Semi-conductor Detectors
HEP and Accelerators

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Outline

- Semiconductor Detectors
  - A Brief Overview
  - Radiation Damage
- Silicon Strip Detectors
- Pixel Detectors
  - Hydrid Pixel Detectors
  - Integrated Devices
    - MAPS
    - DEPFET
    - HV-CMOS and HR-CMOS
  - 3D geometry
- Diamond Detectors
- LHC
- SuperKEKB
- Outlook

Basics

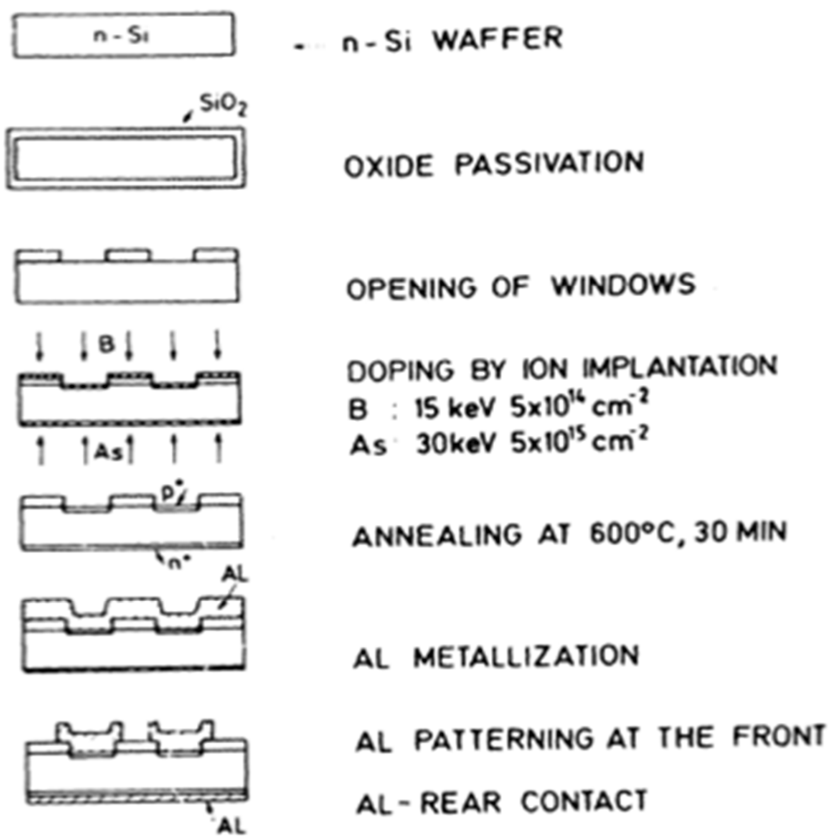


Fig. 2. The planar process for detector fabrication.

Kemmer Process (eg. NIM **226** (1984) 89-93)

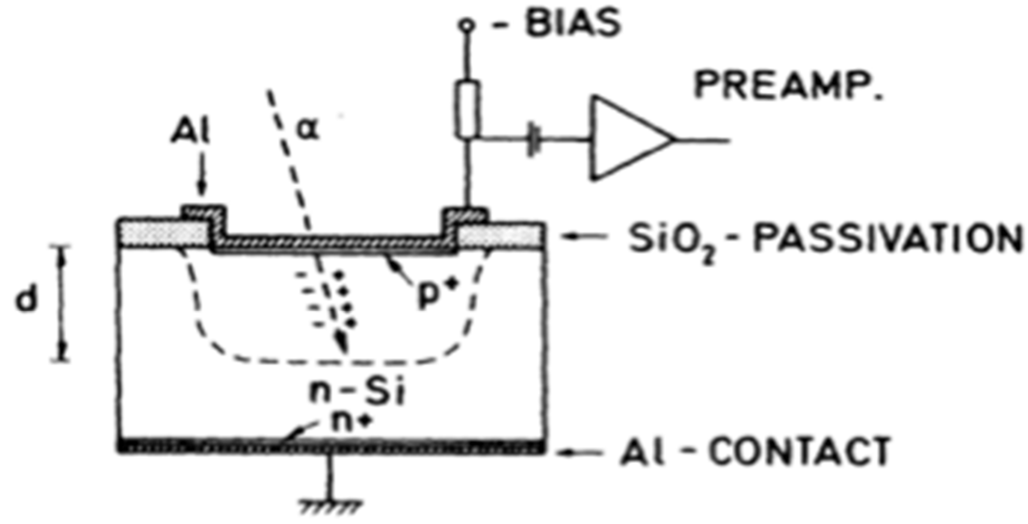


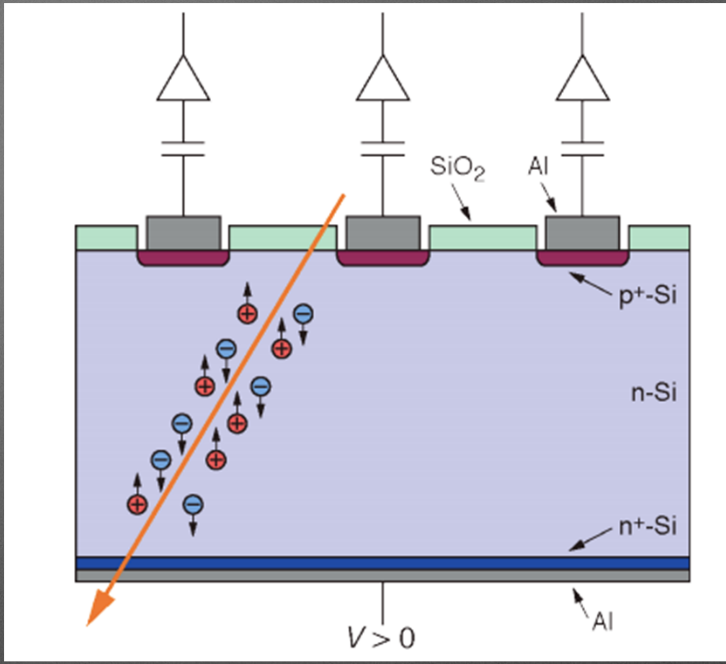
Fig. 1. The p^+n junction detector.

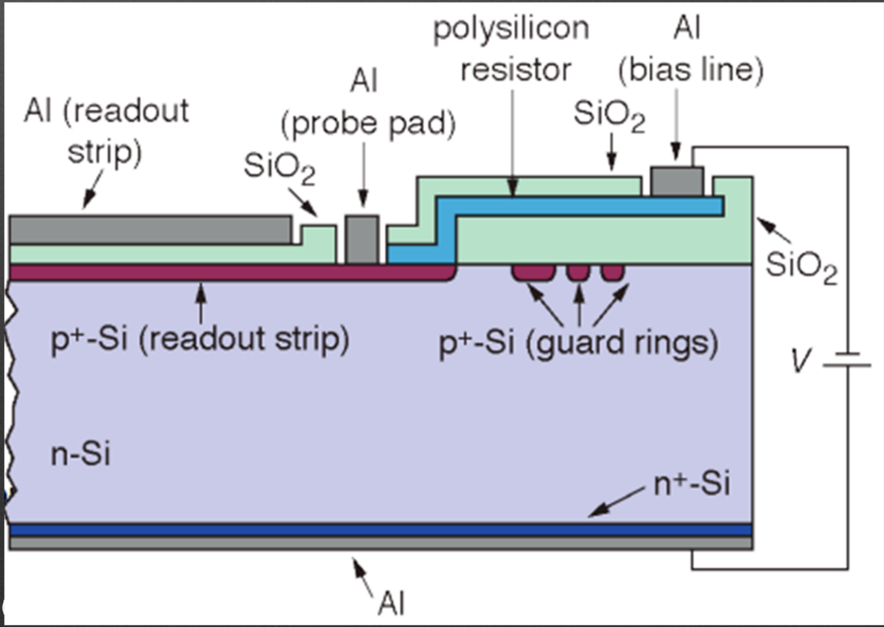
Basic Semiconductor materials:

- Silicon
- Ge
- GaAs
- CdTe
- CdZnTe
- Diamond
- Silicon Carbide, …

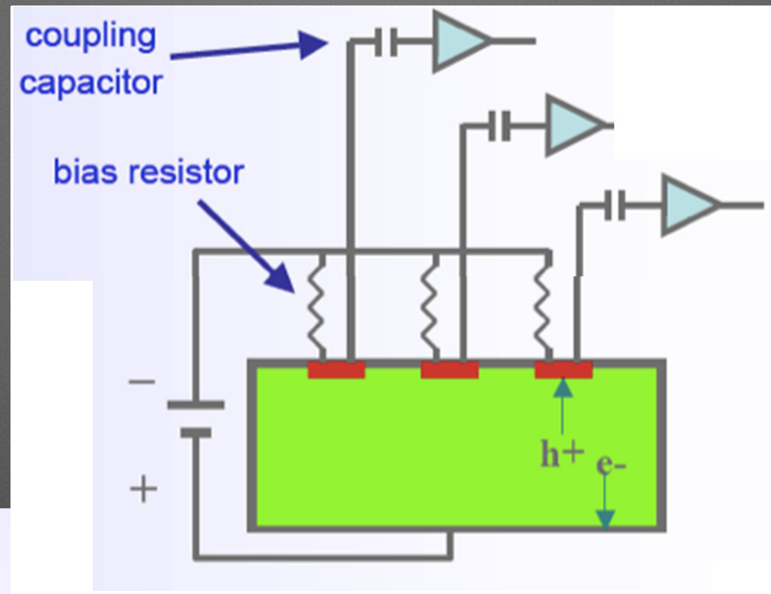
Semiconductor Detectors

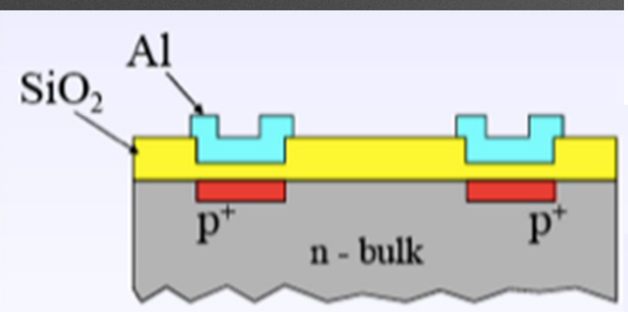
- Semiconductor Diode detectors have been used, and highly evolved for decades.
- Technology highly developed but high specialised.

