WP2: Low Q^2 Tracker - Status

Electron-Ion Collider UK Gathering 2025

Ken Livingston, Dec 2025

Simon Gardner (Glasgow)

Derek Glazier (Glasgow)

Ken Livingston (Glasgow)

Rachel Montgomery (Glasgow)

Gary Penman (Glasgow)

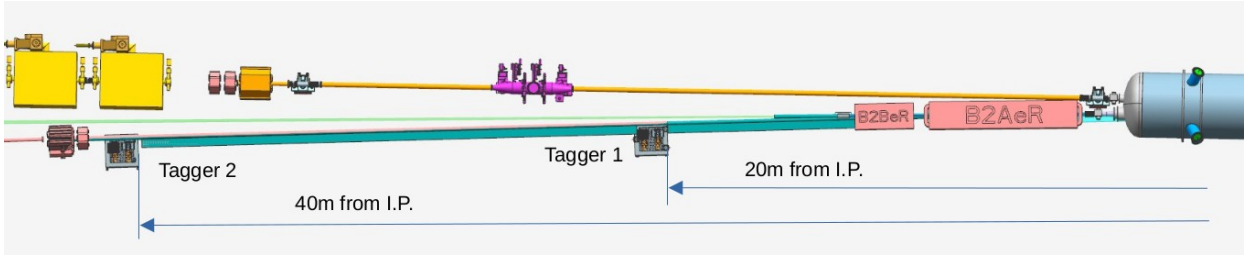
Daria Sokhan (Glasgow)

Dima Maneuski (Glasgow, PPE)

Rob Apsimon (Lancaster, Accel)

Jaroslav Adam (Prague, Calorimeter)

Yulia Furletova (Jlab/EIC, Far Backward)



Outline

Low Q^2 Tagger Overview

Tracker Requirements

Technology

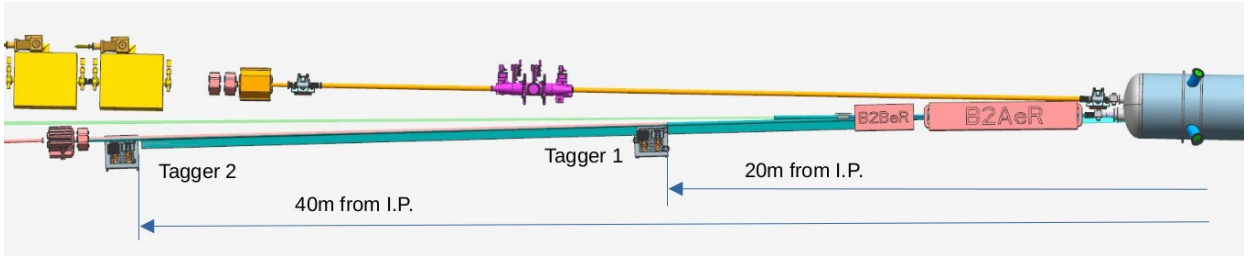
Design

Performance

Current status

Next steps

Summary



Short Xmas Quiz

Short Xmas Quiz

Q1. Who are they ? _ _ _ _ _ _ / _ _ _ _ _ _ _ _

Short Xmas Quiz

Q1. Who are they ? _ _ _ _ _ / _ _ _ _ _ _ _ _

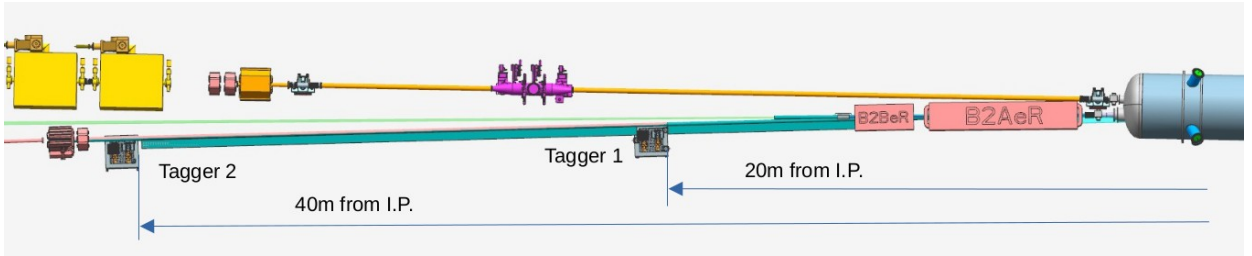
Q2. Who might be their enemies ? _ _ _ _ / _ _ _ _ _ _

Low Q^2 Tagger Overview

Low Q^2 electrons (~0 deg)

(Quasi Real photons)

Missed by main detector



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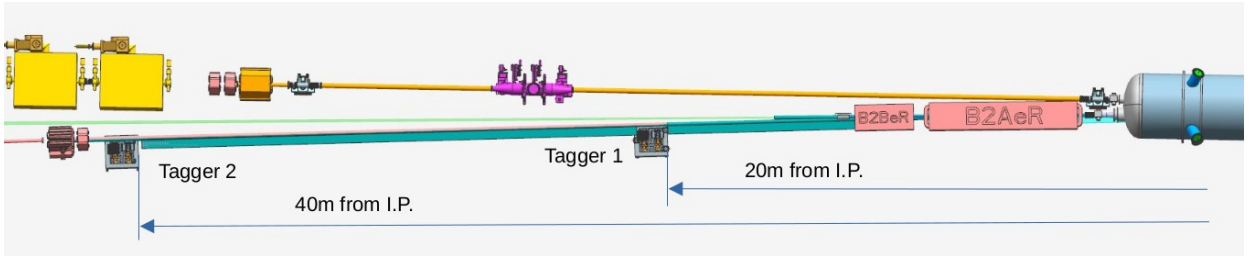
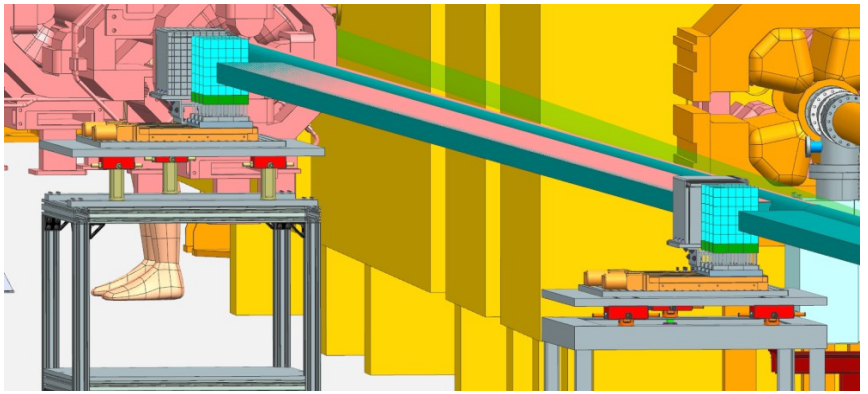


Detectors very close to electron beam

- Swamped by bremsstrahlung electrons
- Detector + DAQ for high BG rates
- Can’t be inside the beam vacuum (yet)
- Complicated beam pipe + window



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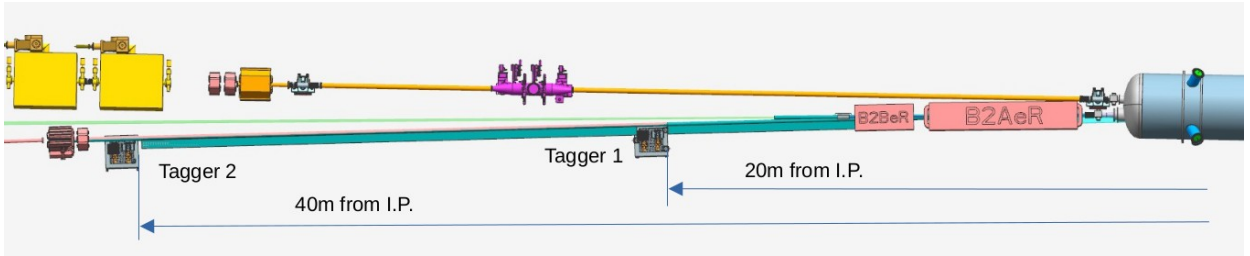

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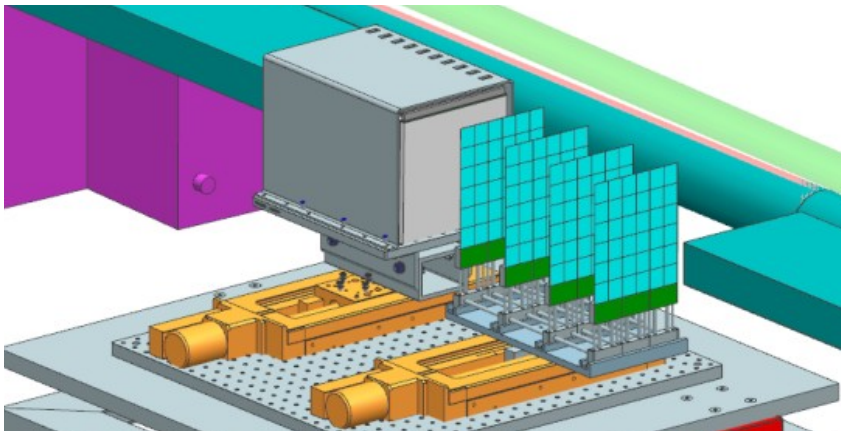

- Tracker + Calorimeter

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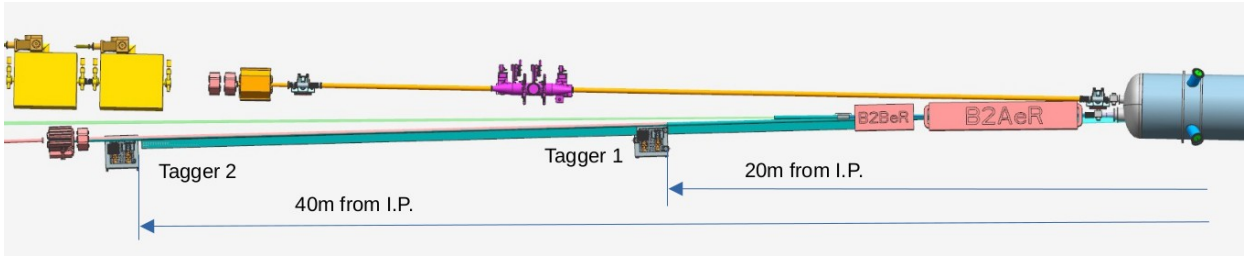

