Enhanced ion heating in short-pulse laser-driven buried-layers for NEET/NEEC

T.E. Cowan[1,2], **Lingen Huang[1]**, T. Kluge[1], M. Bussmann[1]

[1]Helmholtz-Zentrum Dresden-Rossendorf, [2]Technische Universität Dresden

In collaboration with

L. Bernstein, A. Kritcher, R. Shepherd

Lawrence Livermore National Laboratory

Y. Sentoku

University of Nevada, Reno

Markus Roth

Technical Unviersity Darmstadt, and GSI-Darmstadt

Nuclear Fusion: From NIF to the Stars

2014 ACS National Meeting

San Francisco, 11 August 2014

Enhanced ion heating for NEET/NEEC

Motivation

- NEET/NEEC in high rep-rate short-pulse laser experiments
- **CONCEPT:** Enhanced heating in buried layers
  Y. Sentoku et al, Phys. Plasmas **14**, 122701 (2007)

Systematic study of enhanced ion heating

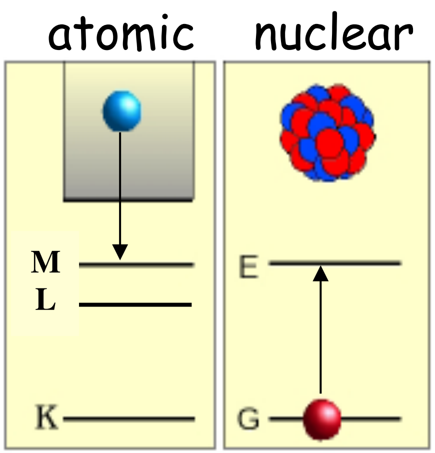
- Full solid density, self-consistent ionization, no numerical heating...
- Parameter dependence of energy transfer and ion heating at high laser intensity
  L. Huang et al, Phys. Plasmas **20**, 093109 (2013)

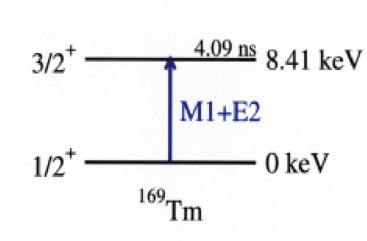
Future work

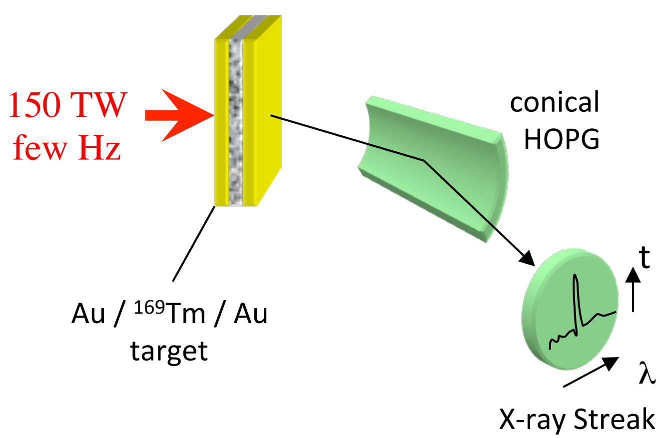
- Simulation of optimized, high Z layers
- Characterization with XFEL at HIBEF

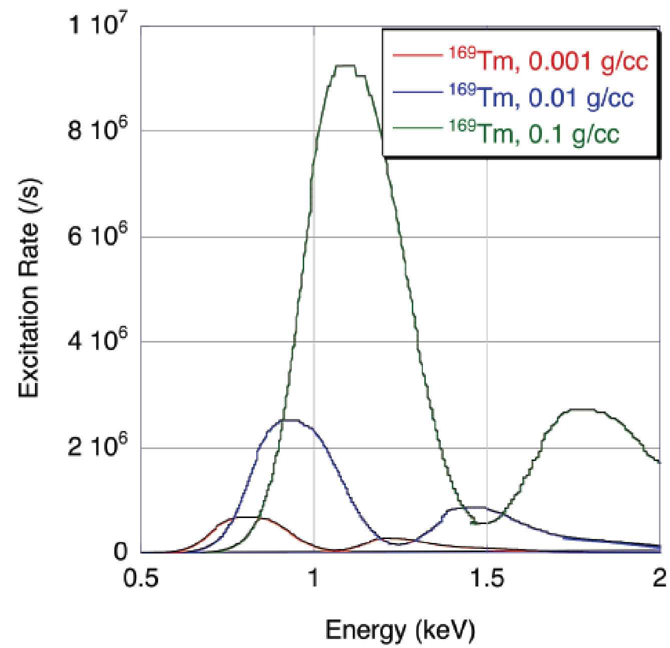
NEEC/NEET with Short Pulse Laser

- ^{169}Tm NEET/NEEC with 150 TW DRACO laser @ HZDR (4 J/30 fs/10 Hz)
- Isochoric heating to keV temperatures (Sentoku et al, PoP 14, 122701, 2007)
- Streaked spectroscopy at 8.4 keV
  → discriminate 4.1 ns nuclear decay from few-ps plasma emission





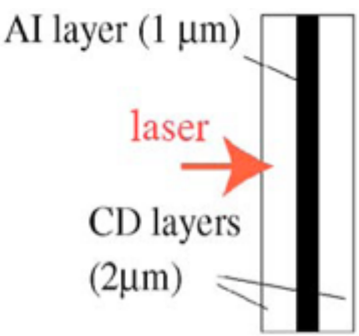


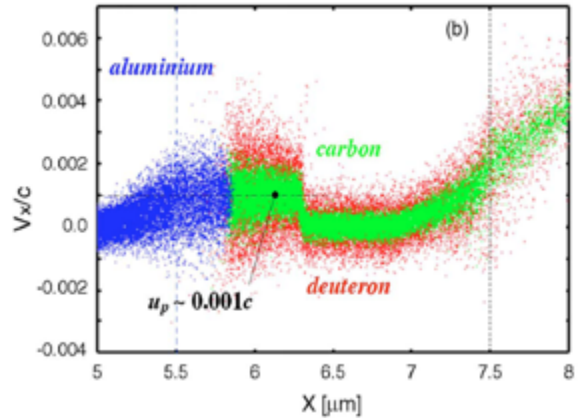


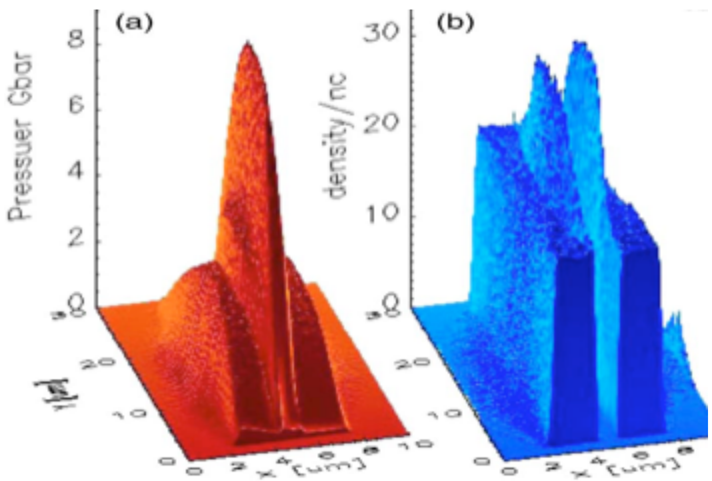
A. Kritcher et al.,
JINA Workshop, London
March 13, 2011

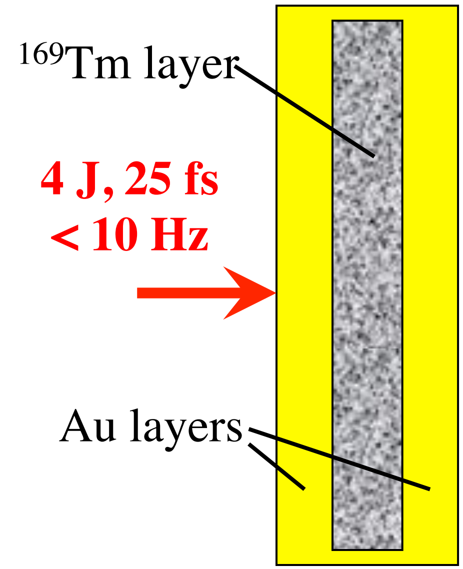
Concept: isochoric heating in buried layers

"Isochoric heating in heterogenous solid targets with ultrashort laser pulses," Sentoku, Kemp, Presura, Bakeman and Cowan, Phys. Plasmas **14**, 122701 (2007)







