Laser-driven Production of Particle Beams and their application to medical treatment

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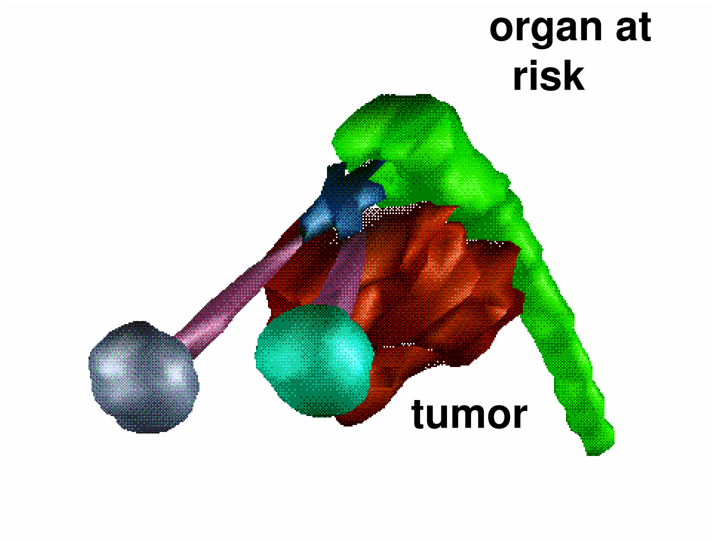
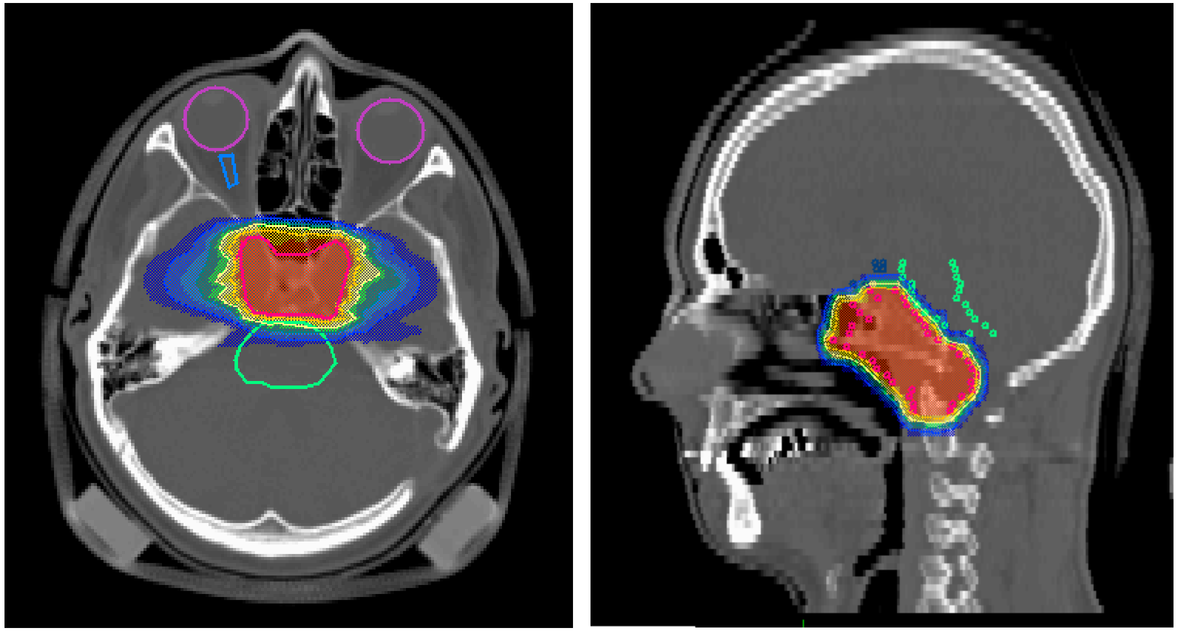
Outline

- The Case
- Laser-driven electrons
  - Potential for Applications in Therapy
  - Use of secondary Radiation
- Laser-driven Ion Beams
  - Properties and Mechanism
  - Damage reports...
  - Experiments
- Applications as Sources for Therapy
  - Transport of laser-accelerated protons
- Summary

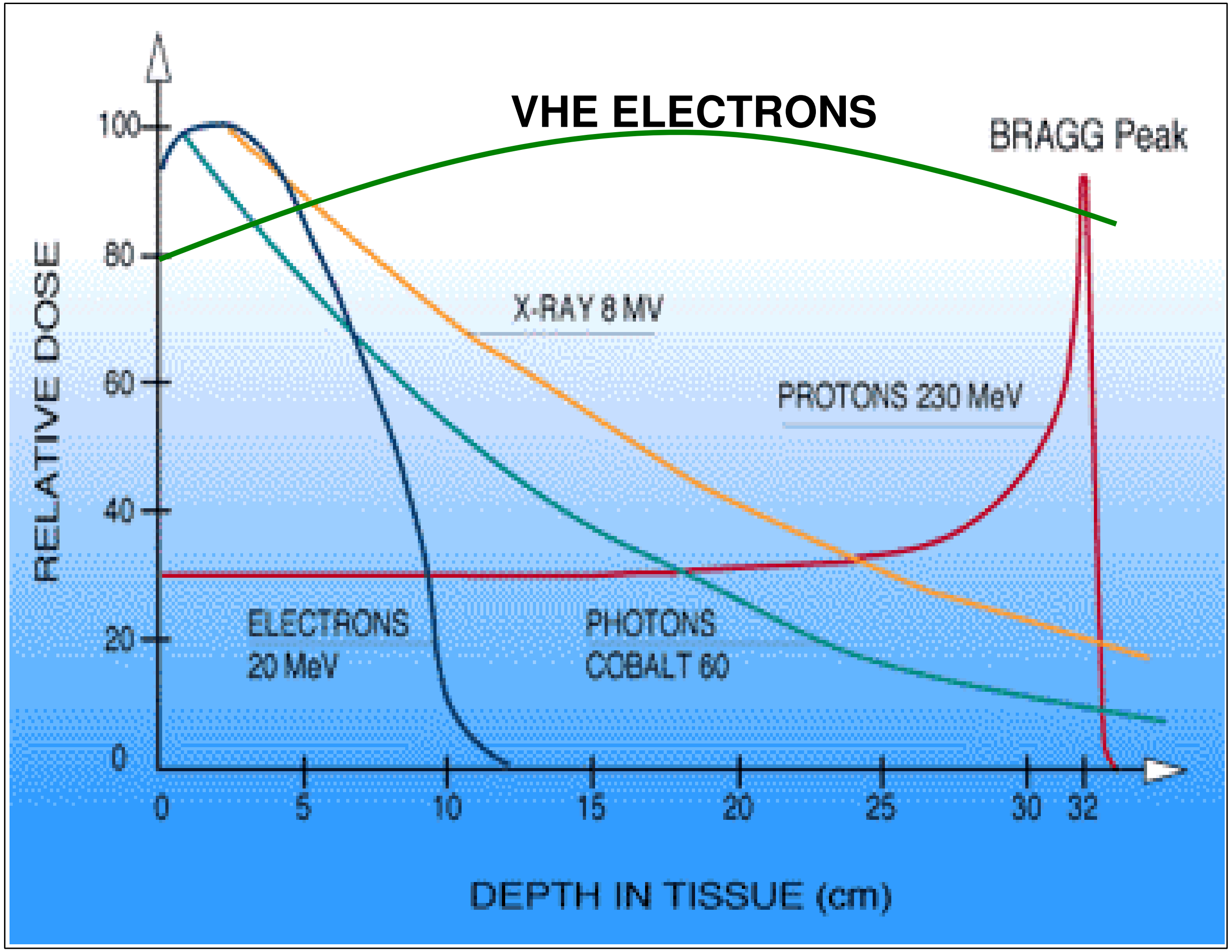
- Locations: brain and base of the skull, prostate, liver, lung
- Profile: deep-seated and radioresistant tumor close to organs at risk



tumor-conformal dose distribution



Dose deposition : Photon X, electrons VHE (very high energy) electrons, & ions



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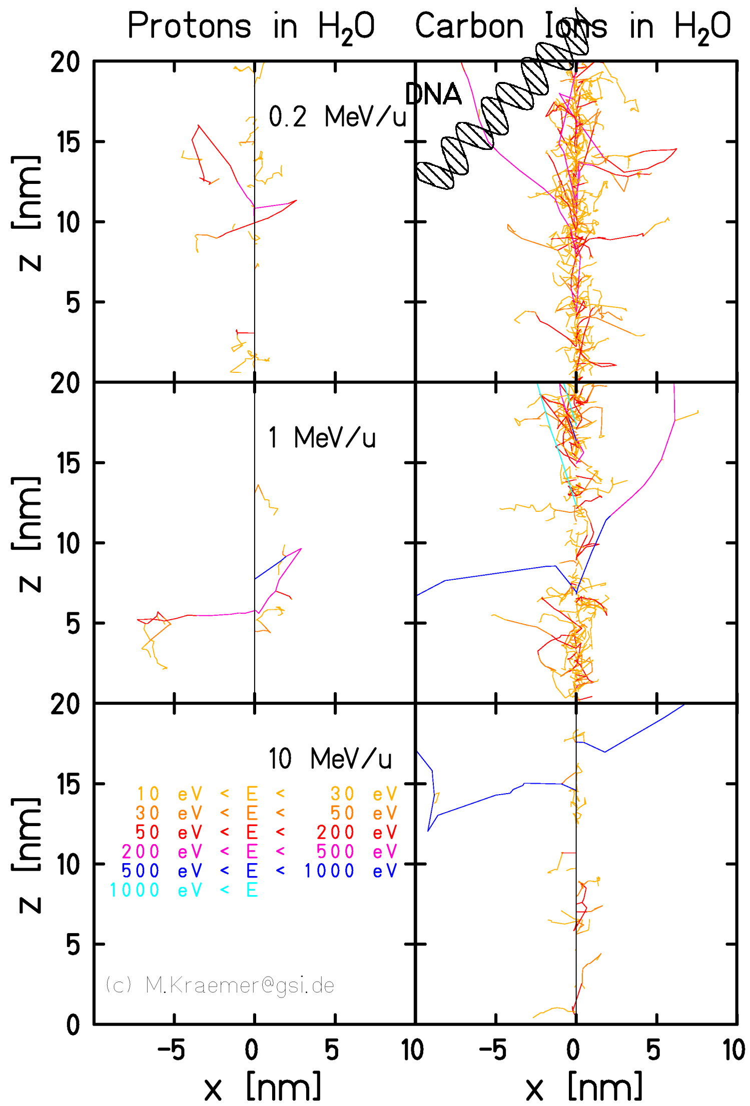
microscopic dose distributions



Advanced / Beam Scanning

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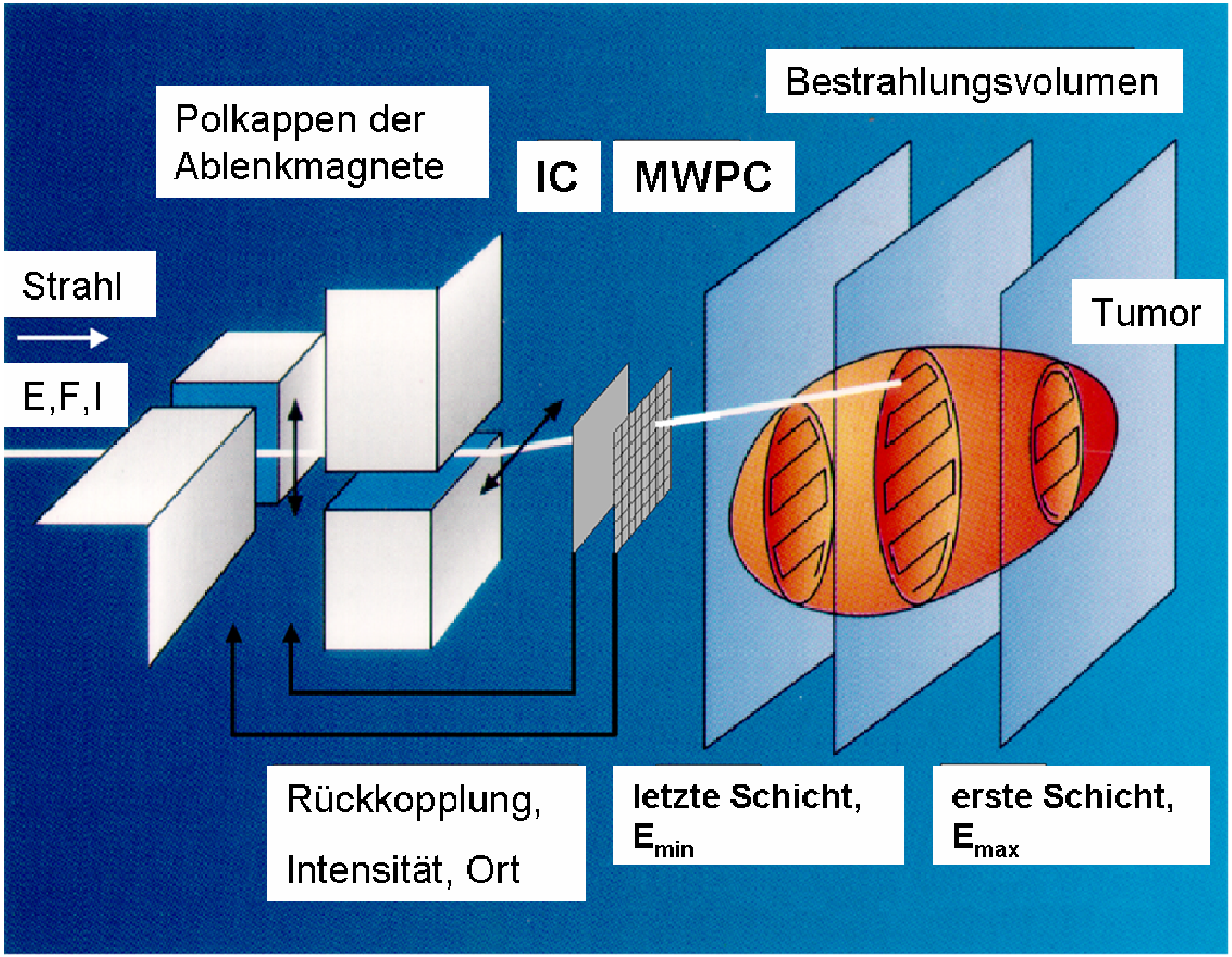
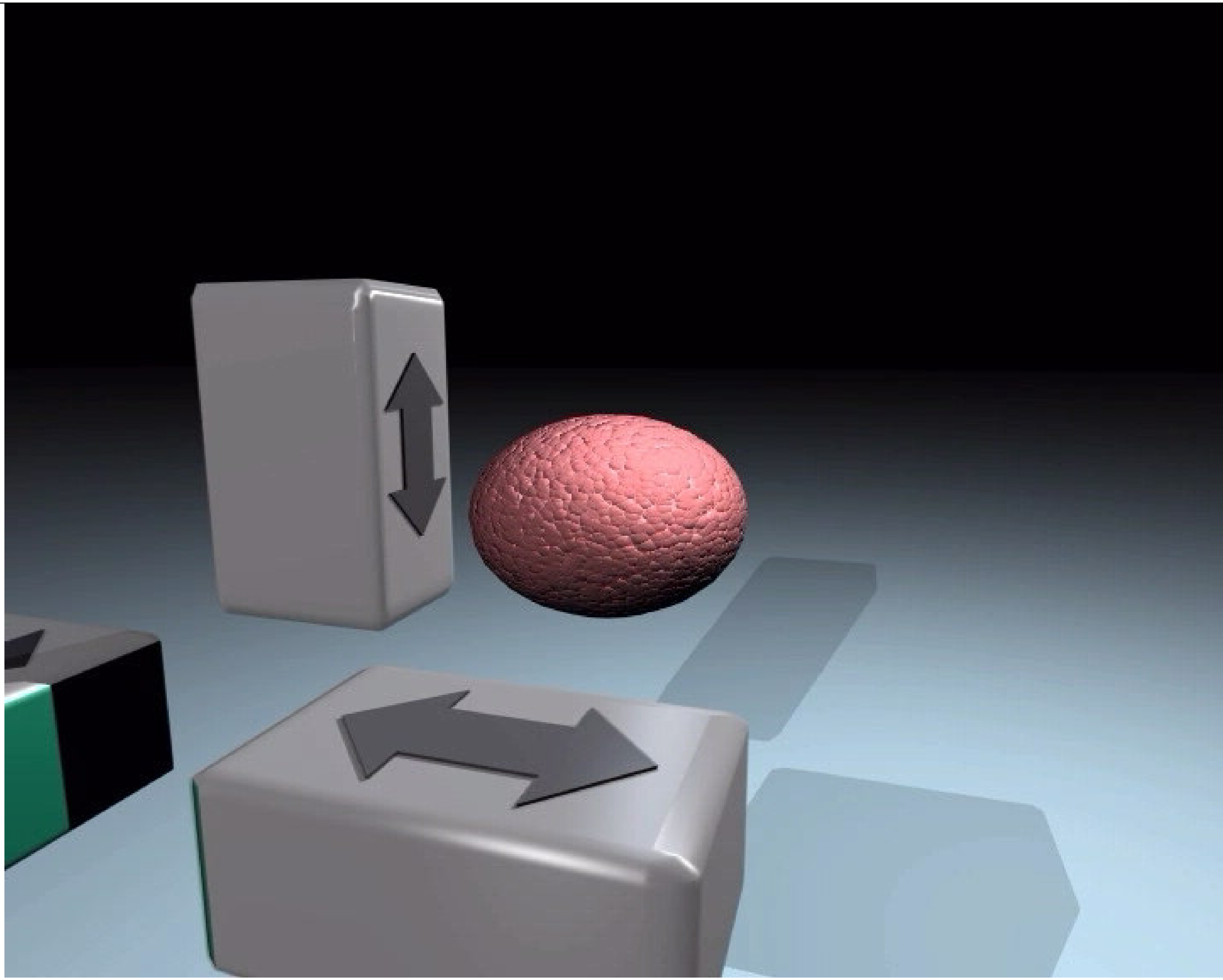
scanning of focussed ion beams in fast dipole magnets

