Sophisticated studies of laser-driven ion acceleration with SMILEI code

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V. Istokskaia *et al.*: A multi-MeV alpha particle source via proton-boron fusion driven by a 10-GW tabletop laser, *Communications Physics* **6**, 27 (2023)

J. Psikal: Laser-driven ion acceleration from near-critical Gaussian plasma density profile, *Plasma Physics and Controlled Fusion* **63**, 064002 (2021)

Outline of the talk

- input from hydrodynamic simulations in SMILEI
- PIC simulation with large range of plasma density
- SMILEI simulation with particle tracking
- ion acceleration from near critical Gaussian plasma density profile

Smilei)

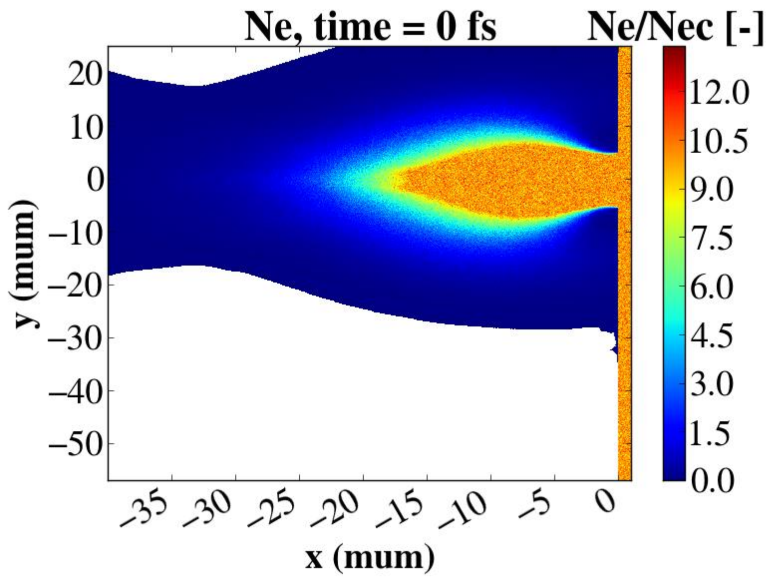
Interaction of ultrashort laser pulse with 2D density profile of preplasma calculated by HD simulation

- interaction with 1.5 ps pulse (max. intensity 10^{17} W/cm^2) which was preceded by 1.5 ps prepulse (with intensity contrast ratio of 10^{-3}), time delay between prepulse and main pulse arrival was 14 ns
- plasma density profile after prepulse interaction with target obtained from HD simulation (FLASH code used)

There are two options in SMILEI code how to setup density of plasma in PIC simulation

- use a mathematical function defined in Python to describe plasma densities in the whole simulation box (impossible or very complicated in this case)
- create HDF5 file which describes positions and numerical weights of all quasi-particles initialized in PIC simulation

density of electrons in the simulation box after initialization of quasi-particles in SMILEI simulation



How to define plasma with large range of densities in SMILEI simulation?

- define minimum and maximum of plasma density in PIC simulation (in our case n_{min}=0.002*n_{ec}, n_{max}=10*n_{ec})
- define minimum and maximum of numerical weights of quasi-particles (in other words, define minimum and maximum of number of quasi-particles per cell – e.g. $NPPC_{min}$=1, $NPPC_{max}$=20)

There are two basic approaches in PIC codes how to setup the number of particles per cell

- the same number of particles per cell for each cell occupied by plasma
- equal numerical weights of all particles (of the same species) in the whole simulation box

both approaches are problematic in the case of large range of densities (several orders of magnitude)

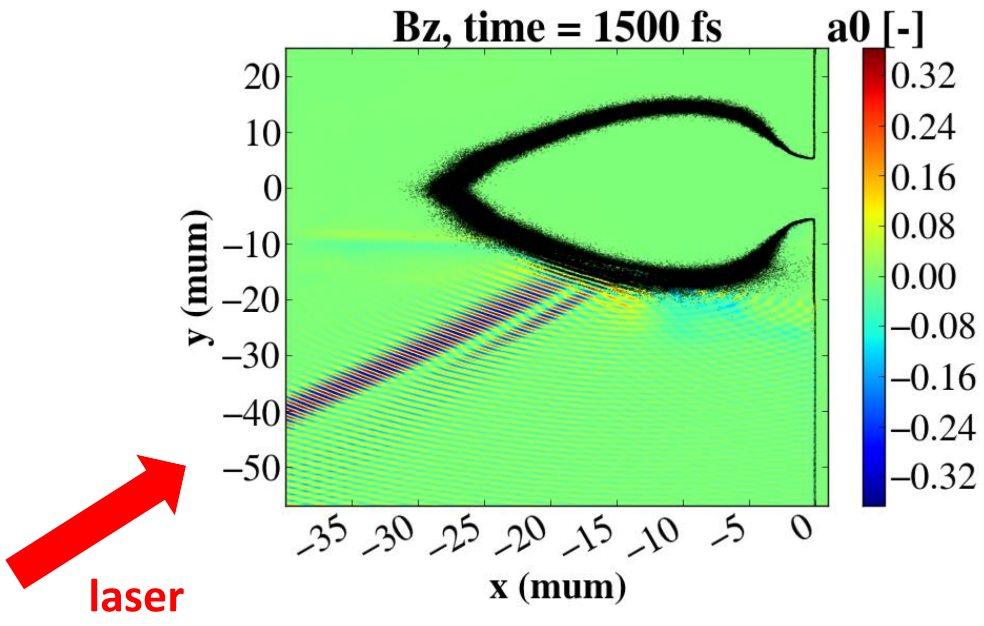
but SMILEI enables to define number of particles per cell as a python function (e.g., depending on plasma density) or to load HDF5 file with pre-determined positions and numerical weights of particles

