# The University of Bergen Proton CT project Update

Pierluigi Piersimoni
*for the*
Bergen pCT collaboration



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UNIVERSITY OF BERGEN

**Organization**

- University of Bergen, Norway
- Helse Bergen, Norway
- Western Norway University of App. Sci.
- Wigner Institute Budapest, Hungary
- DKFZ Heidelberg, Germany
- Heidelberg Ion-Beam Therapy Center (HIT)
- Utrecht University, The Netherlands

**Financing**

- 44 MNOK,
  5 years (2017-2021)

**Status**

- Finishing the optimization of the design
- Start mass-production of ALPIDE chips
- Sensor characterization

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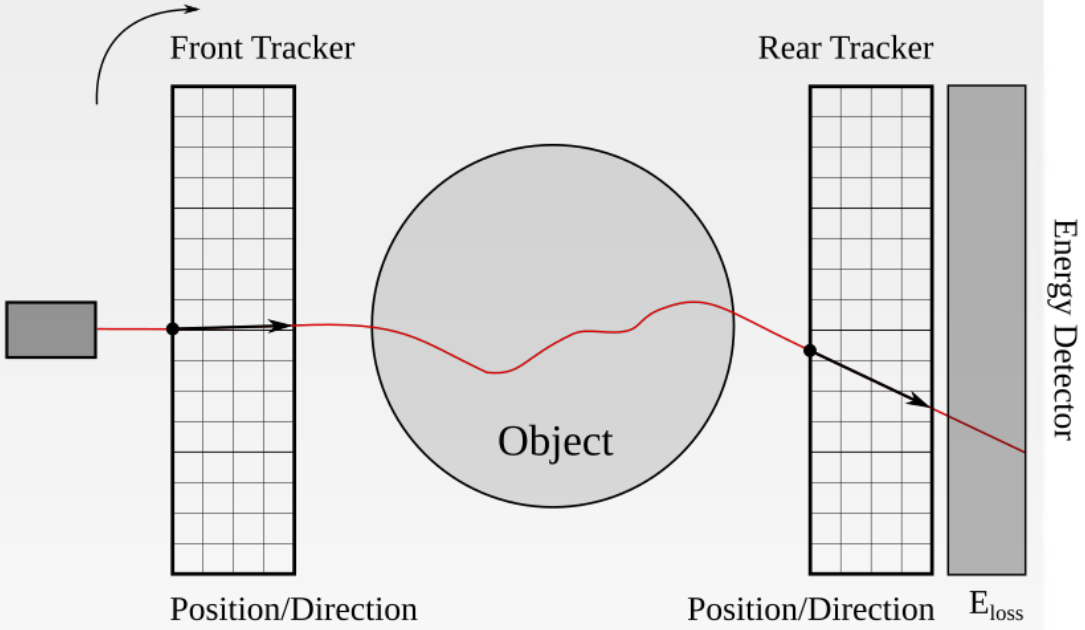
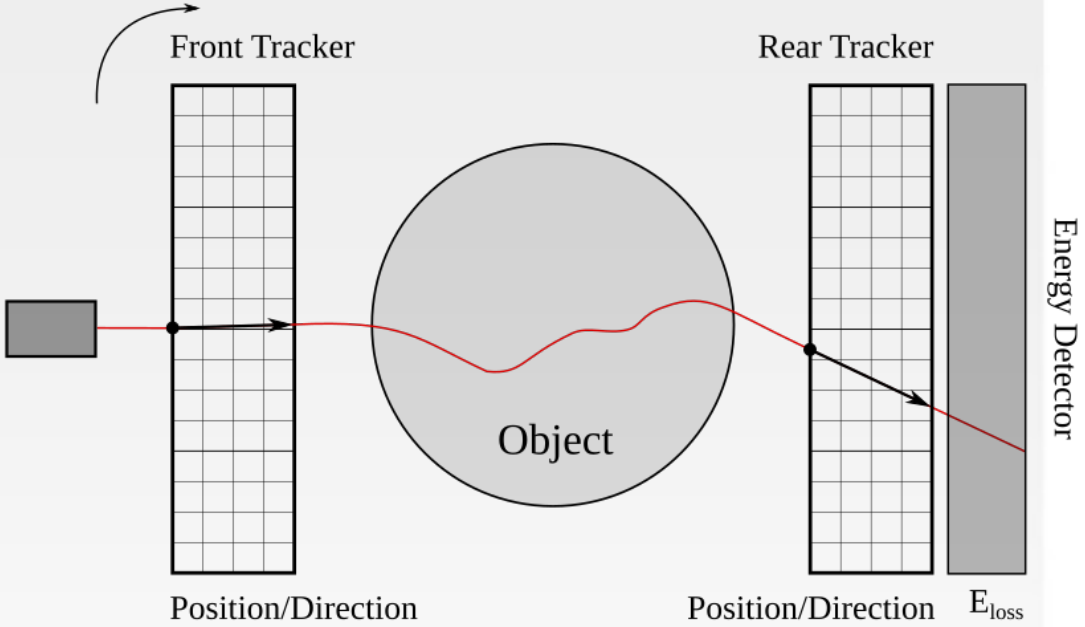
**The Norwegian government has decided to build two particle therapy facilities (Oslo, Bergen), to be operational by 2022**

# The pCT imaging concept



# The pCT imaging concept

Trajectory and residual energy of each **single particle history** crossing an object from different directions



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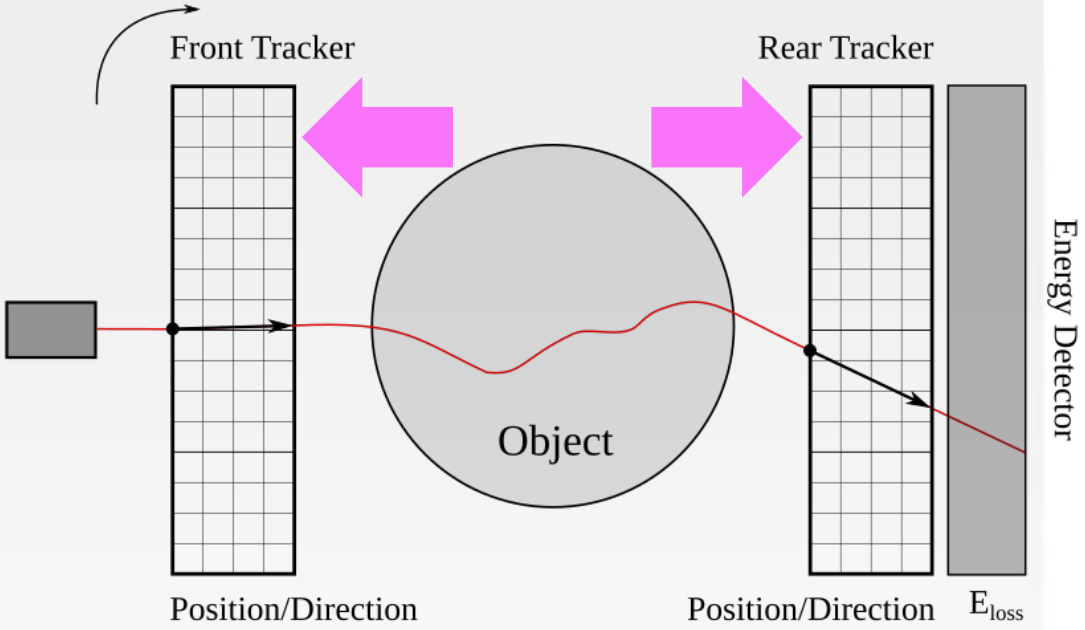
Trajectory and residual energy of each **single particle history** crossing an object from different directions

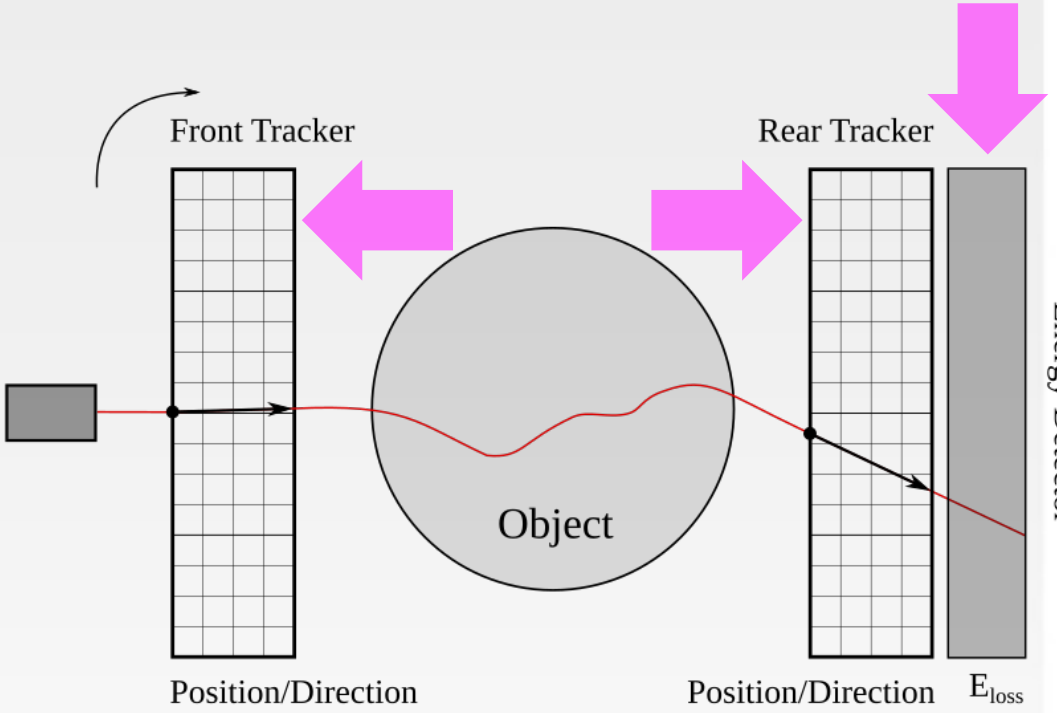
- **Tracker system:**
  entrance and exit points



# The pCT imaging concept

Trajectory and residual energy of each **single particle history** crossing an object from different directions

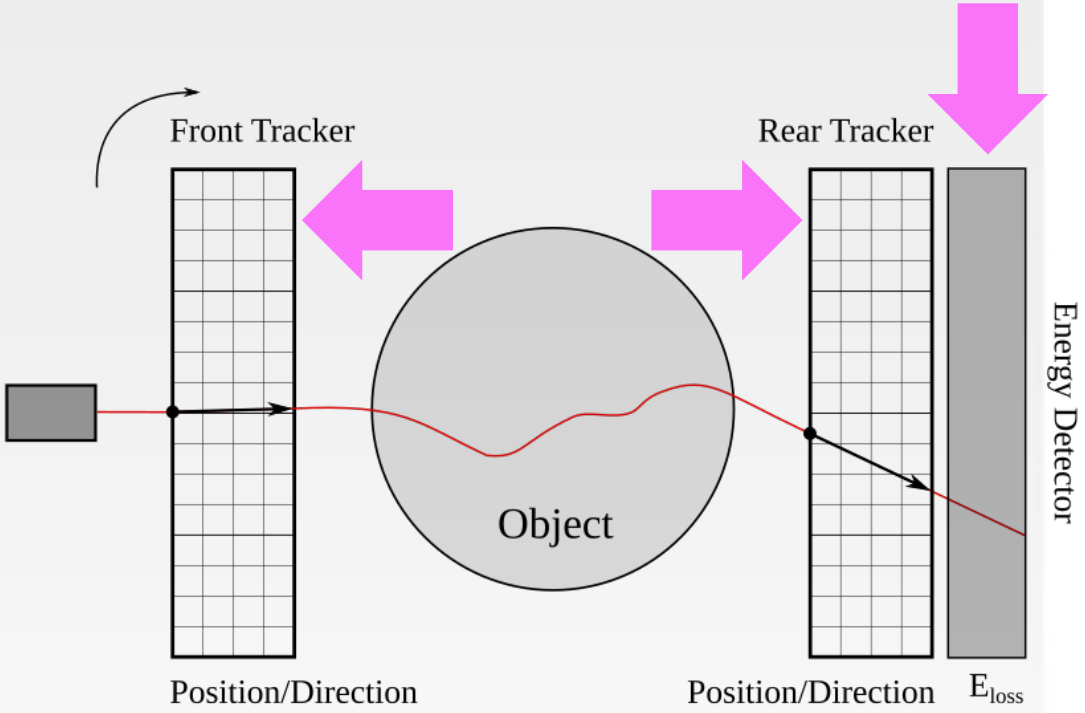
- **Tracker system:**
  entrance and exit points
- **Energy detector:**
  residual energy



