Characterization of Monolithic CMOS Pixel Sensor Chip with Ion Beams for Application in proton Computed Tomography

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on behalf of the Bergen pCT collaboration

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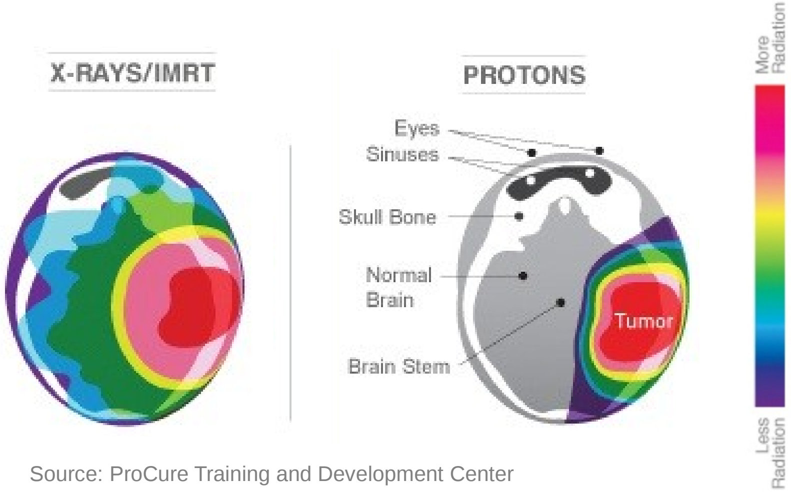
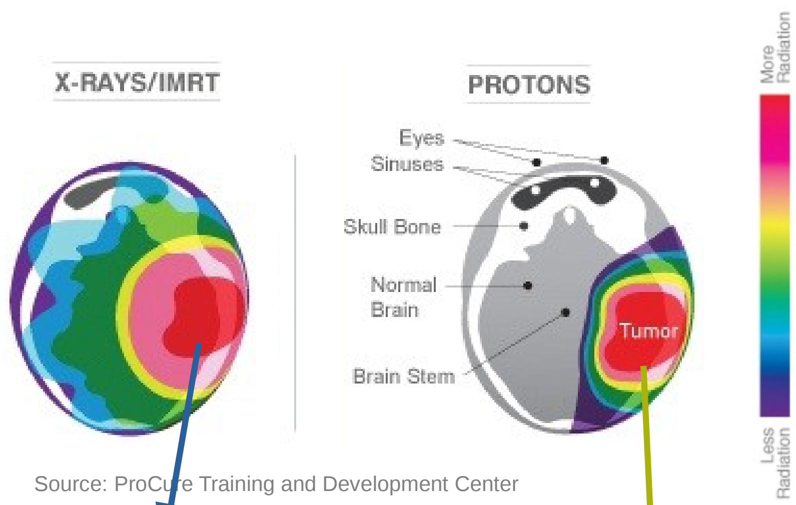
Radiotherapy – Photons vs Ions



Source: ProCure Training and Development Center

- **Radiotherapy: e.g. Brain tumor**
  - Proton delivers less radiation to Brain stem, eyes, and healthy tissue than x-rays

Radiotherapy – Photons vs Ions



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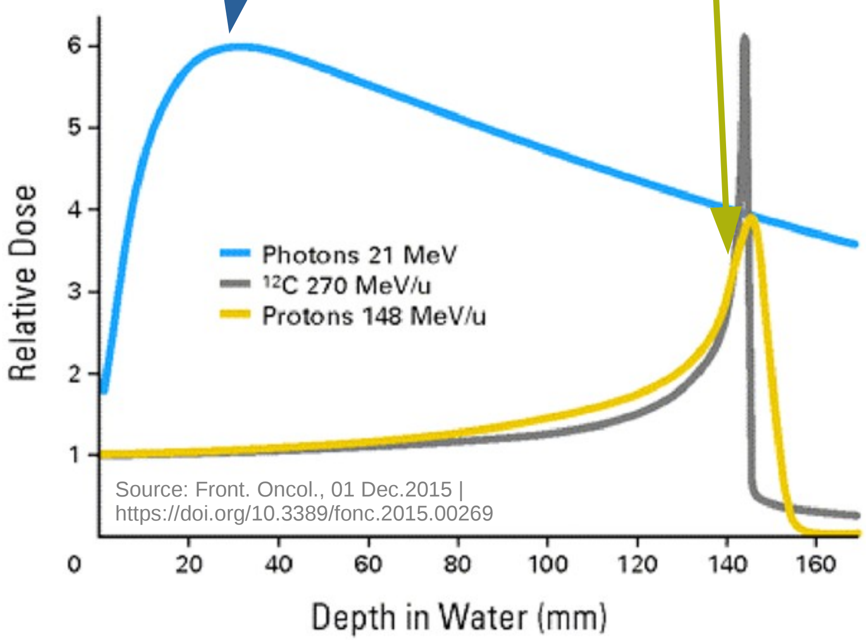


Source: Front. Oncol., 01 Dec.2015 | https://doi.org/10.3389/fonc.2015.00269

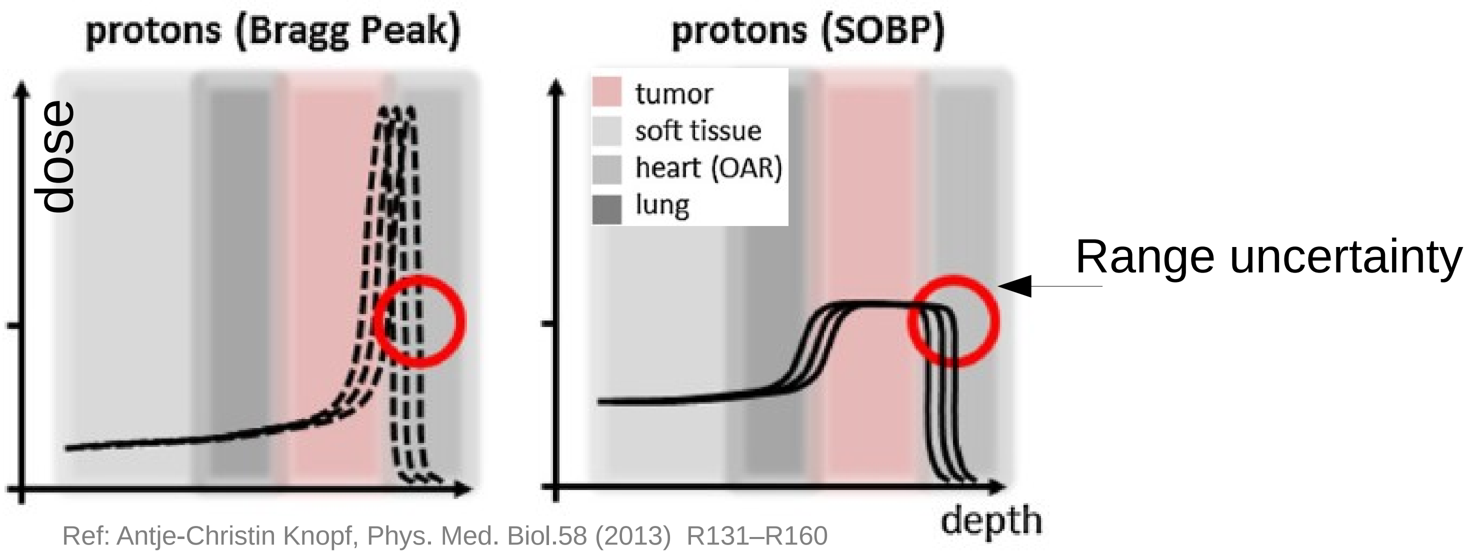
- **Radiotherapy: e.g. Brain tumor**
  - ➔ Proton delivers less radiation to Brain stem, eyes, and healthy tissue than x-rays

- **Depth-dose distributions**
  (superimposed with each other for comparison)
  - **Photons**
    - ➔ high dose in the entrance channel
  - **Ions**
    - ➔ Relatively low dose in the entrance channel
    - ➔ Lose most of their energy in the Bragg peak
    - ➔ Sharp distal fall-off of dose deposition (< mm)

Proton therapy – Range uncertainty

- Proton treatment plans currently use x-ray CT for proton stopping power (RSP)
- Issues with conversion of CT units to RSP → Leads to systematic range errors: 3 to 5 %
- Spread Over Bragg Peak (SOBP) → Uniform dose distribution to the tumor

