

Brief review of high power laser-driven “heavy” ion sources

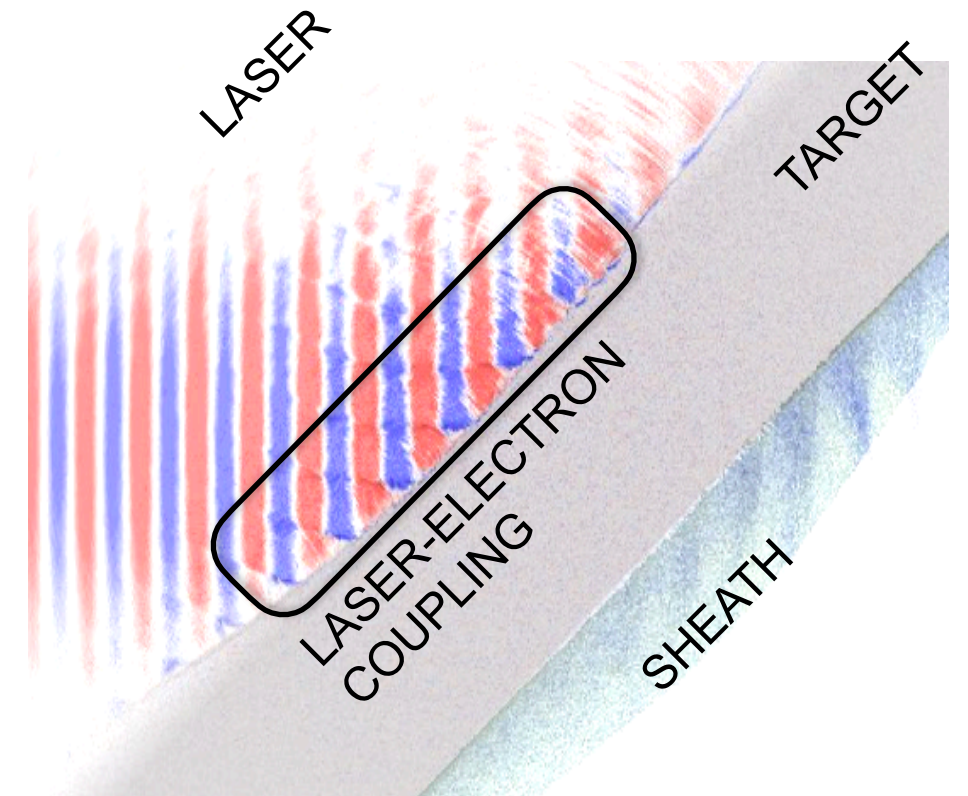
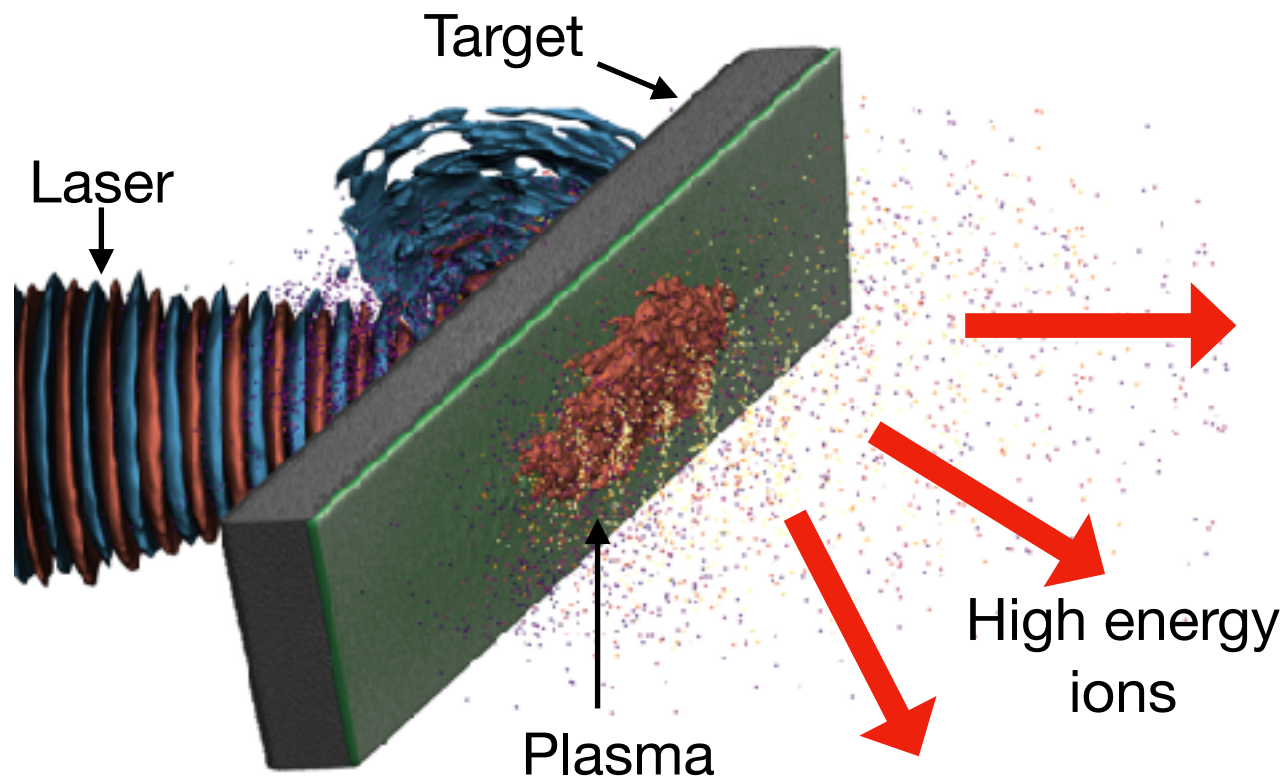
Laser driven ion sources

- 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



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

Laser electromagnetic fields

Energetic electrons

Sheath electrostatic fields

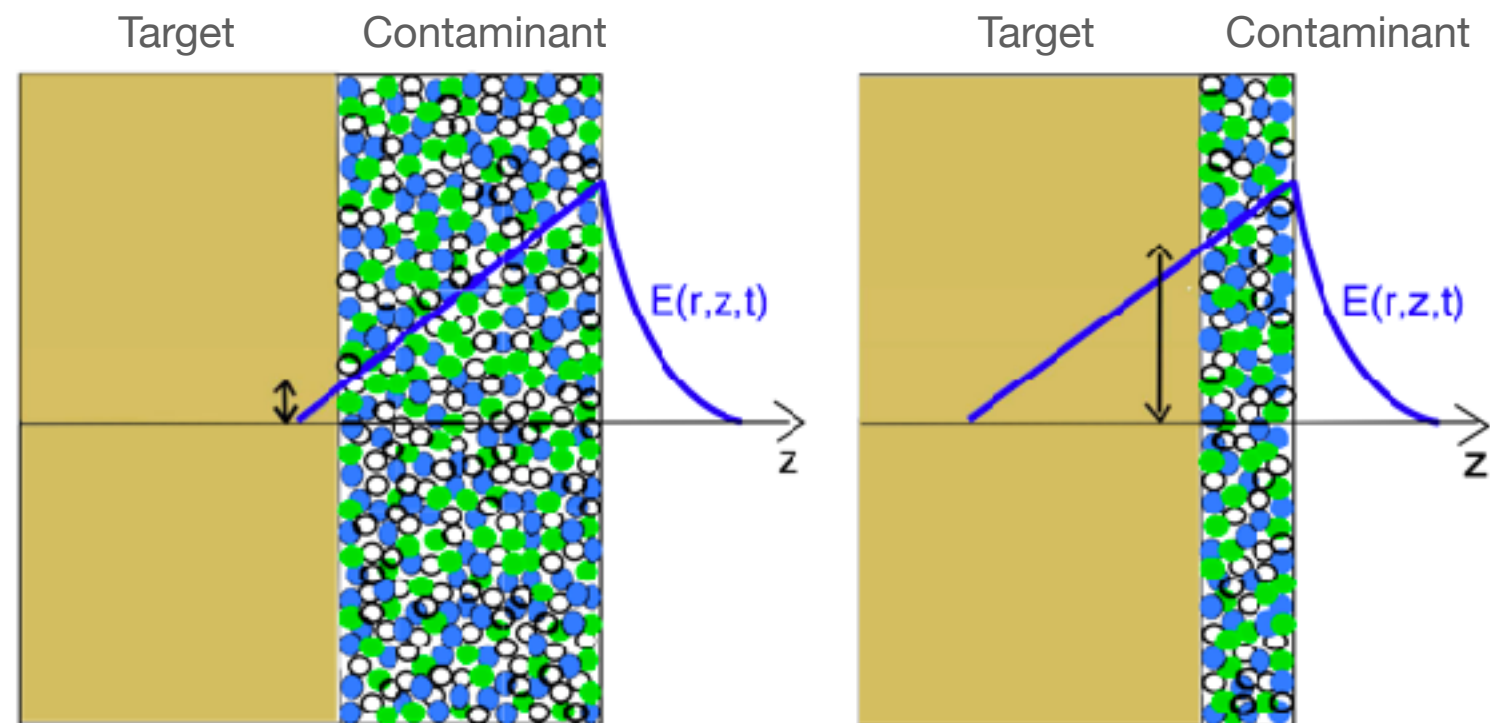
**Source optimisation involves
optimising energy conversion**

Accelerated surface ions

Importance of surface contaminants

TNSA only accelerates surface ions!

