Brief review of high power laser-driven "heavy" ion sources

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LhARA fortnightly meeting, 8th March 2022

Laser driven ion sources

- Heavy ion acceleration from Target Normal Sheath Acceleration (TNSA)

- State-of-the-art in laser ion sources beyond TNSA

- Impact on LhARA R&D

Laser driven ion sources

- **Heavy ion acceleration from Target Normal Sheath Acceleration (TNSA)**

- State-of-the-art in laser ion sources beyond TNSA

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Principle of laser driven ion sources

Target

Laser

Plasma

High energy ions

LASER

TARGET

LASER-ELECTRON COUPLING
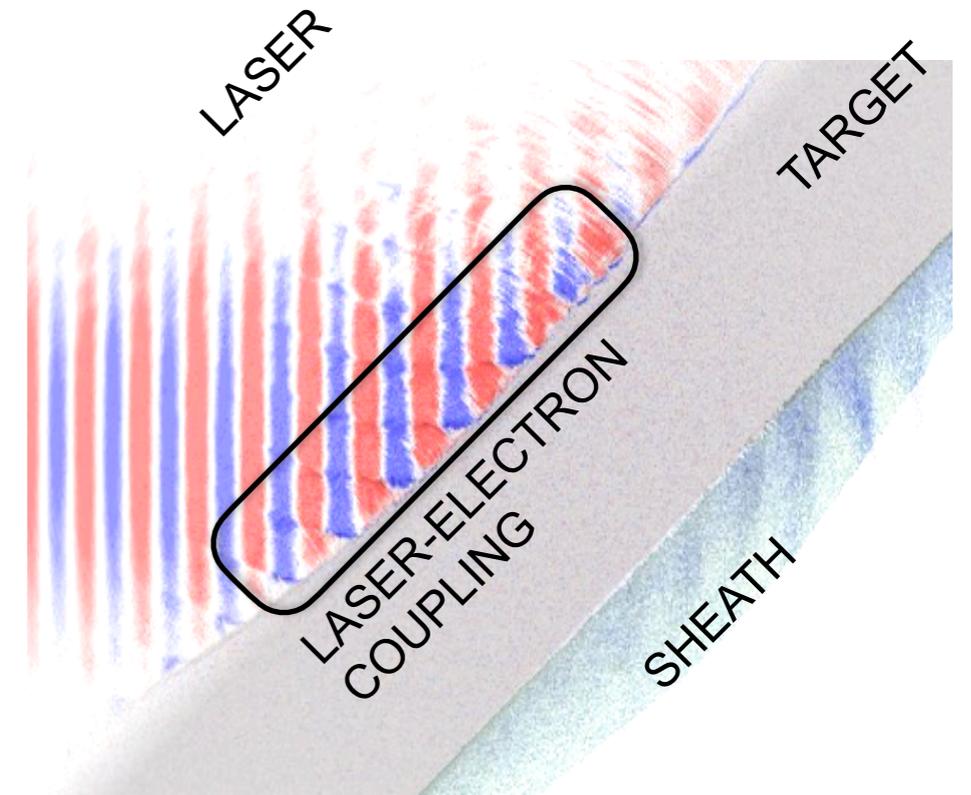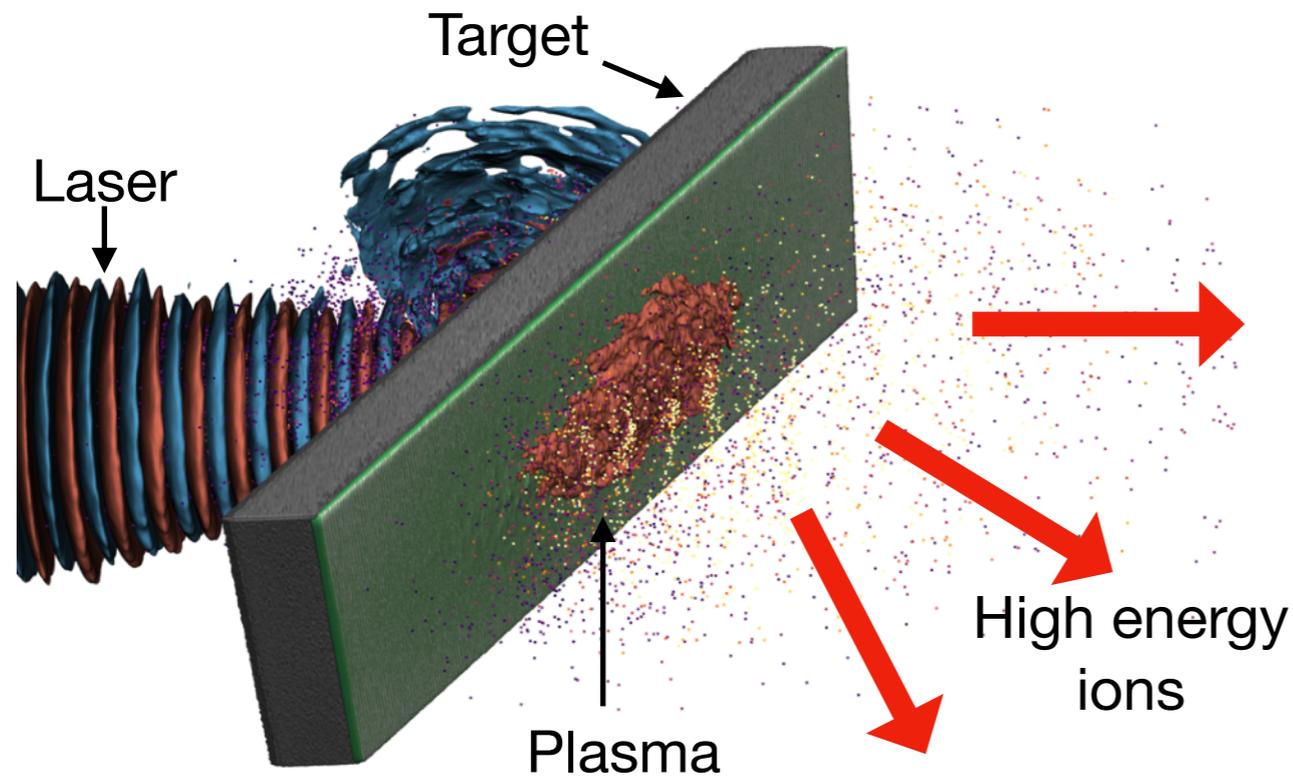
SHEATH

Well understood technique: **target normal sheath acceleration (TNSA)**

Laser electromagnetic fields

Energetic electrons

Sheath electrostatic fields

Accelerated surface ions

Source optimisation involves optimising energy conversion

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Importance of surface contaminants

TNSA only accelerates surface ions!

- Surface contaminants always exist on target foils
  - Typically ~ 1 nm thick
  - Hydrocarbon and water, i.e. a mixture of hydrogen, carbon & oxygen

