Ion Acceleration: TNSA and beyond

Lecture 3

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The Queen's University of Belfast

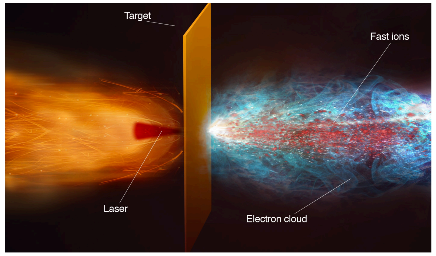
Advanced Summer School on laser-driven sources of high energy particles and radiation
Anacapri, 10-16 July 2017

A-SAIL
ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

Breakdown of lectures

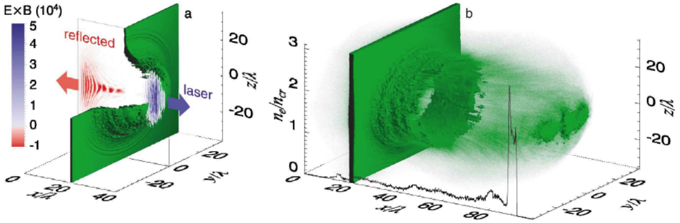
- Lecture 1 : **Sheath acceleration processes**

  (Tue, 9 am , 40 min)



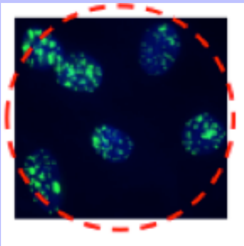
- Lecture 2: **Other mechanisms - new developments**

  (Thu, 3pm, 50 minutes)



- Lecture 3: **Applications**

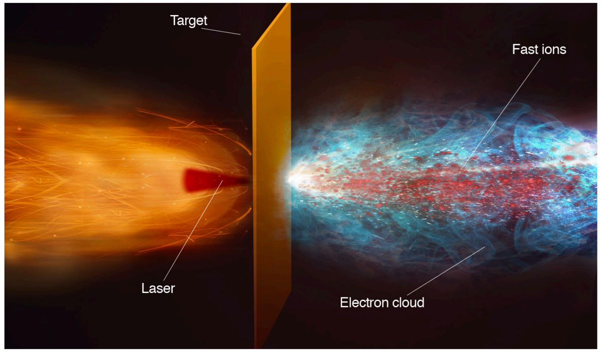
  (Friday, 6.30 pm, 30 minutes)



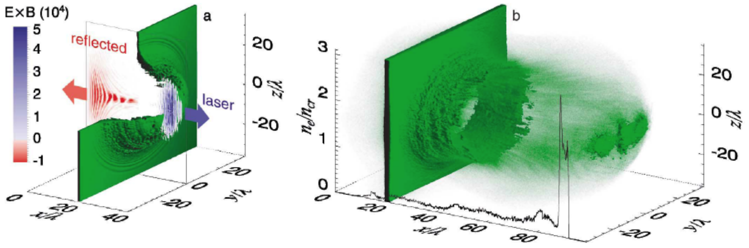
Outline –part 3

- **Applications of Laser-driven ions**

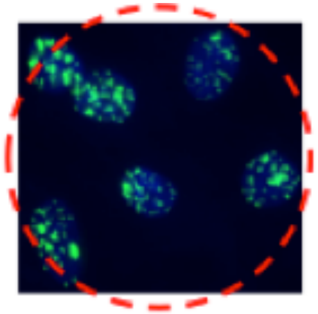
  Advantageous properties of TNSA ions



- **Applications currently implemented**
  - Proton radiography
  - Radiobiology
  - Warm dense matter production
  - Material studies
  - Neutron generation

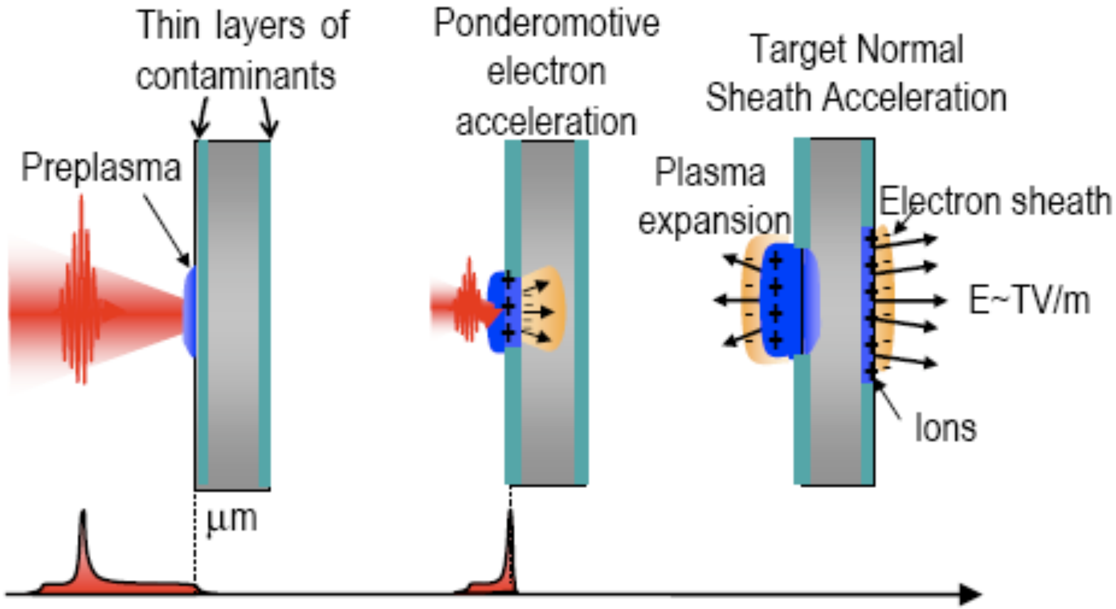


- **Speculative applications**
  - Inertial Fusion Energy (Fast Ignition)
  - Cancer Therapy



Properties of TNSA beams

- **Ultrashort duration**
- **Ultralow emittance**
- **High current : kA range**
- **Ultralarge accelerating fields:**
  - **Divergent (~ 10s degrees)**
  - **Broad spectrum**
  - **Low repetition**



Applications:

- exploiting unique properties of the beams (time duration, divergence, emission quality)
- exploiting compactness of acceleration process to develop new ways to established applications

Applications relying on short burst emission(~ps)

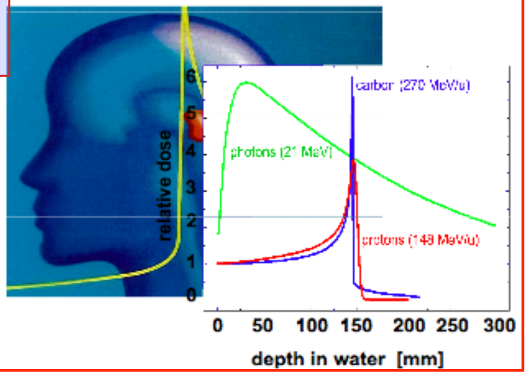
- Particle probing
  - Pump-probe experiments with laser pump, *ion probe*
  - Ultrafast dynamics associated to relativistic electrons

- Ion irradiation:
  - living cells (high dose rate irradiation)
  - Solids : high flux: plasma creation, *warm dense matter*
    - low flux: low track density, *transient damage*

Prospective applications of laser-driven ion acceleration

- Radiography/ deflectometry
- Radiobiology
- Isochoric heating of matter
- Neutron production
- Material studies (Irradiation)
- Cancer therapy
- Production of isotopes for PET
- Fusion Energy (Fast Ignition)
- Particle physics applications

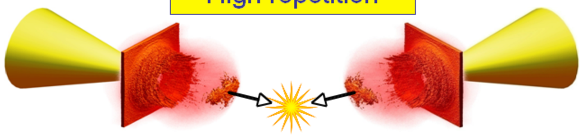
Applications already active with current beams



150-250 MeV protons
Carbon ions at 2-4 GeV

Typical dose fraction: 2-5 Gy
1 Gy ~ 10^{10} p+, ~10^9 C

Very high energy
> GeV (or >>GeV)
High repetition



Mini Black Holes,
Quark-gluon Plasmas

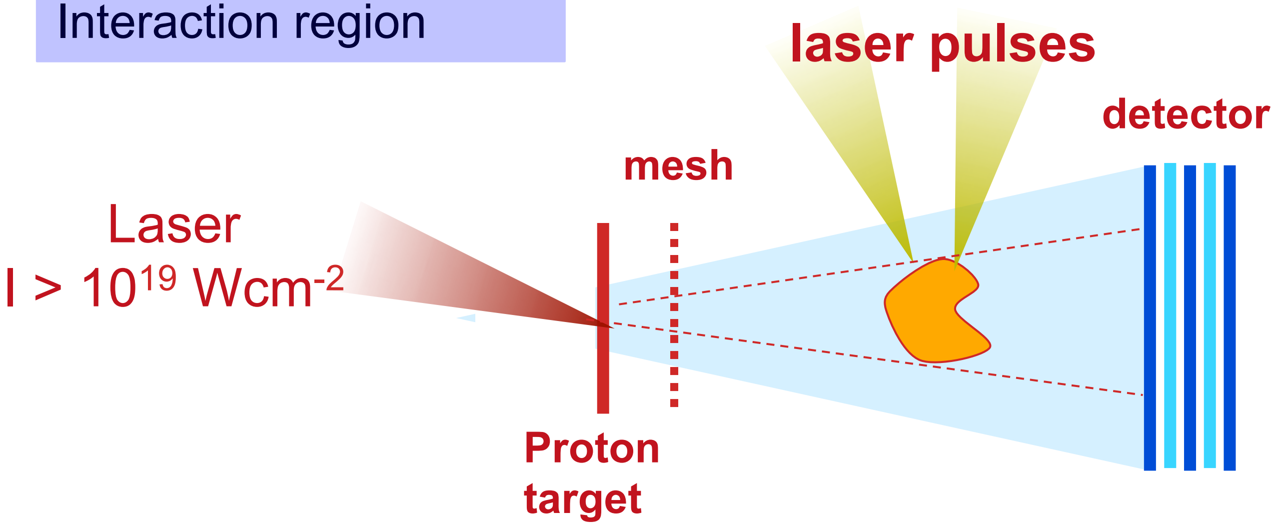
Energies >GeV (high repetition)

Proton radiography/deflectometry

Proton deflections provide a map of electric and magnetic fields in the Interaction region