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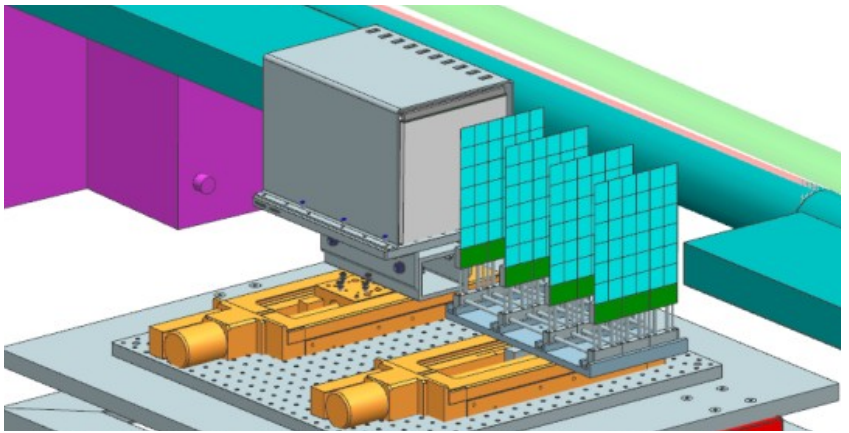
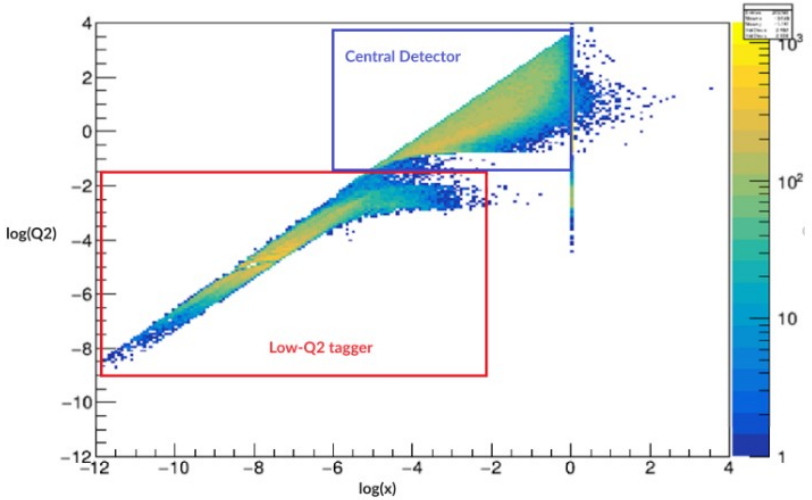


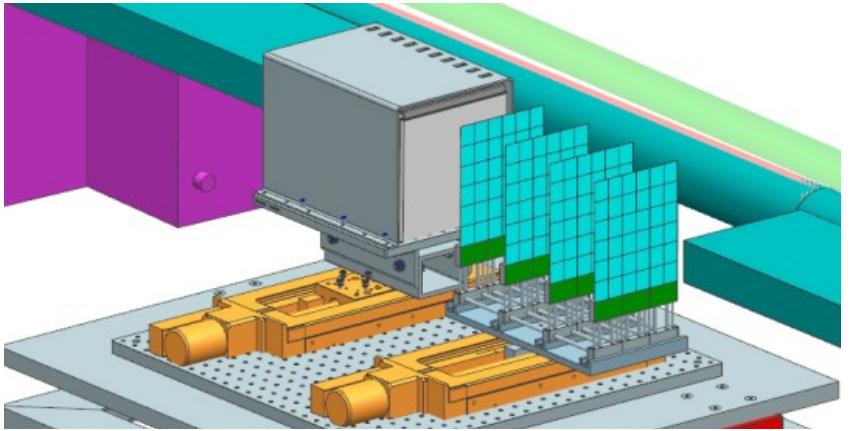
WP2

Tracker + Calorimeter

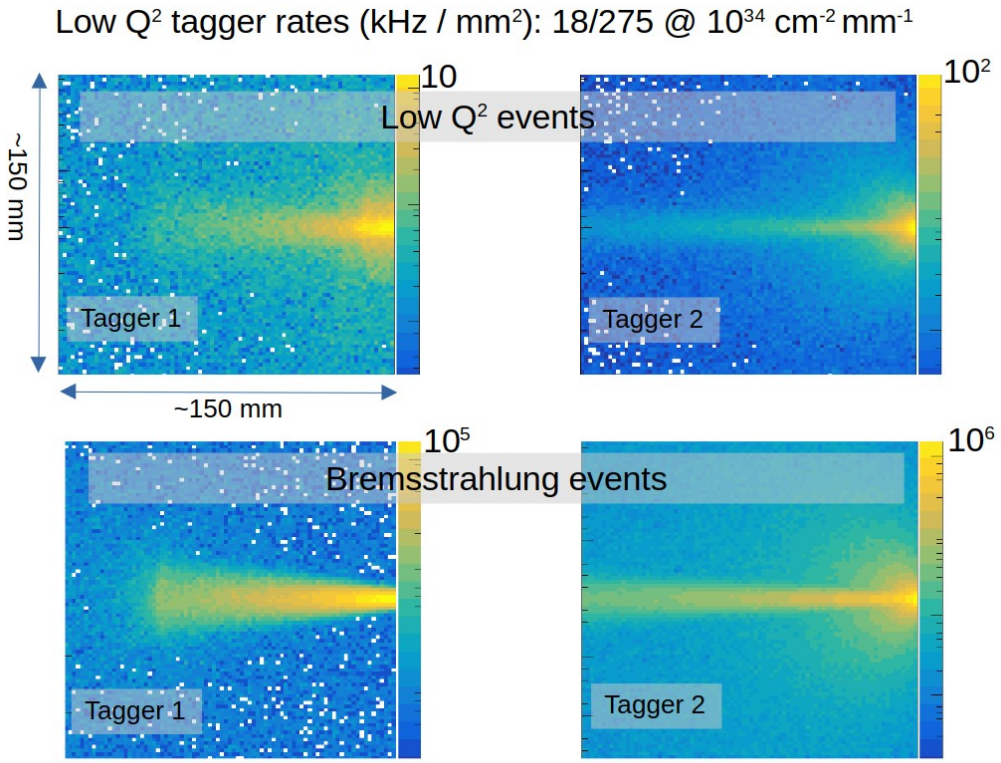
Tracker Requirements

Position res (is everything!):	Q^2, E, P, angle, bg separation: < 100um
Timing res:	separate beam buckets: << 10ns
Rate capability:	Just slightly less than infinity Hz. (Next slide)
Acceptance:	Everything that isn't captured by the main detector, or the magnet. Changing with every beamline design iteration

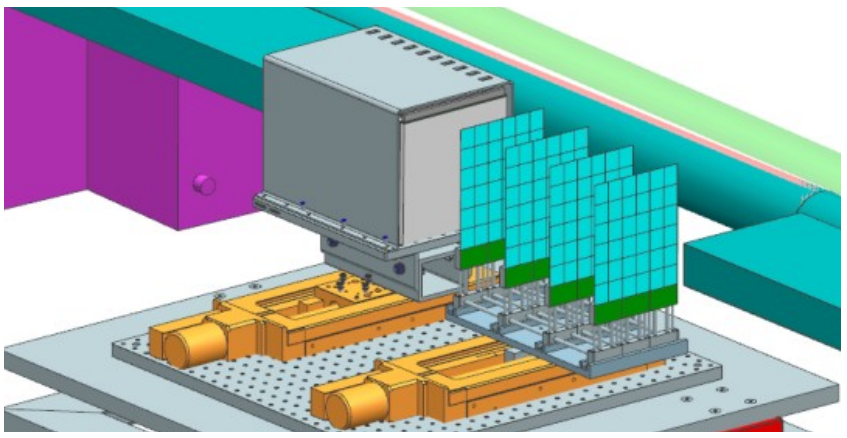




Tracker Requirements
Rates



Raw hits from two taggers	> 10 GHz
Data rate from raw hits:	> 600 Gb/s
Pipeline filter on “hadron” at	~ 500 kHz
Reduced rate to tape:	< 20 Gb/s



Technology

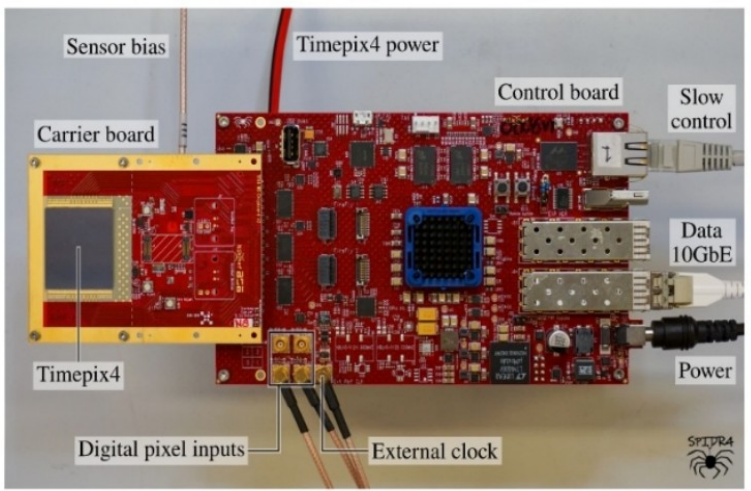
Characteristic	Value
Technology	65 nm - 10 metal
Pixel size	55 x 55 μm
Sensor size	512 x 448 pixels, 4-side buttable
Sensitive area	6.94 cm^2 (2.47 $\times$ 3.0 cm)
Packet size	64 bits
Readout method	data driven
Maximum rate / unit area	3.58 $\times$ 10^6 hits / mm^2/ s
Maximum rate / pixel	10.8 kHz / pixel
ToT Energy resolution	$<$ 1 keV
Time resolution	195 ps
Readout bandwdidth	163.84 Gb/s (16 $\times$ 10.24 Gb/s)

