Laser-Driven Ion Acceleration: mechanisms and state-of-the-art

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ELISS2023
Extreme Light Infrastructure Summer School

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ELI Beamlines Facility
Dolní Břežany, Czech Republic

Outline

- **The "*baseline*" mechanism** – Sheath acceleration (TNSA)
  - Theoretical models/descriptions/ scaling
  - Present status
  - Current research trends/ developments

- **Applications:** radiography, radiobiology

- **Emerging mechanisms/new developments**
  - Target-based schemes for ion transport
  - Radiation Pressure Acceleration: Light Sail
  - Hybrid schemes – relativistic transparency
  - Advanced targetry

A-SAIL
ADVANCED STRATEGIES FOR
ACCELERATING IONS WITH LASERS

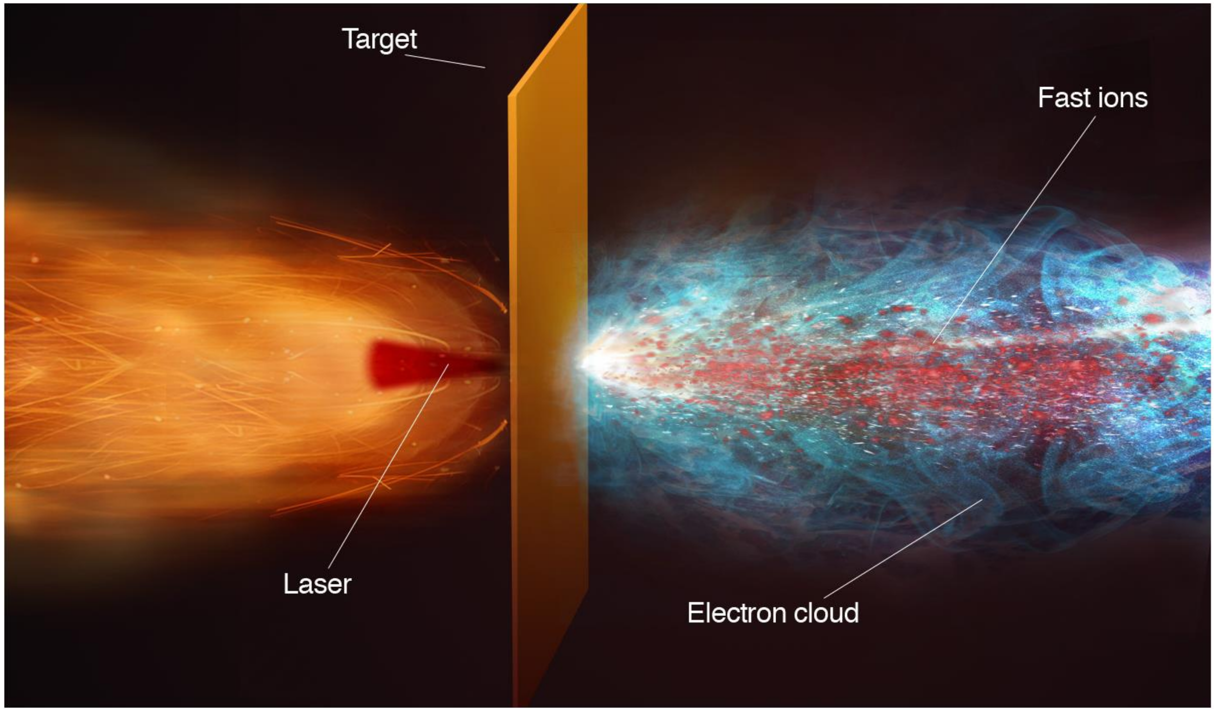
UK RI
Engineering and
Physical Sciences
Research Council

IMPULSE

European Commission

HORIZON 2020

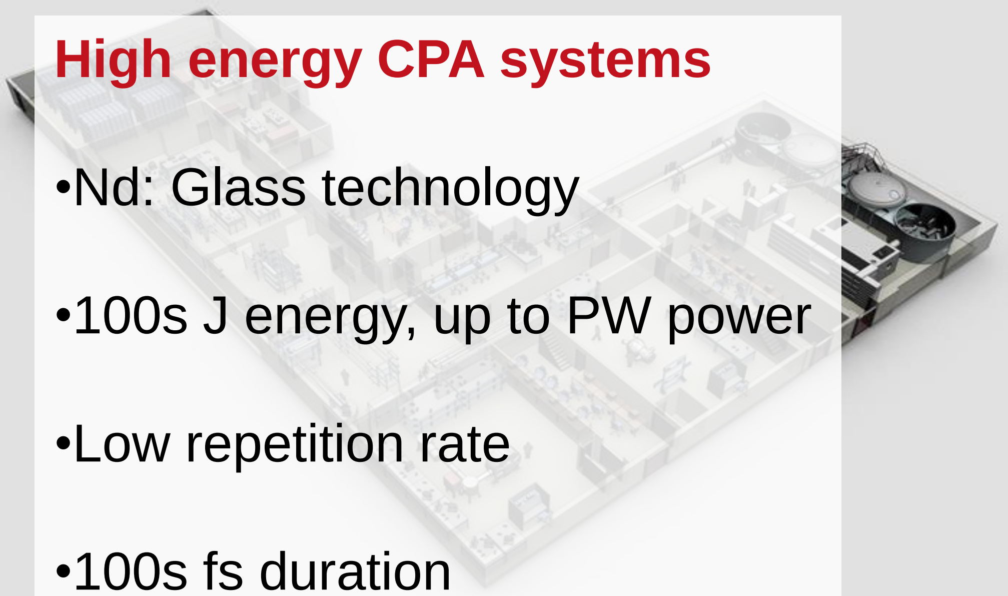
Ion acceleration : some general points



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

- Large accelerating fields sustained by electron-ion separation in a plasma
- Very large fields (up to 10^{13} V/m) applied over very short distances (~μm)
- Mostly solids (high density targets)

Two classes of lasers are mainly used for this work

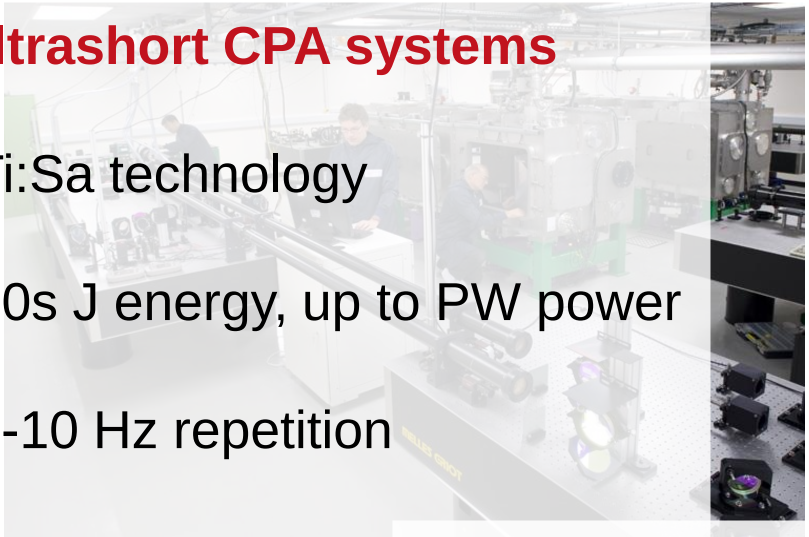


High energy CPA systems

- Nd: Glass technology
- 100s J energy, up to PW power
- Low repetition rate
- 100s fs duration
- I_{max}~ 10^{21} Wcm^2

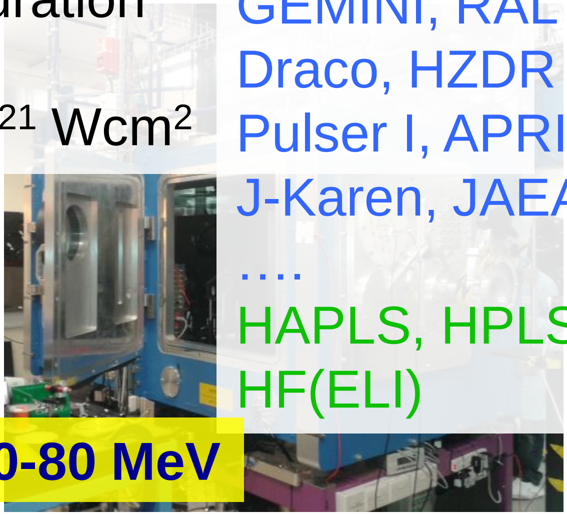
VULCAN, RAL (UK)
Phelix, GSI (De)
Texas PW (US)
…
Aton L4 (ELI Beamlines)

E_{max}~ 100 MeV



Ultrashort CPA systems

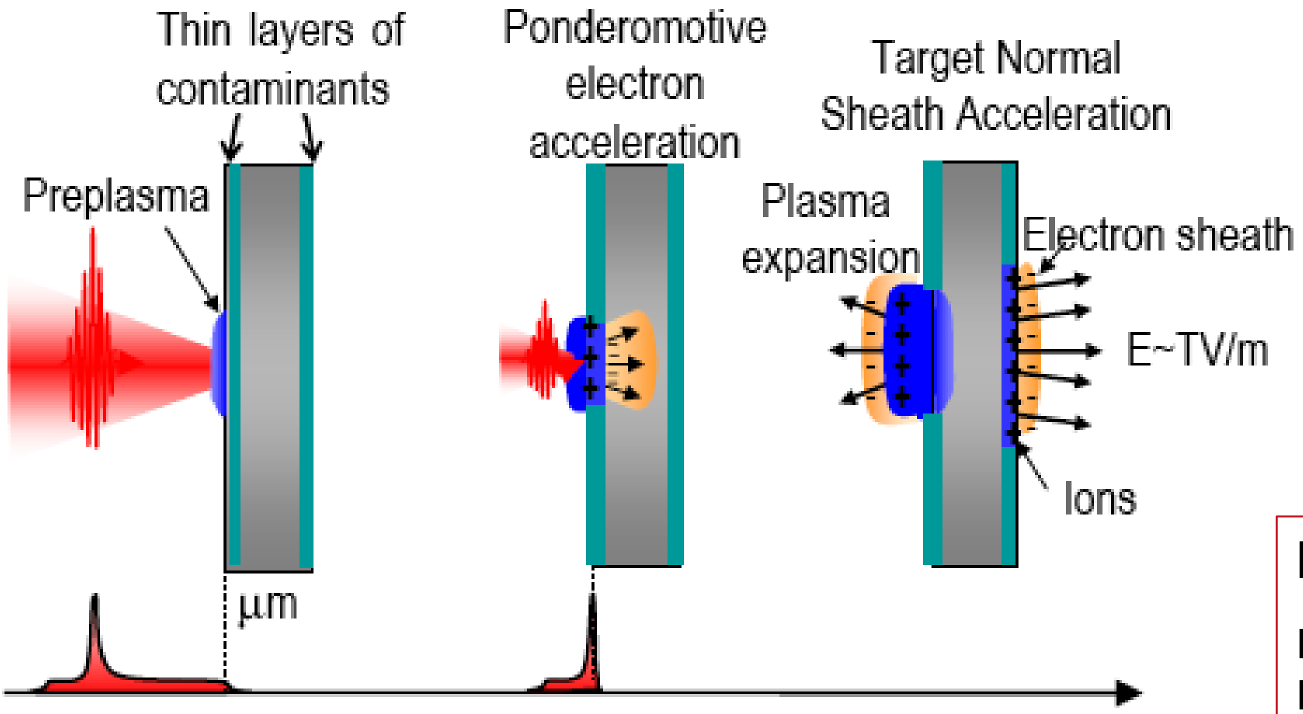
- Ti:Sa technology
- 10s J energy, up to PW power
- 1-10 Hz repetition
- 10s fs duration
- I_{max}~ 10^{21} Wcm^2



GEMINI, RAL (UK)
Draco, HZDR (De)
Pulser I, APRI (Kr)
J-Karen, JAEA (J)
….
HAPLS, HPLS, HF(ELI)

E_{max}~ 70-80 MeV

TNSA source : the mechanism



Target Normal Sheath Acceleration

Initial observations:

Clark *et al*, PRL, 84 ,670 (2000)

Maksimchuk *et al*, PRL, 84, 4108 (2000)

Snavely *et al*, PRL, 85,2945 (2000)

