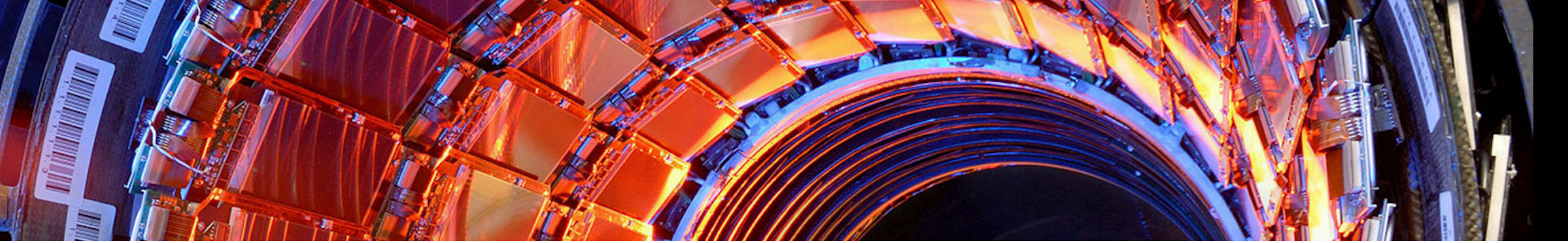


Younes Otarid

On behalf of the DESY CMS Phase 2 Tracker Team

Test-beam qualification of a Pixel-Strip module for the CMS Tracker Phase-2 Upgrade

BEAM TELESCOPES AND TEST BEAMS WORKSHOP
17.04.2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CMS

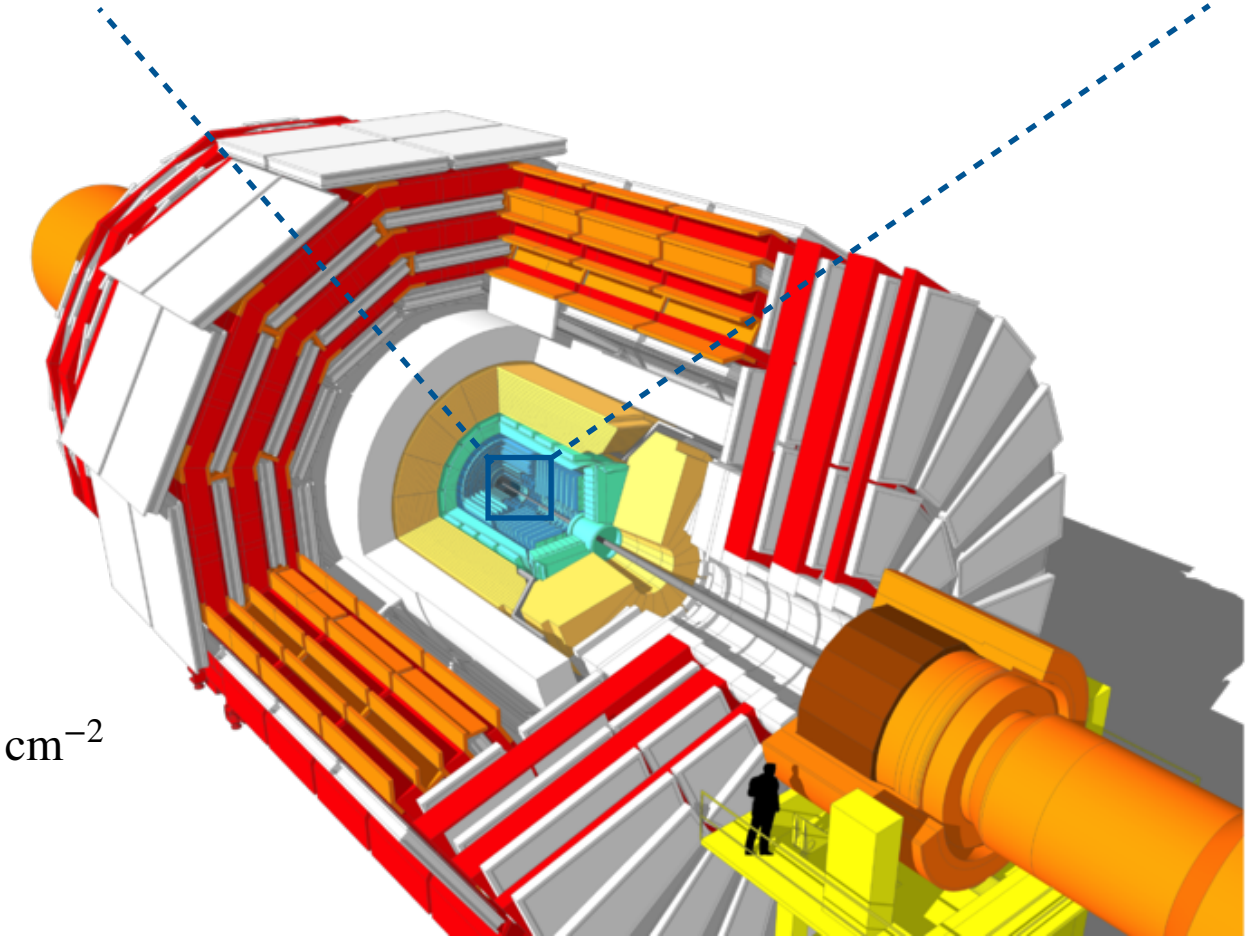
DESY.

Introduction

High Luminosity LHC

Phase-2 Experiments Upgrade

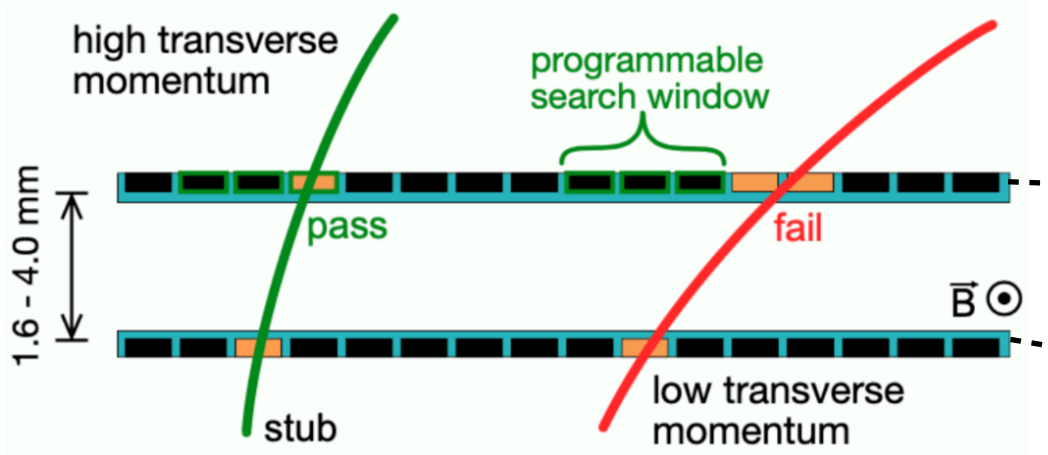
New Tracker
- Radiation tolerant - higher granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η = 4

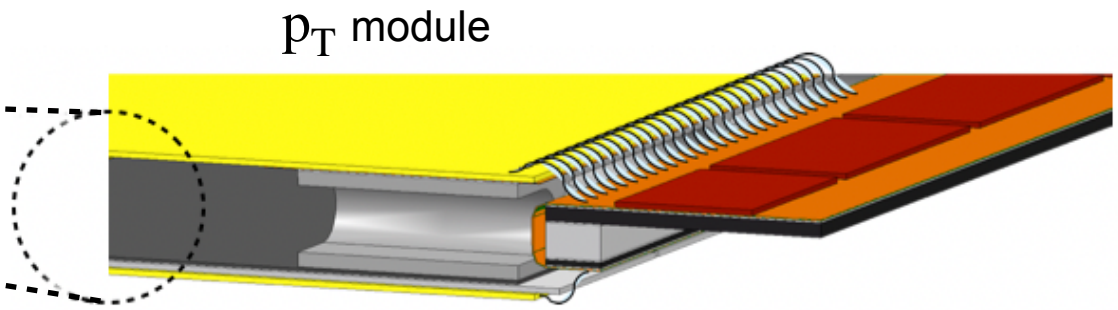


Accelerator performance :
- Peak instantaneous luminosity $5 - 7.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $300\ \mathrm{fb}^{-1}$ / year and up to $3000\ \mathrm{fb}^{-1}$ over 10 years

CMS environment :
- Unprecedented radiation levels up to $1.1 \times 10^{15}\ \mathrm{n_{eq}} \times \mathrm{cm}^{-2}$
- 10 times higher pile-up
- Higher data rates

p_T module concept



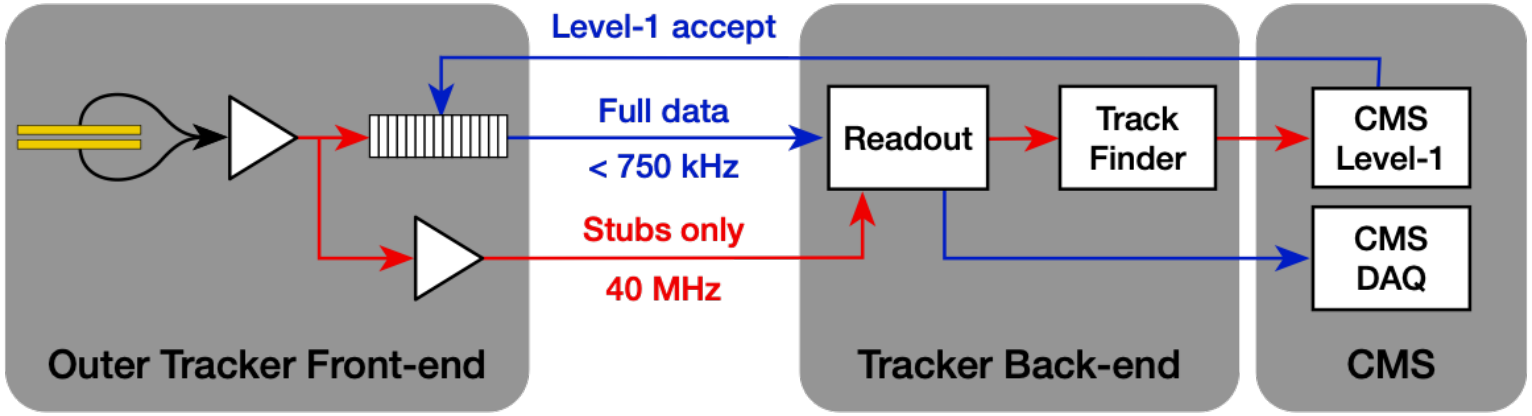


Modules with on-board p_T discrimination

- Strong magnetic field exploited for local p_T measurement
- Correlation of signals from two closely spaced sensors
- Local rejection of low-p_T tracks to reduce data volume

Modules provide both Level-1 and readout data

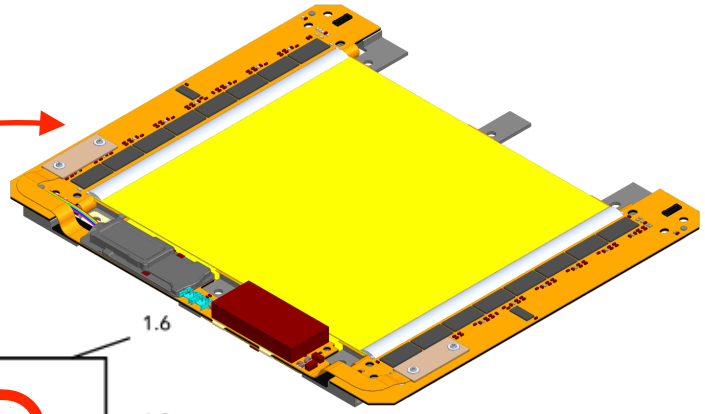
- Level-1 Trigger primitives ("stubs") sent @40MHz
- Full data readout rate up to 750KHz
- "stubs" are used to form Level-1 Track Finding