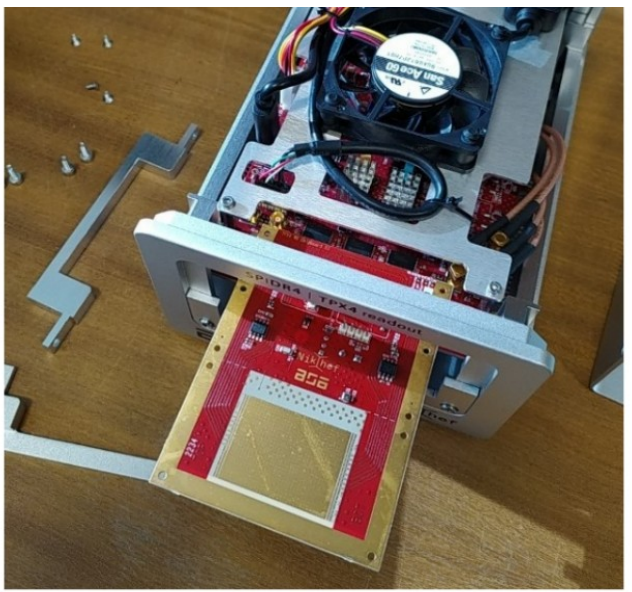
Timepix4 + Si Hybrid, CERN Medipix

X. Llopart et al 2022 JINST 17 C01044

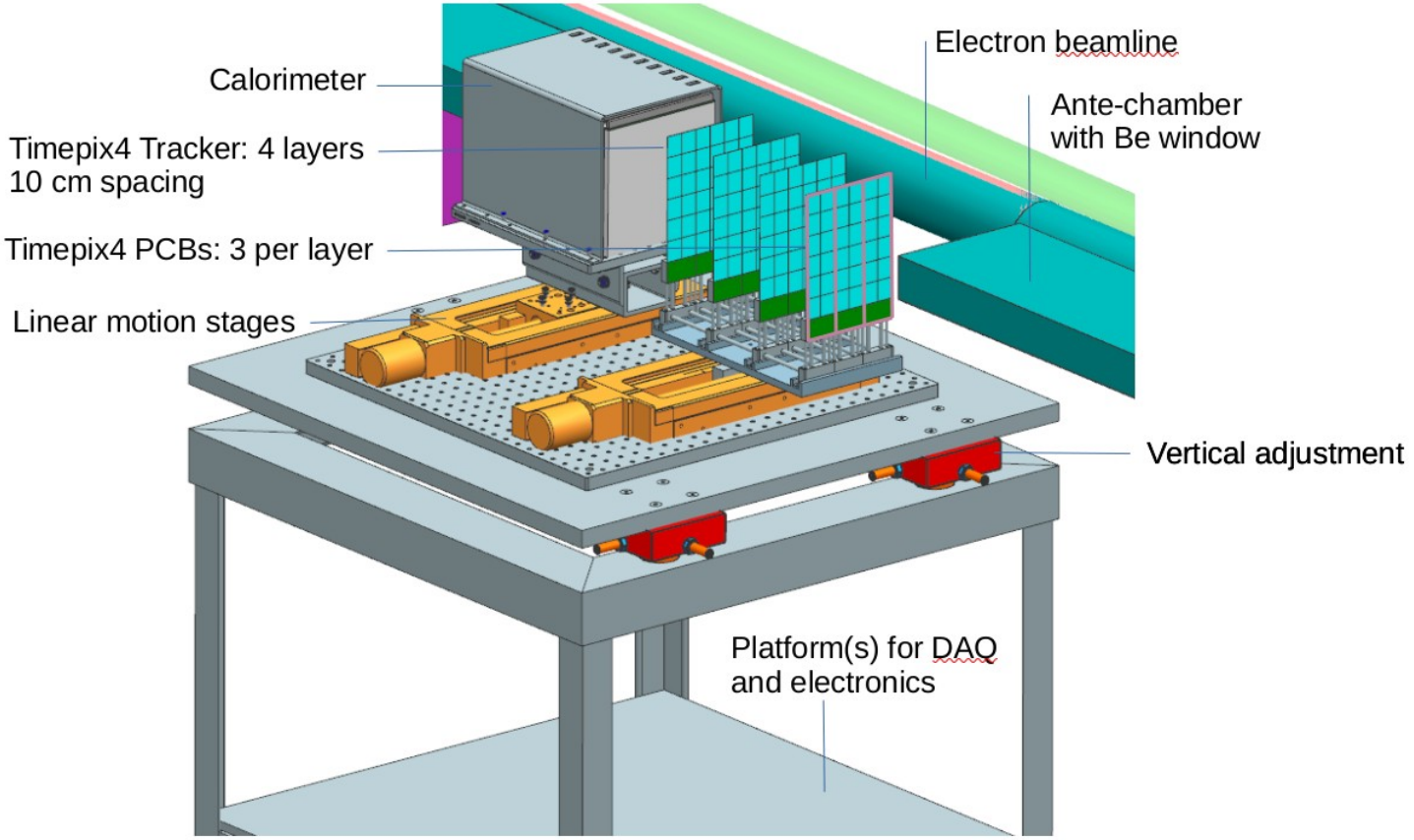
SPIDR4 Readout, NIKHEF

K. Heijhoff et al 2024, pp. 1-1, doi: 10.1109/NSS/MIC/RTSD57108.2024.10657478.

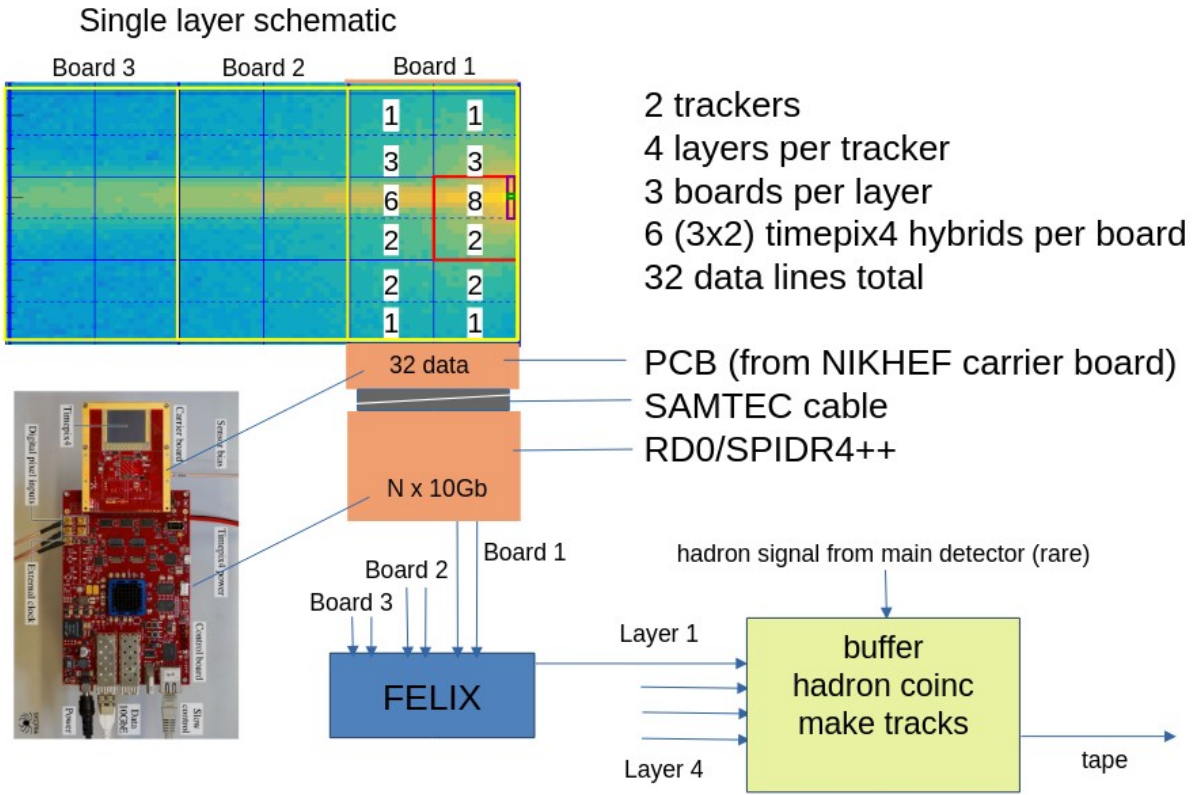


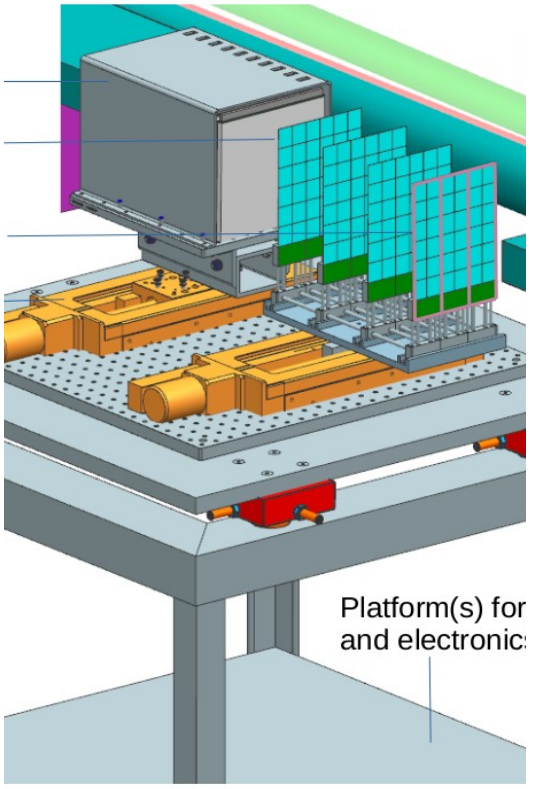


Design

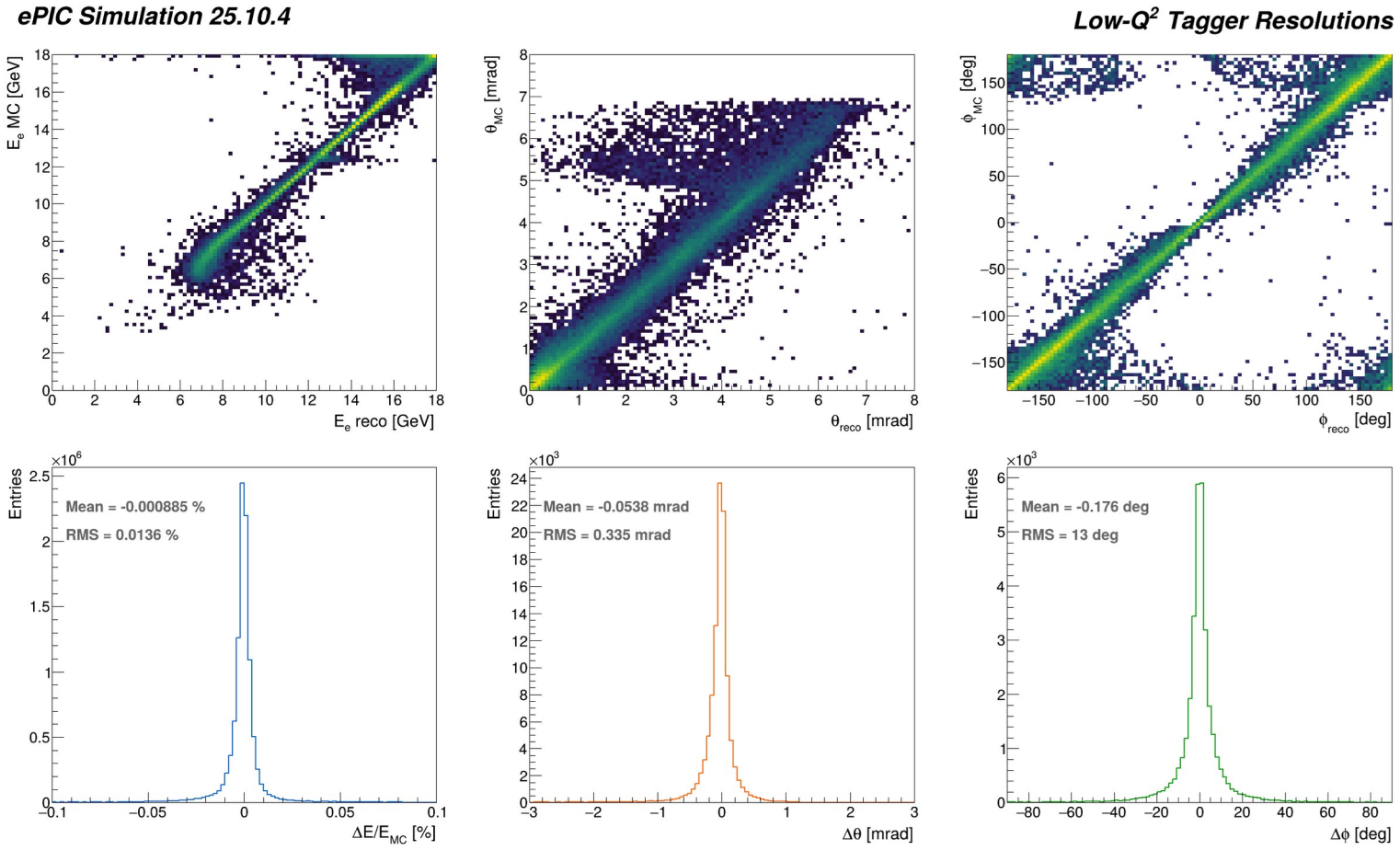

Calorimeter
Timepix4 Tracker: 4 layers
10 cm spacing
Timepix4 PCBs: 3 per layer
Linear motion stages
Electron beamline
Ante-chamber
with Be window
Vertical adjustment
Platform(s) for DAQ
and electronics

Design


Single layer schematic
Board 3
Board 2
Board 1