active variation of the energy, focus and intensity in the accelerator and beam lines

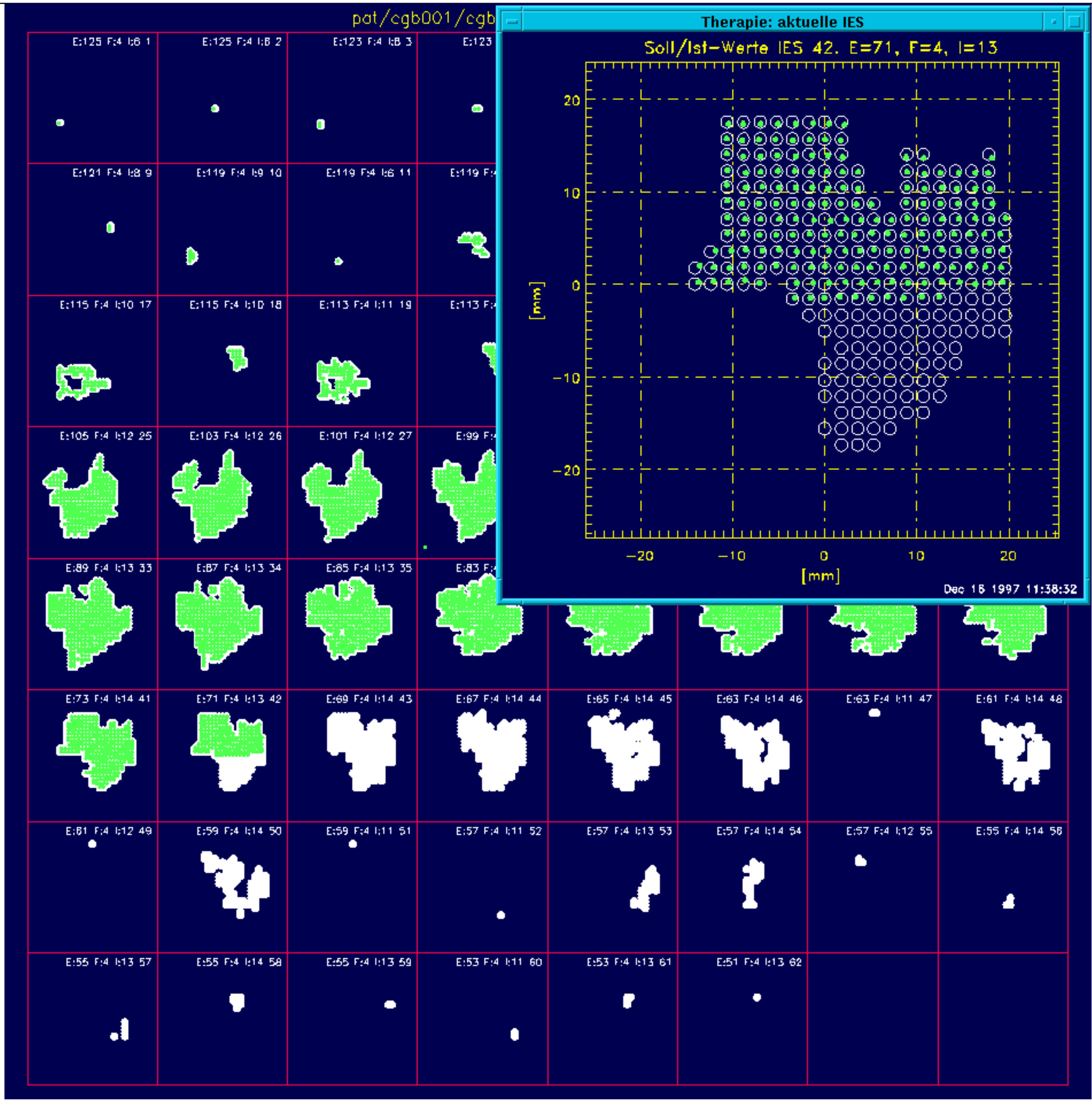
utmost precision via active position and intensity feed back loops



intensity-controlled rasterscan technique @ GSI

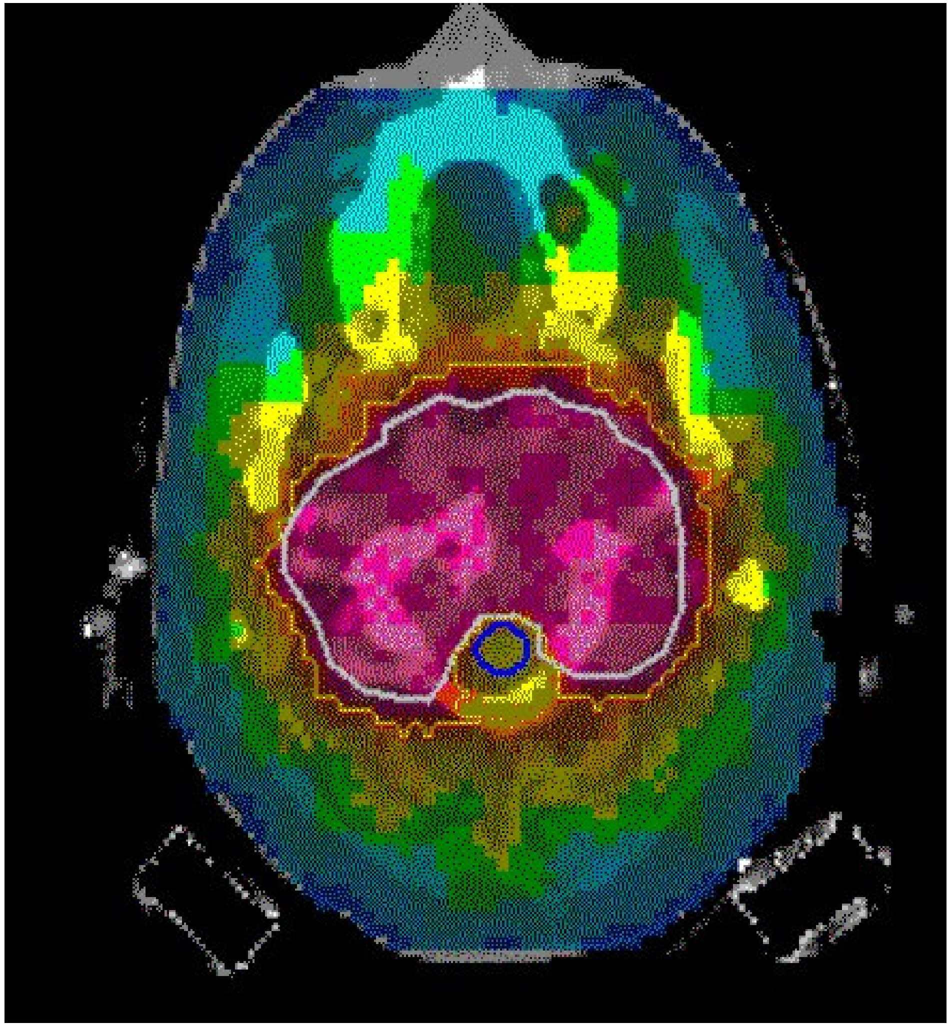


Advanced / Target Volume

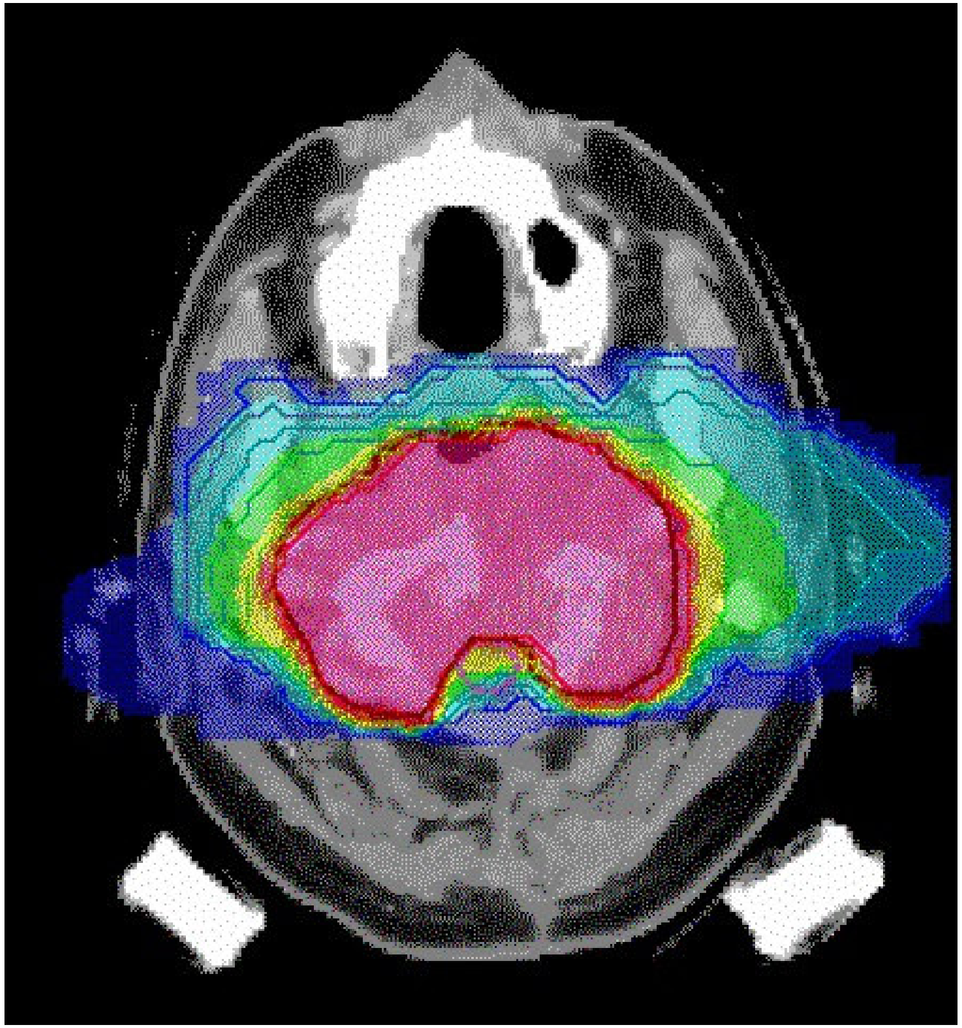


Slices of tumor treated at GSI

IMRT 9 fields



Carbon 2 fields



Ions vs. IMRT

Efficient acceleration in plasmas = compact accelerator ?