- Sheath field penetrates short range into surface
  - Shielded by mobile charges in dense plasma
  - Target material typically not exposed to field
  - Hydrogen preferentially accelerated -> high *q/m*
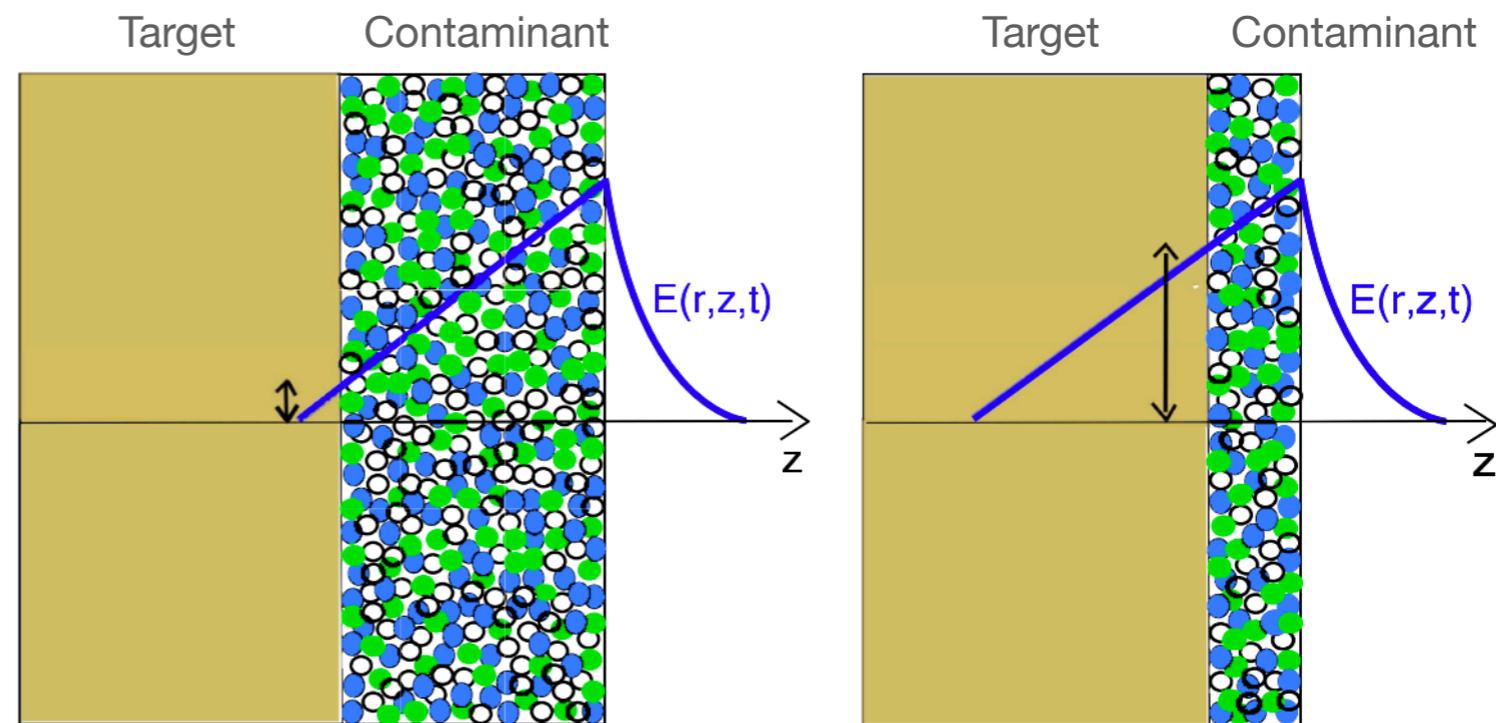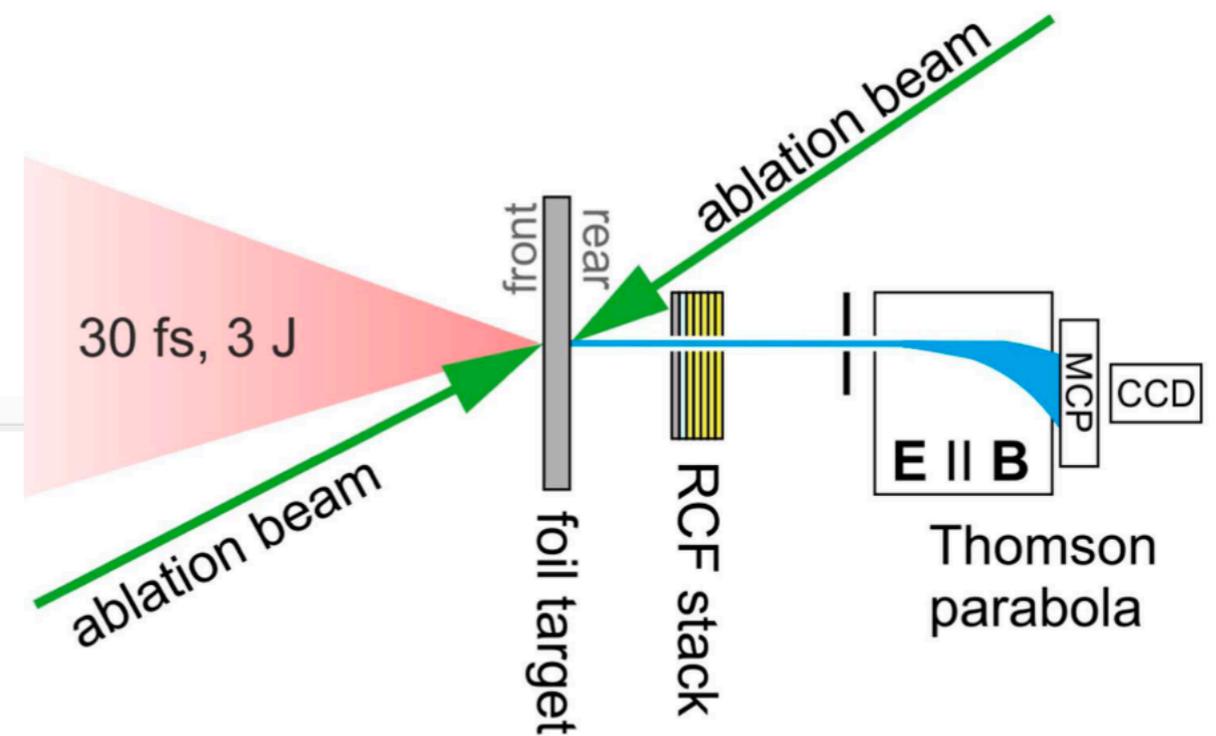

From Hoffmeister et al. PRSTAB 16, 041304 (2013)

