Test beam results on highly irradiated scCVD diamond timing sensors

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(on behalf of the CMS and TOTEM collaborations)

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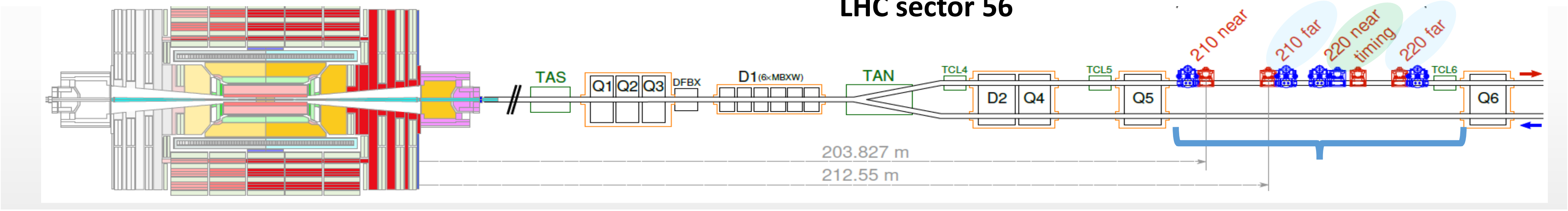
OUTLINE:
- PPS timing detectors
- Irradiation and performance in LHC
- Test beam setup
- Result highlights

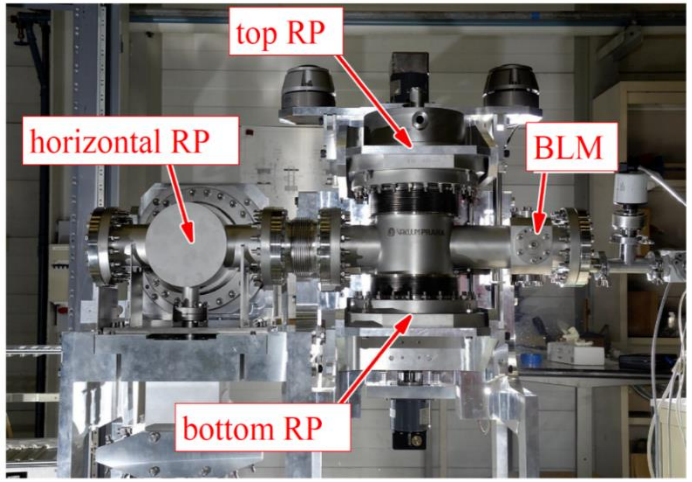
PPS detector

The PPS detector (previously CT-PPS, CMS-TOTEM Precision Proton Spectrometer) extends the physics program of CMS to Central Exclusive Production (CEP) processes, where both protons remain intact after the interaction. PPS can measure the proton kinematics.



Symmetric experimental setup w.r.t. the interaction point

ROMAN POTs



RP: Vacuum vessel entering the beam pipe, can be equipped with many types of detectors. Hosted detectors brought to few mm from LHC beam centre.

Sensors in Run 2

Timing

2016: 4 single diamond planes(SD)

2017: 3 single diamond and 1 UFSD planes

2018: 2 single and 2 double (DD) diamond planes

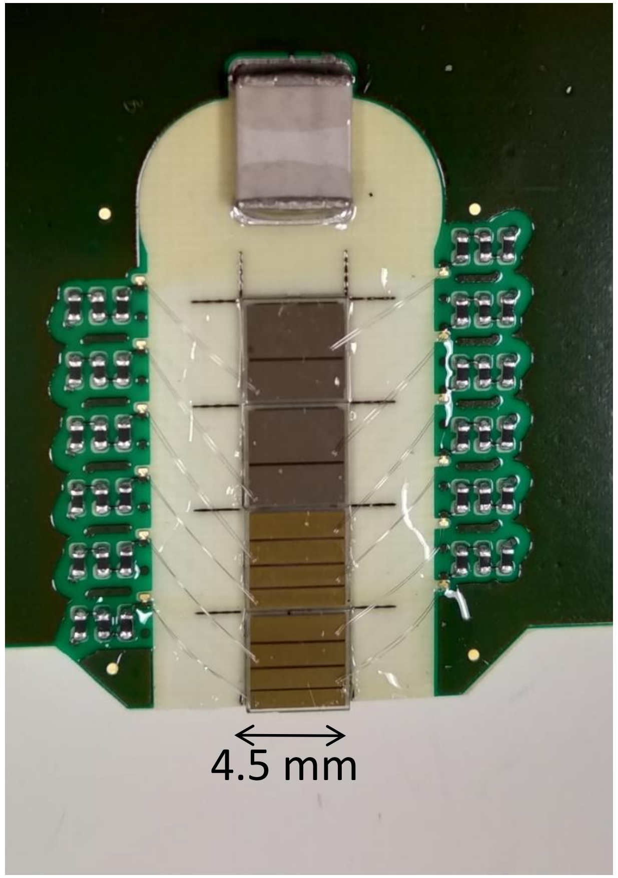
Tracking

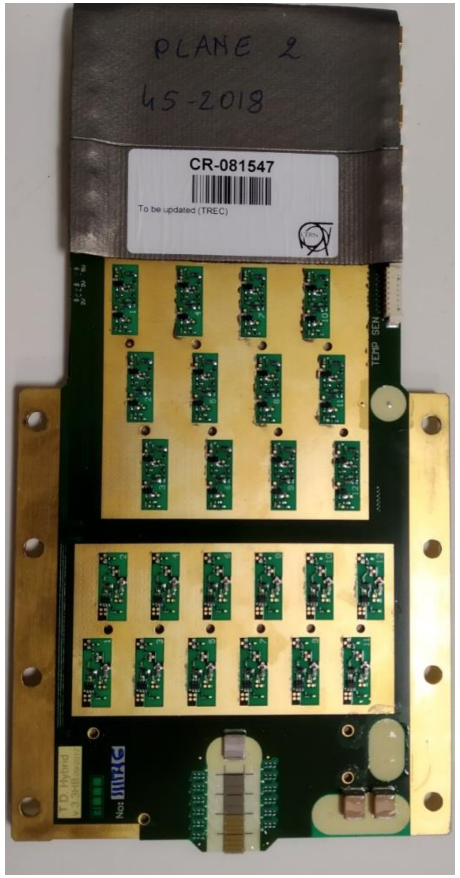
2016: 2 TOTEM strip detector stations

2017: 1 strip and 1 3D pixel stations

2018: 2 3D pixel stations

PPS diamond sensors





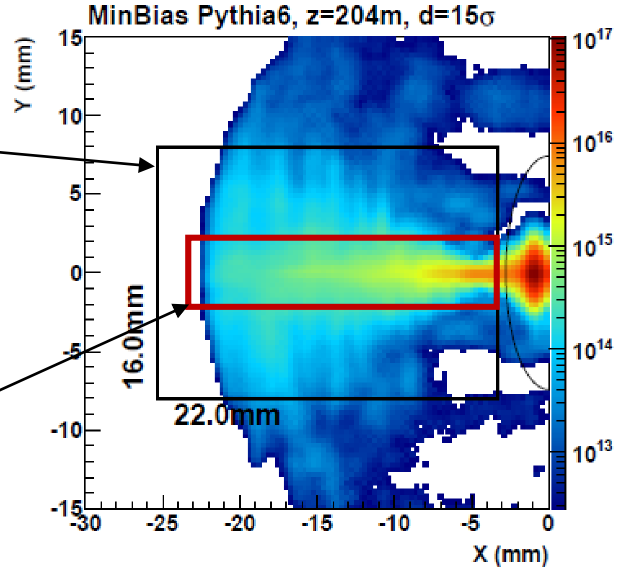
Sensor based on ultra pure single crystal CVD diamonds. Each crystal has dimensions 4.5x4.5x0.5 mm^3 , total area coverage ~ 80 mm^2.