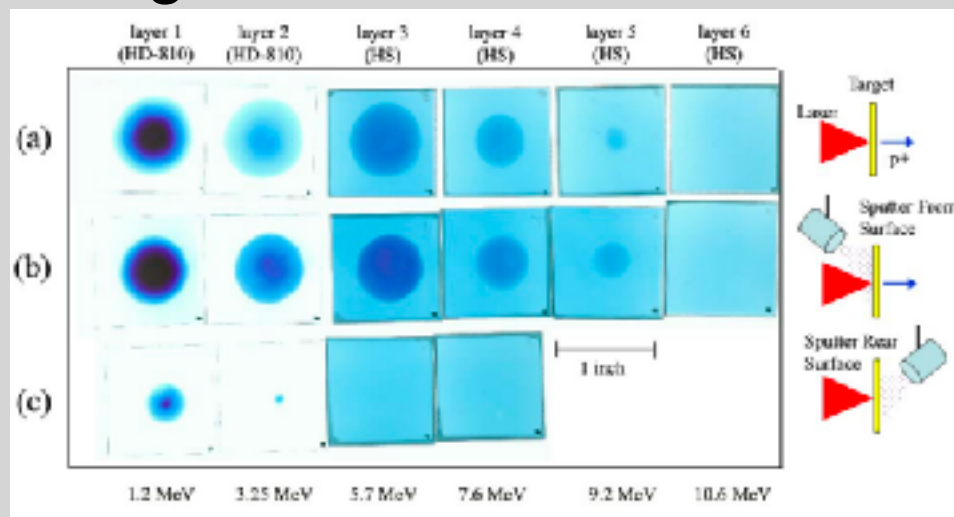
- Surface contaminants always exist on target foils
 - Typically ~ 1 nm thick
 - Hydrocarbons and water
- Field has short range, due to plasma shielding
- Target material typically not exposed to field
- Hydrogen preferentially accelerated \rightarrow high q/m



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

Techniques to remove contaminants

Sputter gun



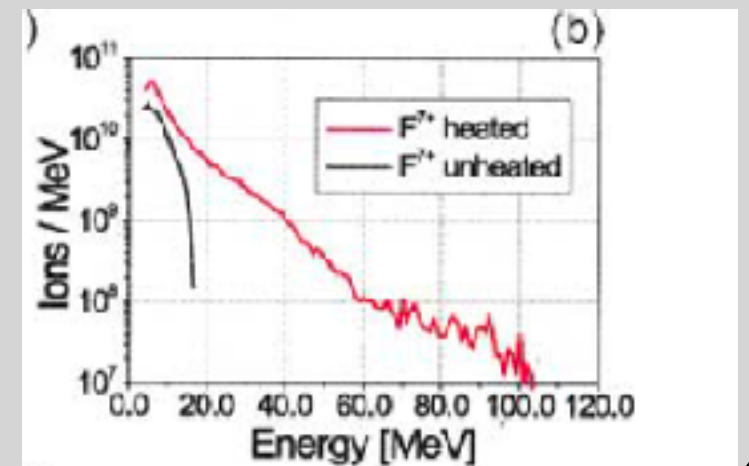
e.g. Allen+ PRL 93, 265004 (2004)

Targeted removal of contaminant

Resistive heating

- Heat entire foil by passing through high DC current

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



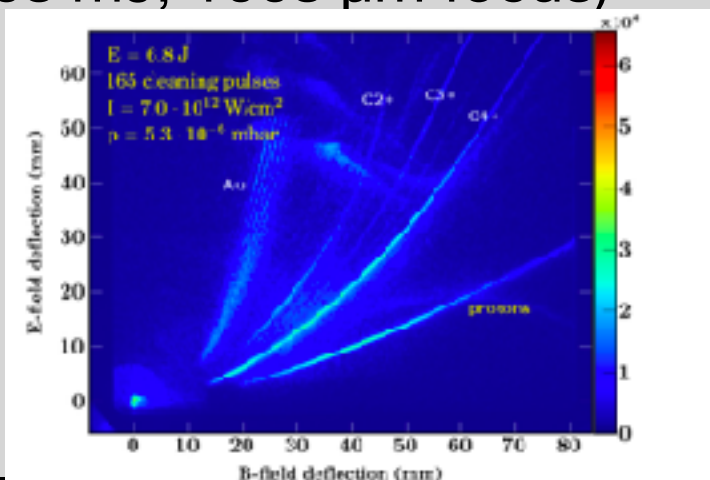
Heat target to “boil off” hydrocarbons - ~1000 K

Pulsed laser cleaning

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

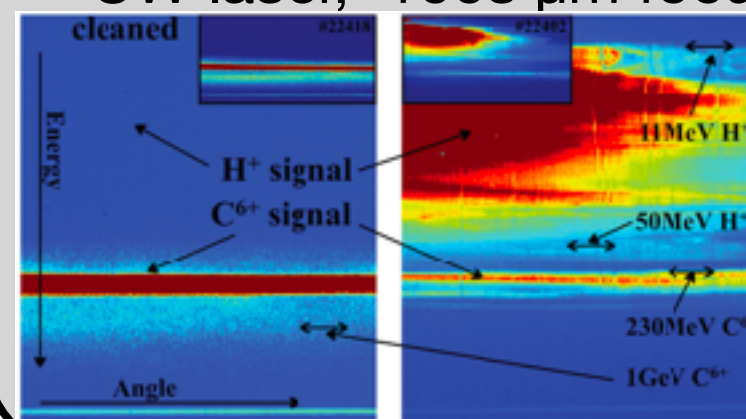
e.g. Sommer+
PPCF 60, 054002
(2018)

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



CW laser cleaning

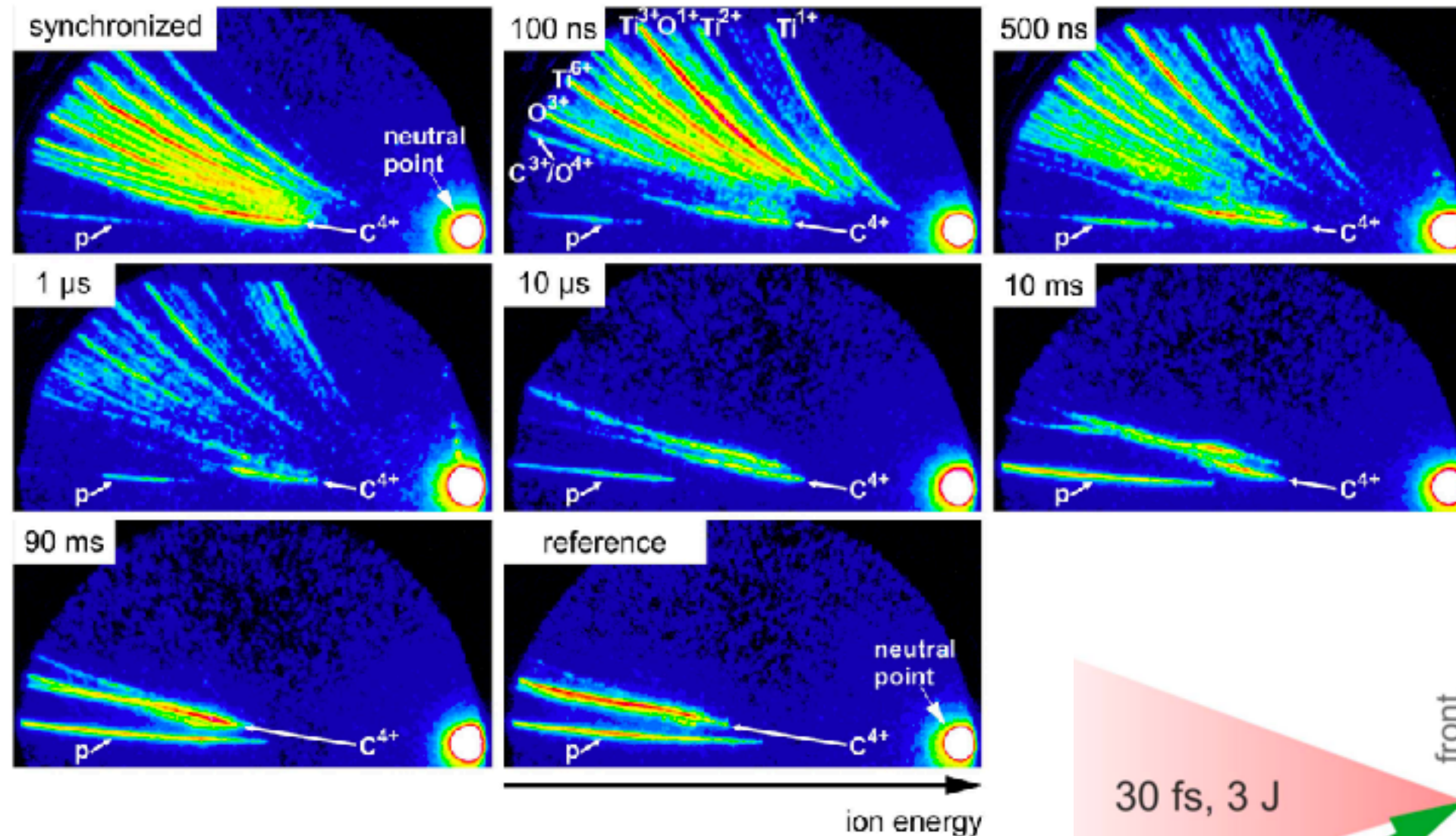
- Heat entire foil by irradiating with ~ 1 W CW laser, 100s μm focus