- at least one quasi-particle per cell for each species should be defined in cells occupied by plasma
- the number of particles per cell can be scaled linearly or logarithmically with initial density

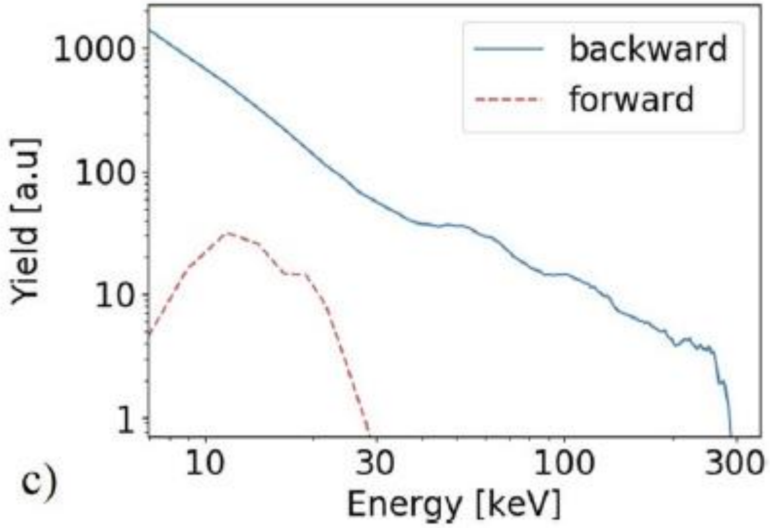
Results of the simulation of ps-pulse interaction with the target

V. Istokskaia *et al., Communications Physics* **6**, 27 (2023)

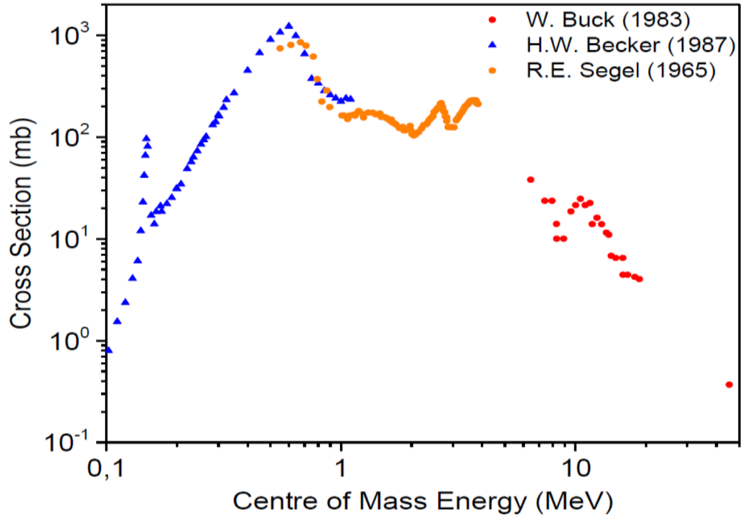
laser peak intensity 8×10^{16} W/cm^2, full pulse duration 3.2 fs ($\cos^2$ shape, corresponds to 1.5 ps pulse in experiment), focal spot size 2.65 µm (FWHM) moved by 50 µm away from the target, CH-BN target (600 nm plastic layer on 3 mm BN substrate) in experiment, $C^{4+}H^{+}$ plasma in simulation



transverse magnetic field Bz during the interaction of the peak laser intensity with the target modified by ps prepulse, showing the incidence and reflection directions of the main pulse approx. 15 µm away from the original target surface; contour of the preplasma having critical density is depicted in black



energy distribution of simulated protons in the forward (into the target) and backward (away from the target) directions



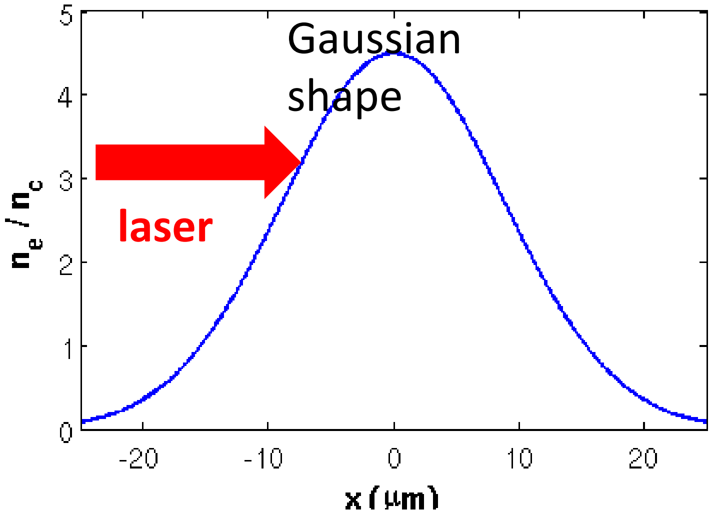
cross-section for proton-boron reaction: 675 keV main peak; 160 keV secondary peak