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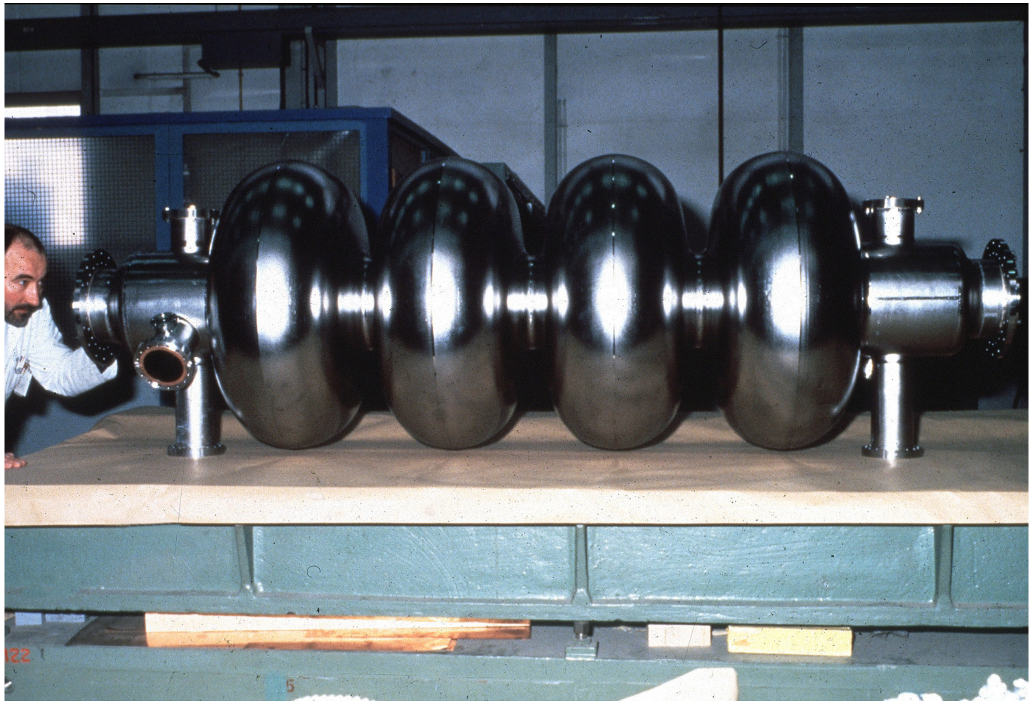
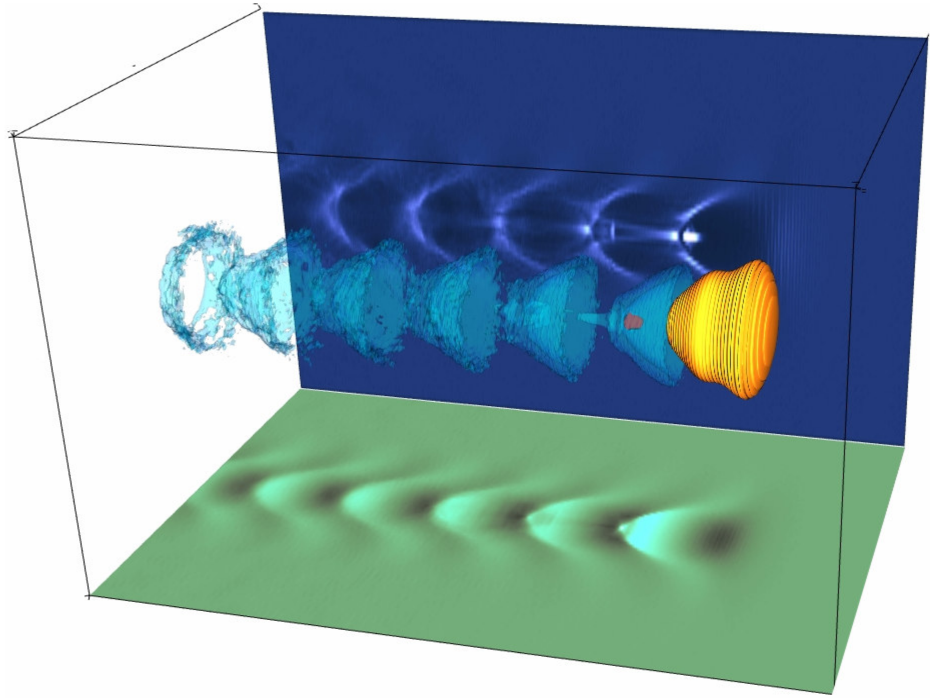
RF cavity : 1 m

Plasma cavity : 1 mm



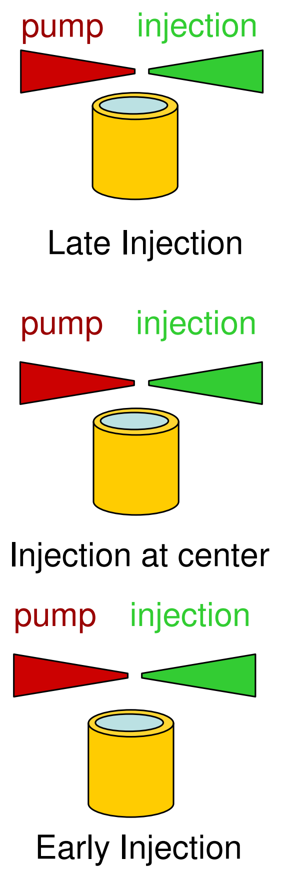


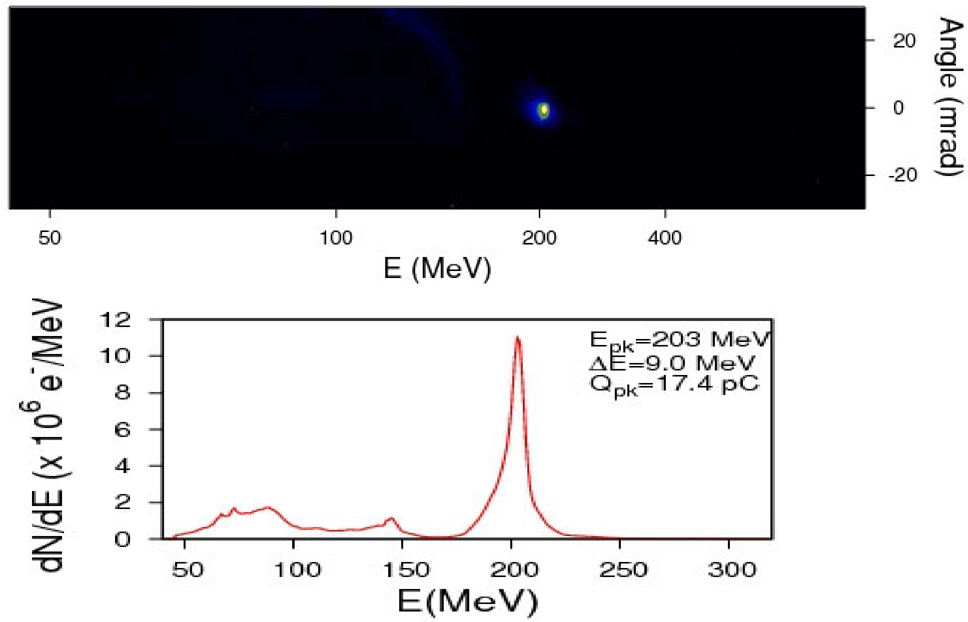
E = 10-100 MeV/m

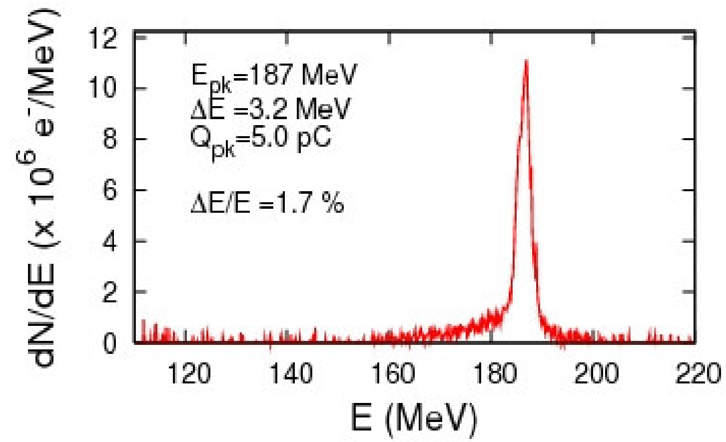
E = 100-1000 GeV/m

courtesy of **V. Malka *et al.*, Science 2002**

Use of a two laser scheme:
Mono energetic e-beam :1% energy spread







J. Faure et al., Nature 2006

Courtesy of Victor Malka

Application to radiotherapy: Improvement of some cancer treatments

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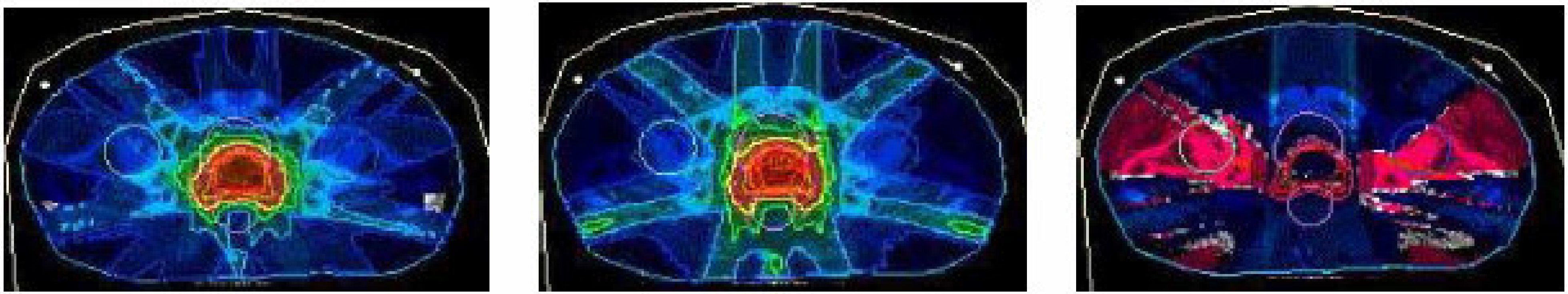
A typical transversal dose distribution with 7 beams.



(a) (b) (c)

Electrons **Photons X** **Différence**

A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved **up to 19%.**

T. Fuchs, et al. soumis à Med Bio
En coll. Avec DKFZ

Use of secondary radiation

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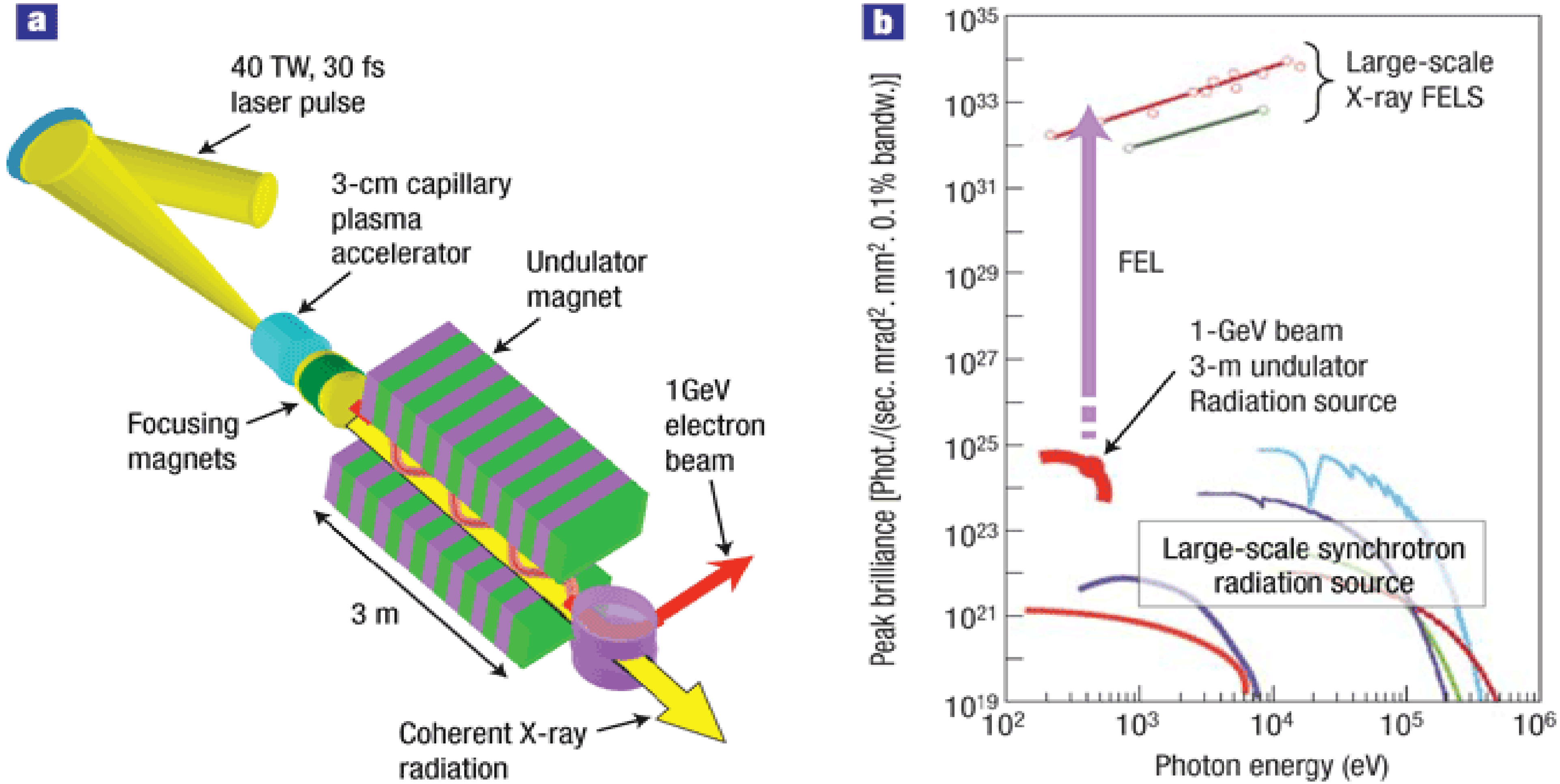
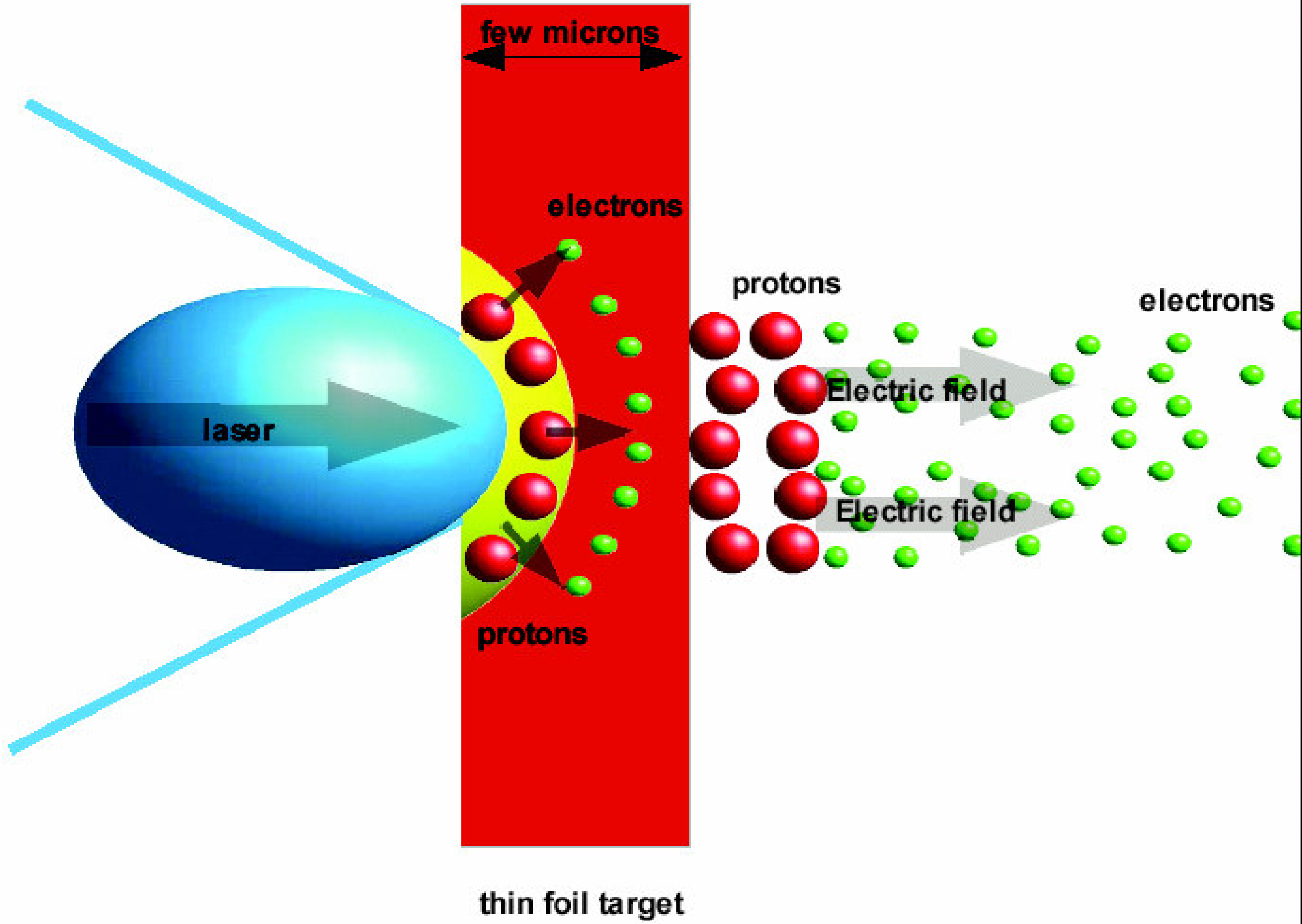
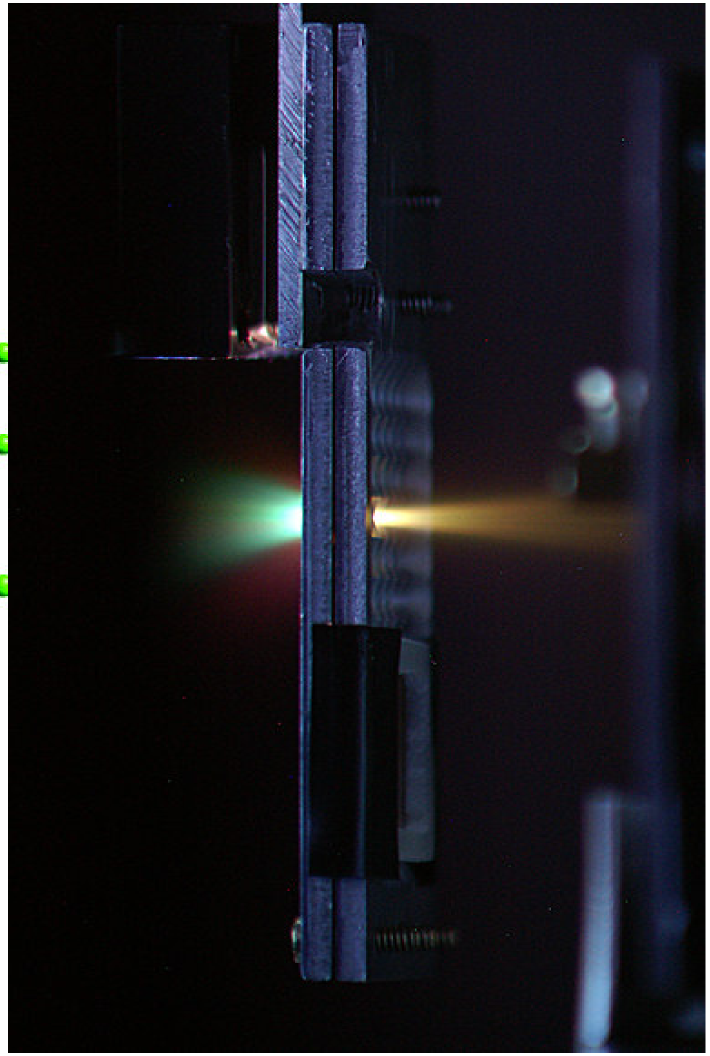
Compact, laser driven FEL's could lead to coherent x-ray radiation for phase contrast imaging