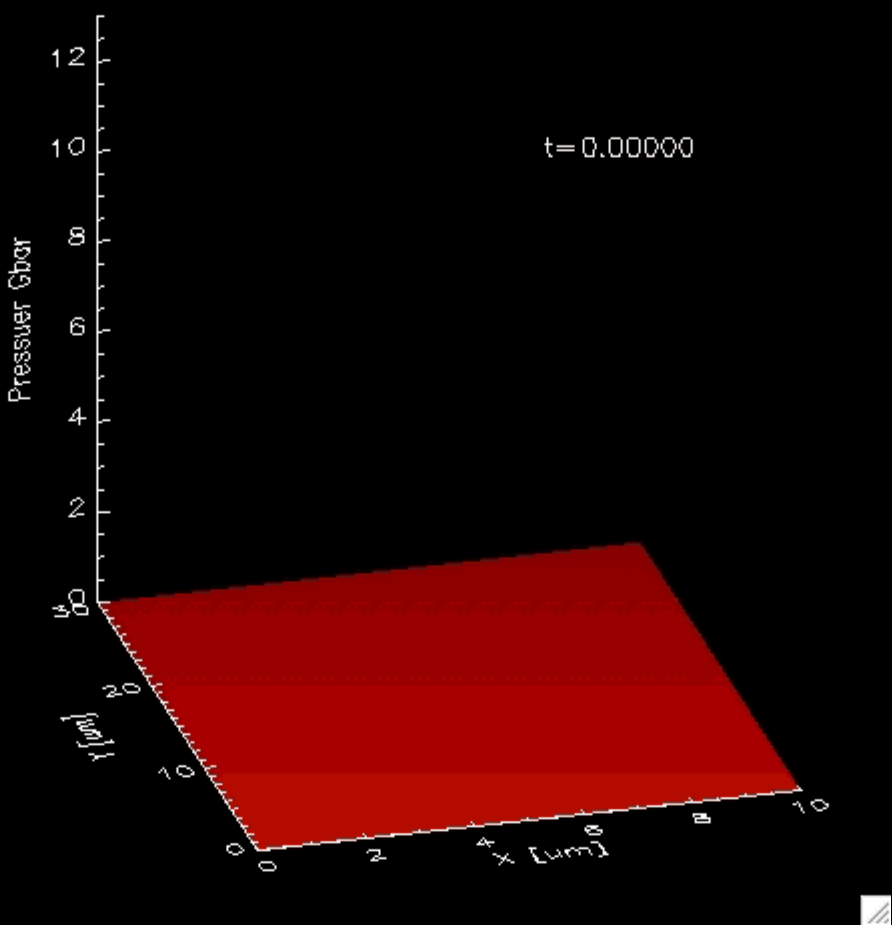


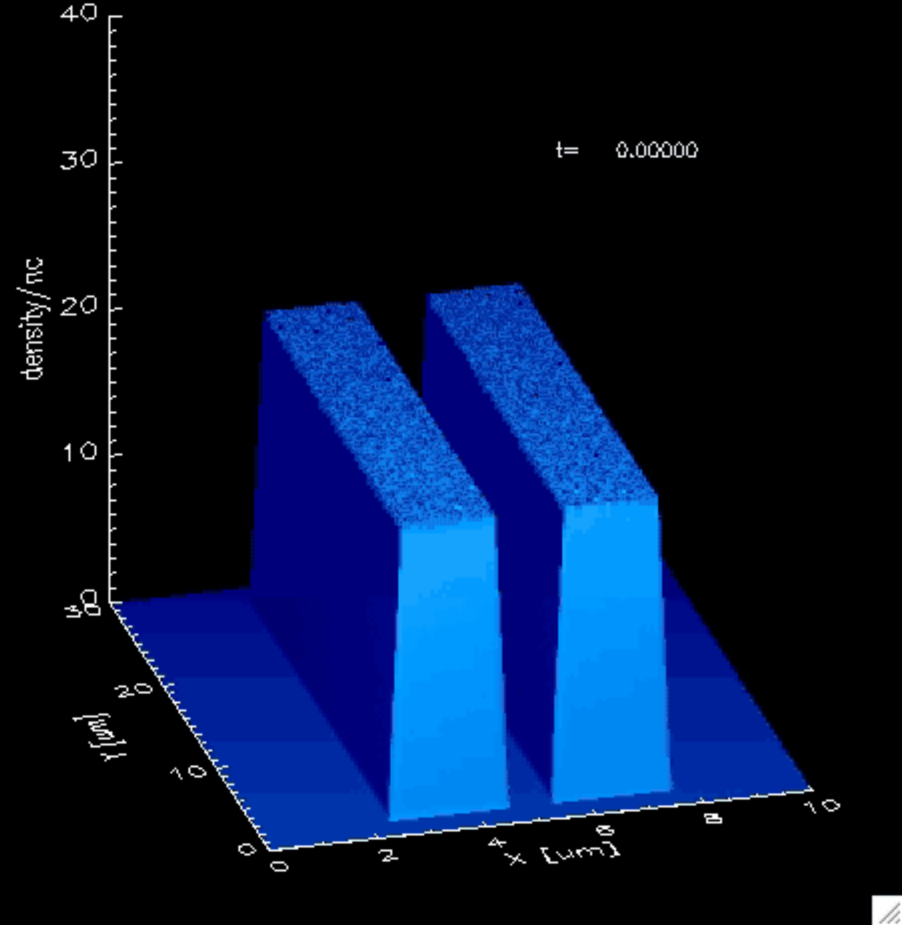
- few keV
- 10 g/cc
- few ps

- Electron pressure-gradient-driven pusher – calculated at 20 n_{cr}
- CD2 chosen, in order to use D-D fusion neutrons as ion diagnostic

Concept: isochoric heating in buried layers

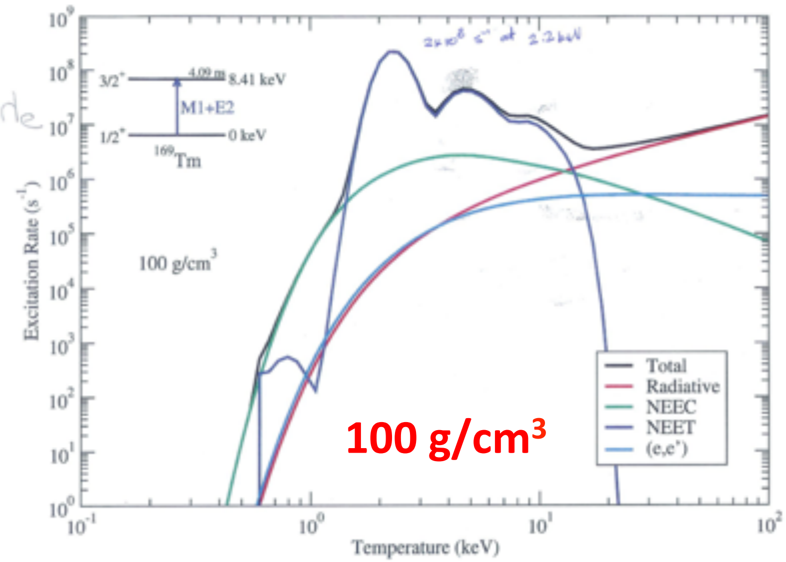
"Isochoric heating in heterogenous solid targets with ultrashort laser pulses,"
Y. Sentoku, A. Kemp, R. Presura, M. Bakeman, T.E. Cowan, Phys. Plasmas **14**, 122701 (2007)

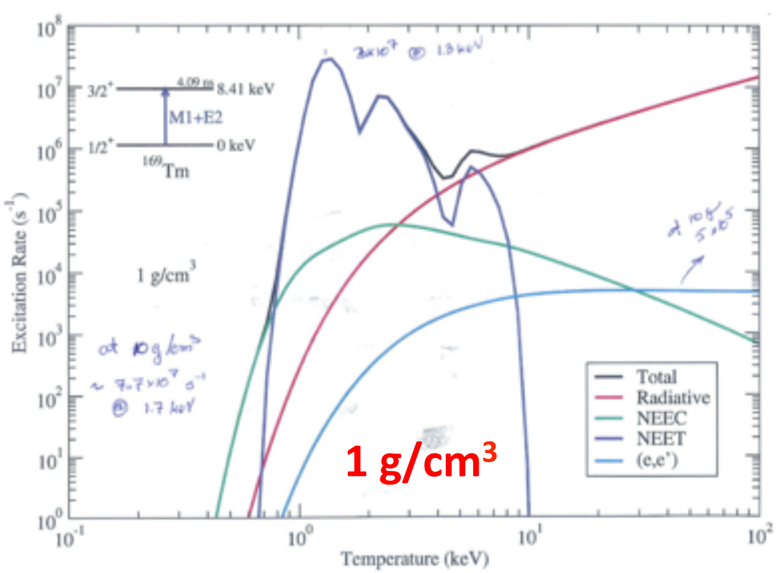




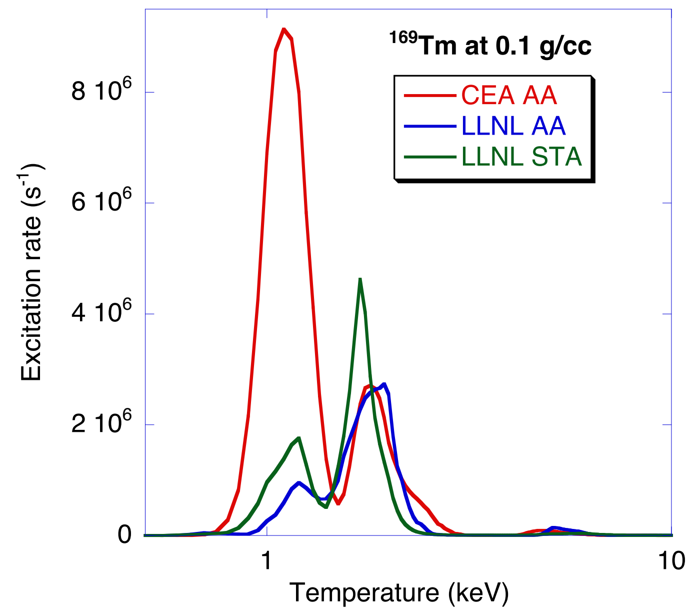
Predicted Excitation Rates in ^{169}Tm

G. Gosselin, CEA





M. Chen/A. Kritcher, LLNL



- kT ~ 1-2 keV,
- solid density ~ 9.3 g/cm^3
- Peak Excitation rate ~7.10^7 /s

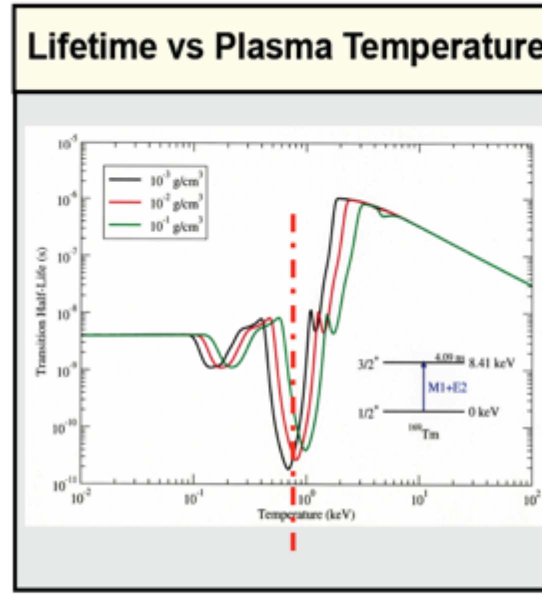
Signal rate predicted in short-pulse NEEC/NEET experiment

- Short-pulse separates excitation from decay
- High Repetition rate allows signal averaging & systematics

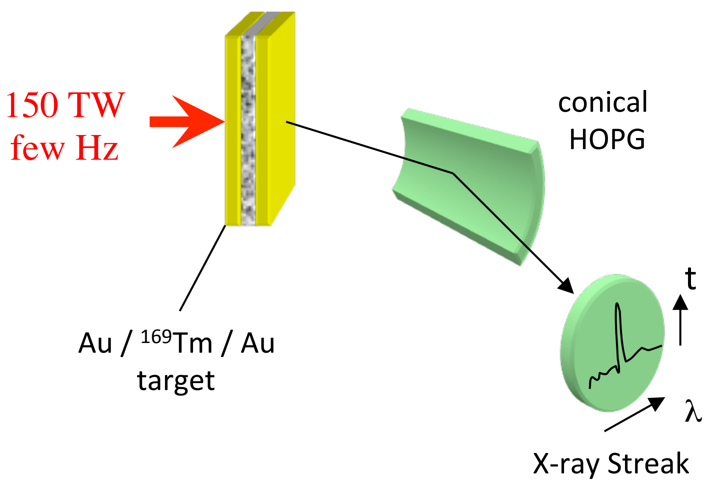
→ Verify excitation rates, and
resolve unknowns (e.g., Lifetime vs. Plasma Temperature)

  - High-rep-rate 150 TW laser “Draco” at HZDR
  - tamped targets – short-pulse isochoric heating
  - large collection HOPG
  - Fast X-ray streak, few ps (plasma emission)
  - Slow X-ray streak, few ns (nuclear decay)

A Kritcher et al., JINA Workshop, March 13, 2011, London



The half-life is predicted to decrease to 30 ps!