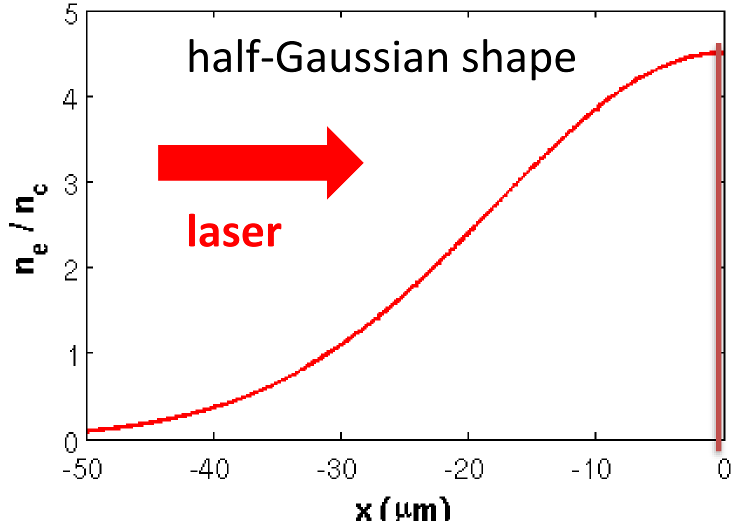
p + ^{11}B → 3α + 8.7 MeV

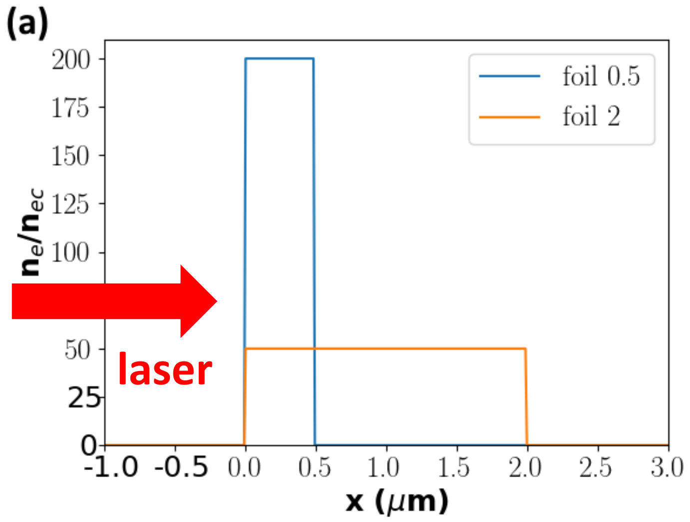
SMILEI simulations with particle tracking

- zeroth simulation run – use TrackParticles diagnostics once (before laser pulse starts to interact with plasma) to initialize ID numbers of all particles and create Checkpoint
- first simulation run – restart from Checkpoint , calculate the whole interaction/acceleration and determine ID numbers of the most energetic ions (e.g., with $\varepsilon_k > ½*\varepsilon_{kmax}$) at the end of the interaction/acceleration
- random selection of those particles (ID numbers); note: use *random_seed* in simulations
- second simulation run – restart from Checkpoint, tracking of the selected ions through the whole simulation run

laser peak intensity 6×10^{21} W/cm^2, pulse duration 30 fs (FWHM), focal spot size 3 μm (FWHM),







Laser-driven ion acceleration from near critical Gaussian plasma density profile

- 2D3V and 3D3V particle-in-cell simulations
- SMILEI code used to analyze trajectories and instantaneous fields affecting the motion of selected particles
- 3D simulations are very challenging in this case (4×10^9 cells and 16×10^9 particles, 300000 CPU core hours per studied case)
  - due to computational constraints, only Gaussian target and 2 μm thick foil were assumed in 3D simulations

supersonic gas-jet:

J. Henares *et al.*, Rev. Sci. Instrum. **90**, 063302 (2019)

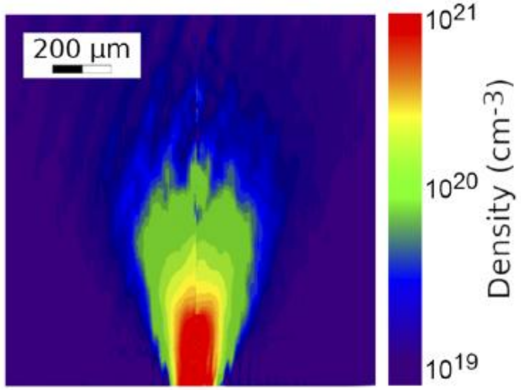
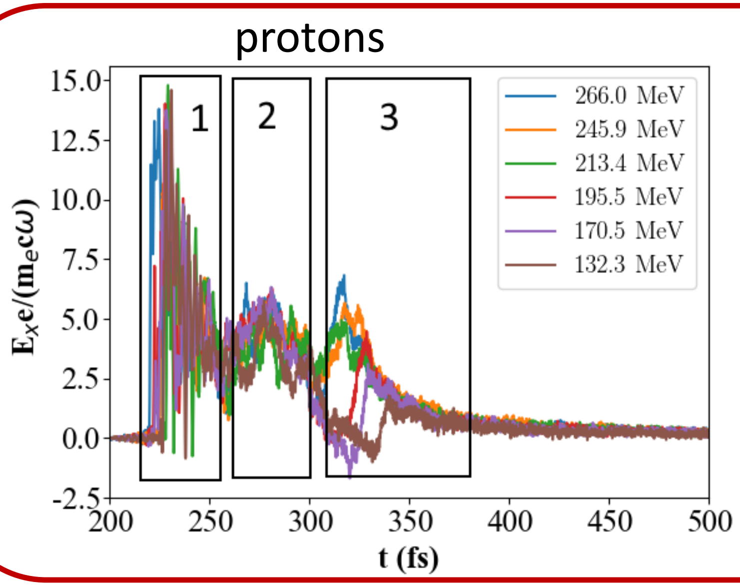


