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Radiation therapy with laser-driven accelerated particle beams: physical dosimetry and spatial dose distribution

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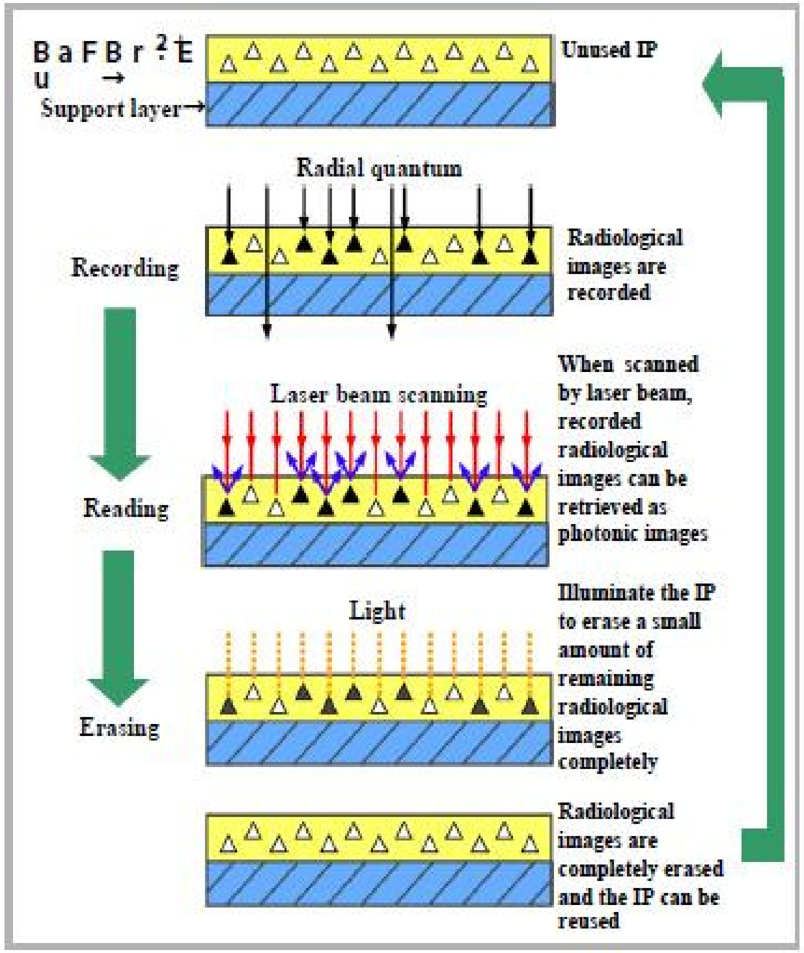
SIEMENS

Overview

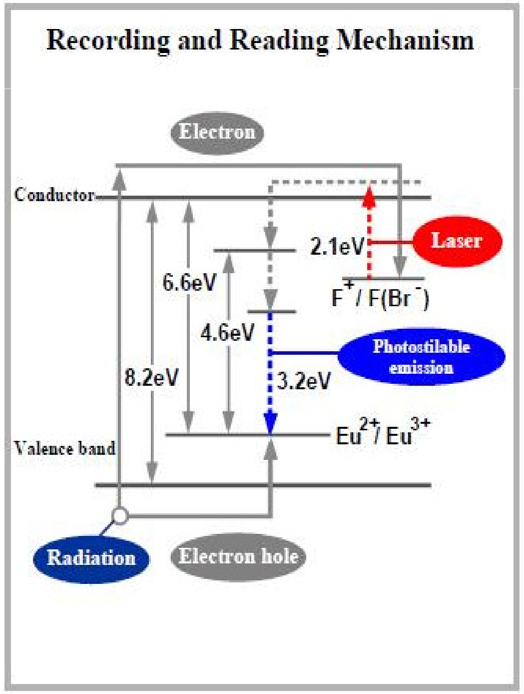
- Calibration of Imaging Plates (IP) for laser-acceleration experiments
- Gafchromic EBT2 - film for biological experiments
- Test of pixeldetectors for laser driven acceleratred (LDA) - ions
- Conclusion and outlook

Imaging plate (IP)

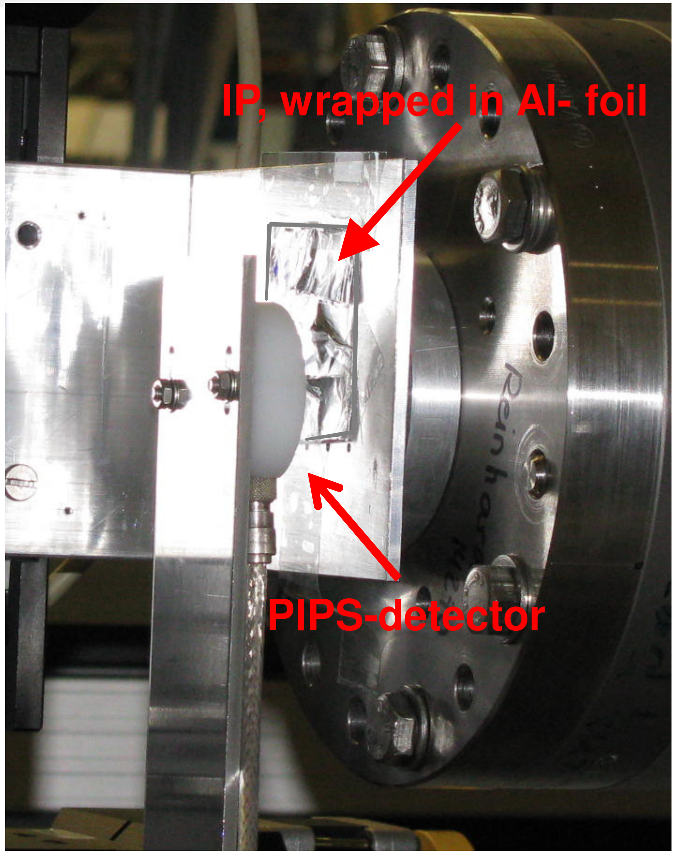
Fujifilm homepage



- Detection based on ***photostimulable luminescence***
- large dynamic range
- ***erasable*** by visible light
- special read - out scanner system