# The pCT imaging concept

Trajectory and residual energy of each **single particle history** crossing an object from different directions

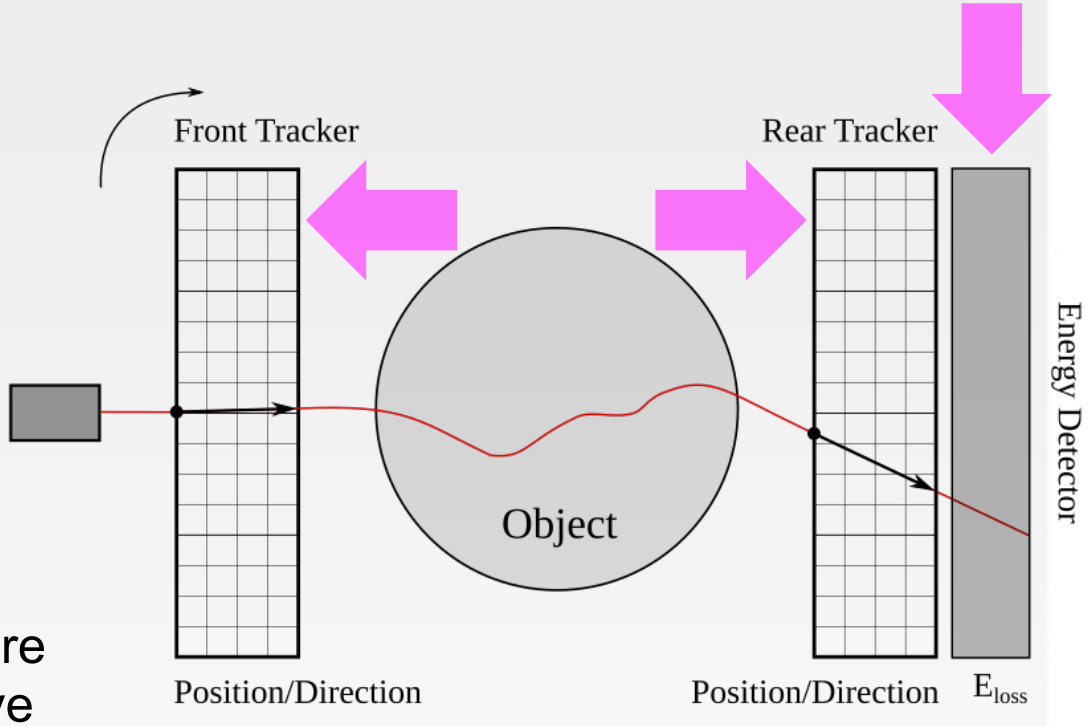
- **Tracker system:** entrance and exit points
- **Energy detector:** residual energy
- Residual Energy into water equivalent path length (**WEPL**)



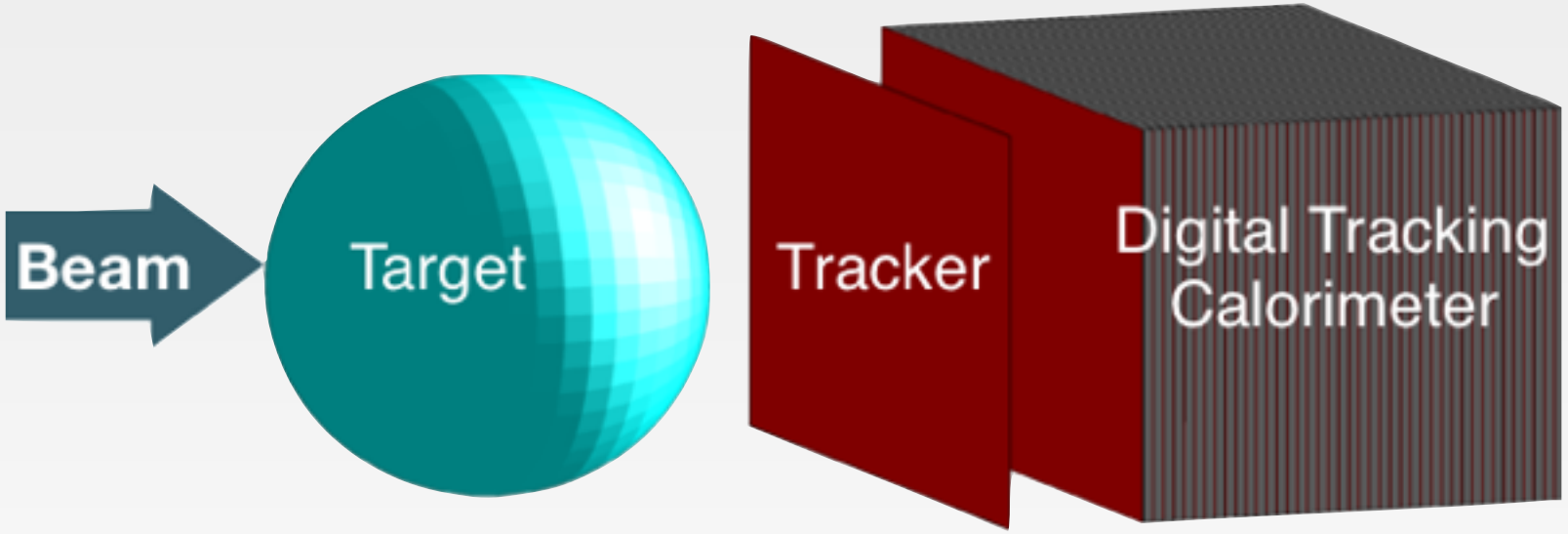
# The pCT imaging concept

Trajectory and residual energy of each **single particle history** crossing an object from different directions

- **Tracker system:** entrance and exit points
- **Energy detector:** residual energy
- Residual Energy into water equivalent path length (**WEPL**)
- WEPL and path information are used to reconstruct the relative stopping power (**RSP**) of each voxel in the target through iterative algorithms



# pCT at Bergen



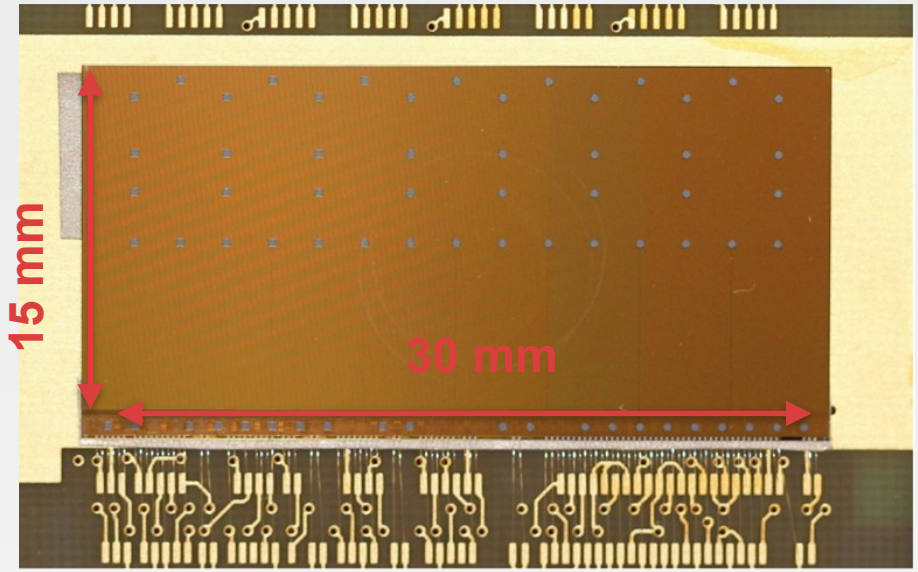

No Front Tracker
assuming thin pencil
beams
direction and position

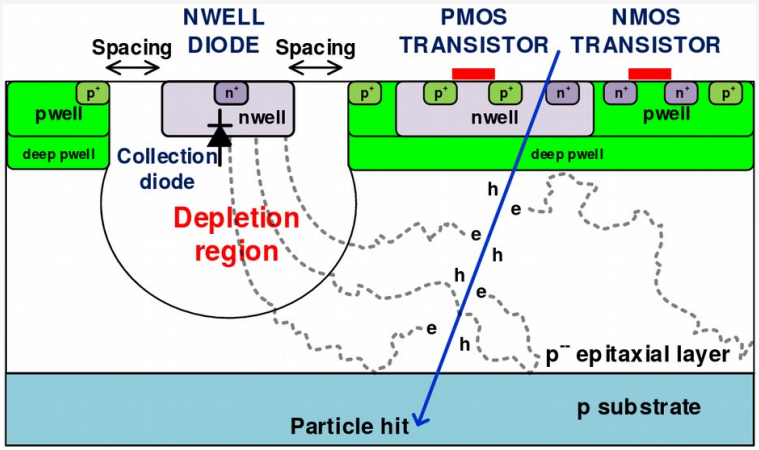
Measure particles
exit position and
direction

Track particles to find
range

# The ALPIDE chip

- The ALPIDE* pixel sensor is a CMOS Monolithic Active Pixel Sensor (MAPS)
- Chip size: 30 mm x 15 mm
- Pixel size: ~ 28 x 28 $\mu m^2$
- Integration time: ~4 µs
- On-chip data reduction




Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

# Design Optimization for the new prototype

**Geometry**

- front area: 27 cm x 18 cm (9 x 12 ALPIDEs per layer)

