Epitaxial silicon for the HL-LHC upgrade

M. Centis Vignali[2], D. Eckstein[1], T. Eichhorn[1],
E. Garutti[2], A. Junkes[2], G. Steinbrück[2]

[1]Deutsches Elektronen Synchrotron, DESY
[2]Institut für Experimentalphysik, Universität Hamburg

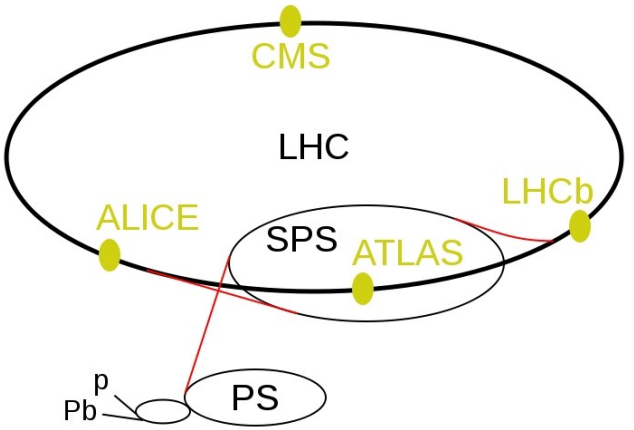
Bundesministerium
für Bildung
und Forschung

HELMHOLTZ
GEMEINSCHAFT

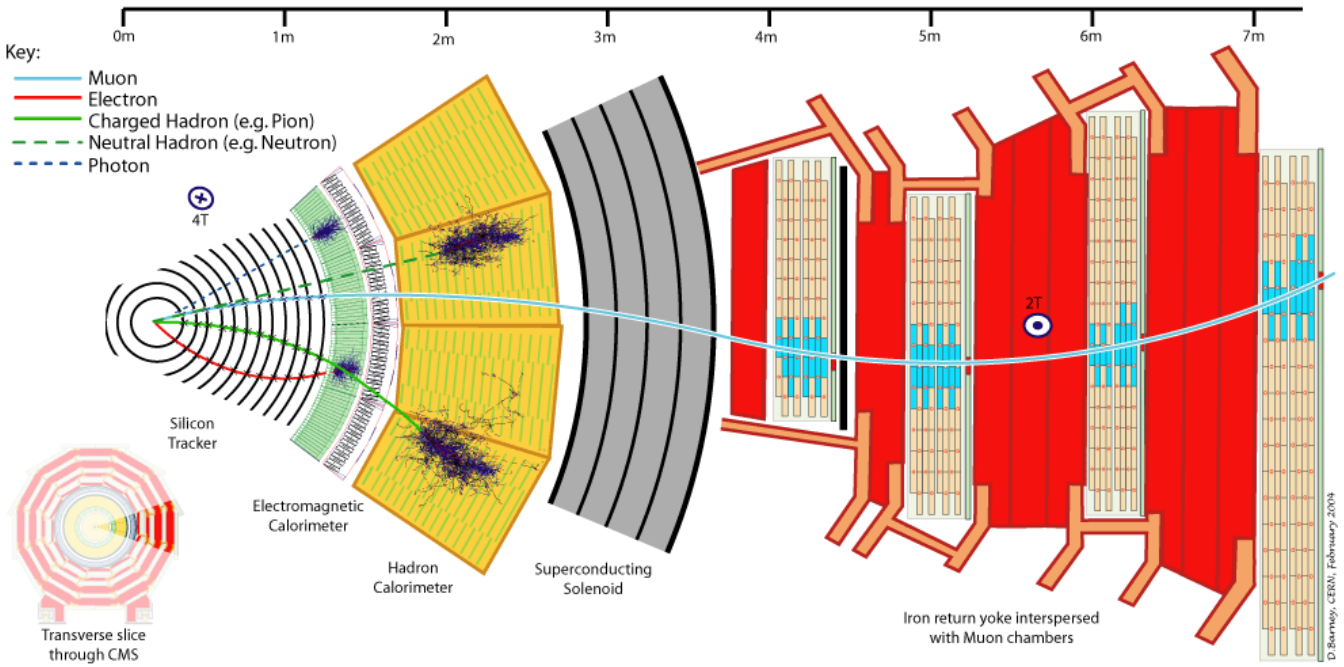
matteo.centis.vignali@desy.de

LHC and CMS

LHC:
- Large Hadron Collider
- Proton-proton and heavy ions collider
- 27 km circumference
- Design center of mass energy 14 TeV
- 4 interaction points

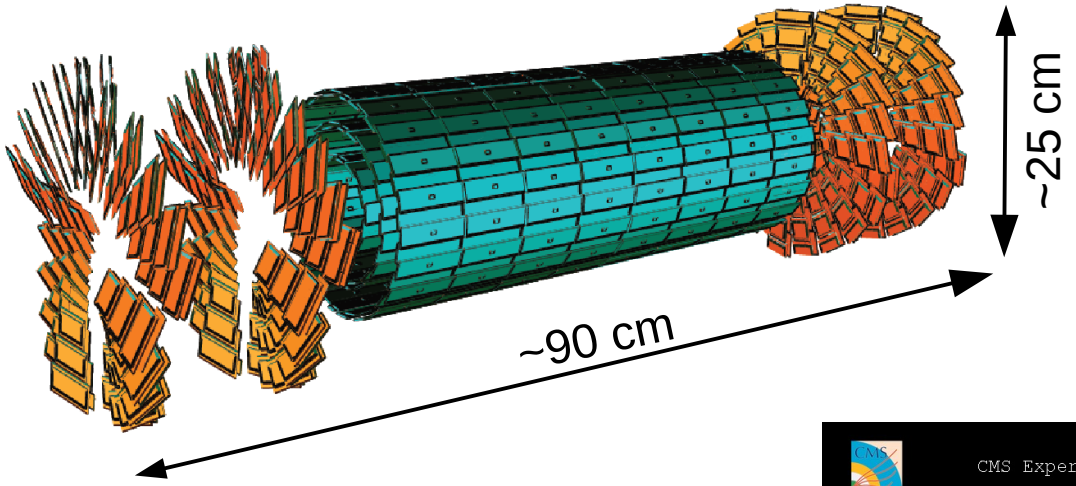


CMS:
- Compact Muon Solenoid
- General purpose experiment
- High luminosity interaction point



Achievements:
- Tests of the standard model
- Discovery of the Higgs boson by ATLAS and CMS

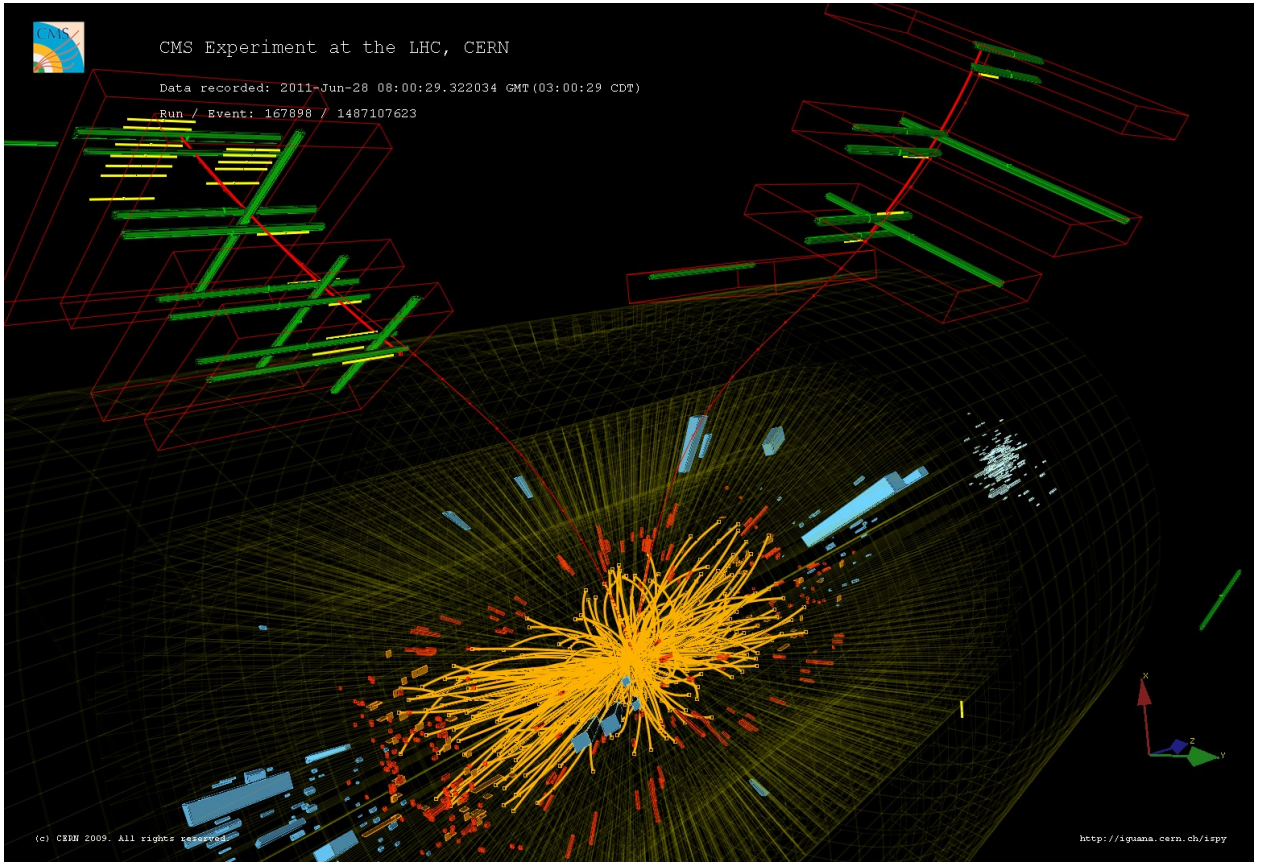
CMS pixel detector



Total area: 0.78 + 0.28 m^2
3 barrel layers
2 endcap discs
66 million 150 x 100 μm^2 pixels
285 µm n^+-in-n sensors
Charge sharing driven geometry