Interaction: from fs to ns pulses, intensities from 10^{15} to 10^{19} Wcm^{-2}

2-D magnified projection of 3-D objects



Beam divergence

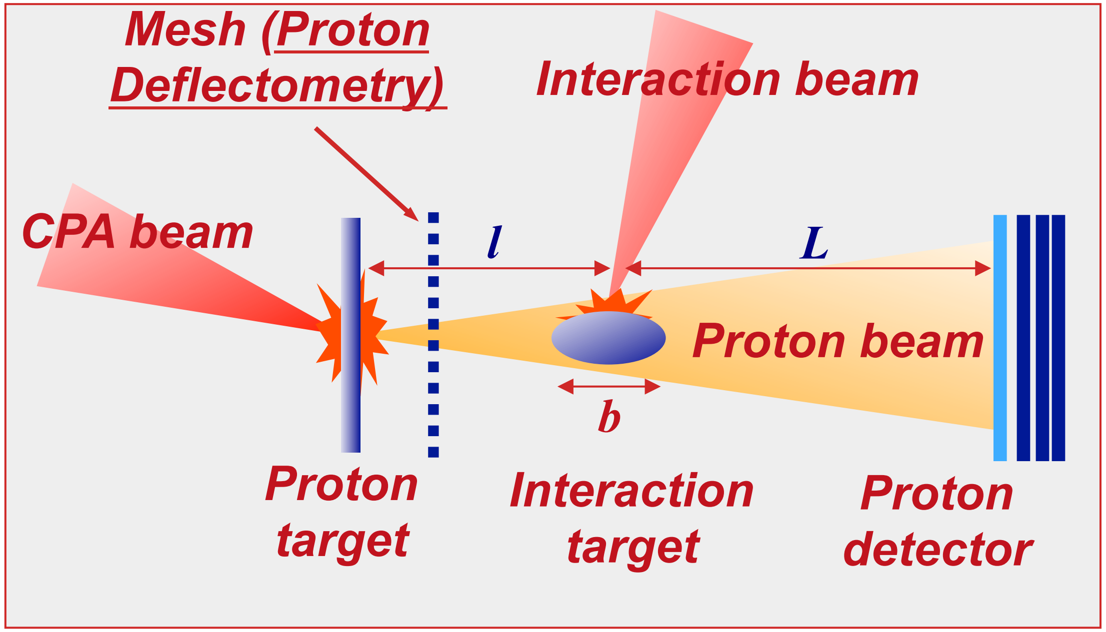
Projection Magnification

~ps temporal resolution
~ µm spatial resolution
Multiframe capability

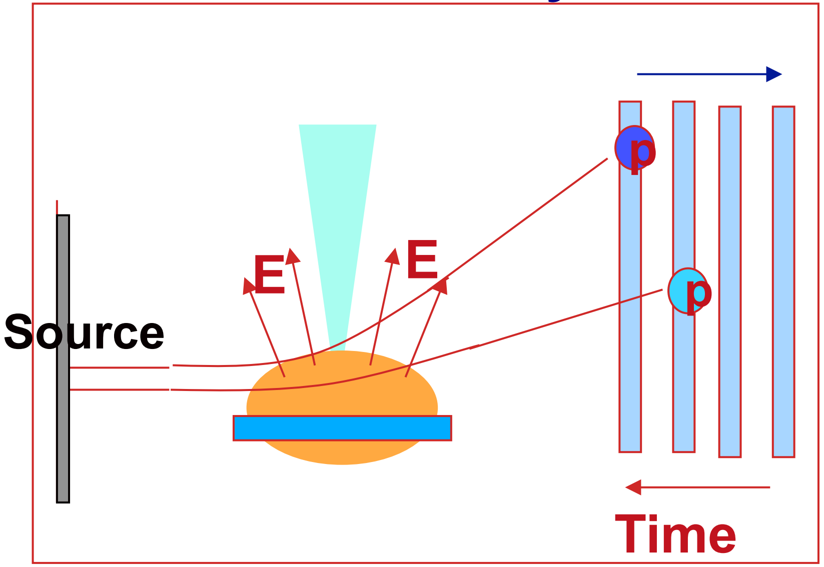
Applied to the investigation of a broad range of phenomena: ultrafast charge dynamics, plasma channelling, e.m. solitons, collisionless shock waves, self-generated magnetic fields…

Proton radiography/deflectometry

Detection of ultrafast field dynamics



Multilayer detector



Spatial resolution ~ μm
Temporal resolution ~ ps

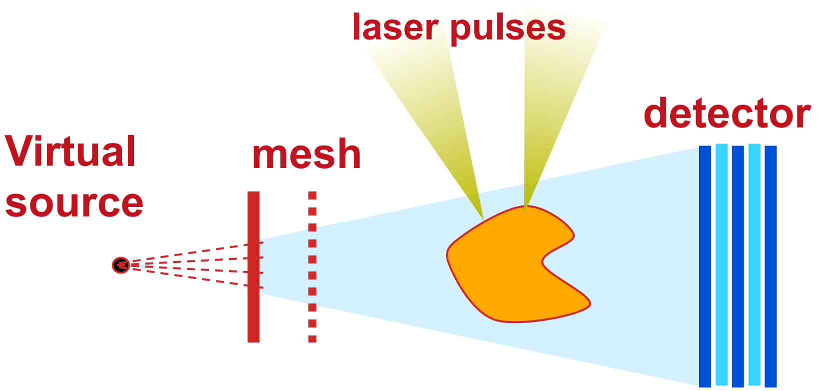
Analysis: match with particle tracing

Bragg peak deposition
Broad proton spectrum
Short burst at source
Time of flight dispersion

Multiframe detection

Layer n ➡ $t_0(E_n)$

Proton probing: spatial and temporal resolution



Spatial resolution ~ µm:

- Virtual source size (~ µm)
- Proton scattering in the sample
- Detector spatial resolution

Temporal resolution ~ ps:

- Short proton burst duration
- Detector spectral resolution
- Proton time of flight through the sample

Broad spectral content +
Time of flight arrangement +
Detector energy selection properties

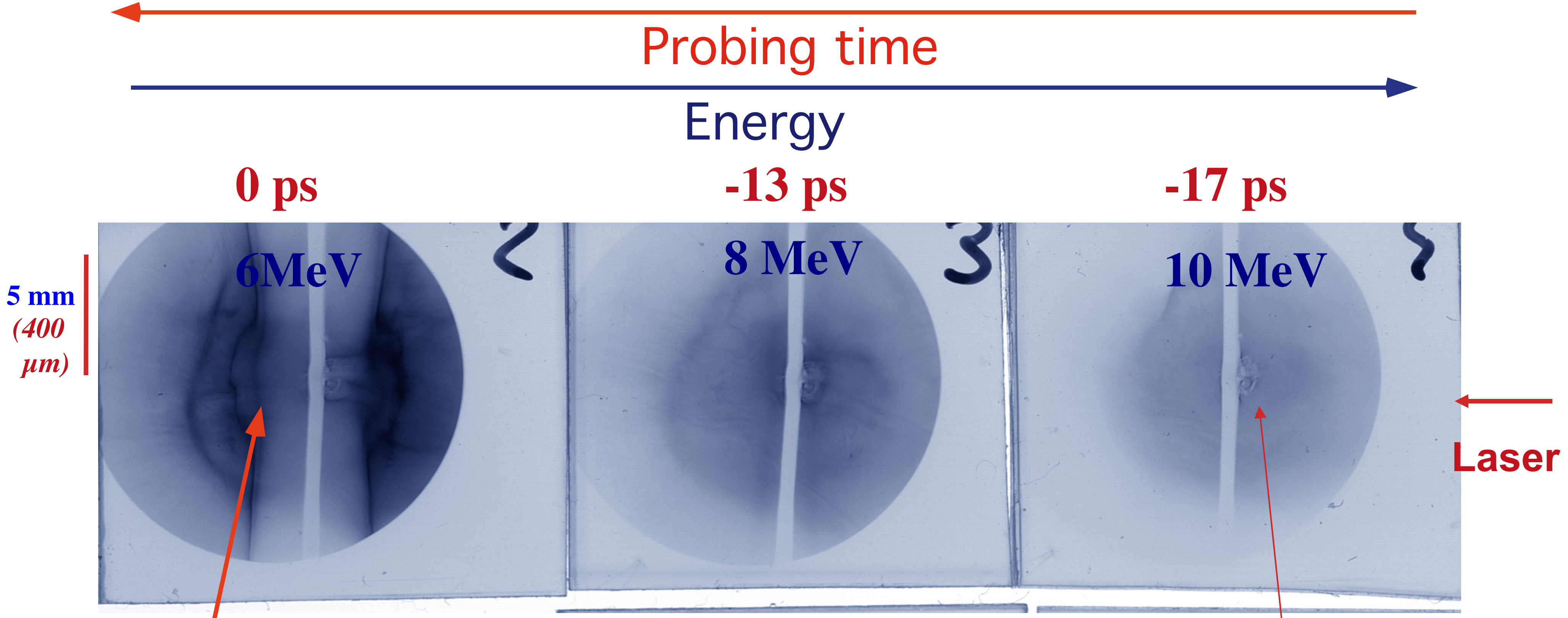
→

Temporal multi-frame in a single laser shot

Ultrafast charge dynamics in ps interaction

M.Borghesi et al, APL, **82**, 1529 (2003)

