technische universität dortmund

Physik E-IV

A Second Life
ATLAS Pixel Detectors in Medical Physics

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Managing expectations

A short introduction

Worked mostly on silicon pixel detectors for ATLAS:

- Pixel, IBL, and ITk
- operation of detector modules (sensor plus ASIC)
  →lab characterisation and commissioning in ATLAS
  →beam tests of prototypes

Joined TU Dortmund University in 2018:

- Still ATLAS: pixel and strip detectors for HL-LHC Upgrade
- Move to Medical Physics → It's a different world out here!
  - Personal dosimetry with MPA NRW
  - Radiotherapy with WPE Essen: IBL detectors
  - Only possible because of very good and enthusiastic students from Physics and Medical Physics!

Materialprüfungsamt Nordrhein-Westfalen

wpe Westdeutsches Protonentherapiezentrum Essen
Ein Tochterunternehmen des Universitätsklinikum Essen

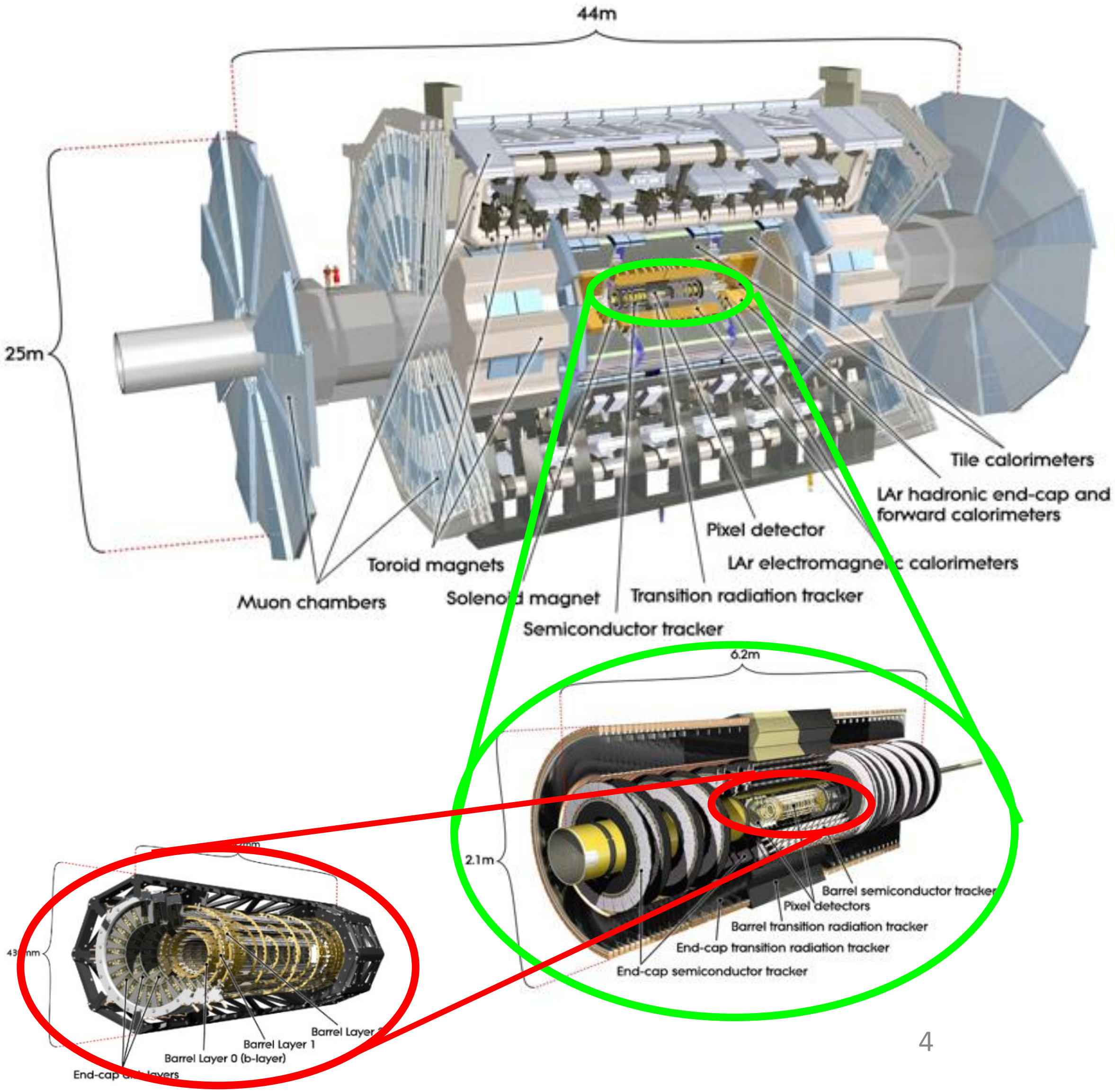
ATLAS

ATLAS

General purpose detector

- access to widest possible physics range
- coverage close to 4π
  - 44m long, 25m high, 7000t
  - ~3000km of cables
  - ~ 100 mio. channels
  - design instantaneous lumi $L=10^{34}cm^{-2}s^{-1}$
  - design pile-up $<\mu>=20$
  - design L1 trigger rate 100kHz

→ At the heart of ATLAS: Pixel Detector



ATLAS Pixel Detectors

Pixel

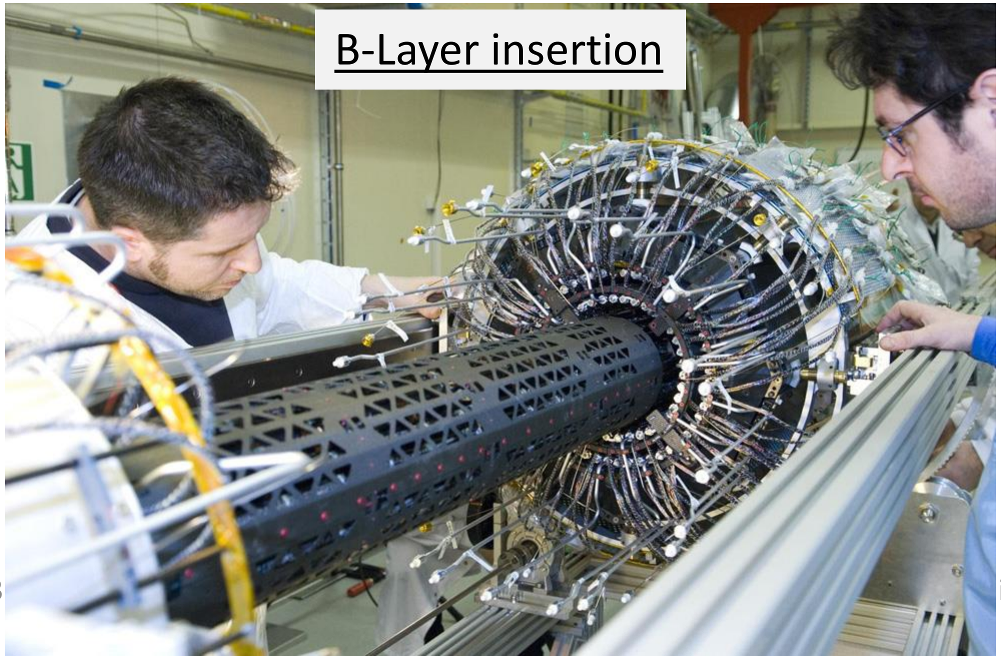
- three barrel/end-cap disc layers
- 80 mio. channels
- 1.7 m^2 active area

IBL

- 4th layer inside B-Layer
- 12 mio. channels
- 0.2 m^2 active area

→ chips and sensors leftover from production

B-Layer insertion



IBL installation

The Inner Tracker Upgrade

<u>High Luminosity LHC</u>

- instantaneous luminosity 5 – 7.5 x 10^{34} $cm^{-2}s^{-1}$
- <μ> = 140 - 200
- integrated luminosity 4000 fb^{-1}

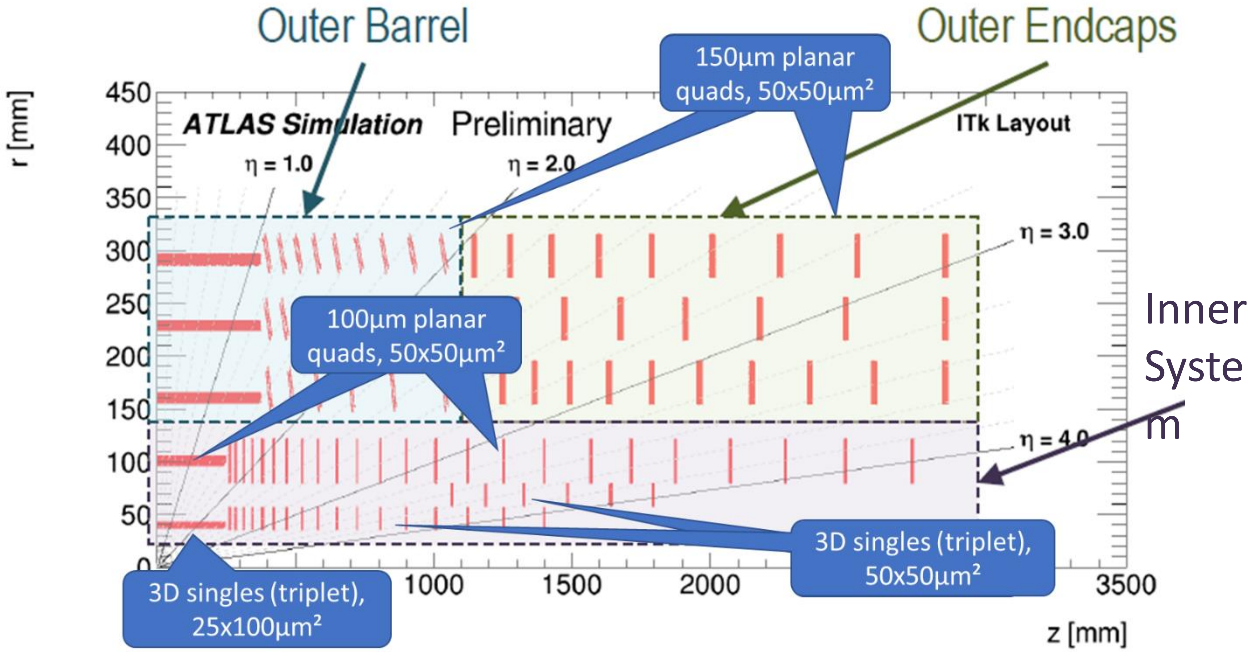
} at the same or better physics performance as for current LHC

<u>Current pixel system</u>
~1.9m² active area
~2000 modules
92 Mega-pixels

→

<u>New ITk pixel system</u>
~13m² active area
9400 modules
1.4 Giga-pixels

→ just starting production of ITk detectors now

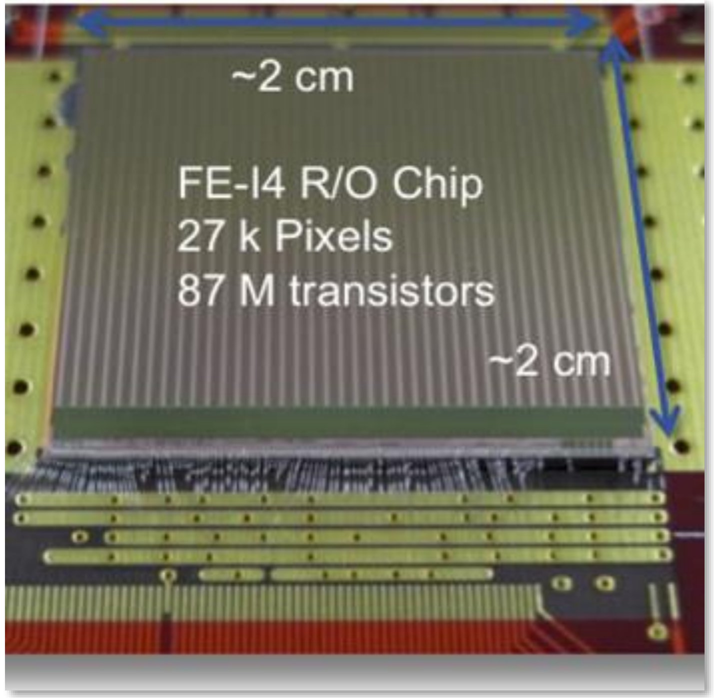


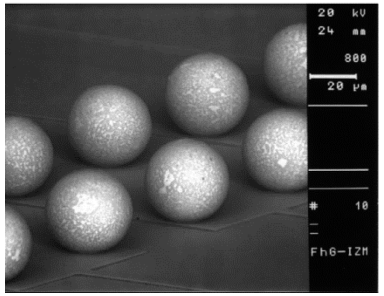
IBL detectors: Tools for medical physics