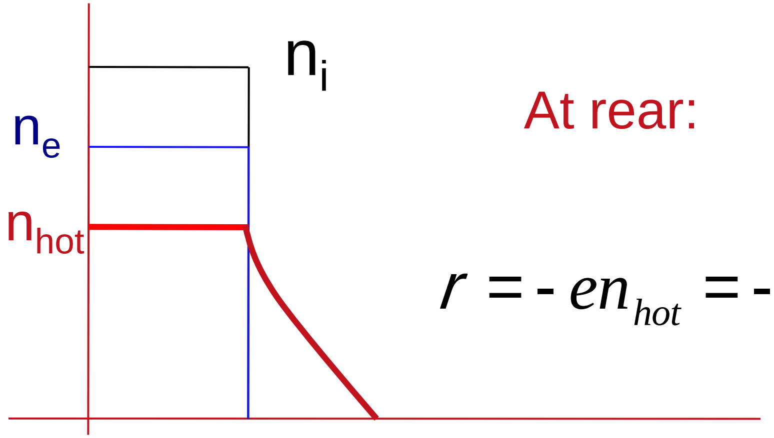
Reviews:

Macchi, Borghesi, Passoni, Rev. Mod. Physics, 85, 751 (2013)

M. Borghesi, in L. A. Gizzi *et al*. (eds.), Springer Proceedings in Physics 231, 143-164 (2019)

High-density, high-energy electrons lead to ultralarge field

S. Wilks *et al*, PoP, **8**, 542 (2001)



At rear:

$$\rho = -en_{hot} = -en_0 \exp\left(-\frac{x}{\lambda_D}\right)$$

$$\nabla \cdot E = \frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$$

$$E(0) = \int_{\infty}^{0} \frac{\rho}{\varepsilon_0} dx$$

$$E(0) = \frac{KT_h}{e\lambda_D} = \sqrt{\frac{n_h KT_h}{\varepsilon_0}}$$

Dependence on n_h and T_h

↓

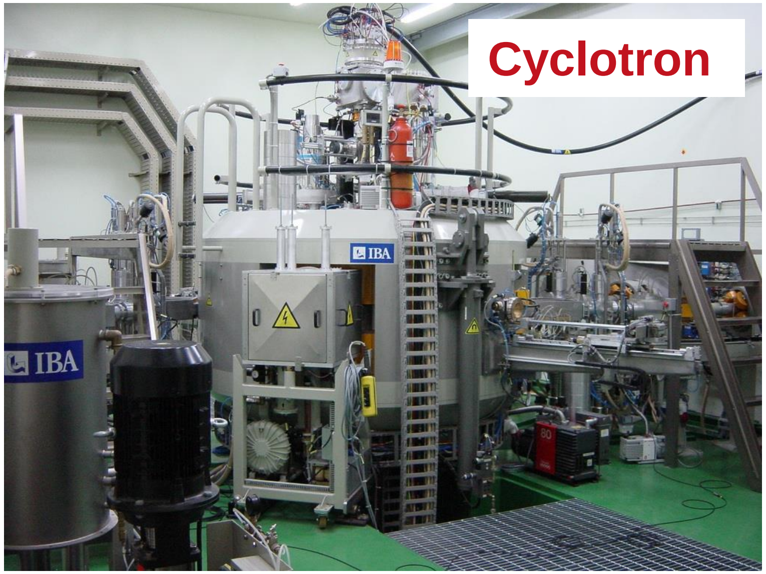
Dependence on laser pulse intensity and energy

Typical values:
λ_D~ 1 μm
T_h ~ MeV

↓

$$E(0) = \frac{10^6 V}{10^{-6} m} \sim TV/m$$

Conventional particle accelerators use much smaller fields



Cyclotron

LINAC

Acceleration by much smaller Electric fields associated to alternating voltages (at RF or microwave frequencies)

E_{max} ~ 50 MV/m

(more than 10,000 smaller than with lasers)

Synchrotron

TNSA beam properties

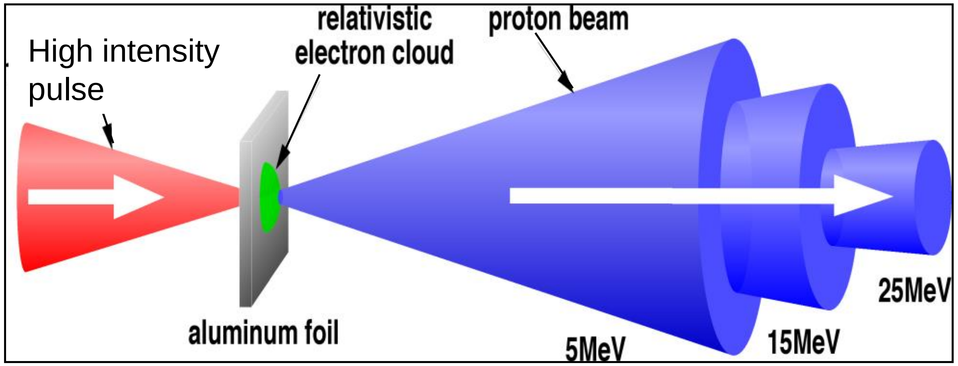
Short duration at source: bursts with duration ~ ps

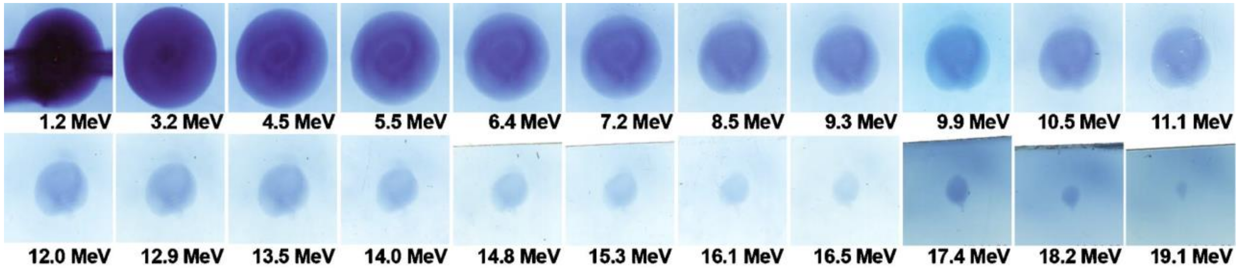
Acceleration time comparable with laser-drive duration

Strong ΔE-Δt correlation: ΔE-Δt < ~ 10^{-6} eV-s (maybe much lower?)

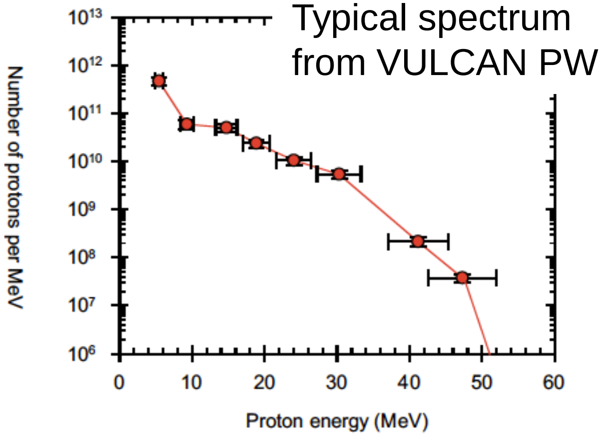
Broad spectrum:

continuum up to 10s of MeV
Decreasing divergence for
increasing energy





F. Nurnberg *et al*, RSI, 80, 033301 (2019)



Typical spectrum
from VULCAN PW

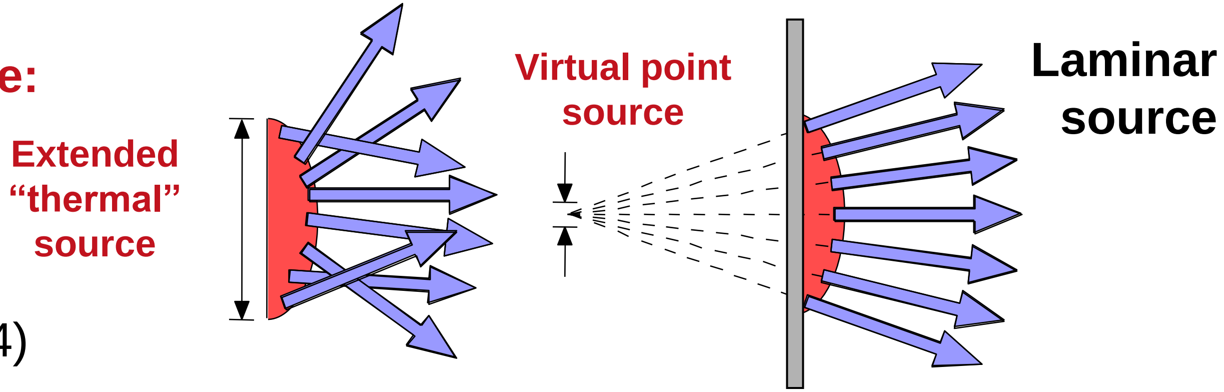
TNSA beams have excellent emission quality

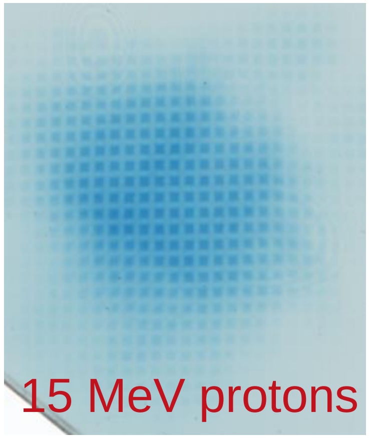
Highly laminar source (virtual point source of ~µm size << *real* source)

Ultralow emittance/ virtual source:

$\varepsilon_N < 0.1\ \pi$ mm.mrad @ 15 MeV

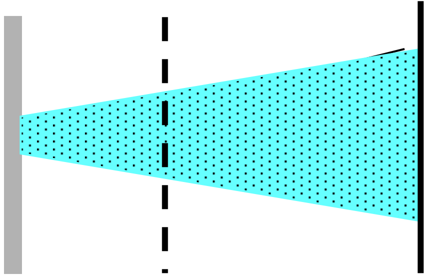
(< 0:004 mm-mrad;
T.Cowan *et al*, PRL, 92, 204801, 2004)





15 MeV protons

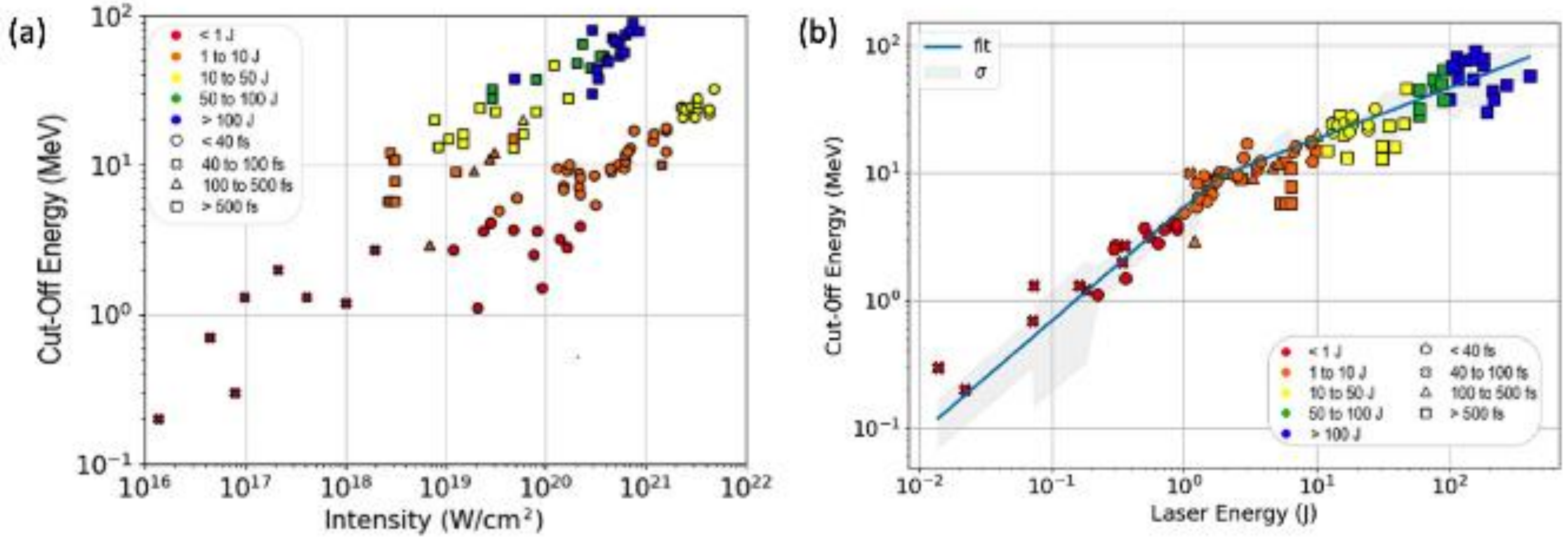
Mesh with 12 µm pitch



CERN proton rf-linac:
$\varepsilon = \mathbf{1.7}\ \pi$ mm-mrad

M.Borghesi *et al*, Phys Rev Lett., 92, 055003 (2004))

TNSA scaling with laser parameters



M. Zimmer et al, Phys. Rev E, **104**, 045210 (2021)

Maximum published TNSA energies: ~85 MeV (Phelix, GSI)

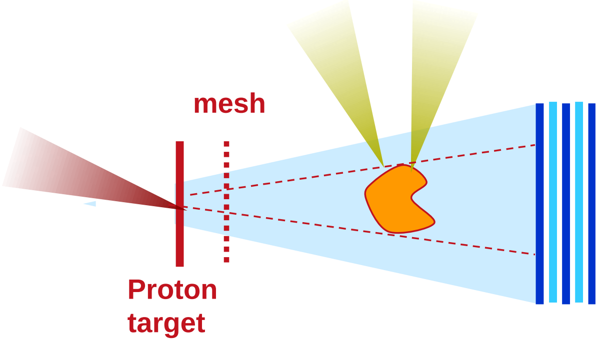
Acceleration more effective with higher energy, longer pulses, at equal intensities

Proton energy will also depend on additional factors: target thickness, laser contrast, spectral phase ….