50 μm Ta wire irradiated with 1 ps, ~10^{19} W/cm^2 pulse



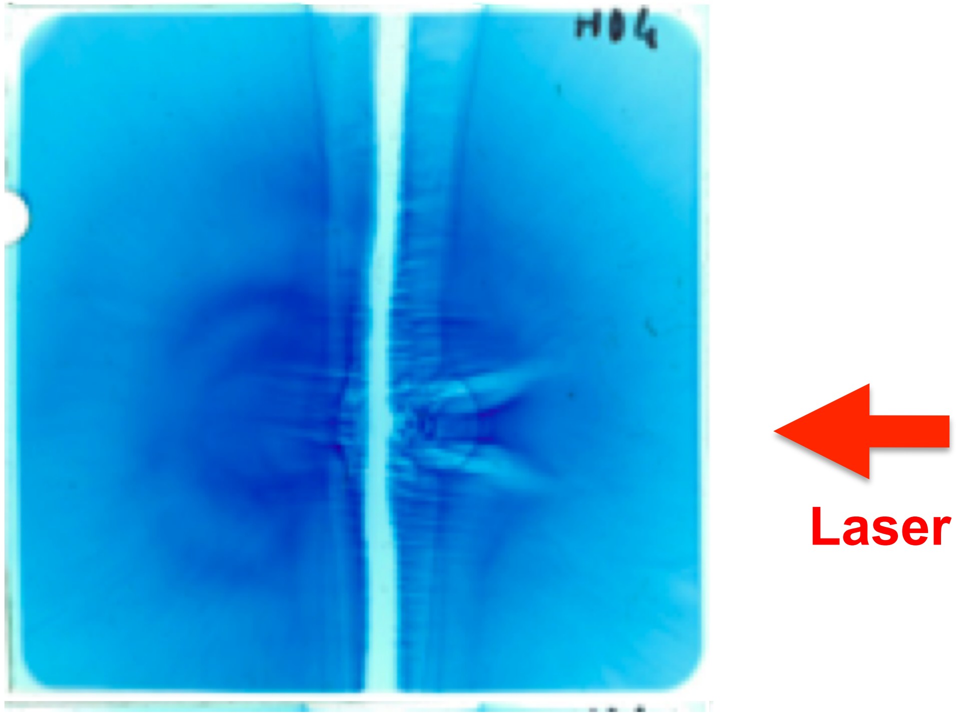
Ion deflection caused by positive electric charging of the target

Preplasma effect

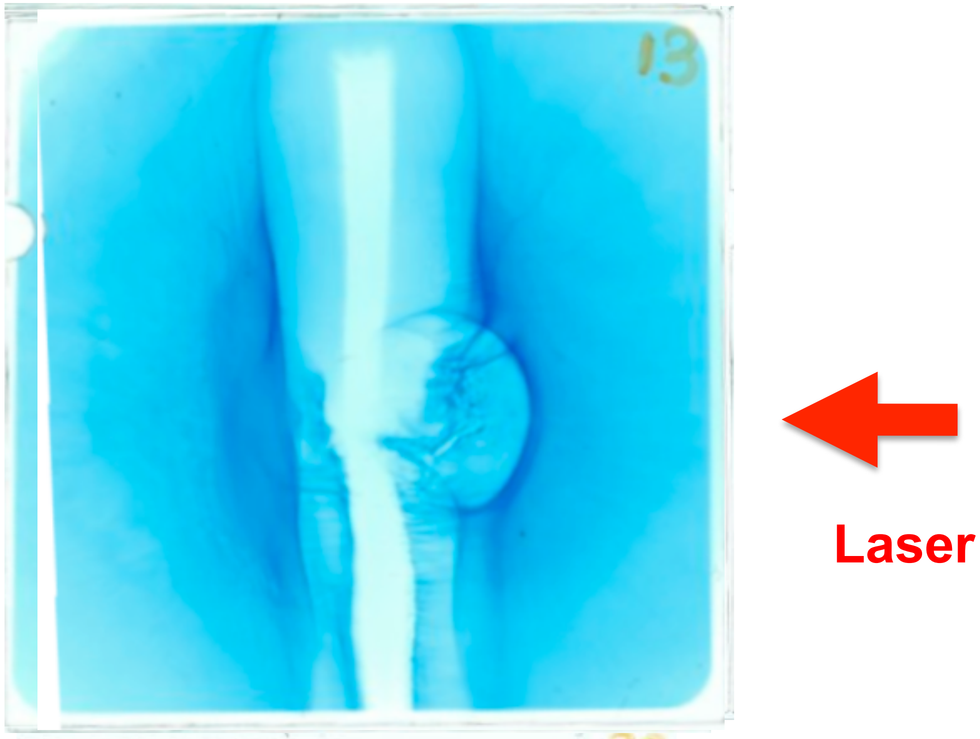
Due to the expulsion of fast electrons the target begins to charge as the interaction pulse approaches peak intensity (Discharges in tens of ps driving large current through wire)

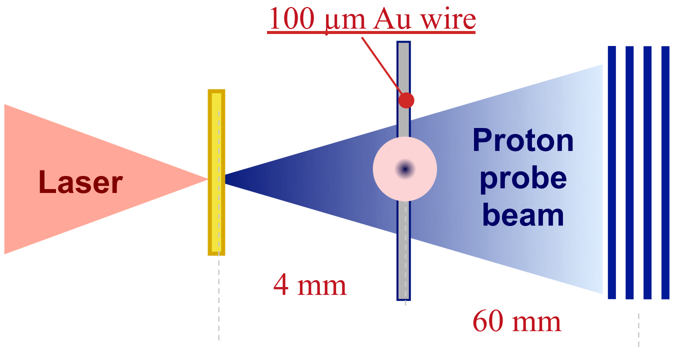
Proton radiography provides multiple snapshots with sub-ps resolution

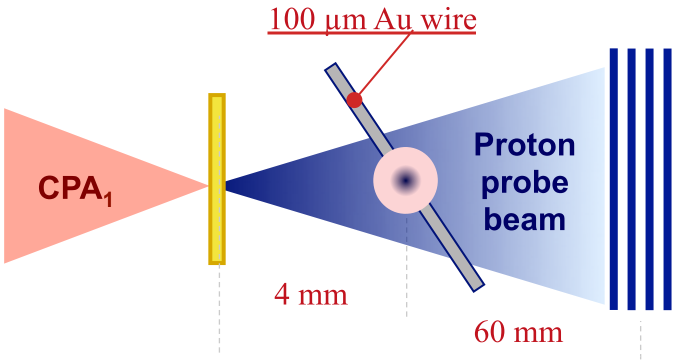
K. Quinn *et al.*, PRL **108**, 135001 (2012)



K. Quinn *et al.*, PRL **102**, 194801 (2009)





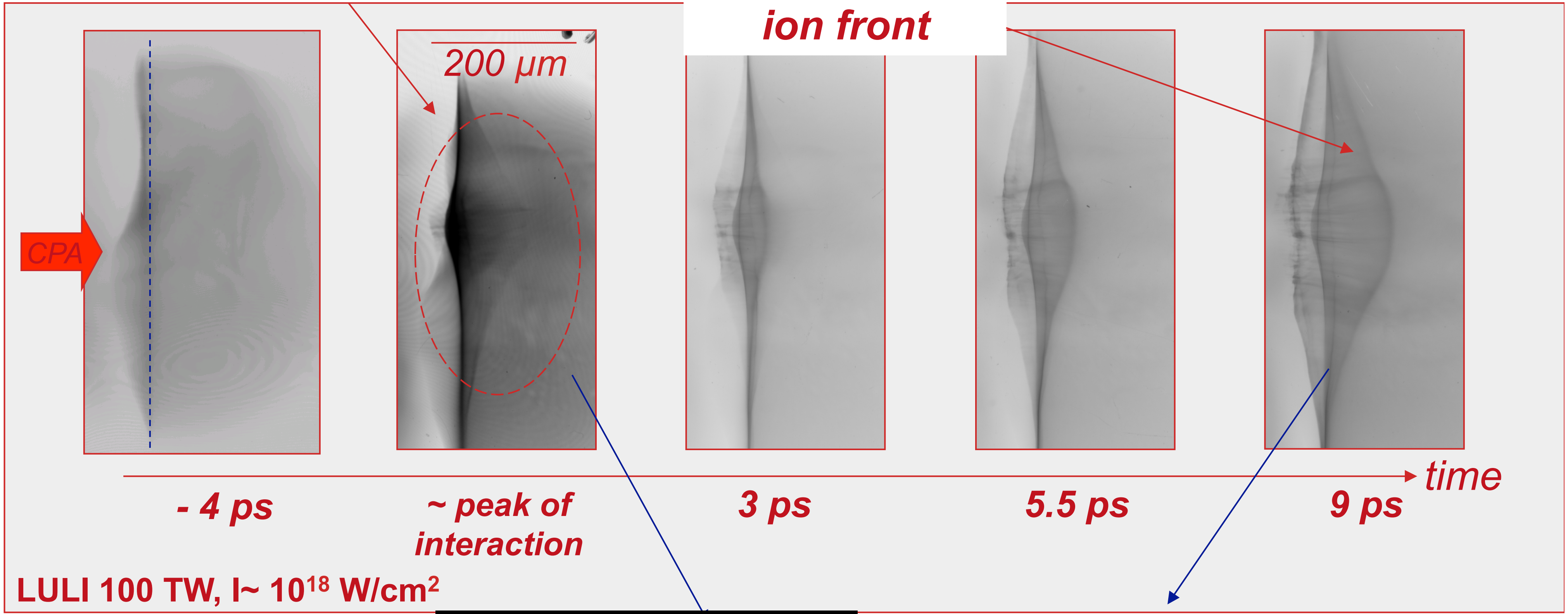


Technique has been employed to visualize the TNSA process

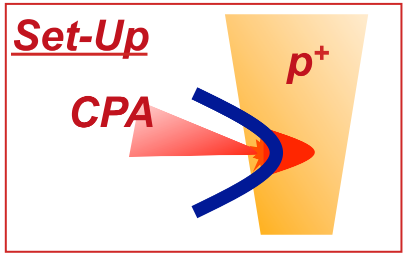
L.Romagnani et al,
Phys Rev Lett,
95,195001(2005)