**longitudinal segmentation**

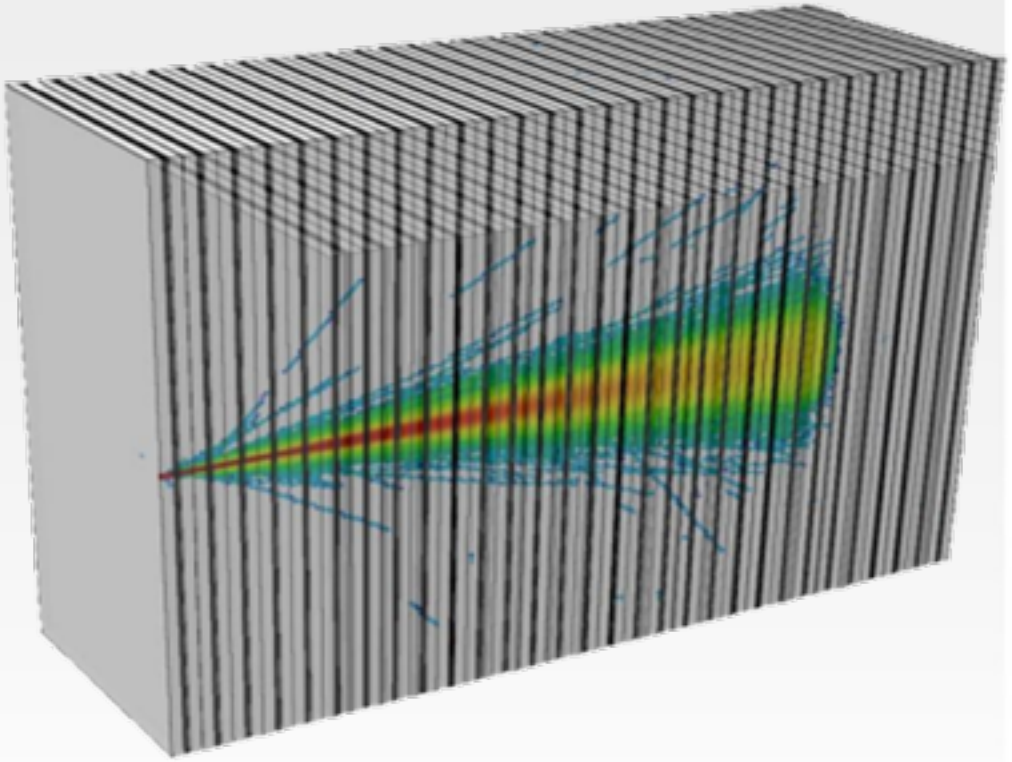
- 41 sensitive absorber layers

**absorber**

- energy degrader
- mechanical carrier
- cooling medium

material choice: Al

thickness: 3.5 mm



Pettersen, H.E.S et al., 2019

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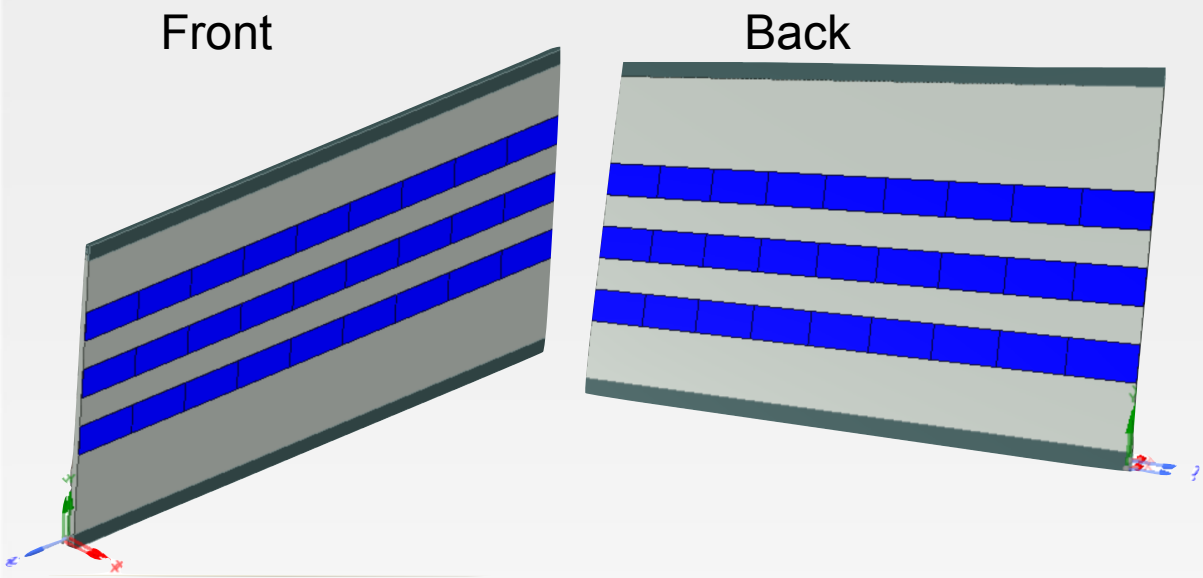


Sensitive area (placement of chips)
12 Rows (6+6), each with 9 chips side-by-side
allowing good temperature distribution

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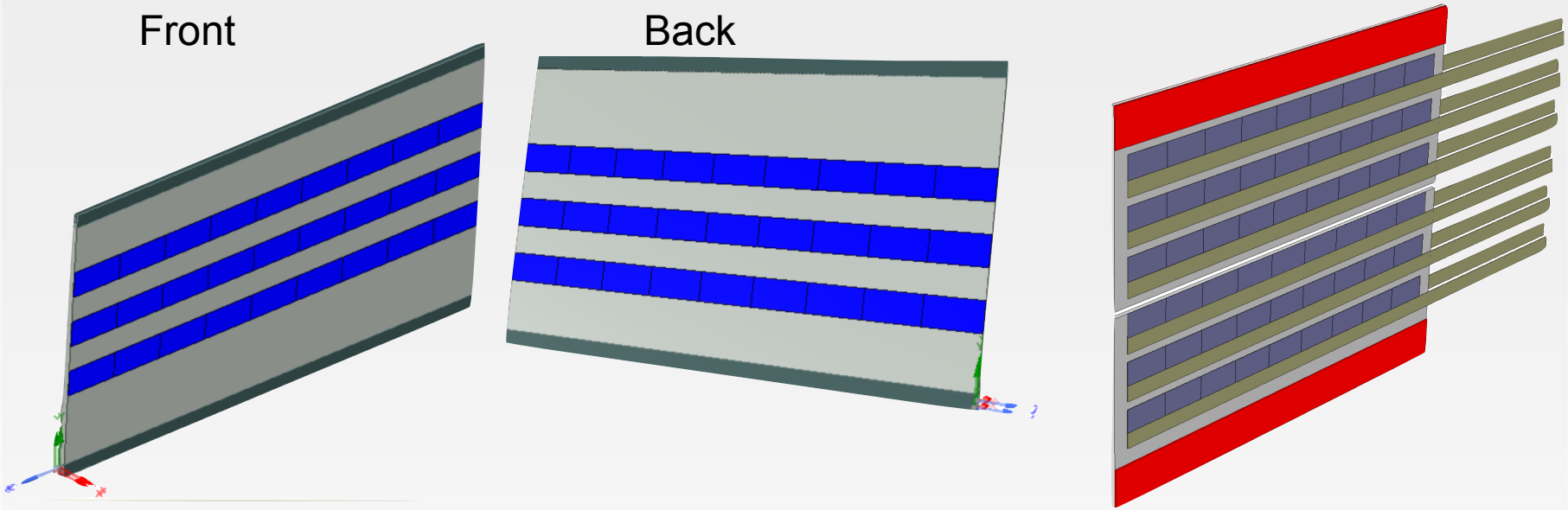


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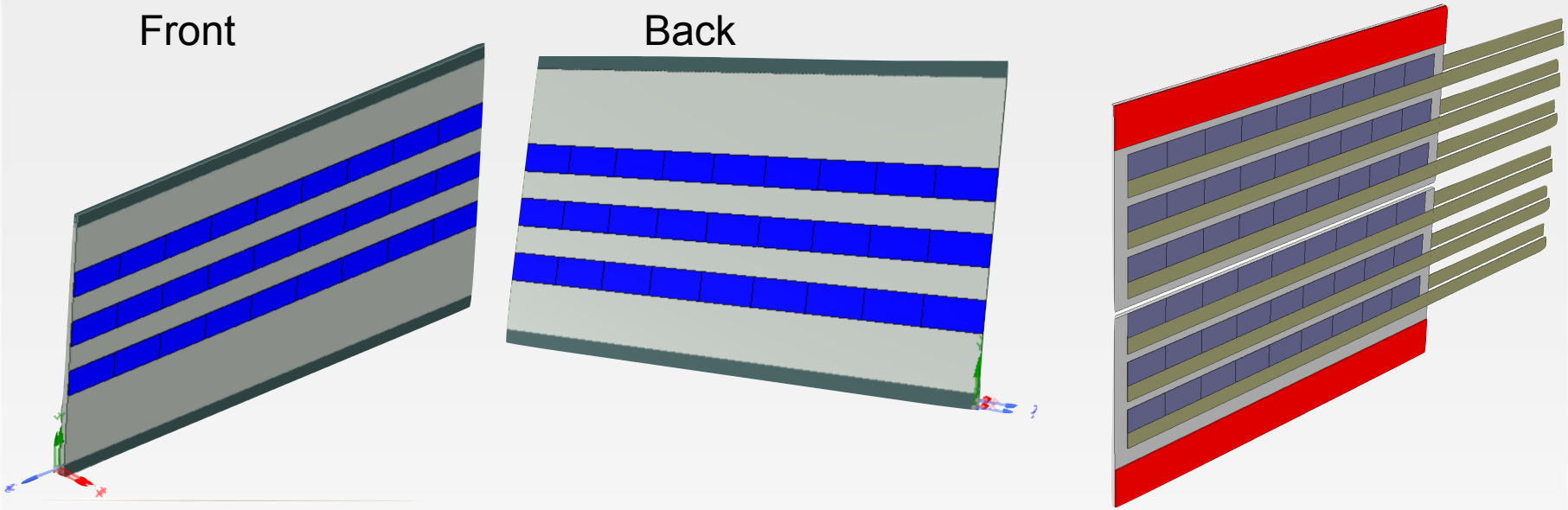



Sensitive area (placement of chips)
12 Rows (6+6), each with 9 chips side-by-side
allowing good temperature distribution

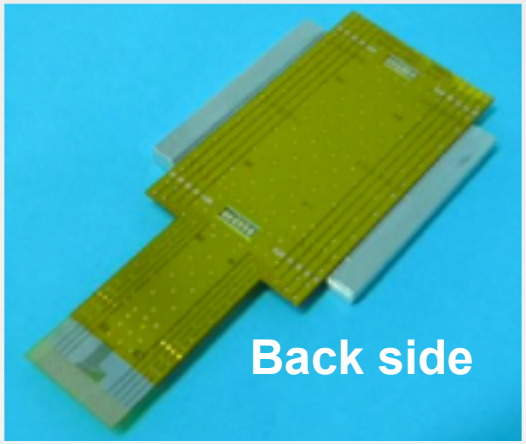
# Electronics

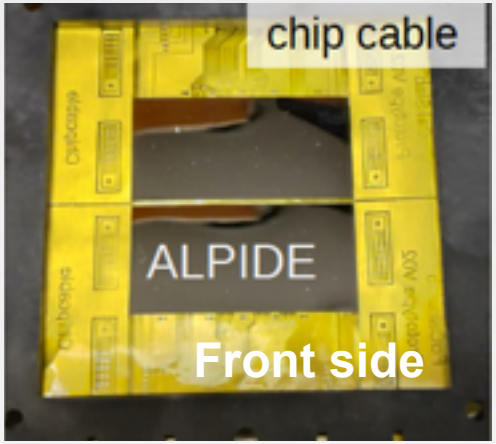
- ALPIDE mounted on thin flex cables:
- Aluminum-polyamide dielectric
- (30 um Al, 20 um plastic)

**Design and production:**

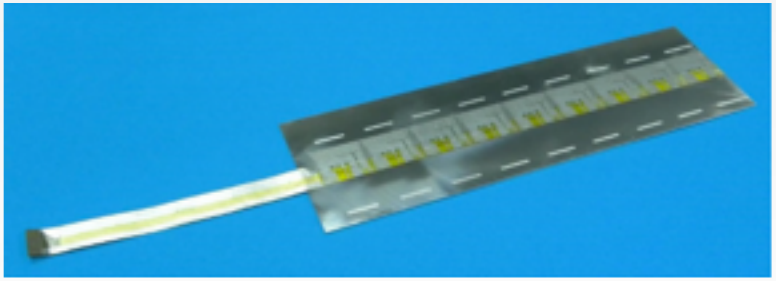
Utrecht University, The Netherlands and LTU, Kharkiv, Ukraine