Calibration at the MLL Tandem accelerator



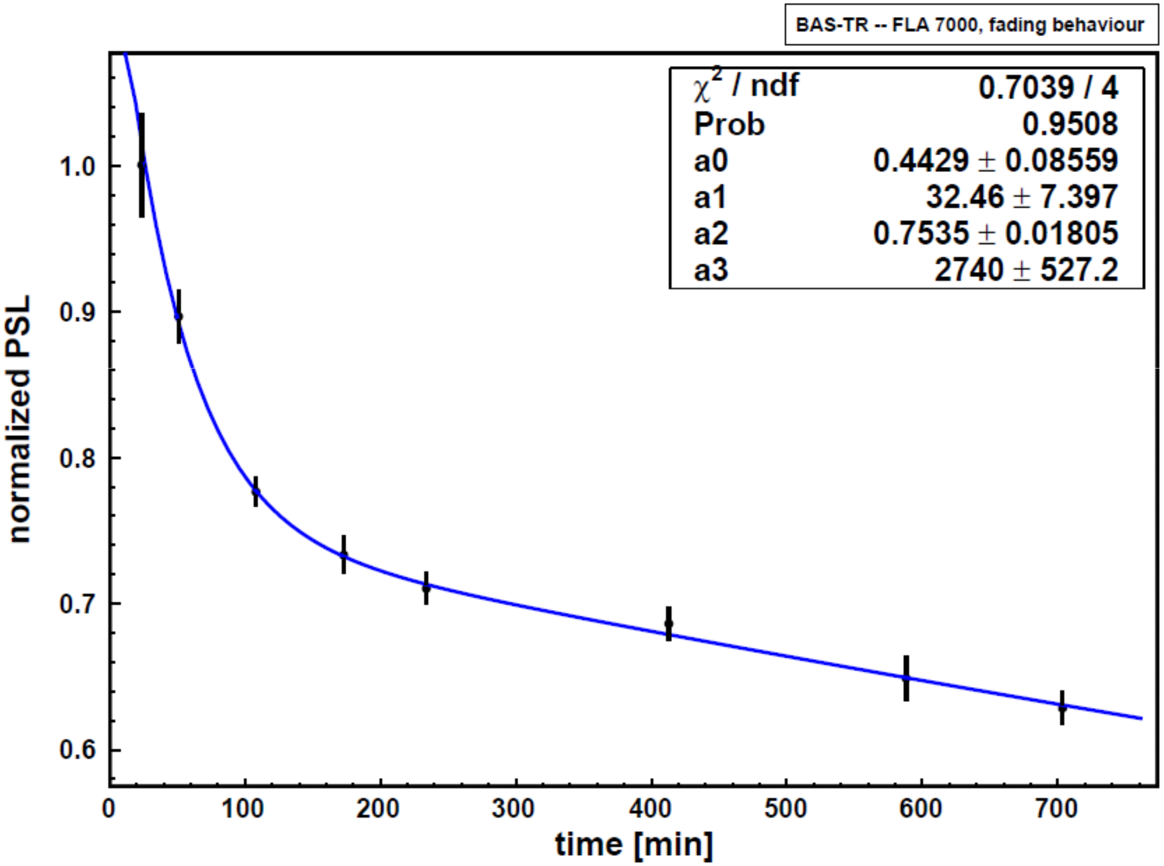
- Image Plate Fujiffilm BAS-TR 2025
  - active layer : 50 μm phosphor ($BaFBr_{0.85}I_{0.15}:Eu^{2+}$)
  - no protection layer
- Image plate reader: FLA 7000
  - fast read-out : 24 x 25 cm ^{2} → 2 min (@ 50 μm pixel size)
- ***Calibration*** and investigation of ***fading behaviour*** in proton beam
  - calibration:
    - energy range [MeV]: 8 – 20
    - Fluence range [p/cm^2] : 10^4, 10^5, 10^6
  - fading: 12 MeV, 10^5 p/cm^2

scanner unit = PSL
(photo***s***timulable ***l***uminescence –value)

$$PSL=\left(\frac{pix}{100}\right)^2 x \frac{4000}{S} x 10^{L\left(\frac{QL}{G}-0.5\right)}$$

L, S, G, pix: scanner parameter, QL: pixelvalue

Signal fading of IP

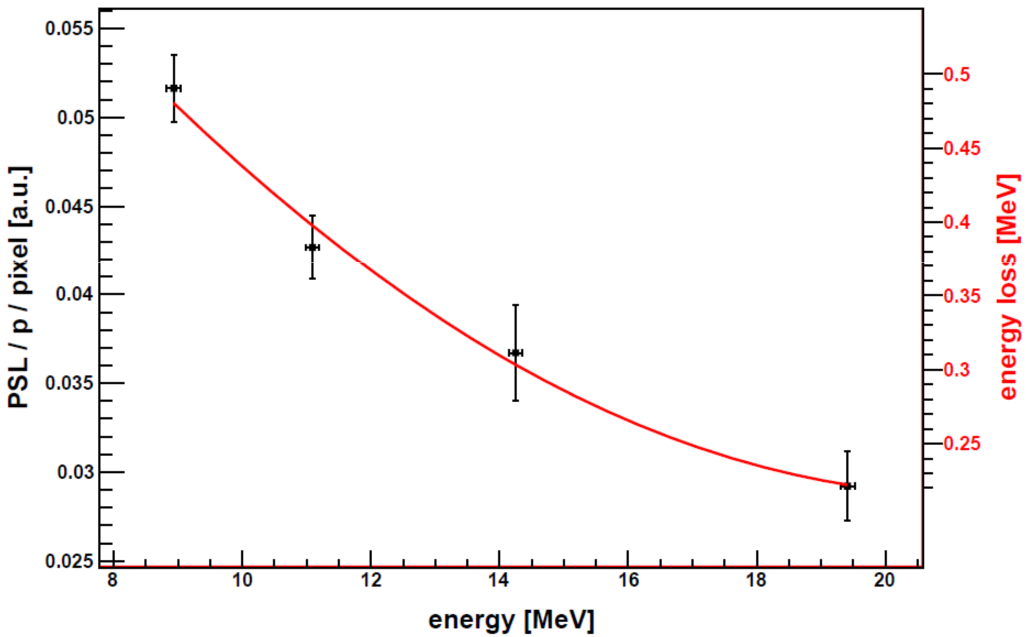


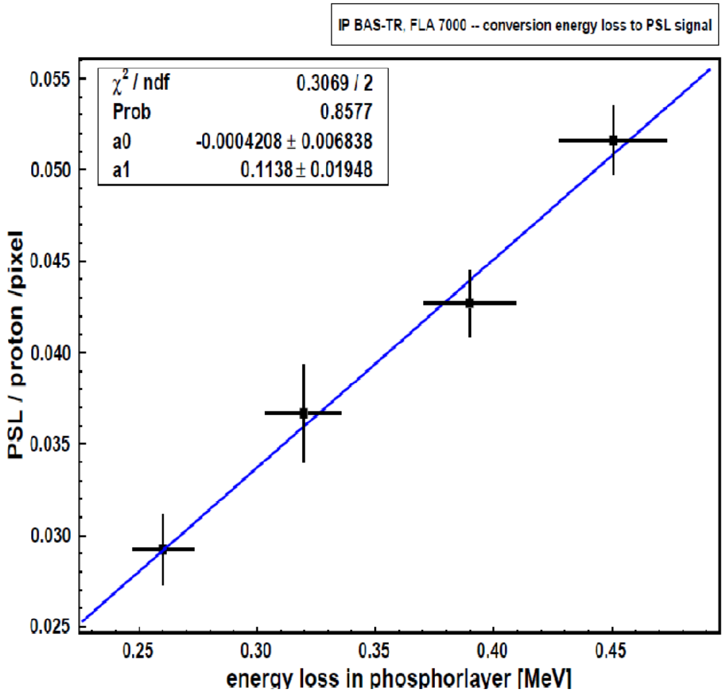
- at least ***2 fading channels*** (fast < 60 min)
- fading curve fitted by 2 decaying exponential functions

$$\frac{PSL(t)}{PSL_0(t_0)} = a_0 \cdot \exp\left(-\frac{\ln 2}{a_1} \cdot t\right) + a_2 \cdot \exp\left(-\frac{\ln 2}{a_3} \cdot t\right)$$