***Kazuhisa Nakajima ,Nature Physics* 4**, 92 - 93 (2008)

Proton acceleration with lasers : Static electric fields





Beam characteristics of laser-virtual cathode sheath accelerators

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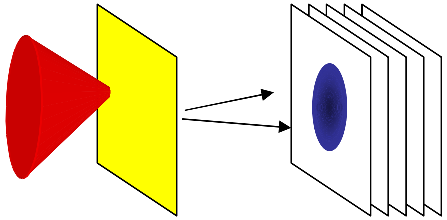


- Transverse emittance: < 0.002 π mm-mrad (cf. RF Linacs ~ 1 π mm-mrad)
- Longitudinal emittance: < 10^{-6} eV-s
  (velocity correlated; synchrotrons ~ 0.1 eV-s)
- Energy spread: 100%
- Bunch charge: 10^{11} – 10^{13} protons or ions
- Source diameter: ~50 μm (fwhm)
- Charge state purity: >80% He-like
- Ion current: ~10 kA (at source)
- Rep-rate: determined by laser driver
- Laser-ion efficiency: > 1% (4-20% observed)

Other proposed mechanisms

RPA for highest intensities

Light pressure drives the electrons forward and Ions have to follow

Radiation Pressure Acceleration:

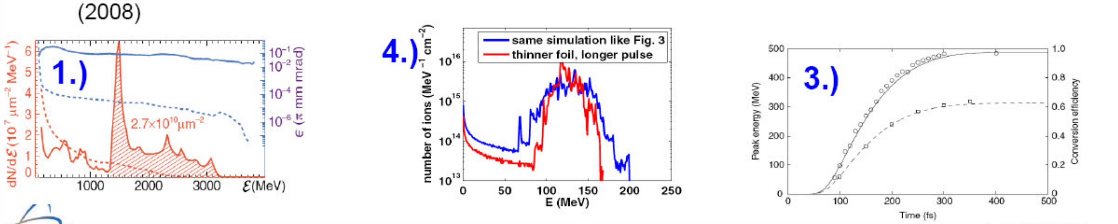
Circular Polarization may enable RPA at „moderate“ intensities (>10^{20} W/cm²).

Radiation Pressure Acceleration with ultraintense lasers has been suggested as an effective ion acceleration mechanism at very high intensities (10^{23}-10^{24} W/cm²):

1. JAERI, Japan: Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime. T. Esirkepov, et al., PRL, 92 (2004)

Circular Polarization enables Radiation Pressure Acceleration (RPA) or Phase Stable Acceleration (PSA) at todays intensities (~10^{20}-10^{21} W/cm²):

2. SIOM, China: Efficient GeV ion generation by ultraintense circularly polarized laser pulse. Xiaomei Zhang, et al., **PoP 14**, 123108 (2007)
3. RAL, UK: Radiation pressure acceleration of thin foils with circularly polarized laser pulses, A. P. L. Robinson, et al., **New Journal of Physics 10**, 013021 (2008)
4. Czech Tech. Univ.: Monoenergetic ion beams from ultrathin foils irradiated by ultrahigh-contrast circularly polarized laser pulses, O. Klimo, et al., **PRST-AB 11**, 031301 (2008)
5. Peking Univ., China: Generating High-Current Monoenergetic Proton Beams by a Circularly Polarized Laser Pulse in the Phase-Stable Acceleration Regime, X.Q. Yan et al., **PRL 100**, 135003 (2008)

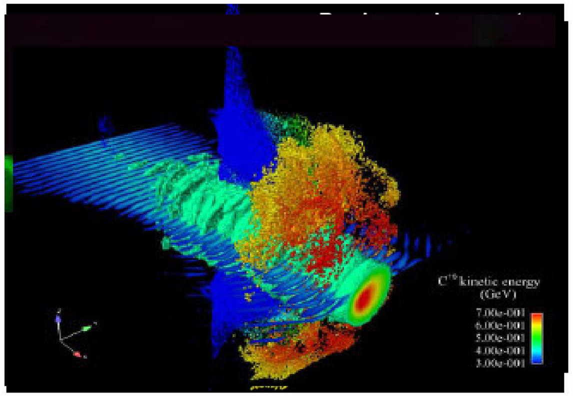


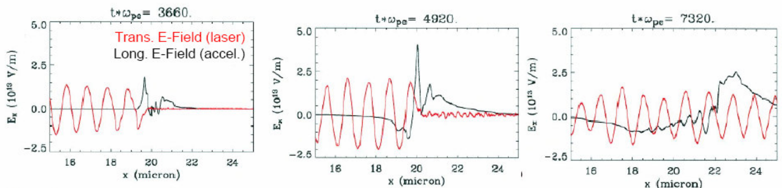
Break-Out Afterburner (BOA) acceleration

BOA proceeds in 3 stages: TNSA, Enhanced TNSA, Afterburner

1. Phase: Standard TNSA - a small fraction of electrons is promoted to ‘hot’ ⇒ modest acceleration
2. Phase: Enhanced TNSA - all electrons are promoted to ‘hot’: ⇒ Field increases, skindepth increases beyond target thickness (breakout).
3. Phase: Afterburner - laser penetrates the target, velocity difference in e- and ion distributions triggers kinetic instability ⇒ Electron transfer energy to ions, laser reheats electrons (afterburner).

- Largest ion energies emitted in an angle in plane orthogonal to polarization plane.
- Accelerating E-Field moves with the Ions





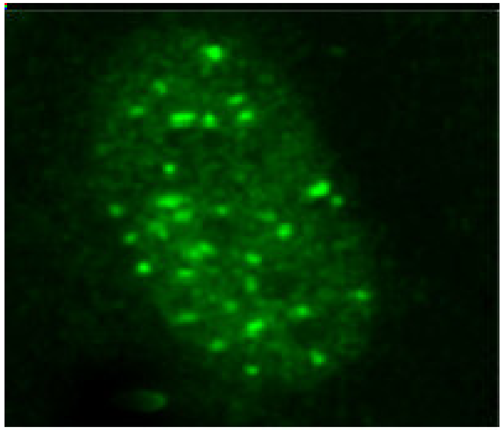
BOA mechanism
second boost of the hot electrons when target becomes transparent

Kinematic Buneman instability

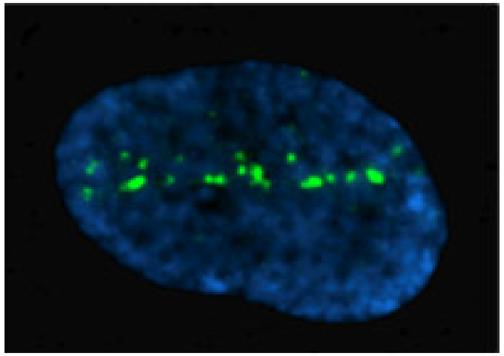
Slides from B.M. Hegelich (LANL)

Properties and Mechanism

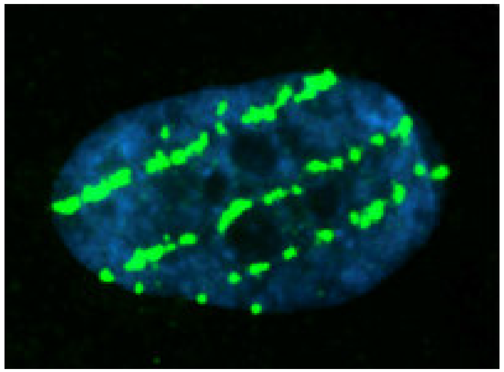
DNA dsb visualized by immunofluorescence of γ-H2AX histone in human skin firbroblasts exposed to 2 Gy of ionizing radiation



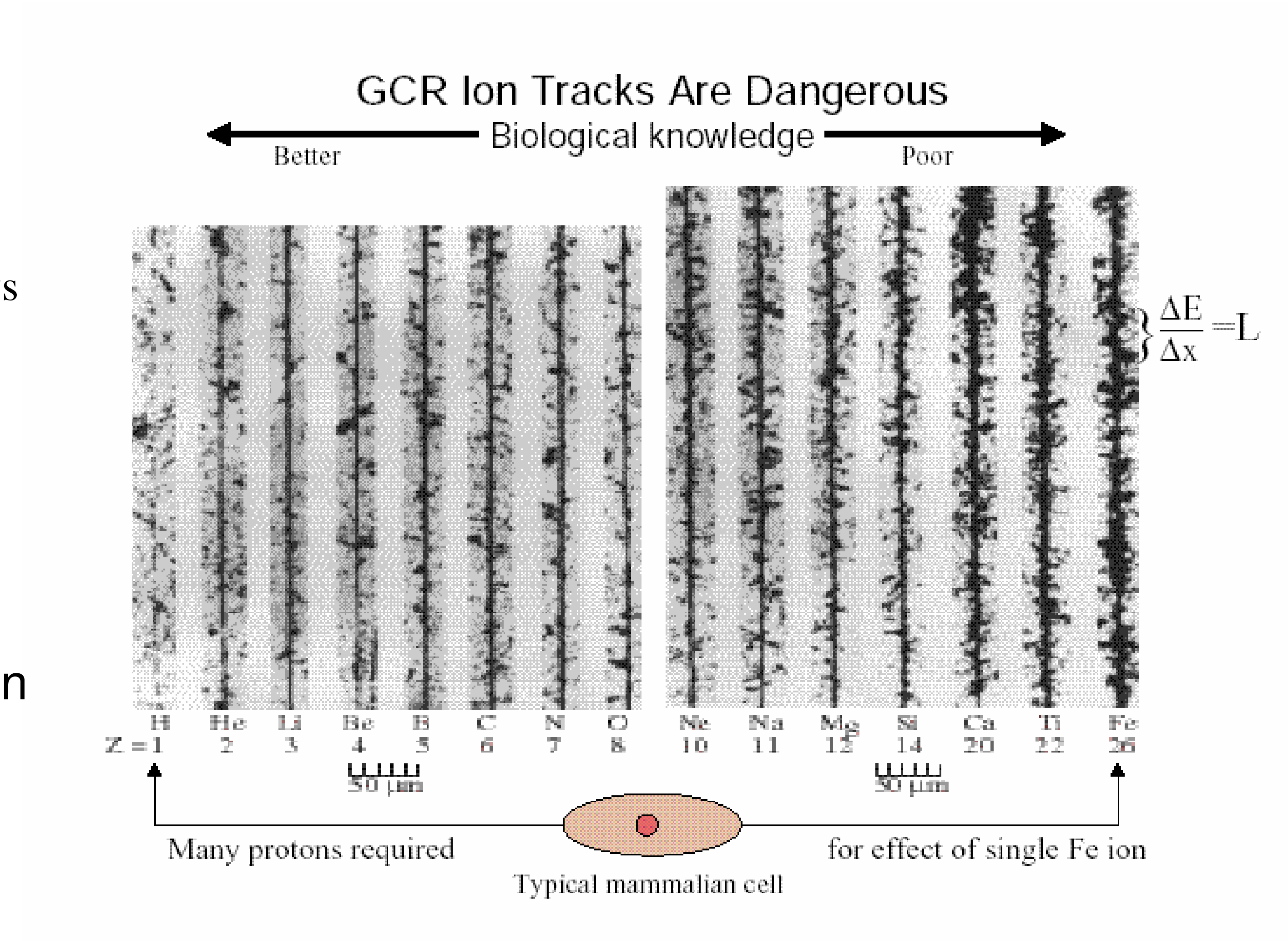
γ-rays



silicon



iron



Cucinotta and Durante, *Lancet Oncol.* 2006

Damage reports...