Impact of contaminant on ion beam
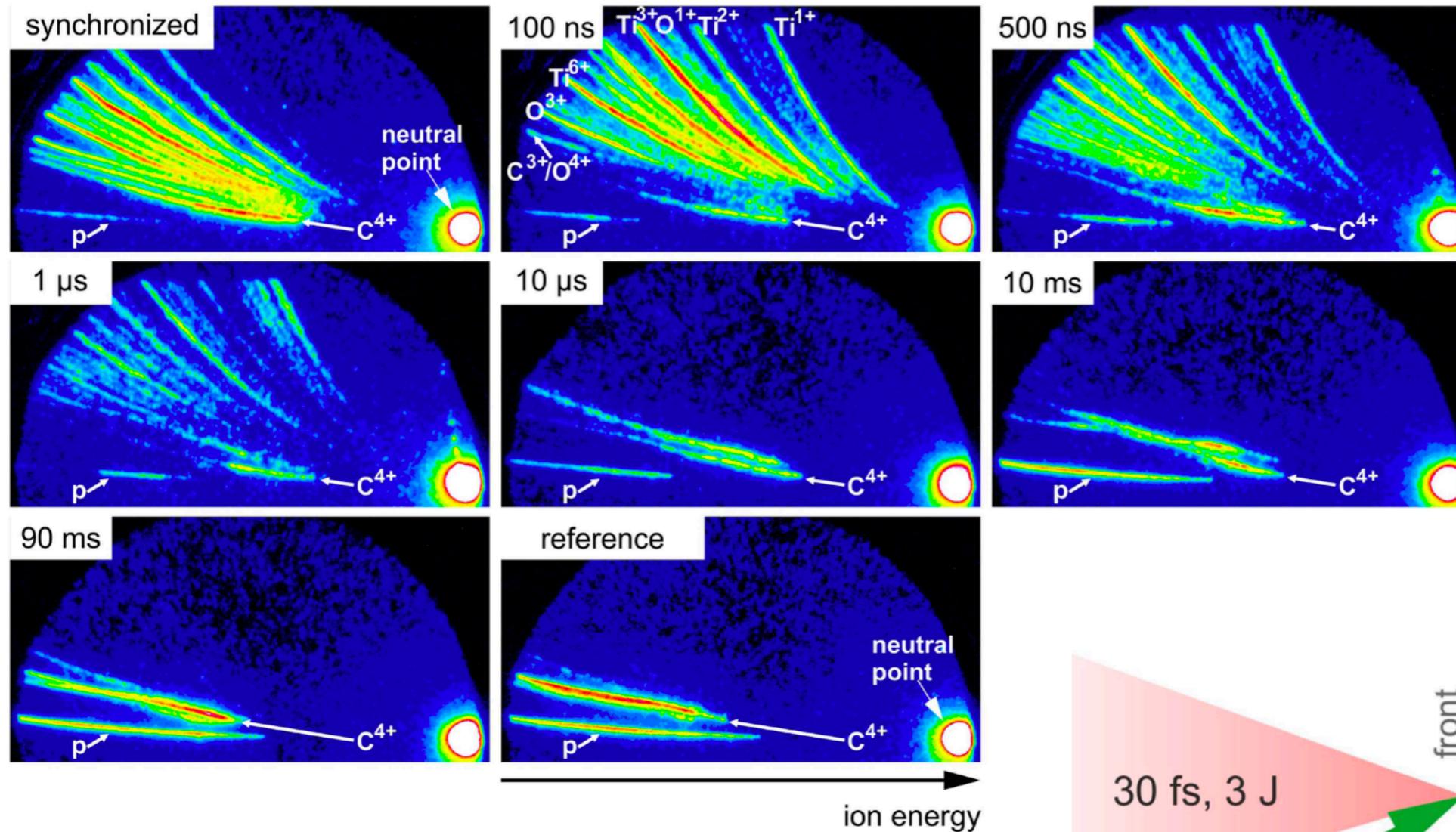
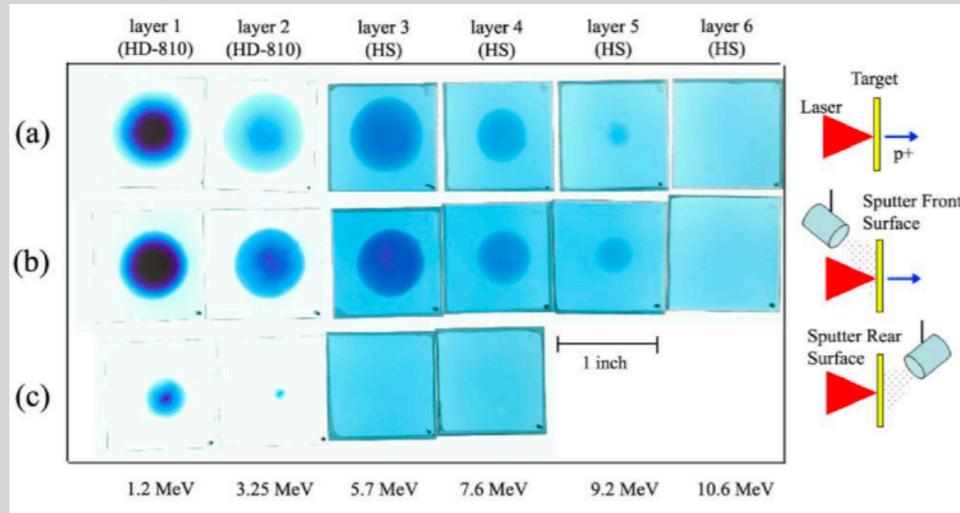From Sommer+ PPCF
60, 054002 (2018)

- Selectively removing contaminants using pulsed laser

- Contaminants resorb on target ~1 μs after removal
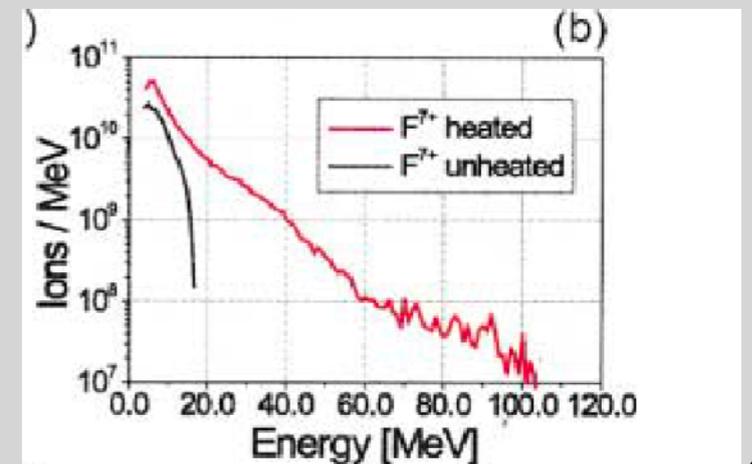
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Techniques to remove contaminants

Sputter gun

e.g. Allen+ PRL 93, 265004 (2004)

Resistive heating

- Heat entire foil by passing through high DC current

e.g. Hegelich+ PRL 89, 8 (2002)

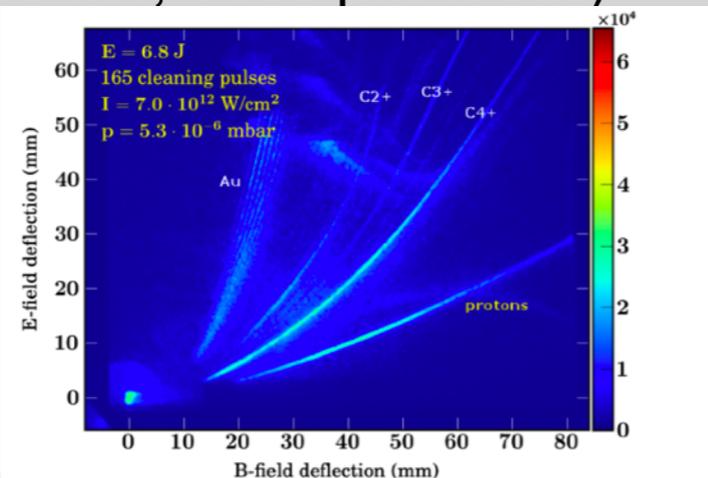
Targeted removal of contaminant

Heat target to "boil off" hydrocarbons - ~1000 K

Pulsed laser cleaning

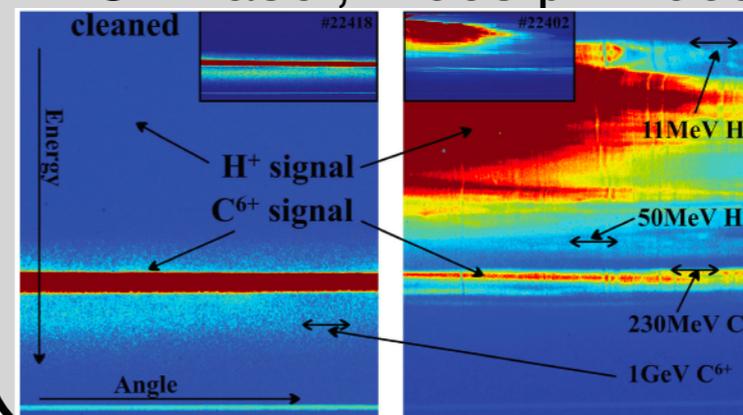- Focus pulsed laser (typically ns or sub-ns, 1-100s mJ, 100s μm focus)

e.g. Sommer+ PPCF 60, 054002 (2018)

e.g. Hoffmeister+ PRSTAB 16, 041304 (2013)