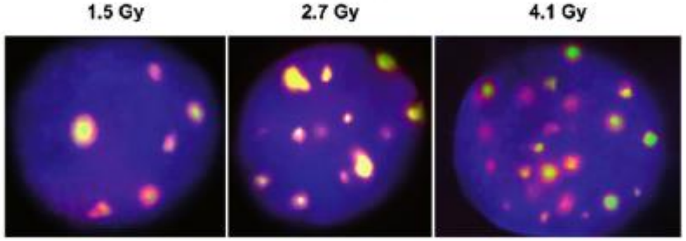
e.g. T. Ziegler et al, Sci. Rep.,11, 7338 (2021)
Significant energy enhancement by spectral phase control (DRACO, HZDR)

Applications of TNSA ions

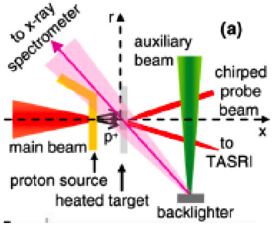
Ultrafast proton radiography



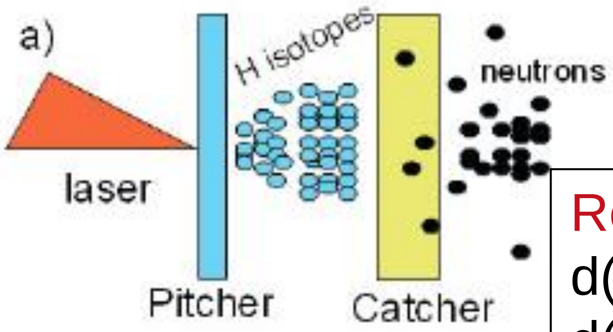
Ultrafast radiobiology (*radiotherapy?*)



Warm dense matter production (isochoric heating)



Neutron generation



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

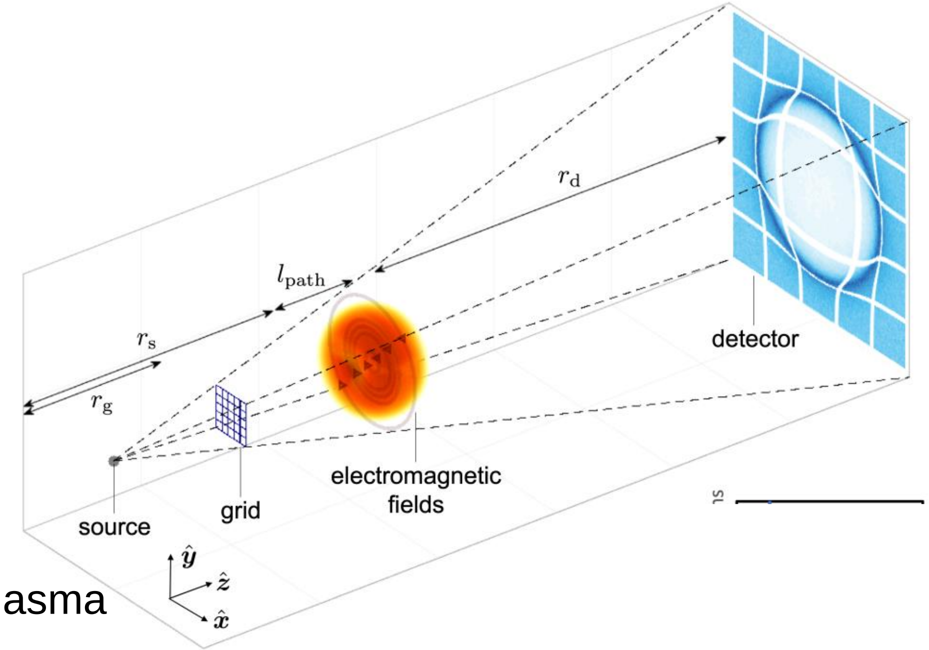
Nuclear Physics
(ELI NP)

\+ Material analysis
Cultural heritage applications
Stopping in plasmas
Fast Ignition for fusion…..

Applications: proton radiography for e.m. field detection

D. Schaeffer et al, Rev. Mod Phys. (2023, in press)
https://arxiv.org/abs/2212.08252

Proton radiography for field mapping
High resolution, multiframing

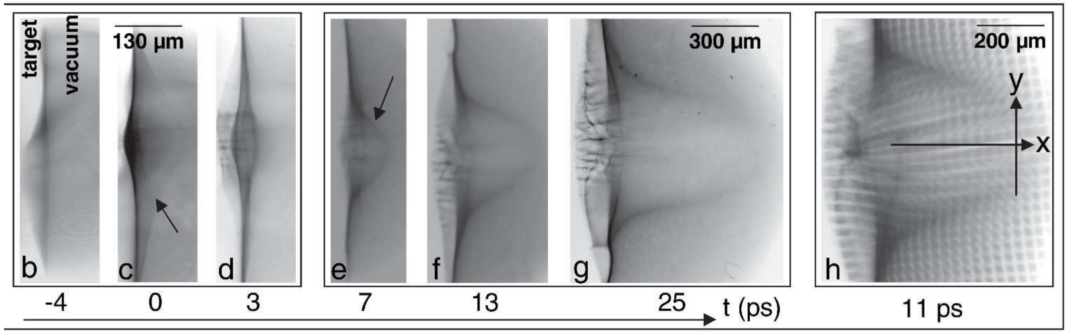


Proton deflection due to E/B fields in plasma is mapped and used to reconstruct field distribution

Developed ~ 20 years ago, it has now become a widely used approach for investigating a broad range of plasma phenomena.

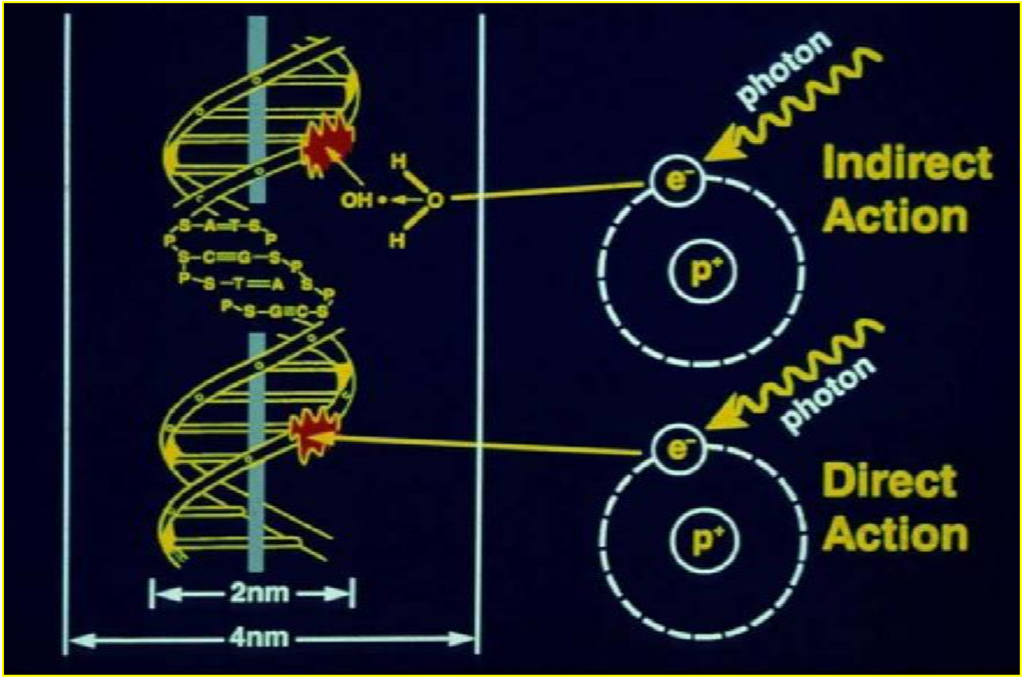
Field maps retrieved by either analytical inversion or by forward projection through a model field distribution by using particle tracing codes.

Example: radiographs of TNSA beam being accelerated
Romagnani et al, PRL, 2005



Applications: radiobiology/radiotherapy

All types of ionising radiation cause damage through two mechanisms:



- **Direct effect**
  -radiation damages DNA in molecules through direct ionisation.
- **Indirect effect**
  -radiation ionises surrounding water molecules, forming free radicals, which damage DNA.

Double strand breaks are difficult to repair, mis-repair can lead to mutations and even cell death.

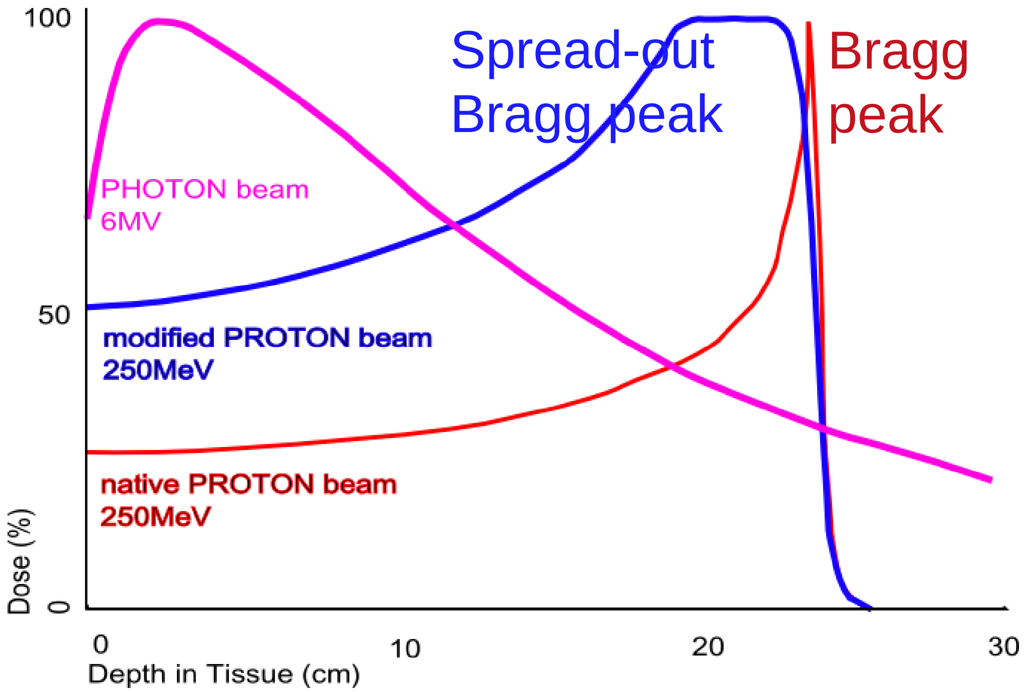
Cancer radiotherapy :
use of radiation (x-ray photons, protons, electrons) for targeted damage to cancer cells

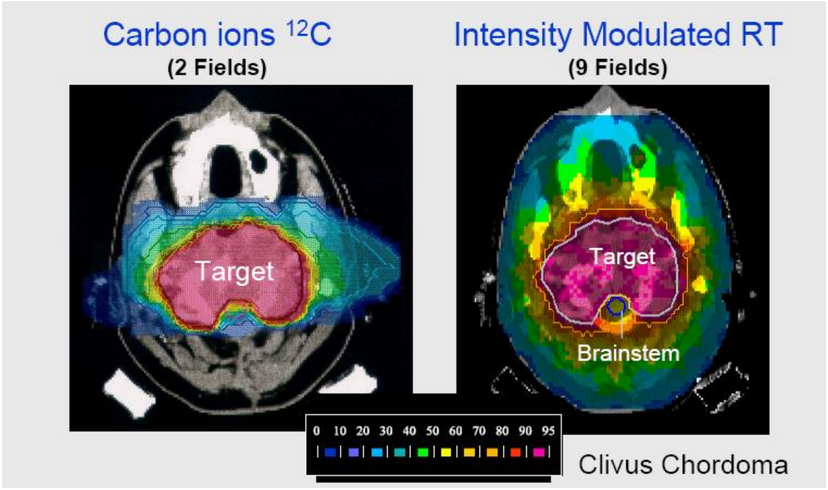
Typical radiation dose: 20-30 Gy (in several fractions)

