DEPFET pixels as a vertex detector for the Belle II experiment

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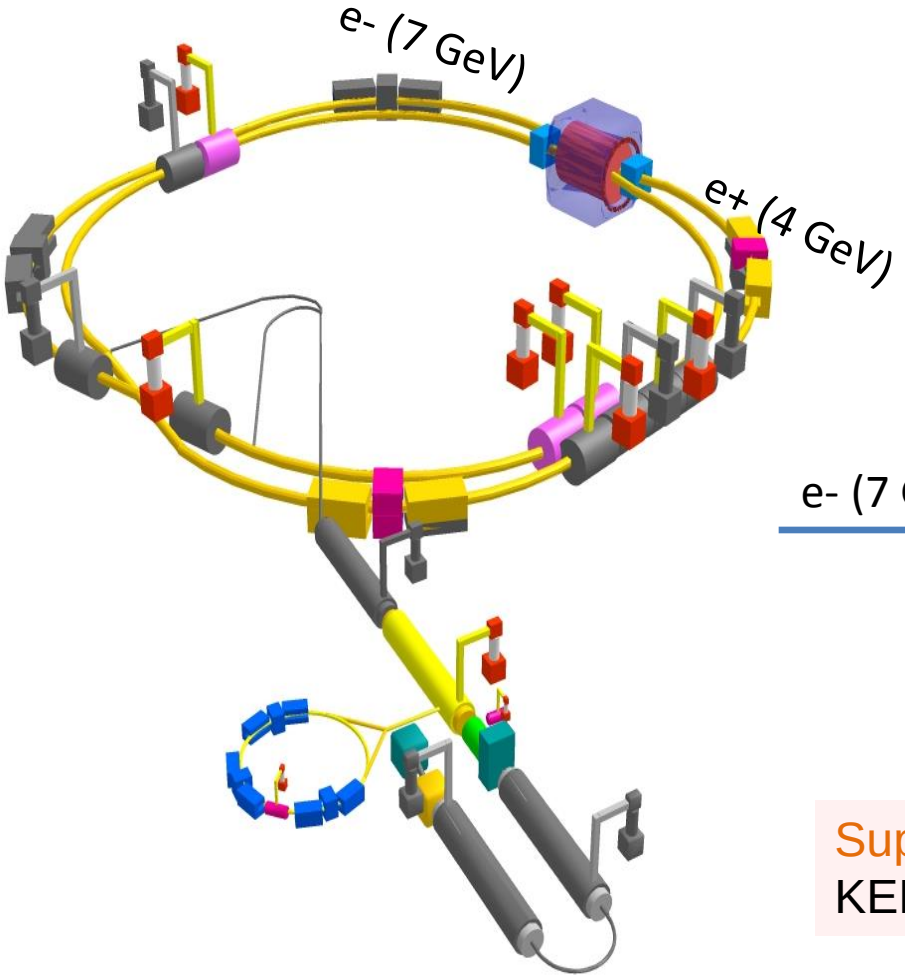
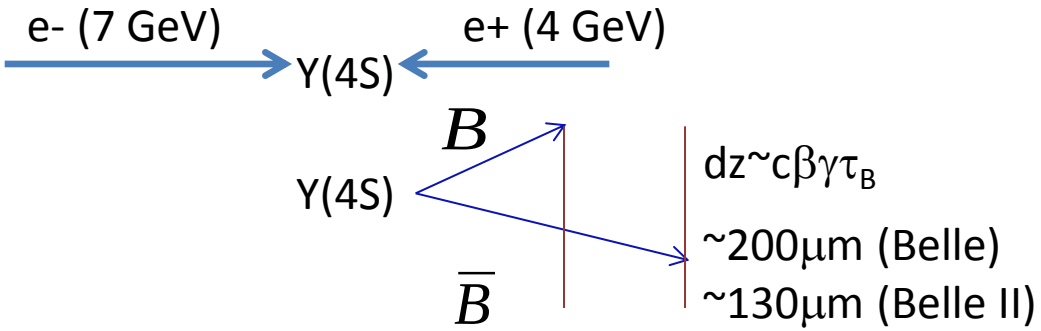
On behalf of the DEPFET collaboration

HSTD9

SuperKEKB (KEKB upgrade)



- Boosted $\Upsilon(4s)$ production by asymmetric e+e- collider
- $\sqrt{s}$ ~10.58GeV
- Target luminosity: $8 \cdot 10^{35} cm^{-2} s^{-1}$
  - 40 times higher than KEKB
- Nano beam scheme



SuperKEKB $\beta\gamma$=0.28 : e-(7GeV), e+ (4GeV)
KEKB $\beta\gamma$=0.42: e-(8GeV), e+ (3.5GeV)

LER (3.5 GeV -> 4GeV):
- Longer Touschek lifetime $\propto E^3$
- Intra-beam scattering effect to emittance

HER (8 GeV -> 7GeV):
- Lower emittance linac beam $\propto 1/E^2$
- Lower Synchrotron radiation loss

Nano beam scheme

Lorentz factor

Beam current

Beam-beam parameter

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

correction coefficient

σ: Beam size

β function: aperture of beam

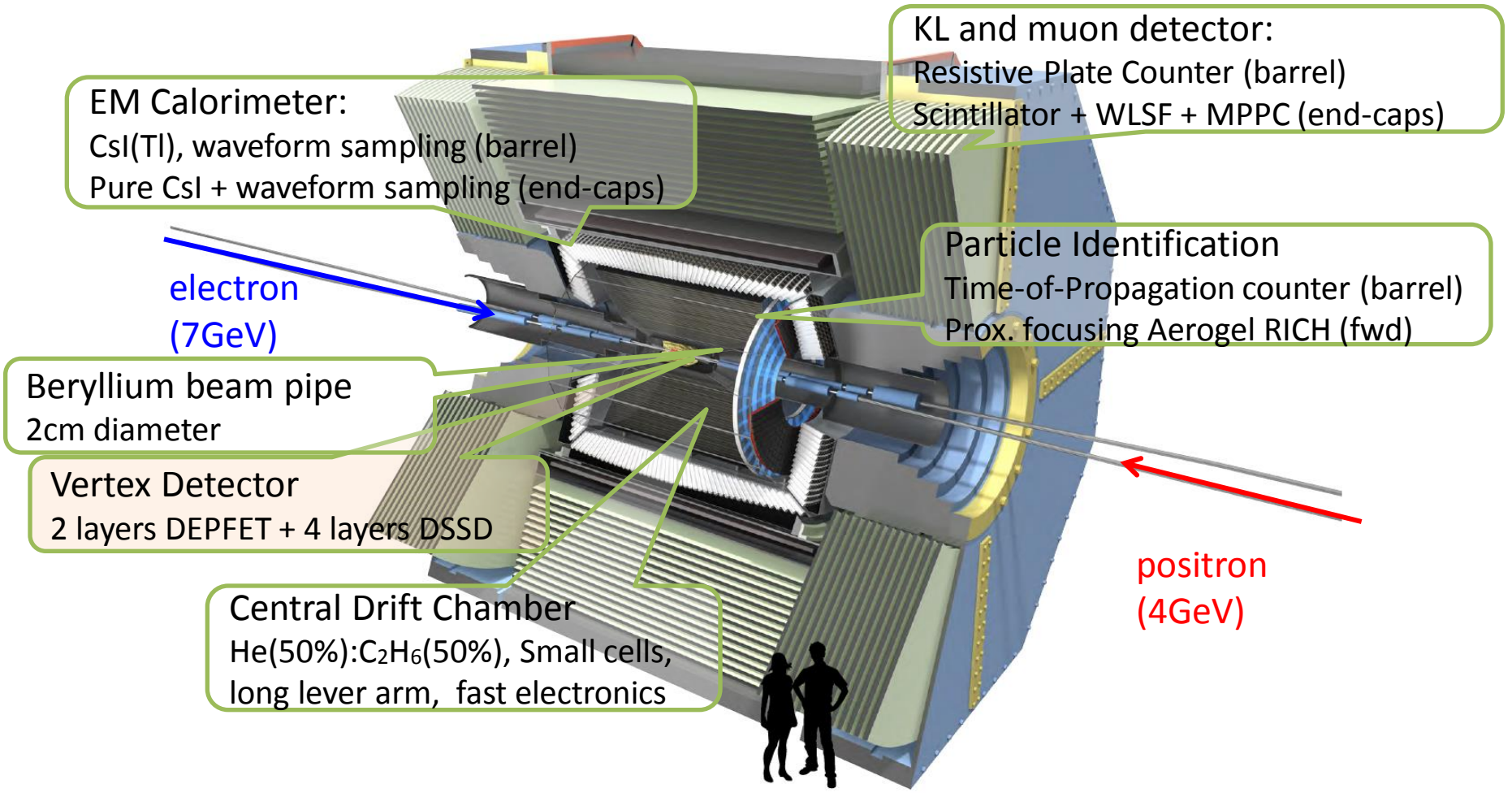
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	φ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	5.3	nm
Beta functions at IP	β_x^*/β_y^*	1200/5.9		3.2/0.27	2.5/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
Vertical Beam Size	σ_y^*	0.94		0.048	0.062	um
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