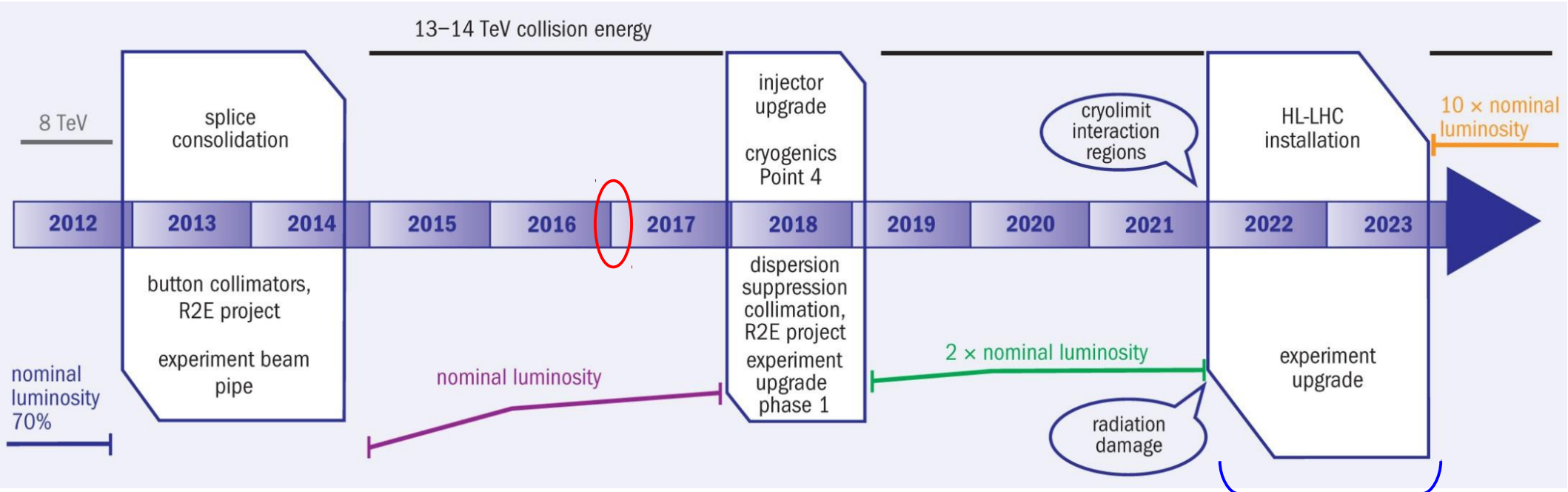
- Several sensor layers
- Cylindrical geometry
- **Measure primary and secondary vertexes**
- High track multiplicity environment
- Fundamental for b-physics
- Resolution ~15 µm

$B_s \rightarrow \mu\mu$ event



LHC timetable

- Luminosity increase to 5 x 10^{34} $cm^{-2}s^{-1}$
- Mean number of interaction per bunch crossing <μ> ~140 (every 25 ns)



Pixel upgrade "Phase I"

- Data losses
  - Buffering
  - Read out speed

↓

New pixel detector installed

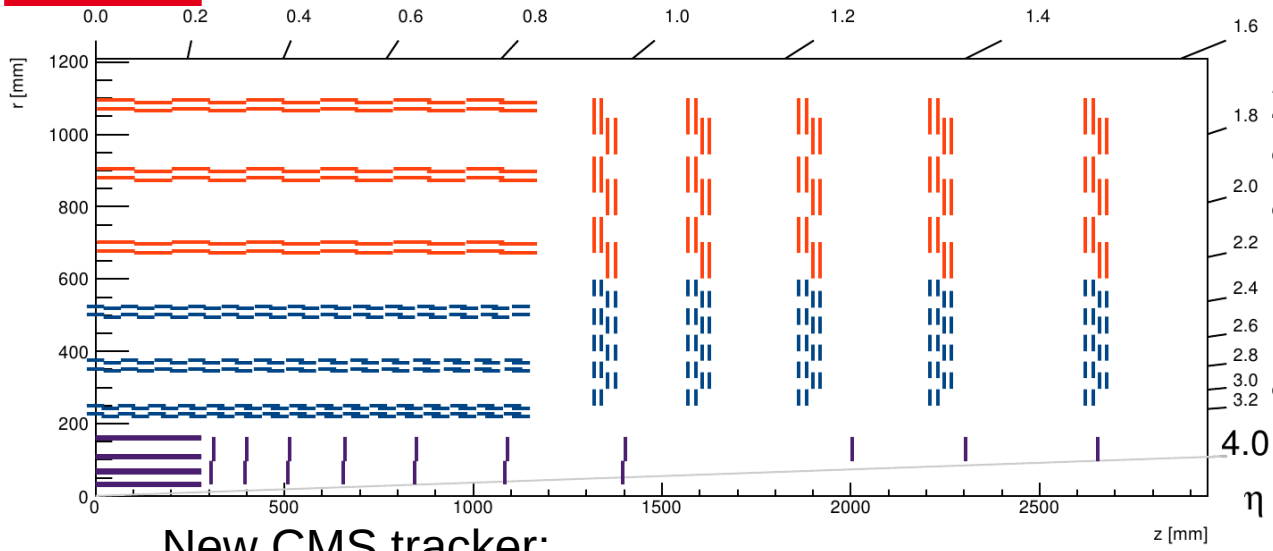
Tracker upgrade "Phase II"

- Radiation damage
- Data losses

↓

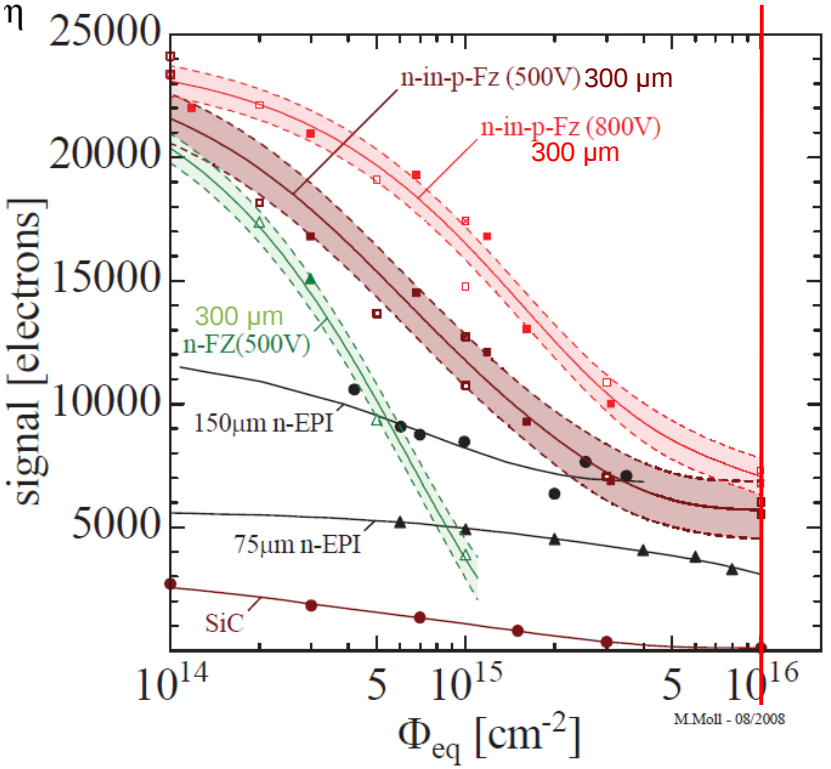
New tracker and new pixel

Motivation



New CMS tracker:
- **Momentum** information to L1 **trigger**
- 2S, PS and pixel modules

2023: High Luminosity-LHC
- Luminosity of 5 x 10^{34} $cm^{-2}s^{-1}$
- Innermost pixel layers after 3000 fb^{-1}:
  - Φ_{eq} ~10^{16} cm^{-2} → bulk damage
  - 5 MGy → surface damage
- New material / design is required, is planar silicon a viable option?