Flash radiotherapy:
Novel concept for radiotherapy
prescribed dose delivered in a single pulse at very high dose rates (10s to 100s of Gy/s) – leading to **reduction of side effects on healthy cells**

Interest in highly pulsed beams

Advantages of using protons/ions over photons





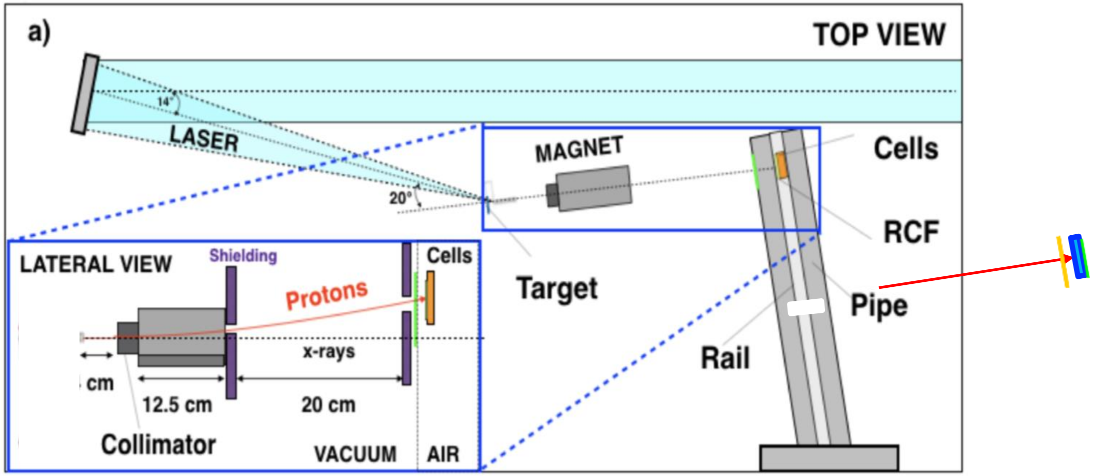
Bragg peak feature allows more targeted dose deposition, and a better sparing of healthy tissues

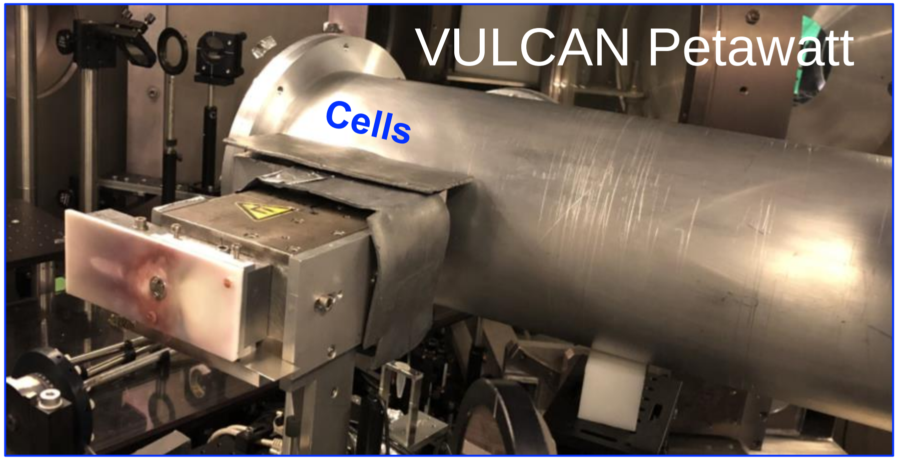

Christie hospital, Manchester

Main reason behind current and growing interest in protontherapy/carbon therapy

Experiments with protons

P. Chaudhary *et al*, Front. Phys. **9**, 624963 (2021)





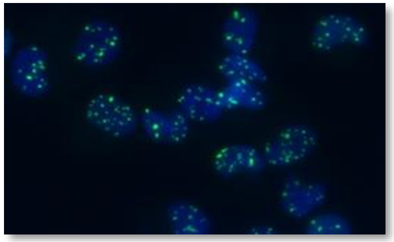
- Compact irradiation arrangements
- Dosimetry
- Biological assays :
  - Quantification of DNA damage
  - Cell survival studies
  - Sub-lethal damage studies

$E_p \sim 35\ MeV \pm 10\%$

Pulse duration **350 ps**

Dose per shot **2 Gy**

Mean Dose rate:
5.7×10^{9} Gy/s

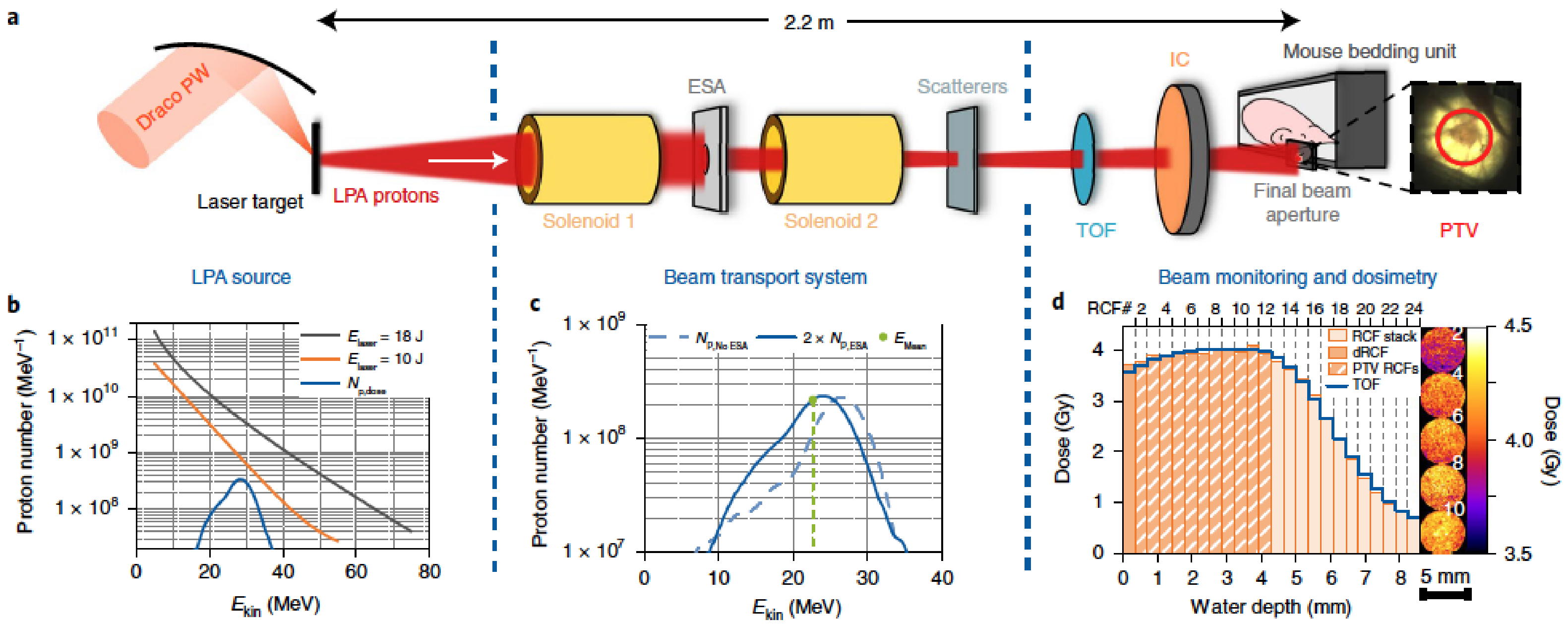


- Normal vs cancer cells
- 2D vs 3D
- Oxygen dependence

Comparator irradiations at conventional (Gy/min) and FLASH (10s Gy/s) dose rates at cyclotron accelerators

First in-vivo irradiations with laser-driven protons

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



ARTICLES

https://doi.org/10.1038/s41567-022-01520-3

nature physics

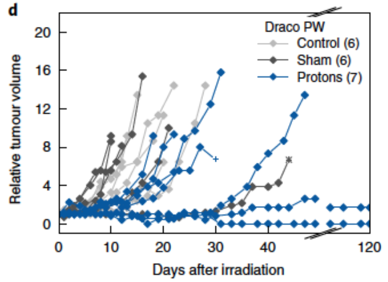
Check for updates

OPEN

Tumour irradiation in mice with a laser-accelerated proton beam

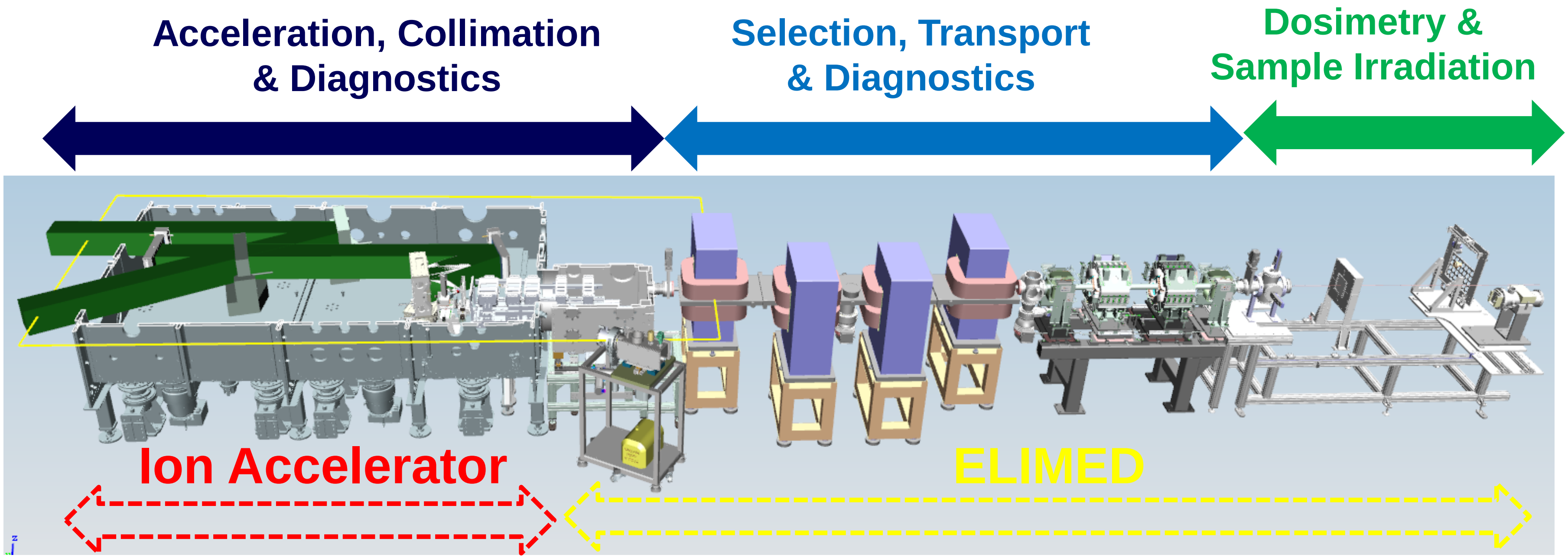
Florian Kroll[1]✉, Florian-Emanuel Brack[1,2], Constantin Bernert[1,2], Stefan Bock[1], Elisabeth Bodenstein[3], Kerstin Brüchner[1,2,3], Thomas E. Cowan[1,2], Lennart Gaus[1,2], René Gebhardt[1], Uwe Helbig[1], Leonhard Karsch[1,3], Thomas Kluge[1], Stephan Kraft[1], Mechthild Krause[1,3,4,5,6,7], Elisabeth Lessmann[1], Umar Masood[1], Sebastian Meister[1], Josefine Metzkes-Ng[1], Alexej Nossula[1], Jörg Pawelke[1,3], Jens Pietzsch[1,2], Thomas Püschel[1], Marvin Reimold[1,2], Martin Rehwald[1,2], Christian Richter[1,3,4,5,6], Hans-Peter Schlenvoigt[1], Ulrich Schramm[1,2], Marvin E. P. Umlandt[1,2], Tim Ziegler[1,2], Karl Zeil[1] and Elke Beyreuther[1,3]