Detector requirements:

- Sector resolution of 10-30 ps is the final goal.
- High efficiency for MIP detection
- High radiation hardness (up to $\sim 5 \cdot 10^{15}$ $\mathrm{p/\,cm^2}$ for 100 $\mathrm{fb^{-1}}$, highly non uniform)
- Low density/thickness detector (to fit more planes inside a RP and reduce material budget)
- Detector must operate in a vacuum

Area covered by tracking station

Area covered by timing station

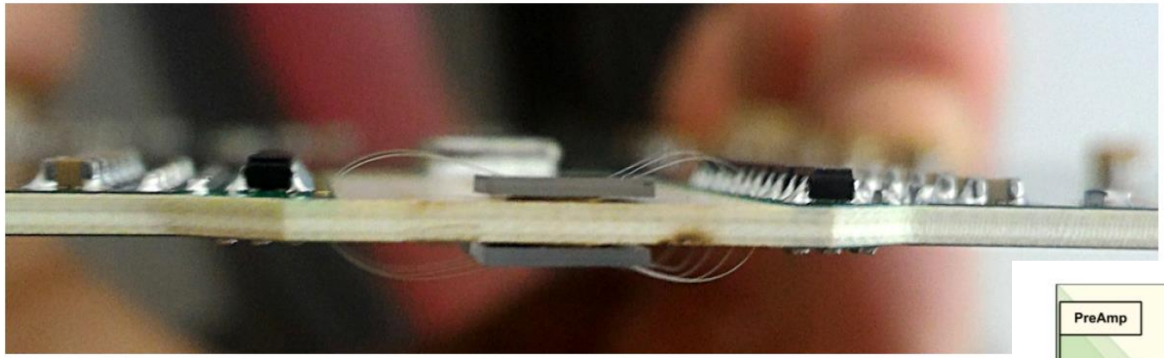


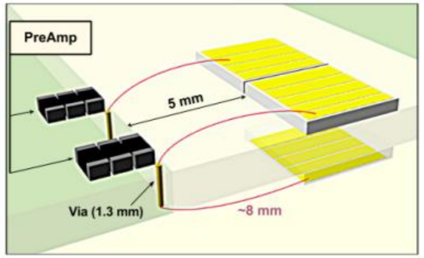
Simulated particle flux for 100 $\mathrm{fb^{-1}}$ (full Run2)

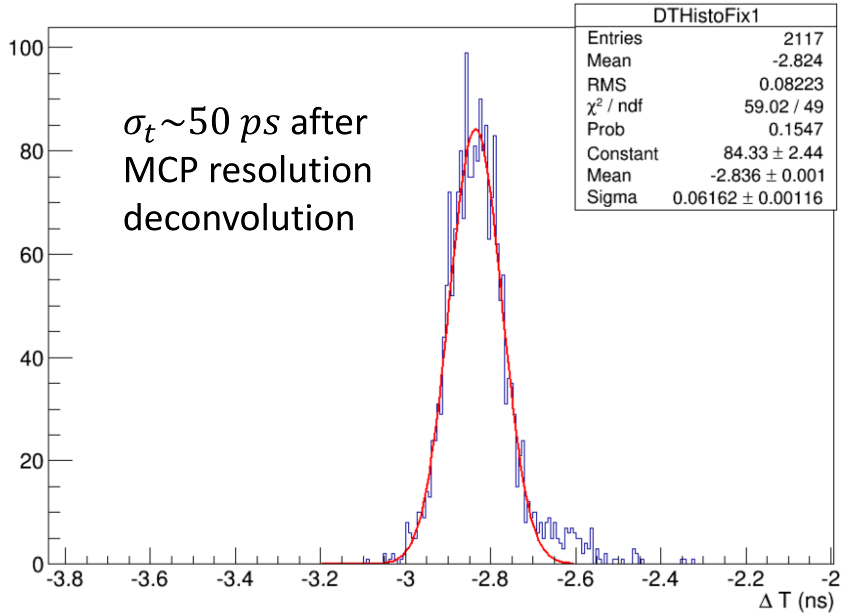
Double diamond performance

JINST 12 (2017) no.03, P03026

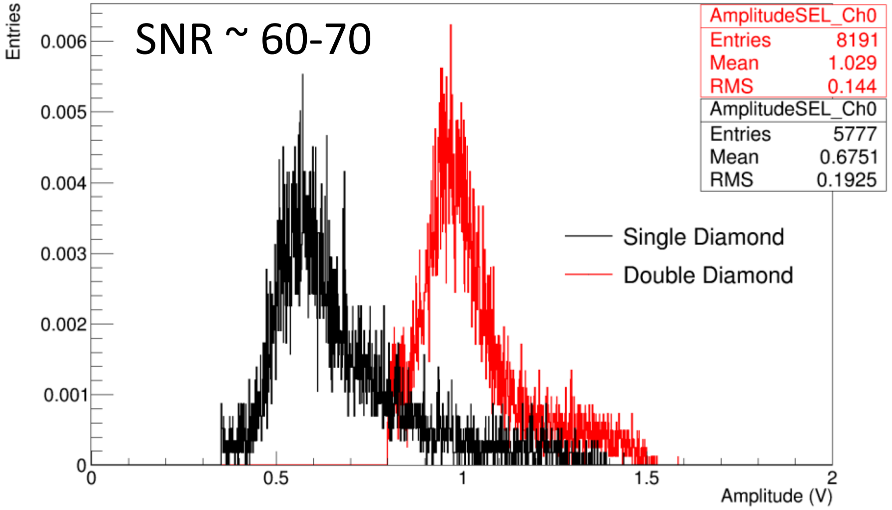
Sensor readout performed with oscilloscope. Actual sensor technology limit.







Time difference distribution between DD and reference MCP ($\sigma_{t,MCP} \sim 40\ ps$)



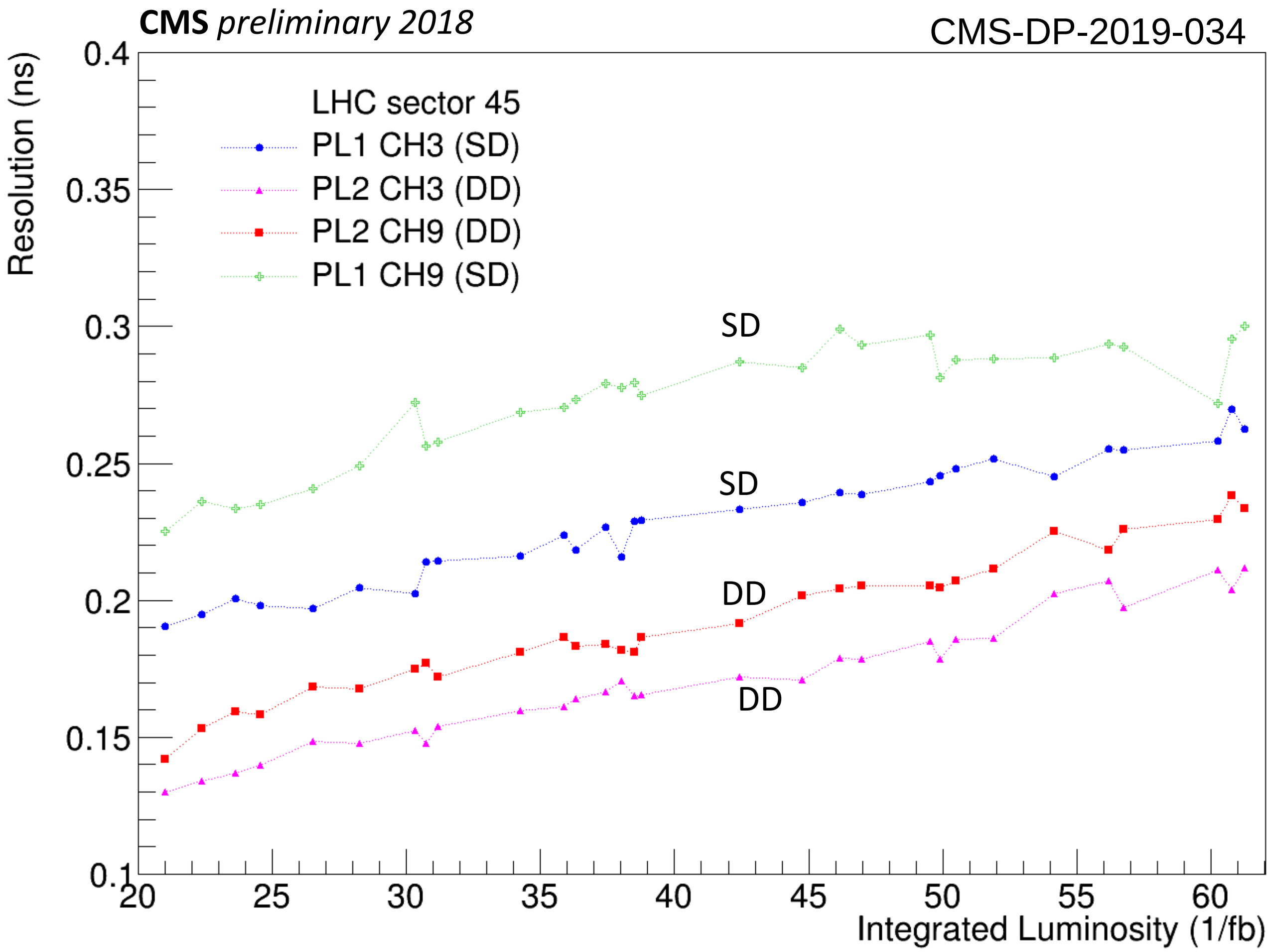
Signal amplitude comparison between DD and SD

Signal from corresponding pads is connected to the same amplification channel:

- Higher signal amplitude
- Same noise (pre-amp dominated) and rise time (defined by shaper)
- Higher sensor capacitance
- Need a very precise alignment

Better time resolution (factor ~1.7) w.r.t SD

Resolution vs integrated Luminosity in LHC Run2



Comparison of the resolution in two planes vs integrated luminosity in Run2. Calibration data available only after TS1 (20 fb^{-1}).