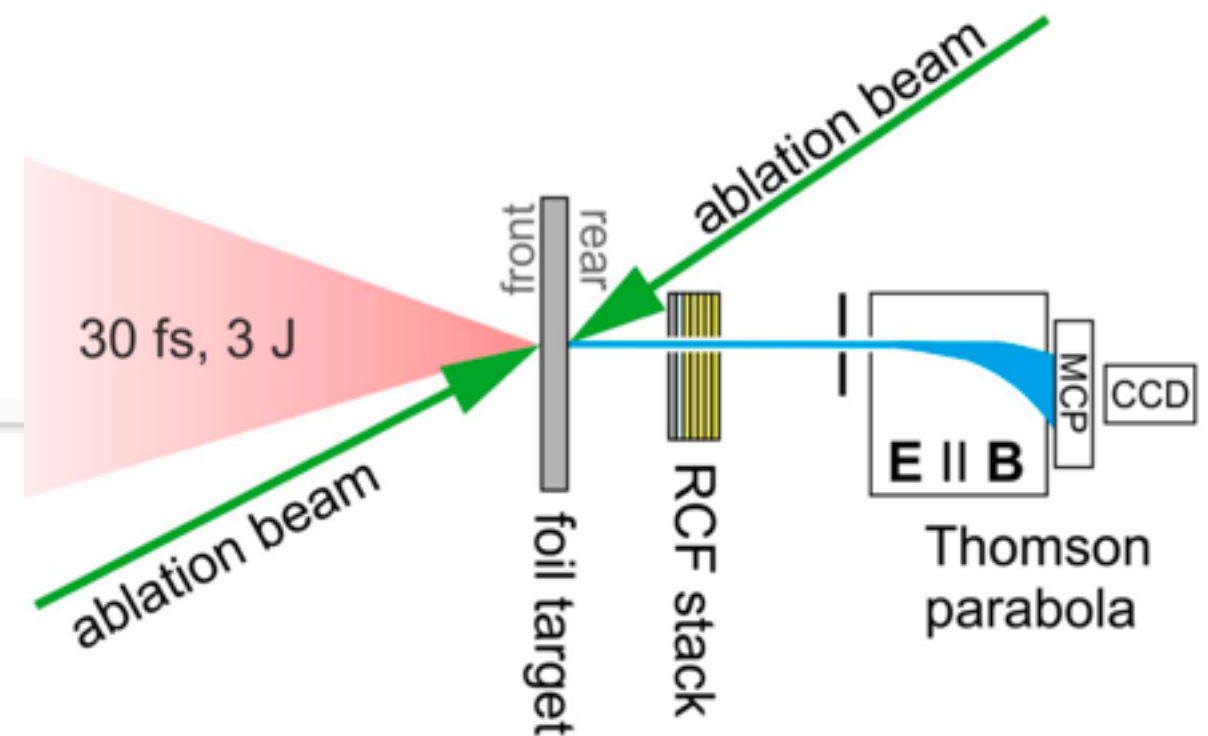
e.g. Safranov+
Phys. Plasmas 25,
103114 (2018)

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

Impact of contaminant on ion beam



From Sommer+ PPCF
60, 054002 (2018)

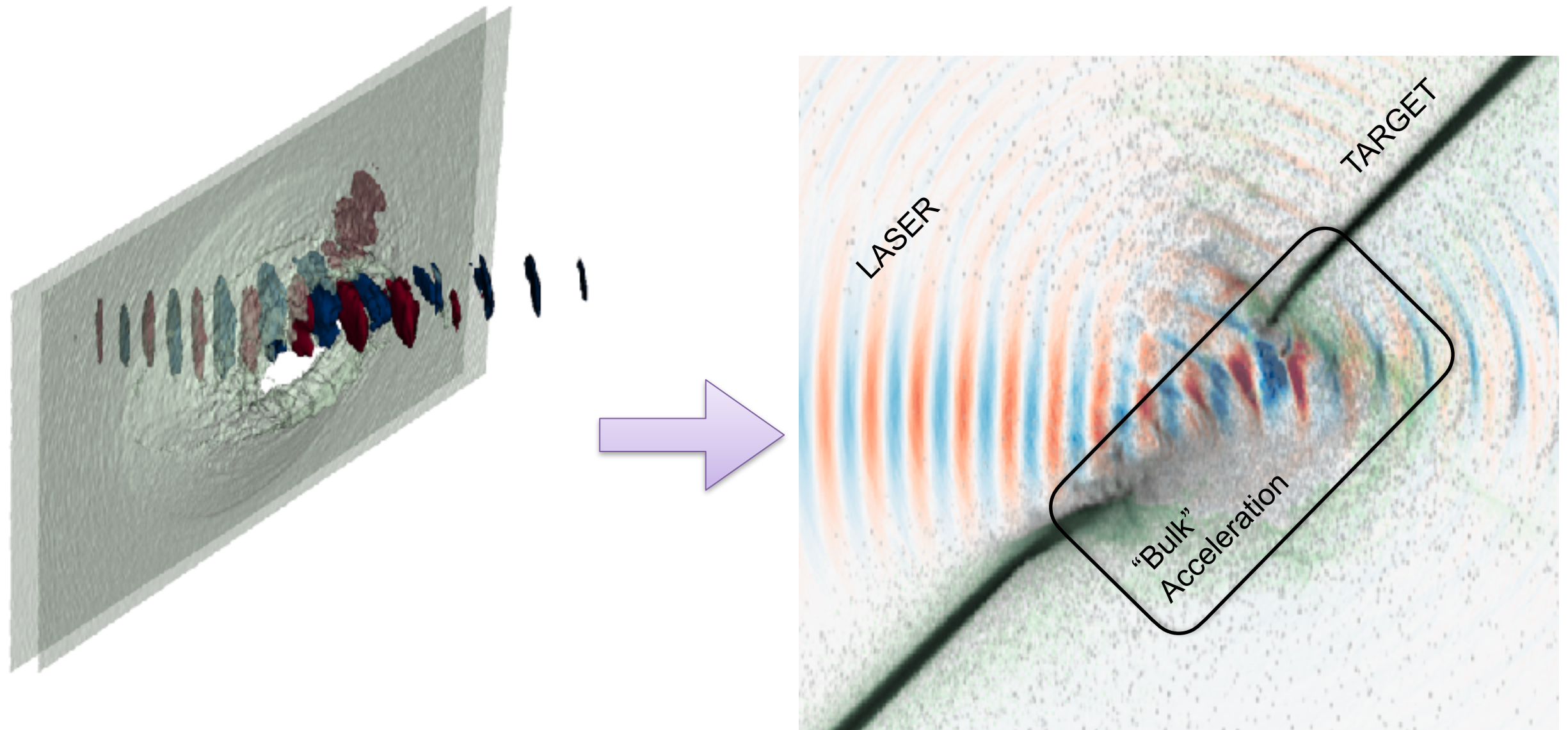


- Selectively removing contaminants using pulsed laser
- Contaminants resorb on target $\sim 1 \mu\text{s}$ after removal

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



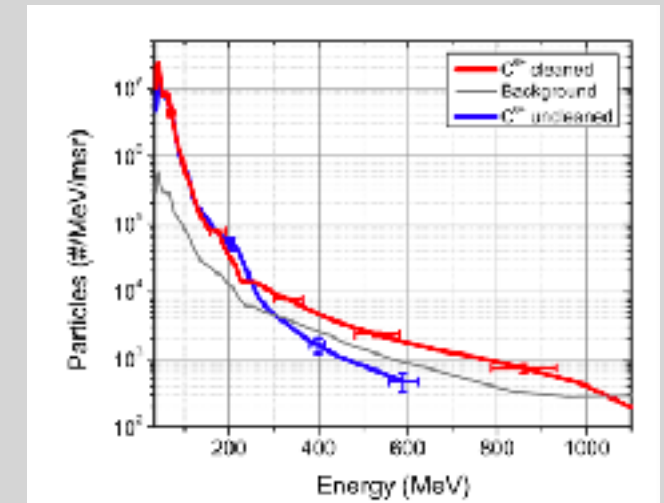
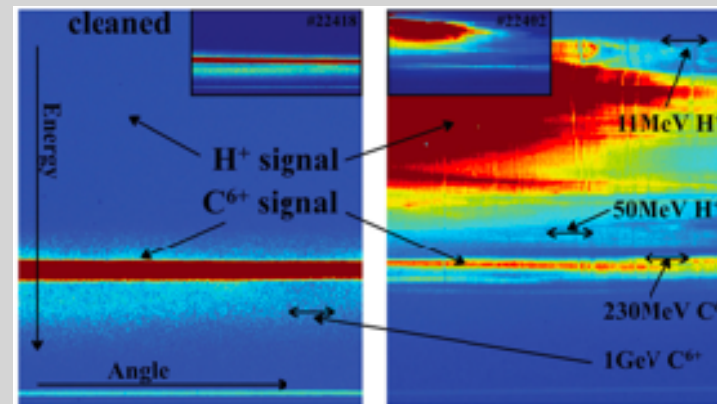
- Various schemes to accelerate the target “bulk”
- Typically use ultra-thin (sub 100 nm foils), accelerated via laser radiation pressure or enhanced thermal pressure
- Other schemes use ion accelerating shockwaves traversing low density targets