F. Kroll et al, Nature Phys., **18**, 316 (2022)



Tumour growth monitored after irradiation

ELIMAIA beamline @ ELI Beamlines



Acceleration, Collimation & Diagnostics

Selection, Transport & Diagnostics

Dosimetry & Sample Irradiation

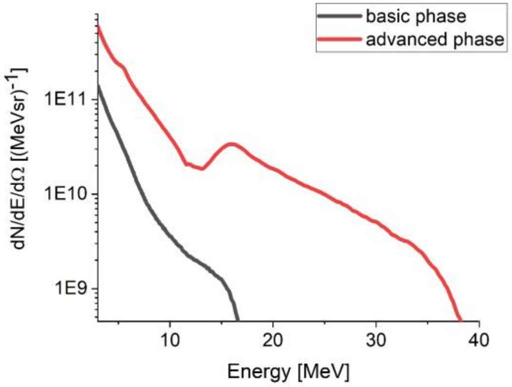
Ion Accelerator

ELIMED

Beamline commissioning ongoing

FLAIM flagship experiment (2024)

Flash and ultrahigh dose-rate radiobiology with Laser Accelerated Ions for Medical research



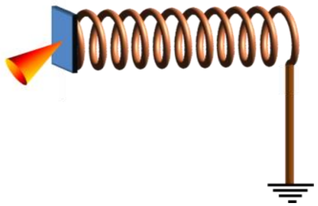
Current source performance

New developments and mechanisms

Coil targets for TNSA conditioning

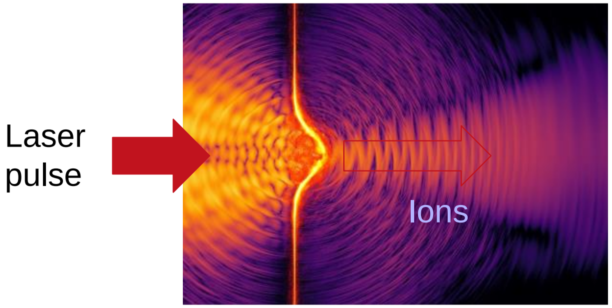
Divergence control

Spectrum/energy enhancement



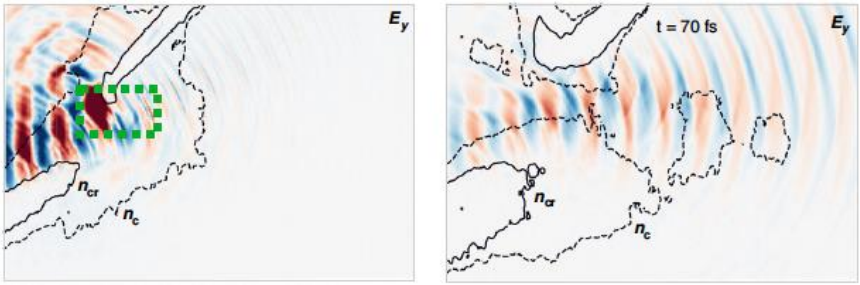
Radiation pressure acceleration

Bulk ion acceleration from ultrathin foils (e.g. Carbon)



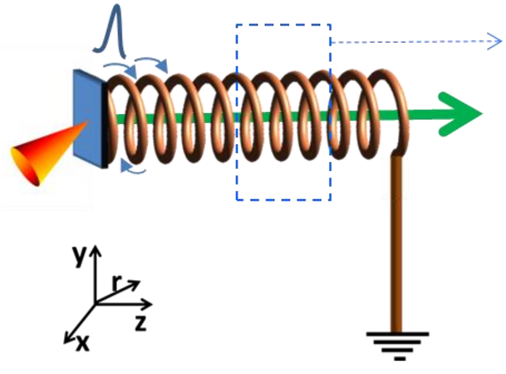
Relativistic transparency/hybrid schemes:

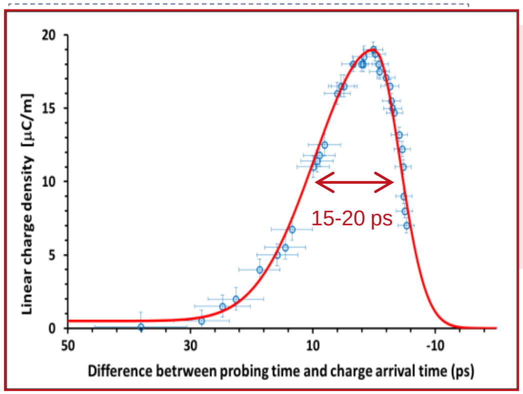
Bulk acceleration
Enhanced coupling to lighter species



Coil targets for proton beam optimization

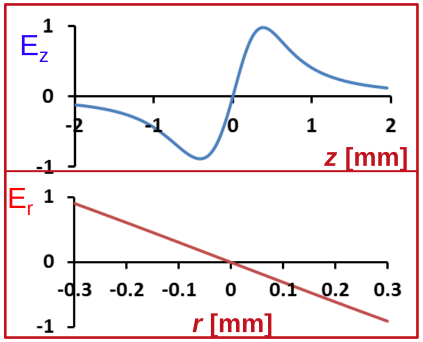
S.Kar *et al*, Nature Comm., **7**, 10792 (2016)



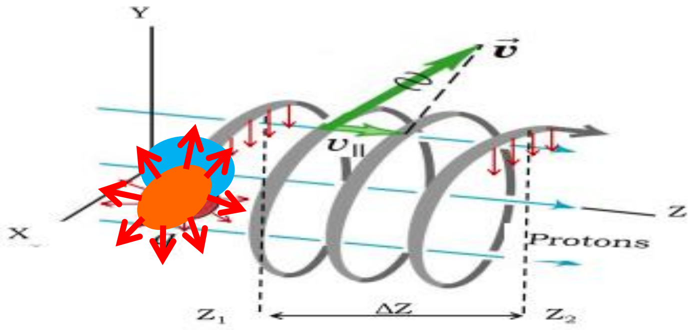


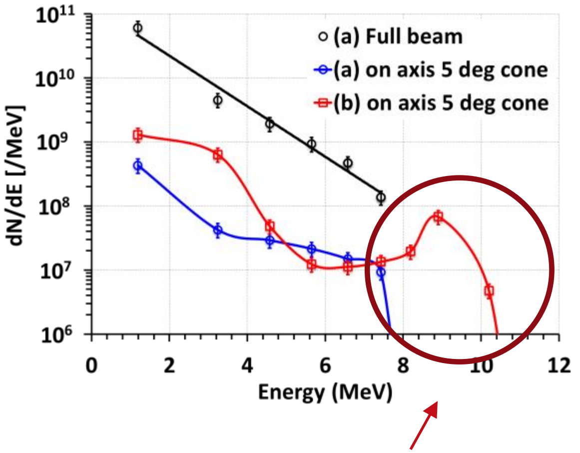
EM pulse propagating along coiled wire at v ~ c

The field structure is essentially equivalent to the field of a **charged ring**

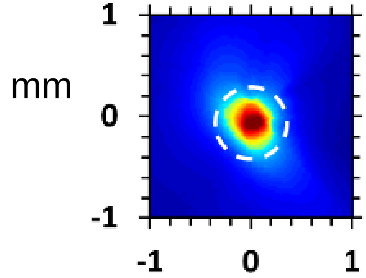


Choice of geometry(coil diameter, pitch) allows "longitudinal" synchronization with a group of protons





Re-accelerated bunch



⇒ Divergence < 1°
measured at 35 mm
from the target

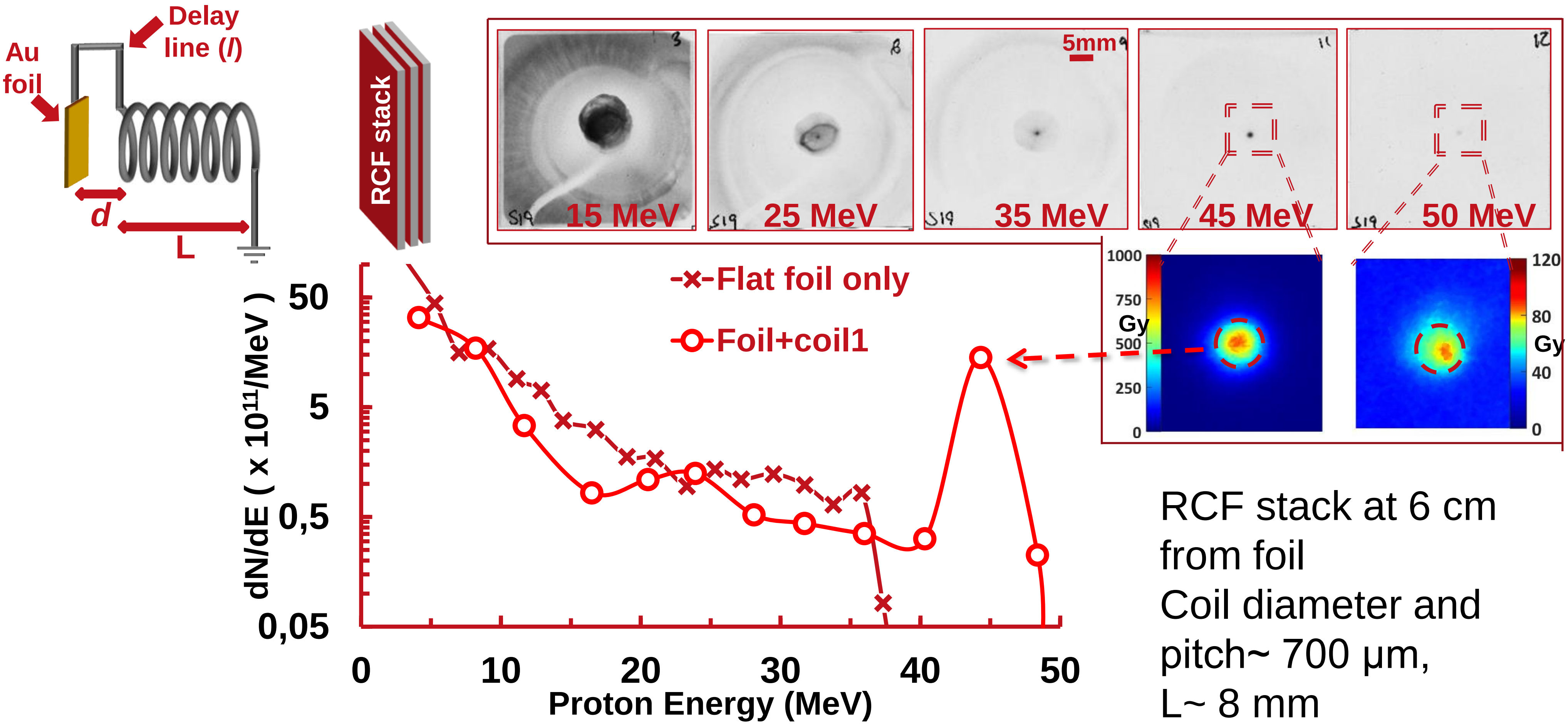
ARCTURUS laser, Dusseldorf (De)

High energy implementation

H.Ahmed *et al*, Sci. Rep., **11**, 699 (2021)

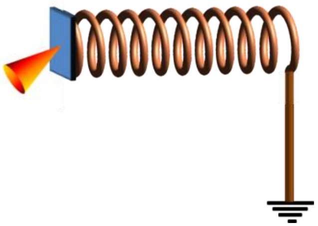
Data obtained using Titan Laser, LLNL:

~ 120 J in ~ 0.6 ps, f/3 focusing, Intensity ~2x10^{20} W/cm^2



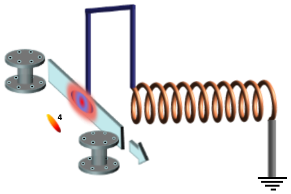
RCF stack at 6 cm from foil
Coil diameter and pitch~ 700 µm,
L~ 8 mm

Implementation on ELIMAIA



From single shot

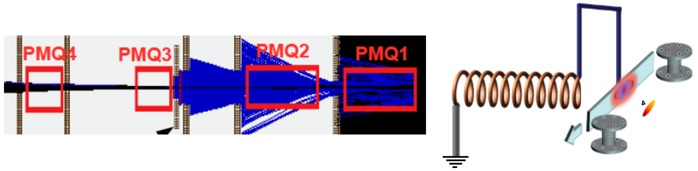
to rep-rated operation



- tape drive target
- EMP propagation through vacuum gap

Injection into ELIMAIA

Significant flux/dose increase:
Contribution to ELIMAIA flagship exp.