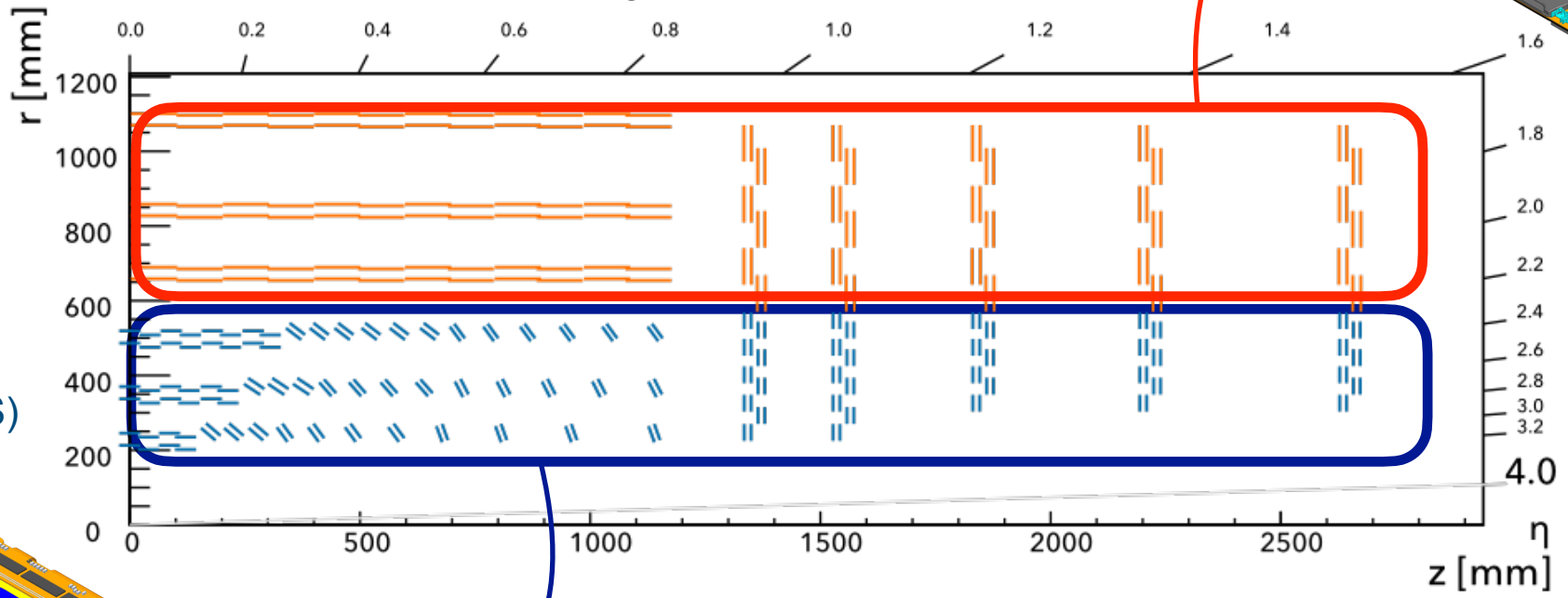
CMS Outer Tracker upgrade

Layout with 6 barrel layers and 5 end cap double disks

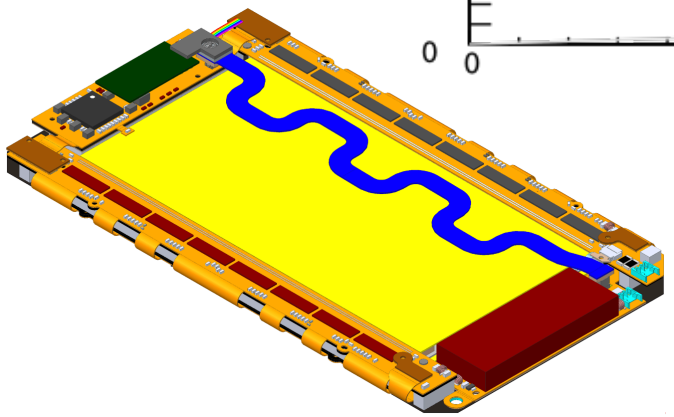
- Stack of two strip sensors at r > 60 cm (2S)
- Sensor spacings : 1.8 mm and 4 mm



Strip-Strip (2S) Modules

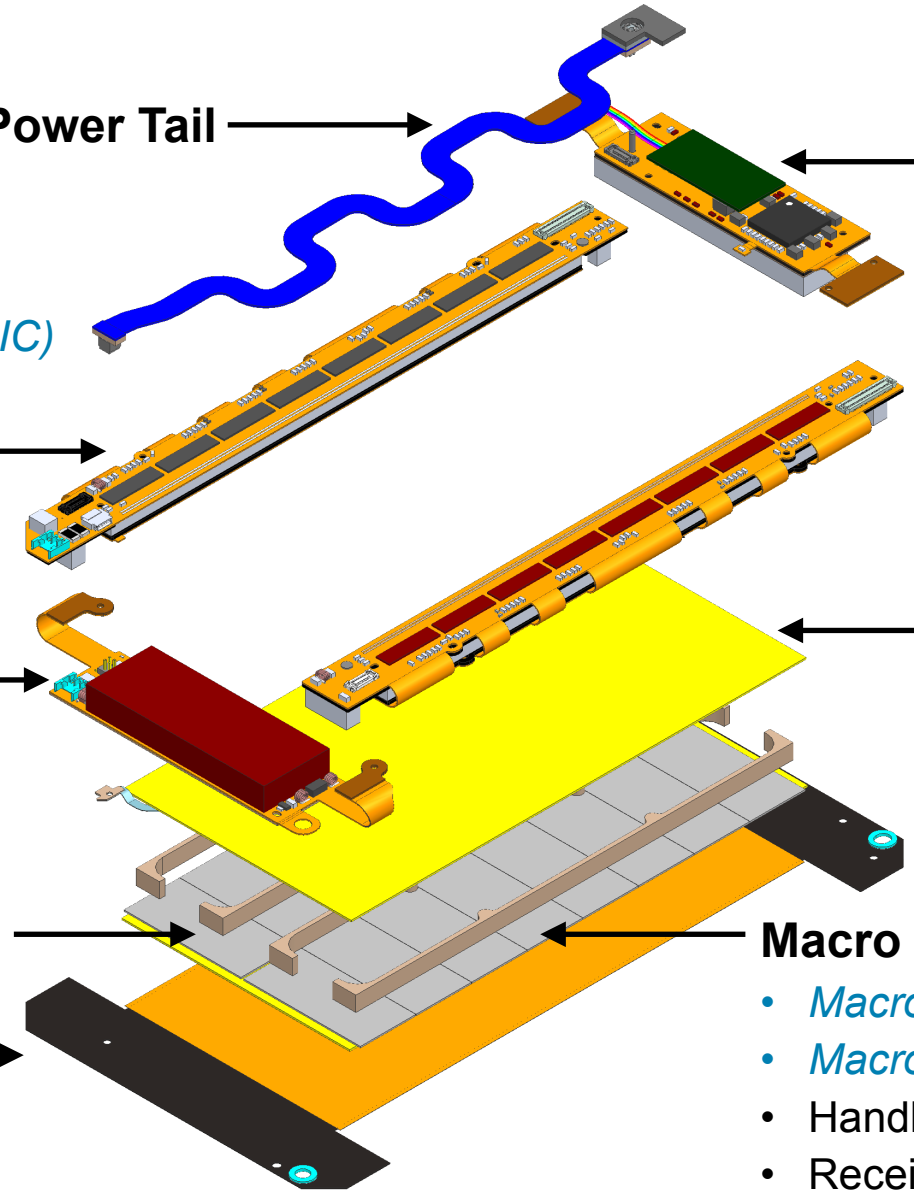


Pixel-Strip (PS) Modules



- Stack of pixel and strip sensor at r < 60 cm (PS)
- Sensor spacings : 1.6 mm, 2.6 mm and 4 mm

Pixel-Strip module design



Front-End Hybrid
- *Single-Strip ASIC (SSA)*
- *Concentrator Integrated Circuit (CIC)*
- Handles signal from strip sensor
- Transfers data to MPA
- Aggregates data from MPA

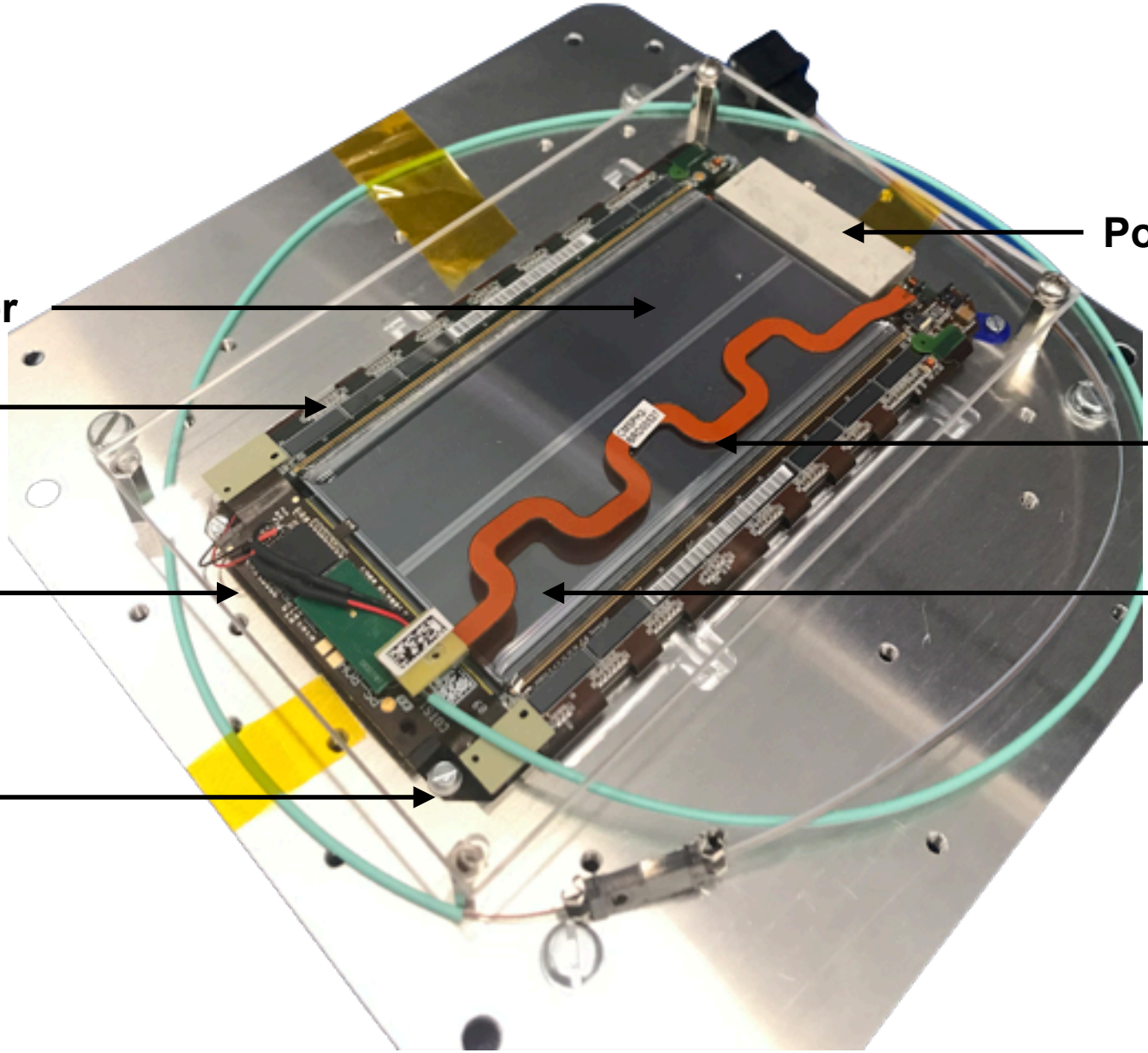
Power Hybrid
- DC-DC converter
- Distributes power