Demonstration of high energy C^{6+} generation

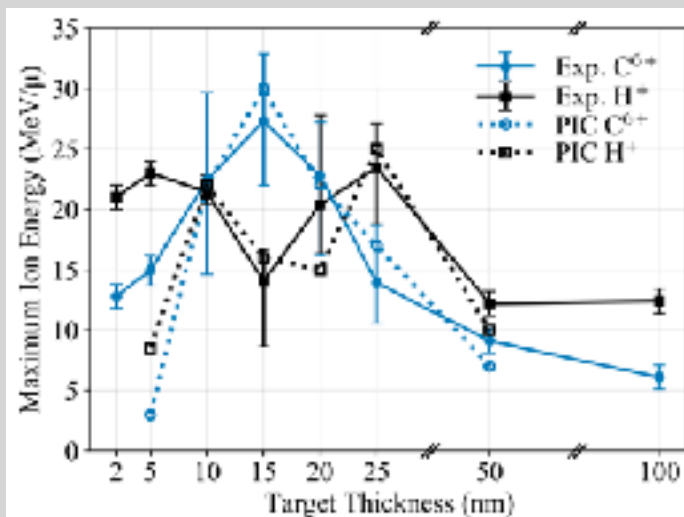
- Higher laser energy leads to higher carbon energies
- Typically maximising energy and flux requires sub-micron foils, ultra-high contrast
- All difficult to do at high repetition rate

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

>80 MeV/u ions using 100 J class laser irradiating sub-micron foils

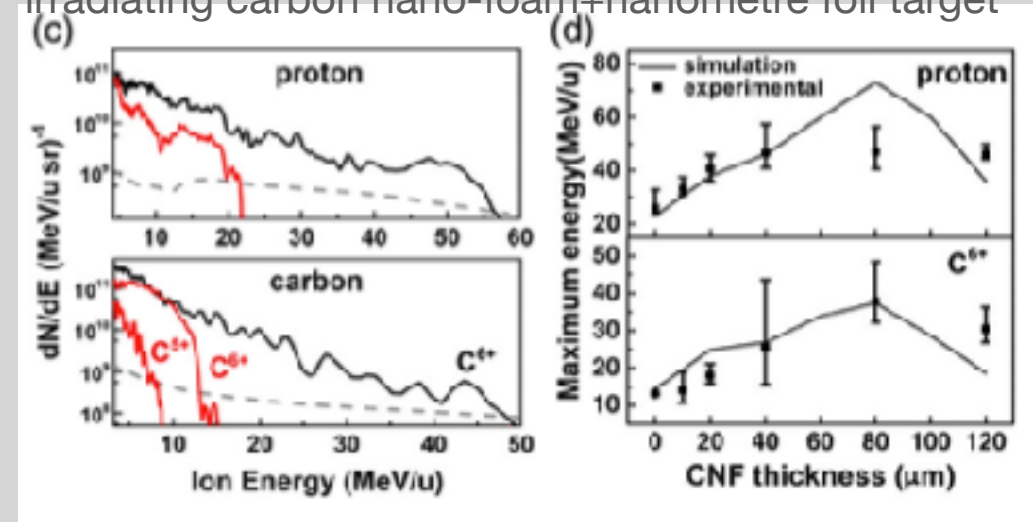


>30 MeV/u using ultra-high contrast 10 J class lasers irradiating ~few nanometre foils



McIlvenny et al. Phys. Rev. Lett. 127, 194801 (2021)

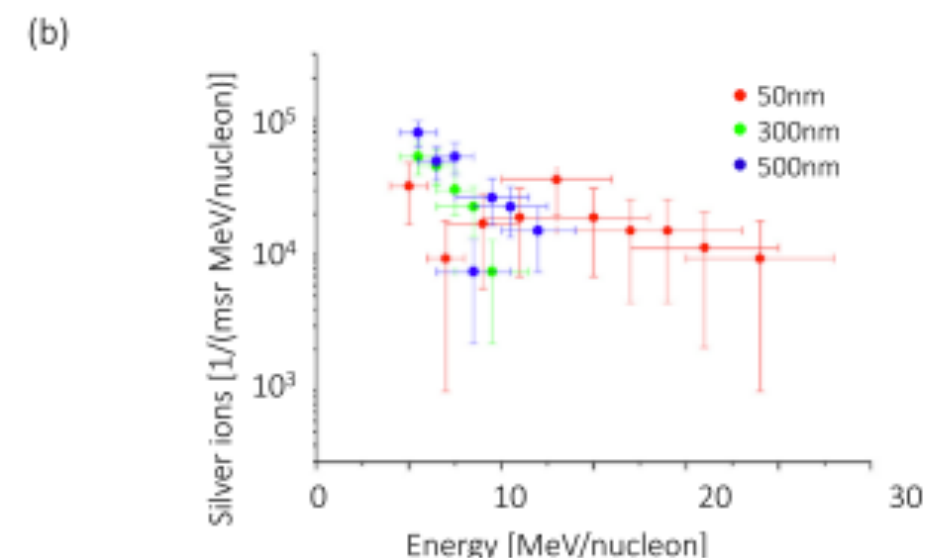
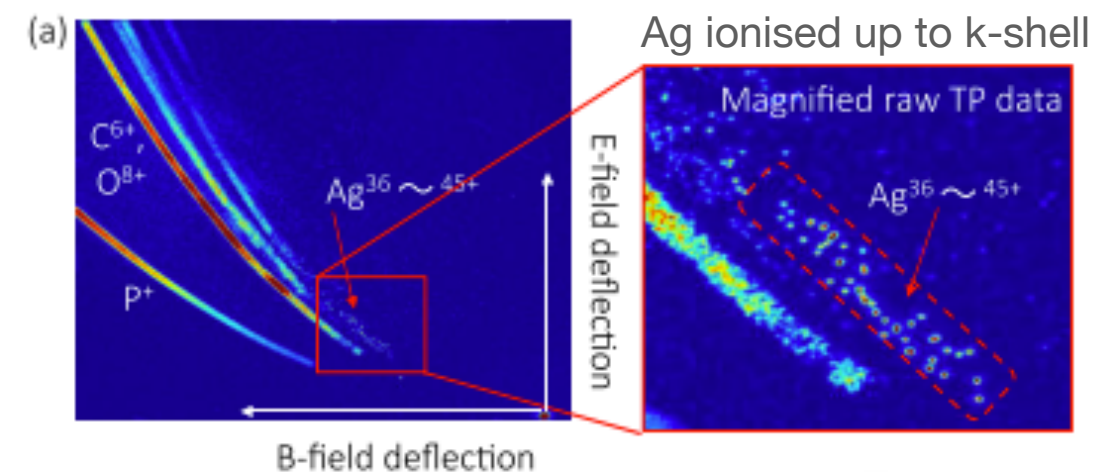
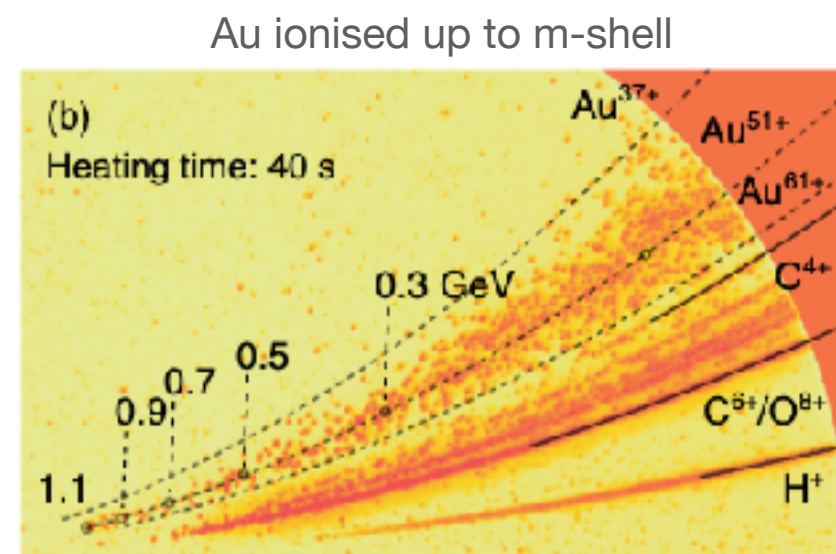
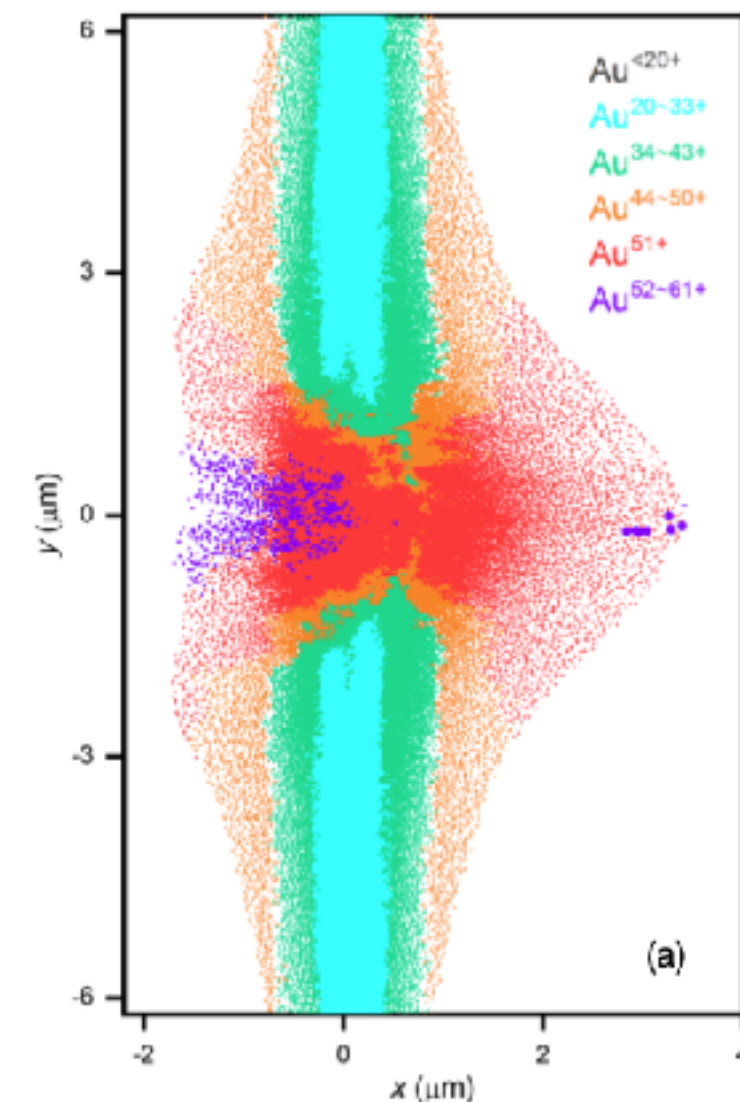
>40 MeV/u using ultra-high contrast 10 J class lasers irradiating carbon nano-foam+nanometre foil target



