The LHCb Timepix3 telescope

3rd BTTB workshop at DESY
20 January 2015

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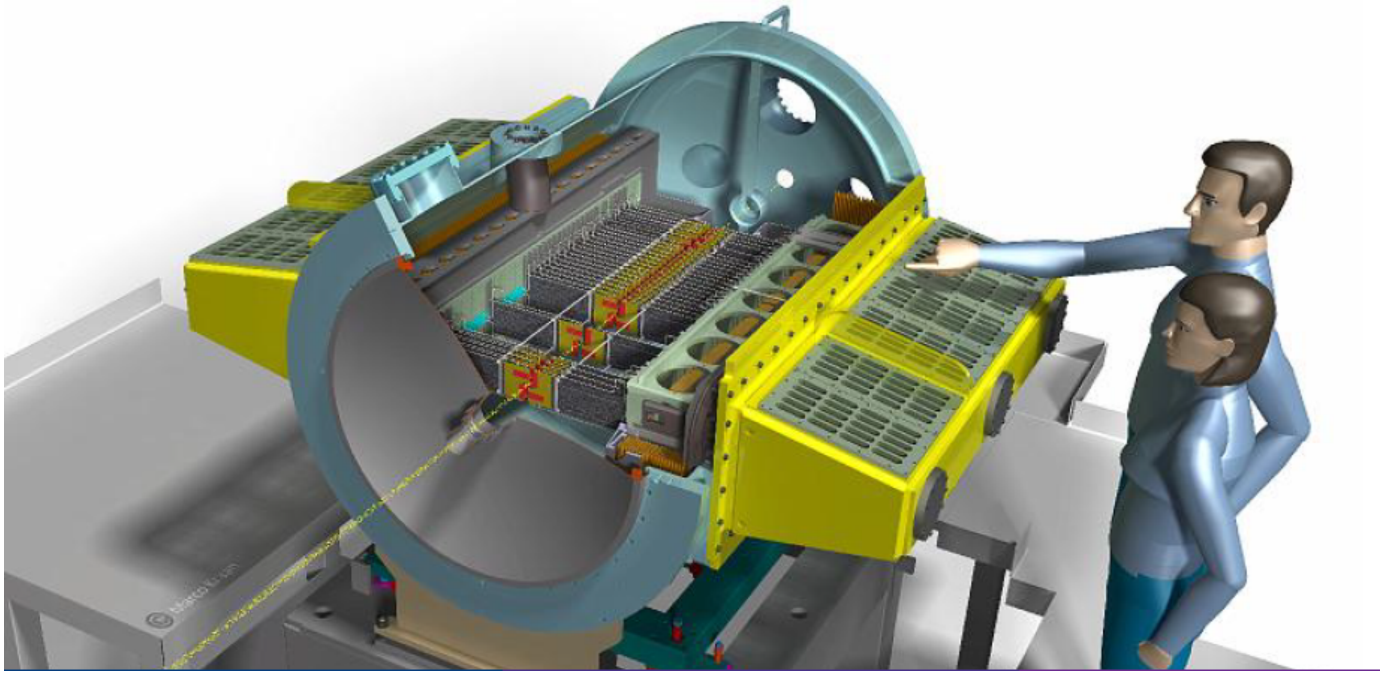
on behalf of the LHCb VELO testbeam crew

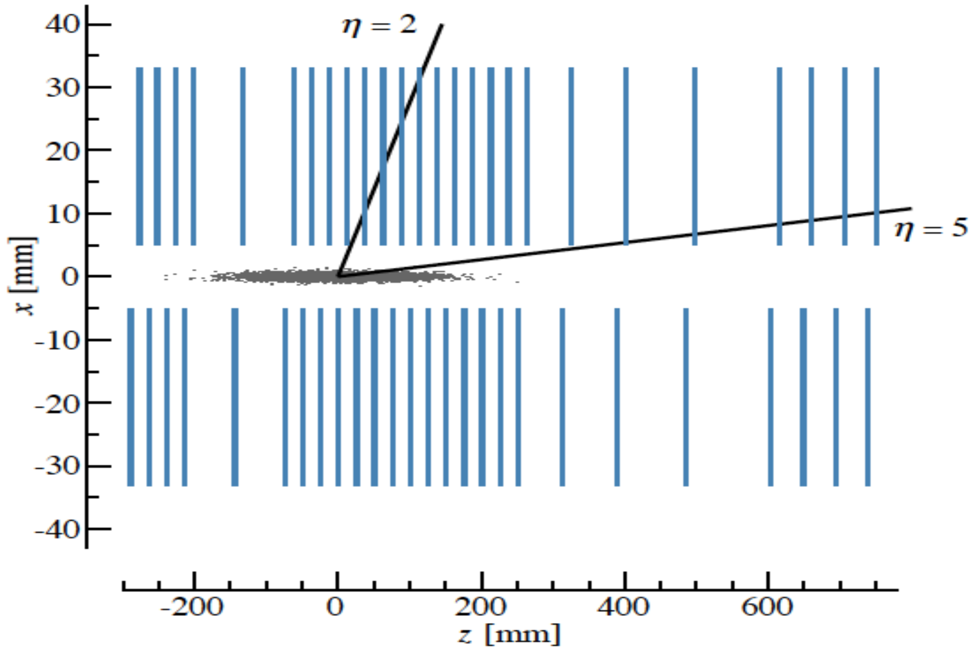
Bristol, CERN, Manchester, Nikhef,
Oxford, Santiago, Rio

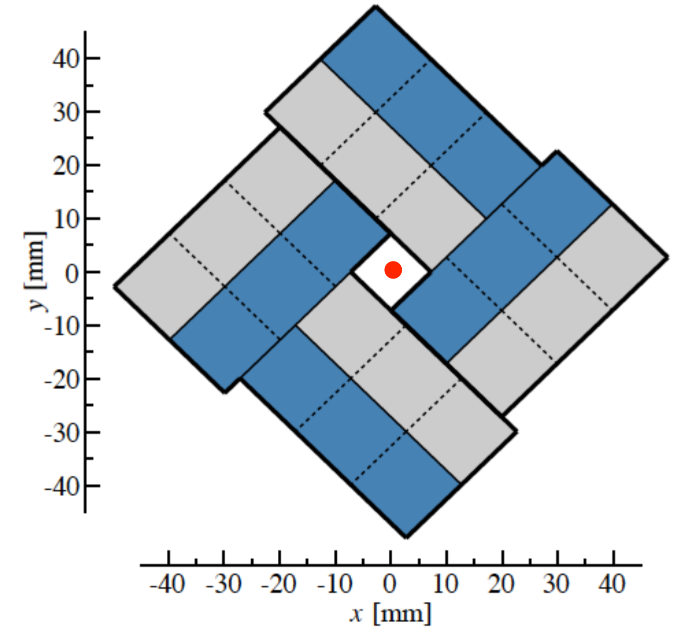
Short introduction to LHCb VELO upgrade

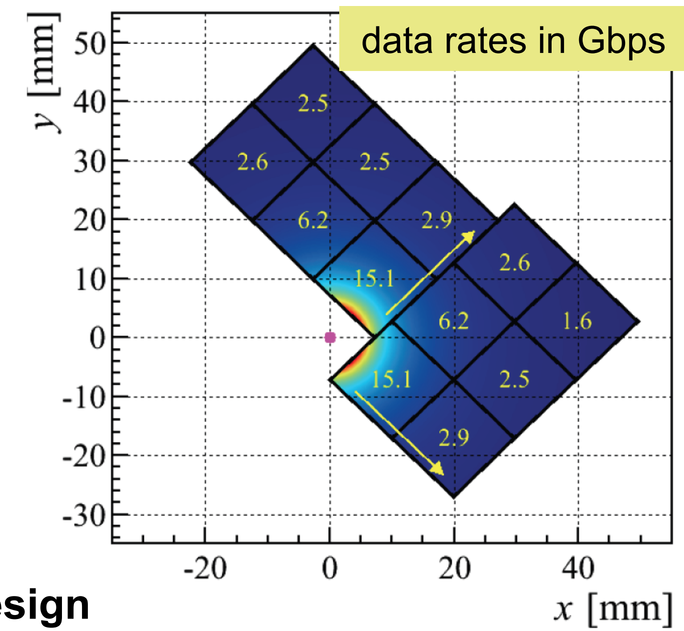
- LHCb will upgrade its vertex detector (VELO) in 2018/2019
- From silicon strips to silicon hybrid pixels
- Experiment is (HW) trigger-less -> all data to CPU farm
  - for the Vertex detector alone this means 2.7 Tbits/s
- Develop VeloPix ASIC that can cope with high rates (and radiation)
- Collaboration with Medipix group on chip design
- VeloPix derived from Timepix3



Timepix3 -> VeloPix



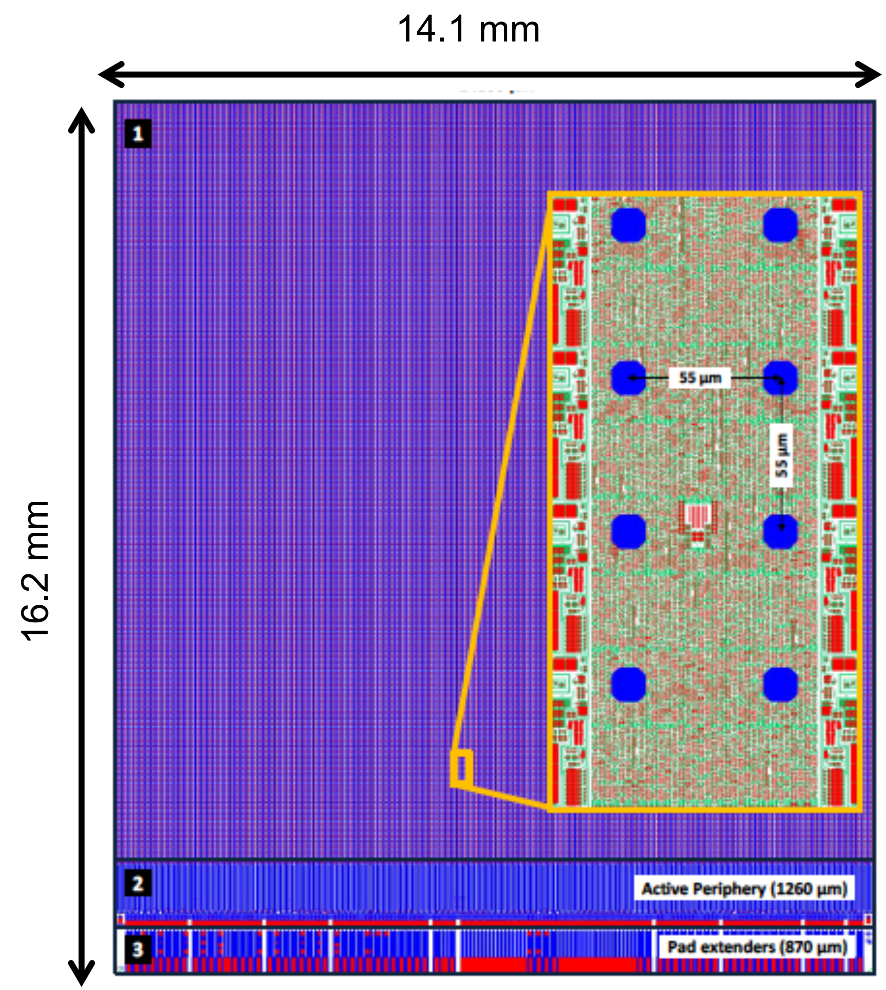




- VeloPix has to handle ~10x more hits than TPX3
- -> increase output bandwidth from 5 -> 20 Gbit/s
- -> group information in 2x4 superpixels
- -> remove fast timing, and ToT information
  - ToT is measured, but not sent off chip
- Total dose at tip of sensor ~ 400 Mrad
  - highly non uniform irradiation -> complicates sensor design

