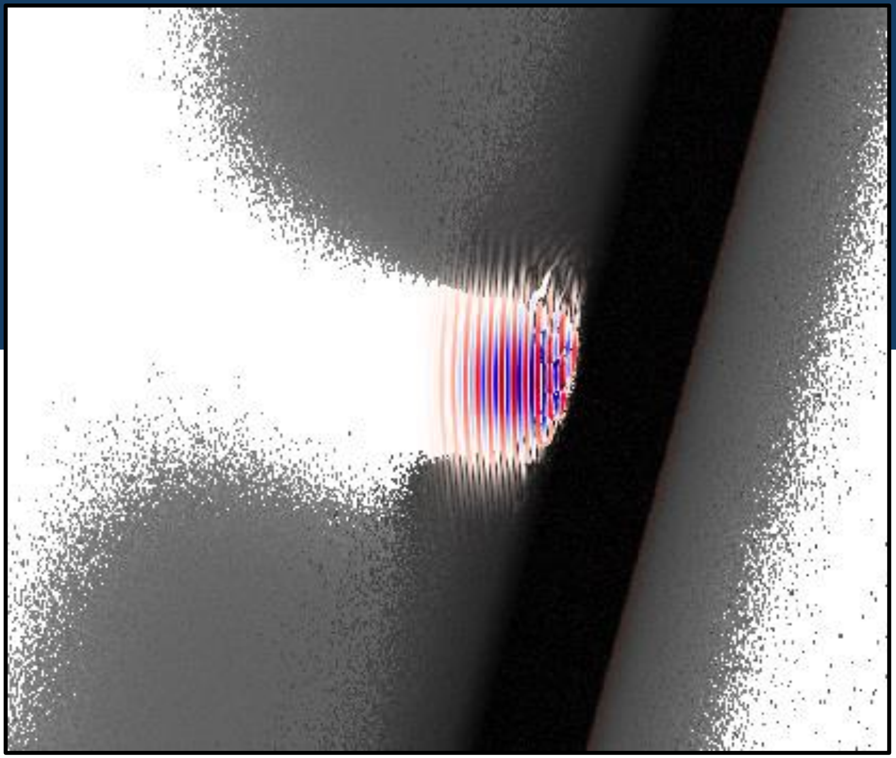
WP2: Update on the simulations of the LhARA proton source



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Acknowledgements

Nicholas Dover (Imperial College London)

Ross Gray (University of Strathclyde)

Charlotte Palmer (Queen's University Belfast)

Elisabetta Boella (Lancaster University)

Simulations performed on SuperMUC-NG (LRZ, Germany) under PRACE allocation and ARCHER2 (EPCC, UK) under EPSRC allocation

Outline

- Since the LhARA 12 month review we investigated the effect of:
  - laser spot-size
  - density of the hydrogen contaminant layer

TODAY

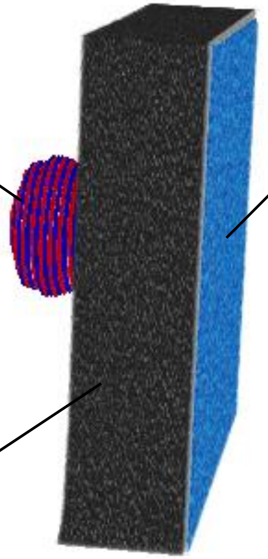
  - laser angle of incidence
  - realistic preplasma density (modelled using laser contrast measurements at SCAPA)
  - optimisation routines in finding optimal target density profiles

… **on proton acceleration from a solid target via TNSA** using:

- full 3-D Particle-In-Cell (PIC) simulations
- 2-D PIC parameter scans
- hydrodynamic simulations

Modelling expected and optimal SCAPA conditions based on previous 3-D PIC simulations

$I = [8 — 10] \times 10^{20}$ W/cm^2
λ_0 = 800 nm
a_0 = [19.32 — 21.60]
τ_{FWHM} = 25 fs
w_0 = 1.5 μm
p - polarised



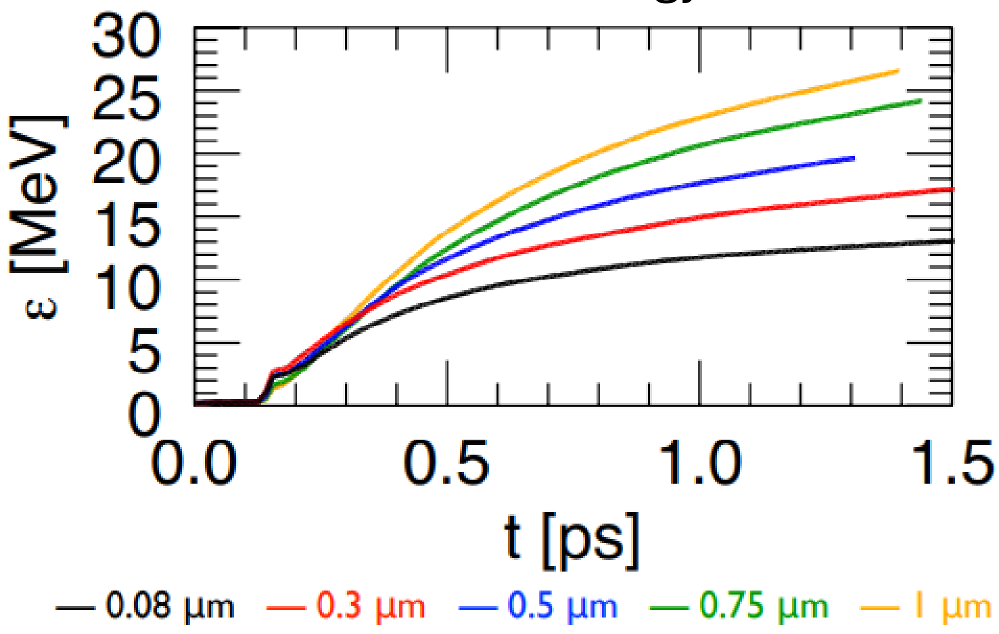
H^+ layer
n_{H+} = 1.15 n_c
L_{H+} = 31.83 nm

Al^{3+} foil
n_{Al3+} = 70 n_c
L_{Al3+} = [2 — 6] μm

E. Boella, full 3-D PIC simulations

$I = 1 \times 10^{21}$ W/cm^2, 6 μm thick target

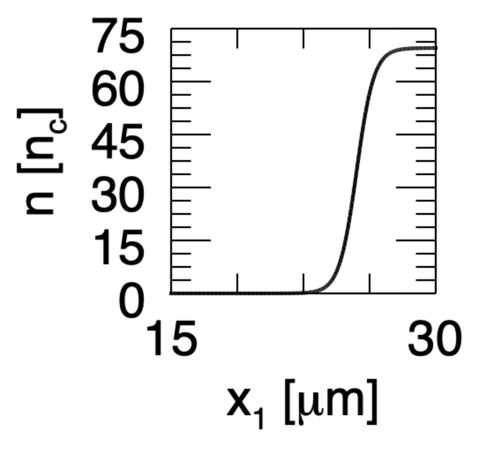
(LhARA CM#4)



Pre-plasma scale length

Laser "prepulse" modelled using hydrodynamic code
→ resulting "preplasma" density fed into the PIC simulations

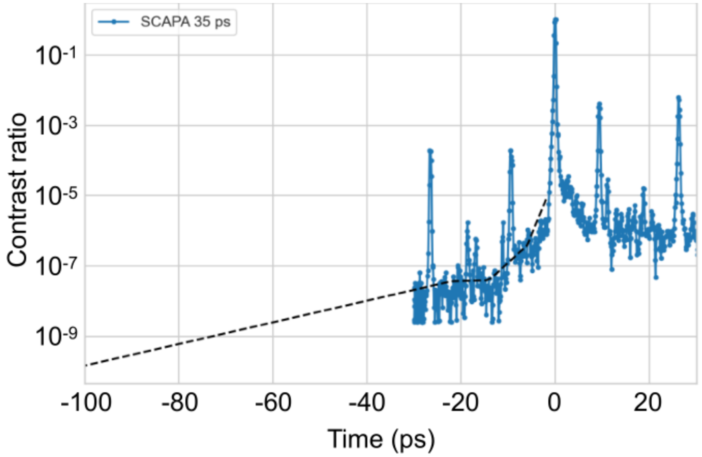
Idealised preplasma profile



$$n_{Al^{3+}} = 70\,\frac{n_c}{2}\left[\tanh\left(\frac{x_1 - x_{1,0}}{L_g}\right) + 1\right]$$

