Detection of laser-accelerated ions

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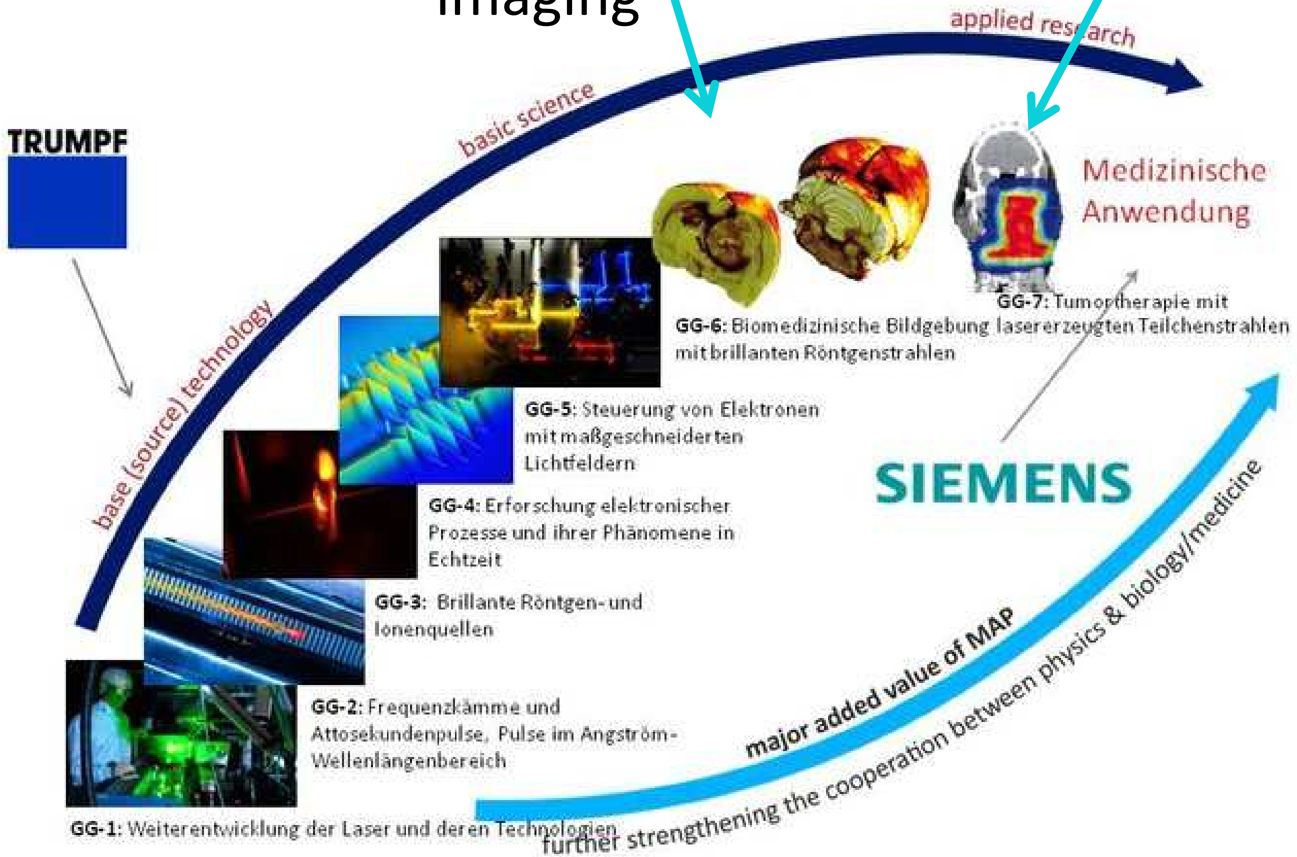
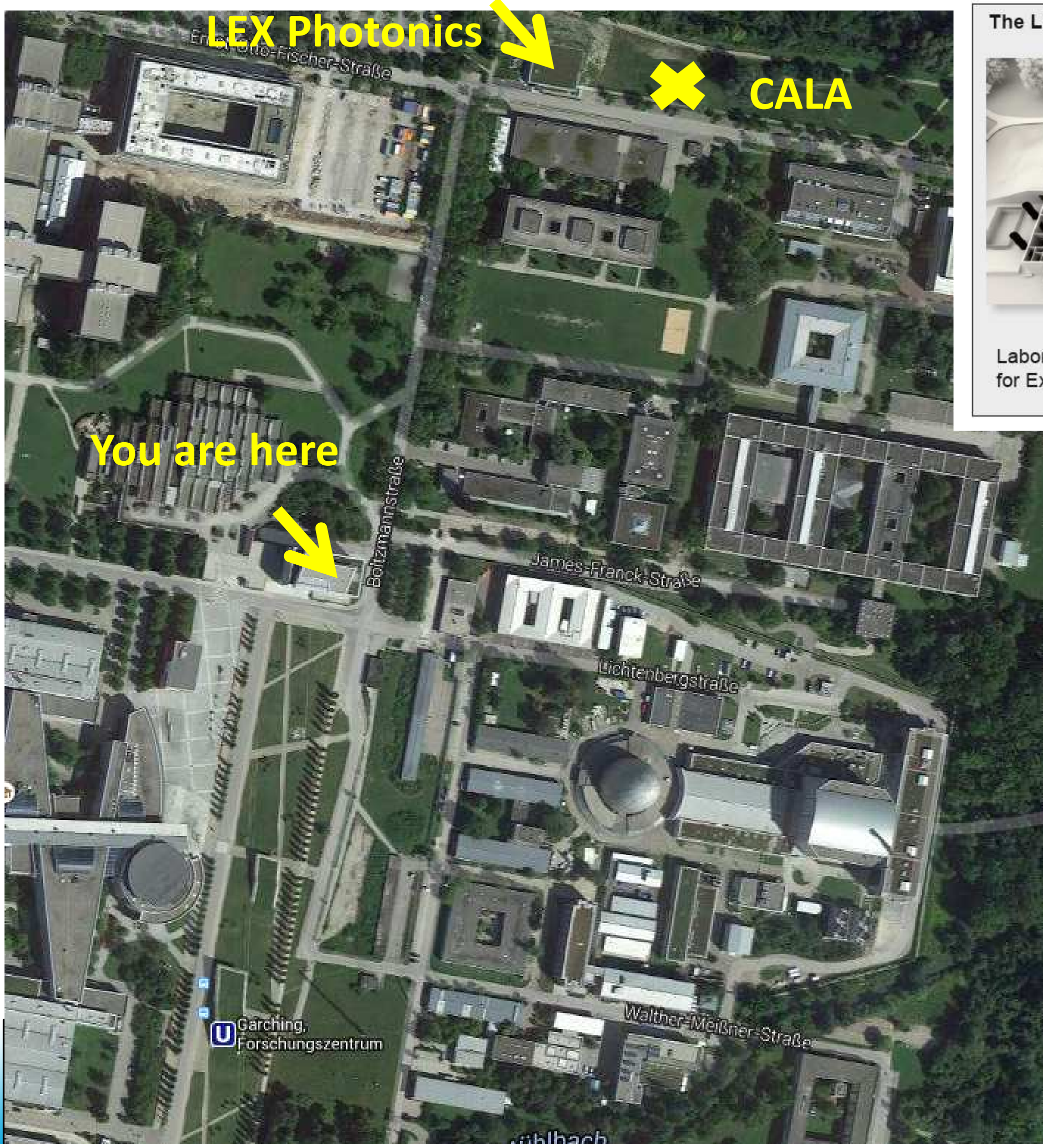
Medical applications:

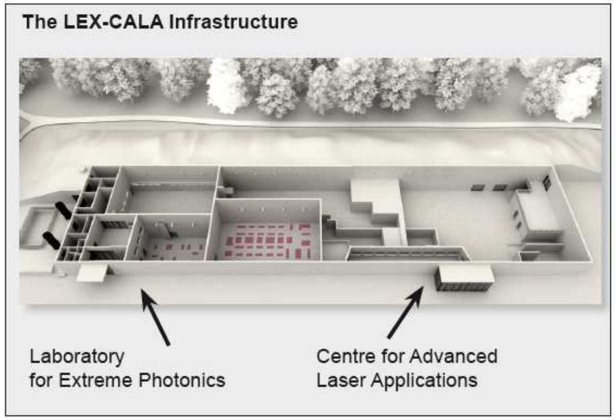
Brilliant X-rays for biomedical imaging

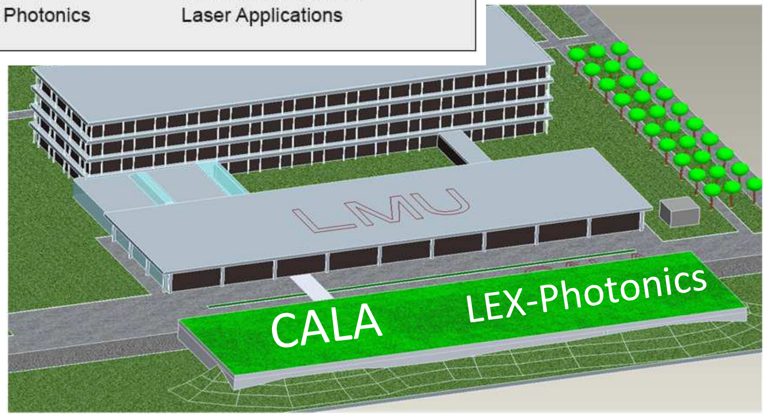
Radiation therapy with laser accelerated particles