Effects on the molecular time scale

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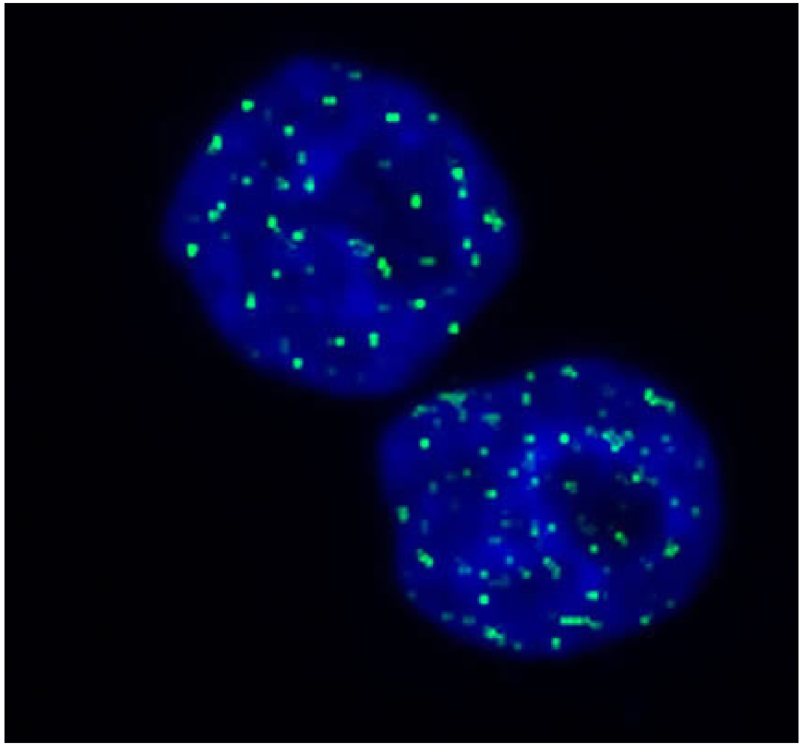
- Chance to hit DNA a second time before first damage is repaired (critical flux > 10^8 p/cm^2) and beyond.

- Induce free radicals by water radiolysis close to DNA damage

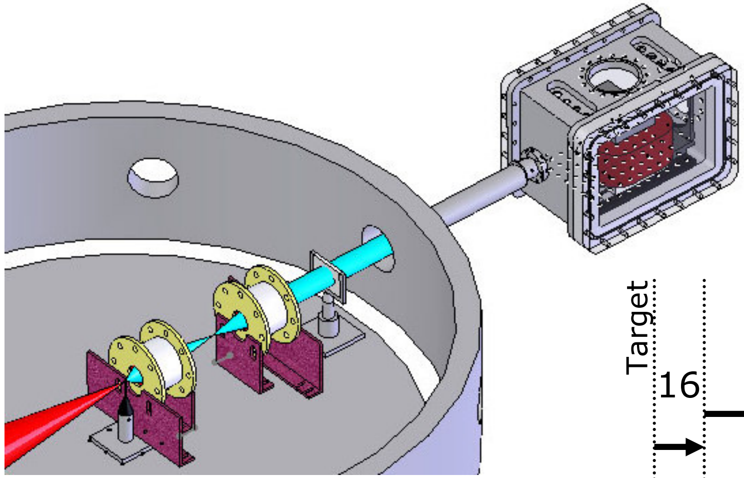


γH2AX foci following exposure of human epithelial cells to protons. Each green spot correspond to a distinct DNA double-strand break.

Damage reports...

Recent experiments

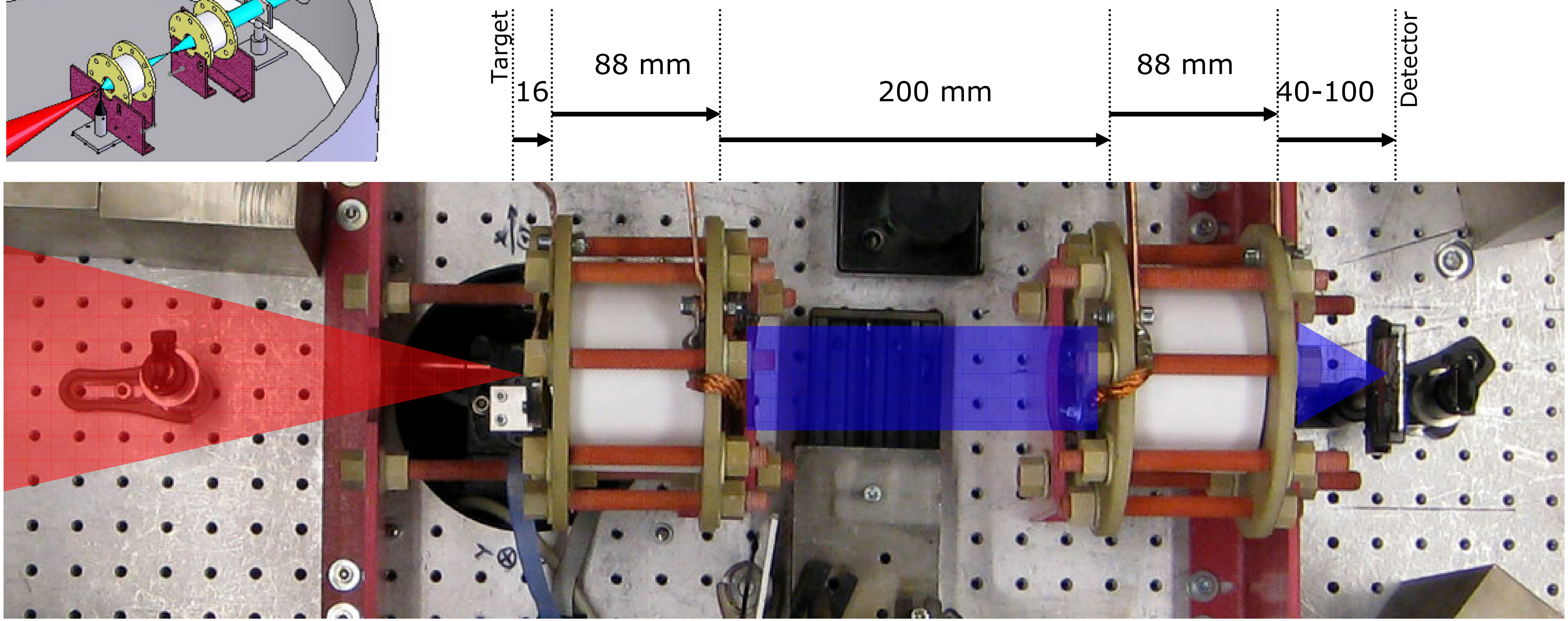
Proton beam collimating/focussing at PHELIX



Advantage of combination of two solenoids:

-Energy selection

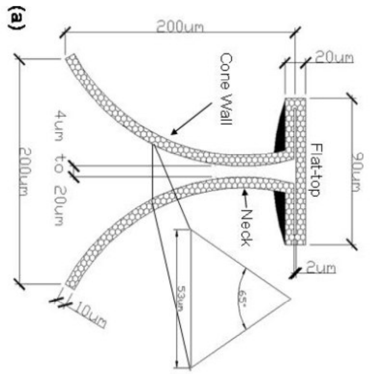
-Transport and focussing

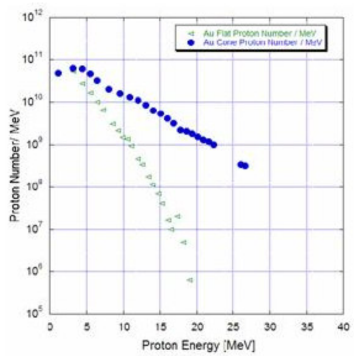


Experiments

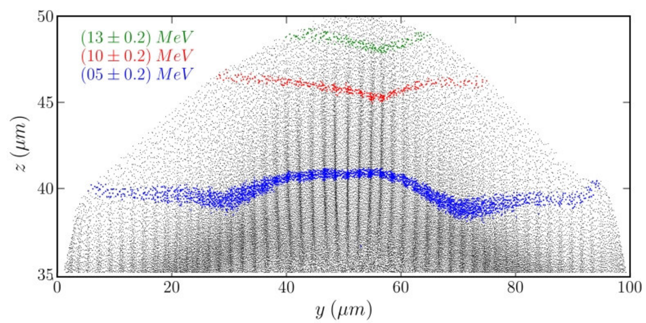
Proton flux increase by special cone target:

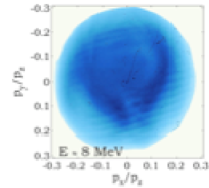
laser

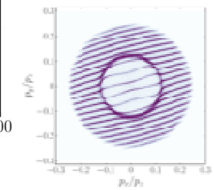




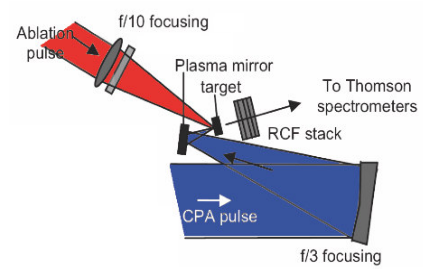
Expansion modeling and PIC-simulations:

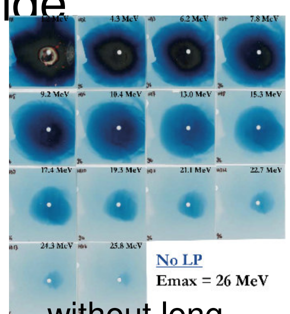




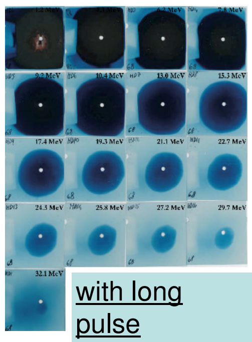


Proton beam profile homogenization by contr. pre-plasma at front side:



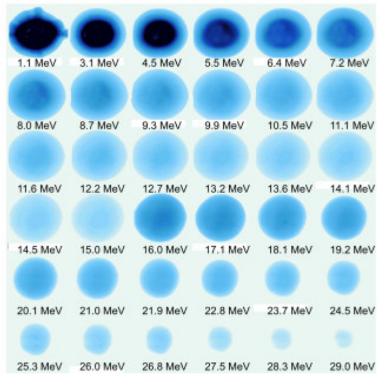


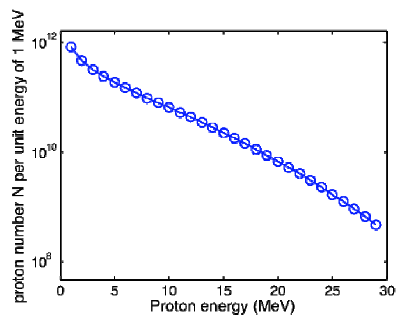
without long pulse
E_{max} = 26 MeV



with long pulse
E_{max} = 32 MeV

First proton-acceleration at PHELIX:





LAP for Therapy: Issues and Options

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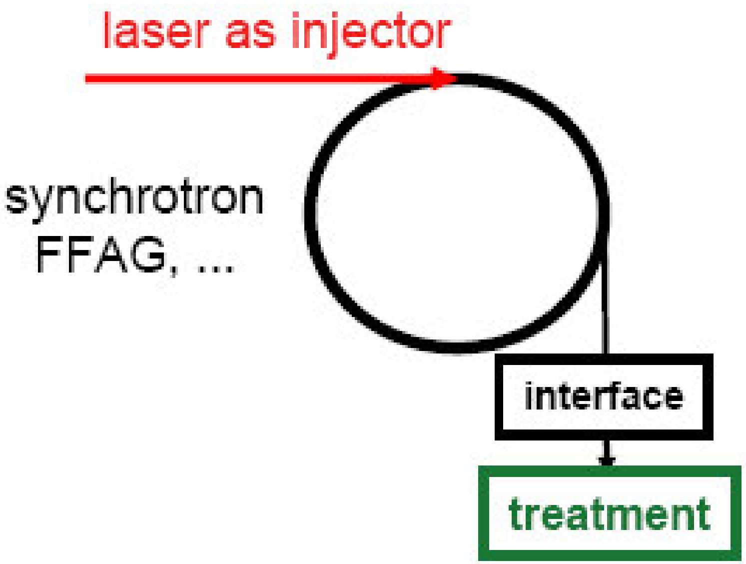
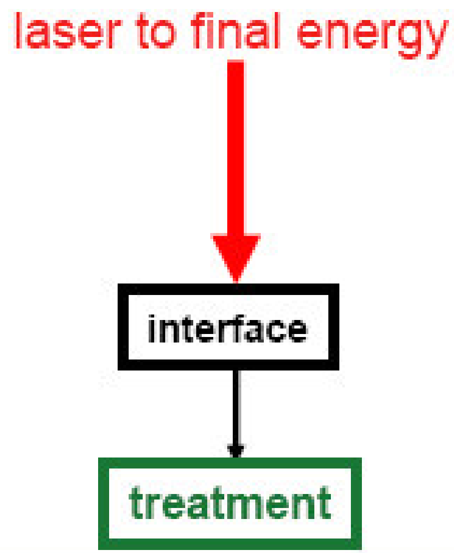
A. Laser acceleration replacing "injector linac" + conventional postaccelerator (circular)





B. Full laser acceleration
→ p to 250 MeV or C to 350 MeV/u
→ transferred to patient

HIT / General Requirements

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▪ **ions**	**:**	**p**	**$^{3}He^{2+}$**	**$^{12}C^{6}$**	**$^{16}O^{8+}$**
▪ **energies (MeV/u)**	**:**	**48**	**72**	**88**	**102**
(255 steps)		**-220**	**-330**	**-430**	**-430**

- **beam spot size : 4 - 10 mm (2d-gaussian)**

  (4 steps)