Calibration at the MLL Tandem accelerator

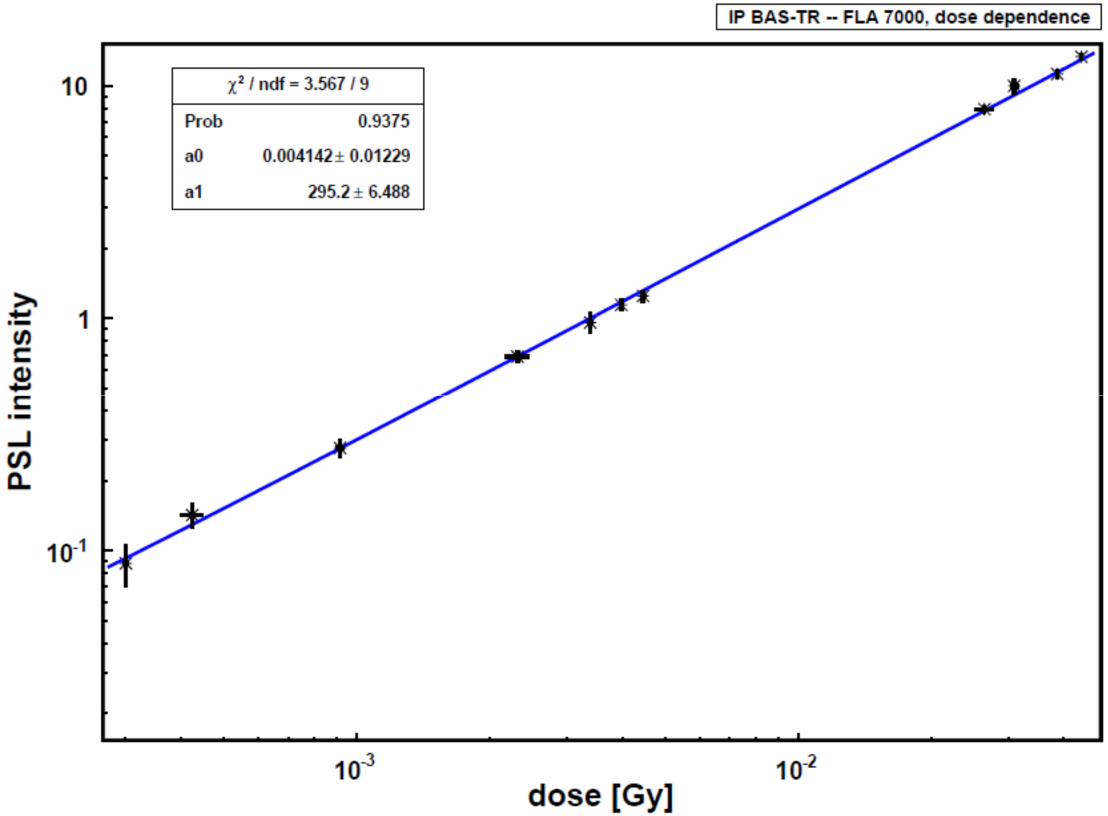
- SIMNRA 6.04 simulation → simulation of energy loss in active layer





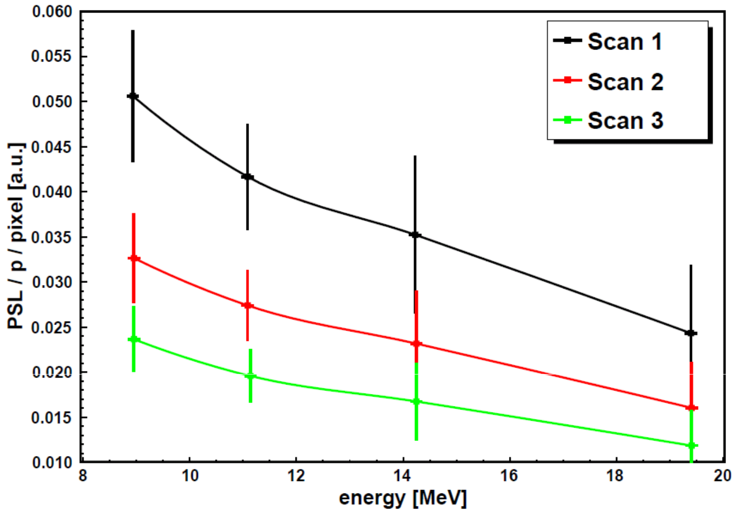
$$\frac{PSL}{proton \cdot pixel} = a_1 \cdot \Delta E - a_0$$

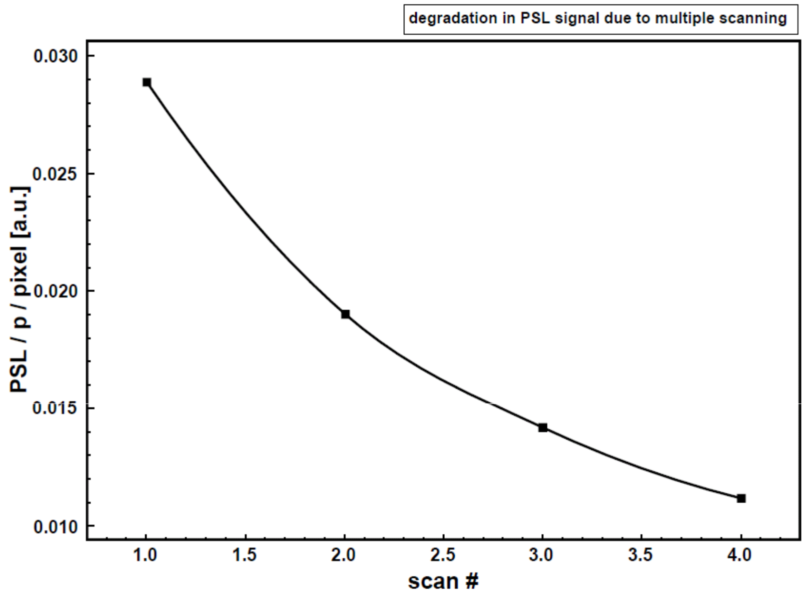
ΔE: energy loss in phosphor layer

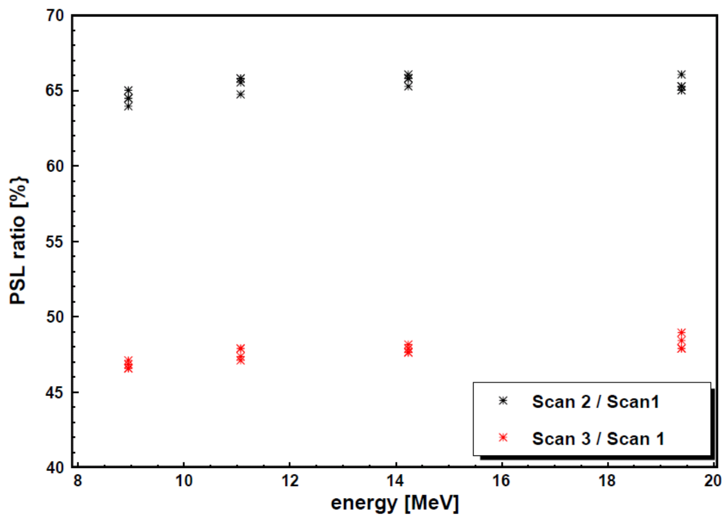


- E > 8 MeV:
  - no LET – dependence observed
  - PSL-signal proportional energy loss
  - ***linear dose response (D < 50 mGy)***