LEX/CALA: infrastructure



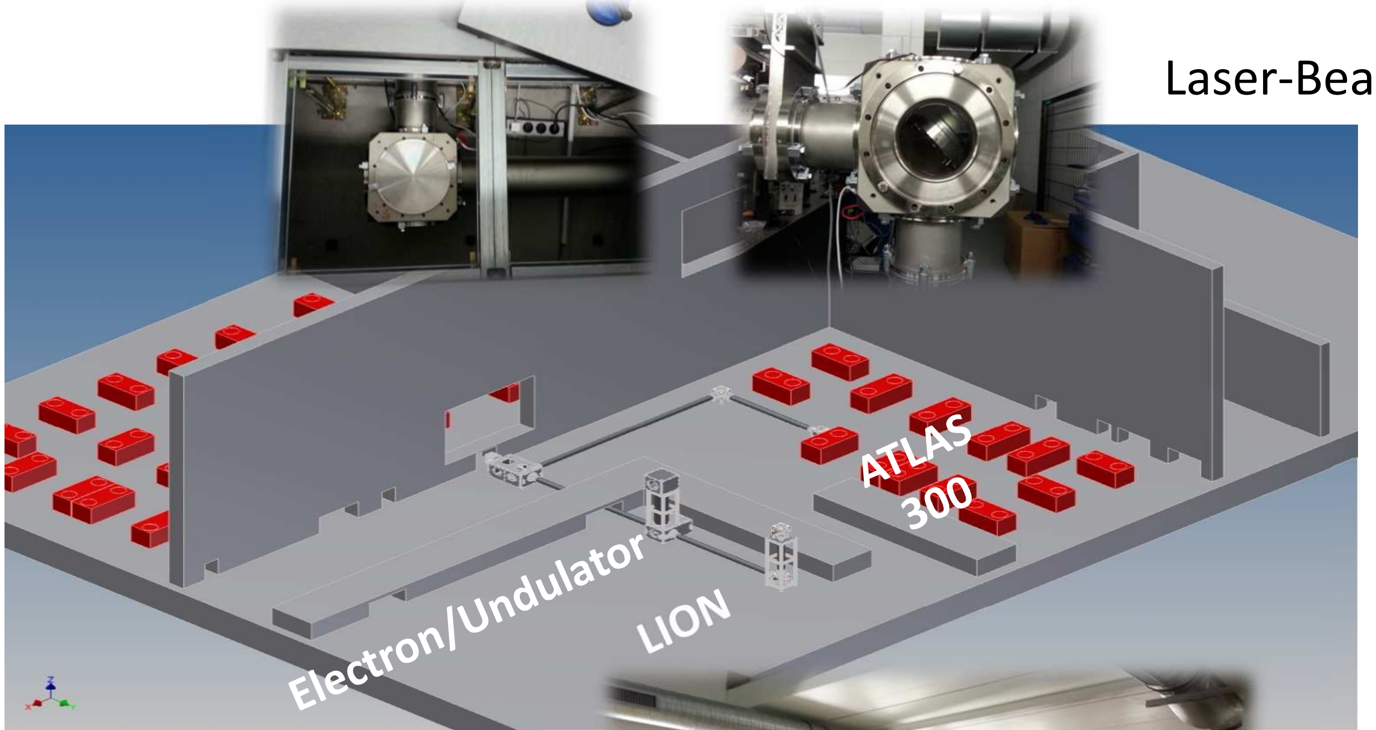




LEX-Photonics:	6J, 20 fs, 5 Hz
CALA:	60J, 20 fs, 1 Hz
	~500 mJ, 5 fs, 1 kHz

Setup at LEX Photonics

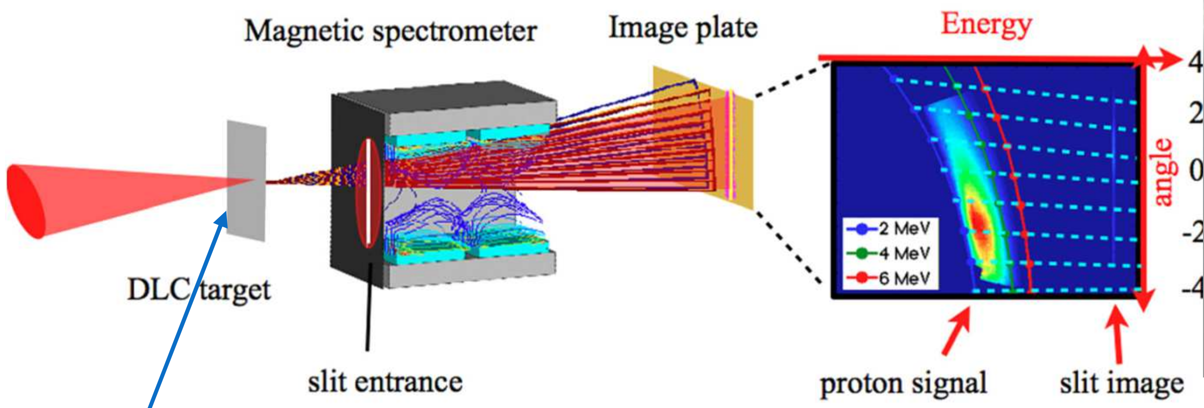
Laser-Beam Delivery

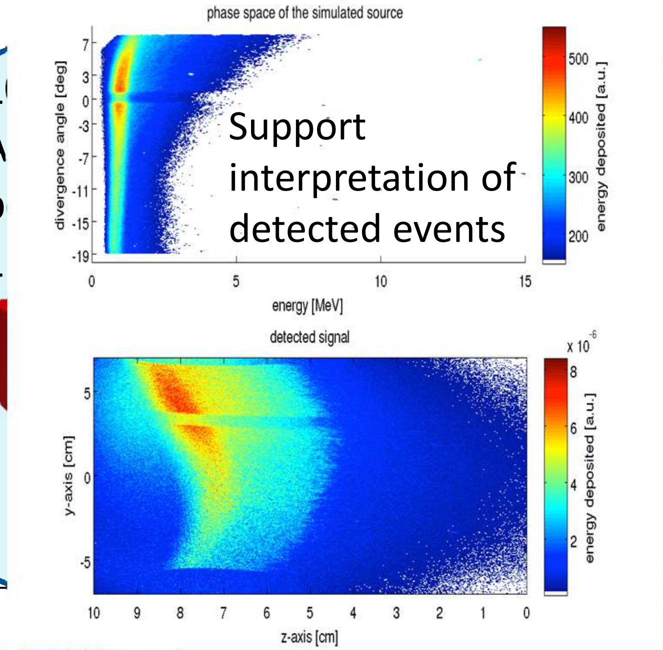


Ion source:
ready to rep-rate

LION target chamber
(prototype for CALA)

Complete Modelling





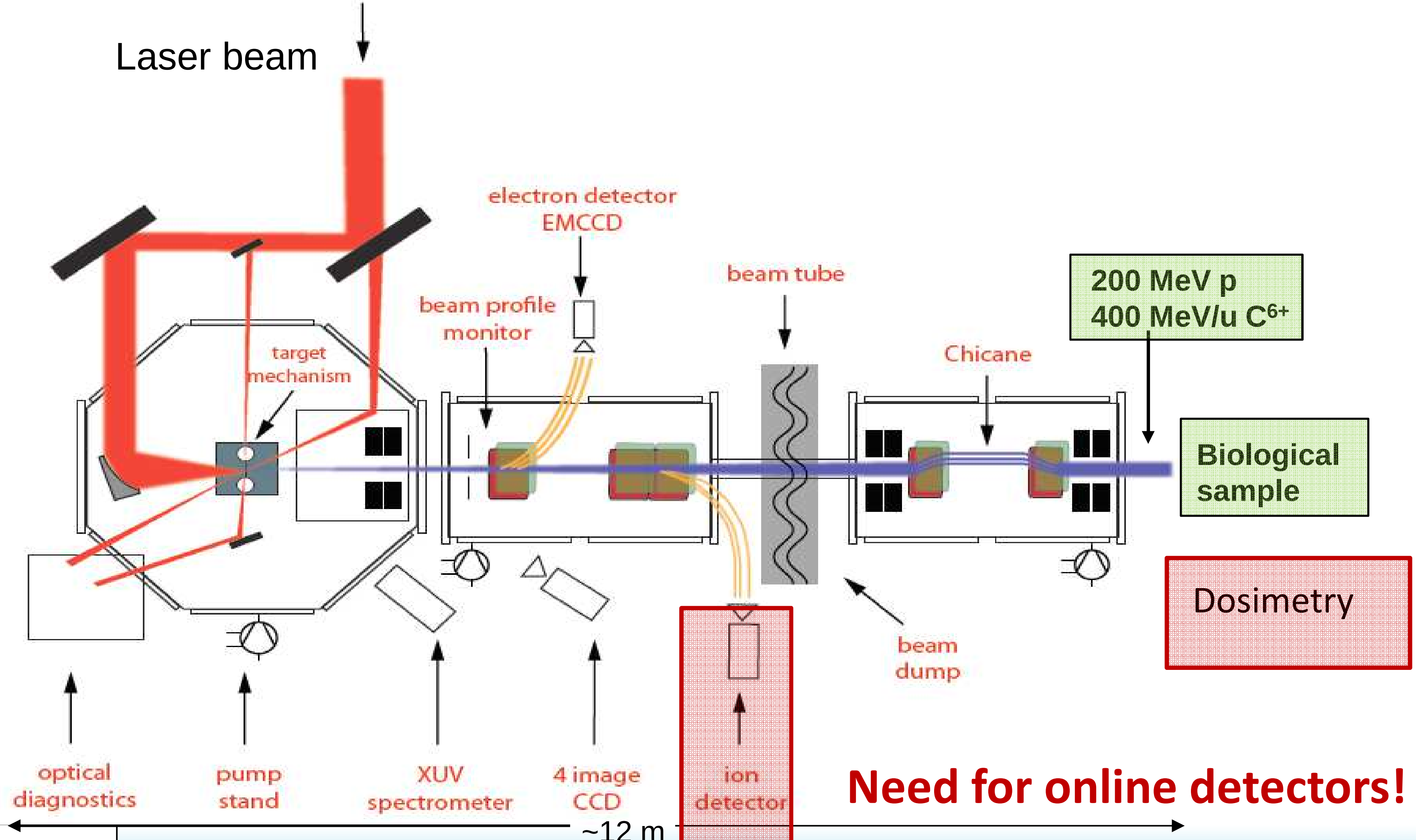
Support interpretation of detected events

Monte Carlo simulations (Deddes, Parodi)

Online Diagnostics

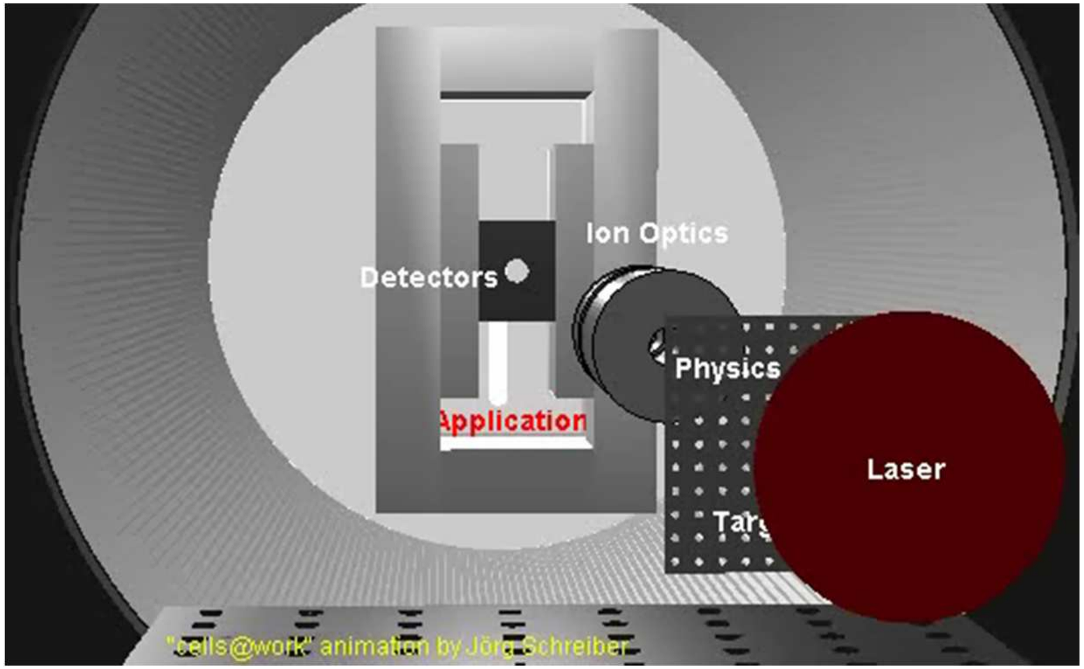
(Reinhardt, Parodi)

Laser-driven ions: LION



Need for online detectors!