× 20

× 2

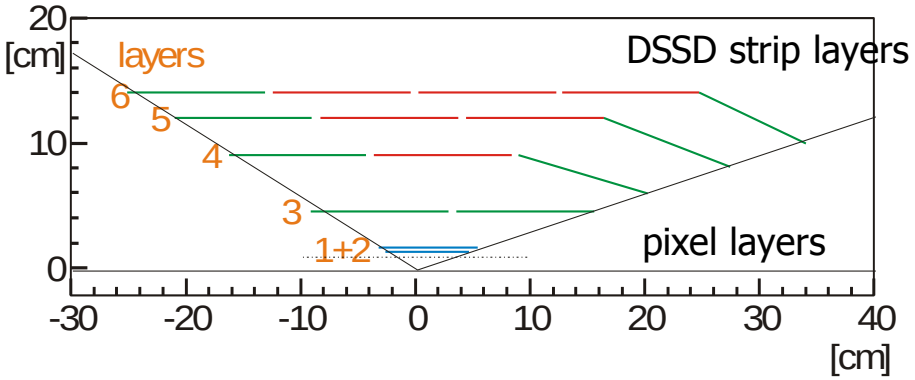
Belle II detector

Higher backgrounds (× 20) ⇒ higher occupancy, radiation damage
Higher event rate ⇒ faster trigger, DAQ, computing
Special requirements, e.g. hermeticity (ν reco.)

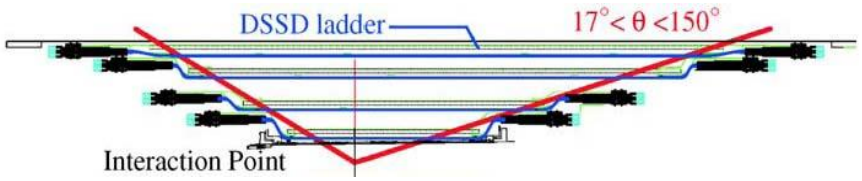


Vertex detector upgrade

Belle II: Pixels (2 layers) + SVD (4 layers)

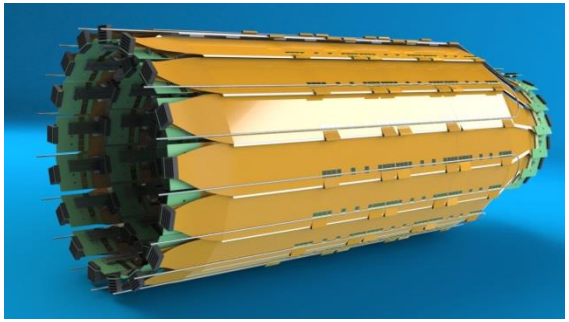


Belle: SVD (4 layers)

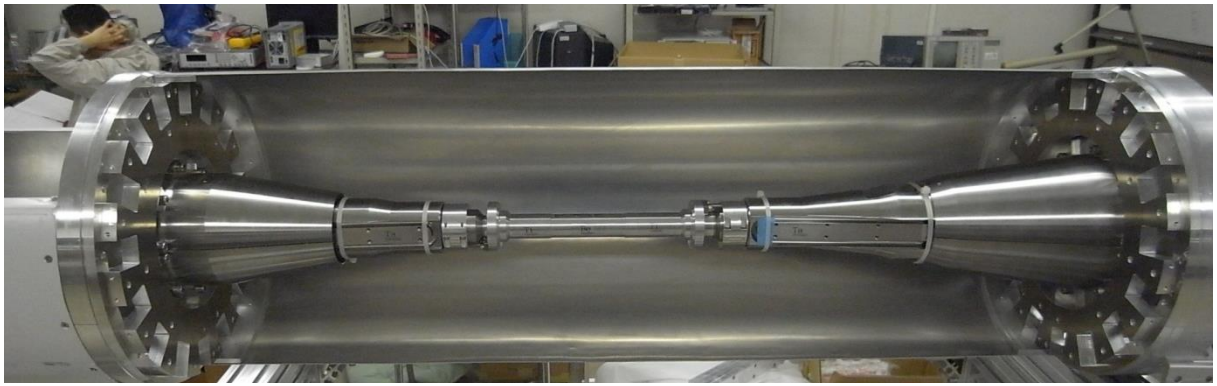


DEPFET Pixel Mockup

Silicon Vertex Detector



- Inner most layer: 2cm (Belle) -> 1.4cm (BelleII)
- Outer coverage: 8cm (Belle) -> 13.5cm (BelleII)



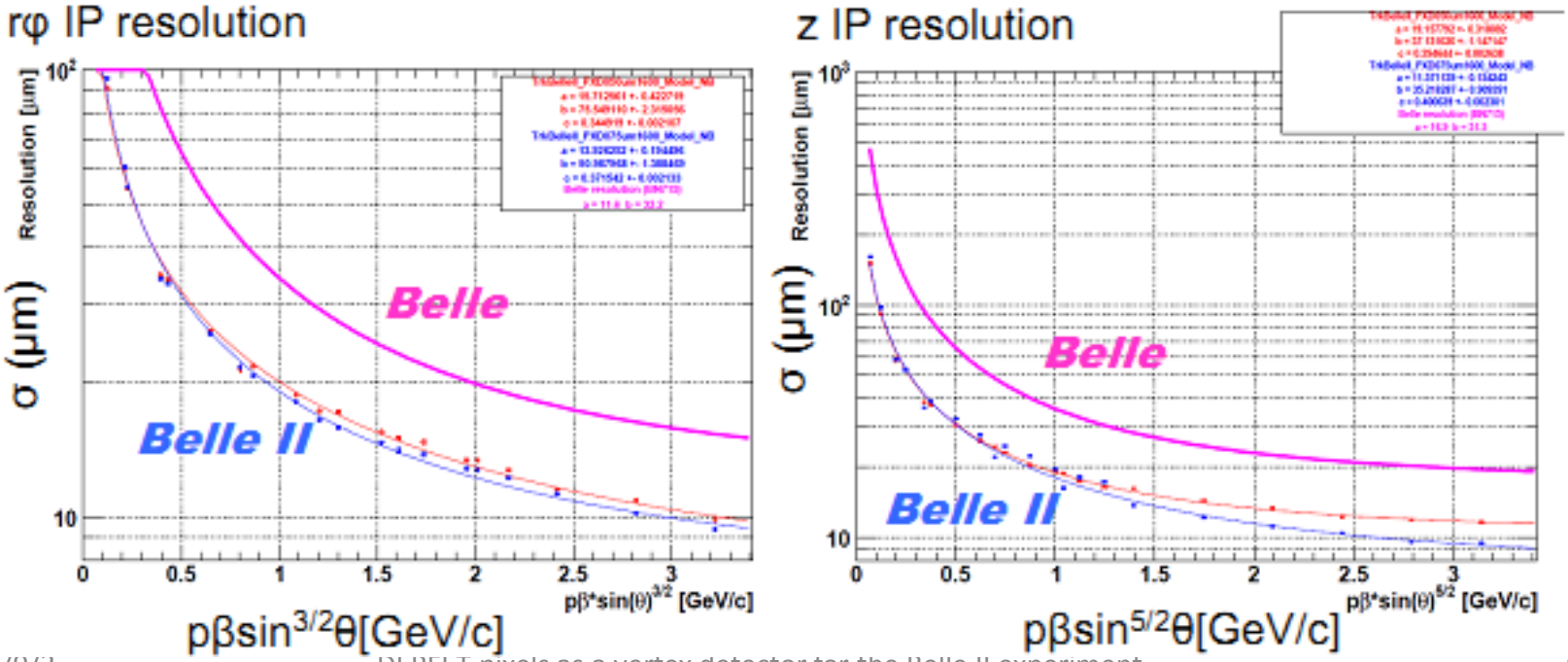
Beam pipe inner radius: 10mm (15mm : Belle)

