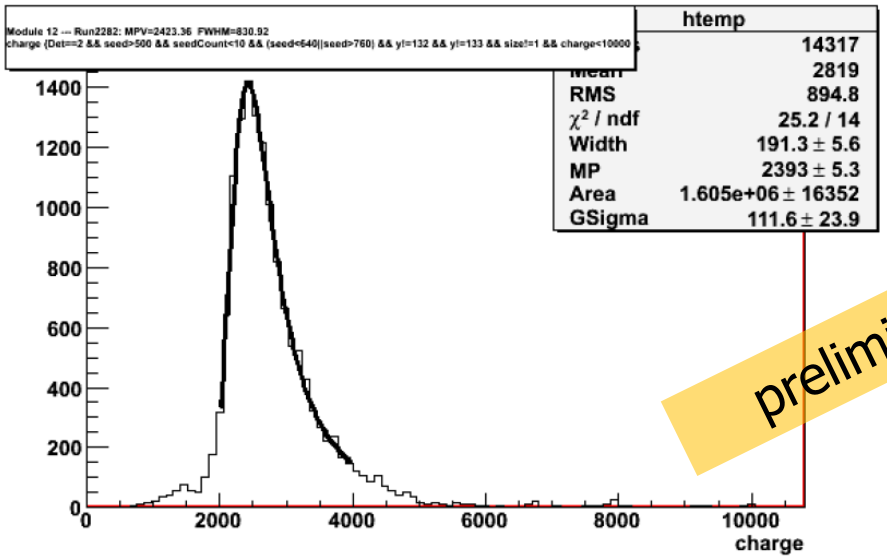


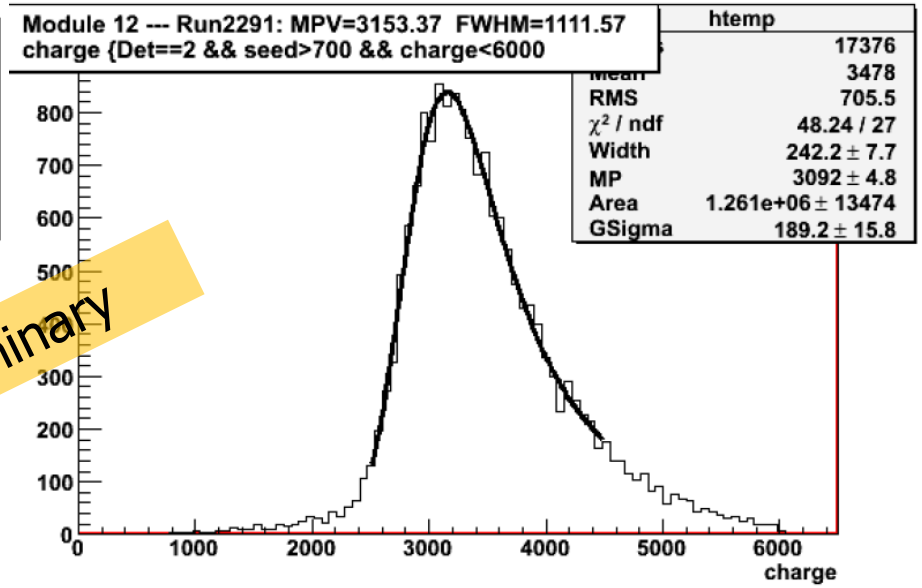
- MPV=1715 ADU (mip 131keV)
- Seed= 900 ADU
- g_q=363 pA/e$^-$ and S/N=128

TB2009

- TB2009, 120 GeV pions, 90˚, 32 x 24 μm^2 pixel,
- L=6 μm
- capacitively coupled clear gate → better clear

- TB2009, 120 GeV pions, 90˚, 20 x 20 μm^2 pixel,
- L=5 μm (just 1 μm shorter) → higher g_q ....





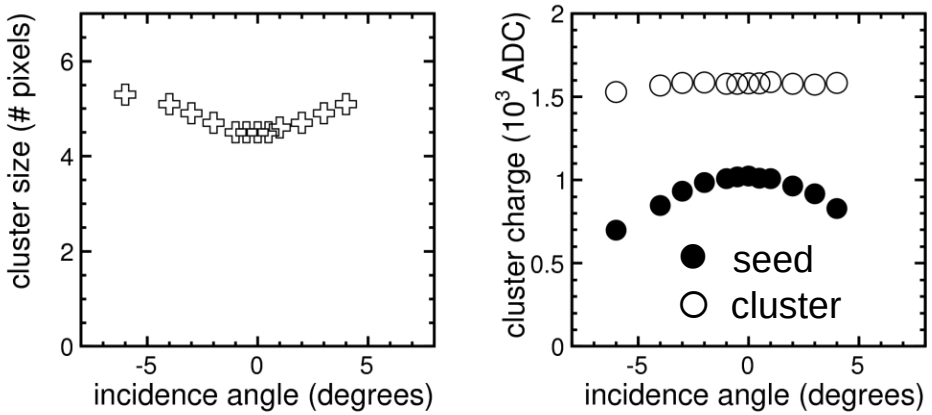
preliminary

- ❑ MPV=2423 ADU (mip 131keV)
- ❑ $g_q \approx$ 500 pA/e$^-$ and S/N ≈ 160

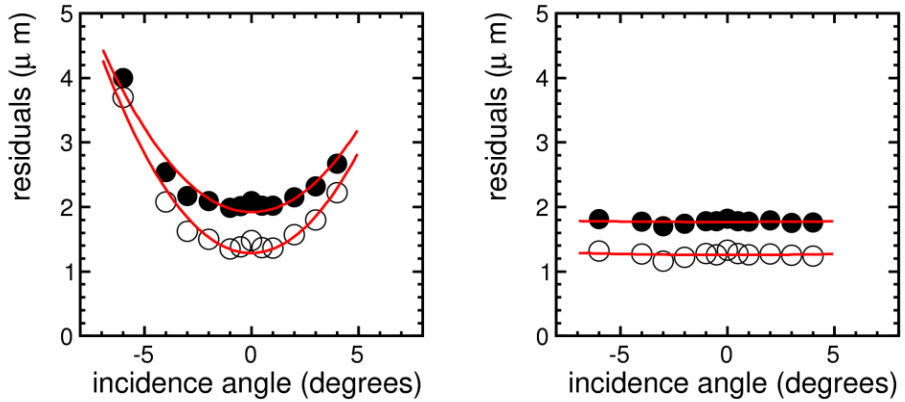
- ❑ MPV=3153 ADU (mip 131keV)
- ❑ $g_q \approx$ 650 pA/e$^-$ and S/N ≈ 200

TB2008: angular scan

TB2008, 120 GeV pions, 90˚±5˚ , 24 x 24 μm^2 pixel



- stronger charge sharing → cluster size bigger
- total charge does not change (of course)
- residuals and resolution degrades strongly beyond 4˚
- slight improvement of the x residuals between 1˚ and 3˚



● Residuals in y
○ Resolution in y

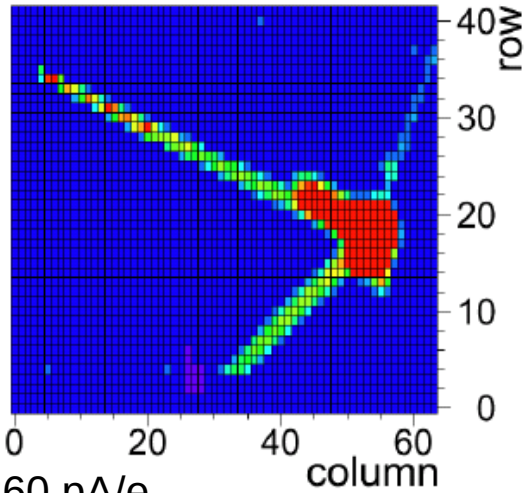
● Residuals in x
○ Resolution in x

→ Important input for the simulation chain (digitizer)

→ Extrapolation to thin sensors and optimization of the sensitive thickness for Belle II