These are LHC tracking detectors, which means

+ hit efficiency for single charged particles >98.5% before irradiation
+ pixel size 50x250 µm² → spatial resolution ≈ 14µm
+ 336x80 pixels → active area 16.8 x 20.0 mm² per chip
+ radiation hard: 250 Mrad & $5 \times 10^{15}\ n_{eq} cm^{-2}$
+ designed for minimum inactive area around edge

- clock frequency 40 MHz → timing resolution 25 ns
- avg. hit rate with <1% data loss: 400 MHz/cm² ≡ 60kHz/pixel
- max sustained trigger rate: 200kHz
- resolution of charge measurement (ToT): 4 bit
- max charge ~100 ke





They are also hybrid detectors

+ can connect to different sensors
    - mostly planar Si
    - looking into diamond
- extra cost and material

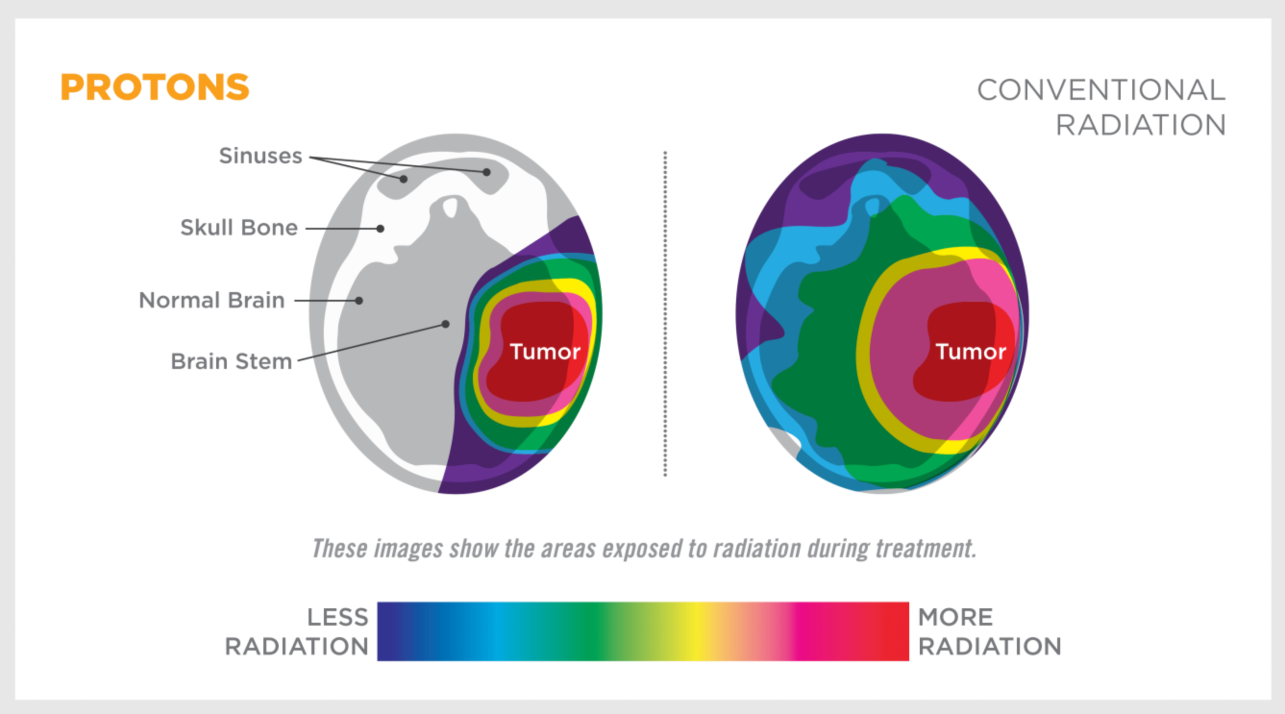
Biggest advantage: Easily available still

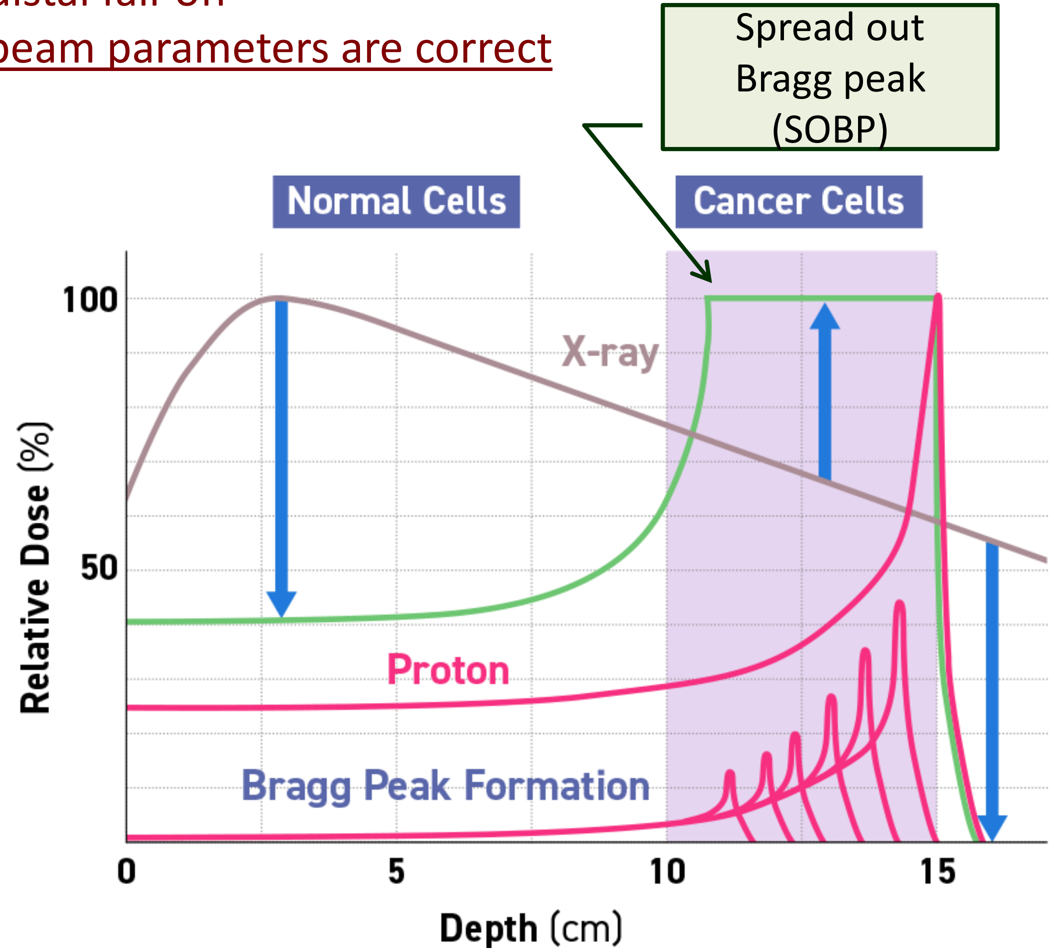
Applications in Proton Therapy

Proton Therapy in a nutshell

- Dose (≈energy) deposition of protons through direct ionization (Bethe-Bloch) → limited range in matter for each proton
- Most dose deposited towards end of range (Bragg-Peak) → sharp distal fall-off
- Dose deposition can be highly conformal to the tumour volume if beam parameters are correct

→ Quality Control Very Important





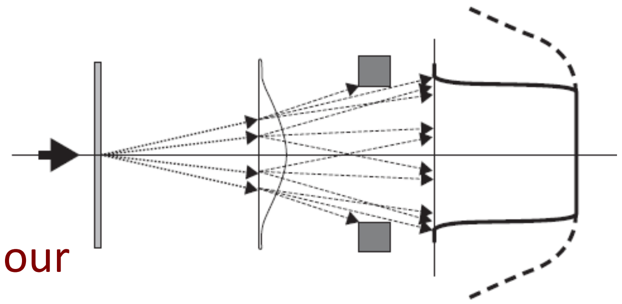
Beam delivery systems

Most treatment centres use (isochron-)cyclotrons to generate treatment beams with constant energy of up to ~225 MeV
Issue: Beam from the accelerator typically small diameter (≤cm), while target volume large (~3 … 40cm) and 3D!

→ Fast energy modulation via rotating modulator wheels, i.e. varying thickness material (dE/dx)

→ Either: Beam broadening in Double scattering systems
1. First, uniform scatterer to widen beam
2. Second, contoured scatterer to homogenize field
3. Contoured range compensator to account for the shape of the body

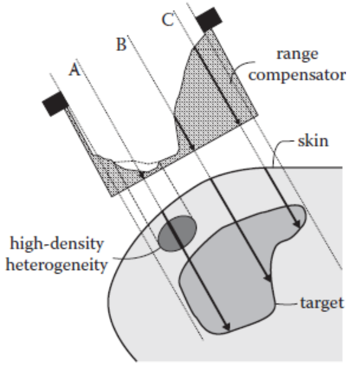
→ One large field, conformal along beam axis, which is scanned over the tumour

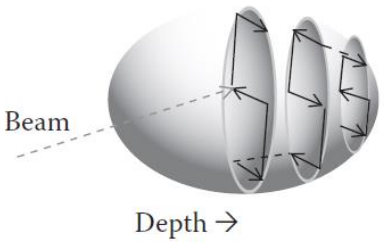


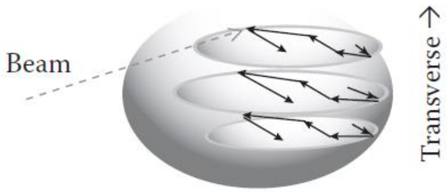
→ Or: Pencil beam scanning
1. Scan small beam spot across tumour volume
2. Modulate energy to irradiated different depths

} or vice versa

→ Dose deposition conformal in all three dimensions, technologically more complex







Figures borrowed from Paganetti et al., Proton Therapy Physics

WPE-UK Essen

Close collaboration with West German Proton Therapy Centre in Essen

- one of the leading proton radiotherapy institutes in Germany
- four treatment rooms, using IMPT on ENT tumours, cranial base and prostate tumours, as well as for irradiation of tumours in the central nervous system and the entire craniospinal axis
- strong focus on treatment of paediatric patients, where high precision is most important (long-term side effects)
- all manners of beam delivery systems
    - double-scattering, uniform scanning, pencil beam scanning
    - protons up to 226 MeV

wpe Westdeutsches Protonentherapiezentrum Essen

Ein Tochterunternehmen des Universitätsklinikum Essen

Application: Accelerator QA

Quality assurance - 1

To do machine QA correctly, we have to answer two questions:

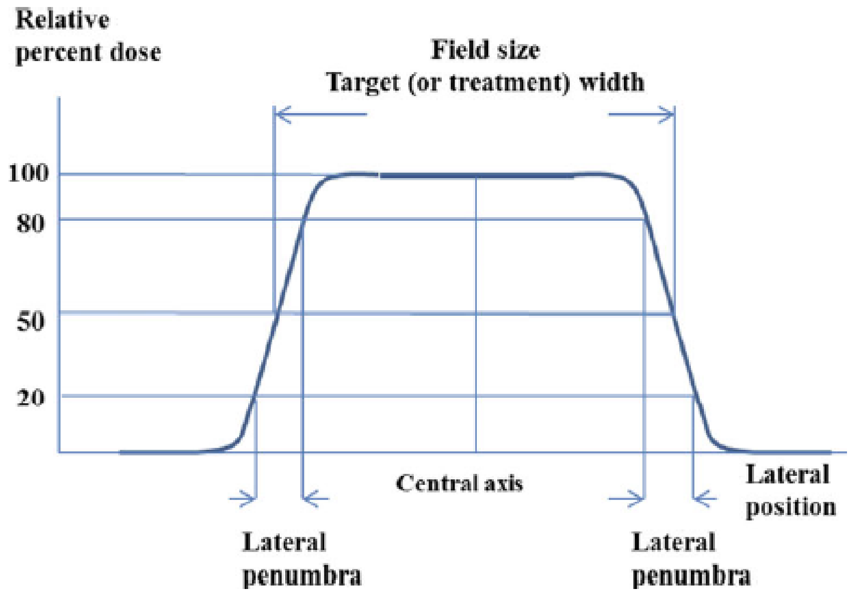
1. What do we want?
2. When do we want it?