Two types of degradation identified:

1. General resolution loss: radiation damage on sensor and electronics close to the beam (pre-amplification stage).

2. Localized damage on the sensor in the most irradiated area ($\sim 1\ \mathrm{mm}^2$). Damage could be due to creation of trapping centers in the bulk or at the metallization interface.

<u>DD resolution at beginning of data taking estimated $\sim$100ps</u>

Source of time performance degradation w.r.t. test beam:

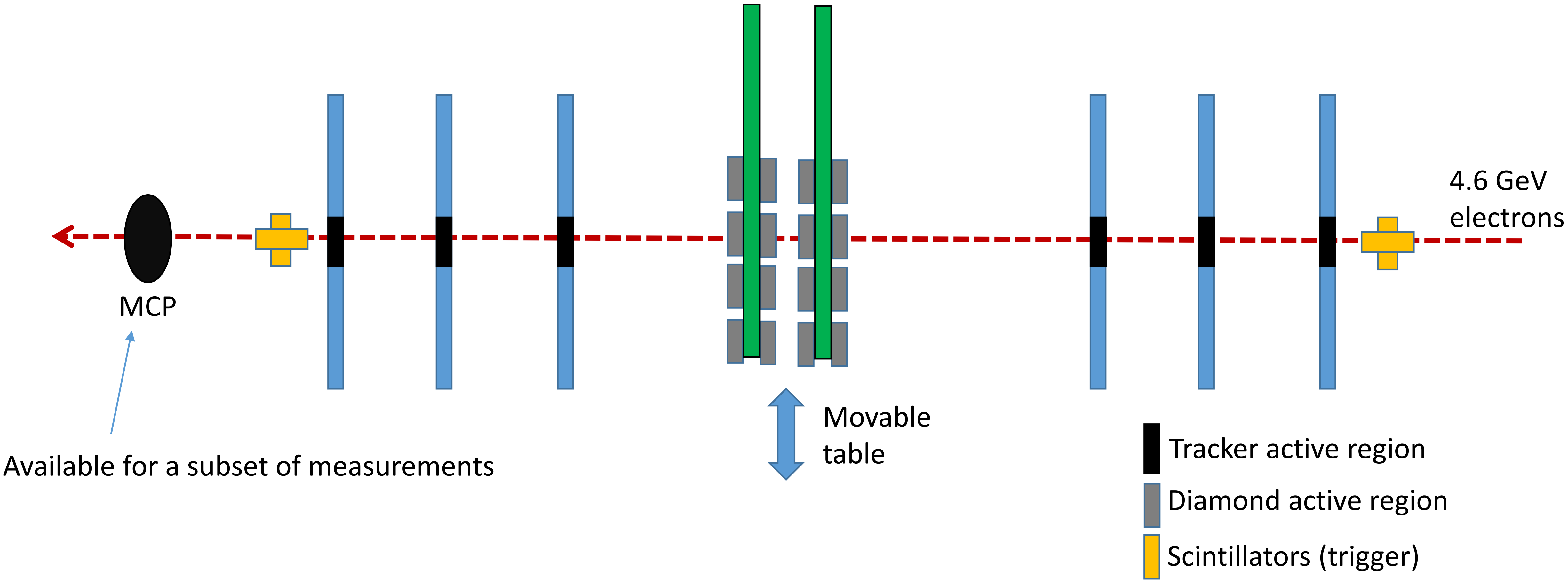
- LV/HV reduced
- Digitization: discriminator (NINO) and TDC (HPTDC)

Resolution in double diamond detectors factor 1.7 better, as expected.