CW laser cleaning

- Heat entire foil by irradiating with ~ 1 W CW laser, 100s μm focus
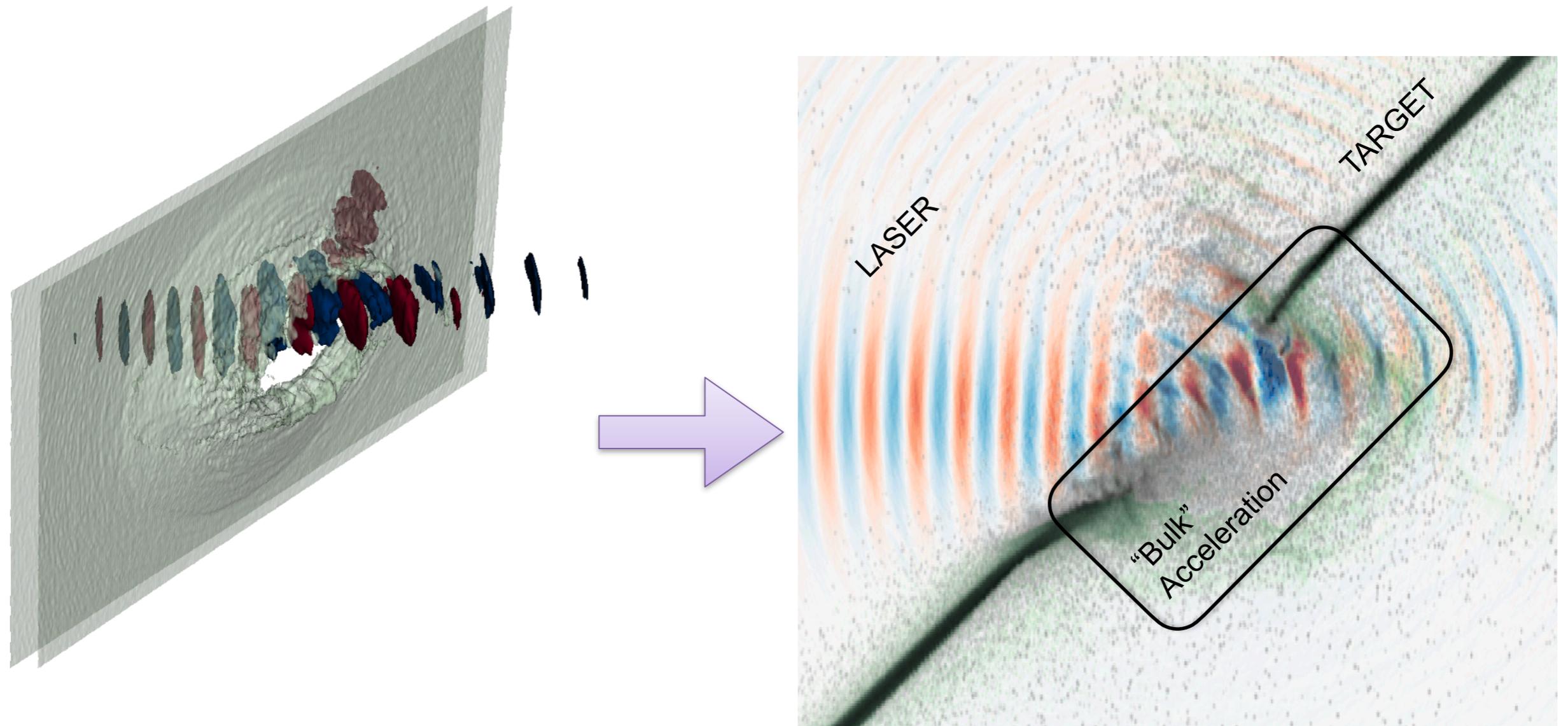

e.g. Safranov+ Phys. Plasmas 25, 103114 (2018)

e.g. Jung+ Phys. Plasmas 20, 083103 (2013)

Laser driven ion sources

- Heavy ion acceleration from Target Normal Sheath Acceleration (TNSA)

- **State-of-the-art in laser ion sources beyond TNSA**

- Impact on LhARA R&D

# Beyond TNSA- volumetric acceleration

- Various schemes to accelerate the target "bulk"
- Typically use ultra-thin (sub 100 nm foils), accelerated via laser radiation pressure or enhanced thermal pressure
- Other schemes use ion accelerating shockwaves traversing low density targets

Demonstration of high energy C⁶⁺ generation

- Higher laser energy leads to higher carbon energies

- Typically maximising energy and flux requires sub-micron foils, ultra-high contrast