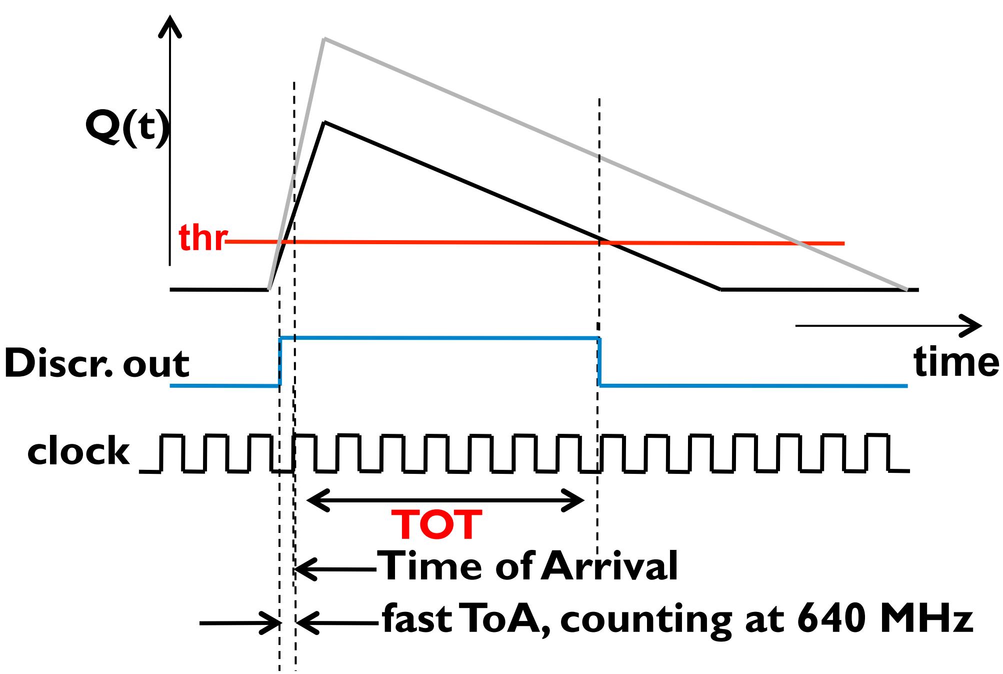
Timepix3

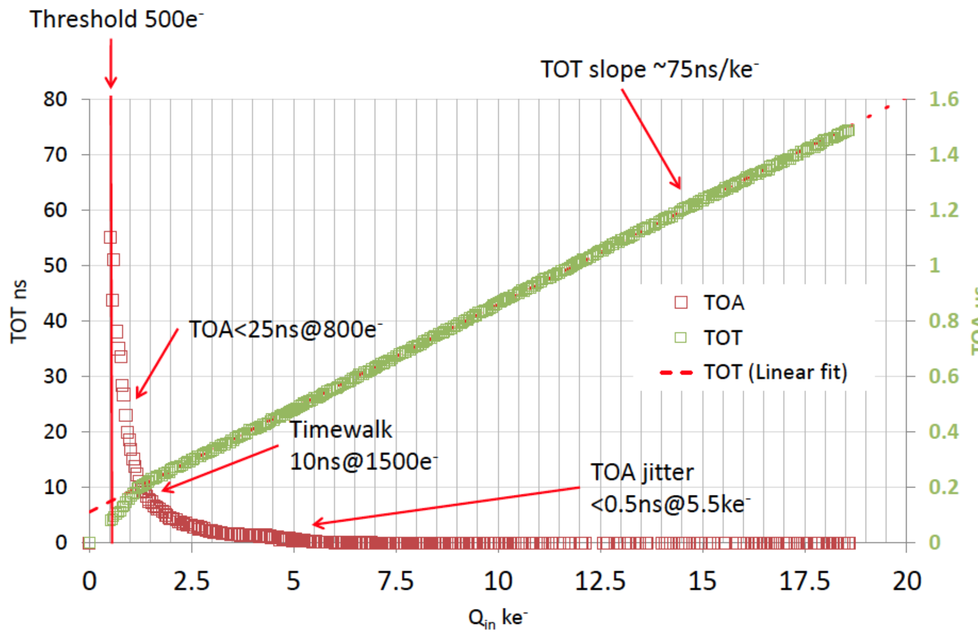
- **Developed by medipix3 collaboration**
  - designed by CERN, with contributions from Nikhef and University of Bonn
- **Key features:**
  - 55 μm pixel pitch
  - matrix of 256 x 256 pixels
  - simultaneous time-of-arrival (ToA) and time-over threshold (ToT)
  - 1.56 ns time resolution
  - hit rate of 40 $Mhits/cm^2$
  - data driven readout
  -
- **First chips in Q4 2013**



ToA and ToT

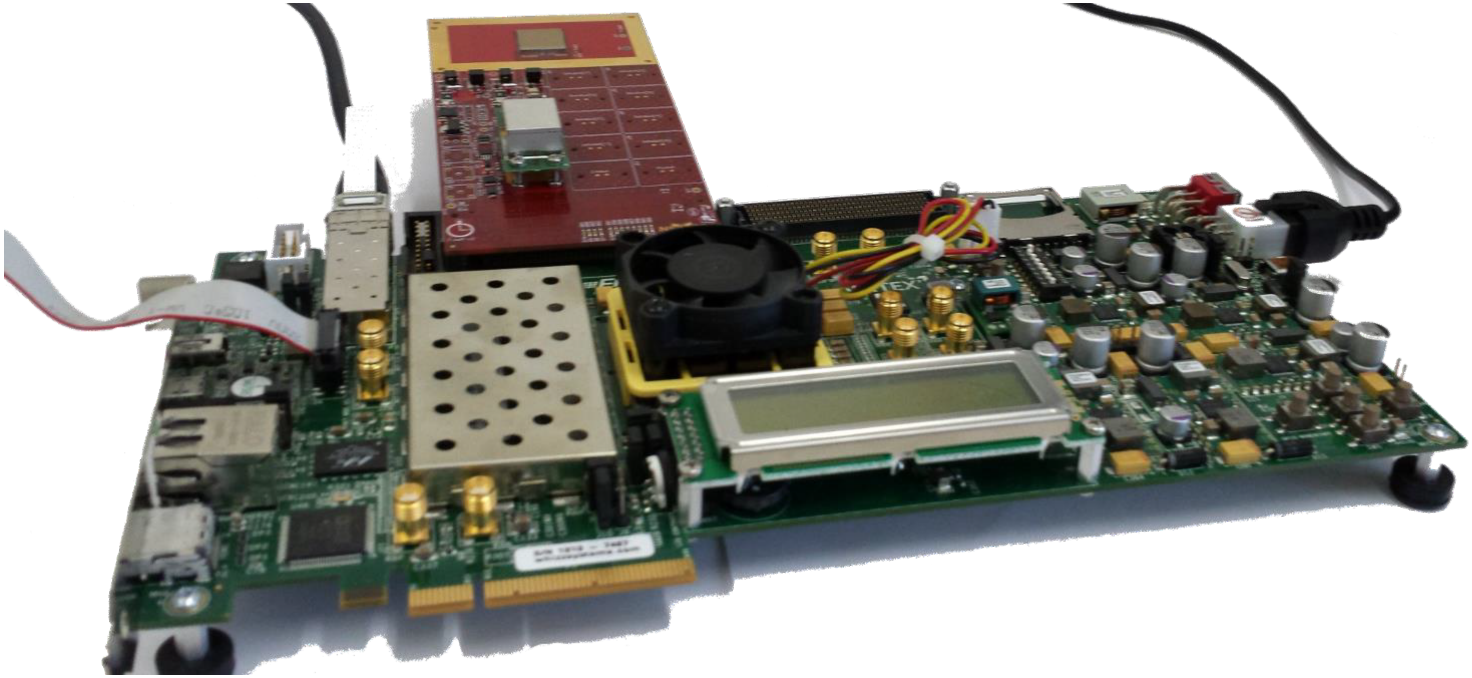
- **Front-end rise time < 25 ns**
  - **relatively low time walk**
- **Configurable discharge current for ToT measurement**
  - **trade charge off resolution versus dead time**
- **Pixel dead time depends on charge**
- **The moment of transmission of the packet is (somewhat) random**





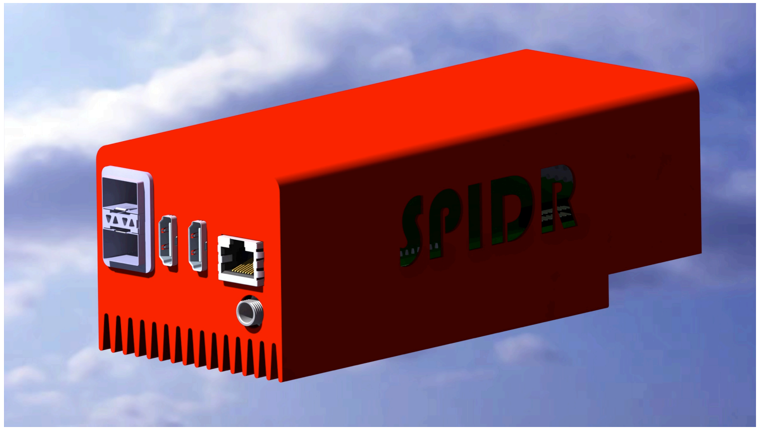
Readout

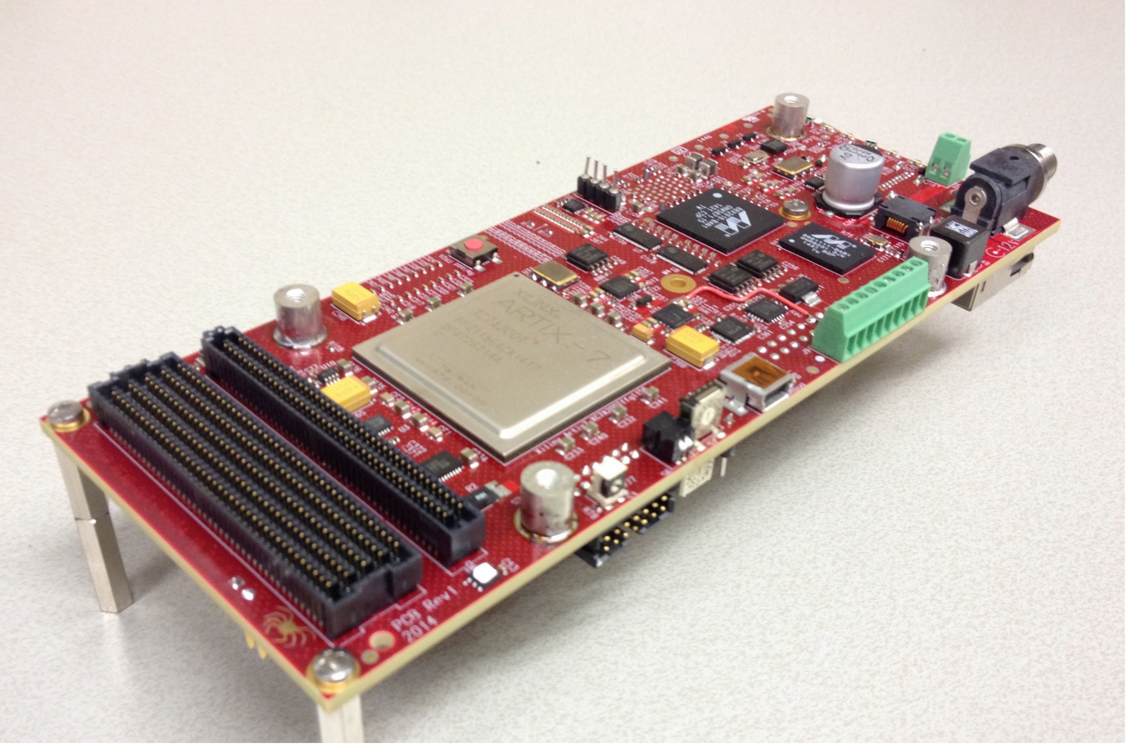
- SPIDR (Speedy PIxel Detector Readout) for TPX3 and MPX3
  - developed at Nikhef with contributions from CERN/CLIC
  - prototype using Xilinx VC707 evaluation board
- 1 and 10 Gbit ethernet
- 2 FMC ports, up to 8 TPX3 per FMC
  - for max speed, only 1 TPX3 per SPIDR (6 Gbps)
- TDC input with ~300 ps resolution
- C++ API