Test Beam

TB2009	Best DUT (20x20μm²)		Telescope (32x24μm²)	
120GeV pions	X	Y	X	Y
Residuals	1.54	1.42	1.98	1.61
Resolution	1.10	1.00	1.60	1.20

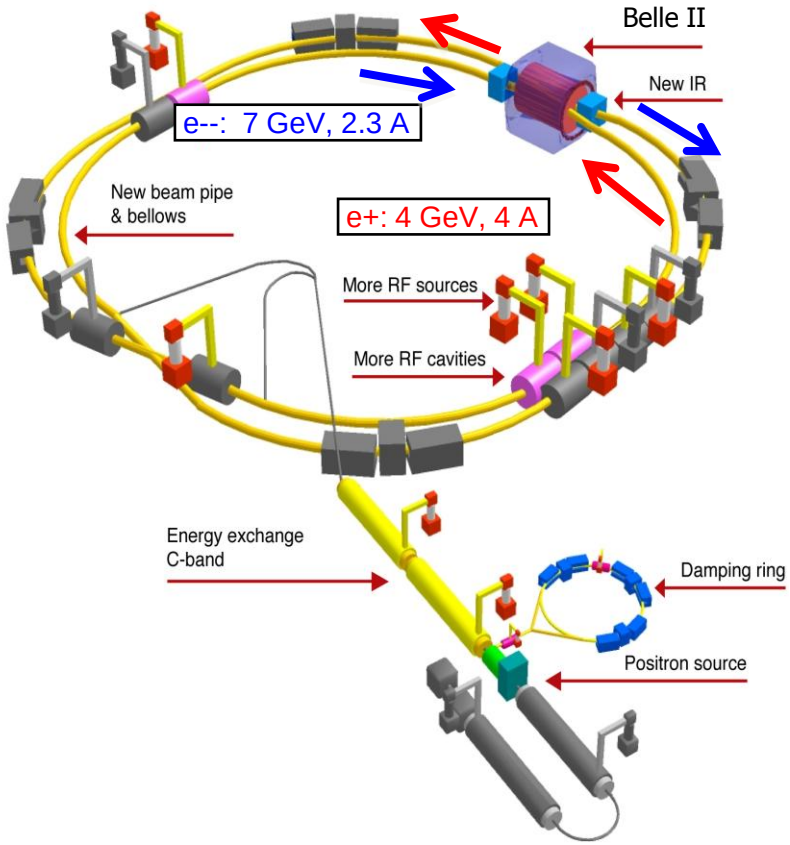


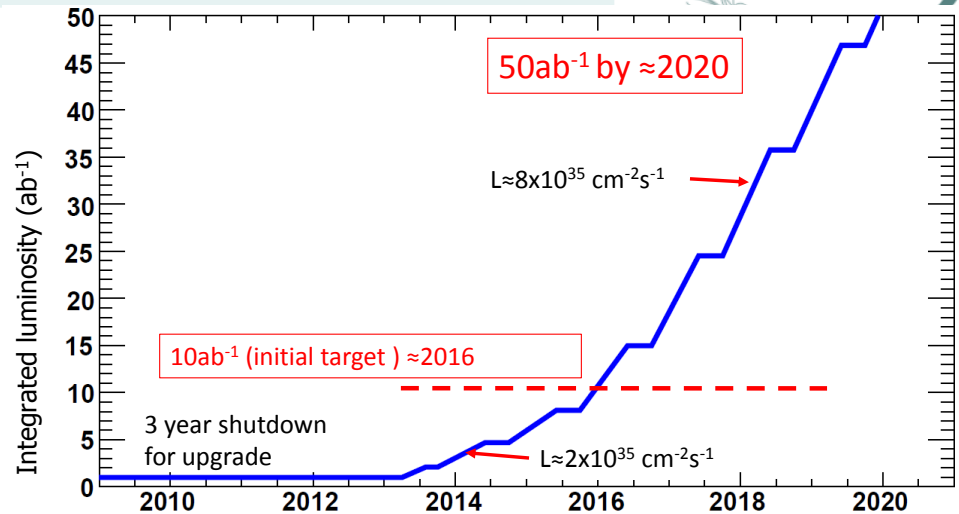
Check performance of different designs

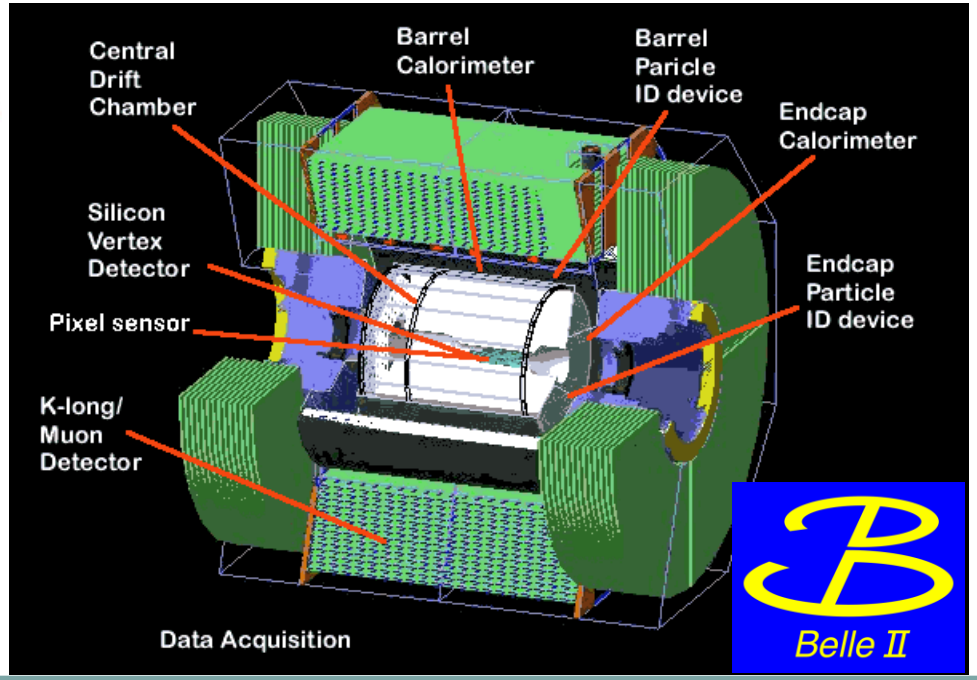
common clear gate:	L=6 μm:	g_q = 360 pA/e
capacitively coupled clear gate:	L=6 μm:	g_q = 500 pA/e
common clear gate:	L=5 μm:	g_q = 650 pA/e

Results are for ILC designed sensors (small pixel pitch) and thick detectors
Comparison and tuning of MC simulations => performance at Belle II

SuperKEKB and Belle II







Vertex Detector upgrade
DEPFETs are chosen for the VDX
(scheduled 2014)

ILC vs. Belle II

Higher beam induced background at superKEKB

-QED background, beam-gas interactions and synchrotron radiation

ILC needs excellent IP resolution over a large momentum range:

- Low material → thin ladders down to the very forward region
- Good single point resolution (σ = 3-5 µm) → small pixels (24µm)

superKEKB is dominated by low momentum tracks (< 1GeV/c):

- Low material!!!
- but IP resolution always dominated by MS error (beampipe & 0.14%X_0 Si) of ~ 9 µm at 1 GeV/c

→ Modest intrinsic resolution of σ ~ 10 µm sufficient: pixels could be larger

Belle II:
- more challenging than ILC! (background, radiation, power)
- tight schedule (2014) to develop a compete detector system

Focus on Belle II,
→ will boost detector R&D for future e^+e^- colliders

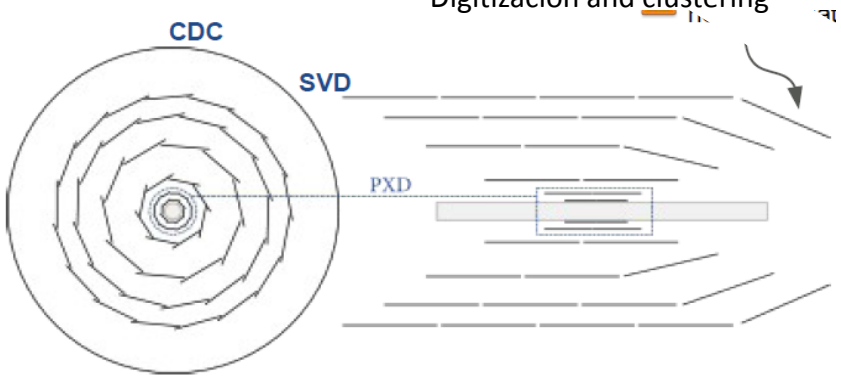
Tasks: optimize for larger pixels and radiation hardness