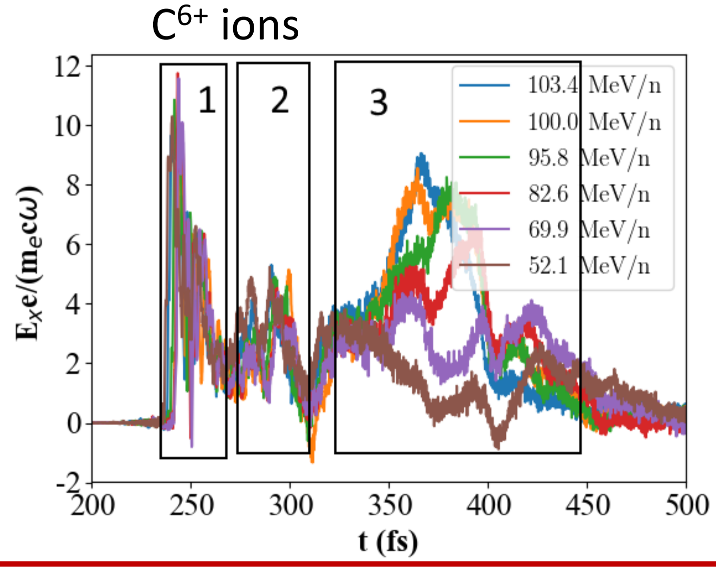
figure: molecular density of nitrogen at 1000 bars backing pressure

critical plasma density for 800 nm laser $n_{ec} \approx 1.7e{+}21\ cm^{-3}$ ($n_e \approx 7e{+}21\ cm^{-3}$ for N^{7+} plasma)

- smooth density profile of plasma before the main pulse imposes less strict requirements on the ultrashort laser pulse contrast compared with thin foils
- Gaussian density profile is relevant for supersonic gas jet and more realistic than NCD uniform plasma layer for expanded ionized thin foils

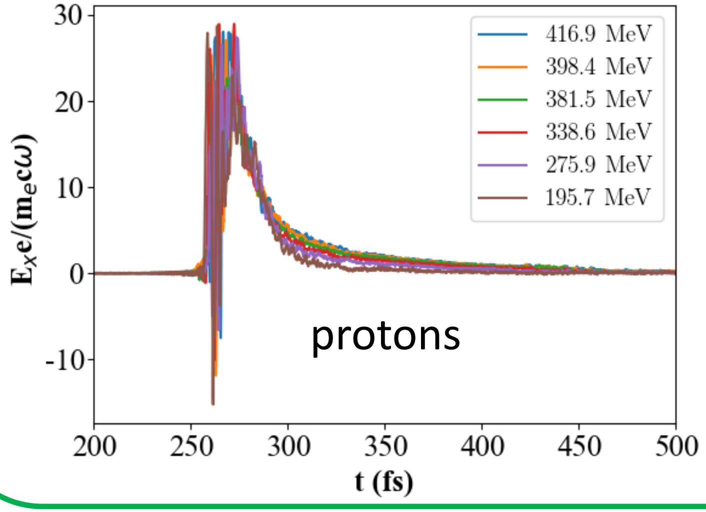
Development of accelerating fields for the sample of representative high-energy ions