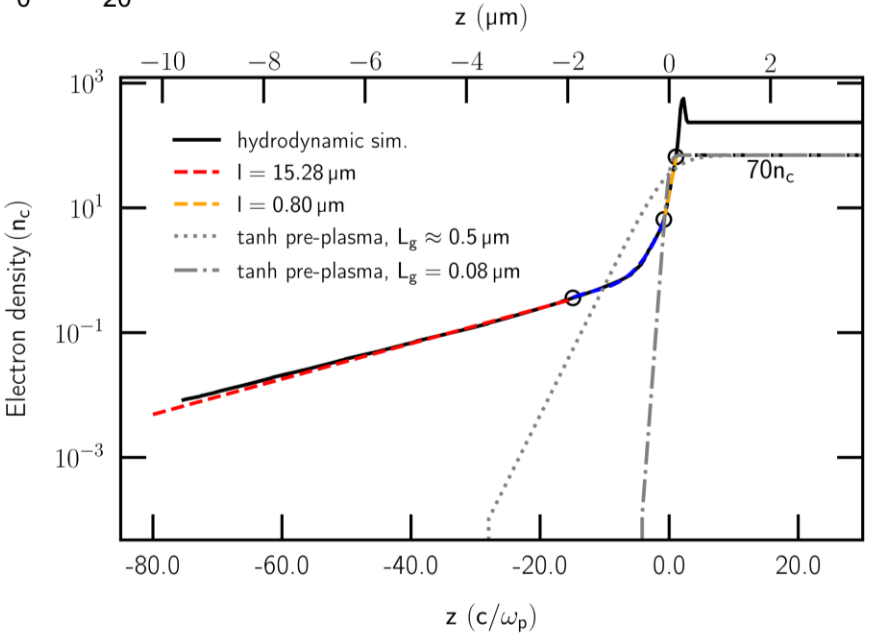
$x_{1,0}$ = 25.5 µm

L_g = [0.08 — 1] µm



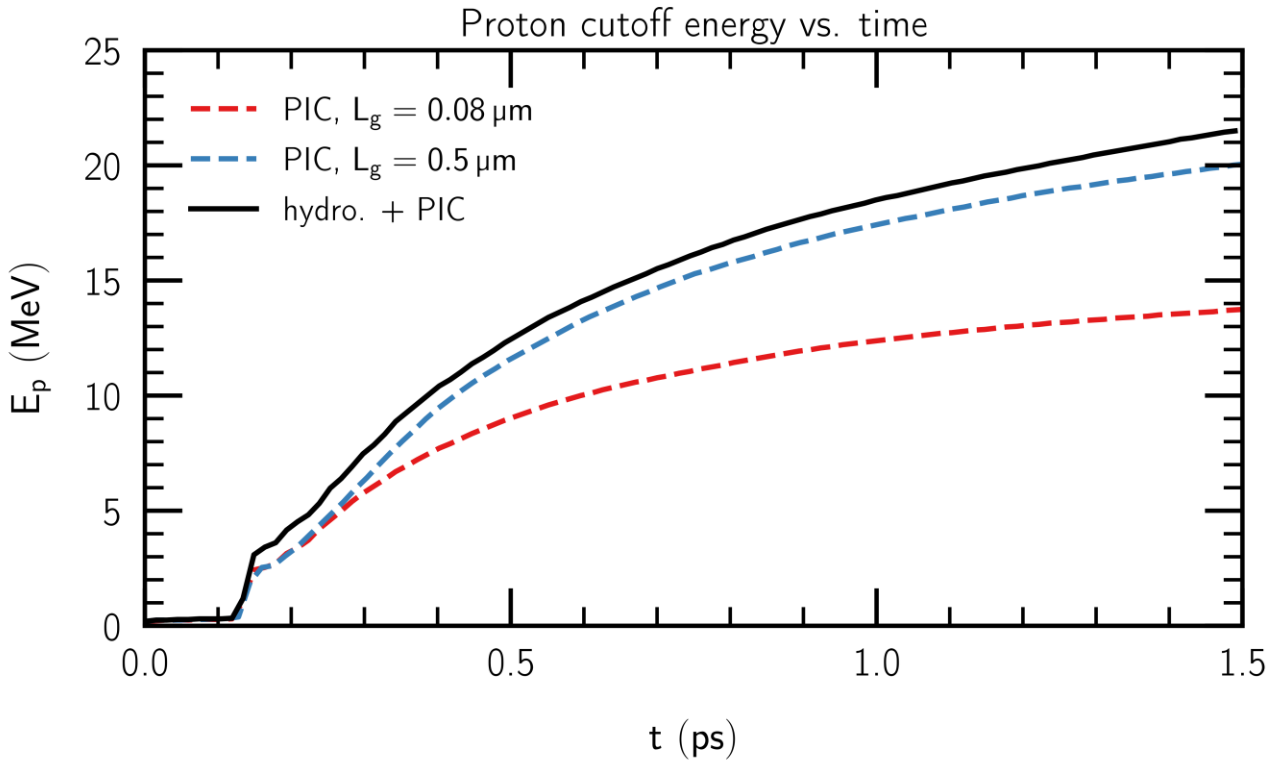
N. Dover, hydrodynamic simulation using preliminary pre-pulse measurements from SCAPA

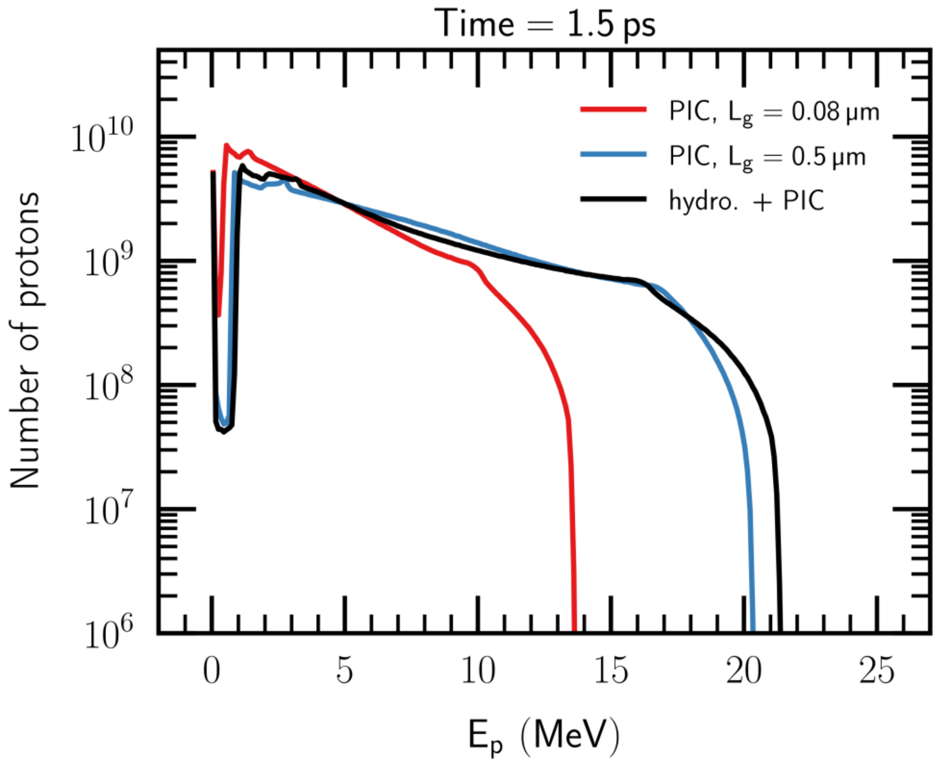
Output from FLASH code using the laser contrast curve for SCAPA



Laser "prepulse" modelled using hydrodynamic code
→ resulting "preplasma" boosts proton energies

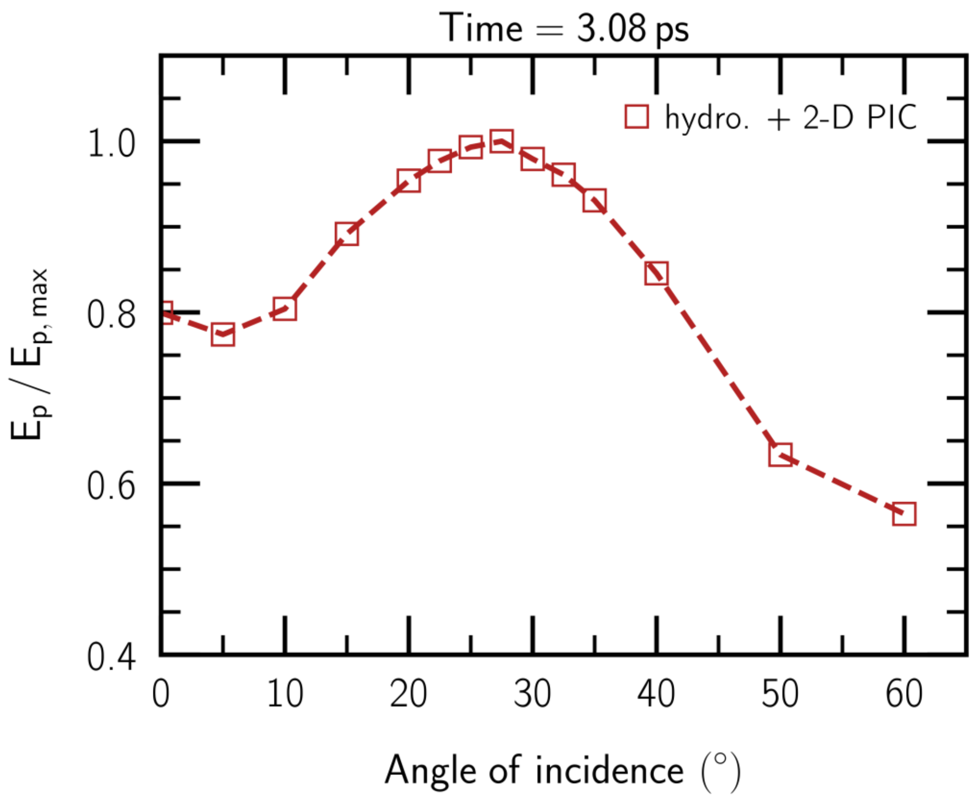
- Different preplasma profiles can lead to similar boost in the proton cutoff energy

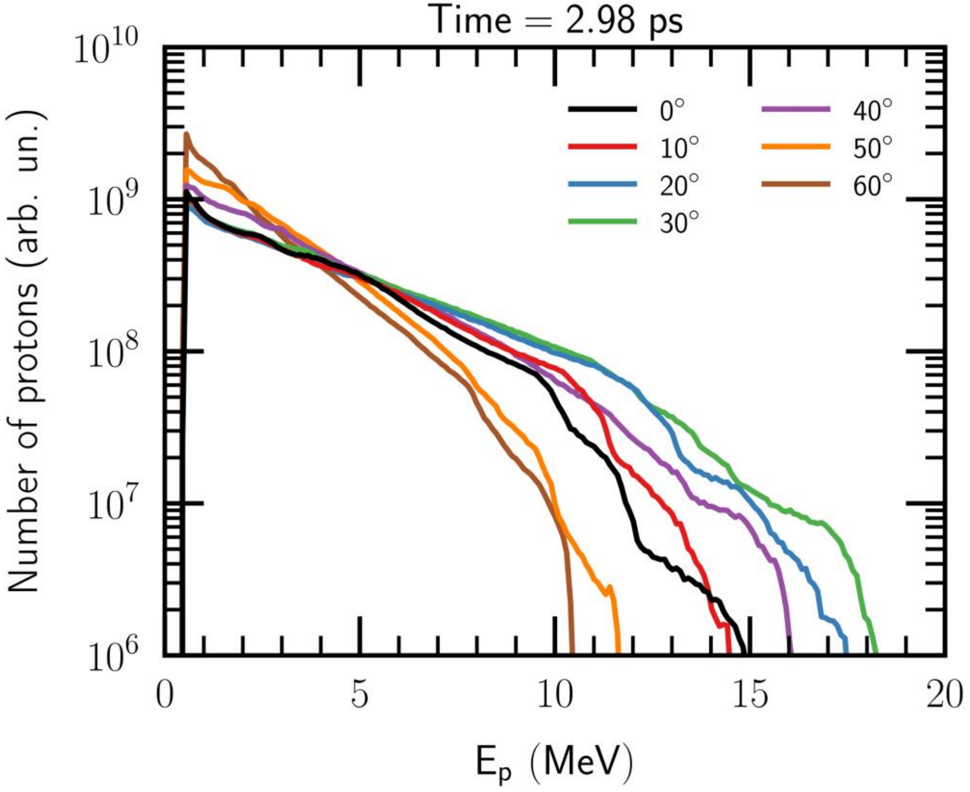




2-D simulations predict an optimal angle of incidence of the laser → increase in the proton cutoff energy and particle flux

