Medium to high Z-ion beams from laser-plasma interactions

M.Borghesi

Centre for Light-Matter Interactions, Queen’s University Belfast (UK)

QUEEN'S UNIVERSITY BELFAST | 180 YEARS

ICIS 2025 OXFORD

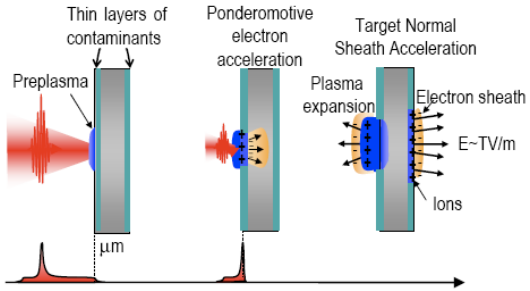
Outline

- Context – laser-driven acceleration
- Surface acceleration: TNSA process
- Bulk acceleration mechanisms
- Experiments on:
  - – carbon acceleration
  - - gold acceleration

Laser-driven ion acceleration : some general points

- Several, fundamentally different mechanisms
- Large accelerating fields sustained by electron-ion separation in a plasma
- Very large fields (up to 10TV/m) applied over very short distances (~μm)
- Interaction mostly with solids/high density targets

Target Normal Sheath Acceleration

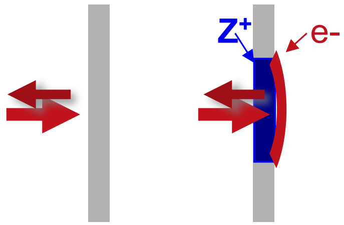


Acting at target surface

Volumetric mechanisms:

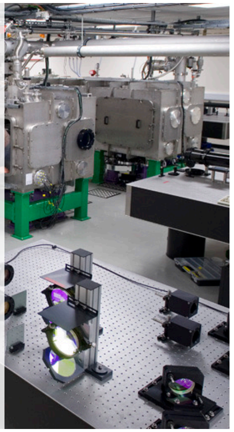
Radiation Pressure Acceleration

Relativistic Transparency Acceleration



Acting on target bulk

What lasers are needed?



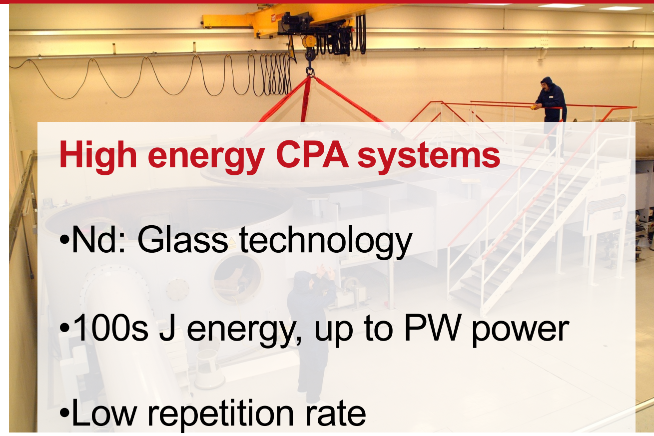
Ultrashort CPA systems

- Ti:Sa technology
- 10s J energy, ~ PW power
- 1-10 Hz repetition
- 10s fs duration
- I_{max}~ up to 10^{21-22} W/cm^2

ASTRA GEMINI, EPAC (RAL, UK)
Draco, HZDR (De)
Pulser I, APRI (Kr)
J-Karen, JAEA (J)
ELI Beamlines
…..

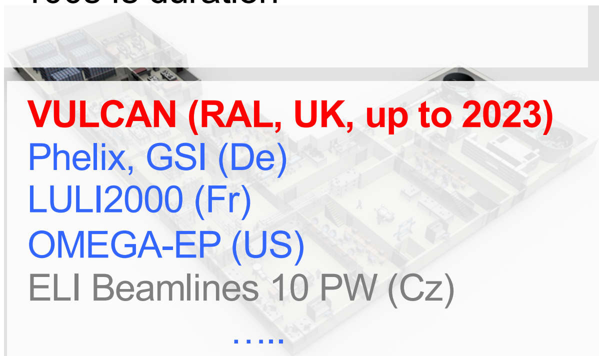
Multi-PW systems:
APOLLON (Fr)
ELI-NP (Ro)
Zeus (US)
CALA (De)
SULF, SG-II, SEL (China)
VULCAN 2020 (UK)
…

I ~ 10^{23-24} W/cm^2



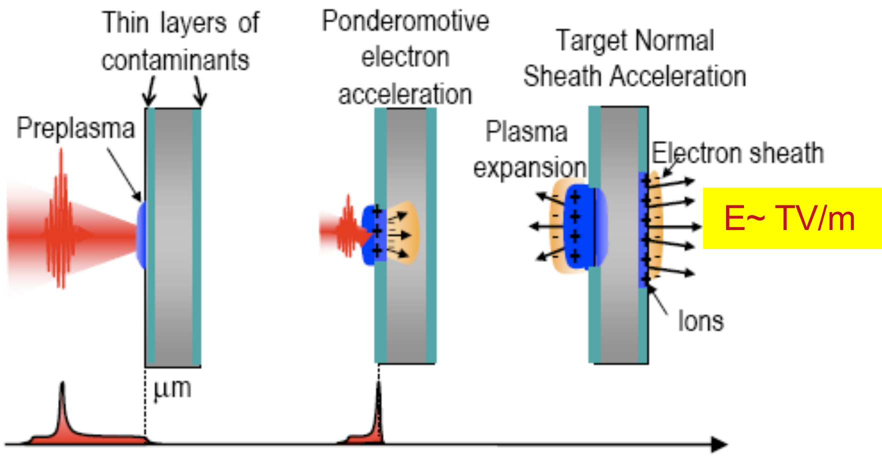
High energy CPA systems

- Nd: Glass technology
- 100s J energy, up to PW power
- Low repetition rate
- 100s fs duration



VULCAN (RAL, UK, up to 2023)
Phelix, GSI (De)
LULI2000 (Fr)
OMEGA-EP (US)
ELI Beamlines 10 PW (Cz)
…..