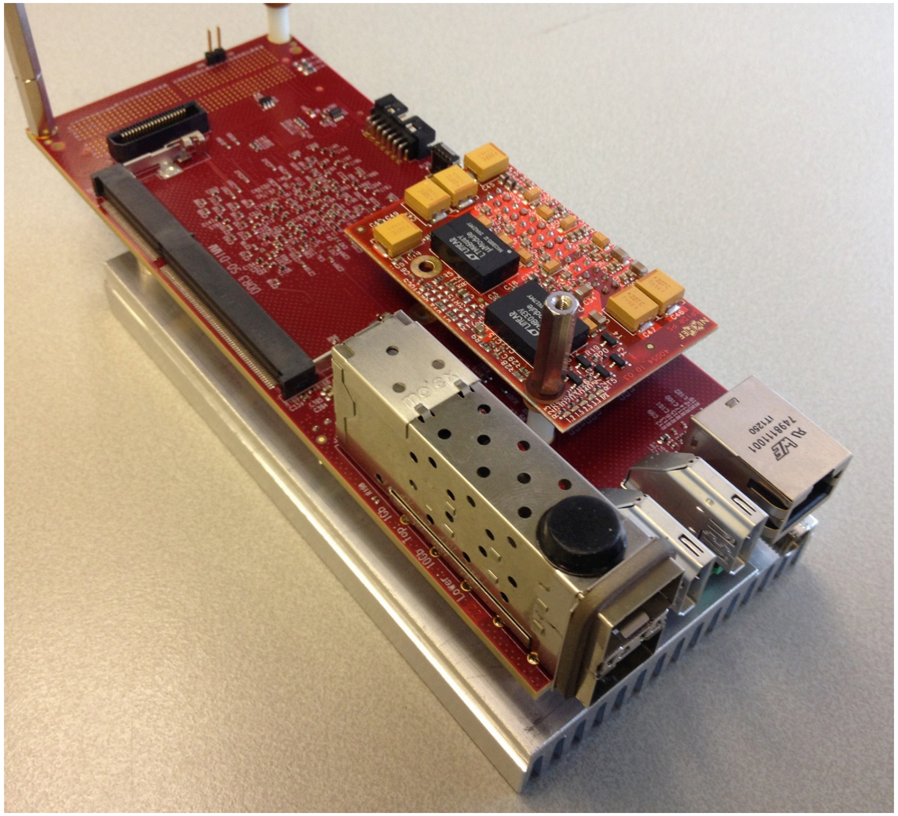


compact SPIDR

- Smaller form factor
- 22 layer board
- All cable connections on one side
- First boards being tested/debugged

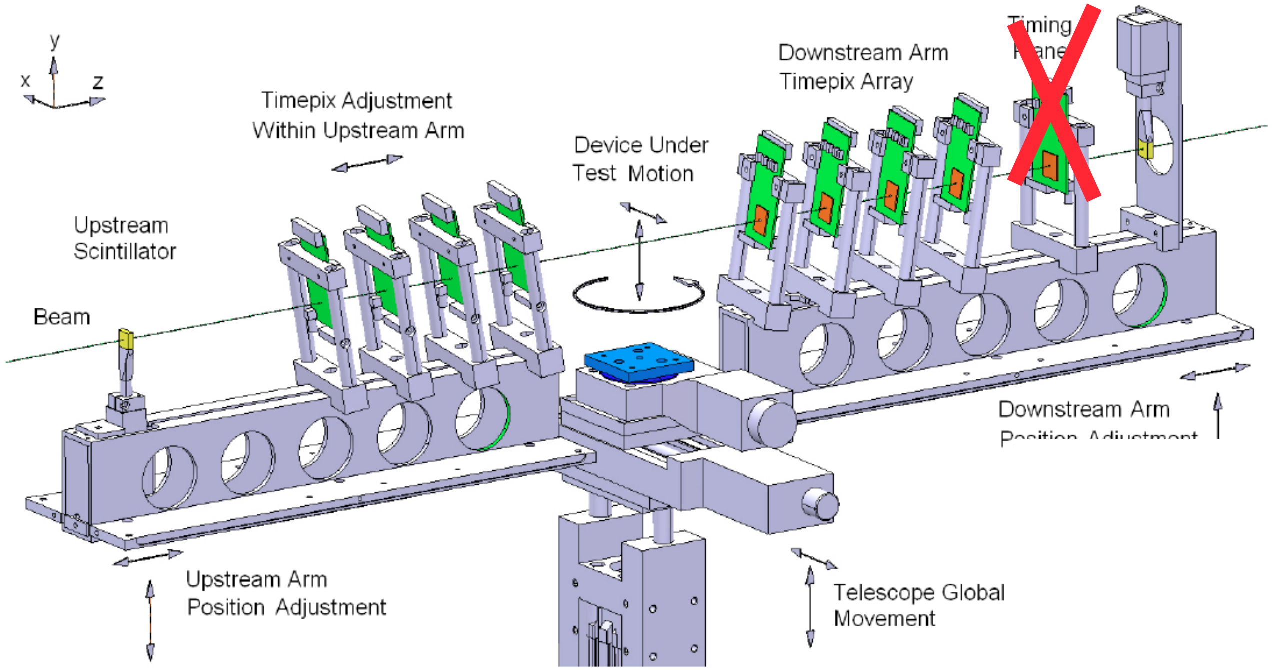






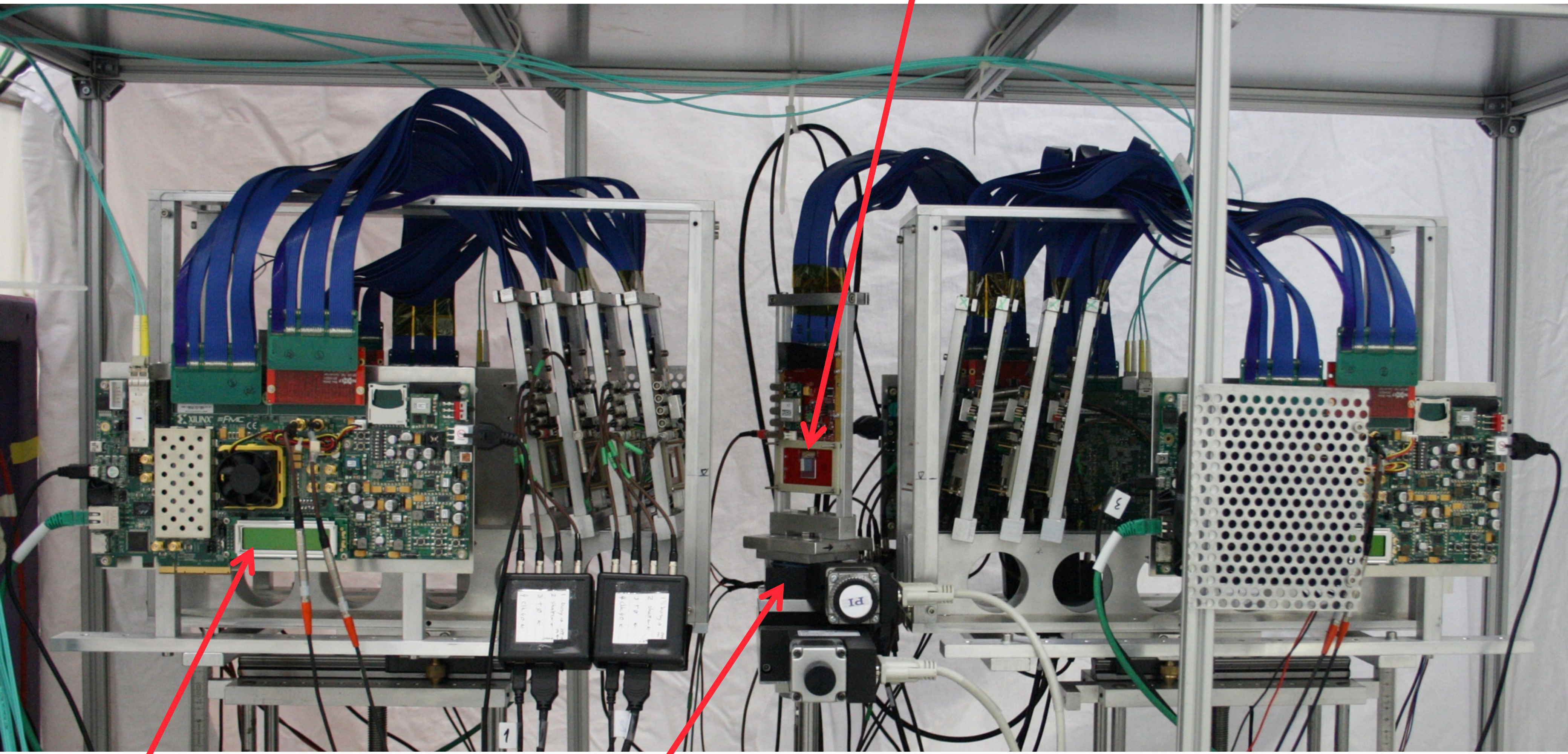
Goals of the Timepix3 telescope

- Build a high speed telescope for VELO upgrade sensor studies
- at the same time thoroughly test the Timpix3 ASIC
  - Timewalk, noise, gain, cross talk, high-rate behavior, data processing features.
- Have built a telescope with 8 planes of Timepix3, active area of 2 cm^2
- > 10 Mtracks/s, data driven readout
- Telescope doesn't need a trigger, but scintillators triggers are provided for "external" users



Complete telescope, July 2014 at PS

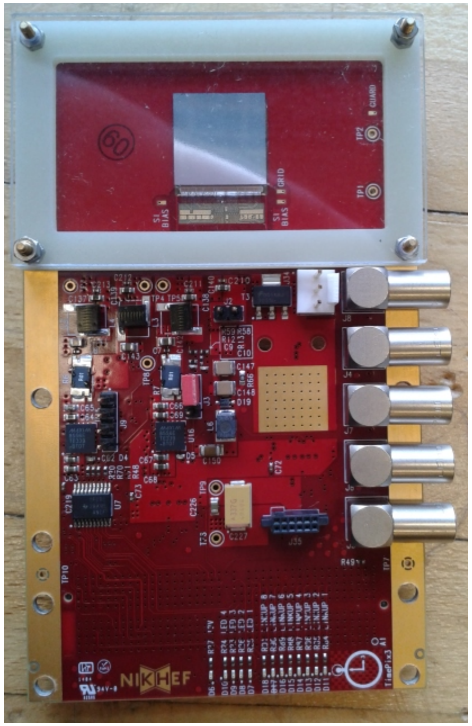
Device under Test (DuT)



SPIDR

motion stages

Sensor planes



- Currently 300 μm p-on-n Advacam sensors on 700 μm ASIC
  - will be replaced by 200 μm sensor on thinned 200 μm ASIC
- Mounted on chipboard, PCB cut away behind sensor
- Sensors rotated & tilted by 9 degrees to optimise resolution
- Threshold @ 1000 electrons

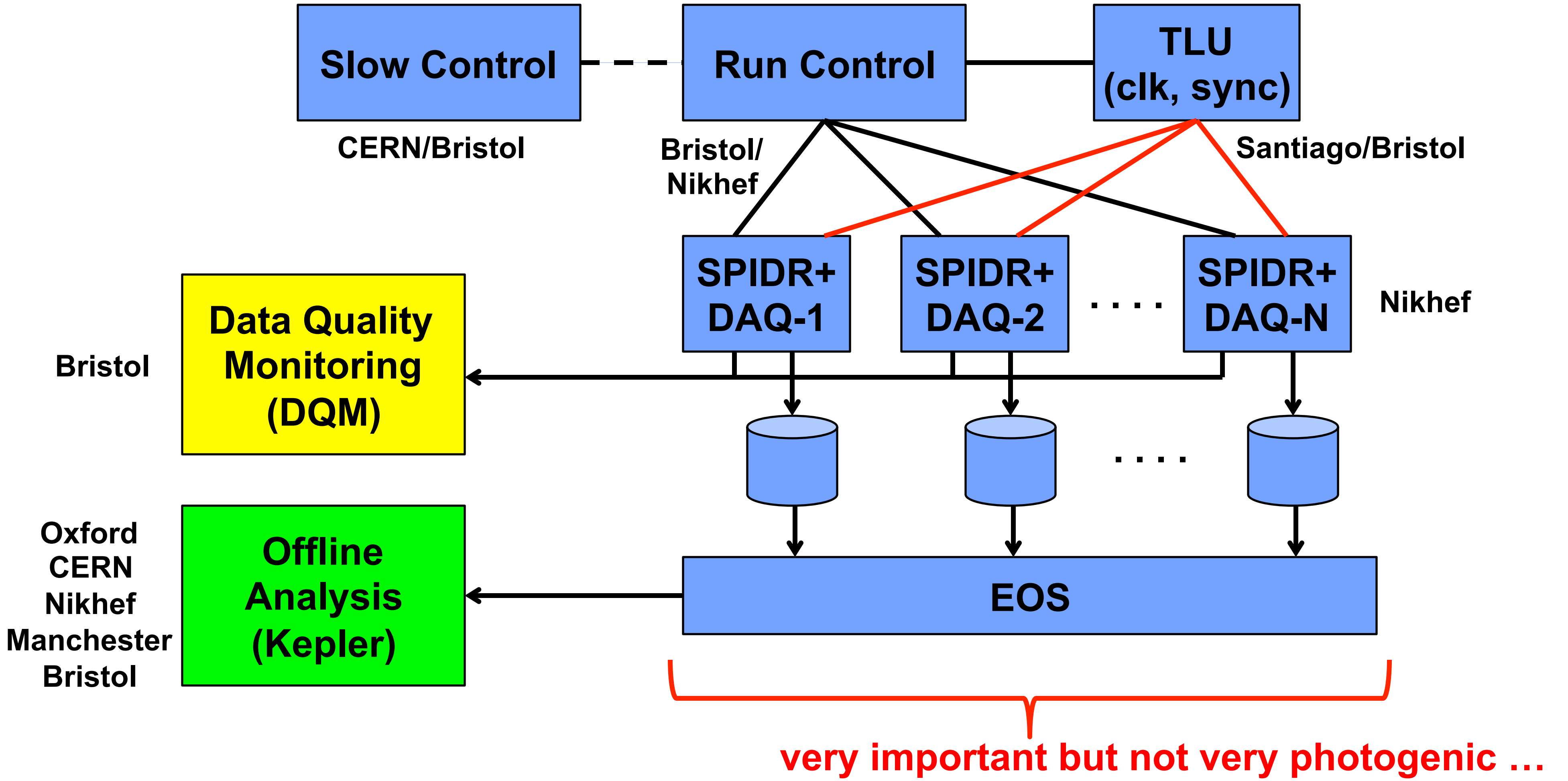
Readout philosophy

- The telescope is (in principle) trigger-less
- When a pixel is hit, it will send out a data-packet with address, time and charge information
- The DAQ PCs continuously record this stream of pixel packets