- All difficult to do at high repetition rate

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

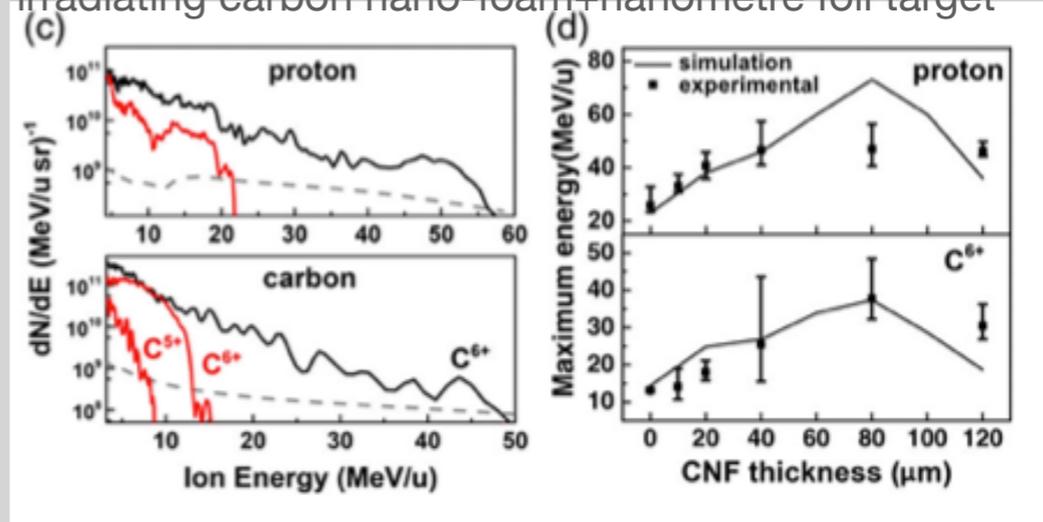>80 MeV/u ions using 100 J class laser irradiating sub-micron foils
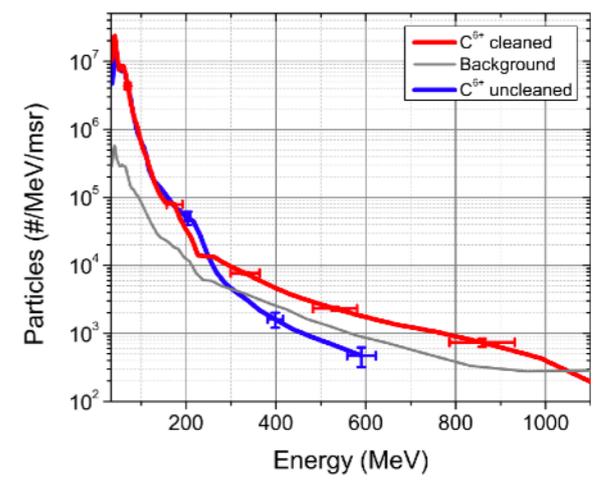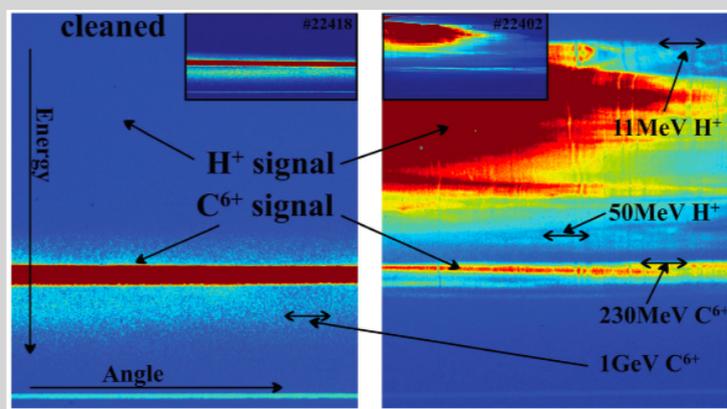
>30 MeV/u using ultra-high contrast 10 J class lasers irradiating ~few nanometre foils
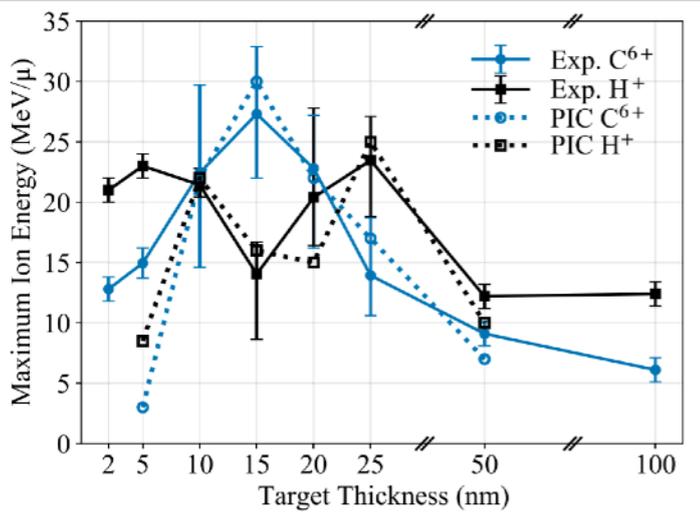
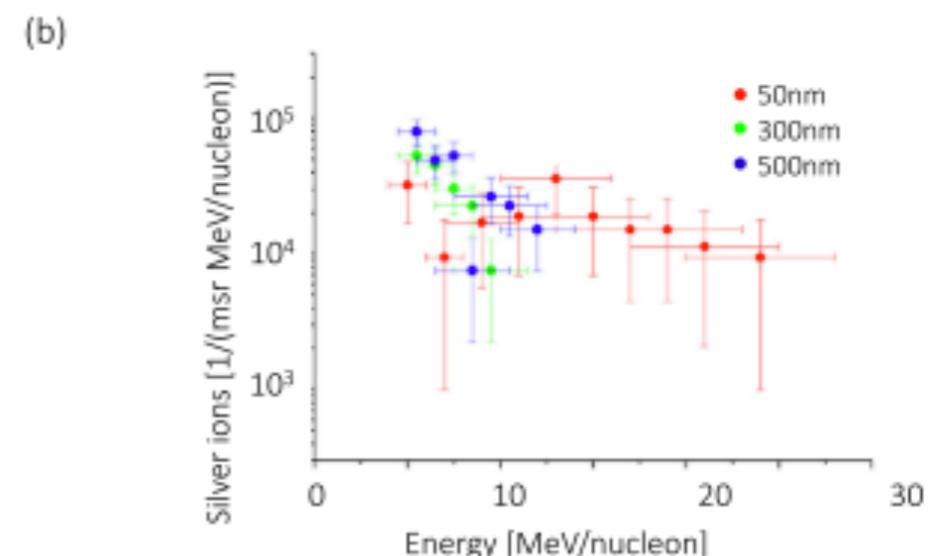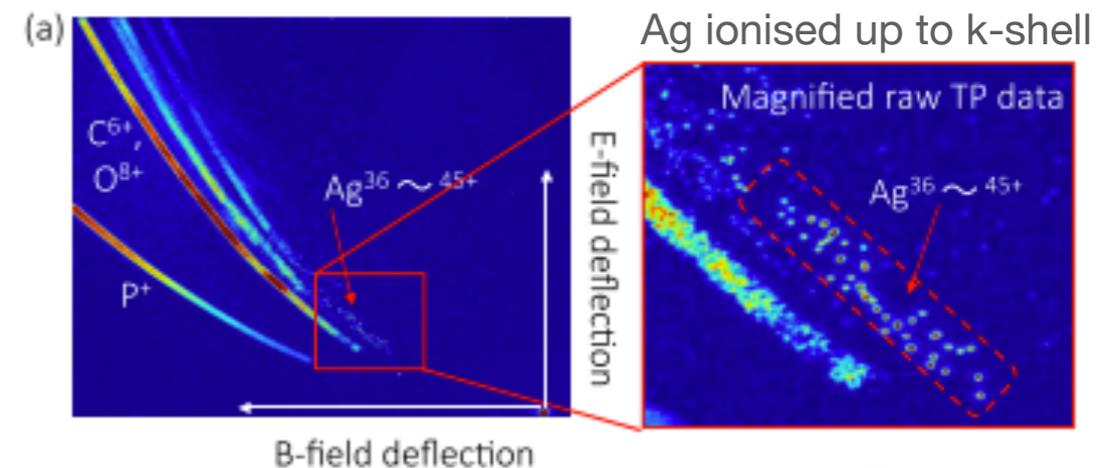McIlvenny et al. Phys. Rev. Lett. 127, 194801 (2021)

>40 MeV/u using ultra-high contrast 10 J class lasers irradiating carbon nano-foam+nanometre foil target

Ma et al. Phys. Rev. Lett. 122, 014803 (2021)

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Accelerating higher-Z ions with high charge states

- Can accelerate higher-Z ions with >10 MeV/u energies (> GeV total energy) and relatively high charge states from source

- Typically require ultra thin foil made of desired ion type

- Ionisation to high charge states requires emphasis on maximising laser intensity

Au ionised up to m-shell

Ag ionised up to k-shell

Wang+ Phys. Rev. X 11, 021049 (2021)