Signal decrease due to multiple scanning







Signal decrease [%]:

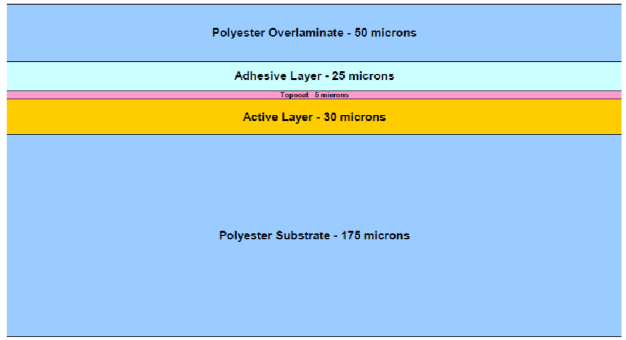
Scan #1 → Scan #2 (34.87 +/- 0.60) %

Scan #1 → Scan #3 (52.51 +/- 0.63) %

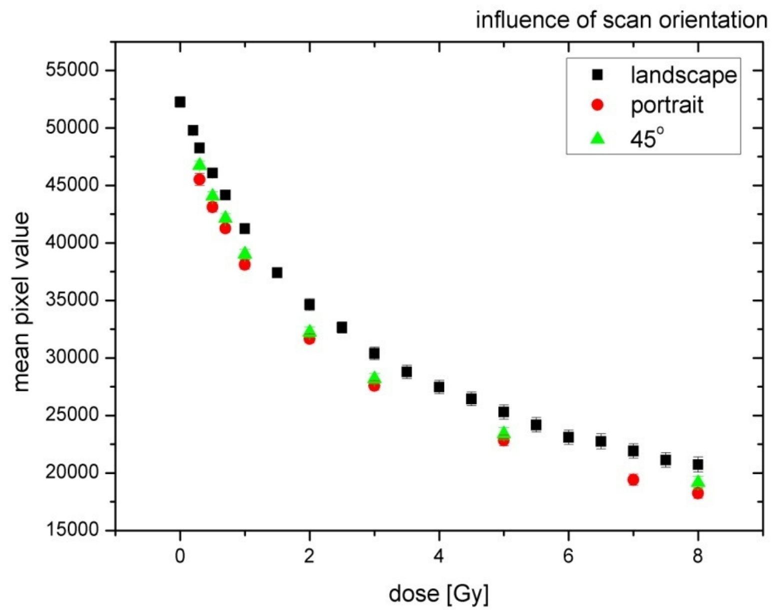
Scan #2 → Scan #3 (27.09 +/- 0.61) %

Gafchromic EBT2 films

- Gafchromic EBT 2 films
  - self-developing
  - polymerization → blue colour
  - read-out with ***flatbed scanner***
  - analysis of red colour channel
    → ***dose range 0.2 - 10 Gy***



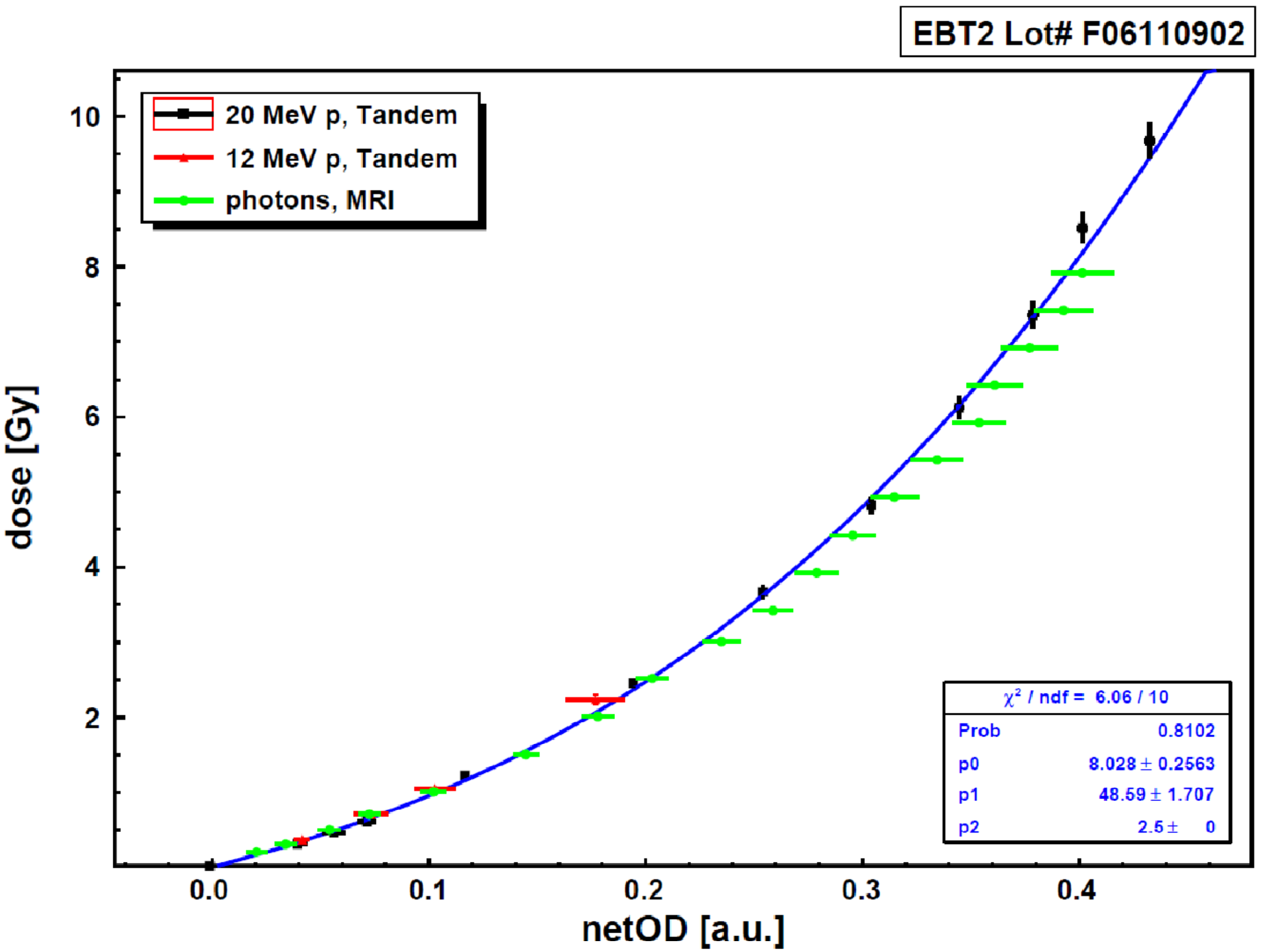
- Epson Perfection V 700 Photo
  - 1200 dpi resolution
  - 16 bit / colour channel
  - landscape orientation
  - read-out at earliest 40 h after irradiation