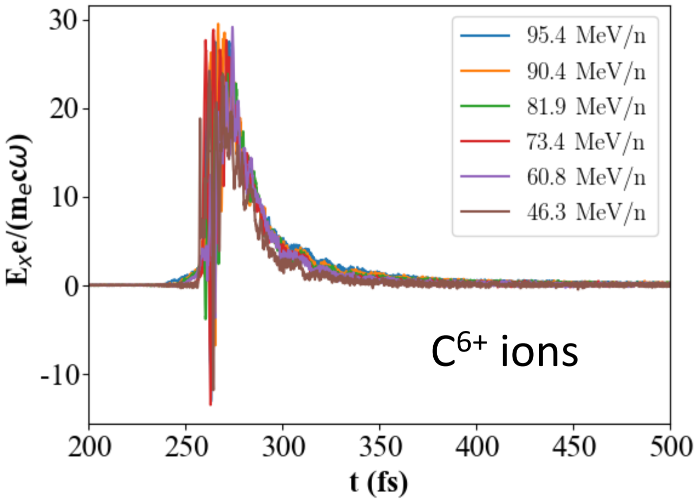




Gaussian profile

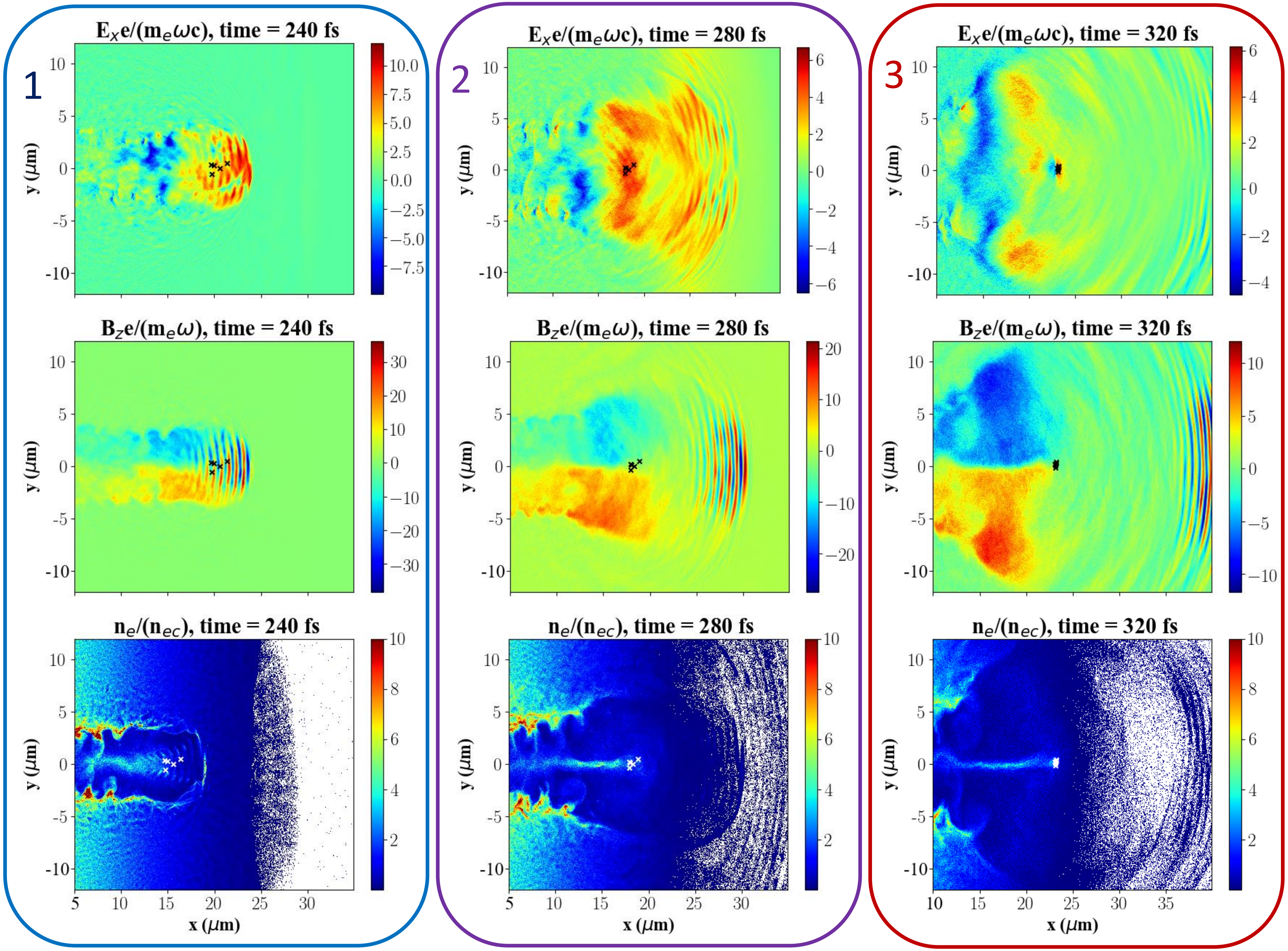
1) initial acceleration phase induced by electron bunches carried by the laser wave
2) second acceleration phase induced by expanding magnetic field
3) third acceleration phase induced by electron filament generated behind the laser wave



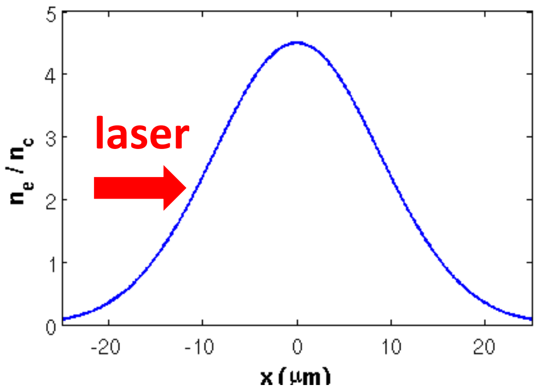


half-Gaussian profile

- acceleration induced by electron bunches carried by the laser wave
- this acceleration can be enhanced by expanding magnetic field along the target surface and by sheath field from expanding hot electrons