	ILC	Belle II
occupancy	0.13 hits/µm²/s	0.4 hits/µm²/s
radiation	~100 krad/year	~1 Mrad/year
Duty cycle	1/200	1
Frame readout time	25 µs – 50 µs	20 µs
Pixel size	25 x 25 µm²	50 x (50-75) µm²

Full simulation chain

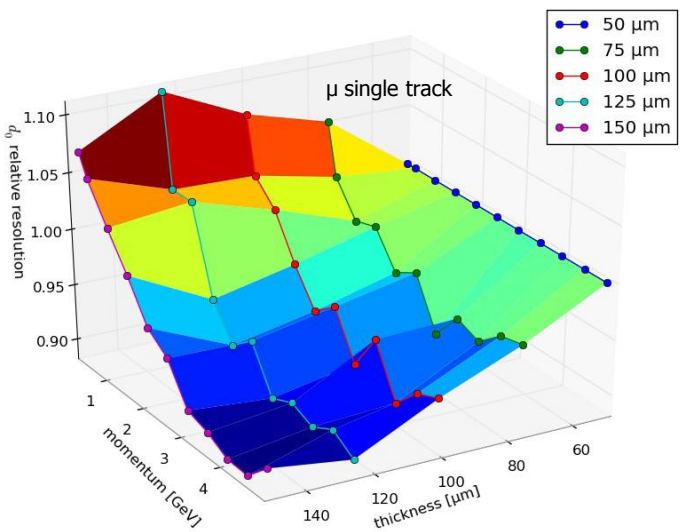
Detector simulation → PXD/SVD Simulation → Track reconstruction → Analysis

Detector simulation	PXD/SVD Simulation	Track reconstruction	Analysis
Particle gun (single event) EvtGen (physics event) Mokka geometry	Ionization points Signal points Electronic noise Digitizacion and clustering	Marlin tracking PXD+SVD+CDC	Physics channels

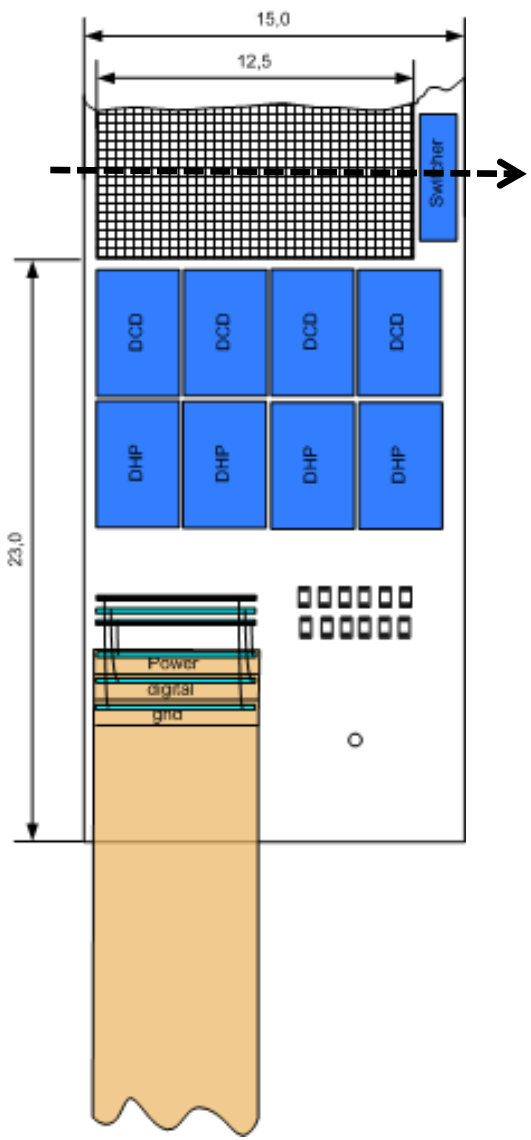


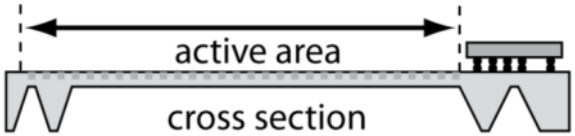
- Digitizer (Geant4) tuned with TBeam data:
- Electric noise
- Electric field in Si (charge collection time)
- Lorentz angle in magnetic fields

Optimization studies:
- Sensor thickness
- Pixel size
- Inner layer radius



Belle II ladder



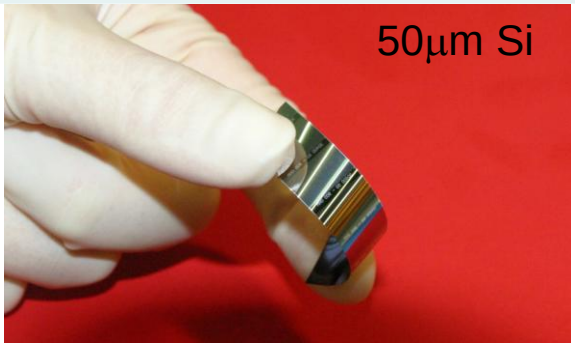


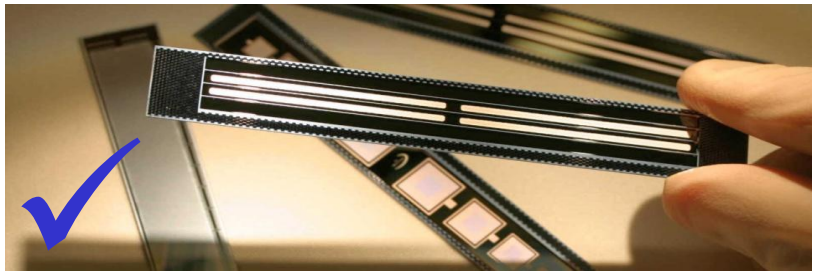
- All silicon module, sensitive area (DEPFETs) thinned
- Length: 90mm (inner), 123mm (outer), divided in half ladders
- 23 mm insensitive silicon on both sides (EOS)
- ASICs flip chipped to silicon substrate
- Insensitive part used as substrate for ASICs (MCM-D)

	Inner layer	Outer layer
# ladders	8	12
Radius	1.4 cm	2.2 cm
Pixel size	50x50 μm^2	50x75 μm^2
# pixels	1600(z)x250(R-ϕ)	1600(z)x250(R-ϕ)
Thickness	75 µm	75 µm

Belle II PXD in total ~8Mpixels

Sensor Thinning





Need thin (50µm-75µm) self supporting all silicon module

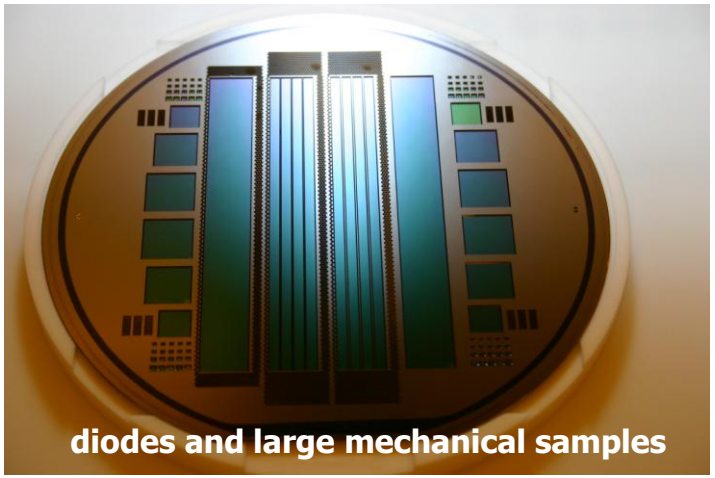
Process backside
e.g. structured implant