Short-lived (~ps) deflection at peak of interaction

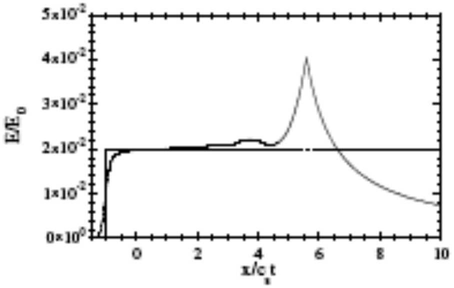
Expansion of bell-shaped ion front



LULI 100 TW, I~ 10^{18} W/cm^2



Initial large(10^{11} V/m) E field

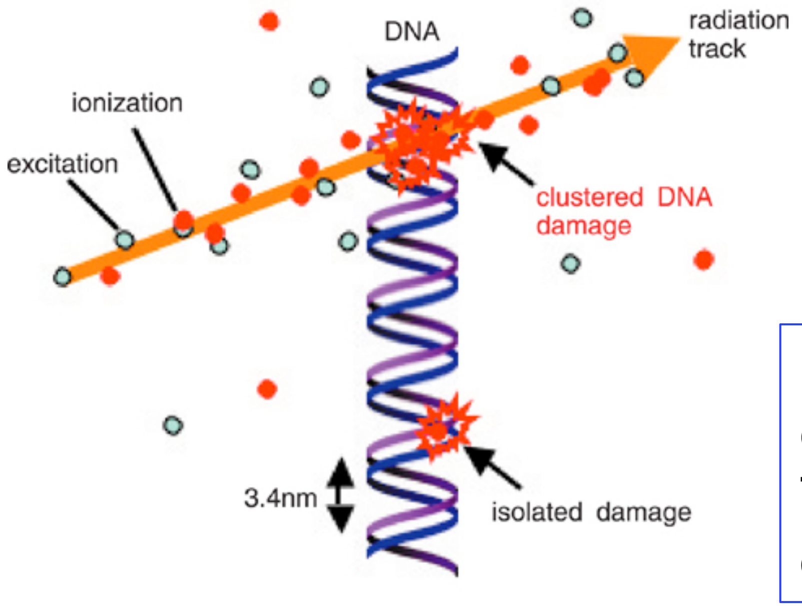


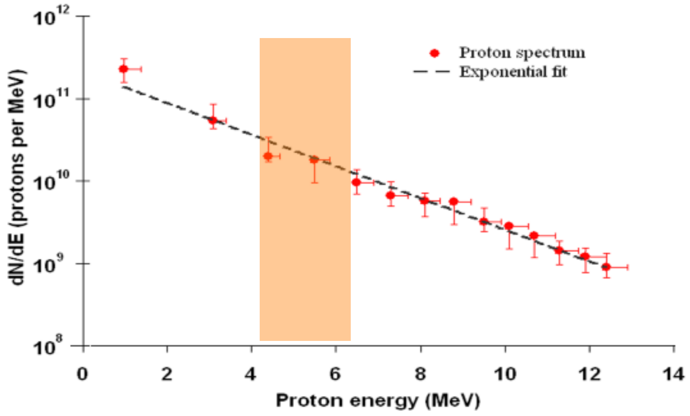
E field at Ion front

(Mora,PRL03)

Ion radiobiology at ultra-high dose rate

Study of damage inflicted on cells irradiated by protons beams





Laser-driven ions (TNSA) within a range ΔE are emitted at the source within a time ΔT< ps.
Time of flight dispersion @ ~ 10s of cm results in dose deposition in 100s ps - ns pulses

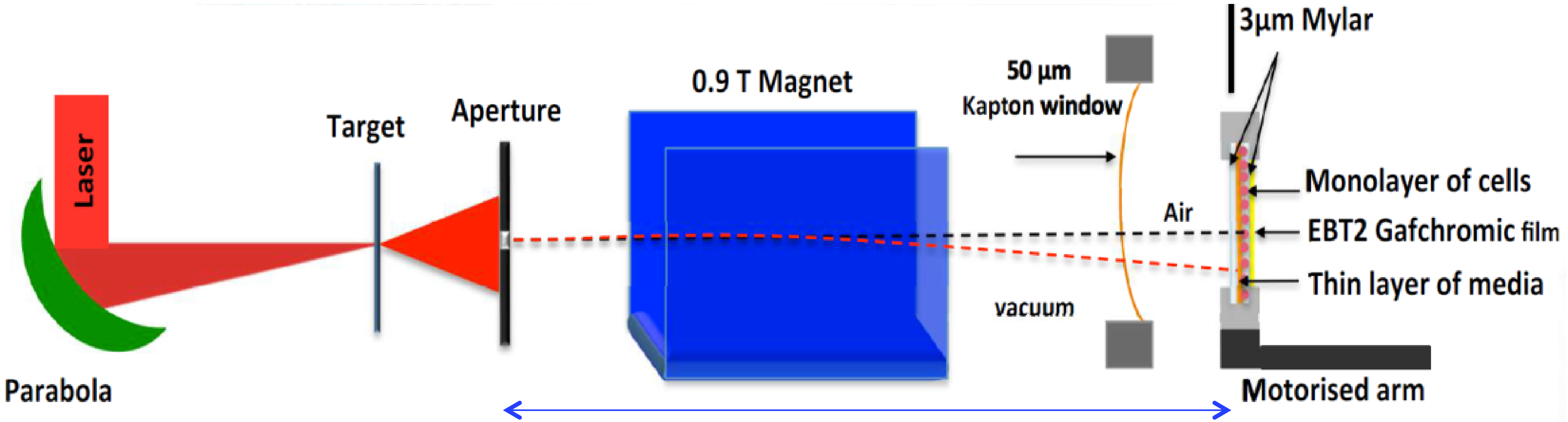
Dose rates > 10^9 Gy/s can be achieved (compare with Gy/min used in radiotherapy or ~30Gy/s deliverable by a continuous beam)

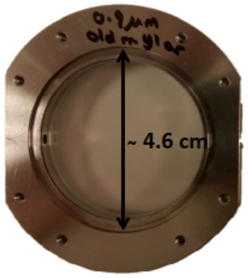
Novel regime of radiobiology - several possible effects discussed in the literature (collective effects, oxygen depletion, decoupling of direct and indirect damage)

Experimental arrangement

F. Hanton, submitted (2017)

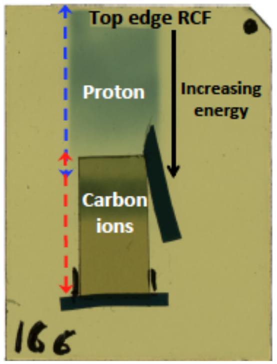
Use of ultrathin (25 nm) C foils at I~ 3 10^{20}W/cm^2 allows simultaneous irradiation with H^+ and C^{6+} at very different LET at ~Gy dose





Human fibroblast cells (AG01522) are irradiated at doses of ~ Gy in pulses < 1 ns (single shot)

Dose rates > 10^9 Gy/s



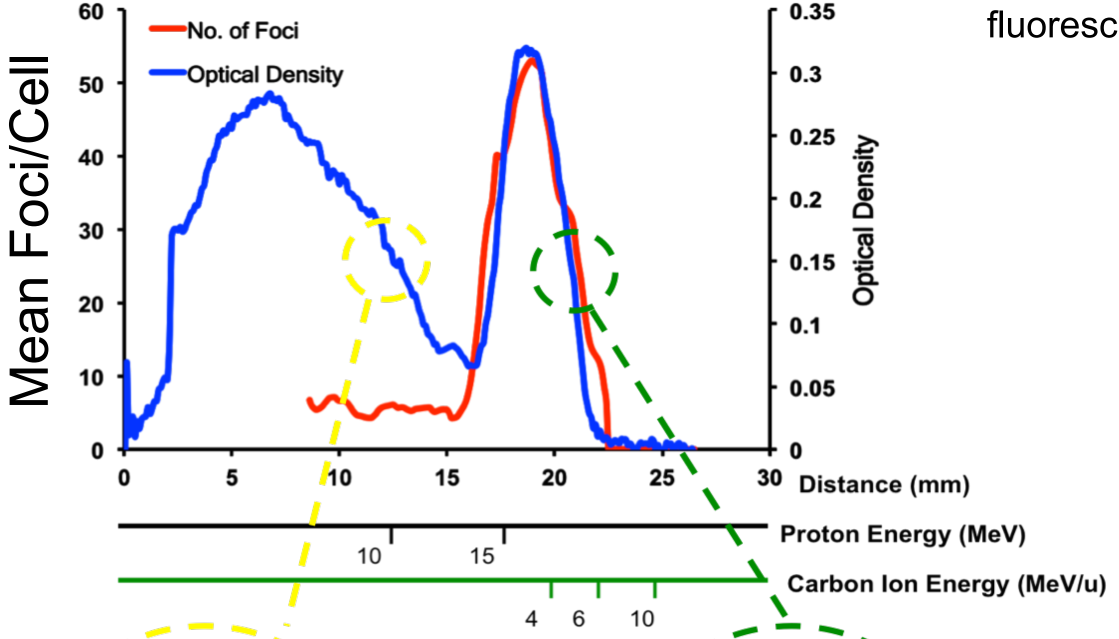
Dynamics of DNA repair following ion irradiation

Cell irradiation → Cell fixing → Cell staining → Counting of foci

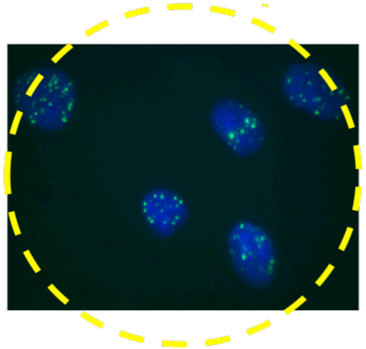
Process involving
an agent which binds to DSBs

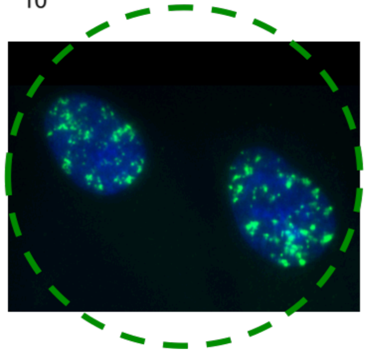
Foci (regions of
accumulation of the agent)
are highlighted , e.g. by
fluorescence