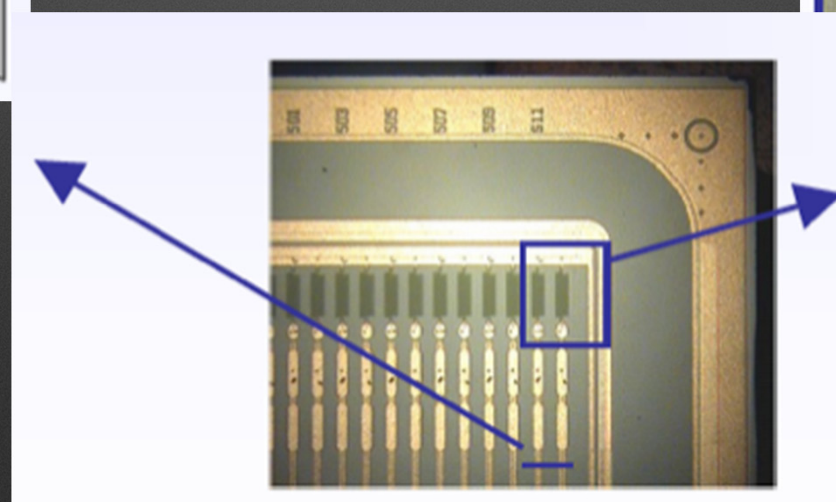


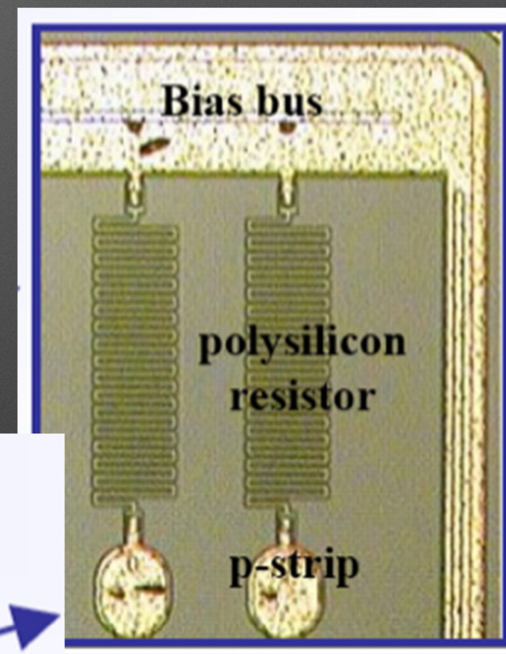


Sophisticated integration …

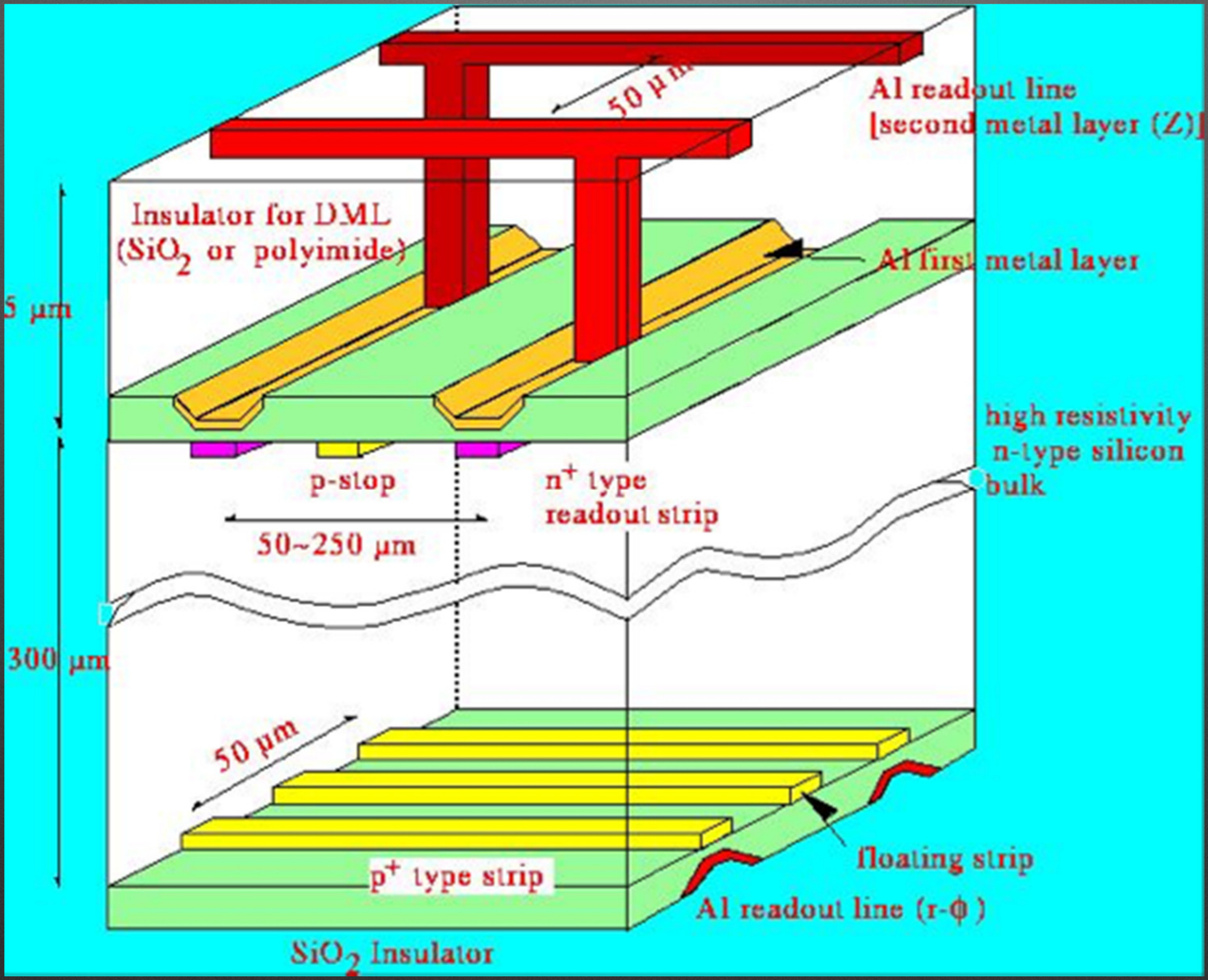




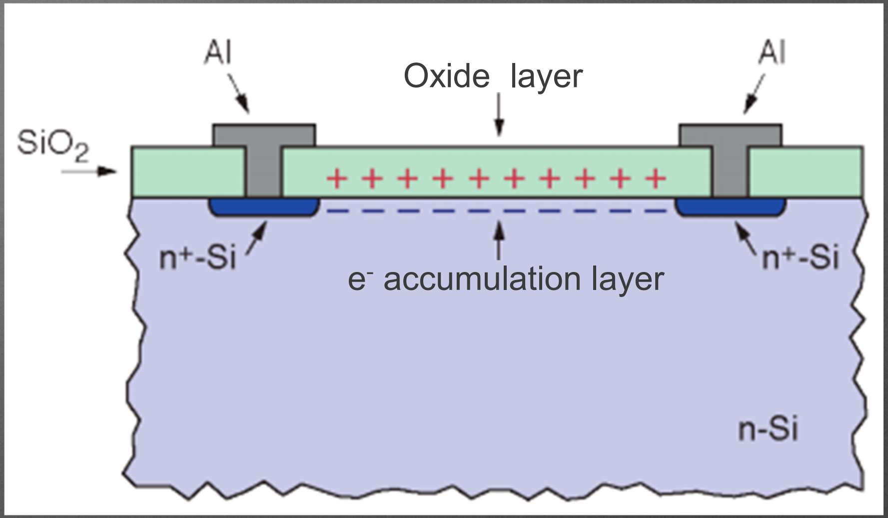


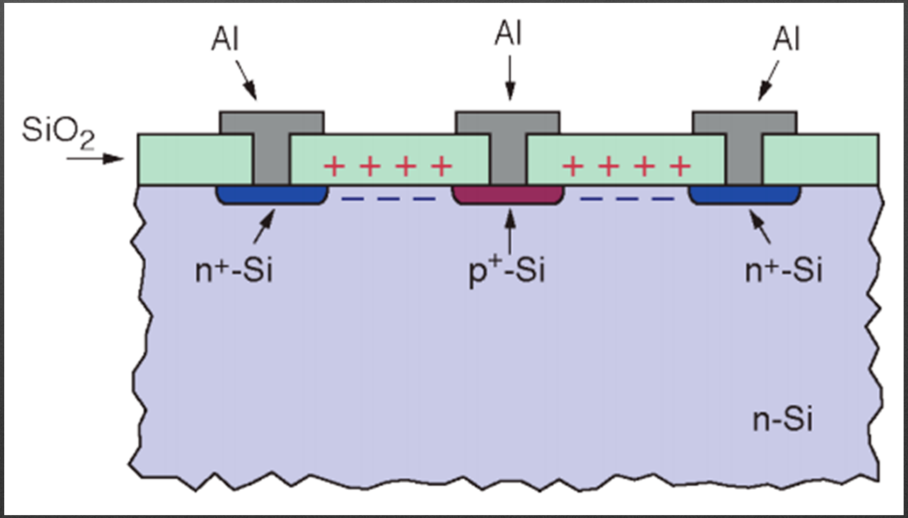


Double-sided Silicon Detectors



- n-side (back-side)
  - positive (fixed) charge at SiO_2 - Si interface attracts electrons to n-side.
  - Electron accumulation shorts n-side electrodes
  - p^+ “isolation” required





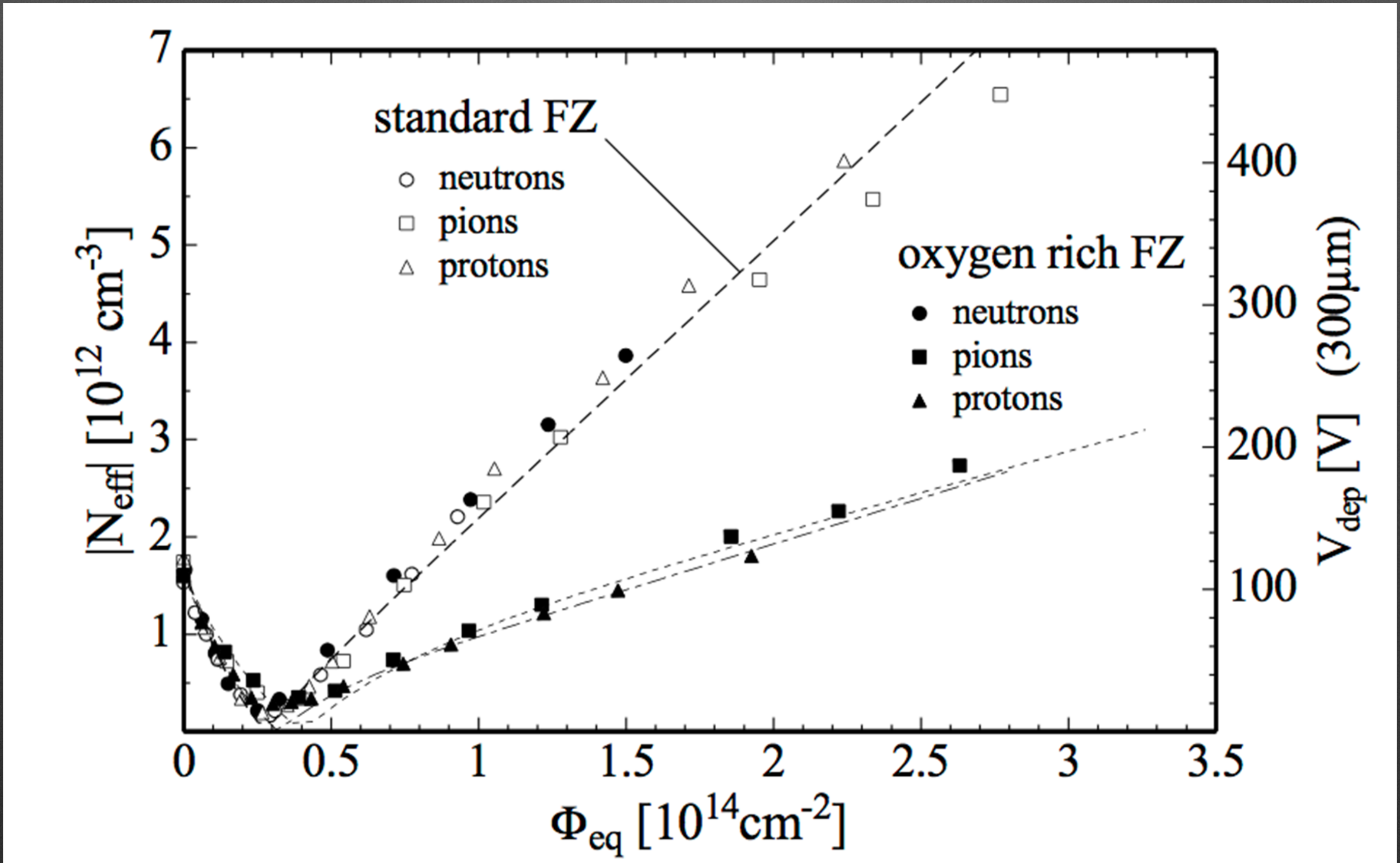
Radiation Damage

Three main macroscopic effects are seen in high-resistivity diodes following energetic hadron irradiation:

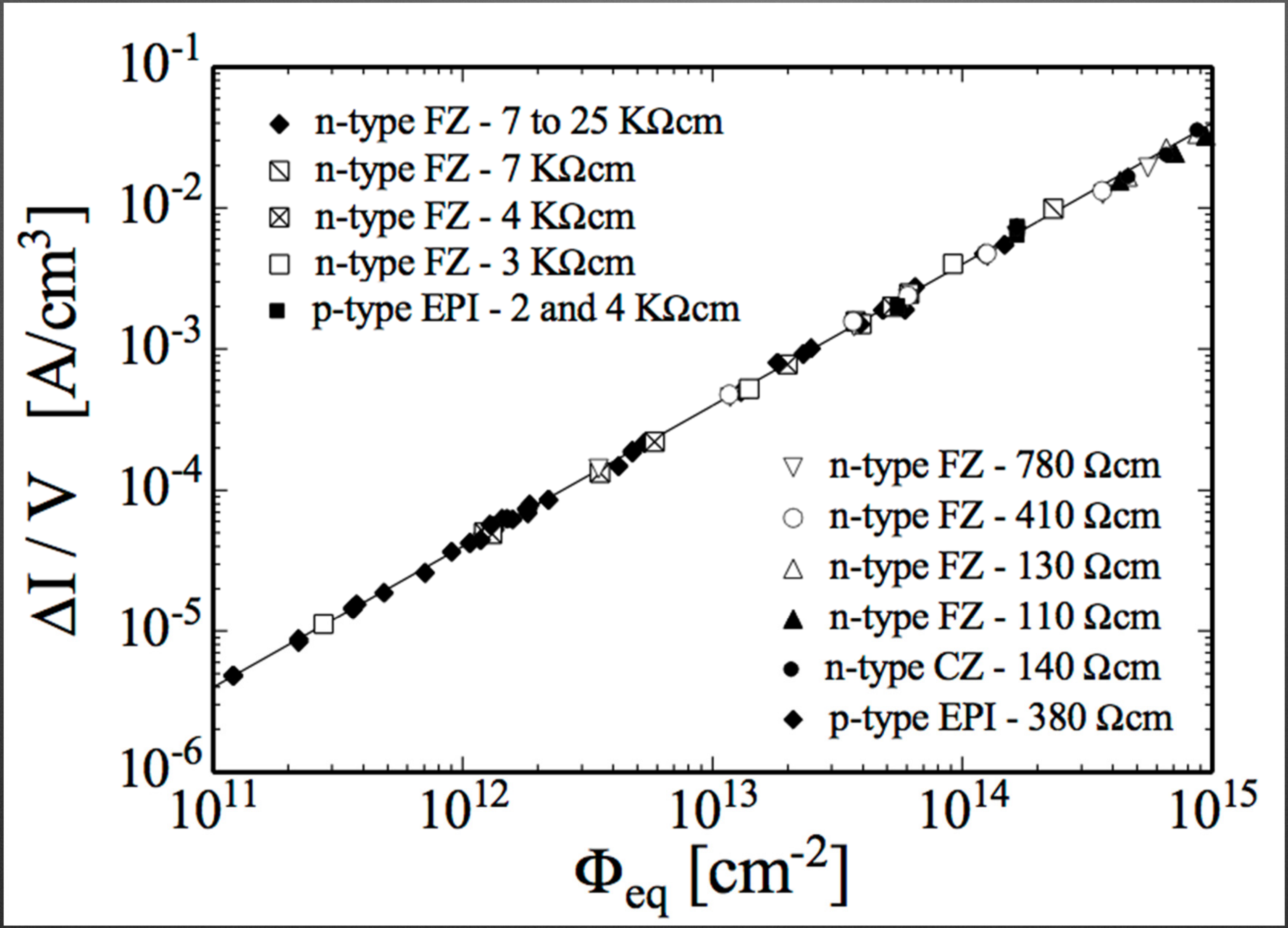
- Change of the doping concentration with severe consequences for the operating voltage needed for total depletion.
- Fluence proportional increase in the leakage current, caused by creation of recombination/generation centres
- Deterioration of charge collection efficiency due to charge carrier trapping leading eventually to a reduction in the signal height produced by mip's.