pixel value (pv) converted to netOD:

$$netOD = \log\left(\frac{pv_{bg}}{pv_{irr}}\right)$$

Calibration at the MLL Tandem accelerator



$$D = p_0 \cdot netOD + p_1 \cdot netOD^{2.5}$$

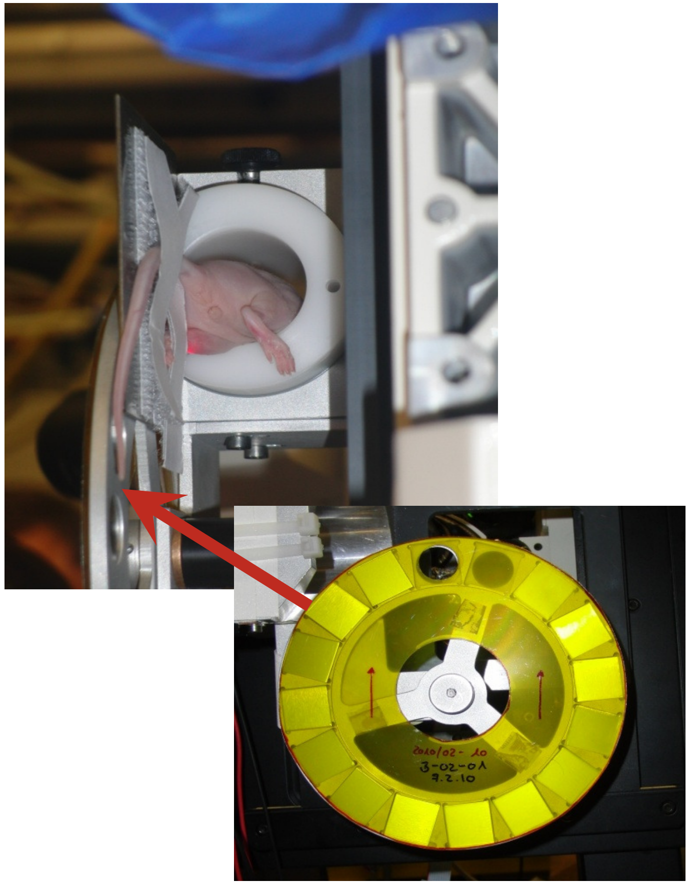
Film - dosimetry in mouse experiment

- Difference in relative biological effectiveness due to irradiation mode? (continuous vs. pulsed)
  → measure delay in tumour growth after irradiation

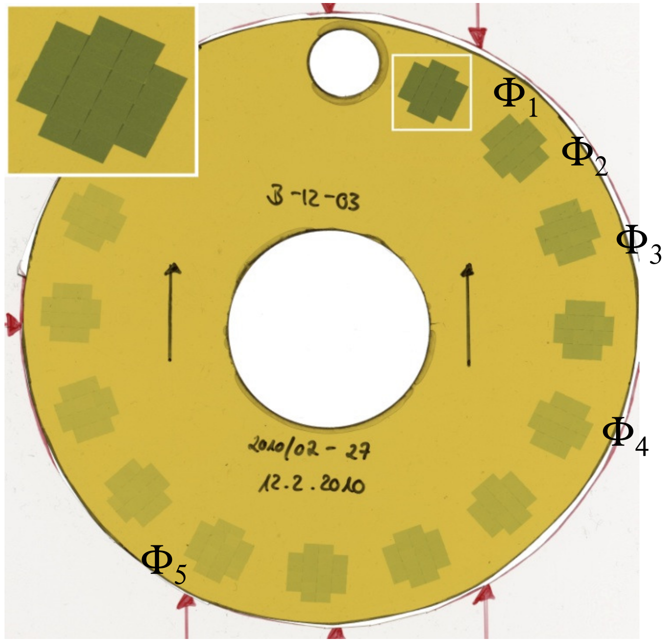
- ***23 MeV p***: ***< 6 mm range*** in water
- ***spatial dose distribution*** required

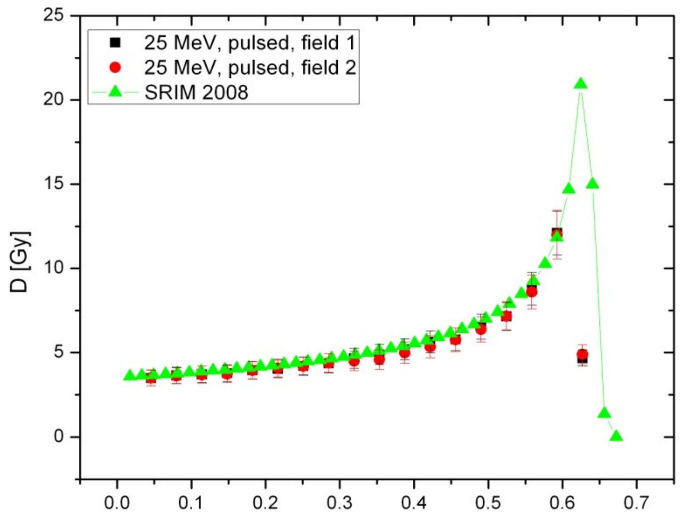
  → ***Gafchromic EBT2 - films*** for fluence measurement

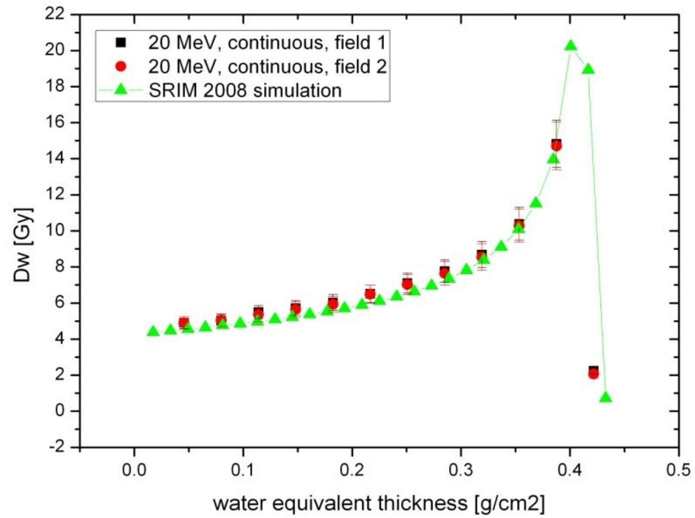
- ***PTV dose:*** ***20 Gy***, using 5 fluences
  → dose range on film: ***0.54 Gy - 4.00 Gy***