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

Accelerating higher-Z ions with high charge states

- Can accelerate higher-Z ions with >10 MeV/u energies ($> \text{GeV}$ 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



Multitude of different ion types generated from foils

071101-6 Schreiber, Bolton, and Parodi

Rev. Sci. Instrum. **87**, 071101 (2016)

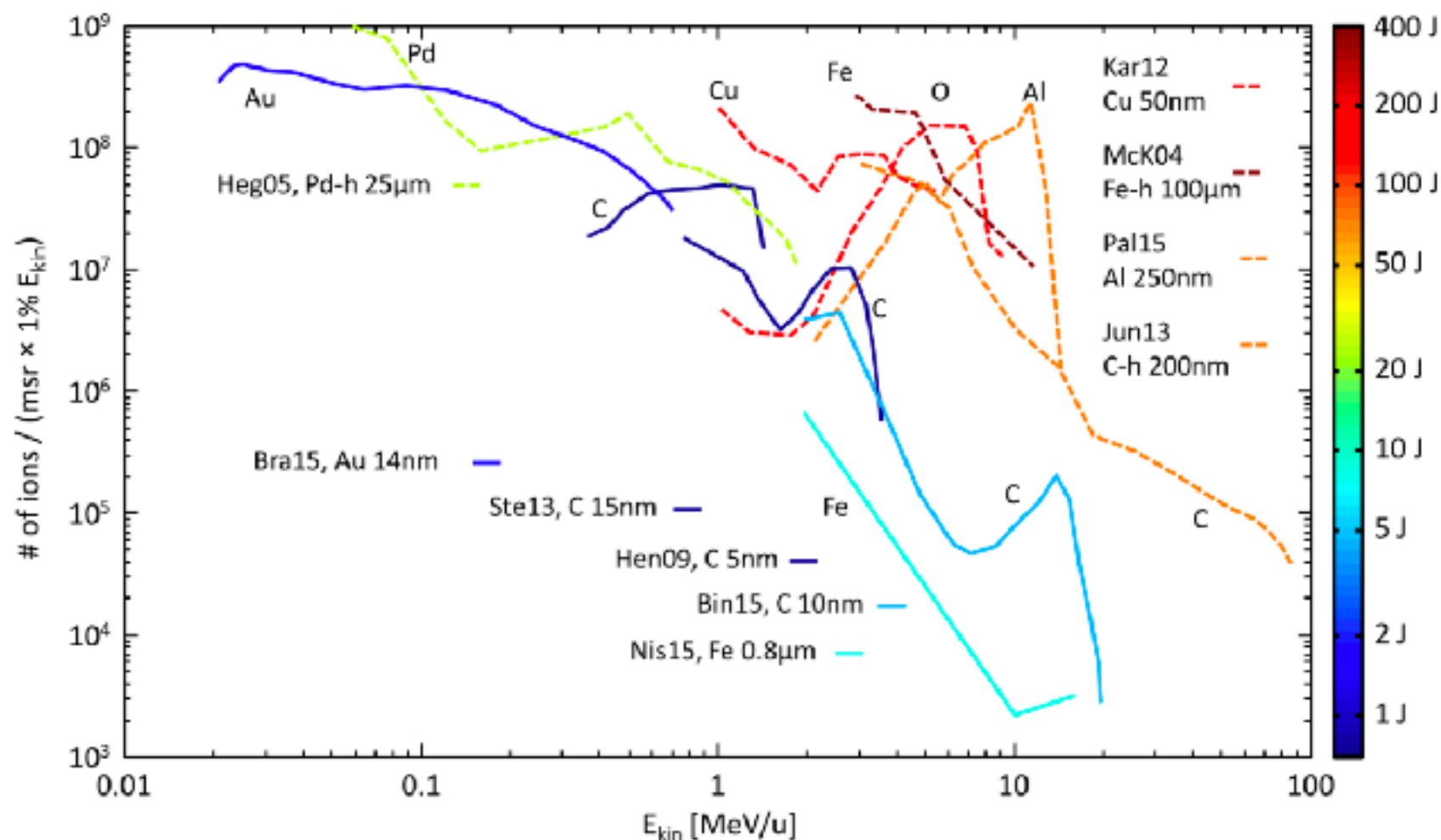
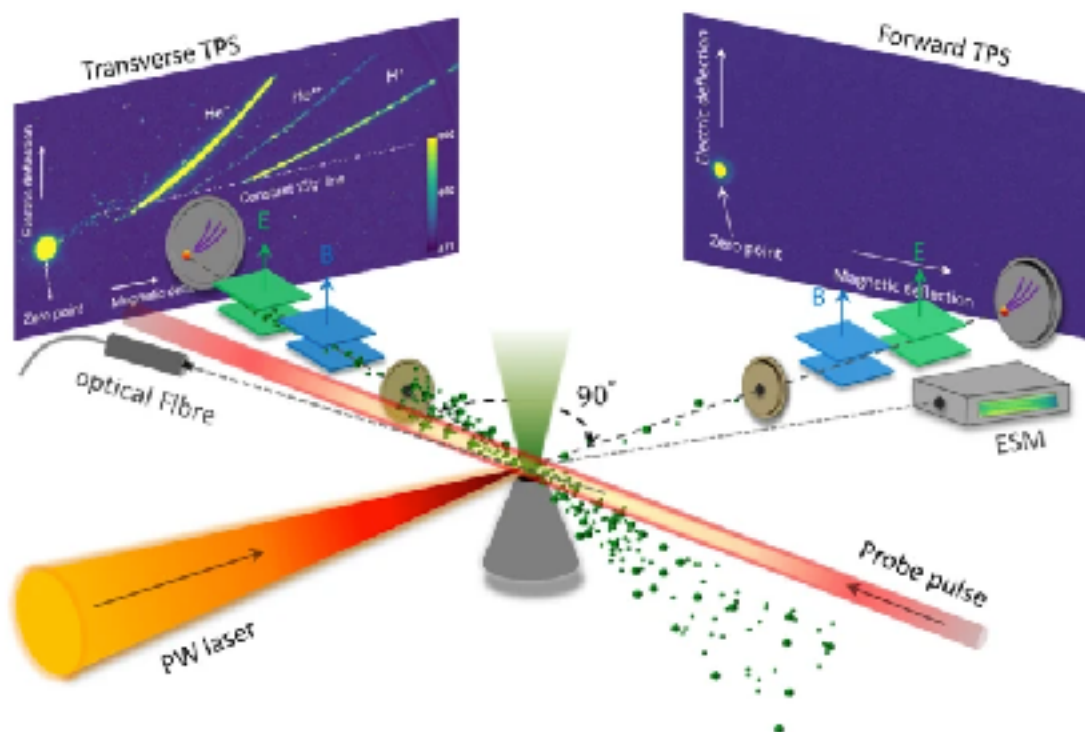


FIG. 5. Reported differential spectra of other ions from “Glass”- (dashed) and “Ti:Sa”- laser systems (solid) plotted in terms of kinetic energy per nucleon. The color bar represents the laser energy on target. The dominant target element and target thickness are indicated, as well as whether the targets 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