Somewhat surprising to a physicist (or a german?): No standard exists! They're shooting proton beams at people…
→ Recommendation by American Association of Physicists in Medicine (AAPM) task group 224 published in June 2019

What do we need to monitor? (Where Pixel Detectors can help)

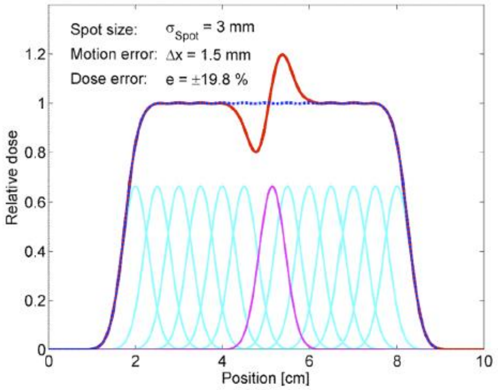
1. Double scattering system
    - (reproducibility of) lateral field position & size
    - dose homogeneity across the field (± 2%)
    - width of lateral penumbra (± 2mm)

    → depends on gantry mechanics/angle



Quality assurance - 2

2. Pencil Beam Scanning
   - (Reproducibility of) Beam position
   - (Reproducibility of) FWHM of beam spot
   - spot shape

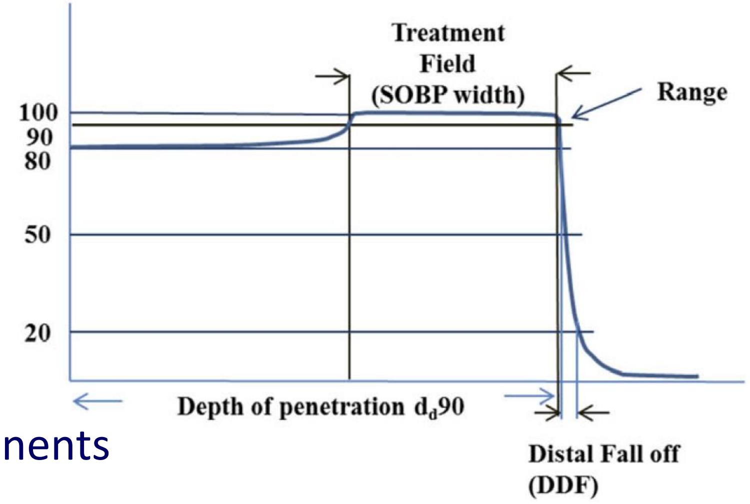


tolerance scales with spot width:
dose uniformity ≤ 3%
➔ require shift < 13% of spot size, e.g. 0.4mm for 3mm spots

3. All systems
   - constancy of dose calibration, i.e. dose per Monitor Unit (MU) (± 2%)

   - (Reproducibility of) Beam energy, i.e. depth of Bragg peak in water
   - Energy deviation, i.e. distal fall-off
   - width of the SOBP (modulator wheel, range shifter)

   → measure depth dose curve in water



Plus MANY checks of instruments, interlocks, mechanics, and general system components

Instruments

Currently in use: A combination of
- large area, thin parallel plate ionization chambers for dosimetry
- multi-layer ionization chambers exist for dosimetry
- small, “point-like” ionization chambers for beam profiles

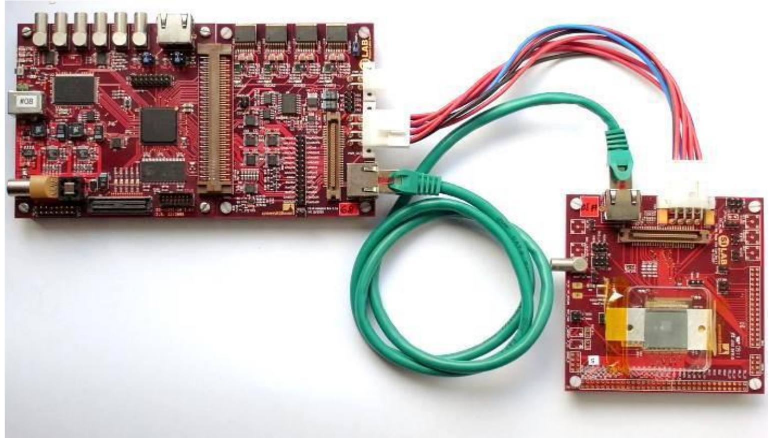
- alternatives:
  - film dosimetry
  - scintillating devices with CCD cameras (LynxPT, et al.)
  - 2D ionization chambers (MatriXX PT, et al.) for beam profile ⟵ very promising, but sampling frequency, i.e. spatial resolution, marginal
  - strip-chambers (MSGC, Si) “in the near future”

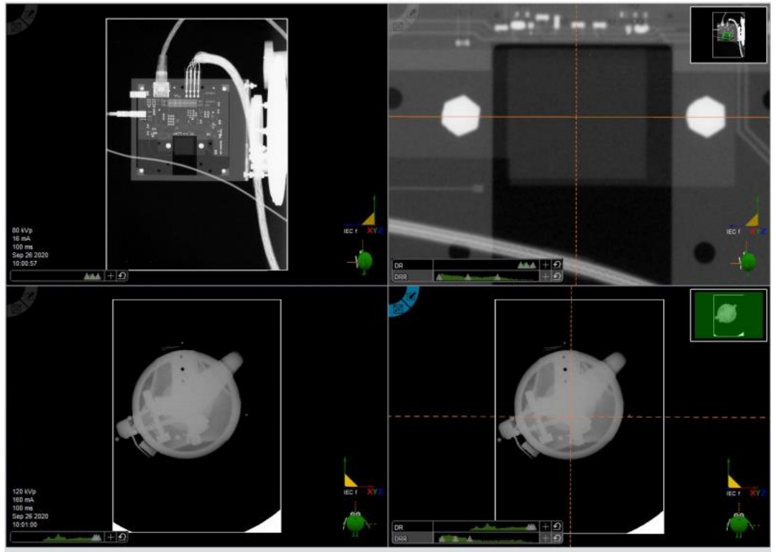
Daily QA per treatment room: 30 min to 1h, driven by setup of multiple instruments
➔ Can we help?

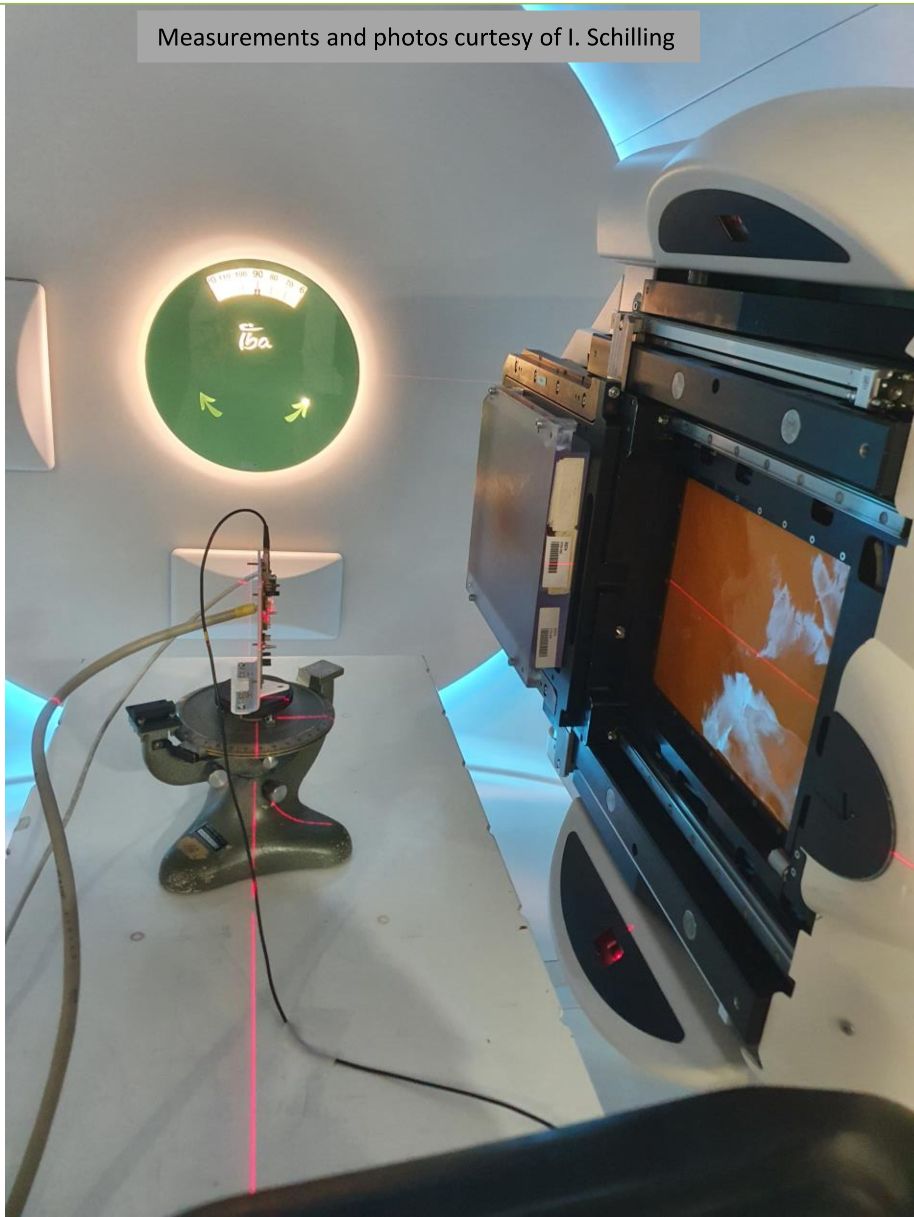
Setup

One rainy Saturday morning in late September:

- FE-I4 module, 200µm n-in-p sensor
- positioned at the isocenter ("focus"), manual alignment
- irradiated with individual fields, 50…400MU each







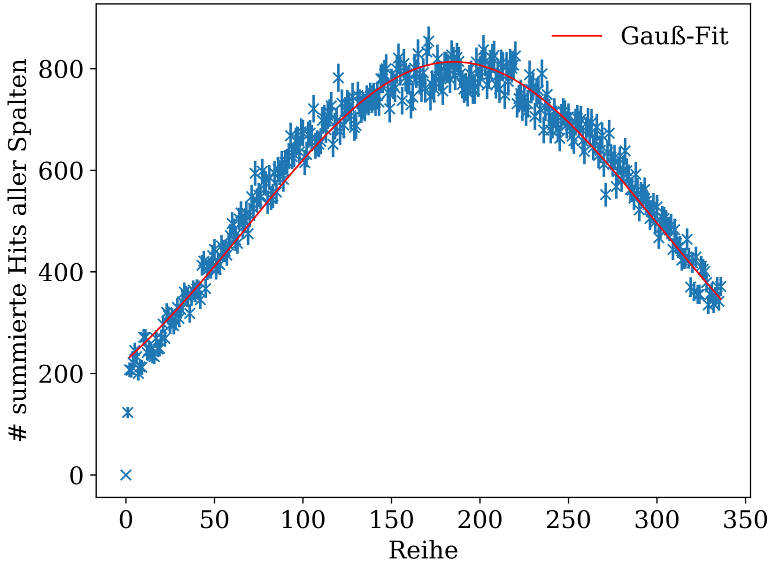
Measurements and photos curtesy of I. Schilling