Assay: 53BP1
Immunofluorescence
on Human Fibroblast
cells



10 MeV
Protons
(LET~ 5 KeV/μm)

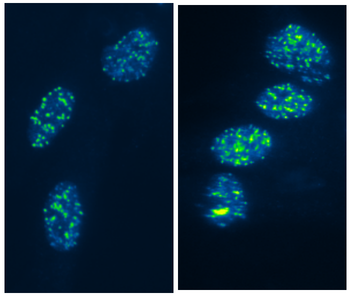




5 Mev/u
Carbon ions
(LET~ 300 KeV/μm

Data indicate more complex, unreparable damage is inflicted by the Carbon ions

F. Hanton et al, submitted (2017)

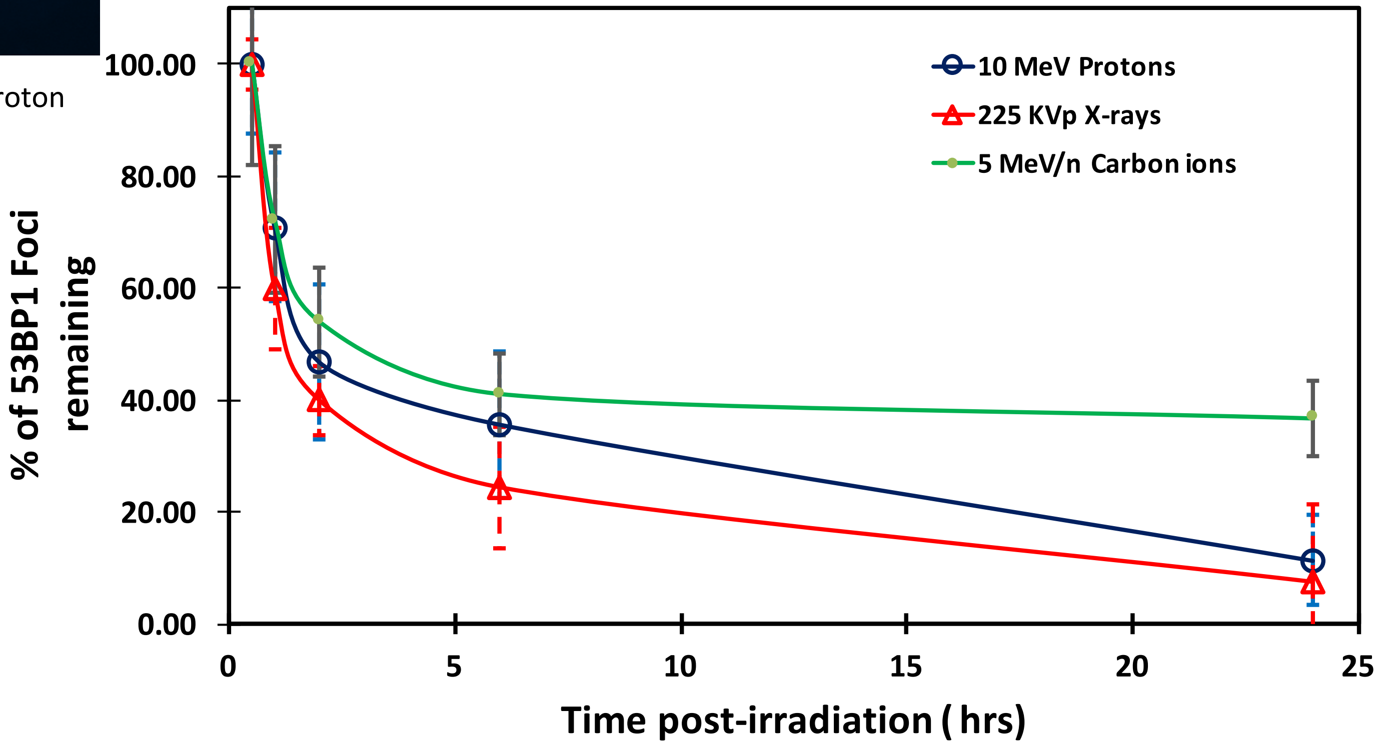


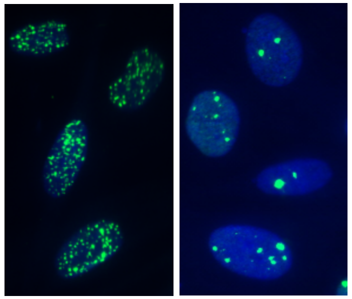
carbon proton

0.5 h

Carbon: LET~ 200 KeV/µm

Protons: LET~ 5 KeV/µm



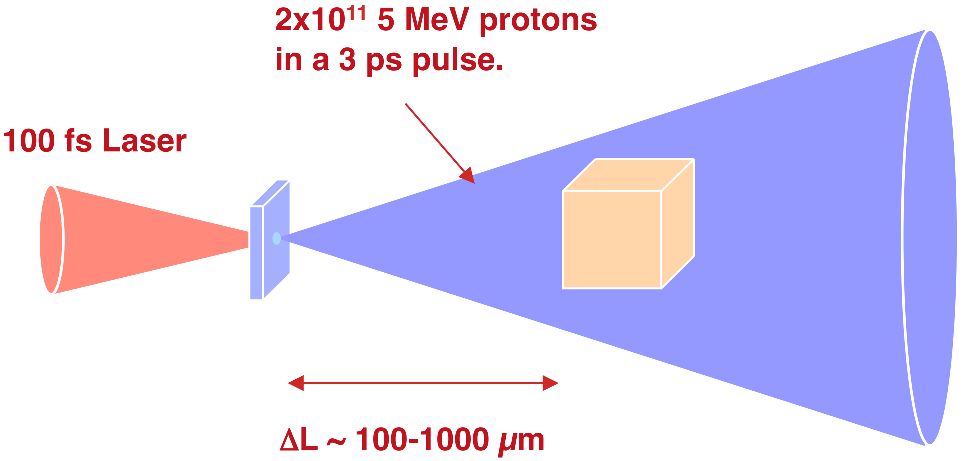


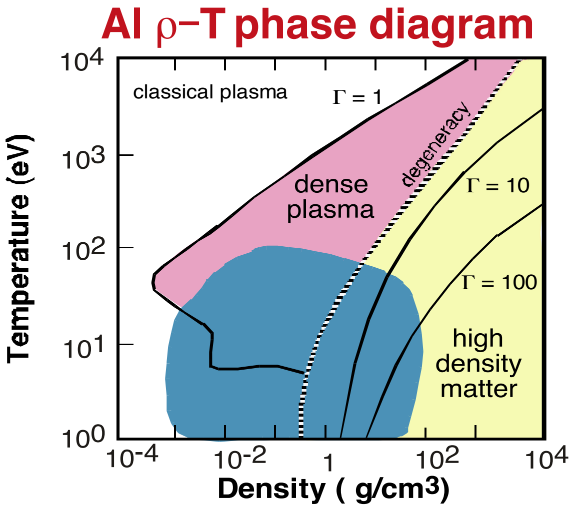
carbon proton

24 h

Typical proton flux sufficient to heat and ionise materials at solid density

P. Patel et al., PRL 91 125004 (2003)





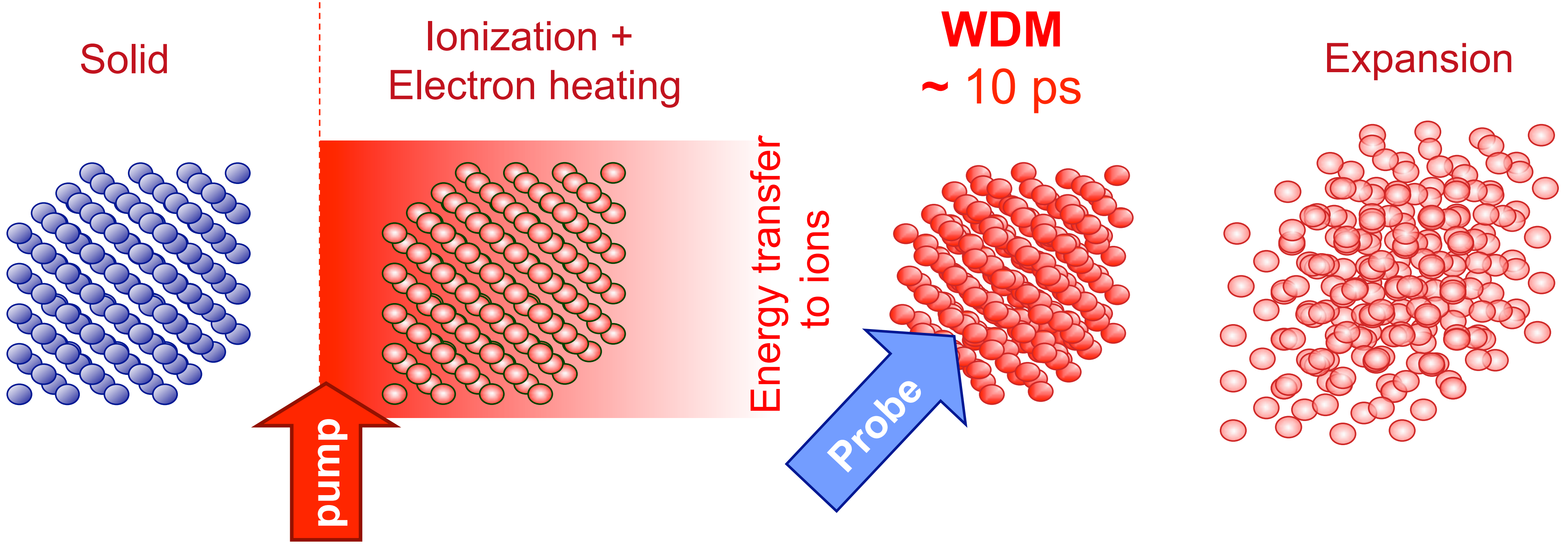
$$\Gamma = \frac{(Ze)^2}{a\, k_B T}$$

Isochoric proton heating may enable us to produce long-lived, uniform, solid density plasmas at several eV (Warm Dense Matter)

Crucial points:

1. Energy deposition is volumetric (uniform heating)
2. Energy deposition takes place in a short time (10s of ps), much shorter than hydrodynamic plasma expansion

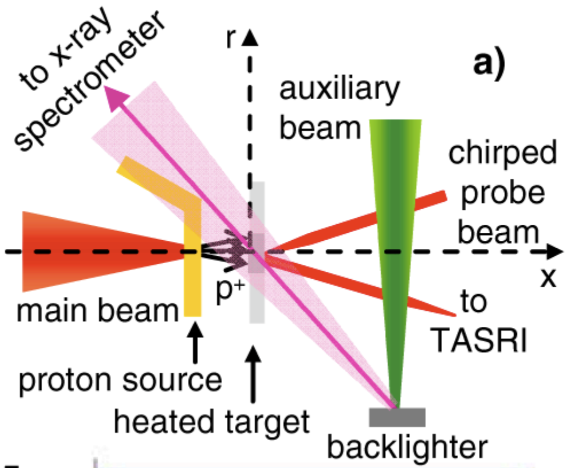
Recent application: ultrafast generation & probing of transient WDM state of matter