Wafer bonding
SOI process

Thinning of top
wafer (CMP)

Processing

etching of handle
wafer (structured)



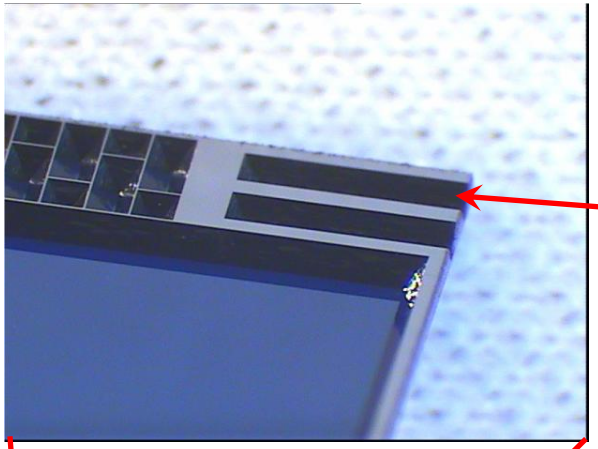
First thin Belle II DEPFET prototypes are in the final stage of the production

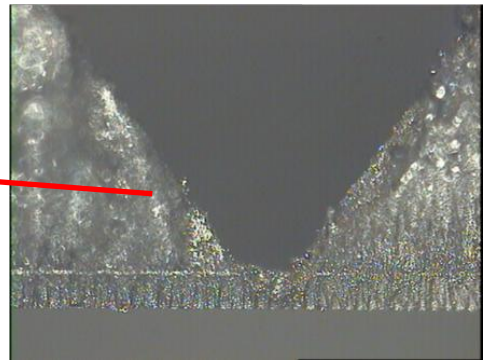
Micro joint between half-ladders

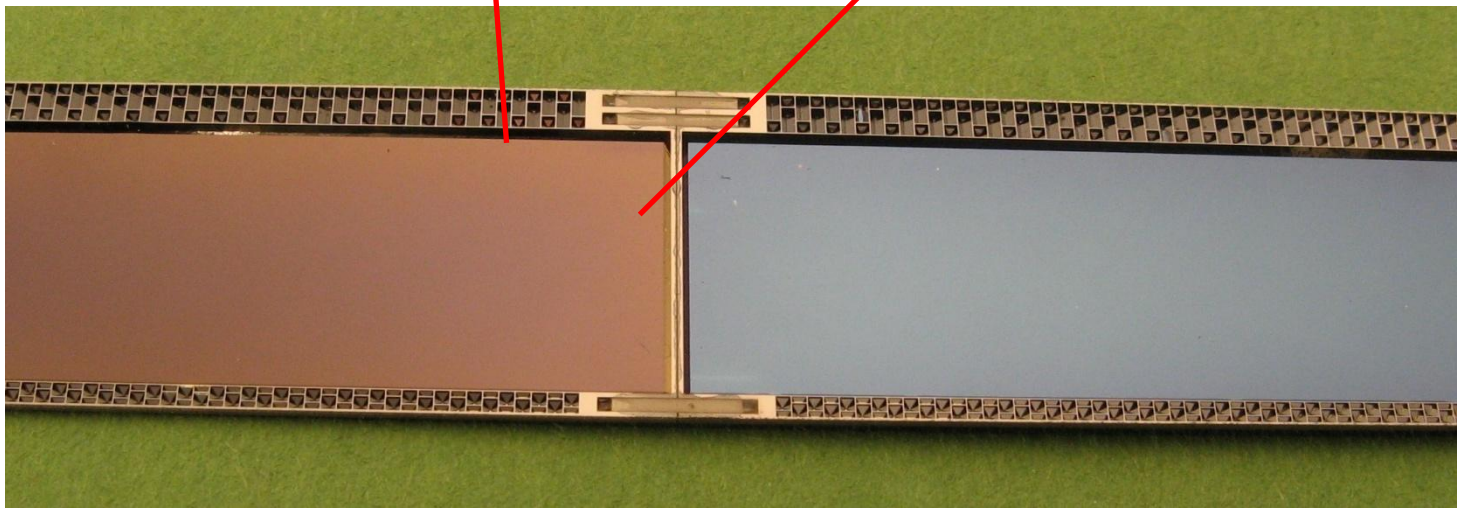
-butt joint between two half-ladders

-reinforced with 3 triangular ceramic inserts at the frame

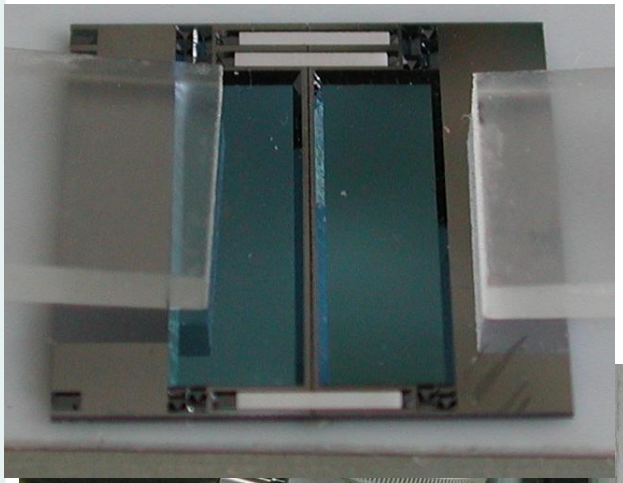
-about 2x300µm dead area per ladder

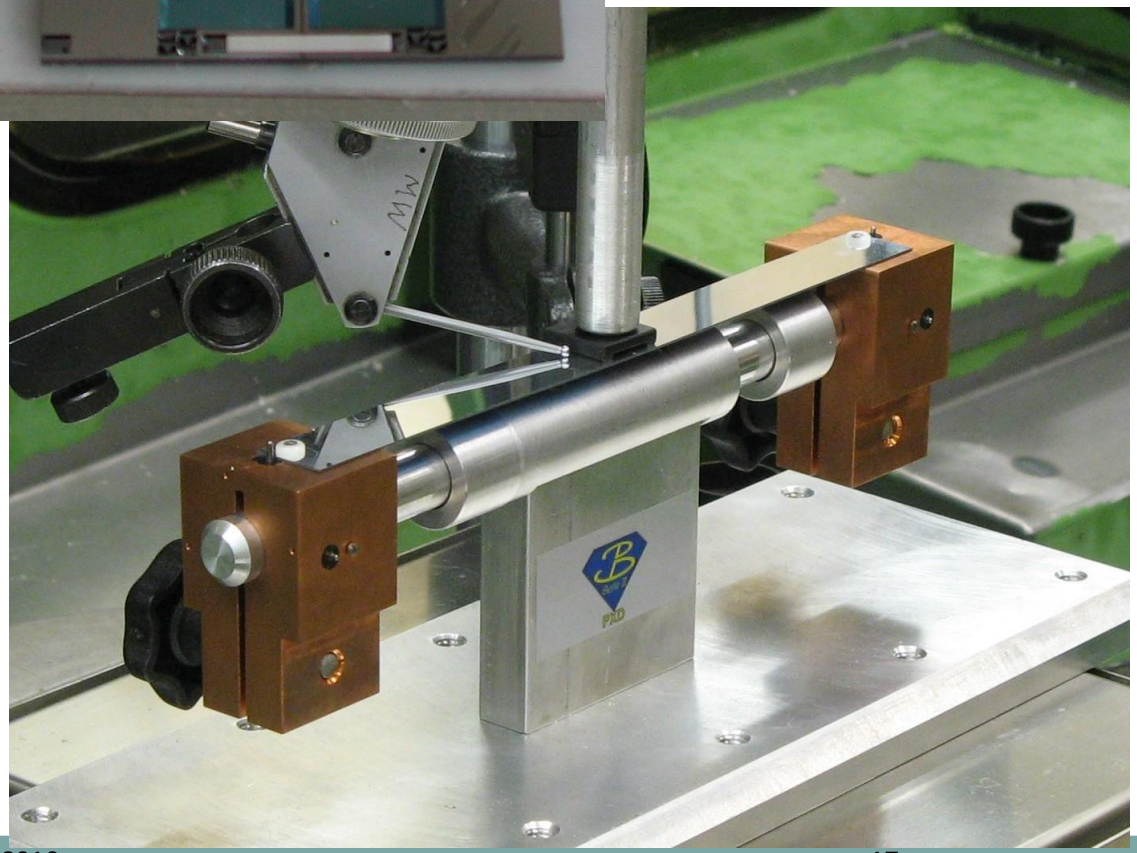


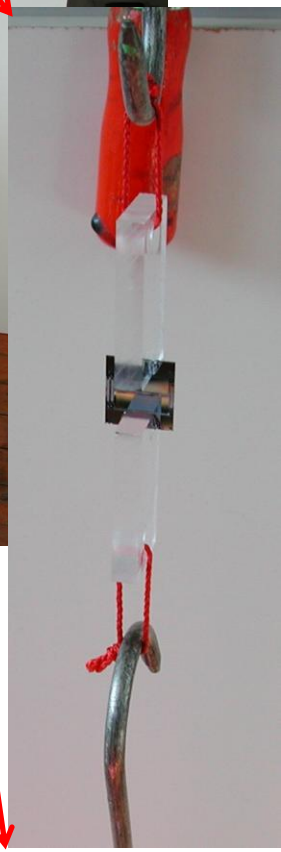




Micro joint between half-ladders







Material budget – measured!!

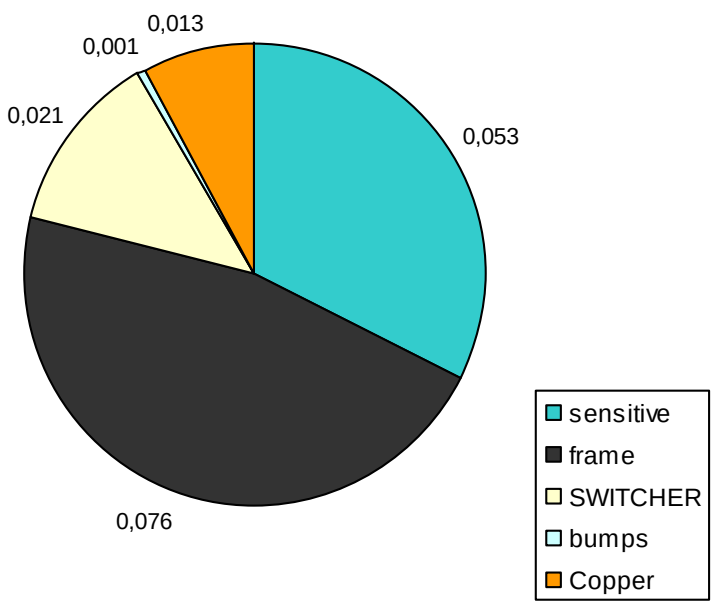
Mass of a 1st layer ladder including EOS, Si only: 1.10 g
Mass of a 2nd layer ladder including EOS, Si only: 1.24 g

Mass in the sensitive region only, **1st layer**, 90x15 mm^2: **0.36 g**