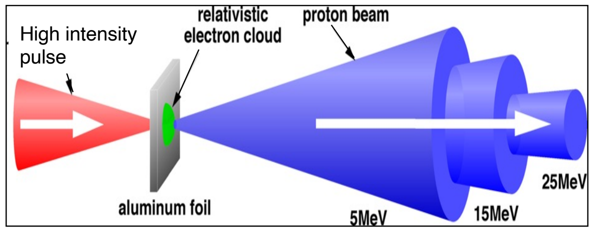
Target Normal Sheath Acceleration (TNSA)



Mechanism acts on ions present at surface:
…surface contaminants! (typically H, C, O)

Protons (higher Z/A) more efficiently accelerated – and shield higher fields from other species

Protons dominate TNSA beams



TNSA proton beam properties

High laminarity

High brightness:

10^{11} –10^{13} protons/ions per shot

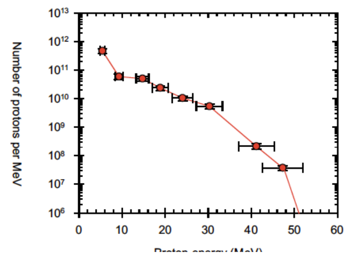
Short duration at source:

bursts with duration ~ ps

Multi-Mev energies:

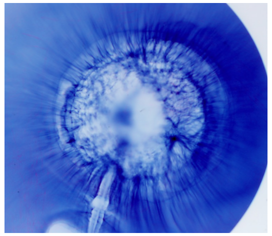
continuum up to 10s of MeV in a divergent beam

E_{max} ~ 85- 100 MeV

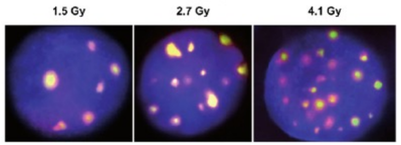


Applications of laser-driven ion beams

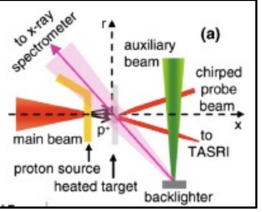
Ultrafast proton radiography



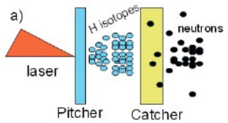
UHDR proton radiobiology



Warm Dense Matter studies



Neutron generation



Higher-Z sources with similar properties would extend application range:

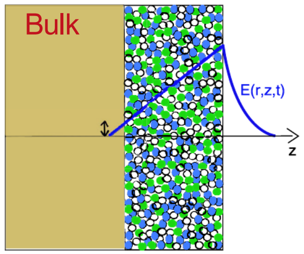
- UDHR ion radiobiology/radiotherapy (e.g. carbon FLASH)
- High Energy density studies
- Nuclear astrophysics (e.g. fission-fusion reaction)
- Inertial Confinement Fusion (Fast Ignition)
- Injection in further acceleration stages

Recent review:

J.Badziak, J. Domanski, Photonics, **12**, 184 (2025)

TNSA acceleration of higher-Z species

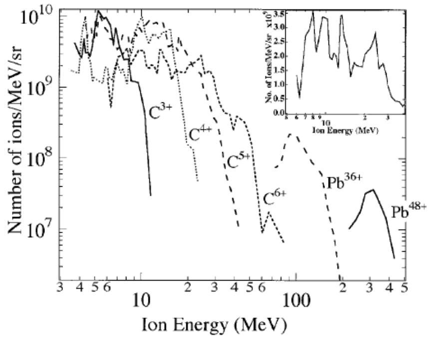
Contaminants



TNSA acceleration of bulk species typically inefficient

$E_{ion}/n << Z/A\ E_{proton}$

$n_{ions} << n_{protons}$



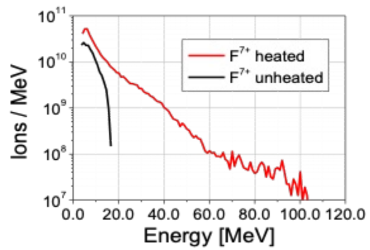
E.L.Clark et al, PRL, 85,1654 (2000)

How to make TNSA acceleration of bulk species more efficient?

- Depletion of contaminant layer (possible at high laser fluence)
- Removal of contaminants

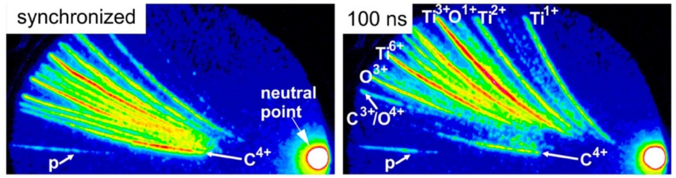
Ohmic target heating

Target: 50 μm W + 1 μm CaF_2



M. Hegelich *et al*, PRL, **89**,085002 (2002)

Laser ablation/ desorption/heating



P. Sommer *et al*, PPCF, **60**, 054002 (2018)
G. Hoffmeister *et al*, Phys. Rev. ST, **16**, 041304 (2013)
S.Kojima *et al,* MRE, **8**, 054002 (2023)
…

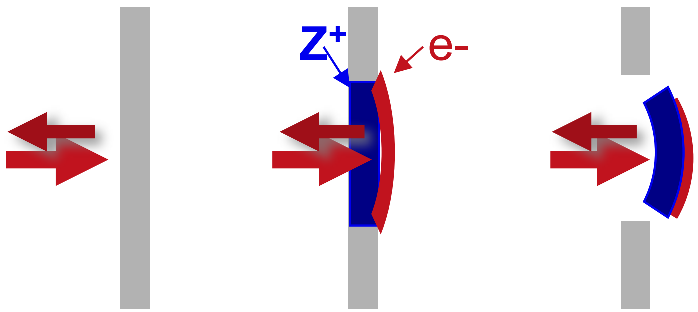
Pulsed, low-energy lasers
CW lasers
Induction heating