Accelerating ions from gas targets

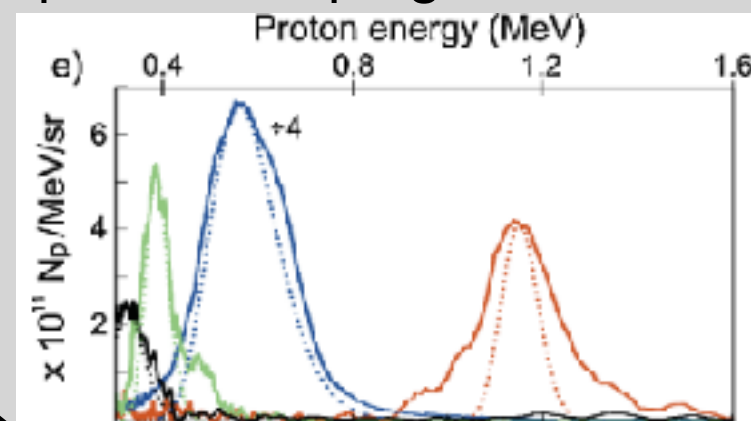
- Gas targets typically have lower density and hard to confine spatially
- Various acceleration schemes under development, but optimisation is still poorly understood
- Acceleration can be transverse to laser, or longitudinal depending on scheme

Figure 1



Collisionless shock wave acceleration

Longitudinal or transverse acceleration, spectral shaping

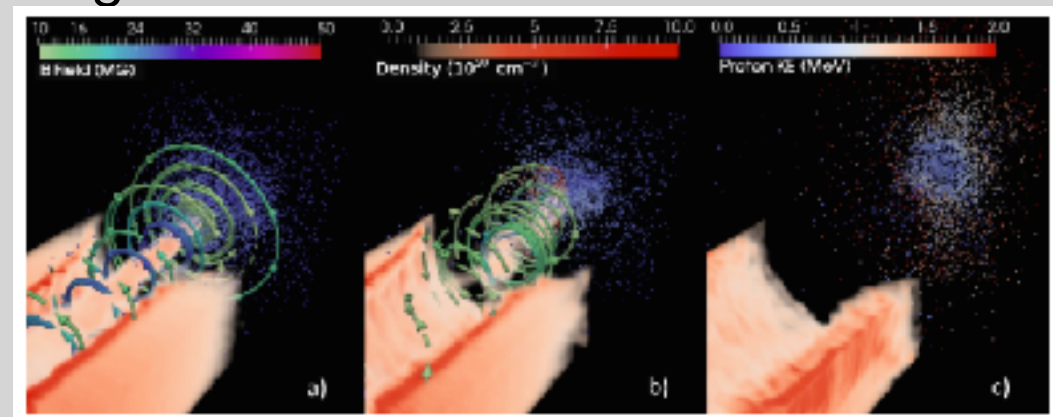


e.g. Palmer+ PRL 106, 014801 (2011)

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

Magnetic vortex acceleration

Longitudinal acceleration



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

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**

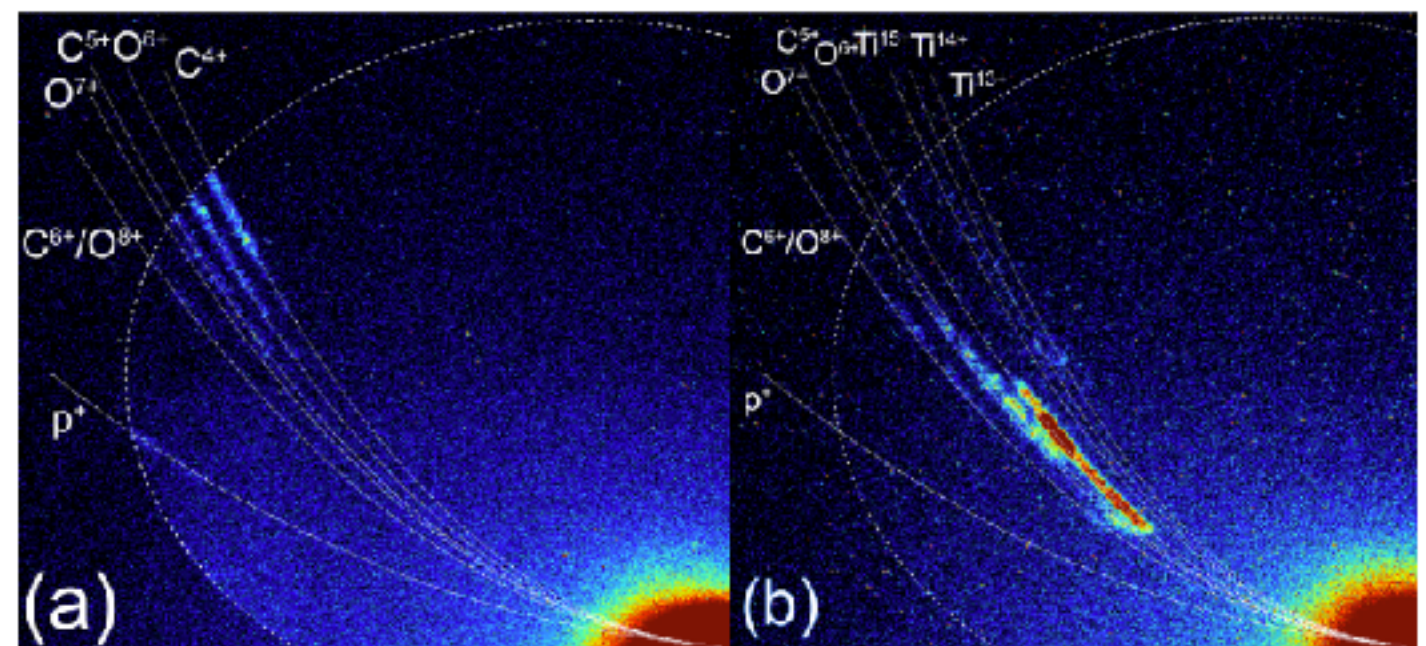
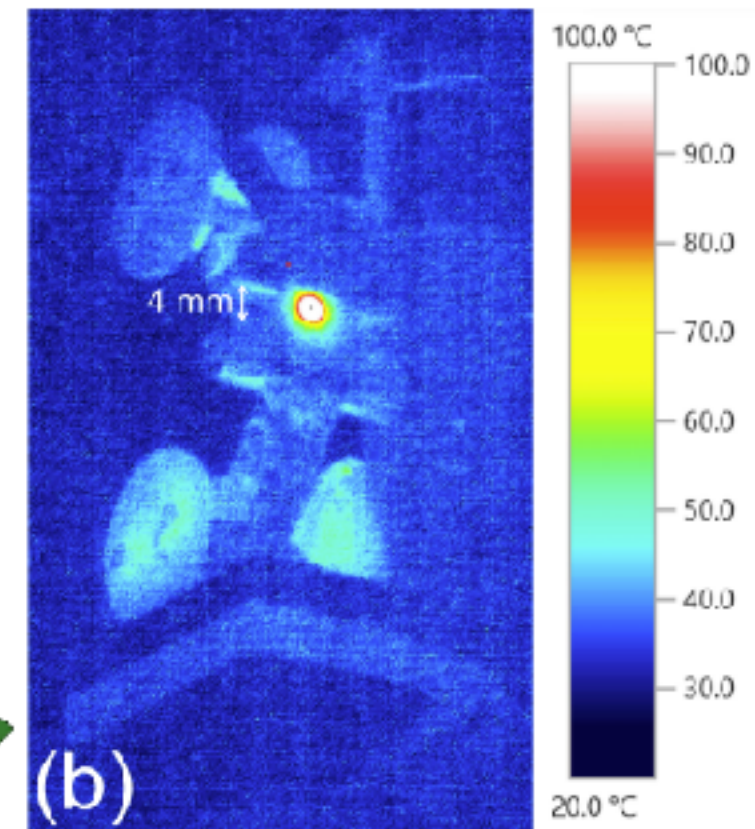
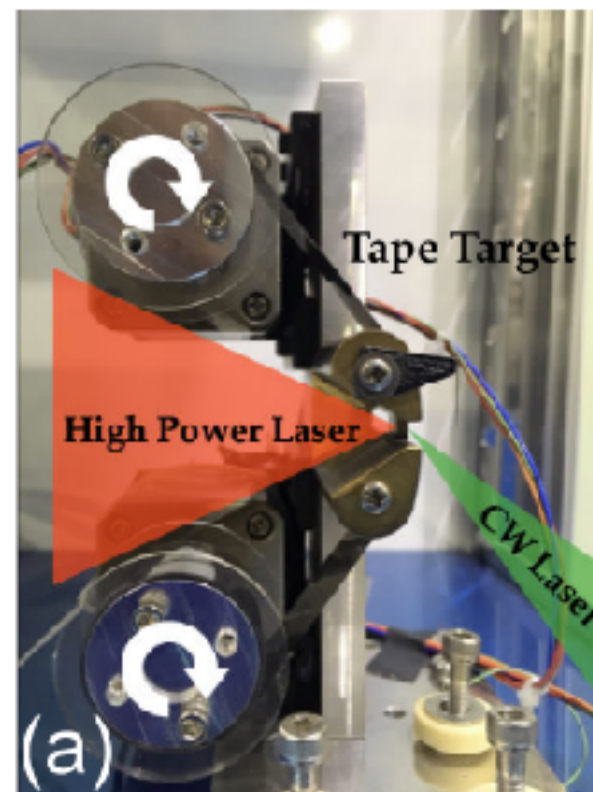
LhARA specific considerations for ion source

- All studies so far done at low repetition rate ($\ll 1$ 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

Kondo et al. Crystals 10, 837 (2020)