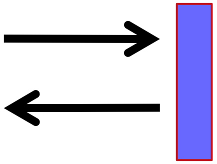
Deployment of compact beamline in ELIMAIA acceleration station

First user experiment on ELIMAIA: October 2023 (PI: S.Kar, QUB)

Beyond TNSA – Radiation Pressure Acceleration

Radiation pressure upon light reflection from a mirror surface:

$$p_R = \frac{2I_L}{c}$$

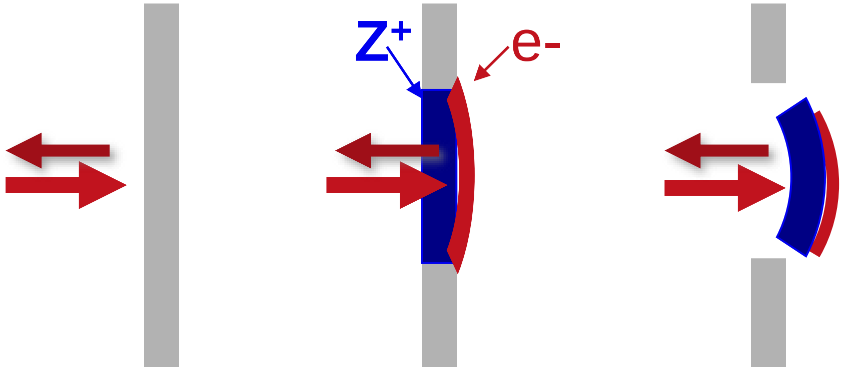


P_L=60 Gbar
@ 10^{20} Wcm^{-2}

- **Bulk acceleration mechanism**
- **Fast scaling with intensity**

Target **must stay opaque**:

Potential issues → Electron heating
Target disassembly
Transverse instabilitie



Most efficient with ultrathin foils (nm-scale) – ***Light Sail*** RPA

Experimental requirements:

- Ultrashort pulses
- Temporal “cleaning”
- Circular polarization

T.Esirkepov, et al. PRL., **92**, 175003 (2004)
APL Robinson et al, NJP, **10**, 013021 (2009)

Radiation pressure in laser matter interaction

In a plasma the effect is felt by the electrons via the ponderomotive force

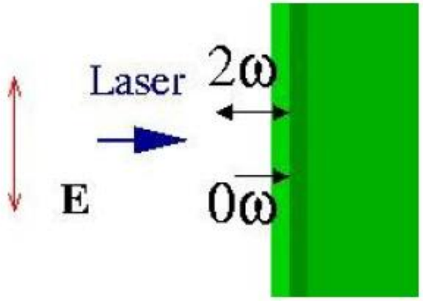
$$f_p = -\frac{m}{4}\frac{\partial}{\partial x}v_{os}^2(x)\left(1-\cos 2\omega_0 t\right)$$

Non-oscillating term Oscillating term

Steady pressure, transferred to ions via space-charge

JXB heating, hot electrons

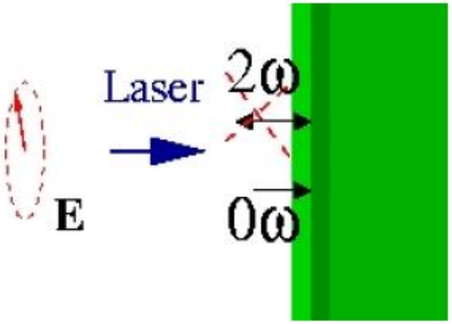
Normally, the electron heating effect masks any steady pressure effect



Linear polarization

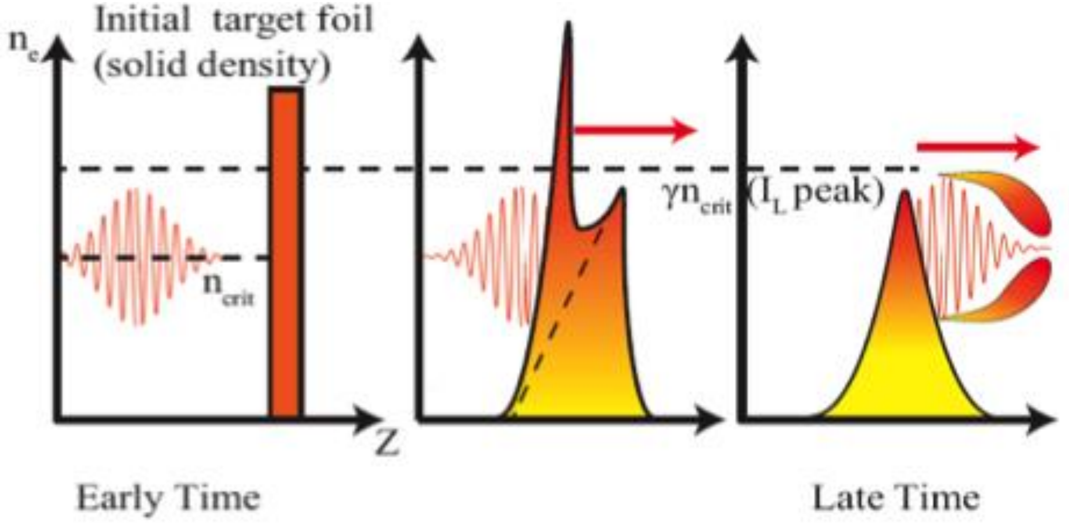
Laser-polarization can be used to control the balance between the two terms

A.Macchi *et al*, PRL **94**, 165003 (2005)

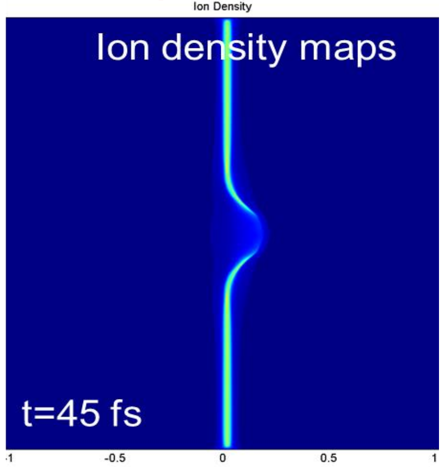


Circular polarization

Role of target transparency

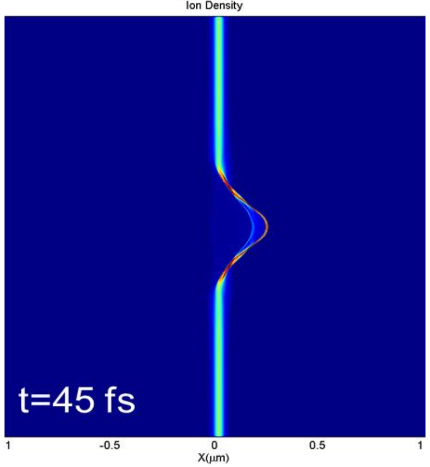


Linear polarisation



Transparency-ion acceleration

Circular polarisation



Radiation pressure acceleration

For an electrons oscillating in an intense field:

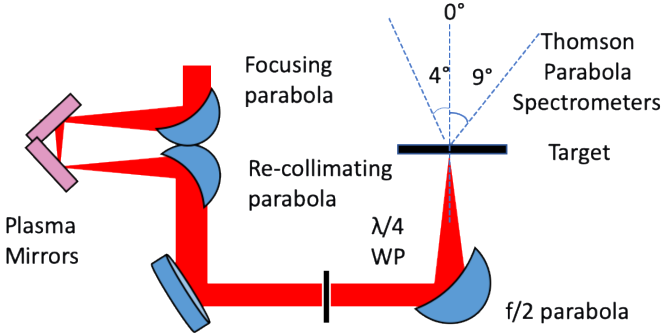
$$m_e = \gamma m_{e,0} \qquad \gamma = \sqrt{1 - \frac{v_{os}^2}{c^2}} = \gamma(I)$$

$$n_c = \frac{\varepsilon_0 m_e \omega^2}{e^2} \Rightarrow n_c^* = \gamma n_{c,0}$$

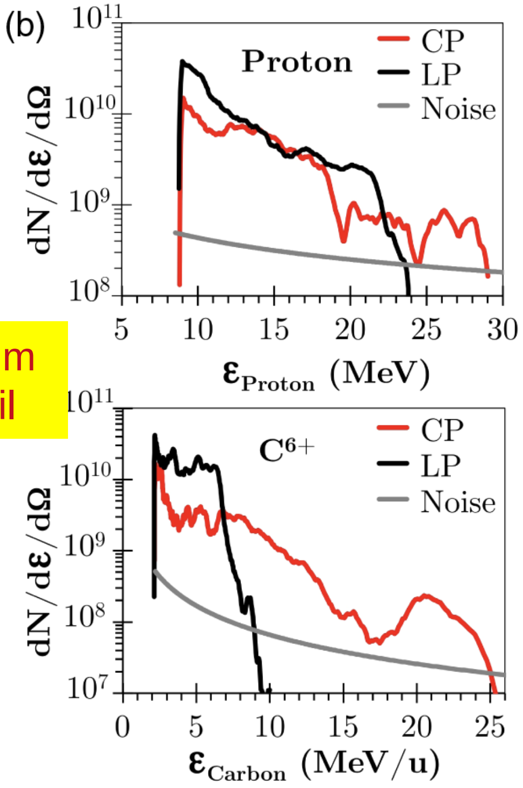
A decompressing foil will become transparent at the time at which the peak density equals $\gamma n_{c,0}$

Experiments with ultrathin foils – efficient Carbon acceleration

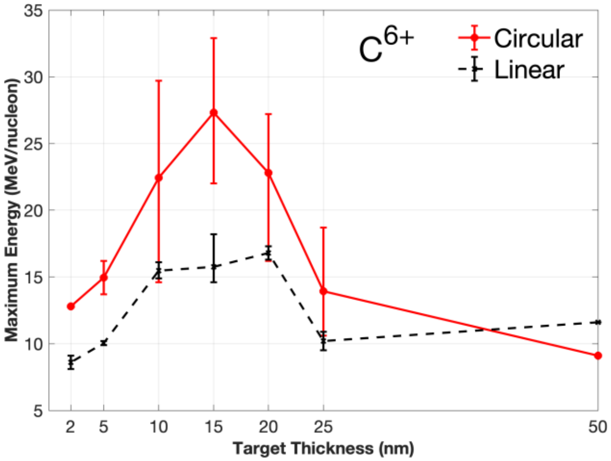
C. Scullion et al, PRL, **119**, 054801 (2018)
A. McIlvenny et al, PRL, **127**, 194801 (2021)



GEMINI: 40 fs, 6 J, ~ 5 10^{20} W/cm^2, plasma mirror for contrast enhancement, polarization control



10 nm
C foil



Optimum target thickness
for Carbon acceleration

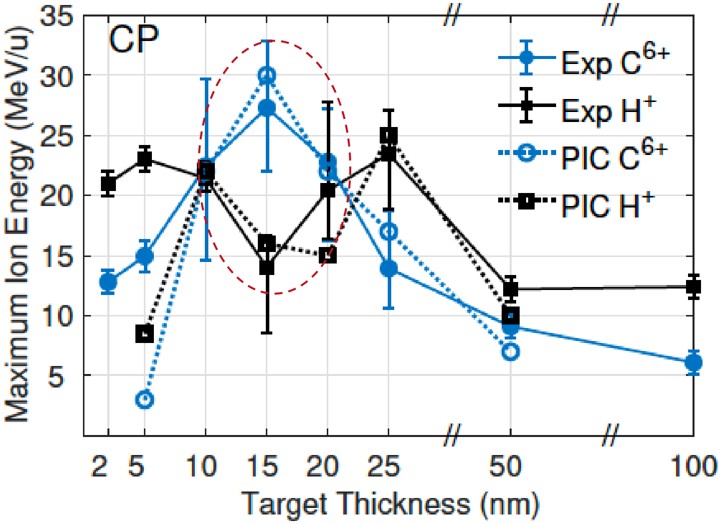
Optimum thickness for LS-RPA:

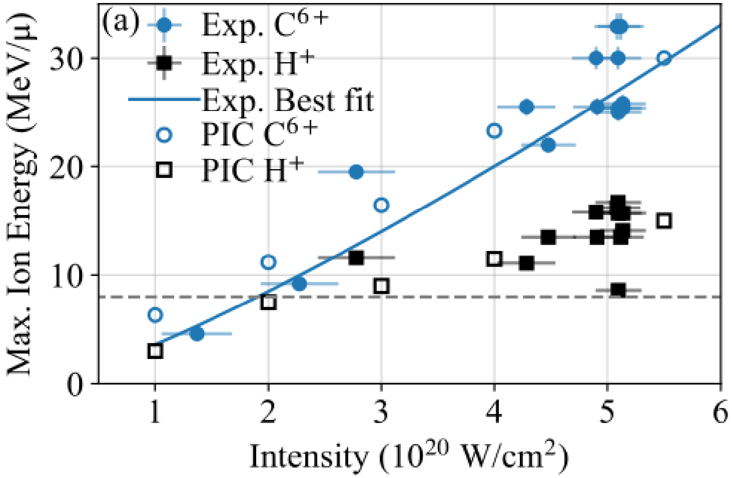
$$\eta \approx \pi \frac{n_0}{n_c}\frac{\ell}{\lambda} \sim a_0$$

- **Strong dependence on polarization, onset of Light Sail acceleration**
- **Circular polarization leads to reduced heating and delayed transparency**
- **Existence of an intensity dependence, optimum target thickness**

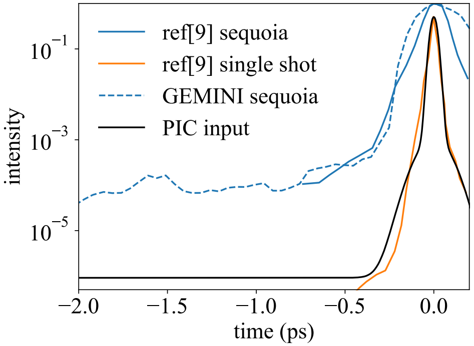
"Proton-free" high- energy carbon beams

A. McIlvenny *et al*, PRL, **127**, 194801 (2021)





At the optimum thickness, precursor energy leads to pre-expansion of protons, which are not accelerated efficiently.