- The reconstruction SW relies on timestamps

- The offline software will merge the files, sort/filter/collect hits, and reconstruct tracks
- The online monitoring SW does something similar, but simpler. It will get a private sample of the data directly from the SPIDR boards

telescope DAQ / software overview



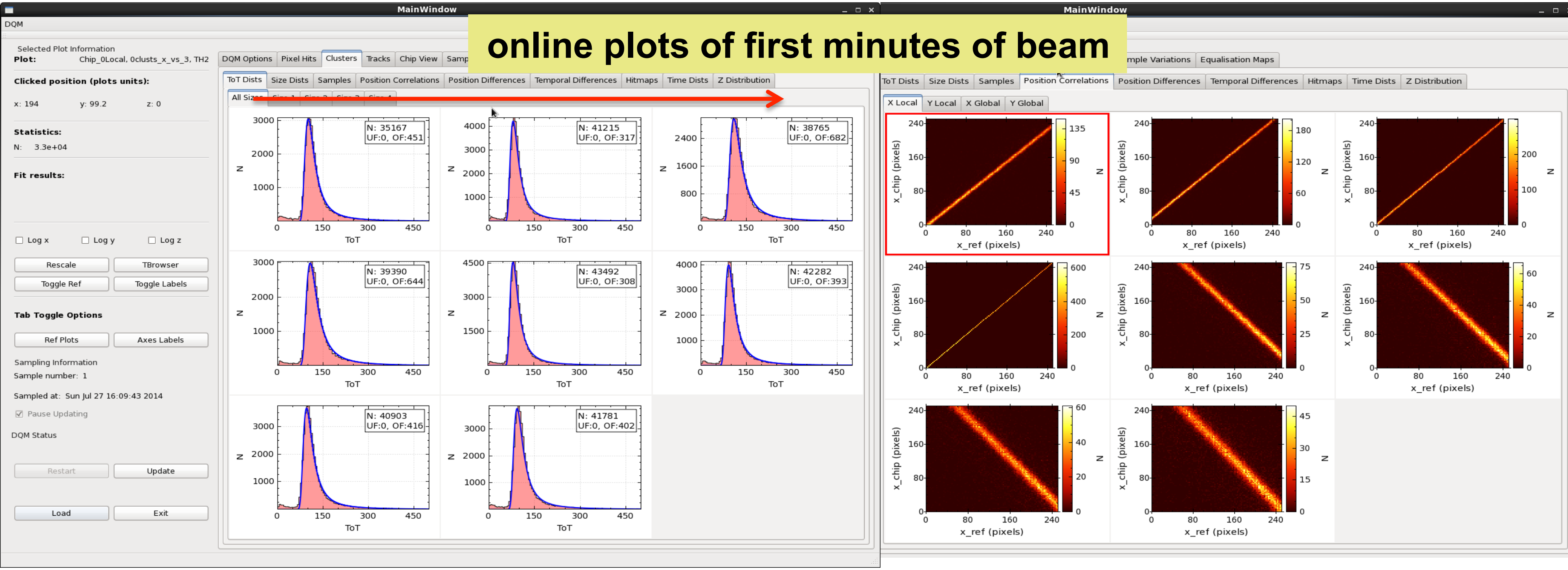
Data driven, no trigger, just like the LHCb upgrade


Data Quality Monitoring
Slow control
Run Control + DAQ

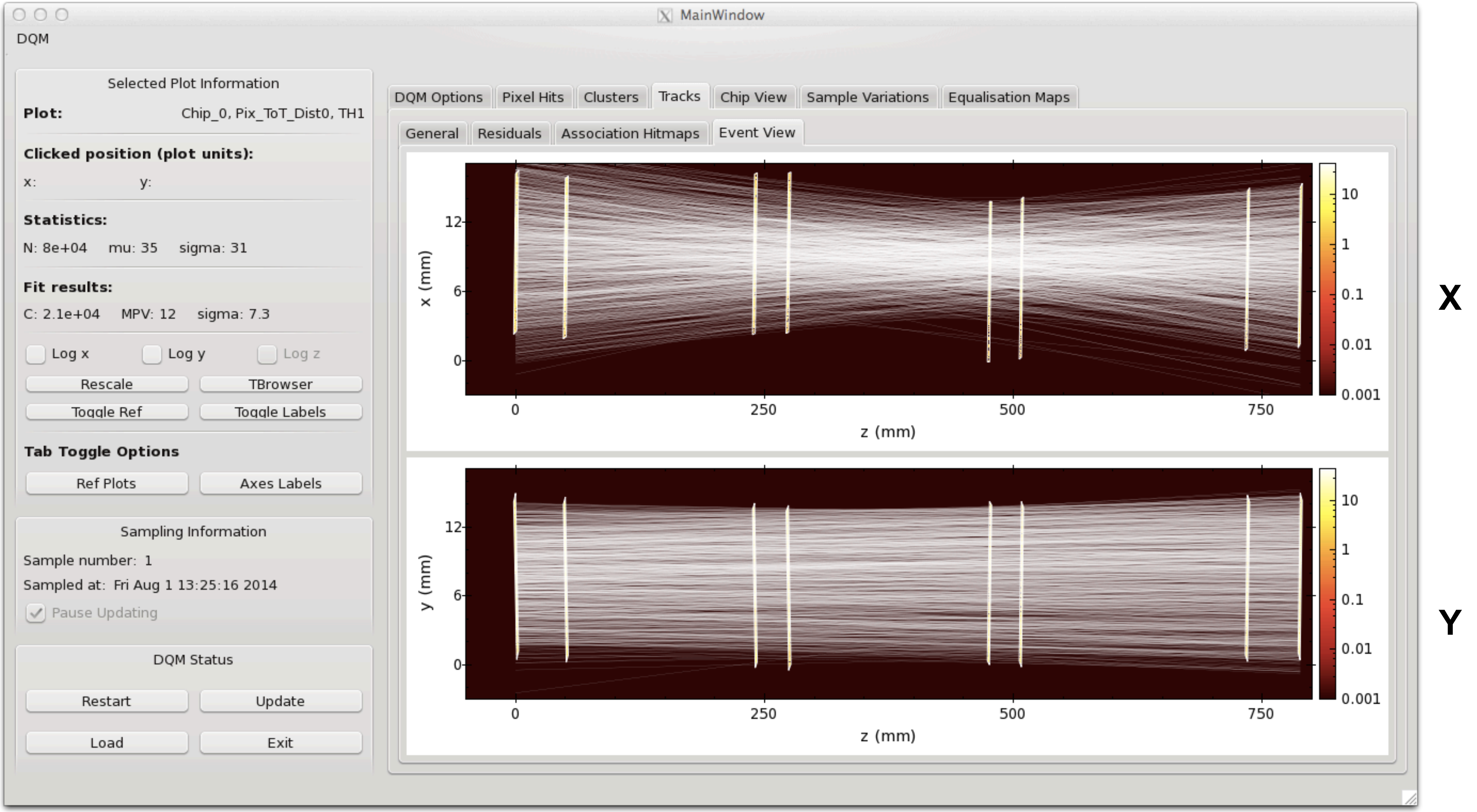
Data Quality Monitoring

- Online check of data quality on sample of data
- Stand-alone C++ package using Qt and ROOT libraries
- "Basic" plots of hitmaps, correlations, Landaus
- But also tracks (once aligned)
- All available from day 1 !!

online plots of first minutes of beam



First tracks in online display next day after first alignment



Offline software

Kepler

- Offline software package to analyze the testbeam data
- Based on LHCb Gaudi framework
- Distinguish between events (e.g hit, cluster) and tools (e.g. fit)
- Time-stamped tracks can be provided for “external” users

Software chain:

1. time ordering of data
2. clustering using time and spatial information
3. track finding / pattern recognition
4. track fitting, least squares or Kalman filter

Alignment

- Align on residuals
- Track based global alignment (Millipede)
- Simple recipe for users, takes O(few minutes) for complete alignment

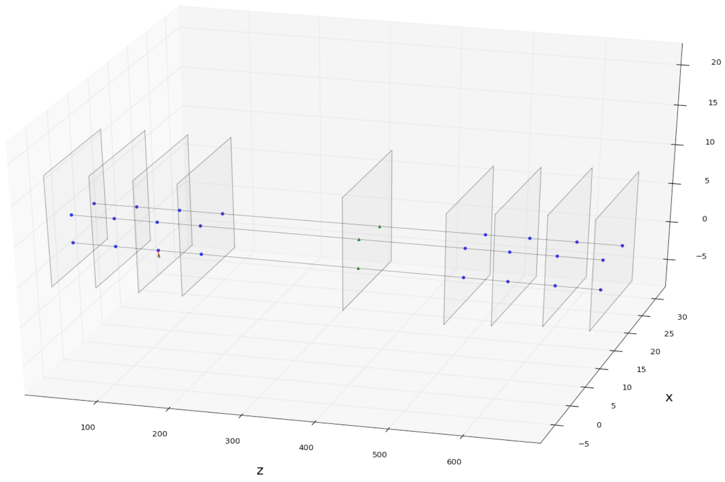
First performance plots

PRELIMINARY

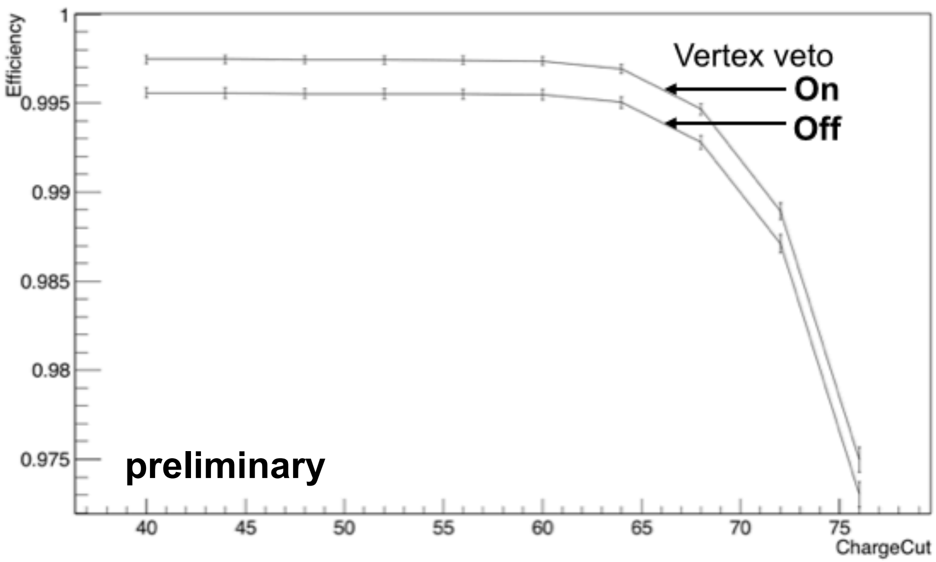
- Typical running conditions 1E6 tracks / spill (SPS)
  - also runs taken with 2.5E7 tracks /spill, DAQ ran fine
  - online plots look OK, detailed analysis required to spot drop in efficiency
- 1000 electron threshold
- telescope bias voltage at 100 or 150 Volts
- number of masked pixels 30 – 50 per plane

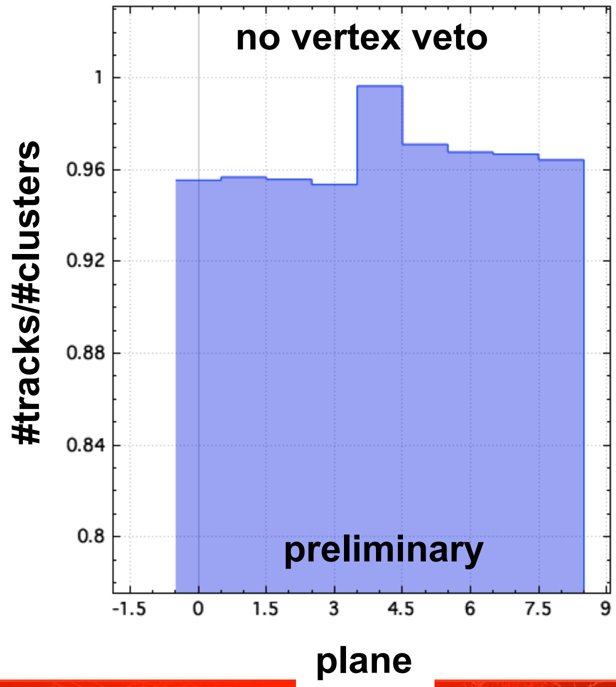
Efficiencies

- Work in progress!
- Cluster finding efficiency close to 100%
- "track reconstruction efficiency" > 95%
  - Require a cluster in each plane cluster
  - FOM: track/cluster ratio
- Rest is mainly partial tracks, secondaries etc.