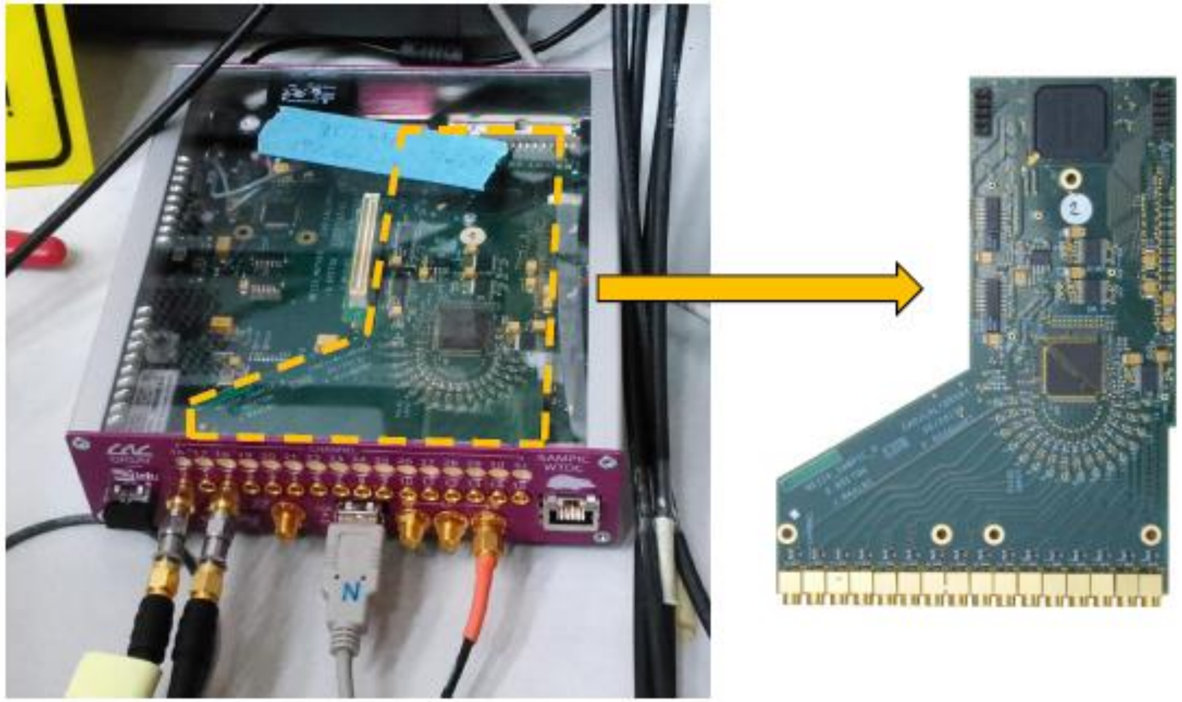
Test Beam detector scheme

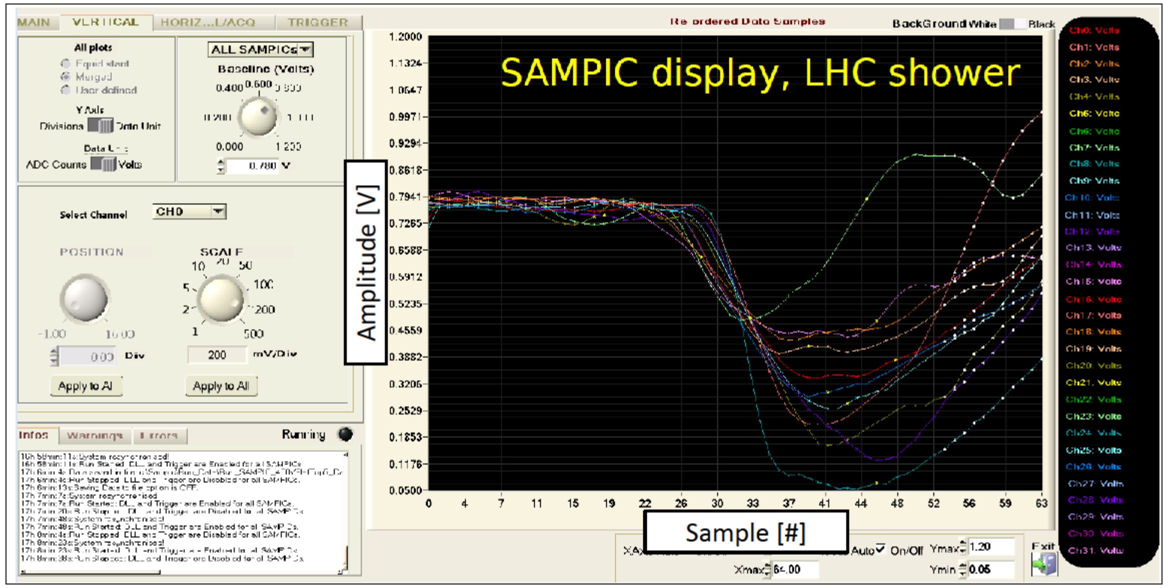
Hybrid boards used in 2018 (4xSD, 4xDD) were tested in May 2019 at the DESY test beam line TB24.
Each diamond has been put in the middle of the tracker and ~3M tracker events collected.

AZALEA tracker (EUDET series) available -> position dependent measurements



Sensor readout

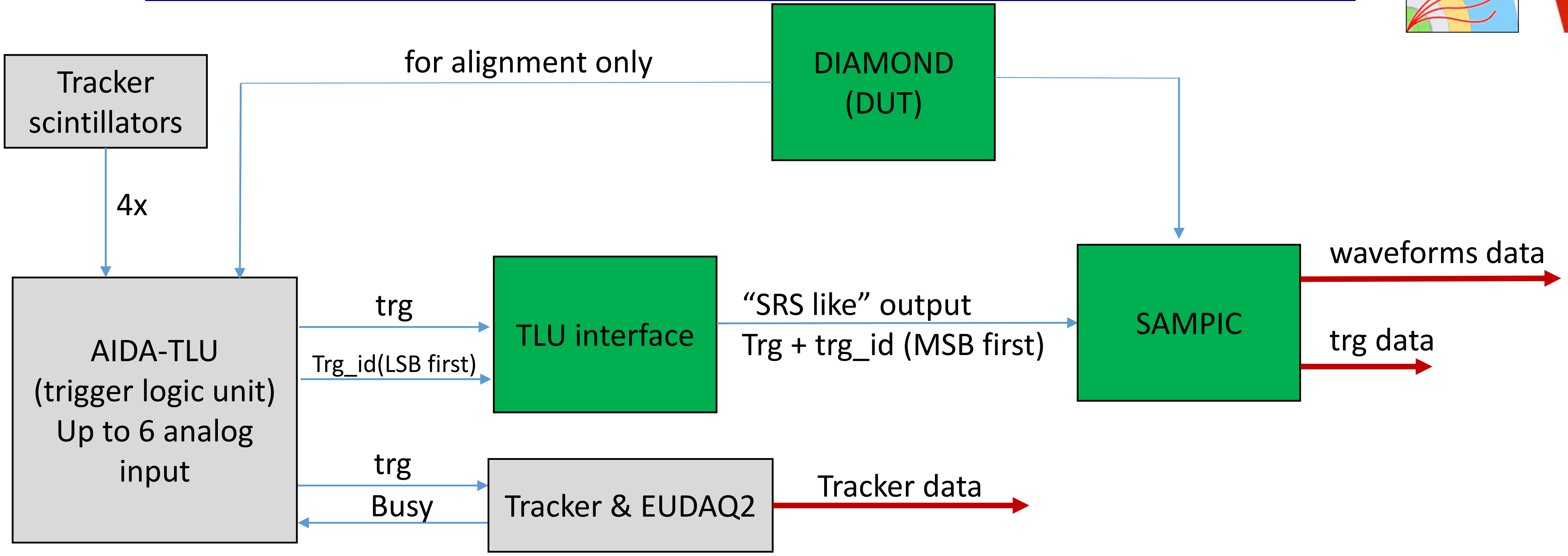




- ➢ 32 channels
- ➢ Up to 64 sample/hit @ 10 GSa/s (used at 6.4 GSa/s in the present work)
- ➢ 1.5 GHz bandwidth
- ➢ 8-11 bit resolution
- ➢ 0.25-1.6 µs channel dead time

- Self trigger (2ns max latency on central)
- No event building
- Each sampled signal sent out
- Separate trigger data stream (id/timestamp) available

Test Beam hardware scheme

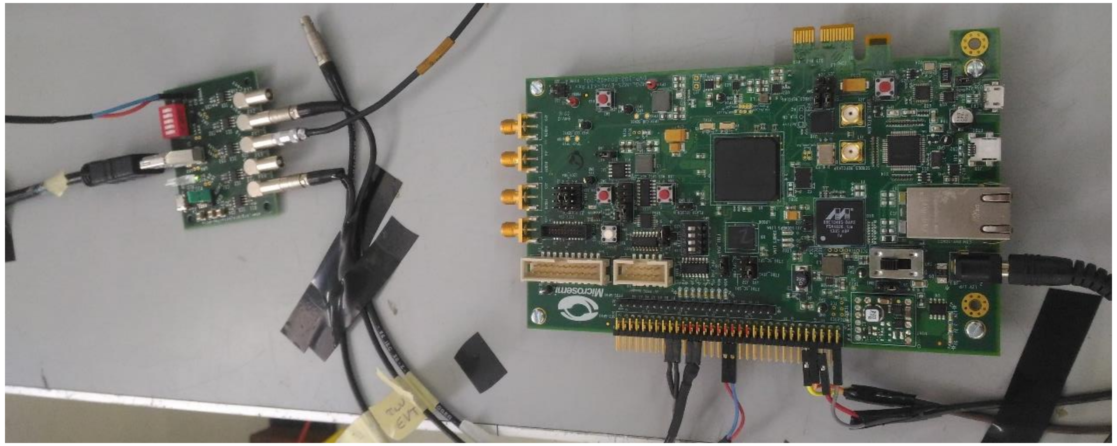


For each trigger generated by AIDA-TLU a trigger timestamp is generated inside the SAMPIC. Offline event building can be done matching waveform and trigger timestamps.
Tracker data reconstructed through EUTelescope framework.

To assure data synchronization Trigger_id from AIDA-TLU was readout and included in SAMPIC data stream and used to merge DUT and tracker data.

- Efficiency
- Signal quality
- Charge sharing/induction
- Radiation damage
- Signal amplitude uniformity
- Timing