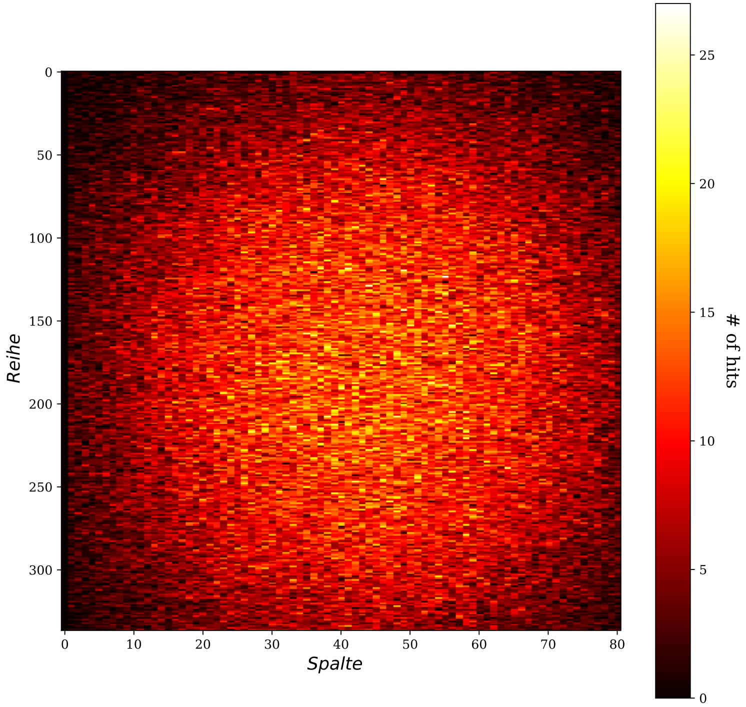
PBS spot parameters

Single 400MU field, scan duration ≤10s

- beam energy 100 MeV
- expected sigma ≈5.53mm → measured (5.78 ± 0.03)mm

- Spot position: σ_{peak} ≈ 100µm (mechanical alignment only)
- Spot width: σ_{FWHM} ≈ 30µm
- 2D Gaußfit → shape of beam spot



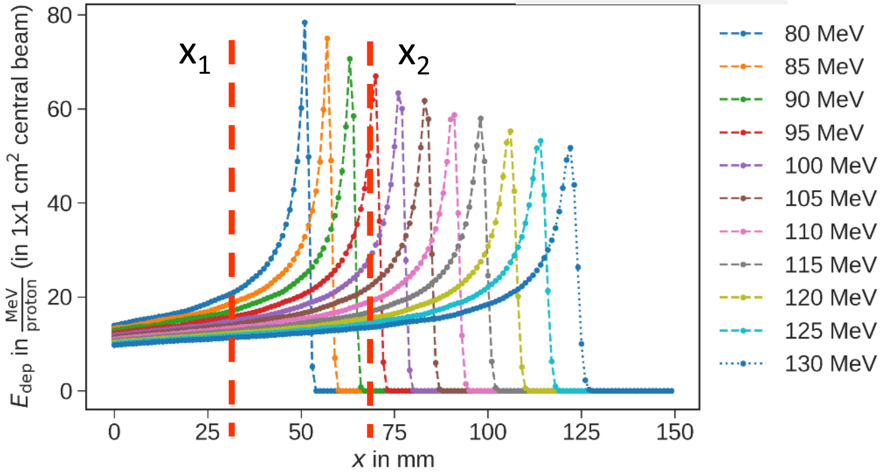


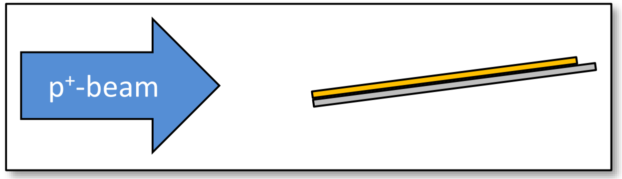
Beam energy

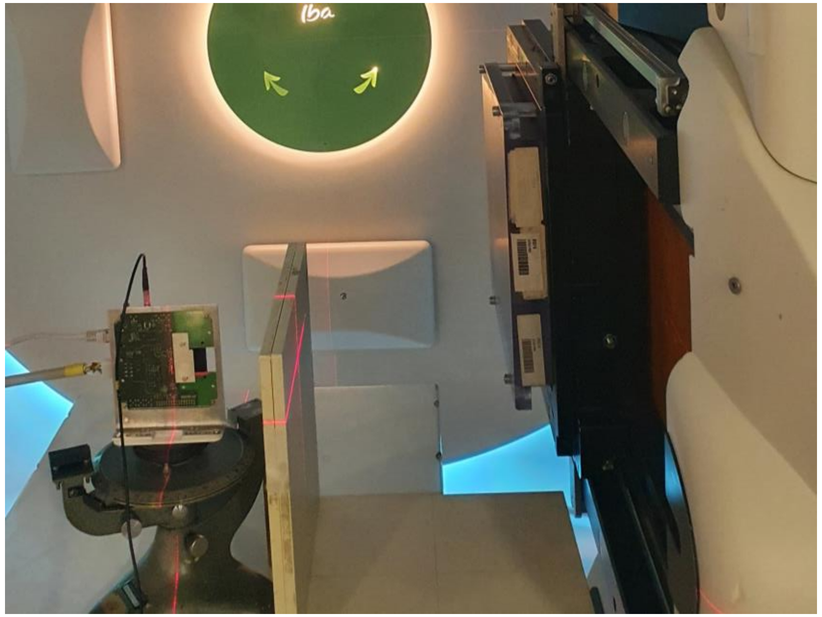
Two approaches

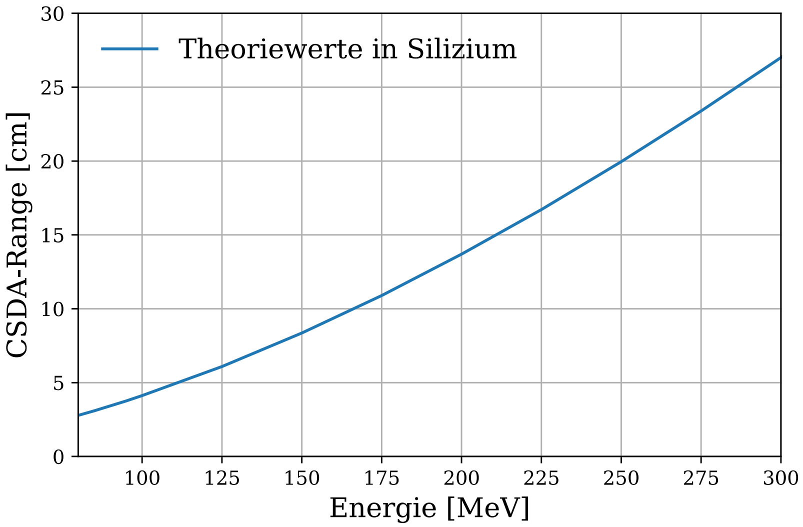
1. measure deposited energy at two points of depth dose curve (x_1 and x_2)
   → $\Delta(dE)$ proportional to E_0
   1a. keep adding range shifters until protons are stopped before reaching the sensor → depth dose curve
2. measure dE along a long track in the silicon at grazing beam incidence

Curtesy of F. Mentzel







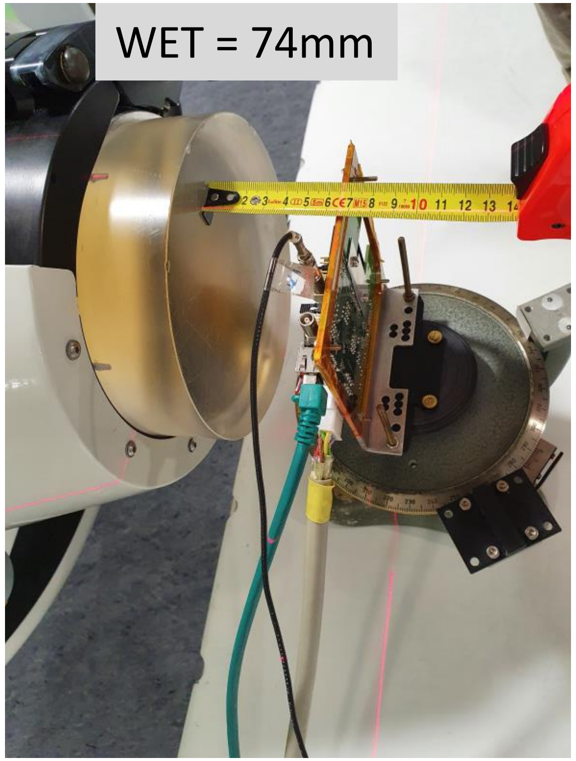


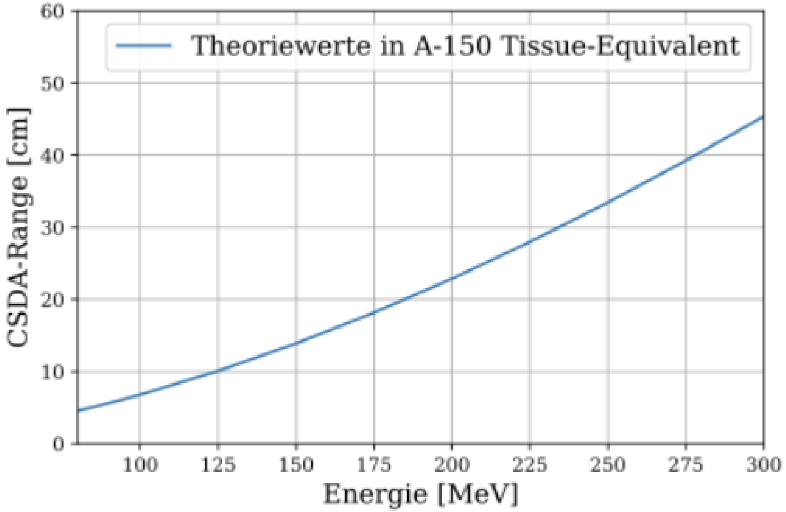
CSDA range of 100 MeV protons in silicon ~4cm

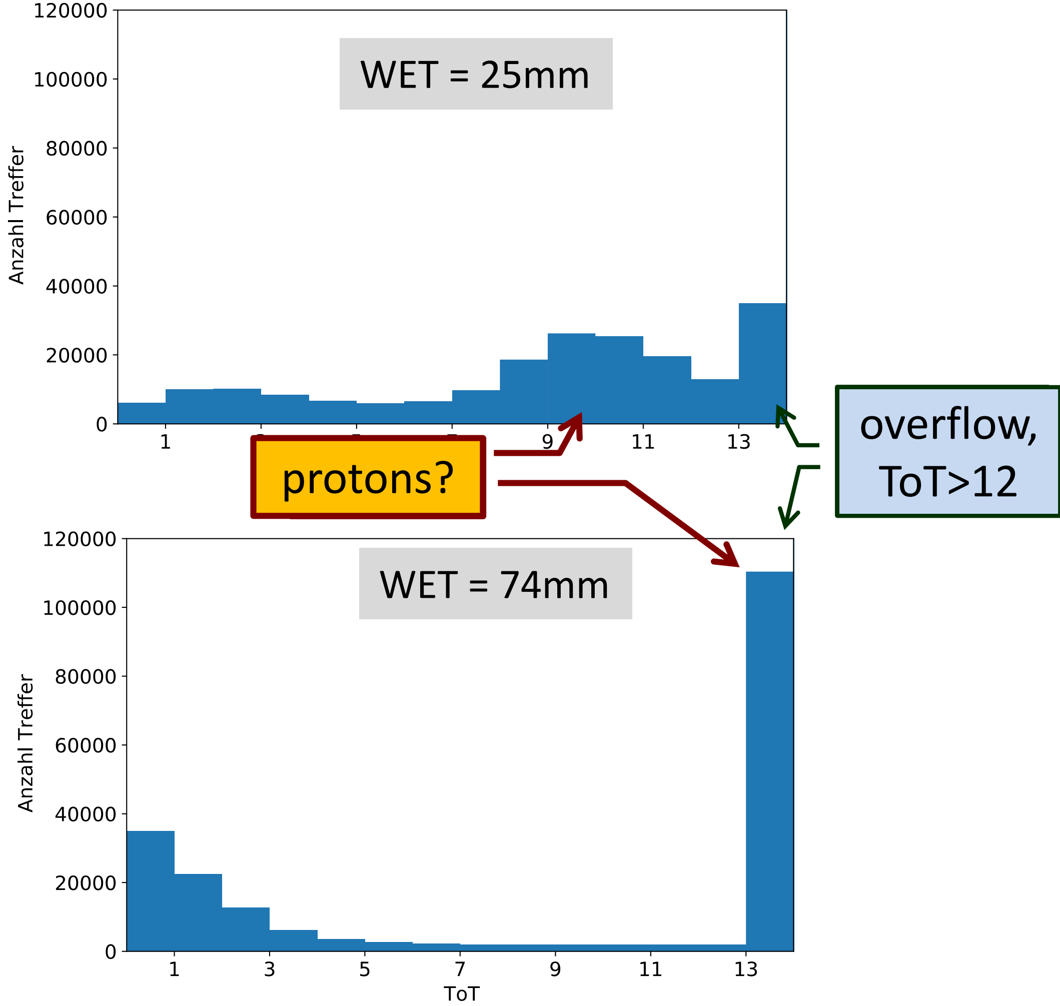
→ still had to add range shifters…

Depth dose curve

- different thickness range shifters to degrade energy (expected range at 100 MeV: 7.7cm)
- measure deposited energy via ToT distribution
  → effect is visible, but no quantitative measurement possible
- ToT distribution depends strongly on chip parameters
  → improve tuning for next time