Belle II pixel detector

Belle II environment:

- Occupancy : 0.4 hits/μm^2/s
- average particle momentum: ~500 MeV
- Radiation tolerance: > 1Mrad/year
- Acceptance: 17^0-155^0
- Higher vertex resolution -> lower material budget

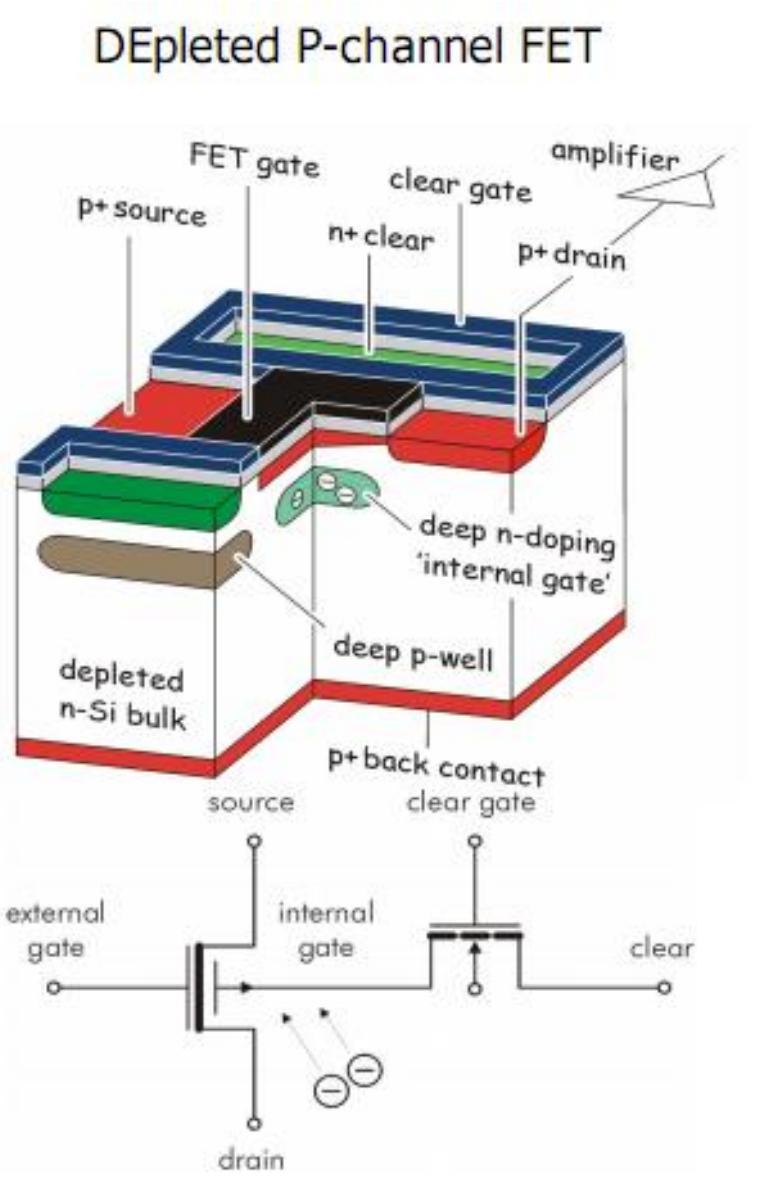
(Since Lorentz boost factor on Belle II is 67 % of Belle case, vertex resolution should be better according to this)



DEPFET- Depleted P-channel Field Effect Transistor

- Each pixel work as a p-channel FET on a completely depleted bulk.
- The signal electrons created in depleted bulk drift to the “internal gate”.
- Internal amplification ->q-I conversion:

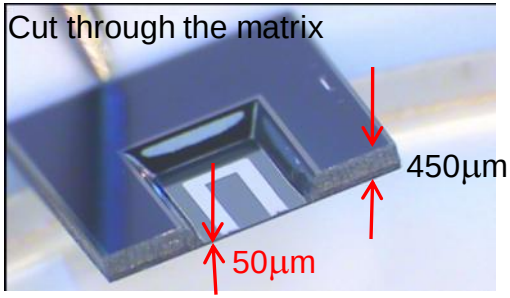
  g_q~ 0.4 nA/e
- 6000 e- and hole pairs in Depleted bulk for MIP, ~50 nA noise



The advantage of the DEPFET sensor are:

-Large signal from the depleted bulk
-Low noise due to low capacitance and
-internal amplification
-Low power consumption
-Fast readout (~100 ns/pixel)

Thinning technology



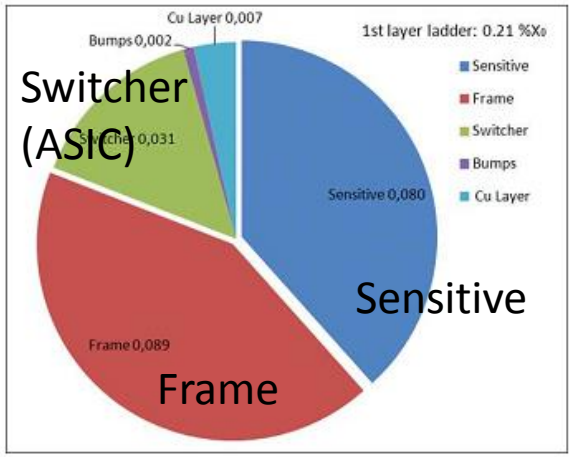
- Most of the tracks at Belle II are at low momenta and vertexing performance is limited by multiple scattering. The high S/N of a DEPFET allows for very thin detectors reducing MS error substantially.