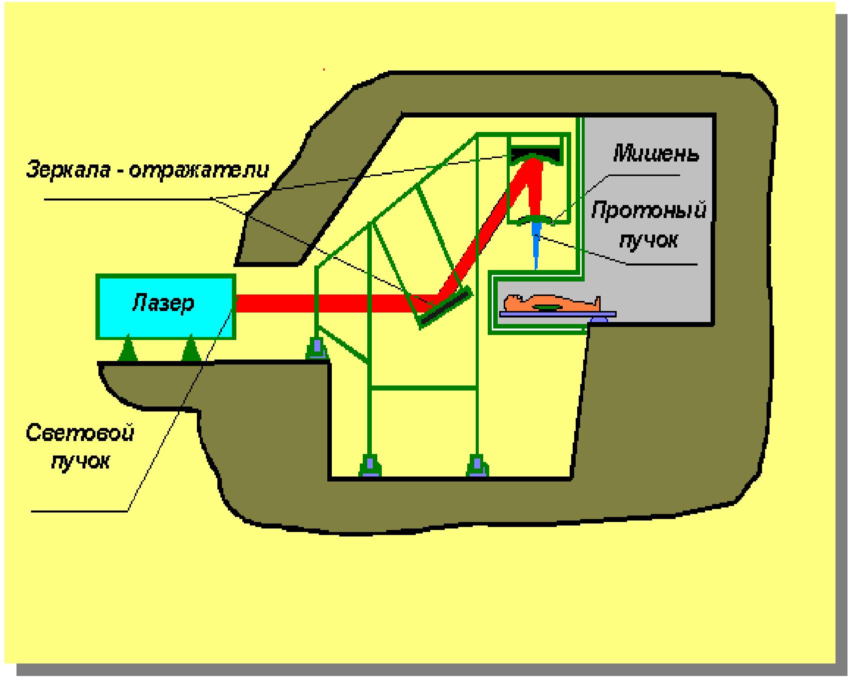
- **treatment caves : 3 (2 horizontal, 1 iso-centric gantry)**

- **QA and research : 1 (1 horizontal)**

Russia: courtesy of Prof. S. Bulanov

PRESENT-DAY SYSTEM

SUGGESTION



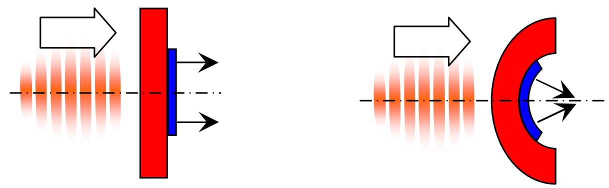
General scheme of the GANTRY:

1. bending magnets;
2. quadrupole lenses;
3. couch (positioner);
4. dose delivery and monitoring system;
5. procedure room;
6. concrete shielding.

Magneto-optic system must be precisely manufactured and capable of being rotated as a whole (~100 tons !).

GANTRY IS NOT REQUIRED

DOUBLE-LAYER TARGET



S. Bulanov,V.Khoroshkov, PPHR 5/2002

Planned Experiments at GSI

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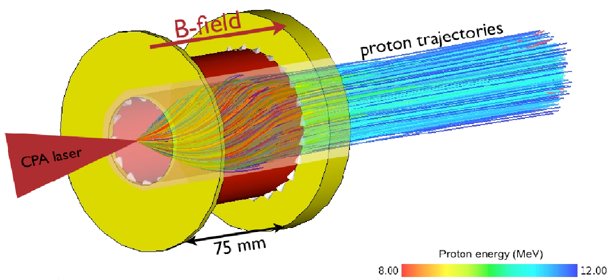
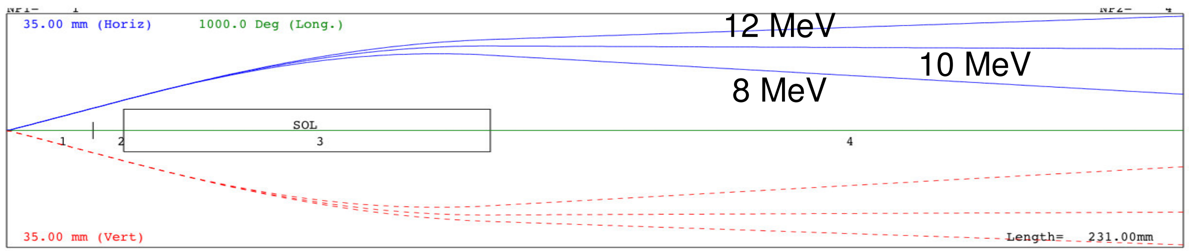
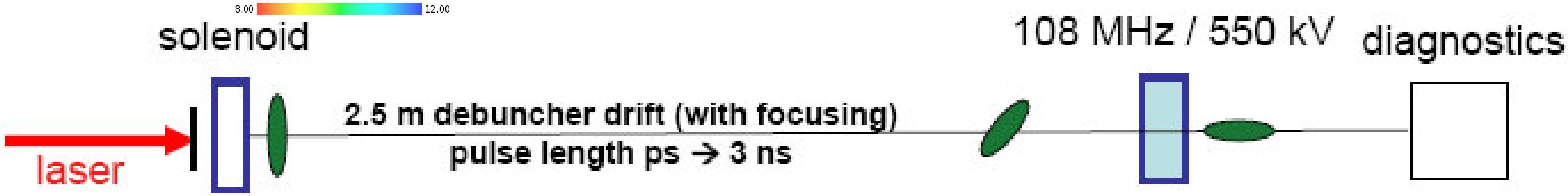






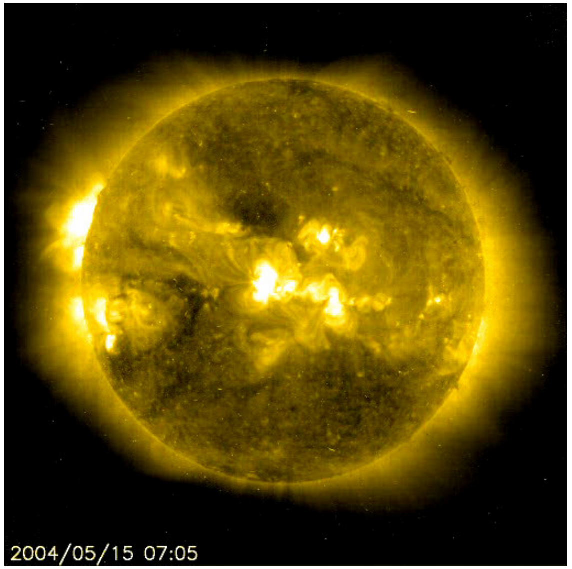
vary distance
- helps to lower B-field
study B-field screening
study electron dynamics

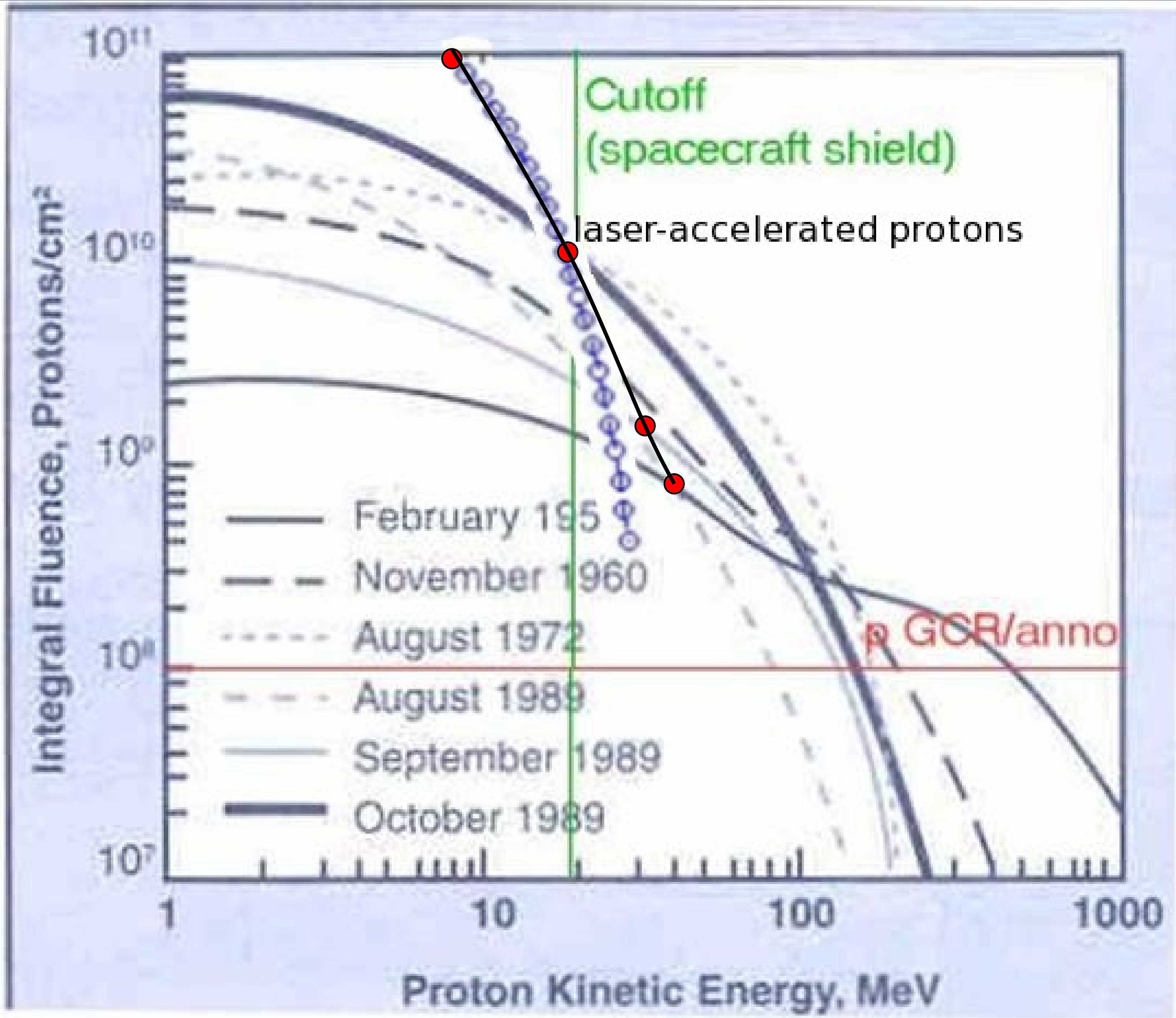
RF bucket capture

6D phase space density + transmission

<u>Partners:</u>
GSI
TU Darmstadt (M. Roth project leader)
Helmholtz Center Jena
U Frankfurt IAP → 352 MHz CH post accelerator option)

Solar particle events

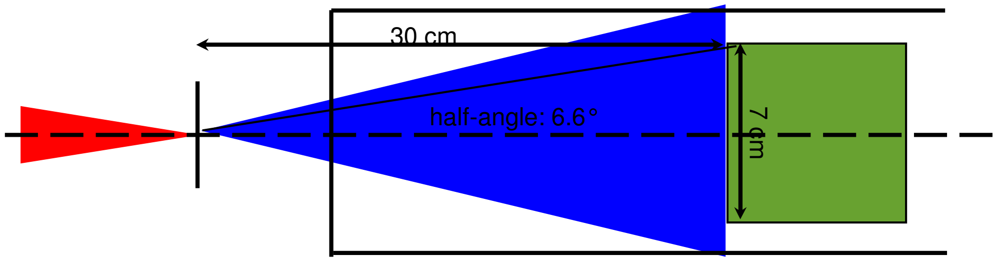




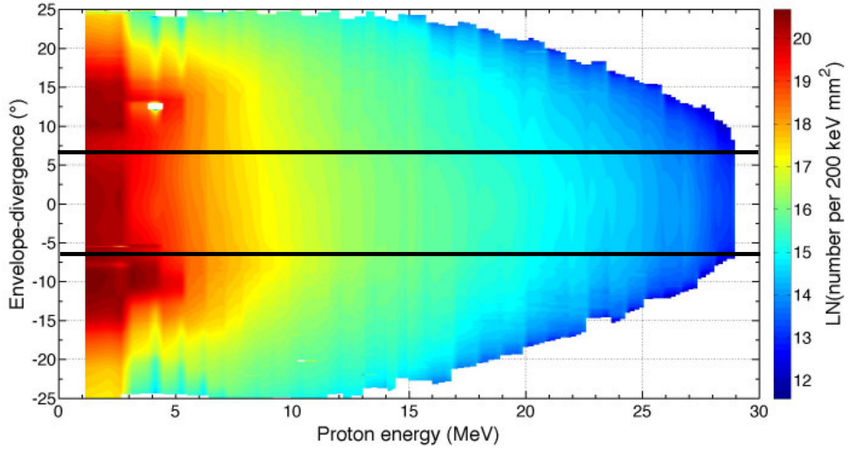
Experiments

Cell irradiation experiment

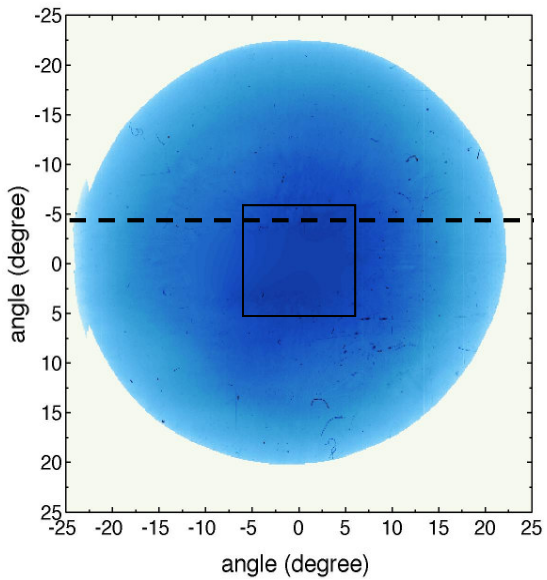
- target set-up:



- beam smoothness: 5% mean deviation



- 15 MeV protons:



5% inhomogeneity

particle number estimation (13 MeV):