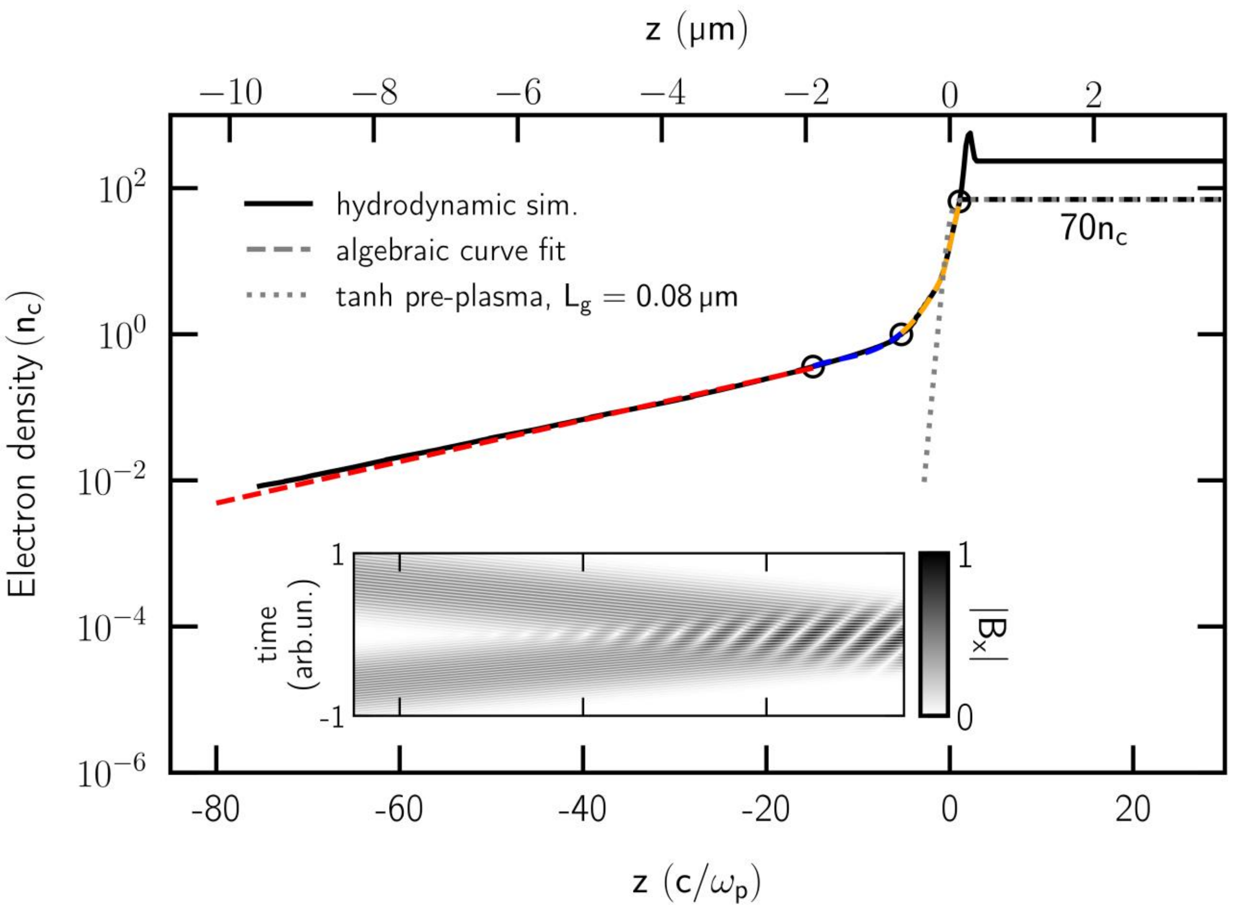
- PIC scan with **realistic preplasma** density profile (from hydrodynamic simulation)
  - 2-D because of the comparatively larger simulation domains required

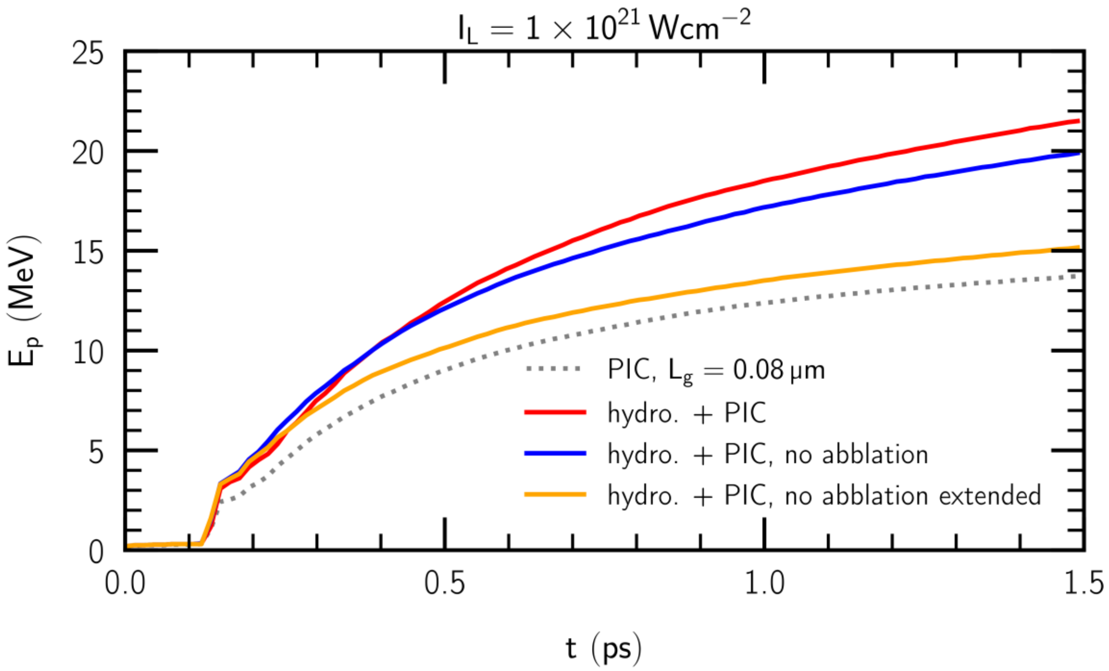




Near-critical density region of the preplasma generates most of the overall proton energy boost

$I_0 = 1 \times 10^{21}\ \mathrm{W/cm^{-2}}$, $a_0 = 21.6$, 6 µm Al target

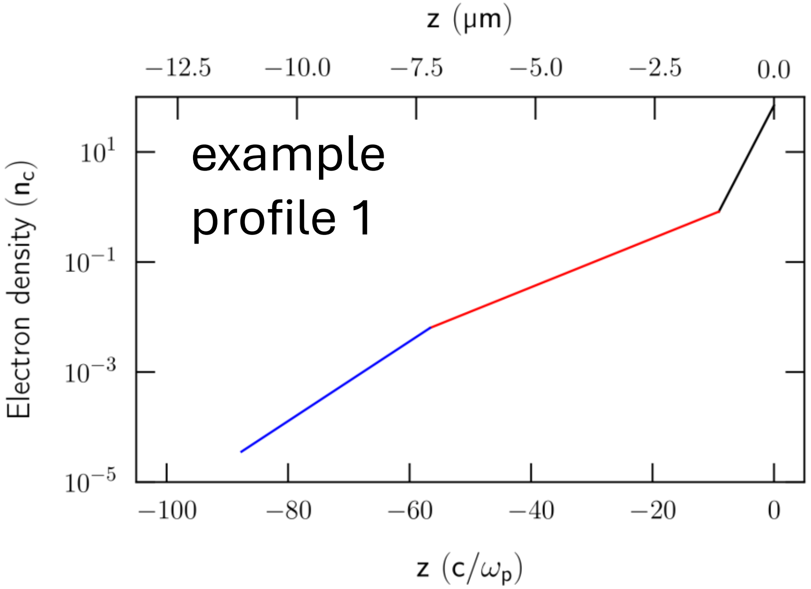


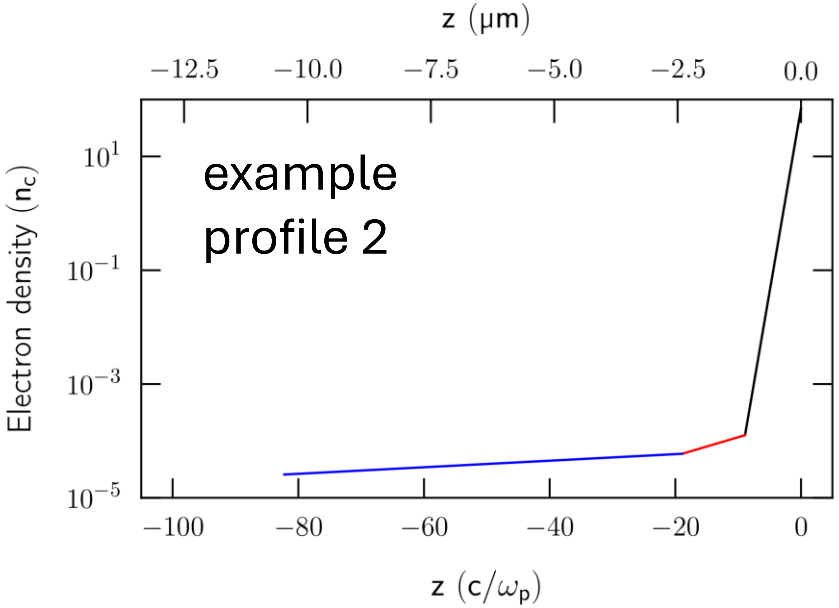


Searching for the optimal pre-plasma density profile at normal laser incidence (1)

- 3 different scale lengths (to mimic the typical profiles from hydro. sim./experiments)
  - 6 free parameters, 1 objective function (cutoff proton KE)

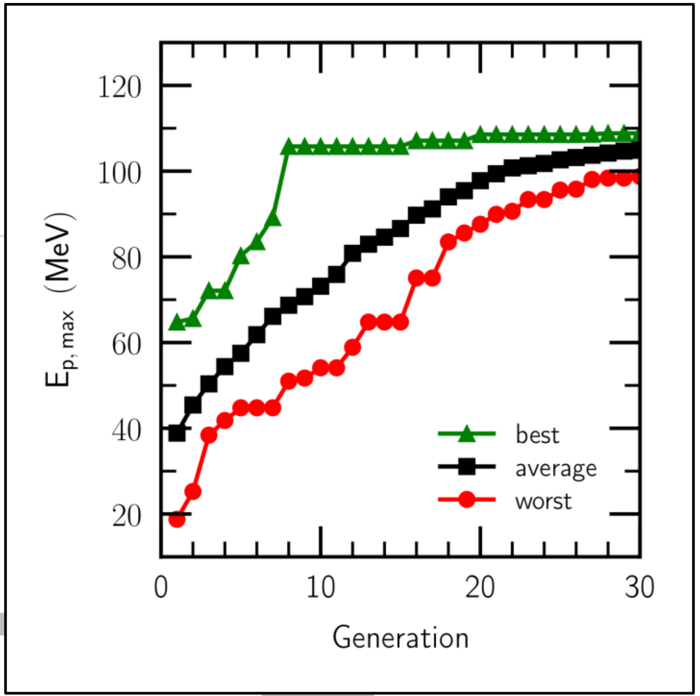
- just a few constraints
  - $n_e > 10^{-5} n_c$
  - pre-plasma region $\leq 100 \frac{c}{\omega_p}$ (~12.5 μm)
  - monotonously decreasing density from target front-surface to vacuum