} Heating to 100s°

Advanced mechanism accelerate ions directly from the target bulk

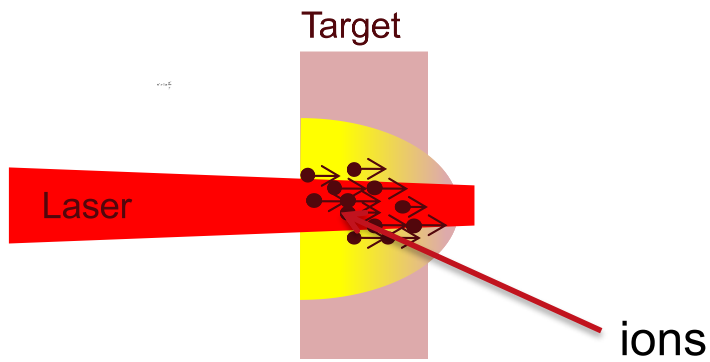
Volumetric acceleration processes employing ultrathin foils (~10s-100s of nm thick)

Radiation Pressure acceleration



Pressure applied to opaque target upon reflection

Acceleration in transparent targets



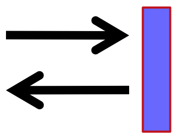
Electron heating and acceleration within the target bulk

Hybrid scenarios combine these two phases in cascade

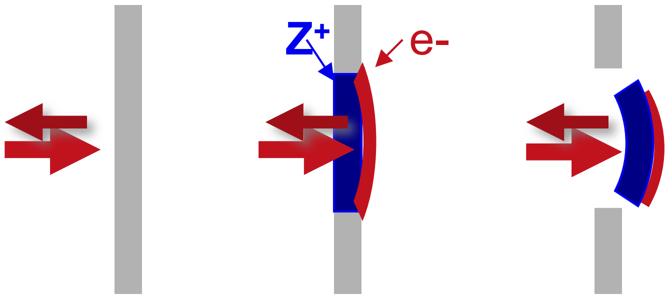
Radiation Pressure Acceleration (RPA)

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**

Momentum conservation ➡ $E_{ions} \sim (I\,\tau/\eta)^2$

Intensity, Time, Areal density

$\eta = m_i n_i d$

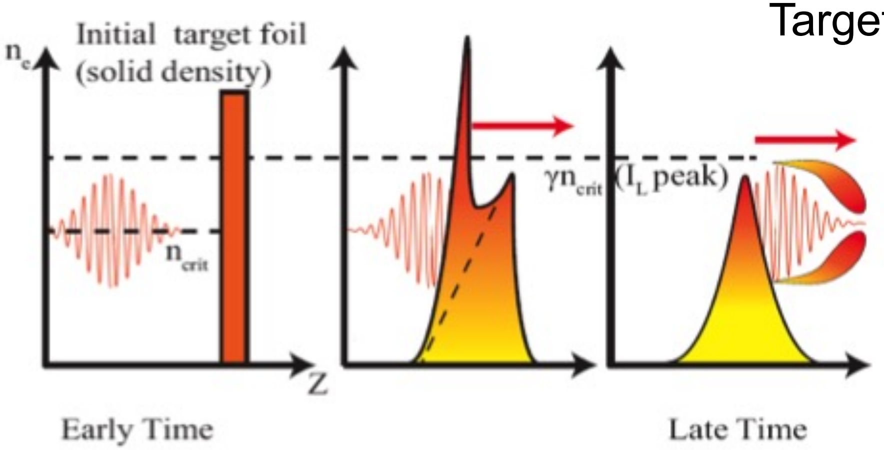
Most efficient with ultrathin foils (nm-scale) – ***Light Sail*** RPA

Target **<u>must stay opaque</u>**

Light sail concept:
In principle equally efficient on all ions

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

Due to electron heating, a thin target will decompress during laser pulse



Target becomes transparent to laser radiation when

$$n_{e,peak} < \gamma n_c$$

Relativistic transparency

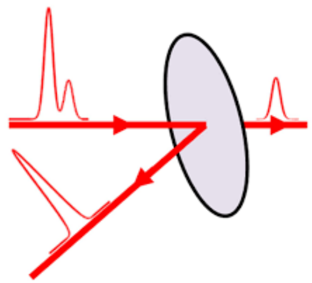
$$n_c = \frac{\varepsilon_0 m_e \omega^2}{e^2}$$ Critical density

$$\gamma = \sqrt{1 - \frac{v_{os}^2}{c^2}} = \gamma(I)$$

Using **circularly polarized laser pulses** reduces significantly electron heating and can delay target transparency, prolonging the radiation pressure acceleration phase

Ideal requirements for RPA:

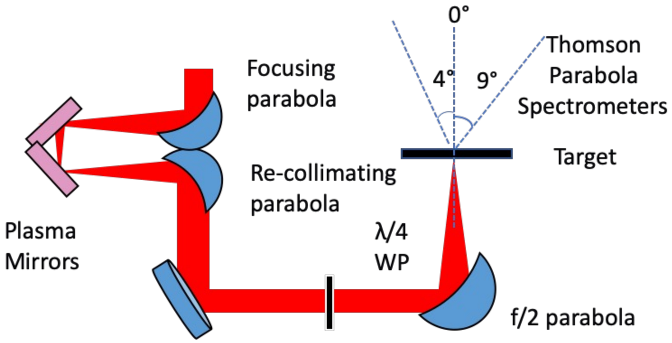
- Ultrathin targets (nm range)
- Very high laser contrast (**plasma mirrors**)
- Normal incidence
- Circular polarization