Nishiuchi+ Phys. Rev. Res. 2, 033081 (2020)
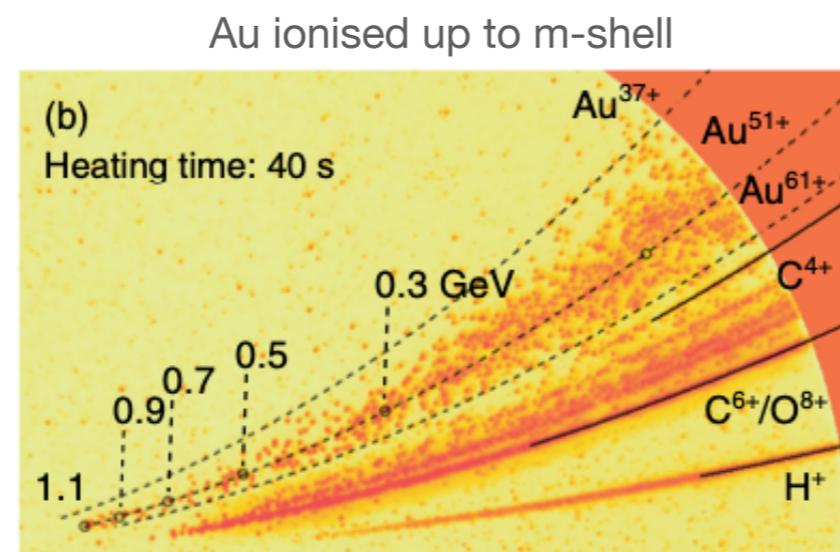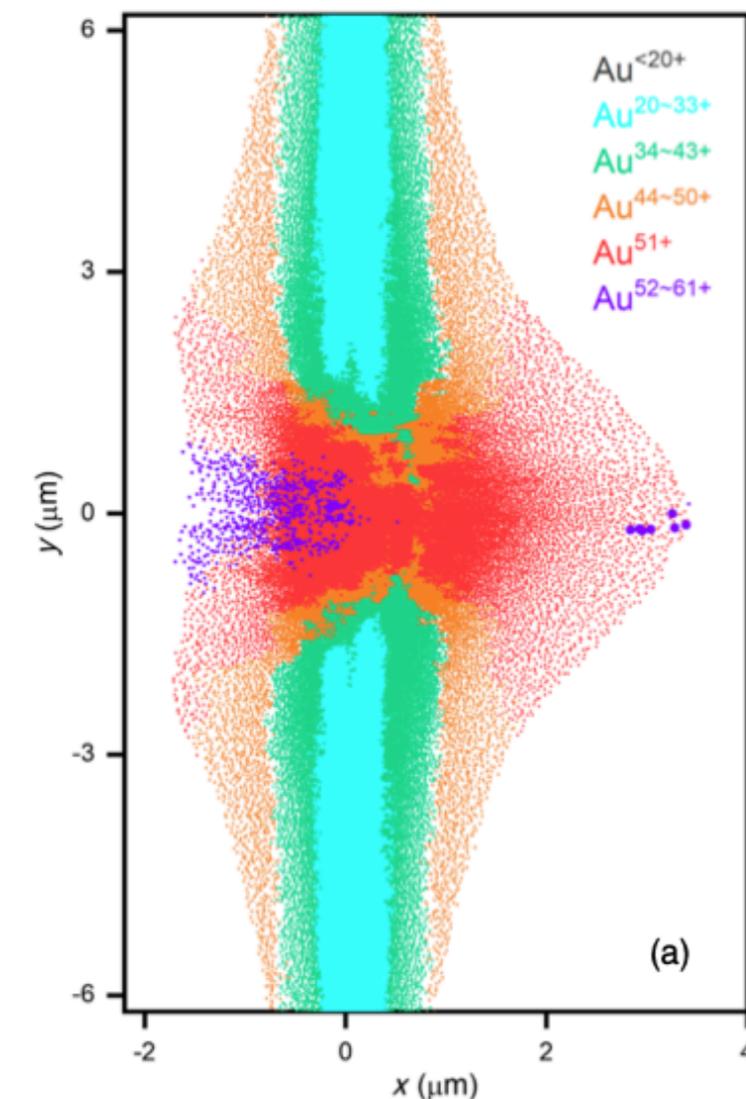
Multitude of different ion types generated from foils
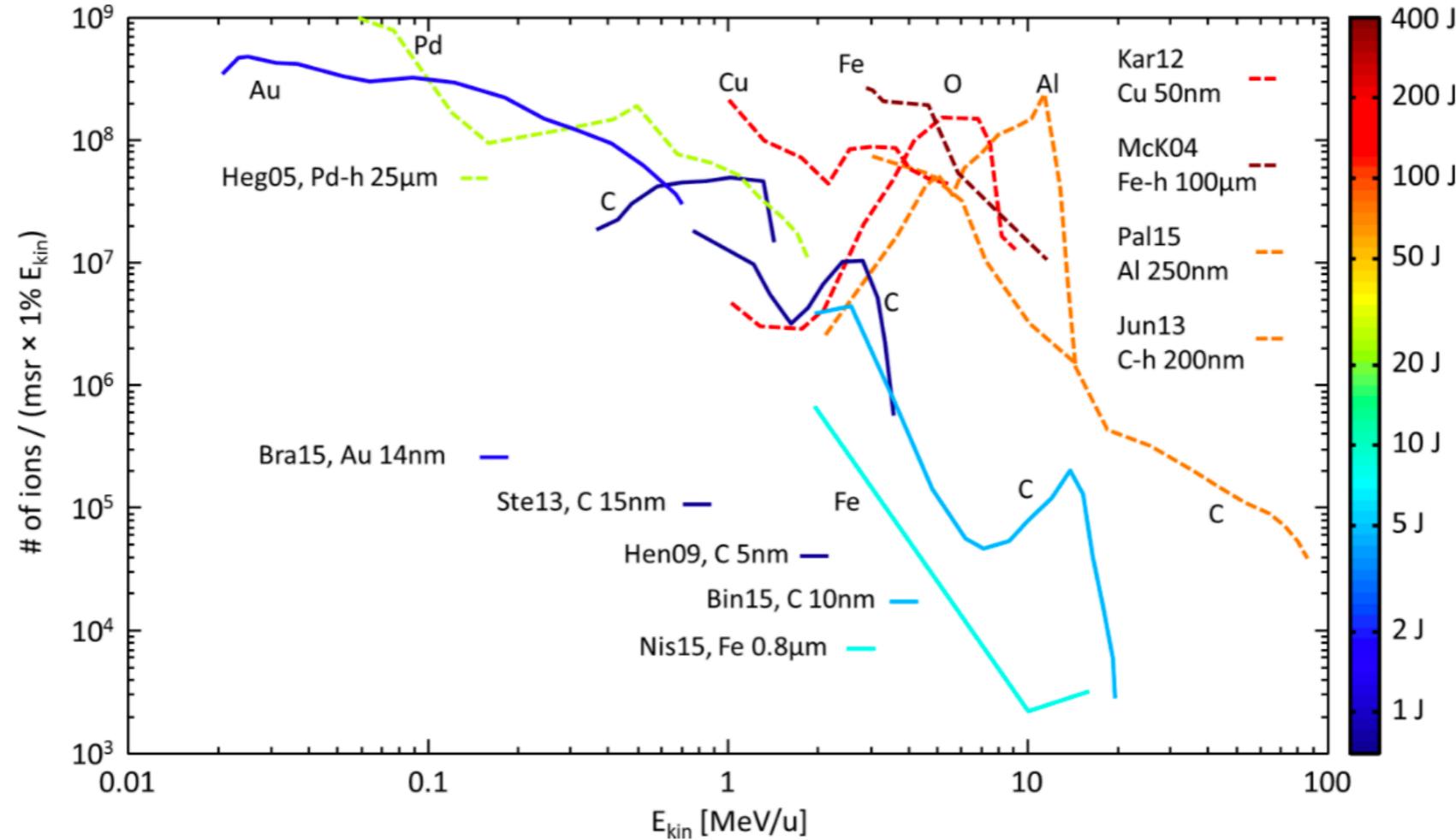
FIG. 5. Reported differential spectra of other ions from "Glass"- (dashed) and "Ti:Sa"- laser systems (solid) plotted in terms of kinetic energy per nucleon. The color bar represents the laser energy on target. The dominant target element and target thickness are indicated, as well as whether the targets were heated (-h). The dominantly accelerated ion species is marked at the corresponding lines. Publication legend: McK04,[17] Heg05,[26] Hen09,[7] Kar12,[21] Jun13,[27] Ste13,[28] Bra15,[29] Bin15,[8] Nis15,[30] and Pal15.[31]

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Accelerating ions from gas targets

- Gas targets typically have lower density and hard to confine spatially

- Various acceleration schemes under development, but optimisation is still poorly understood

- Acceleration can be transverse to laser, or longitudinal depending on scheme

Collisionless shock wave acceleration
Longitudinal or transverse acceleration, spectral shaping
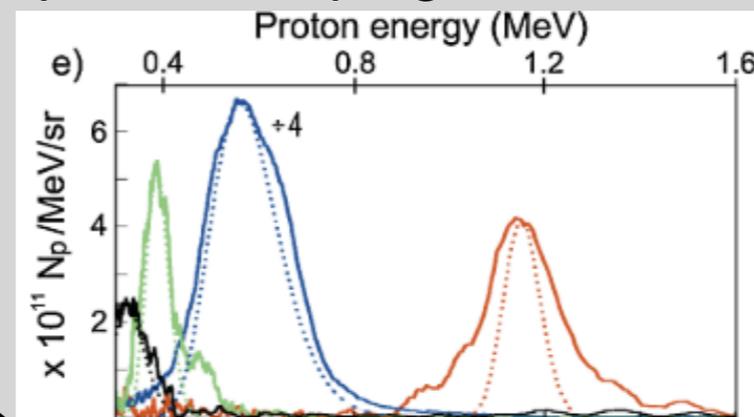
e.g. Palmer+ PRL 106, 014801 (2011)

e.g. Singh+ Sci. Rep. 10, 18452 (2020)