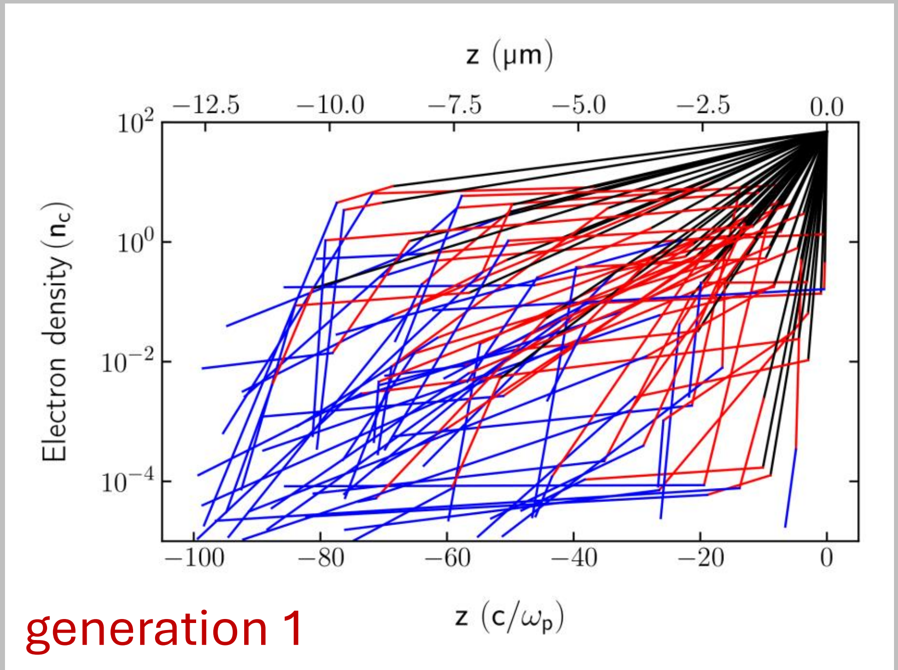


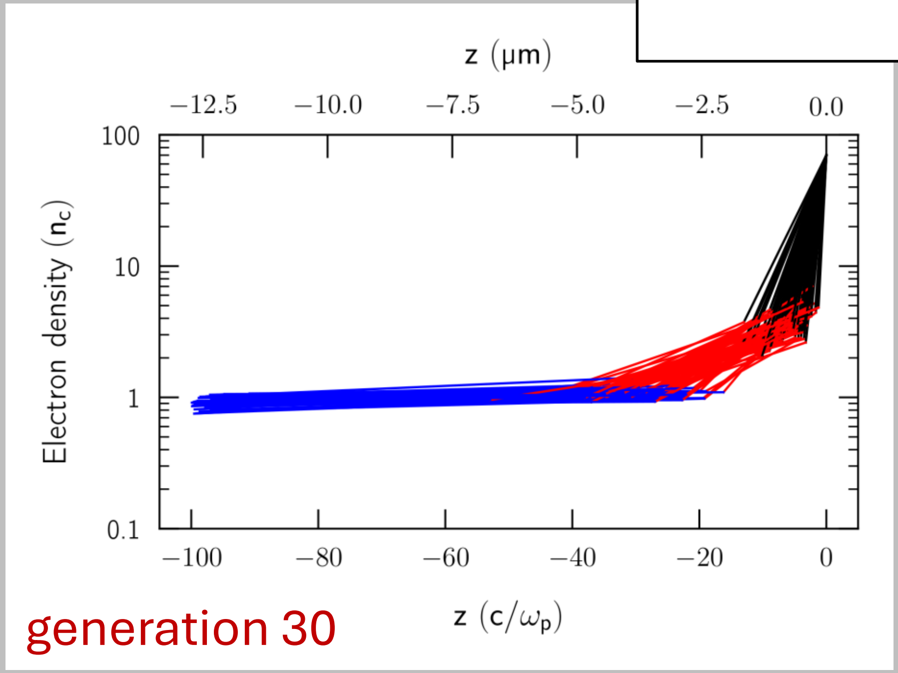


Searching for the optimal pre-plasma density profile at normal laser incidence (2)

- 2-D PIC scan + evolutionary algorithm
  - Differential Evolution (due to relative simplicity)
  - 60 members in each generation
  - start with random generation

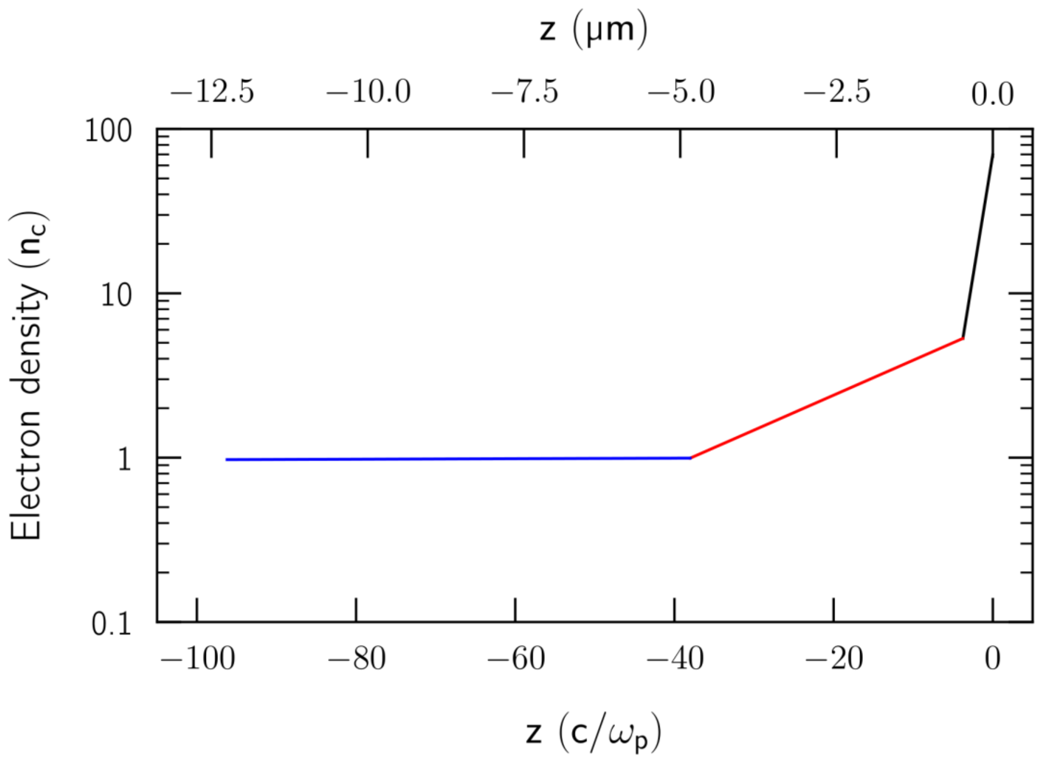


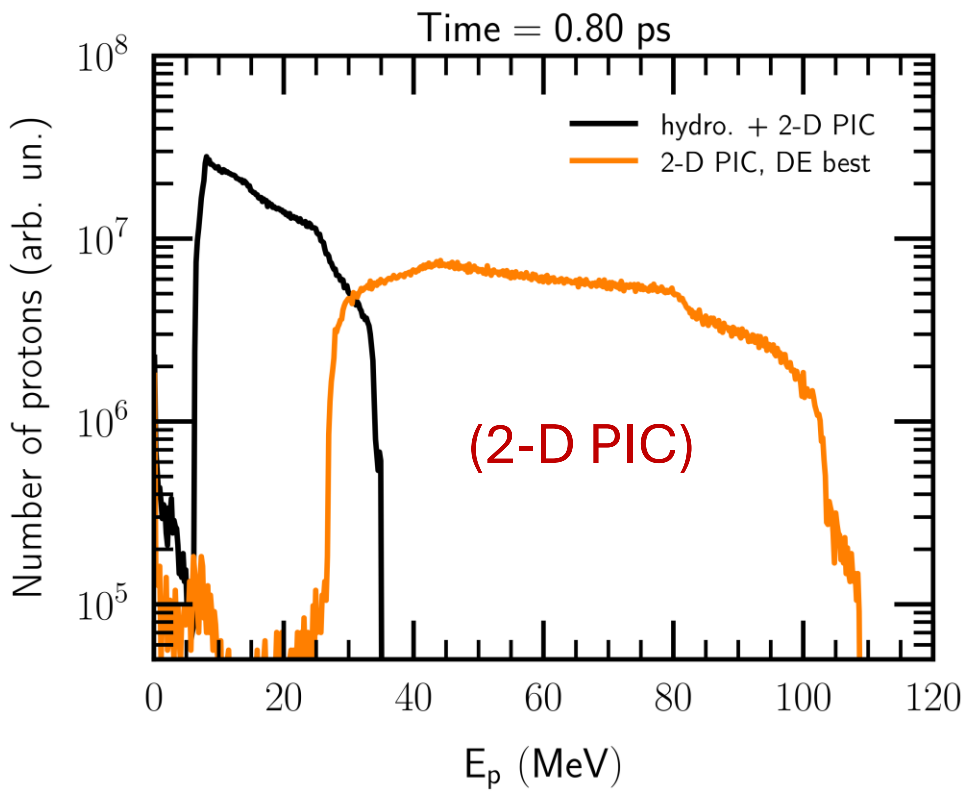




At normal laser incidence, near-critical foam-like pre-plasma provides the largest proton energy boost in 2-D PIC simulations

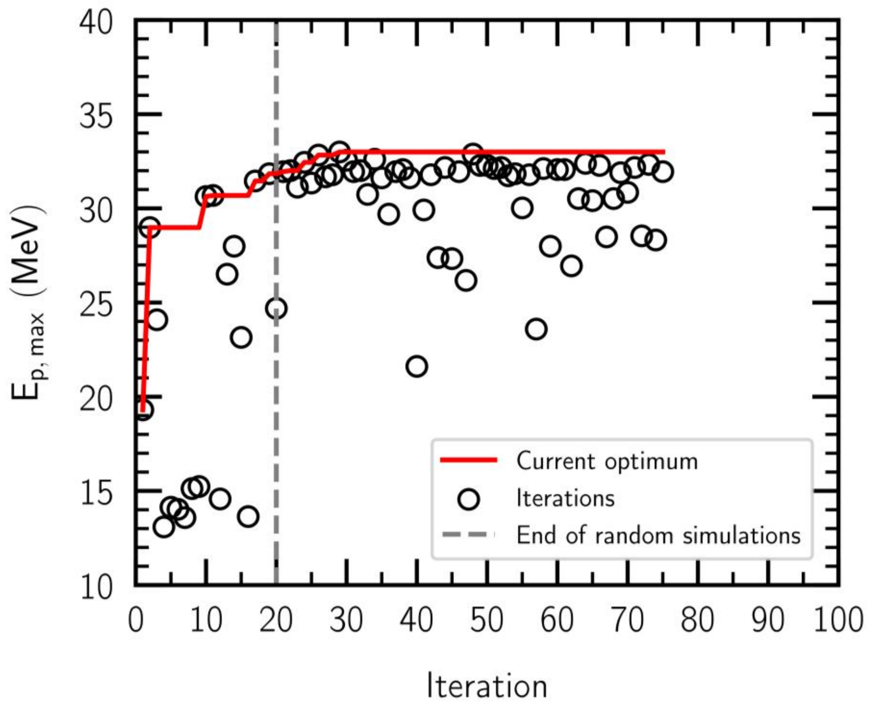
- Optimal pre-plasma density found by DE algorithm: **foam-like continuous layer** with
  - density $\approx 1\ n_c$
  - scale-length $\sim\infty$
- Difficult to achieve experimentally at high repetition