Wafer bonding SOI process

Thinning of top wafer (CMP)

Processing

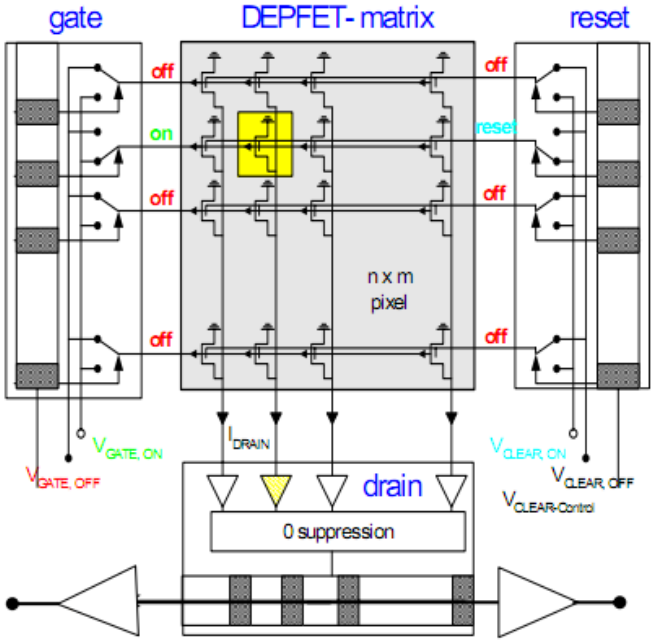
etching of handle wafer (structured)

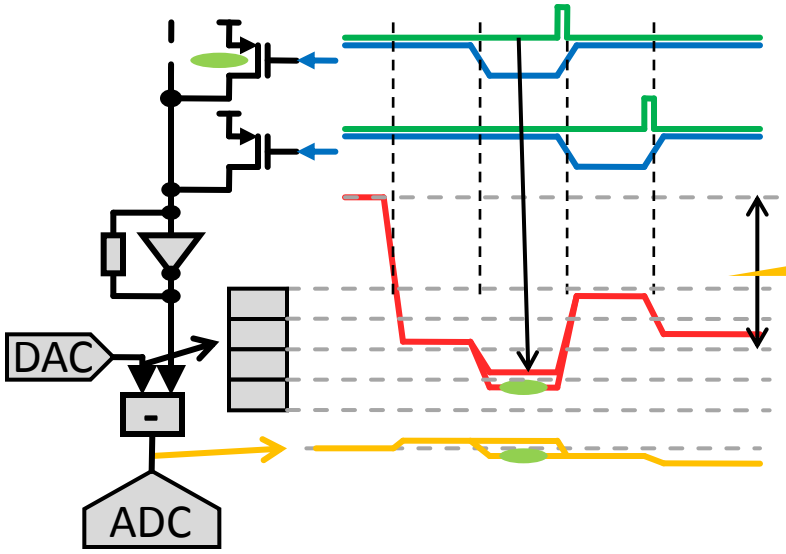


Sensor thickness: 75 µm
(optimized for vertex resolution)
~0.21 % X_0 for layer

All silicon module

Read-out scheme





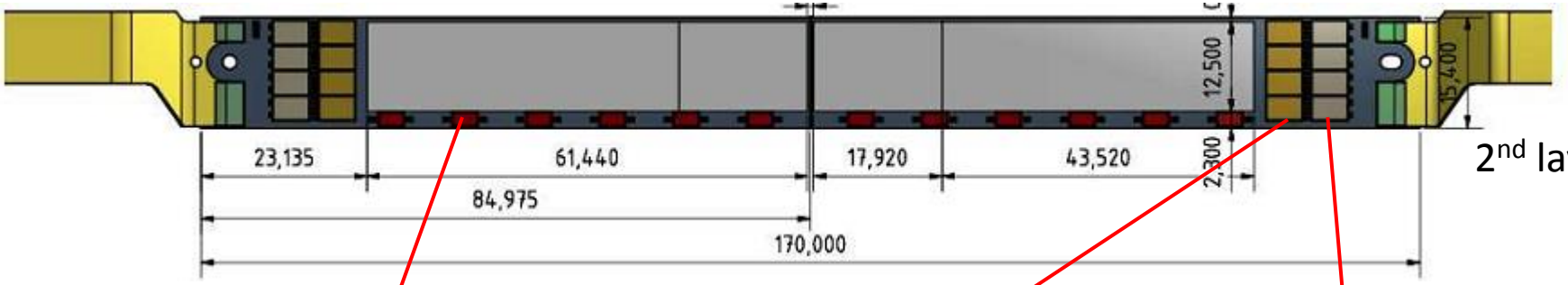
- DEPFET pixel arranged in grid
- Row wise read-out mode
  - "Rolling shutter mode"
  - 20 μs/frame (4 rows in parallel)
- Row selected with external gate and clear of internal date
  - Switcher
- Digitizing drain current
  - Drain Current Digitizer(DCDB)
- Pedestal subtraction and zero suppression for each pixel
  - Data handing processor(DHP)

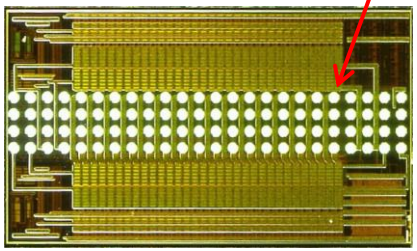
Average Pedestal Current ~**50 μA**
Common mode correction in a row: 200 μA

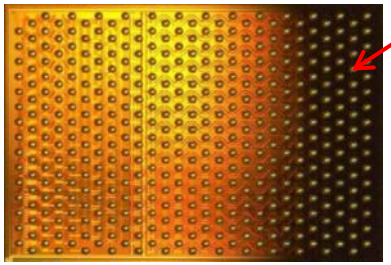
Rough Pedestal Fluctuation compensation~**32 μA**

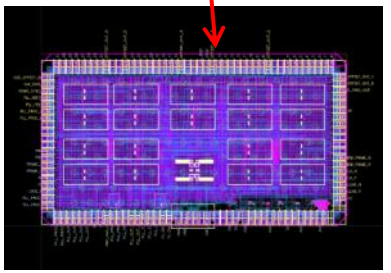
Signal ~ 0.4nA/e
= **2-3 uA** (75μm Si)
ADC range :**16 μA**

ASICs









Switcher
Control of gate and clear
32 x 2 channels
Switches up to 30V
AMS 0.18 µm HV technology
Tested up to 36 Mrad

DCDB
Amplification and digitization of DEPFET signals
256 input channels
8-bit ADC per channel
92 ns sampling time
UMC 180nm,
rad hard design

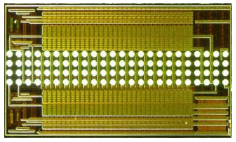
DHP
Signal processor (320MHz)
Common mode correction
Pedestal subtraction
0-supression
Timing and trigger control
TSMC 65nm, rad hard design

PXD assembly

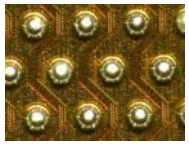
Sensor processing: Munich

Wafer level testing
Munich

Thinning, cutting, Munich

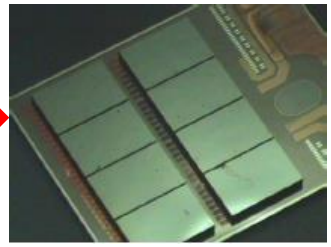


Switcher:
Heidelberg



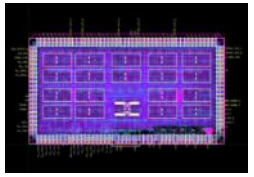
Bumping
Heidelberg

Pobe card test



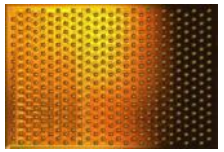
Flip Chip: in Germany (IZM)
Tests, Rework: Valencia