Gaussian target

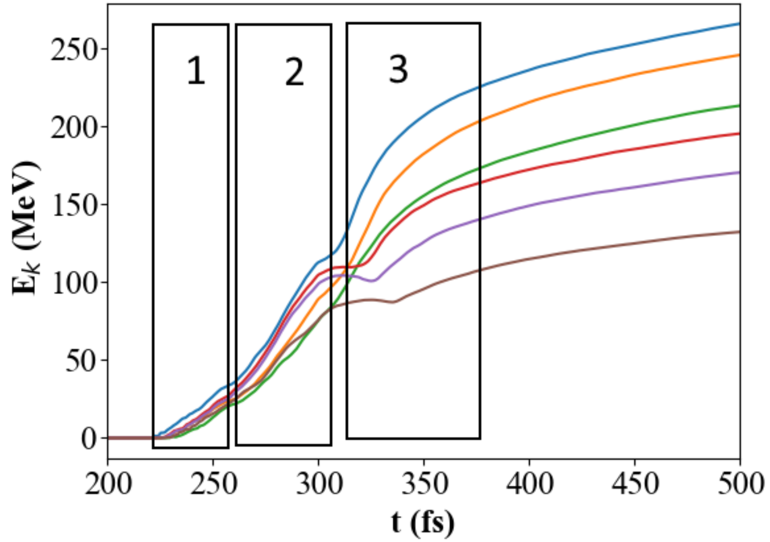


longitudinal electric fields, transverse magnetic fields and electron densities at time moments corresponding to three acceleration phases for the most energetic protons

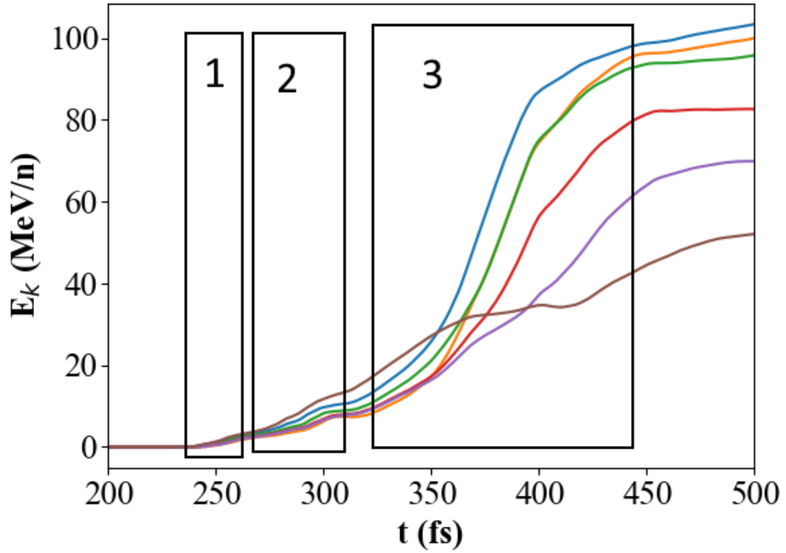
positions of the most energetic protons marked by black (white) crosses