Bragg peak in Silicon

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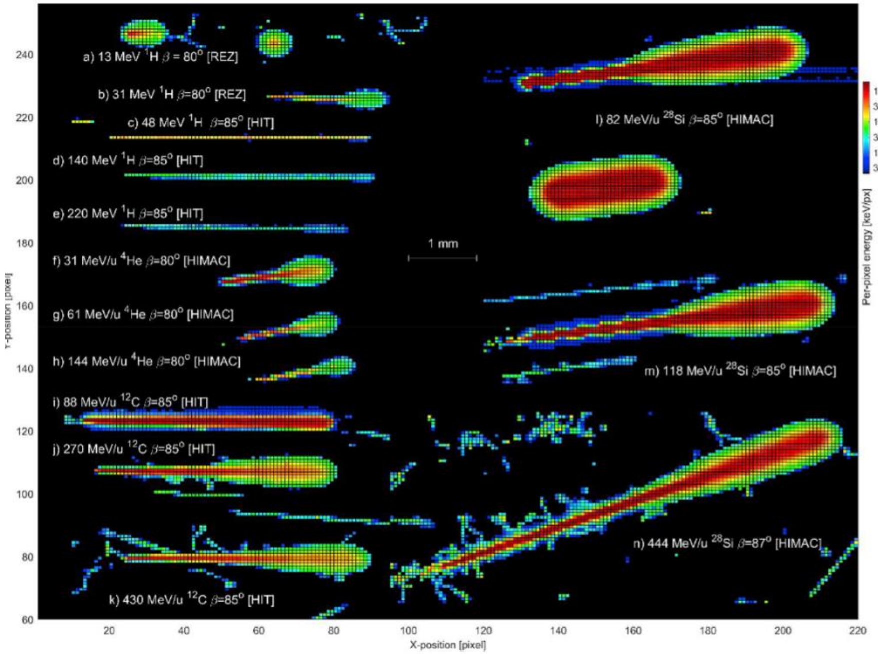
What we wanted to see

from ADVACAM's MiniPIX-TimePIX camera

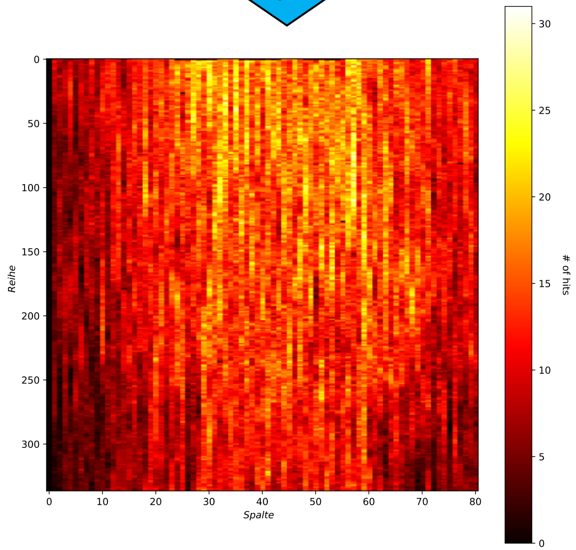


What we did see

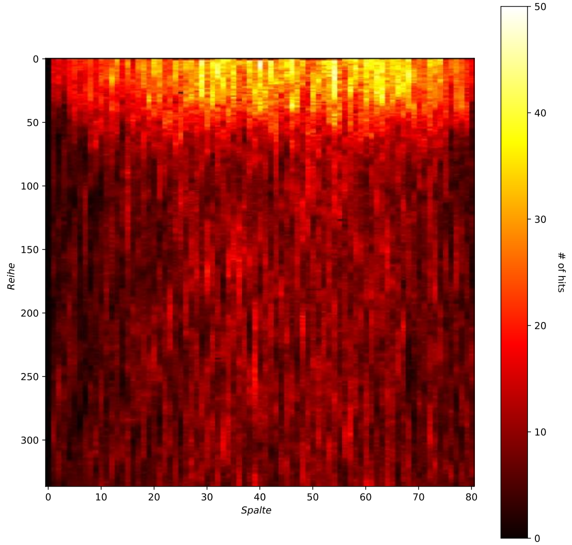
Energy resolution probably too low
(it's a tracking chip…)

p

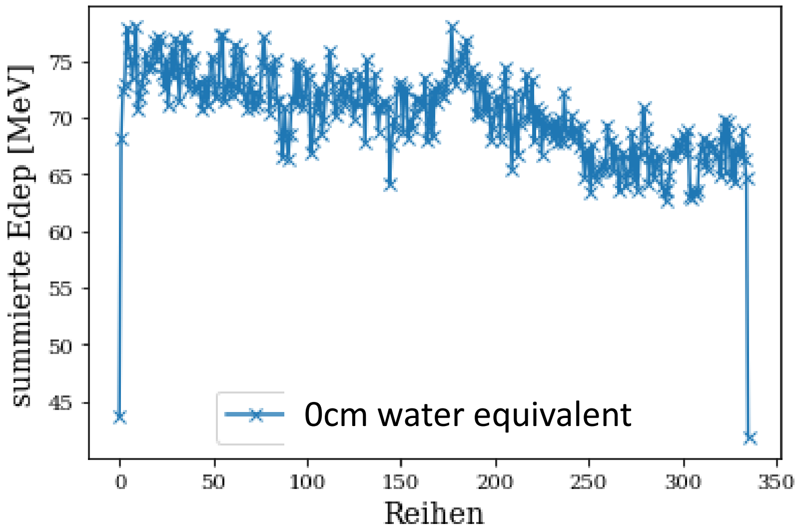
WET = 0cm

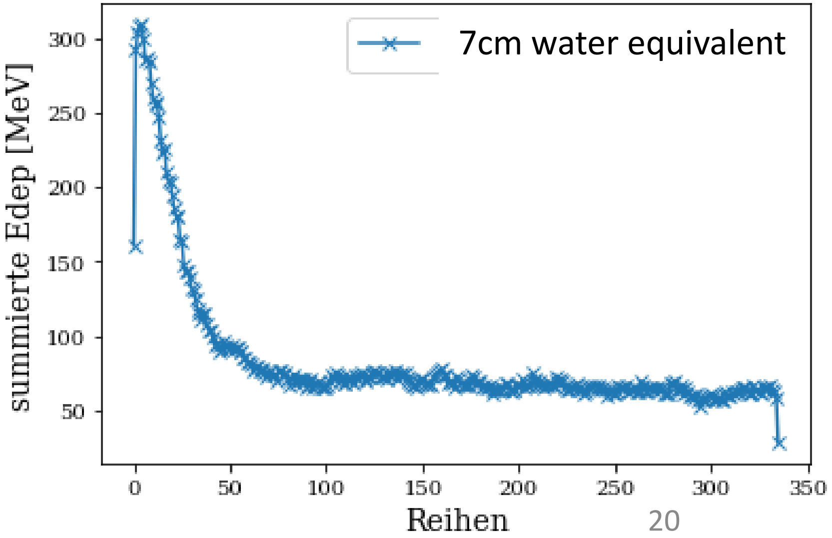


WET = 7cm



dE vs depth





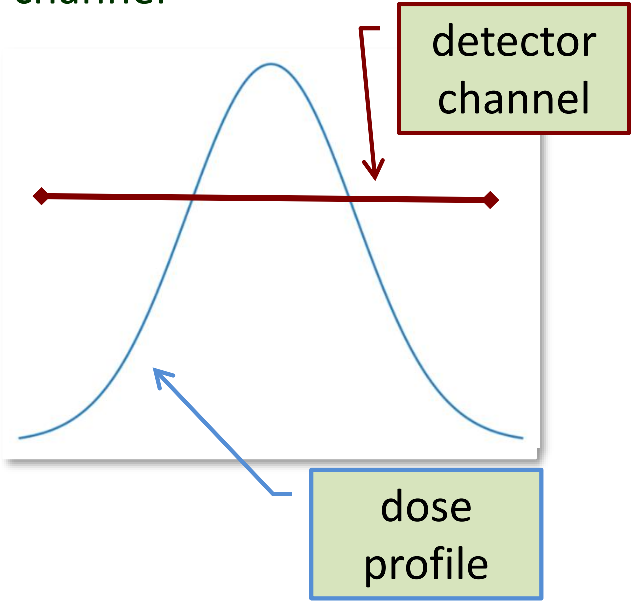
Application: Small field dosimetry

Small fields

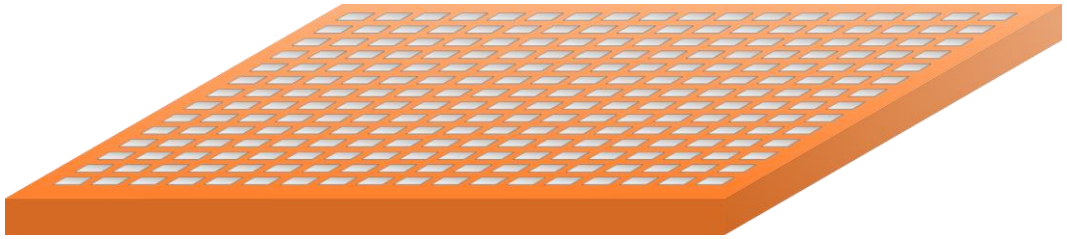
As imaging technology improves, so do targets for radio therapy become smaller

→ high spatial precision dose delivery requires small detector size

- standard radiotherapy ionization chambers have relatively large sensitive volumes per channel
  → partial volume averaging of the dose profile
- esp. for protons: LET varies as function of depth (i.e. local proton energy)
  → can significantly impact detector response



Require small sensitive volumes to accurately measure high-gradient fields,
ideally a large array of them to save time (less to no scanning across extended field)



Curtesy of F. Mentzel

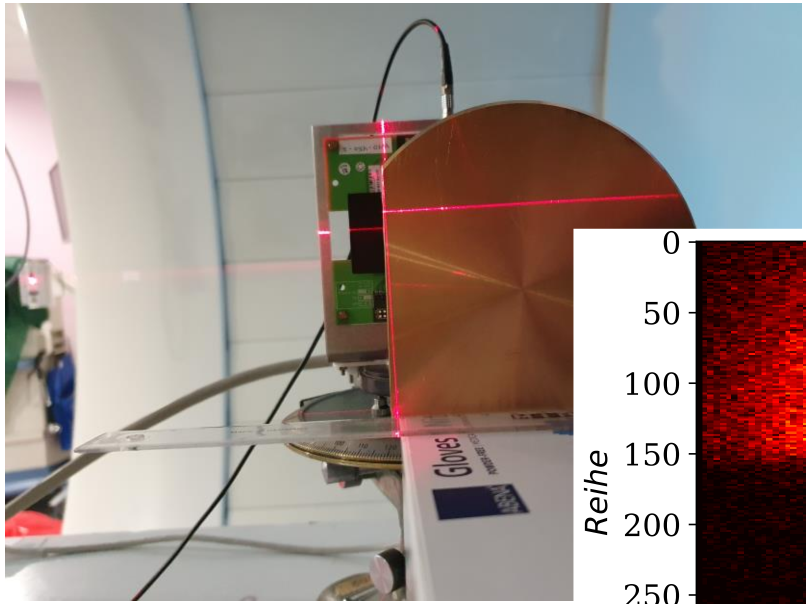
Small Field Dosimetry

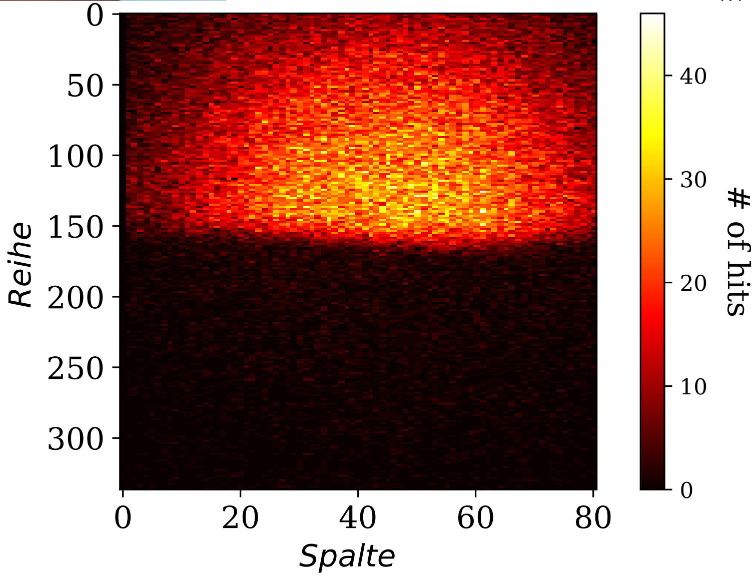
Spare healthy tissue by conforming irradiated volume as well as possible to tumour