1 1
3 3
6 8
2 2
2 2
1 1
32 data
N x 10Gb
Board 1
Board 2
Board 3
FELIX
hadron signal from main detector (rare)
Layer 1
Layer 4
buffer
hadron coinc
make tracks
tape
2 trackers
4 layers per tracker
3 boards per layer
6 (3x2) timepix4 hybrids per board
32 data lines total
PCB (from NIKHEF carrier board)
SAMTEC cable
RD0/SPIDR4++


Platform(s) for
and electronic

Performance



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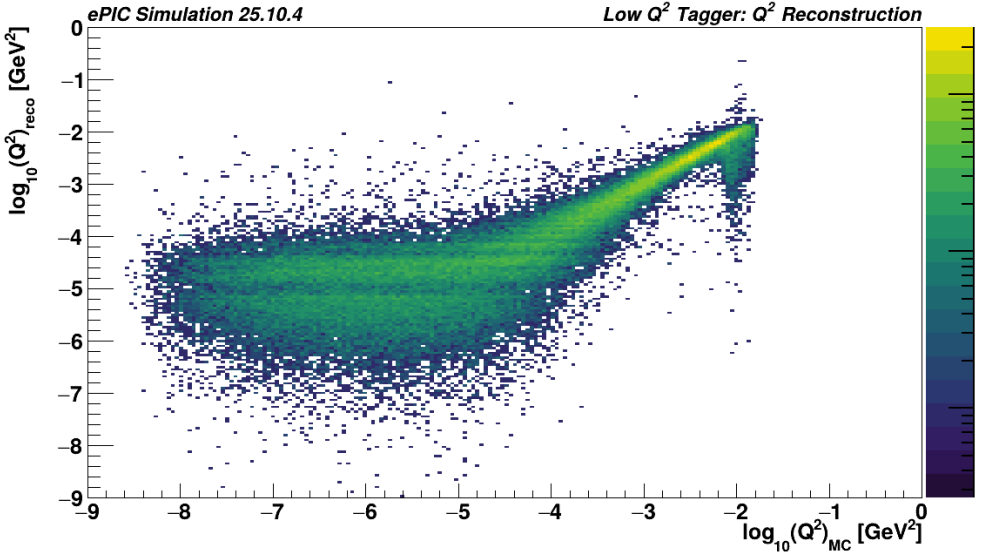

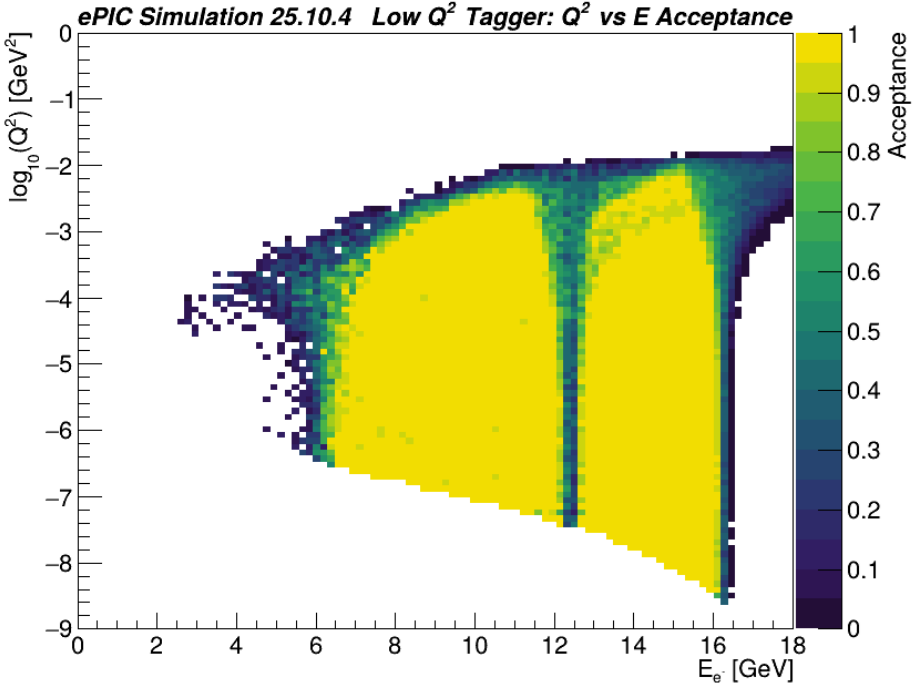

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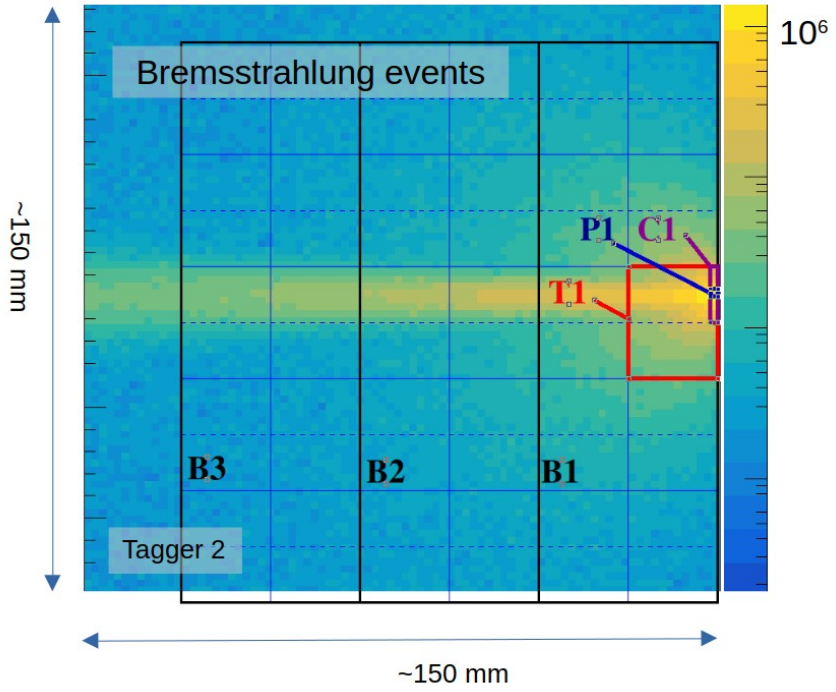
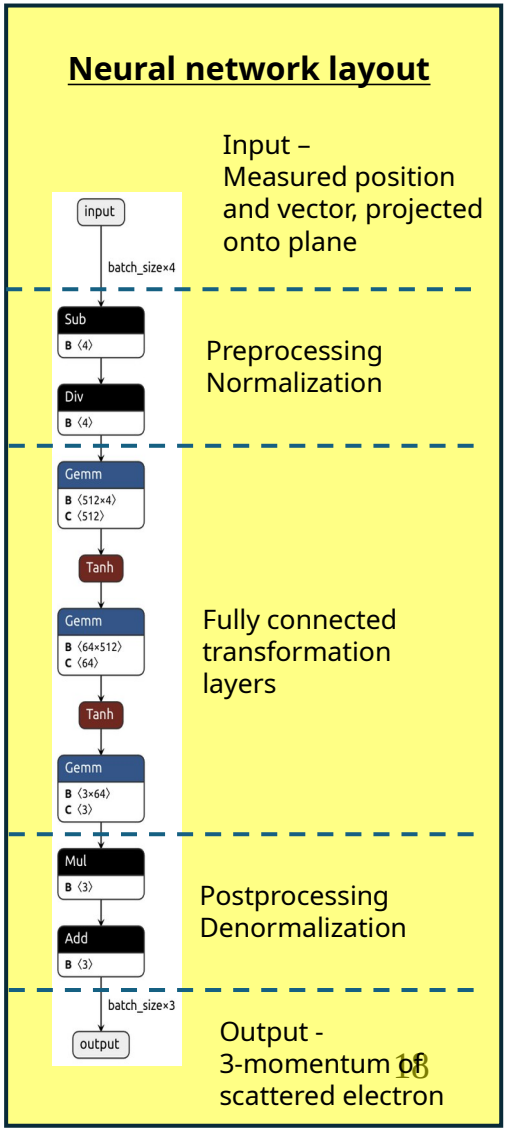