$$V_{dep} = \frac{q_0}{2\varepsilon\varepsilon_0}|N_{eff}|d^2$$

- Defect Engineering
- Thin detectors
- High Bias Operation



$$I = \alpha \cdot \Phi_{eq} \cdot V$$

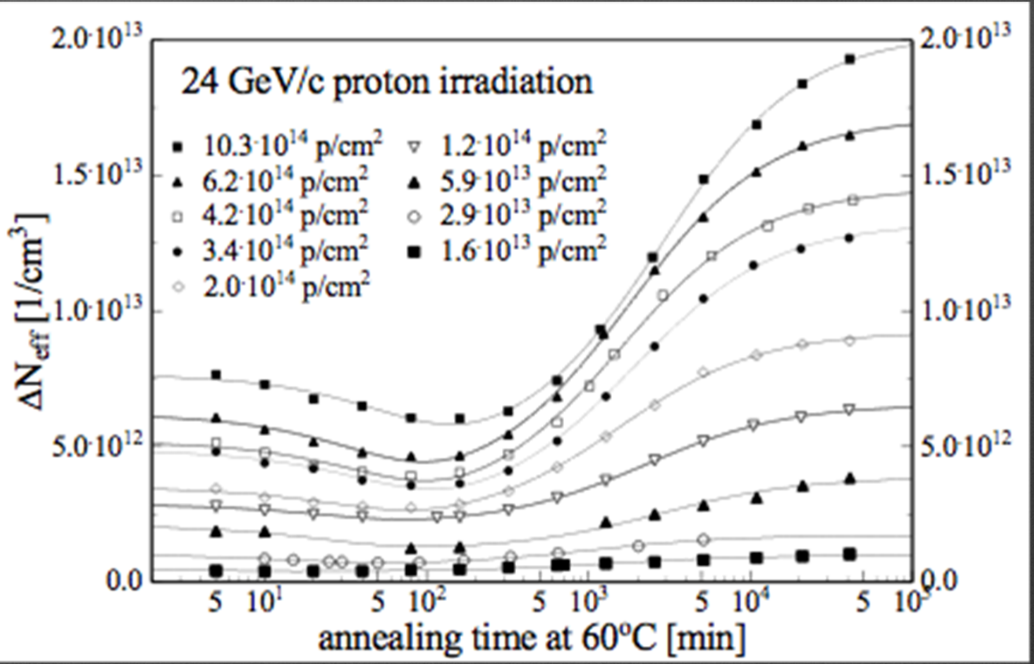


Effect of Temperature

- Strong current reduction with reduced temperature.
- (also Current Annealing)

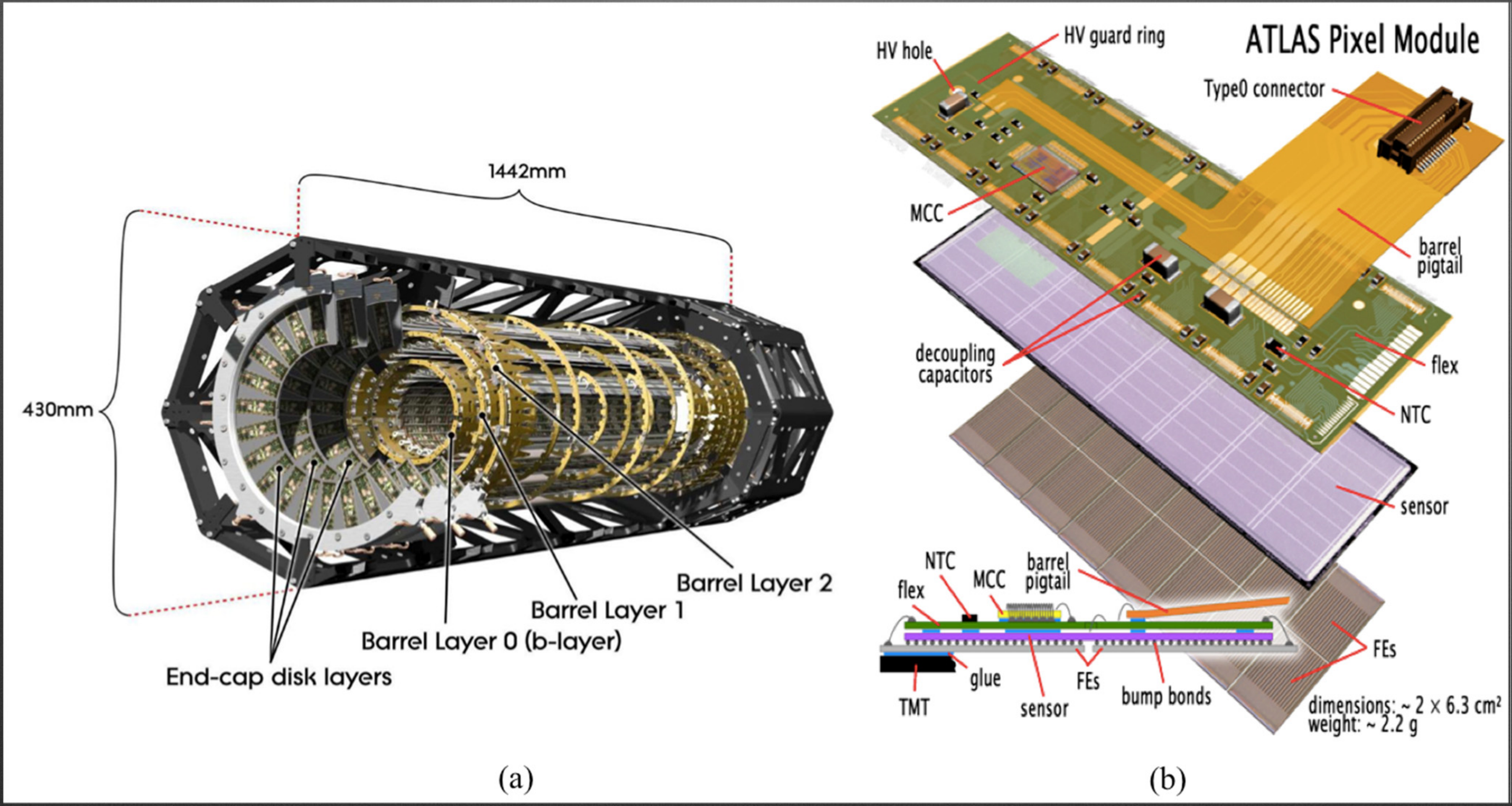
$$I(T) \propto T^2 \exp\left(-\frac{E_g}{2k_B T}\right)$$

- Reverse Annealing of Effective Carrier concentration



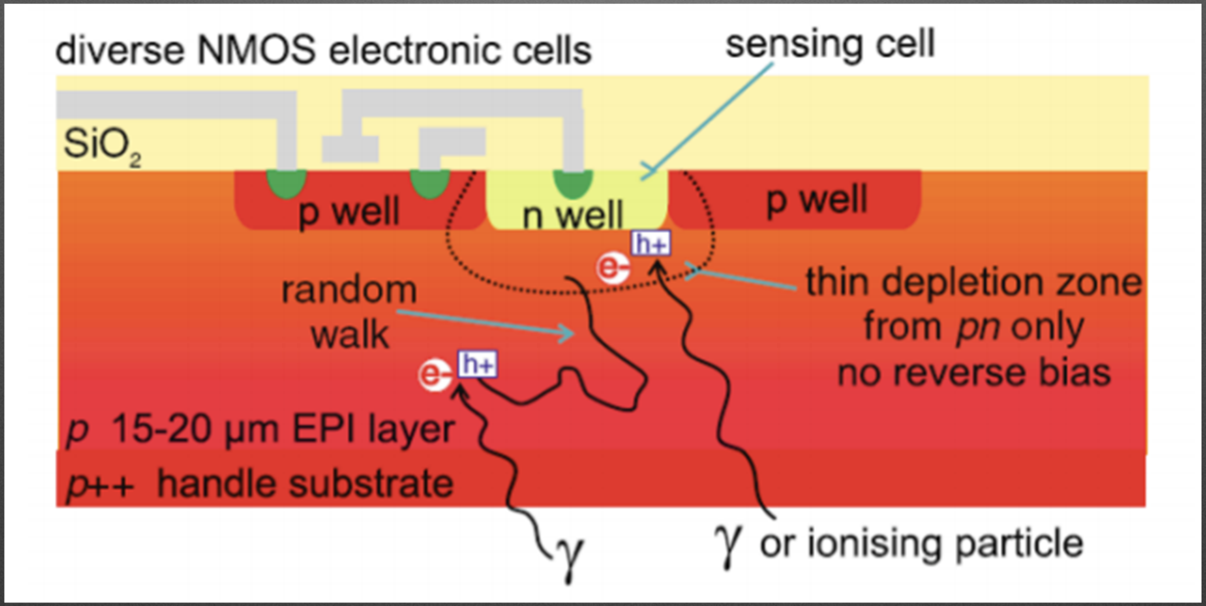
Hybrid Pixel Detectors

- Electronics chip and sensor chip independently produced, bump bonded



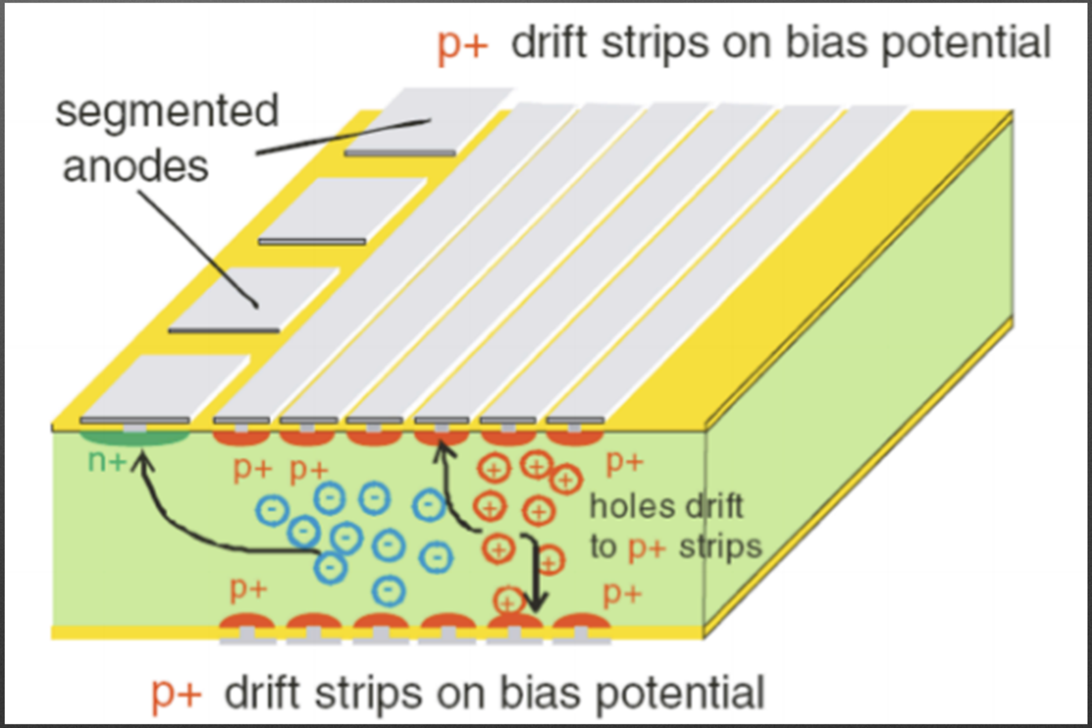
Integrated Pixel Detectors - MAPS

- Electronics and detector element on a single substrate



Silicon Drift Detectors

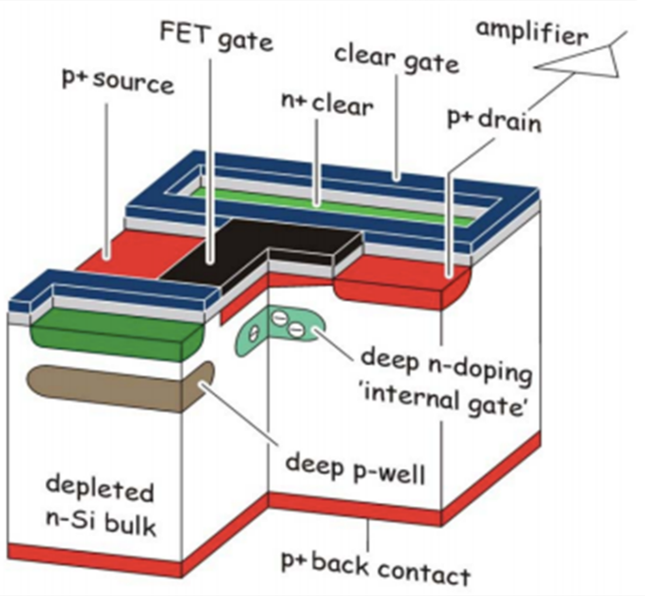
- Positive Electrodes set up Drift Potential
- Electrons drifted to readout anode pads.
- Time/position -> 2D position.