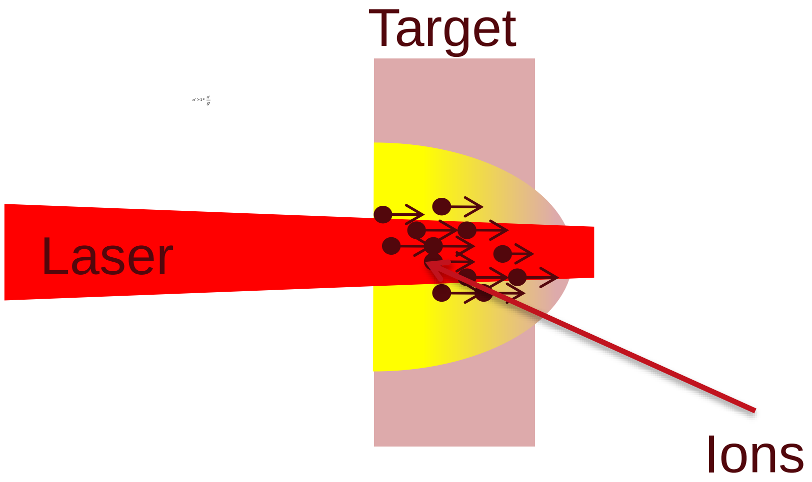


Modelling the laser rising edge on ps time scales is key to understanding the different species dynamics

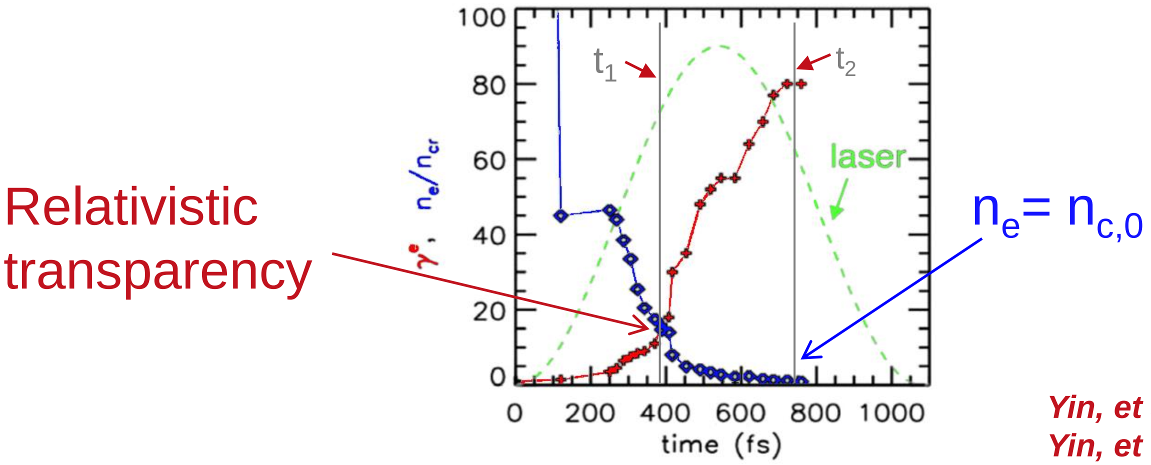
Possibility of **pure Carbon** acceleration at high energy

Application to Carbon radiobiology: P. Chaudhary et al, PMB, 68, 025015 (2023)

Ion acceleration in the relativistic transparency regime



- ☐ Thin targets <<1μm
- ☐ Acceleration from bulk/volume
- ☐ Mainly effective with ps/100s fs pulses
- ☐ Linearly polarized pulses

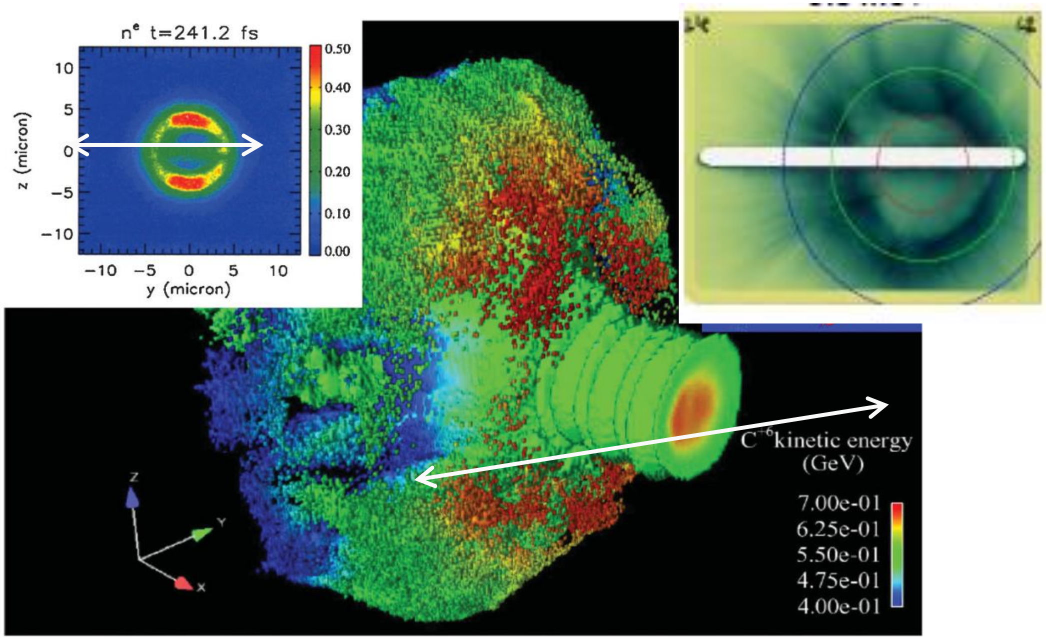


If the laser intensity peaks just after transparency, an enhanced electron heating, and an enhanced coupling of energy into ions is observed. A name initially used for this regime was Break Out Afterburner (BOA)

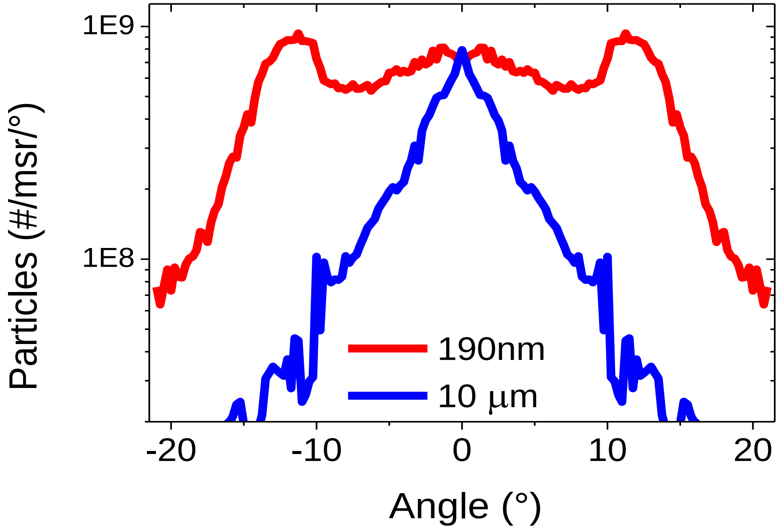
Yin, et al., Laser and Particle Beams 24 (2006),
Yin, et al., Phys. Rev. Lett. 107, 045003 (2011)
Yin, et al., Phys. Plasmas 18, 063103 (2011)

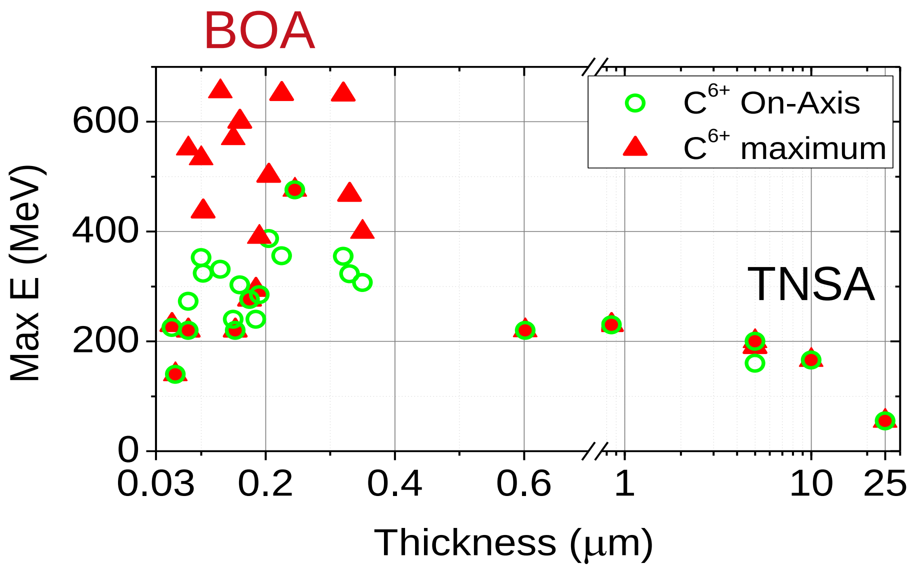
Ion lobes and azimuthal symmetry in BOA

LANL, US



[1]L. Yin, et al., Phys. Rev. Lett. 107, 045003 (2011)





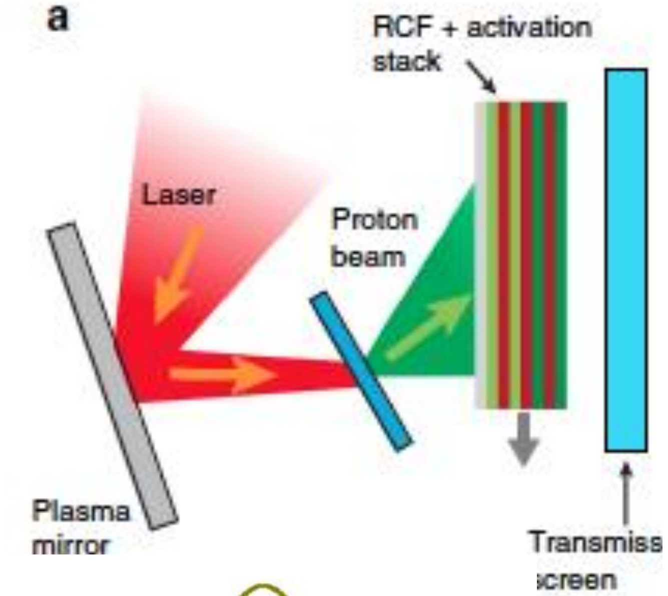
This regime is characterized by a ring-like angular profile with off-axis energy maxima, which are thickness dependent for fixed laser conditions.

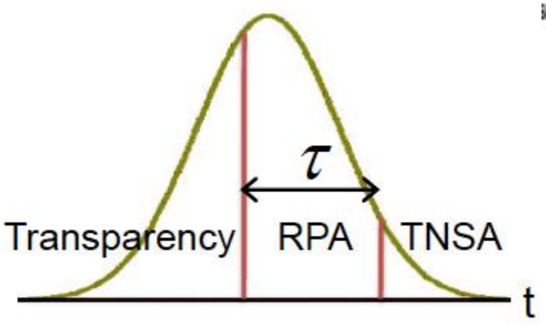
Spectra are broadband and continuous.