Test Beam

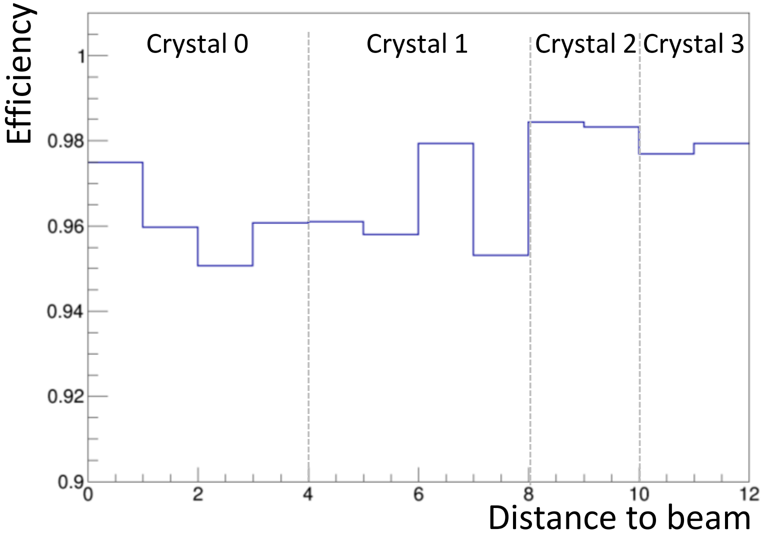


TLU interface

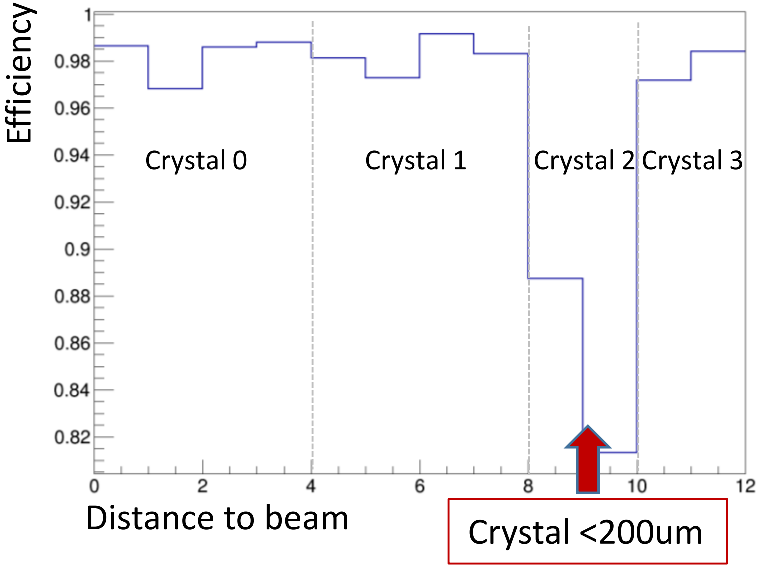
PPS timing sensors

DD Core Efficiency

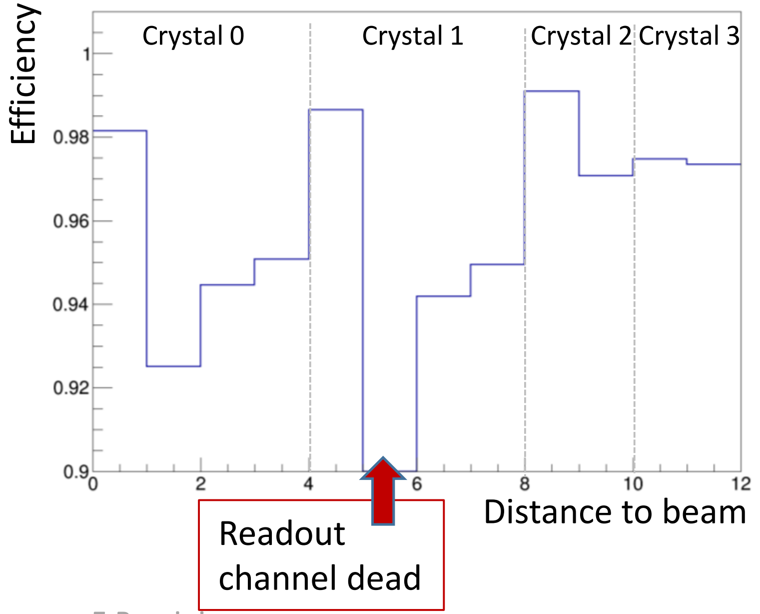
DD plane 2 sector 45



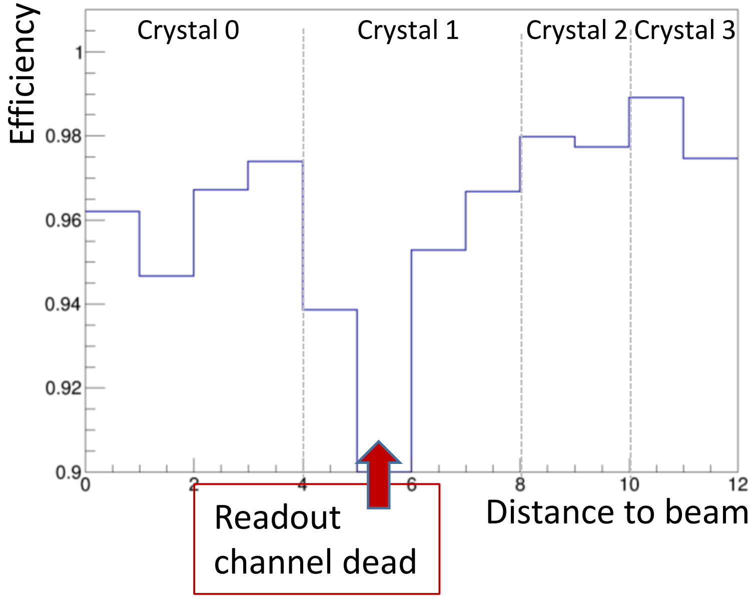
DD plane 3 sector 45



DD plane 2 sector 56



DD plane 3 sector 56



Event selection criteria:

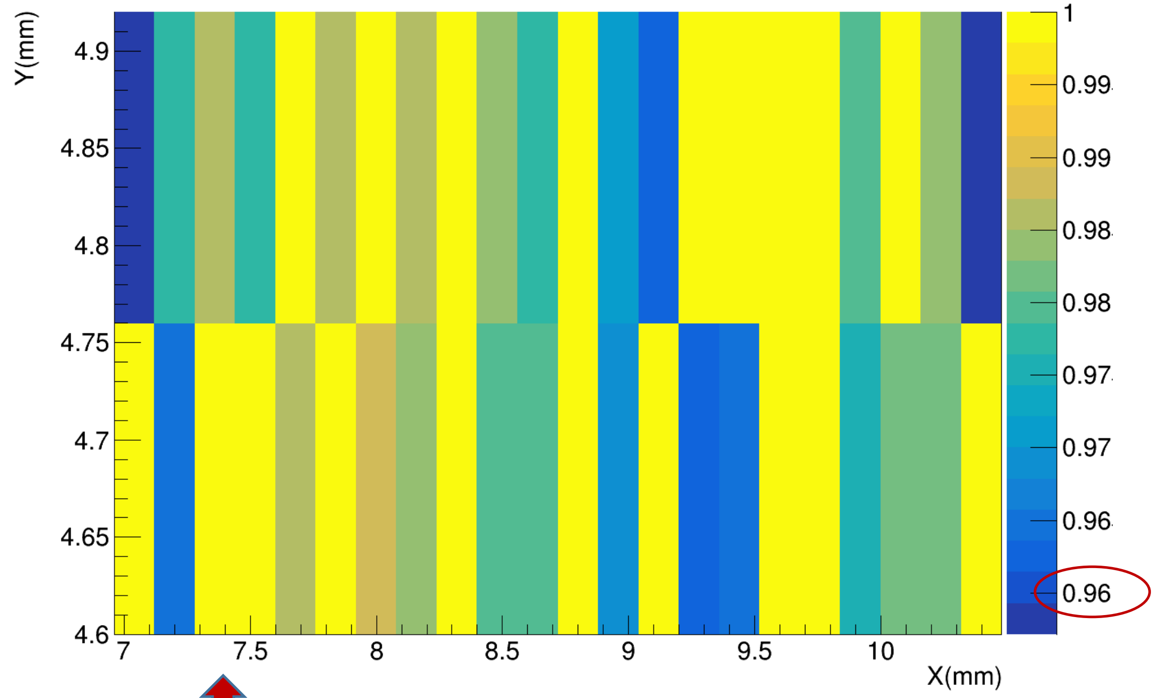
- Only one track in the tracker
- Corresponding pad on the other DD plane with a signal above threshold