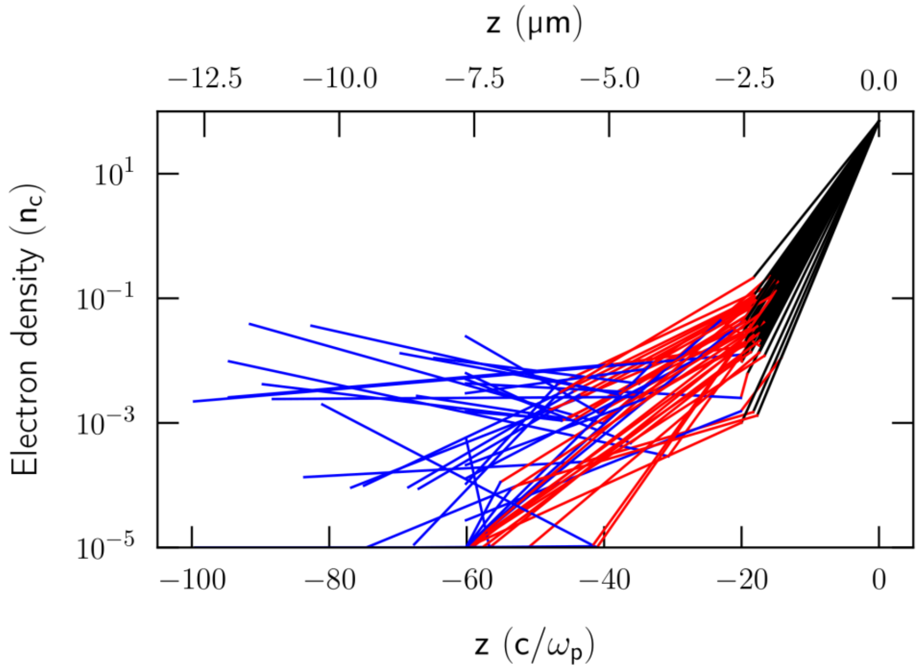




Searching for the optimal pre-plasma density profile at oblique laser incidence (30°)

Preliminary work





- Optimal pre-plasma density search implemented using
  - 2-D PIC scan
  - Bayesian optimisation
- Larger simulation domain required to mitigate edge fields and to fit rotated target

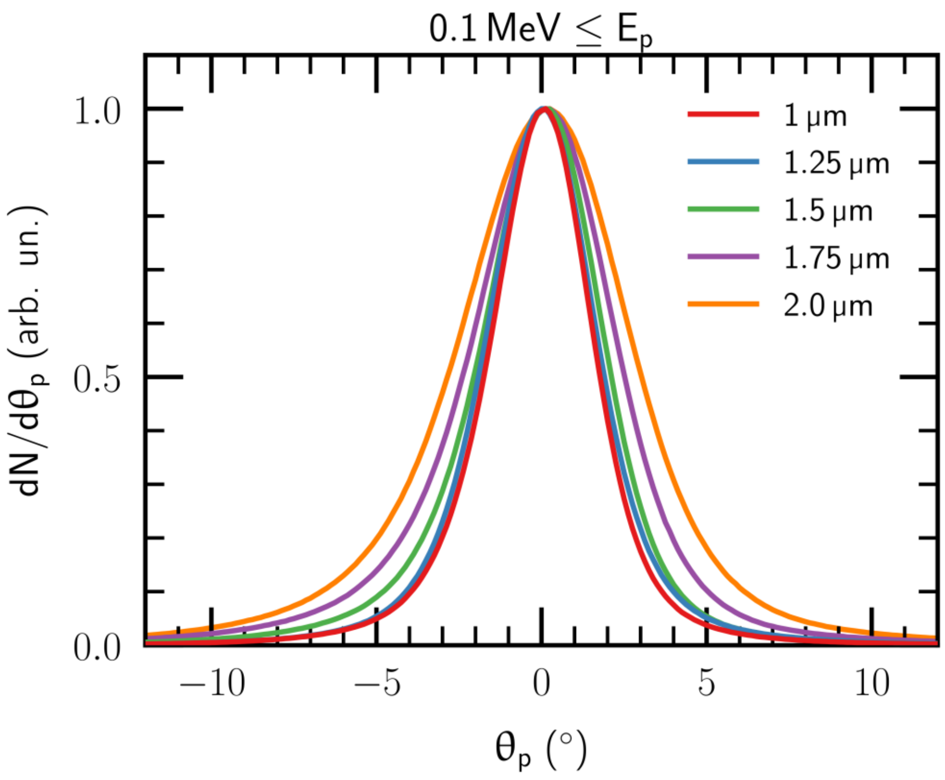
Summary

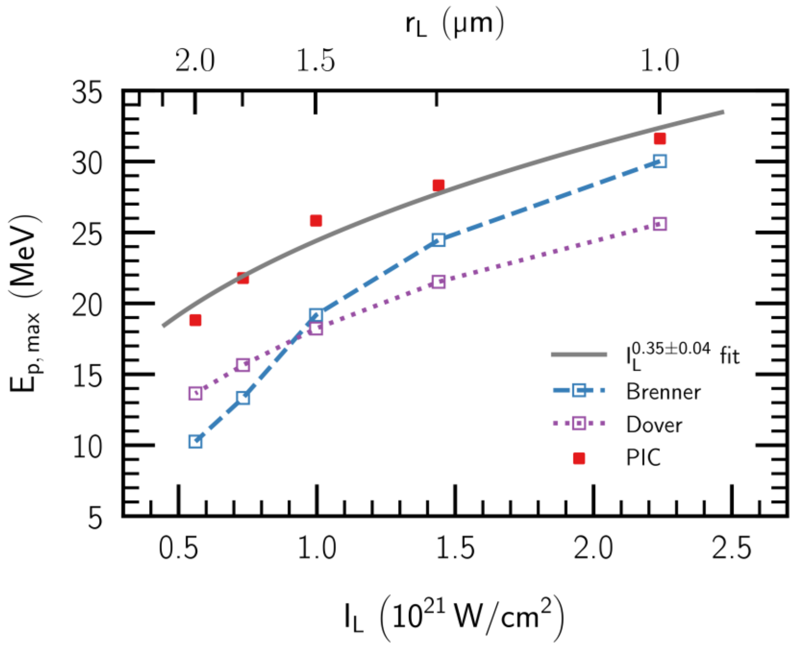
- We explored via 2-D scans and full 3-D Particle-In-Cell simulations the interaction of the SCAPA laser with Aluminium foils.
- We linked different regions and scale-lengths of the pre-plasma with lower or higher boost in the maximum energy of the protons generated via TNSA.
- 2-D PIC simulations predict higher proton energies for lasers incident at angles just below 30°.
- We found a potentially optimal pre-plasma density profile that may increase the proton cut-off energy for fixed laser parameters and target thickness.
- We implemented two optimisation schemes that we plan to use in finding suitable laser contrast curves (and/or prepulse shape and timing) that could generate optimal preplasma density profiles

Backup

Smaller laser spot size leads to less divergent TNSA protons

- 6 μm thick Al^{3+} target (70 n_c),
- pre-plasma scale-length ~0.5 μm





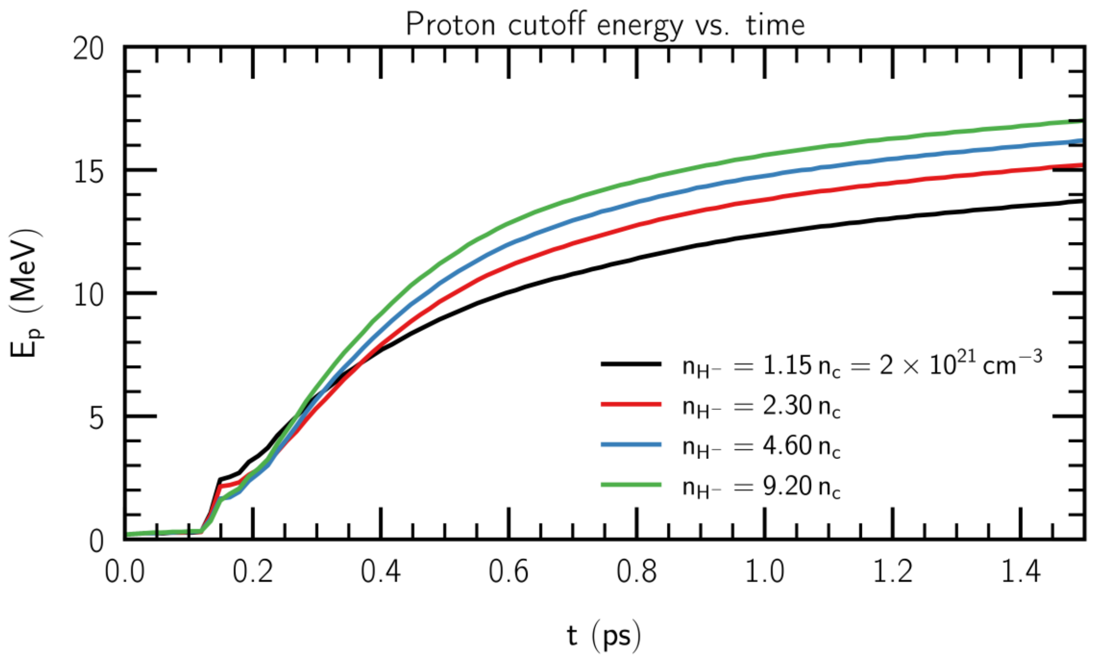
- TNSA models
  - Brenner *et. al.* (modified Mora)
    - $\eta = 0.5$, T_e from sim.
  - Dover *et. al.* (modified Schriber)
    - $\eta = 0.5$, $\theta_e = 10°$

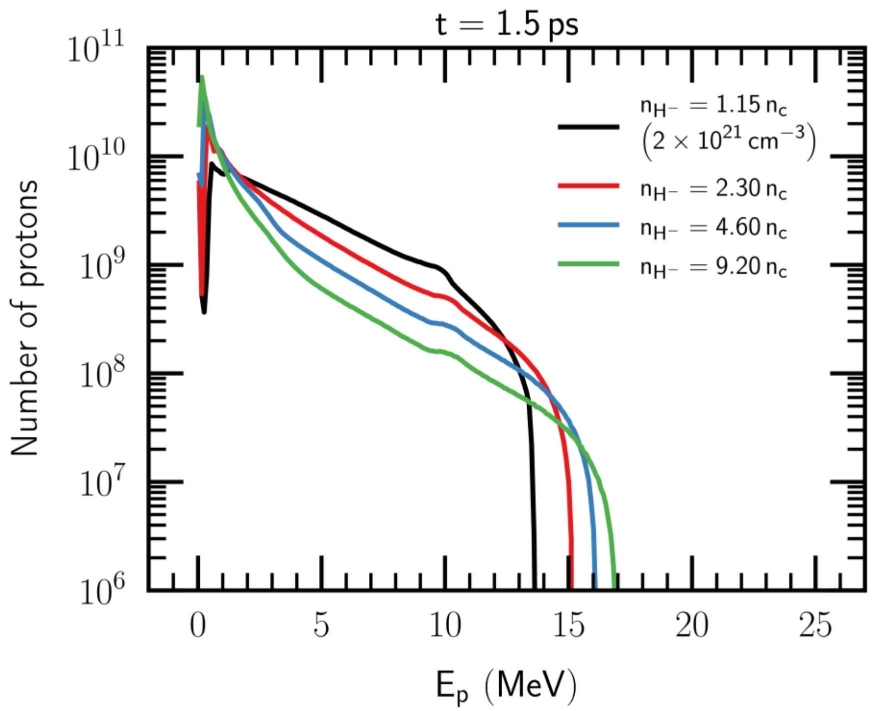
Smaller laser spot size leads to less divergent TNSA protons