**Intermediate prototype**
chip cable with two ALPIDEs



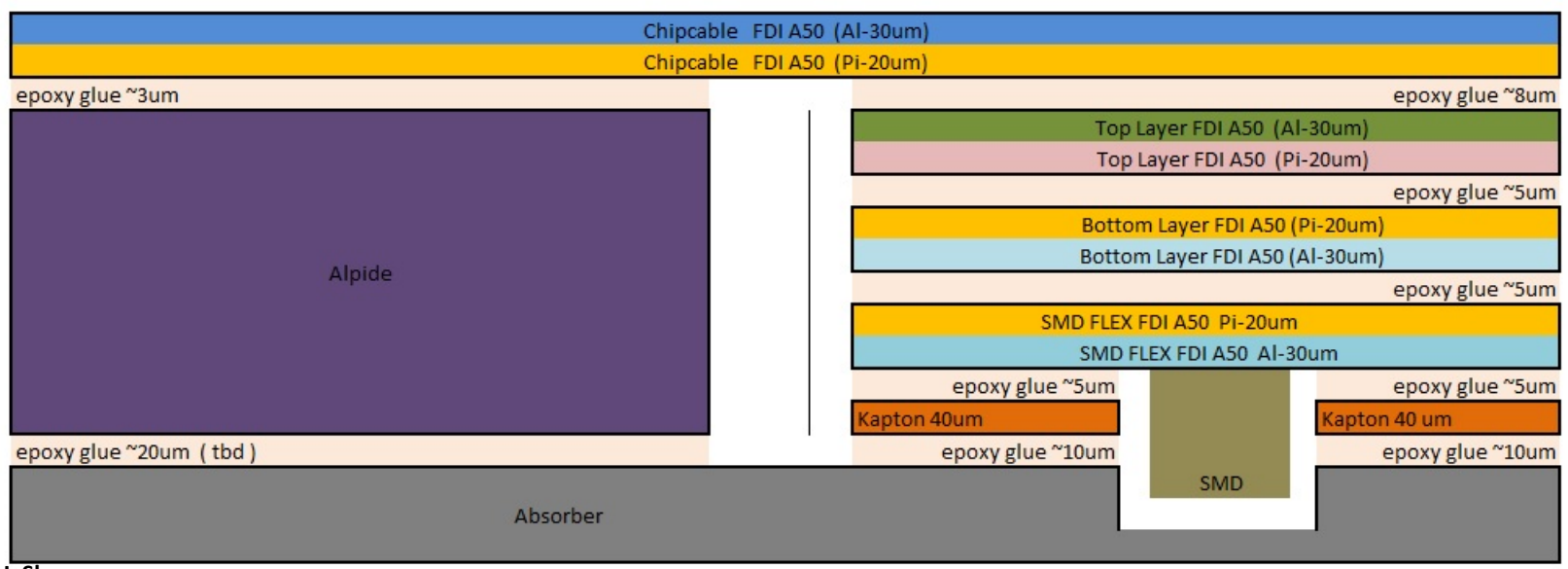

**Final system**



Flexible carrier board modules
(1 x 9 chips)

Flexible carrier board modules
(3 x 9 chips)

# Design Optimization for the new prototype




**Offered by LTU, Slava**

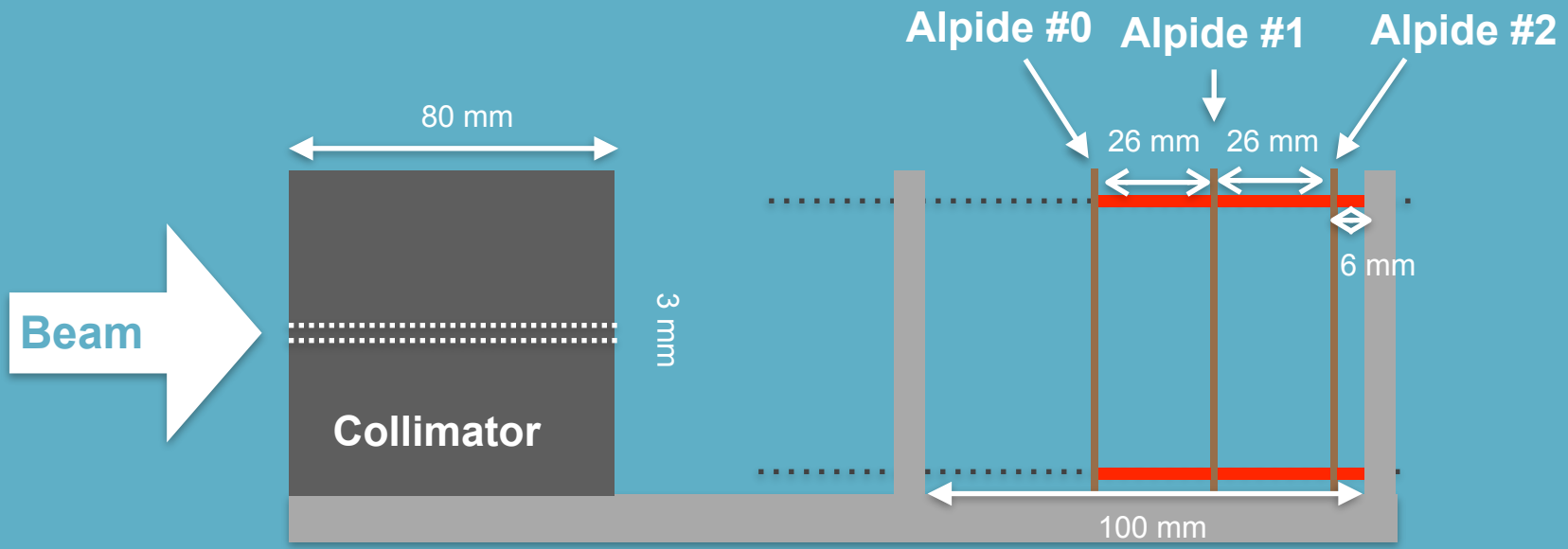
- Chip size = 1.5cm x 3cm
- Sensitive area = 18cm x 27cm

- Space for data readout strip
- Cooling methods & coolant channel

- Homogeneity

# Experiment at HIT with 3 Alpide chips

## July 2018



# Experiment at HIT with 3 Alpide chips

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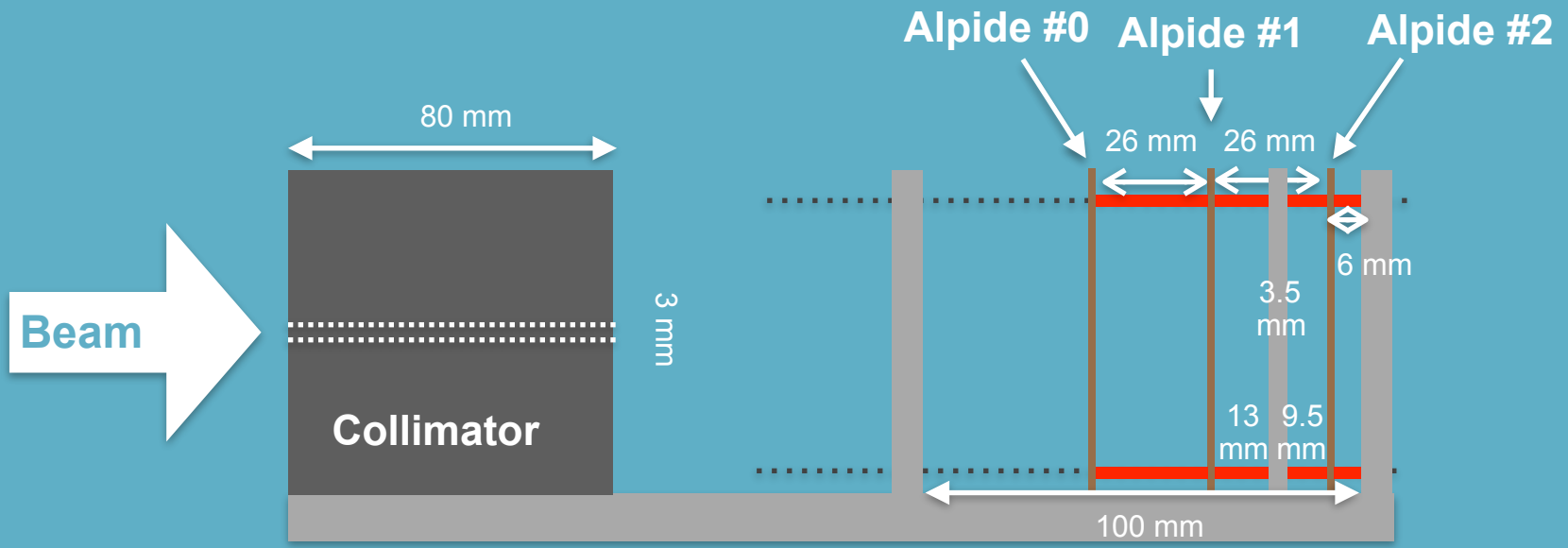

# Experiment at HIT with 3 Alpide chips

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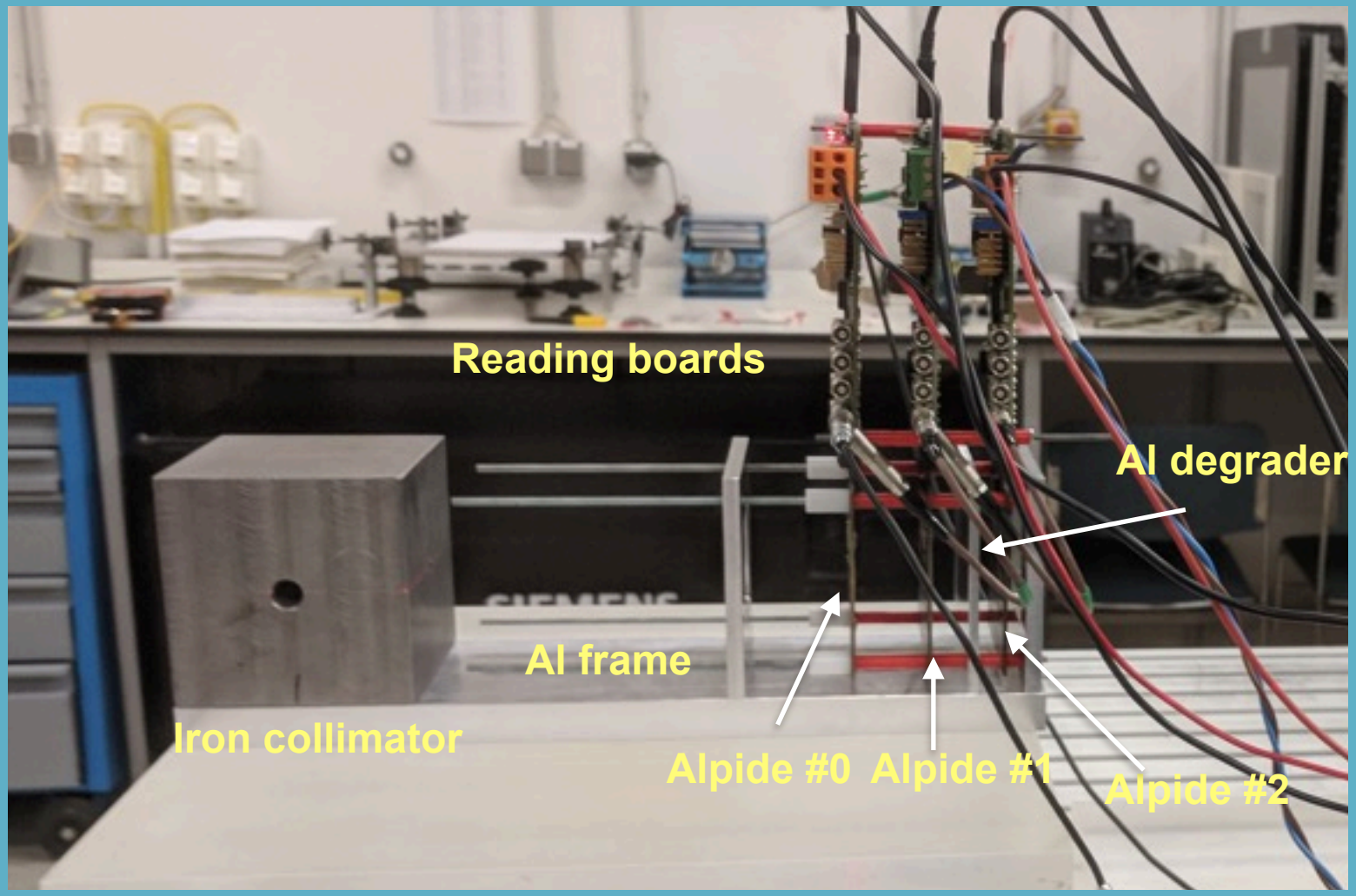