- kT ~ 1-2 keV, ~solid density, ~ 10 μm^3
- Rate ~7.10^7 /s, Int. Conv. Coeff. α=263.5

$N_\gamma \sim (4x10^{11}$ nuclei$)(7x10^7)(10^{-12}$ s$)(1/\alpha) \sim 10^5$ per shot

HOPG efficiency ~ few 10^{-4}, $Q_E \sim 0.2$

Signal: (few γ / shot) × (few shot / s) ~ 10 s^{-1}

Enhanced ion heating for NEET/NEEC

Motivation

- NEET/NEEC in high rep-rate short-pulse laser experiments
- **CONCEPT:** Enhanced heating in buried layers

  Y. Sentoku et al, Phys. Plasmas **14**, 122701 (2007)

Systematic study of enhanced ion heating

- Full solid density, self-consistent ionization, no numerical heating...
- Parameter dependence of energy transfer and ion heating at high laser intensity

  L. Huang et al, Phys. Plasmas **20**, 093109 (2013)

Future work

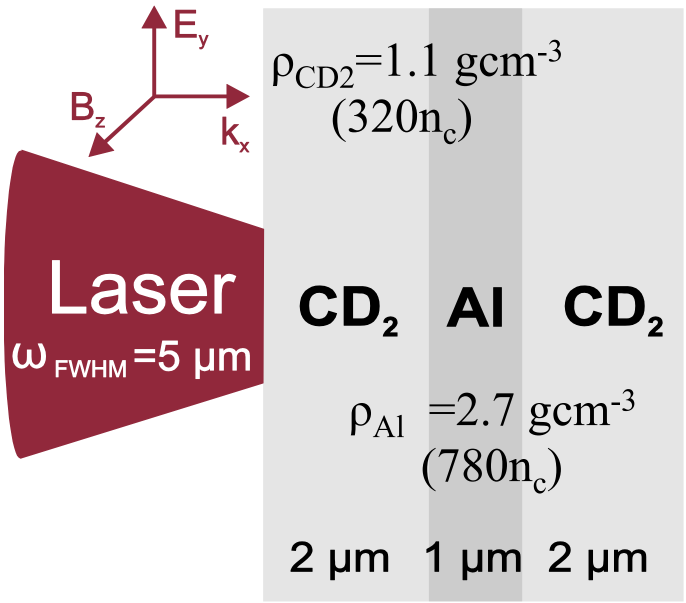
- Simulation of optimized, high Z layers
- Characterization with XFEL at HIBEF

Particle in Cell simulation parameters

Laser parameters

τ_{FWHM} [fs]	I_0 [W/cm²]				
	2×10^{19}	5×10^{19}	1×10^{20}	2.8×10^{20}	5×10^{20}
500	3 J	7.5 J	15 J	42 J	75 J
400	2.4 J	6 J	12 J	-	60 J
300	1.8 J	4.5 J	9 J	-	45 J
200	1.2 J	3 J	6 J	-	30 J
100	0.6 J	1.5 J	3 J	-	15 J

Target configuration

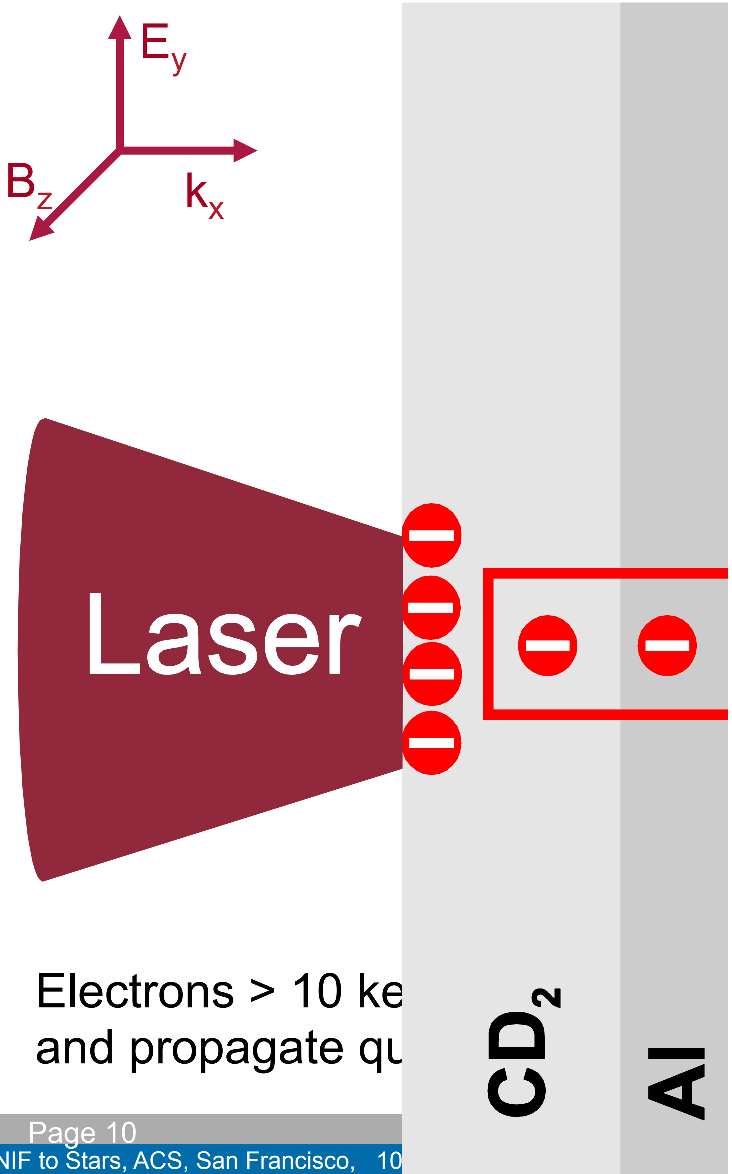


Numerical parameters

- $N_x \times N_y$ = 9000 x 4500
- $\Delta x \times \Delta y = \lambda_0 / 150 \times \lambda_0 / 150$
- $\Delta t = \Delta x / c$ (Directional splitting)
- $\omega_{plasma} \Delta t \approx 1.2 < 2$
- Deuteron / Carbon / Aluminum ion number per cell : 24 / 12 /18
- maximum macro particle number : ~ 0.5×10^9
- macro particle per real particle : ~ 1000
- interpolation order : 4

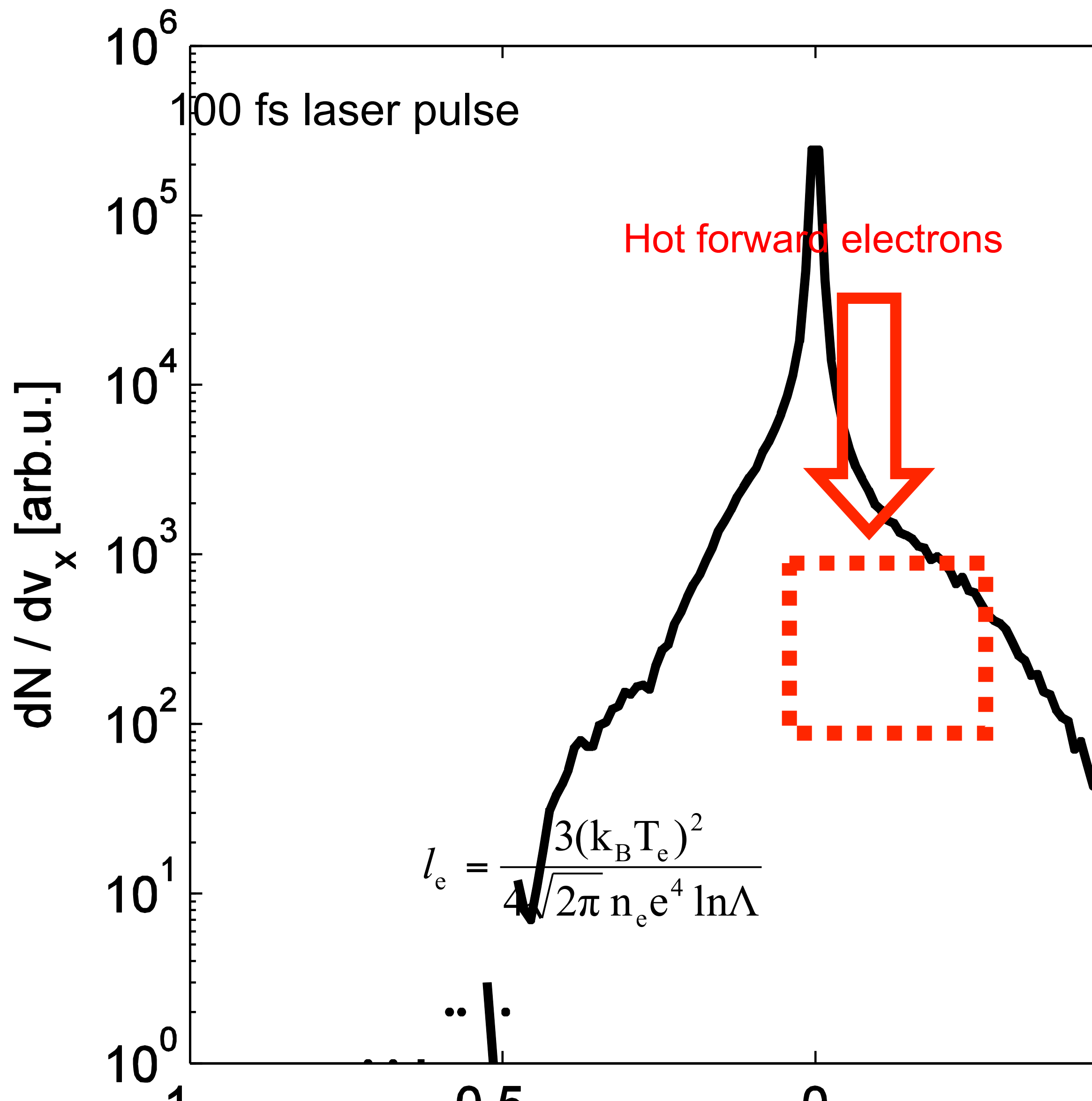
Ion heating dynamics in buried layer targets