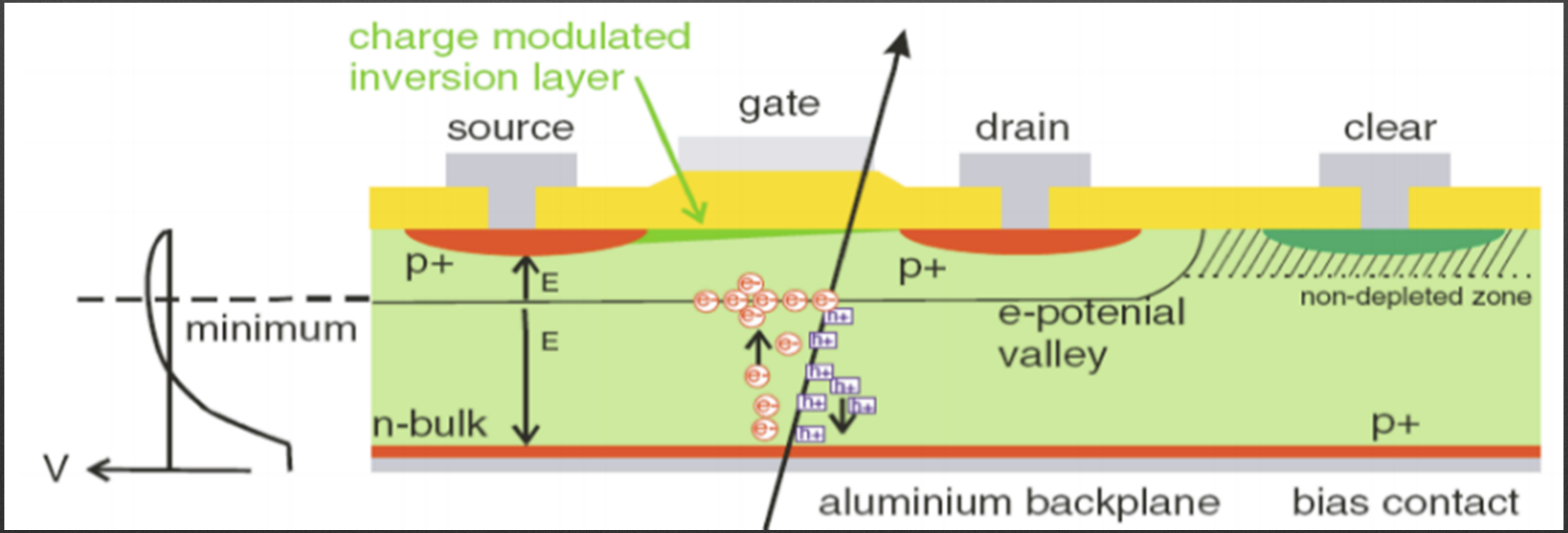


F. Hartmann, Springer, 2009

Integrated Pixel Detectors - DEPFET

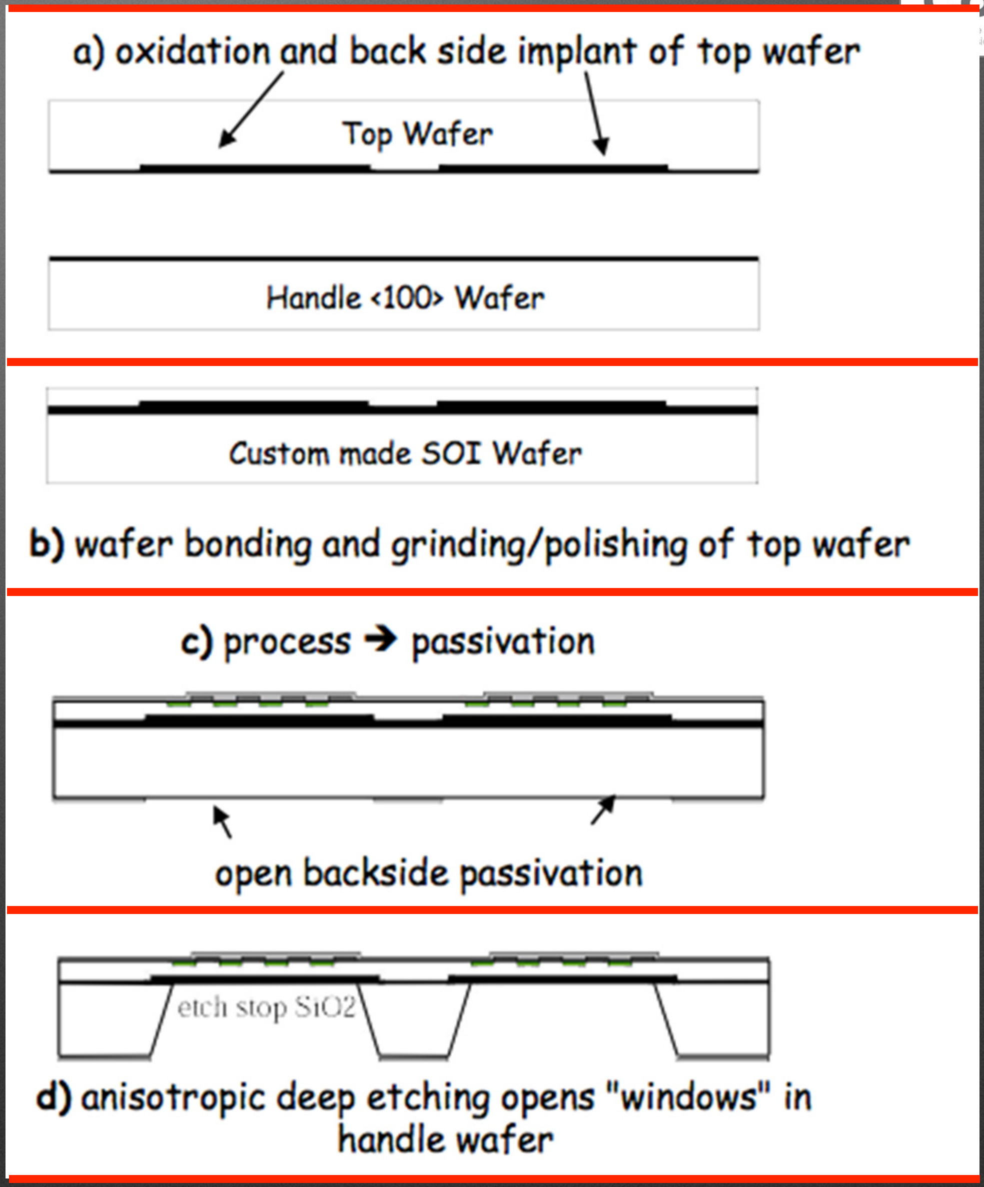
- Belle II Pixel detector





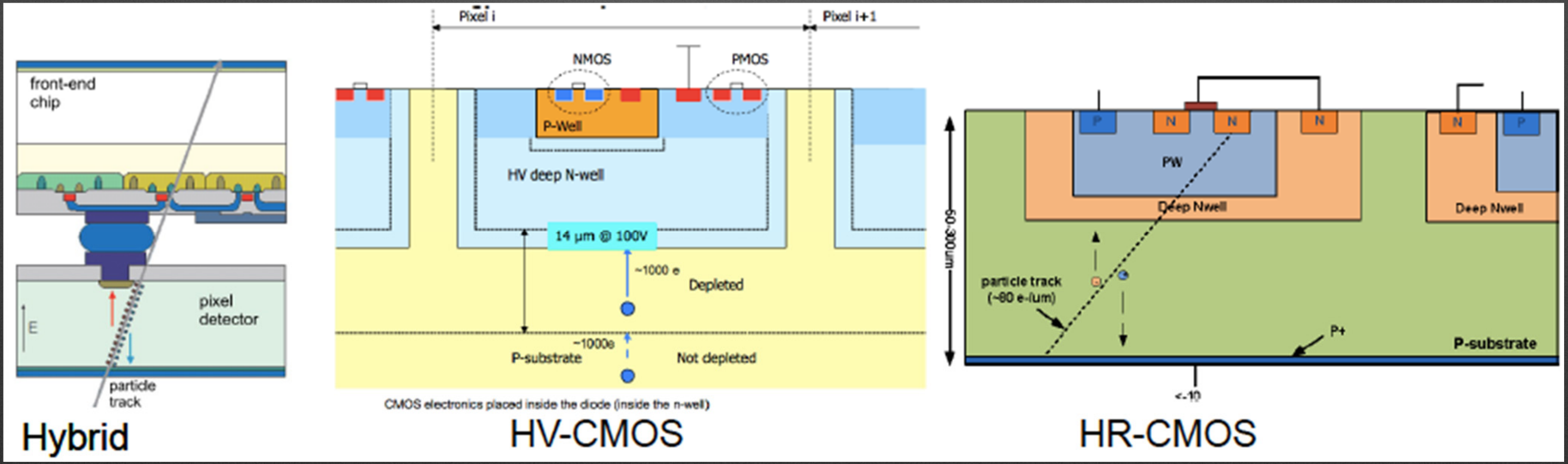
Thinning of silicon detectors

- eg. Belle II PXD
- Rather complicated process.
- Major benefits

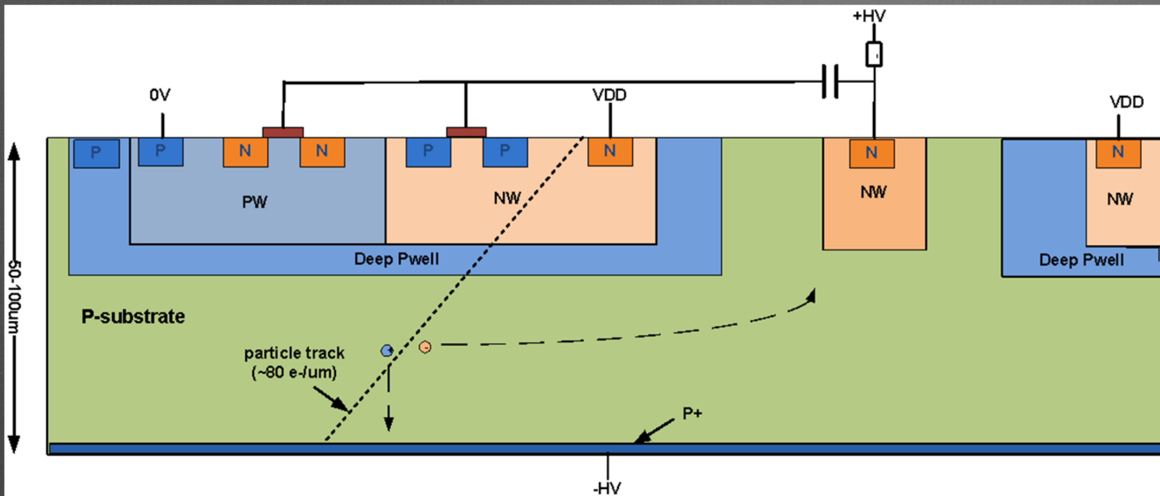


Integrated Pixel Detectors: HV-CMOS and HR-CMOS

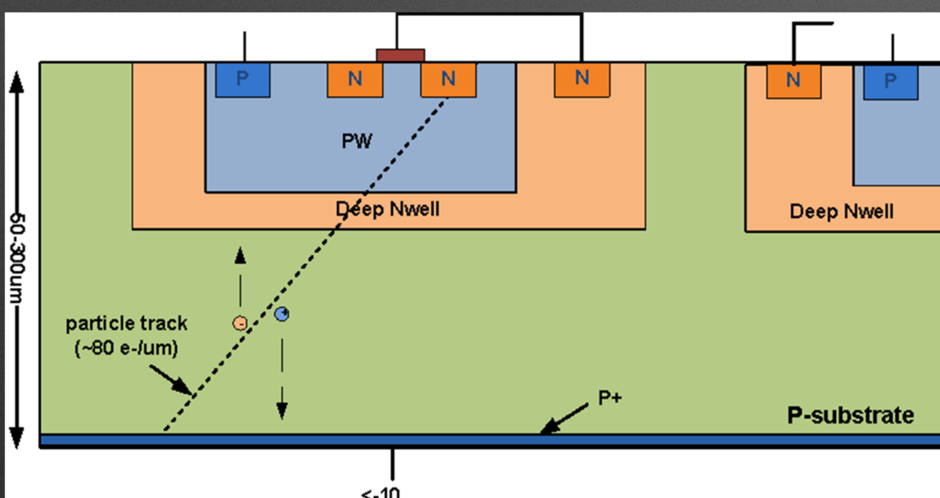
- With a High Resistivity Substrate, the depletion region can be increased over that of the MAPS detectors.
- CMOS processing widely available, adaptable to HV and HR modification



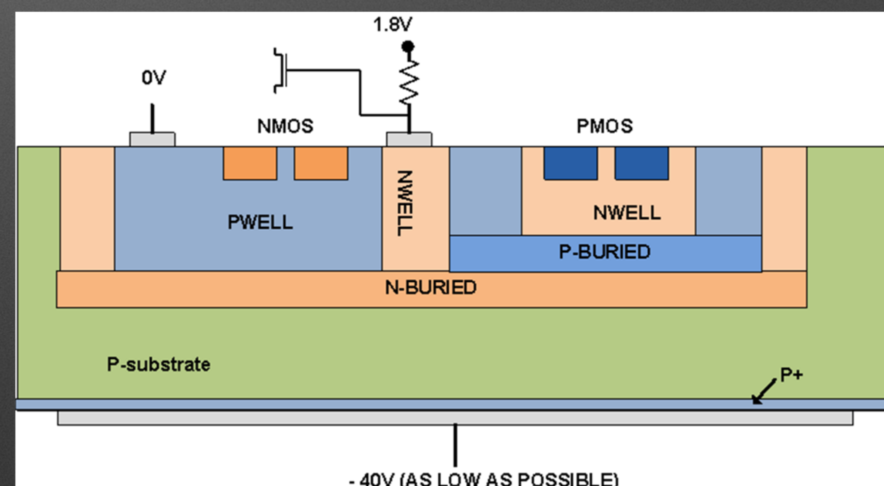
HR-CMOS Options



Drift structure



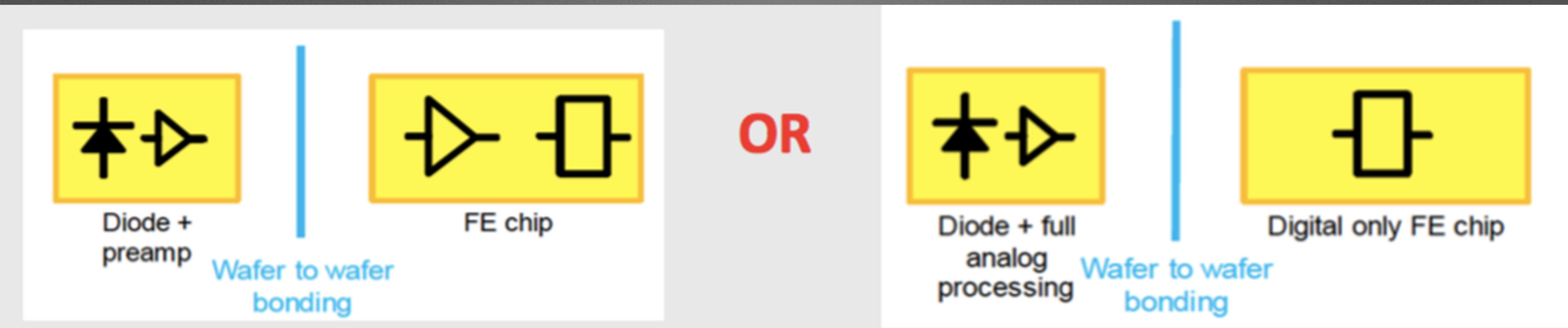
Simple well structure



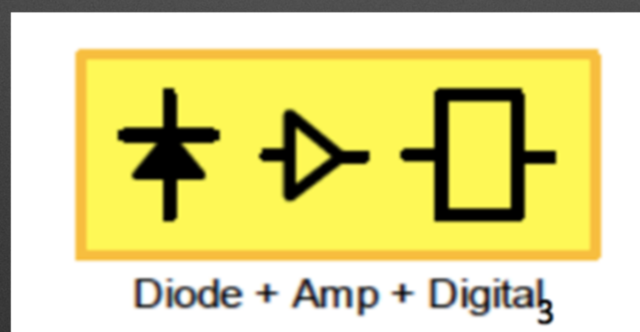
Triple Well Structure

Integration Possibilities, HV-CMOS/HV-CMOS Hybrid Pixel Development

- Amplifier / Discriminator (~100 transistors) per Pixel, Bonded to Digital R/O Chip (>100M transistors)