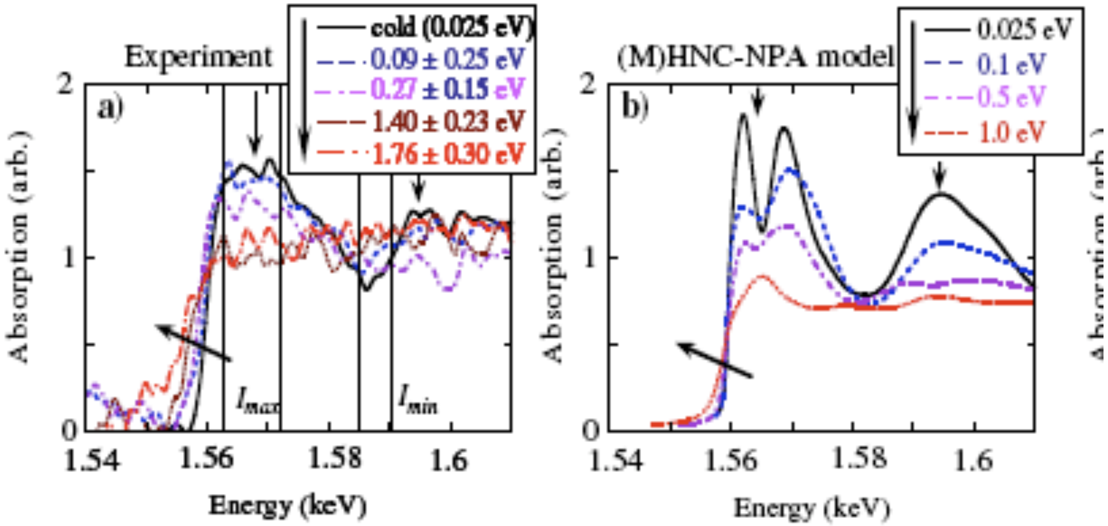


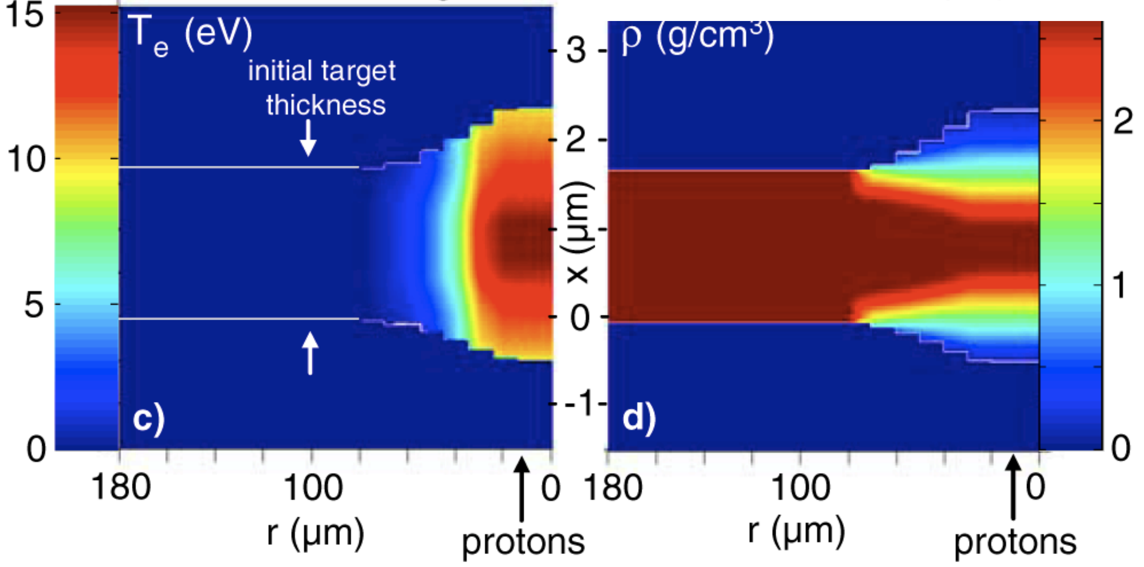
Probing the local atomic structure of the matter and the its temperature

WDM studies – melting of Aluminium/Carbon

A.Mancic et al, Phys. Rev. Lett. 104, 035002 (2010)
A. Pelka et al, Phys. Rev. Lett, 105, 265701 (2011)







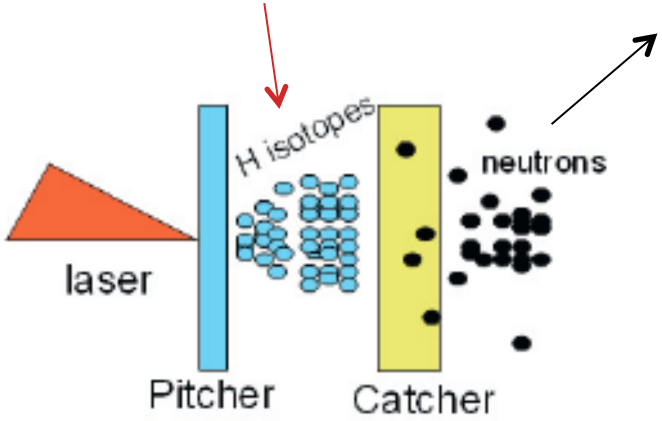
Diagnostic: XANES (x-ray absorption near edge spectroscopy)

Comparison with QMD calculations yield a time of < 10 ps for loss of short range ordering during solid-plasma transition

Neutron production employing laser-driven ions

e.g. S.Kar *et al*, NJP, **18**, 053002 (2016)

Ions



Neutrons

~10s MeV energies

Beamed emission

Short pulse (~ns)

10^9-10^{10} n/shot

Reactions:
$d(d,n)^3He$
$d(p, n+p)^1H$,
$^7Li(p,n)^7Be$,
$^9Be(p,n)^9B$
…..

✓ Cost ✓ Compactness ✓ Radiation confinement

✓ Synchronization with other pump/probe pulse

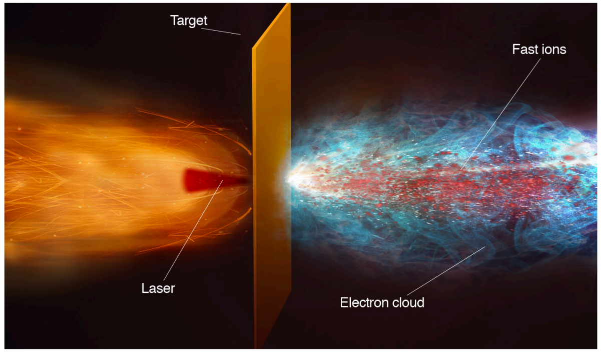
Opportunities ?
Fast neutron radiography (active interrogation)
Material studies (radiation damage)
EOS of matter under extreme conditions
Moderation to epithermal range demonstrated

Cfr ISIS spallation source:
5 10^{14} n/pulse, ~ms duration

Outline –part 3

- **Applications of Laser-driven ions**

  Advantageous properties of TNSA ions



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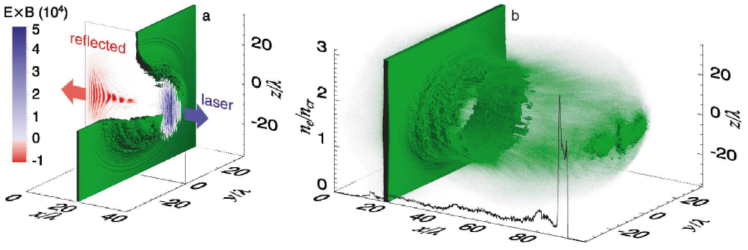
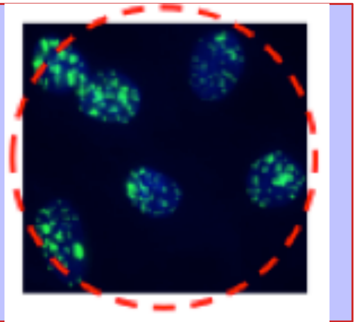
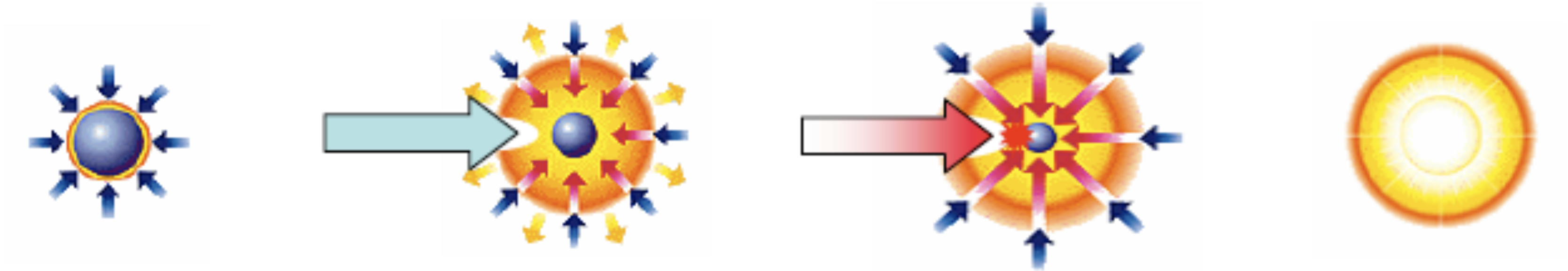


- **Speculative applications**
  - Inertial Fusion Energy (Fast Ignition)
  - Cancer Therapy



Fast Ignitor approach employs particles accelerated by high intensity lasers

Ignite the fuel directly
using e-beam, p-beam or KE from multi-PW laser interaction