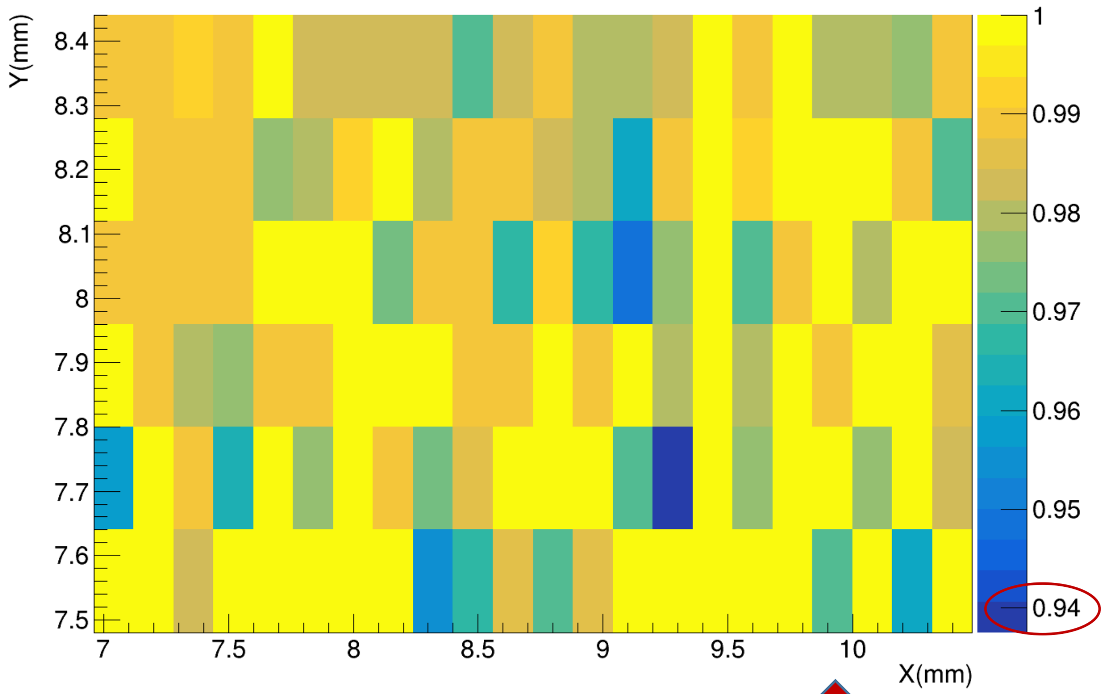
Pad core is defined with a clearance of 300 μm in X and 200 μm in Y from metallization borders.

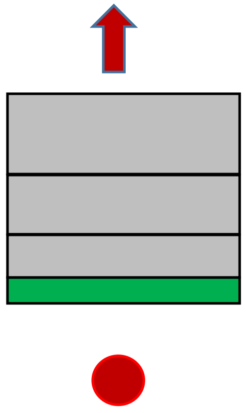
High efficiency for all pads found after irradiation.

Noise contamination evaluated for each pad using dataset where the pad was outside the tracker active region. Noise contamination well below 1% for all pads.

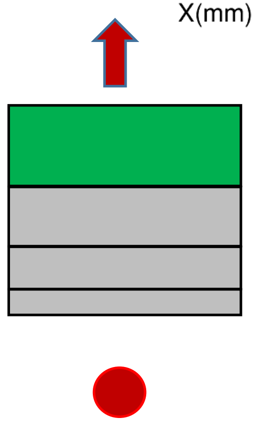
Core efficiency (DD)







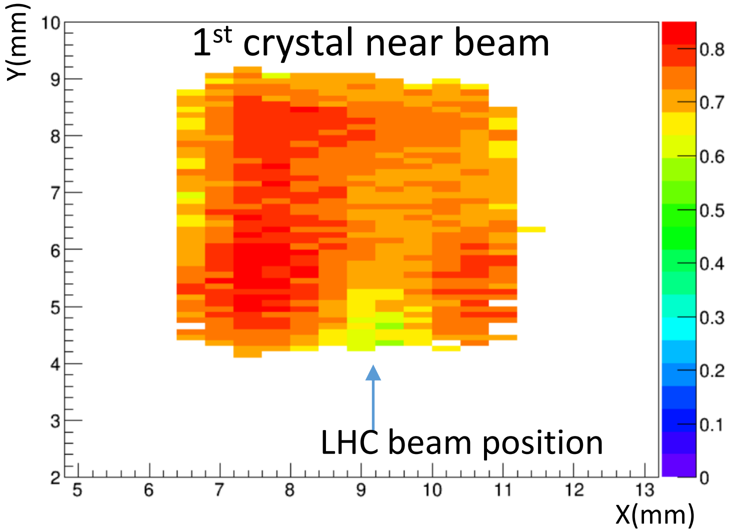
Pad core is defined with a clearance of 300 µm in X and 200 µm in Y from metallization borders.



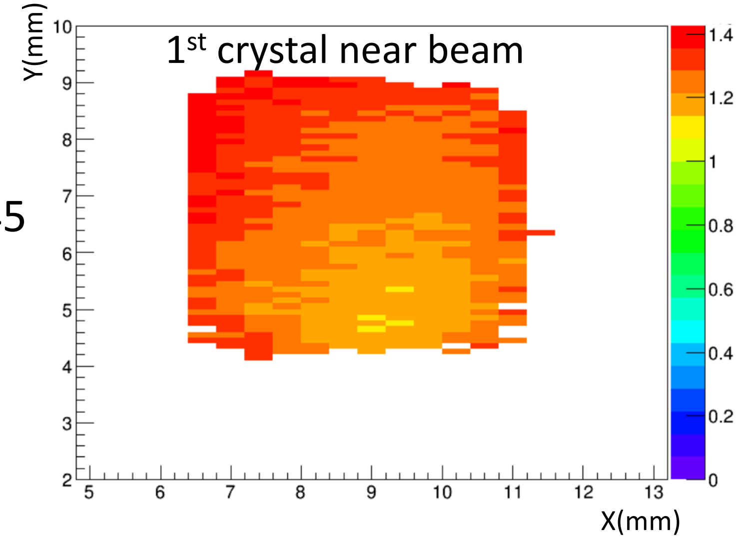
No evidence of efficiency loss in DD for the most irradiated pad (with test beam settings) .

Localized damage in DD

Average signal amplitude w.r.t. position (V)

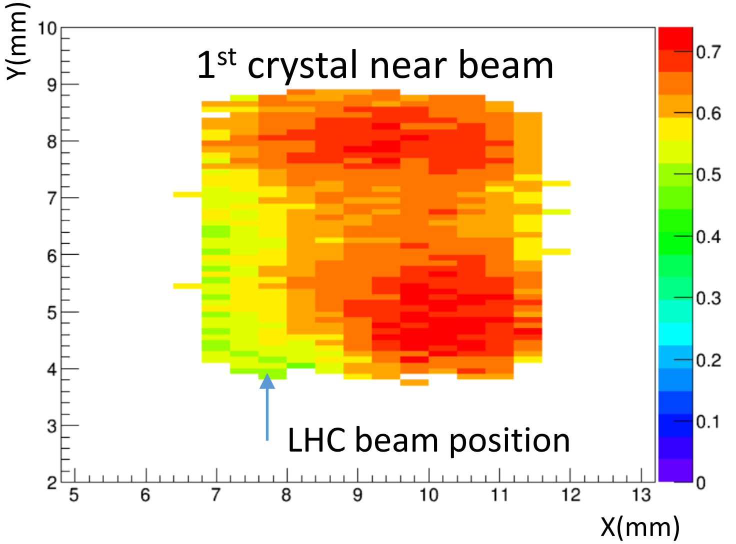


Average Rise Time w.r.t. position (ns)

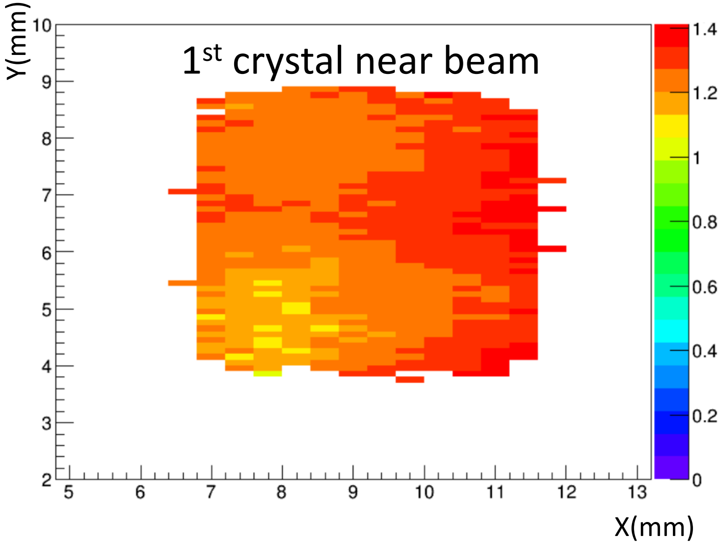


Sector 45

Average signal amplitude w.r.t. position (V)



Average Rise Time w.r.t. position (ns)