Laser generated fast electrons propagate into target

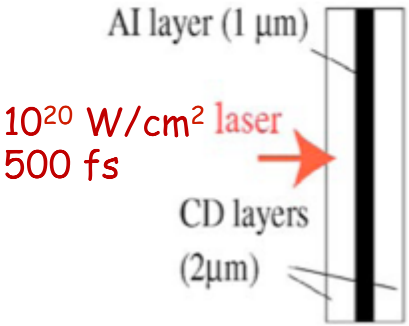


Electrons > 10 ke
and propagate qu

Velocity distribution for all electrons along laser axis



Ion heating dynamics in buried layer targets

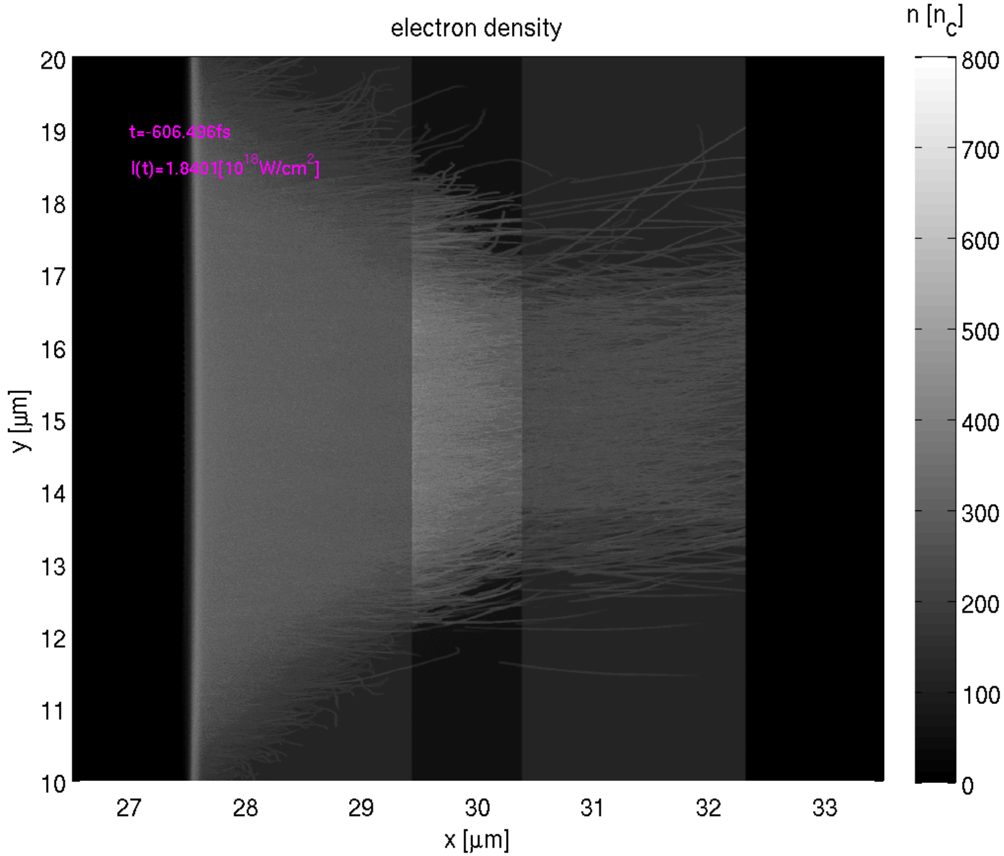


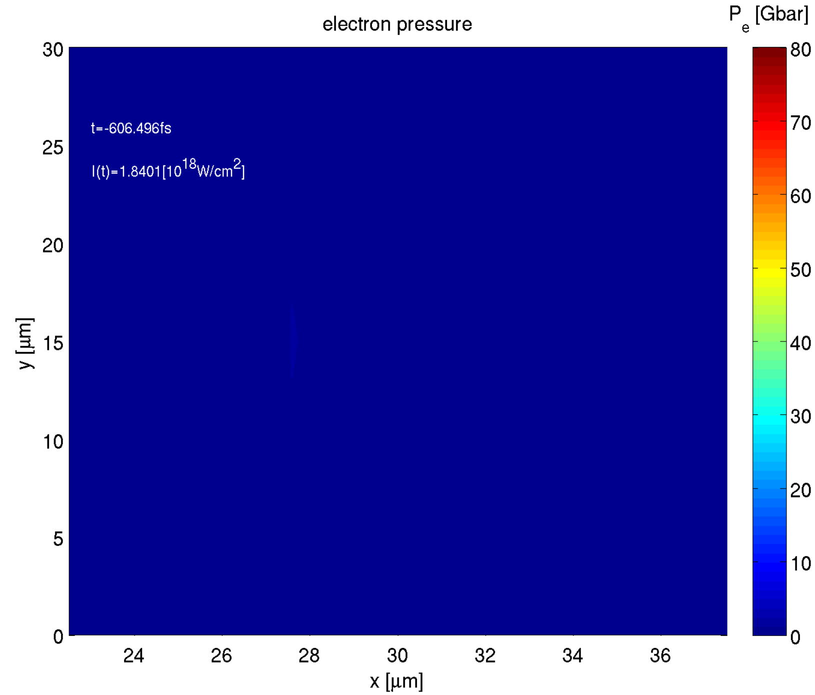
PICLS2d @ solid density
Ionization & collisions

L. Huang, M. Bussmann et al.,
Phys. Plasmas **20**, 093109 (2013)

Processes:

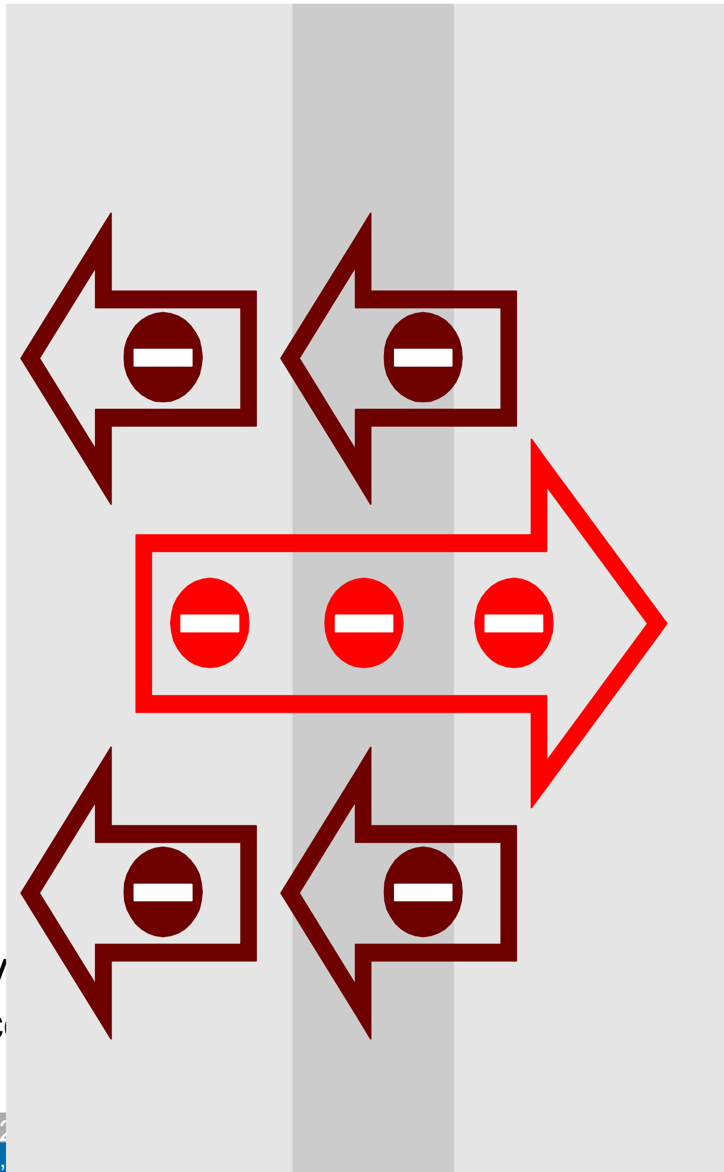
- Ionization dynamics
- e^- filamentation
- Hole-boring
- Channeling (hydro)
- Ion heating
- Interface "shocks"
- Colliding shocks
- Magnetic filaments



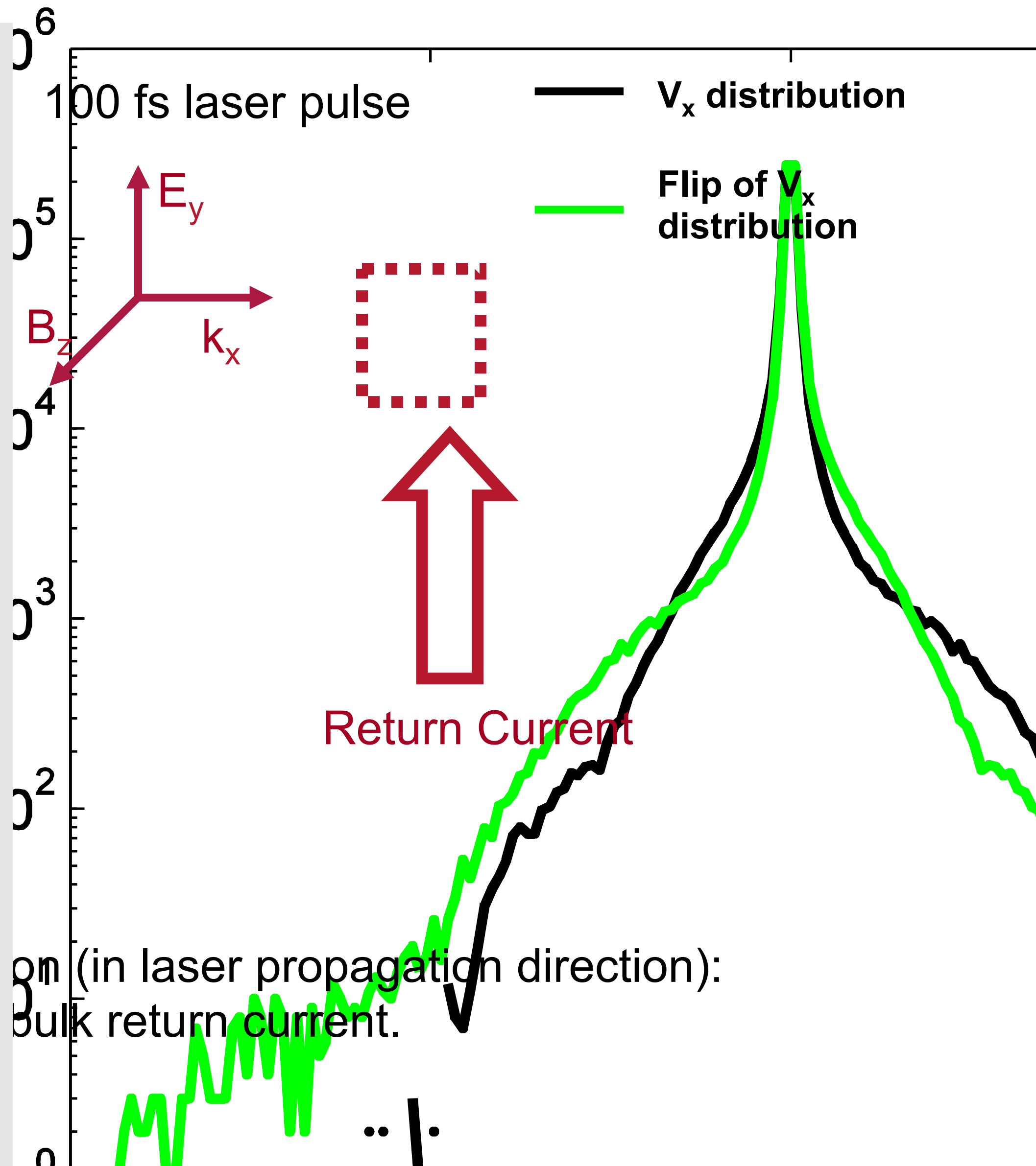


Ion heating dynamics in buried layer targets

Net return current



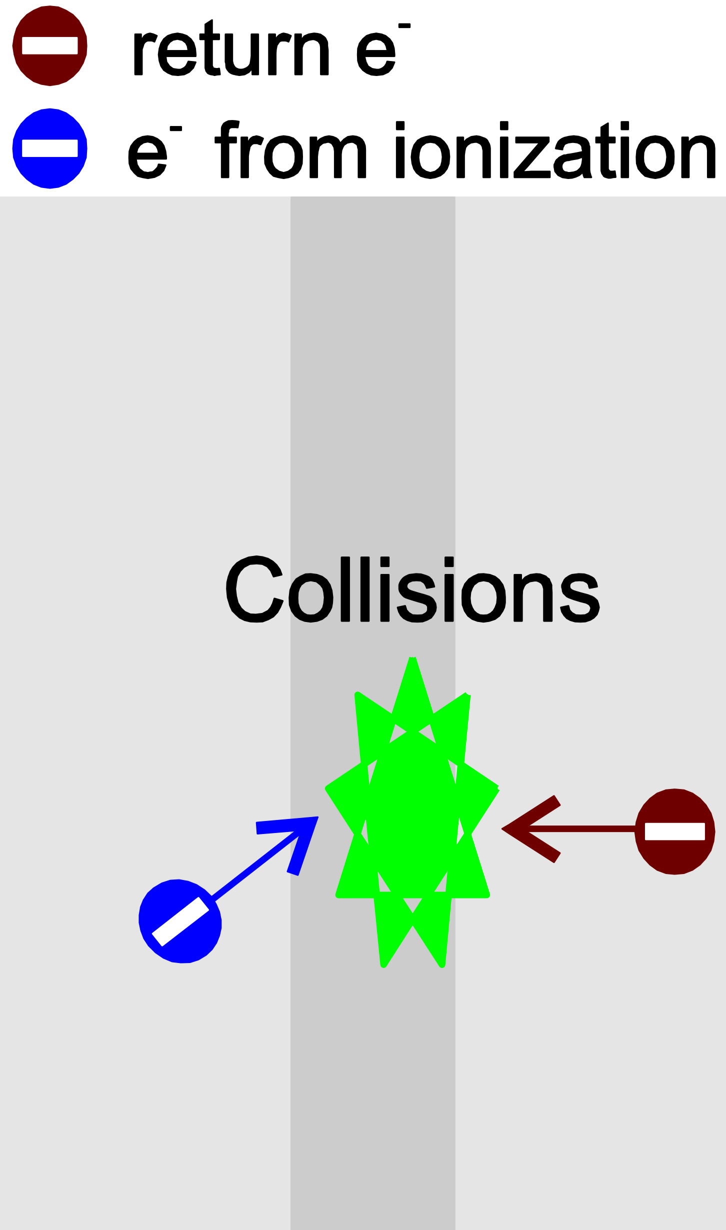
Velocity distribution for all electrons in laser axis