Pobe card test

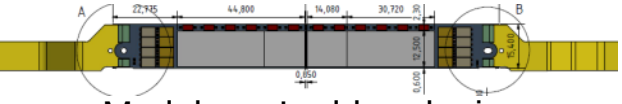


DHP, Bonn

Pobe card test



DCD, Bonn



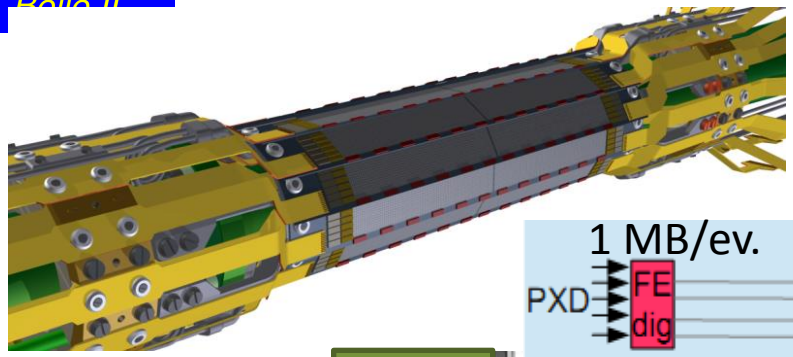
Module- > Ladder glueing
Kapton addition, Tests
Munich