Read-Out Hybrid
- *Low-power Gigabit Transceiver ASIC*
- *VTRx+* optical module
- Transmits data over optical fibre

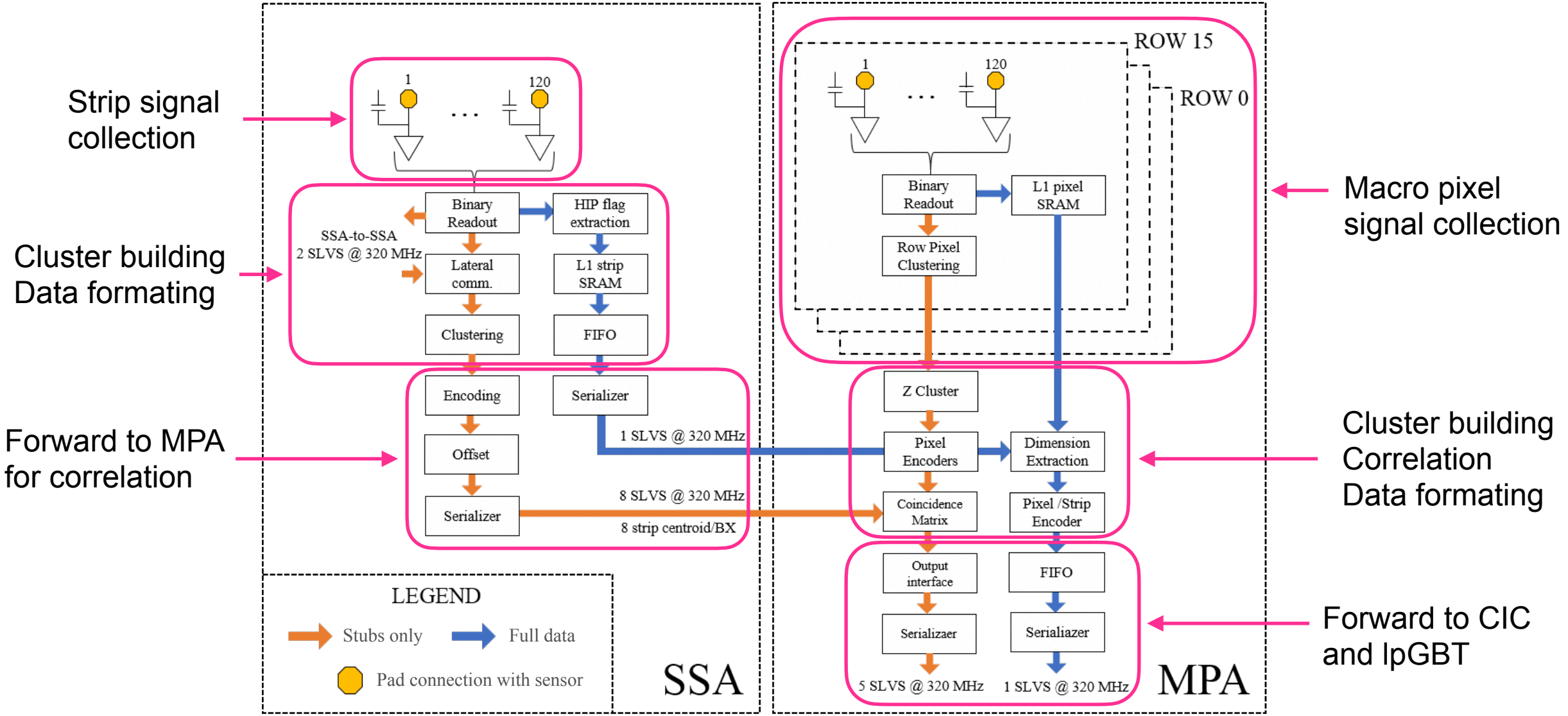
Silicon Strip Sensor
- *10 x 5 cm Silicon Strip Sensor*
- *2.5 cm long strips, 100 um pitch*

Macro Pixel Sub Assembly (MaPSA)
- *Macro Pixel ASIC (MPA)*
- *Macro Pixel Silicon sensor 1400 x 100 um*
- Handles signal from pixel sensor
- Receives data from SSA
- Correlates signals from both sensors

Pixel-Strip module assembly



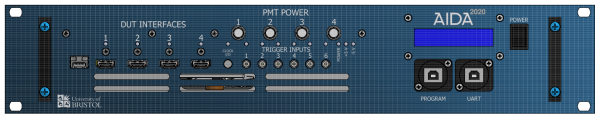
Front-end data flow (MPA-SSA)

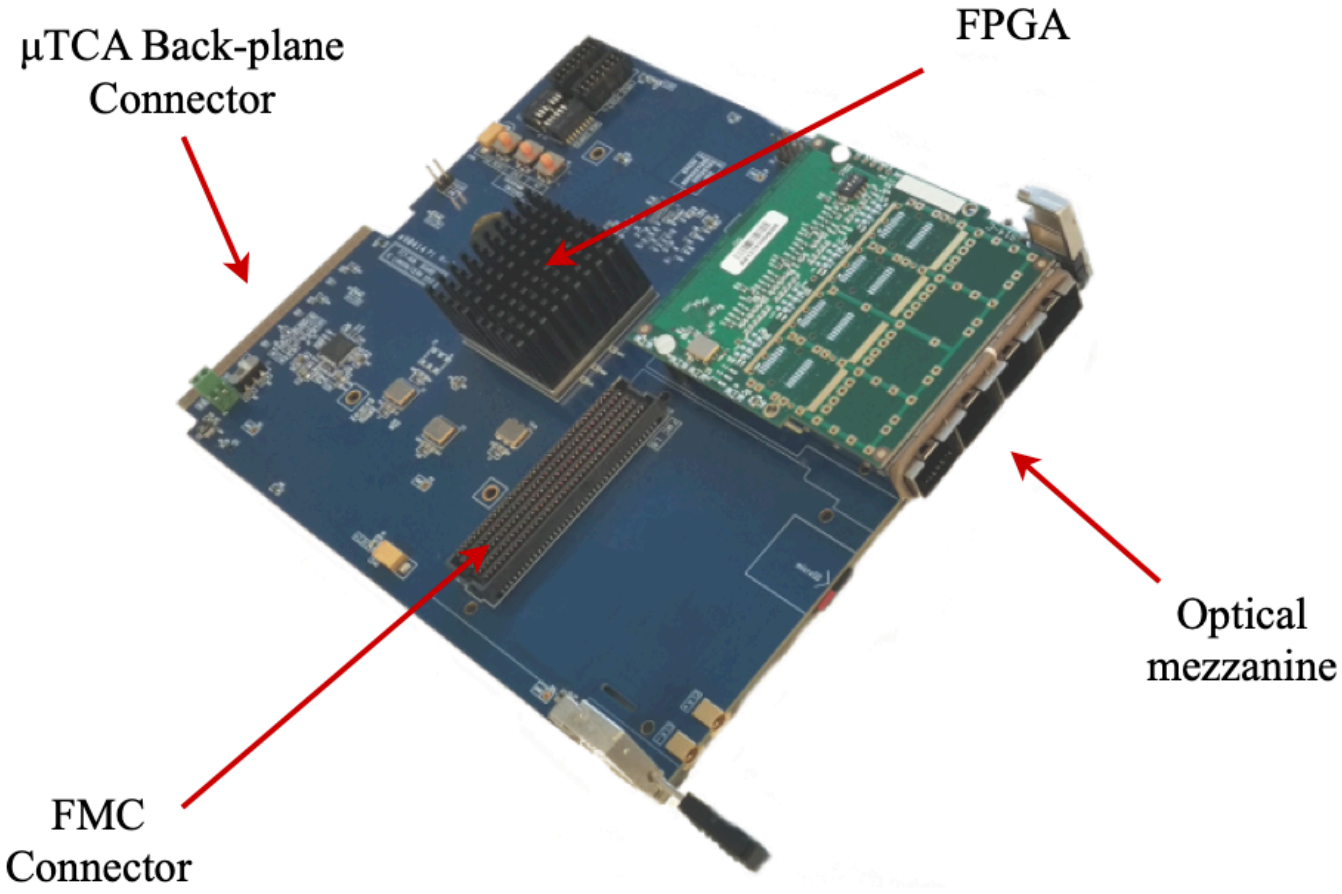


Back-end system

- Exploits ***FC7*** MTCA-compatible AMC for generic data acquisition and control applications
  - Kintex-7 FPGA
  - 2 FMC Connectors
  - Advanced clock distribution system
  - External DDR3 memory
  - …

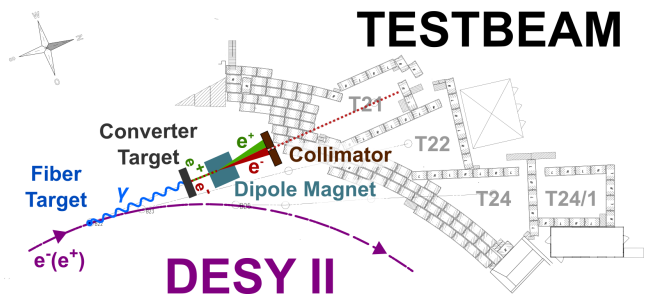
- Several custom interface are supported by the system in case of needed synchronous operation
  - Trigger Logic Unit (TLU)
  - DIO5 (5 LEMO I/O)
  - …