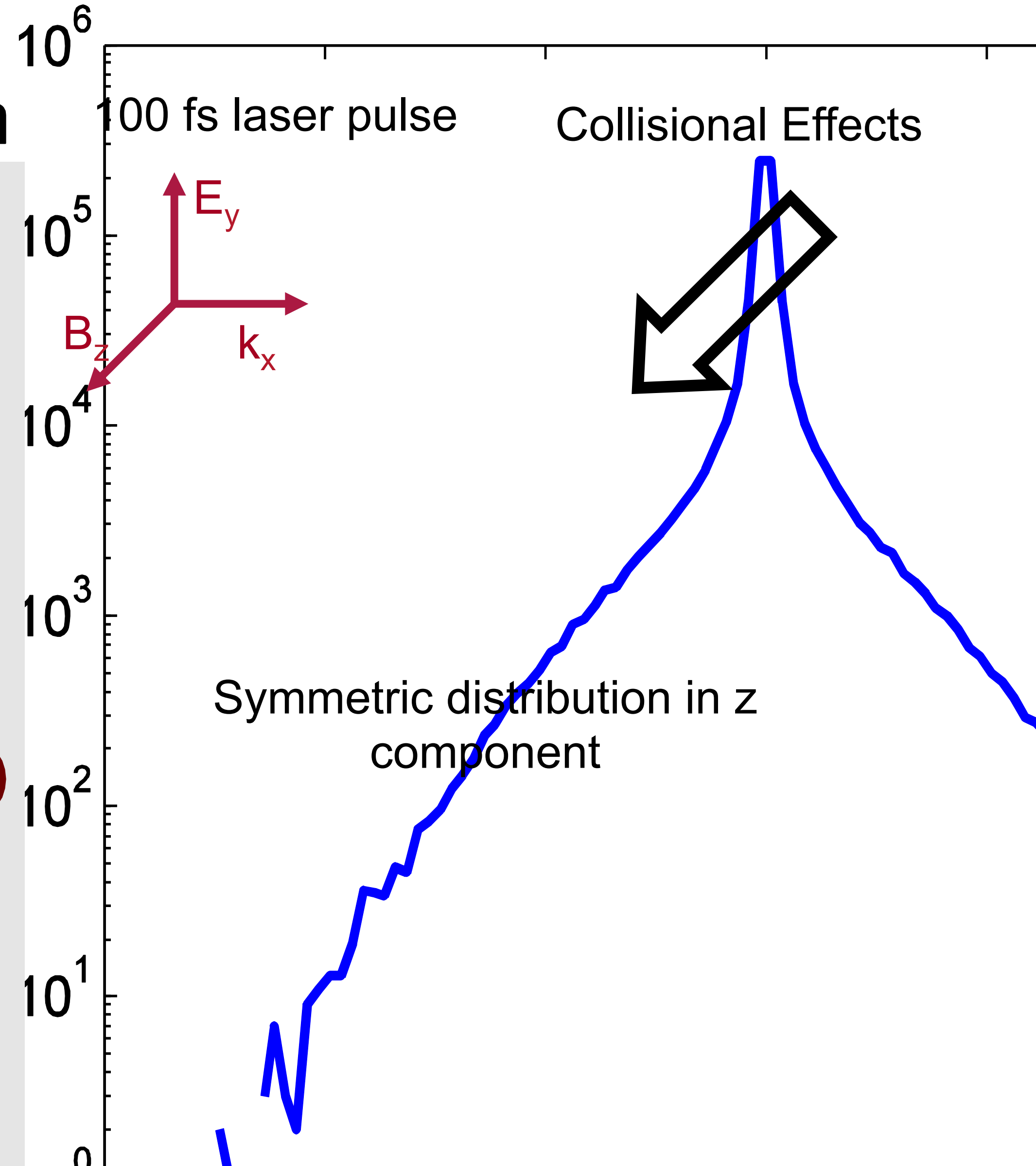
Asy… on (in laser propagation direction):
exc… bulk return current.

Ion heating dynamics in buried layer targets

Collisional heating of electrons



Velocity distribution for all electrons in transverse direction

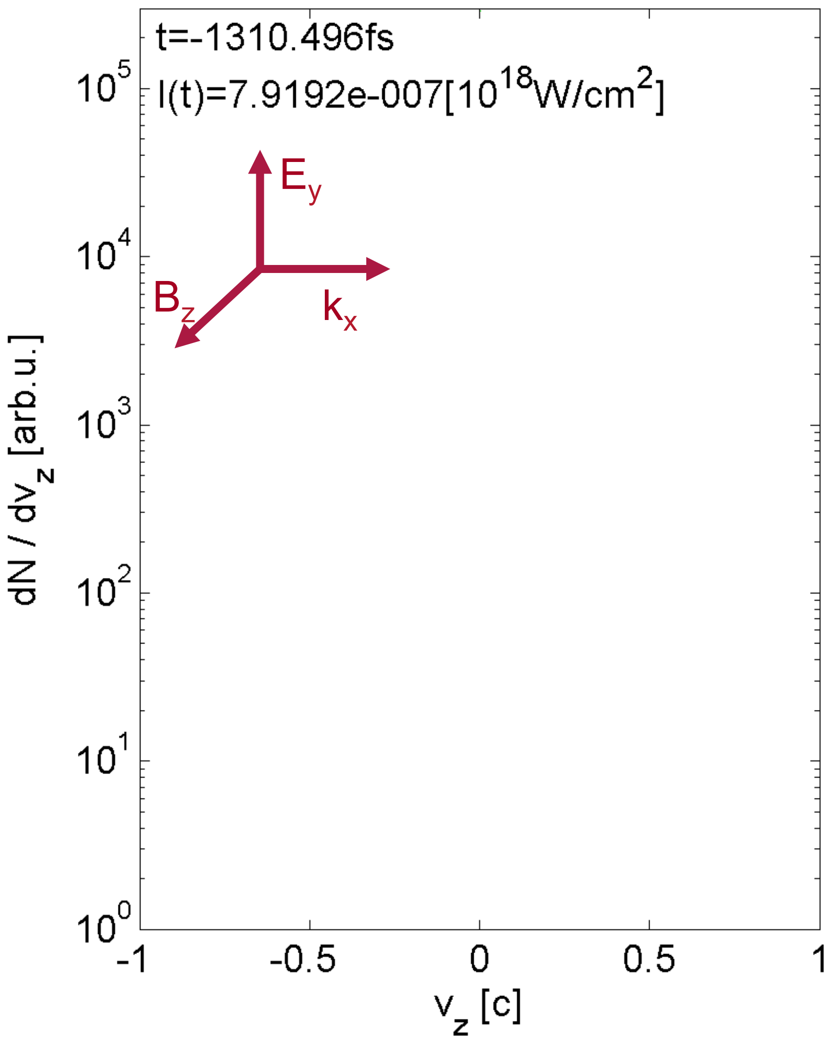


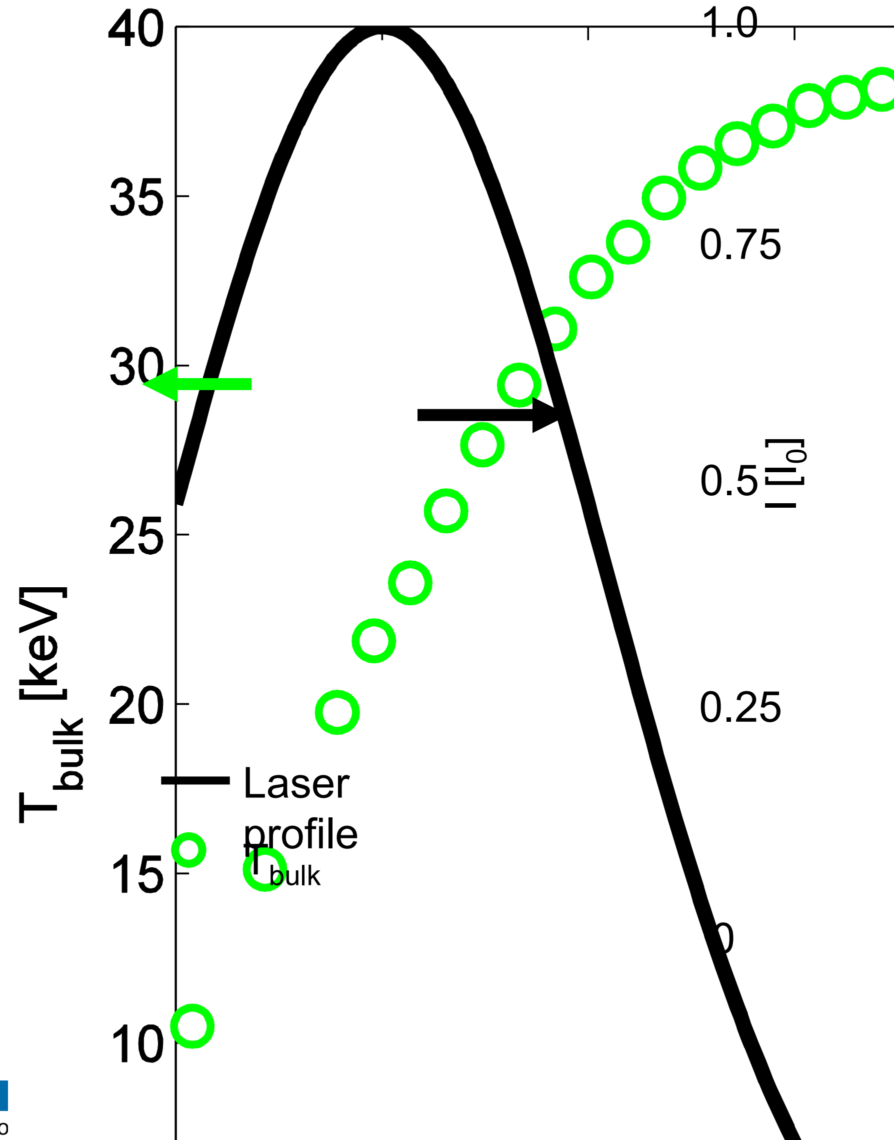
“Retu
collisi
transv

Ion heating dynamics in buried layer targets

Temporal evolution of bulk electron temperature

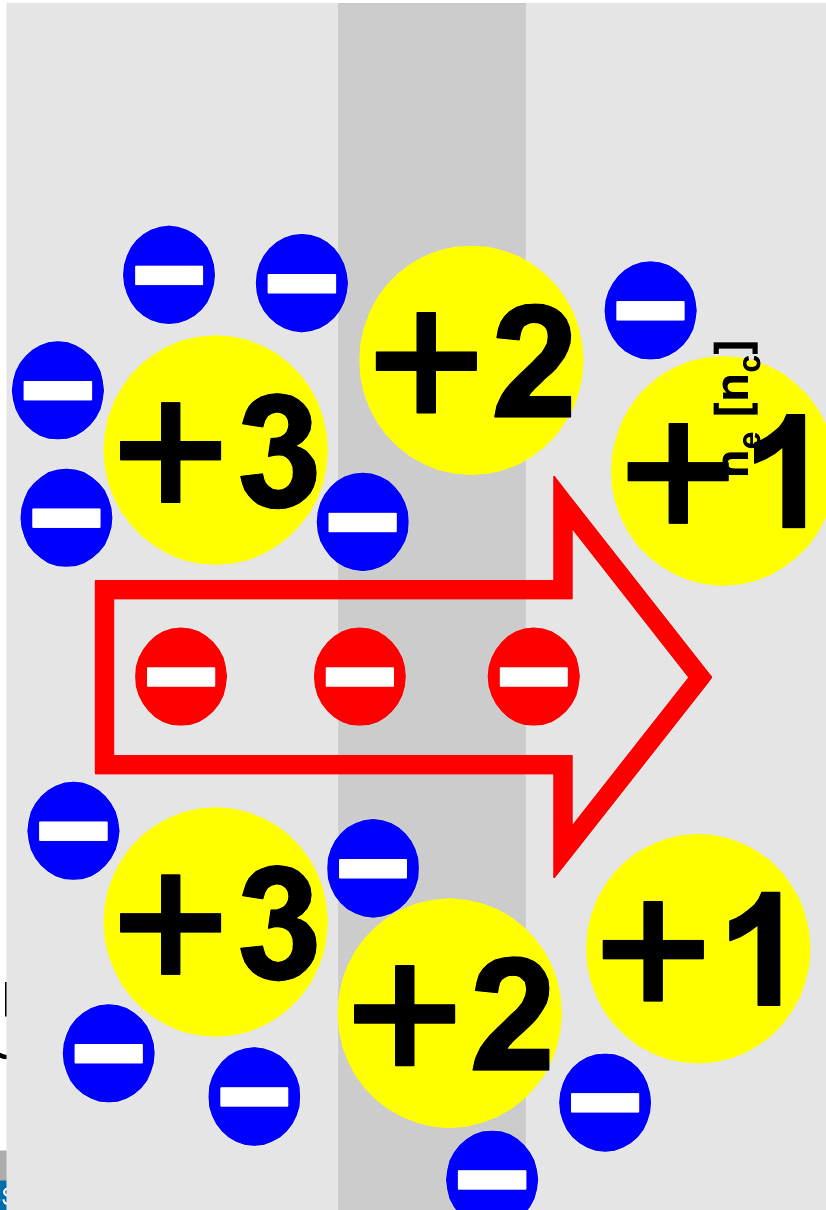
electron velocity distribution → electron thermal temperature