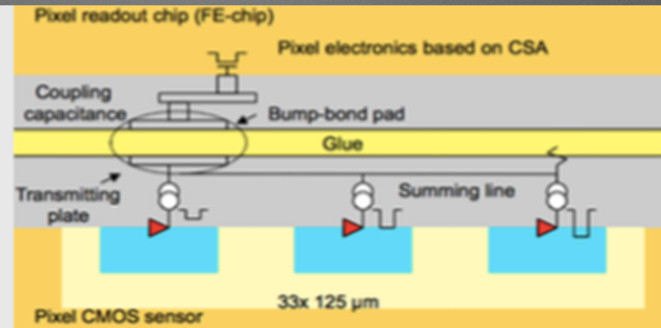
- Long-term aim: full integration on single, depleted substrate:



F.Hugging, Bonn - AIDA-2 15/4/2014

glue bonding

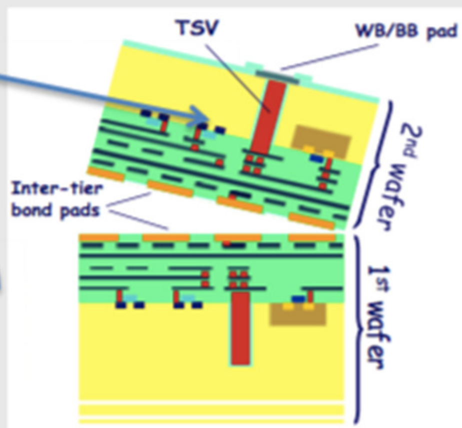
capacitive coupling using glue bonding

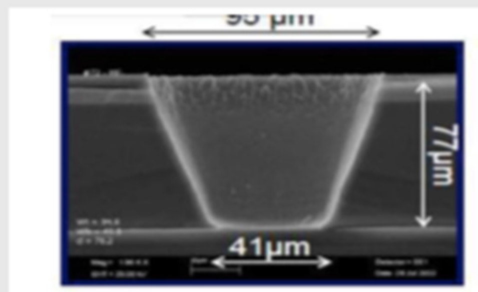


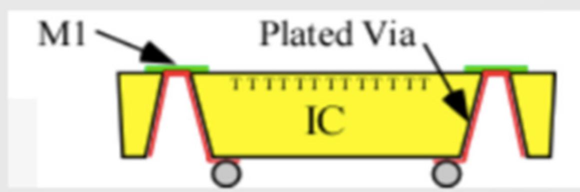
FE-I4

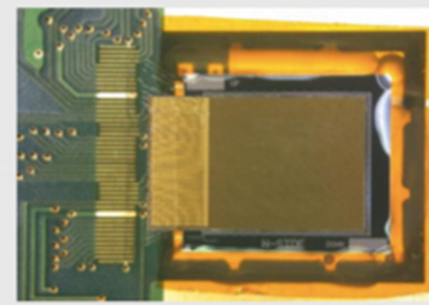
HV-CMOS
(I. Peric et al)

TSVs







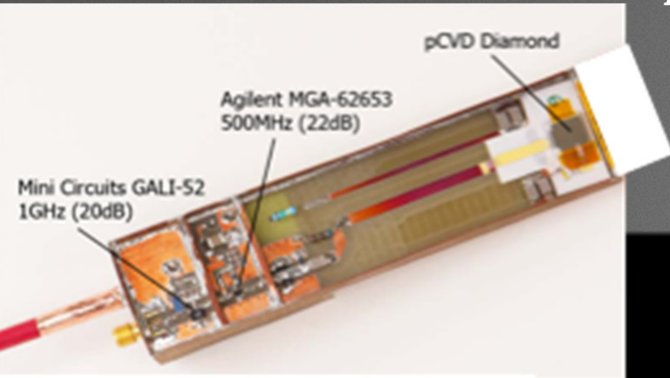


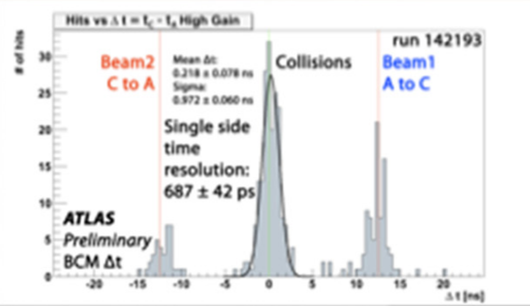
FE-I3 operated through TSVs

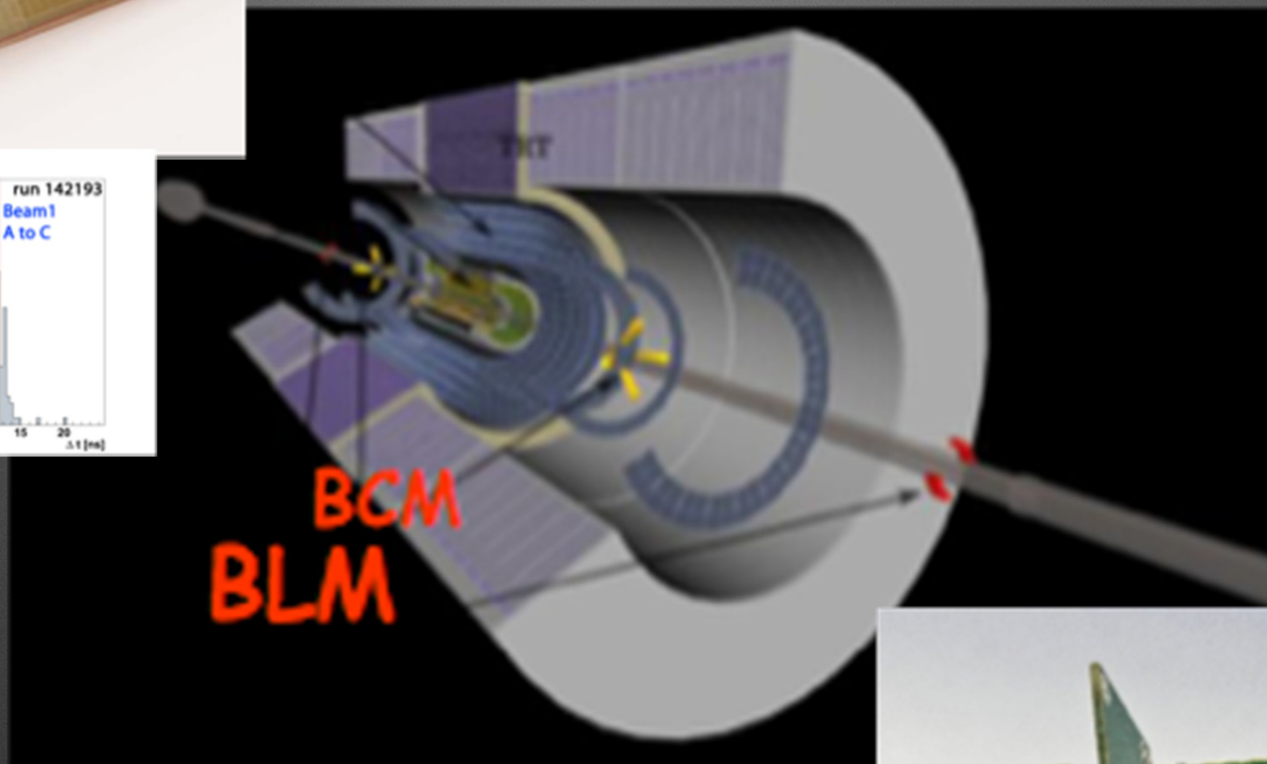
M. Barbero, T. Fritzsch, L. Gonella, F. Hügging et al., JINST 7 (2012) P08008