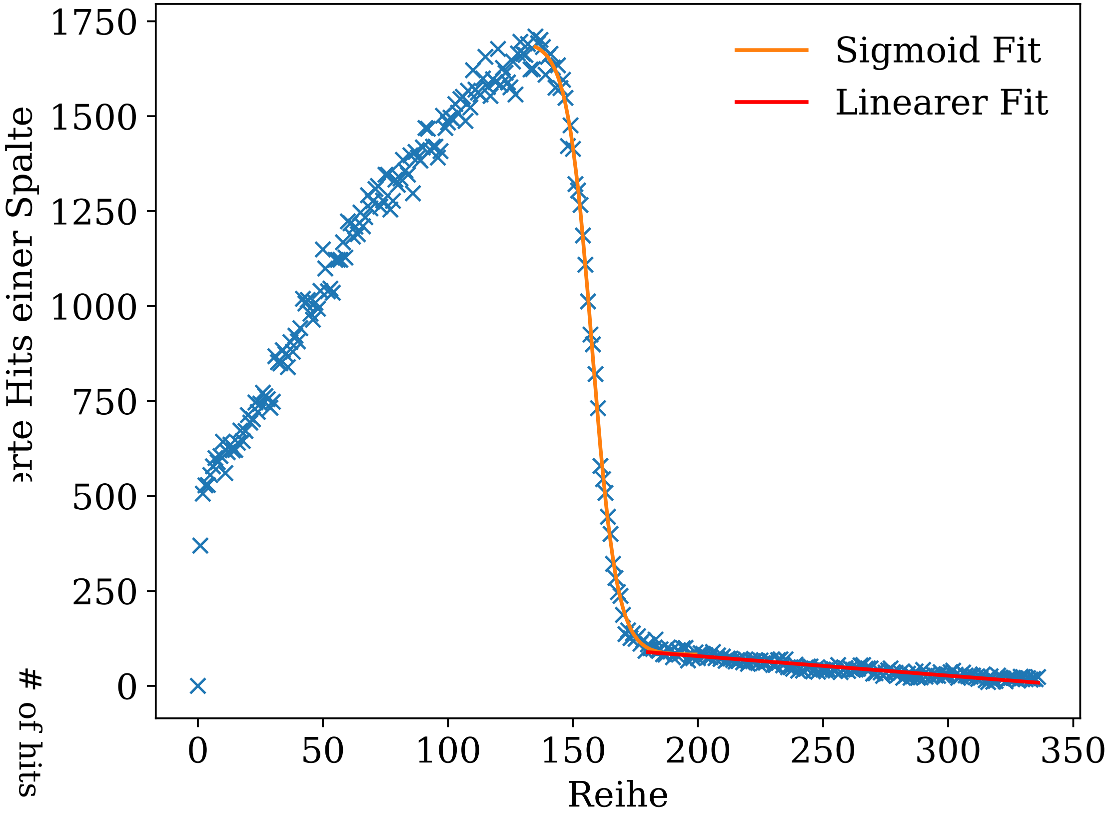
→ need for sharp contours in the field

- single PBS spots
- conformal absorber

➔ Imaged straight edge of a brass absorber (100MeV)



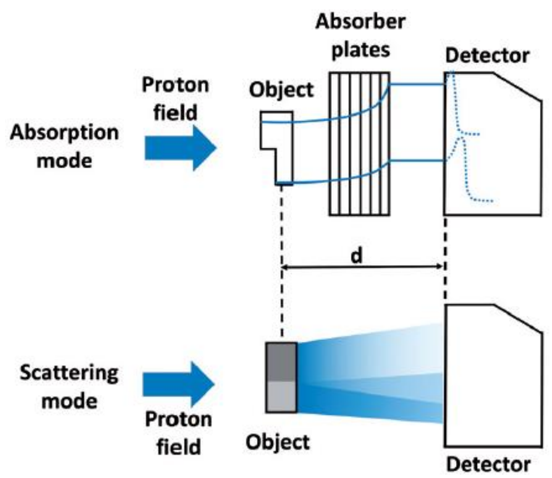


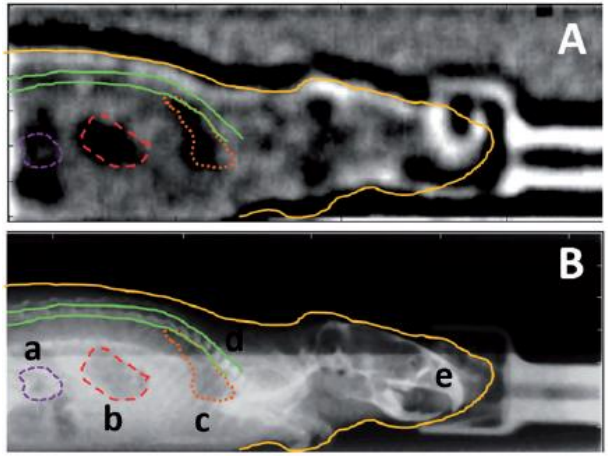


80%-20% slope (penumbra) covers 13 pixels
→$\sigma_{80\text{-}20}$(fit)=20µm (in this setup)

Further applications

pCT & pRadiography





J. Müller et al, Acta Oncologica, 56:11, 1399-1405

Proton radiography

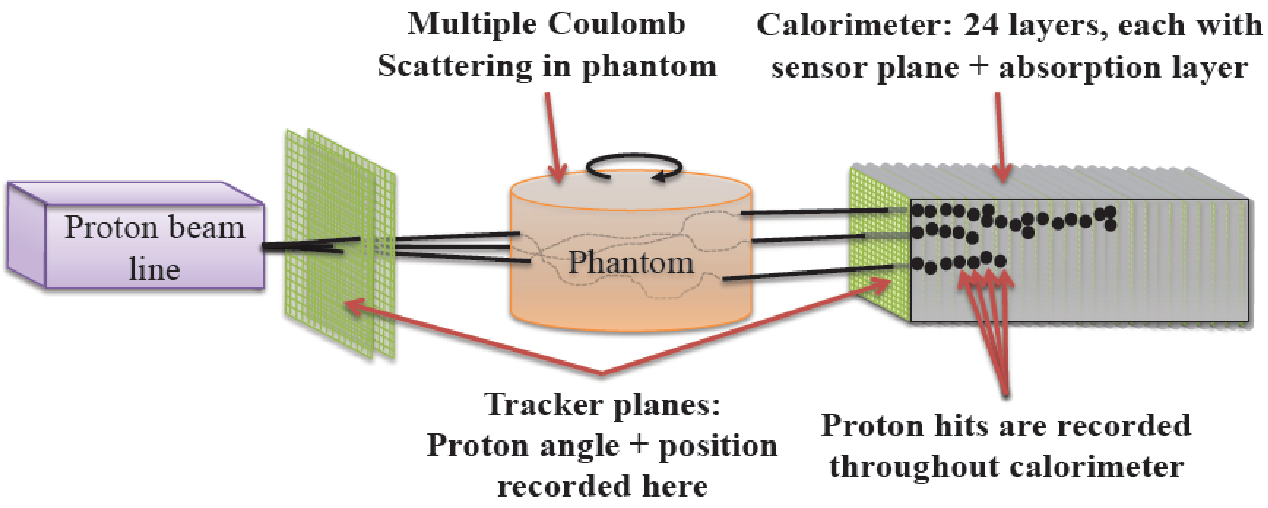
- combine scattering and absorption images
  → positioning of a patient on treatment bed
- dual energy pRad can yield WEPL maps
- tested with mice using Lynx scintillation detector

→ might profit from direct image acquisition

Proton CT

→ Physicist: low momentum test beam telescope

- tracking planes upstream and downstream of patient
- planes need to be
  - thin → minimal MCS
  - fast → high beam intensity
  - small pixels → distinguish many protons per frame
- building full Geant4 simulation

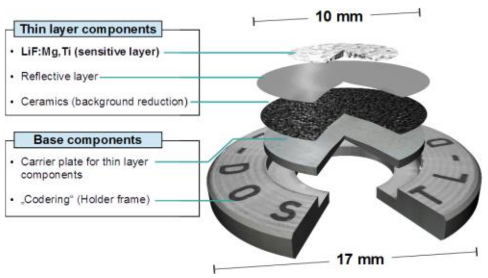


Helge Egil Seime Pettersen, University of Bergen technische universität dortmund

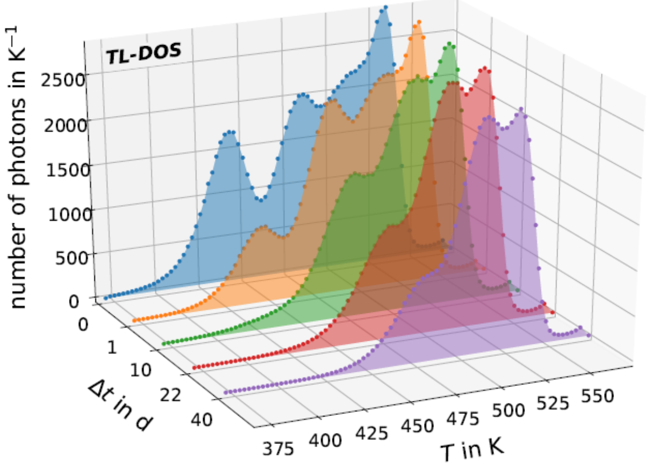
And Now for Something Completely Different…

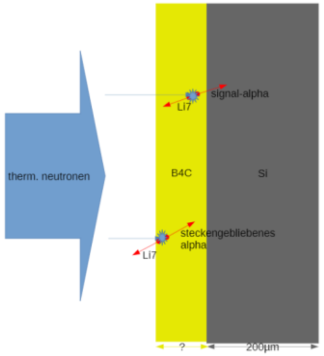
Personal dosimetry: TL-DOS

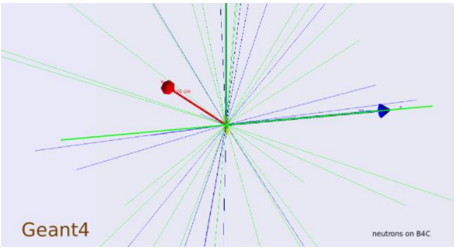
- studying fading of thermoluminescent material to extract more information from data
  → time of exposure, type of radiation
- GC simulation using CNNs



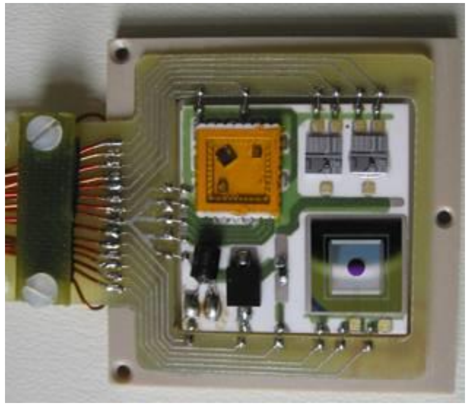
Curtesy of Robert Theinert







Inspired by:
ATLAS Radmon,
JSI Ljubljana



Environmental dosimetry

- monitor neutron flux with a counting system
  - simulate silicon sensor coated with $^{10}B_4C$
    $^{10}\mathrm{B} + n \rightarrow ^{7}\mathrm{Li} + \alpha$
  - detector coating in-house, end of March
- monitor radiation damage in LEO satellites
  - driving factor for mission duration
  - characterizing rad damage in COTS components
  - monitor NIEL, TID, SEE with a light-weight system

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Summary

- We are starting to transfer our experience from HEP into Medical Physics…
  - Detector development
  - Geant4 simulation and Machine Learning
- … and learning a lot
  - nomenclature, procedures, standards (and lack thereof)
  - What is important in clinical application vs what is technologically possible

- Applications in proton radiotherapy
  - first tests show promise for use of pixelated detectors in Machine QA and Small Field Dosimetry
    - next steps: thinner, faster monolithic detectors; large area arrays → CMOS Pixel Detectors?
  - starting to look into proton radiography and proton CT with Si Pixel Detectors