Sector 56

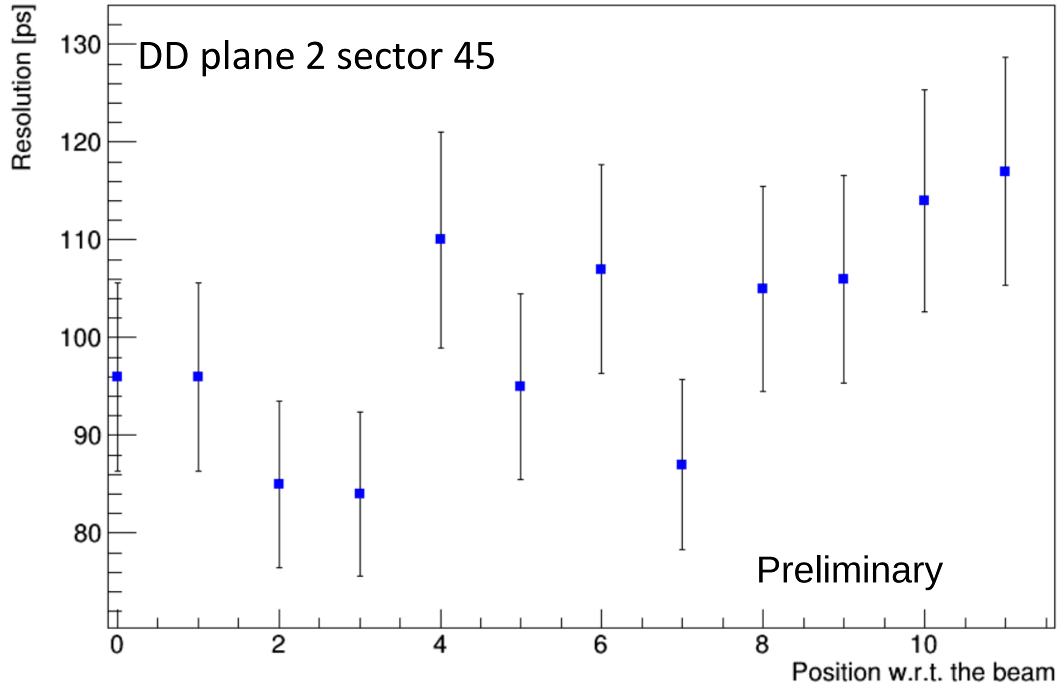
Test beam settings:

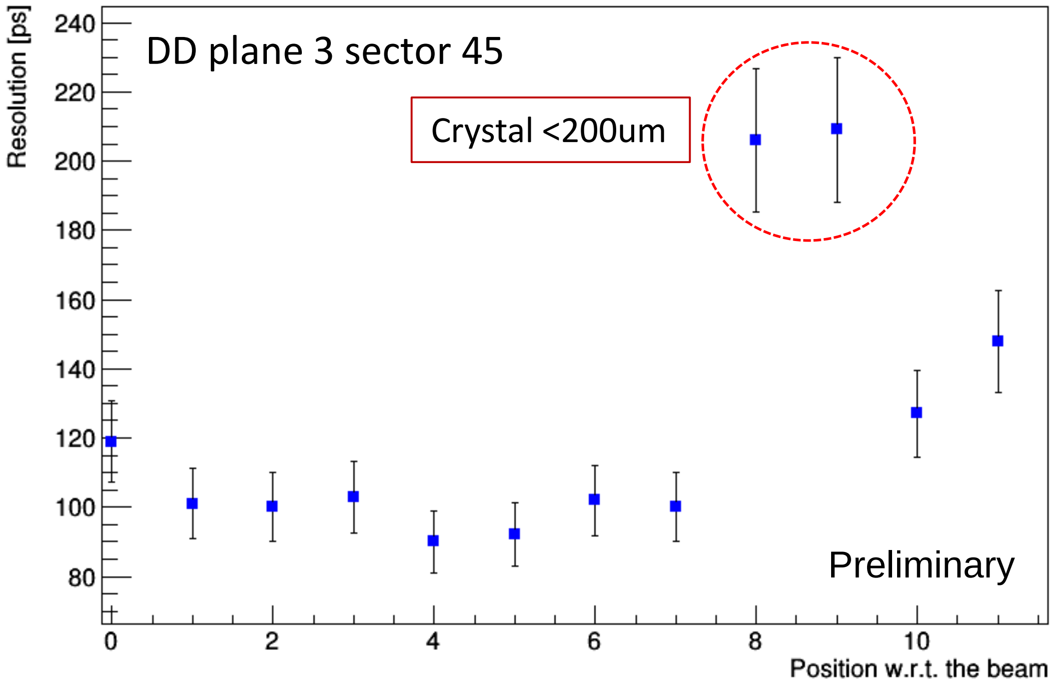
- nominal LV
- HV @ 500V

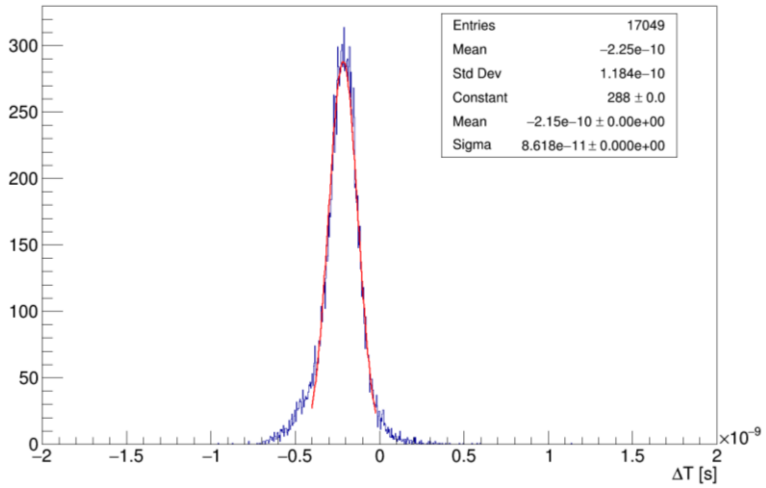
Reduction (~20%) of signal observed in the area with highest irradiation, partially compensated by faster rise time.

Crystals used in Run2 have been removed from hybrid boards. They will be etched and a new metallization will be applied. A new test beam campaign will clarify if the damage is in the crystal bulk or at the contact interface.