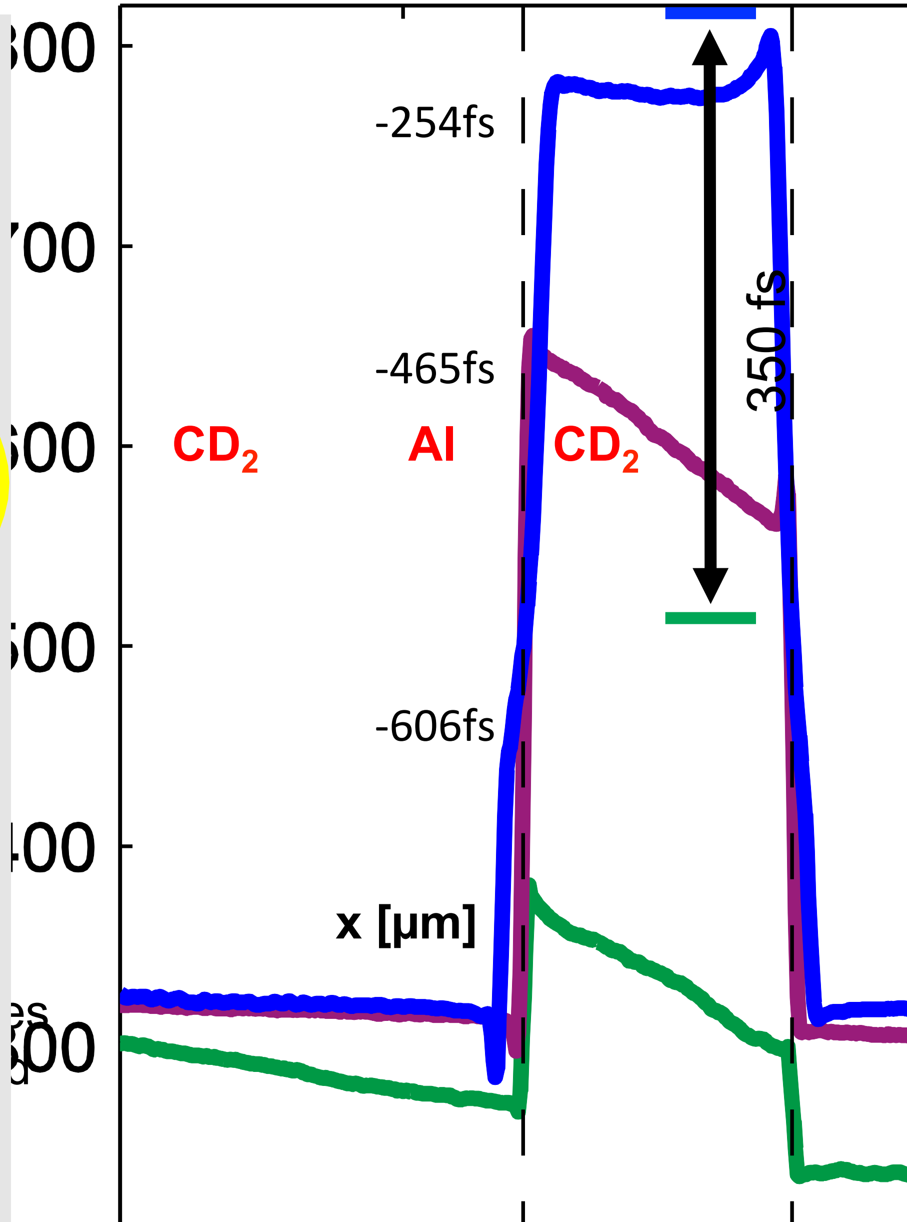




Ion heating dynamics in buried layer targets

Ionization evolution: creates more free electrons

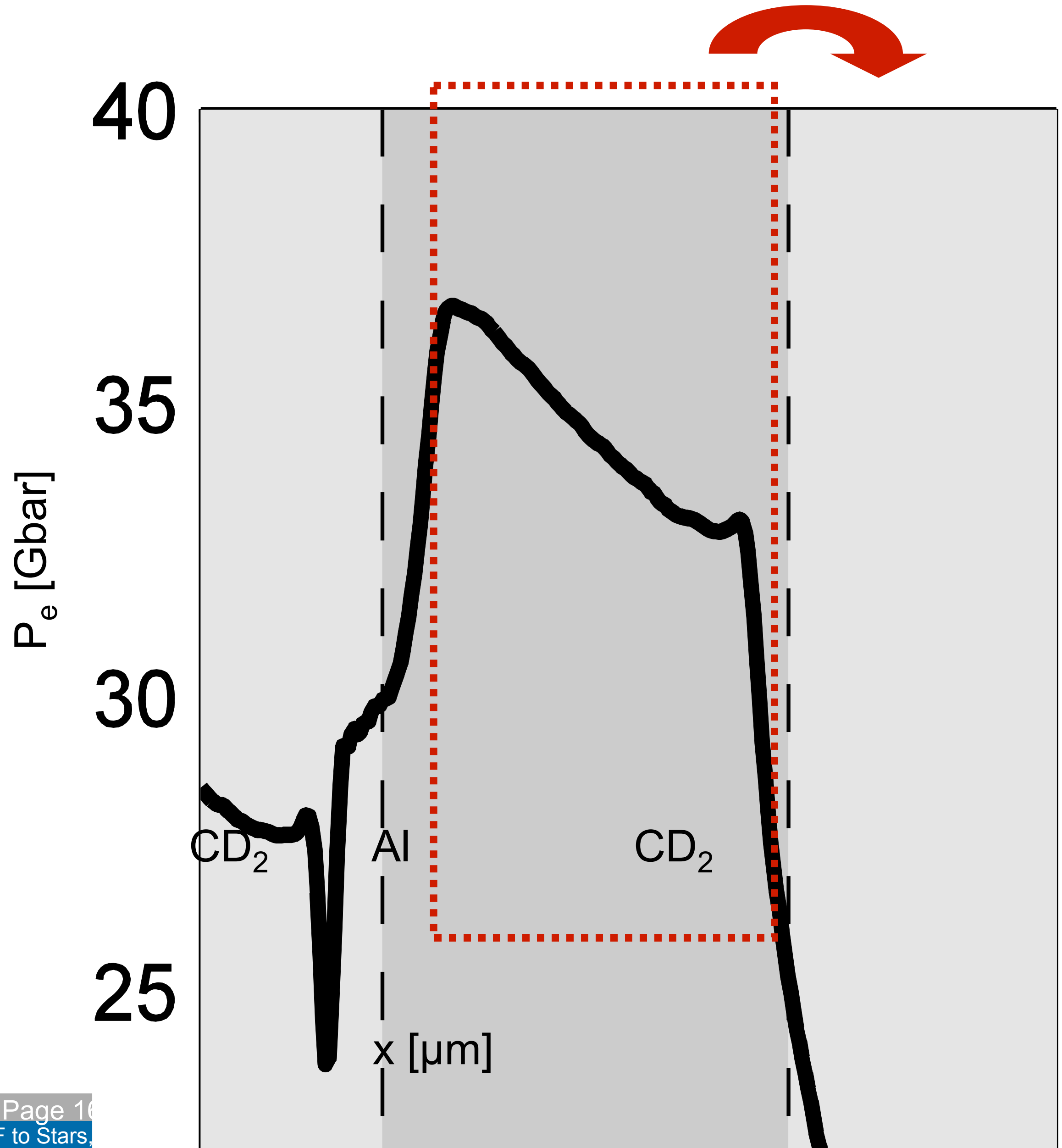


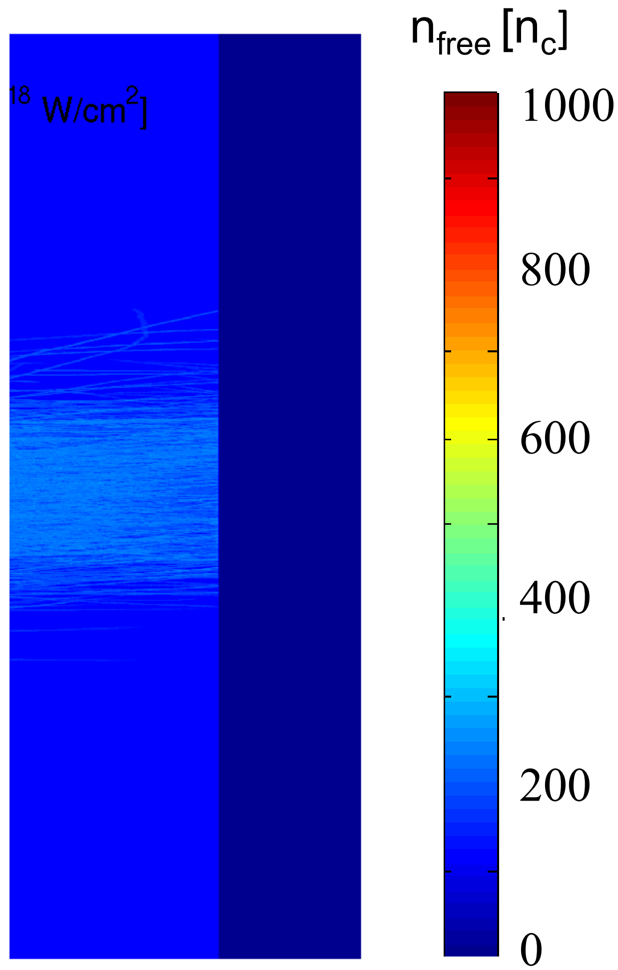


→ Coll
→ At ~

Ion heating dynamics in buried layer targets

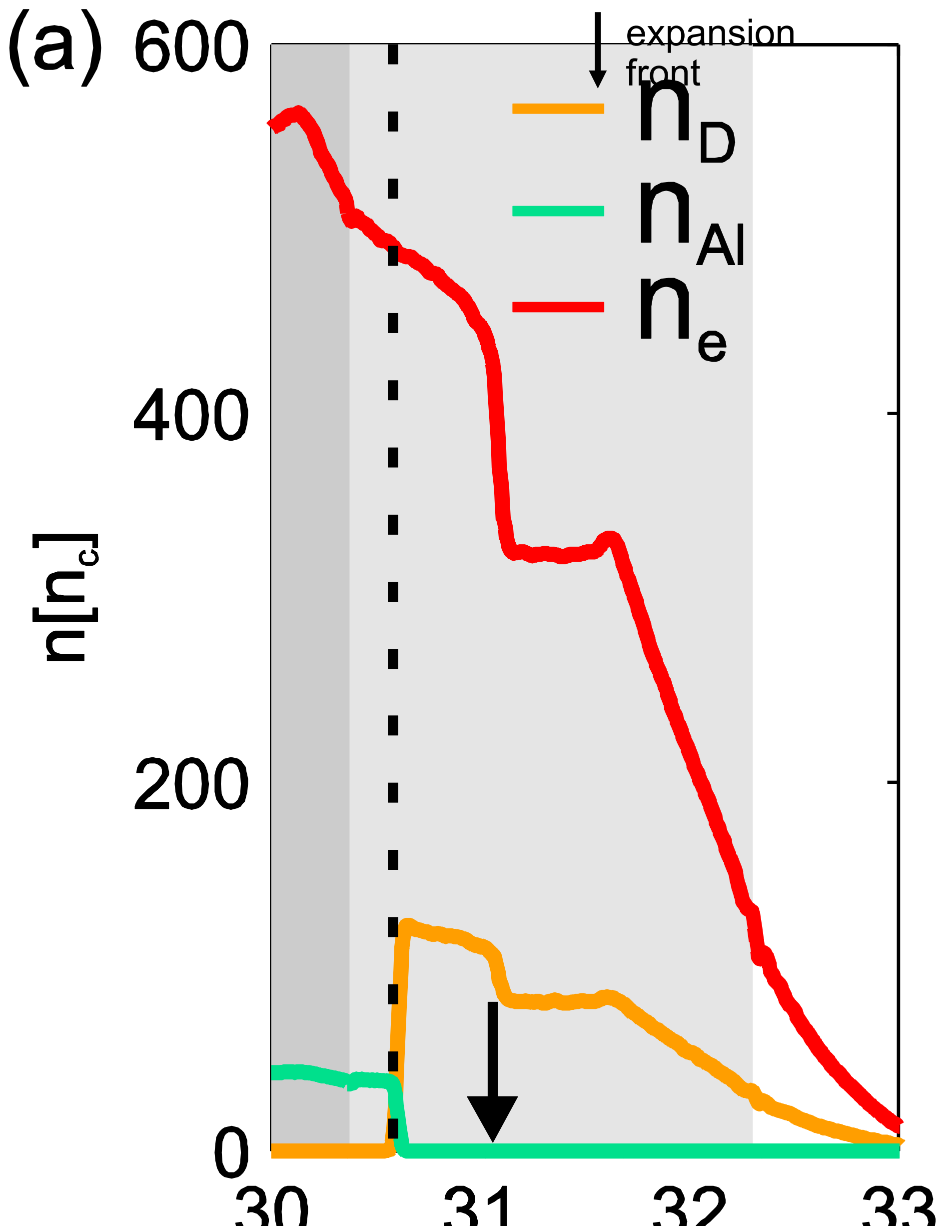
Internal expansion driven by electron pressure gradient driven



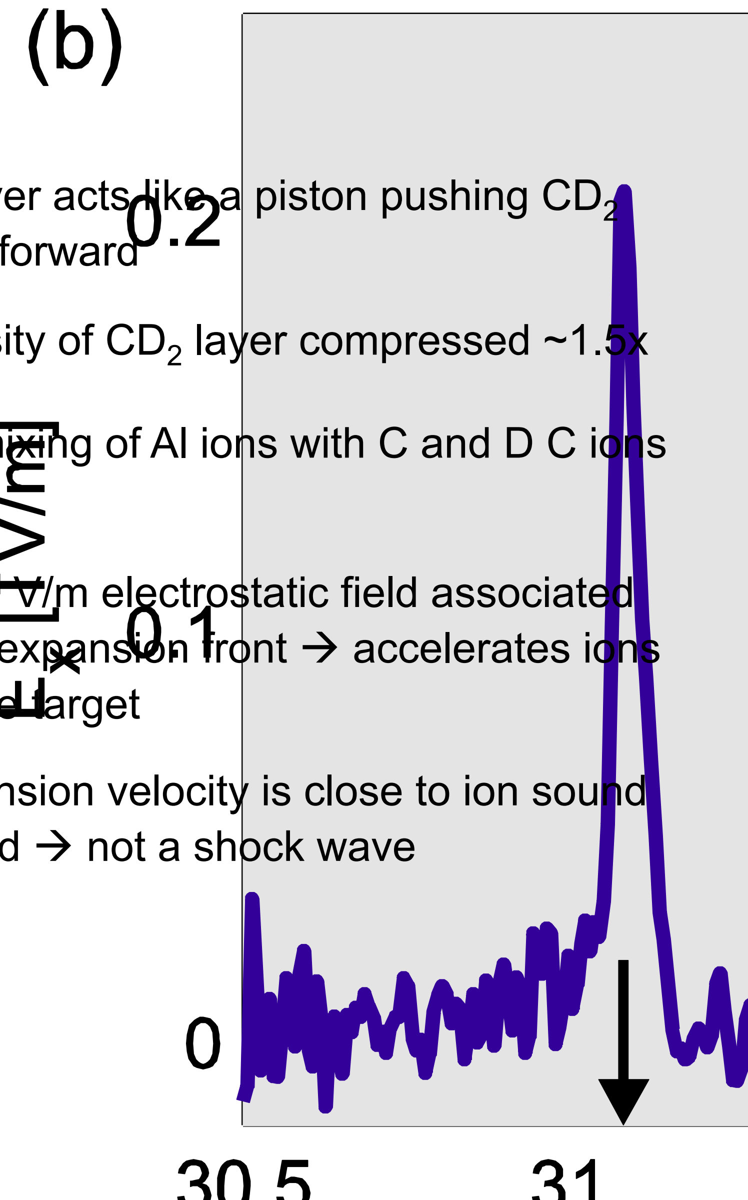