Effect of uncertainties to depth dose curves



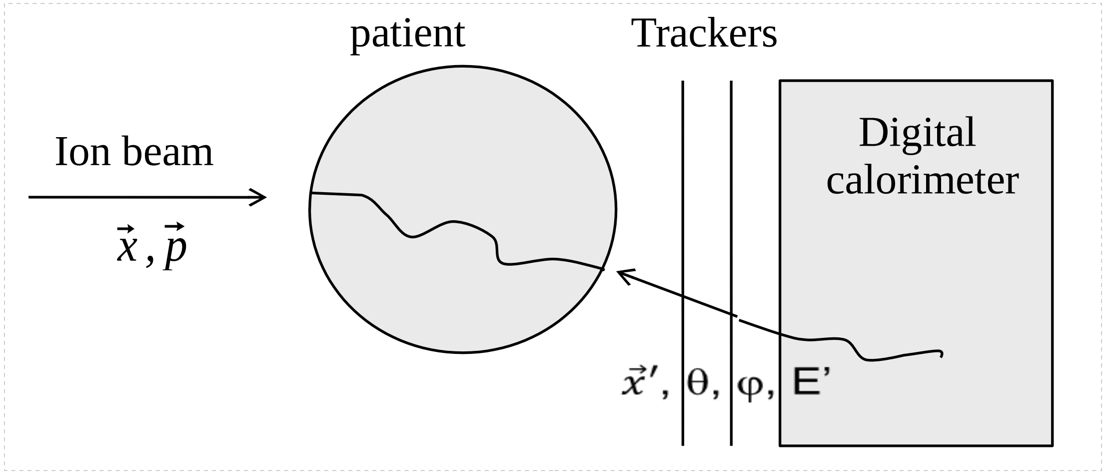
Ref: Antje-Christin Knopf, Phys. Med. Biol.58 (2013) R131–R160

OAR: Organ at Risk

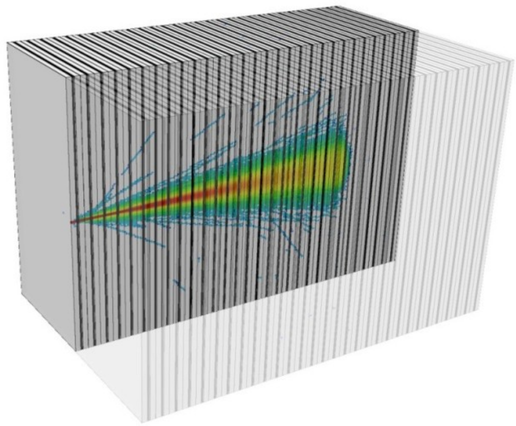
- Imaging with proton (pCT) to get proton stopping power → Range errors < 1%

Bergen pCT - design

- **Conceptual design**



Simulated ion-beam shower in digital calorimeter

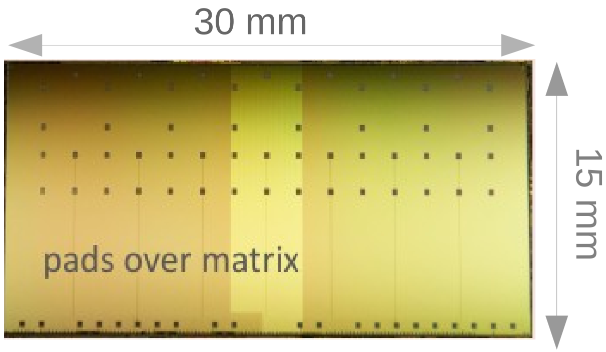


- $\vec{x}, \vec{p}$ given by beam optics and scanning system
- $\vec{x}', \theta, \phi$ have to be measured with high precision
  - Position resolution ~ 5 µm with minimal MS i.e. very thin first two tracking layers

- **Extremely high-granularity digital calorimeter** for tracking, range and energy-loss measurement
- **Technical design**
  - Planes of CMOS sensors: Monolithic Active Pixel Sensors (MAPS) as active layers in a sampling calorimeter and aluminum (3.4 mm thick) as absorber

ALPIDE - **AL**ICE **PI**xel **DE**tector

- Developed for the upgrade of the ALICE Inner Tracker System
- Tower jazz 180 nm CMOS Imaging process
- Dimensions
  - Chip size 15 mm x 30 mm
  - Chip thickness 50 µm or 100 µm
  - No. of Pixels 512 x 1024 pixels (~ 0.5 M)
  - Pixel size 27 µm x 29 µm



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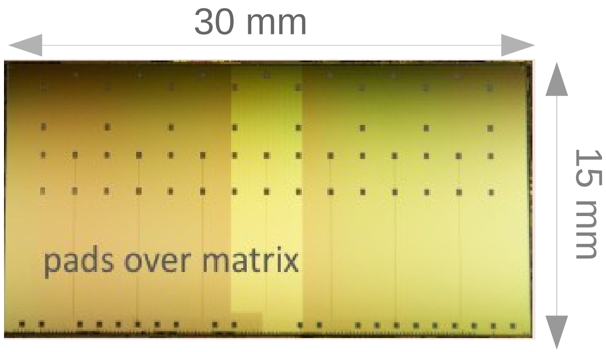
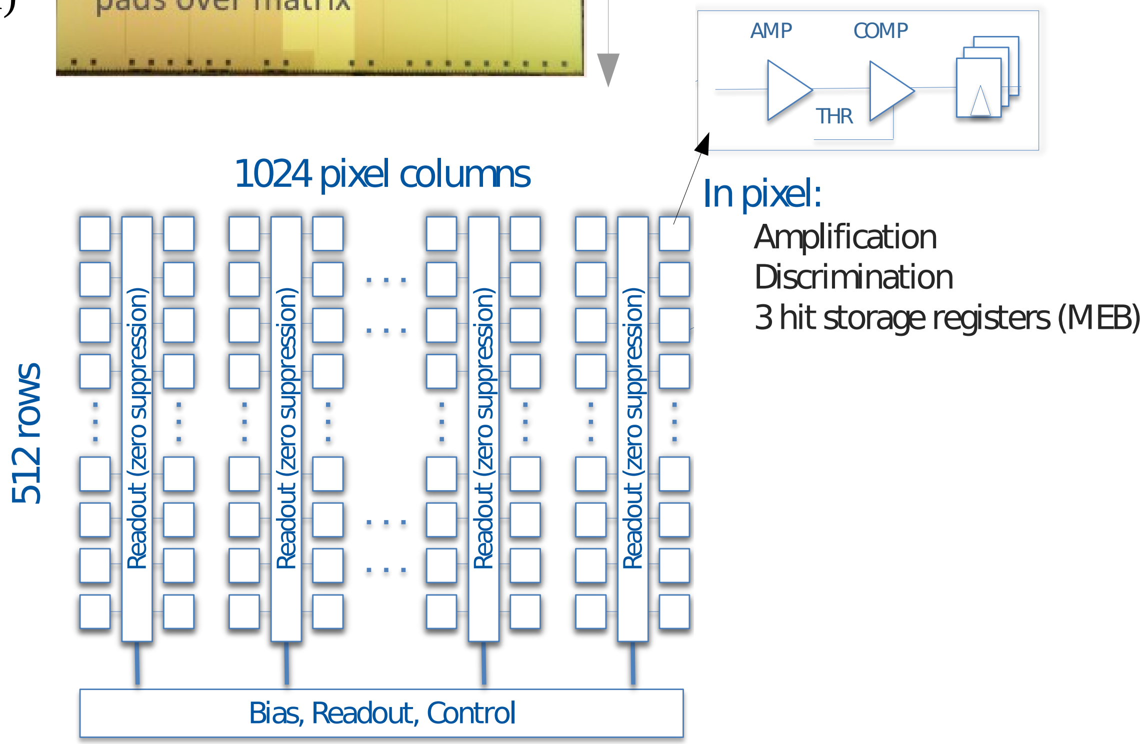
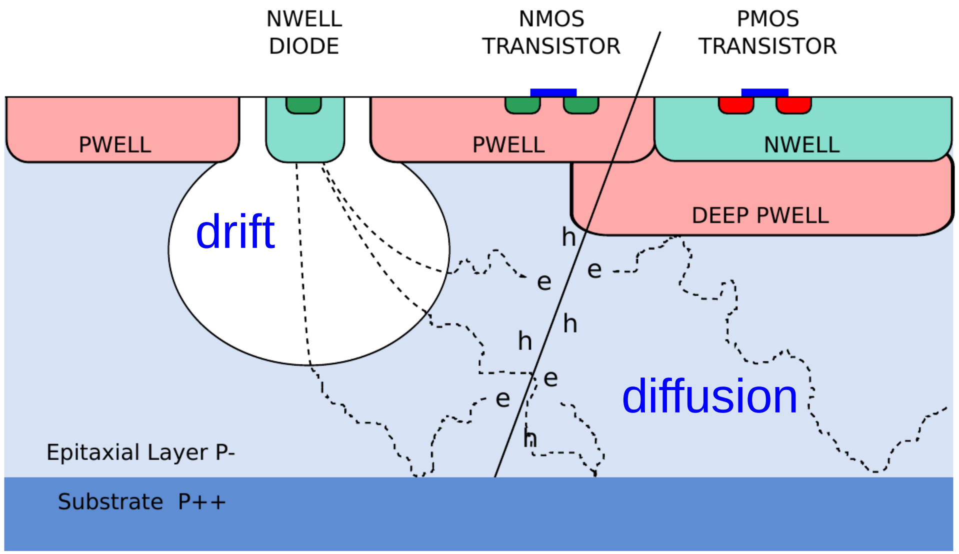
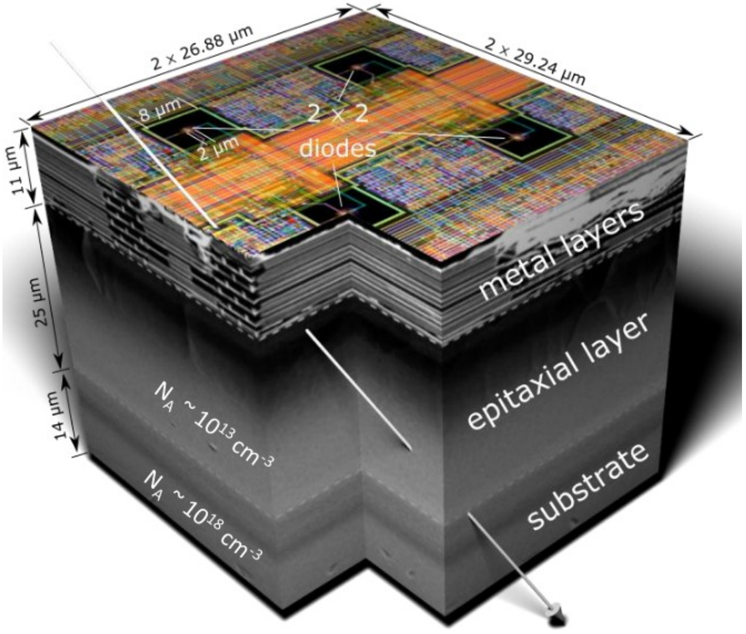