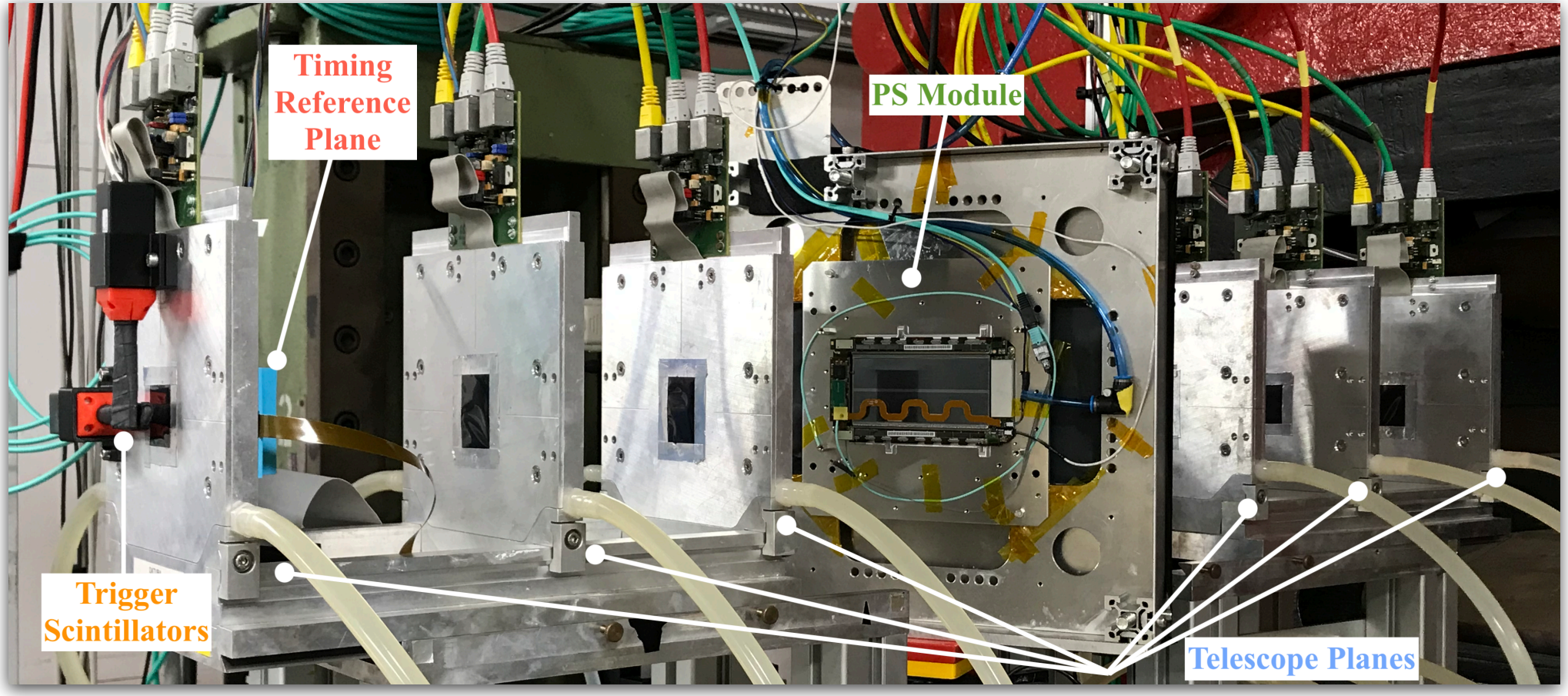


Test-Beam Qualification

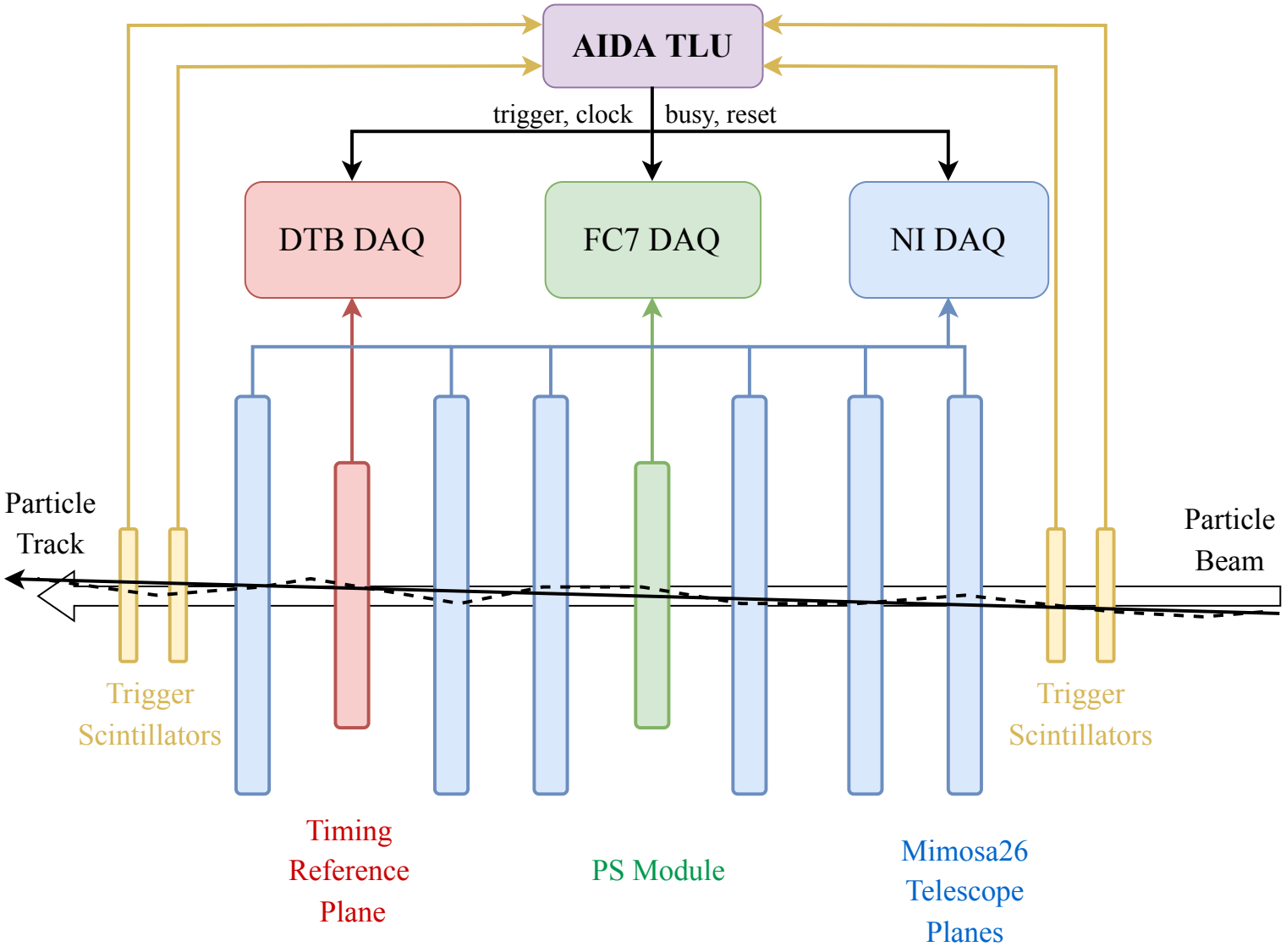
Experimental setup

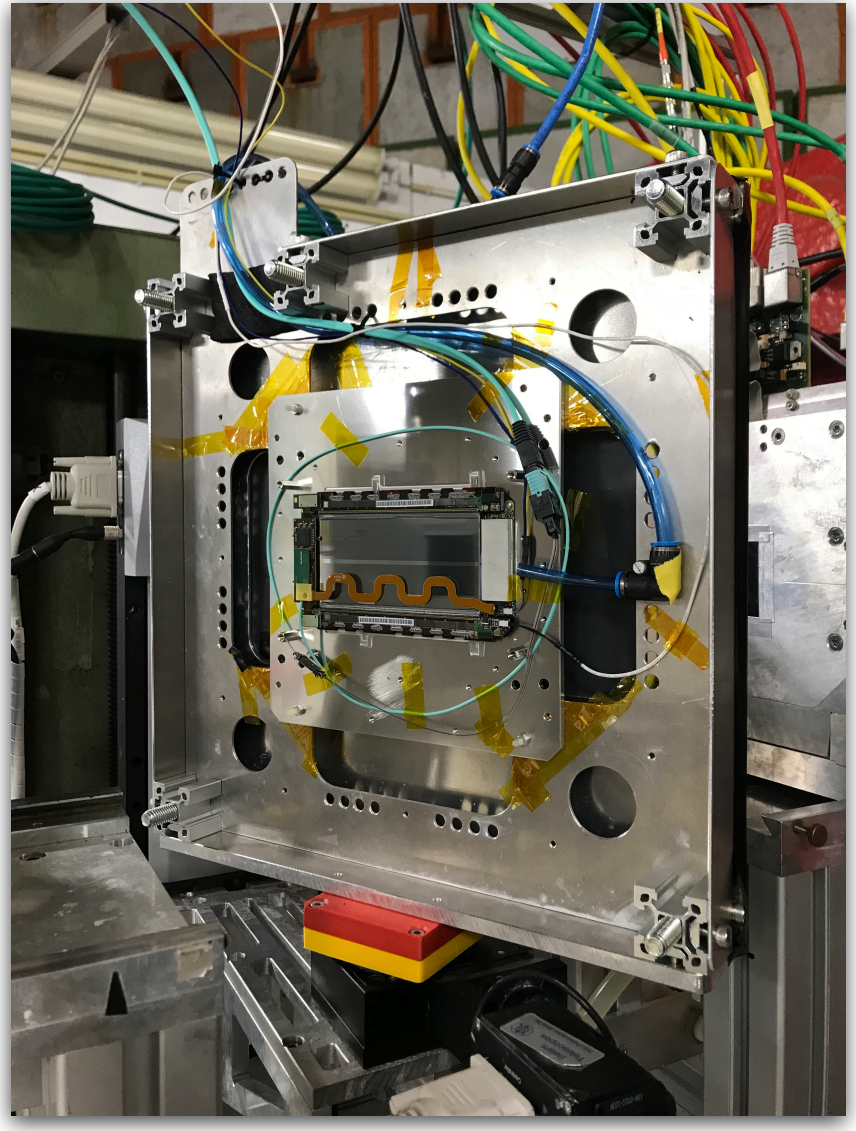


- 4 GeV/c electron beam
- DATURA Beam Telescope
- CMS BPIX reference plane
- Trigger scintillators
- AIDA TLU
- EUDAQ2

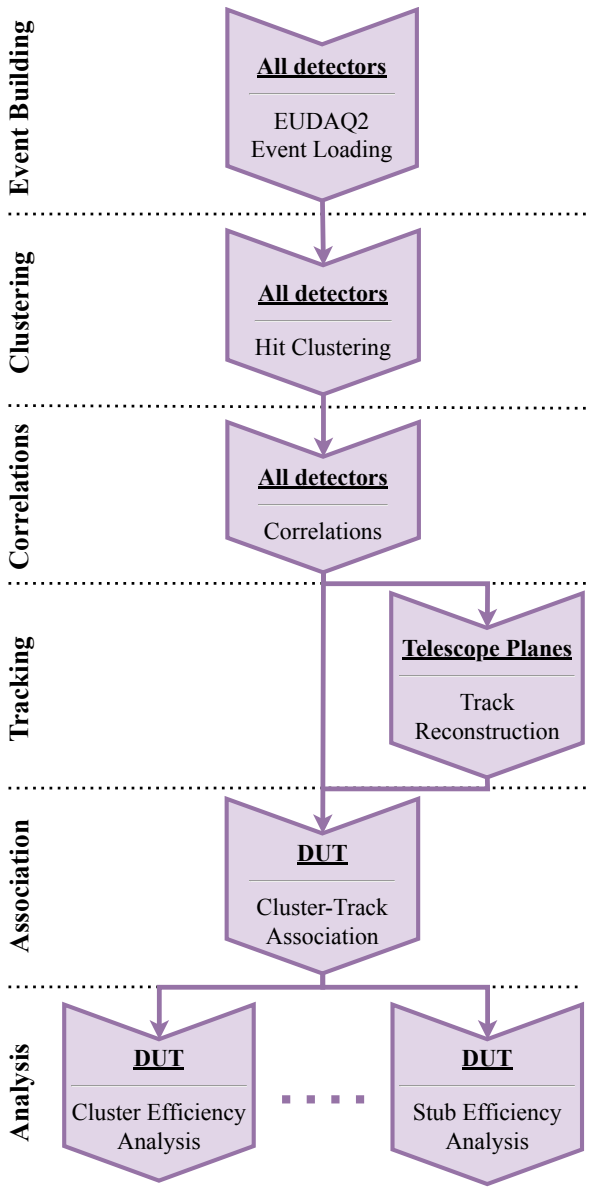


Data acquisition scheme





Reconstruction and analysis



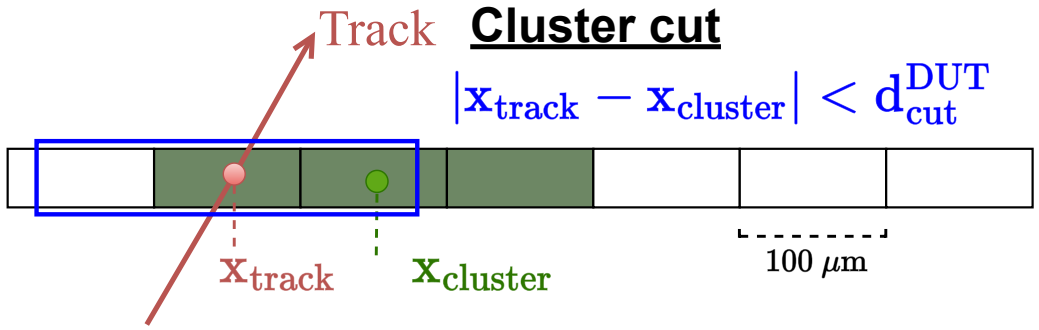
Corryvreckan

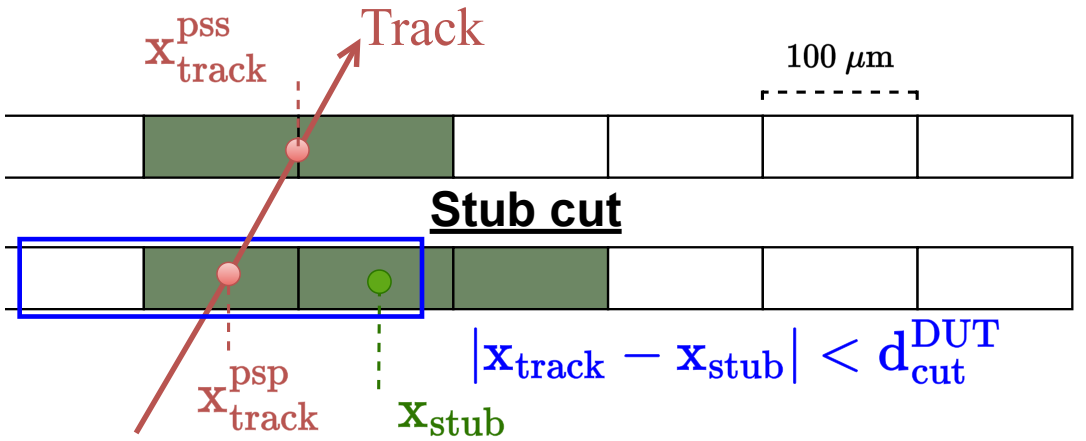
The Maelstrom for Your Test Beam Data

- Iterative pre-alignment using *Prealigment* module and *maximum* method
- Iterative alignment using *AlignmentDUTResidual* module and *GBL* model
- New EUDAQ Tag-based event filtering feature implemented (merged)
- New *BigPixelDetector* module implemented to support BPIX reference module pixel geometry (not merged)
- Cluster efficiency studies using *AnalysisEfficiency* module
- Cluster size and resolution studies using *AnalysisDUT* module
- *AnalysisStubEfficiency* module implemented for *stub* analysis (not merged)