- 6 μm thick Al^{3+} target (70 n_c),
- pre-plasma scale-length ~0.5 μm

energy	J	3.75	3.75	3.75	3.75	3.75	3.75
on taget	J	0.9375	0.9375	9.38E-01	0.9375	0.9375	0.9375
duration	fs	25	25	25	25	25	25
power	TW	35.25	35.25	35.25	35.25	35.25	35.25
w0	micron	1	1.25	1.5	1.58	1.75	2
I	W/cm^2	2.24E+21	1.44E+21	9.97E+20	9.00E+20	7.33E+20	5.61E+20
lambda	micron	0.8	0.8	0.8	0.8	0.8	0.8
a0		32.4	25.92	21.6	20.52	18.52	16.2
				Data already present			
		completed	completed	Baseline simulation		completed	

H+ density on back of the target plays a role in the proton cutoff energy and energy spectrum

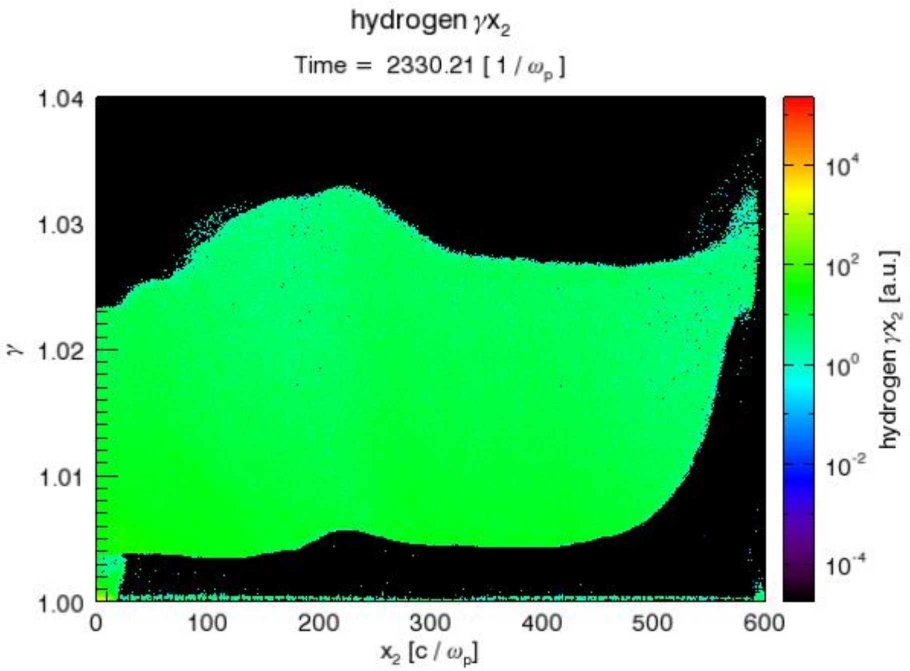




- 6 μm thick Al^{3+} target (70 n_c), pre-plasma scale-length 0.08 μm
- 31.8 nm thick H^+ contaminant layer

- H^+ density needs to be tuned for quantitative comparison to experiments

Searching for the optimal pre-plasma density profile at oblique laser incidence (30°)



- Optimal pre-plasma density search implemented using
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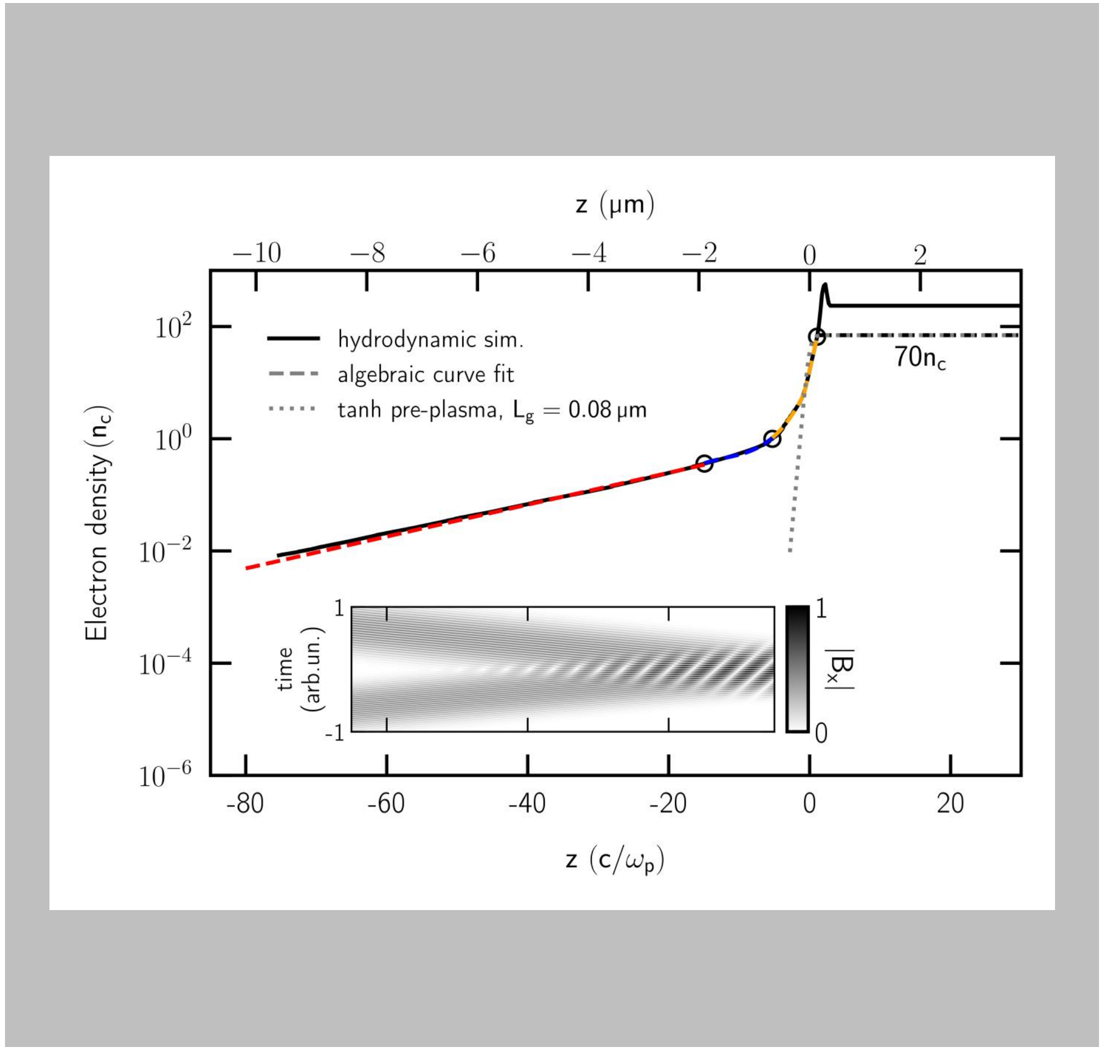
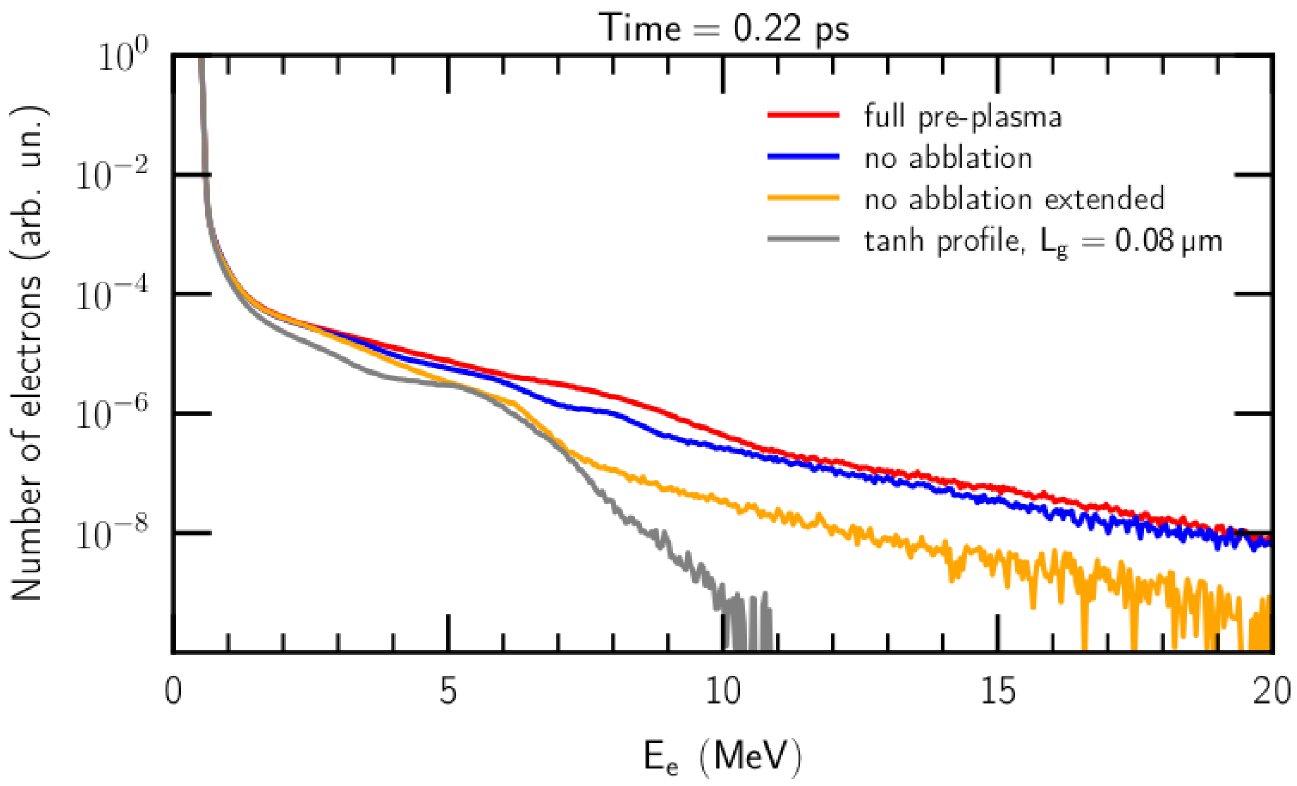
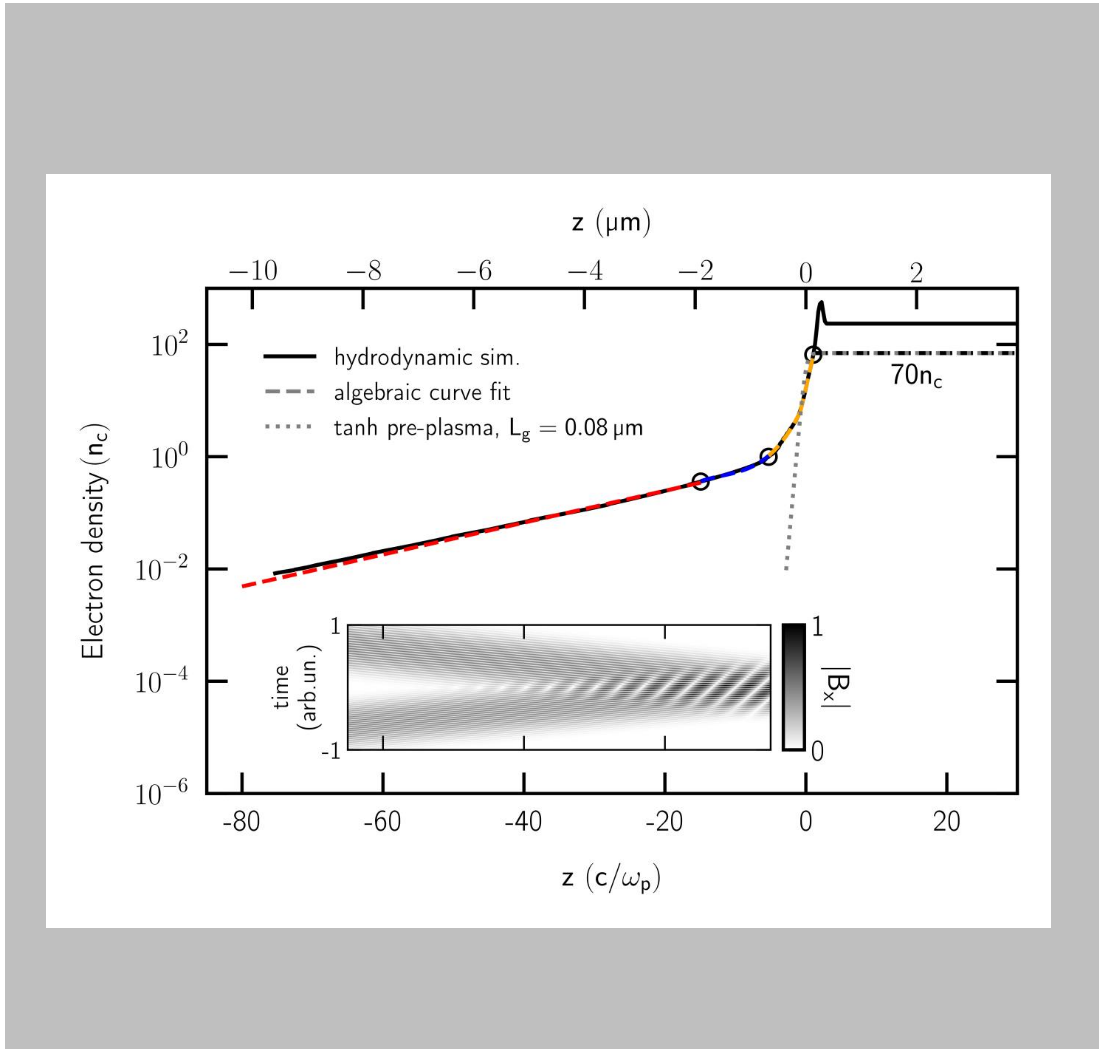
Contribution of different regions of the pre-plasma to the proton acceleration