# Helium ions

**5 Energies (FWHM)**

- 220.5 MeV/u (10.1 mm)
- 200.38 MeV/u (10.2 mm)
- 50.57 MeV/u (20.6 mm)
- 100.19 MeV/u (12.9 mm)
- 150.11 MeV/u (11.1 mm)

**Triggering**

- 10 μs, 30 μs

**Collimator**

- 3 mm, 10 mm

**Beam**

- 12 s extraction time
- ~100 ±50 kHz intensity hitting the collimator

# Protons

**3 Energies (FWHM)**

- 221.06 MeV (12.6 mm)
- 200.11 MeV (12.8 mm)
- 48.12 MeV (32.7 mm)

**Triggering**

- 30 μs

**Collimator**

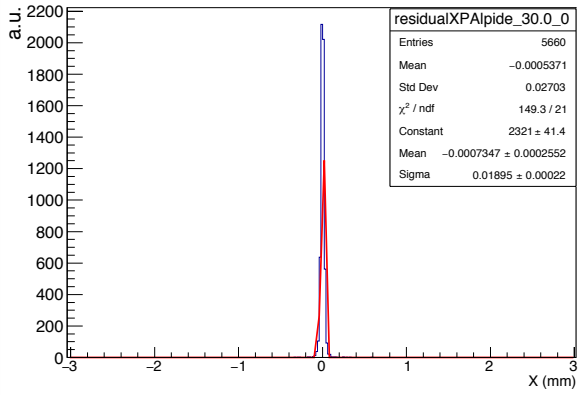
- 3 mm

**Beam**

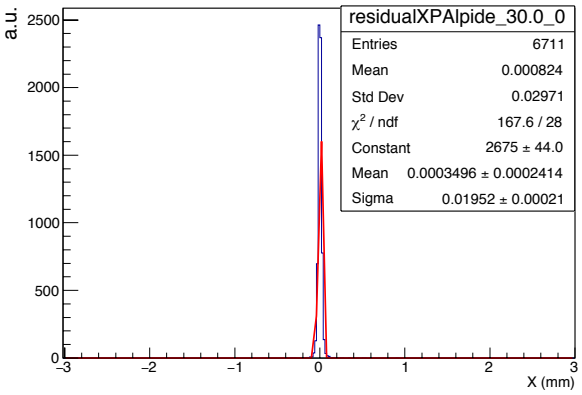
- 12 s extraction time
- ~100 ±50 kHz intensity hitting the collimator

