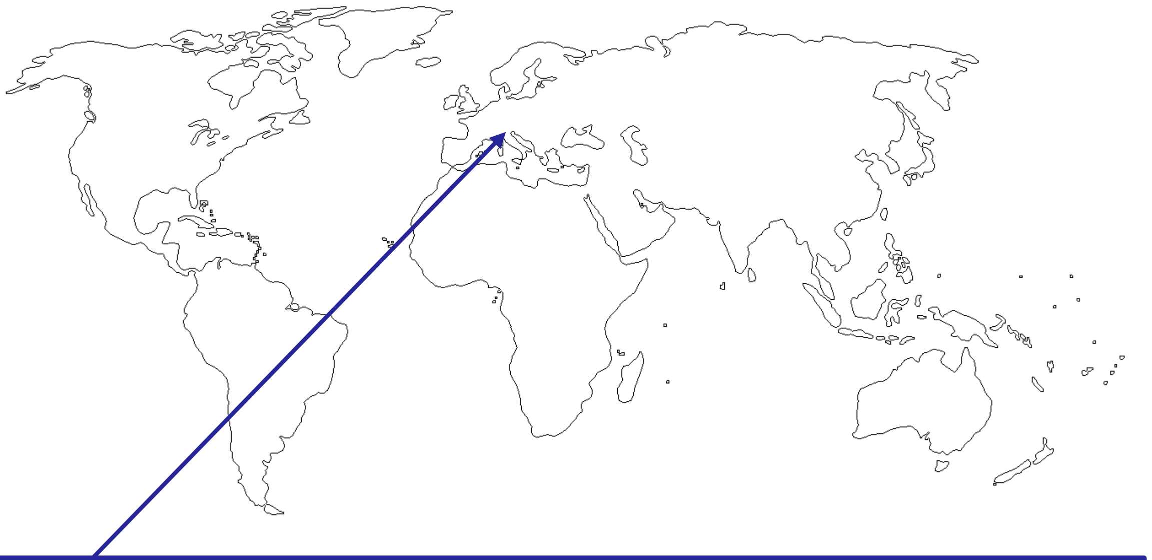
International Conference on High Energy Density Physics

POLITECNICO DI MILANO

Electron heating in sub-ps laser plasma-interaction

Lorenzo Cialfi

Co-authors and Sponsors



“ENSURE” project

European Research Council

Supercomputing facility (Bologna, IT)

CINECA
Consorzio Interuniversitario

Research group (Milano, IT)

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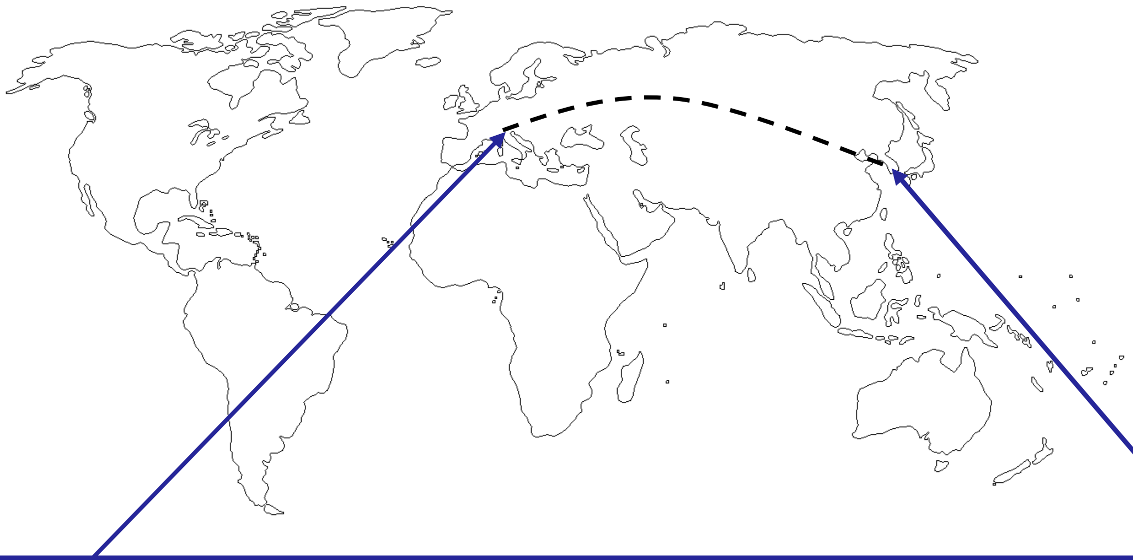

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Experimental campaign (Gwangju, South Korea)

- Il Woo CHOI
- I Jong KIM
- Karol JANULEWICZ
- H.W. LEE
- J. H. SUNG
- S.K. LEE
- C. H. NAM

Outline of the presentation

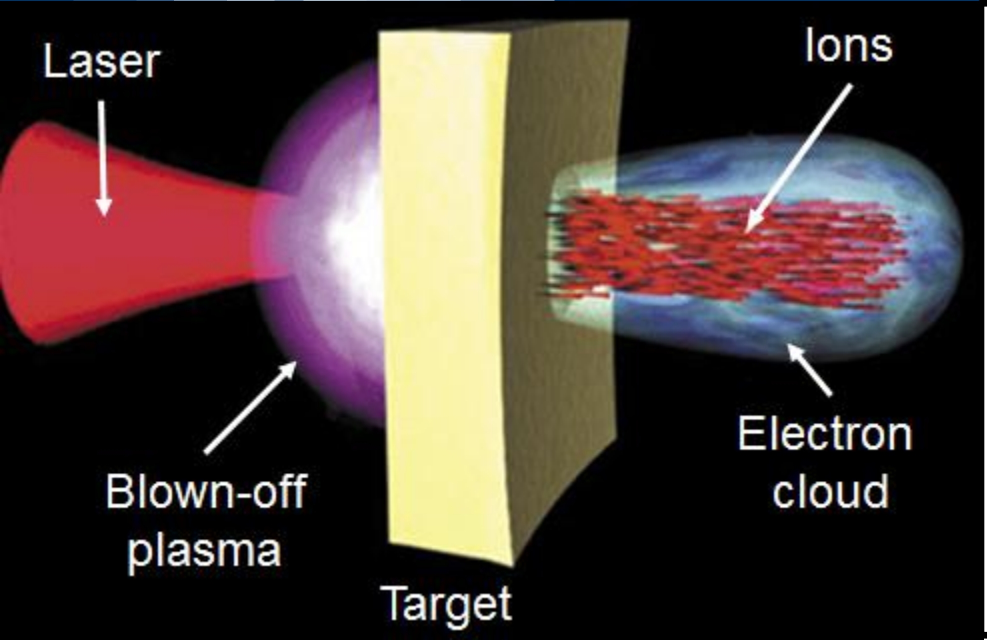
I. Introduction
  → Laser induced ion acceleration
  → Electron heating: state of the art

II. Proposal of scaling law for electron temperature
  → Different experimental paramenters

III. Numerical Campaign
  → Parametric study

IV. Scaling law & Ion acceleration model
  → Benchmark with experimental results

Laser driven ion acceleration



Laser

- I > $10^{19}\ {}^{W}/{}_{cm^2}$
- Duration < ps
- Focal spot ~ µm

- **Taget**
- Thickness: µm/nm
- Foils

Interesting features:

- Compactness
- Choerence
- Tunable energy
- Cheaper (?)

Potential applications:

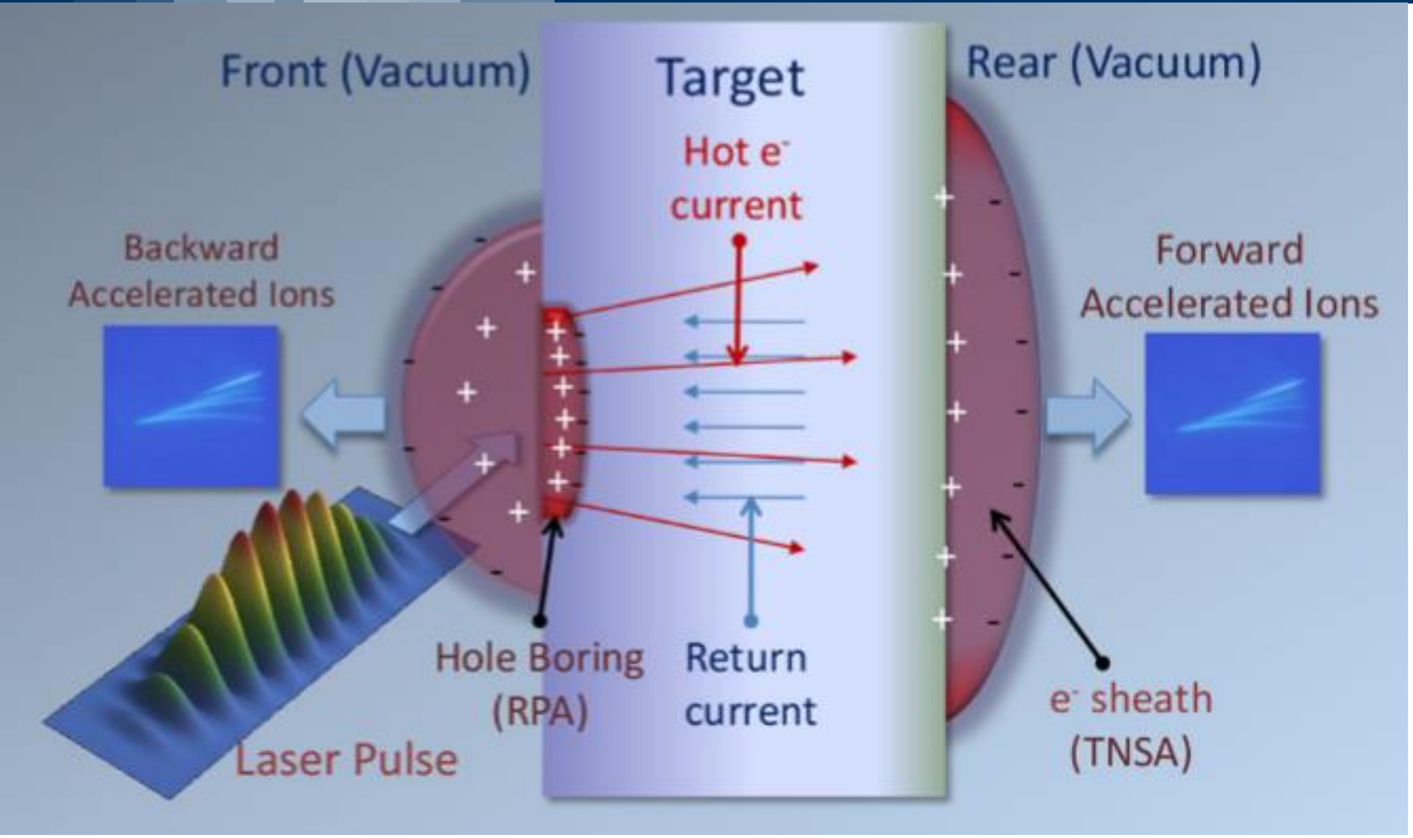
- Proton imaging/radiography
- Material irradiation
- Isotope/neutron production
- Fast ignition
- Hadrontherapy

Required upgrades:

- Better performances
- High repetition rate (> Hz)
- Better control over the technique

A. Macchi, M. Borghesi, M. Passoni,
Rev. Mod. Phys., 85 751 (2013)

Target Normal Sheath Acceleration (TNSA)



Many acceleration mechanisms

Target Normal Sheath Acceleration (TNSA)

Electron heating

↓

Electron expansion

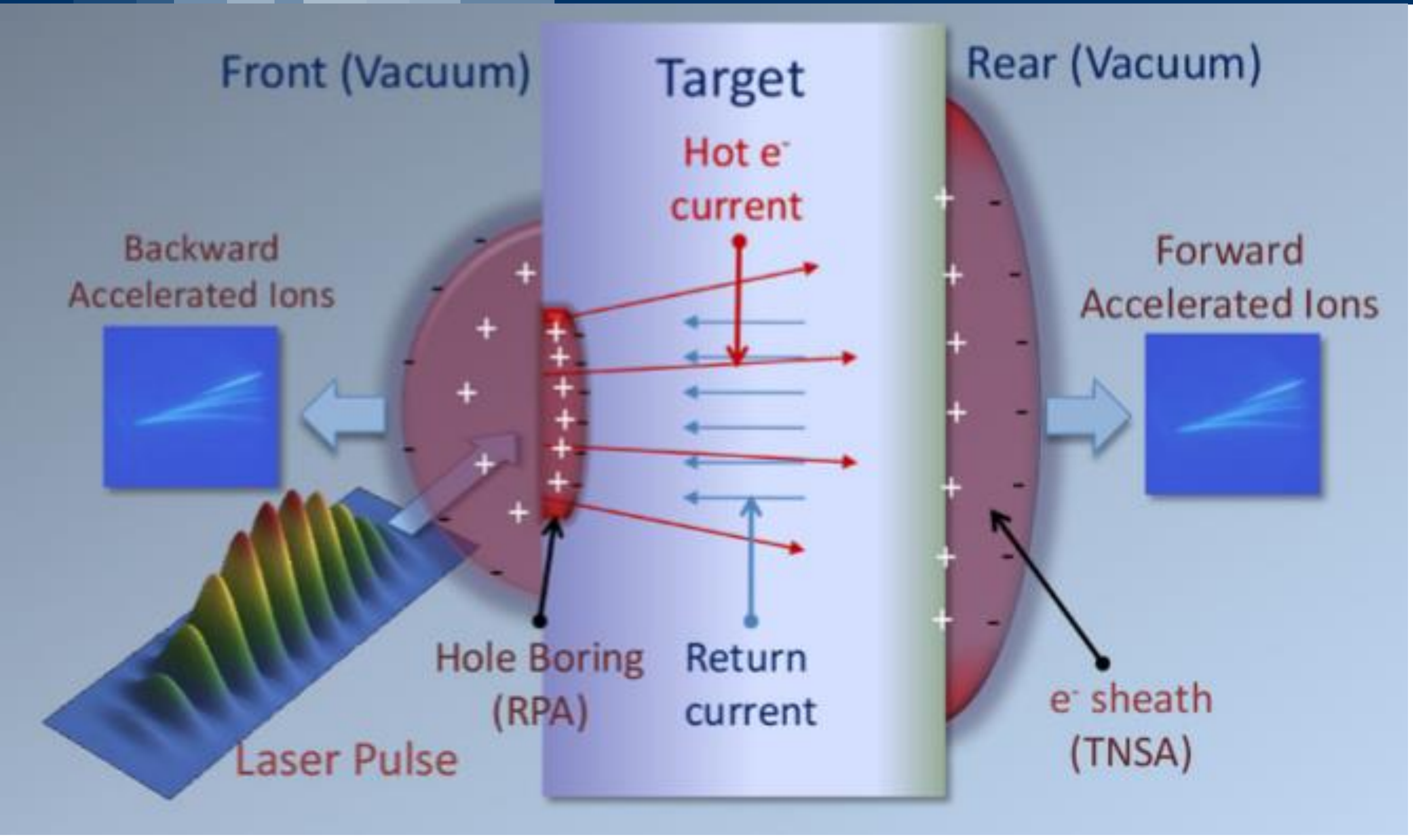
↓

Charge separation

↓

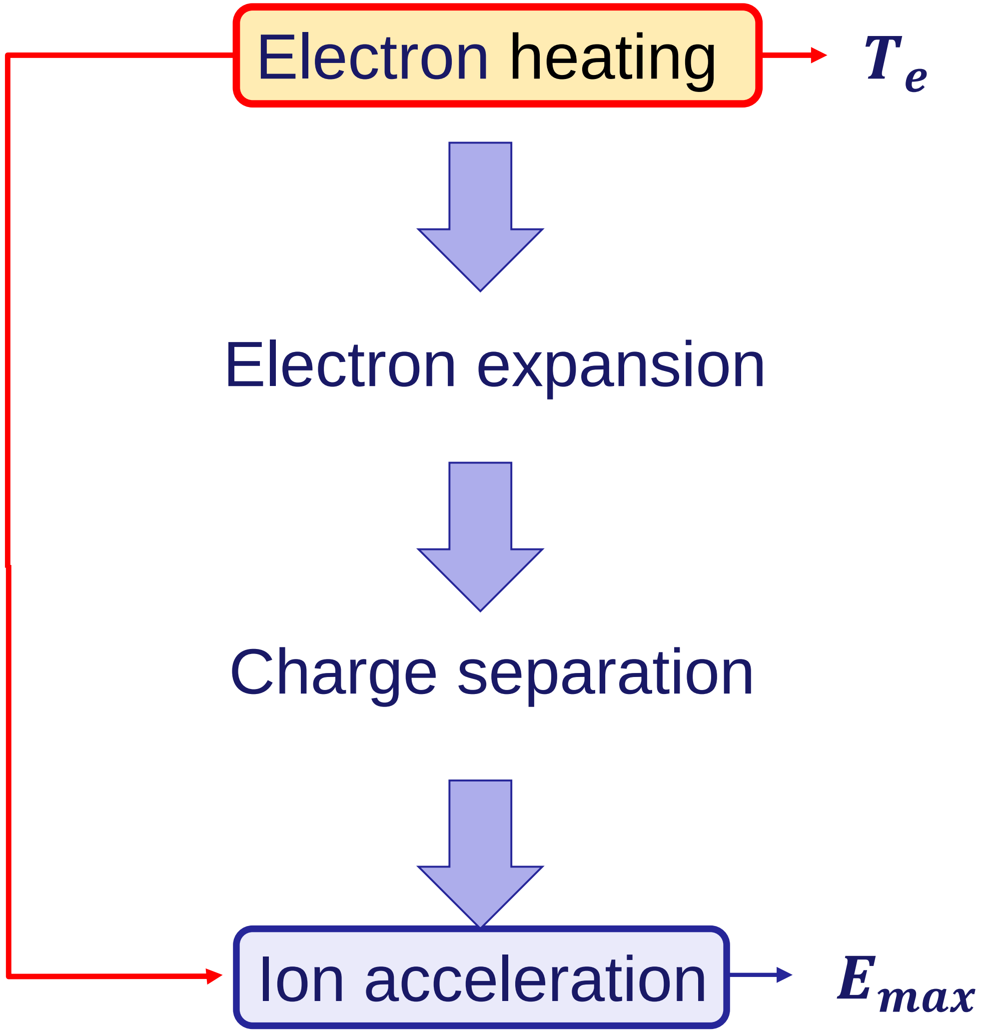
Ion acceleration

Target Normal Sheath Acceleration (TNSA)