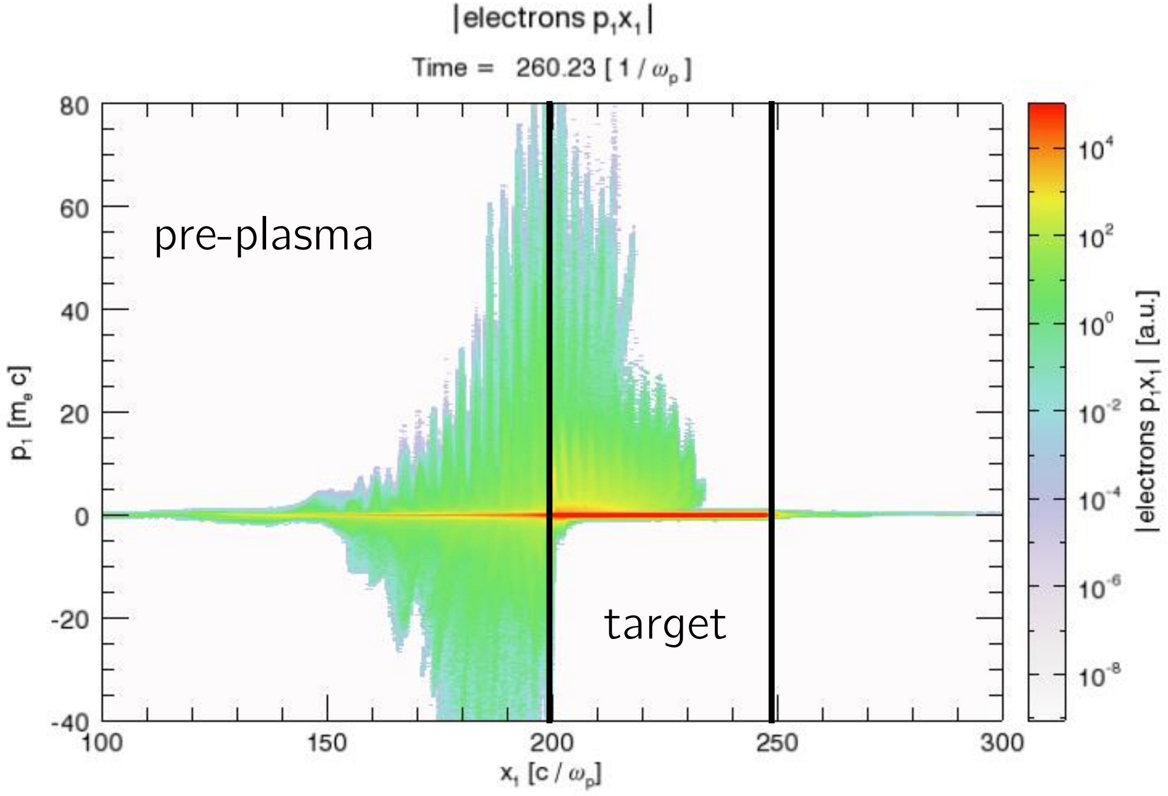
- $I_0 = 1 \times 10^{21}$ W/cm^{-2}, $a_0 = 21.6$