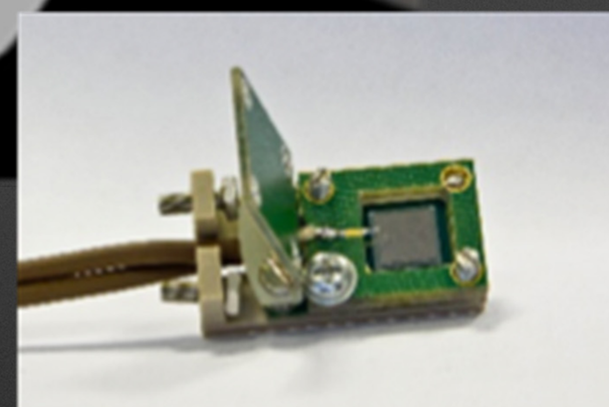
wafer to wafer bonding

ATLAS Diamond Beam Condition Monitor and Beam Loss Monitor



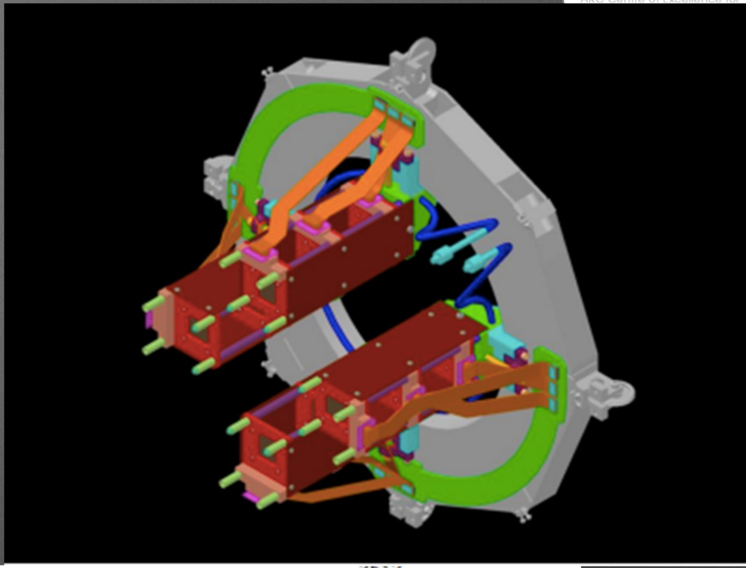


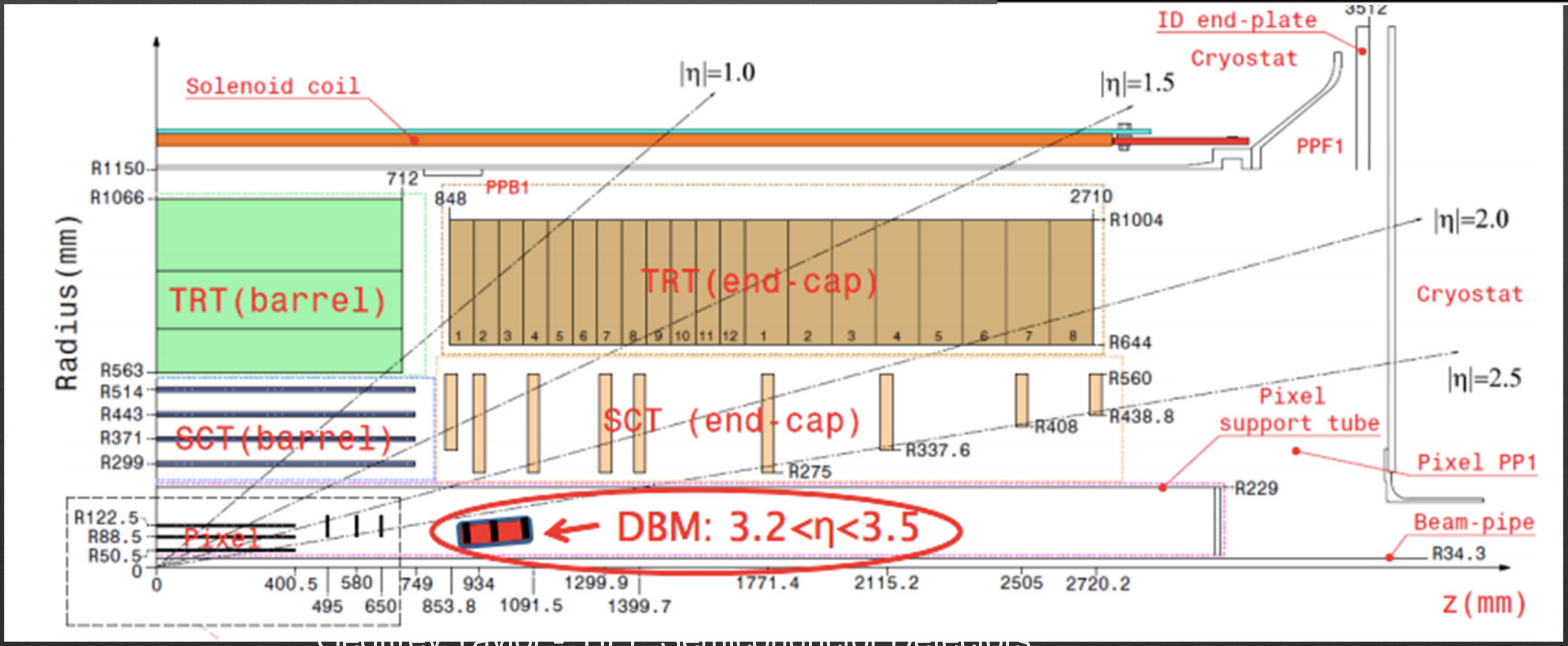




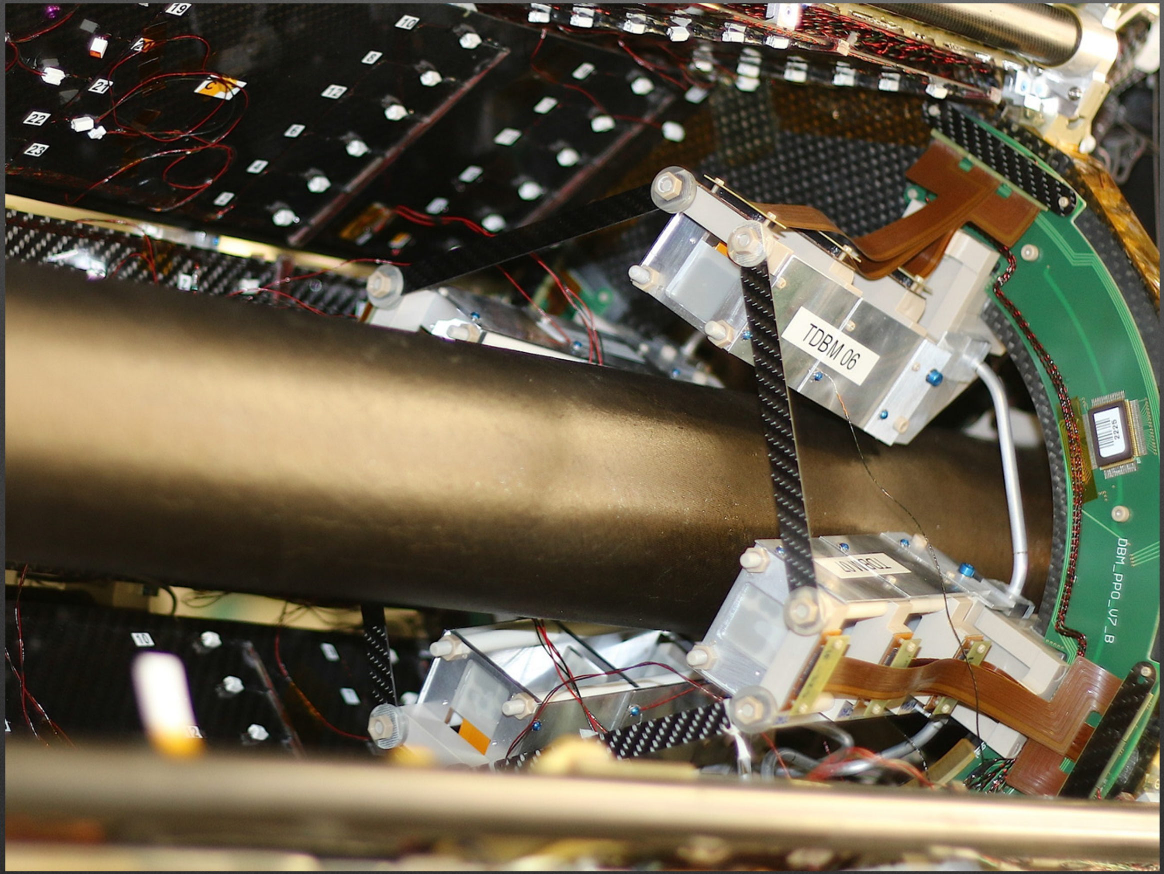
Diamond Beam Monitor

- Diamond offers advantages:
  - radiation hardness
  - fast signal response
  - simple processing





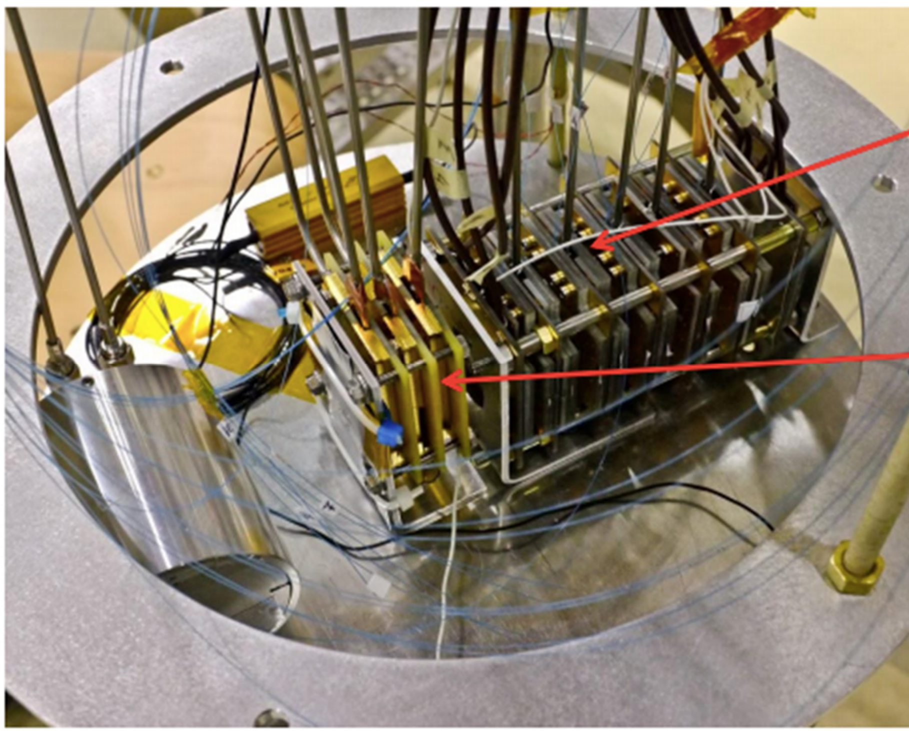
Diamond Detectors



Diamond Beam Monitor
IBL Pixel Layer

Si/Diamond as Cryogenic BLM

- Both seem capable of operation at LHe temperatures
- Suggest operation of BLM within magnet cryostat



6 p^+-n-n^+ silicon detectors of 4.5, 200, 500 and 10k Ωcm resistivity with Al metallisation (The thickness of the samples was of 300 µm.)

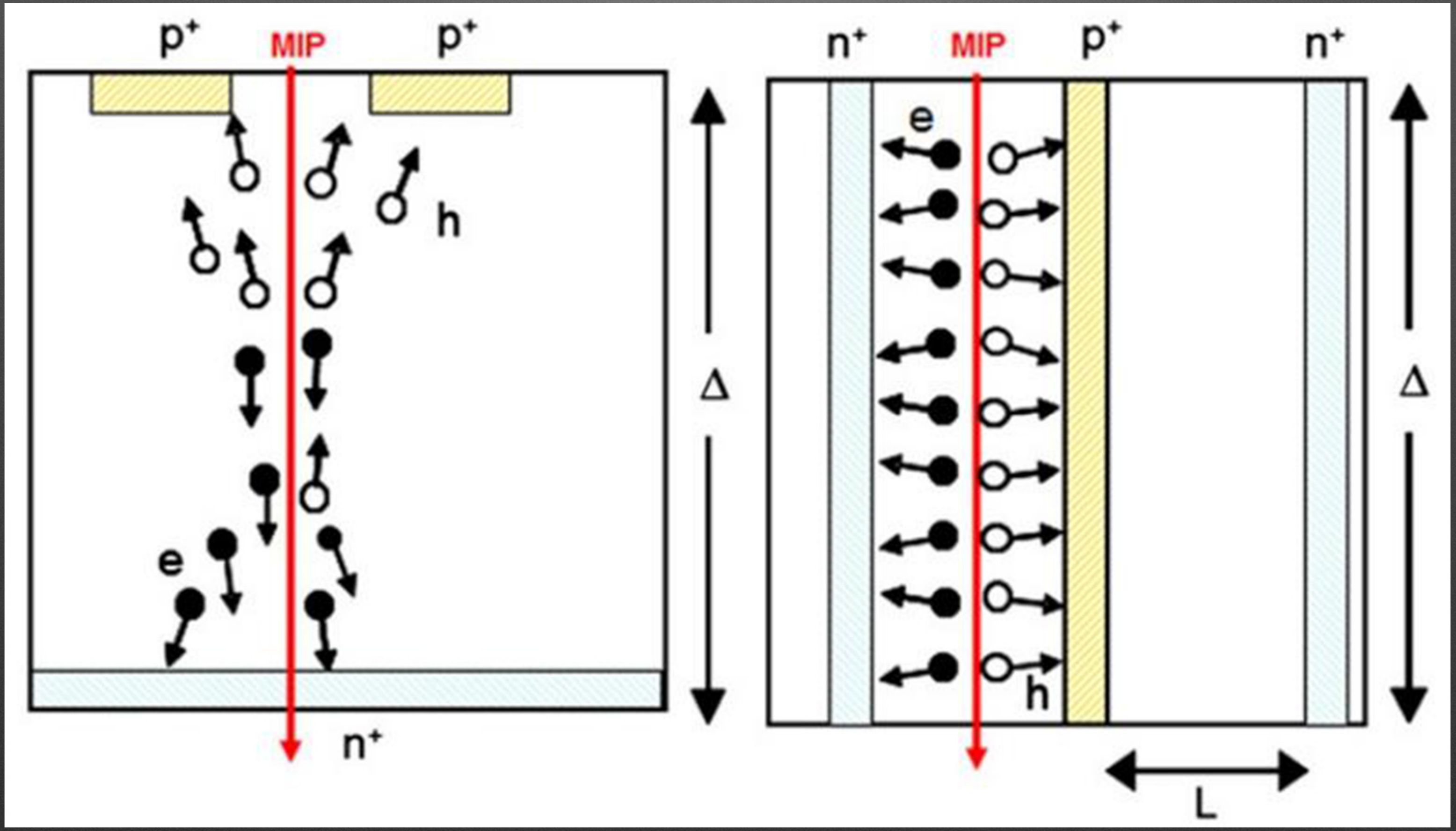
2 scCVD diamond detectors with a double layer metallisation of gold and titanium and a thickness of 500 µm.

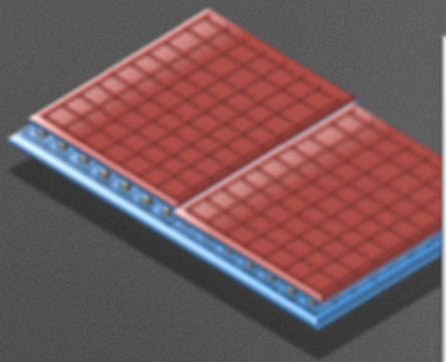
DC current generated by the beam was measured.

Kurfurst et al., NIM A782 (2015) 149

LHC

- Diamond detectors in beam monitoring.
- 3-D Detectors in ATLAS vertex detector



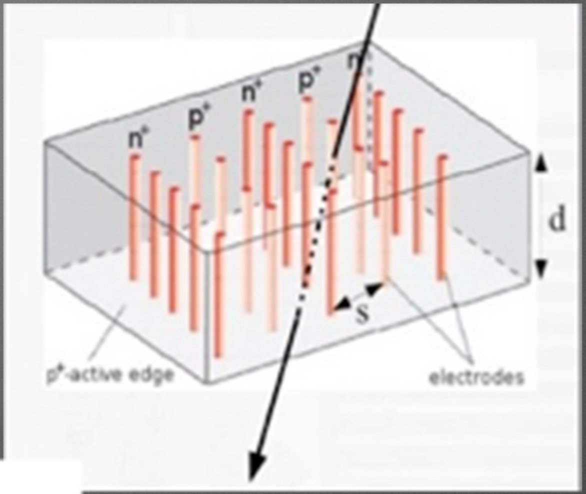


Planar Sensor

- "classic" sensor design
- oxygenated n-in-n
- 200μm thick
- Minimize inactive edge byshifting guard-ring under pixels (215 μm)
- Radiation hardness for IBL to $5\times10^{15}\ n_{eq}/cm^2$, tested up to $2.4\times10^{16}\ p/cm^2$

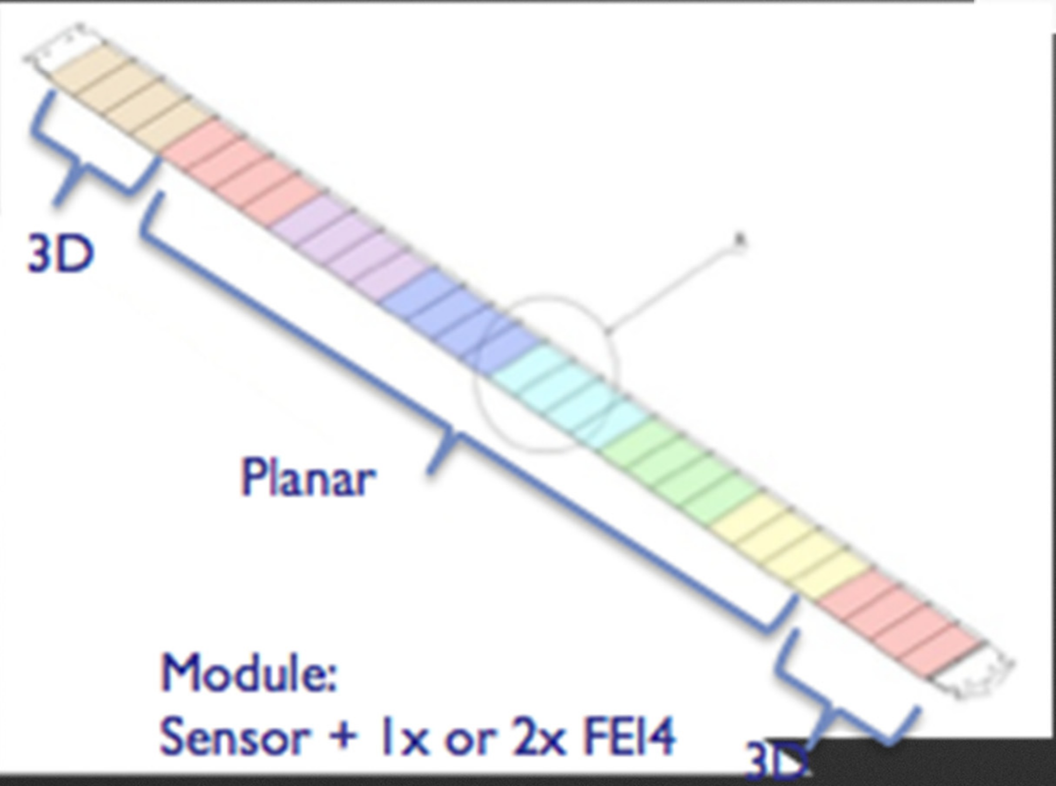
FE-I4 Pixel Chip (26880 channels)

19 x 20 mm² 130 nm CMOS process, based on an array of 80 by 336 pixels (each 50 x 250 μm²)