Many acceleration mechanisms

Target Normal Sheath Acceleration (TNSA)



Electron heating → T_e

Electron expansion

Charge separation

Ion acceleration → E_{max}

Modelling TNSA

Possible approaches:

- Quasi stationary models

$$E_{max}(ions) = Z_i k_b T_e \left[\varphi^* - 1 + \frac{\beta\,(\varphi^*,\varsigma)}{I(\varphi^*,\varsigma)e^{\varsigma+\varphi^*}}\right]$$

M. Passoni and M. Lontano, Phys. Rev. Lett., vol. 101, p. 115001 (2008).

- Fluid models

$$E_{max}(ions) = 2Z_i k_b T_e ln^2\left(\tau + \sqrt{\tau^2 + 1}\right)$$

P. Mora, Physical Review Letters, V 90 N 18 (2003)

- Hybrid models

$$E_{max}(ions) = Z_i k_b T_e f(q)$$

B. J. Albright, et al., Physical Review Letters, 97:115002 (2006).

Modelling TNSA

Electron temperature → key parameter

Possible approaches:

- Quasi stationary models

$$E_{max}(ions) = Z_i k_b \boxed{T_e}\left[\varphi^* - 1 + \frac{\beta\,(\varphi^*,\varsigma)}{I(\varphi^*,\varsigma)e^{\varsigma+\varphi^*}}\right]$$

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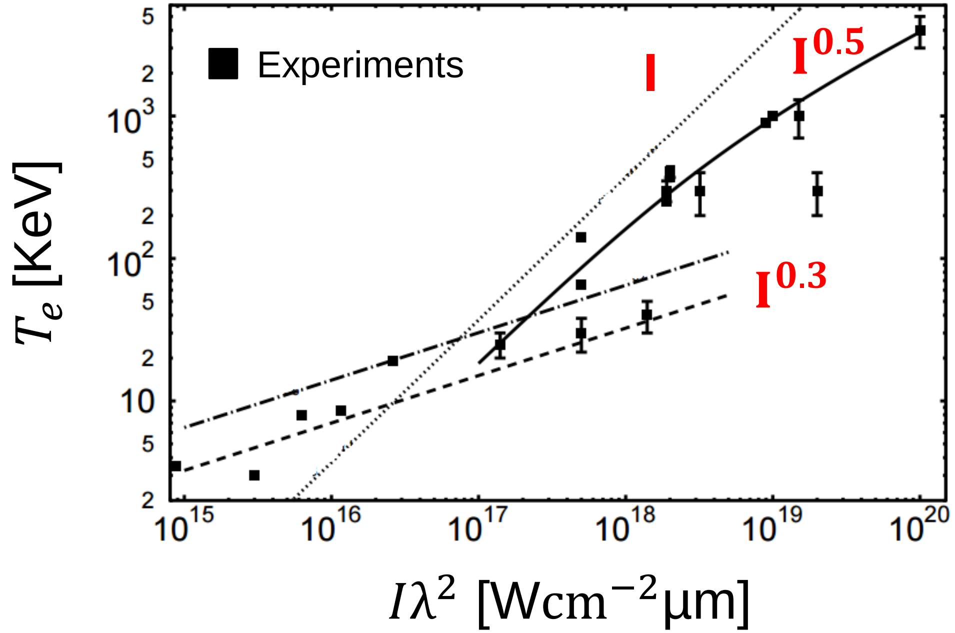


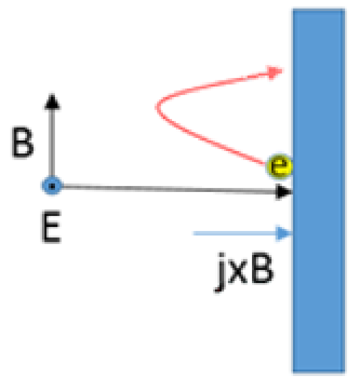
P. Gibbon; Short Pulse Laser Interaction with Matter; Imperial college press (2005)

Laser intensity dependence
Other dependences ?

Electron temperature

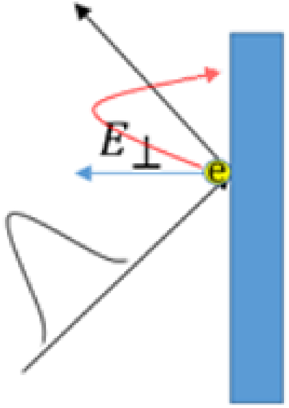
- **Collisional heating** → e-i collisions → $\nu_{ei} \propto Z n_e (T_e)^{-\frac{3}{2}} \ln(\Lambda)$, $T_e \propto I^{1/3} t^{1/6}$ → not efficient for high intensities and short pulses
- **Resonance heating** → $T_e \propto (I\lambda^2)^{1/3}$ → efficient for long pulses (~ps) and plasma gradients (µm)
- Ultra-intense laser (I > $10^{18} W/cm^2$) + Sharp-edged micrometric solid targets

jxB heating



Collisionless

Brunel effect



Ponderomotive scaling

$$T_e[MeV] = 0.511\left[\sqrt{1+\boxed{\frac{I\lambda(\mu m)^2}{1.37\cdot 10^{18}}}} - 1\right]$$

$$\frac{a_0^2}{2}$$

Interaction efficiency

$$\eta = \frac{1}{\pi a_0}\left[(1+f^2 a_0^2 \sin^2\theta)^{1/2} - 1\right]\frac{\sin\theta}{\cos\theta}$$

Electron temperature

- **Collisional heating** → e-i collisions → $\nu_{ei} \propto Z n_e (T_e)^{-\frac{3}{2}} \ln(\Lambda)$, $T_e \propto I^{1/3} t^{1/6}$ → not efficient for high intensities and short pulses
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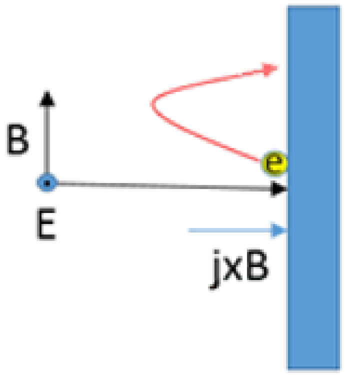

Collisionless

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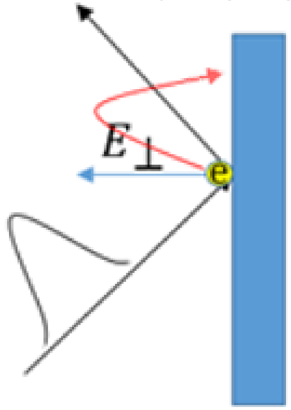

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Micrometric plain solid targets: scaling law proposal

- **jxB heating**
  → hp: No angular dependence
  → Ponderomotive scaling

Brunel effect
→ interaction efficiency
→ $T_e \; \alpha \; \frac{\eta \, E_{laser}}{N_e}$

Hp: combined heating

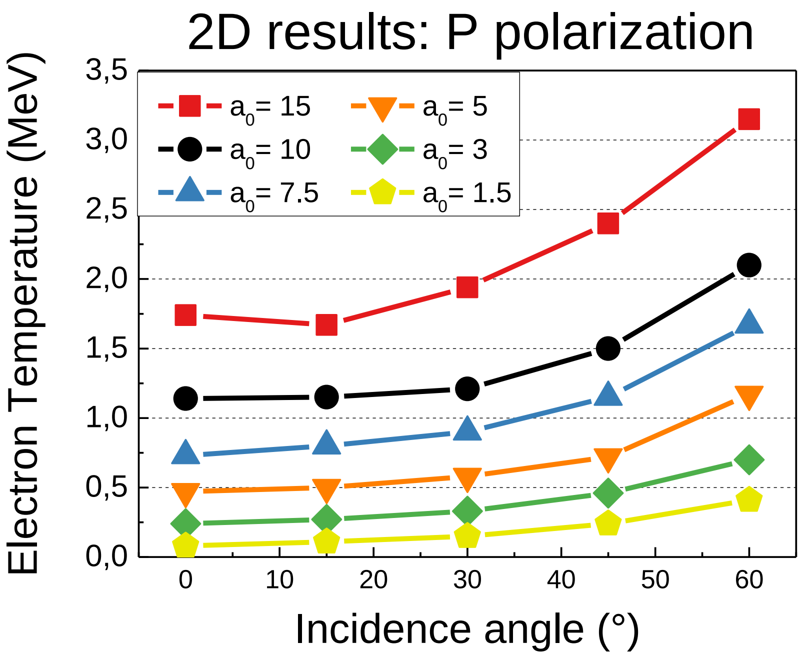
$$T_e[MeV] = 0.511 \cdot C_1(a_0, pol) \cdot \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1 \right) + 0.511 \cdot C_2(a_0, pol) \cdot \left(\sqrt{1 + 2{a_0}^2 sin^2\,\theta} - 1 \right) \cdot \tan\theta$$