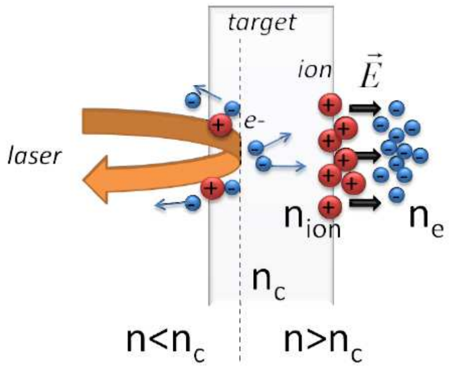
Laser-driven ion acceleration



- Laser-Pulses accelerate ions to MeV/u over several µm's within less than 1 picosecond
- Large ion number in very short time and typically very broad spectrum
- So far mostly single shot/proof of principle experiments

Laser-driven ion acceleration

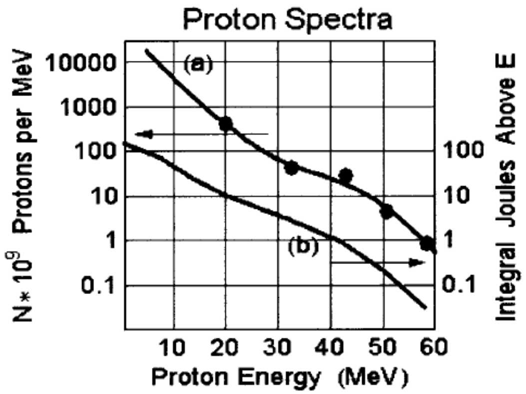
Target Normal Sheath Acceleration (TNSA)



micrometer thick foils

Maximum proton energies ~ 60 MeV

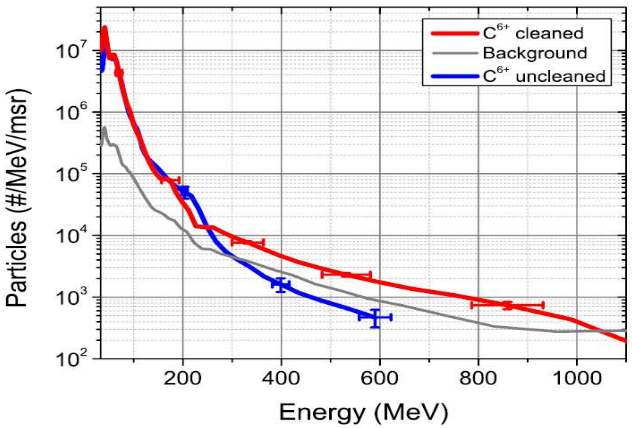
Snavely, PRL (2000)



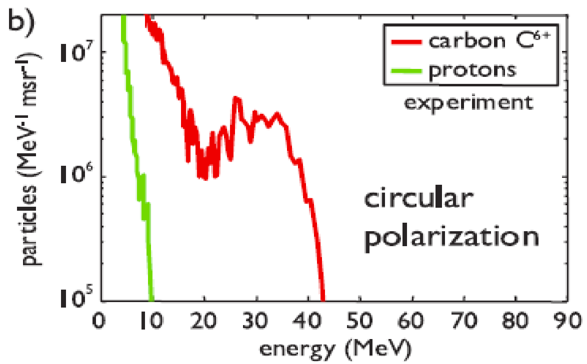
Radiation Pressure Acceleration (RPA)

nanometer thick foils

record carbon energy > 1 GeV

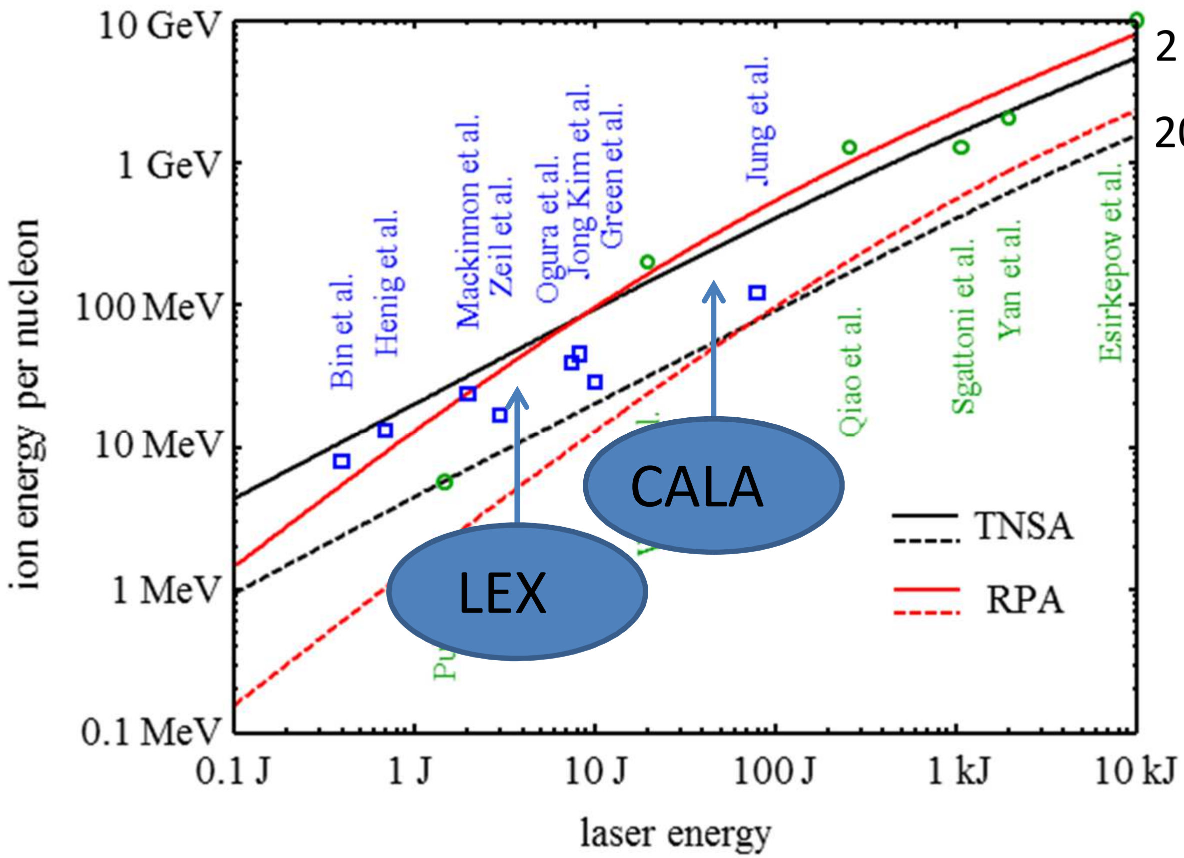


D. Jung *et al.*, Phys. Plasmas **20**, 083103 (2013):



A.Henig et al., Phys. Rev. Lett. 103, 245003 (2009):
1st experimental demonstration of RPA

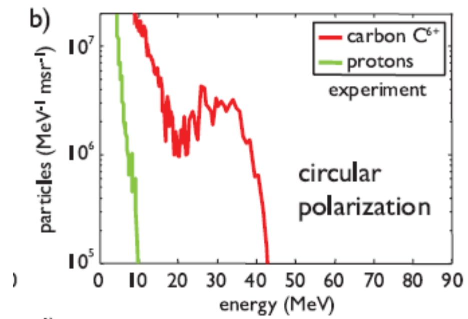
Ion energy frontier



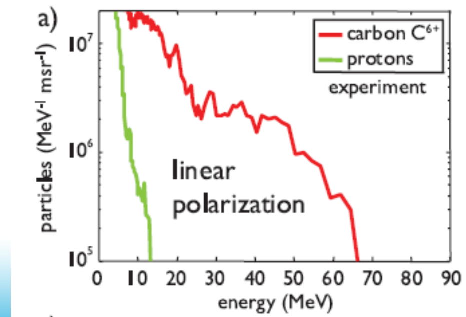
2 µm focus

20 µm focus

RPA: many ions, possibly mono-energetic



TNSA: few ions, exponential spectra

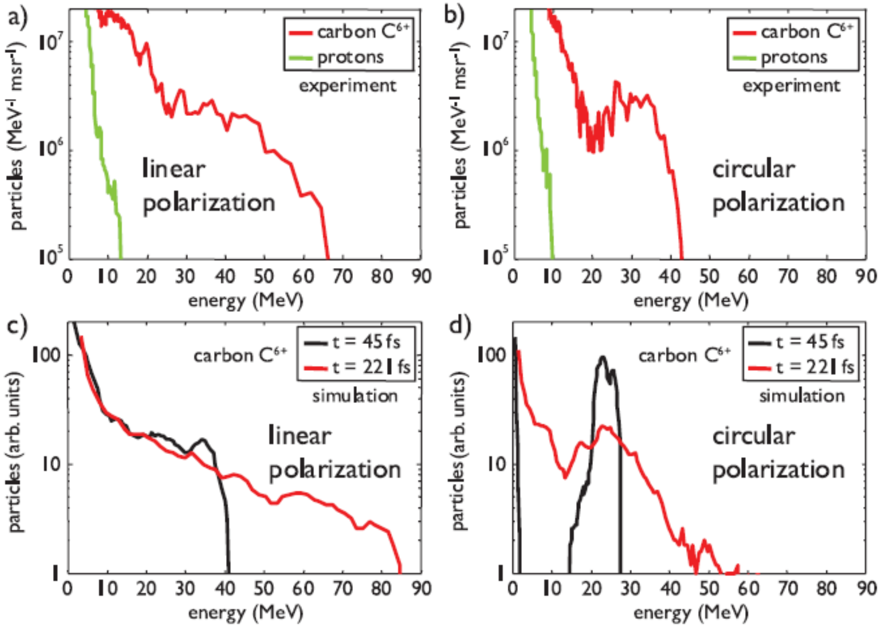


J. Schreiber *et al.*, High Power Laser Science and Eng. 2, e41 (2014)

Detection of laser-accelerated ions

Characteristics of laser-accelerated proton (ion) beams

TNSA RPA



A. Henig et al, PRL 103 (2009)

- ***Ultra-short (<= ns)*** and ***highly intense (> 10^7 ions/cm^2)*** ion pulses
- EMP presence
- Mixed radiation background
- ***Large energy spread*** of ions

→ ***Challenge for any electronic online detector but also dosimetry***

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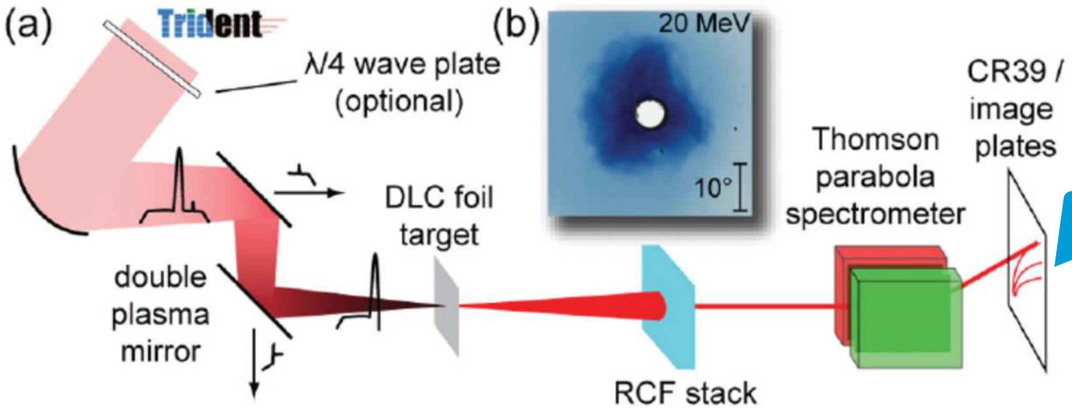
Table 1. Detectors commonly used for laser-driven ion diagnostics and measurements. Sensitivity: L: light, UV: ultraviolet, x: x-rays, e-: electrons; the notation '•' represents 'sensitive'.