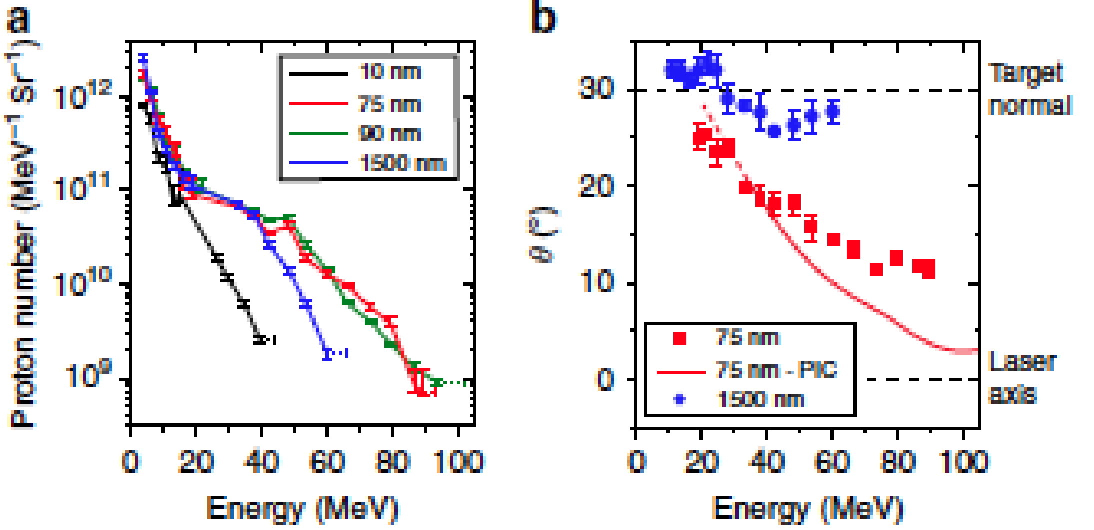
D.Jung *et al*, NJP, **15**, 023007 (2013)

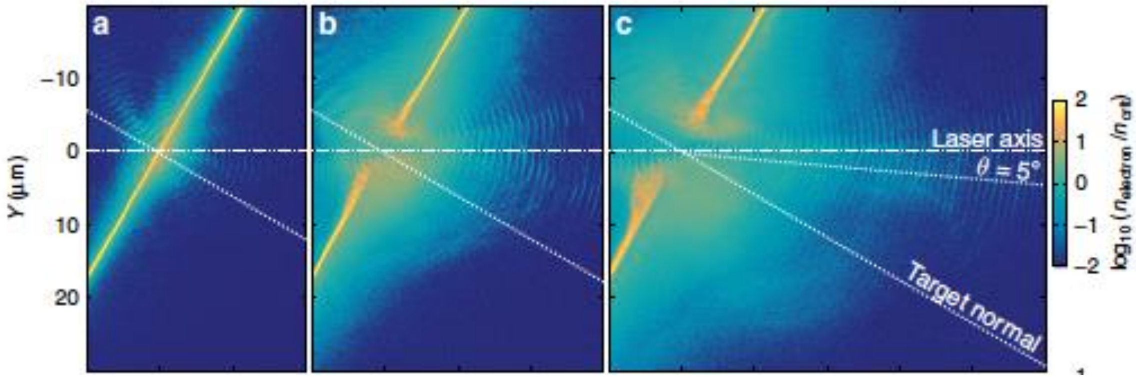
Record energies (~ 100 MeV) obtained through a hybrid scheme (TNSA/RPA+ transparency enhancement)

VULCAN PW laser, ~1 ps, LP, 90 nm CH,





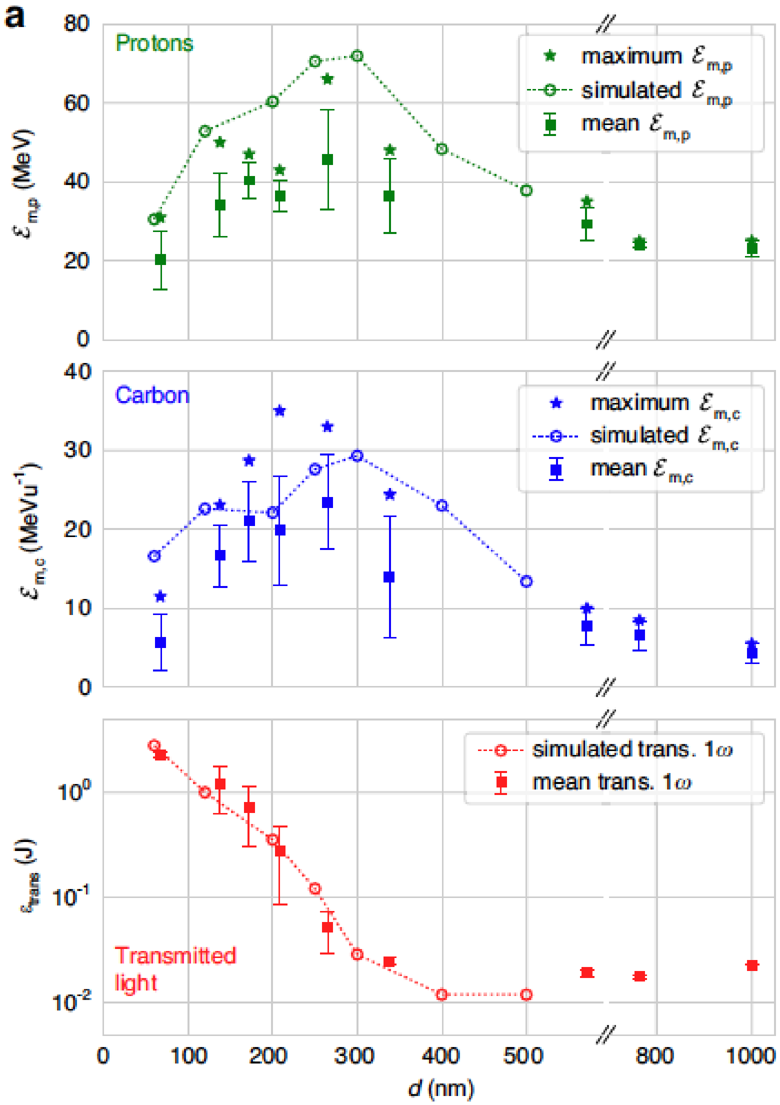




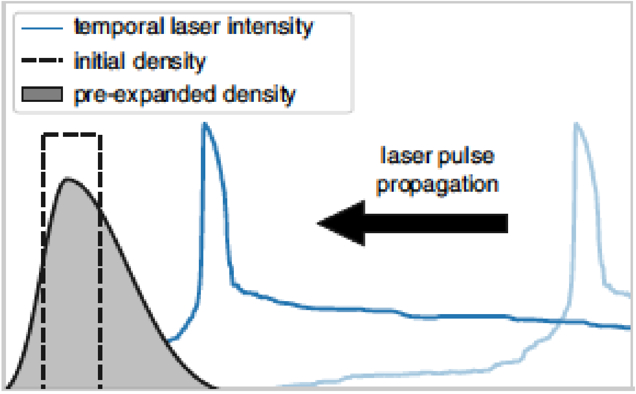
A. Higginson et al, Nature Comm., **9**, 724 (2018)

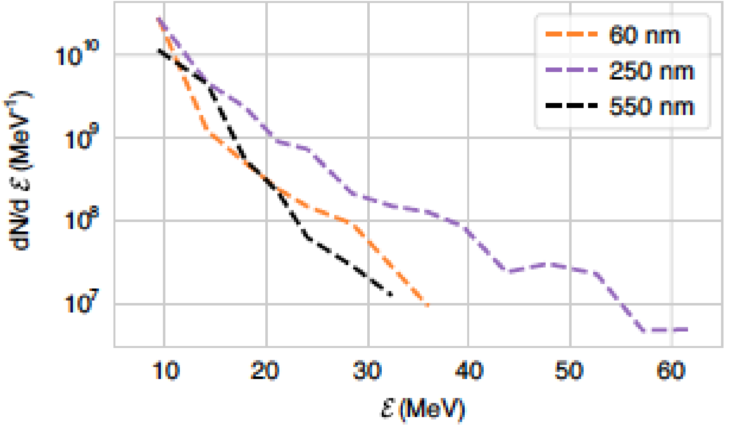
Optimization through controlled pre-expansion also demonstrated with ultrashort pulses

N. Dover et al, Light: Sci App., **12**, 71 (2023)



J-Karen laser, 45 fs, 10 J,
no plasma mirror, linear polarization





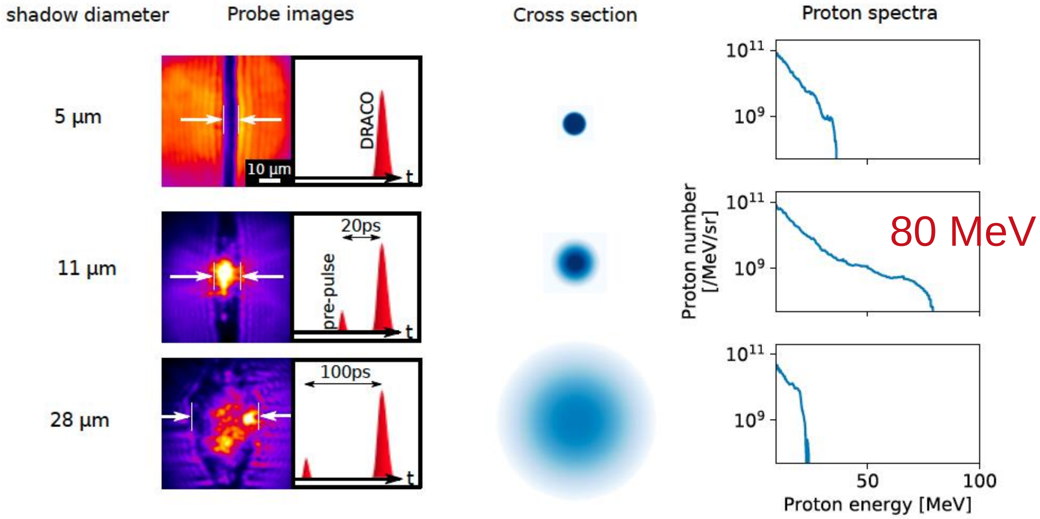
Novel target technology for high repetition operation

Cryogenic targetry

Pure hydrogen target
Continuous flow
Intermediate density ~ 30 n_c

M. Rehwald et al, Nature Comm, **14**, 4009 (2023)

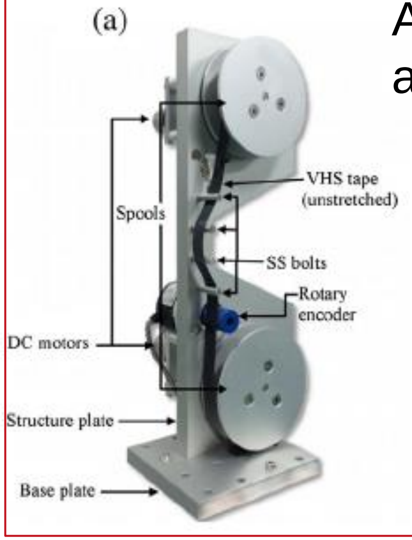
DRACO @ HZDR, 18 J, 5 10^{21} W/cm^2



80 MeV

Mechanism: I. Gothel et al, PPCF, 64, 044010 (2022)

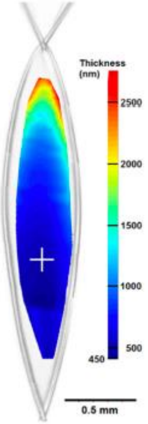
Tape drives



Mechanical refreshment
Automated control
and optimization

B.Loughran *et al*, HPLSE, 11, e35 (2023)

Water jets



~500 nm thick sheets
Low density vapour environment
Enhanced proton energies and collimation

J.T. Morrison et al, NJP, 20, 022001 (2018)

M. Streeter et al, submitted (2023)

Conclusions

- **Laser-driven ion acceleration** is a technology **radically different** from established acceleration methods, with unique properties that are already being exploited for applications using the established **TNSA mechanism**

- The ultrashort time structure of the ion pulses can be exploited for **dose deposition at ultra high dose rates**, and is of particular relevance in the context of the growing interest in FLASH radiotherapy

- We have discussed opportunities for acceleration and delivery of carbon ions (**RPA on ultrathin foils**), conditioning and reacceleration of TNSA protons (coil targets), energy enhancement in transparency regimes.

- Ongoing technological developments (multi-PW systems, 10Hz delivery) promise significant progress in performance of laser-ion accelerators (energy ranges, repetition rate, etc.) which will increase further their application range

Contributors

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