Film dosimetry in mouse irradiation







irradiation mode	*mean dose [Gy]*	*deviation to target dose (20 Gy) [%]*
pulsed (12 mice)	***17.30 +/- 0.43***	13.5 %
continuous (11 mice)	***19.21 +/- 0.83***	4,1 %

Test of pixel detectors as LDA - detectors

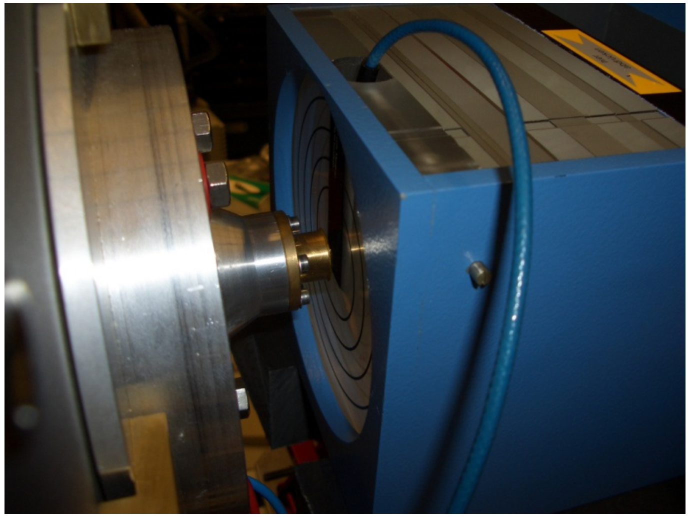
Detectors in Radiation therapy - state of the art

- Requirements for dose monitors / dosemeters
  - high dose accuracy (+/- 3 %)
  - real - time measurement and fast response
  - no LET dependence
  - no change in beam quality

- IAEA TRS 398
  "Absorbed Dose Determination in External Beam Therapy"

  - p: 50 MeV - 250 MeV
  - C: 100 MeV/u - 450 MeV/u

  - Standard based on absorbed dose to water measured by ionisation chamber (IC)



Ionisation chamber in water phantom

Consequences in ion beam therapy (IBT) due to acceleration mechanism

LDA - ions for IBT:

fs - laser pulse → intense ns - ion pulses

	conventional accelerator	***laser - driven accelerator***
particles per fraction	10^7 - 10^9 particles / cm^2	
T_{irr} ***/ voxel***	~ 100 ms	~ ns
dose rate	***~ Gy / s***	***10^8 Gy /s***
dose accuracy	***+/- 3%***	

New questions

- ***biological response***
- ***treatment modality/planning***

- ***dosimetry***

→ online - detectors?

→ new dosimetry standard for pulsed ion beams?

Required dose accuracy makes problem even more sophisticated !

What about standard dosimetry?

	conventional accelerator	*laser - driven accelerator*
dose rate	*~ Gy / s*	*10^9 Gy /s*

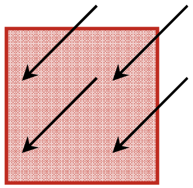
LDA -Detectors → NO ONLINE INFORMATION

Ionisation chambers → SATURATION PROBLEMS

⟶ *different kind of online - detector required*

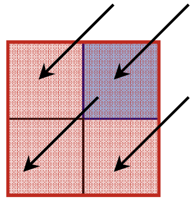
What about a pixeldetector as dose monitor?

- real - time measurement
- spatial dose distribution



A, N

$$\Phi = \frac{N}{A} = const$$



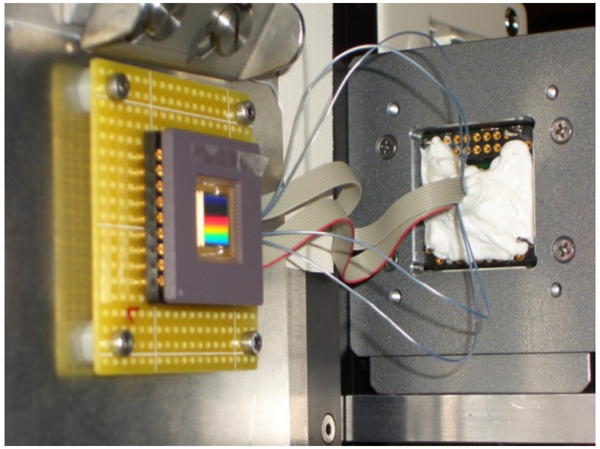
$^1/_4$ A → $^1/_4$ N

10^8 particles / cm² = 1 particle / µm²

Kappa DX4 1020 - An "off - the - shelf" camera system

CCD camera ***Kappa DX4 1020***

- Kodak Interline Transfer CCD KAI 1020
- 1004 x 1004 pixel with 7,4 µm pitch
- 16 bit digitalisation
- sensor mounted on separate board
- *but* optimized for optical applications



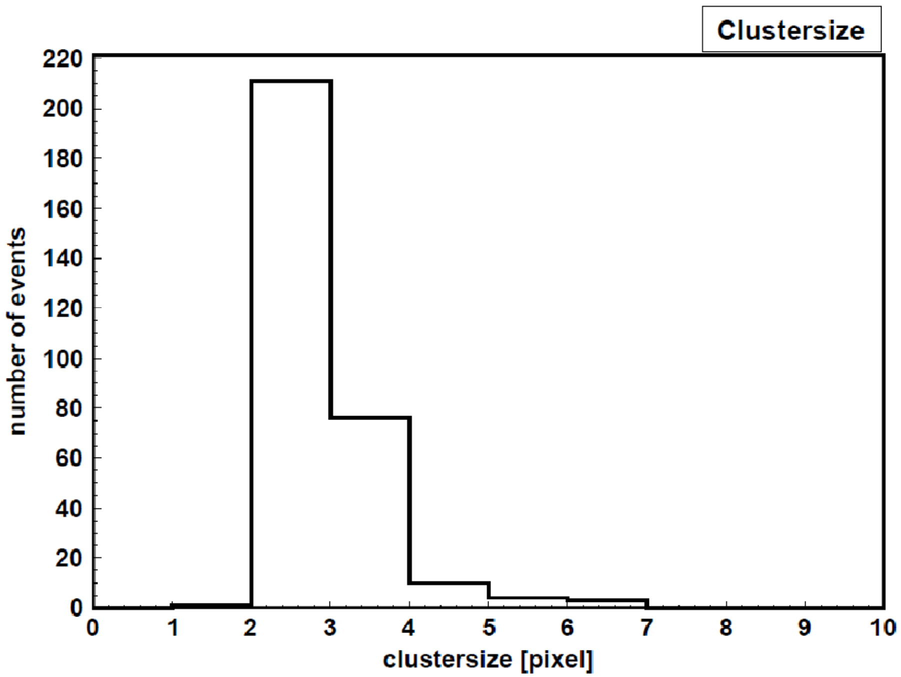
Test of system at MLL Tandem accelerator in Garching