- Digital readout with priority encoder
- Continuous and triggered readout
- Performance
  - Efficiency > 99% for MIPs
  - Max particle rate 100 MHz / cm²
  - Fake-hit rate ~ 10^{-10} hit/pixel/event
  - Spatial resolution ~ 5 µm
  - Power consumption 300 nW/pixel



ALPIDE – working principle



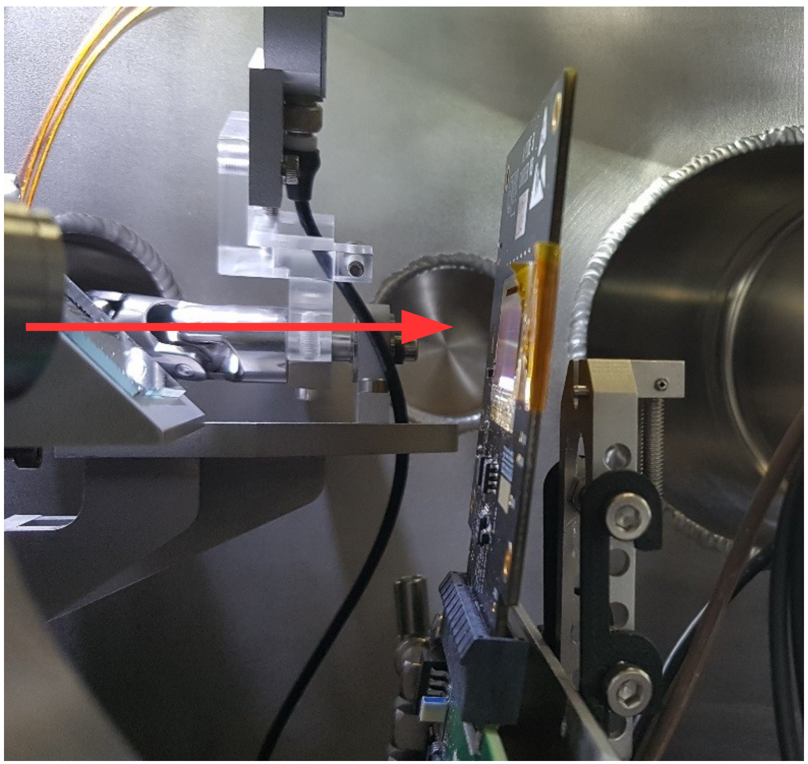


- High-resistivity (> 1 kΩ cm) p-type epitaxial layer (25 µm)
- Diode size (2-3 µm) – 100 times smaller than pixel size – low capacitance – high S/N
- Deep PWELL shields NWELL of PMOS transistors – allows full CMOS circuitry in active area
- Possible to reverse bias (up to -6 V)

Micro beam test

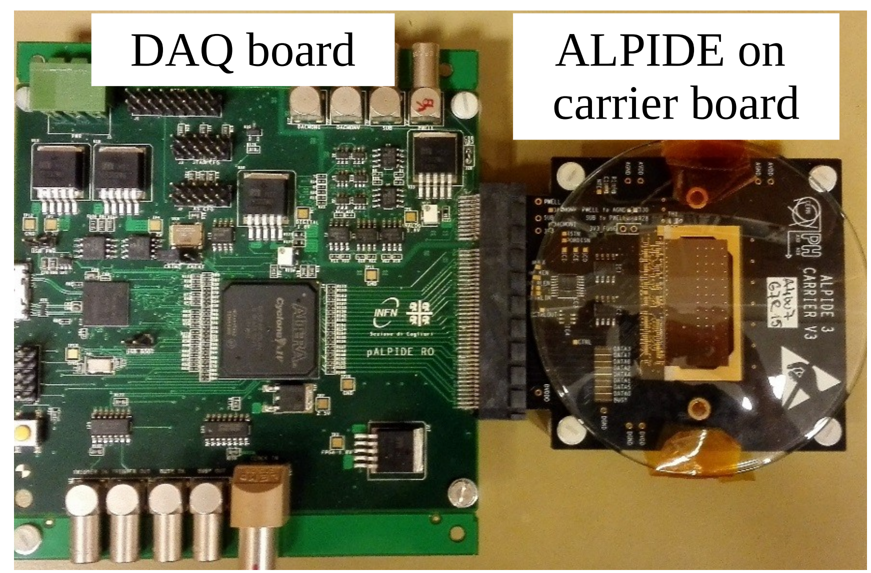
Aim: Study the effect of beam position on cluster size

Test done at Australia Nuclear Science and Technology Organization (ANSTO) in Australia



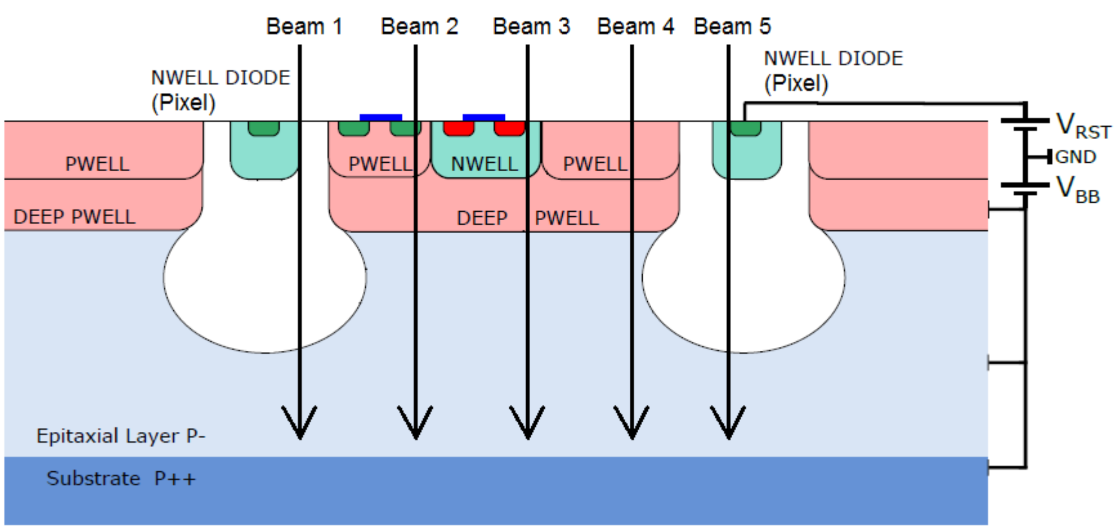
ALPIDE inside the vacuum chamber
ALPIDE tilted by ~ 5^0
Beam direction shown by Red arrow

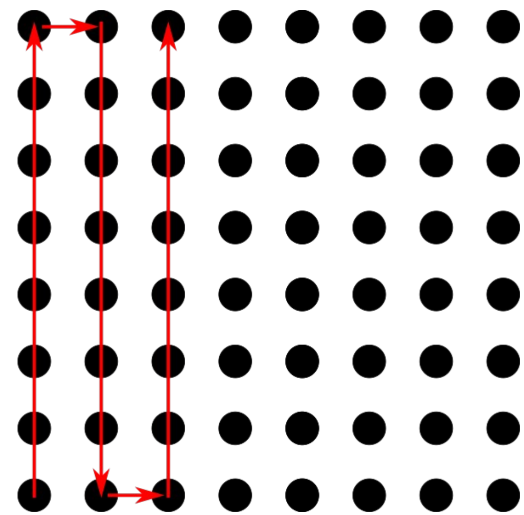
- Test parameters
  - Ion beam: Helium-4
  - Energy: 10 MeV (± 0.1 MeV)
  - Beam size: 1 µm
  - Rate: 2 k to 10 k ions/sec
  - Trigger freq. (period): 100 kHz (10 µs)
  - Bias Voltage: 0 V and -3 V



Micro beam test

- ALPIDE surface was raster scanned
  - Spot size 1 µm
  - Area 128 x 128 µm²
  - Dwell time 200 ms / spot
  - Single pixel size 27 µm x 29 µm