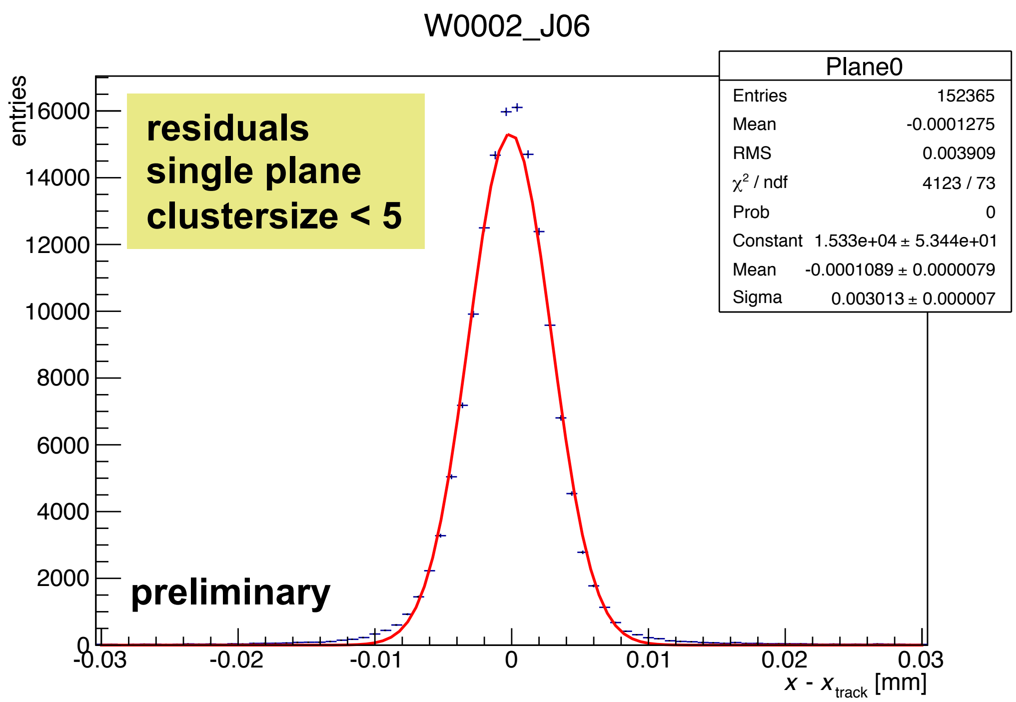


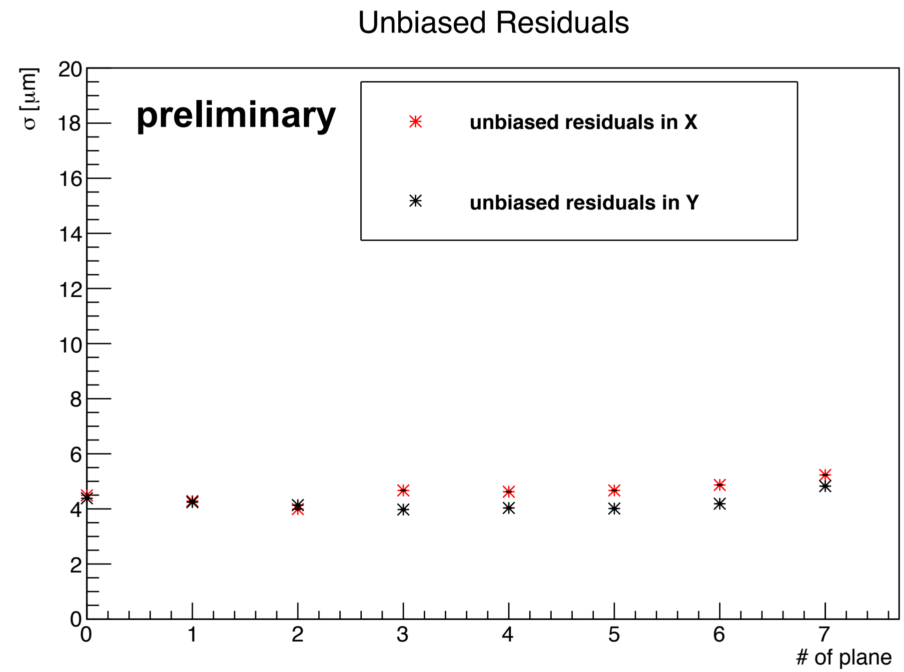
hit finding efficiency





Resolution

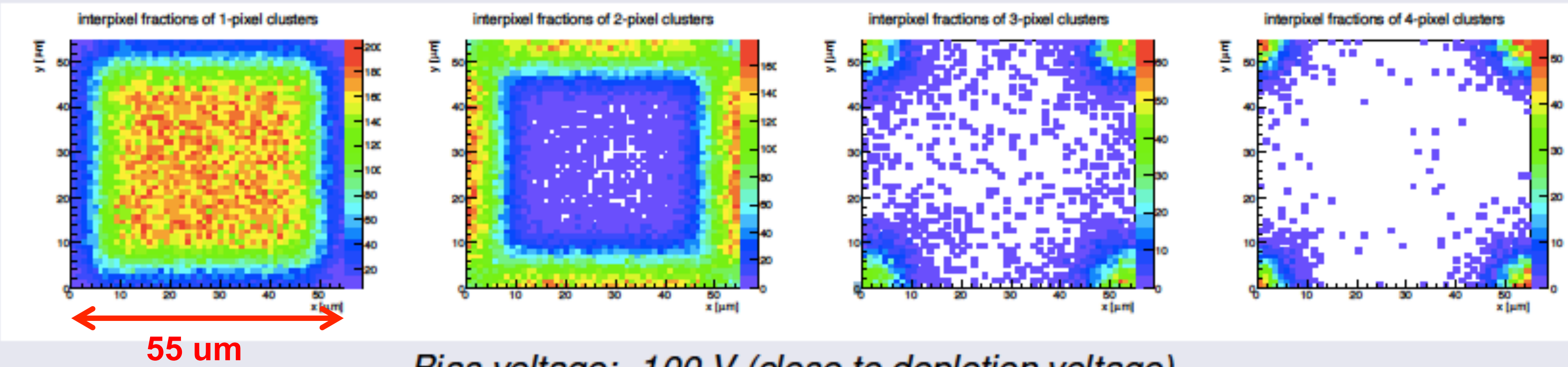




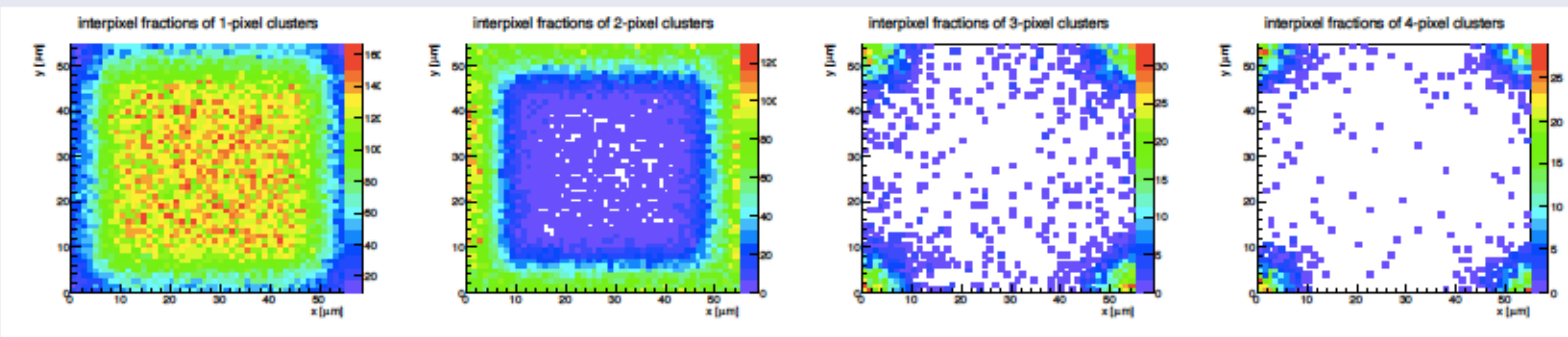
- **180 GeV beam**
- **Single plane residuals 4 – 5 μm**
  - **no charge calibration, eta-function yet implemented**
- **hence telescope pointing resolution close to 2 μm**

Interpixel fractions

- Interpixel fractions of 1,2,3 and 4 pixel clusters (sensor perpendicular to the beam)



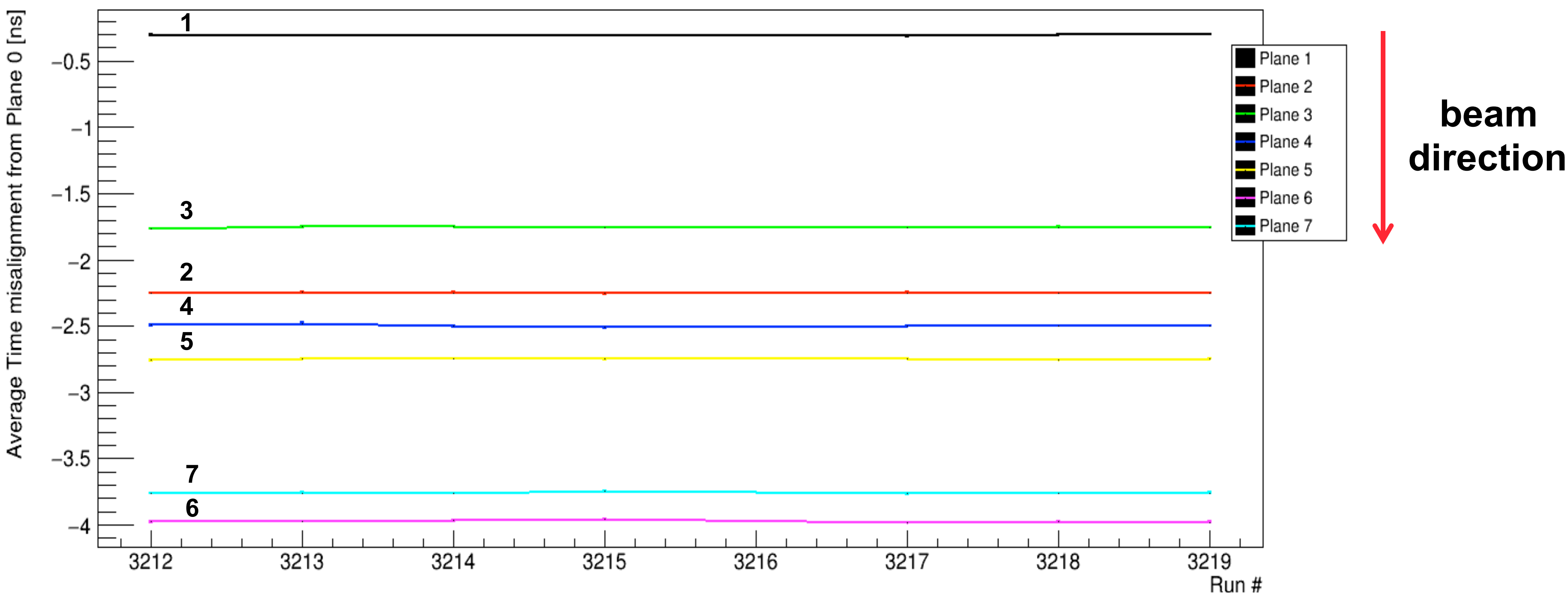
Bias voltage: -100 V (close to depletion voltage)