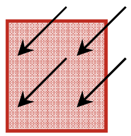
	Spatial resolution	Time resolution	Treatment/ display time	Single-particle sensitivity	Dynamic range (DR)	Sensitivity L	Sensitivity UV, x	Sensitivity e-	Features/refs
Solid-state nuclear track detectors, e.g. CR-39 (allyl diglycol carbonate), etc	~ a few to a few tens of μm (pit size, depends on the ion kind and energy and etching time)	No	A few hours (etching, scanning, pit counting)	Yes	$\sim 10^2$–10^6 (background $\sim 10^2$–10^4 cm^{-2}, saturation $\sim 10^6$–10^8 cm^{-2})	—	—	—	(1) Sensitive to ions only[a], single particles
Radiochromic film (RCF)	~3–10 μm (film, scanner)	No	Several minutes (scanning)	No	$\sim 10^2$–10^3 (e.g. 10–10^4 Gy)	—	•	•	(2) Self-developing
Imaging plate	Sub-100 μm (scanner)	No	Several minutes (scanning)	No	$\sim 10^5$	—	•	•	(3) Reusable, high DR
Activation	Sub-mm (contact radiography)	No	Tens of minutes–a few hours (decay time)	No	Very high ($>10^5$)	—	—	—	(4) Very high DR
Micro-channel plate (MCP)+phosphor screen + CCD	~several 10 s of μm (imaging system)	~a few 100 ps (MCP gate time)	~a few seconds (CCD readout)	Yes	$\sim 10^3$	—	•	•	(5) Online, single particles
Scintillator + gated I-CCD or EM-CCD	~several 100 μm (multiple scattering, imaging system)	~a few 100 ps (scintillation time)	~a few seconds (CCD readout)	No	$\sim 10^3$	•	•	•	(6) Online, stackable in depth

Detection of laser-accelerated ions

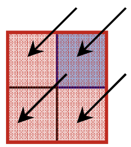


Pixel detector as online detector in Thomson spectrometer:

Advantages of pixel detectors



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



A, N

$^1/_4$ A → $^1/_4$ N

- ✓ real time measurement
- ✓ excellent spatial resolution
- ✓ good energy resolution

10^8 particles / cm² = 1 particle / µm²

Munich Tandem Accelerator

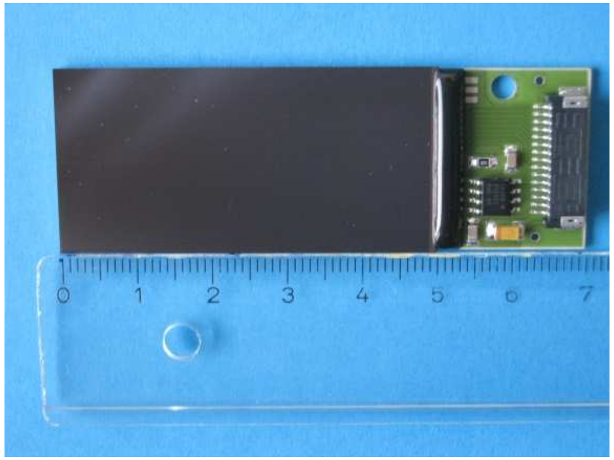
Unique possibilities to test detector response:

- protons: 8- 25 MeV
- 3 irradiation modes:
  - single particle
  - continuous
  - ***pulsed:*** ***10^7 protons /cm²/ ns***
    - → ***similar to laser ion pulse***

Investigated detector systems:

- ***Kappa DX-4*** *(commercial system)*
- ***Timepix*** *(scientific & commercial system)*
  - *collaboration with IAEP CTU Prague*
- ***RadEye*** *(commercial system)*

Detector system



RadEye 1 sensor
Silicon pixel detector
512 x 1024 pixel
48 µm pixel pitch
25 x 50 mm^2 sensitive area

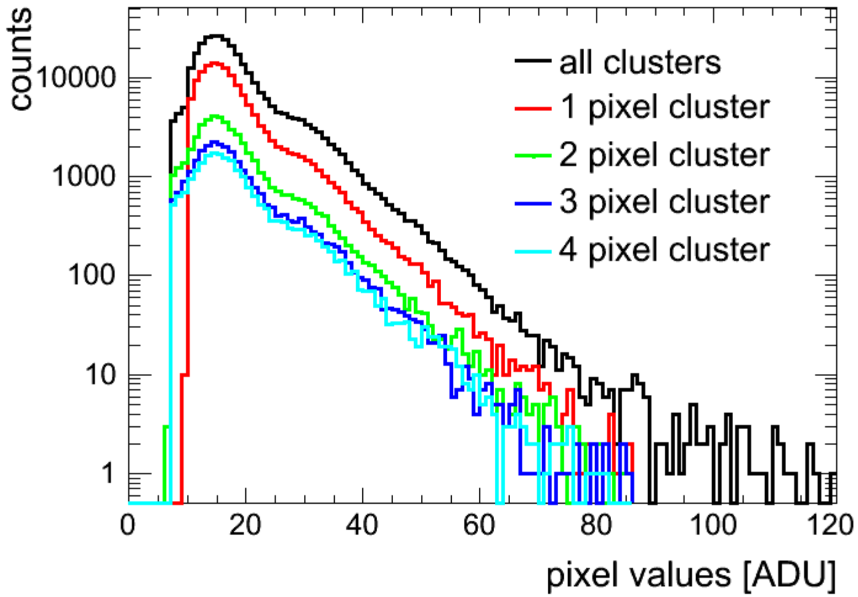
Read-out electronics
Parallel read-out of 4 sensor modules
50 x 100 mm^2 sensitive area

Compact stand-alone system combines computer control and read-out electronics

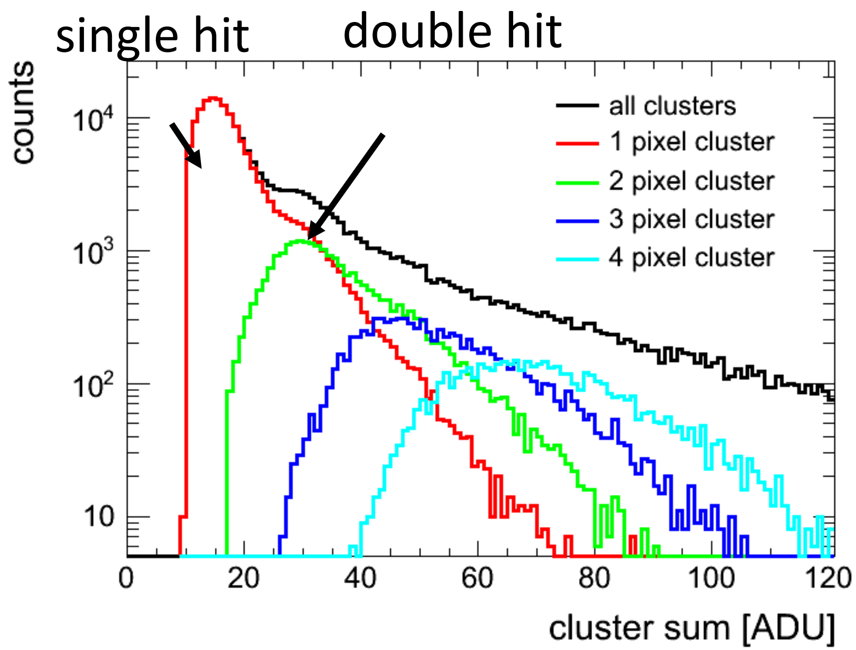
Single proton sensitivity

Munich 14 MV Tandem accelerator
- continuous beam
- 15 MeV protons
- ~ $10^4 p/cm^2/s$

Cluster pixel distribution:



Cluster distribution:



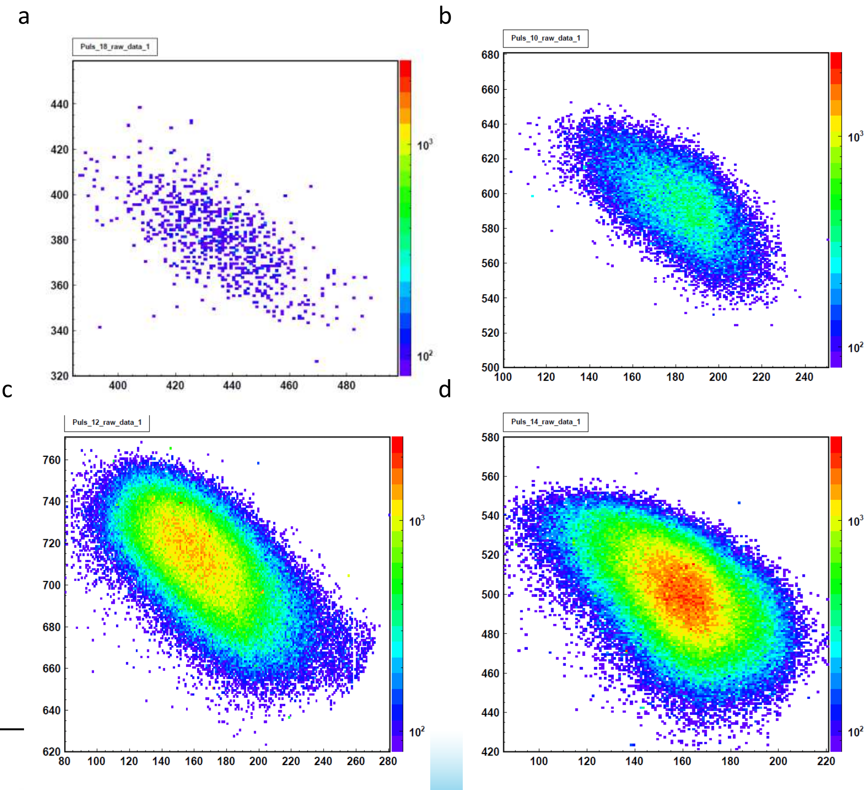
✓ ***No charge sharing effects observed***

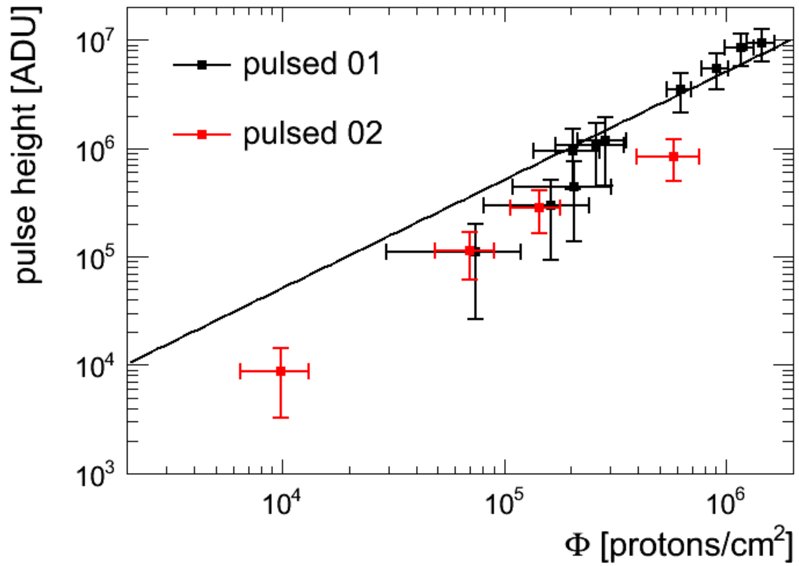
✓ ***Single and double hits can be distinguished***