PXD Assembly,
Munich

To KEK

Mech. Components
Munich

PXD readout



Two layers
R=14 mm
R = 22mm

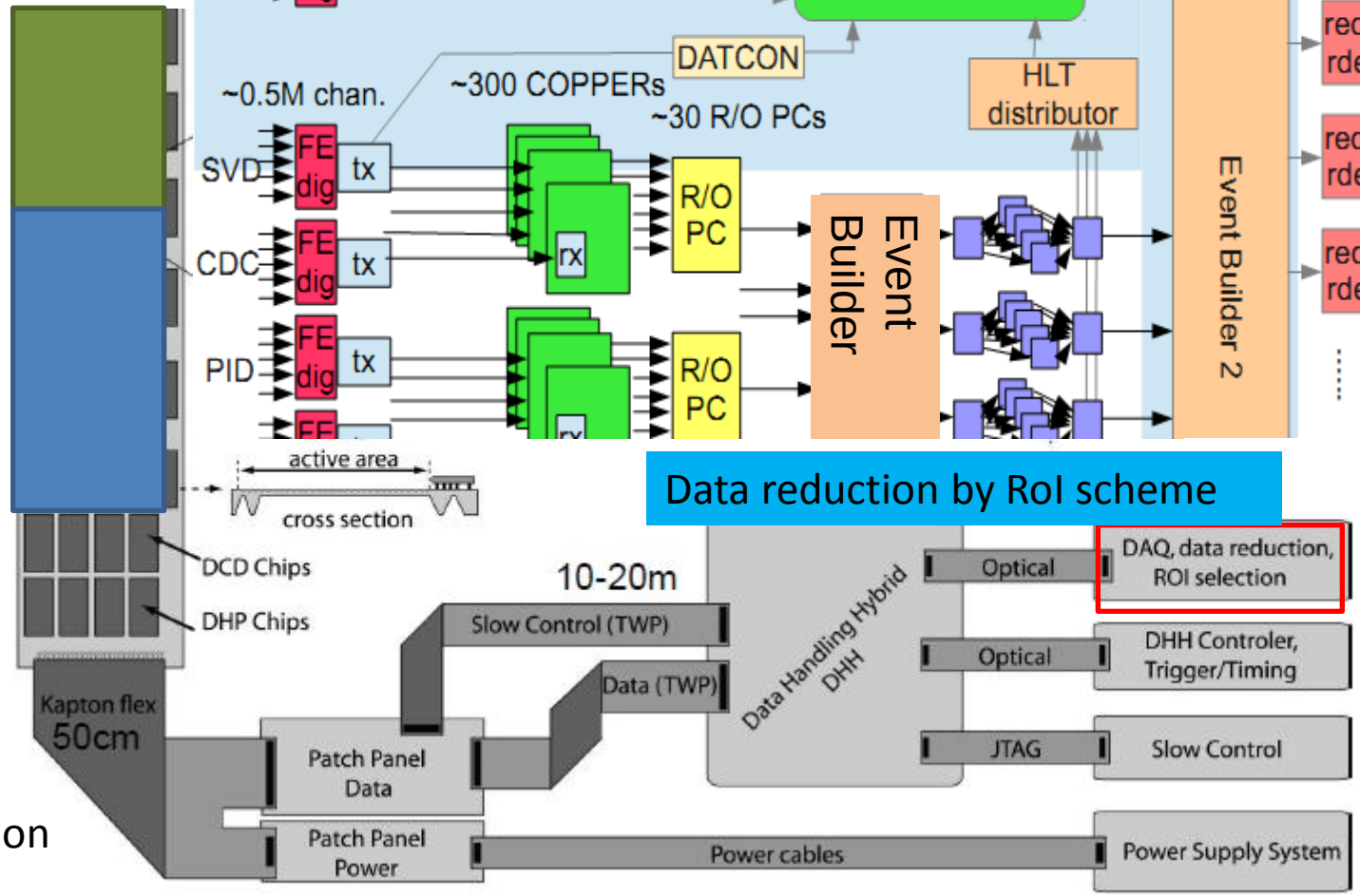
8 ladders,
12 ladders

256 lines
1st:50 x 55 μm²
2nd:50 x 70 μm²

512 lines
1st:50 x 60 μm²
2nd: 50 x 85 μm²

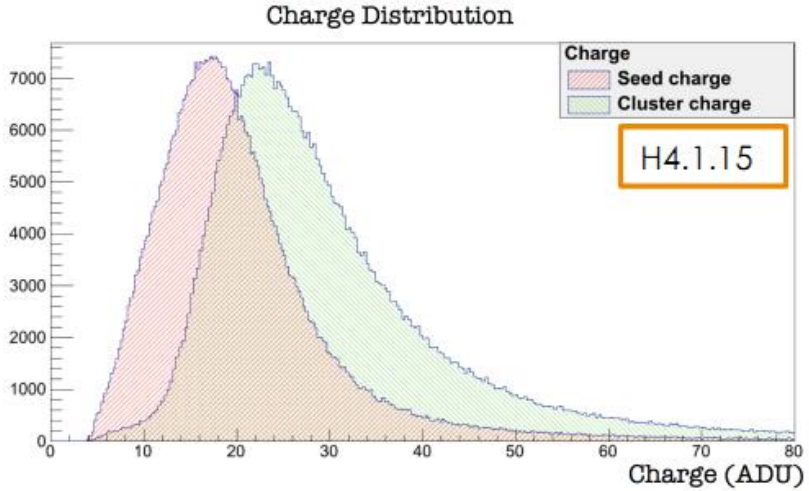
80Gbit/s

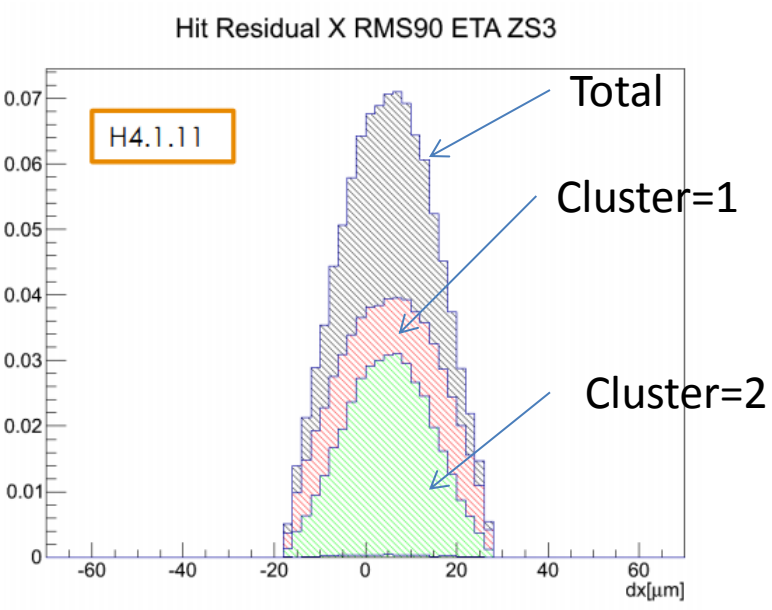
4 Gbit/s by
Zero suppression



Performance

- Beam test by 120 GeV pion beam
- Position resolution =8μm
- S/N=30~40

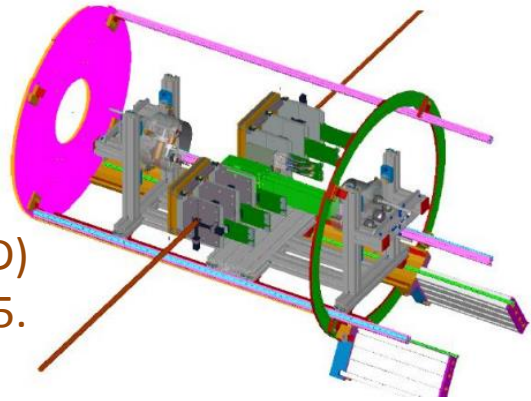




6 μm gate length

Prototype	$MPV_{Cluster}$ (ADU)	$Mean_{Noise}$ (ADU)	S/N
H4.1.04 (Golden)	10.7 ± 0.1	0.5	21.3 ± 0.2
H4.1.11 (Platinum)	20.9 ± 0.3	0.6	33.5 ± 0.5
H4.1.15 (Diamond)	23.9 ± 0.3	0.6	41.5 ± 0.4

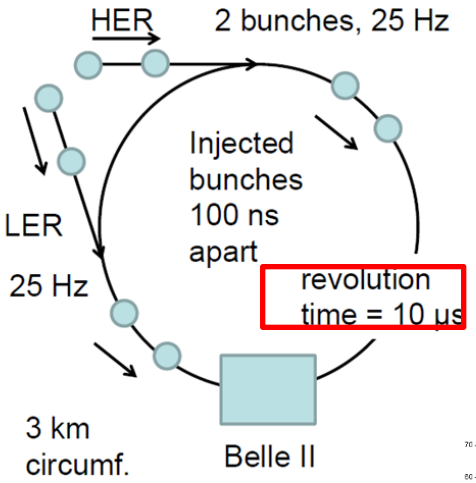
4 μm gate length (Baseline)

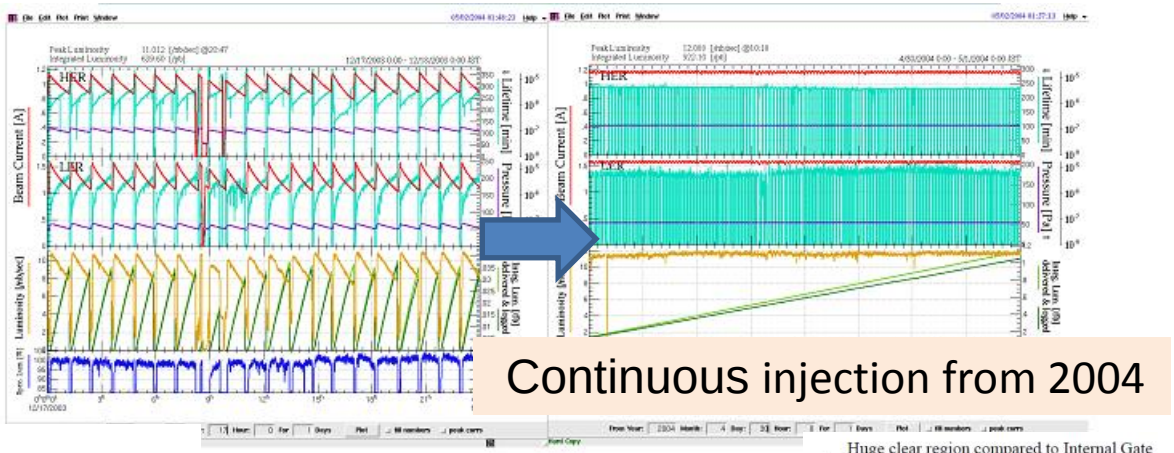


4GeV electron beam test of VXD (2 PXD+ 4 SVD) with mini Belle II DAQ is scheduled in Jan. 2015.

($g_q \sim 1/L^{3/2}$: L is gate length)

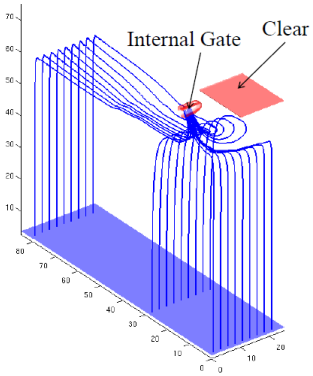
Gated mode (Blind mode for injection BG)



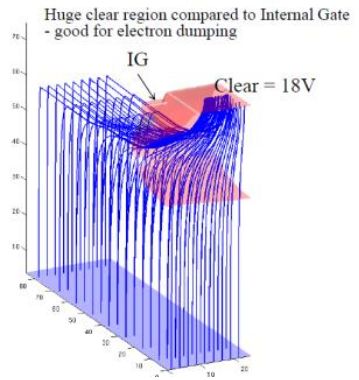


Continuous injection from 2004

Normal operation:
Signal charge drifts into internal gate



Gated operation
Charges from background drift directly to clear gate



Sensor filled with hits from injected bunches for each turn for 4ms passing Belle II
=> ~ 20% dead time

PXD readout takes 20us for one frame

Gating : Sensor is made blind for a short time during high background (noisy bunch)
Signals detected in the clean period before are preserved

BG sources and Radiation tolerance

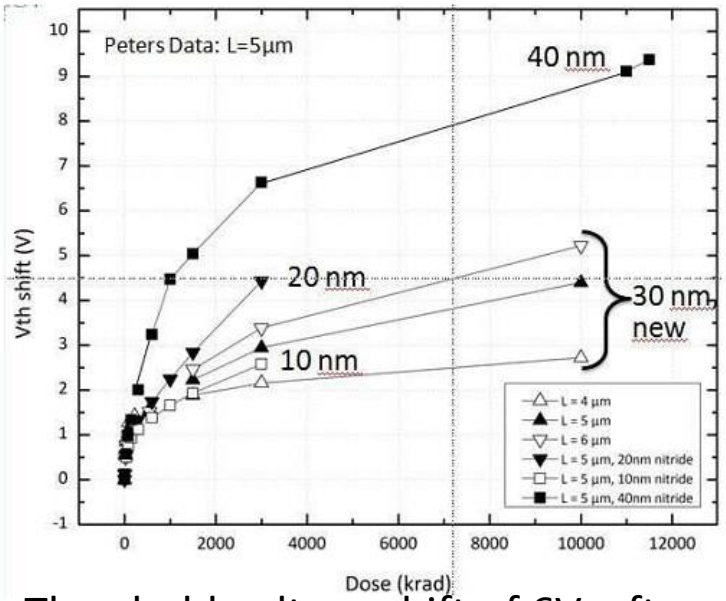
- Radiation environment
  - 4-fermion final state QED process
  - Touschek effect
  - Beam-gas interactions
  - Synchrotron radiation
  - Radiative Bhabha scattering