Experiments with ultrathin foils – efficient Carbon acceleration

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

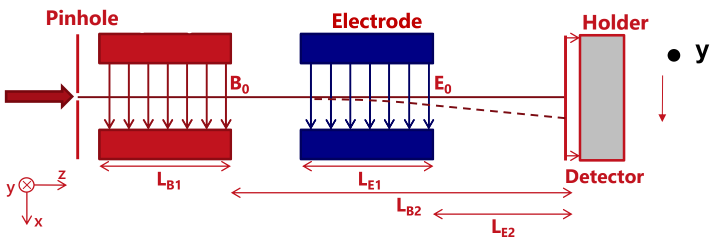
QUEEN'S UNIVERSITY BELFAST



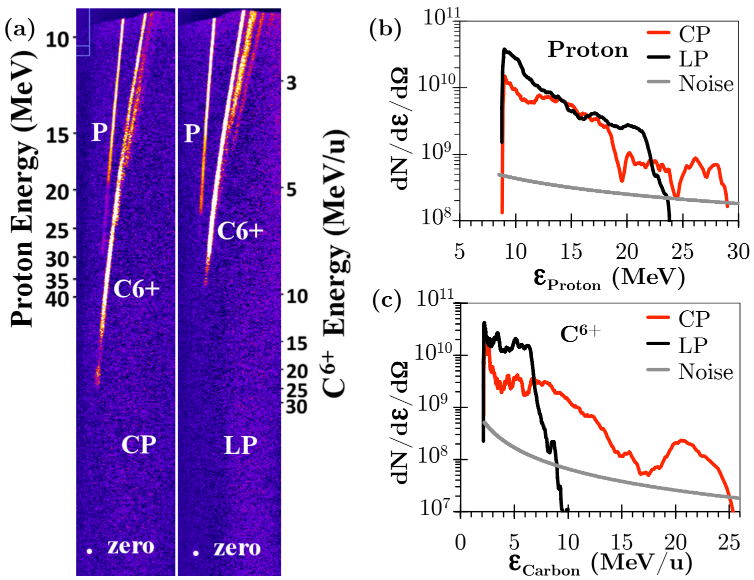
GEMINI laser at CLF/RAL

40 fs, 6 J, ~ 5 10^{20} W/cm², plasma mirror for contrast enhancement, polarization control

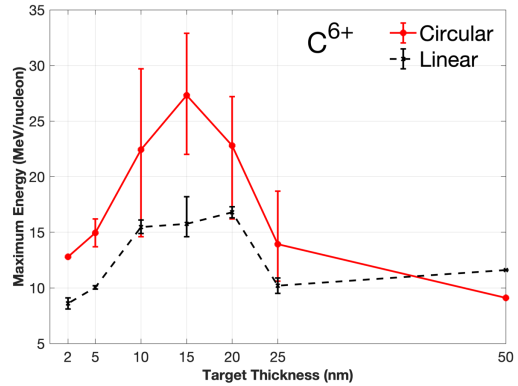
Thomson parabola spectrometer



Amorphous Carbon: 10 nm



Thickness dependence

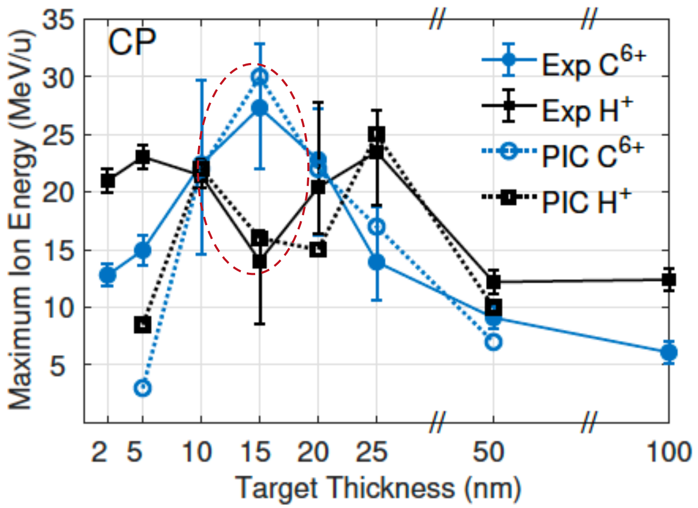


Optimum target thickness for Carbon acceleration

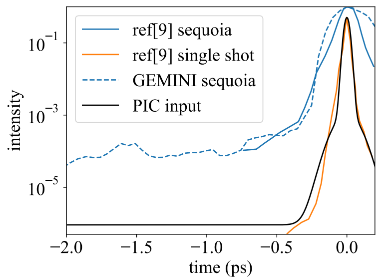
- Strong dependence on polarization
- Circular polarization leads to reduced heating and delayed transparency
- Existence of an intensity dependence, optimum target thickness

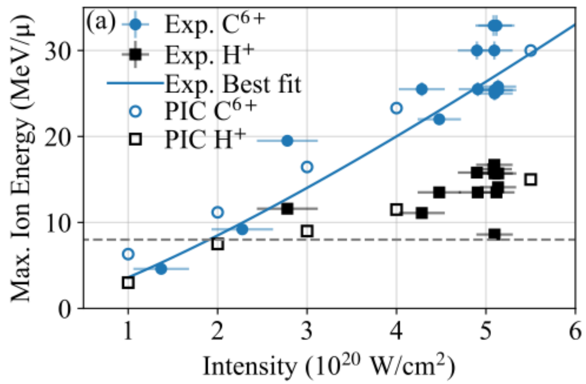
"Proton-free" high- energy carbon beams

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.
(Self-cleaning of target)



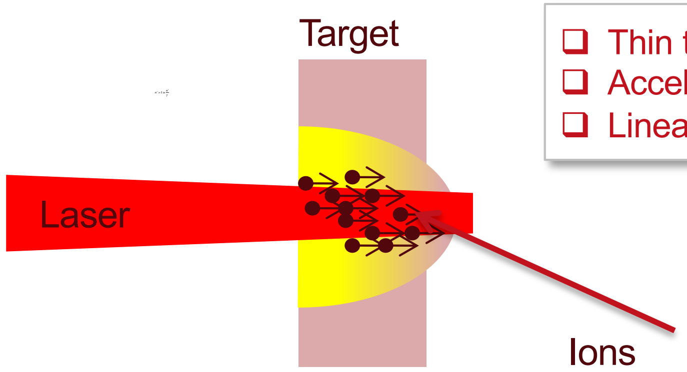


Modelling the laser rising edge on ps time scales is key to understanding the different species dynamics