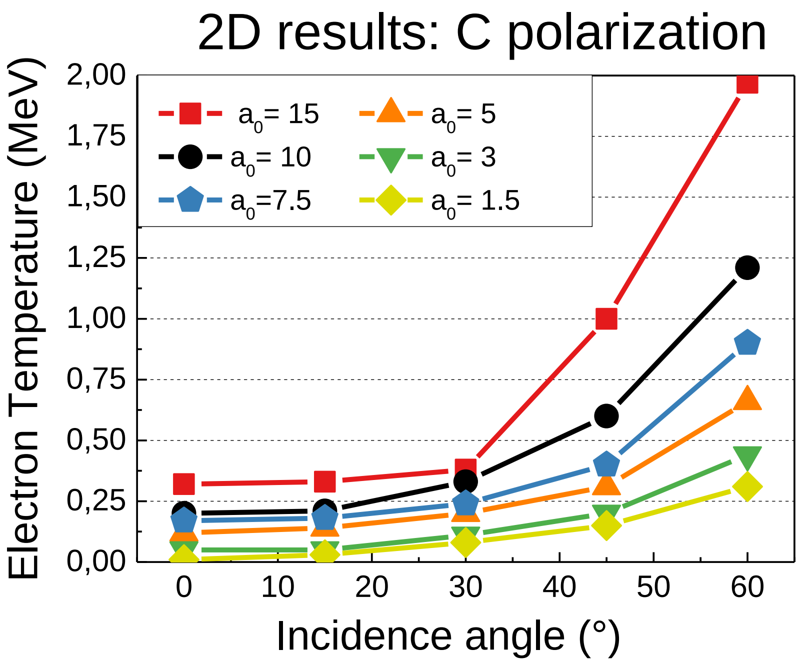
$\boldsymbol{C_1}(a_0, pol)$ & $\boldsymbol{C_2}(a_0, pol)$: ?
→ Numerical simulations → Temperature fit

Particle In Cell (PIC) simulations: Electron temperature

Target
Composition : $Al^{9+} + H^{+}$ (contaminants)
Thickness : 0,5 µm and 50 nm contaminants
Density: 80 n_c and 4 n_c

Laser
Intensity: $1.5 < a_0 < 15$
Incidence angle : 0 – 15 – 30 – 45 - 60°
Polarization: P-, C-, S-


2D results: P polarization


2D results: C polarization

- Angular dependence: P and C polarization
- S polarization (requires 3D simulations) constant temperature

Particle In Cell (PIC) simulations: Electron temperature

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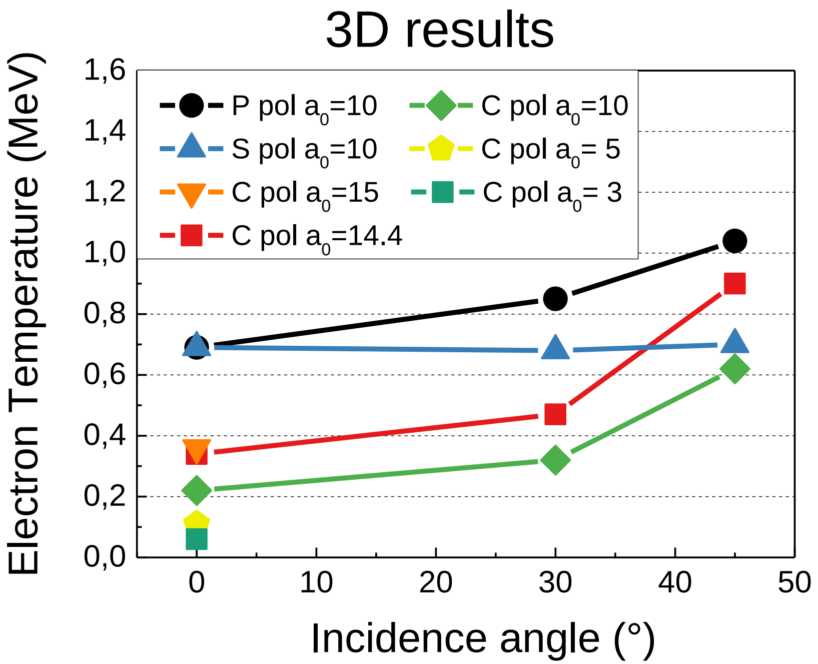
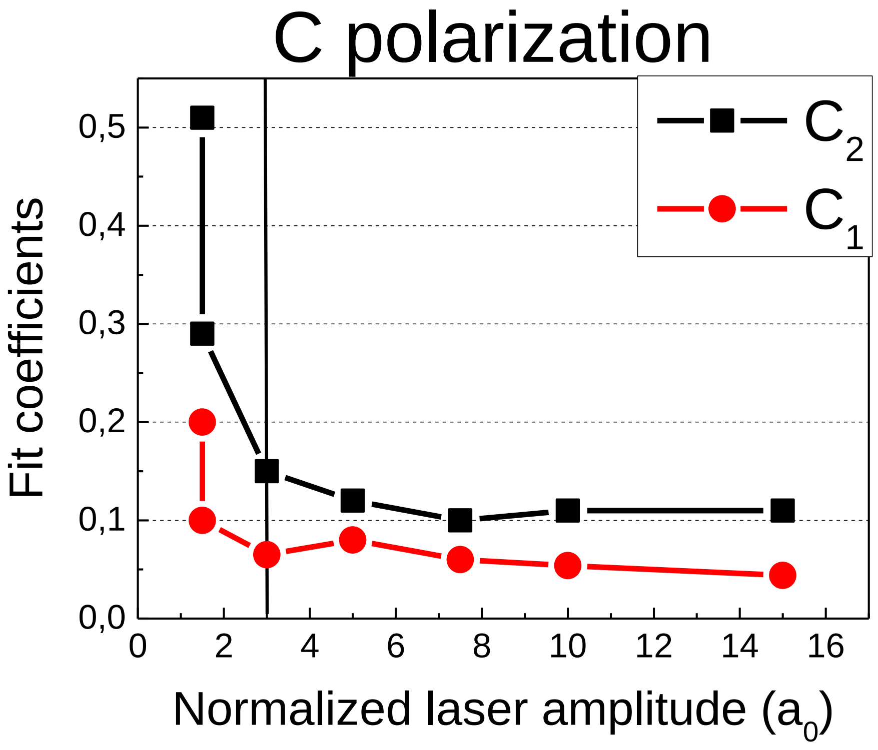
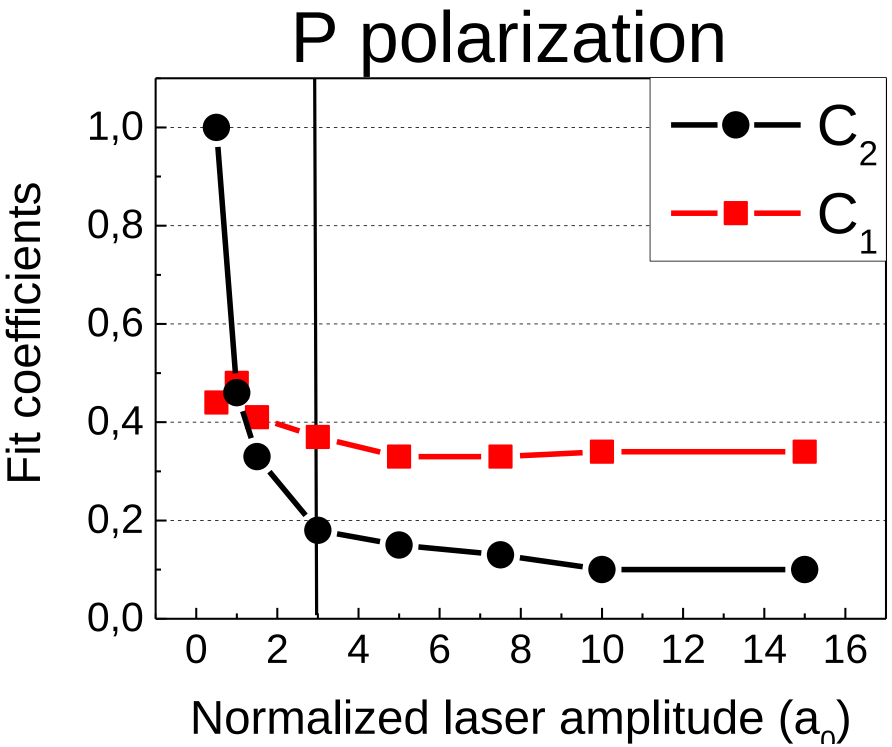


- Angular dependence: P and C polarization
- S polarization (requires 3D simulations) constant temperature