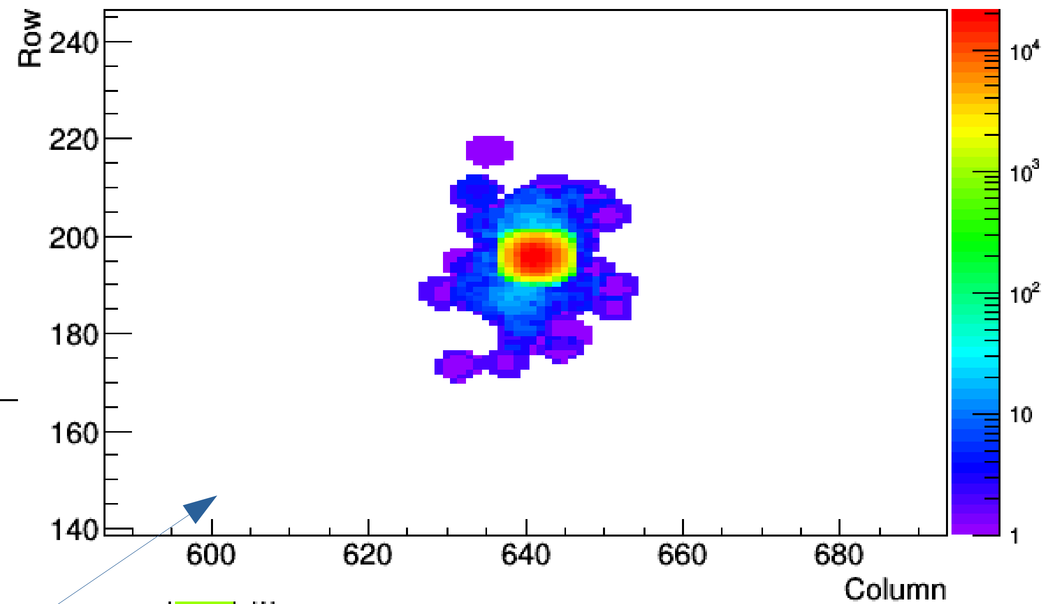


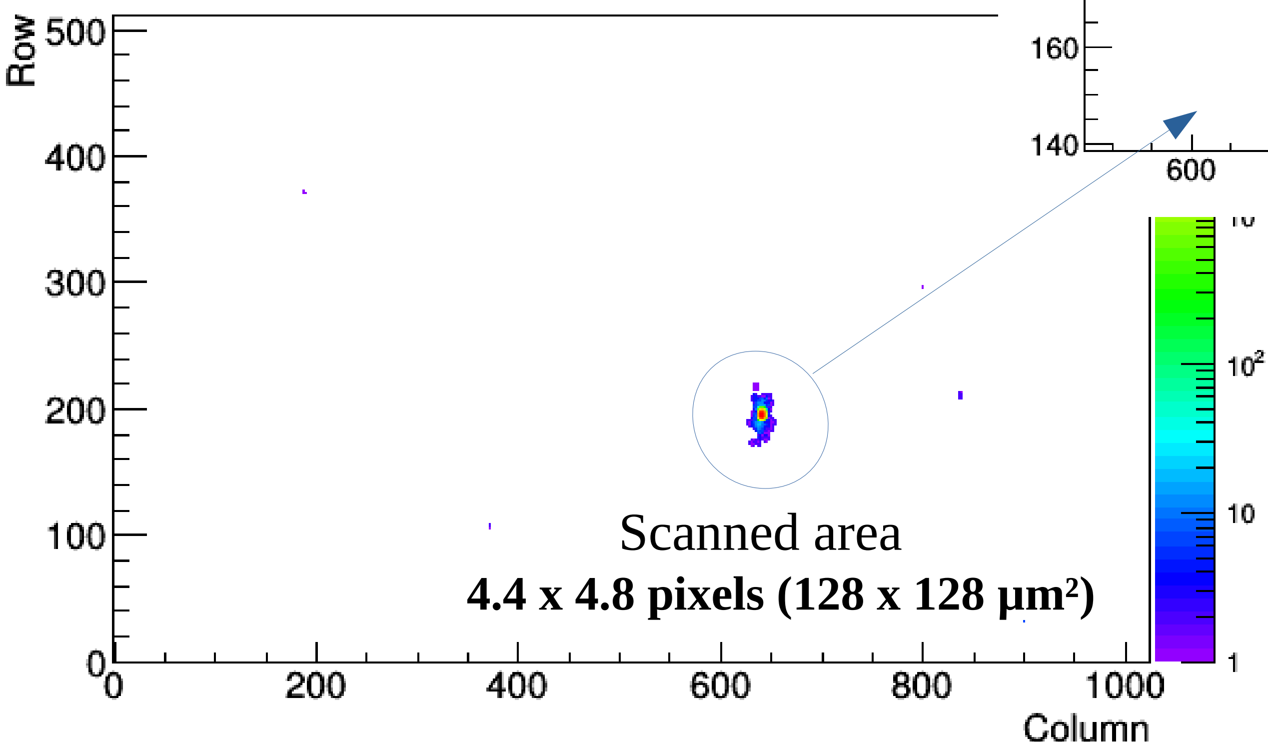


Dot – beam spot
Red arrow – beam spot moving direction
Dwell time – the time spent by beam on a dot

Scanned area

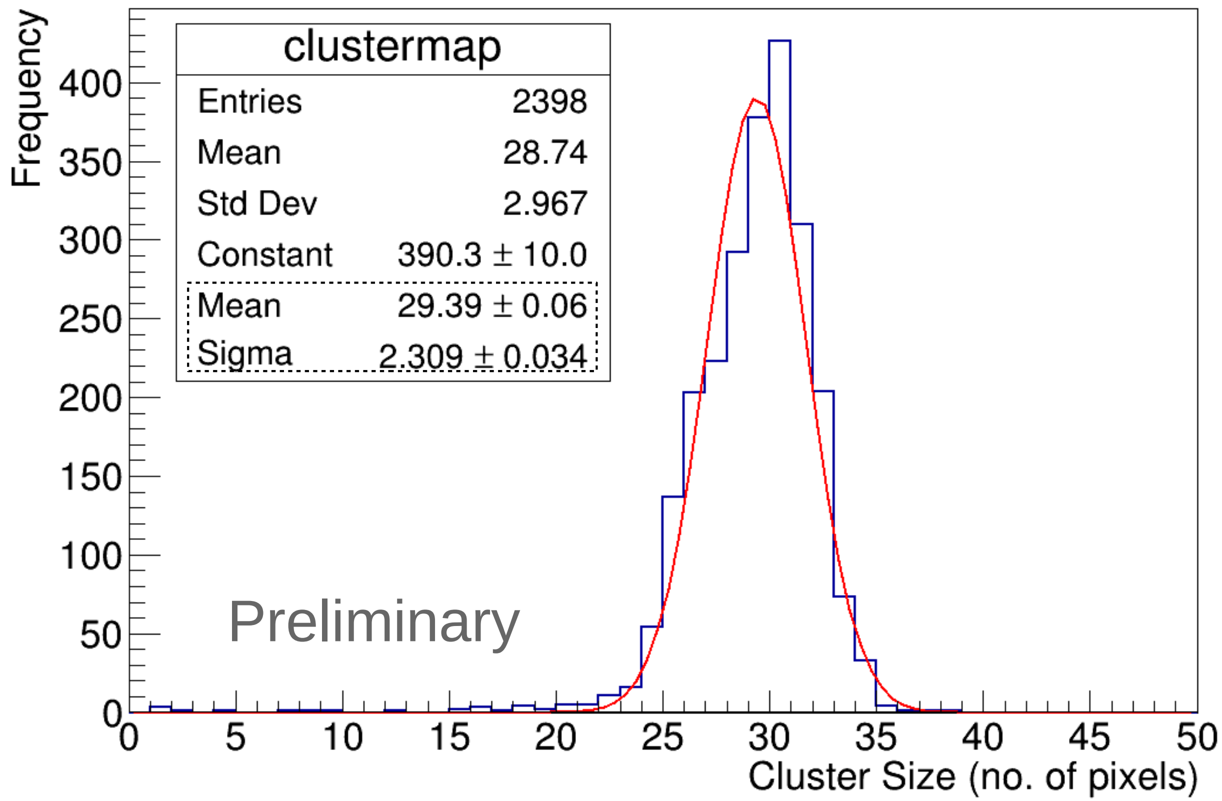
- He4 beam energy 10 MeV
- Beam freq. 10 kHz
- Dwell time 200 ms/spot
- Bias voltage 0 V