ρ_{Si}=2.33 g/cm^3 → eq. Si thickness in sensitive area: 120 µm

X_0(Si)=9.36 cm → Radiation length in the 1st layer: **0.125 %X_0** (Silicon only)

Calculated : 0.164 %X_0 (50 µm top, 450 µm frame)



Theoretical calculation:

sensitive region:	0.053 %
silicon frame:	0.076 %

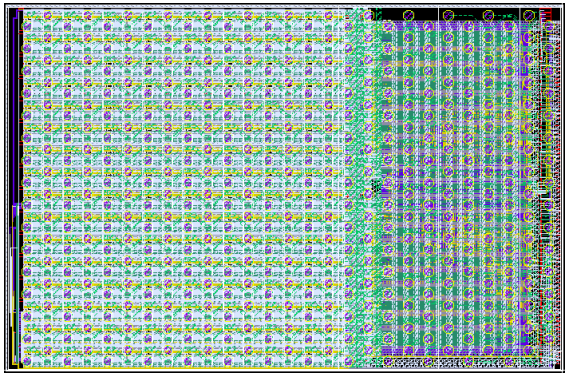
	0.129 %

The rest is the copper layer and bumps ..

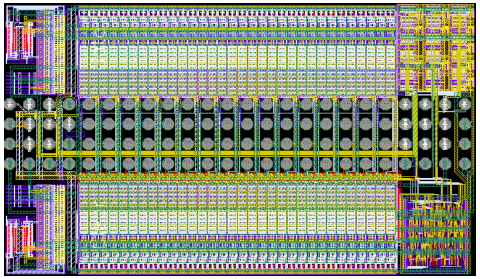
Calculated : 0.18 %X_0 (75 µm top, 450 µm frame)

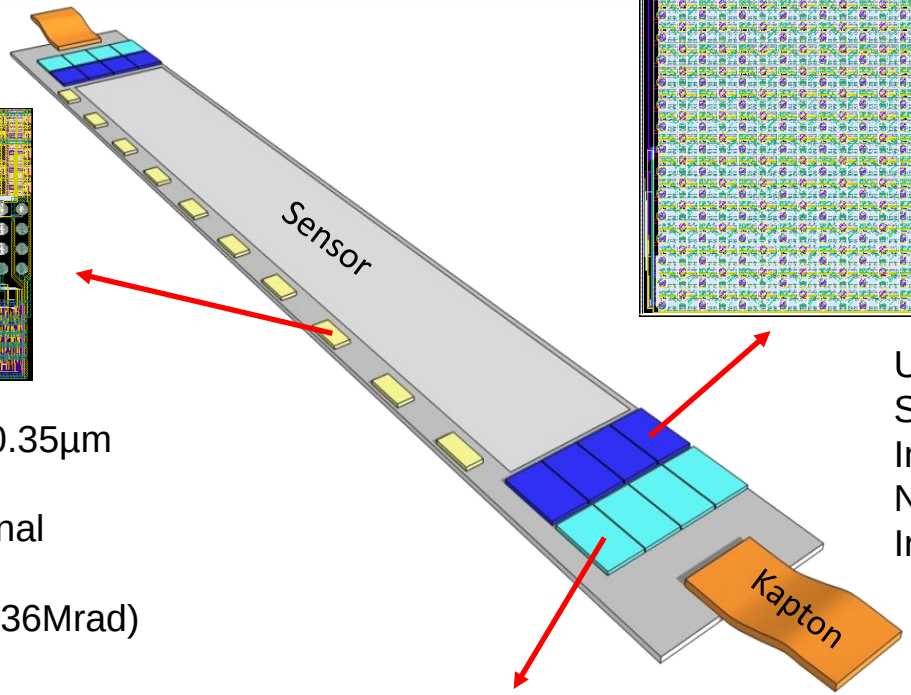
Auxiliary ASICs

DCDB (Drain Current Digitizer for BelleII)
Analog frontend and ADC



SwitcherB
Row control

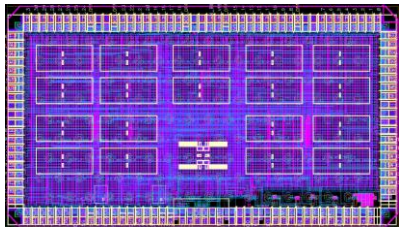




UMC 180nm
Size 3.3 × 5.0 mm^2
Integrated ADC
Noise 40 nA
Irradiation up to 7Mrad

AMS high voltage 0.35µm
Size 3.6 × 2.1 mm^2
Gate and Clear signal
Fast HV up to 30V
Rad. Hard proven (36Mrad)