Thin sensors:
- Smaller signal degradation than thicker ones
- Small signal even before irradiation
  - → challenge for the readout electronics, low thresholds are required
  - → RD 53 collaboration for pixel ROC for the HL-LHC

→ **characterization with MIP-like signals required**

Test beam of thin (100-200 µm) strip sensors to determine material characteristics

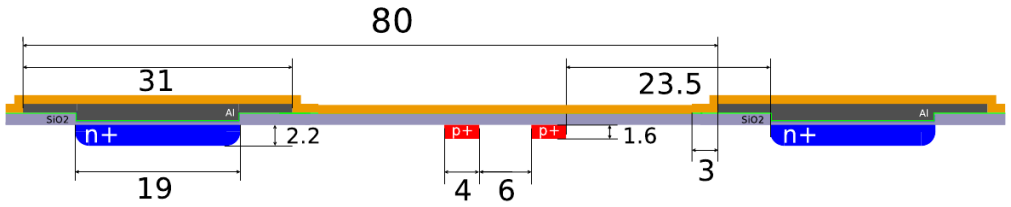
Sensors

Sensors:
- Epitaxial silicon strips of n and p type (p-spray and p-stop isolation)
  - Baby additional from HPK campaign
- 100 µm active thickness
- 80 µm pitch
- Irradiation with 800 MeV and 23 GeV protons
- Fluences up to 1.3 x 10^{16} cm^{-2}
- MCZ and FTH with 200 µm physical thickness
  - Only 1.3 x 10^{16} cm^{-2}

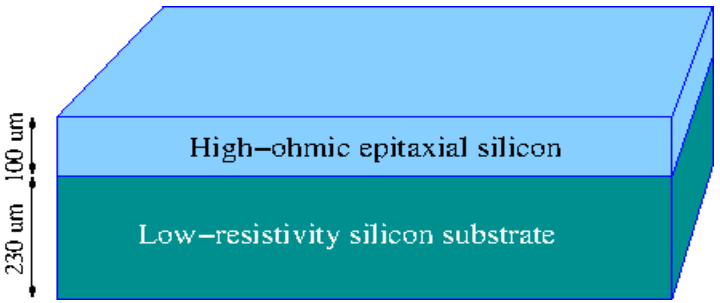
Strips detectors:
- Irradiation of sensor without readout electronics
- Higher noise → hit reconstruction using beam telescope

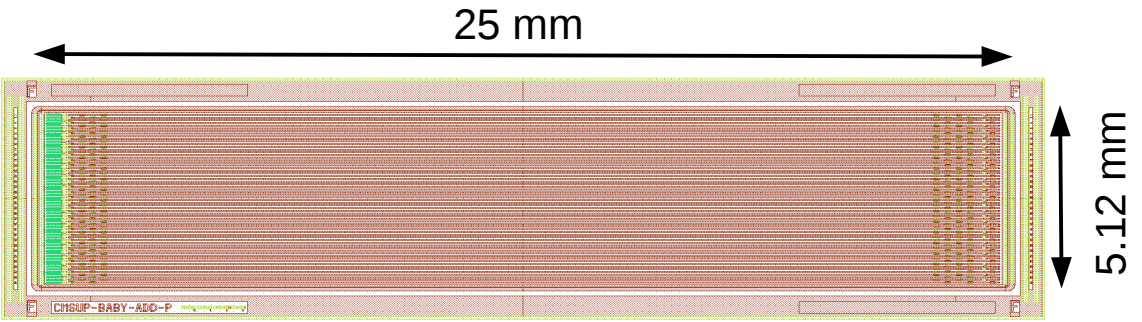
Fake rejection

Unbiased charge collection measurement
(no threshold involved)



Epi sensors

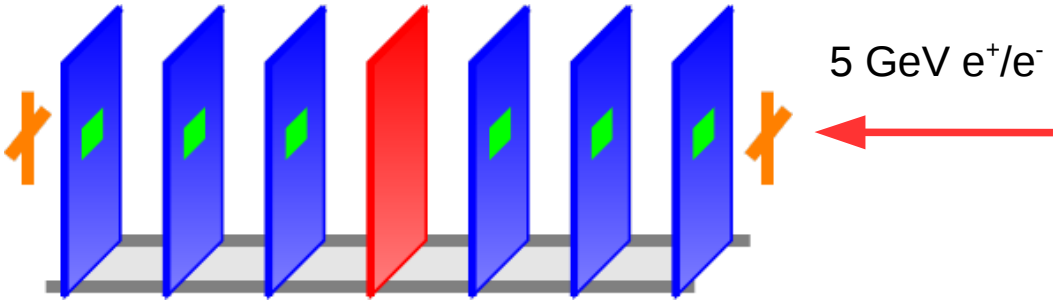


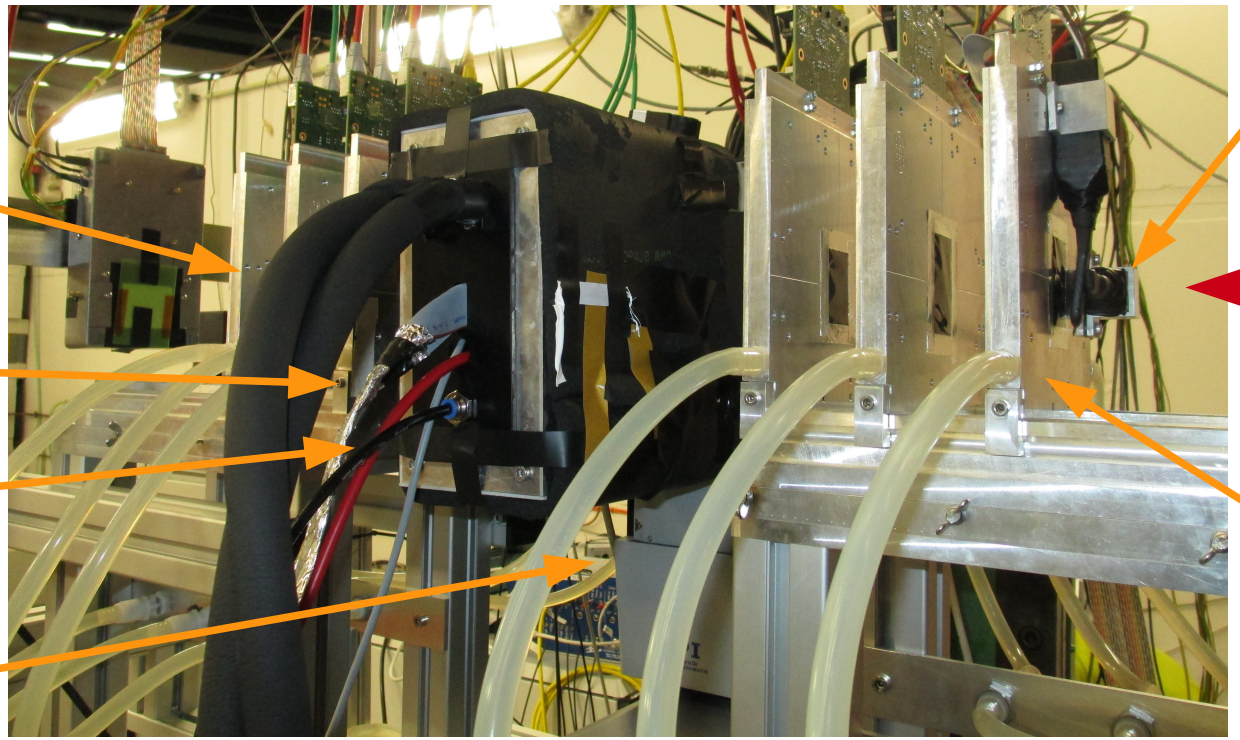


64 AC coupled strips

Setup I

- Beam telescope to reconstruct tracks
  - DATURA and ACONITE
  - EUDET pixel telescopes
- Trigger scintillators to define events
- Cooling for irradiated samples down to -28 ℃
- Moving stage for different incidence angles
- Minimize material in the beam



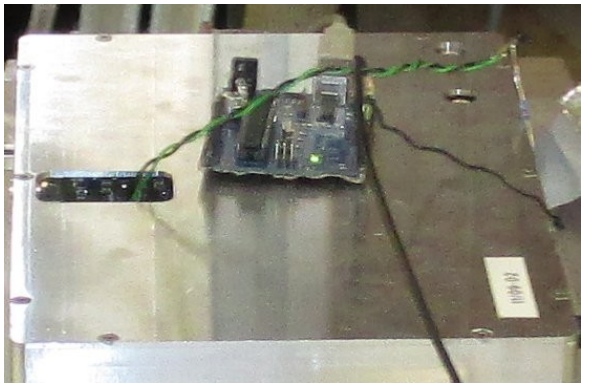


Setup II

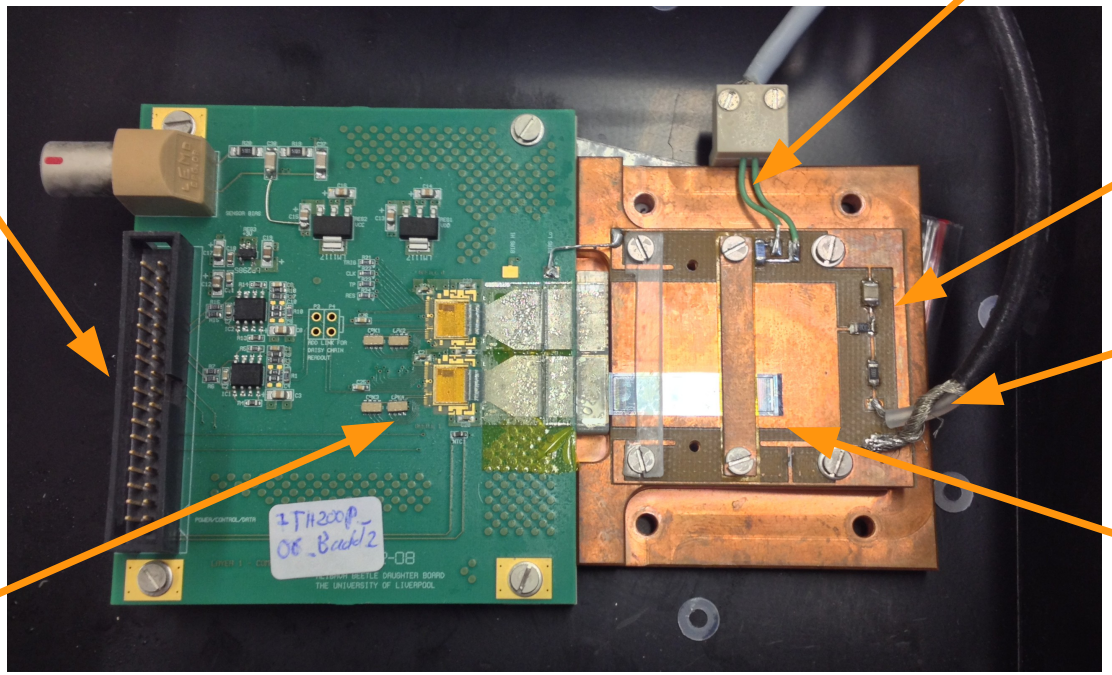
Readout system:

- ALiBaVa (A Liverpool Barcelona Valencia) readout system: mother + daughter boards
- Readout of positive and negative signals
- Based on LHCb strip readout chip
- Triggered readout
- Analog pulse height for 2 x 128 channels
- Maximum event rate ~150 Hz

Mother board

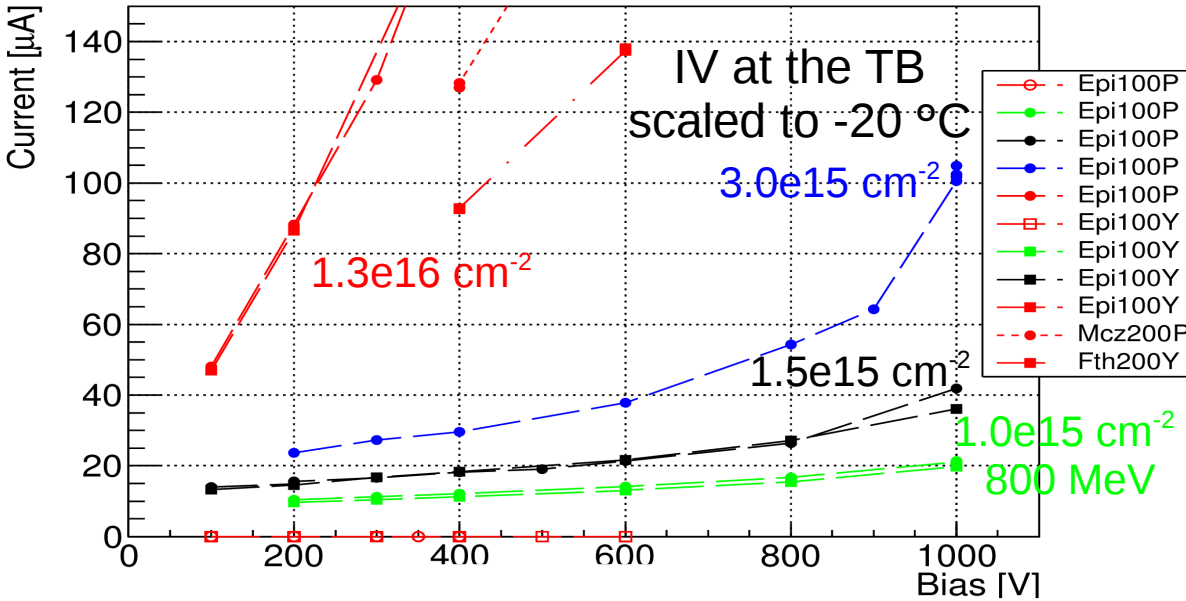


Daughter board



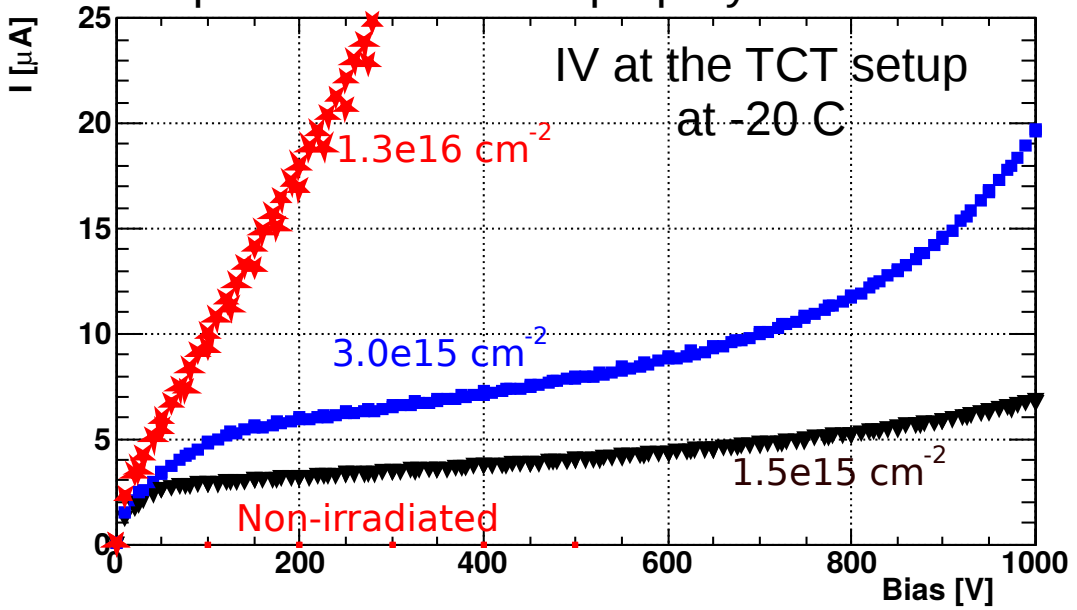
IV characteristic p-bulk sensors

Strip sensors



IV of both diodes and strip sensors show a “soft breakdown”

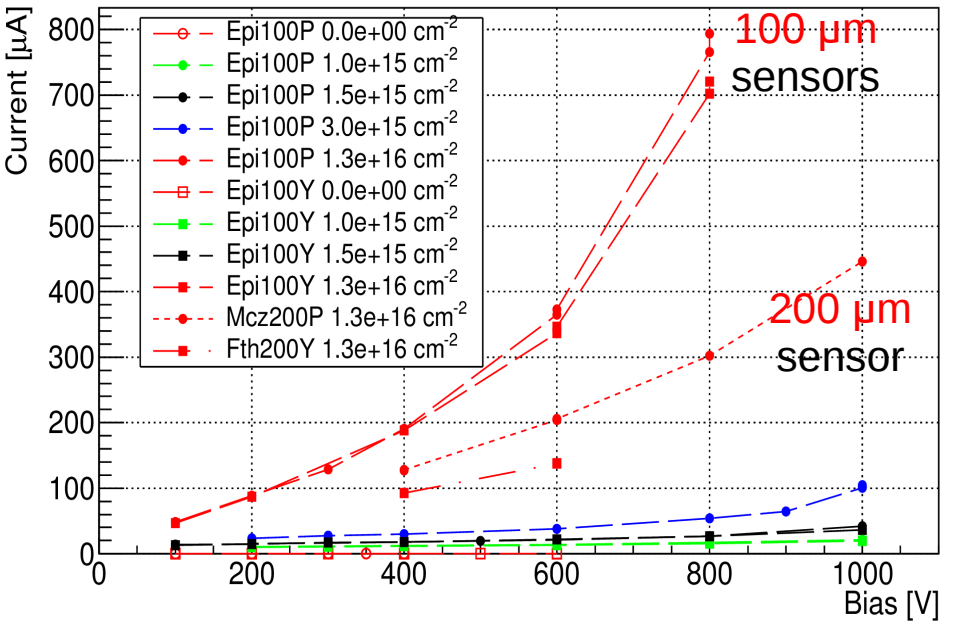
Epi 100 diodes with p-spray insulation



At 1.3e16 cm^{-2} 100 µm sensors draw more current than the 200 µm ones

→ No full depletion

→ Charge multiplication



Cluster definition

Charge definition:

Sum of the signal over 5 strips, centered on the hit one

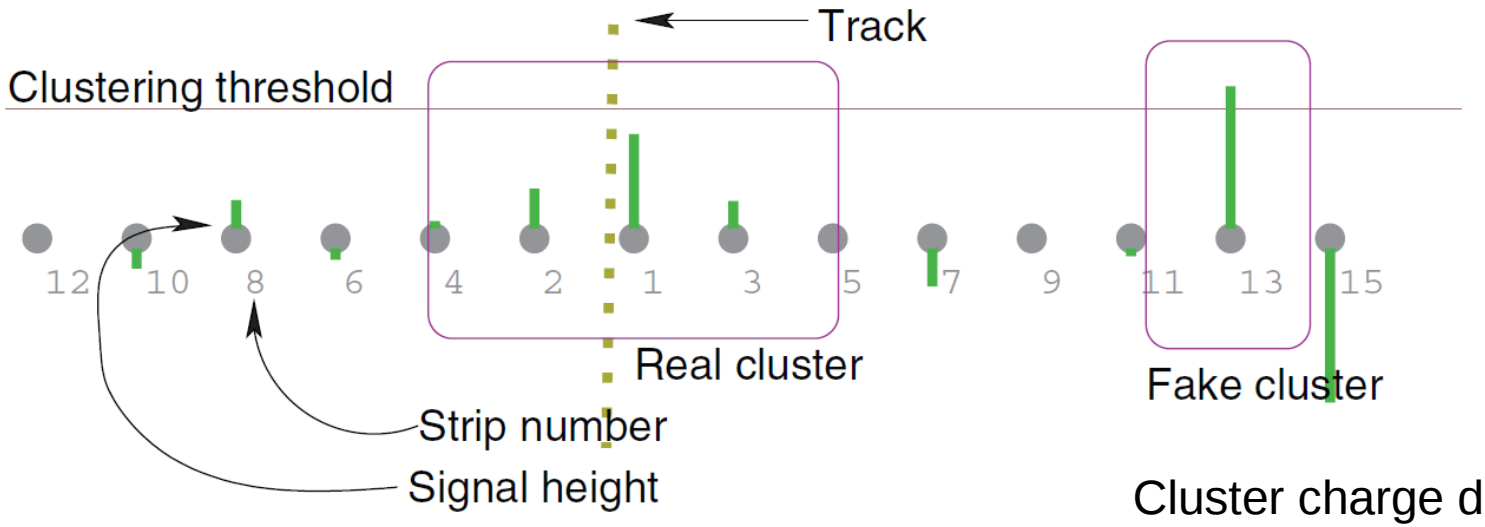
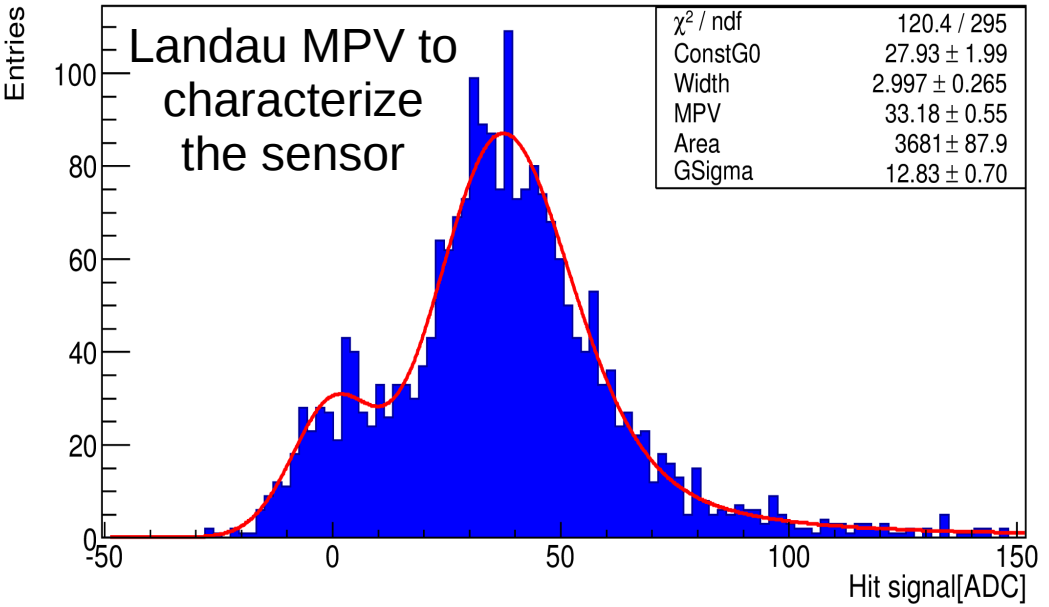


Fig. from T. Mäenpää et al, IEEE 2009

Cluster charge distribution

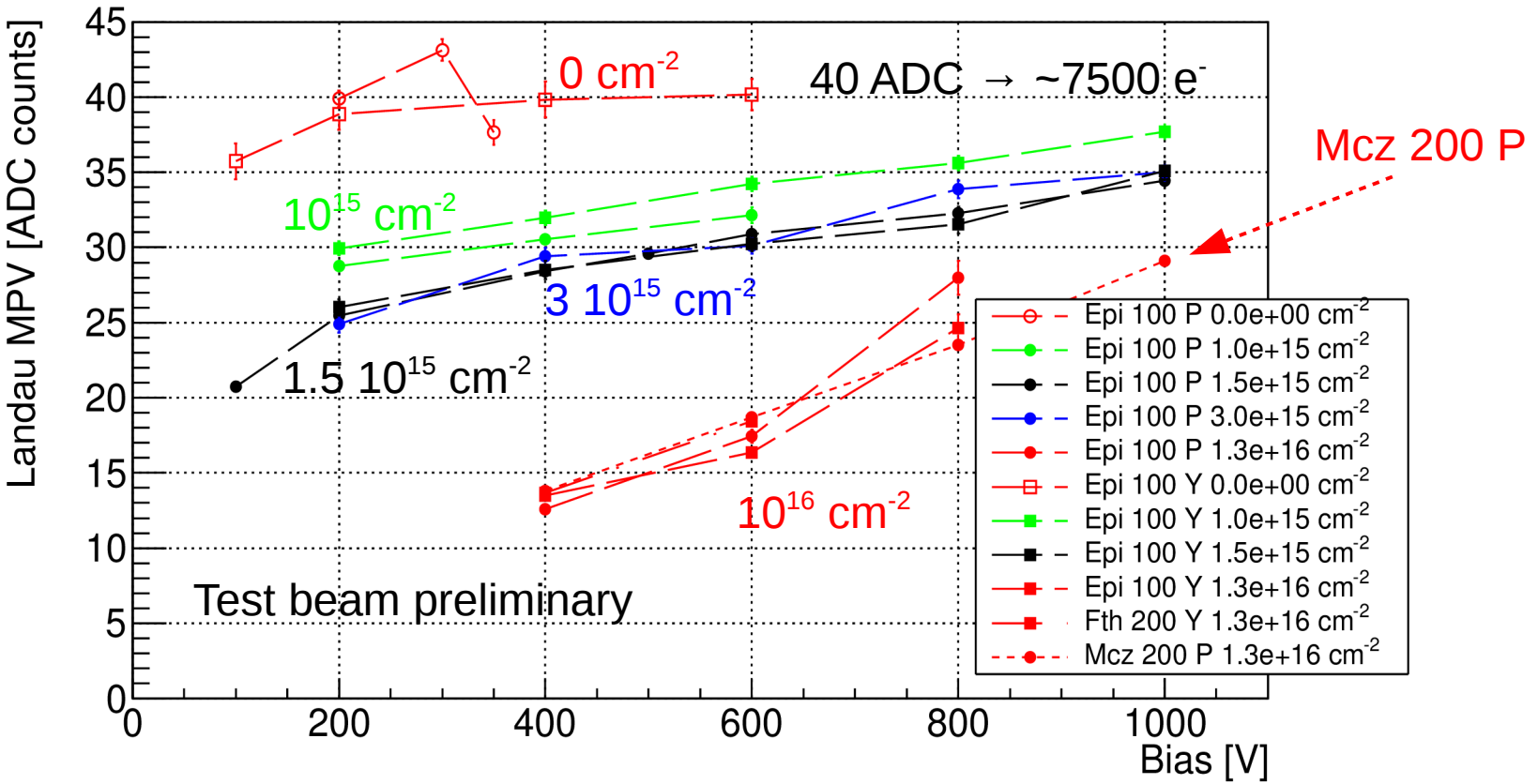


Epi100P, 23 GeV p, 3 x 10^{15} cm^{-2}, -800V, -20 °C

Charge collection

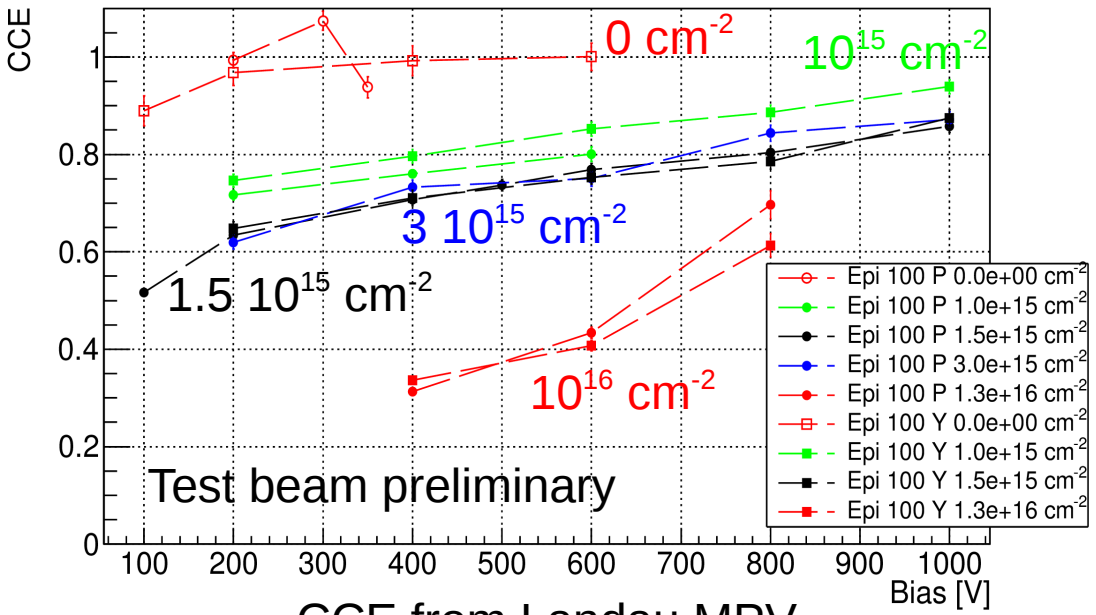
Up to 3 x 10^{15} cm^{-2}:
- **Similar behavior for all 100 µm sensors**
- **No big difference between different fluences**