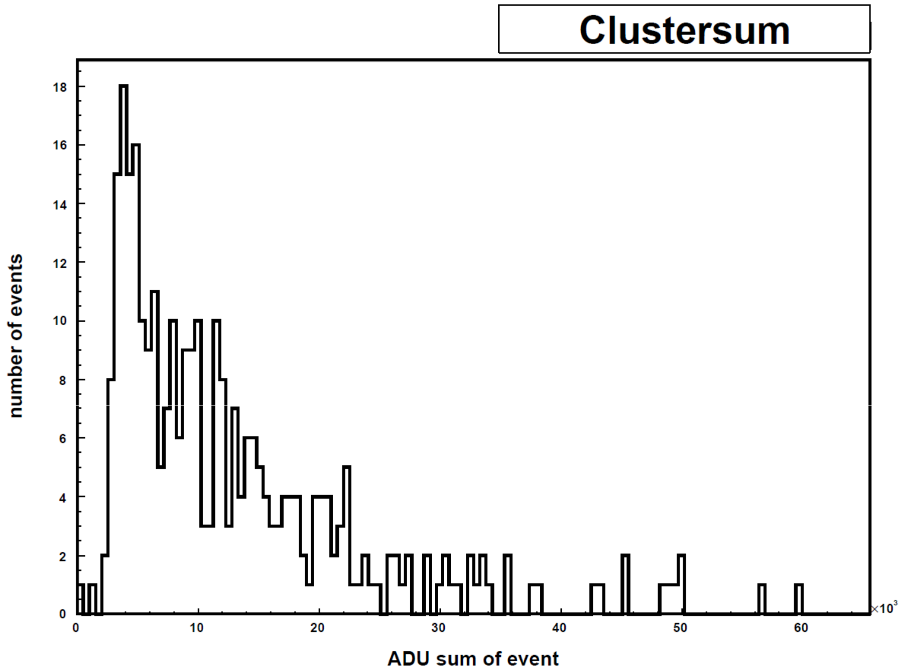
- 20 MeV p @ microbeam facility SNAKE
  - single ion irradiation
  - few µm scanning resolution

- 10 MeV p @ I - 40°
  - continuous irradiation

20 MeV p, microbeam irradiation @ SNAKE

- ***1 p / frame***
- only low statistic
- scan in x and y direction
- blooming in horizontal direction

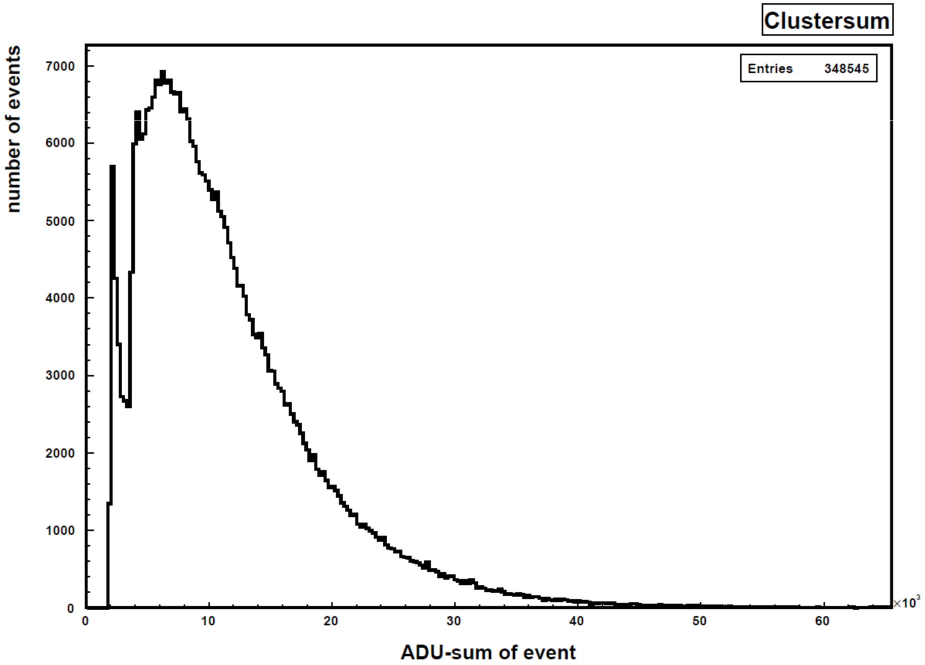


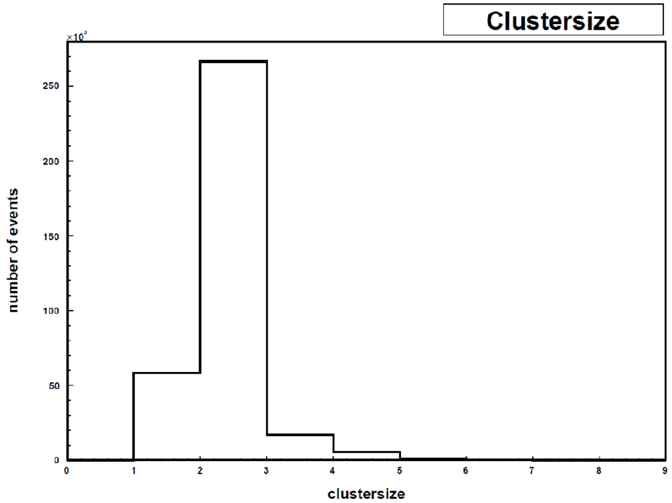


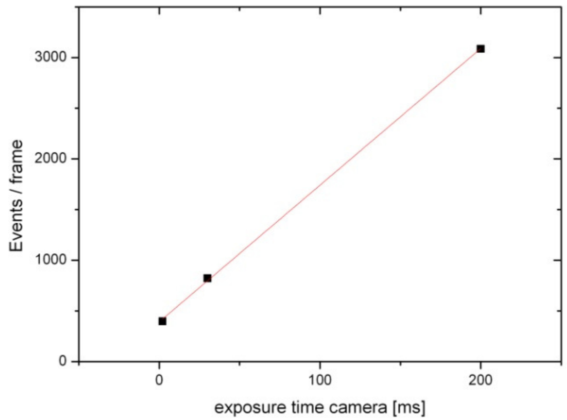
cluster = adjacent pixels with signal above thresolds