- Active in a few other fields as well: ATLAS ITk Pixel and Strip Detectors but also
  - Dosimetry, radiation damage monitoring
  - tempted to also look into space weather instrumentation

  → There is a lot to do out there…

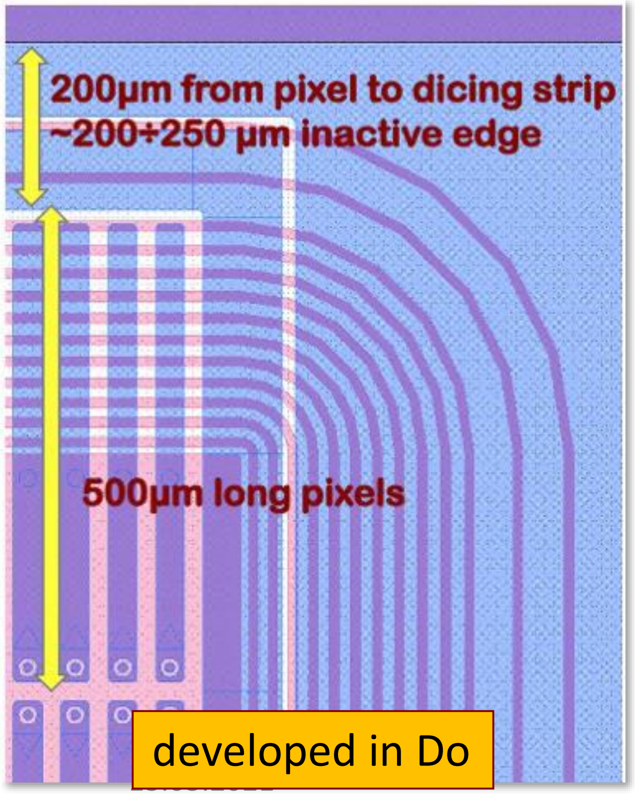
Thank you for your attention

IBL detector modules

Planar Slim Edge Sensors (CiS)

- oxygenated n-in-n silicon; 200 µm thick
- minimize inactive edge

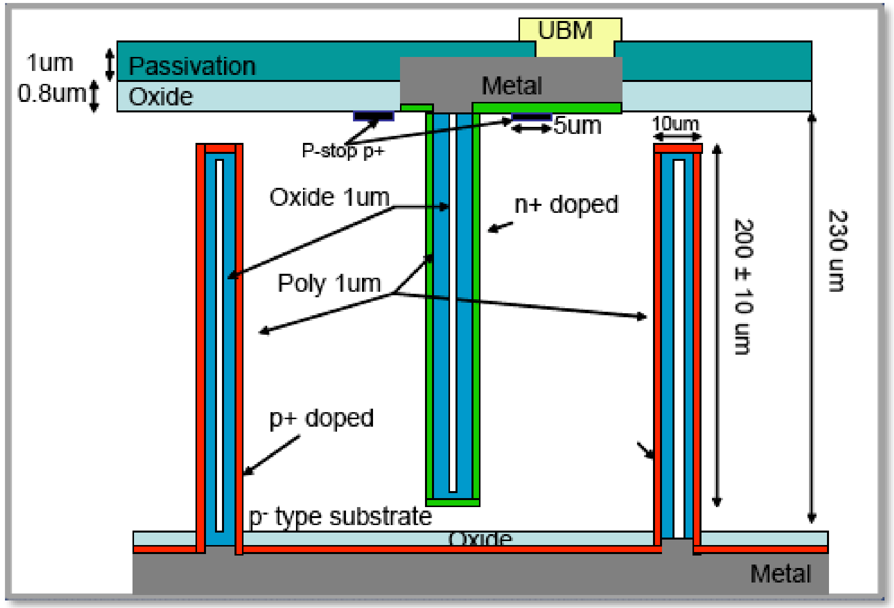
➔ 215 µm inactive edge achieved



3D Slim Edge Sensors (FBK and CNM)

- partial 3D: electrodes etched from both sides
- p-type substrate; 230 µm thick
- no active edge

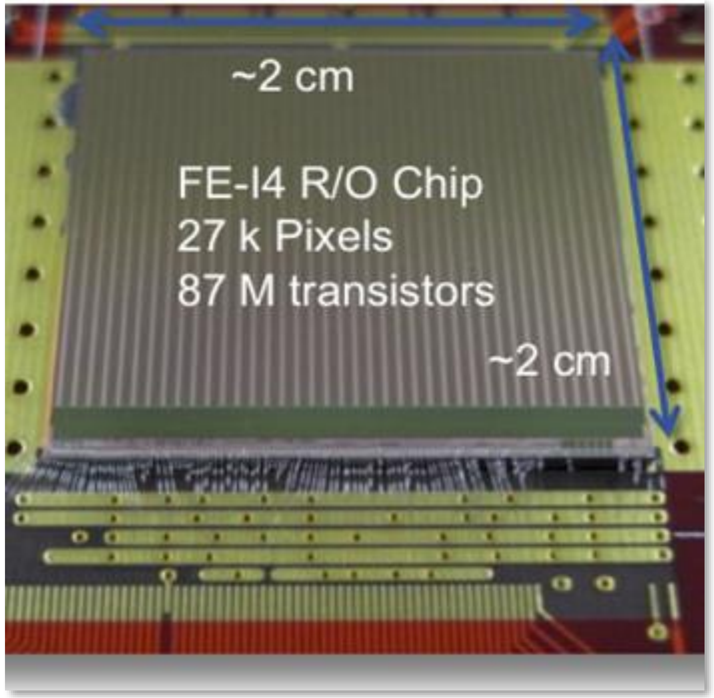
➔ ~200 µm inactive edge achieved



(in FBK "full-3D" columns penetrate full sensor)

Readout: FE-I4B (IBM)

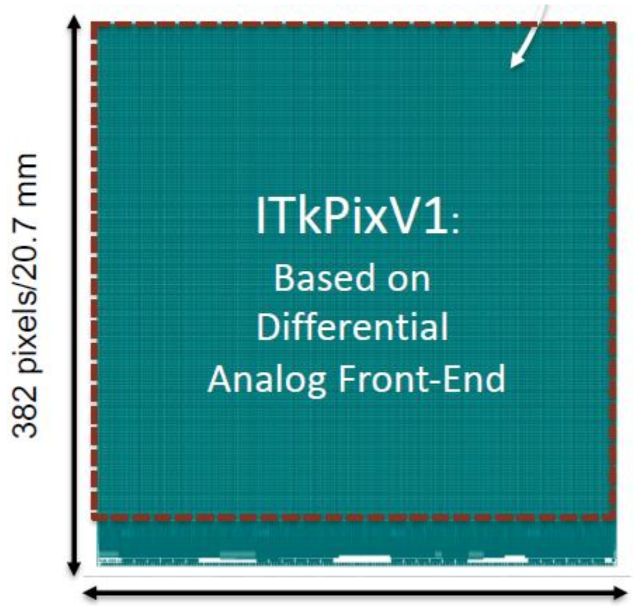
- 130nm CMOS technology
- pixel size 50µmx250µm
- 80x336 = 26880 pixels
- active area ~2cm x 2cm



The ITk Pixel Detector

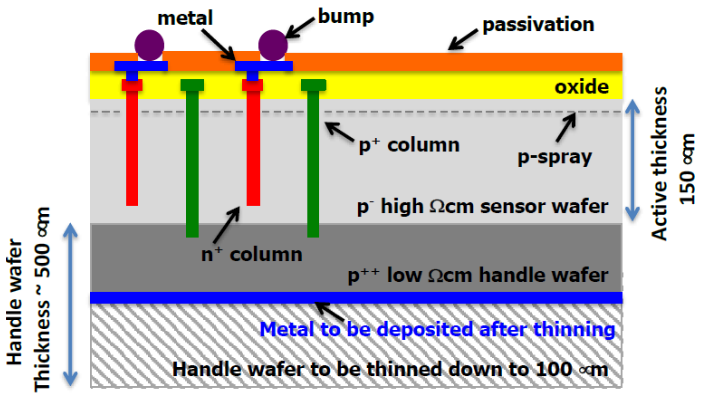
ITkPix r/o chip

- 65nm technology
- in-time threshold < 1ke
- sustained trigger rate: 1 MHz
- hit rate: 3 GHz/cm²
- pixel size: 50µm x 50µm



3D Sensors

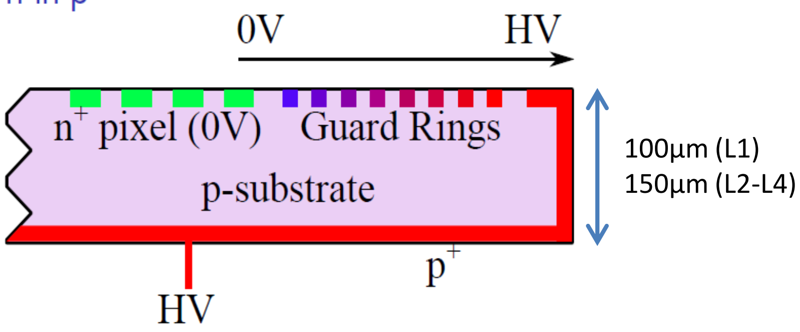
- single-sided processing
- 150µm active + 100µm support
- inactive edge <150µm
- single chip size: 4cm²



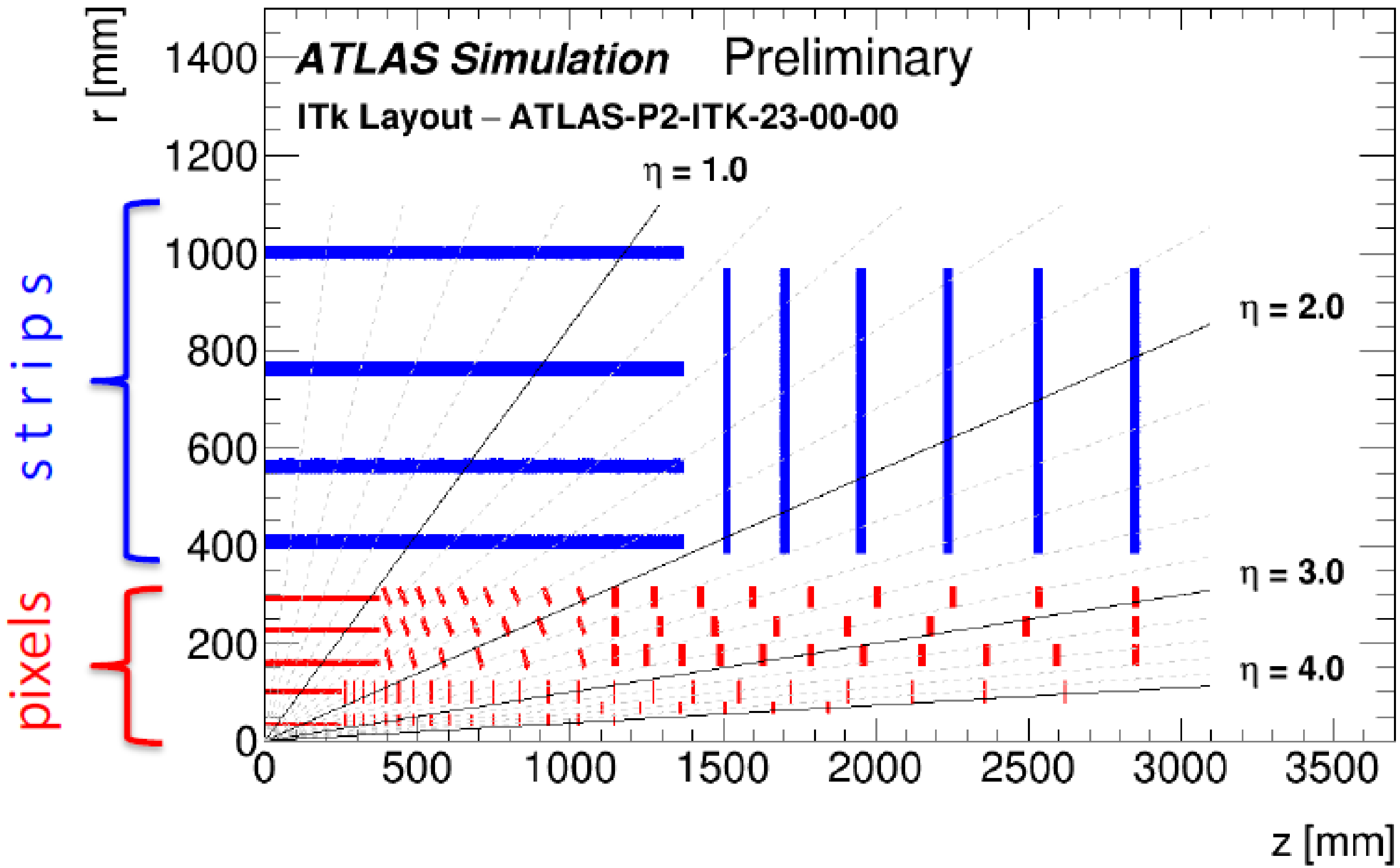
Planar Sensors

- thickness: 100µm (IS), 150µm (OS)
- inactive edge: 250µm (IS), 450µm (OS)
- n-in-p technology, 50µm x 50µm pixels
- quad chip size: 16cm²