Cluster size: High LET micro beam

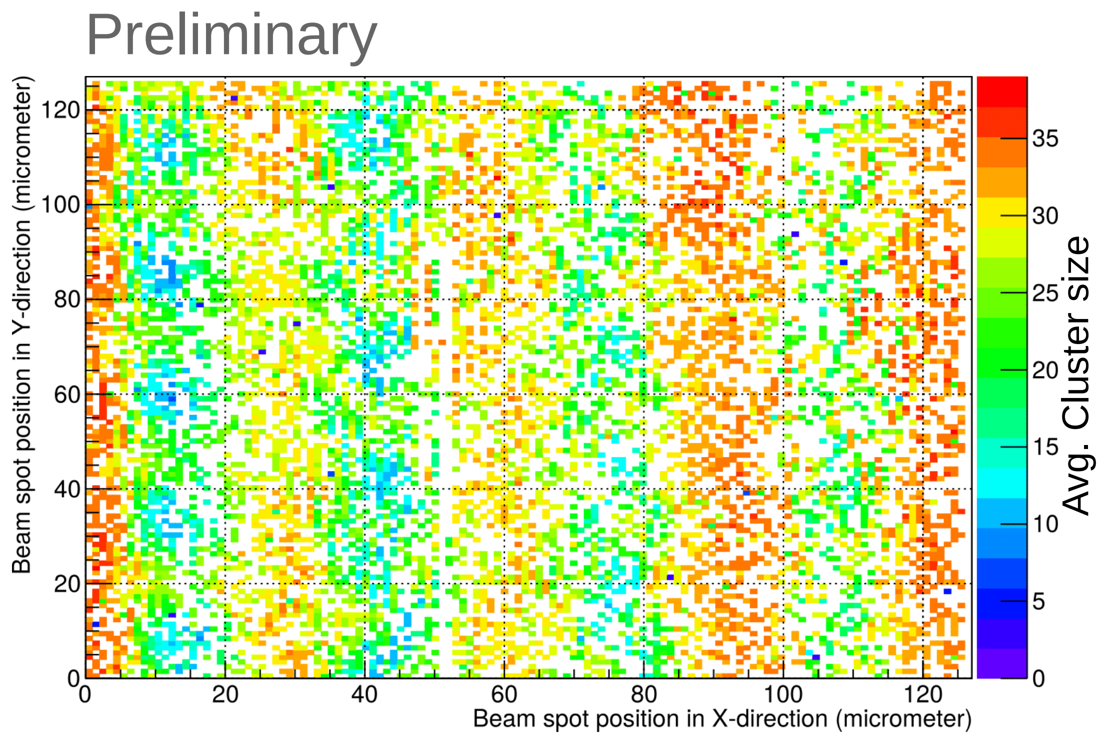
Data set selected for few spots



Possible to record heavy ions with ALPIDE!

LET: Linear Energy Transfer

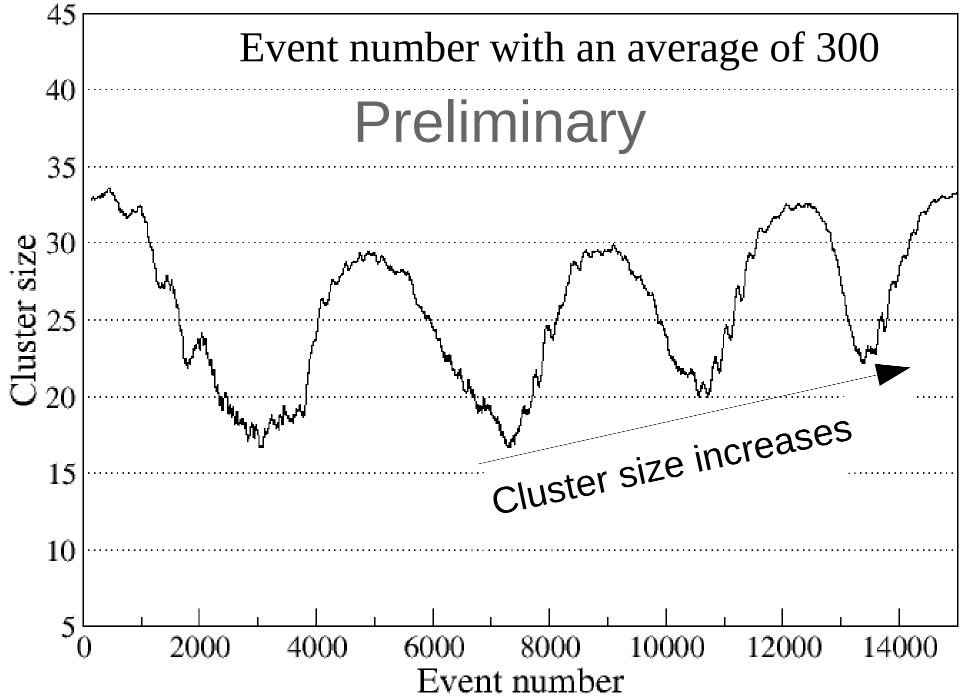
Cluster size map



- Clusters are dependent on the beam position
- Clusters are rather constant in vertical bands visible on various X-values
- Clusters could be smaller
  when the beam is positioned in the vicinity of collection diode than in its periphery
- No direct impact on particle tracking: cluster center is used for particle tracking

Avg. cluster size vs. Event number

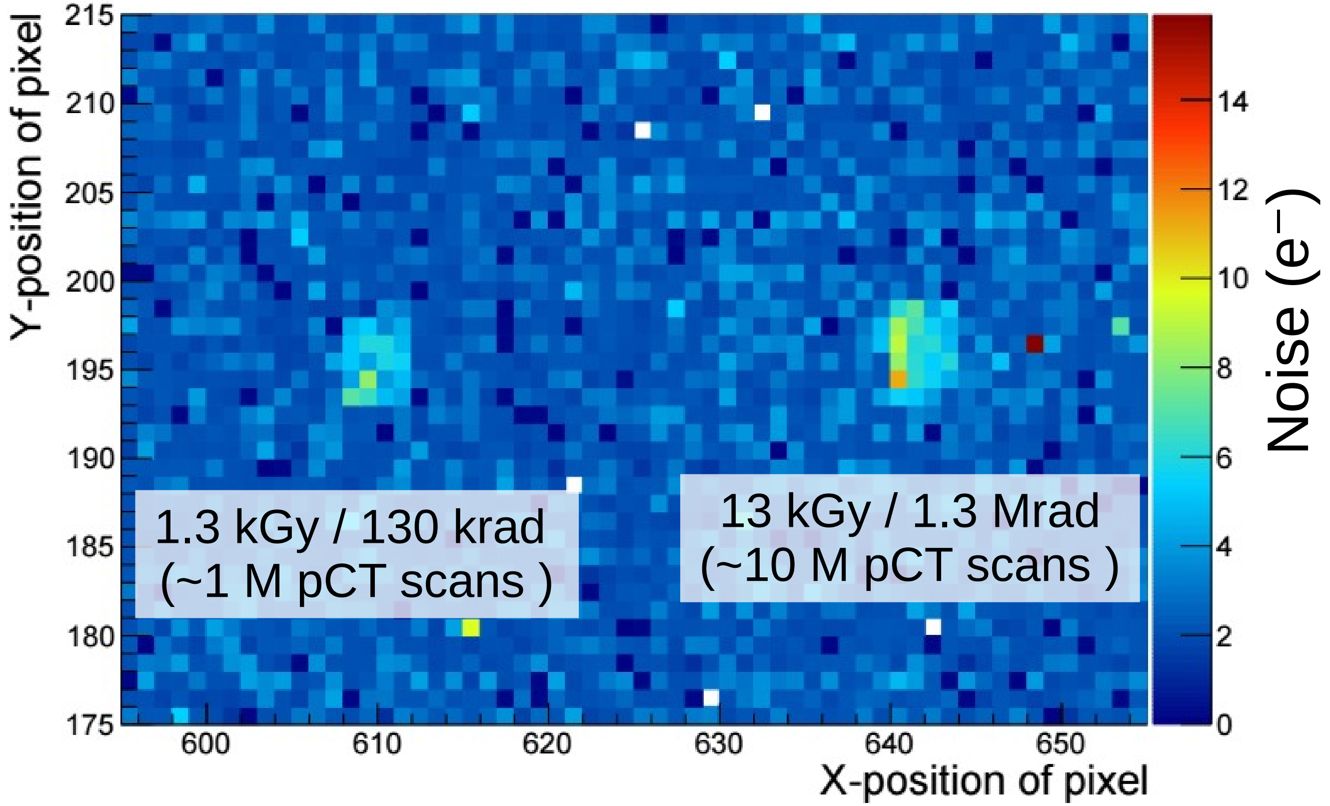
Event number →X - position → Irradiation time



- Beam moving from left to right, across the columns
- Small clusters disappear with time (from event #8000 onwards)
- This could be due to
  - Some areas are slightly more sensitive than others due to process variations
  - Rise in temperature, chip was in vacuum – cooling required (~ 20^{0} C)
  - Small increase in noise due to irradiation

Noise Map: Irradiated ALPIDE

- Scanned two places in ALPIDE:
  - 2 kHz beam freq. (at Right) and 10 kHz beam freq. (at Left)