Lasers or X-rays symmetrically irradiate pellet

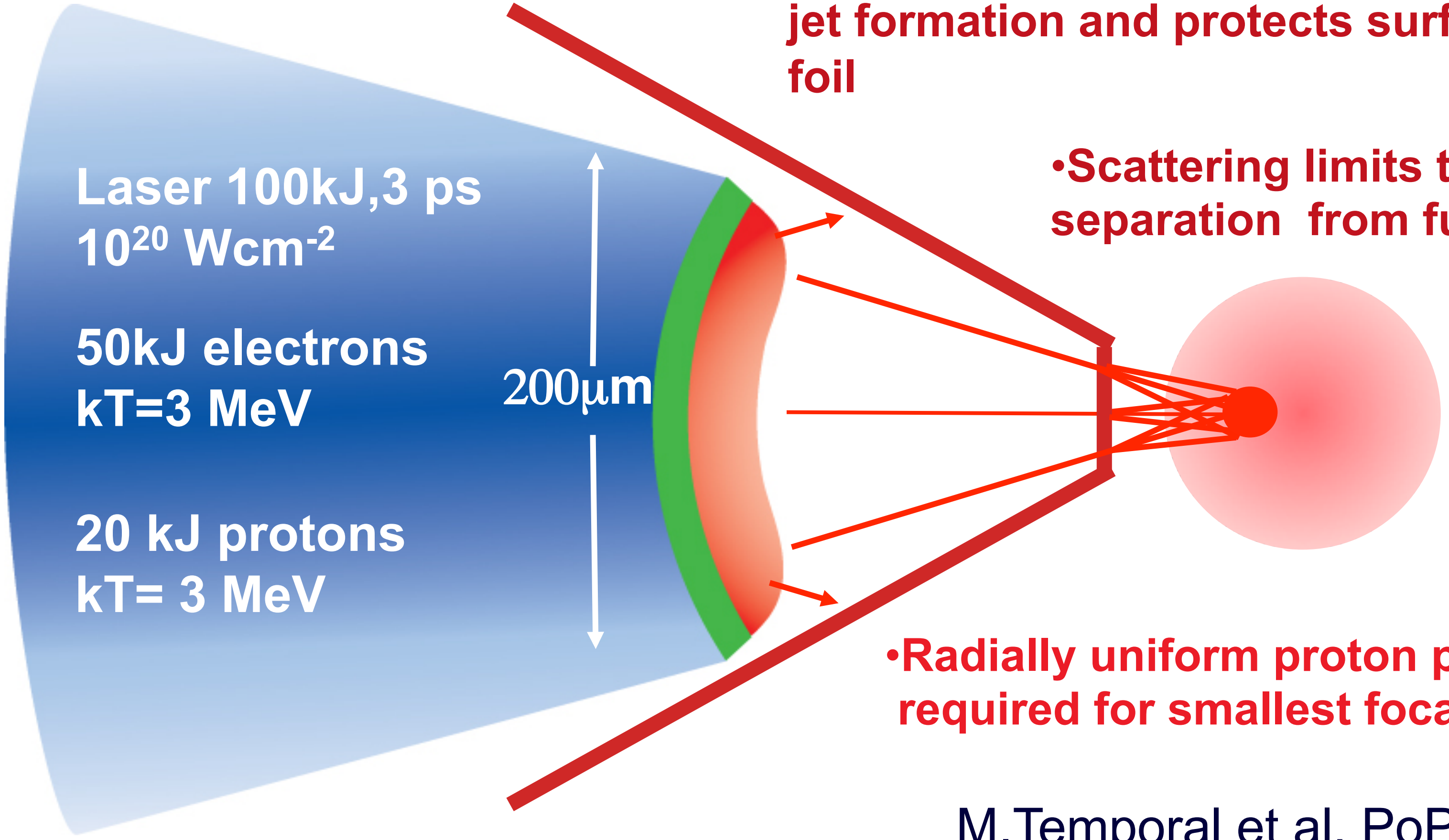
Matter compressed to ~300 gcm^{-3} and a 100 ps “hole-boring” pulse at creates a channel in the expanding coronal plasma

PW laser pulse is launched into channel generating MeV electrons that are stopped in the dense fuel

Off centre spark is formed, creating a burn wave that propagates through the fuel

FI experiments currently pursued on FIREX (Japan)

A conceptual design for proton fast ignition illustrates the issues



Laser 100kJ,3 ps
10^{20} Wcm^{-2}

50kJ electrons
kT=3 MeV

20 kJ protons
kT= 3 MeV

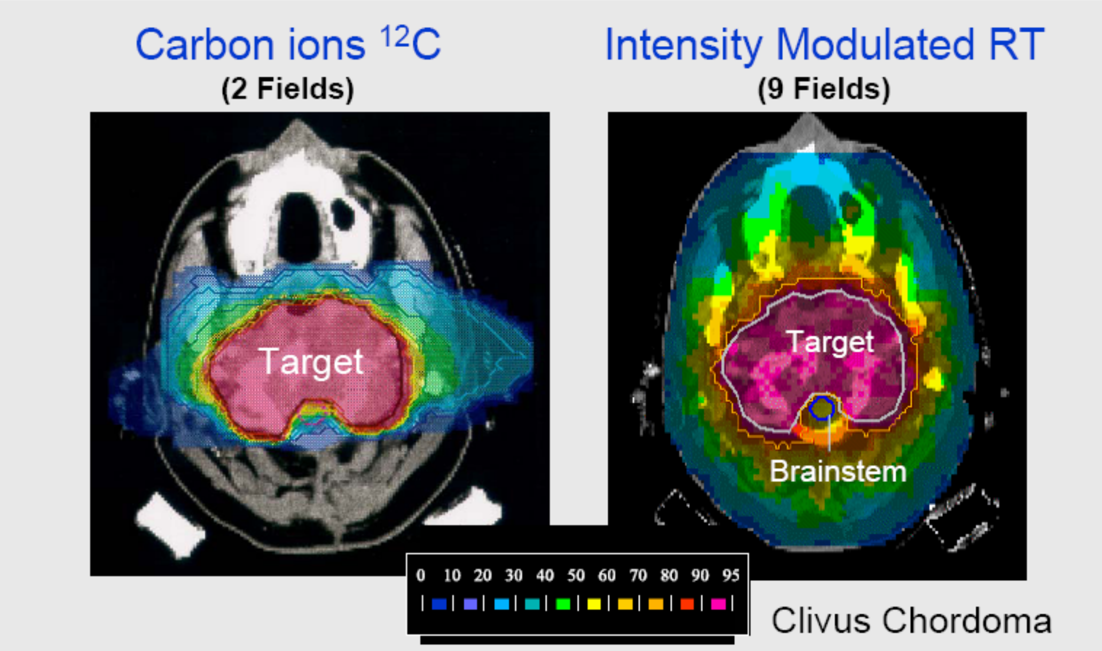
200μm

- Cone maintains vacuum region for proton plasma jet formation and protects surface of proton source foil
- Scattering limits thickness of cone tip and separation from fuel
- DT fuel at 500g/cc
- 60 μm ignition spot (same as electron ignition)
- Radially uniform proton plasma jet required for smallest focal spot
- Proton source foil protects rear surface from pre-pulse
  - thickness limits conv. efficiency

M.Temporal et al, PoP, **9**, 3098 (2002)
V. Tikhonchuk, T. Schlegel, Proc. Of SPIE, **8080**, 80801-G1 (2011)

Hadrontherapy treatment

Proton and Carbons from RF accelerators
are currently used for treating a number of tumours

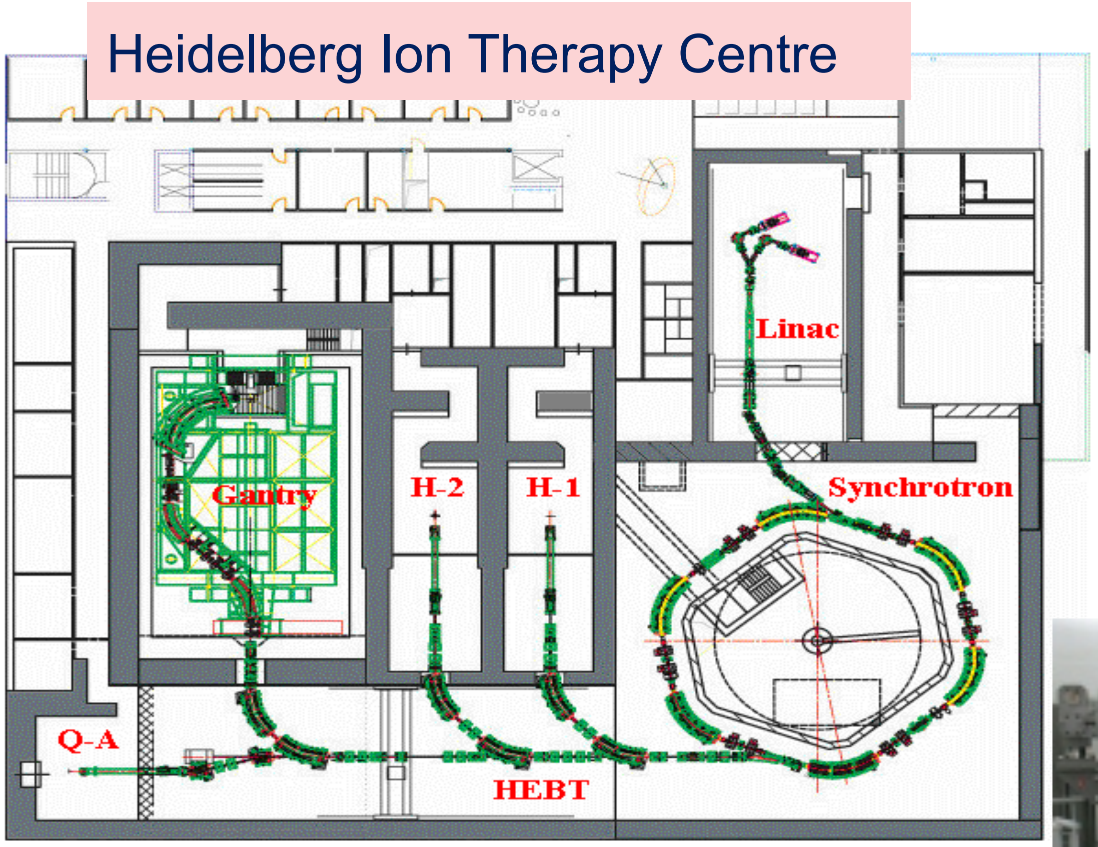


Energies required:
60-250 MeV (protons)
or 100-450MeV/u (**C-ion**)

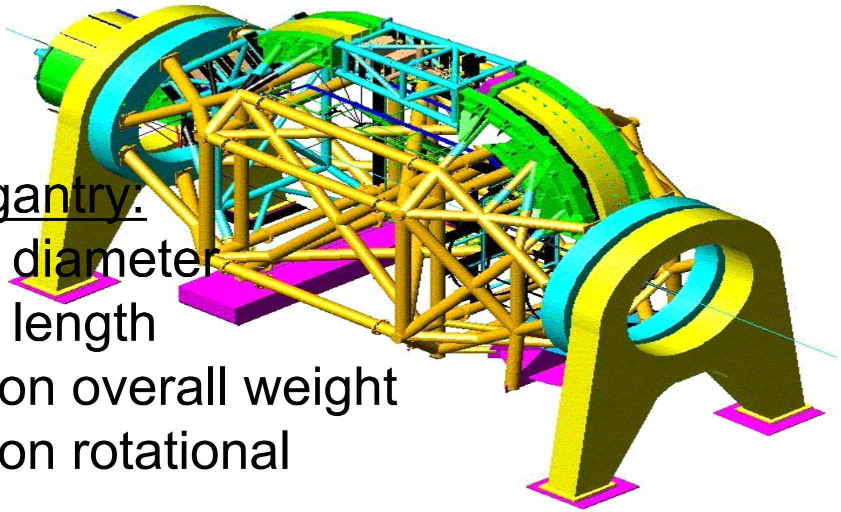
Typical dose fraction: 2-5 Gy
1 Gy ~ 10^{10} p+, ~10^{9} C in 5x5x5 cm^3
(delivered in few minutes)

Better localization + increased biological effectiveness leads to improved clinical outcomes for many prescriptions
(~10% of cancer could be better treated by ions, only 0.1% are)

Ion Therapy costs


Heidelberg Ion Therapy Centre

3m thick walls and roof shielding



Ion gantry:
13m diameter
25m length
600ton overall weight
420ton rotational

Accelerator
4m diameter
60 tons
500nA, 250MeV

V acility

S %)

Demand for treatment much higher than offer -
scope for investigating alternative approaches for future therapy

Is there scope for laser-driven ion therapy?