P1: Hottest pixel
C1: Hottest column
T1: Hottest Timepix4 Hybrid
Bn: Boards with tiled Timepix4s

Component	Event Rate	Unit	Data Rate (Gb/s)
Maximum Hits			
Pixel (P1)	70 (100)	kHz	
Double column (C1)	5 (5.5)	MHz	
Timepix4 (T1)	0.6 (2.5)	GHz	38 (163)
Board (B1)	1.5 (5.0)	GHz	96 (326)
Integrated Hits			
Tracker 1	2	GHz	130
Tracker 2	7	GHz	480
Tracker Total	**9**	**GHz**	**600**
Integrated hits in coincidence with hadron (500 Hz)			
Signal	300	MHz	4
Signal + BG + random sample	1500	MHz	$<$ **20**

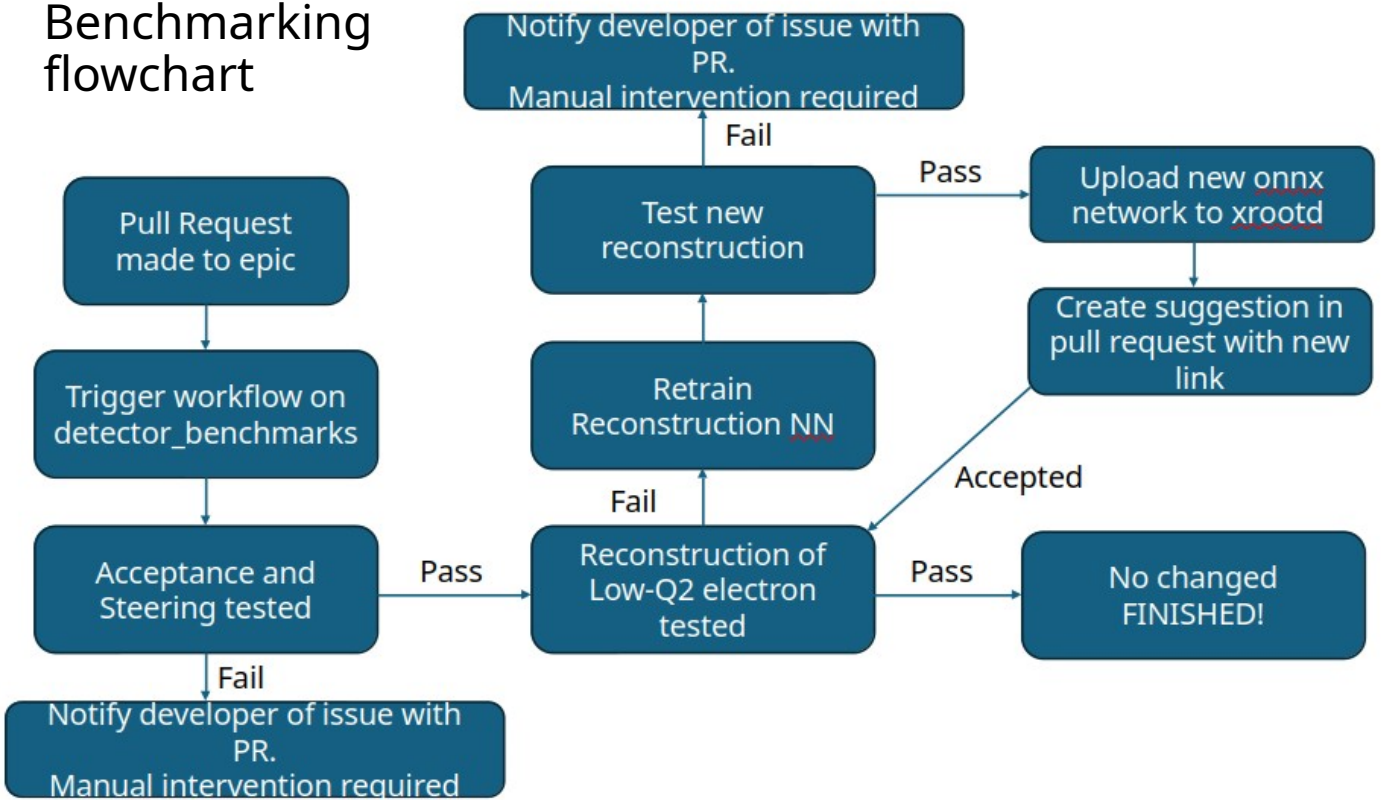
Current status
Simulation, reconstruction, benchmarking

- NN transforms measured vector at tagger into electron momentum at IP.
  - Currently implemented as default method in EICrecon.
- The network is sensitive to, and needs retraining when these change:
  - Beamline optics (Will break reconstruction)
  - Tagger or exit window material (May change resolutions and biases)
  - Tagger layer or station locations (May change resolutions and biases)
  - MC sample (Uneven distribution over the phasespace results in sample bias)
- Benchmark set up to automatically test and retrain NN for any geometry change through the epic/detector_benchmarks CI tests
  - Creates code suggestion on triggering PR to update location of new onnx artifact uploaded by benchmark to xrootd server.