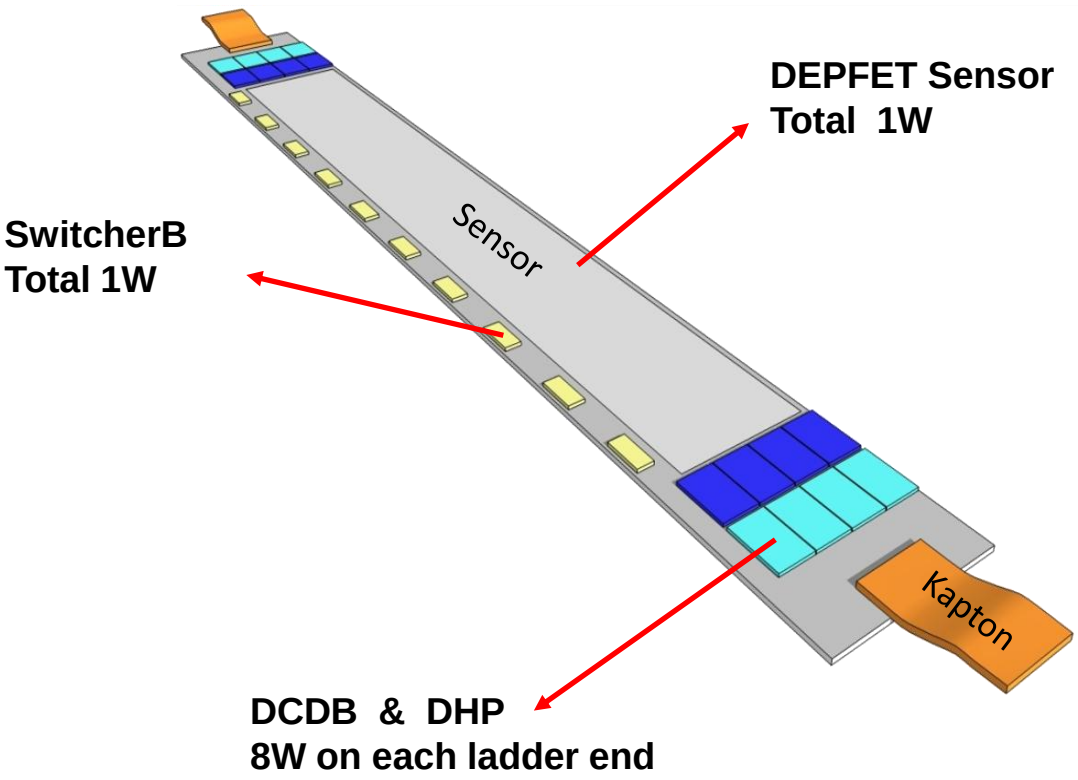
DHP (Data Handling Processor)
Data reduction and Processing



IBM CMOS 90nm
Stores raw data and pedestals
Common mode and pedestal correction
Data reduction (zero suppression)
Timing signal generation

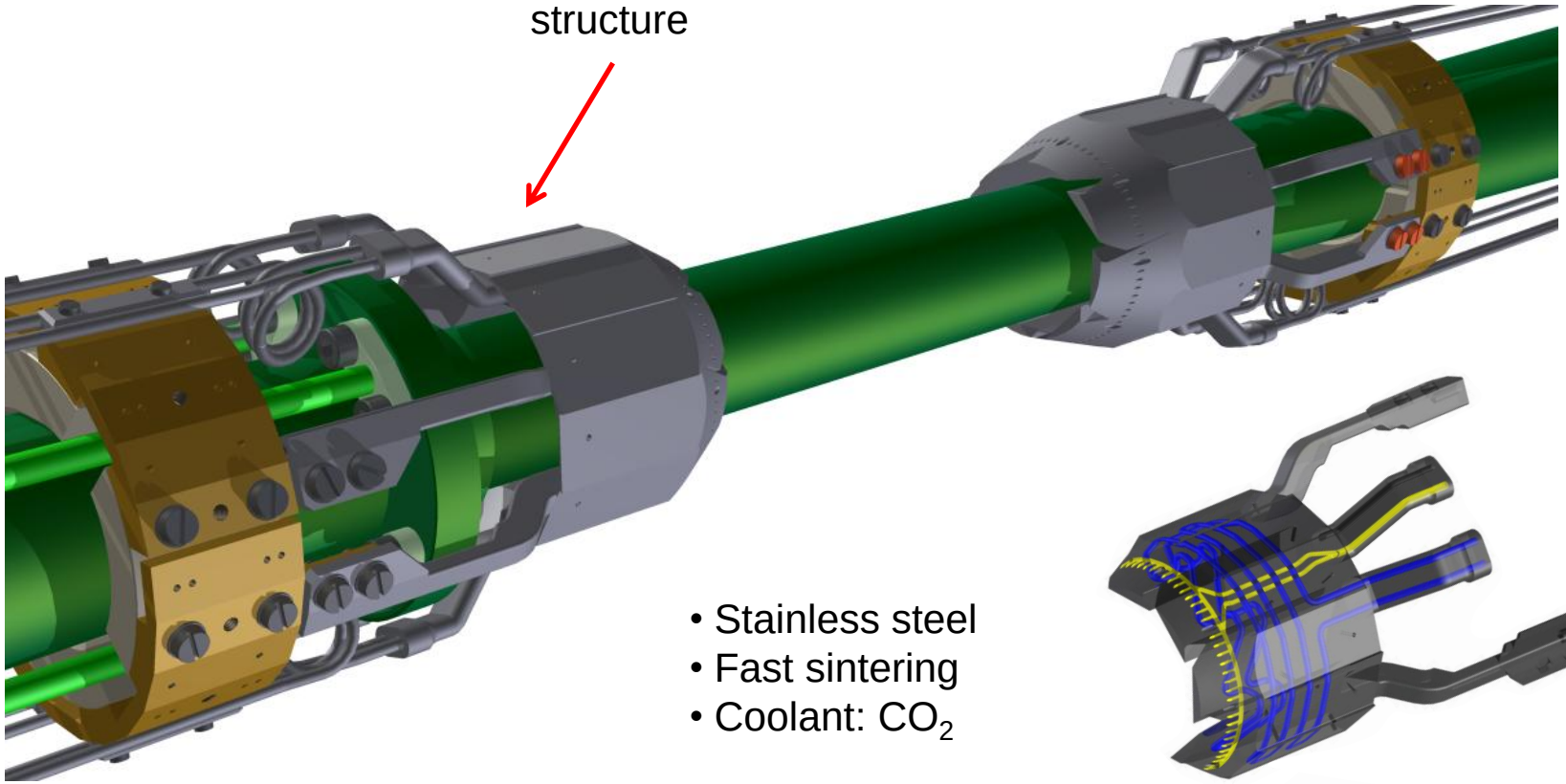
Switcher, DCD: Heidelberg U.
DHP: Bonn U., Barcelona U.