2×10^{10} protons

half-angle divergence: 23 degree

distance of sample - target: 5-25 cm

beam radius: 2.1-25 cm

particles per square-micron: 0.5-14

NAIS
Nuclear Activation Imaging Spectroscopy

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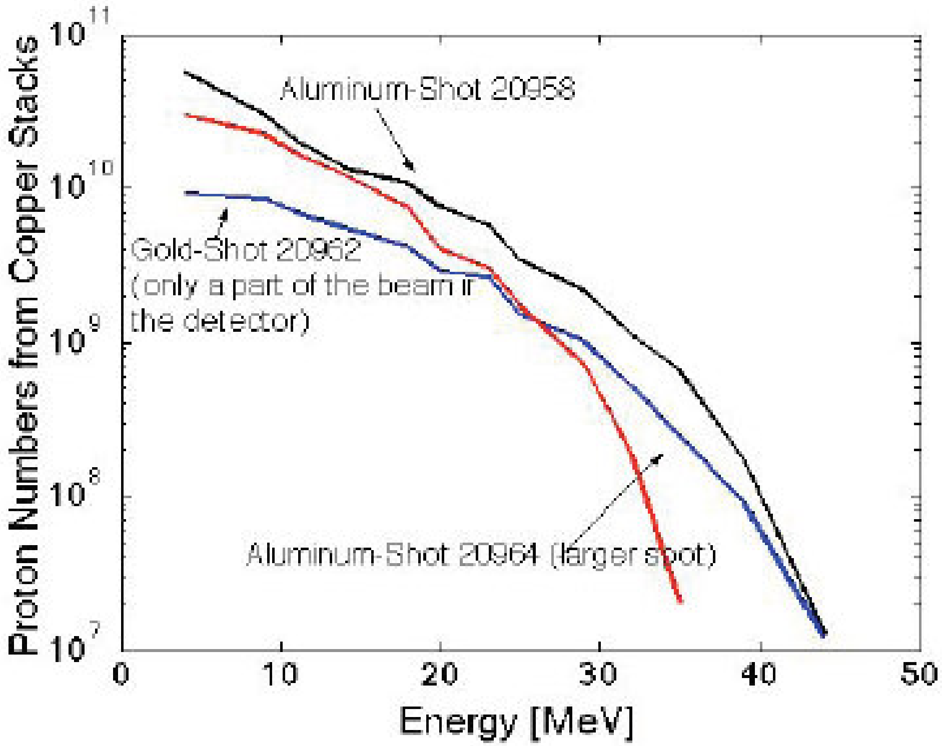
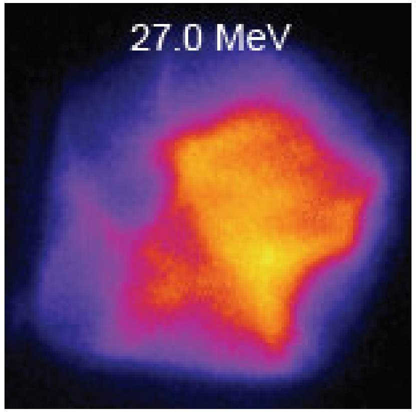
Nuclear activation of copper: $^{63}Cu + p \rightarrow {}^{63}Zn^{*} + n$

radioactive half time for $^{63}Zn^{*}$: 38 minutes

coincidence measurement:



autoradiography:



Los Alamos NATIONAL LABORATORY | TRIDENT Los Alamos | Sandia National Laboratories | ZBeamlet

Proton focusing using Hemispherical Targets

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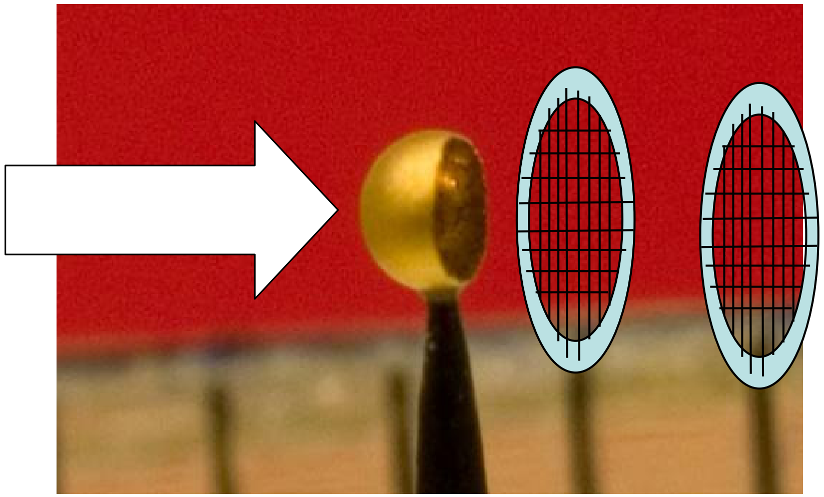
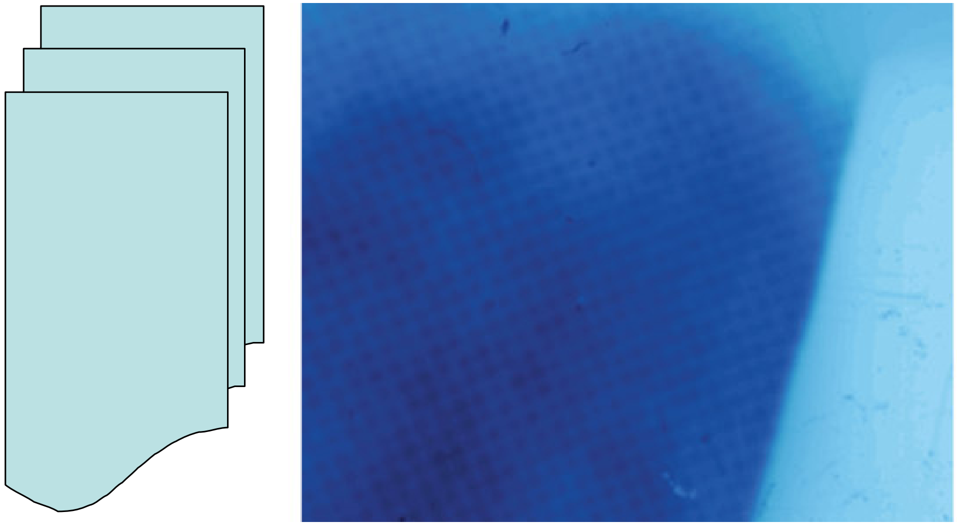
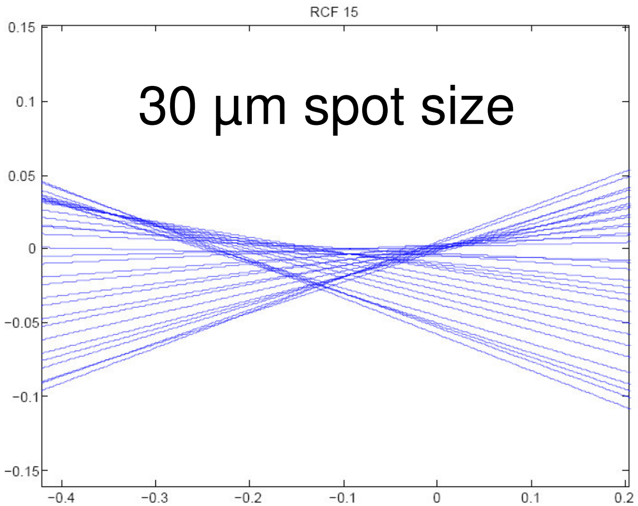
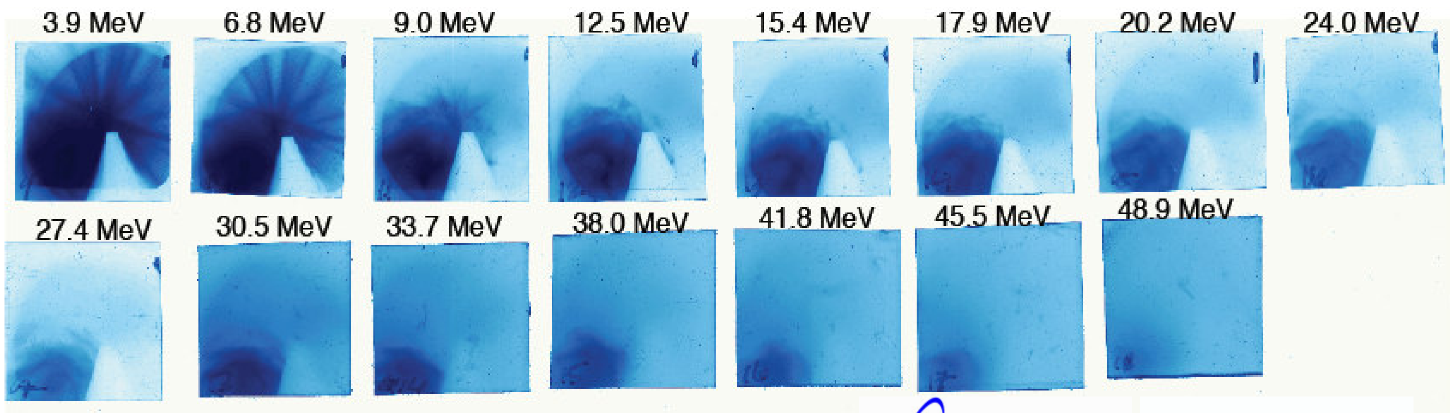




Hemisphere target - diameter: 750 μm





50 µm spot instead of 10 µm → 4% of Intensity on target

→ 55 MeV instead of 40 MeV

Los Alamos NATIONAL LABORATORY

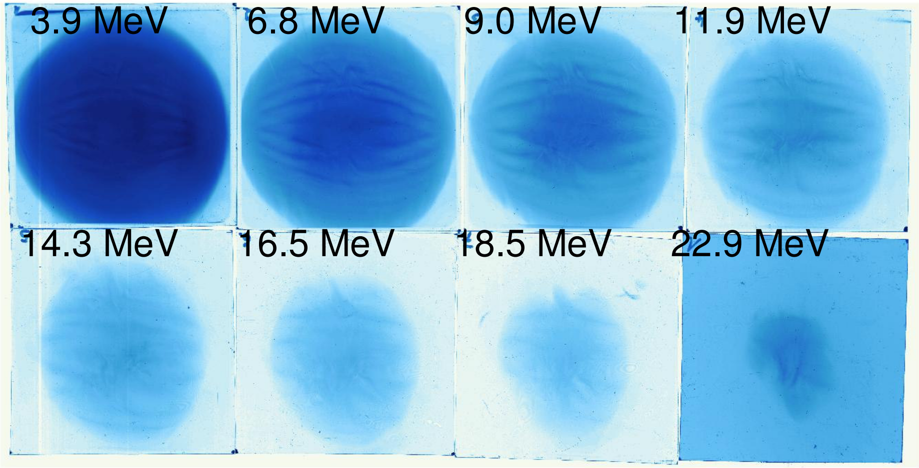
TRIDENT Los Alamos

Sandia National Laboratories

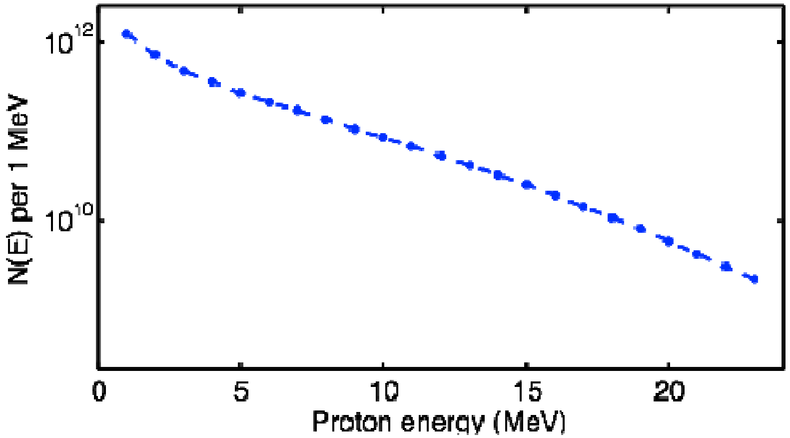
ZBeamlet

shot 5: 10µm flat foil / 96 J / defocus by 180µm

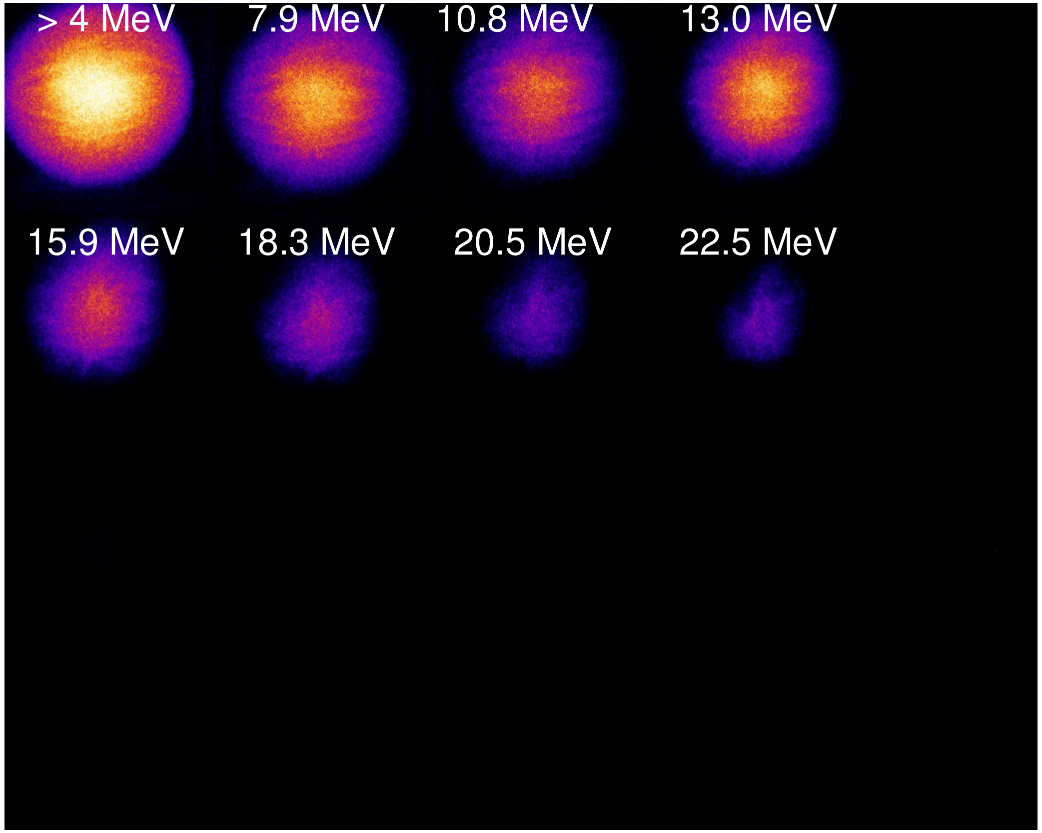
RCF



fit with $dN/dE=N_0/E^*\exp(-(E^2/T^2_{hot}))$, weighted with energy deposition
N_0 = 1.80e+12
kT = −12.44 MeV
Conversion efficiency (> 4 MeV): 2.46