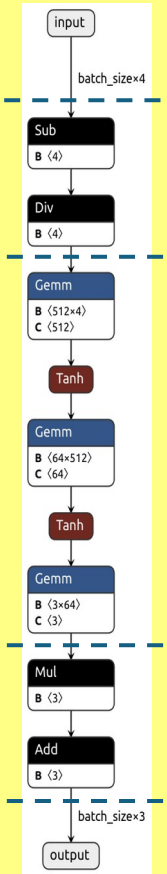


Current status
Simulation, reconstruction, benchmarking

Benchmarking flowchart



Neural network layout



Input –
Measured position and vector, projected onto plane

Preprocessing
Normalization

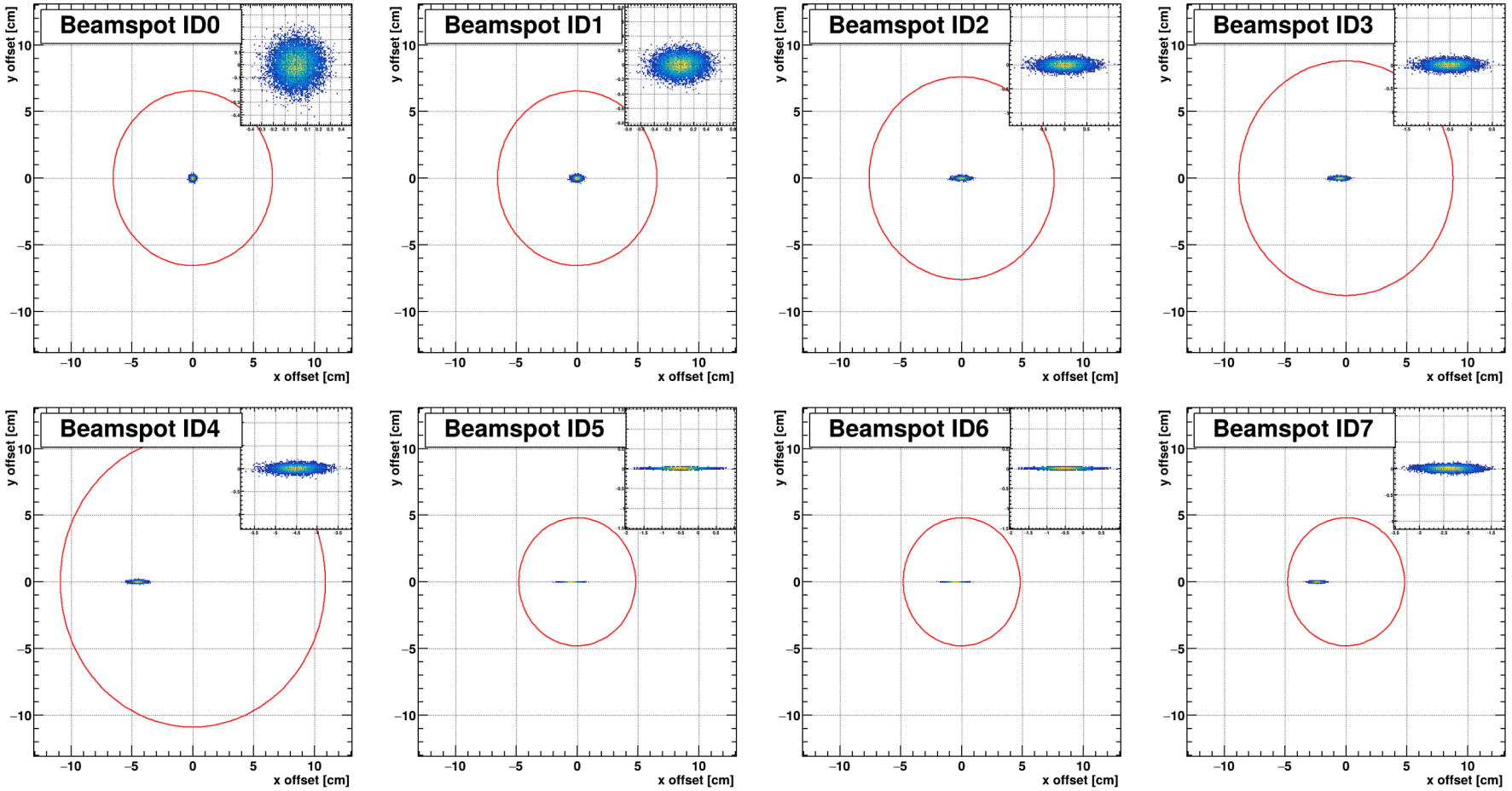
Fully connected transformation layers

Postprocessing
Denormalization

Output -
3-momentum of scattered electron

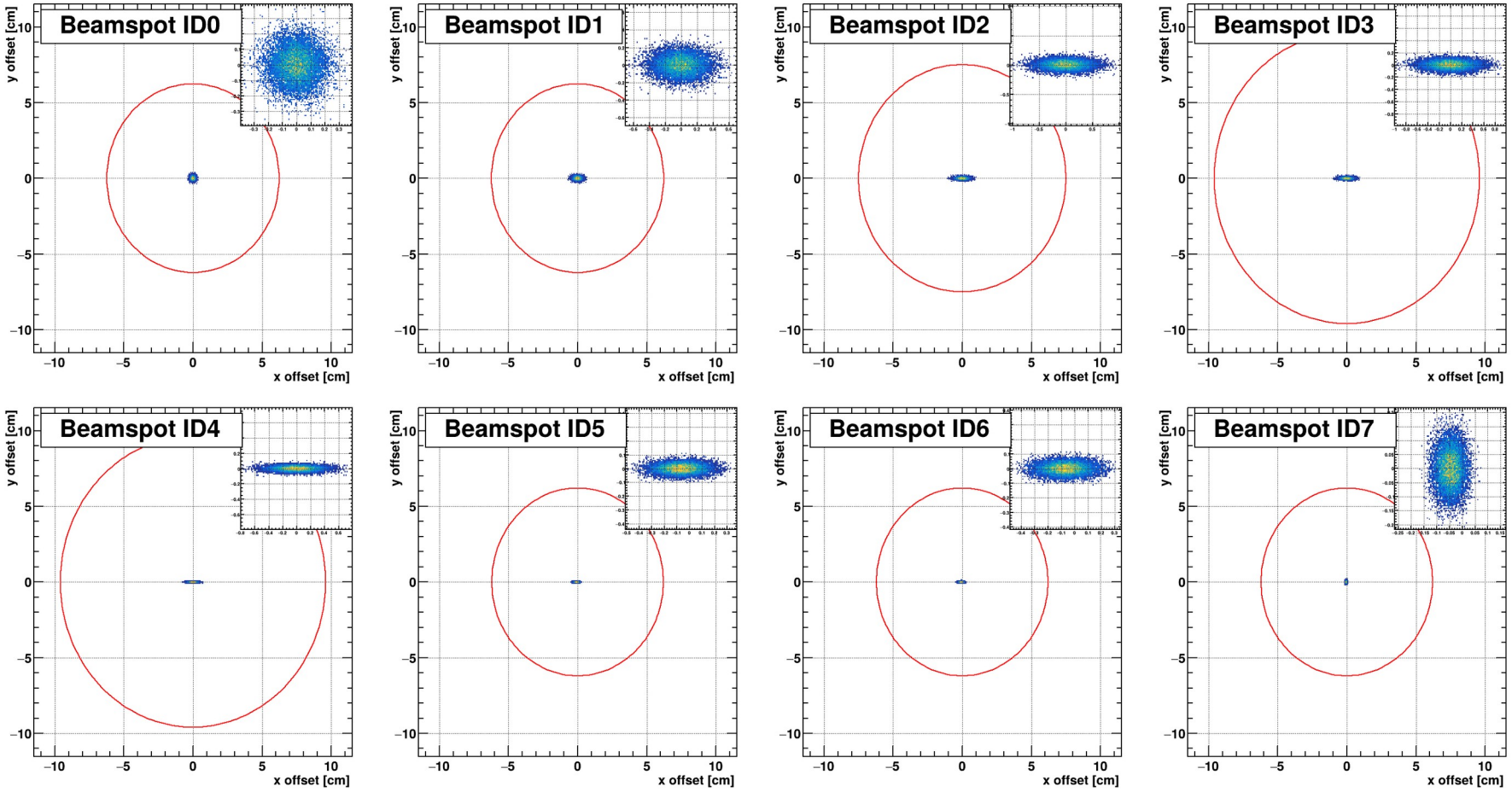
Far Backward Steering and Acceptance

Current Beamline: Beamspot off center of O3eR (ID5)



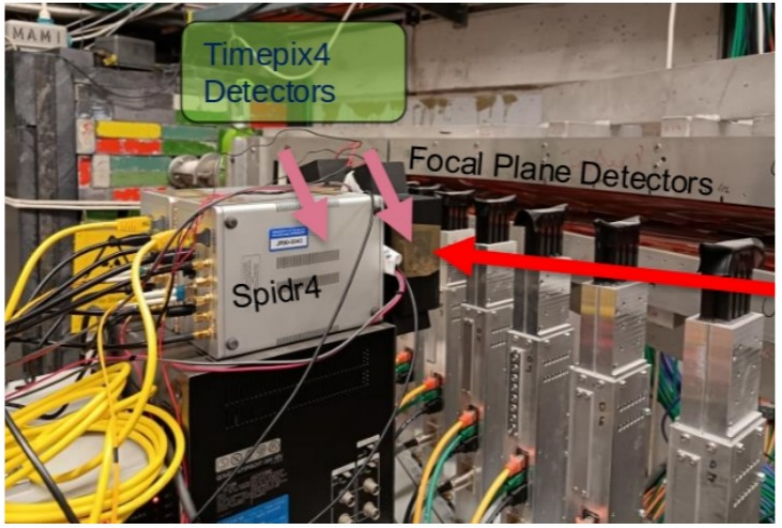
Far Backward Steering and Acceptance

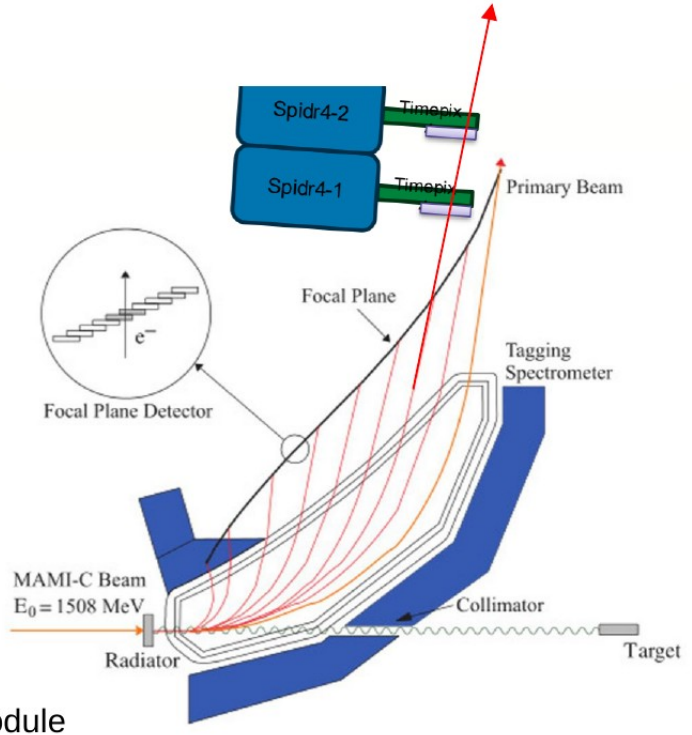
Updated Beamline: Nicely centered beam



Current status
Mainz beam test

Two layer Timepix4 tracker on focal plane of bremsstrahlung tagger

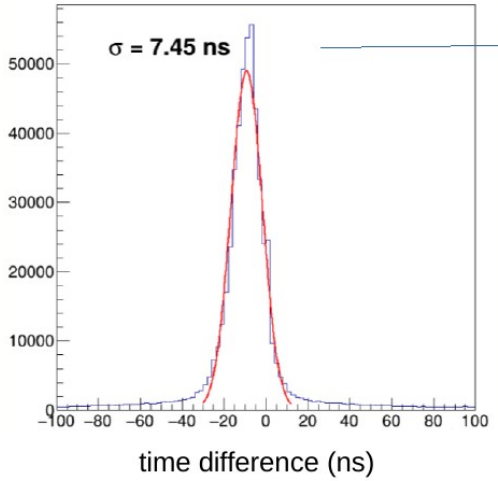




Setup

Control:	1G Wired ethernet
Data:	2 x 10 Gb Fibre readout to server
Sync:	External 40MHz clock via NIKHEF control module
Time ref:	Tagger focal plane scintillator <1ns.

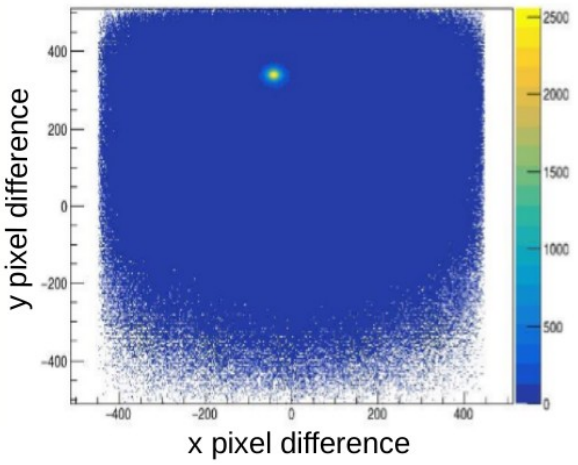
Current status
Mainz test – first results with Timepix4

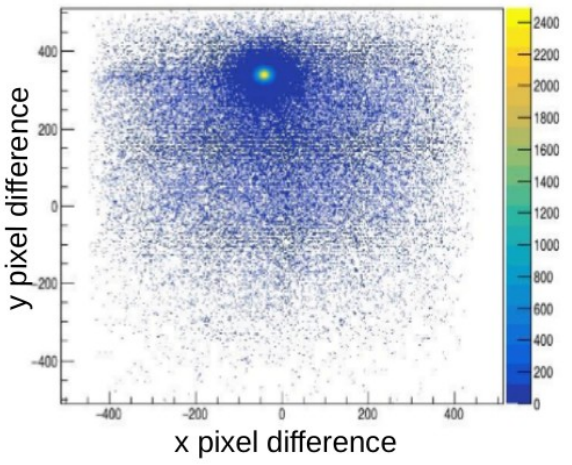


7.34 ns uncorrected (300um Si)