# Results - Alignment

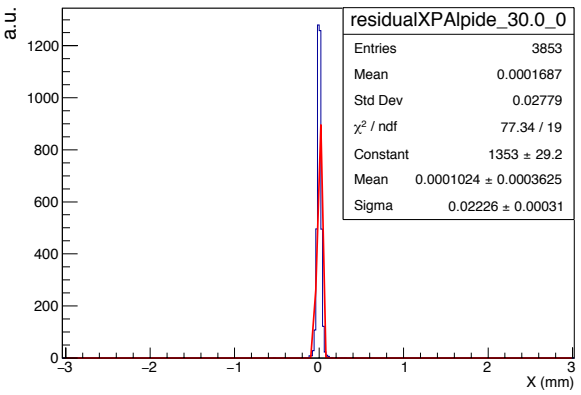
220 MeV/u



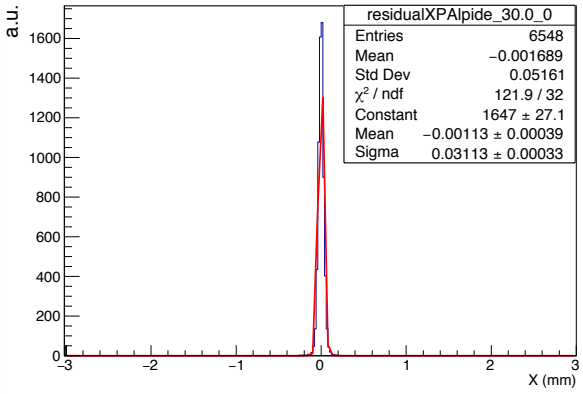

200 MeV/u



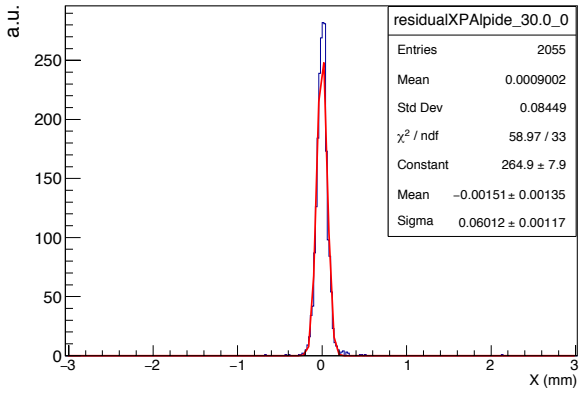

150 MeV/u

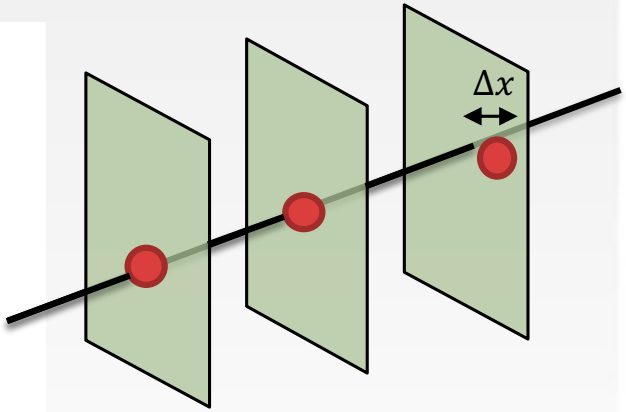



100 MeV/u




50 MeV/u



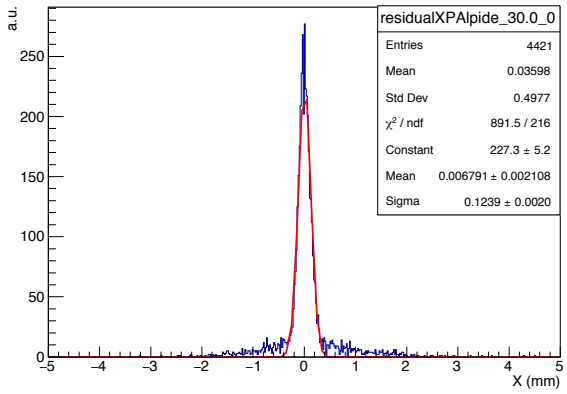

- 5 Energies
- Triggering:10 μs

- Collimator: 3 mm
- ~80 kHz $^4$He rate

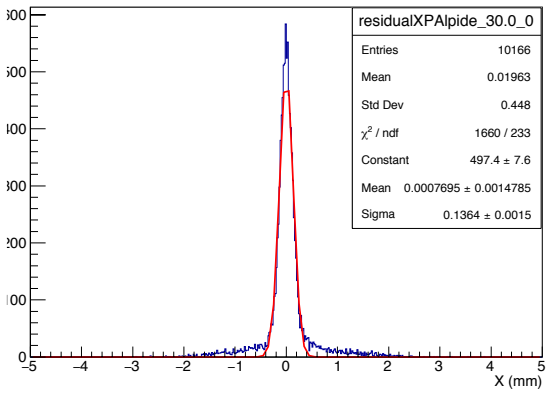
- Δx<0.06 mm
- **NO Al degrader**

# Results - Alignment

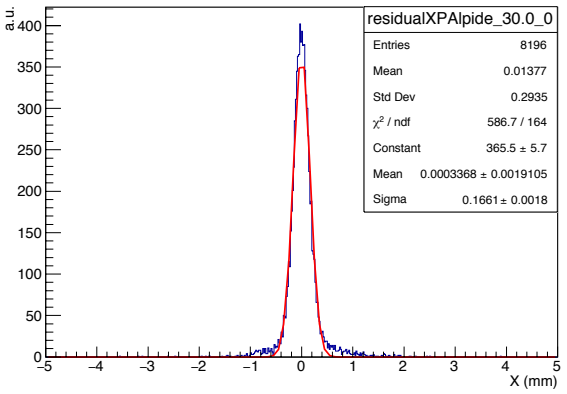
220 MeV/u



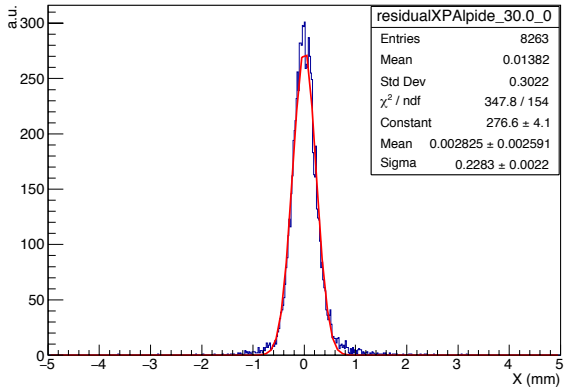

200 MeV/u



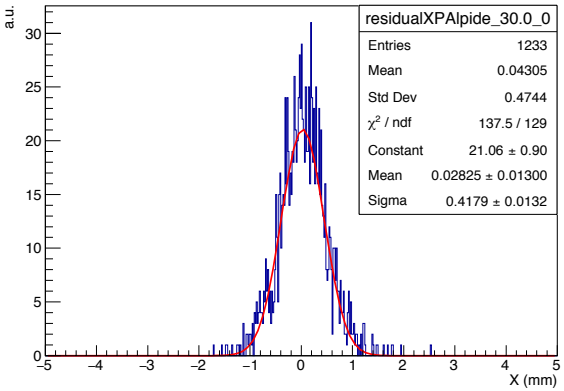

150 MeV/u

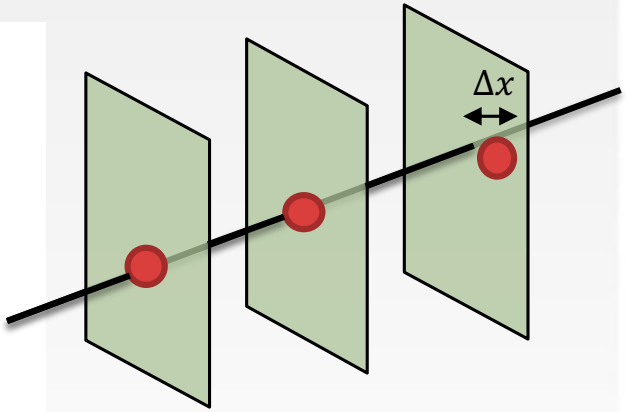



100 MeV/u




50 MeV/u



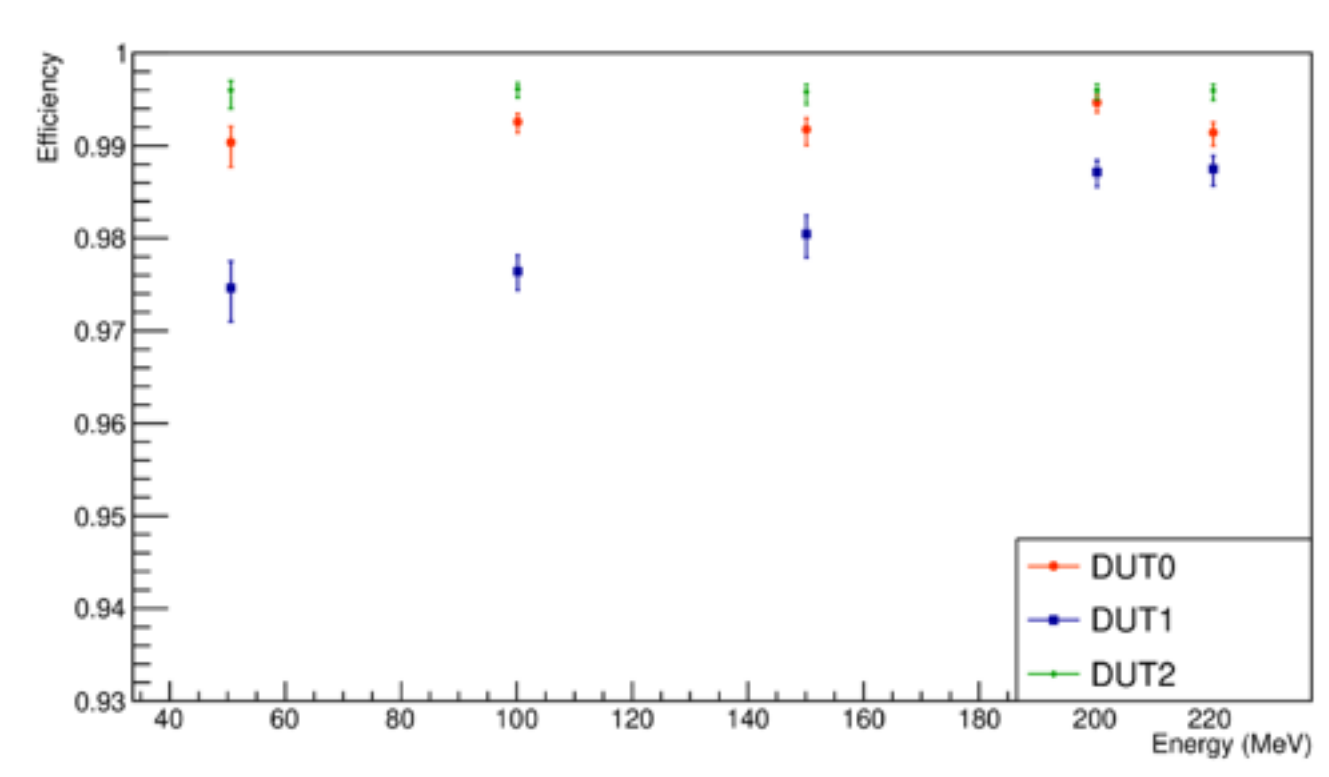




- 5 Energies
- Triggering:10 µs

- Collimator: 3 mm
- ~80 kHz $^4$He rate

- Δx<0.5mm
- **+ Al degrader**

# Results - Efficiency

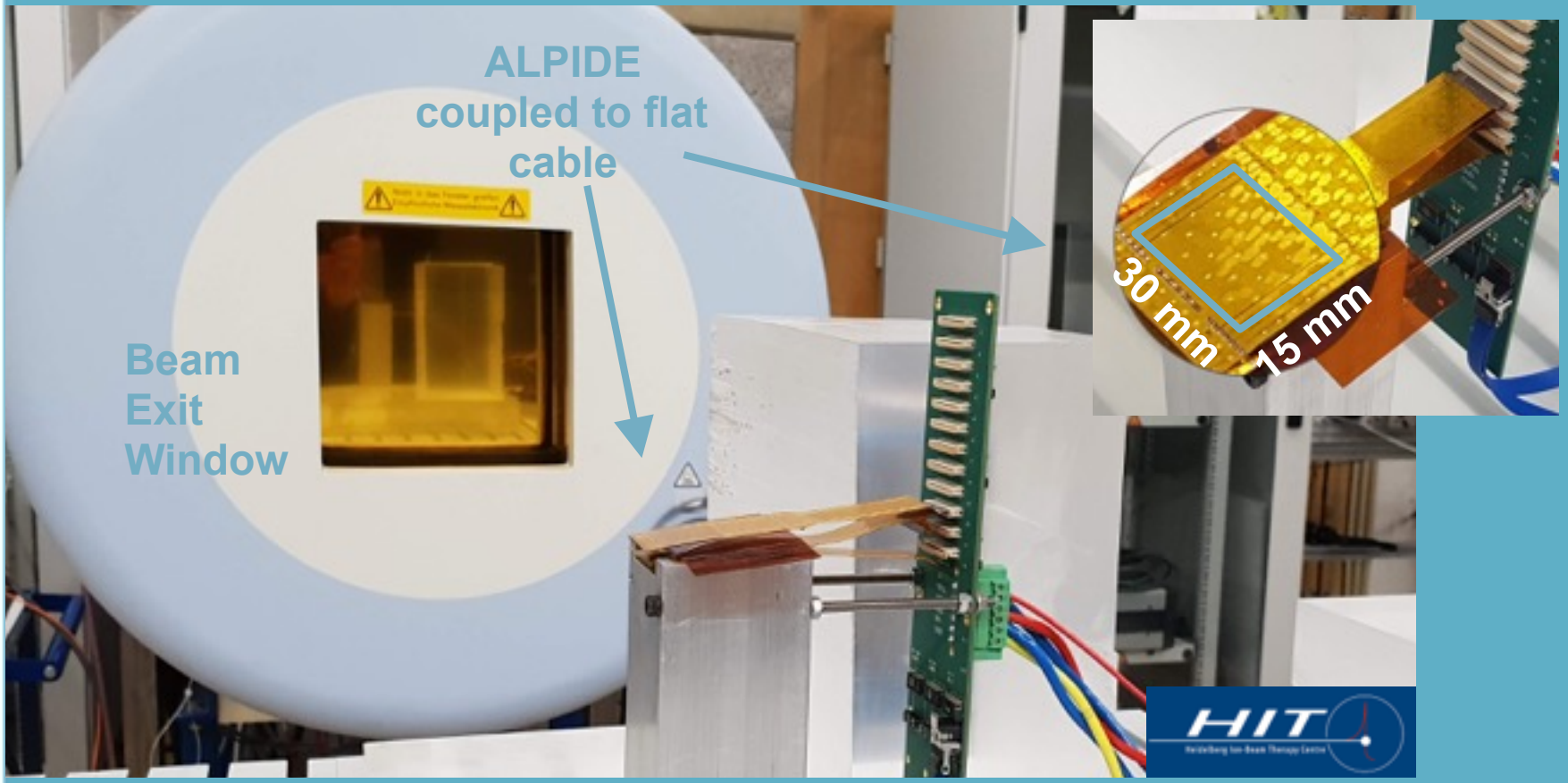



- 5 Energies
- Triggering:10 μs
- Collimator: 3 mm

- >97% tracking efficiency in 3 layers

- ~80 kHz $^{4}$He rate

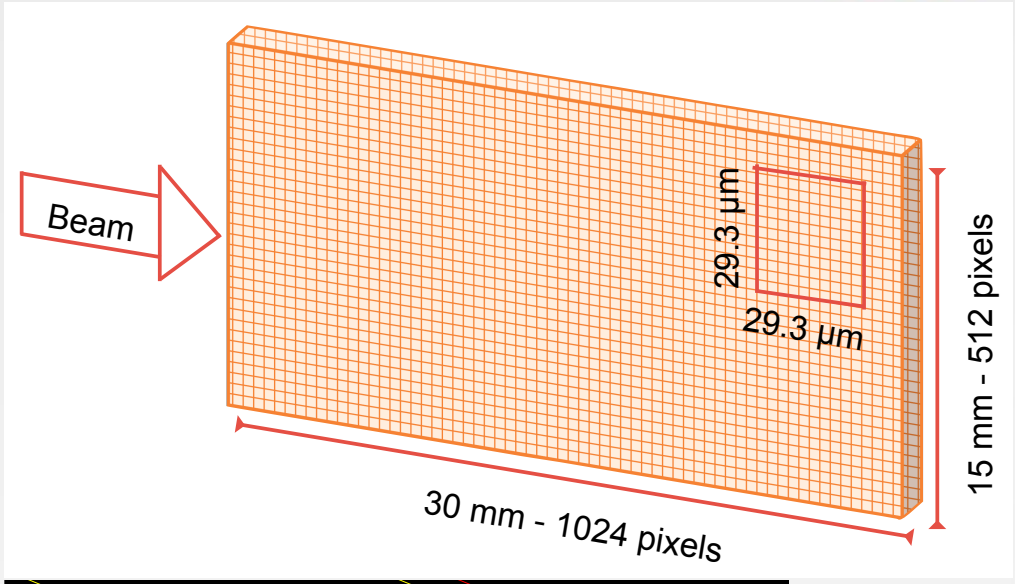
# Experiment at HIT with single ALPIDE chip
# December 2018

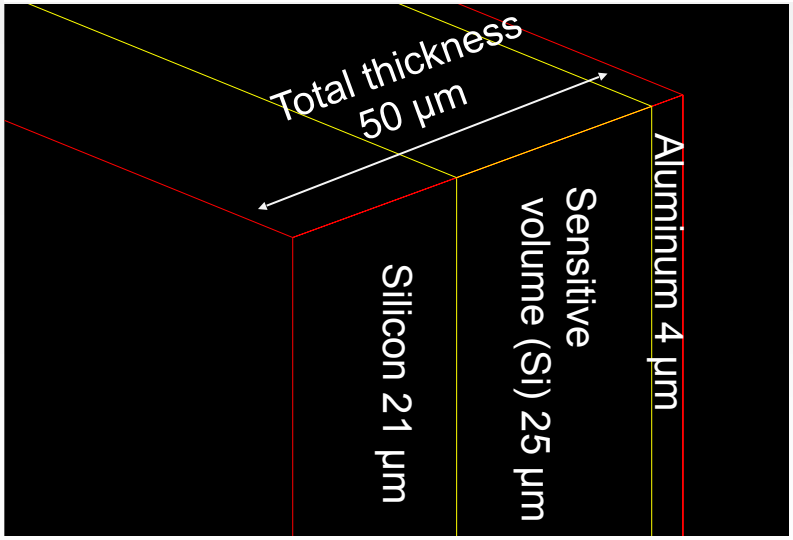



- $^{12}C$ ion beam
- Energy: **140.4 MeV/u**
- Range in silicon ~25 mm
- FWHM: 6.9 mm

# The Monte Carlo simulation

- TOPAS *[1] version 3.1.p03 with Geant4 *[2-4] version 10.03.p01
- The standard physics list for the TOPAS application was activated
- ALPIDE simulated as silicon box with size:
  30 mm × 15 mm × 0.050 mm
- Sensitive volume:
  30 mm × 15 mm × 0.025 m
- Number of voxels: 1024 × 512
- TOPAS dividable component feature used




*[1] Perl J, et al., *Med. Phys.* 2012; 39: 6818–6837.
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*[3] Allison J, et al., *IEEE Trans Nucl Sci.*, 2006; 53: 270–278.
*[4] Allison J, et al. *N.I.M. A*, 2016; 835: 186 – 225.