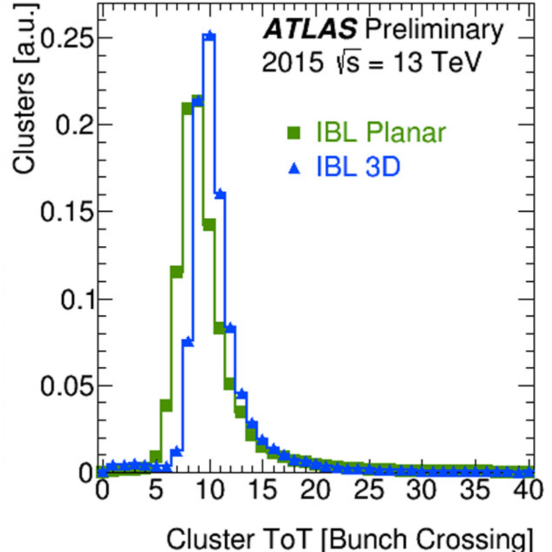


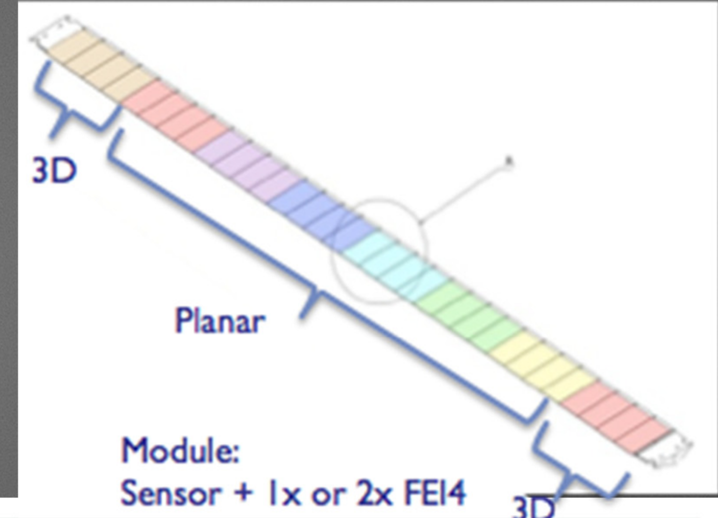
3D Sensor

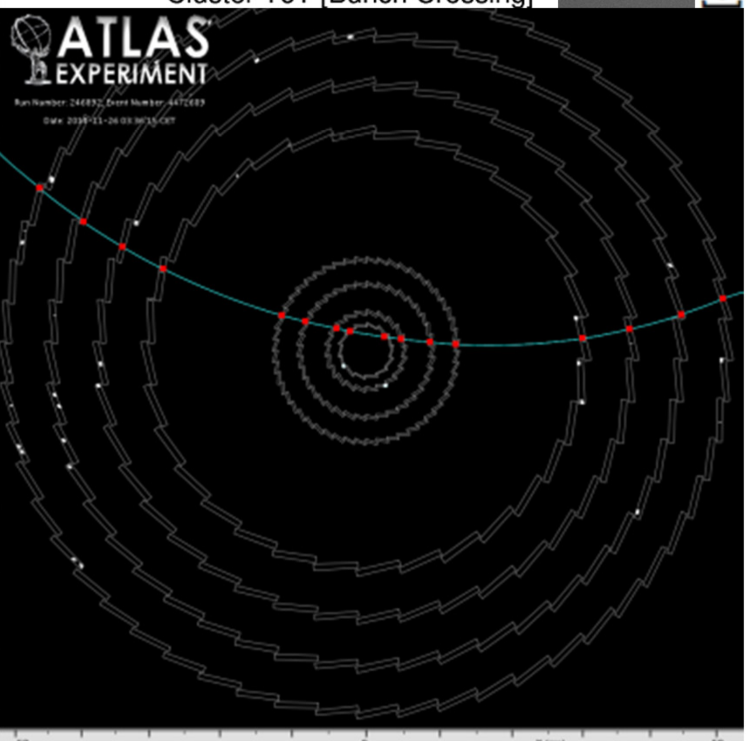
- Both electrode types are processed inside the detector bulk
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage

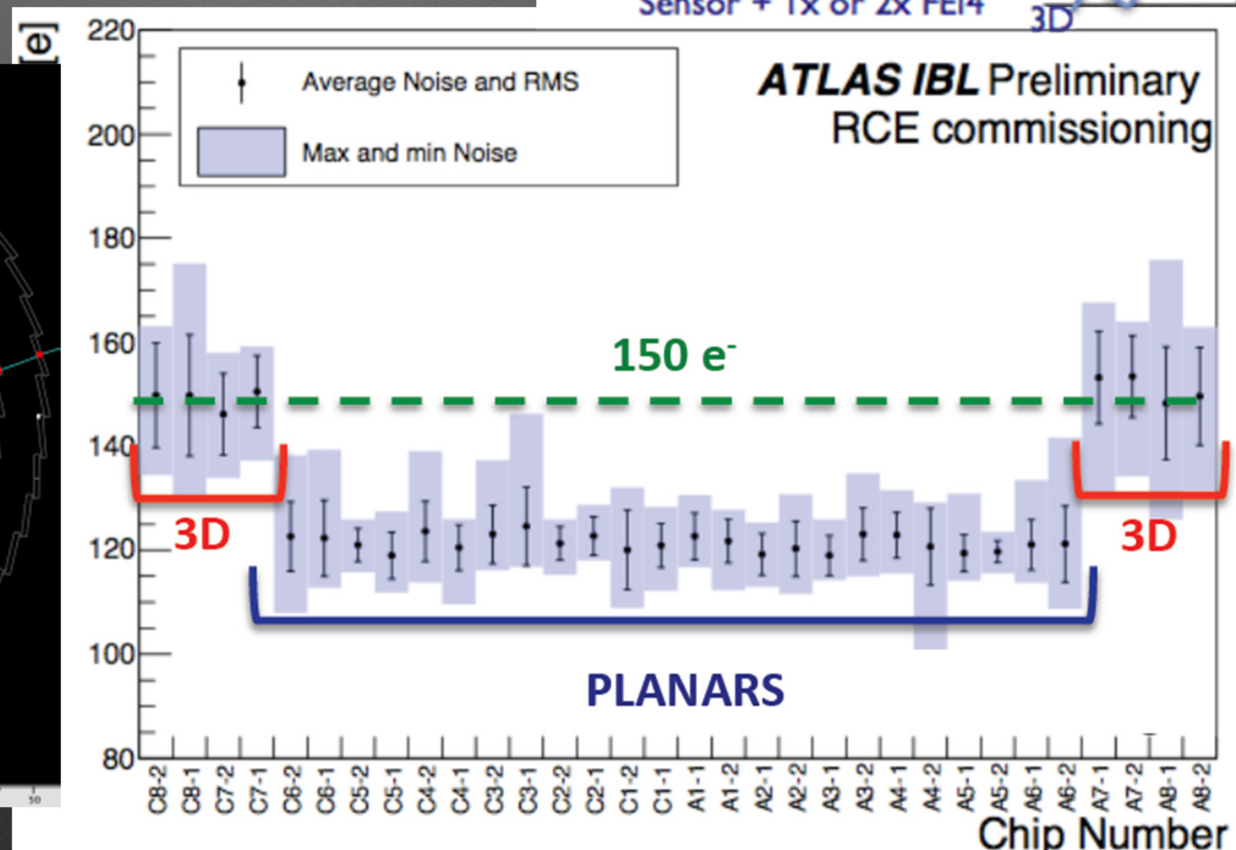


From talk, J. Lange, ATLAS 3D Group
RD50 Workshop 22-24 June, 2015


ATLAS Preliminary
2015 √s = 13 TeV
IBL Planar
IBL 3D
Clusters [a.u.]
Cluster ToT [Bunch Crossing]

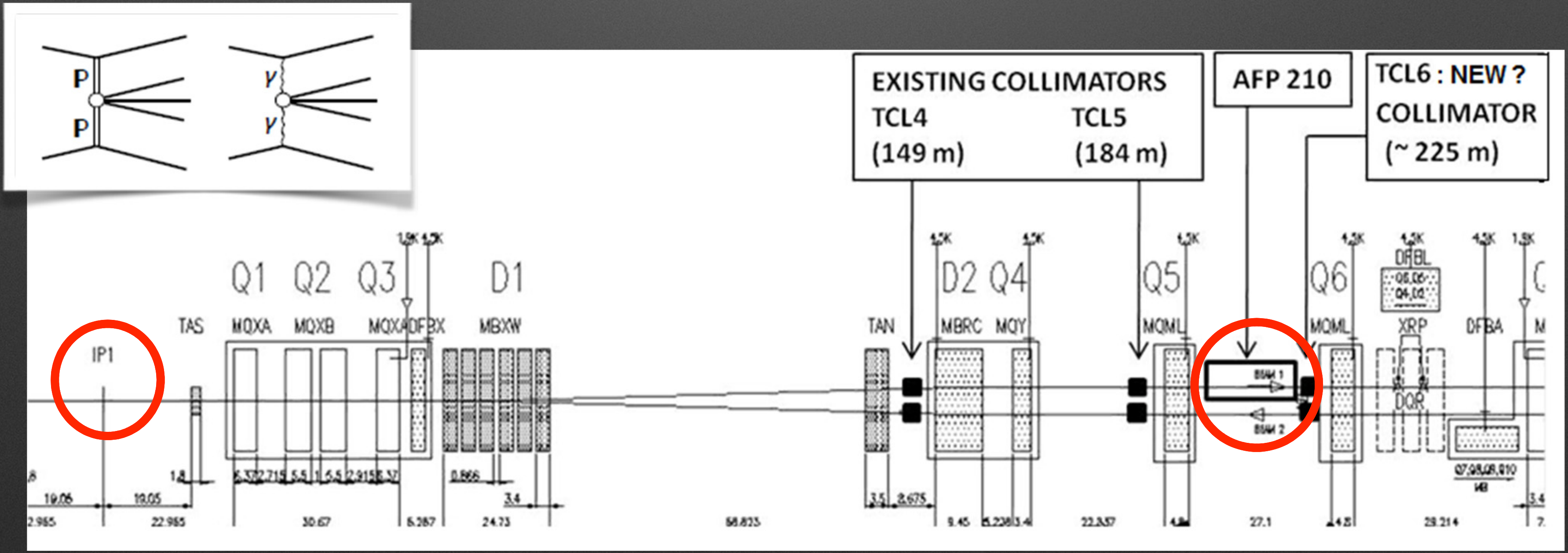

3D
Planar
Module:
Sensor + 1x or 2x FEI4
3D

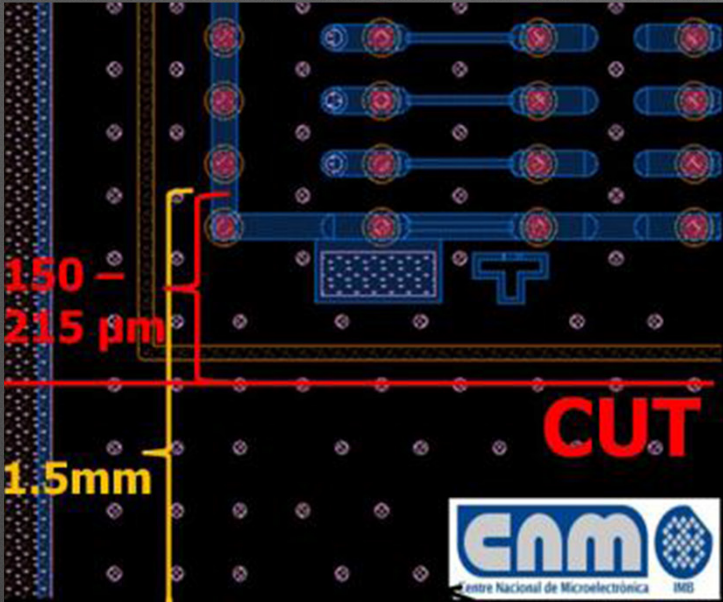

ATLAS EXPERIMENT

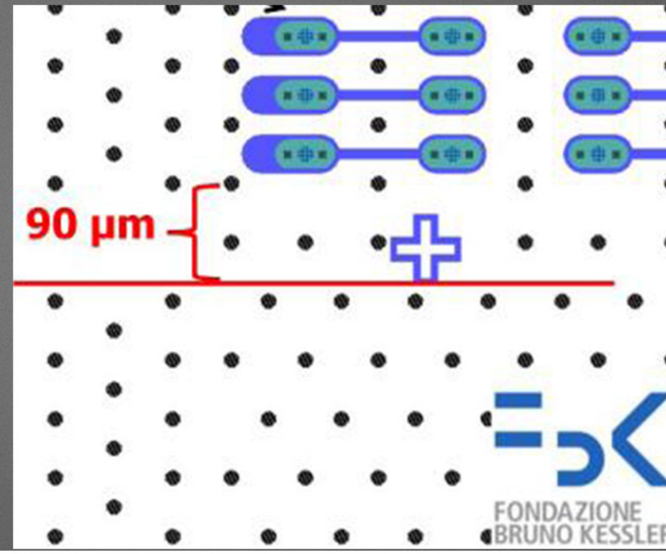

Average Noise and RMS
Max and min Noise
ATLAS IBL Preliminary
RCE commissioning
150 e-
3D
3D
PLANARS
Chip Number
C8-2 C8-1 C7-2 C7-1 C6-2 C6-1 C5-2 C5-1 C4-2 C4-1 C3-2 C3-1 C2-2 C2-1 C1-2 C1-1 A1-1 A1-2 A2-1 A2-2 A3-1 A3-2 A4-1 A4-2 A5-1 A5-2 A6-1 A6-2 A7-1 A7-2 A8-1 A8-2