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

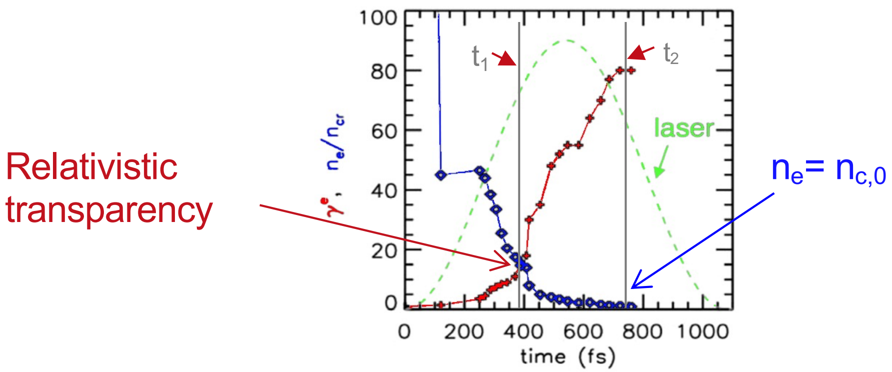
Carbon beam used in radiobiology experiments: P. Chaudhary *et al*, Phys Med Biol. **68**, 025015 (2023)

Relativistic transparency acceleration

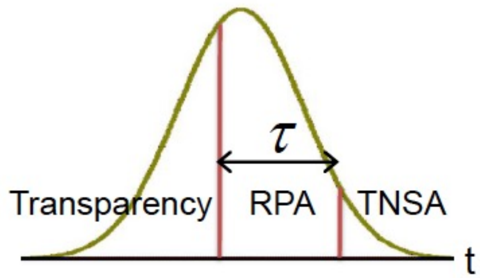


- ❑ Thin targets <<1 μm
- ❑ Acceleration from bulk/volume
- ❑ Linearly polarized pulses

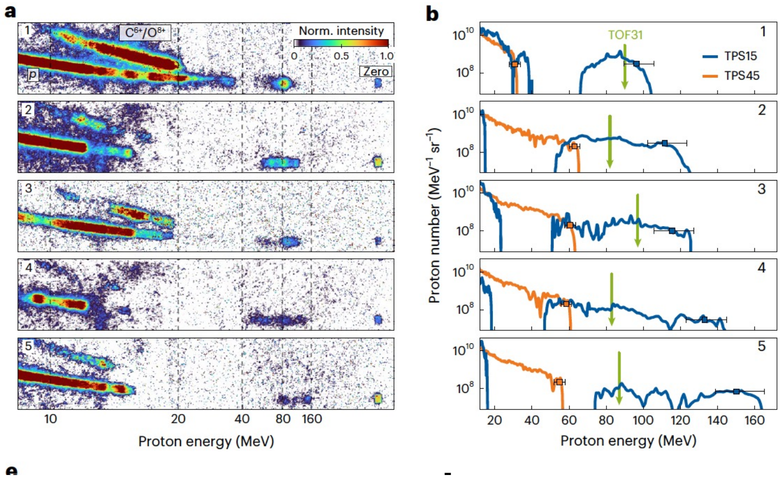
- Tailored foil expansion by varying target thickness
- Relativistic transparency close to peak of the pulse
- Efficient coupling to electrons in dense plasma
- Enhancement of accelerating fields



In a realistic scenario, acceleration often consists of a *cascade* of multiple mechanisms

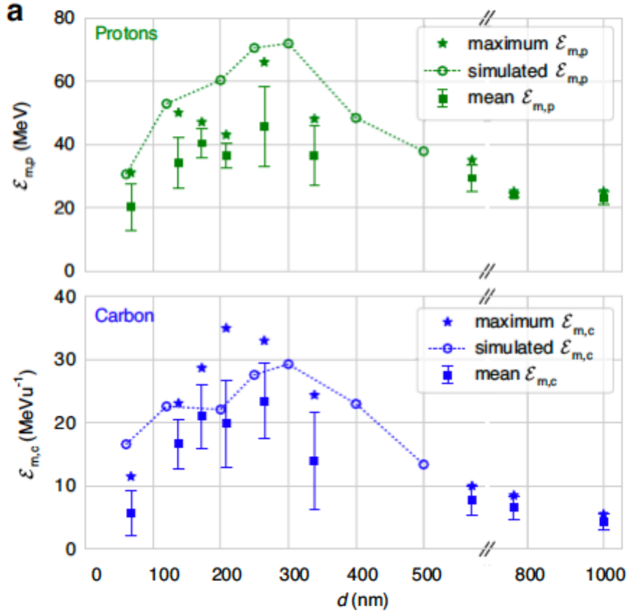


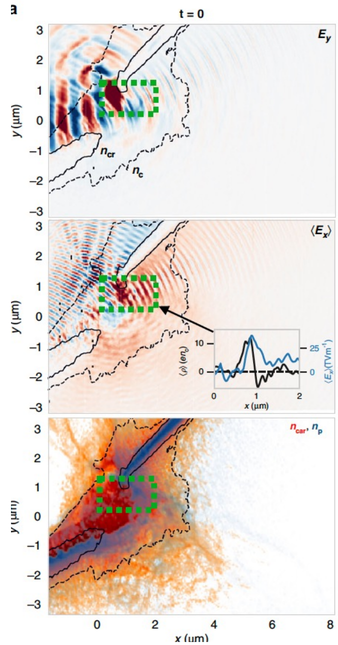
Hybrid processes lead to efficient multispecies acceleration



Record 150 MeV proton energy on DRACO PW pulse (Dresden), from 150 nm CH foil
Single plasma mirror
Most proton energy gained in transparency phase

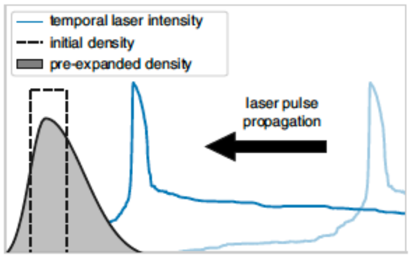
T. Ziegler *et al*, Nature Phys, **20**, 10138 (2024)