Contribution of different regions of the pre-plasma to the proton acceleration

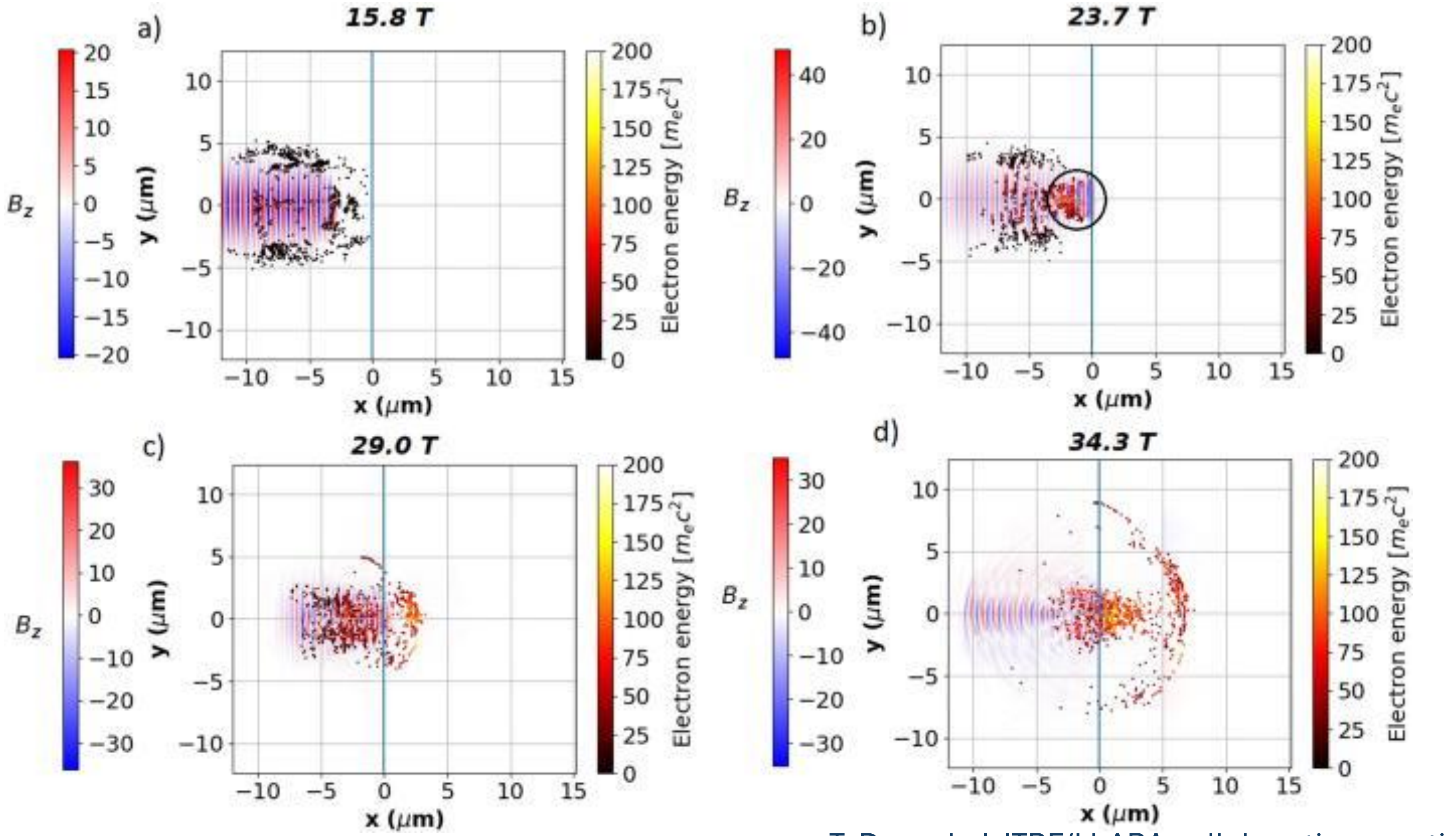


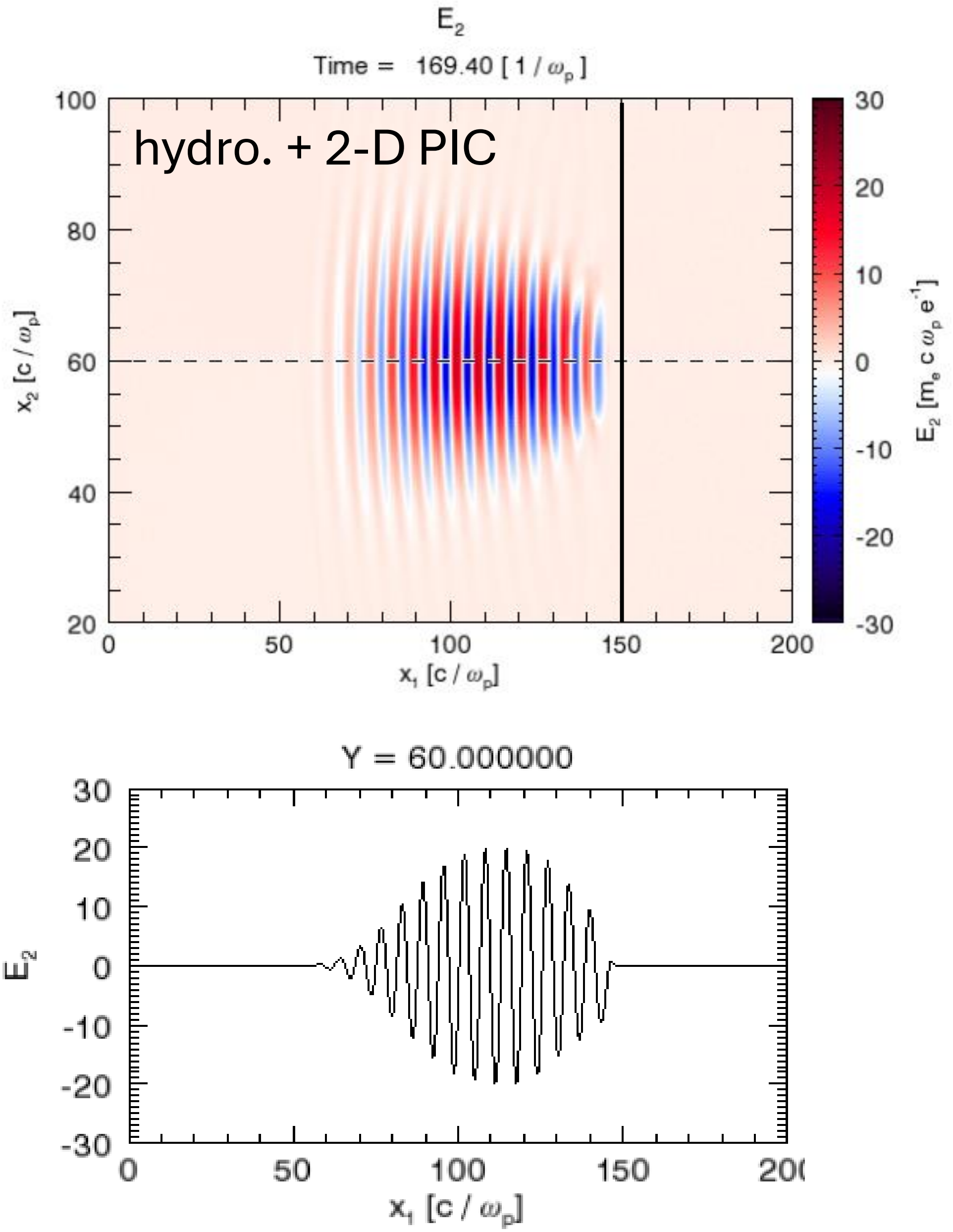
- $I_0 = 1 \times 10^{21}$ W/cm^{-2}, $a_0 = 21.6$

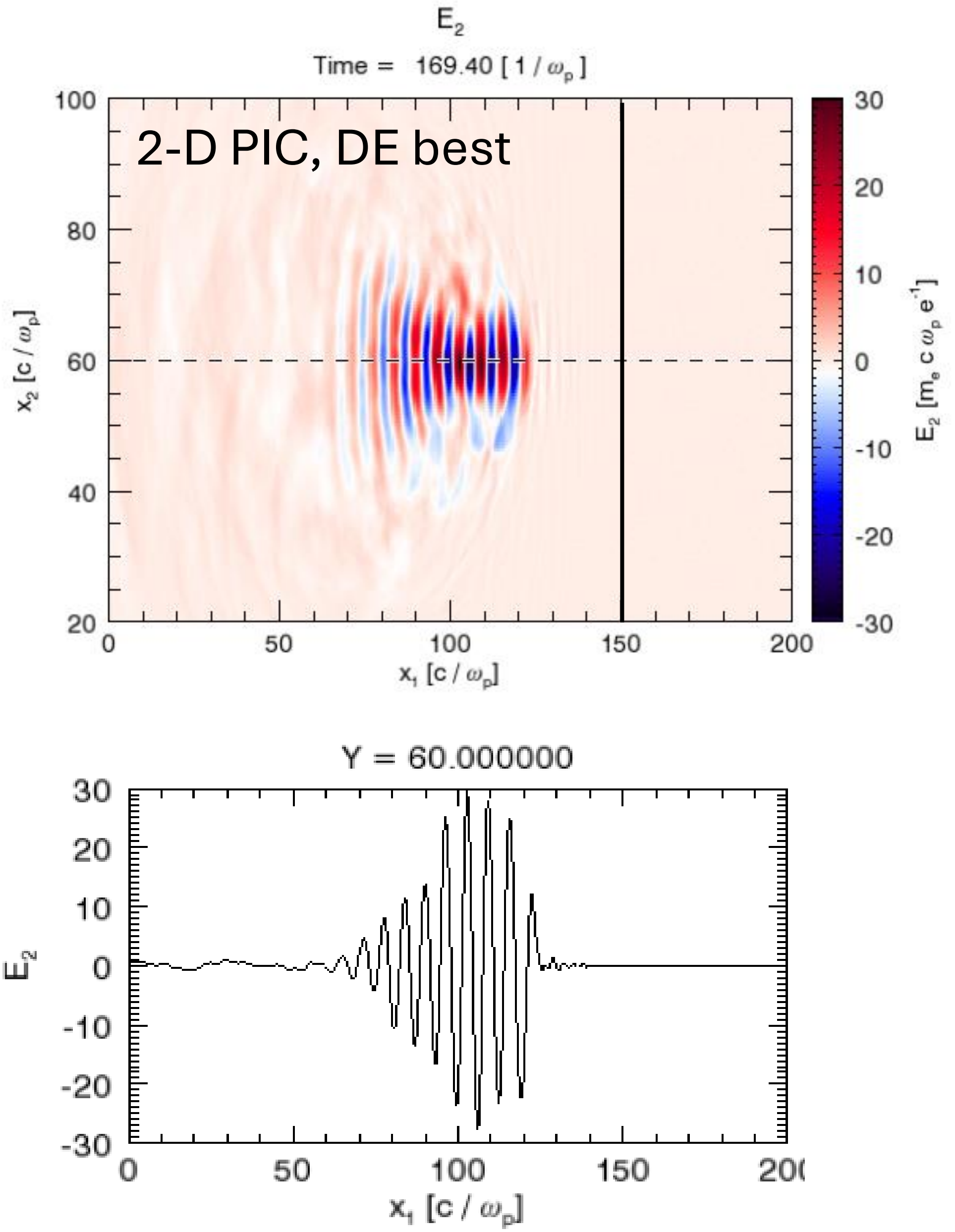


From: **The role of standing wave in the generation of hot electrons by femtosecond laser beams incident on dense ionized target**

Phys. Plasmas. 2021;28(2). doi:10.1063/5.0031555




E2
Time = 169.40 [1 / ωp]
hydro. + 2-D PIC
x2 [c / ωp]
x1 [c / ωp]
E2 [me c ωp e-1]
Y = 60.000000
E2
x1 [c / ωp]


E2
Time = 169.40 [1 / ωp]
2-D PIC, DE best
x2 [c / ωp]
x1 [c / ωp]
E2 [me c ωp e-1]
Y = 60.000000
E2
x1 [c / ωp]

DOI: 10.1103/PhysRevE.85.036405

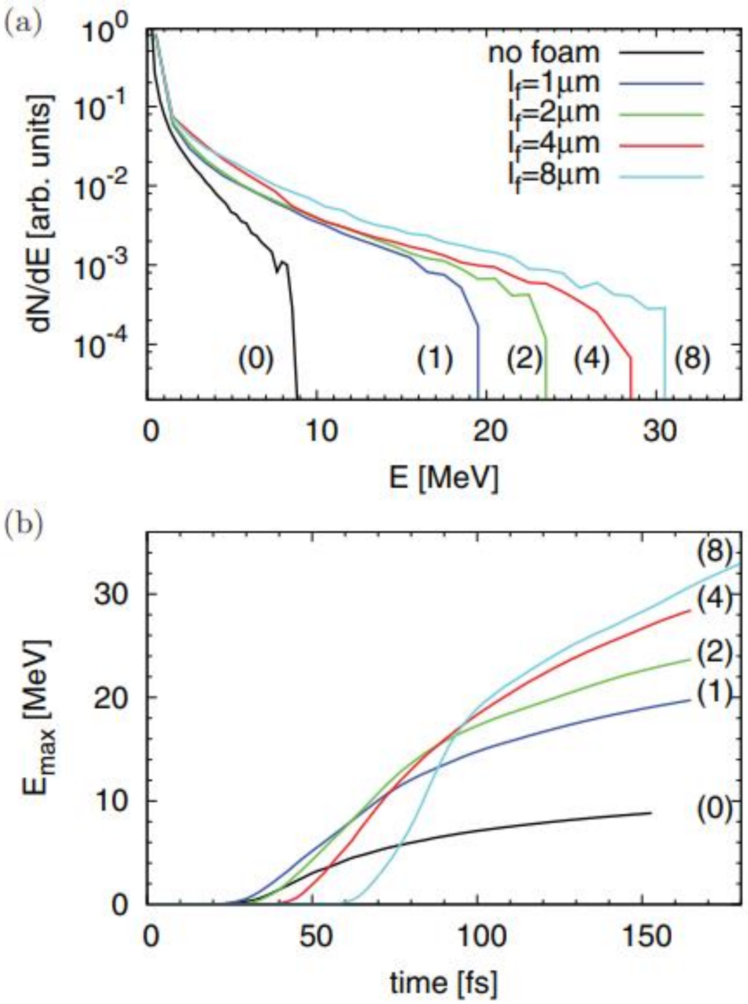


FIG. 4. (Color online) (a) Proton energy spectra at $t = 166$ fs considering a laser with $a_0 = 10$ and foam layer with density $n_f = n_c$. (b) Maximum proton energy evolution with respect to time for different foam thicknesses ($a_0 = 10$, $n_f = n_c$). In both panels the foam thickness is written next to the corresponding line (0: no foam; 1: $l_f = 1$ µm etc.).

Phys. Plasmas **20**, 013101 (2013)