OPPORTUNITIES:

First proposed in :

S.V. Bulanov *et al*, Phys. Lett. A, **299**, 240 (2002)
E. Fourkal et al, Med Phys., **30**, 1660 (2003)
V. Malka, *et al*, Med. Phys., **31**, 1587 (2004)

Reduced cost/shielding:

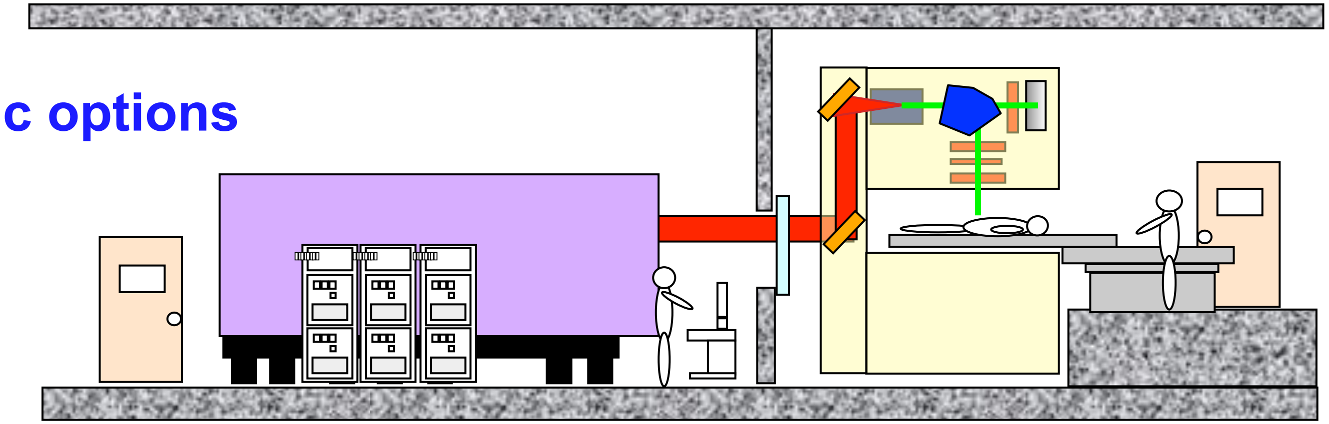
- Laser transport rather than ion transport
  (vast reduction in radiation shielding)
- Possibility to reduce size of gantry

Flexibility:

- Possibility of controlling output energy and spectrum
- Possibility of varying accelerated species
- Spectral shaping for direct "painting" of tumour region

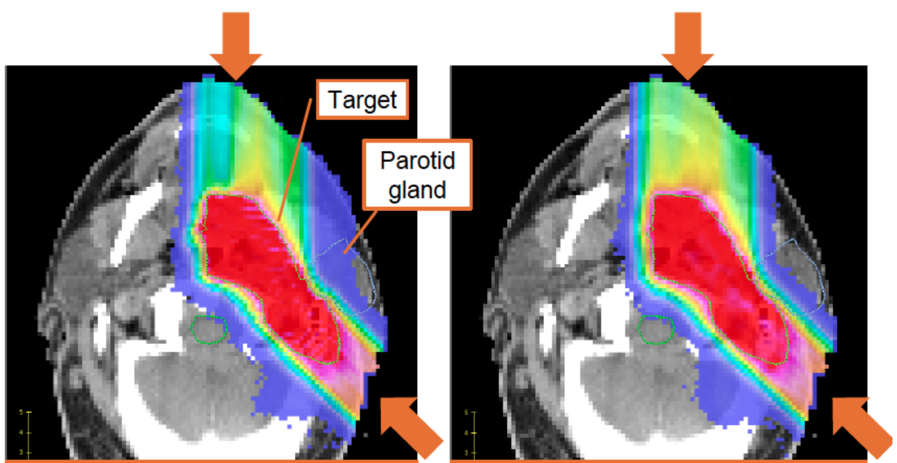
Novel therapeutic/diagnostic options

- Mixed fields: x-ray + ions
- In-situ diagnosis
- Proton radiography/PET…



Design/feasibility studies for laser-driven therapy

Treatment plans employing laser-driven protons

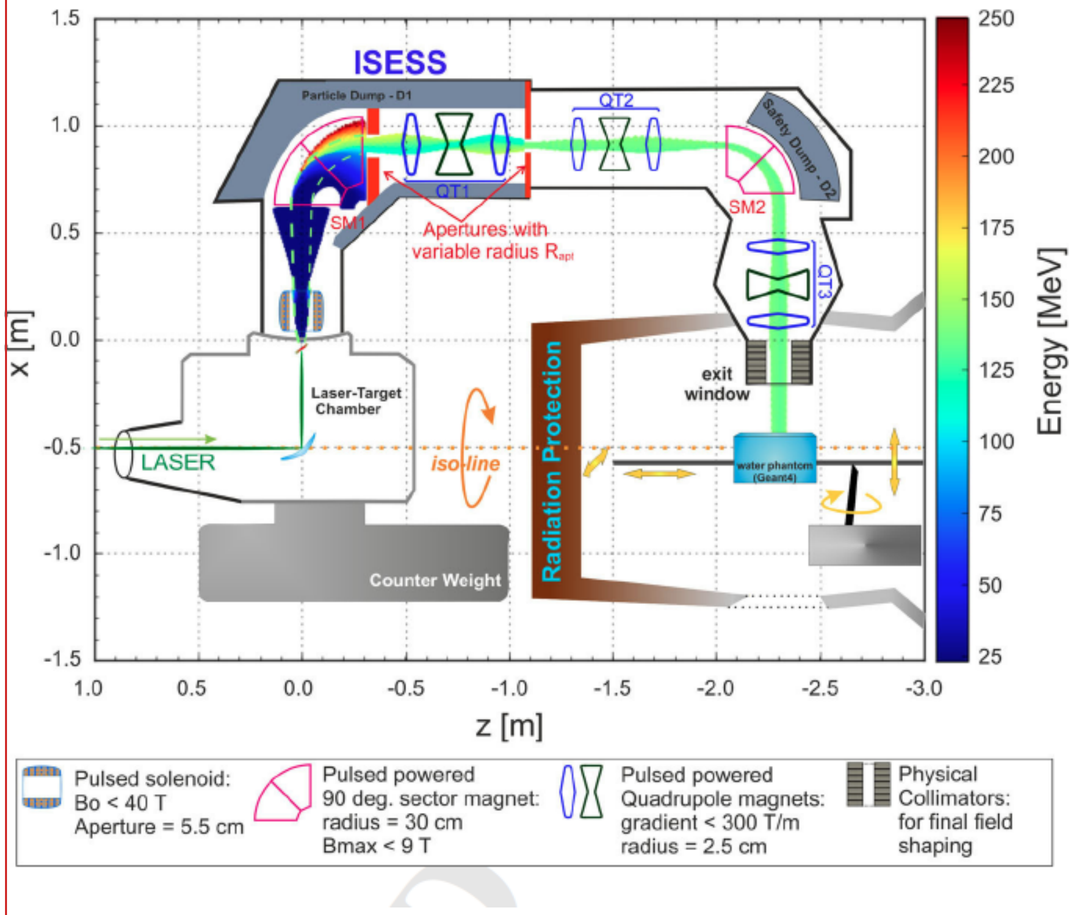


Standard plan
narrow energy spectra: 68 064 shots

Adapted plan
broad energy spectra: 5538 shots
second. radiation reduced by factor 14

Schell and Wilkens,
Med. Phys., **37**, 5330 (2010)

Design of compact gantries for laser-driven protons



U. Masood et al, Appl. Phys. B, 117, 41 (2014)

Summary/ conclusion

Lectures have provided an overview of development and state of the art in laser-driven ion acceleration

- Target Normal Sheath Acceleration
  (development, basic process, modelling and optimization)

- Emerging acceleration mechanisms
  (Radiation Pressure Acceleratio, shock acceleration, Relativistic transparency)

- Applications
  (radiography, WDM, neutrons, radiobiology, IFE, cancer)

Some review papers

A.Macchi, M.Borghesi and M. Passoni, *Ion acceleration by superintense laser-plasma interaction*, Rev. Mod. Phys., **85**, 751 (2013)

A Macchi, A Sgattoni, S Sinigardi, M Borghesi, and M Passoni, *Advanced strategies for ion acceleration using high power lasers*, Plasma Phys. Control. Fusion , **55**, 124020 (2013)

M.Borghesi, *Laser-driven ion acceleration: state of the art and emerging mechanism*s, Nuclear Instr. Methods A, **740**, 6 (2014)

M. Borghesi, A. Macchi, Laser-Driven Ion Accelerators: State of the Art and Applications, in: *Laser-Driven Particle Acceleration Towards Radiobiology and Medicine*, ed. by A. Giulietti (Springer, 2016)

M. Borghesi et al, *Fast Ion Generation by High-Intensity Laser Irradiation of Solid Targets and Applications*, Fusion Science and Technology **49** (2006), 412

Other review papers

- J. Schreiber, P. R. Bolton, K. Parodi, “Hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications, Rev. Sci. Instrum. **87**, 071101 (2016)

- J. C. Fernández, et al, *Fast ignition with laser-driven proton and ion beams*, Nucl. Fusion **54** (2014) 054006

- H. Daido, M. Nishiuchi, A. S. Pirozhkov, *Review of Laser-Driven Ion Sources and their Applications*, Rep. Prog. Phys. **75** (2012) 056401