Bias voltage: -500 V (over depleted)

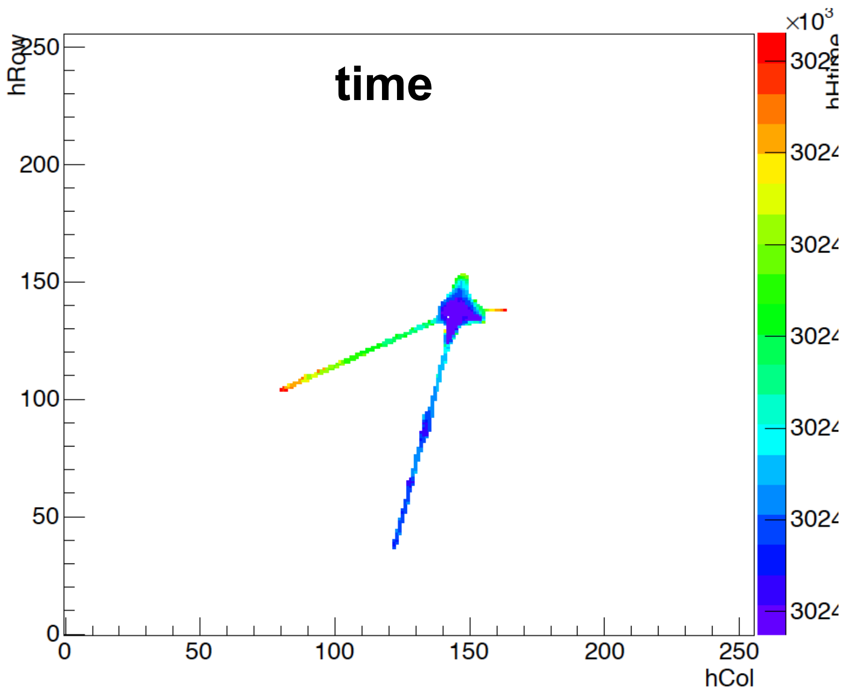
Timing of sensor planes

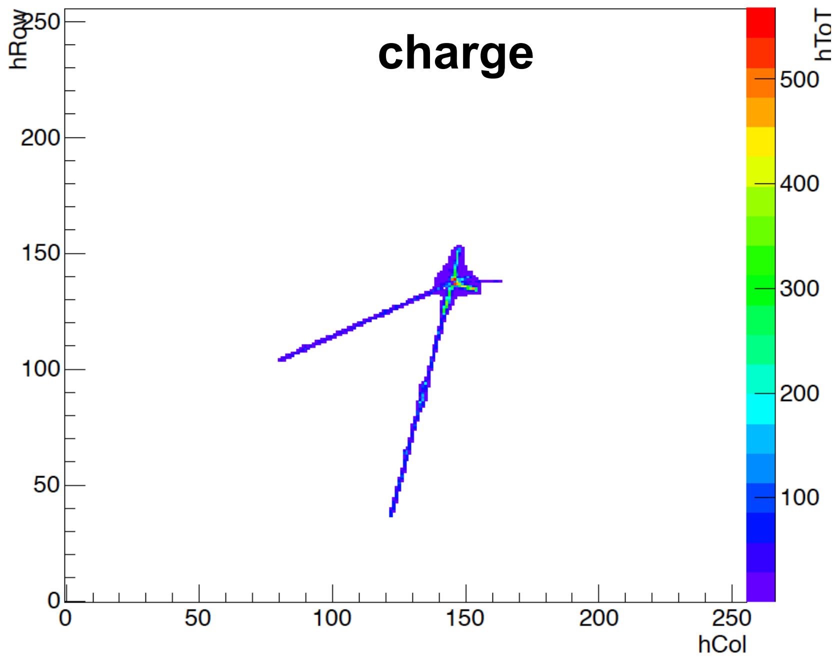
- Average time offset w.r.t. plane-0
  - earliest hit in the cluster
- Stable timing from run to run
- Looks even like time of flight



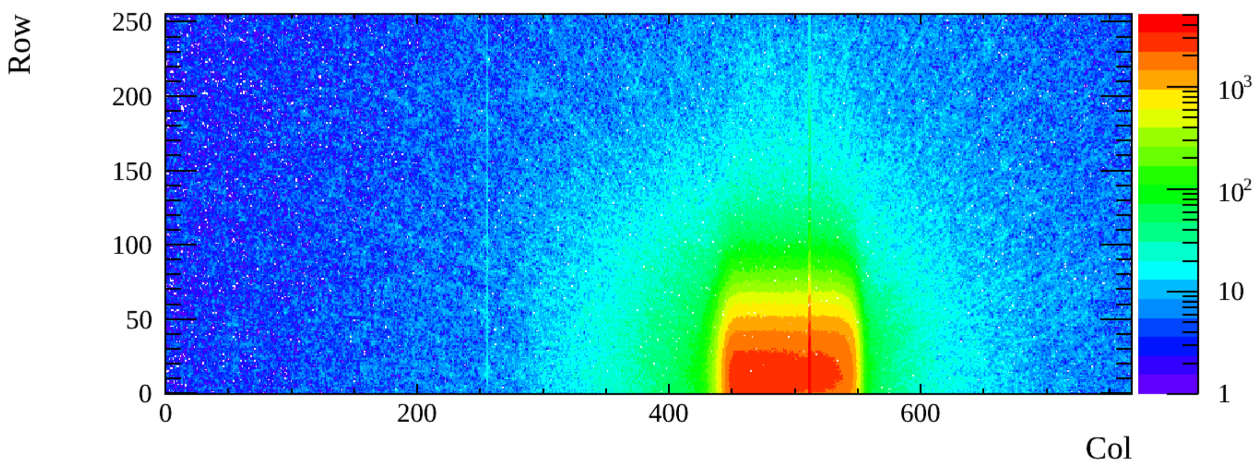
Nuclear interactions in the telescope

- **Simultaneous time and charge readout**
- **Nuclear interactions typically unwanted, but**
- **Provide a wealth of information to debug the system**



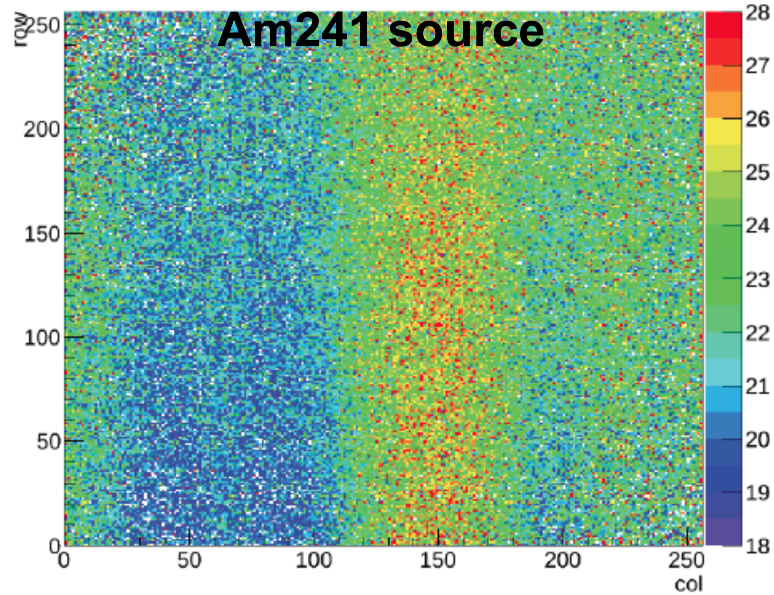


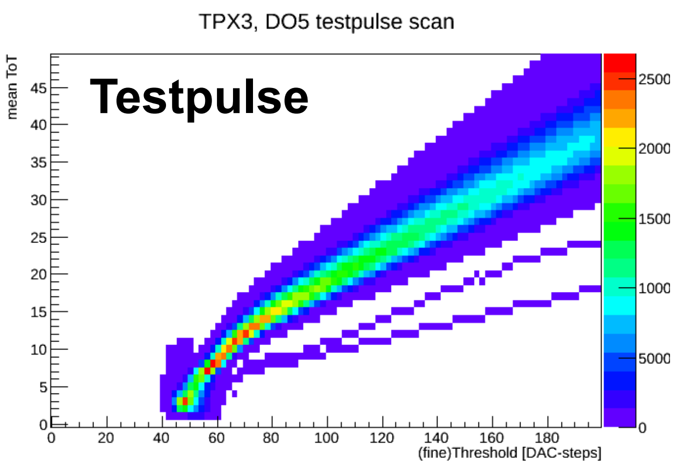
Some more results

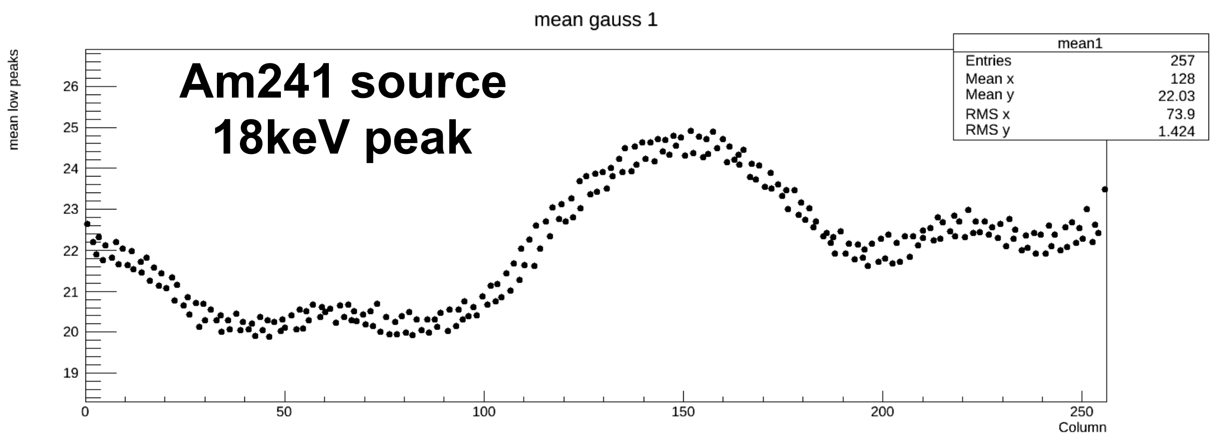


Gain calibration

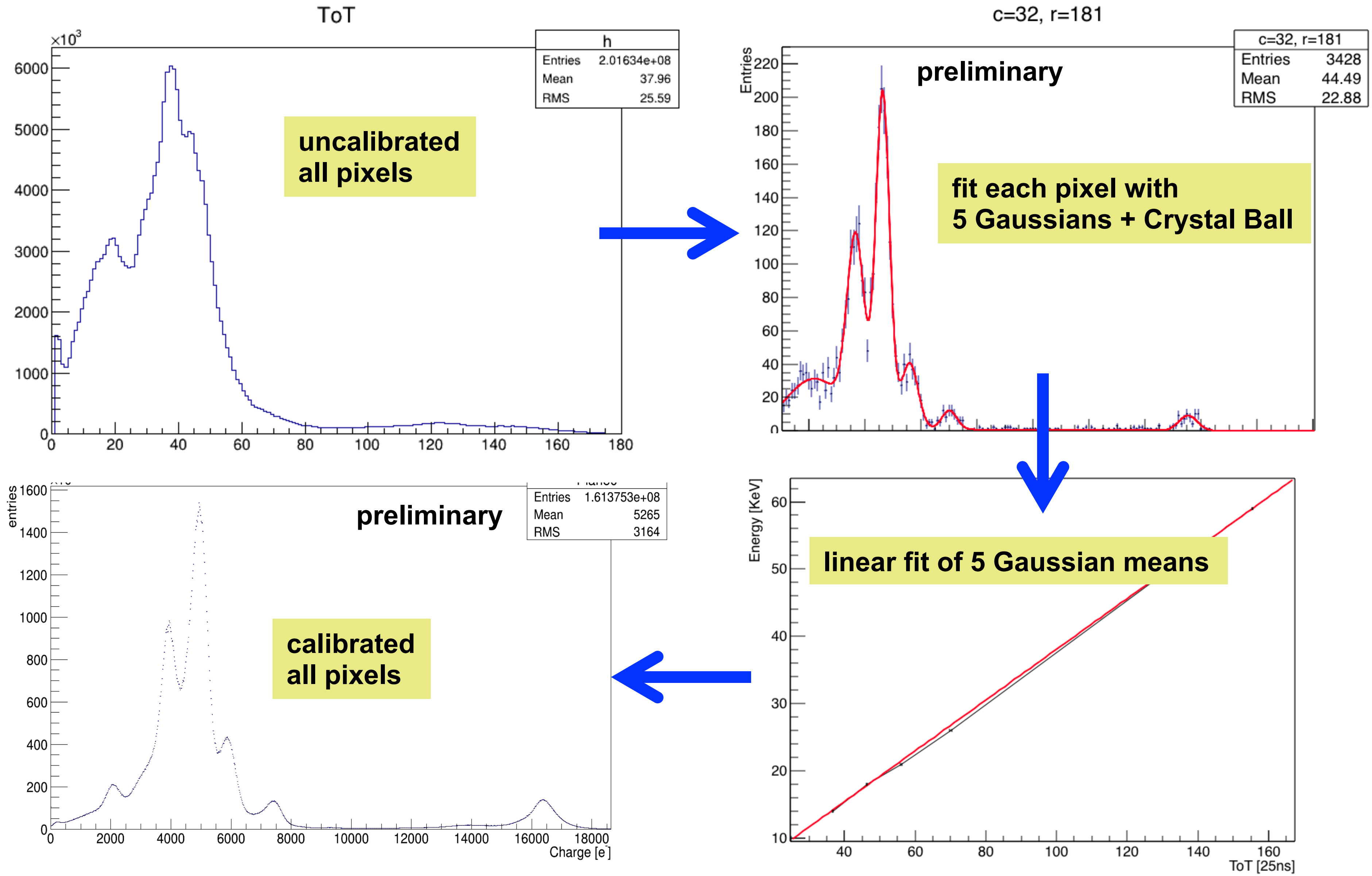
- Gain varies from pixel to pixel
  - Strong variation over columns
  - Due to chip layout, will be improved in next version
- and ToT not linear to charge, near threshold
- Can be calibrated with testpulse/source
- Verification of absolute calibration at synchrotron