Figure 1
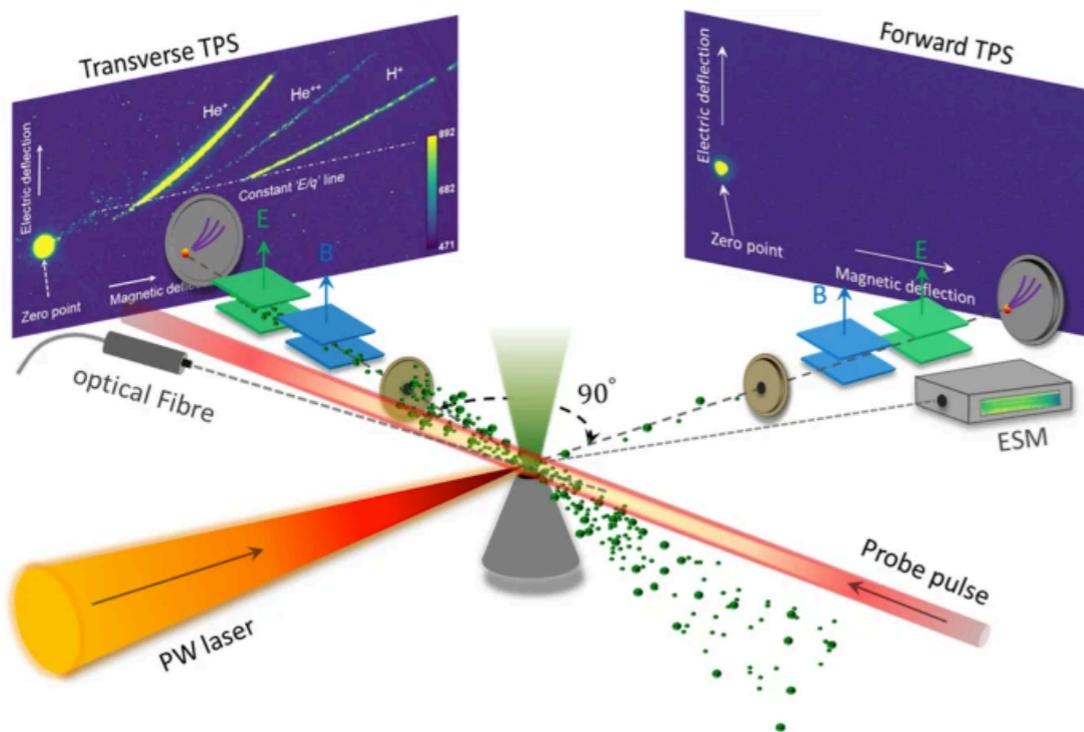
Magnetic vortex acceleration
Longitudinal acceleration

e.g. Helle+ PRL 117, 165001 (2016); Park+ Phys. Plasmas 26, 103108 (2019)

Laser driven ion sources

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- State-of-the-art in laser ion sources beyond TNSA

- **Impact on LhARA R&D**

LhARA specific considerations for ion source
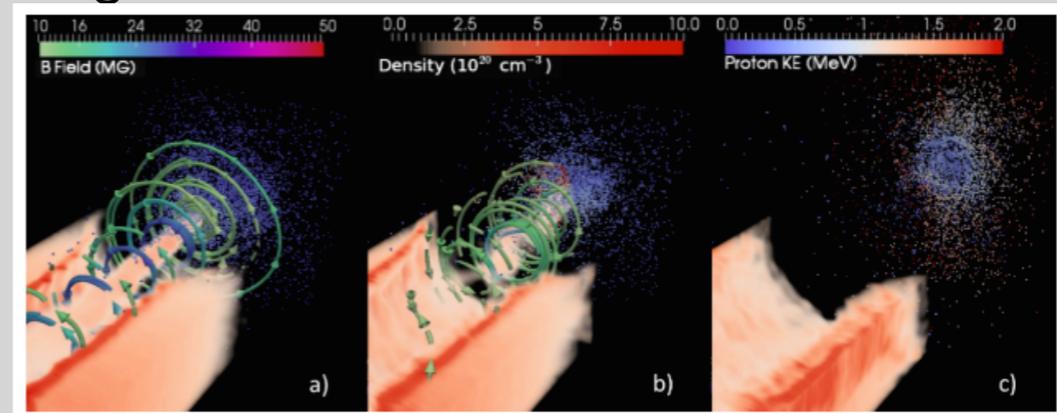
- All studies so far done at low repetition rate (<< 1 Hz)

- Many techniques unsuitable for high repetition rate

- **LhARA will use TNSA acceleration**

  - We have to control which ions are on the surface, which may mean removing contaminant layer

  - We are limited to high repetition targetry

- What materials can we accelerate from a tape?

  - Metal tape (even very high Z)

  - Plastic tape (but mainly H accelerated)

  - Tape with special surface coating

- Planned development of liquid targets (typically water or hydrocarbons)

Contaminant removal from tape target assemblies

- CW laser heating contaminant removal has been demonstrated on tape target at low rep rate

- Irradiated titanium tape, heating time < 100 ms

- CW laser boils off hydrocarbons, exposing oxide layer

- Thermal distortion of foil challenging to deal with

- Pulsed laser cleaning may solve issues, but needs development

Kondo et al. Crystals 10, 837 (2020)