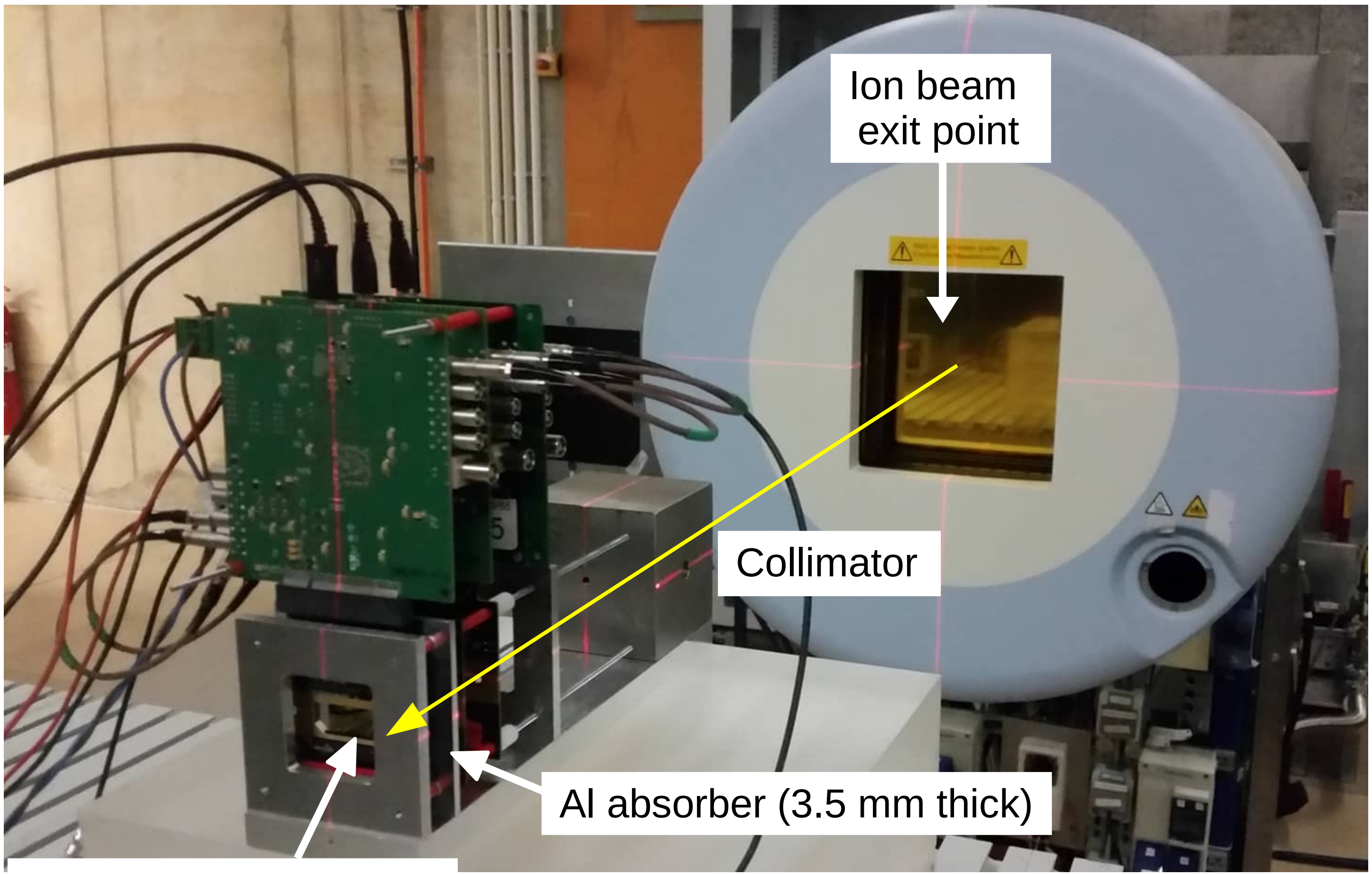


- Increase in noise but ALPIDE was working → No serious issues!!

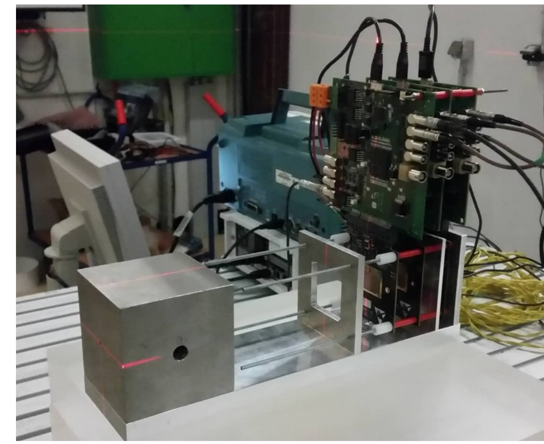
ALPIDE telescope experiment at HIT, Heidelberg

Aim: Ion tracking, clusters vs. ion energy (LET)

Test setup at Heidelberg Ion-Beam Therapy Center (HIT)

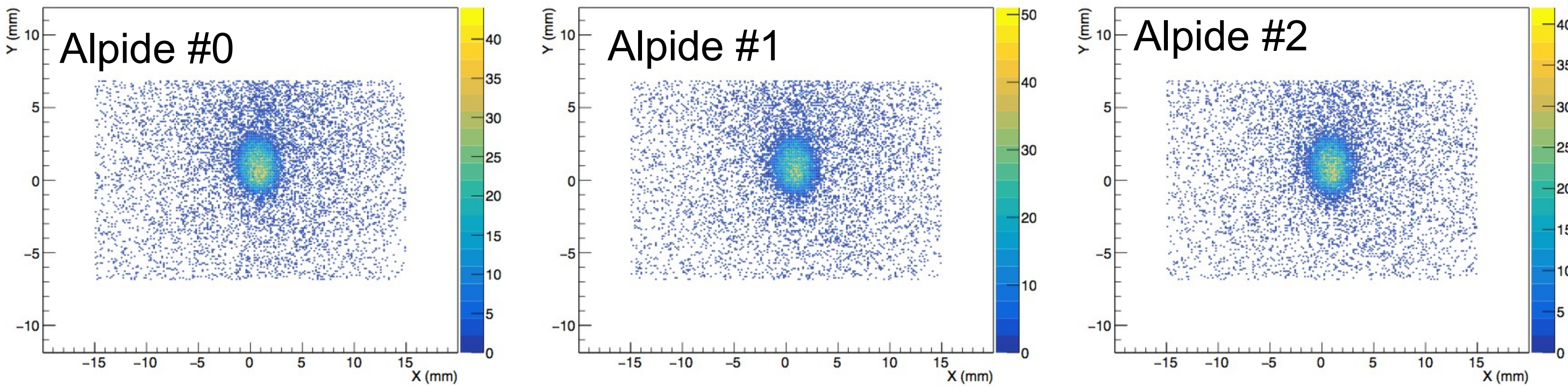


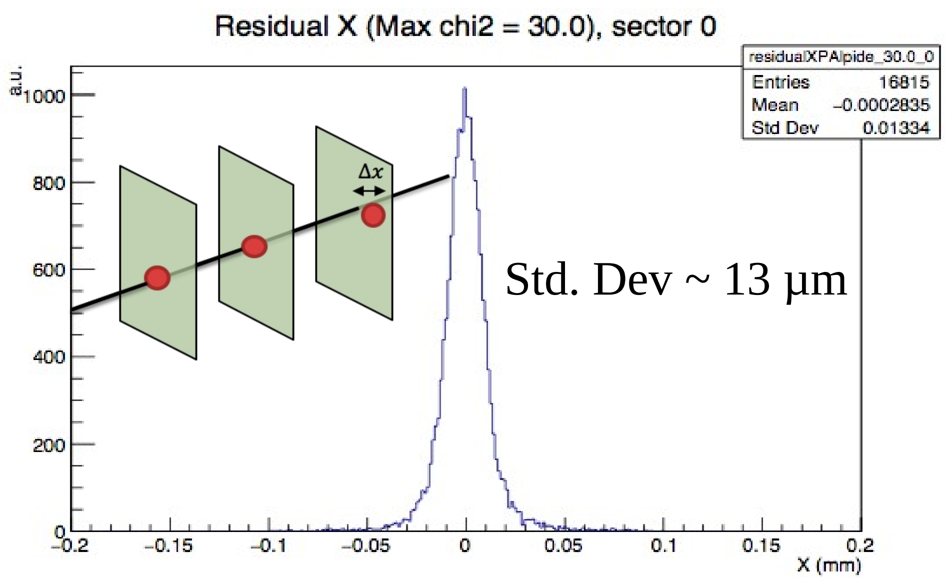
Telescope – 3 ALPIDE



Beam energy (MeV/u)	
Helium	Proton
50.57	48.12
100.19	200.11
150.11	221.06
200.38	
220.5	