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

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

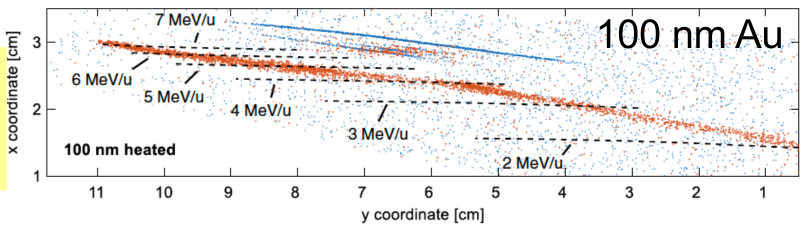


Acceleration of very heavy ions (e.g. Au) can also be achieved

Some challenges:
Limited ionization
Low Z/A
High density
Multiple ions with different Z*

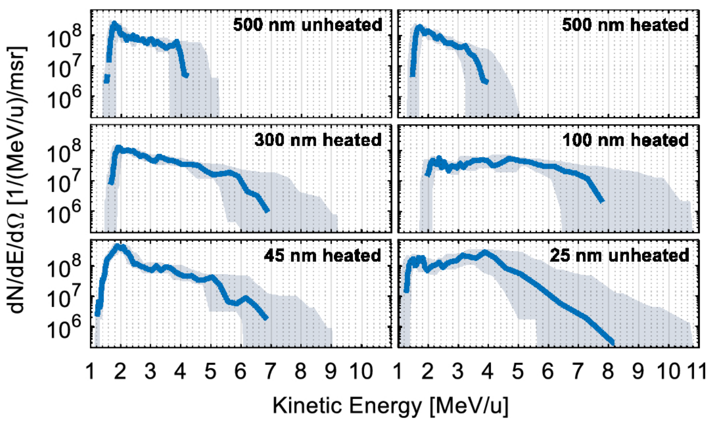
Au Z=79
A=197

F.H. Lindner et al, Sci. Rep., 12,4784 (2022)

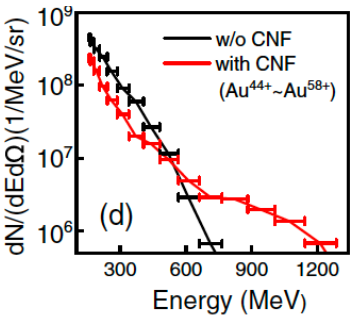


PHELIX (GSI, De)

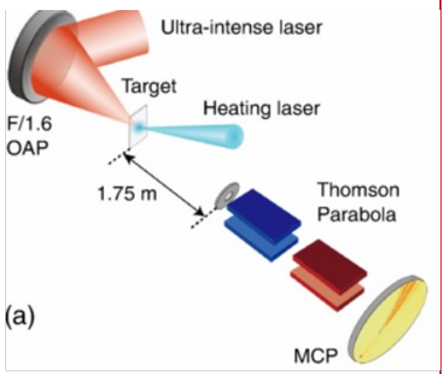
180 J, 500 fs, 2 10^{20} W/cm^2



P. Wang et al, PRX, **11**, 021049 (2021)

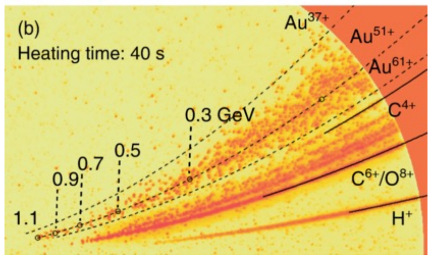


150 nm Au foils



CORELS (Kr)

15J, 22 fs,
10^{22} Wcm^2
High contrast (DPM)



CW target heating

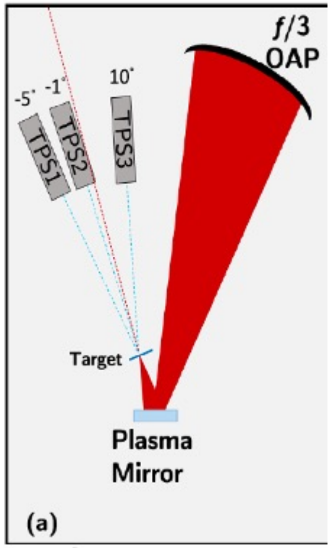
Au acceleration on VULCAN laser

P. Martin *et al*, Commun. Phys., **7**,3 (2024)

VULCAN PW laser. (RAL, CLF)

180 J , 800 fs, 3 10^{20} W/cm^2

Contrast cleaning (Plasma mirror)