3.5 ns after global walk correction

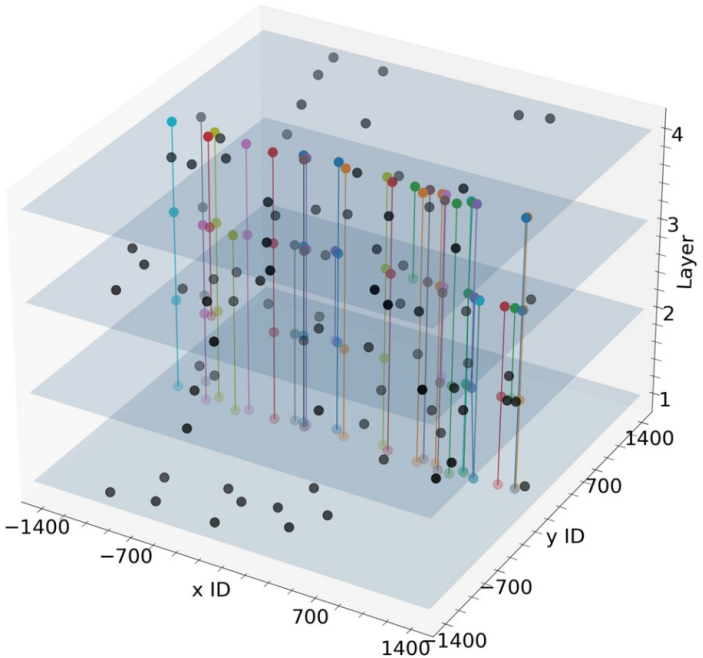
< 0.5 ns expected with 100um Si
after full corrections

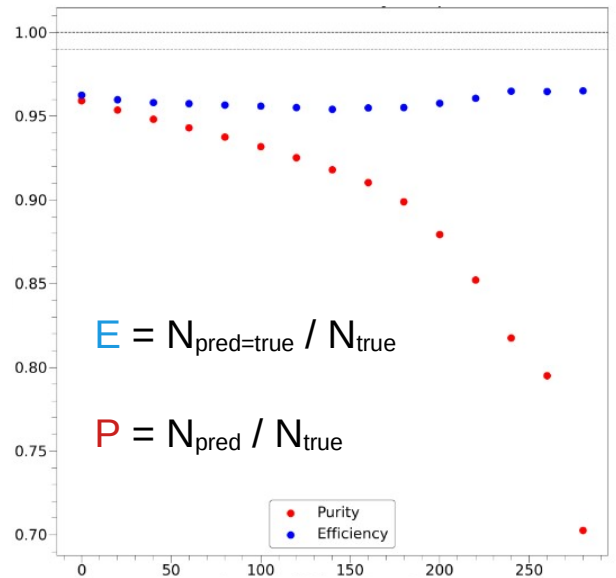




Current status
Tracking

GNN + Object condensation ….. to be implemented on FPGA





No of noisy hits per event

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Next steps
Tracking

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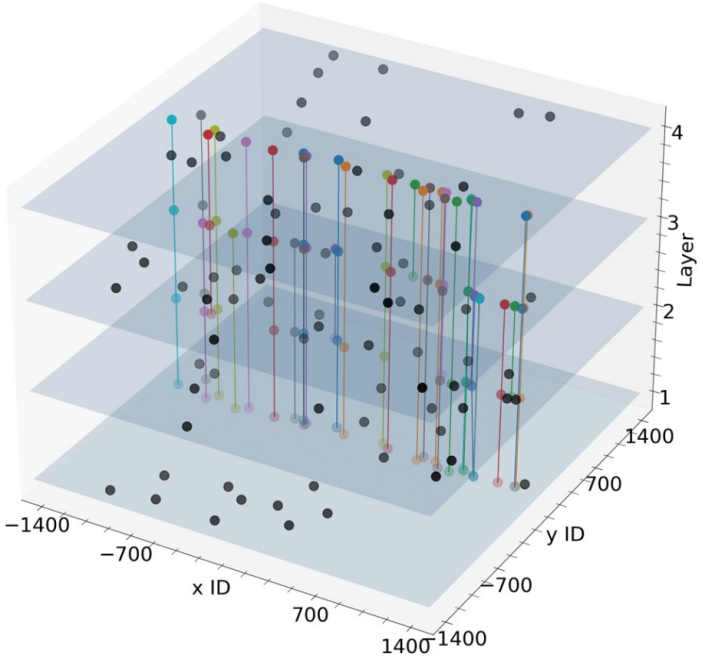

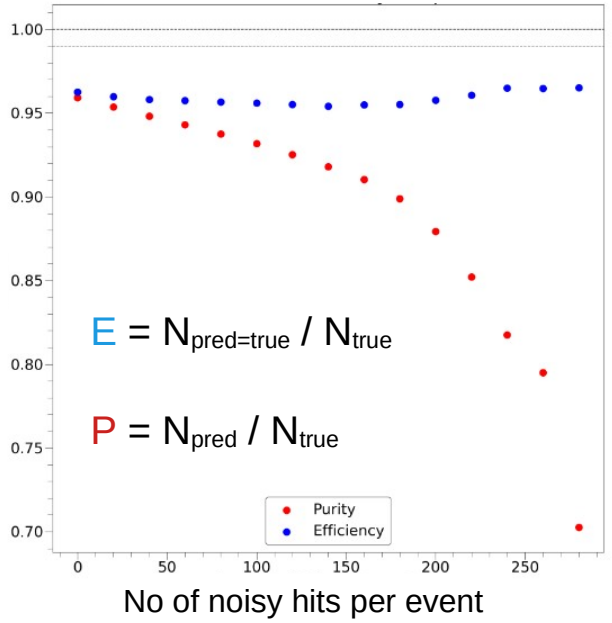

R. Tyson (Newly appointed)

Generalized tracking in high noise environment
(Muon Tomography and EIC)

FPGA

Some lovely new results
… but subject to NDA.

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Next steps
Cooling

Heat per Timepix4: 4.5W
No per Tracker: <144

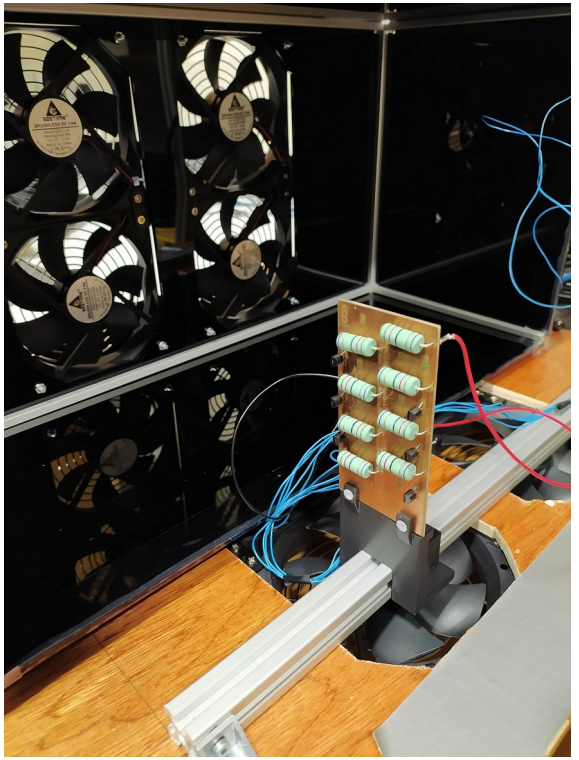
Heat per Tracker: ~500W

Not in Vacuum - Use forced air cooling

Test kit:

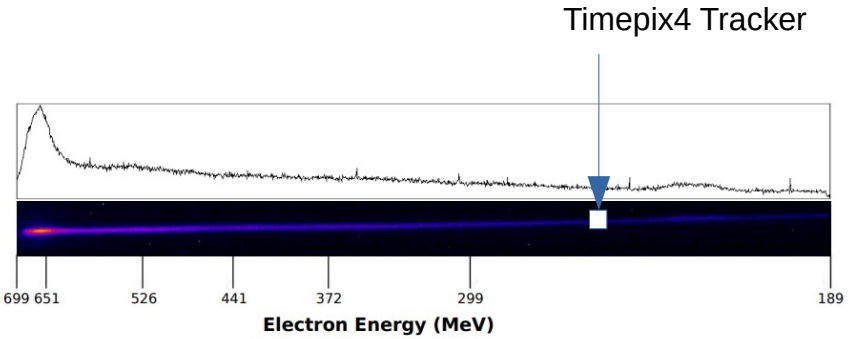
Timepix4: big resistor (TPR)
Layer board: PCB with 8 x TPR + temp sensors

Readout: LED temp displays
Enclosure: Profile + PVC
Cooling: Voltage controlled fans

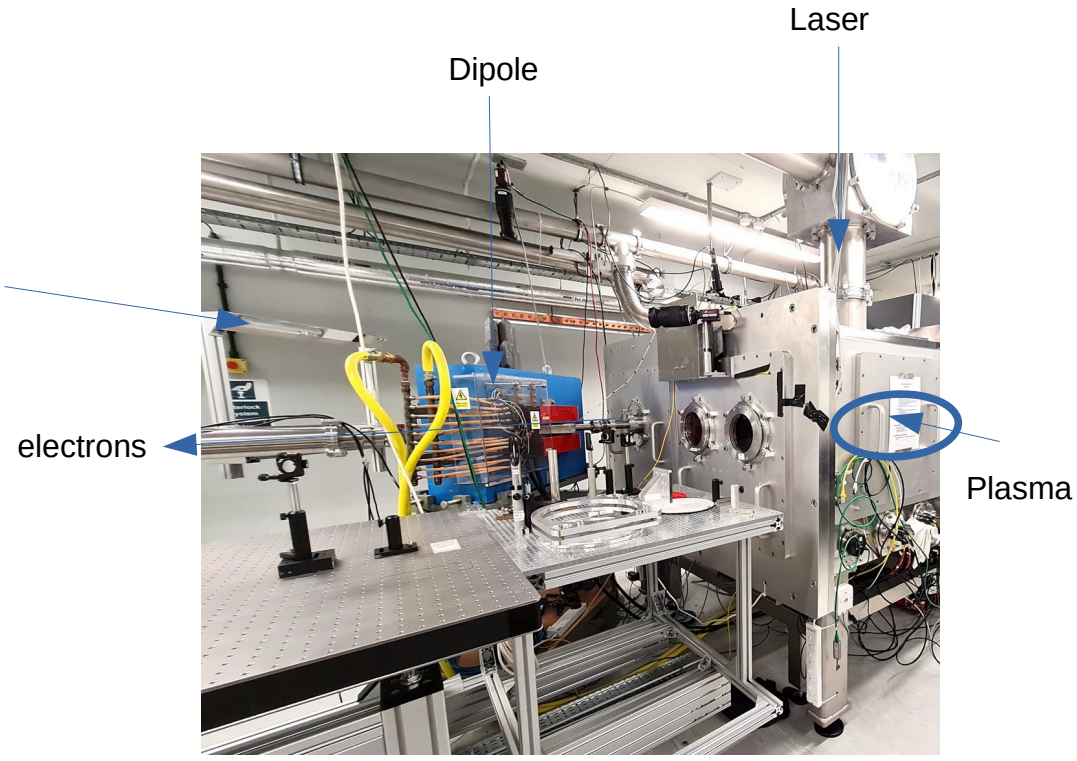


Next steps
Detector tests – could we go to SCAPA

Scottish **C**entre for the **A**pplication of **P**lasma-based **A**ccelerators



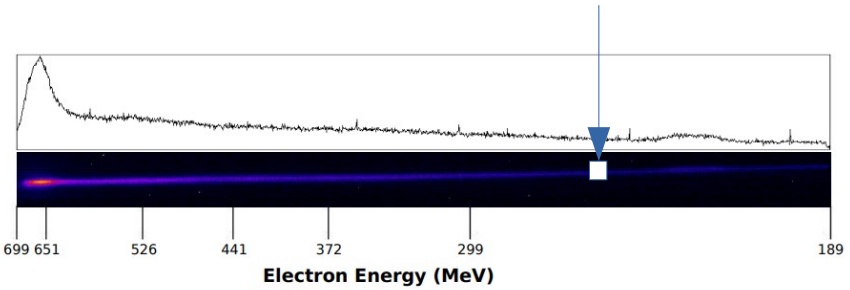
Could we put the tracker after the dipole ?