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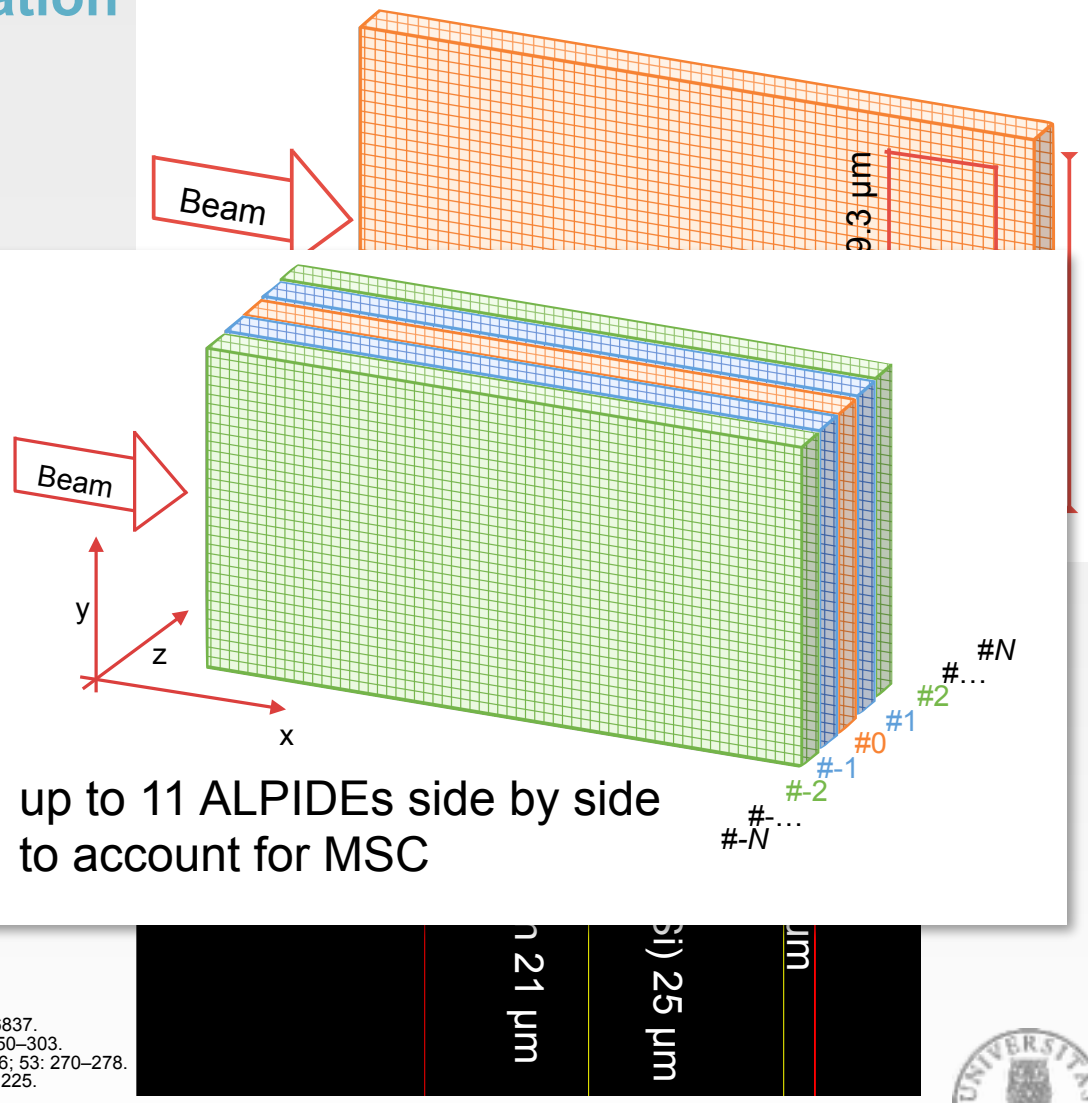
- Sensitive volume:
  30 mm × 15 mm × 0.025 mm
- Number of voxels: 1024 × 5
- TOPAS dividable componen feature used

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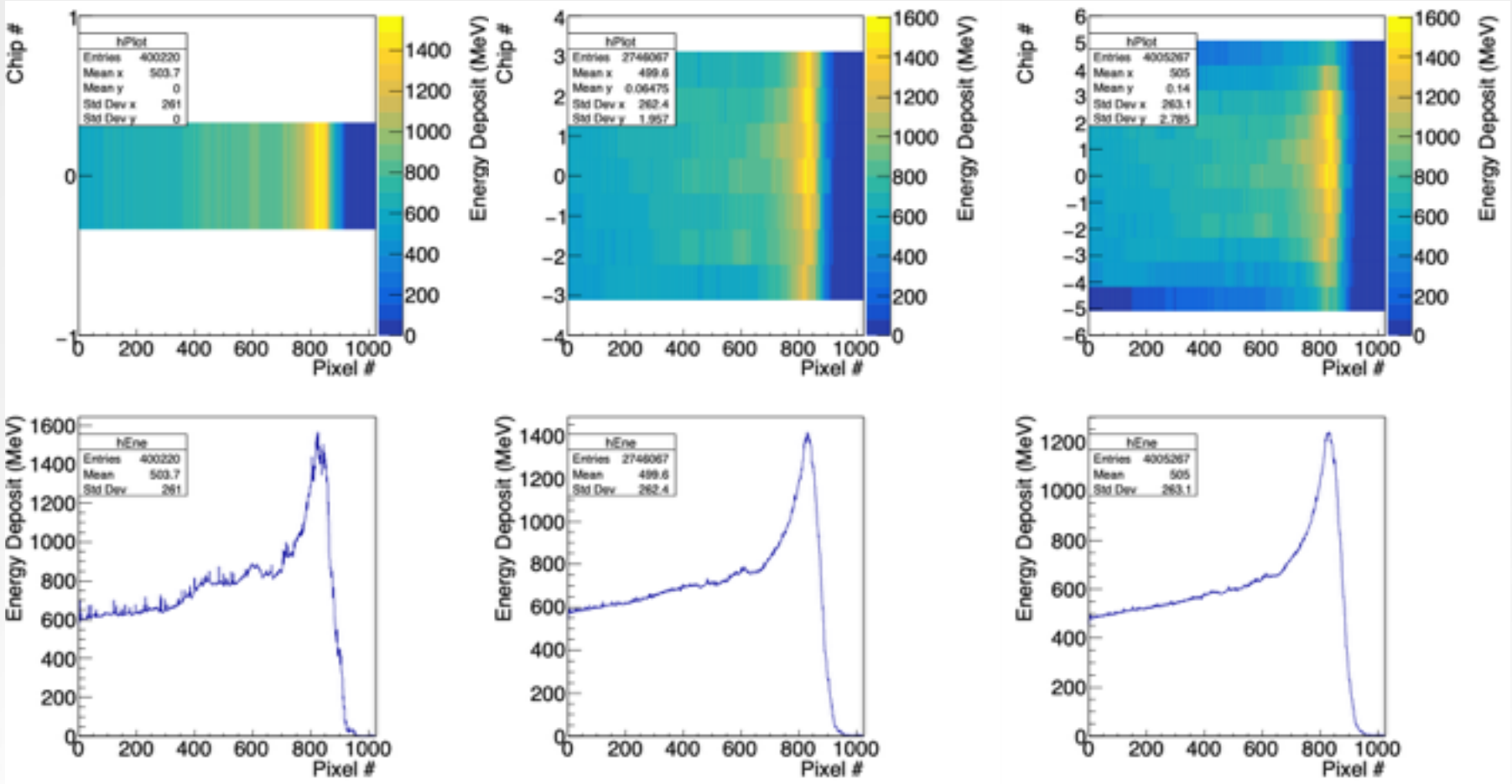
# Simulation results - $^{12}C$



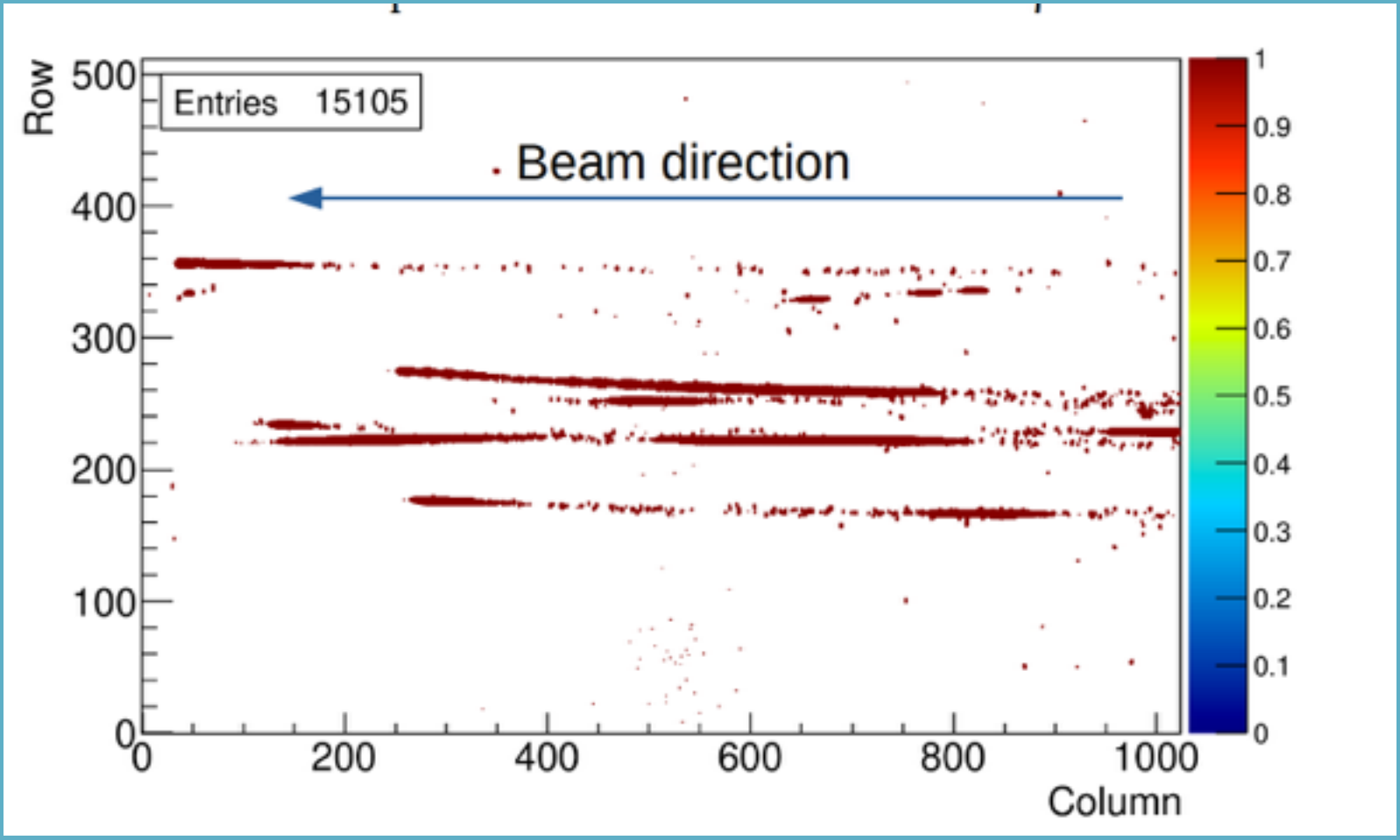

Single chip

7 chips

11 chips

- $10^5$ primary $^{12}C$ ions
- Energy: **140 MeV/u**
- Range in silicon ~25 mm
- beam spot: 0.25 x 10 $mm^2$