Contribution of three acceleration phases in the Gaussian target

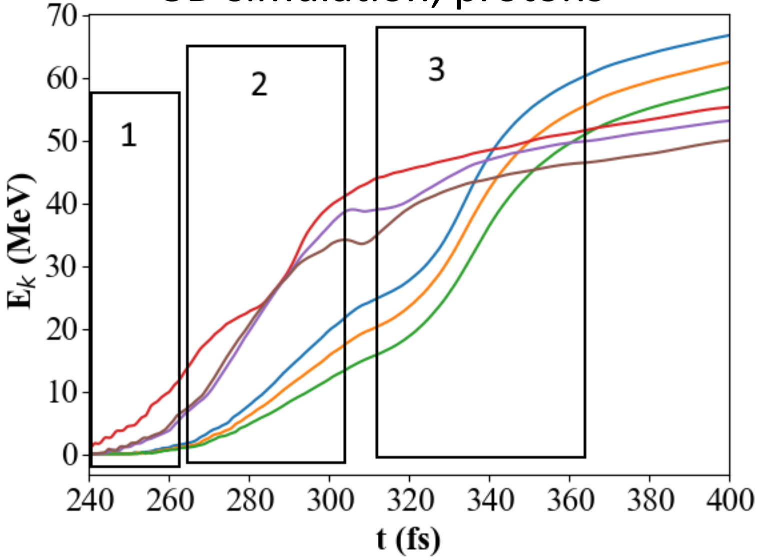
2D simulation, protons



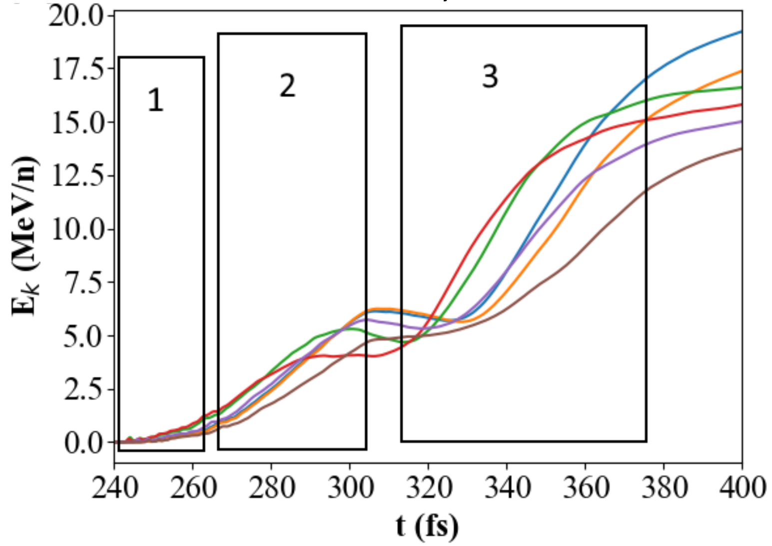
2D simulation, C^{6+} ions



3D simulation, protons



3D simulation, C^{6+} ions

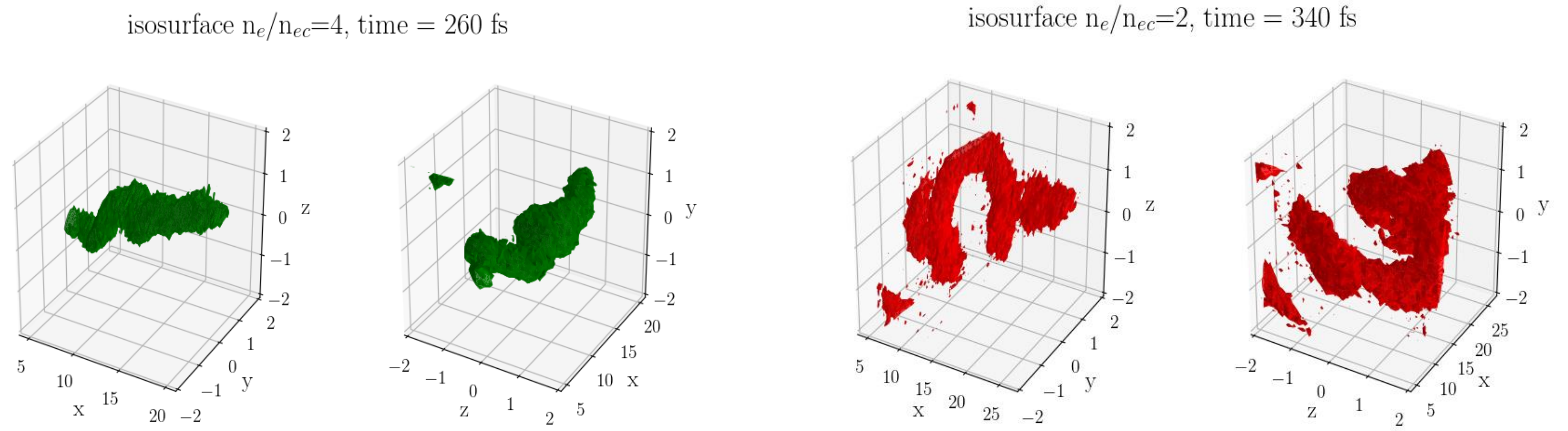


- the velocity of C^{6+} ions is lower compared with the velocity of protons during the third acceleration phase – longer duration of this acceleration phase

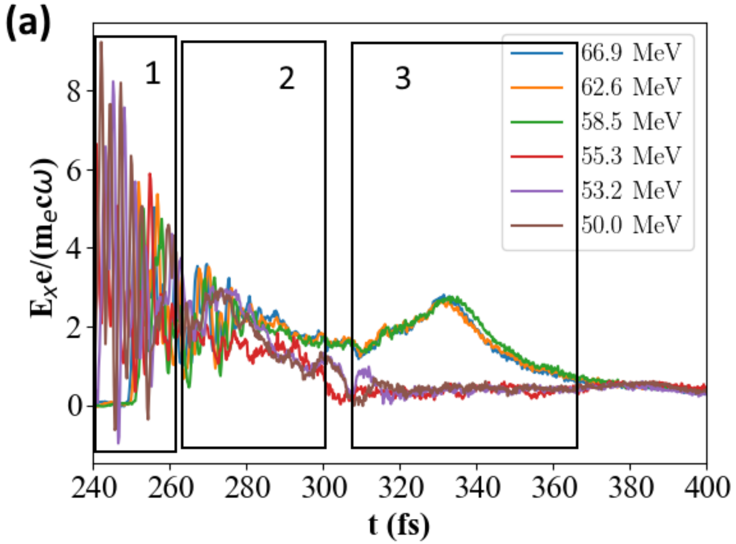
=> larger contribution of the third phase to the acceleration of C^{6+} ions in comparison with protons

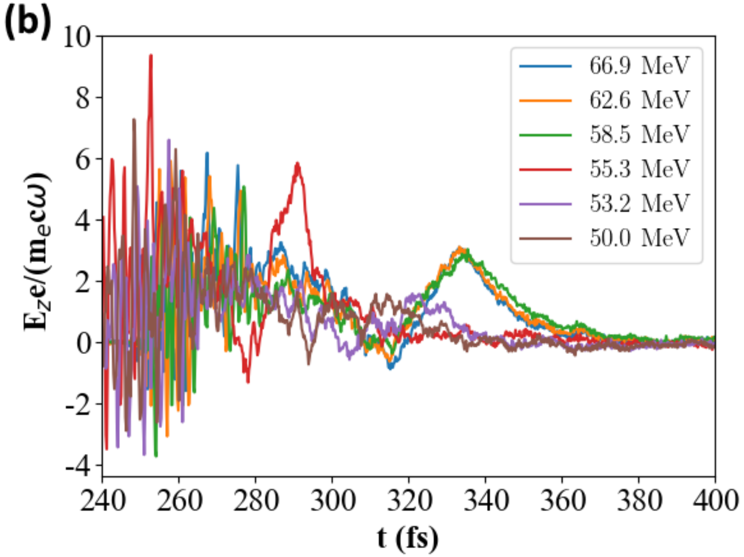
- apex of the filament created in the middle of the plasma channel affects reduced number of the ions in 3D due to simulation geometry => impact of the third acceleration phase lower in 3D compared with 2D