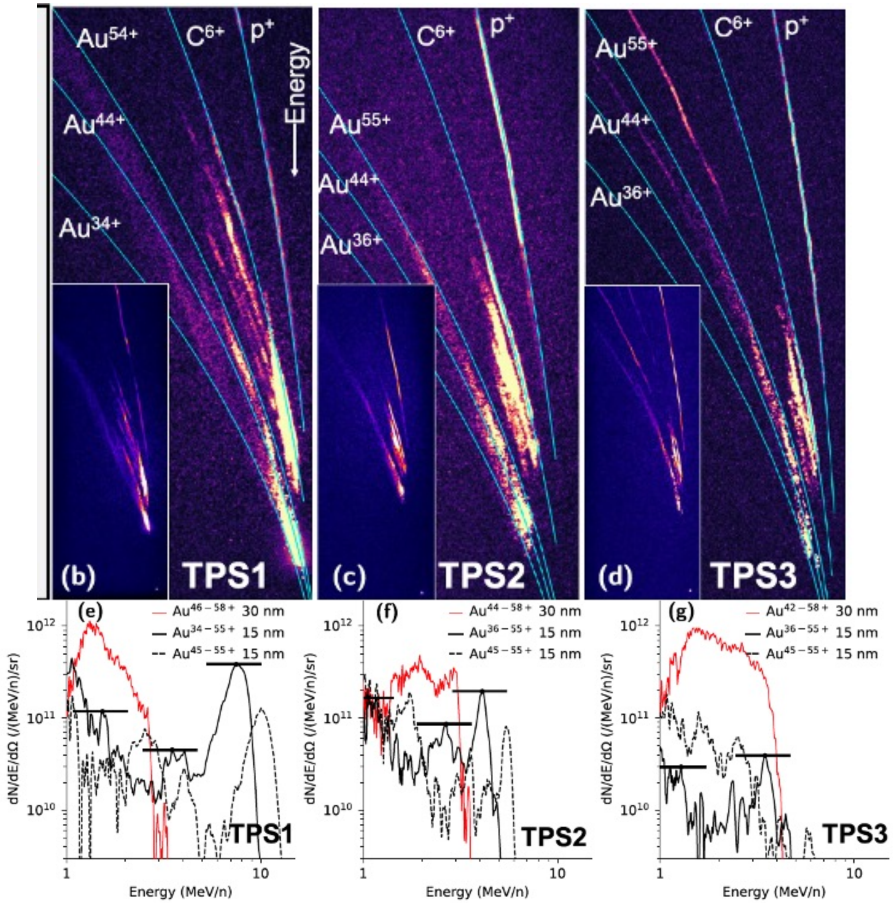


15-30 nm Au foils

High energy Au (up to 10 MeV/n ~ **2 GeV**)

Strong spectral bunching

Very high-flux, collimated Au beamlet (2-3 order of magnitude higher than other work)

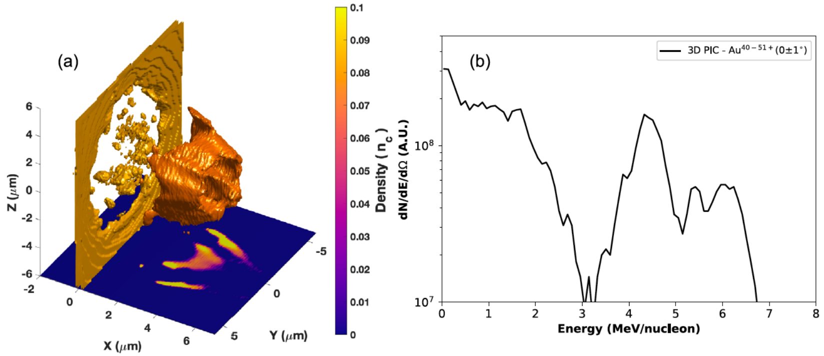


Particle in Cell simulations clarify acceleration process

P. Martin *et al*, Commun. Phys., **7**,3 (2024)

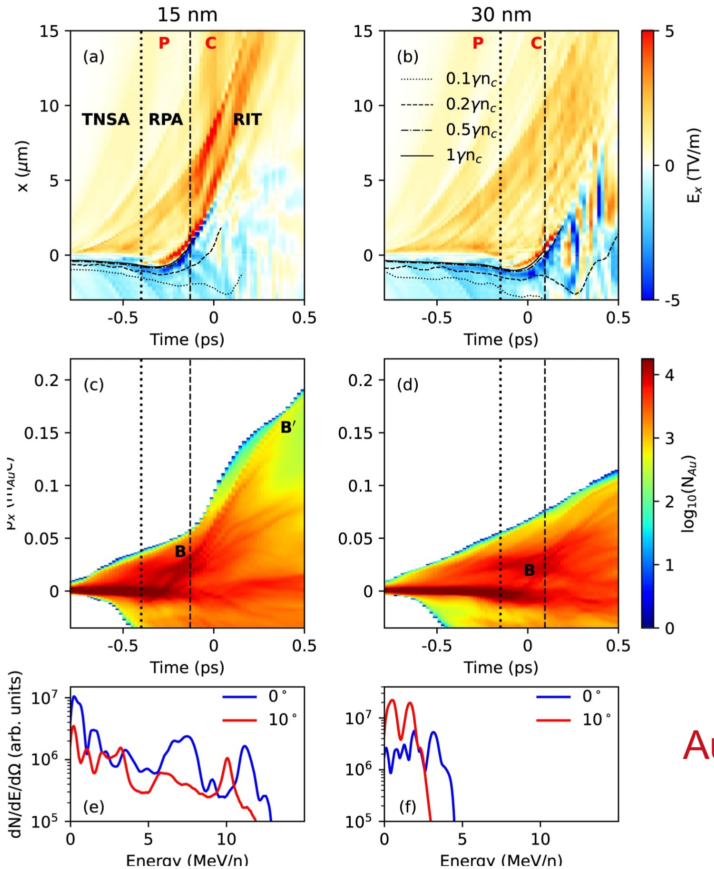
QUEEN'S UNIVERSITY BELFAST

3D PIC, EPOCH



3 phases to acceleration process:

- TNSA acts to remove light ions from the central target region (self-cleaning)
- Radiation pressure bunches high-Z gold ions
- Relativistic transparency phase leads to major energy gain



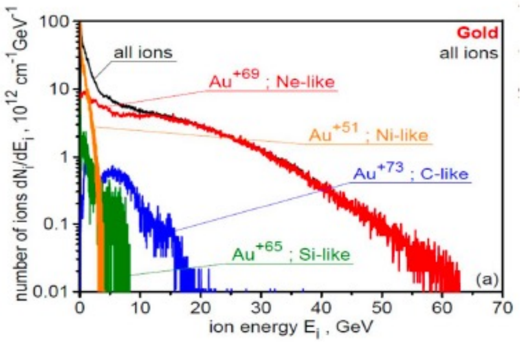
Accelerating field along x vs time

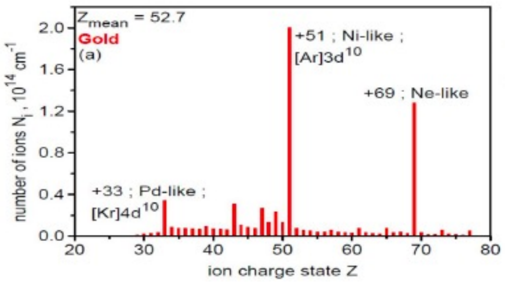
Au-ion momentum vs time

Au energy spectra

Predictions for 10 PW laser pulses

2D3V PIC simulations for 30 fs pulse at 10^{23} W/cm^{2}, circular polarization, 3µm FHWM focal spot