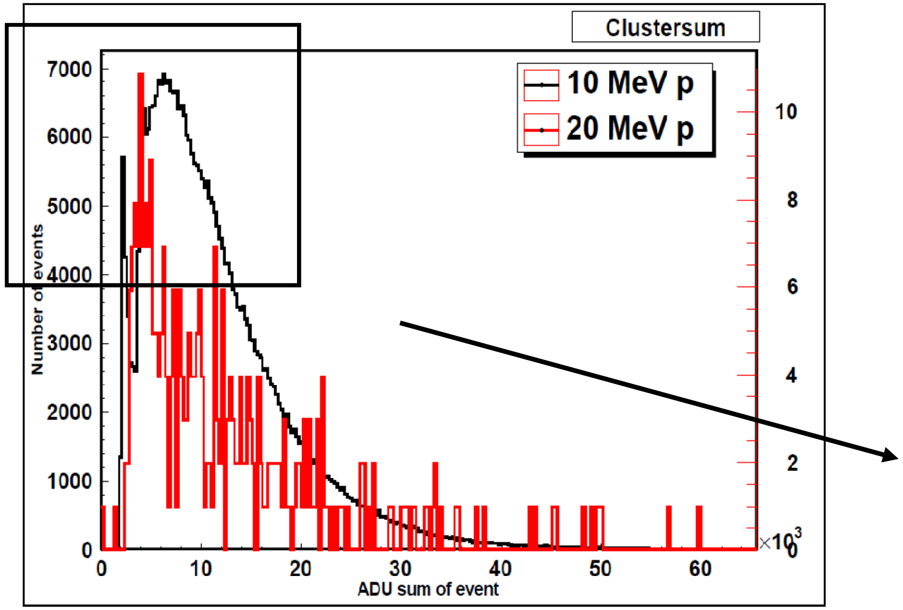
10 MeV p, continuous irradiation @ I - 40°

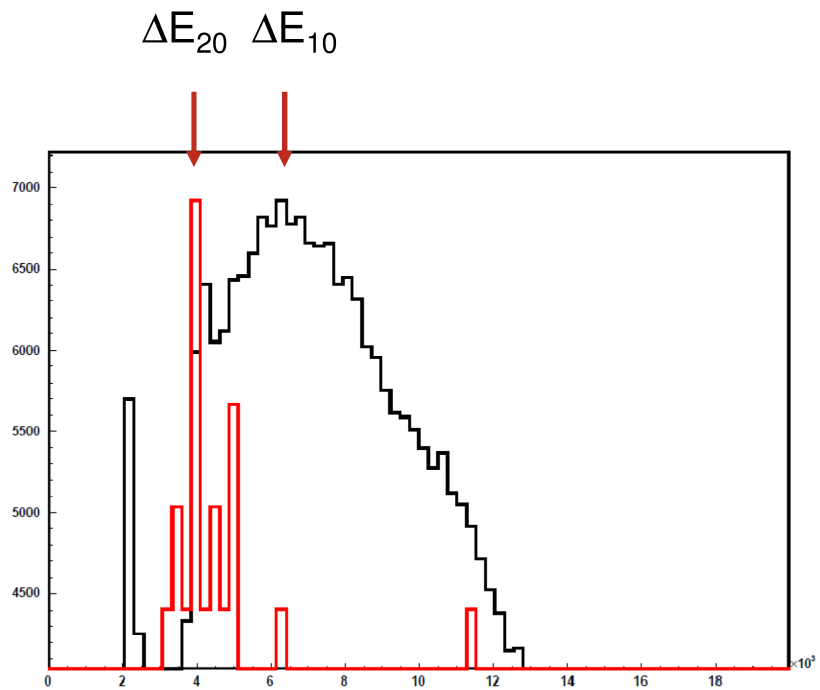
- high statistic
- good linearity with exposure time
- blooming in horizontal direction











energy deposition in 2 µm Si (SIMNRA v 6.04)

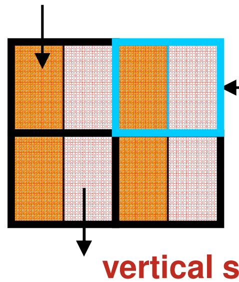
- 20 MeV p: ΔE_{20} = (9,7 +/- 14.2) keV Σ_{ADU} = 3961 → maximum 16 p / pixel
- 10 MeV p: ΔE_{10} = (16,5 +/- 16.5) keV Σ_{ADU} = 6370 → maximum 10 p / pixel

- 200 MeV p ΔE_{200} = 1.68 keV → maximum 100 p / pixel ?

  (SRIM 2008: dE/dx = 0,8443 keV / µm)

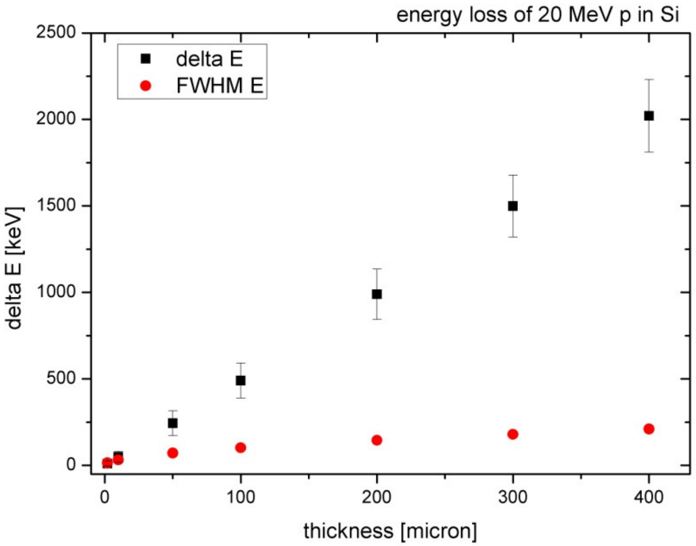
Limits of commercially available detector systems

schematic scetch of interline CCD:



- Promising performance with respect to saturation level
- potential problems due to optimisation for optical applications
  - growing distribution of interline CCDs
    → problems with vertical shift register?
  - depletion thickness ~ few µm
    → energy loss and straggling comparable
  - limited read-out possibilities

Test of more advanced non - optical system like e.g. Medipix (CERN) would be interesting!



New detector systems: Mesytec CCD and Medipix - Chip

- ***Mesytec - CCD***
  - CCD - based system from MBI Berlin
  - System ***developed for LDA- ion pulse detection*** but has never been tested in a proton beam
  - RadEye2 - sensor from Rad-icon
    - 48 x 48 µm² pixel size
    - 1024 x 1024 pixel
    - ***saturation energy 7.2 MeV***

- ***Medipix - Chip***
  - read- out chip developed at CERN
  - ***active pixel sensor*** (APS)
  - 50 x 50 µm² pixel size
  - 256 x 256 pixel
  - ***different detectors*** can be bump - bonded to chip
  - different read - out modes

Conclusion and Outlook

- Imaging Plate
  - *linear dose dependence* for doses < 50 mGy
  - further *calibration for different type of IP and FLA 5100* –IP- reader in November 2010

- EBT 2
  - dosimetry in mouse experiment sucessfully accomplished
    → deviation pulsed / continuous mode has to be investigated further

- Pixeldetectors
  - First tests with commercially available pixeldetector show *promising results*
    → response to pulsed ion beam still has to be tested
    → optimisation for optical applications potentially problematic for charged particle detection
  - Further tests of detector response to *single proton events* as well as *intense proton pulses* using different systems

Kappa DX4 1020	(pulsed)	
Mesytec CCD	(single & pulsed)	in collaboration with MBI Berlin
Medipix - Chip	(single & pulsed)	in collaboration with UTEF CVUT Prague

Thank you for your attention!