Occupancy by each BG source		Layer 1	Layer 2
Touschek	LER	0.1 %	0.07 %
Touschek	HER	0.0 %	0.0 %
Beam-Gas Coulomb	LER	$2 \cdot 10^{-4}$ %	$1 \cdot 10^{-4}$ %
Beam-Gas Coulomb	HER	0.0 %	0.0 %
Radiative Bhabha	LER	$5 \cdot 10^{-3}$ %	$2 \cdot 10^{-3}$ %
Radiative Bhabha	HER	0.03 %	0.01 %
Two-Photon QED		0.8 %	0.2 %
~Total		0.9 %	0.3 %

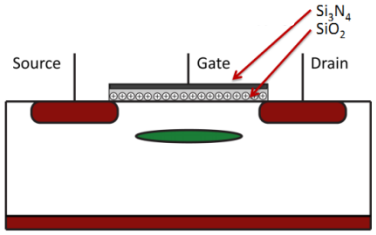
Synchrotron radiation(very preliminary): 0.14 %
(one ladder in horizontal plane: ~1.8%)

Still under investigation

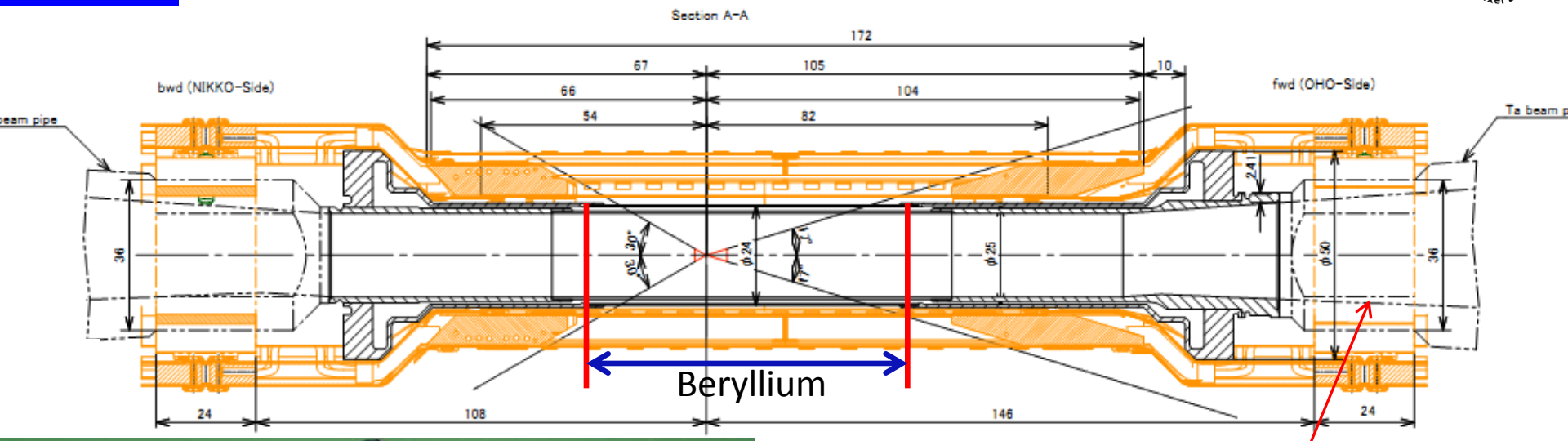
PXD sensor damage by
1, Surface damage or oxide damage
2, Bulk damage

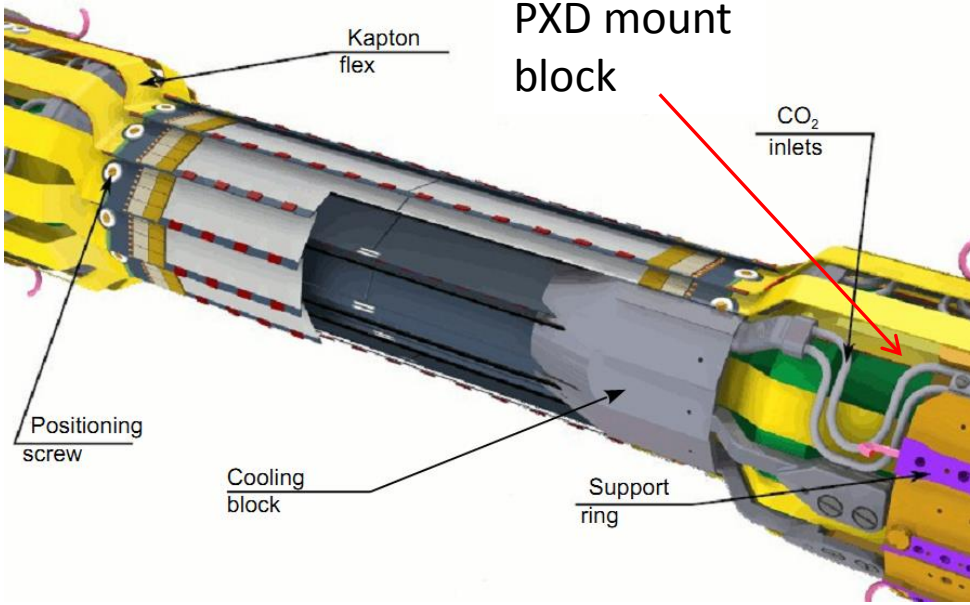


Threshold voltage shift of 6V after 100kG (10Mrad) by optimizing nitride thickness.
(Silicon nitride layer is covered on thin silicon oxide)