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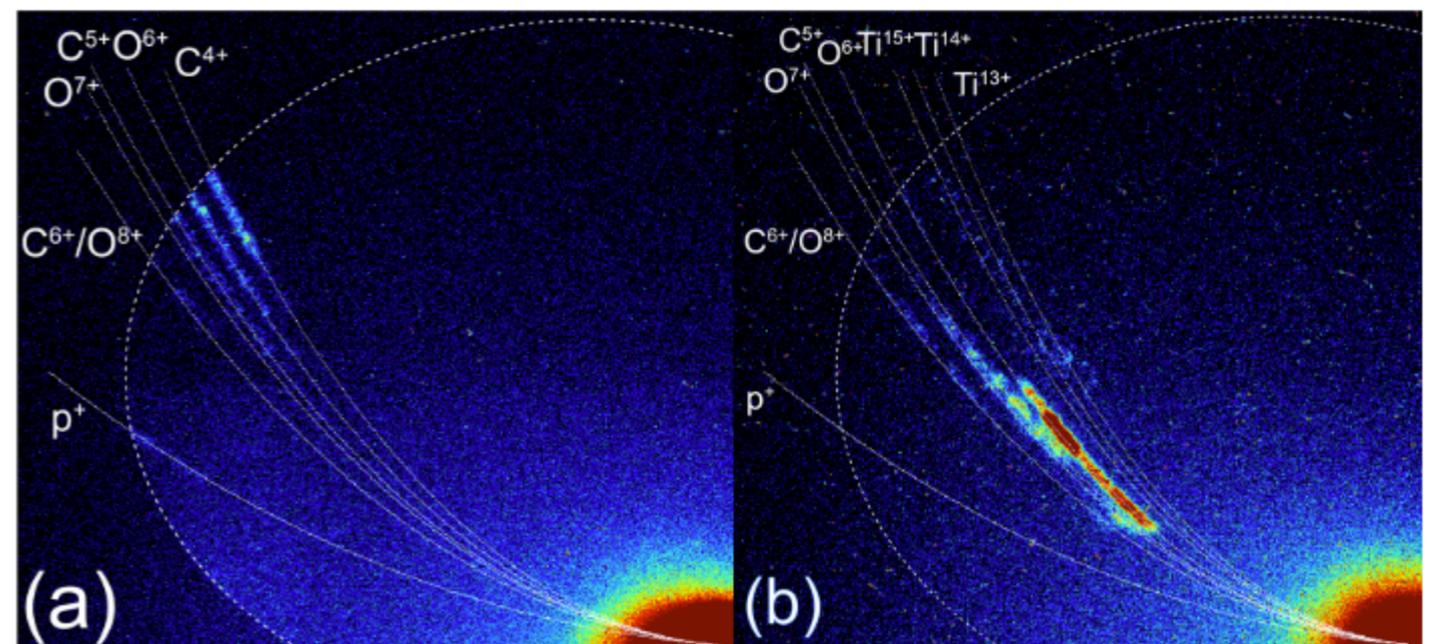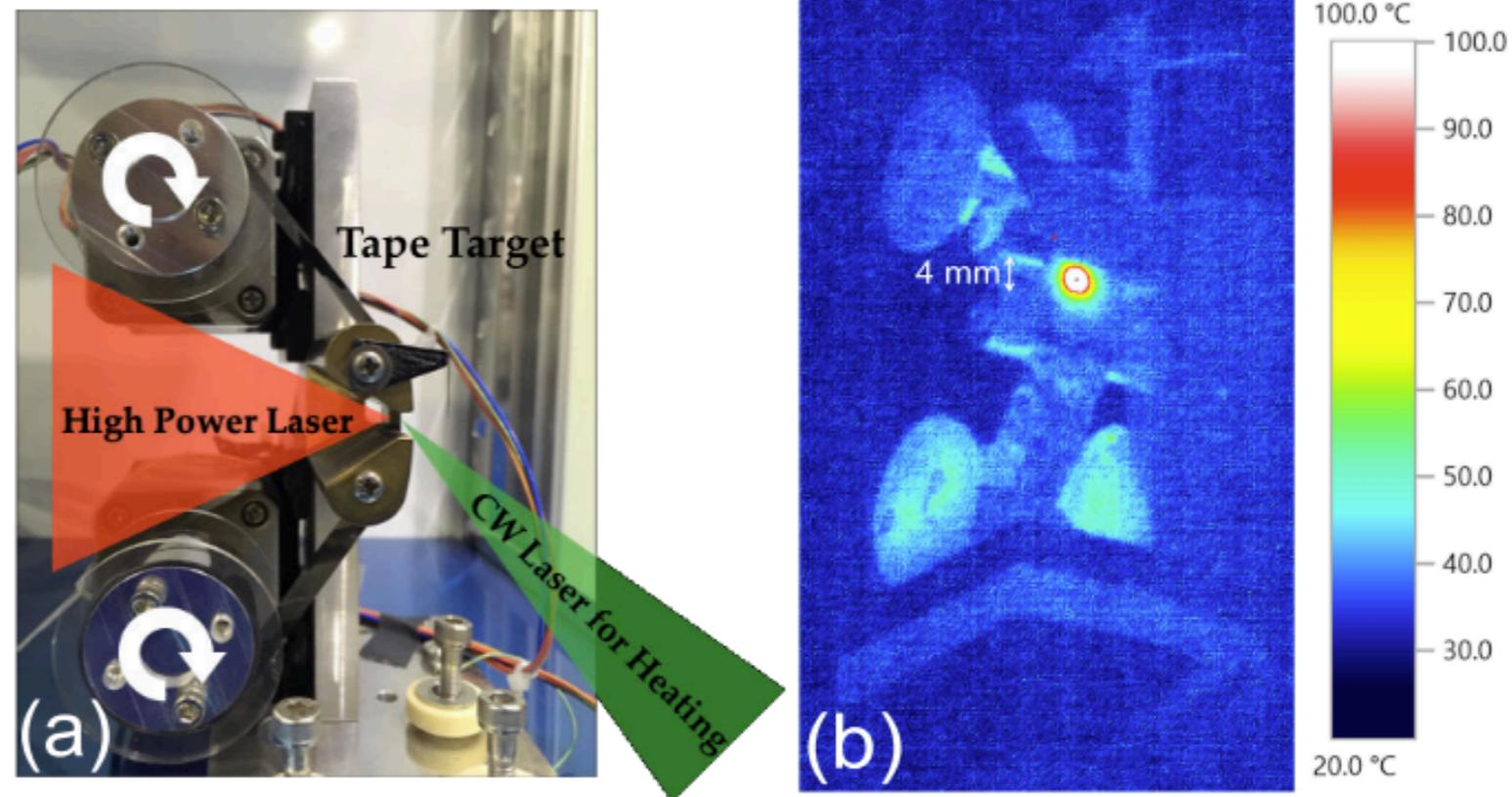
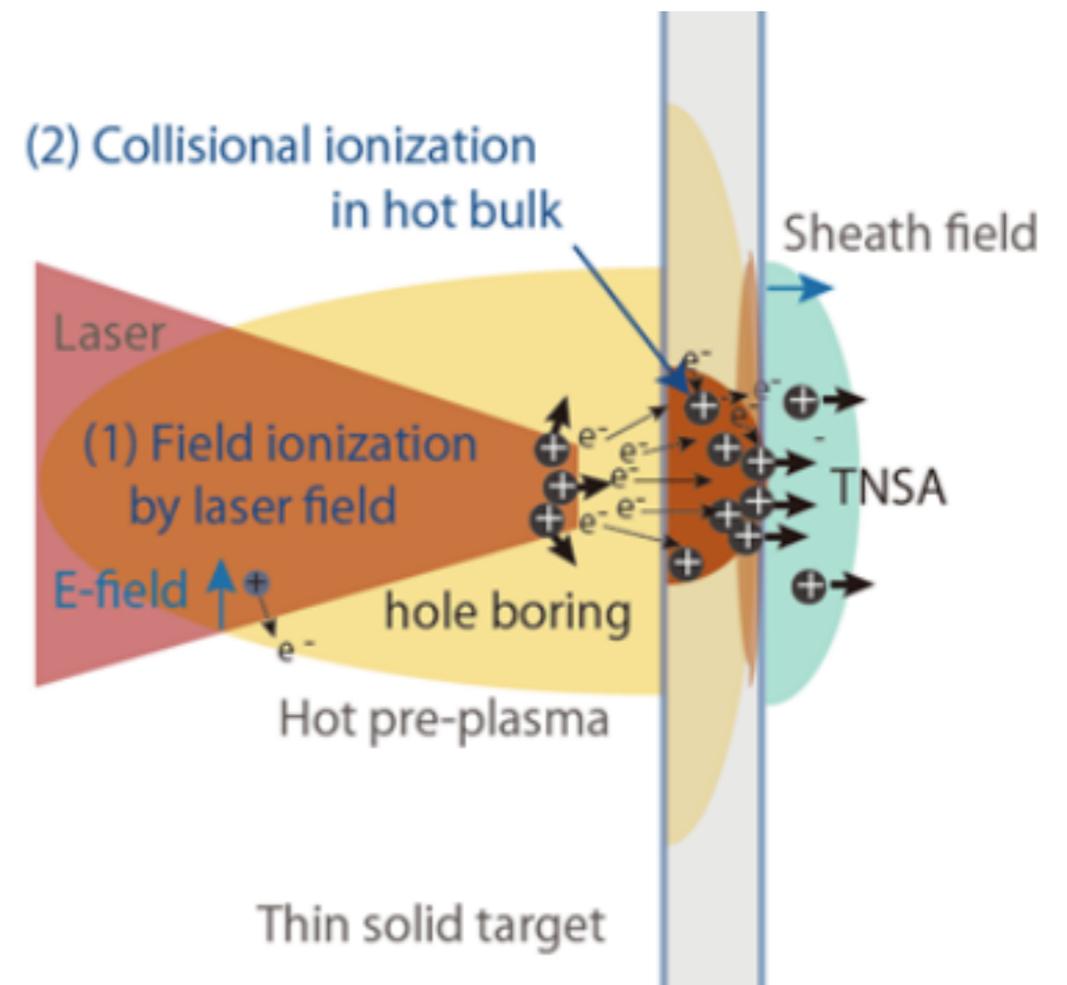# Further considerations for LhARA ion source

- **Beam purity**

  - Typical "cocktail" beam - mixture of ion species, charge states, and energies

  - Challenging to separate ion states with same q/m, e.g. C^{6+} and O^{8+}

- **Diagnostics**

  - Require Thomson Parabola Spectrometers

  - Heavier ions have high stopping power in detectors - saturation and damage in scintillators - needs R&D and calibration

- **Ionisation states**

  - Predicting ionisation level is difficult

  - Needs feedback between experimental and simulation to generate predictive model

(2) Collisional ionization in hot bulk

Sheath field

Laser

(1) Field ionization by laser field

E-field

hole boring

Hot pre-plasma

TNSA

Thin solid target

From Nishiuchi+ Phys. Rev. Res. 2, 033081 (2020)

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Summary & questions

- Laser driven ion sources can produce energetic, highly ionised beams of many different ion types

- Each ion type has its own technical considerations for targetry

- We need to develop technology for high repetition operation, and map out capabilities with LhARA baseline laser

From a radiobiological applications perspective, what ion types should we be focusing on?

How should we identify energy/ionisation state requirements for the source, considering the downstream beamline?