Ion heating dynamics in buried layer targets

Ion collective motion driven by the internal electrostatic field



The f



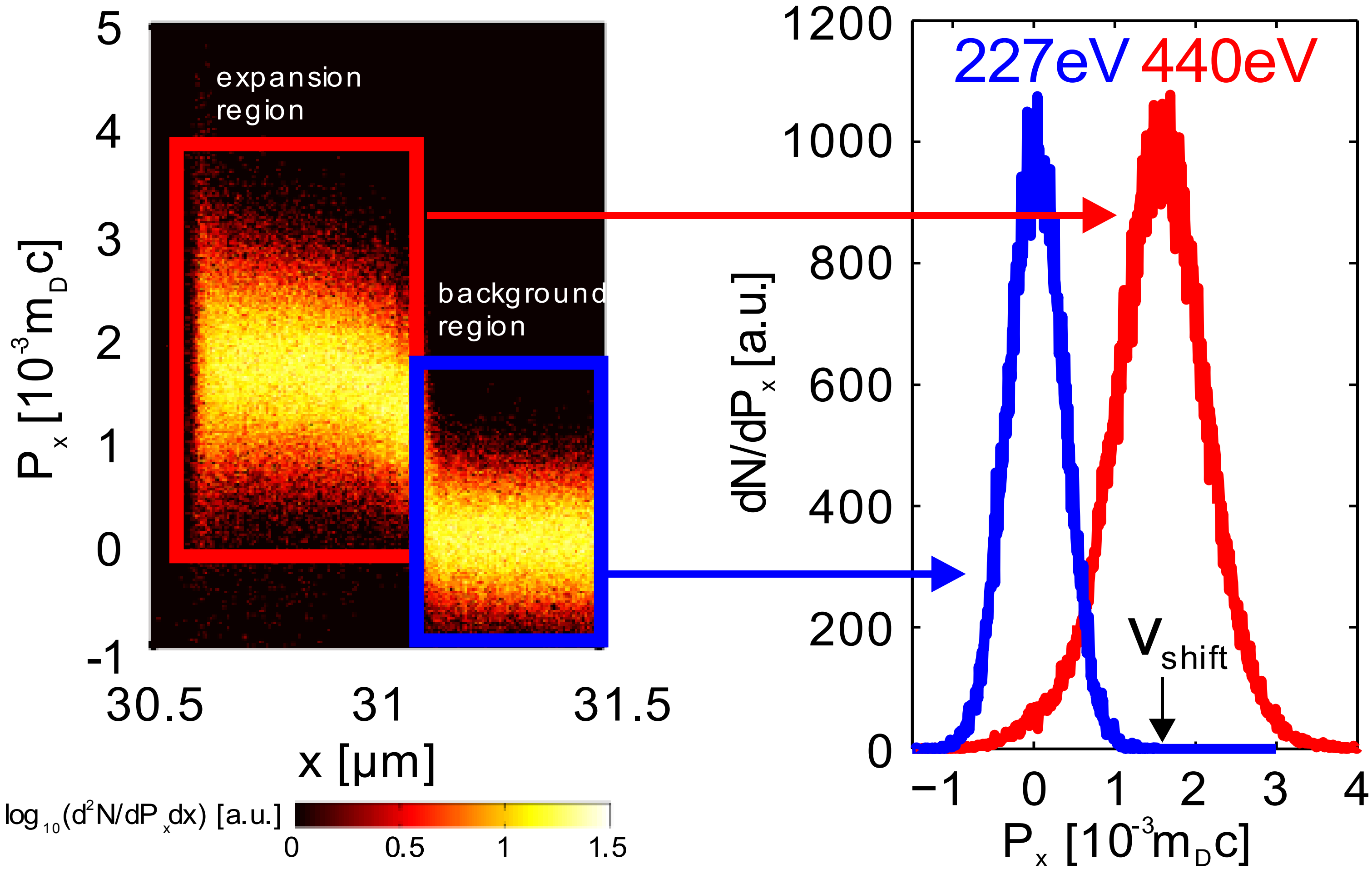
- Al layer acts like a piston pushing CD_2 layer forward
- Density of CD_2 layer compressed ~1.5x
- No mixing of Al ions with C and D C ions
- ~10^{1} V/m electrostatic field associated with expansion front → accelerates ions inside target
- expansion velocity is close to ion sound speed → not a shock wave