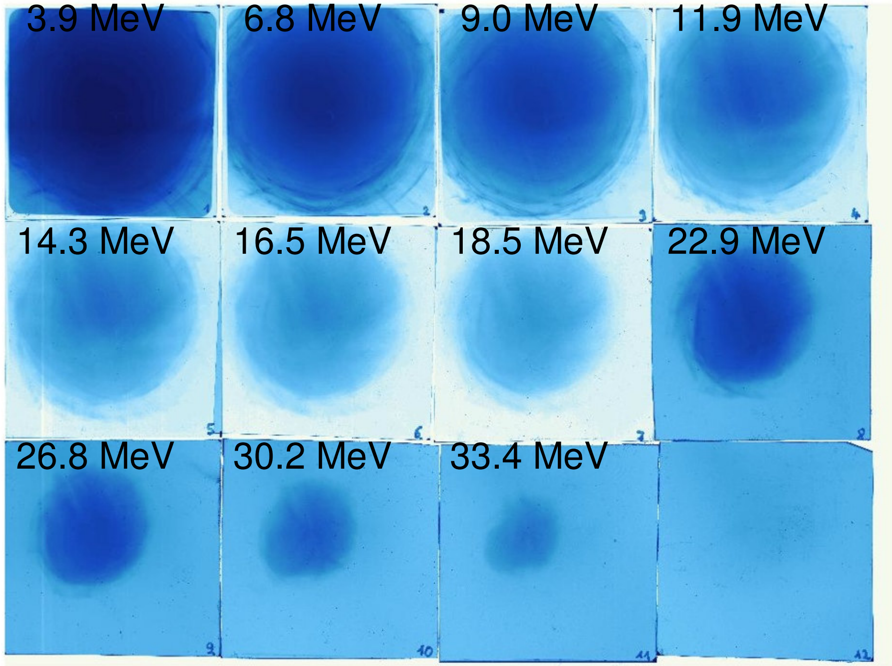


Copper autoradiography

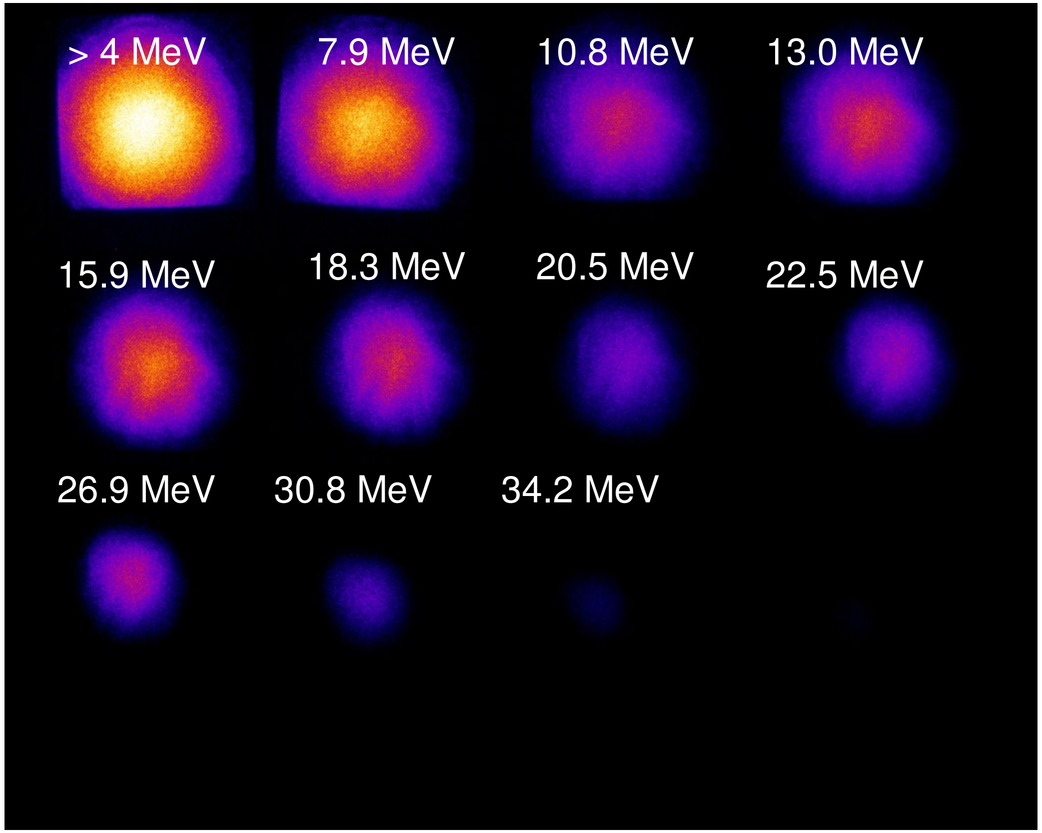


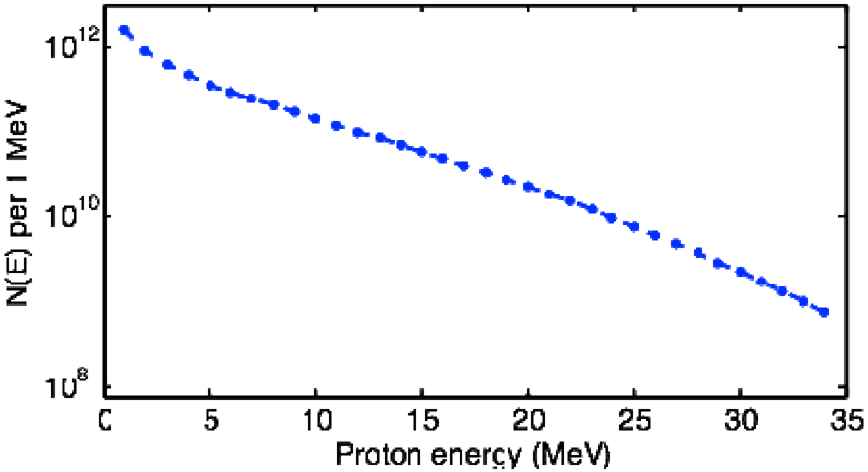
shot 3: Hemi / 116 J / defocus by 180μm

RCF



Copper autoradiography





fit with $dN/dE=N_0/E^*\exp(-(E^2/T^2_{hot}))$, weighted with energy deposition

$N_0 = 2.23e+12$

kT = 16.38 MeV

Conversion efficiency (> 4 MeV): 3.89

Proton spectra / Maximum proton energy

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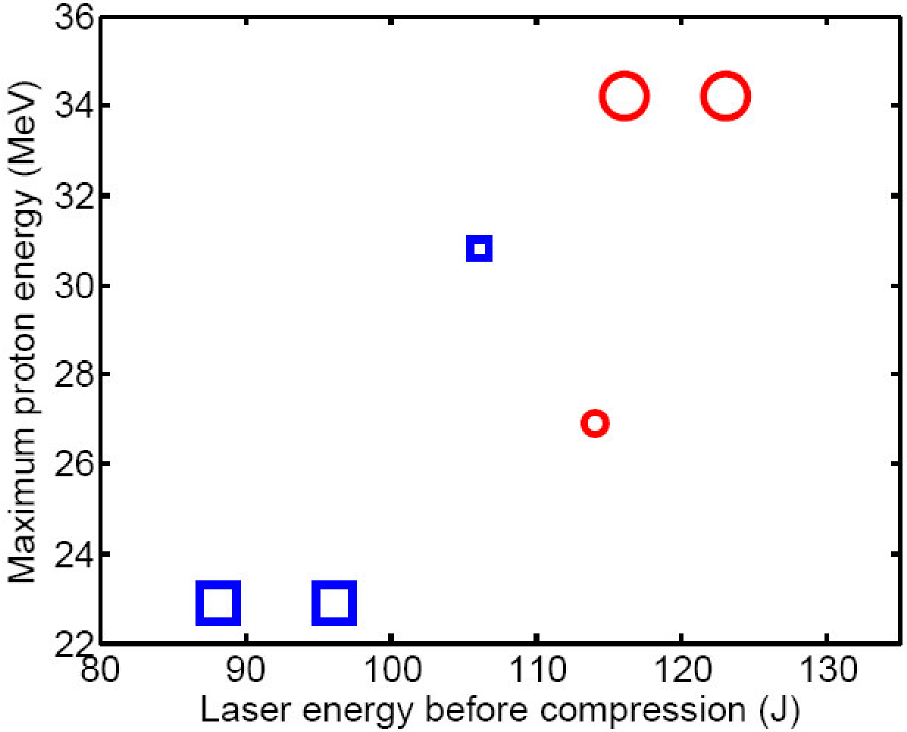

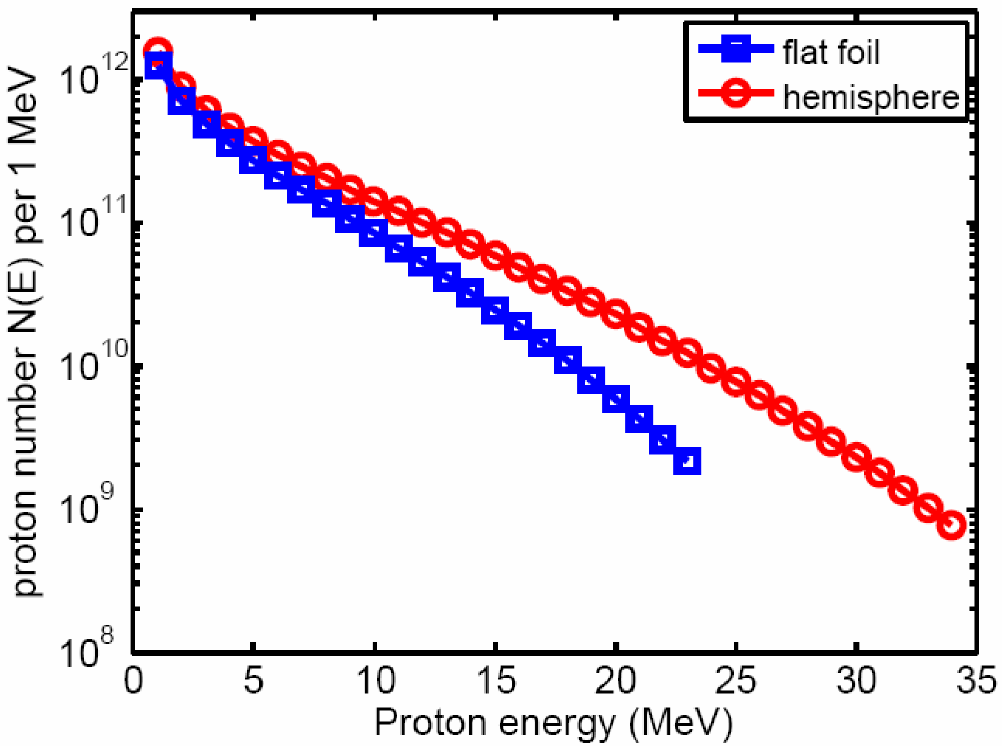

□ - flat foil

○ - hemisphere

GSI PHELIX

Prospects

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- At an energy level of a few tens of Joules high-rep rate, DPSSL‘s are supposed to be available in a few Jears (Mercury, JAERI, POLARIS, LOA)
- „monochromatic“ ion beams have been observed for the first time
- Excellent beam emittance would allow for smaller apertures, higher gradients, smaller accelerators (PET Production, tumor therapy)
- the driving laser system could also be used for e-beam generation, PET-isotope production and coherent x-ray diagnostics at the same time

Vision for a UHI Laser in Medicine

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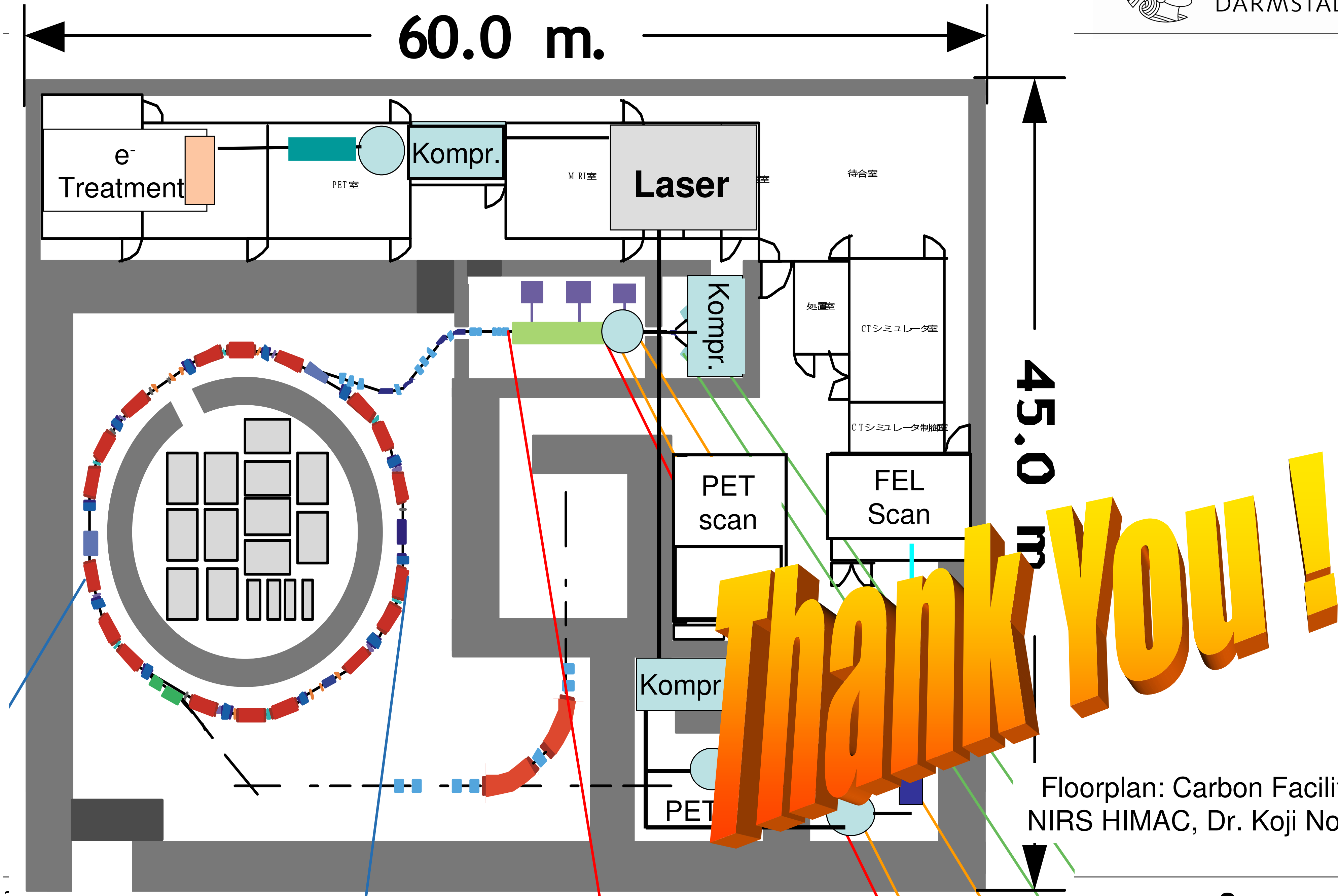

Floorplan: Carbon Facility NIRS HIMAC, Dr. Koji Noda