Efficiency definitions

$$\epsilon_{\text{clusters/stubs}} = \frac{n_{\text{efficient clusters/stubs}}}{n_{\text{ref tracks}}} = \frac{\text{telescope tracks} \in \text{DUT}_{\text{clusters/stubs}} \cap \text{REF}}{\text{telescope tracks} \in \text{REF}}$$





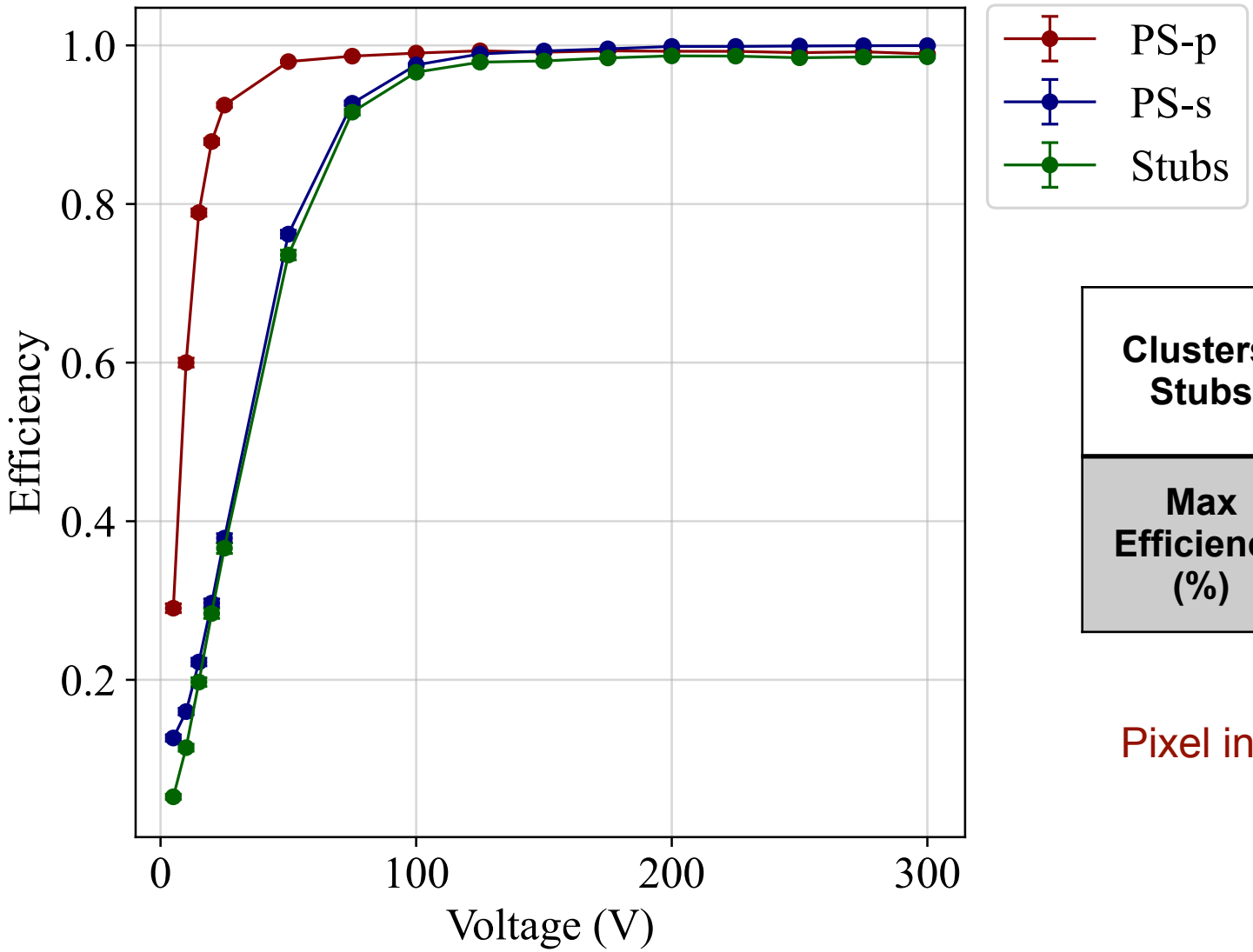
$$|x_{track}^{psp} - x_{cluster}^{psp}| \leq 200\ \mu\text{m} \quad ; \quad |y_{track}^{psp} - y_{cluster}^{psp}| \leq 3000\ \mu\text{m}$$ PS-p clusters

PS-s clusters

$$|x_{track}^{pss} - x_{cluster}^{pss}| \leq 200\ \mu\text{m} \quad ; \quad |y_{track}^{pss} - y_{cluster}^{pss}| \leq 25000\ \mu\text{m}$$

$$|x_{track}^{psp} - x_{stub}^{psp}| \leq 200\ \mu\text{m} \quad ; \quad |y_{track}^{psp} - y_{stub}^{psp}| \leq 3000\ \mu\text{m}$$ Stubs

Efficiency - Bias scan

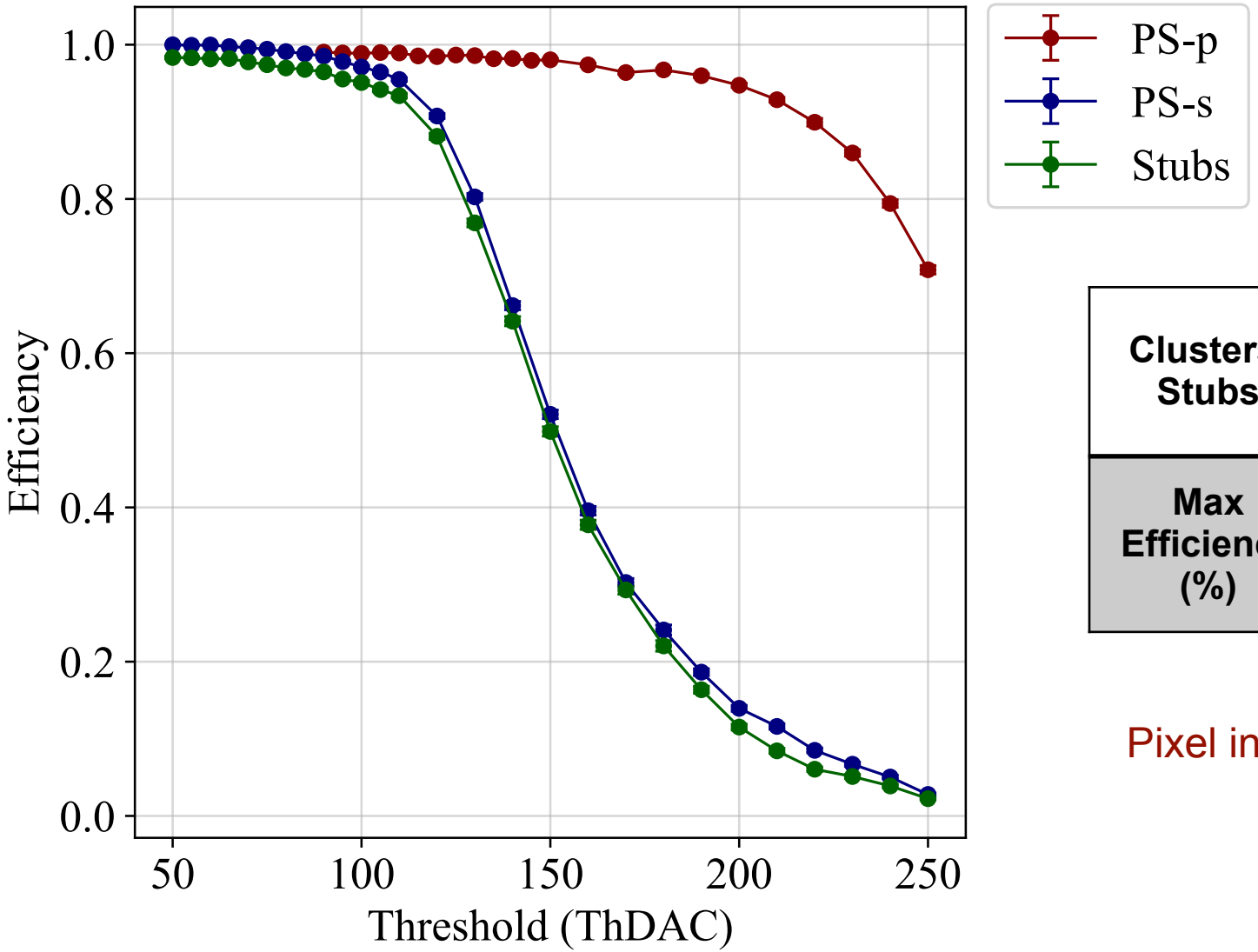


Determination of optimal operation point of bias voltage

Clusters/ Stubs	PS-p	PS-s	Stubs
Max Efficiency (%)	99.31	99.97	98.68

Pixel inefficiency caused by PS-p bias structure Punch-Through Structure (PTS)