Calibration using ^{241}Am



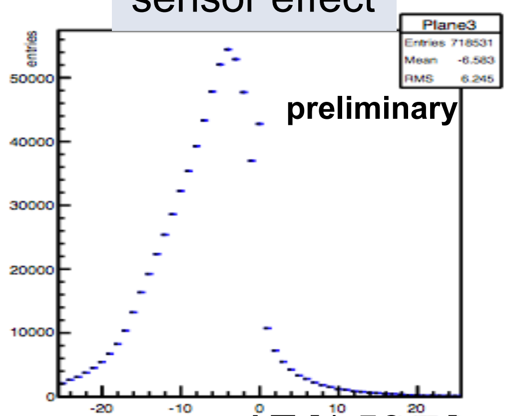
Rio Group

Time of arrival

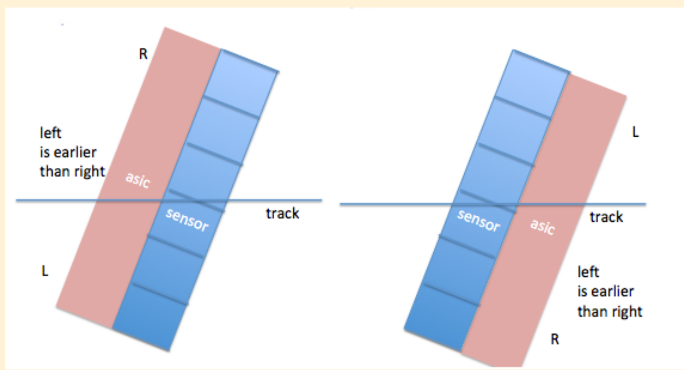
- **For LHCb VELO the hit arrival time is very important**
  - **assign hits to the correct (25 ns) bunch crossing**
- **Time of arrival depends on**
  - **drift time of charge in sensor**
  - **timewalk, small signals cross threshold later**
- **The TPX3 with its high time resolution allows detailed studies**

time difference in two pixel cluster "right–left"

sensor effect

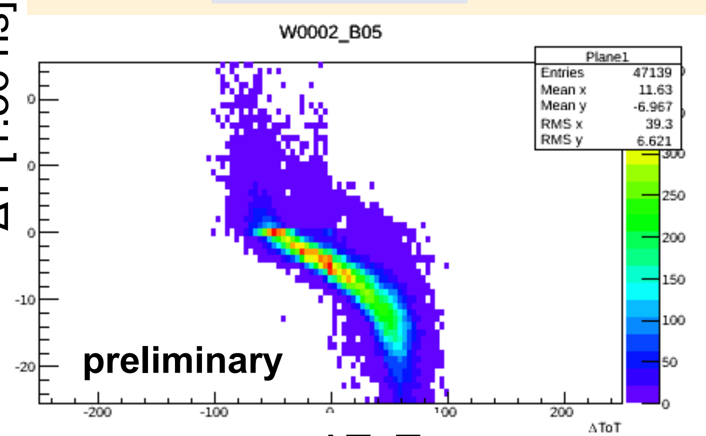


ΔT [1.56ns]



ASIC effect

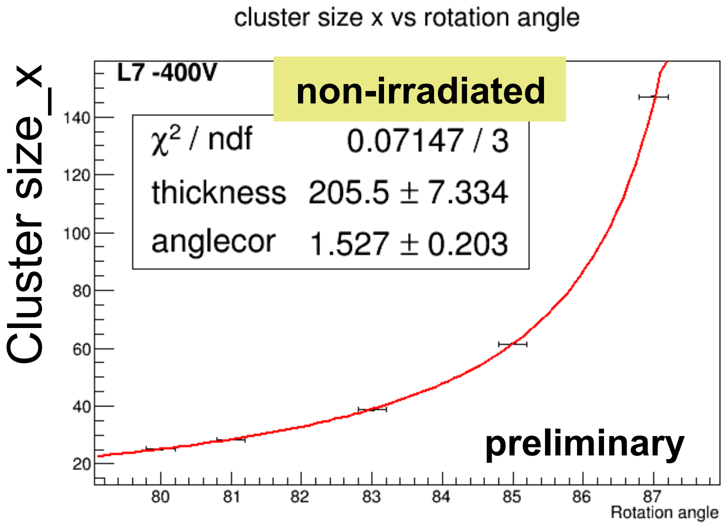
ΔT [1.56 ns]

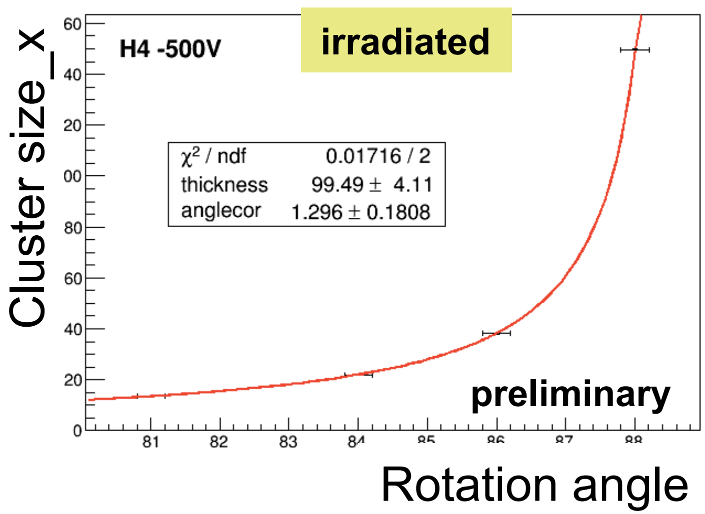


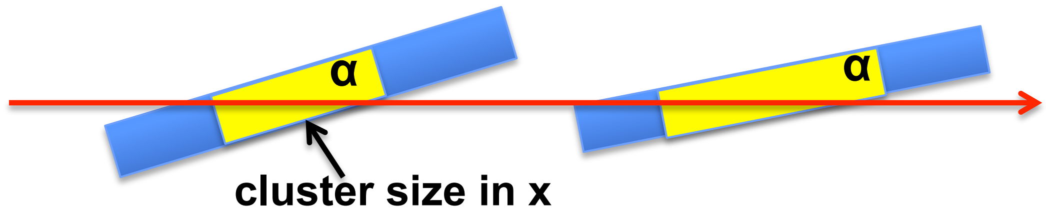
ΔToT

Sensor drift time in order of few ns. (more advanced studies ongoing)
Important feedback for the Velopix

grazing angle





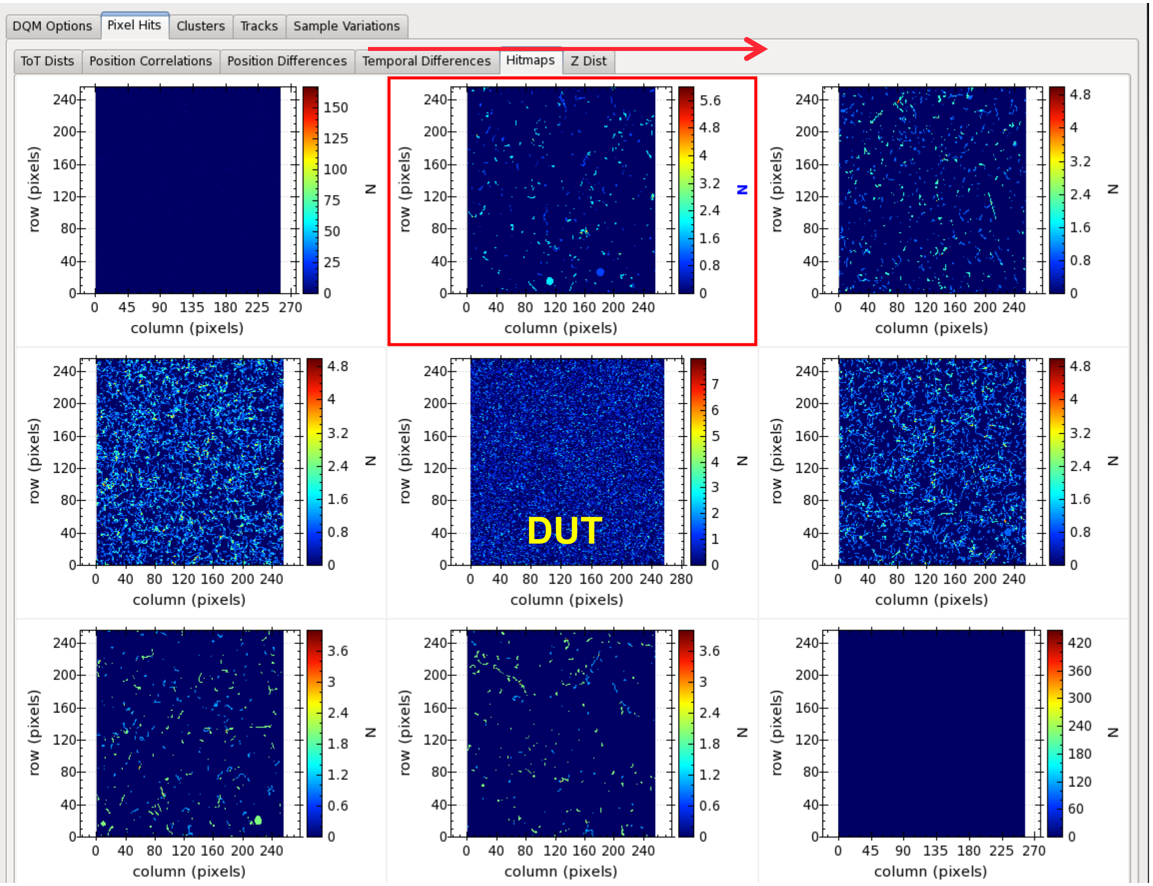


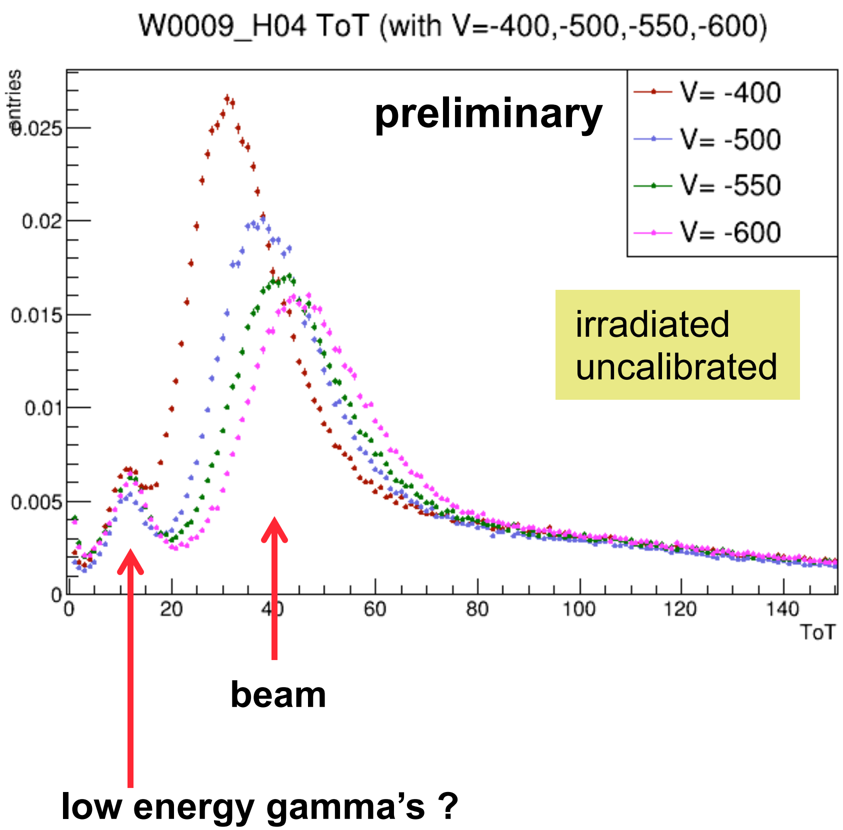
$$\tan(\alpha + \Delta\alpha) = \frac{\mathrm{clSize}_x * 55\mu m}{\mathrm{thickness}}$$