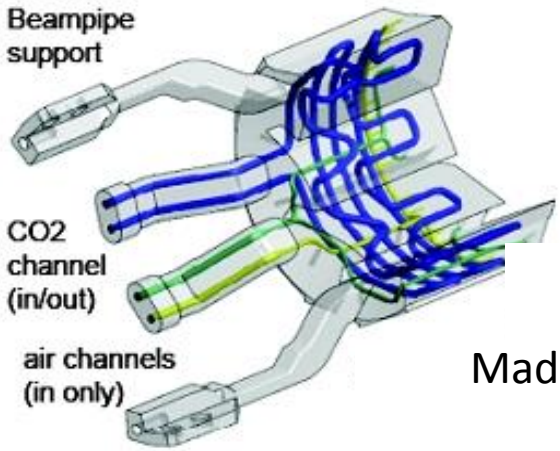


PXD mechanics



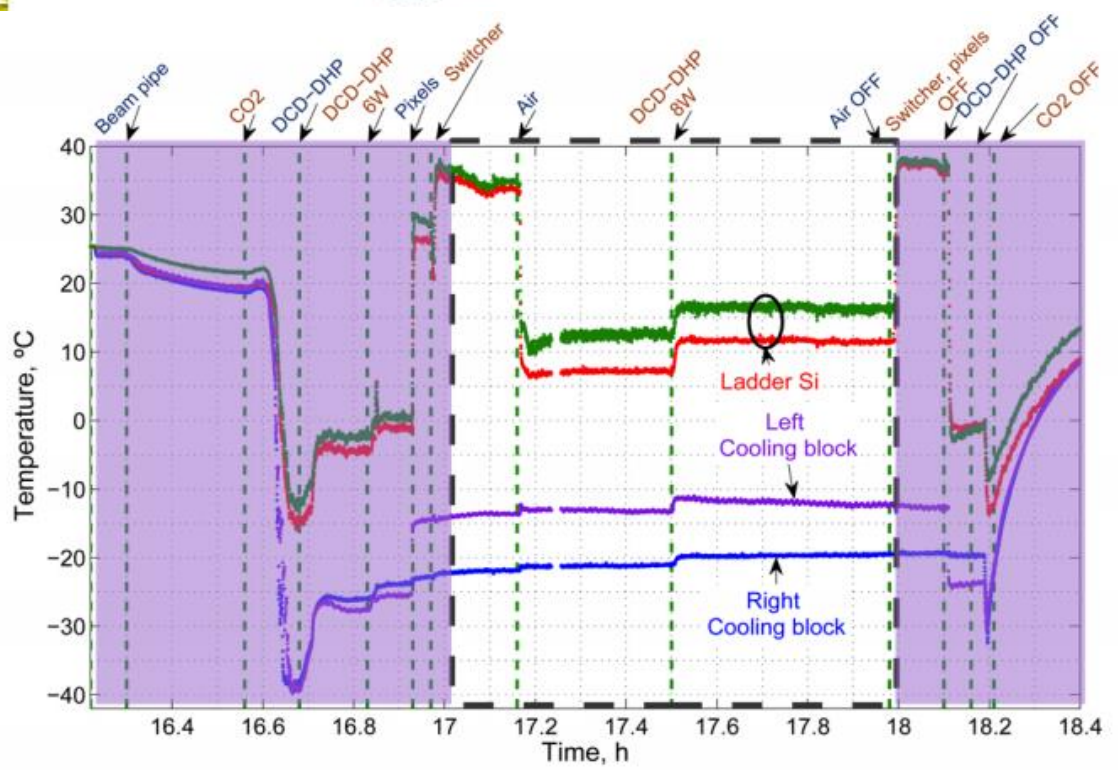


Thermal management



Made by SUS

- 360 W total power dissipation which is dominated by ASIC operation outside the acceptance region
- Mount block cooling by liquid CO2 and air cooling

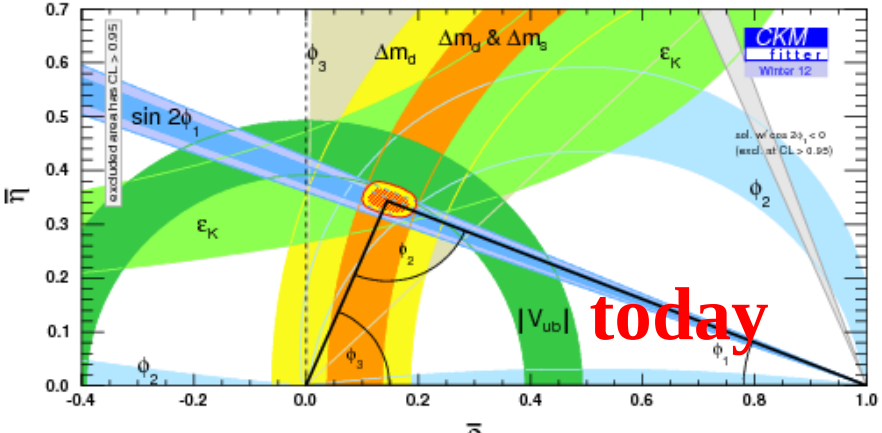


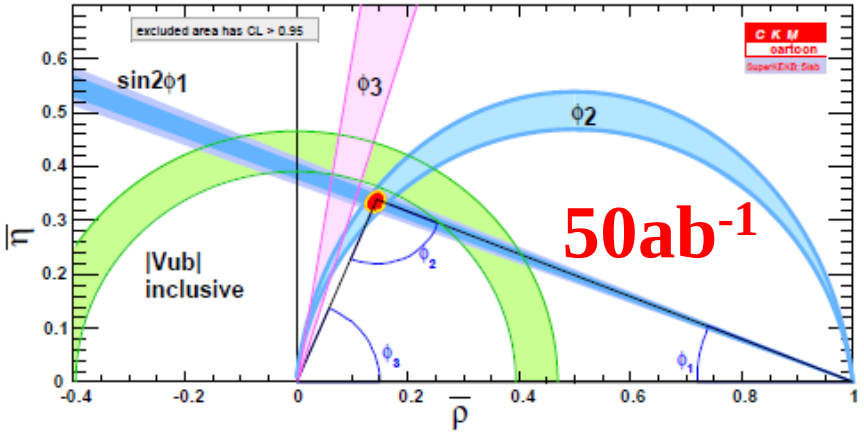
Conclusion

- SuperKEKB with 40 times higher luminosity compare to KEKB provides an opportunity to study high precision indirect searches for Physics beyond SM.
- Pixel detector based on DEPFET technology fits all requirements of
  - Vertex resolution
  - Low power consumption
  - Low material budget
  - Gated mode to blind noise signals from beam injection BG
- The DEPFET PXD has entered the construction phase
  - VXD system combined beam test with scaled down Belle II DAQ is scheduled in coming January.
- PXD system will be assembled in 2015 and first physics runs are scheduled in 2016

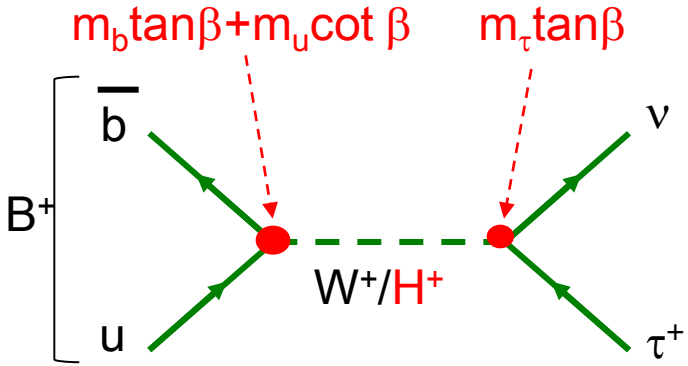
Physics motivation on Belle II

- Improving precision on CKM picture, search for deviations:

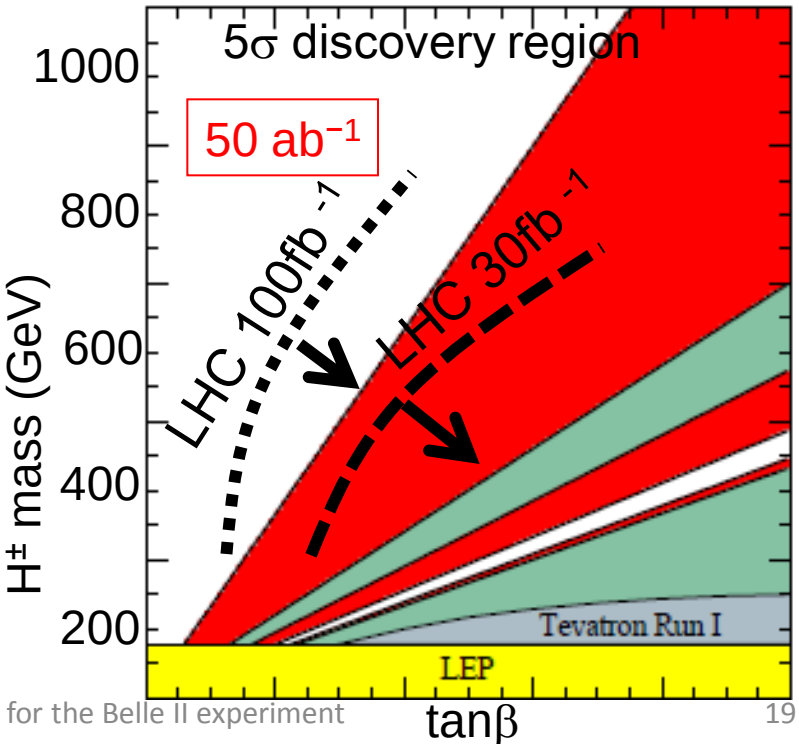




- Complementary to LHC searches
  - Previous examples include modes with missing energy.
  - $B \to \tau\nu$, $B \to D^{(*)}\tau\nu$, $B \to K^{(*)}\nu\nu$



High τ reconstruction eff. Is key.



Belle II Schedule