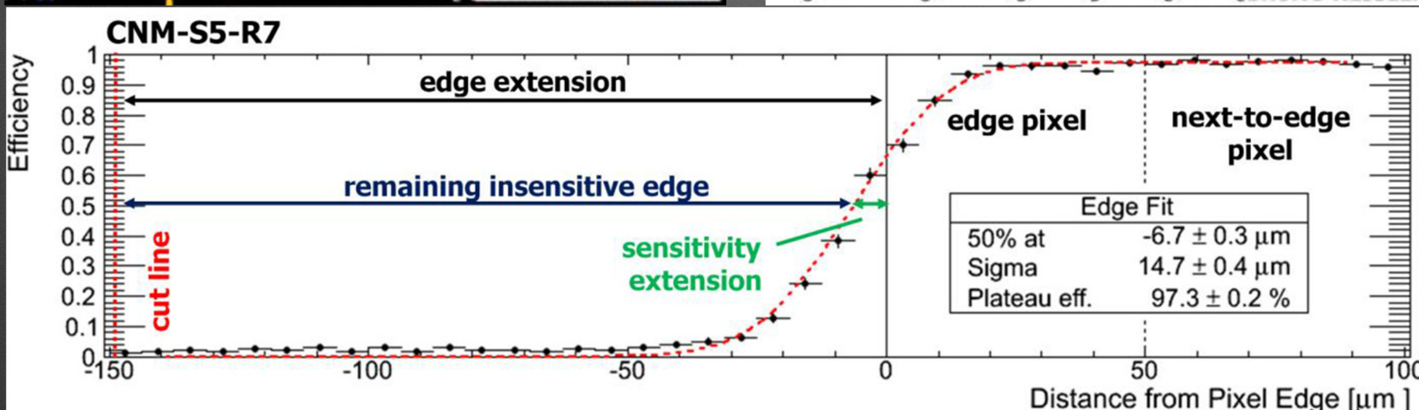
"Forward" Physics Detectors

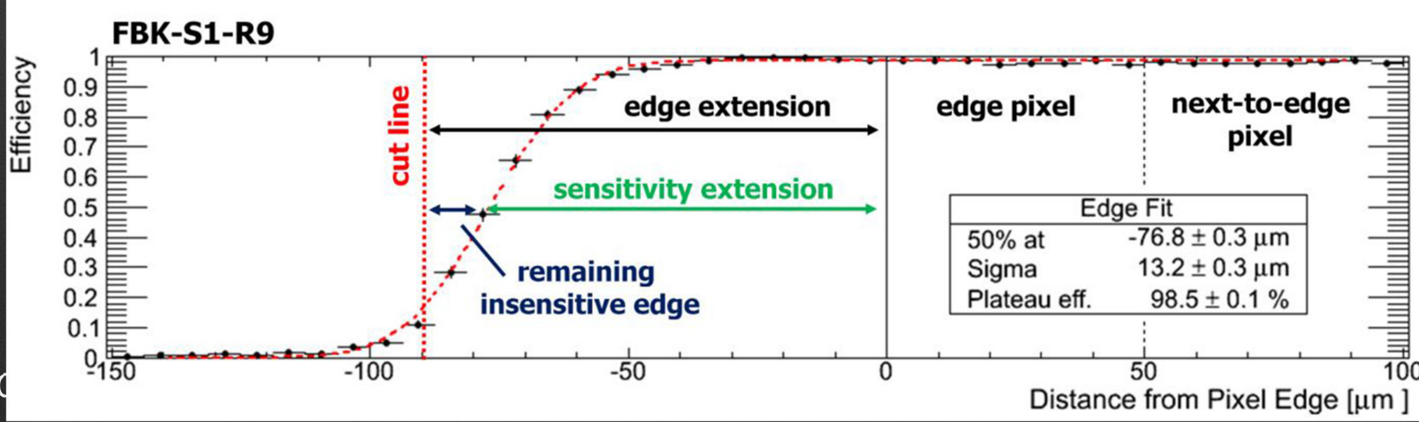
- Very small angle proton scattering:
  - Good spatial resolution (~10um)
  - Sensitivity close to edge.
  - Good radiation intolerance.
  - 3D detectors very promising.











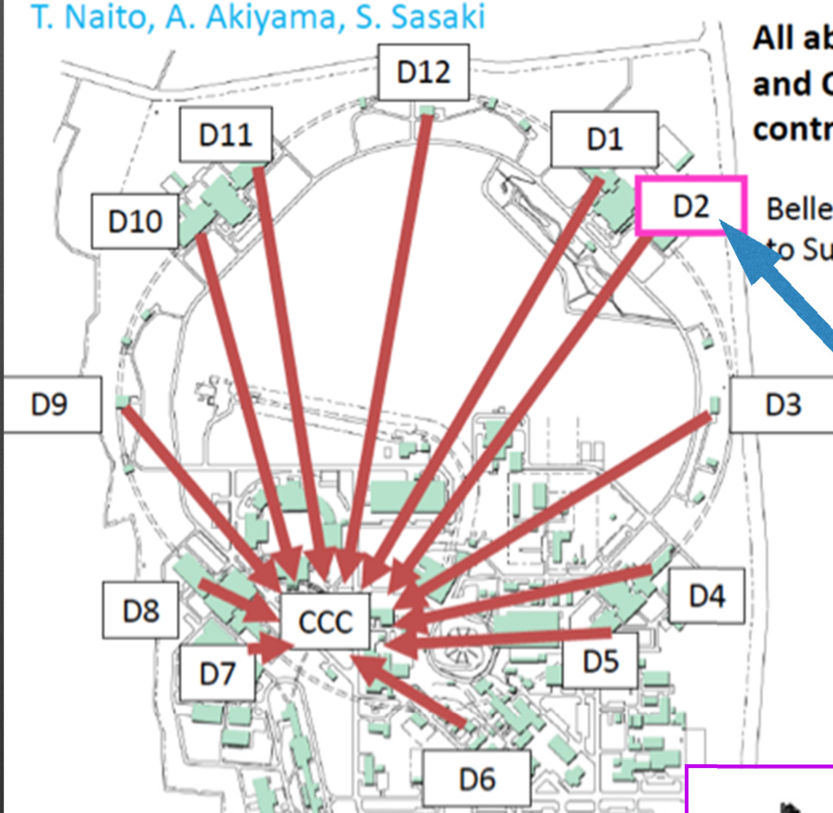
J. Lange et al., JINST 10 (2015) C03031

SuperKEKB - Diamond Beam Monitor

- Belle II Pixel and Strip Vertex Detector (VXD) Abort monitors

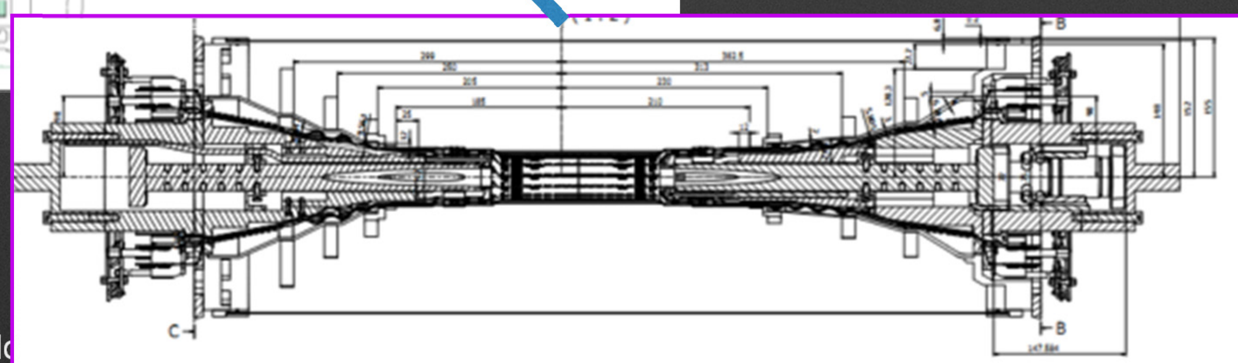
Abort trigger system for SuperKEKB

T. Naito, A. Akiyama, S. Sasaki

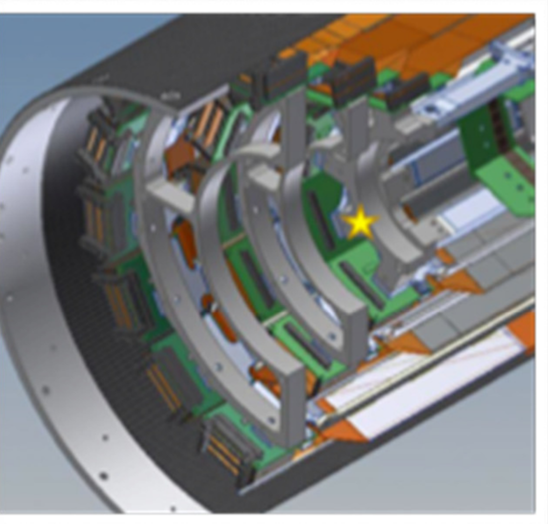


All abort trigger signal is gathered and ORed together, at the SuperKEKB control building.

BelleII Abort signal is sent to SuperKEKB via D2.

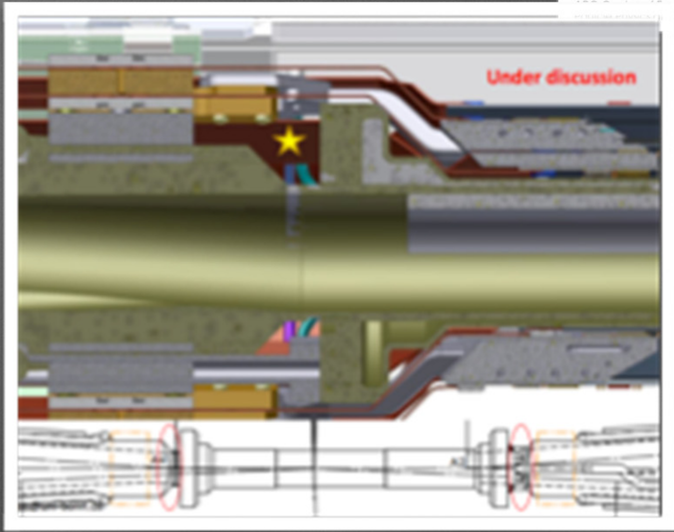


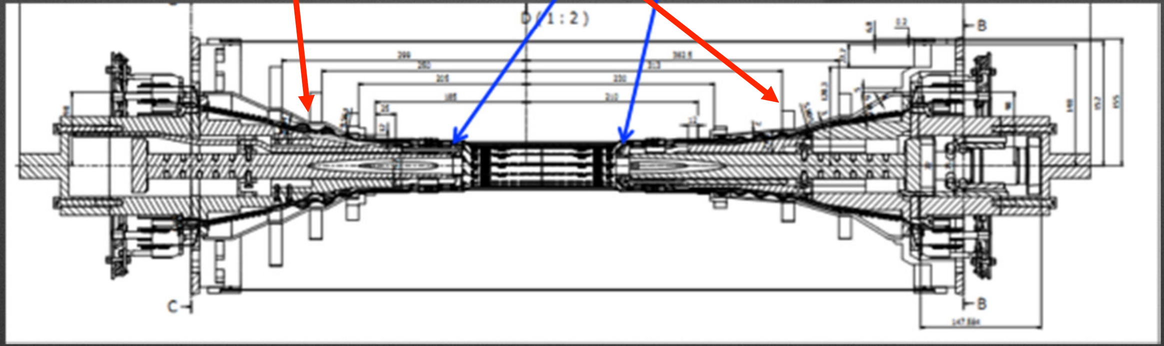
Belle II PXD Beam Abort



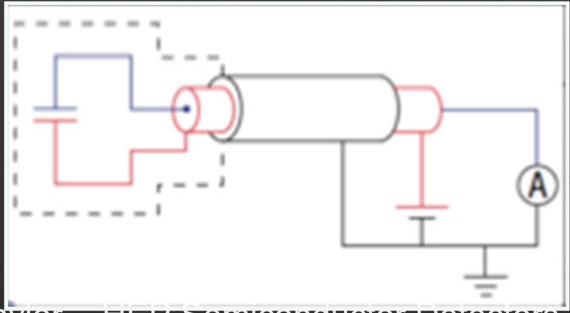
6 + 6 sensors close to SVD L3 support rings

4 + 4 sensors PXD-beam pipe





Shielded diamond sensors

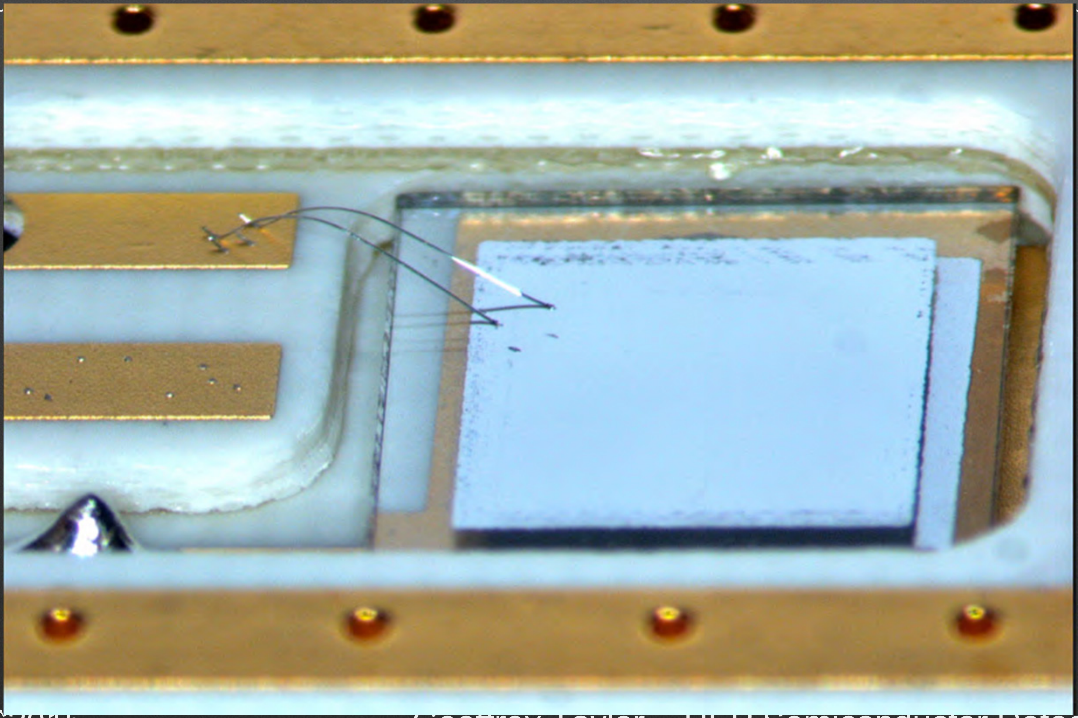


3+15 m (3+40 m) cables
Voltage sources (150÷500 V)
picoAmmeters

– Based on experience from Belle, BaBar, CDF, LHC

– scCVD diamond sensors, measurement of currents:

- typical pCVD sensor @ 500V:
  1nA = 7 mrad/s = 70 µGy/s
- Noise a few pA, in current measurements



Outlook

- Silicon and Diamond detectors effective for both HEP detectors and Beam Monitoring / Beam Loss role.
- Pixel devices essential for high rate / high luminosity environments (SuperKEKB, LHC, HL-LHC)
- Si and Diamond capable of cryogenic operation
- HR-CMOS, HV-CMOS offer future technology for significant integration options.