Estimation of C_1 and C_2 coefficients



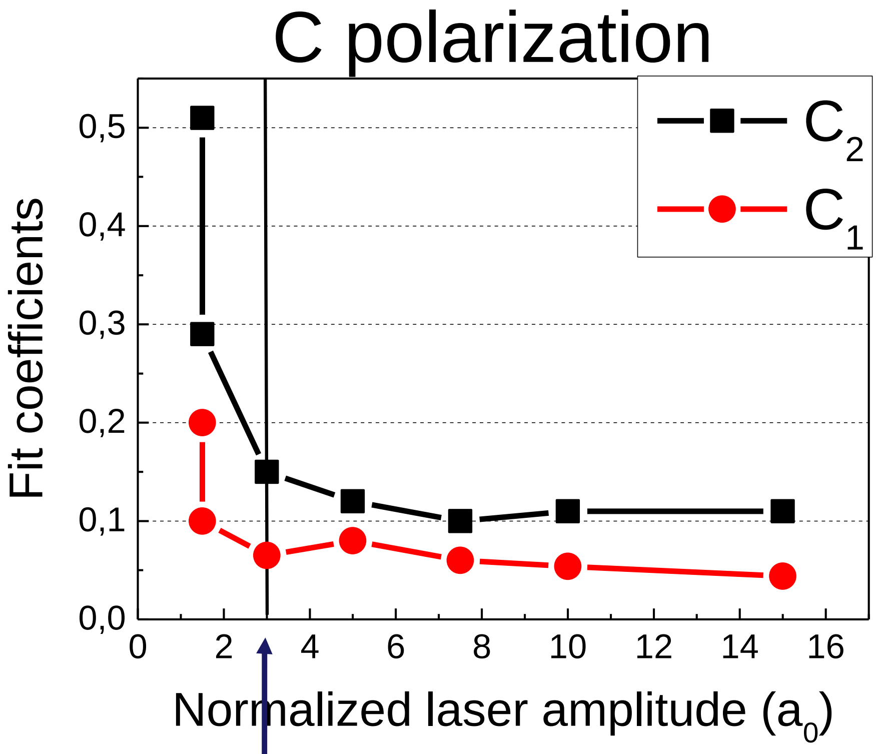


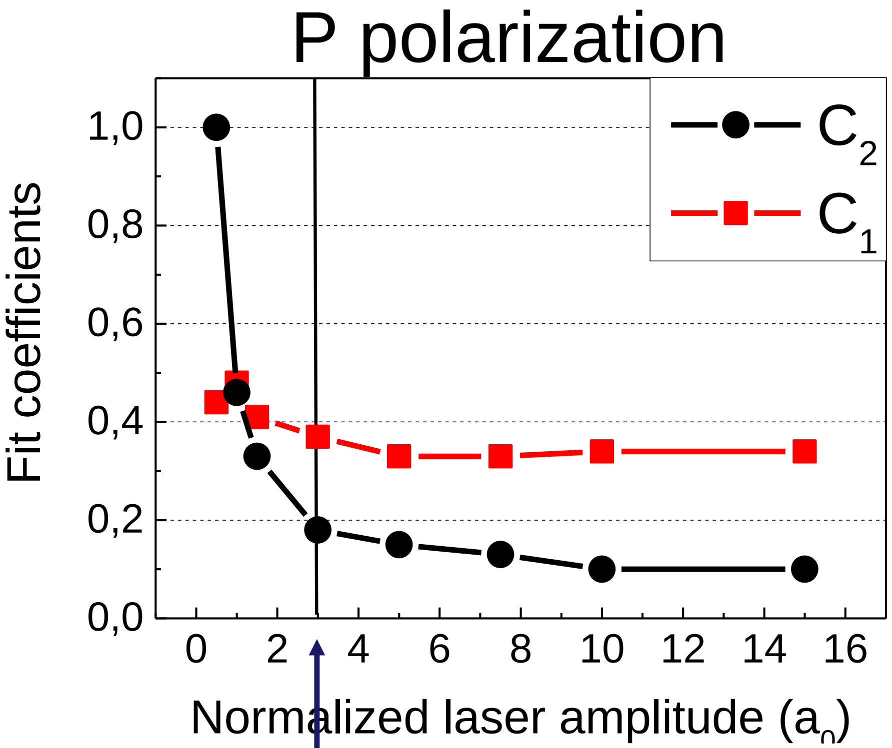
Numerical fit:

$$T_e = C_1(a_0, pol)T_e(\mathbf{J}\mathrm{x}\mathbf{B}) + C_2(a_0, pol)T_e(\mathrm{Brunel})$$

- C_1, C_2 constant for $a_0 > 3$
- C_2(pol S) = 0 (no Brunel)
- C_1(pol S) = C_1(pol P)

Estimation of C_1 and C_2 coefficients





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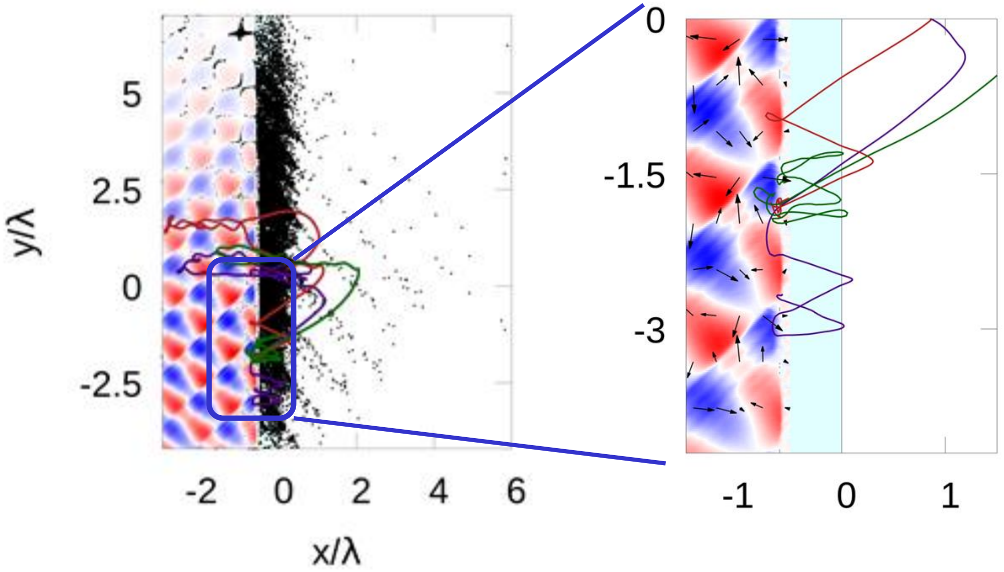
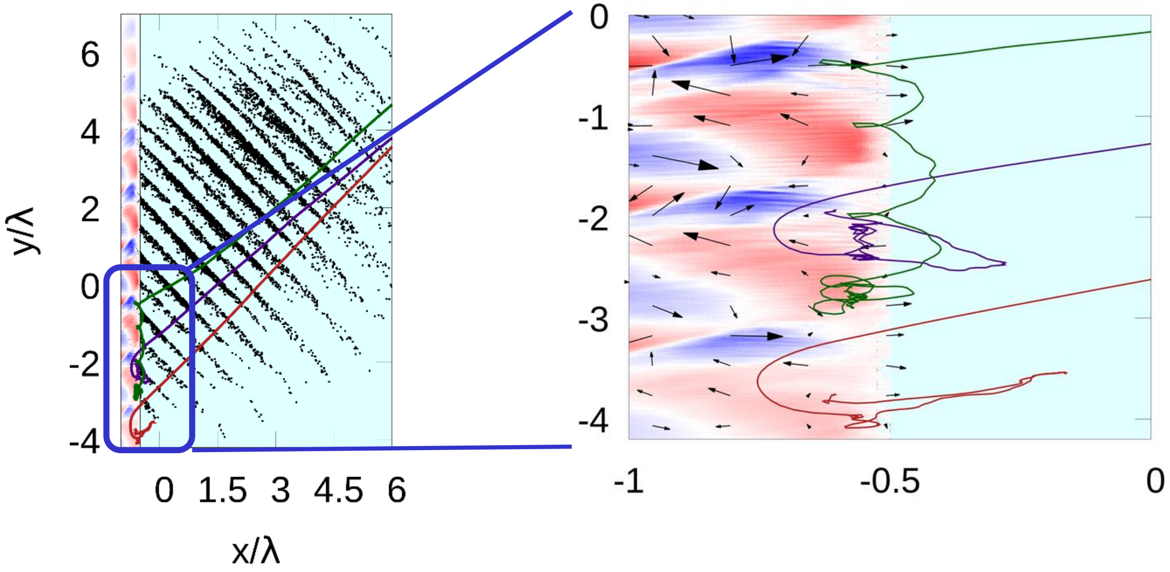
- C_1, C_2 constant for $a_0 > 3$
- C_2(pol S) = 0 (no Brunel)
- C_1(pol S) = C_1(pol P)

Numerical results: electron trajectories

0.5 µm thick Al



15 µm thick Al



Interaction:

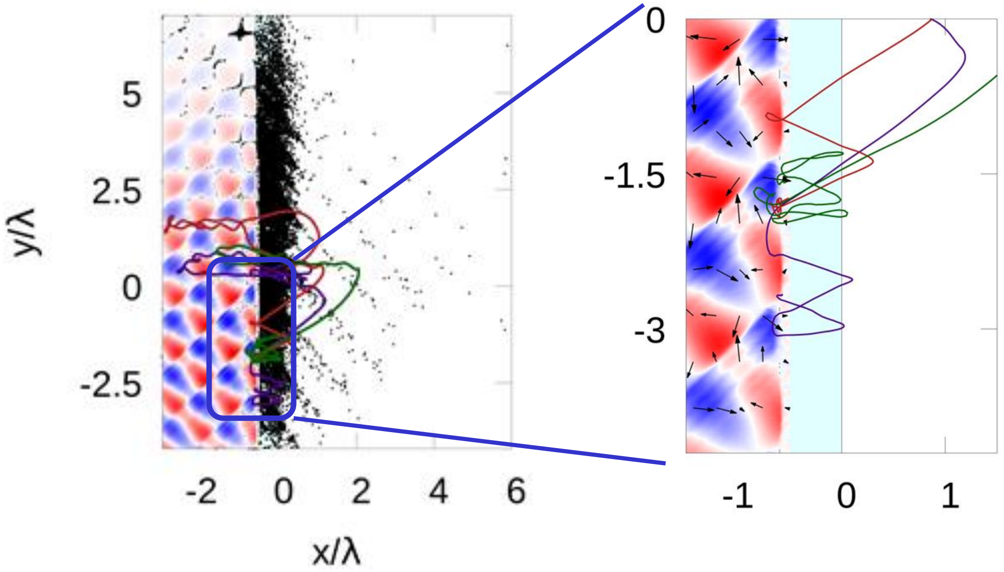
I. Normal oscillations
II. Kick along the laser direction
III. Injection at 2ω