Efficiency - Threshold scan

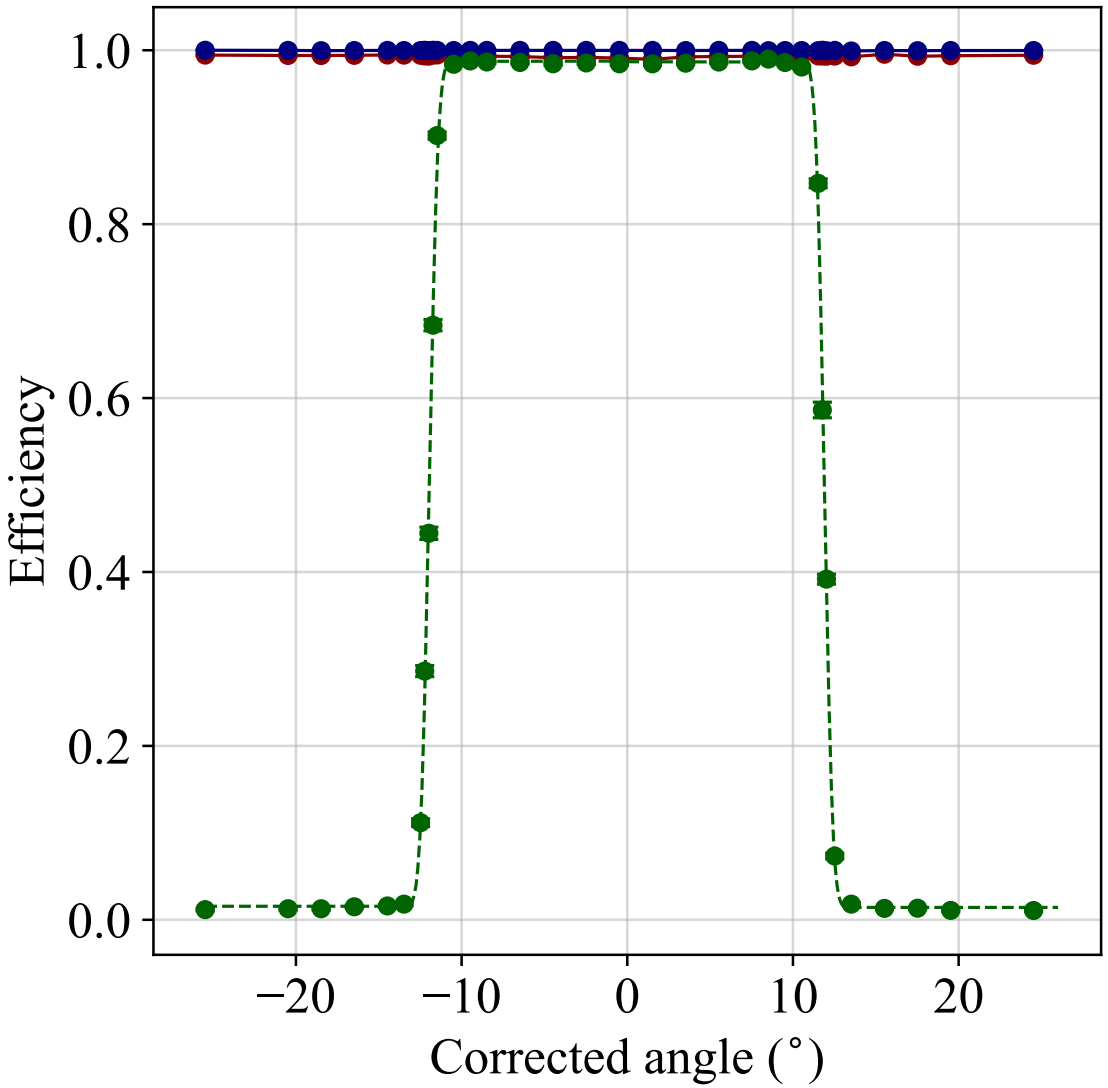


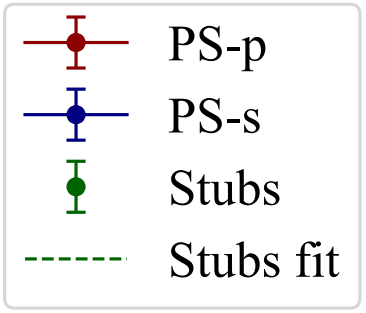
Determination of optimal operation point of signal threshold

Clusters/ Stubs	PS-p	PS-s	Stubs
Max Efficiency (%)	99.03	99.98	98.33

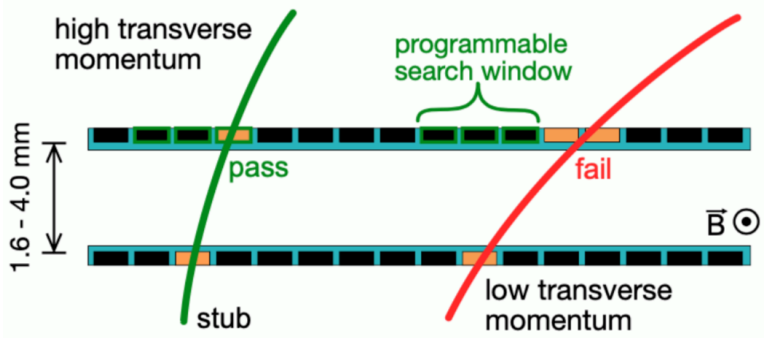
Pixel inefficiency caused by PS-p bias structure Punch-Through Structure (PTS)

Efficiency - Angular scan





Module rotated to emulate bending particles and p_T discrimination



Clusters/ Stubs	PS-p	PS-s	Stubs
Max Efficiency (%)	99.54	99.99	98.98

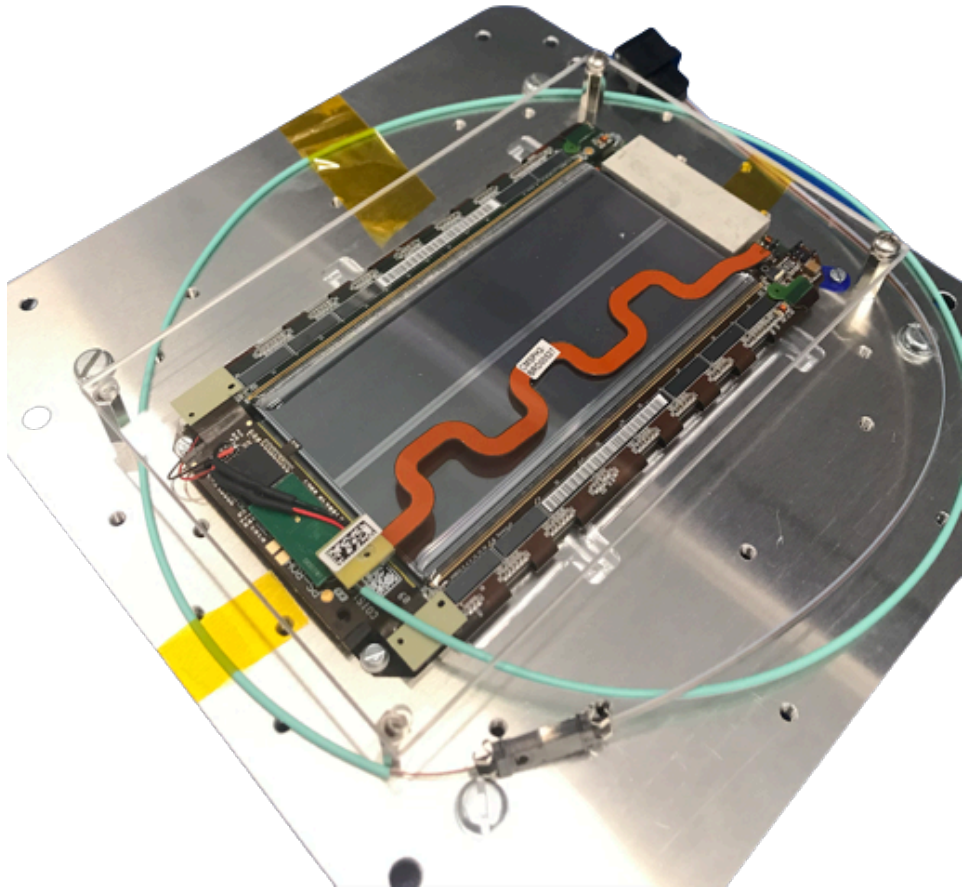
Stub efficiency drop at approximately +/- 12°
Stub logic (p_T discrimination) working as expected

Conclusion

Summary - Outlook

Summary

- Introduction of new Tracker module design for the needs of High Luminosity LHC upgrade
- Momentum discriminating design based on cluster correlation between two closely stacked Silicon sensors
- Pixel-Strip module test-beam qualification results yield excellent efficiency and p_T discrimination performance
- *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)".*



Outlook

- New modules to be assembled with latest hybrid circuit designs
- Performance studies to be reiterated and complemented using irradiated modules

THANK YOU.

Contact

DESY. Deutsches Elektronen-Synchrotron

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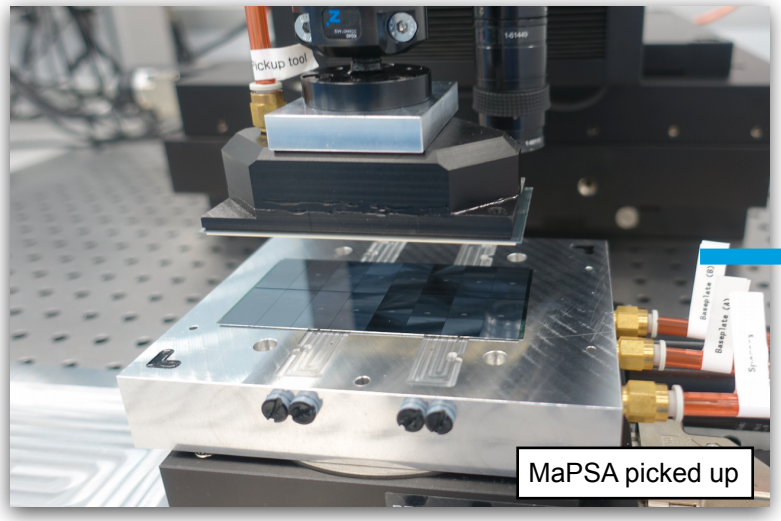
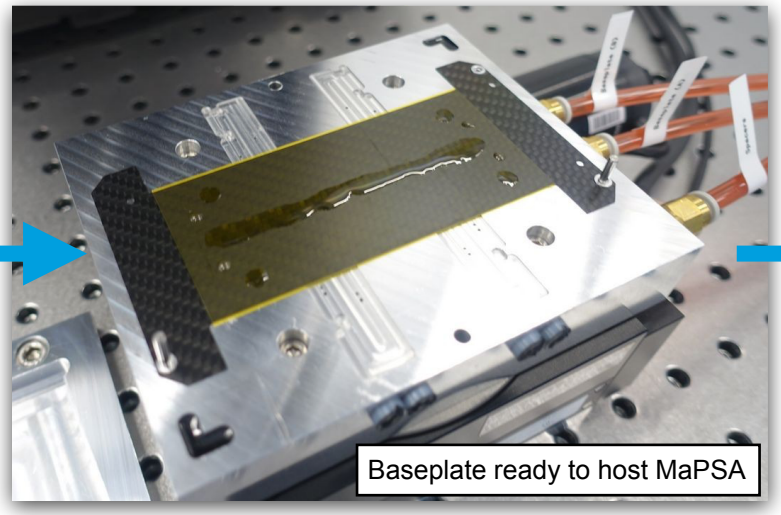
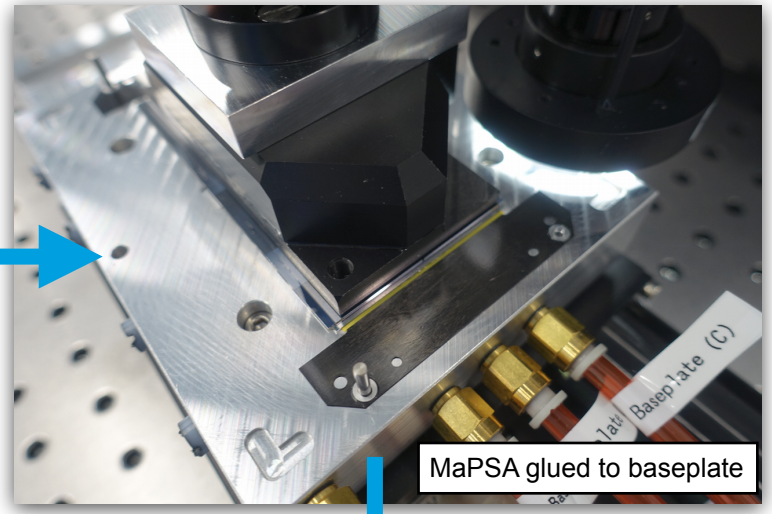
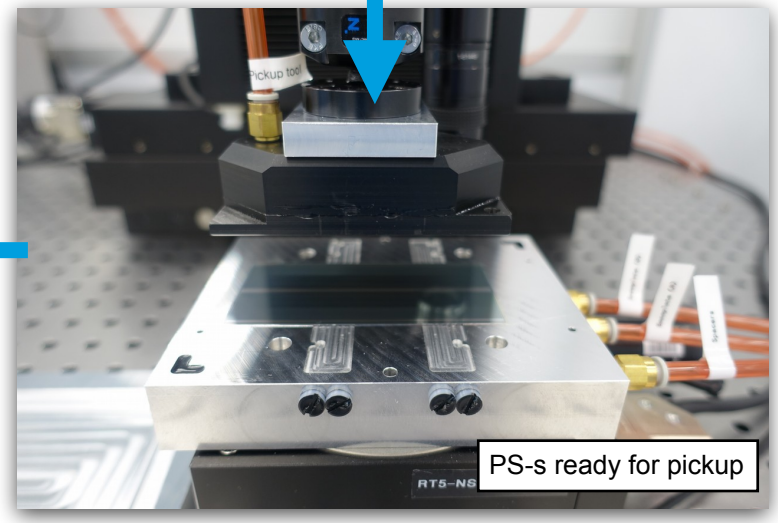
Pixel-Strip silicon module assembly