10^{16} cm^{-2} sensors:
- **100 µm → faster signal recovery**
- **200 µm → higher breakdown voltage**
- **Similar signal height for both thicknesses at highest bias**



CCE Epi 100 p-bulk

Strip sensors at the TB



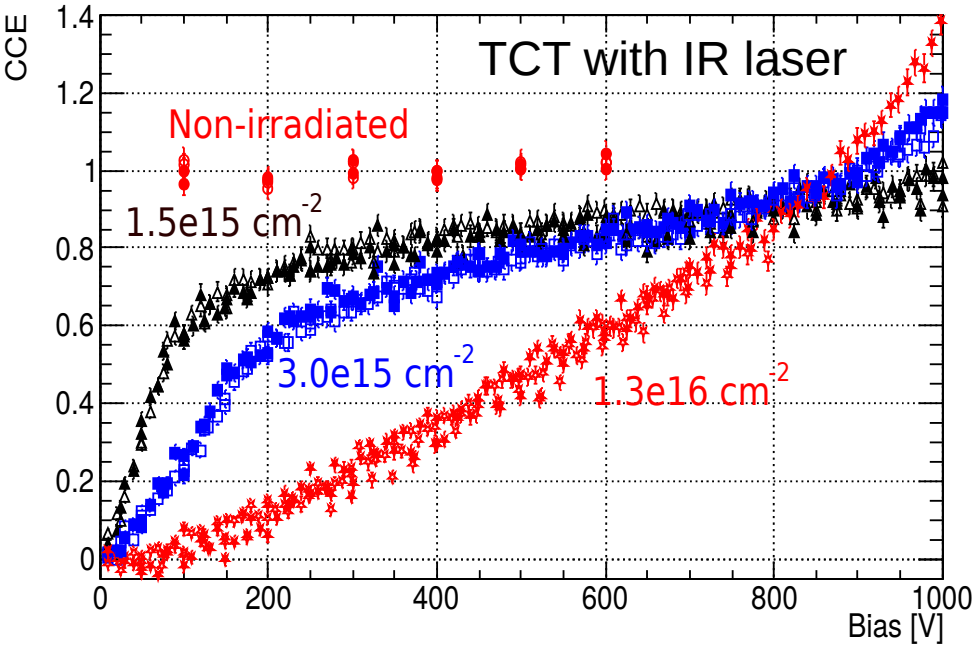
CCE from Landau MPV
Normalization between 200 and 400 V bias

Up to 3 x 10^{15} cm^{-2}:
- **85% collected charge at high bias**

Difference between
TB and TCT data to be studied

Charge multiplication in the diode measurement

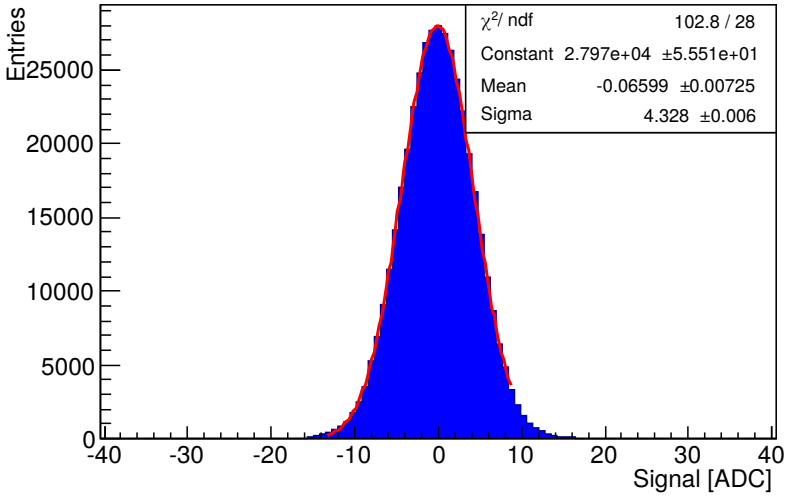
Diodes with p-spray insulation

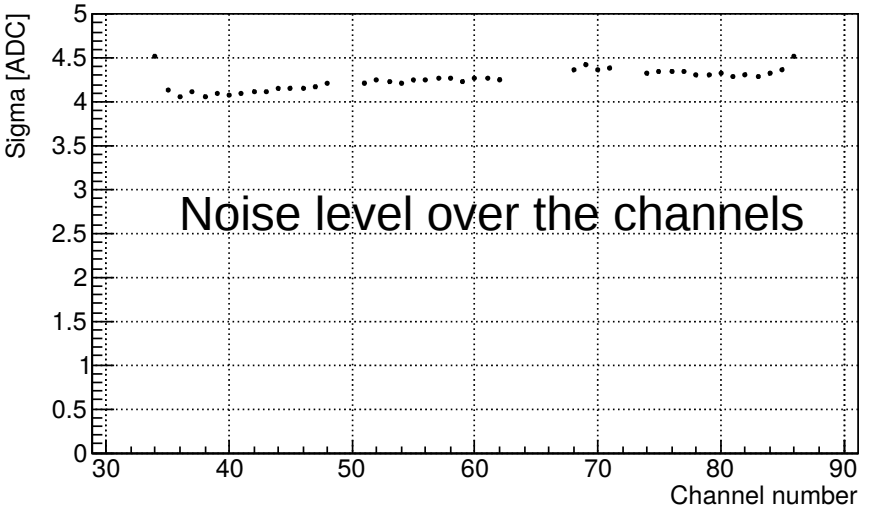


Noise

Signal not associated to a track

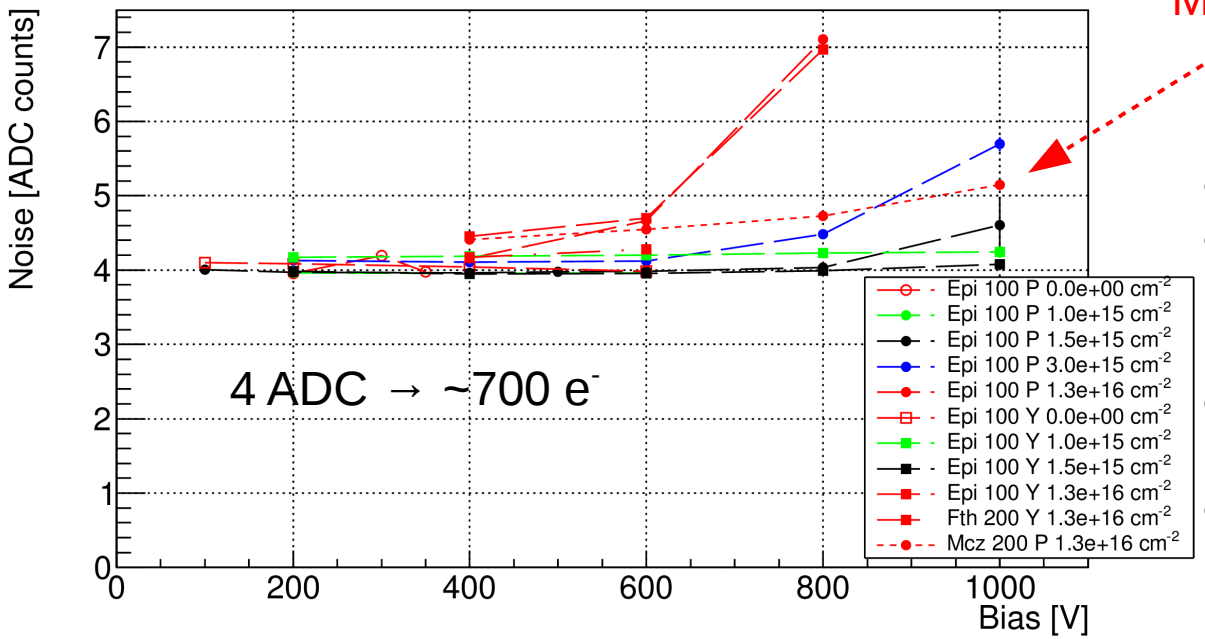
Noise distr for one channel





Epi100P, 23 GeV p, 3 x 10^{15} cm^{-2}, -800V, -20 °C

Mean value single channel noise



Mcz 200 P

Up to 3 x 10^{15} cm^{-2}:

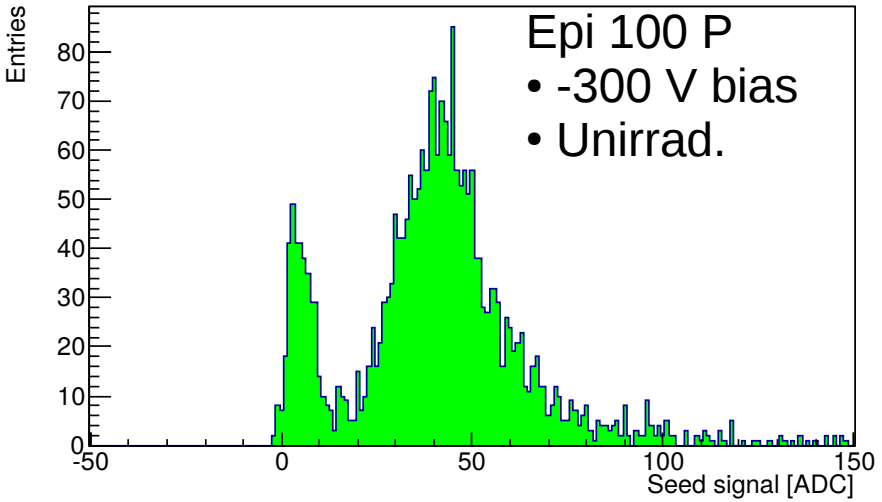
- **Noise levels similar to pre-irradiation**
- Noise increase at high bias

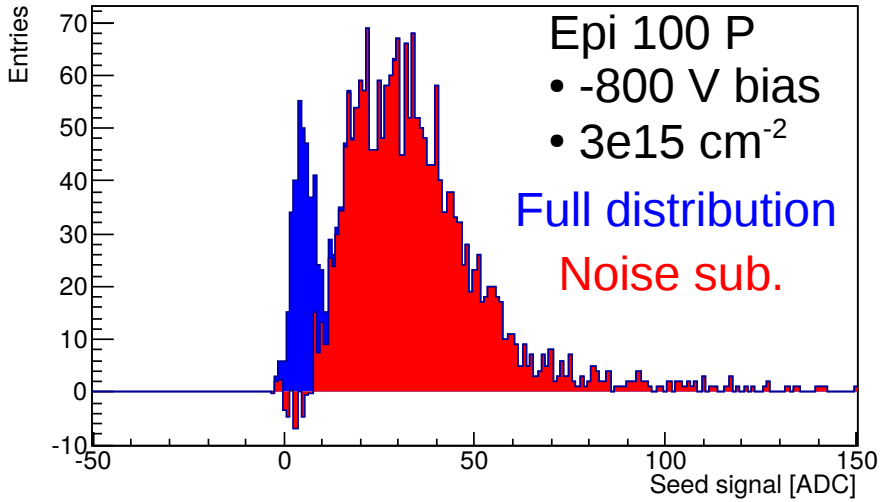
10^{16} cm^{-2} sensors:

- **100 µm → higher noise**
  → charge multiplication?
- **200 µm → better noise figure**

Efficiency Epi 100 p-bulk

Seed strip charge distribution





The distribution gets broader with irradiation
→ influence on detection efficiency

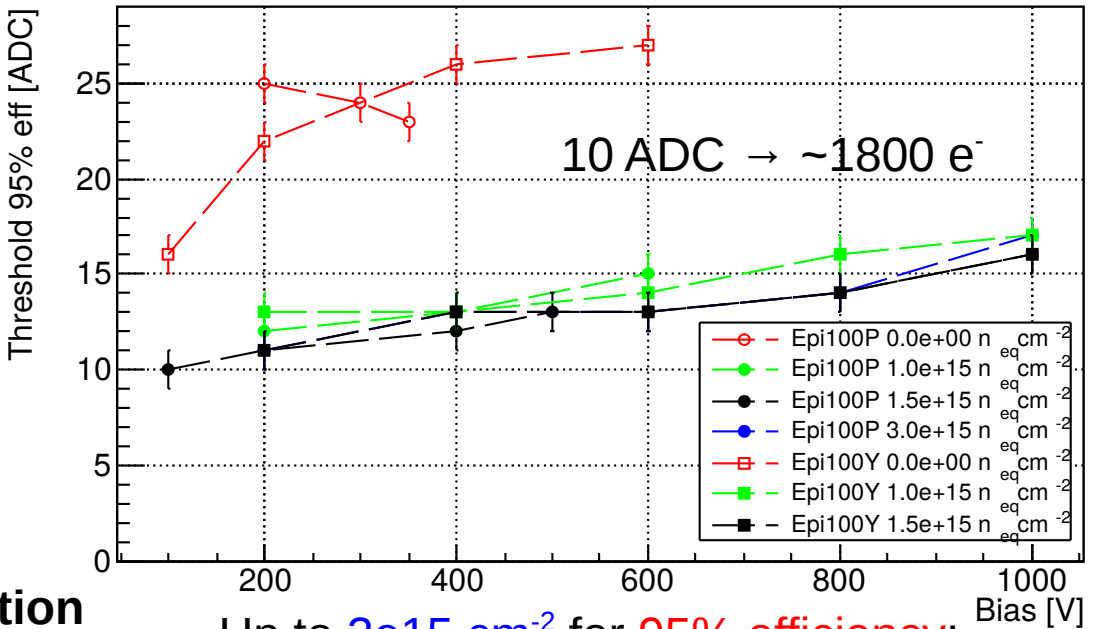
Most pixel systems use a threshold for zero suppression
→ how high can this threshold be?

CMS pixel threshold ~2300 e^-
- Noise < 150 e^-
- Cross talk is a limiting factor

→ efficiency of 99.3-99.8% (layer dependent)

This method can not access efficiency ~99%

Max threshold to have 95% efficiency



Up to 3e15 cm^{-2} for 95% efficiency:
→ **Threshold ~2000 e^-**

Conclusions

First test beam of highly irradiated epitaxial strip sendors

Results from the sensors are promising

10^{15} cm^{-2} sensors:

- **CCE of 85%**
- 95% detection efficiency with ~2000 e^- threshold

Charge multiplication present in CCE measurement of diodes

10^{16} cm^{-2} sensors:

- **100 µm → faster signal recovery with bias, higher noise**
- **200 µm → better noise figure, higher breakdown voltage**

Can 150 µm sensors be a good compromise?
→ next common CMS sensor submission will give the answer!

Special thanks to:

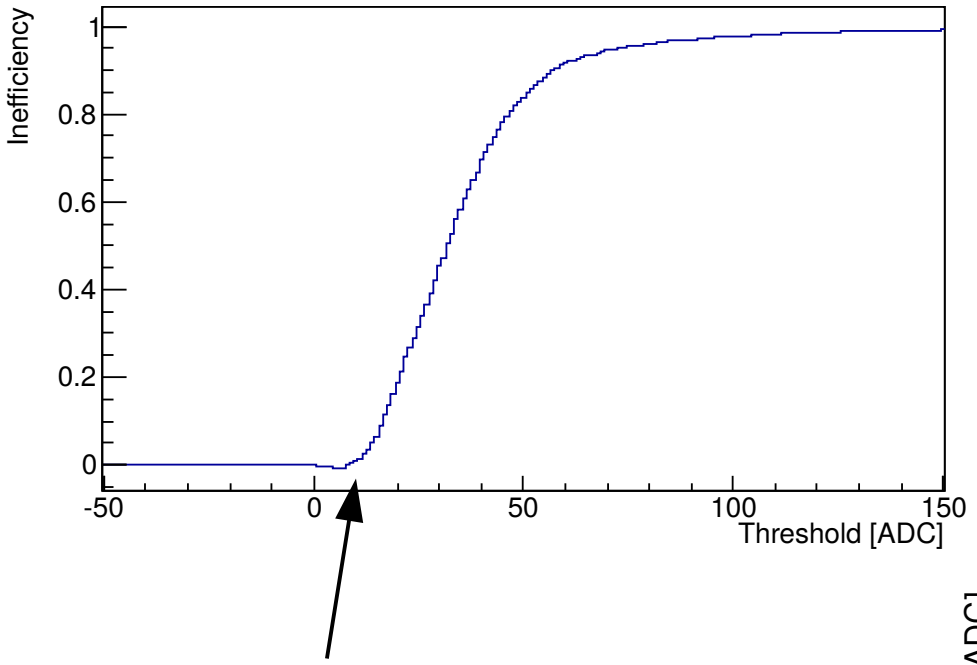
- Test beam shifters
- HIWI students for the TCT measurements

Thank you for your attention!