Thicker targets:

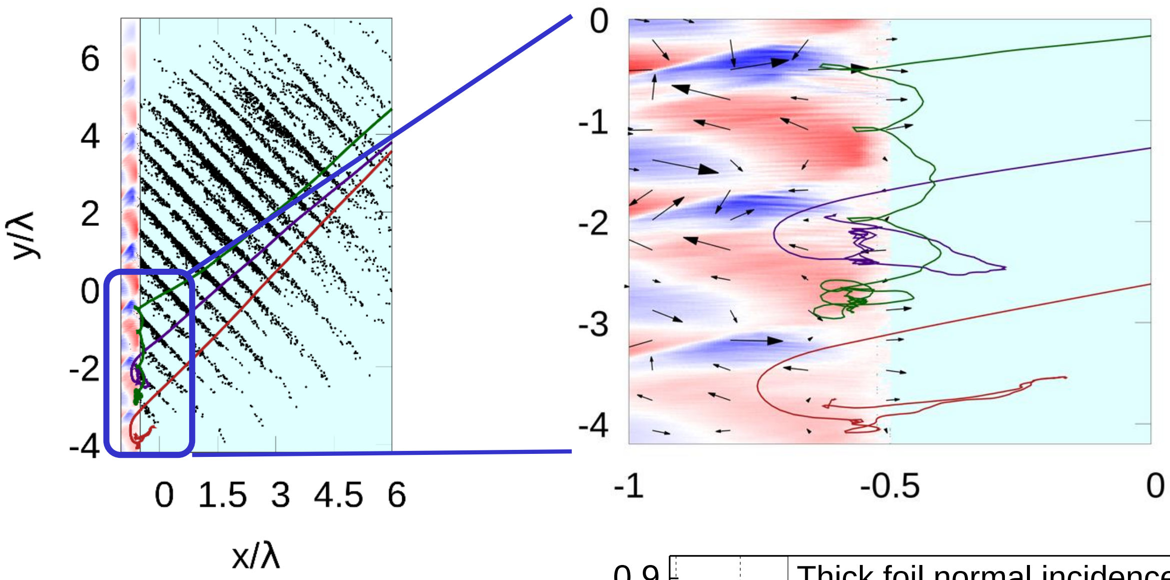
Similar temperatures (20% decrease)
No e^- recirculation → less confinement

Numerical results: electron trajectories

0.5 µm thick Al



15 µm thick Al



Interaction:

- I. Normal oscillations
- II. Kick along the laser direction
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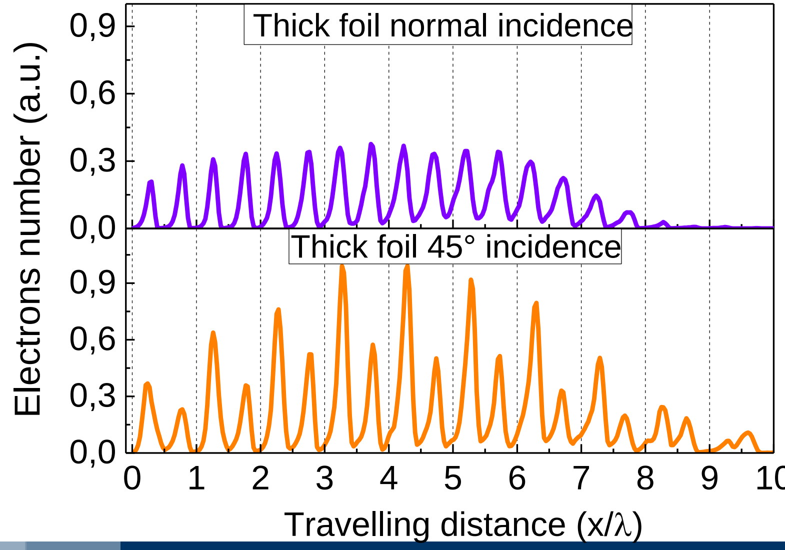
jxB heating

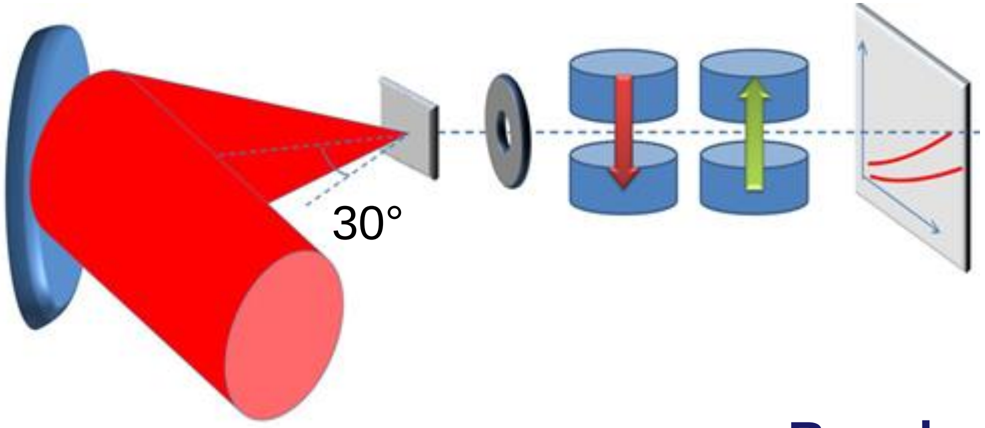
jxB injection at 2ω

\+

Brunel injections at ω



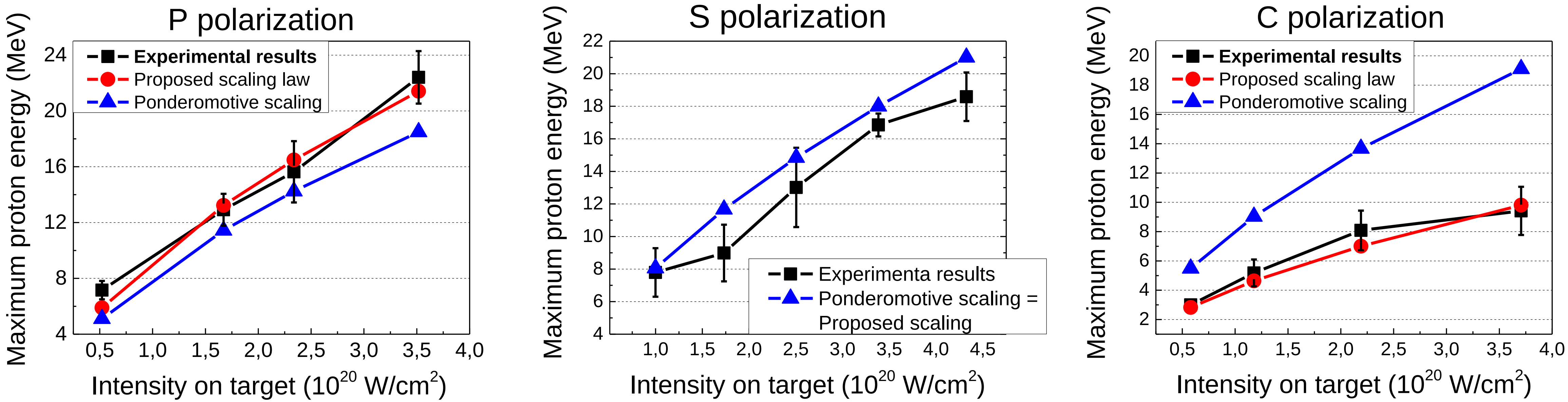
Benchmarks with experiments



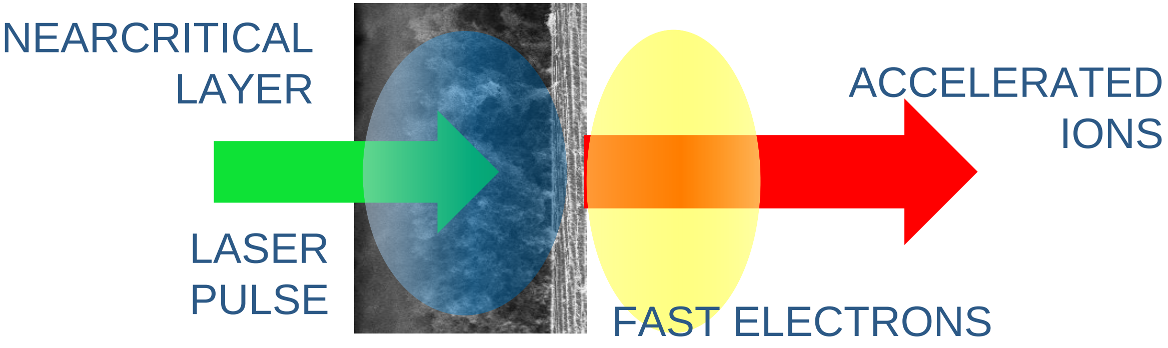
Target:
Simple plain foil
Compositions: Al
Thickness: 0.75 µm