Temperature budget



Support structure

PXD Cooling and support structure

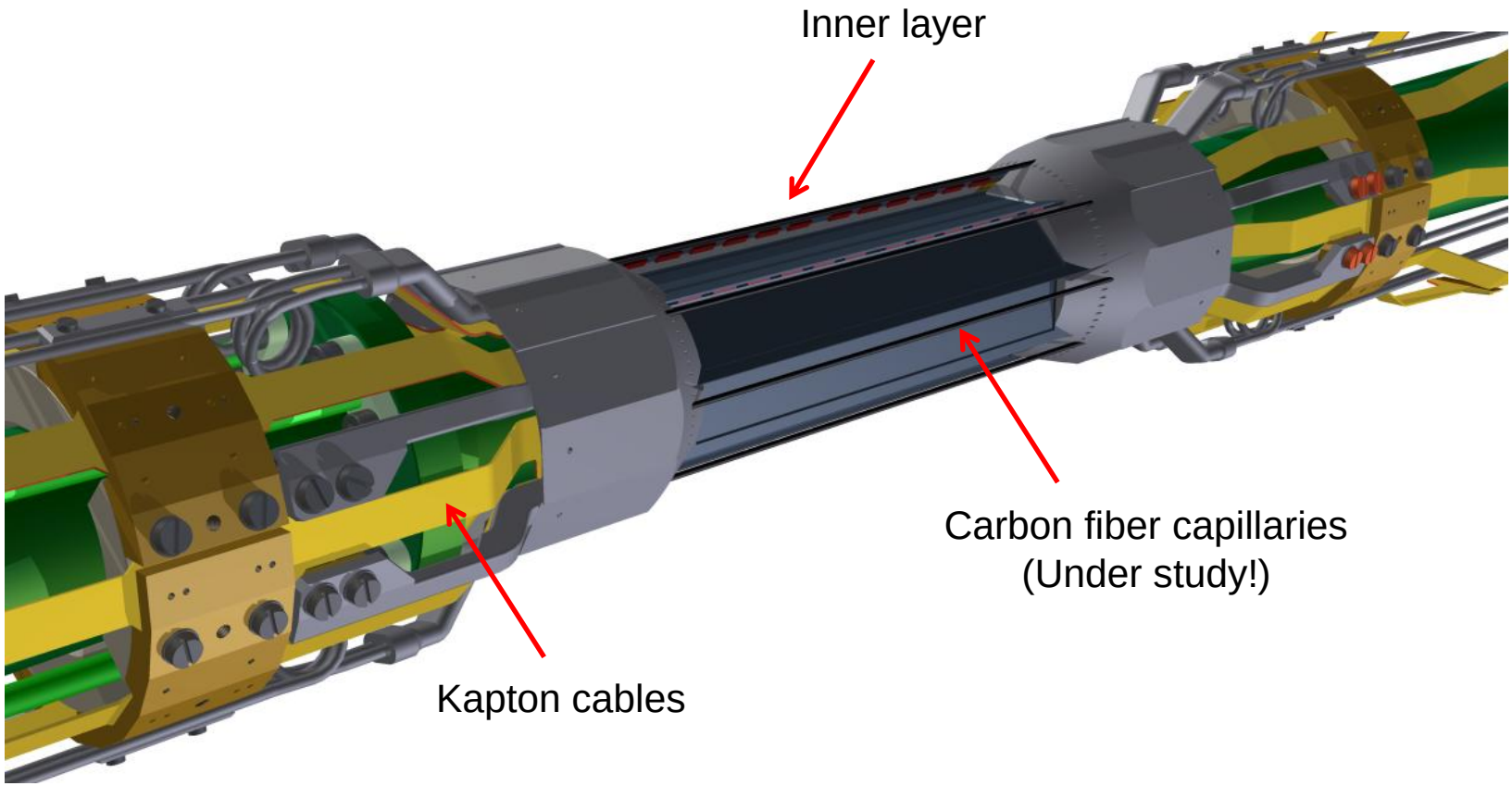


- Stainless steel
- Fast sintering
- Coolant: CO_2

Blue: CO_2 capillaries
Yellow: Air channels

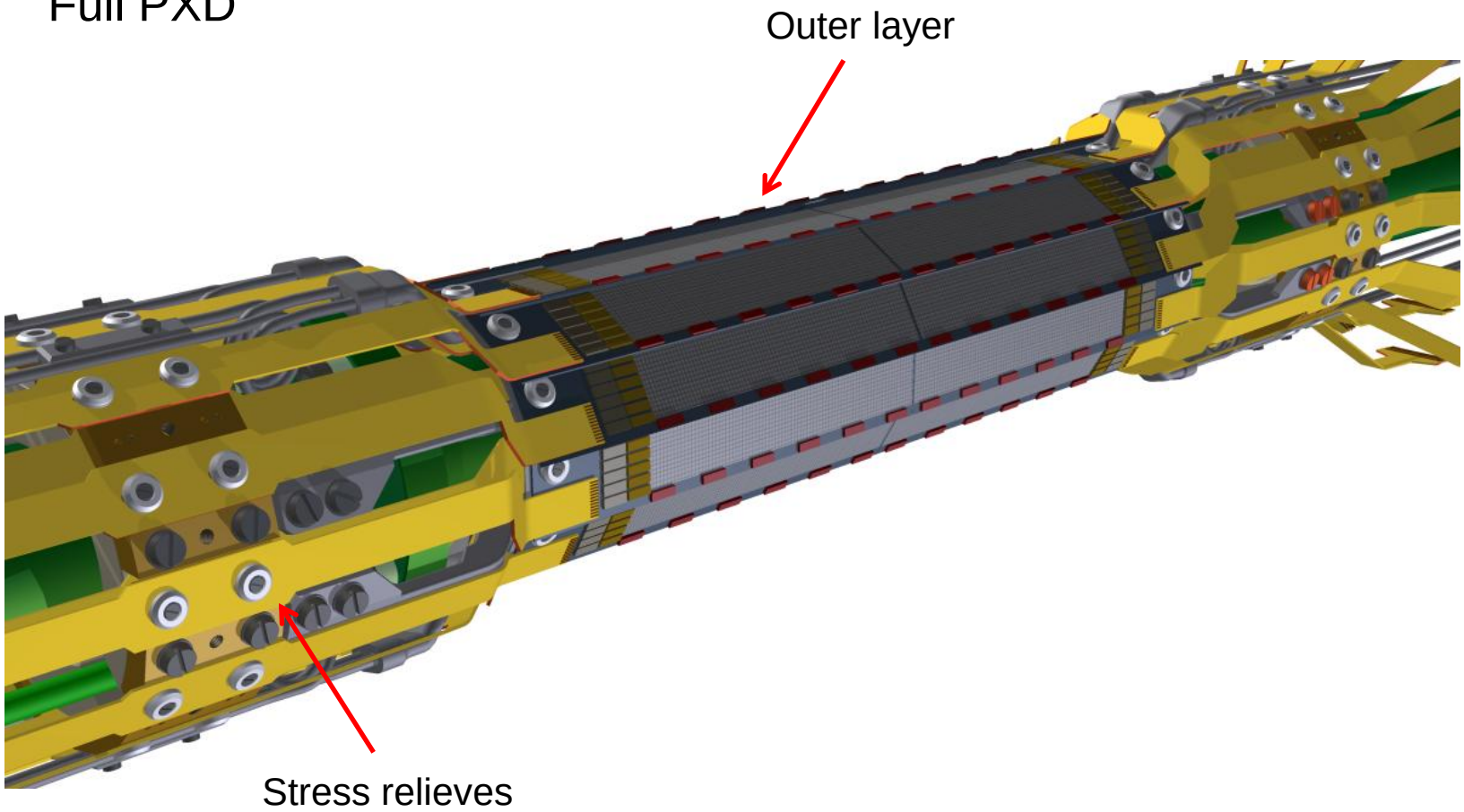
Down to -40ºC in the end of the stave

Support structure

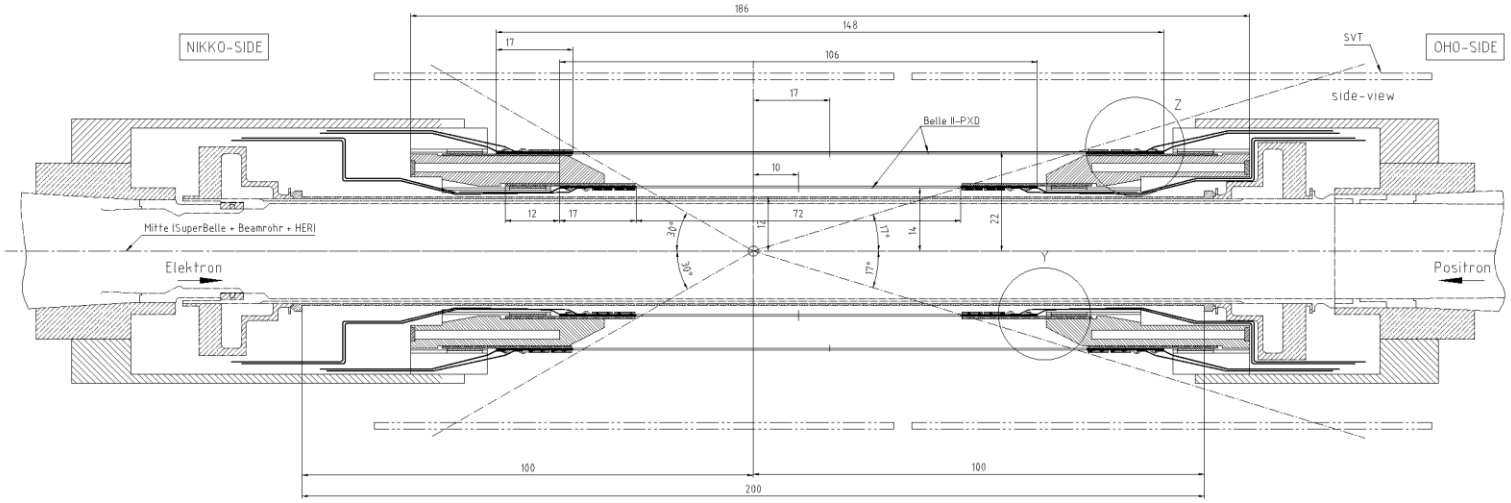


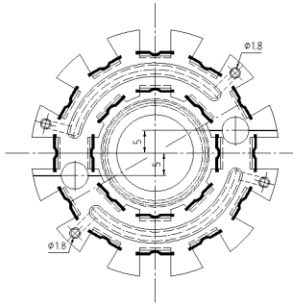
Support structure

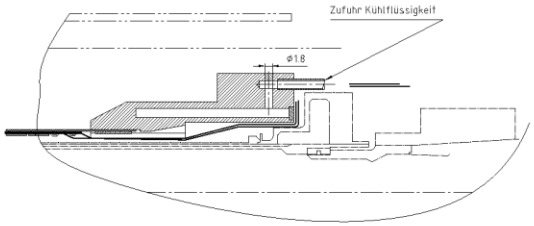
Full PXD

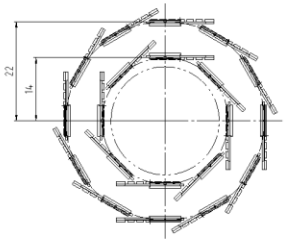


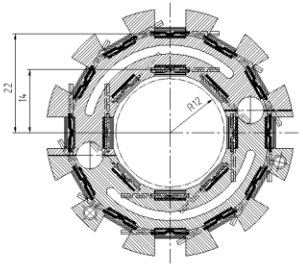
CAD drawings











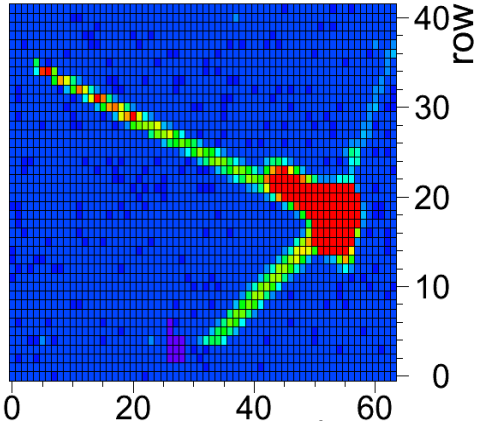
Summary

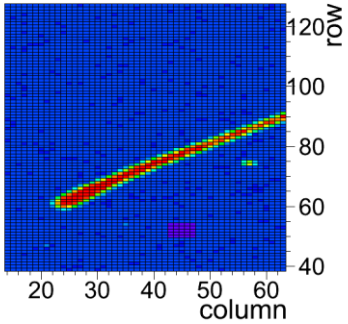
- the high-precision, low mass DEPFET Pixel Detector (PXD) for Belle II is in the construction phase
  - the first thinned sensor prototypes are currently in production (almost done)
  - Work packages within the DEPFET collaboration are covering all aspects of PXD (ASICs, mechanical, thermal, DAQ …)