Beam alignment

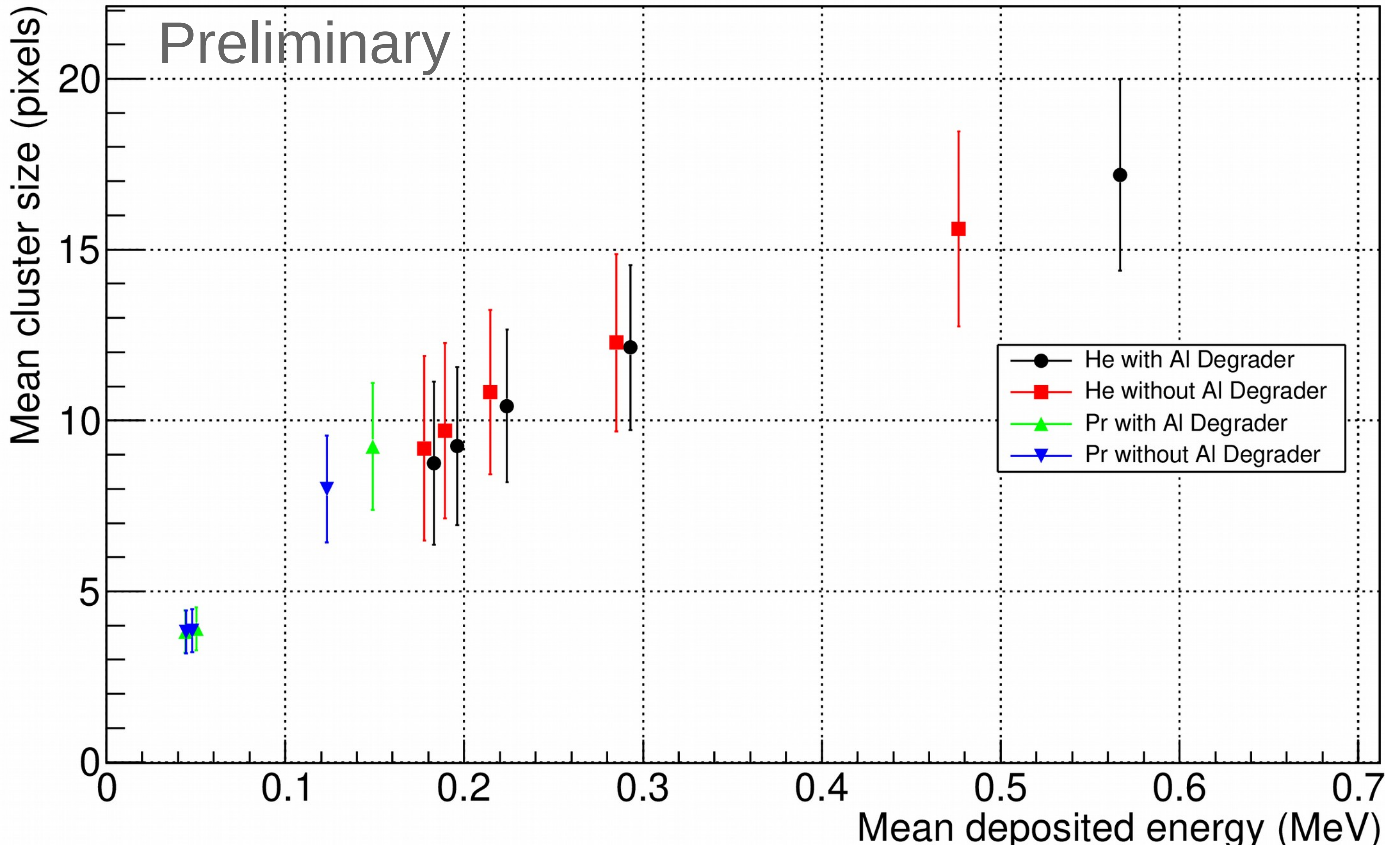




- Energy 220.5 MeV/u (FWHM = 10.1 mm)
- ^{4}He rate ~ 80 kHz
- Time frame 10 µs
- Collimator 3 mm

Cluster size vs. Energy loss in ALPIDE w/o absorber

For proton and helium in layer3

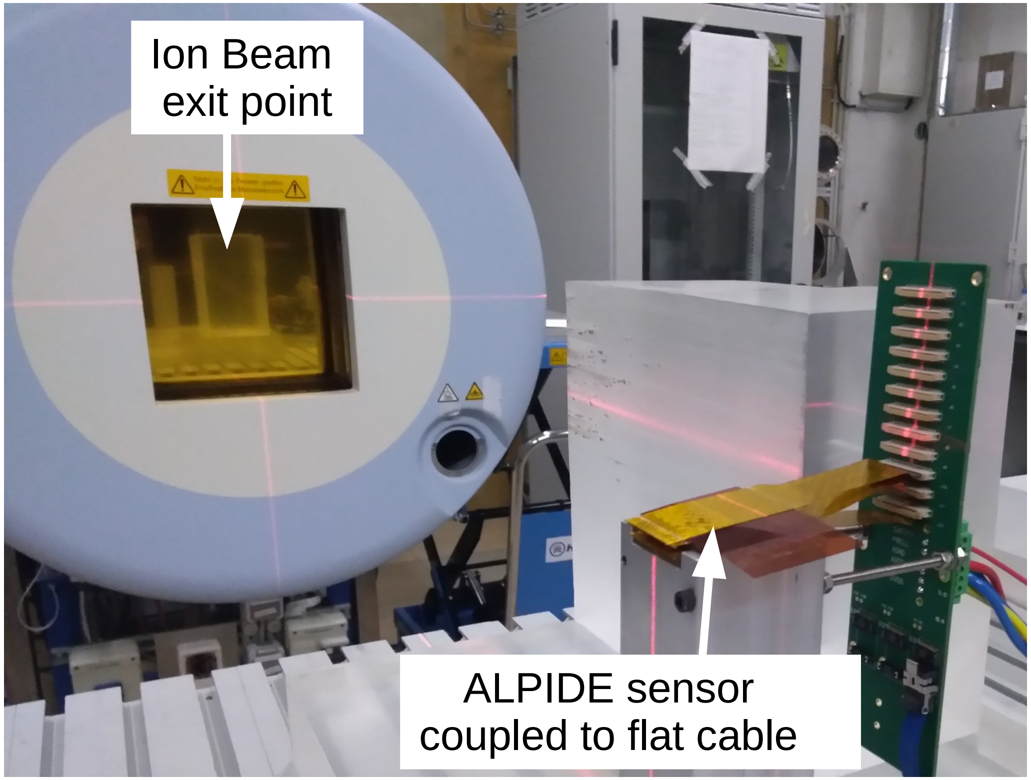


- Ion-energy deposit in ALPIDE obtained using Geant4 simulation
- Tracking of He and p beam is possible down to 50 MeV/c w/o absorber
- Cluster size decreases in proportion with LET
- Proton clusters are smaller than Helium as expected

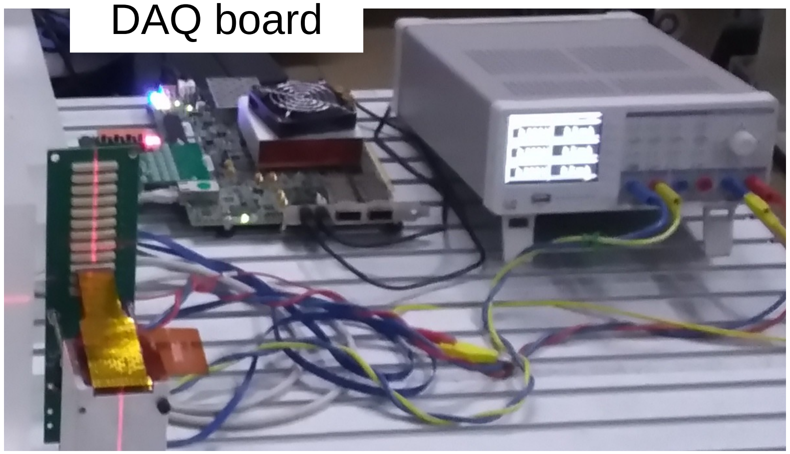
Single ALPIDE experiment at HIT Heidelberg

Aim: Lateral scan of ALPIDE – capture ion tracks for high LET ion beam

Heidelberg Ion-Beam Therapy Center (HIT)