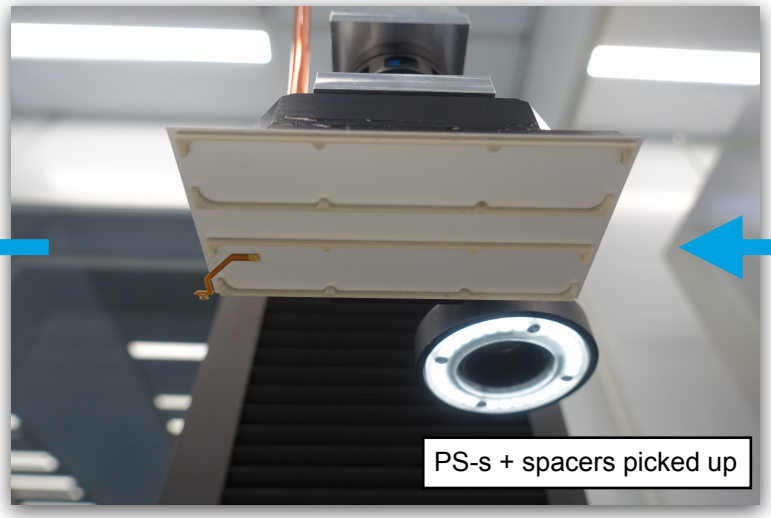

MaPSA picked up

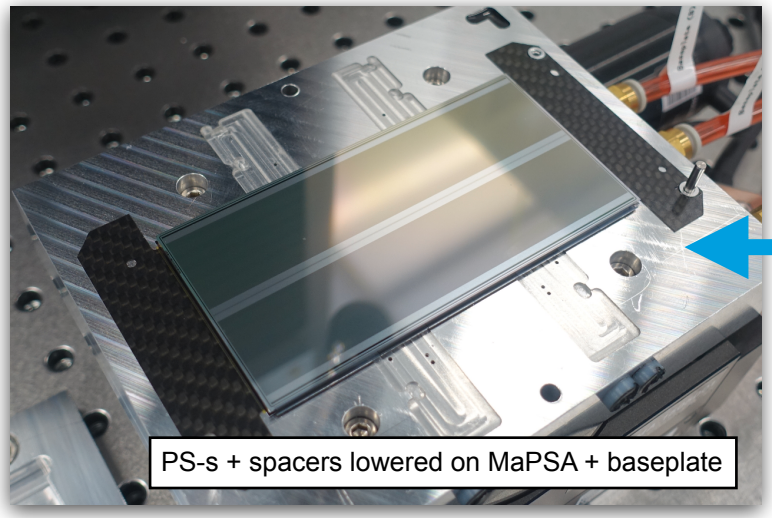

Baseplate ready to host MaPSA



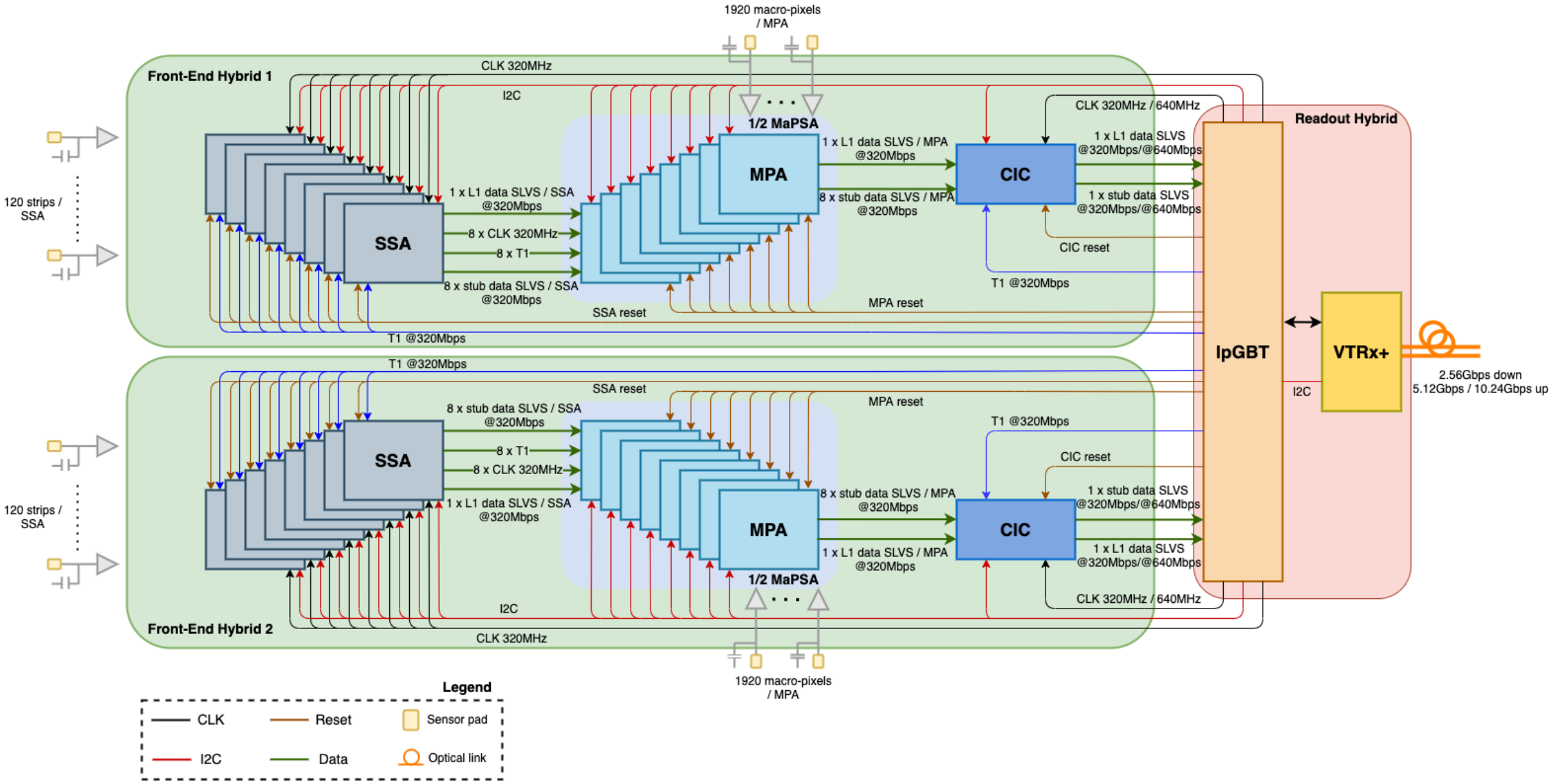
MaPSA glued to baseplate


PS-s ready for pickup

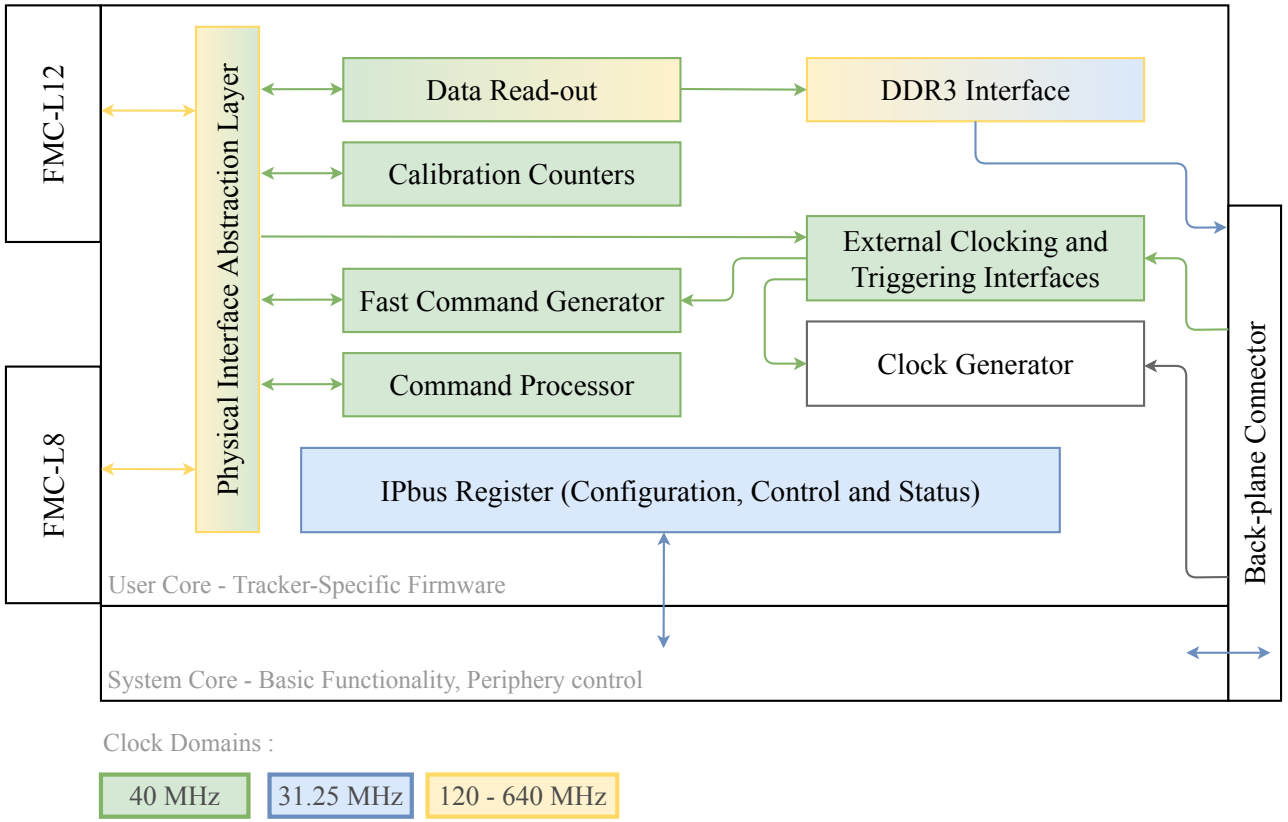

PS-s + spacers picked up


PS-s + spacers lowered on MaPSA + baseplate

Front-end architecture



μDTC firmware



Firmware development specifically dedicated to the prototyping and production phases of the CMS Tracker Phase II Upgrade