Electron filament in the plasma channel in 3D simulation



- the curved structure of the filament (in 3D) affects the angular distribution of high-energy ions

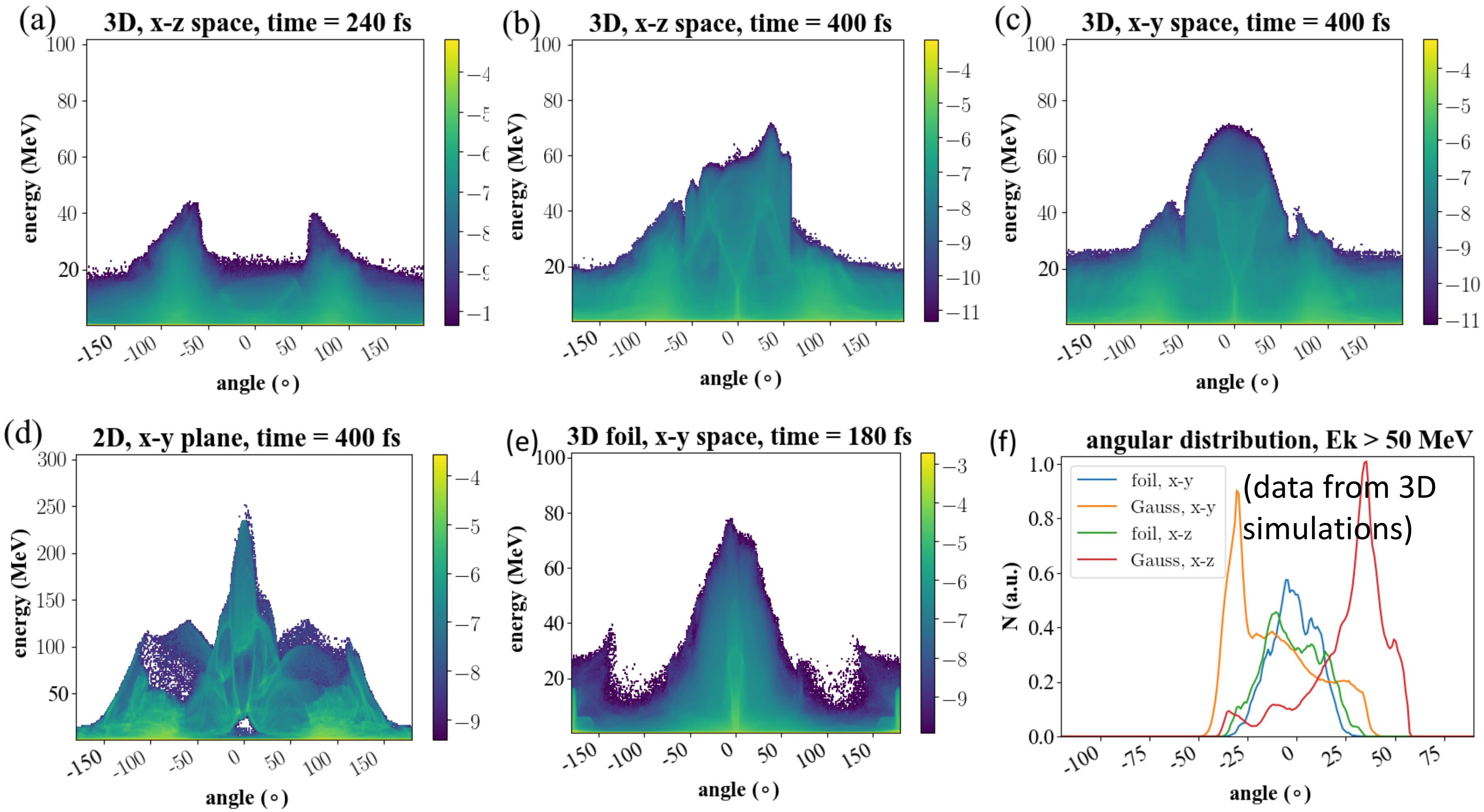




- upper figures: isosurfaces of electron densities inside the plasma channel created behind the laser pulse in NCD plasma layer of Gaussian density profile at two sideviews
- bottom figures: the development of accelerating a) longitudinal electric field (Ex), b) transverse electric field (Ez) for the sample of most energetic protons in the 3D simulation

Energy-angular distribution of accelerated protons

- **broader angular distribution** from NCD Gaussian profile plasma layer **in 3D compared with 2D simulation** (see c) vs. d))
- **larger concentration of the accelerated protons at some direction**, however the **emission direction of the ions is not well predictable** for the Gaussian NCD target compared with the foil (see Fig. f))



the laser beam propagates along x-axis at 0° angle

colorbars show the density of protons (in PIC units) in the energy-angular space in logarithmic scale

Summary

- SMILEI can load large HDF5 files created externally which define positions and numerical weights of all particles initialized in the simulation => possibility to use complicated density profiles calculated from HD simulations
- particle tracking diagnostics in SMILEI enables to investigate acceleration regimes of charged particles in detail, development of fields which affect particles can be compared with pictures showing densities and fields in the whole simulation box (including positions of the particles at corresponding time instants)
- acceleration of ions in near critical density plasma of smooth density profile is relatively complicated => SMILEI diagnostics is able to reveal acceleration mechanisms

Thank you for your attention

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