Intense proton pulse response

Munich 14 MV Tandem accelerator

- pulsed beam
- 20 MeV protons
- 10^4 - ***10^7 p/cm²/ns***





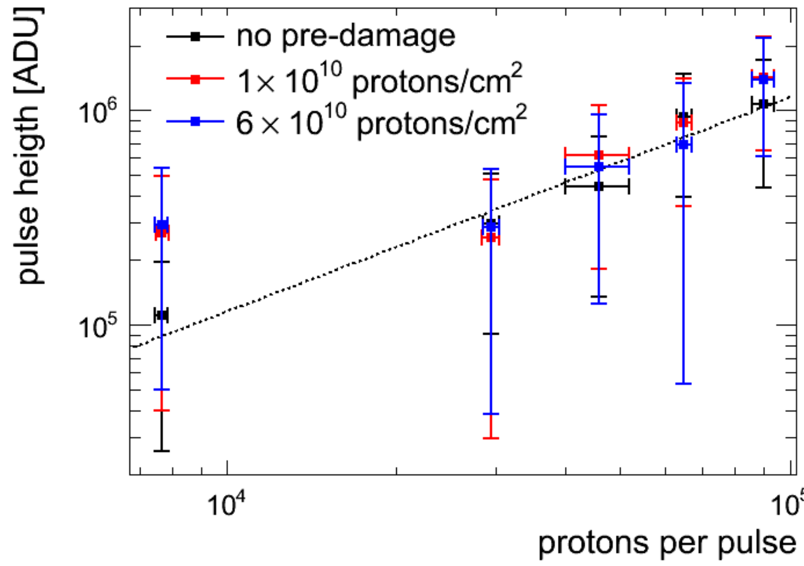
No saturation observed

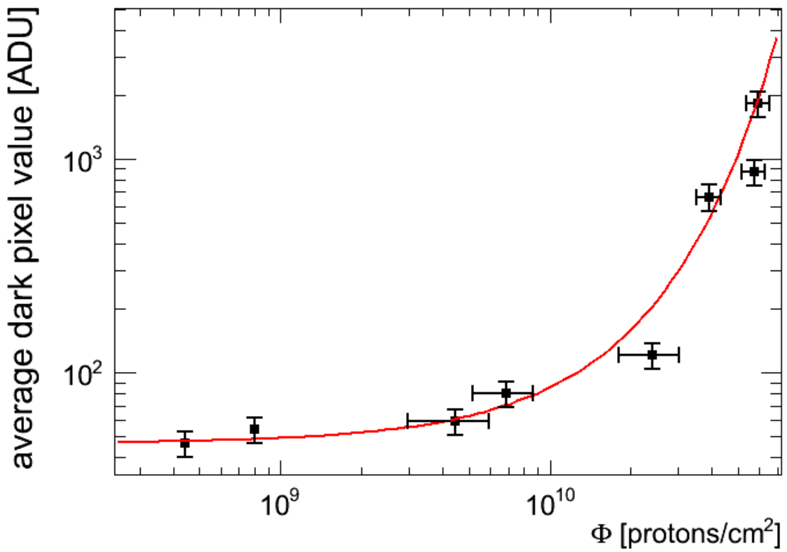
Good agreement to continuous measurements

Radiation hardness

Munich 14 MV Tandem accelerator

- continuous + pulsed beam
- 20 MeV protons
- <= 6 $\cdot 10^{10}$ p/cm²



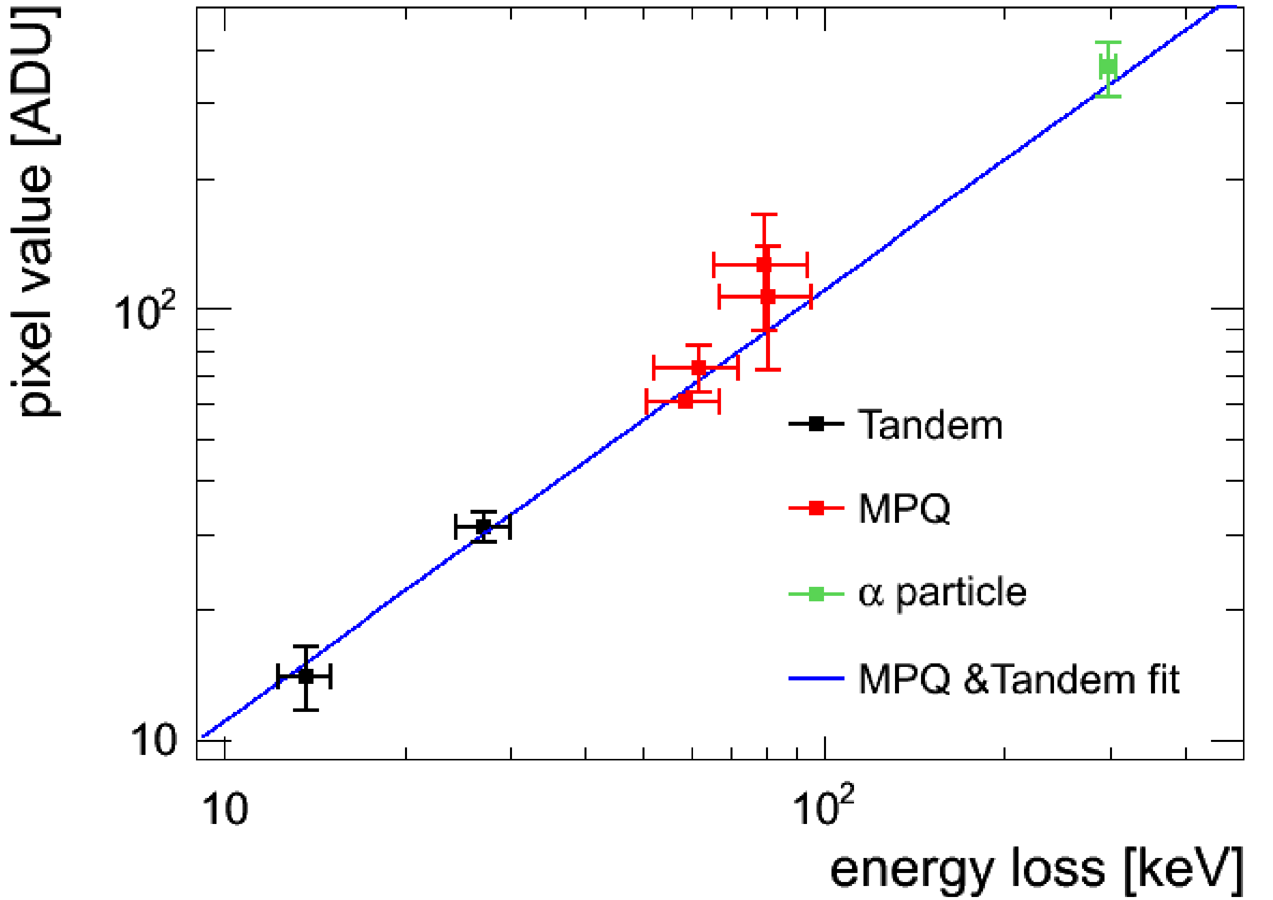


Lifetime ↔ 90% residual dynamic range

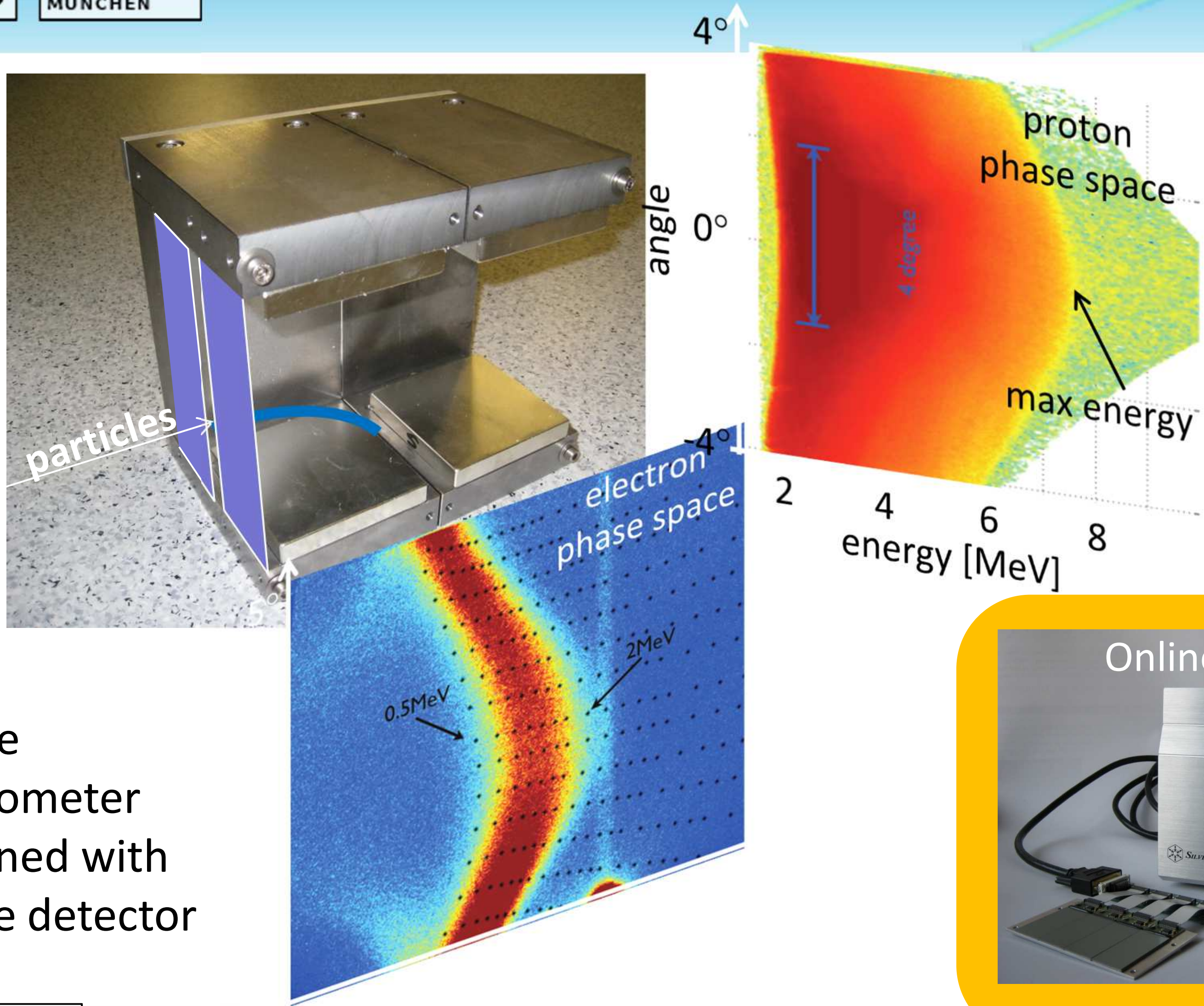
→ ***3000 shots*** (20 MeV, 10^7p/cm²)

System ready for laser-ion-acceleration experiment !