IPbus registers :
- Configuration, control or status monitoring

Clock Generator :
- 40MHz to 640MHz clock generation and distribution

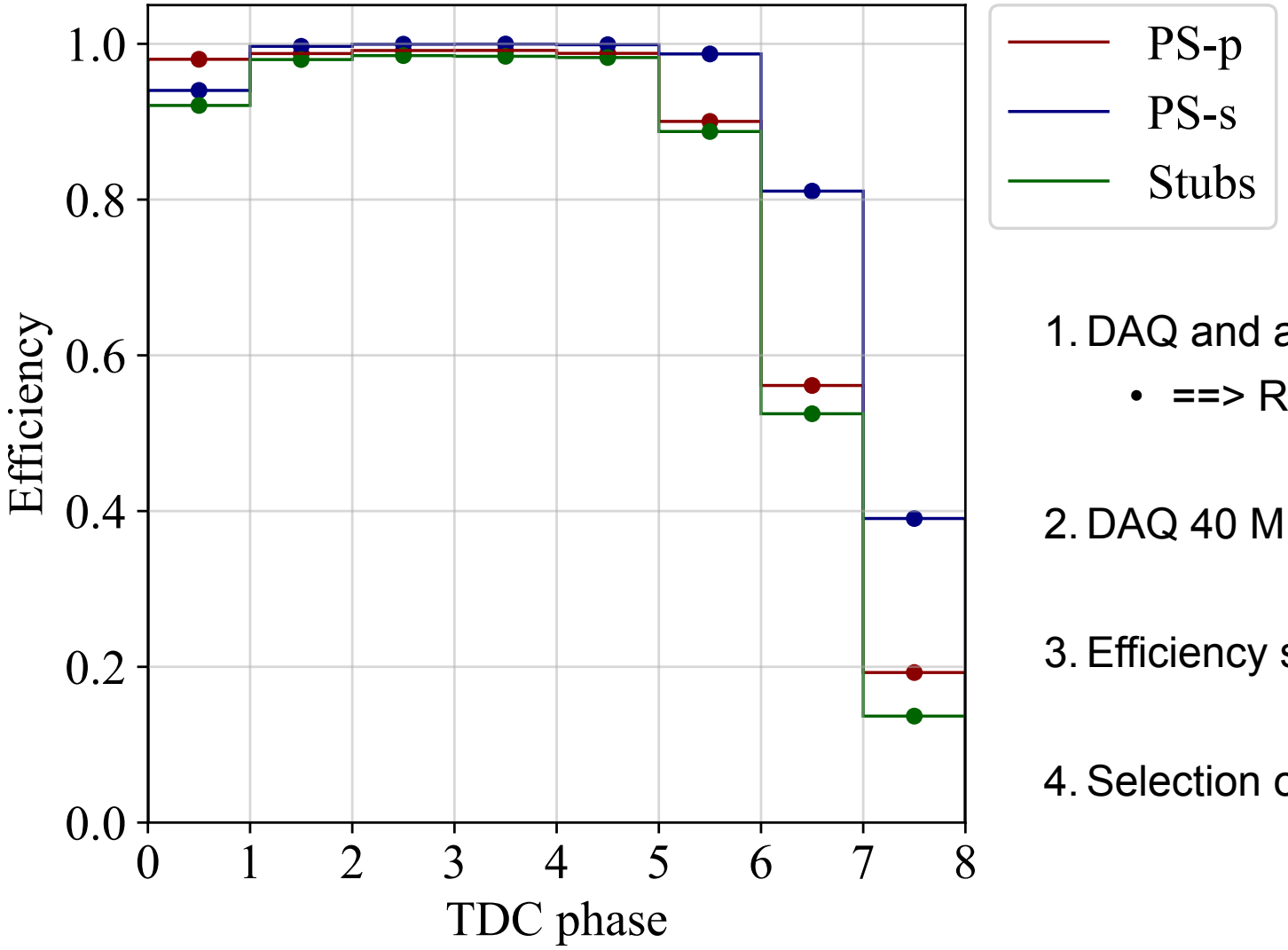
Fast Command Generator :
- Interface for synchronisation, calibration and trigger fast signals

Command Processor :
- Slow control, configuration and calibration

Physical Interface Abstraction Layer :
- Abstract interface for optical or electrical readout

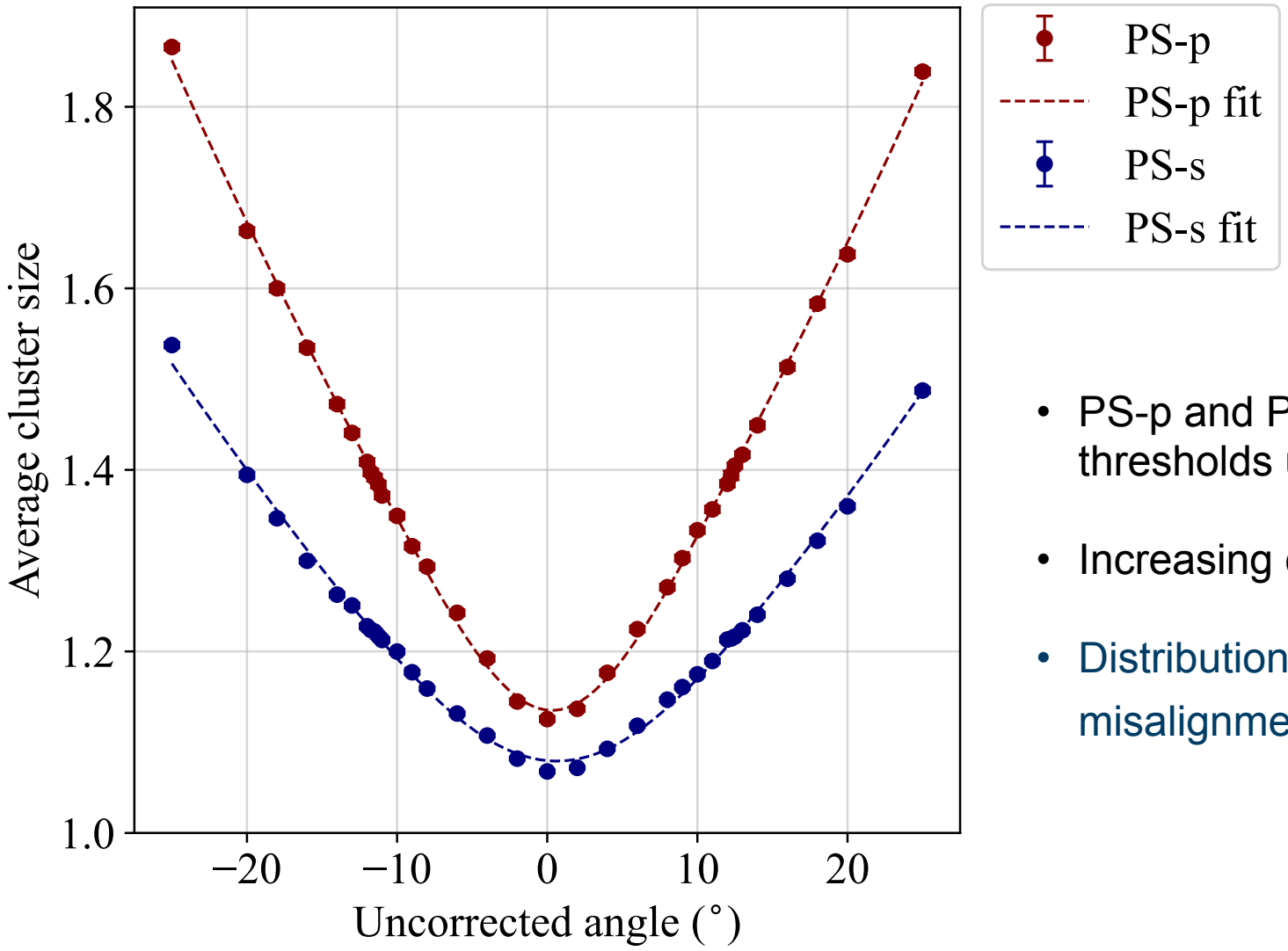
Data Readout :
- Processing and aggregation of data from all connected front-end modules/components

TDC phase selection



1. DAQ and accelerator clock asynchronous
   - ==> Random trigger arrival time
2. DAQ 40 MHz clock sampled at 320 MHz
3. Efficiency subject to TDC phase dependency over 8 bins
4. Selection of high efficiency TDC phases

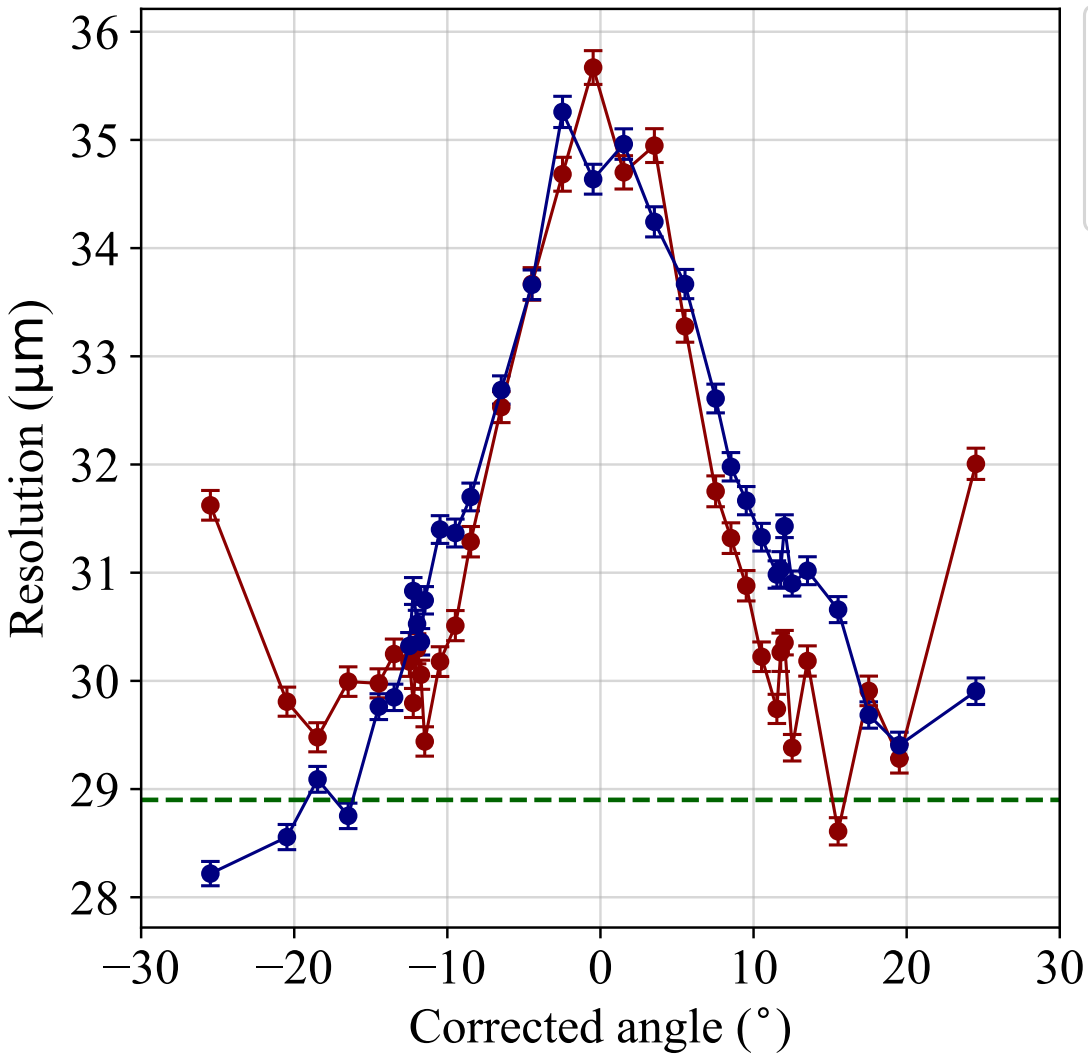
Cluster size - Angular Scan



Determination of cluster size as a function of rotation angle

- PS-p and PS-s differences due to the different signal thresholds used for the MPA and SSA chips
- Increasing cluster size due to charge sharing
- Distributions also used to extract physical misalignment of the module on the rotation stage

Resolution - Angular Scan



Determination of pixel and strip resolutions as a function of rotation angle

- Lack of statistics exacerbated by further event filtering and strong fluctuations still to be understood
- Resolution measured as $\sigma_{\text{int}} = \sqrt{\sigma^2_{\text{meas}} - \sigma^2_{\text{tel}}}$
  - σ_{meas} taken as RMS of residual distribution
  - $\sigma_{tel} = 9.15\ \mu m$ extracted from resolution simulator
- Improved resolution with increasing angle due to charge sharing
- Maximum resolution close to expected $\text{p}/\sqrt{12}$ at around 15°