Carbon beam energy: 140.4 MeV/u

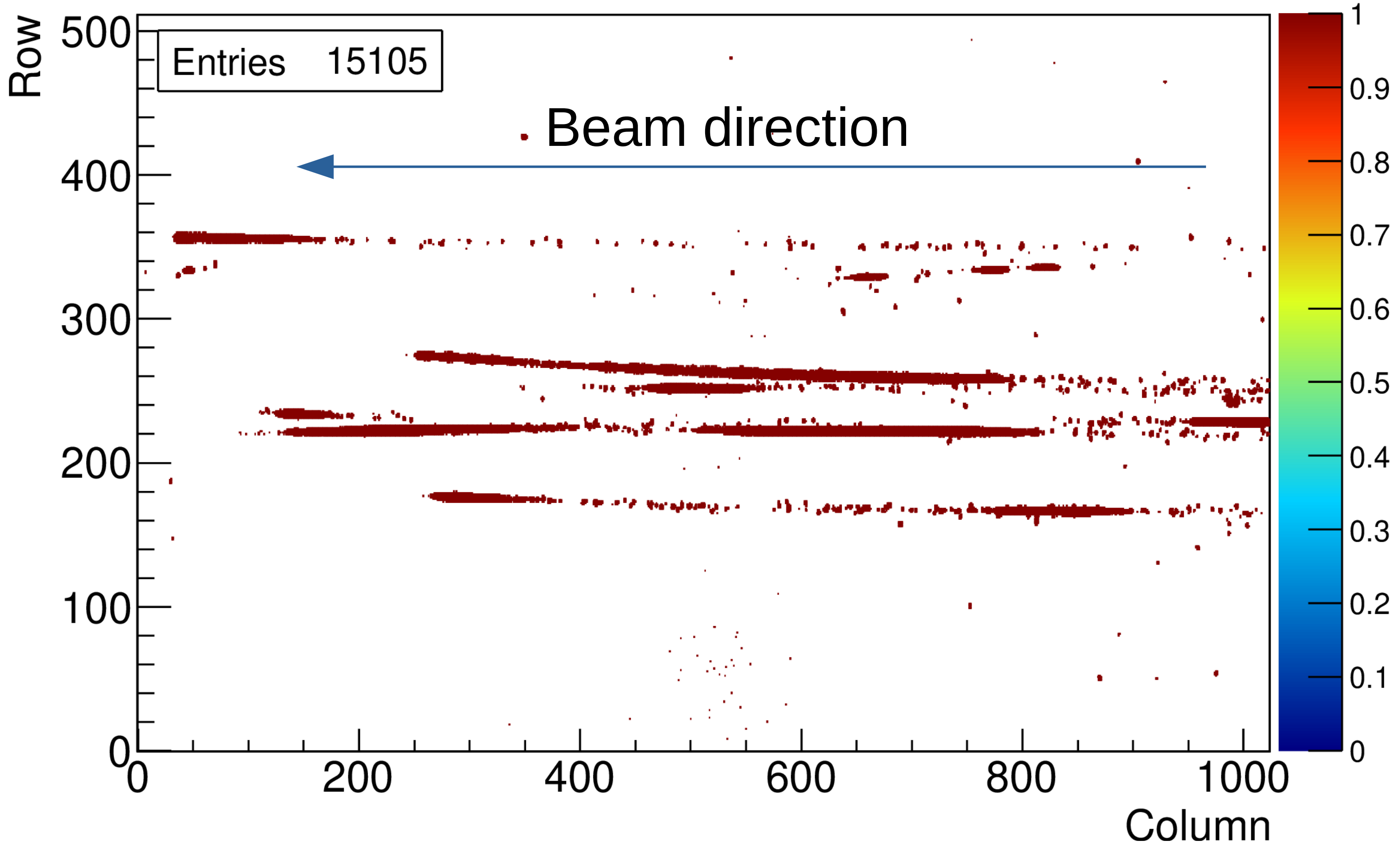


Range of Carbon
in ALPIDE (50 µm thick) ~ 2.5 cm

The ALPIDE chip was kept at few meters away from the beam exit
to stop the beam in sensitive volume of the chip – Record high multiplicity events

Hitmap: Carbon ions

Hitmap of 1 time frame or 1 event = 485 μs

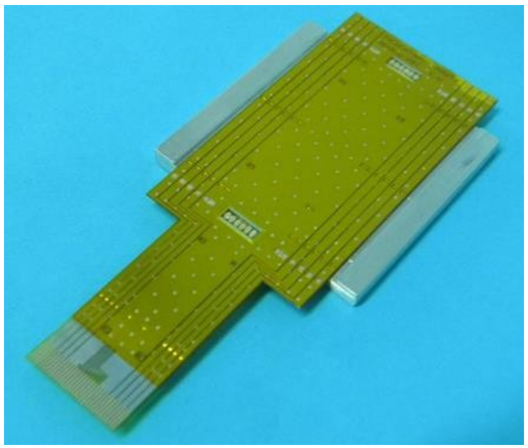


Possible to record high multiplicity event !

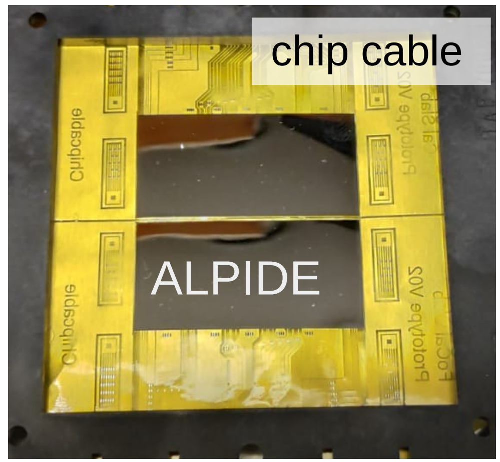
Mounting sensors on flexible cables

Intermediate prototype: chip cable with two ALPIDEs

Back side



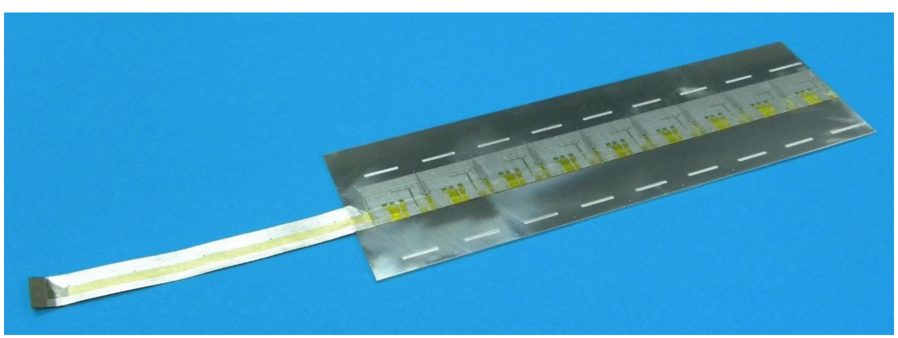
Front side



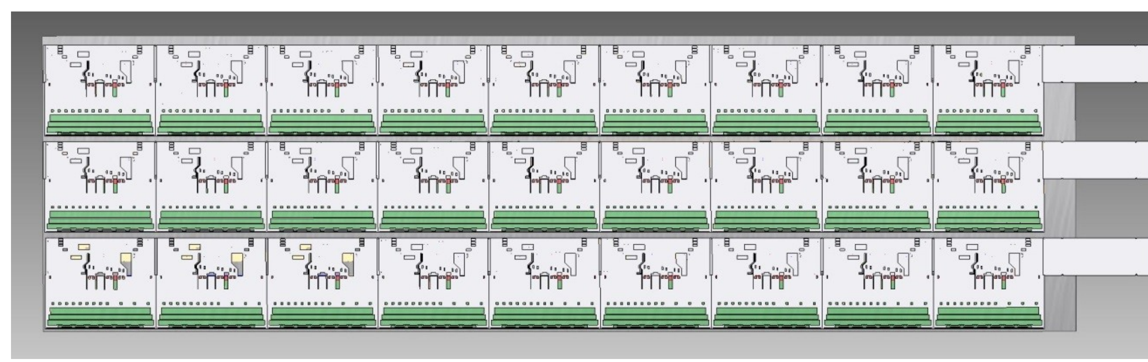
- ALPIDE mounted on thin flex cables: Aluminum-polyamide dielectric (30 um Al, 20 um plastic)
- Design and production: Utrecht University, The Netherlands and LTU, Kharkiv, Ukraine

Final system

Flexible carrier board modules (1 x 9 chips)



Schematic: Flexible carrier board modules (3 x 9 chips)



Summary

- Proton and ion therapy gives better and more precise dose delivery to tumor as compared with photon
- pCT will help to improve uncertainty in range calculations
- Bergen pCT collaboration is building Digital Tracking Calorimeter based on MAP CMOS sensor called "ALPIDE"
- Ion beam test results for ALPIDE are presented

Thank you!

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

HELSE BERGEN Haukeland University Hospital
Western Norway University of Applied Sciences
dkfz.
HIT Heidelberger Ionenstrahl-Therapiezentrum
wigner
Universiteit Utrecht
UiO : University of Oslo

Backup

Imaging with protons – many prototypes

....still no clinical system

Rep. Prog. Phys. **81** (2018) 016701 Review

Table 1. List of some contemporary efforts on prototype pCT systems and particle radiography (pRad) systems with particle tracking. For operational systems the rate is approximately what has been demonstrated to date. Earlier prototypes from the same collaborations are not listed.

Collaboration	Type	Aperture (cm^2)	Tracking technology	WEPL detector technology	Rate	Comment
AQUA [90]	pRad	10×10	GEM	Scint. range counter	10 kHz	1 MHz planned
LLU/UCSC phase-II [51]	pCT	36×9	Si strip	5 scint. stages	1.2 MHz	Operational
Niigata [100]	pCT	9×9	Si strip	NaI calorimeter	30 Hz	Larger, faster instr. planned
NIU, FNAL [93]	pCT	24×20	Sci Fi	Scint. range counter	2 MHz	Not operational
PRaVDA [102]	pCT	4.8×4.8	Si strip	CMOS APS telescope	2.5 MHz	Only tracker operating
PRIMA [95]	pCT	5.1×5.1	Si strip	YAG:Ce calo-rimeter	10 kHz	20×5 cm^2 1 MHz instr. planned
PSI [84]	pRad	22.0×3.2	Sci Fi	Scint. range counter	1 MHz	Program completed
QBeRT [88]	pRad	9×9	Sci Fi	Sci Fi range counter	1 MHz	Also a beam monitor