# Experiment at HIT with single Alpide chip December 2018



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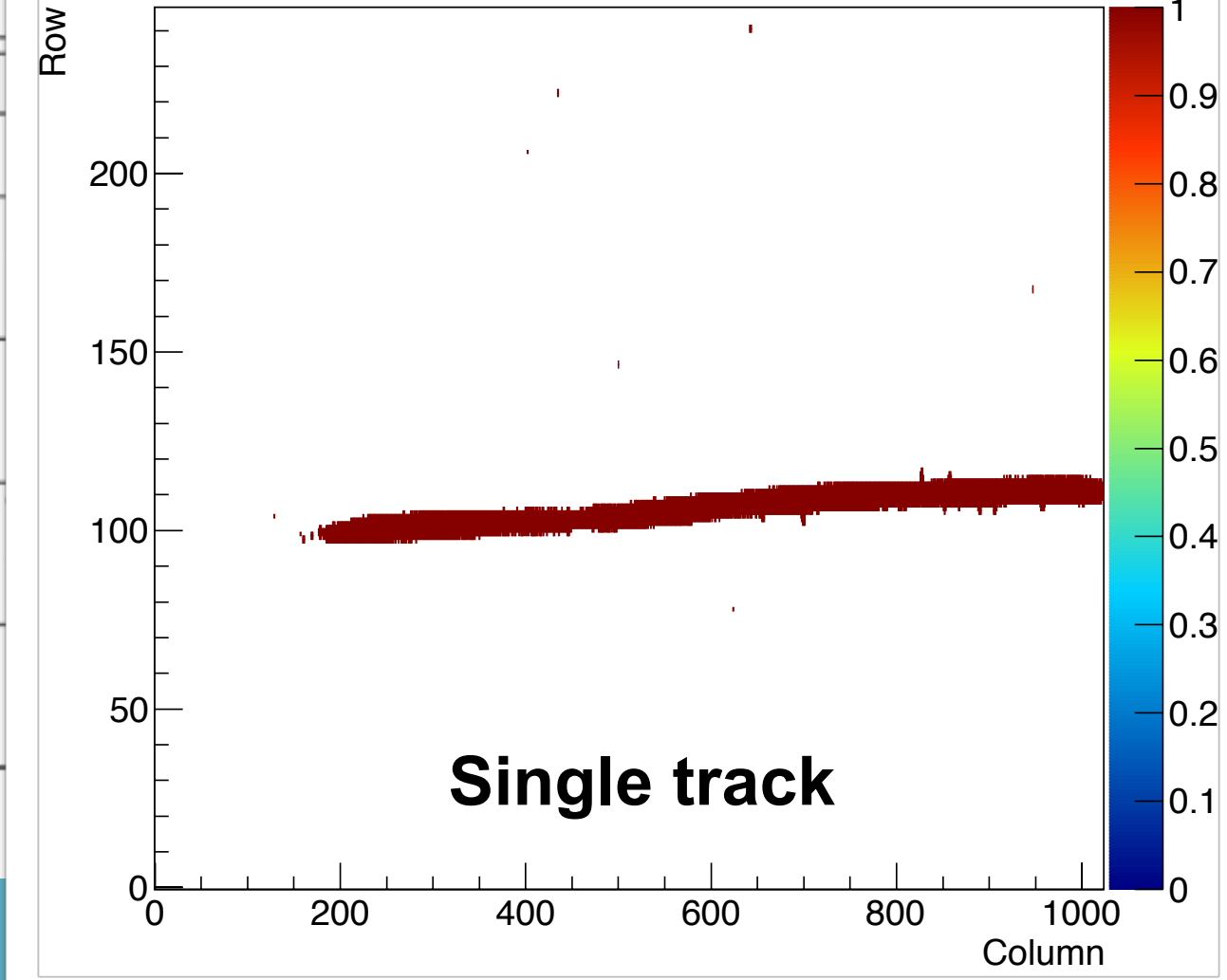


# Transforming Geant4 simulated data into “real” data

- Provide method for transforming simulated data to “real” data
- Confirm correctness of firmware test software stack
- Confirm correctness of data format parser
- Enables development start of analysis software framework

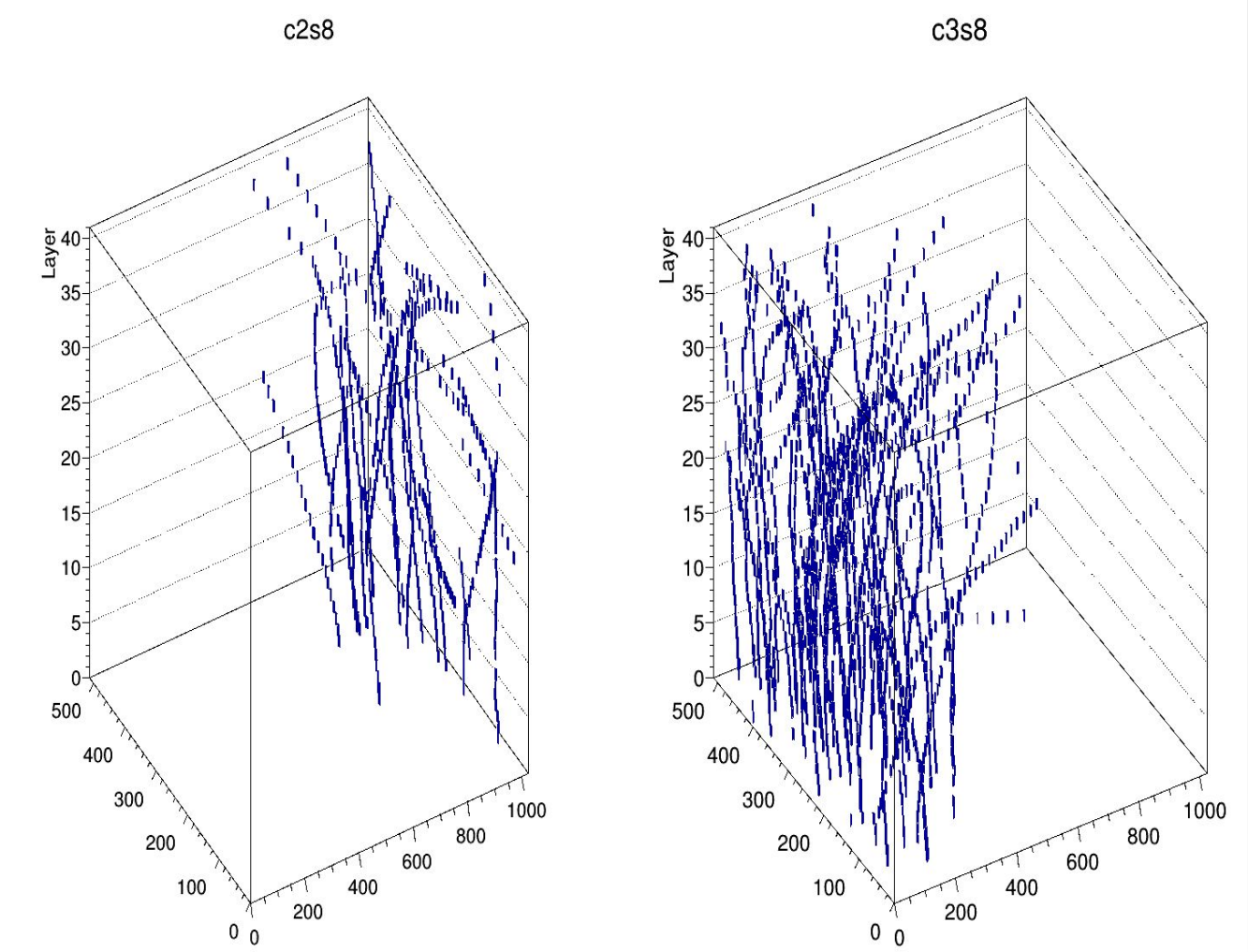
# Simulation of the Digital Tracking Calorimeter

- Determine geography of hit.
- Create row_col file for each chip, sorted by timestamp.
- posX [-135, 135] mm,
  posY [-67.5, 67.5] mm,
  posZ [0, 175] mm, <-- Longitudinal axis
- eventID [0,650k], (primaries, ~ 9 activated pixels per primary)
- clockTime [0, 6.5k * (10 μs / 25 ns)] (100 protons per readout) parentID [0, >0] 0 for primary particles, >0 for secondaries.

# XY for each frame to ALPIDE Format

- Two steps
  XY to ALPIDE Encoder Format
- Region / Encoder ID / Address
  ALPIDE Encoder Format to ALPIDE Data format
- Parse data and write a ROOT file with all the simulated tracks in the 41 layers

# First results



# Summary

- Bergen pCT collaboration is building Digital Tracking Calorimeter based on MAP CMOS sensor called “ALPIDE”
- The ALPIDE is being tested with ions at energies used in clinical practice
- The mechanics and the electronics of the new prototype are being optimized
- Parallel project on dosimetry with the ALPIDE chip
- Develop of parsing: Cluster sizes, put tracking algorithms to the test, add background noise, add random noisy pixels, add random dead pixels, add random time drift

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Haukeland universitetssjukehus

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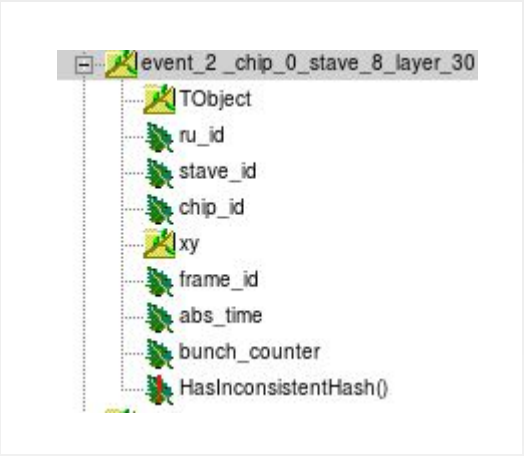
# ROOT format




- Uint8_t ru_id
- Uint8_t chip_id
- Uint8_t stave_id
- Uint32_t frame_id
- std::vector<std::pair<uint16_t,uint16_t>> xy
- Uint8_t bunch_counter (resolution 200 ns) - alpide clock domain
- Uint32_t abs_time (resolution 8.33 ns) - pRU clock domain
- Two clocks can be used to confirm synchronization

# Parser

0x697002000000000000000004000012C0

0x2970A0C8C636F9193AF67F3EF80CB0FF

0xA970000000000000000000040000000D

- Create root tree
- Convert hex to binary
- Determine if word is pRU header, pRU data word, pRU empty frame or pRU trailer
- Insert information to vector
- Check for errors in pRU trailer.
- Decode Alpide data
- Write to file

# XY for each frame to ALPIDE Format

- Two steps
  XY to ALPIDE Encoder Format
- Region / Encoder ID / Address
  ALPIDE Encoder Format to ALPIDE Data format

```
1  0 0
2  0 1
3  0 2
4  0 3
```

```
1  header A000
2  region_header C0
3  data_short 4000
4  data_short 4001
5  data_short 4400
6  data_short 4401
7  trailer B0
```

# ALPIDE Format to pRU Format

- Based on FPGA firmware
- Operation confirmed by simulations

```
1  header A000
2  region_header C0
3  data_short 4000
4  data_short 4001
5  data_short 4400
6  data_short 4401
7  trailer B0
```

```
40000200000000000000000300000000
0000A000C040004001440044014800B0
80000000000000000000000400000000E
40000200000000000000000500000000
0000A000C040004001440044014800480
000001B0FFFFFFFFFFFFFFFFFFFFFFF
```