Time performance



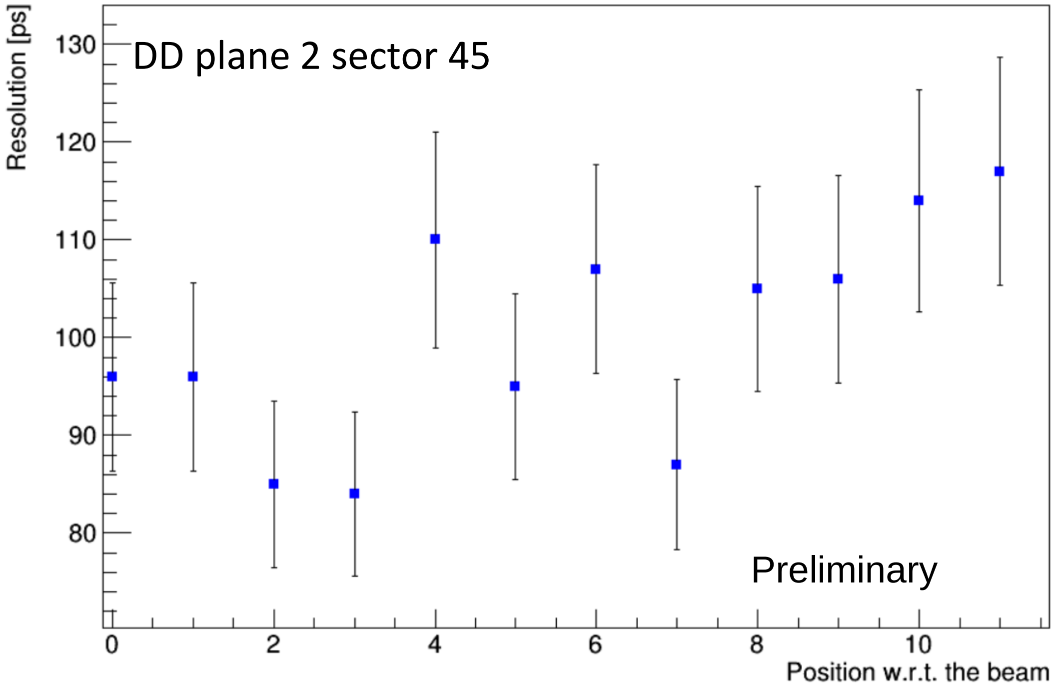


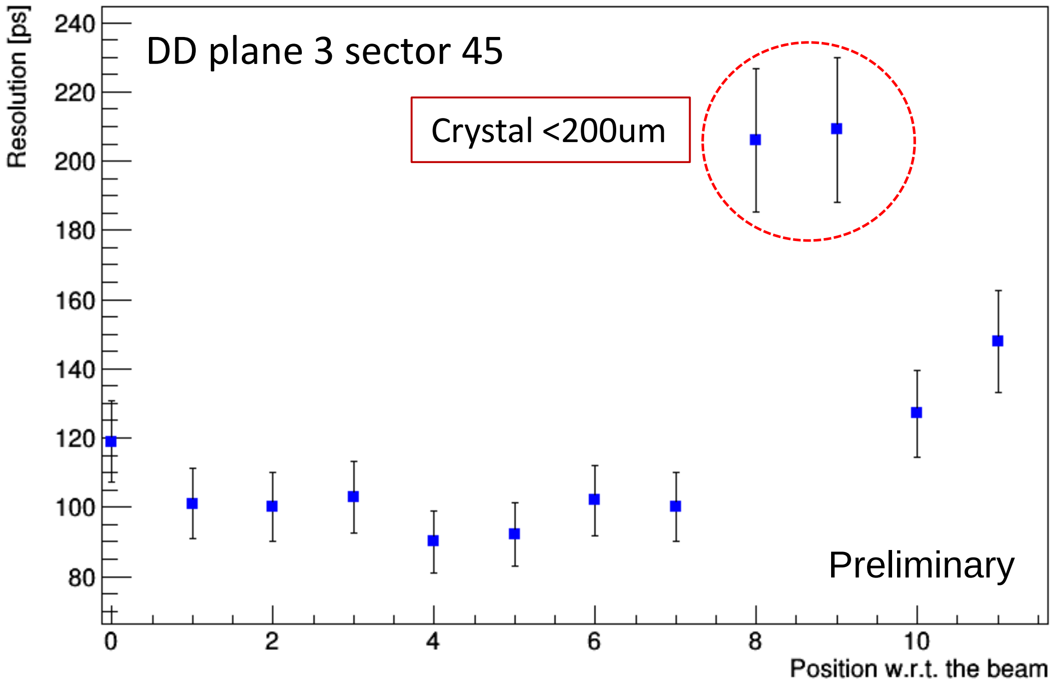


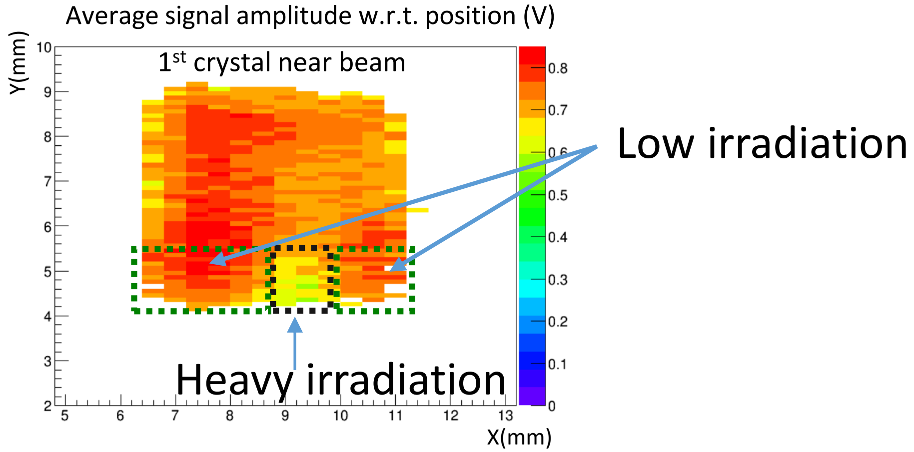
Pad timing resolution evaluated using MCP as reference.
Resolution of MCP << diamond resolution -> $\sigma_{\Delta T} \sim \sigma_{diamond}$

Results confirm a timing resolution degradation as observed in LHC data.
No correlation with the irradiation field on the crystals, in agreement with a damage delivered to pre-amplification stage.
Error bars take into account systematic uncertainties.

Time performance



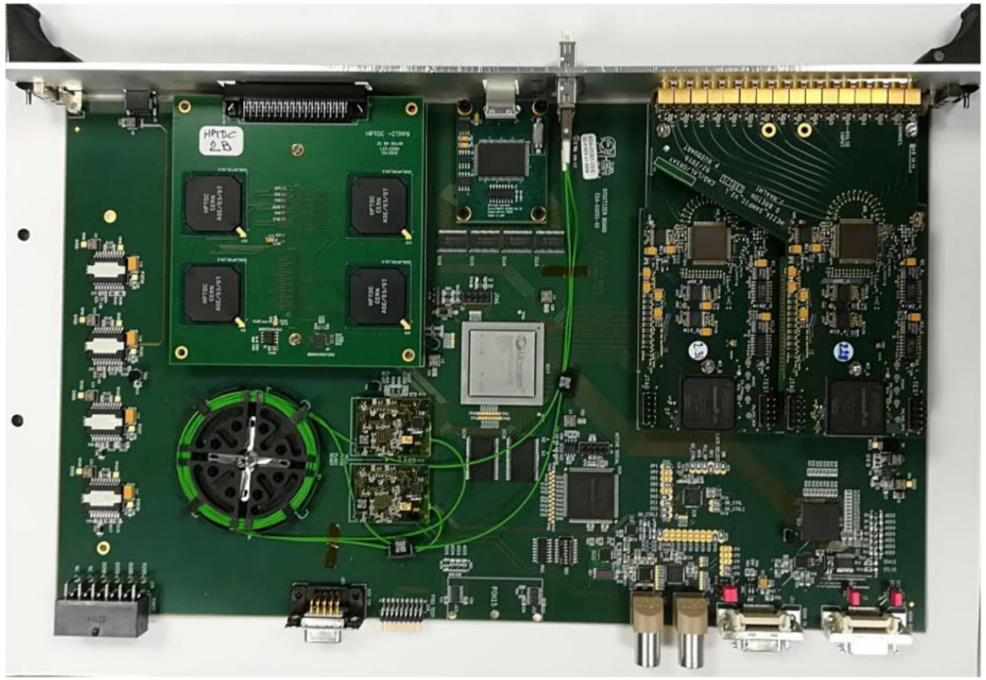




Pad timing resolution evaluated using MCP as reference.
Resolution of MCP << diamond resolution -> $\sigma_{\Delta T} \sim \sigma_{diamond}$

Timing studies carried out in the most irradiated area ($\sim 1\ \mathrm{mm}^2$, limited statistics available).
No significant degradation of timing precision w.r.t. less irradiated area has been found.

Ongoing development of test beam setup



Readout will be based on the CMS/TOTEM Digitizer board:

- ➢ General purpose readout and control board
- ➢ Application specific mezzanines can be designed
- ➢ Radiation tolerant design. Main FPGA from Microsemi (SmartFusion2)

Main firmware features:

- Data packet reception from SAMPIC (1 packet/hit)
- Data packet sanity check
- Fast command decoding and event timestamp generation
- Raw hit selection based on triggered event list
- <u>Event building</u>
- Data compression
- Interface to optical transceiver / USB

During LHC Run2 the *Digitizer board* has been used from TOTEM/PPS timing detectors (UFSD/diamond):

- ➢ Can host 2 SAMPIC mezzanines (32 channels)
- ➢ Can be readout and controlled trough optical link and USB
- ➢ Firmware developed for 200 KHz trigger rate.

Integration of the system in the EUDAQ framework discussed in L.Forthomme's talk.

Conclusions

- TOTEM and CMS have developed new timing detectors based on scCVD diamonds.
- High improvement (factor 1.7) in performance is achieved using the double diamond architecture
- Sensors operated in the LHC in 2018 were exposed to a highly non-uniform irradiation field with peak up to $\sim 5 \cdot 10^{15} \mathrm{p/\ cm^2}$.

- Test beam campaign has been carried out at DESY with 4.6 GeV electrons. Tracker available (AZALEA, EUDET-type tracker)
- Timing (SAMPIC) and tracking data were merged offline trough the TLU event id

- Efficiency of irradiated sensor still very high, also in the irradiation peak.
- Reduction (~20%) of signal observed in the area with highest irradiation.
- Results confirm a timing resolution degradation as observed in LHC data, in agreement with a damage delivered to the pre-amplification stage.
- No significant degradation of timing precision w.r.t. less irradiated area has been found.

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)