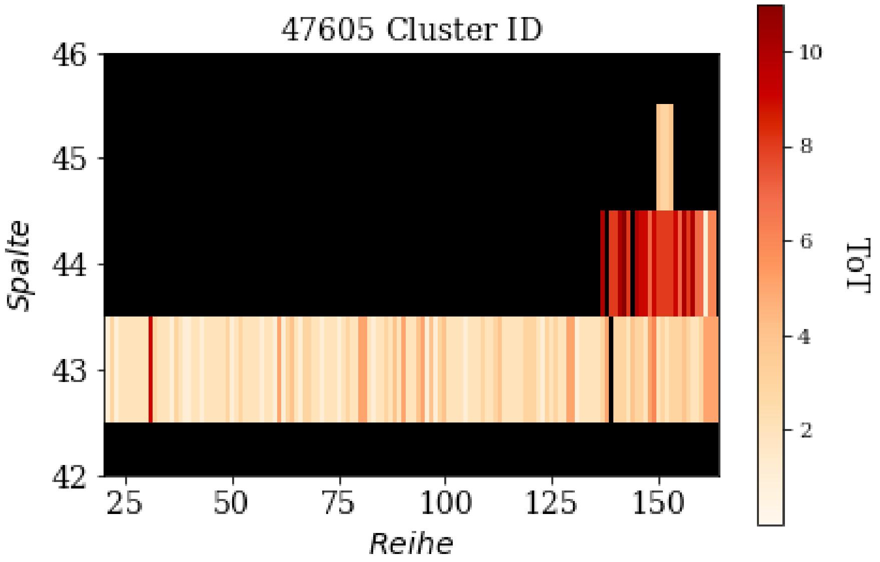
n-in-p

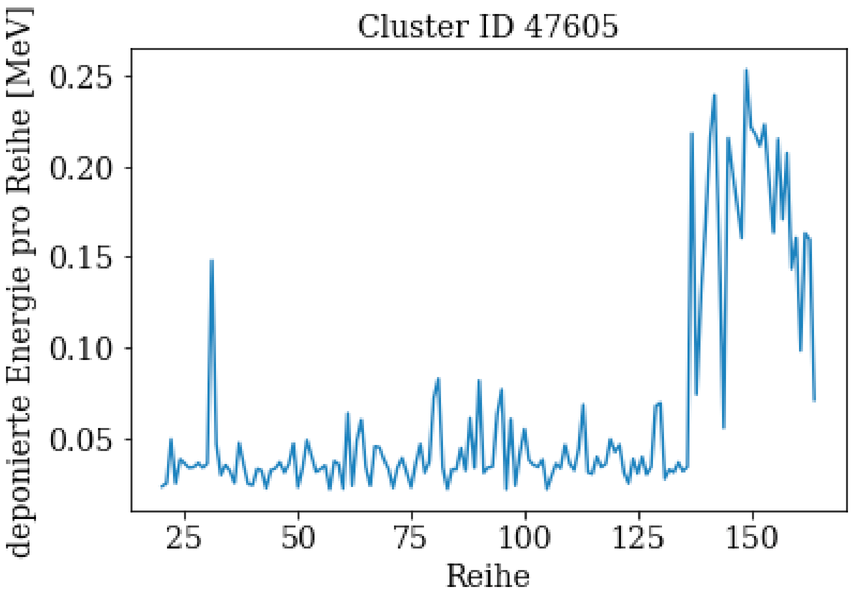


ATLAS ITk Layout



Bragg-Peak in clusters



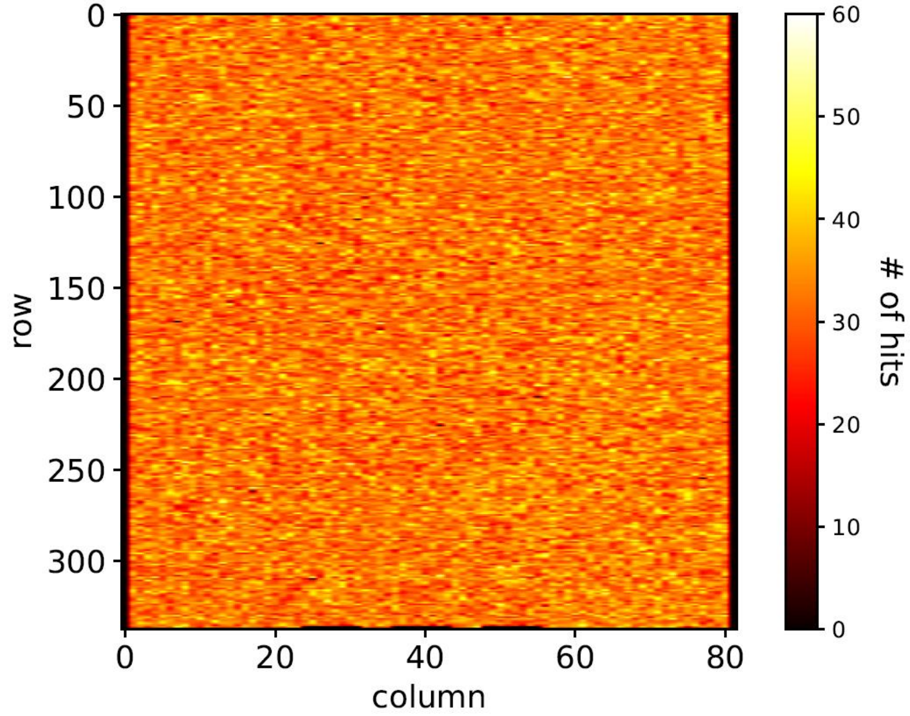


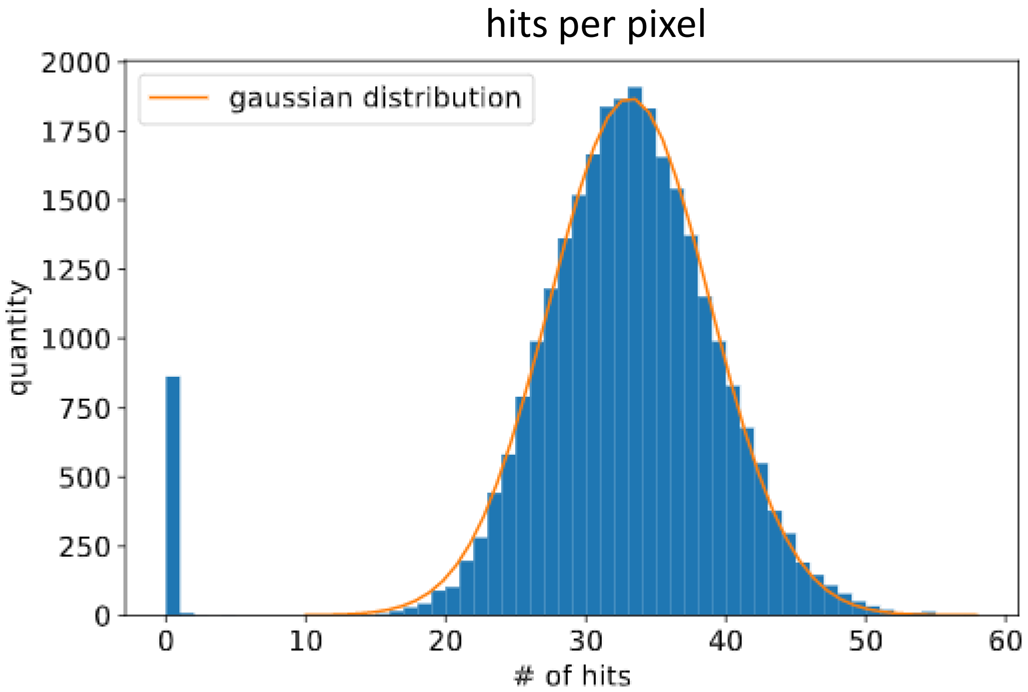
DS field homogeneity

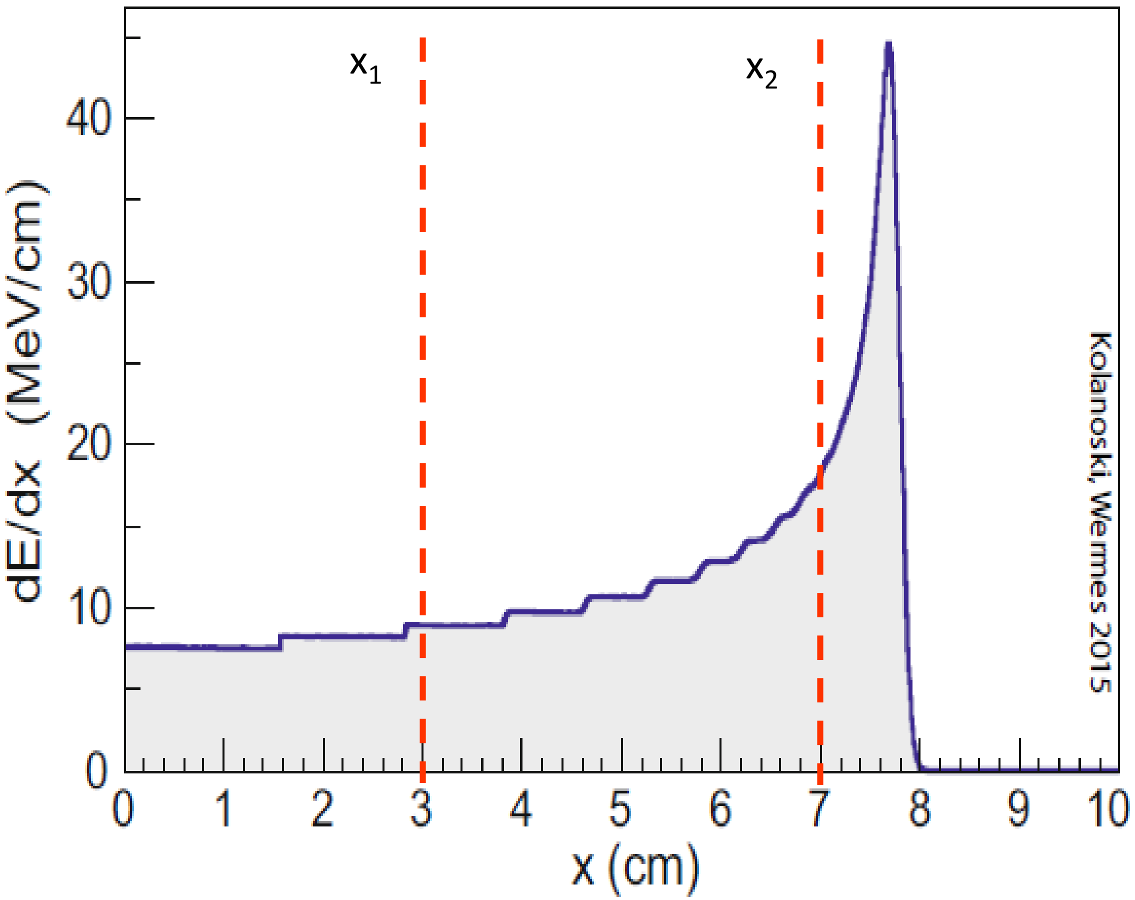
Single DS field, 10cm x 10cm, detector in central region

- requirement: flatness ≤ ±2% wrt commissioning data

Measured across full sensor: μ=33.1, σ=8.1 → flatness ≈ 24.5%
But: apparently usually defined within 3mm x 3mm → flatness ≈ 6%
➔ need better understanding of definitions, but the detector works…






x1
x2
40
30
20
10
0
dE/dx (MeV/cm)
0 1 2 3 4 5 6 7 8 9 10
x (cm)
Kolanoski, Wermes 2015