  - this project gives a strong push for the DEPFET@future e^+e^- colliders, many techniques developed for Belle II are also applicable at future e^+e^- colliders

- testing infrastructure is being set up, a high-precision "plug-and-play" DEPFET telescope is ready for the prototype tests in the beam

- results of the recent beam test in summer 2009 at the CERN SPS show a substantial improvement of the internal amplification and the S/N of the system – an important step for the design of the final Belle II sensors

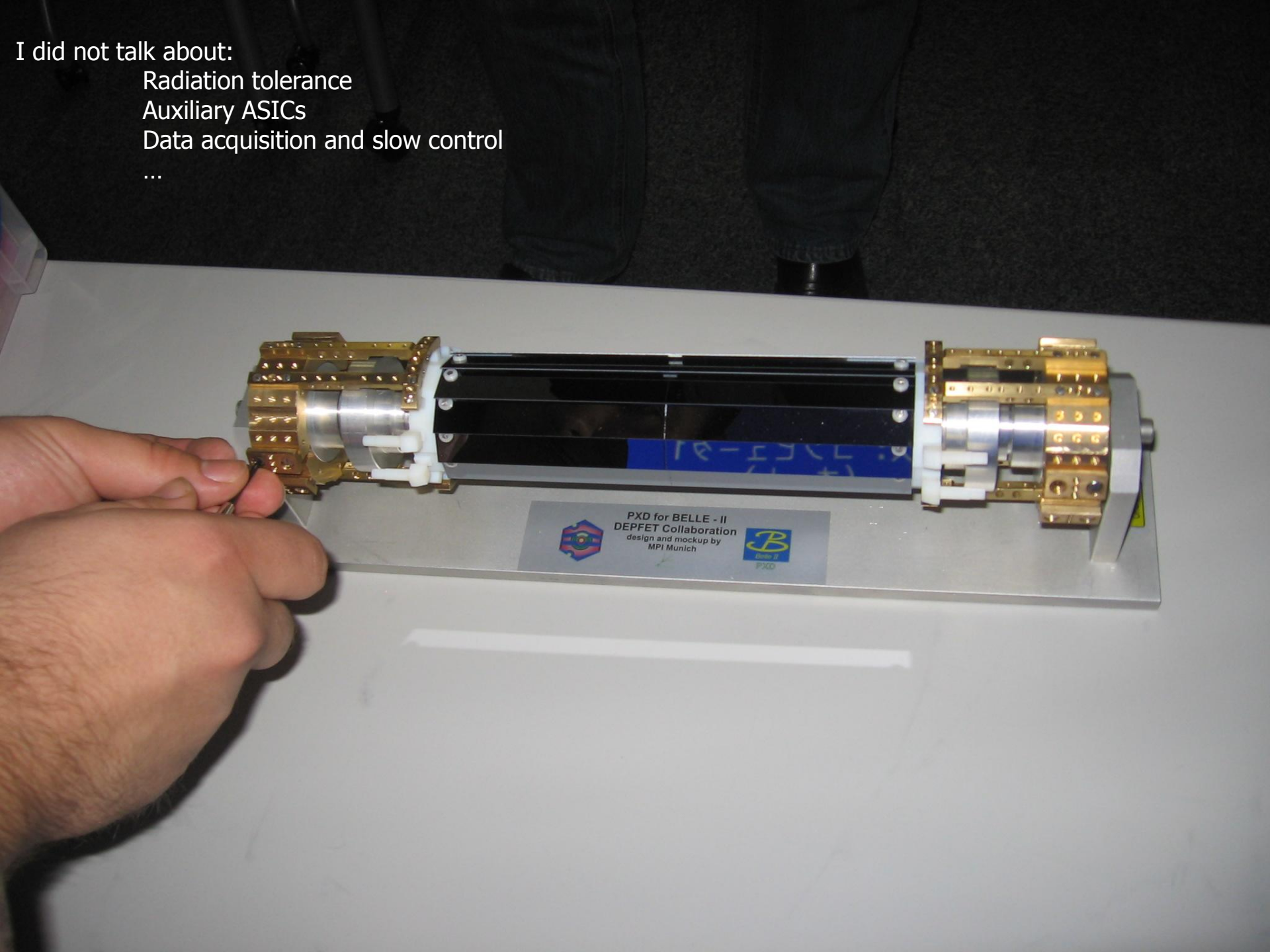
- this high-precision telescope with its huge S/N may lead to more insight in what is going on when a charged particle interacts with the silicon of the sensor





I did not talk about:

- Radiation tolerance
- Auxiliary ASICs
- Data acquisition and slow control
- …




NIKKO-Side
PXD for BELLE - II
DEPFET Collaboration
design and mockup by
MPI Munich
Belle II
PXD