Energy conversion: 1.11 +/- 0.09 ADU/keV



LEX LION Diagnostic

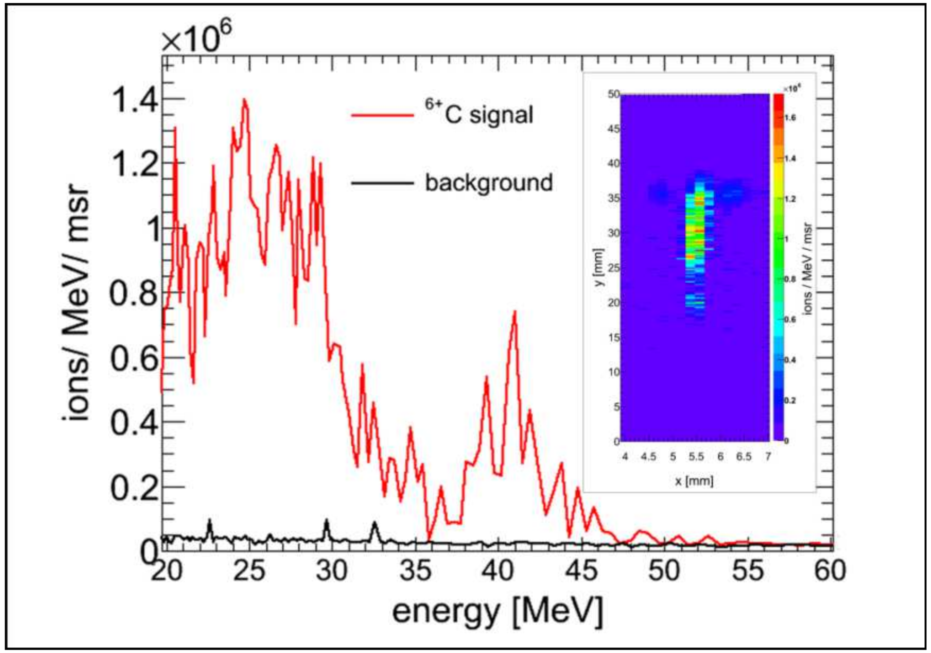


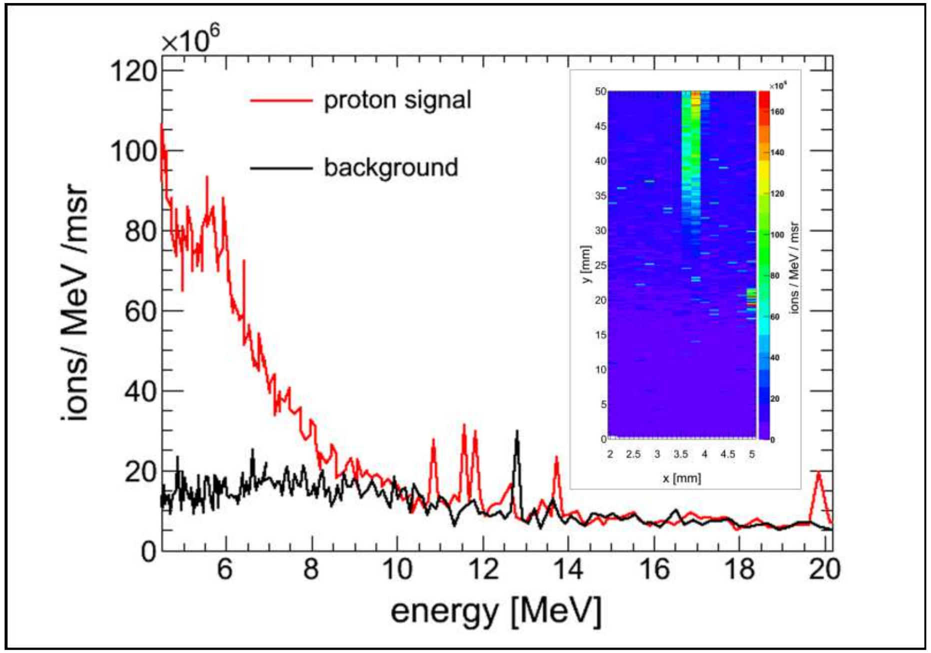
Particle spectrometer combined with RadEye detector

Astra Gemini Experiment

→ simultaneous detection of protons and ^{6+}C-ions

→ 10% accuracy in particle number determination possible



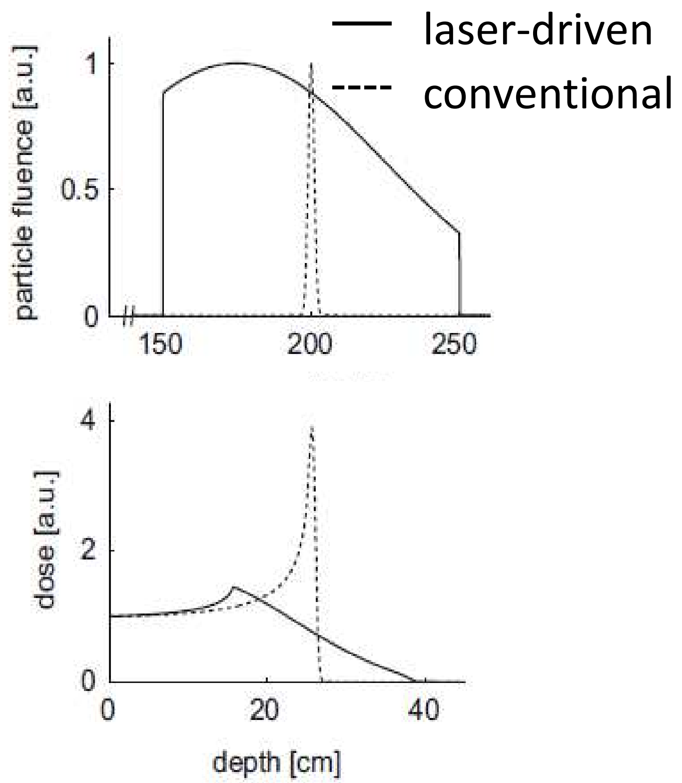


S. Reinhardt *et al.*, Journal of Instrumentation 8, 03008 (2013)

Dosimetry of laser-accelerated ions

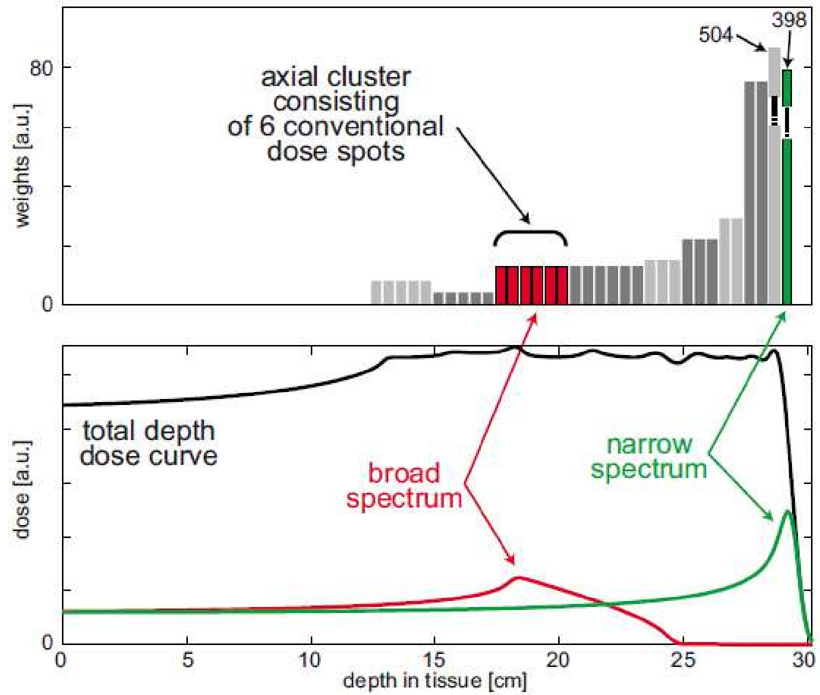
Radiotherapy with laser-driven ion beams

MAP main goal: Radiation therapy with laser-accelerated ions



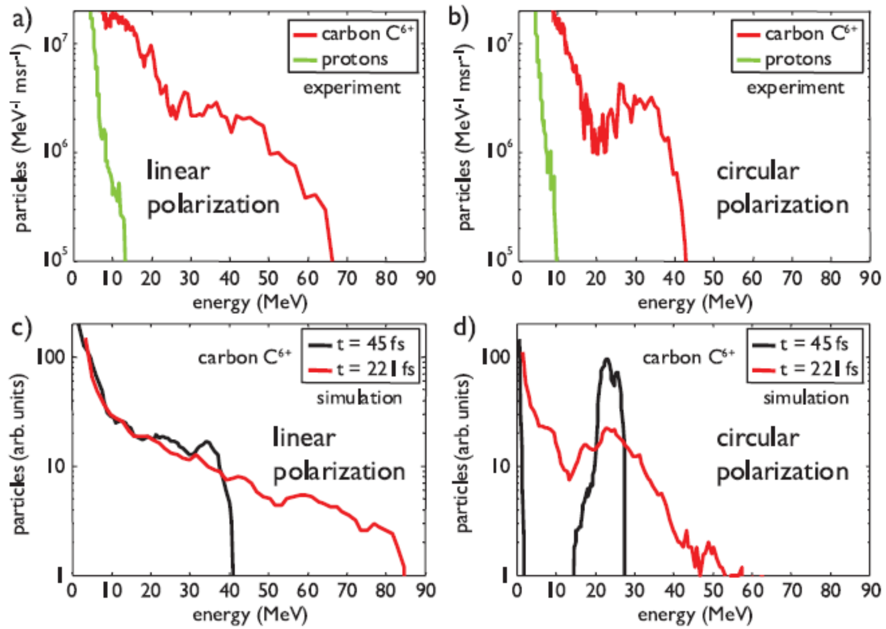
S. Schell et al, Med Phys 37 (2010)

Main idea:
Exploit broad energy spectrum to generate SOBP



Characteristics of laser-accelerated proton (ion) beams

TNSA RPA



A. Henig et al, PRL 103 (2009)

- ***Ultra-short (<= ns)*** and ***highly intense (> 10^7 ions/cm^2)*** ion pulses
- EMP presence
- Mixed radiation background
- ***Large energy spread*** of ions

→ ***Challenge for dosimetric measurements***

→ ***Investigation of biological response required***

Dosimetry of laser-accelerated ions

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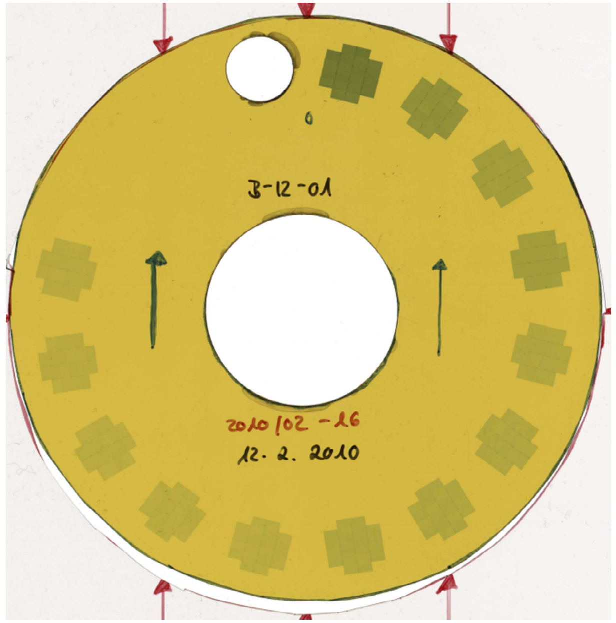
MAP: Radiation therapy with laser-accelerated ions

→ Bio-medical studies at LEX/CALA → ***Dosimetry***

- ***Special dosimetric application***
  - high pulse dose rate (> Gy/ns)
  - Low energies
    (protons < 20 - 30 MeV @ LEX)