Backup

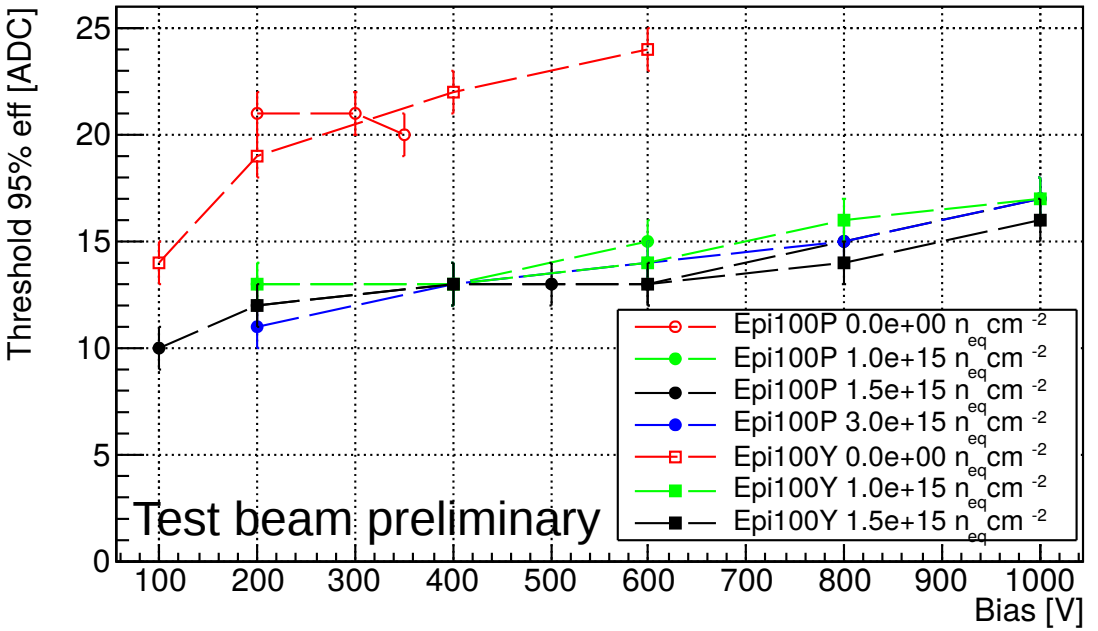
Efficiency estimation

Normalized integral of BG sub histo



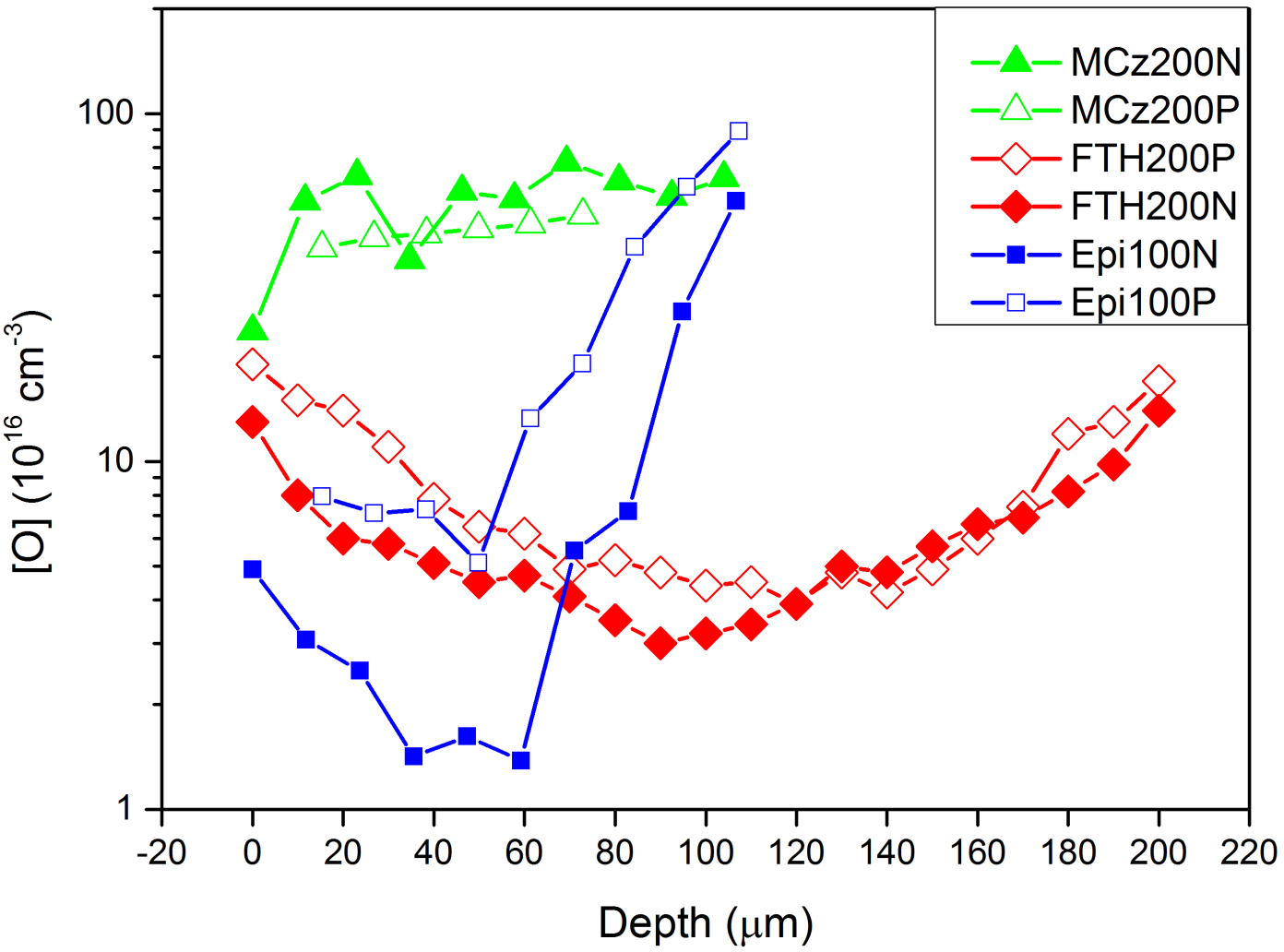
Bumps due to BG subtraction

Threshold to get 95% efficiency

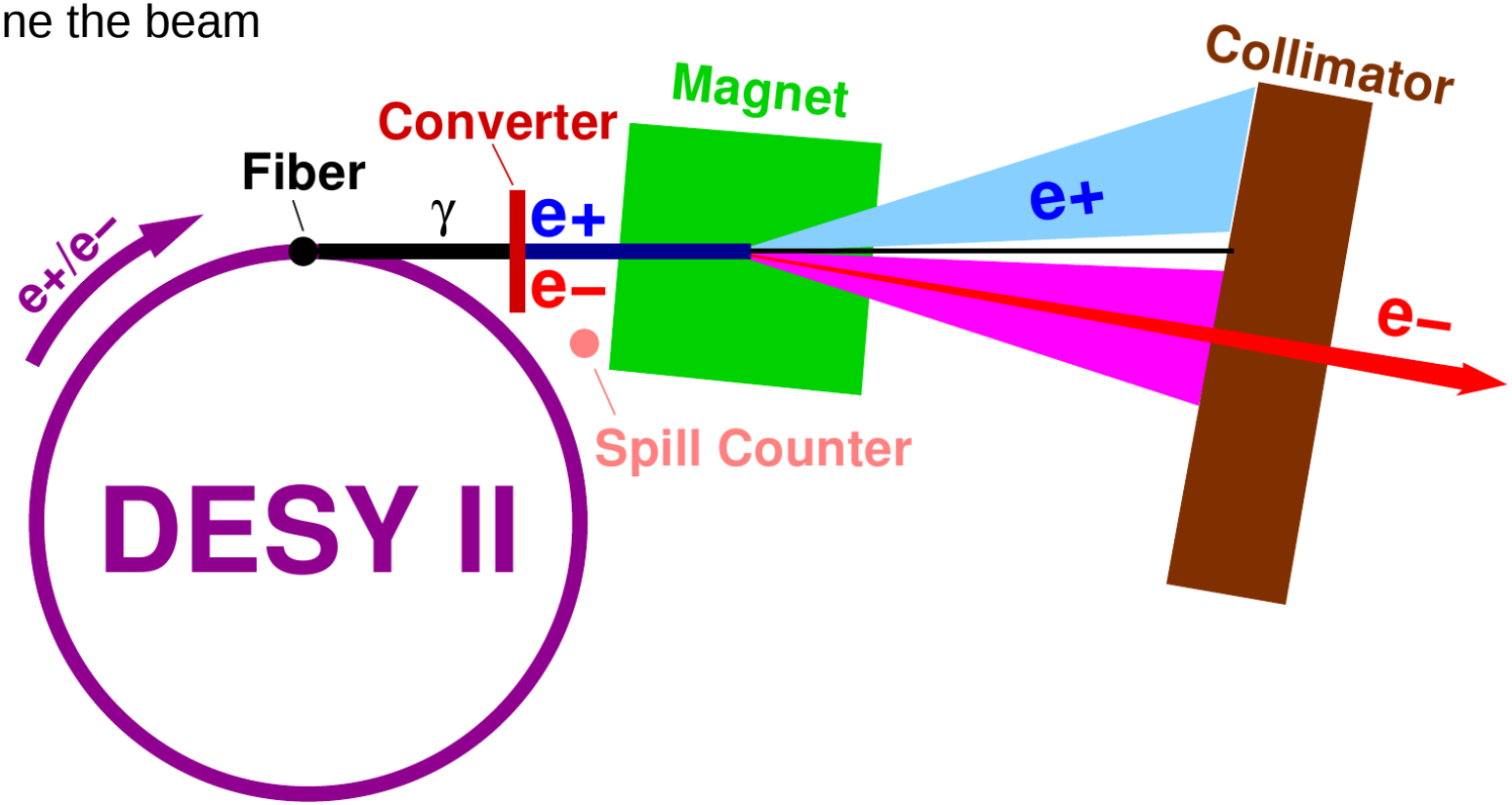


Same plot for 99% too much influenced by bumps

Oxygen content



Beam generation at DESY II

Beam generation at DESY test beam:

- Bremsstrahlung on C fiber
- Conversion in e^+e^- on a metal target
- Momentum selection using a magnet
- Collimator to define the beam