- CW laser heating 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



Contaminant removal from tape target assemblies

Matter Radiat. Extremes 8, 054002 (2023); doi: 10.1063/5.0153578

- Resistive heating of tape also demonstrated

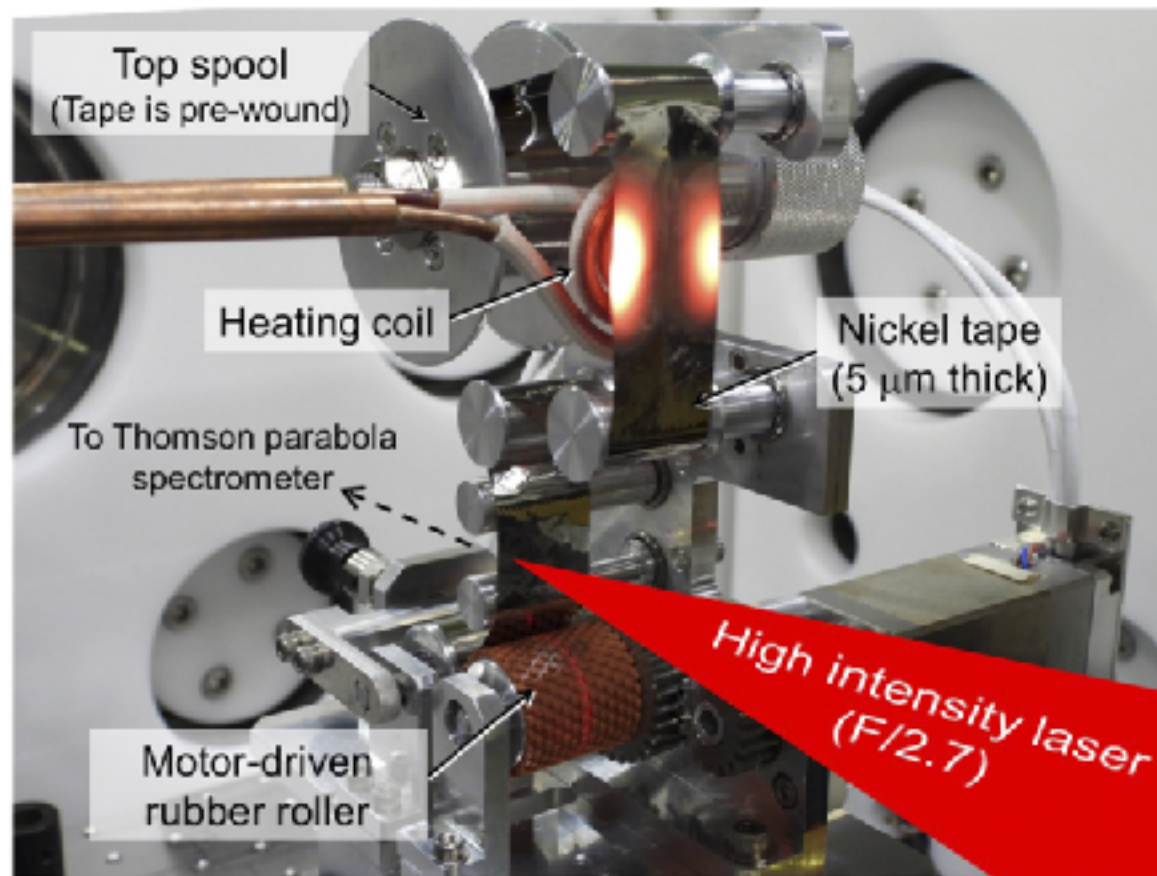
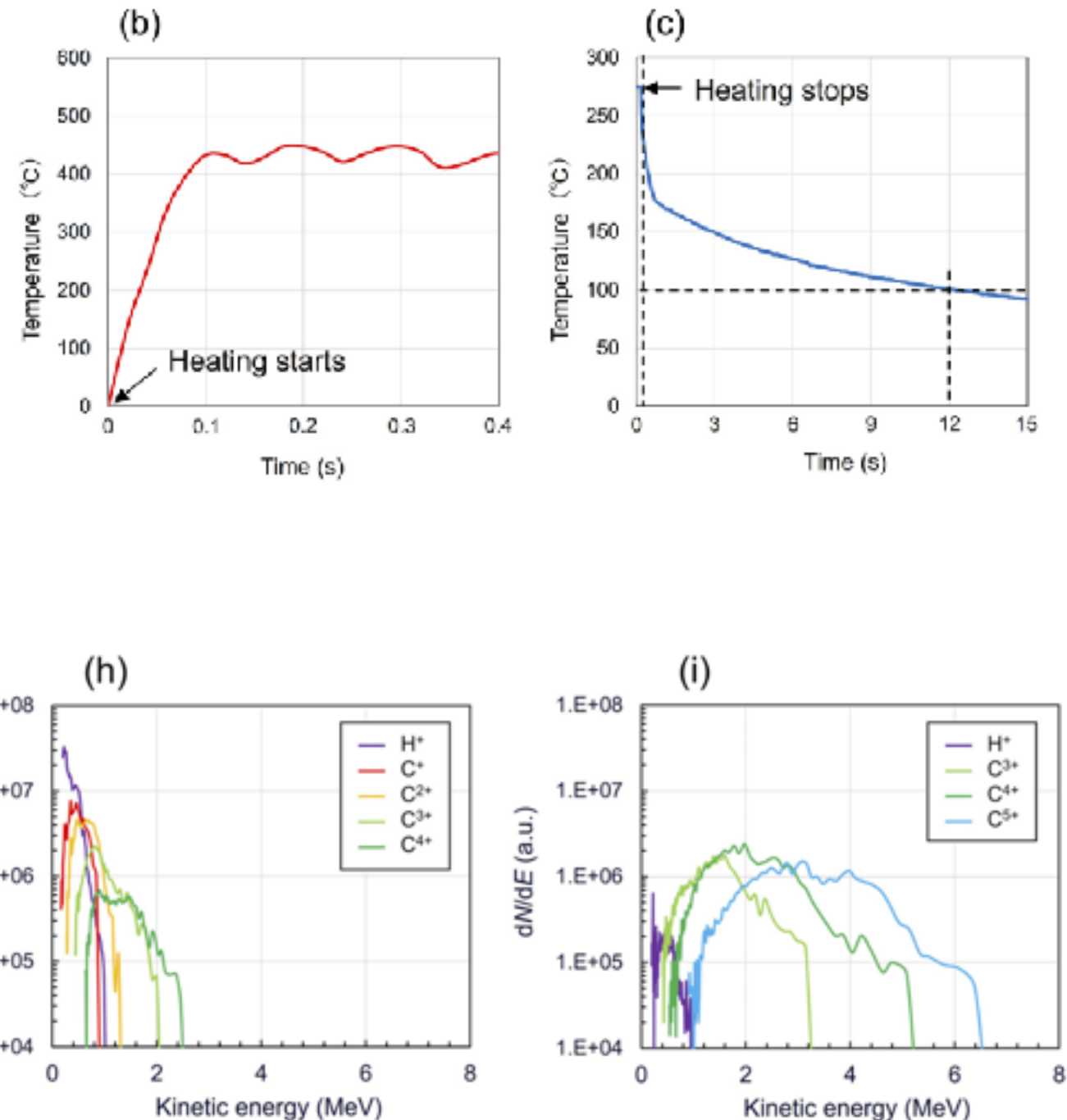
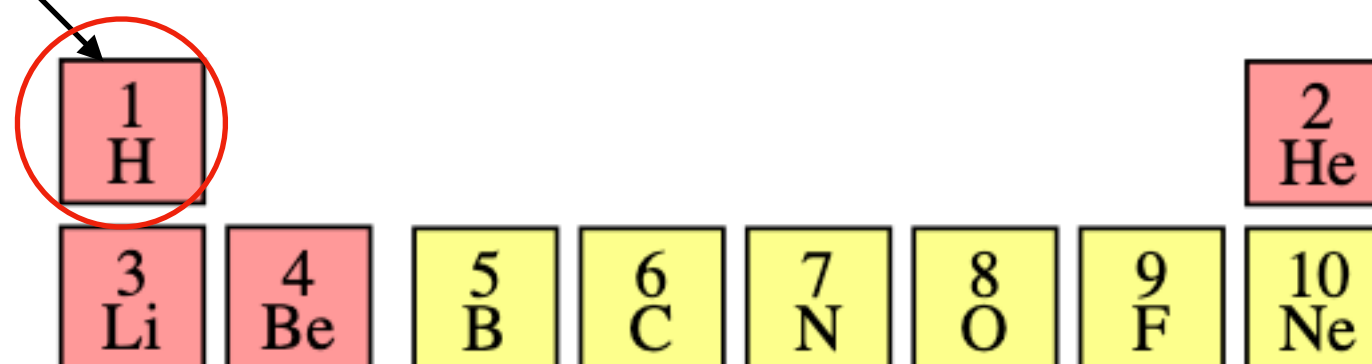


FIG. 3. Experimental setup for the demonstration of laser-driven carbon-ion acceleration using an induction heater.