Next steps
Detector tests – could we go to SCAPA

Scottish **C**entre for the **A**pplication of **P**lasma-based **A**ccelerators

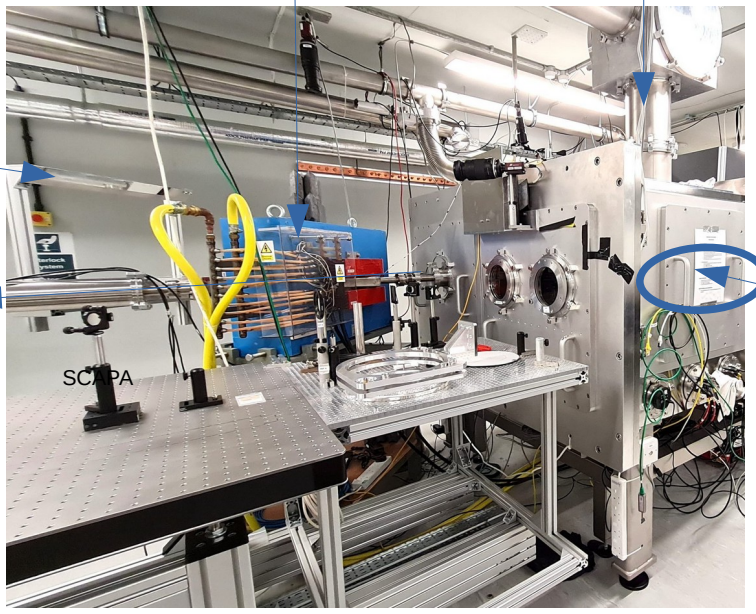
Timepix4 Tracker



Laser

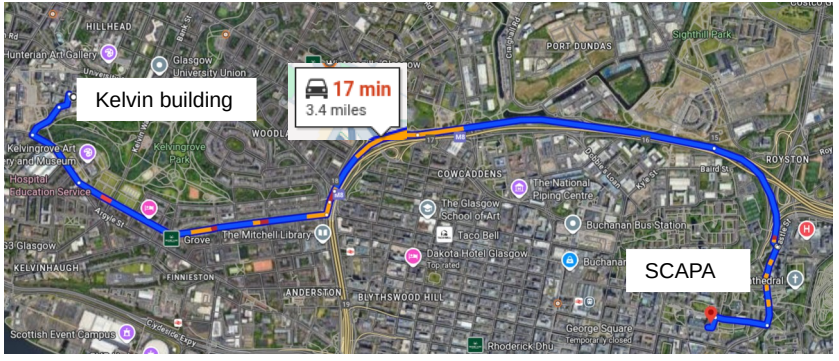
Dipole

electrons



Plasma

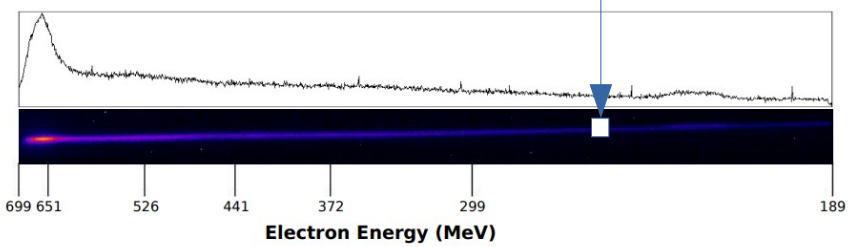
One very big advantage



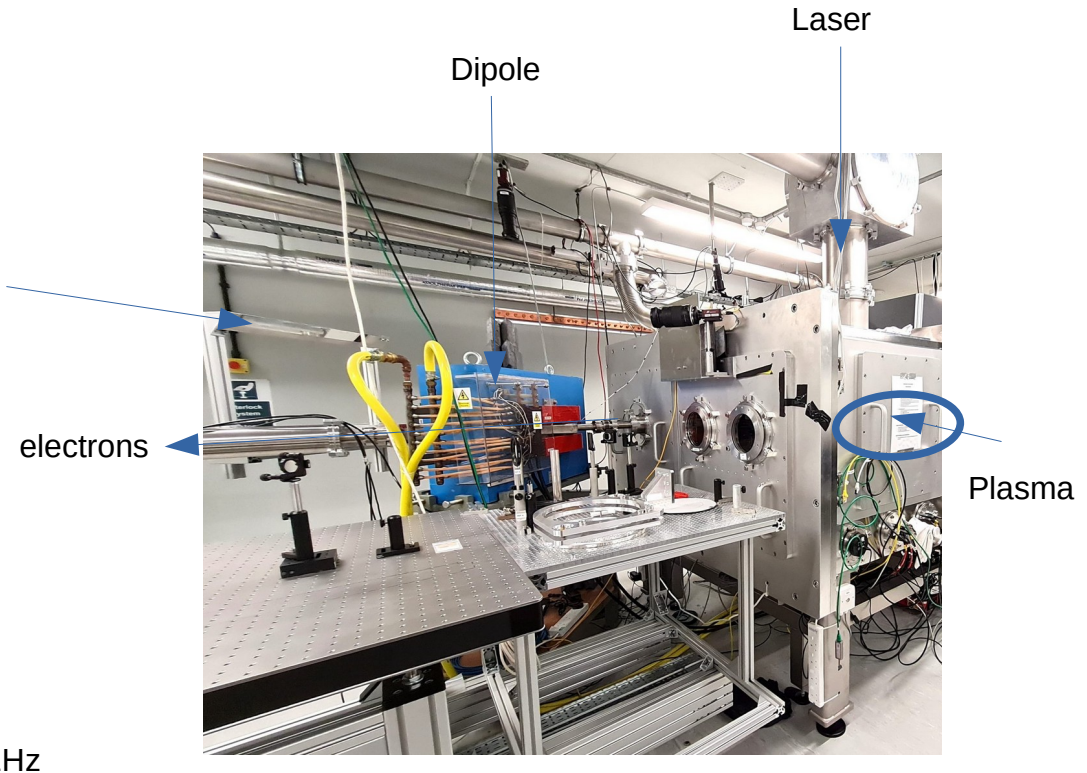
Mainz. Far away …. and with post-Brexit customs rules

Next steps
Detector tests – could we go to SCAPA

Scottish **C**entre for the **A**pplication of **P**lasma-based **A**ccelerators



Maximum electron energy (broadband energy spectrum)	600 MeV
Maximum bunch charge per shot (across entire energy spectrum)	200 pC
Maximum pulse repetition rate	1 Hz
Maximum shots in a day	18,000 (5 hours @ 1 Hz)
Beam diameter at 2 m from source (typical target sample location)	10 mm
Pulse duration at 2 m from source	10 ps



However, it can deliver ~10^9 electrons in a 10ps burst at 1Hz

Turn it down ? Make a secondary beam ? Visiting SCAPA for discussions in Jan 2026

Next steps

……

Final design of beamline (ePIC)
    Final design of trackers

More tests – SCAPA or overseas
    New 4 layer test telecsope
    Firefly readout fancy FPGA

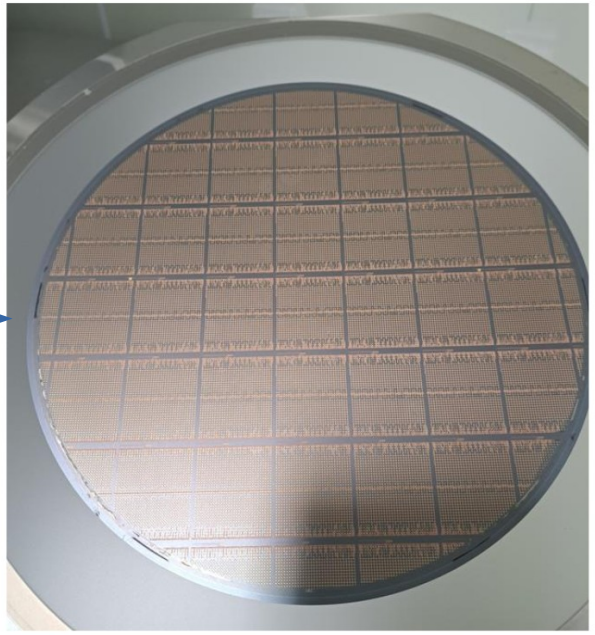
TSVs (Through Silicon Vias)

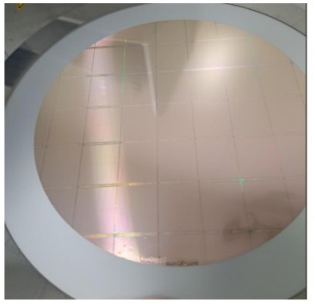
Layer board to be designed

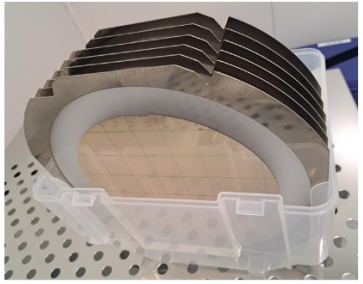
Clustering, tracking, FGPA, pipelining

DAQ Software chain

Timepix4V0, V1, V2 and V3 Processed wafer delivered by LETI in December







Summary

Design concept for Tracker is complete.

Technology is Timepix4

First beam tests and readout tests completed

Performance (from simulation and design and tests)
- Well within requirements.

Next steps:
- More tests
- TSVs
- PCB design and build
- Mech design