al Beamlin

P
NIF t

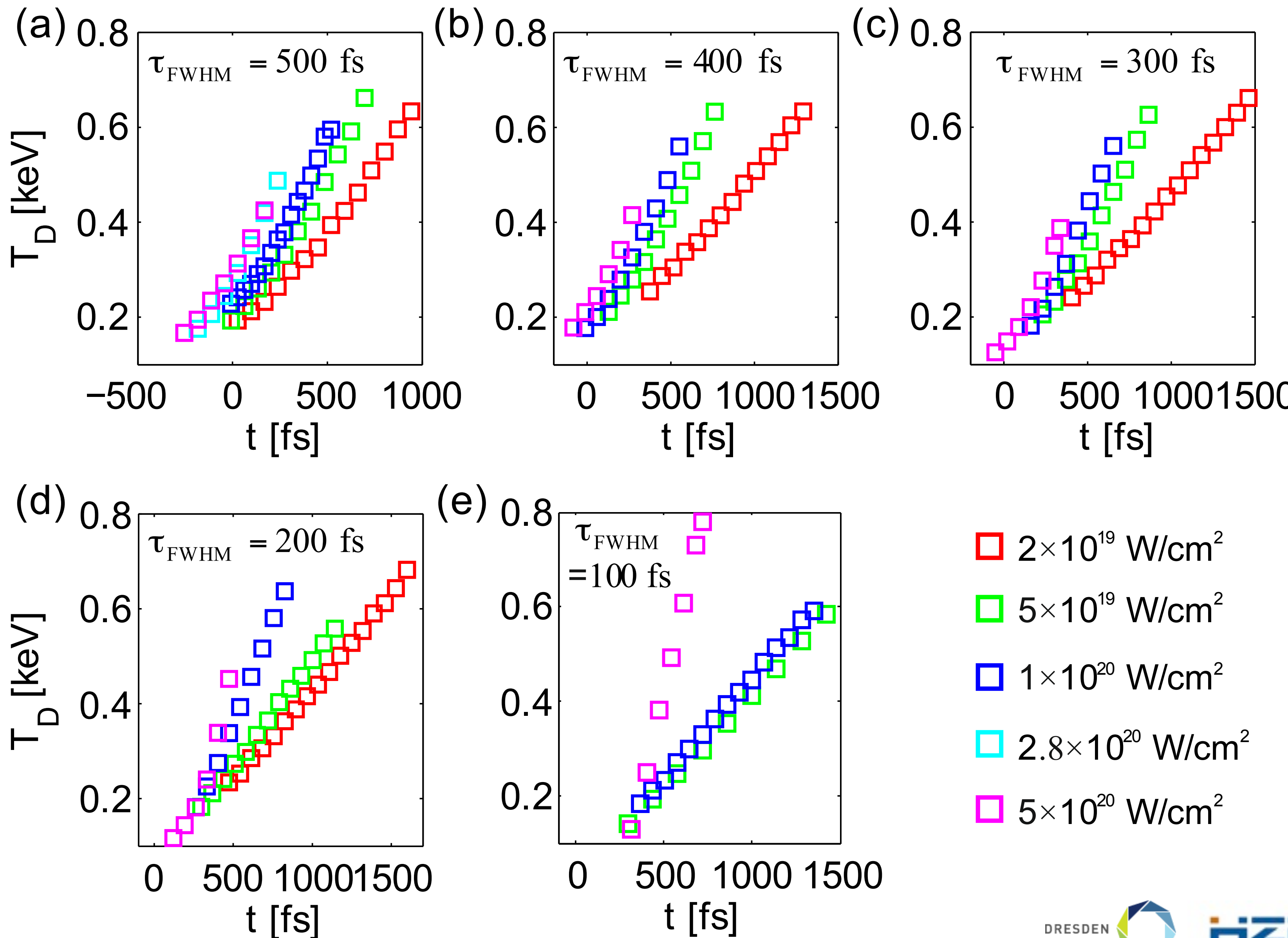
Ion heating dynamics in buried layer targets

Enhanced **ion** heating by the internal expansion

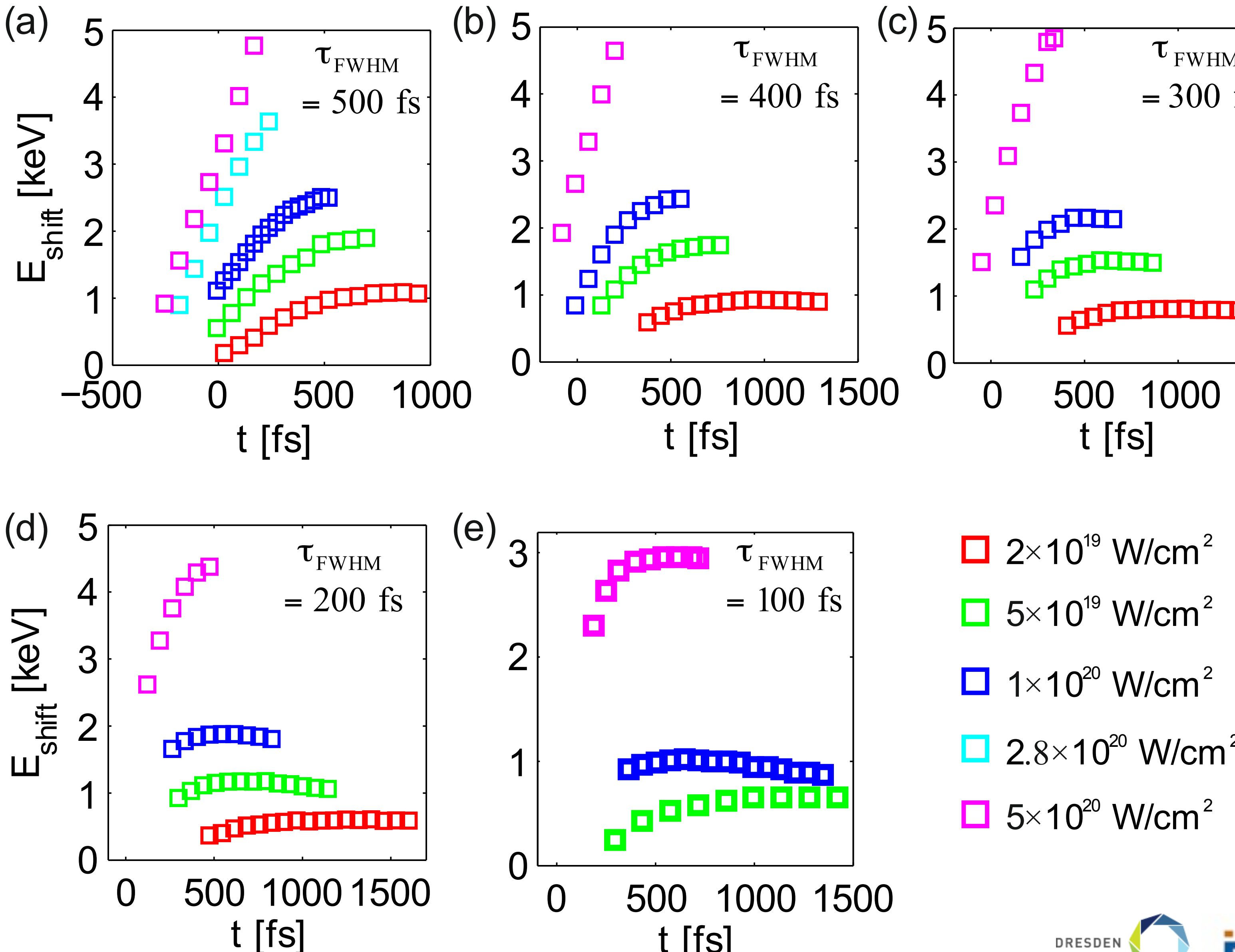


Internal expansion region: ion beam kinetic energy transferred to ion thermal temperature → enhanced ion heating

Scaling of deuterium thermal temperature in the expansion region

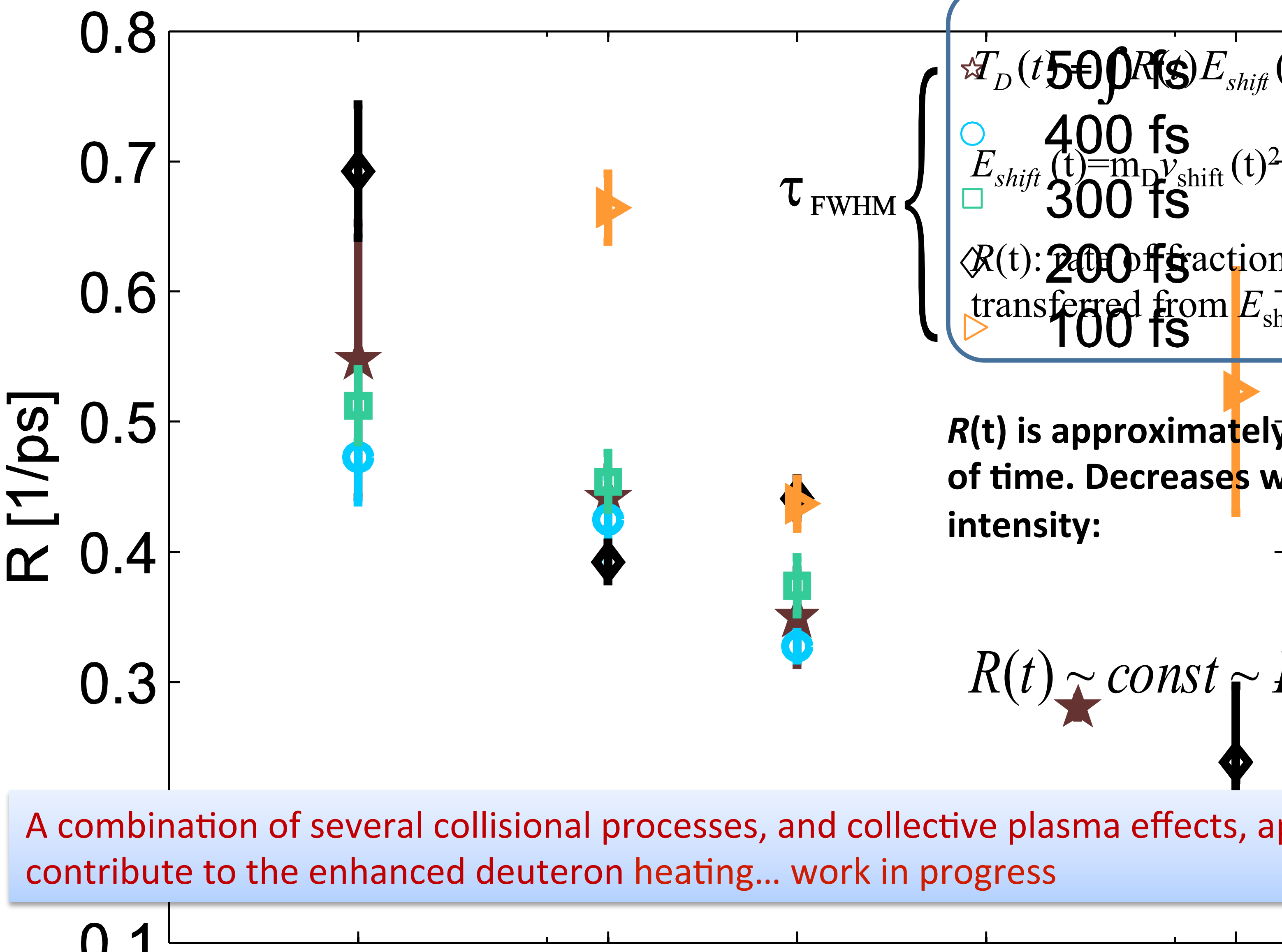


Scaling of deuterium beam kinetic energy in the expansion region



Ion heating dynamics in buried layer targets

Scaling of **<u>ion</u>** heating – fractional energy transfer rate, R(t) from directed ion kinetic energy to transverse, thermal energy



$$T_D(t) = \int R(t) E_{shift}(t)dt + const.$$

$$E_{shift}(t) = m_D v_{shift}(t)^2/2$$

R(t): rate of fractional energy transferred from E_{shift} (t) to T_D(t)

***R*(t) is approximately independent of time. Decreases weakly with intensity:**

$$R(t) \sim const \sim I^{-0.29}$$

A combination of several collisional processes, and collective plasma effects, appear to contribute to the enhanced deuteron heating… work in progress

Enhanced ion heating for NEET/NEEC

Summary

- Numerical stable (!) simulations of buried layer heating at solid-density (!)
- Self-consistent treatment of electron return current, collisional ionization and bulk electron heating, and collisional ion heating
- Dense plasma pusher – directed ion acceleration
- Collisional ion energy transfer to thermal motion
- Up to keV temperatures predicted (2D, but not optimized)
- Energy transfer rate decreases with increasing laser intensity (roughly consistent with ion collision frequency)
- Buried layer ion heating *might* be able to reach NEET/NEEC relevant conditions

Enhanced ion heating for NEET/NEEC

Future work

- Optimize layer thickness and elemental composition
- Extend to high Z, relevant for NEET/NEEC nuclides
- Use DD neutron yield to verify ion heating
- Use neutron energy versus angle to determine DD-beam fusion (shift), from thermal fusion (broadening).
- Combine NEET/NEEC with XFEL probing (coherent diffraction imaging, Thomson scattering), to simultaneously determine ion density and temperature

  -- Example, HIBEF at European XFEL

Thank you for your attention….