- Development of ***film dosimetry*** protocol:
  Radiochromic EBT2/EBT3

- Application in cell and mouse tumour irradiation



Gafchromic EBT film

Polyester Laminate - 50 microns
Adhesive Layer - 25 microns
Topcoat - 4.5±0.5 microns
Active Layer - 30±3 microns
Polyester Base - 175 microns

EBT2

same active layer

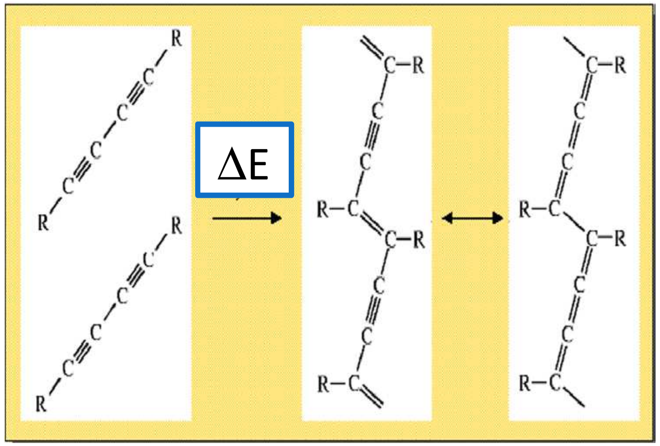
Lithium pentacosa-10,12-diynoate (LiPCDA)

EBT3

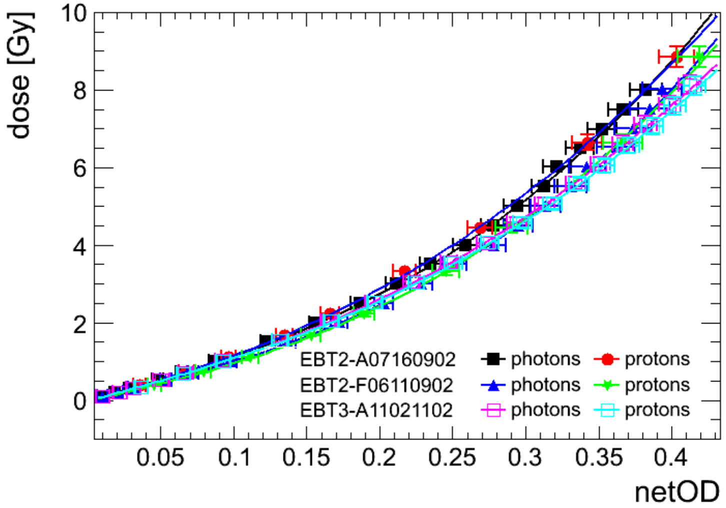
but **symmetric configuration**

Matte Polyester Substrate - 125 microns
Active Layer - 27±3 microns
Matte Polyester Substrate - 125 microns

✓Dose range: ***0.2 - 40 Gy***
✓Water-equivalent
✓Sub-mm spatial resolution
✓2D read-out by RGB flatbed scanner
✓Self-developing by polymerization



Film dosimetry in proton beams



EBT2 vs. EBT3:

No general response difference

- No particle type dependence
  - ➢ difference photons-protons < 3.0 %
- Intra-batch variations < 2.5 %
- Batch-to-batch variations < 11.5 %

Problem:

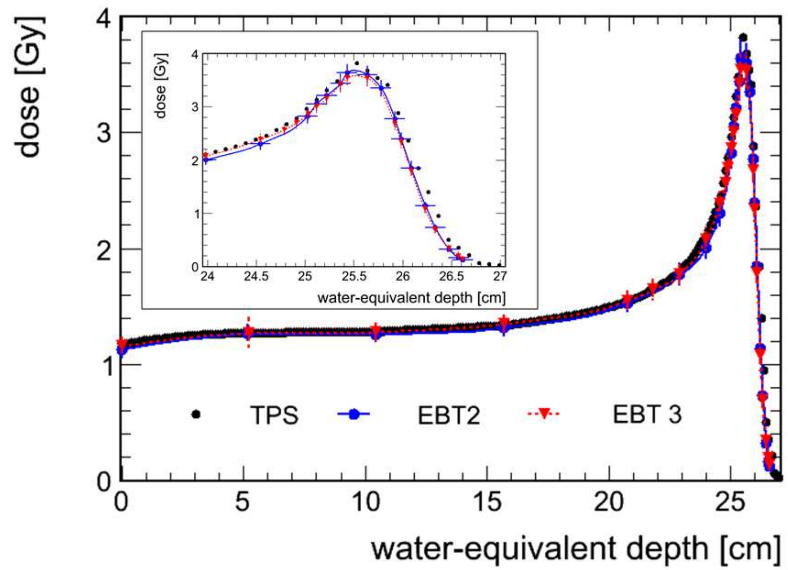
➢ dose under-response in Bragg Peak region (high LET)

➢ already known from other radio-chromic films

S. Reinhardt et al, Med. Phys. 39 (2012)

S. Reinhardt et al, Rad Env Biophys (2015)

DOI 10.1007/s00411-014-0581-2



Mouse tumour irradiation at the MLL Tandem accelerator

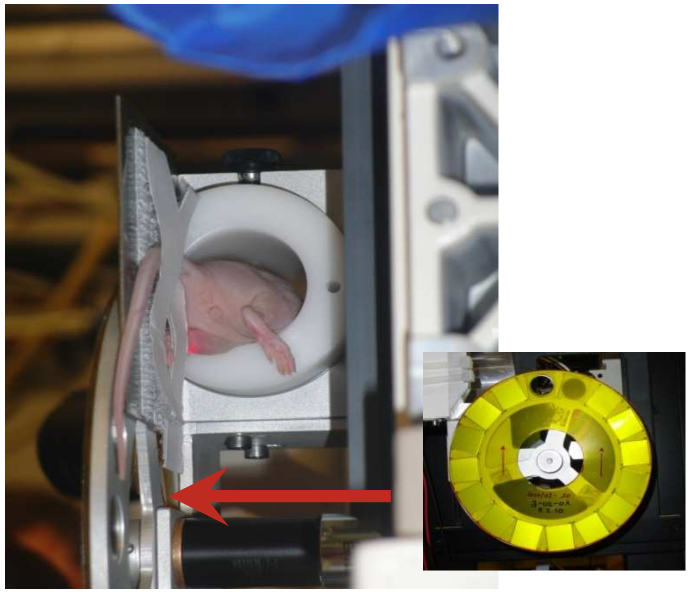
- RBE Difference due to irradiation mode? (continuous vs. pulsed)

- ***23 MeV protons***:

  < 6 mm range in water

- ***spatial dose distribution*** required

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



- ***PTV dose: 20 Gy***, using 5 fluences

  → dose range on film: ***0.54 Gy - 4.00 Gy***

Mouse tumour irradiation at the MLL Tandem accelerator

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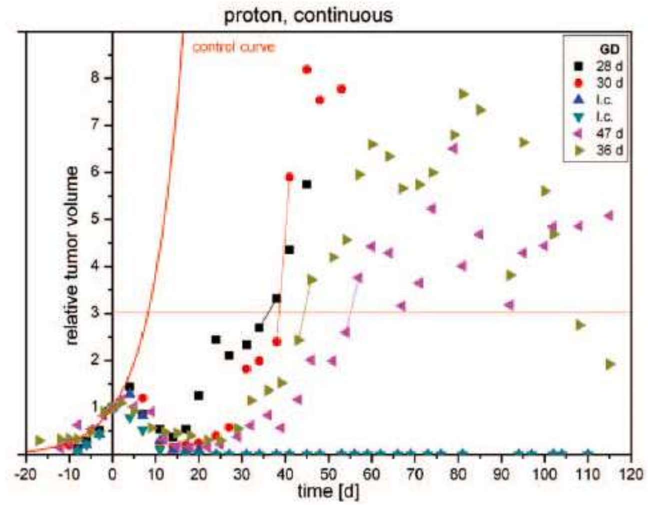
O. Zlobinskaya et al, Rad Res 181(2014)

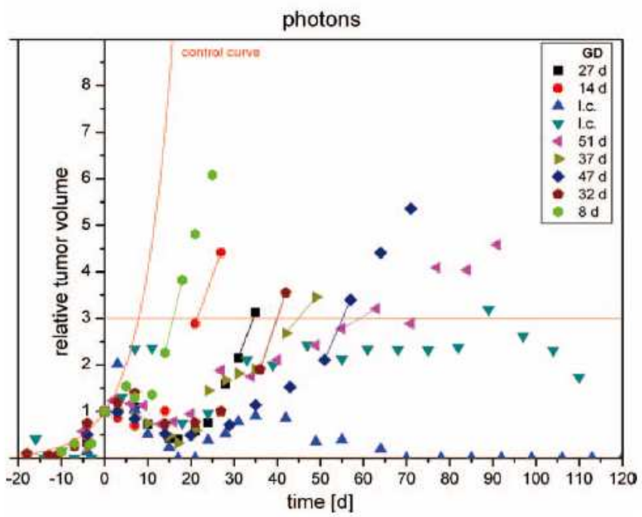
Our *in vitro* and *in vivo* studies showed no evidence of a substantially different radiobiology associated with the ultra-high dose rate that characterizes protons generated from advanced laser technology.

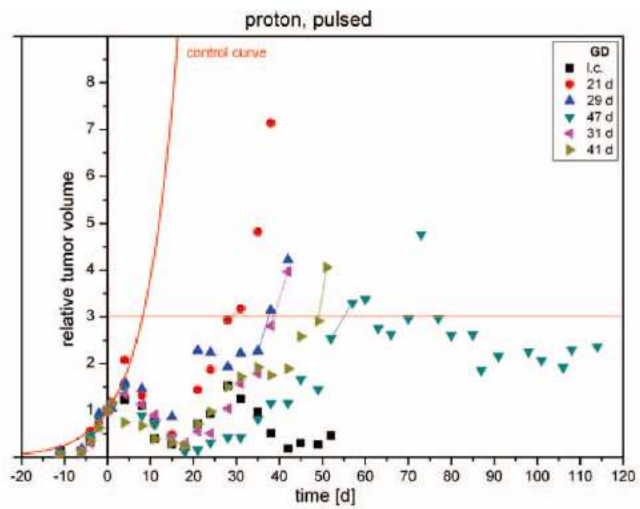
We conclude that dose prescription for pulsed protons can be based on established therapeutic concepts for protons. However, one should bear in mind that differences in the RBE values smaller than 10% cannot be excluded yet and should be accounted for in dose constraints for organs at risk.