- **Grazing angle data powerful tool to understand sensor behavior.**
- **Confirmation that sensitive volume in HPK sensor is 200μm thick.**
- **Effective thickness decreases**
  - **for under-depleted sensor**
  - **irradiated sensor**

Dec. 2014: first irradiated sensor as DUT

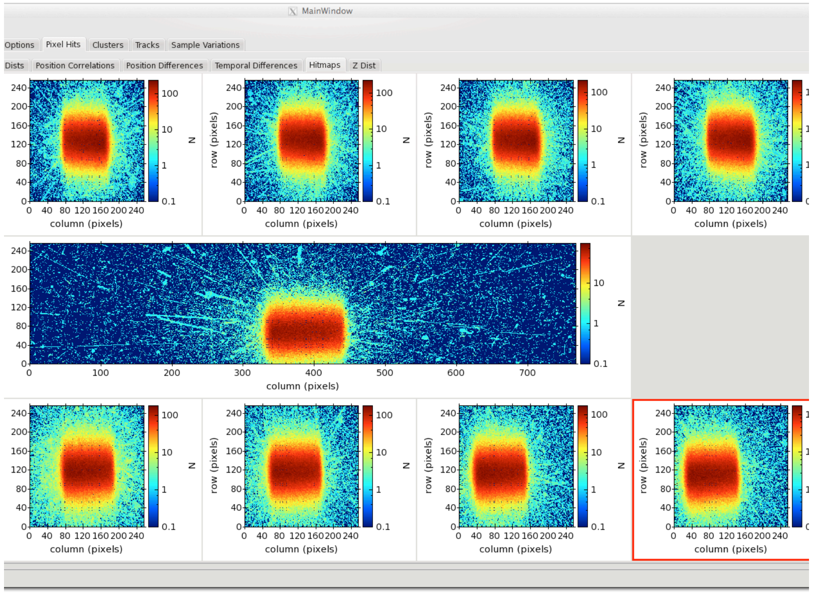
- 200 μm n-on-p
- Irradiation at JSI reactor to 4 x 10^{15} 1 MeV n_{eq}/cm^2
- no beam, hits in sensor surrounding DUT
- background from radioactive DUT





Conclusions & Outlook

- New Timepix3 telescope assembled in July 2014
- Excellent telescope performance
- Very good data sets, many billions of tracks on disk
- First results coming out, many more results still to come from 2014 data
- VELO test beam program continues in 2015.
  - Different sensor designs, (non-)uniform irradiated sensors, variation in fluences.



Many thanks to all people who contributed to chip design, mechanics, cooling, software, DQM, shifts, SPS/PS operation etc. etc.

BACK UP

HW interface to the telescope

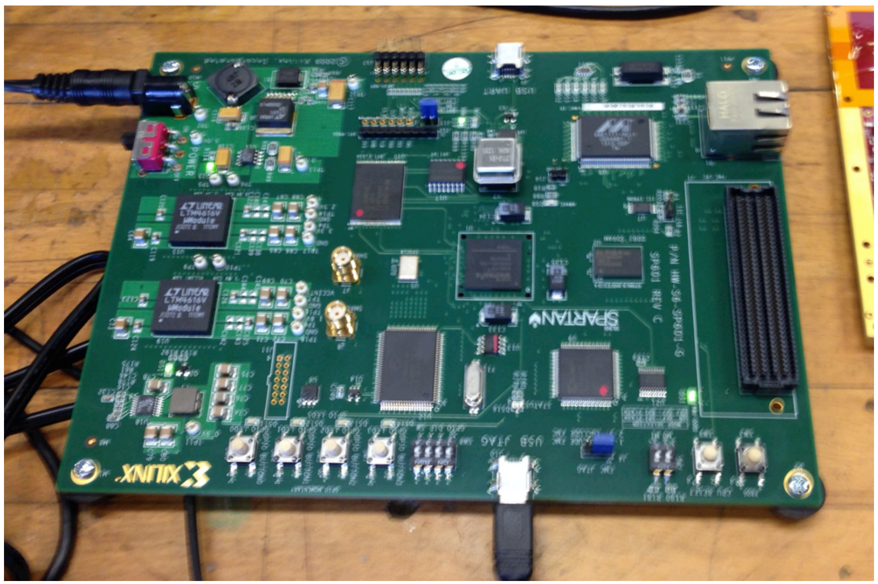
Telescope central logic unit "TLU" provides 4 signals (LVDS level)

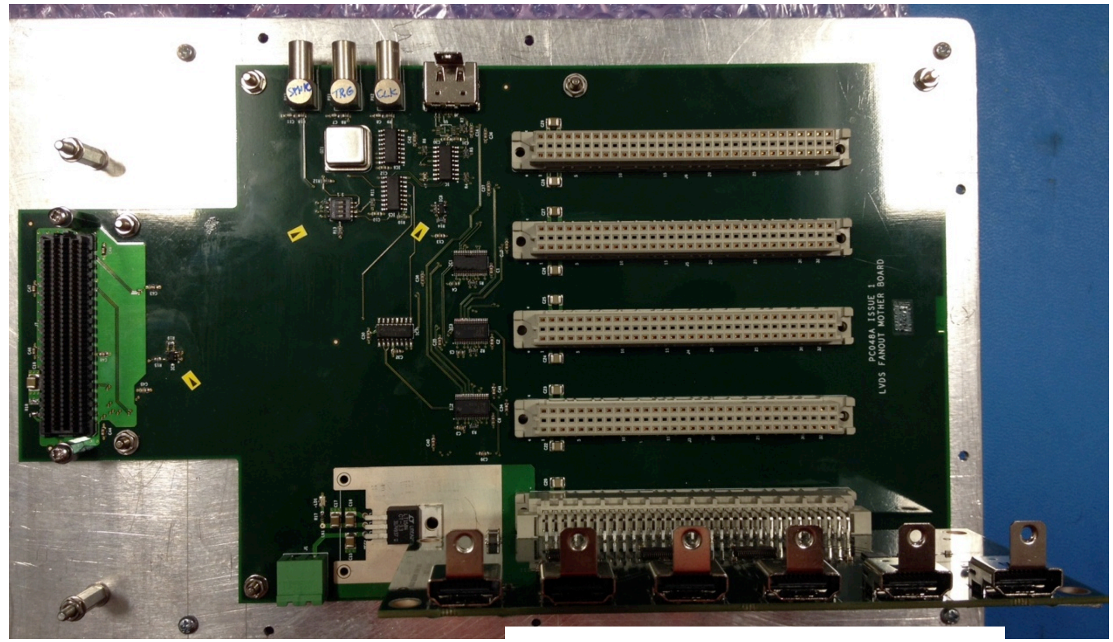
- 40 MHz system clock (output)
- T0-sync (output)
  - Resets all time counters in SPIDR and TPX3
- Shutter (output)
  - Synchronous start / stop signal
- Busy (input)
  - Couples to shutter signal
  - Not intended as trigger gate

- In addition there is a Trigger input on each of the SPIDR systems
  - timestamps rising (or falling) edge of signal
  - resolution ~ 300 ps

TLU

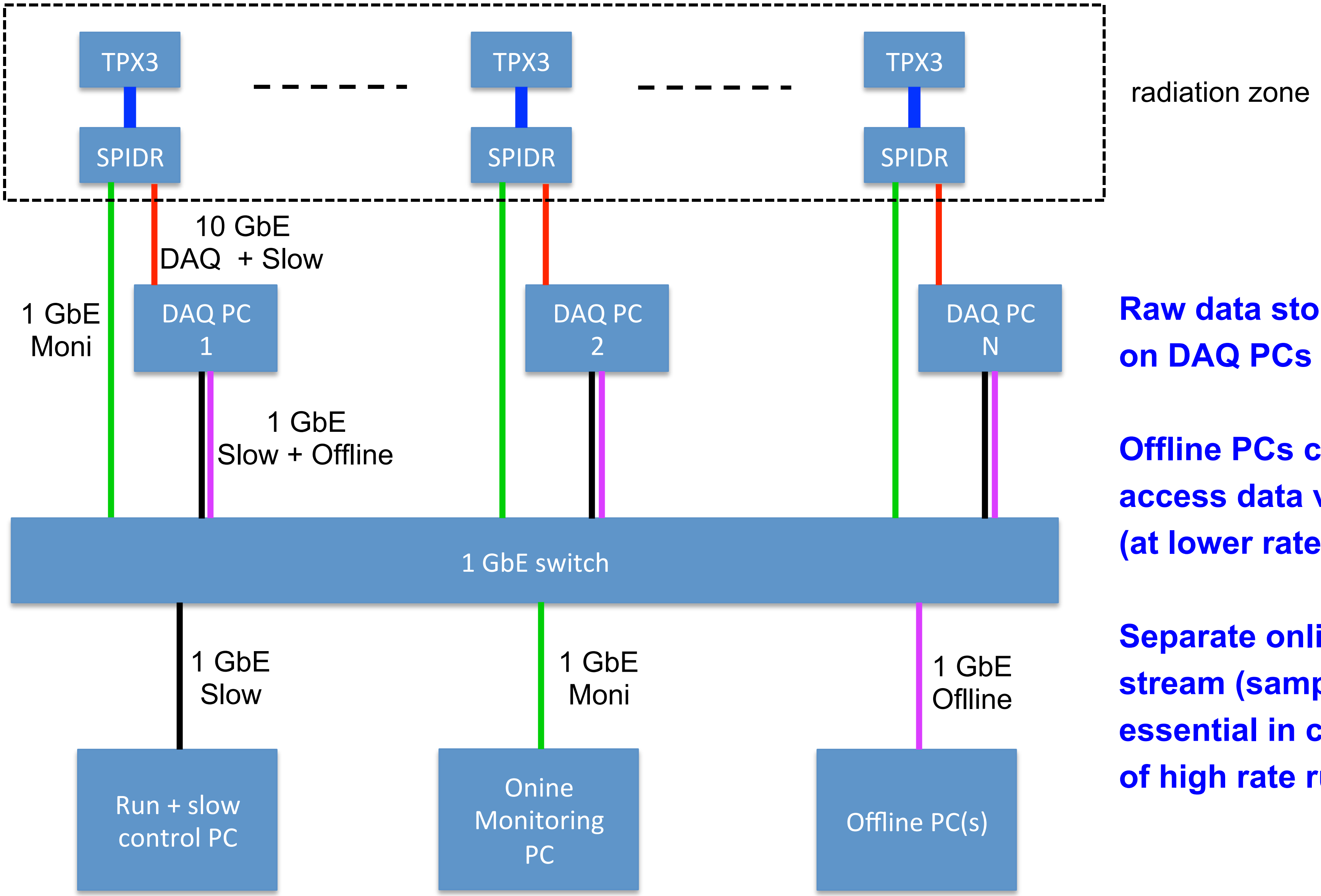
TLU = Telescope Logic Unit (since it does not provide triggers)
HW supplied by Bristol, firmware by Santiago





6 channel daughter board

Network / Data flow



Raw data stored locally on DAQ PCs

Offline PCs can access data via NFS mount (at lower rate)

Separate online monitoring stream (sample of data), essential in case of high rate running

Slow control

- Telescope equipped with 2 sets of motion stages for Device under Test
  - centre of telescope, ~2 um pointing for 180 GeV beam, but space constrained
  - behind the telescope, ~6 um resolution
- X/Y translation + rotation stage
- Labview controlled
- Temperature + humidity sensors
- Water + Peltier cooling system for DUT
  - few Watts cooling power at -30 degrees
- HV control

- Logging of all conditions

improvements

- true online monitoring
- thinner readout ASICs, and sensors
- documentation
- user friendliness
- considering to make a trigger in the FPGA