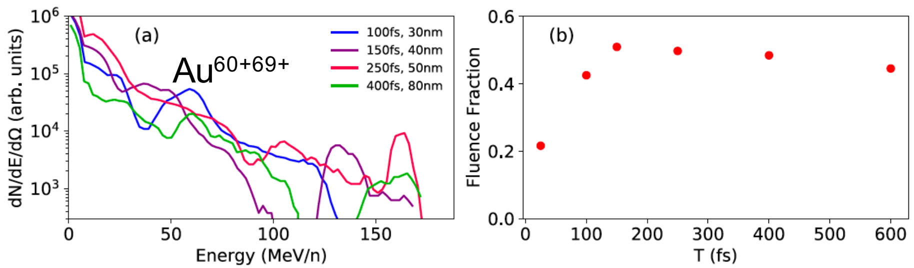




50 nm Au targets

J.Badziak, J. Domanski, Photonics, **12**, 184 (2025)

10 PW pulse (25 fs, 250 J) stretched to longer pulse duration and optimizing target thickness - 2D PIC simulations



- Dense bunches appear in coincidence with extended RPA phase
- Energies overestimated due to reduced dimensionality, but 10s GeV Au with spectral bunches are a reasonable prediction

P. Martin *et al*, Commun. Phys., **7**,3 (2024)

Summary

- Laser-acceleration is a versatile approach for accelerating ions of very different charge and mass
- Established sheath acceleration techniques (TNSA), mostly active on proton contaminants, typically require surface cleaning techniques for accelerating efficiently higher-Z ions
- Volumetric acceleration processes emerging with ultrahigh laser intensities and ultrathin targets allow more efficient energy coupling to the bulk ions
- Current PW systems allow high-flux, ~ GeV level acceleration for medium and high-Z species, with opportunity for progressing to 10s of GeV energies with 10 PW lasers

Acknowledgements

QUB: *S. Kar, A. McCay, D.Molloy, C. Scullion, A.McIlvenny, P. Martin, L.McCollum, F. Hanton, D. Gwynne*

INO-CNR : *A. Macchi*
LULI- Ecole Polytechnique: *L. Romagnani*
ELI-NP *: D. Doria*
CLF STFC*: H. Ahmed, J.Green*
STRATHCLYDE**:** *D.McLellan, P.McKenna*

LASERS 4 EU

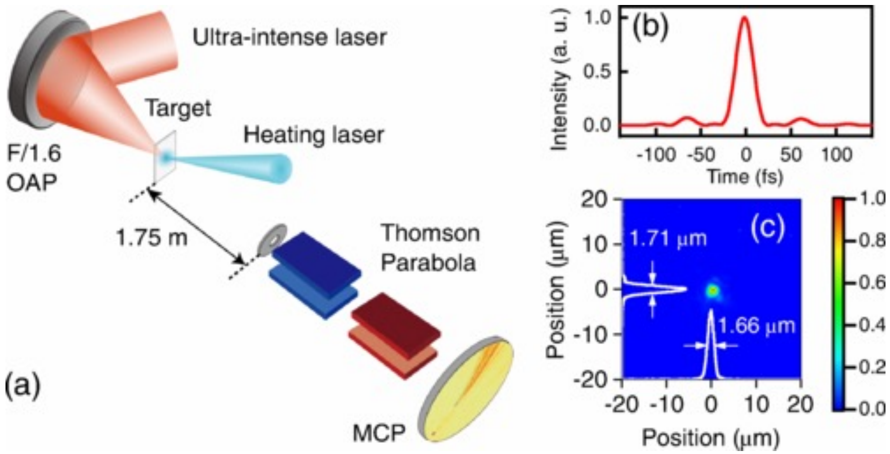
UKRI Engineering and Physical Sciences Research Council

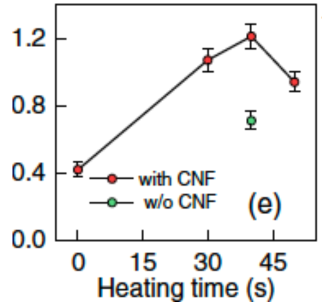
UKRI Science and Technology Facilities Council

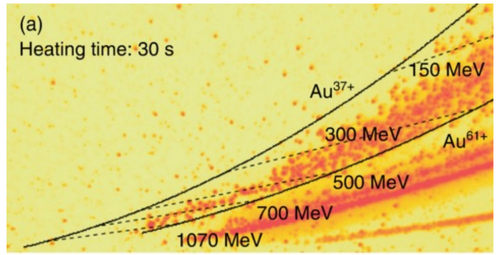
Acceleration of Au ions from thin, heated targets

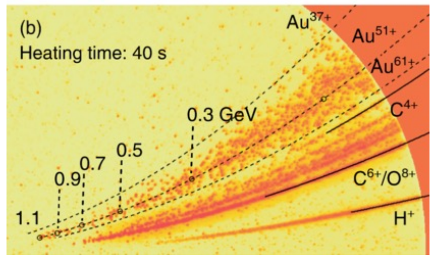
P. Wang et al, PRX, **11**, 021049 (2021)

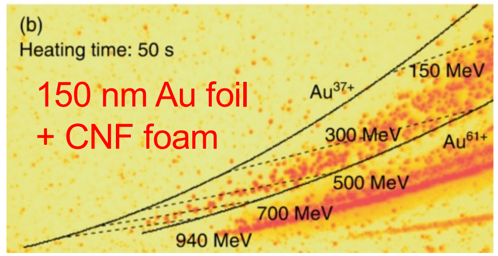
4 PW laser @ CORELS (Gwangju)











15J, 22 fs, 10^{22} Wcm^2

High contrast (DPM)

Heating by CW illumination

Dependence on heating time

TNSA mechanism (?)

Au ionization up to 61+ observed

Maximum Au energies ~ 1.1 GeV