RBE values:

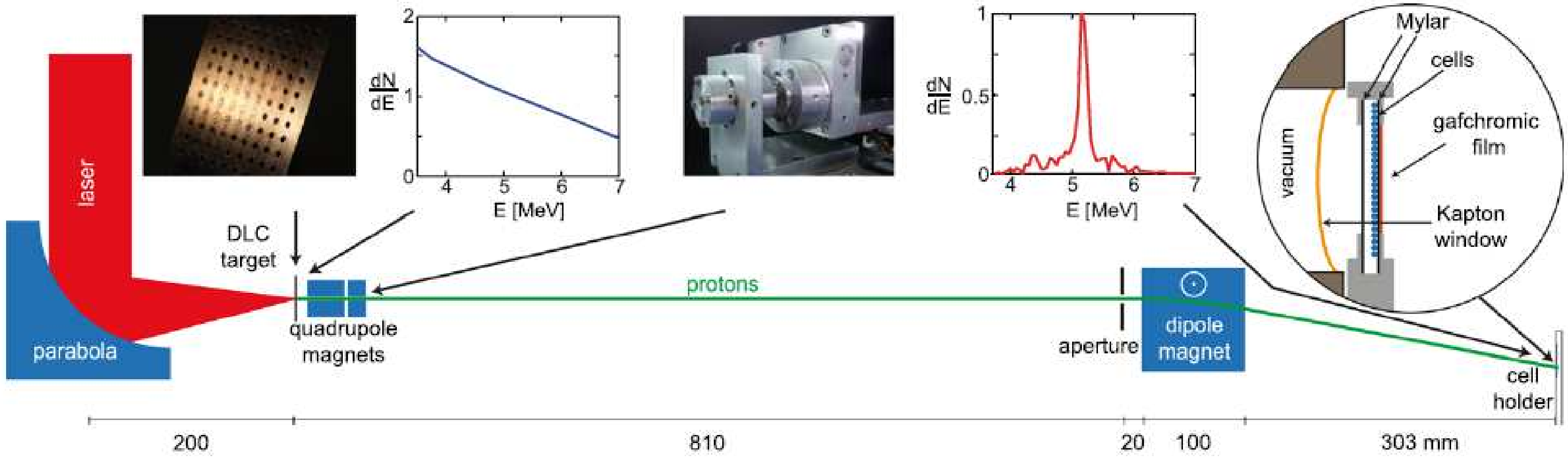
- pulsed beam
  1.22 ± 0.19
- continuous beam
  1.10 ± 0.18

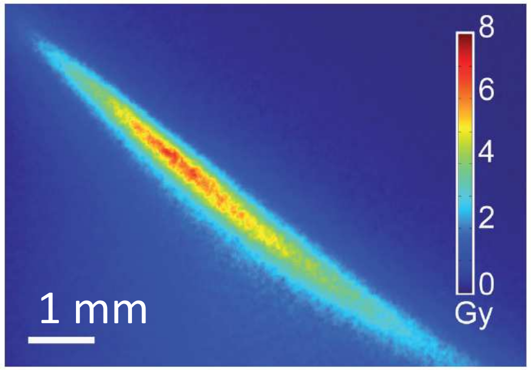


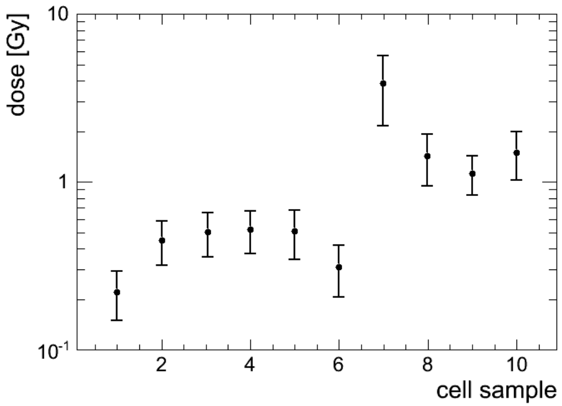


Cell irradiation at the MPQ ATLAS laser

J. Bin et al, APL 101 (2012)

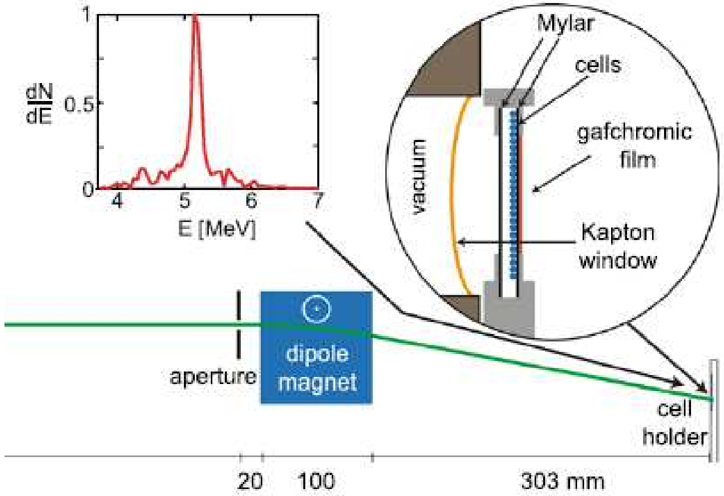


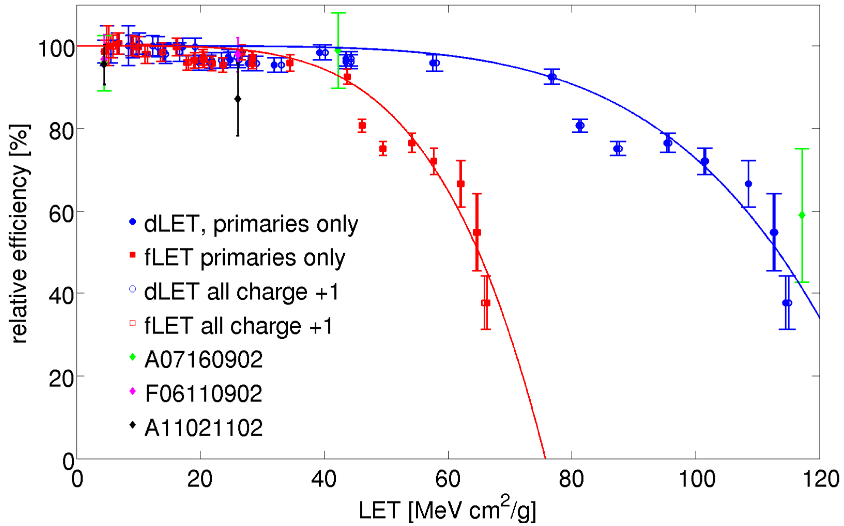




Delivery of single shot doses up to 7 Gy to living cells (HeLa)

Cell irradiation at the MPQ ATLAS laser

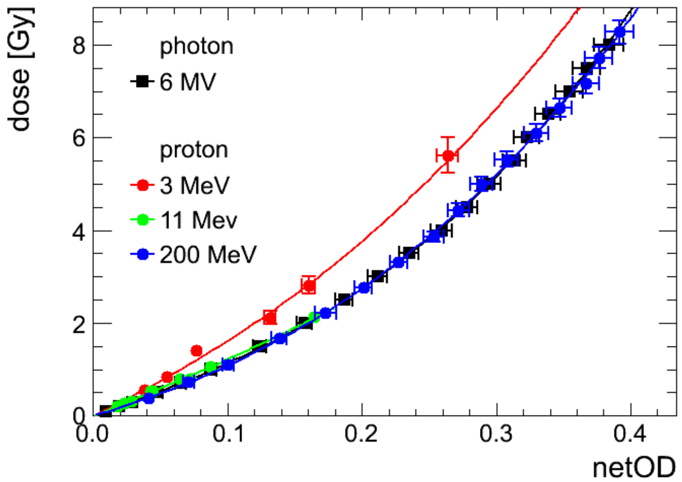




MPQ cell irradiation experiment

3.1 MeV protons @ active film layer

- ➢ considerable LET dependence
- ➢ low energy calibration required



S. Reinhardt et al, Rad. Env. Biophys. (2015)

Cell irradiation at the MPQ ATLAS laser

J. Bin et al, APL 101 (2012)

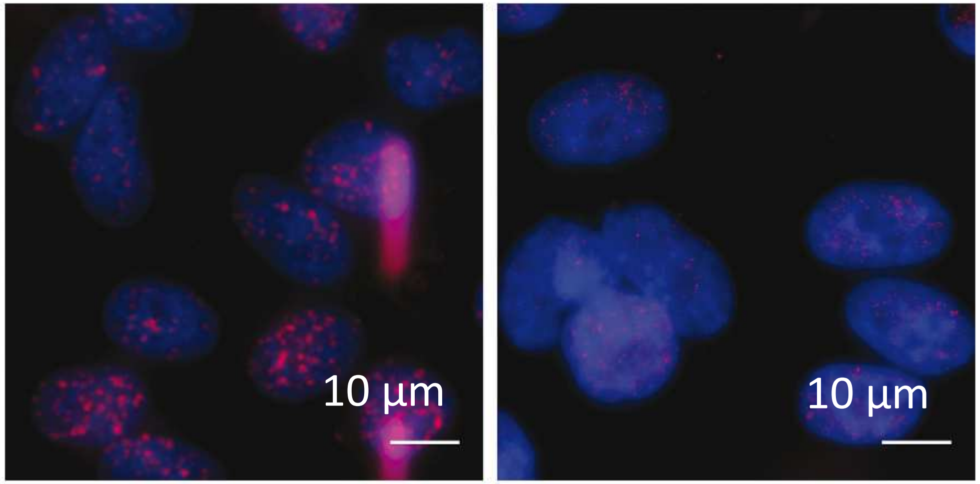


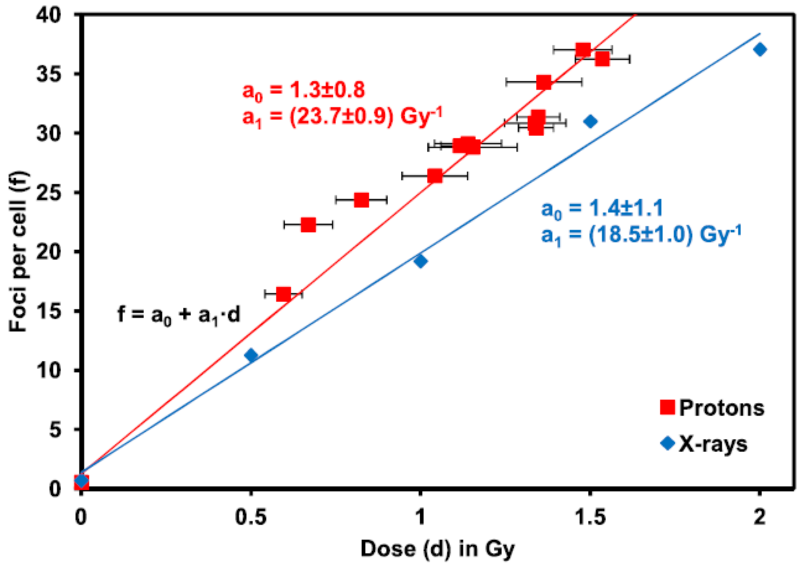
FIG. 5. Initial DNA damage in HeLa cells. (a) Sample exposed to a mean dose of 1.0 Gy and (b) corresponding unirradiated control. Foci of γ-H2AX (red) and cell nuclei (blue) are shown (3D microscopy, maximum intensity projections, background correction, contrast enhanced). The red vertical bars in (a) are part of the grid used for spatial registration (Fig. 4). Horizontal scale bars, 10 μm.

Irradiation of HeLa cells:

RBE for induction of repari foci

$$1.3 \pm 0.3$$

No new radiobiogolical effects by single high pulse dose rate $\sim 10^9 \frac{Gy}{s}$



Conclusion and Outlook

Gafchromic films

- EBT3 and EBT2 show similar performance
- Film dosimetry in low energy proton beams possible

RadEye-Detector

- ***Single proton sensitivity***
- Limited energy resolution
- Sufficient radiation hardness
- ***Linear pulse dose response up to 10^7 p/cm^2***

Outlook

- *RadEye in routine use for laser accelerated ion detection in LEX*
- *New detector developments required for ion detection in CALA*
- *Online dosimetry required for future experiments in LEX/CALA*

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Thank You !