Producing different ion species

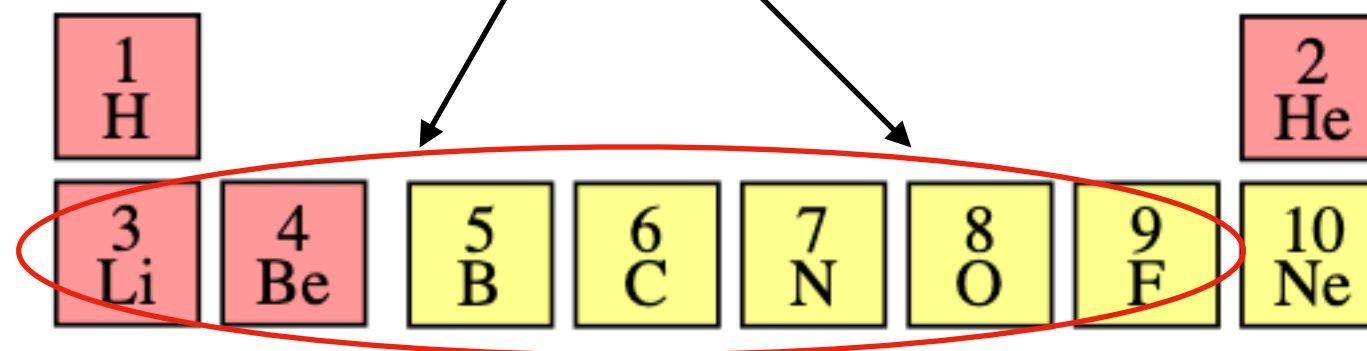
Easy to produce from
contaminants on any
solid material, or liquids/
cryogenic targets



1 H							2 He
3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne

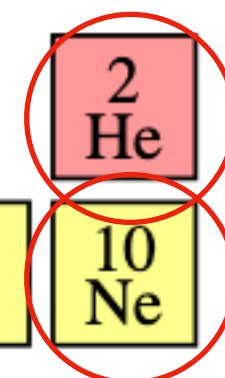
Producing different ion species

Can be found in pure foils, in compounds or
e.g. oxide layers. R&D required to
conceptualise and develop high repetition
target delivery system



Producing different ion species

Extremely challenging for
LhARA-type laser systems,
significant R&D needed!



Gas jets? No one has
demonstrated high
energies/flux using
Ti:Sapph drive laser

1
H

3
Li

4
Be

5
B

6
C

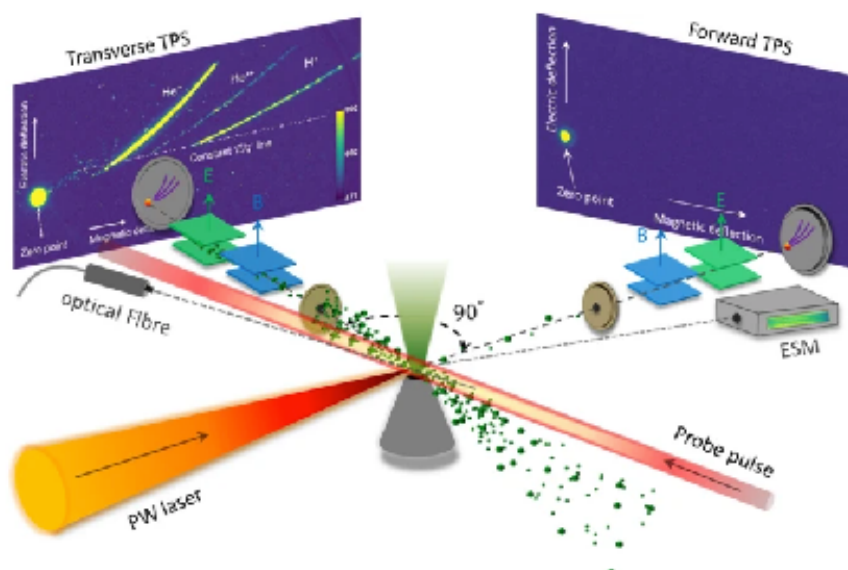
7
N

8
O

9
F

10
Ne

Figure 1

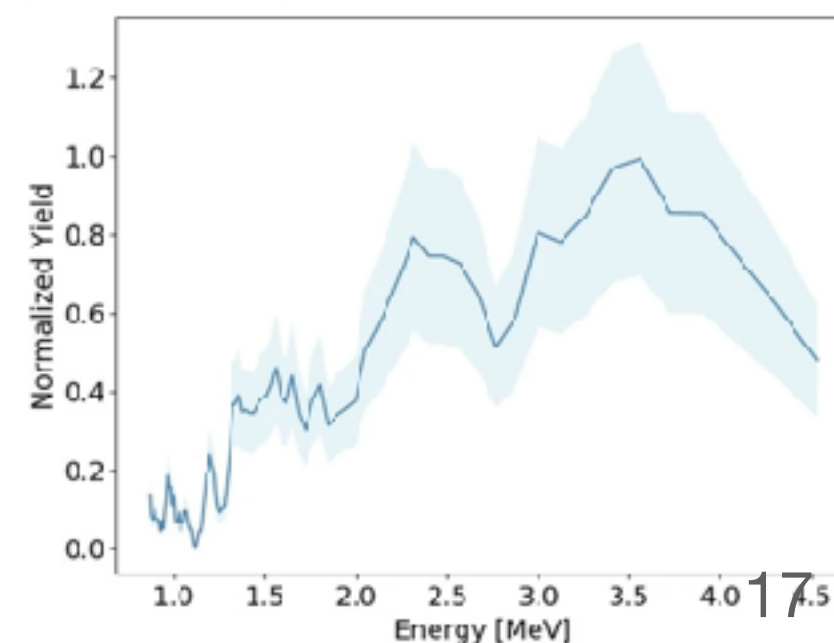


e.g. Singh+ Sci. Rep.
10, 18452 (2020)

For He, induced
nuclear fusion
reactions?
Optimisation and
potential flux not
understood

e.g. Istokskaia+ Comm. Phys. 6, 27
(2023)

Fig. 3: Alpha particles energy distribution.



Further considerations for LhARA ion source

- **Beam purity**

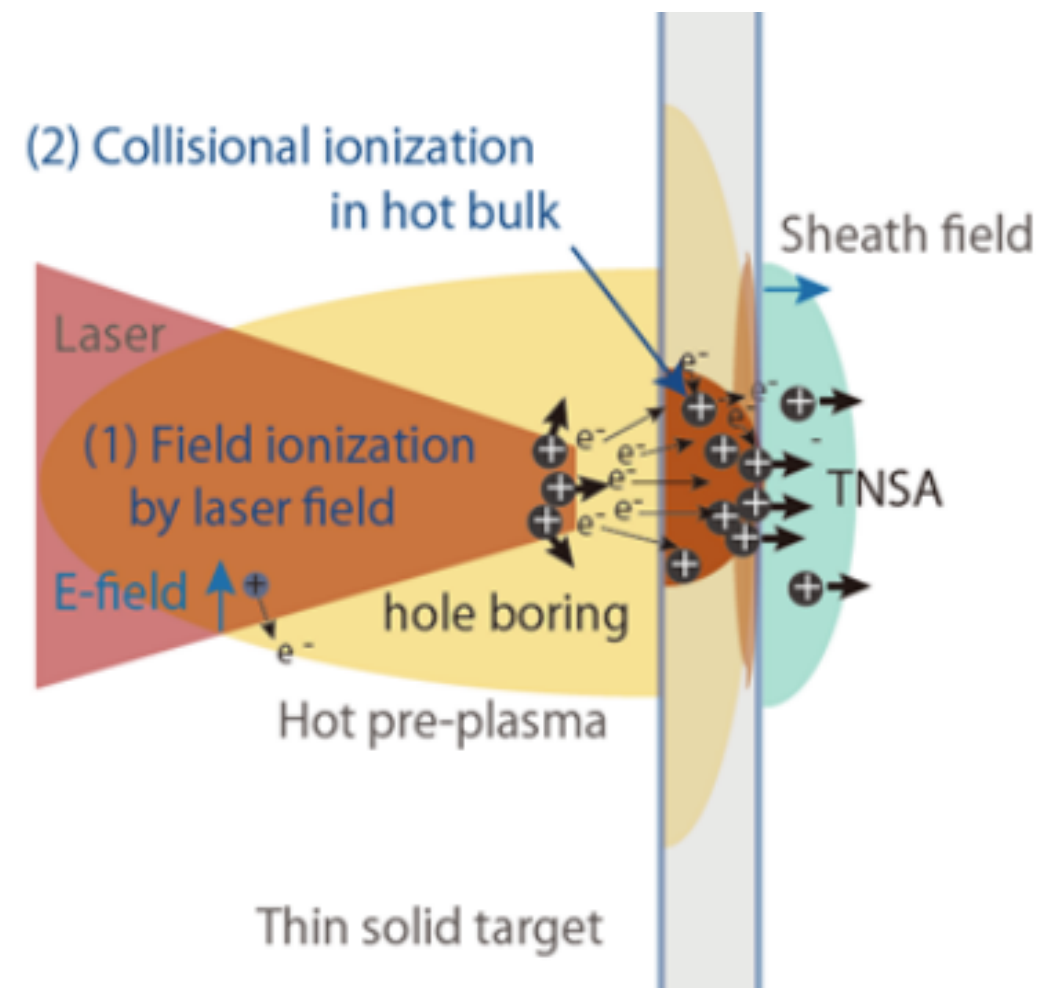
- Typical “cocktail” beam - mixture of ion species, charge states, and energies
- Challenging to separate ion states with same q/m , e.g. C^{6+} and O^{8+}

- **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 and simulating ionisation level is not always easy



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

Summary & questions

- Laser driven ion sources can produce energetic, highly ionised beams of many different ion types
- In general, similar properties to laser driven protons, albeit at lower flux/energy
- Each ion type has its own technical considerations for targetry - significant R&D needed for high rep rate