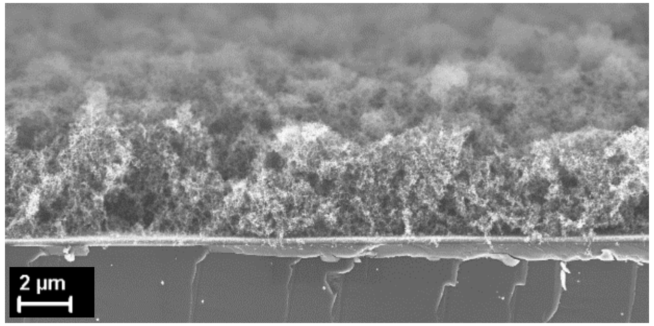
Laser: Ti:Sapphire
I < $4.2 \cdot 10^{20}\, {}^{W}/_{cm^2}$
Laser polarization: P-, S-, C-

Benchmark with experimental results



Foam-attached targets





SOLID FOIL + LOW DENSITY LAYER

- Volume & Surface interaction mechanisms

Foam deposition: Pulsed Laser Deposition (PLD)

- Micrometric-scale near-critical density
- Nanometric (~ 20-30 nm) over-dense clusters

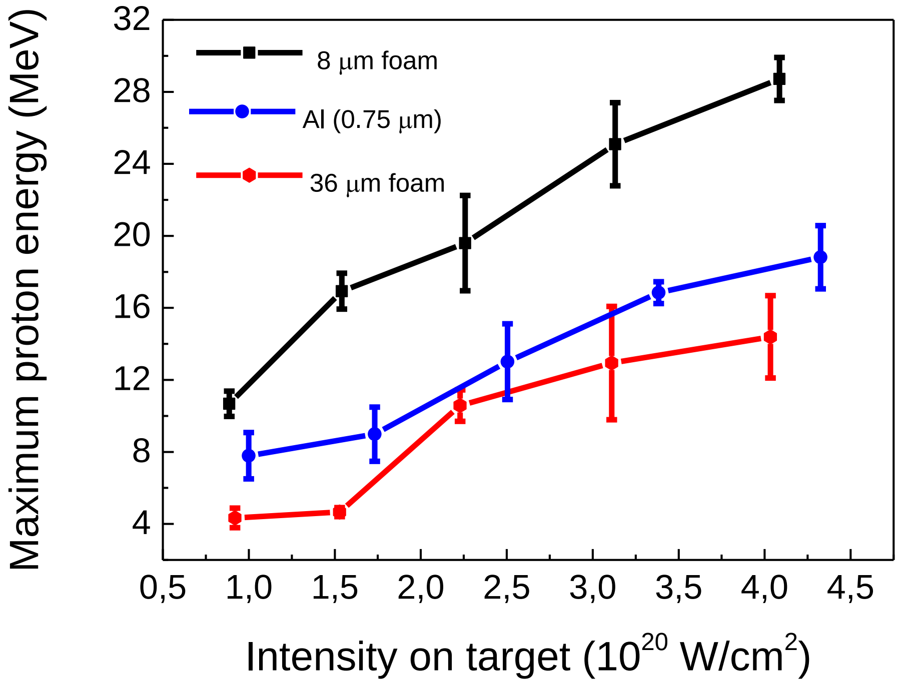
Enhanced TNSA

- Higher laser energy absorption
- Enhanced electron production
- Enhanced number and maximum energy of accelerated ions

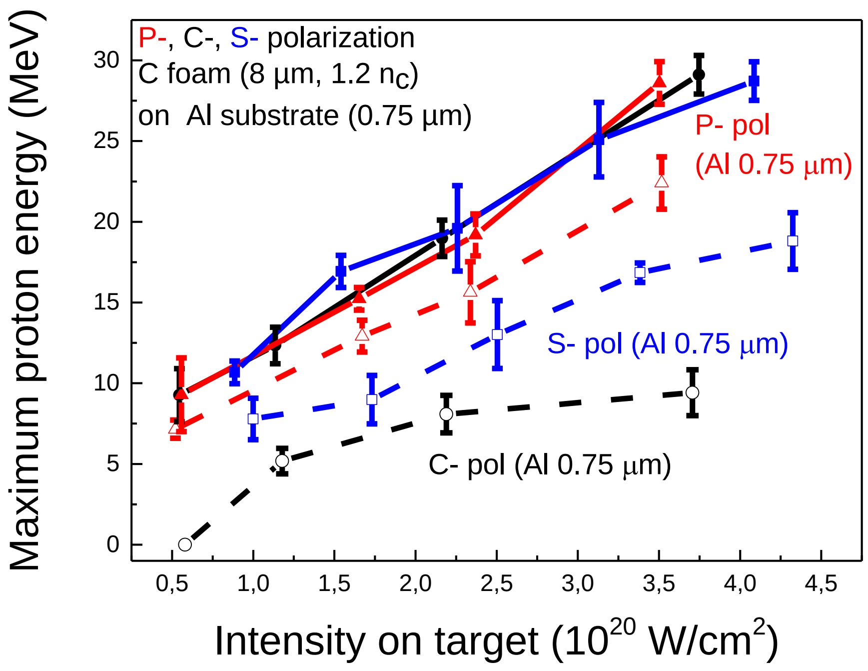
T. Nakamura *et al.*, Phys. Plasmas, 17 113107 (2010)
A. Sgattoni *et al.*, Phys. Rev. E, 85 036405 (2012)

Experimental results

Role of Foam thickness (p-pol.)



Role of laser polarization



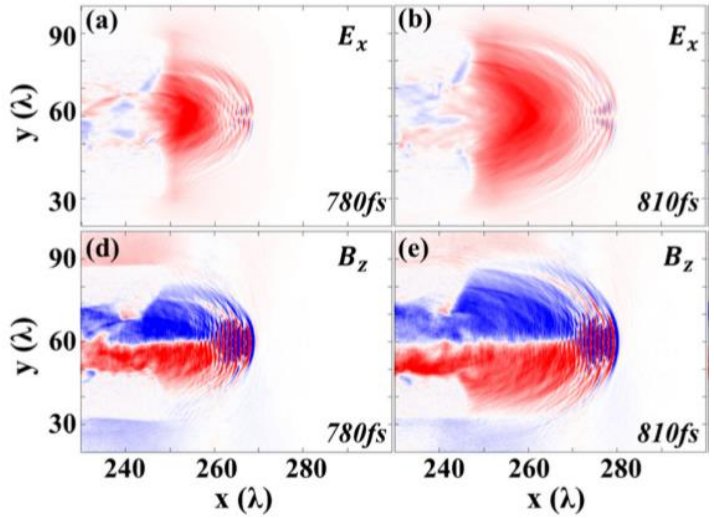
- Higher energies
- More Ions (>50%)

- $E_{max} \propto I$
- Foam targets: no pol dependence
- Best coupling with 8 μm foam

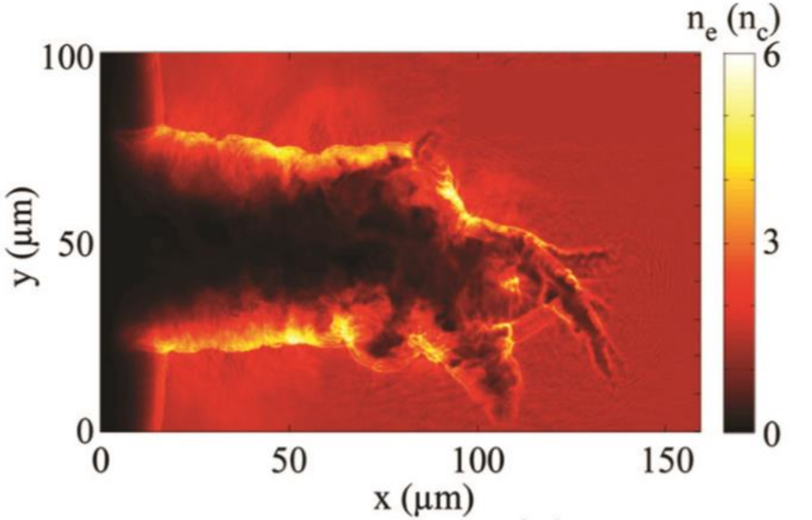
Electron heating in near critical plasmas

Richer physics

- Magnetic dipole generation
- Self focussing
- Filamentations
- Two stream instabilities



Y. J. Gu, et al.; Physics Of Plasmas 21, 063104 (2014)



L. Willingale et al; Physics of Plasmas 18, 056706 (2011)

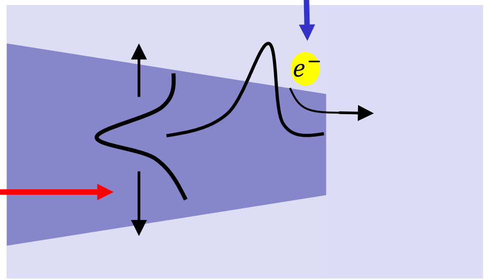
Simplified physical picture:

- Pulse erosion $T_e \sim I$

$p \sim p_{//} \, \alpha \, a_0^2$

- Ponderomotive expulsion $T_e \sim I^{1/2}$

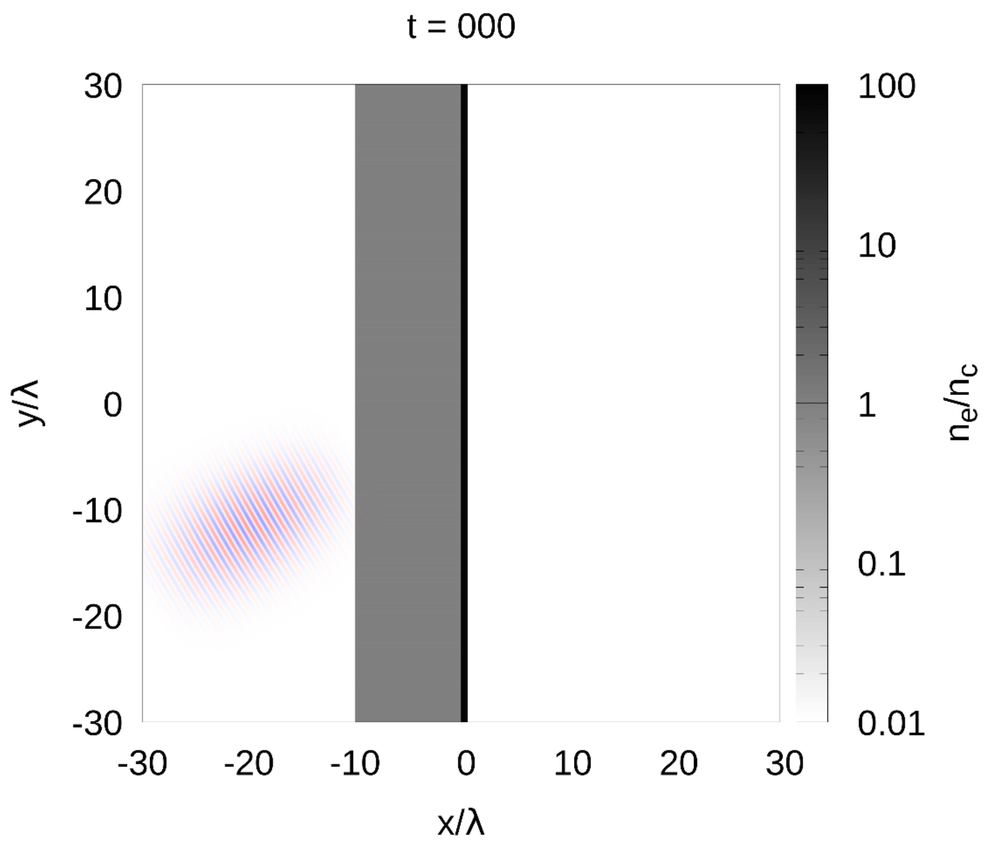
$p \sim p_{\perp} \, \alpha \, a_0$



A P L Robinson et al; Plasma Phys. Control. Fusion 53 (2011) 065019

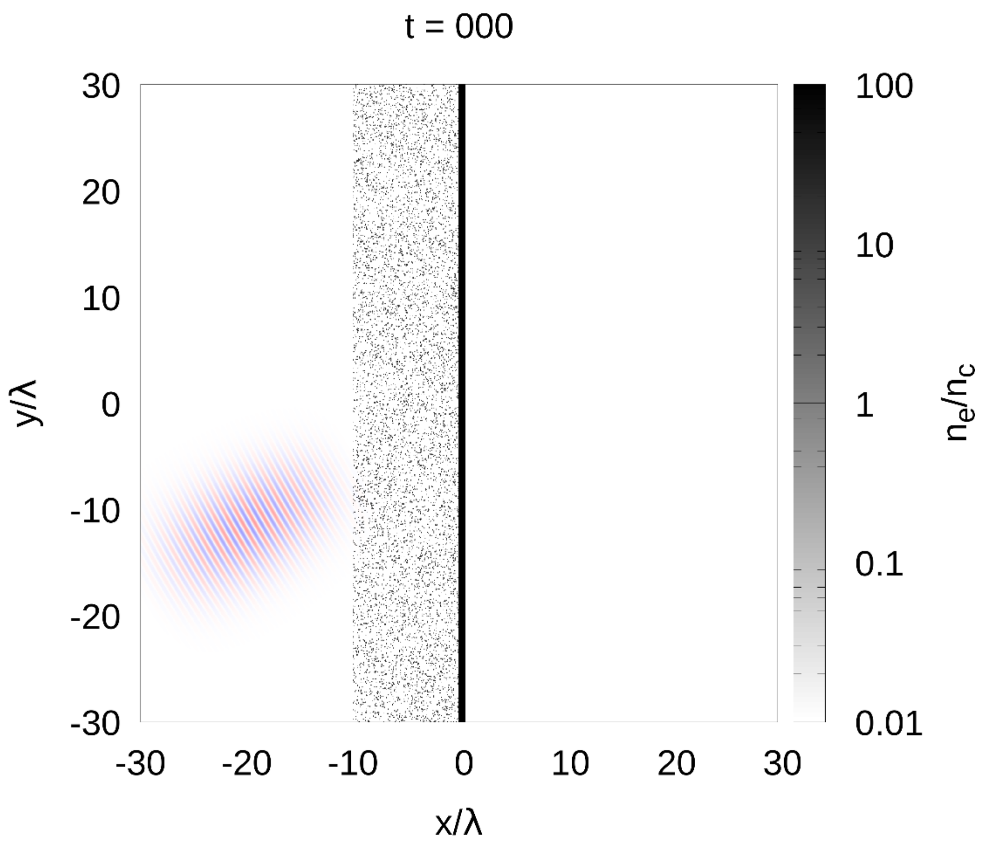
Interaction with foam attached targets

Homogeneous foam



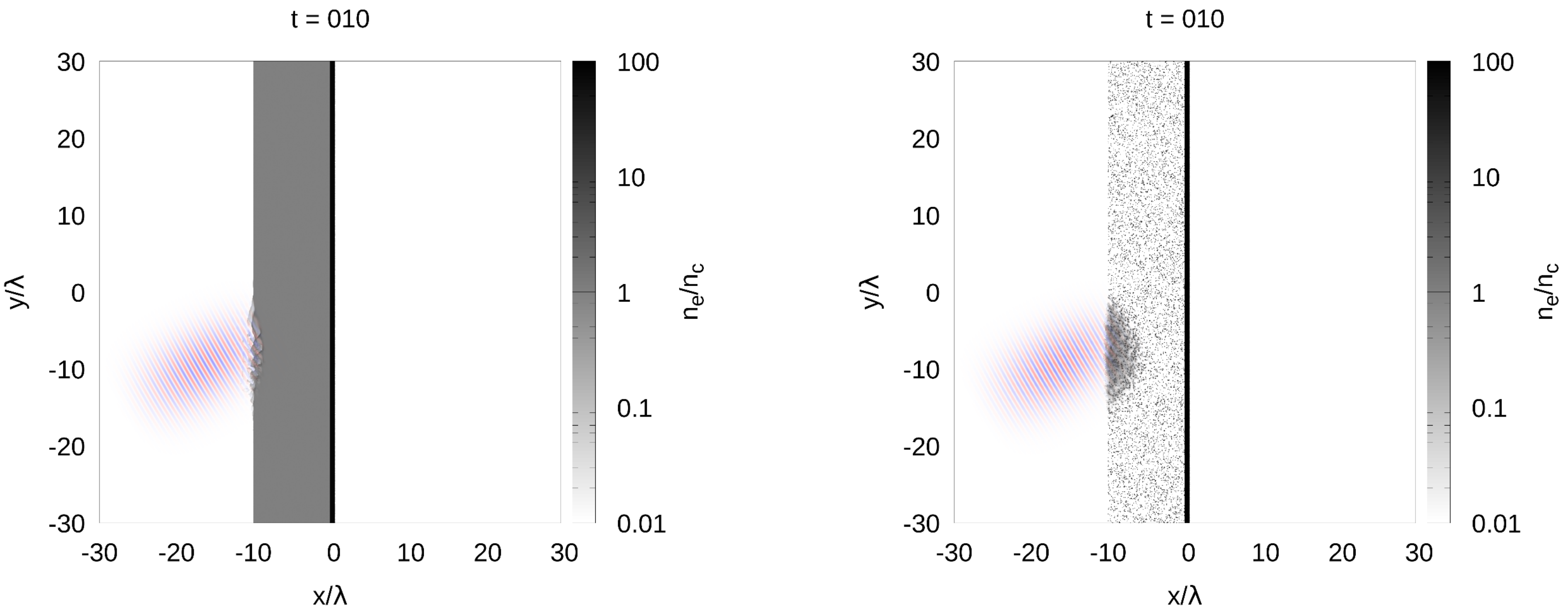
Homogeneous foam
$n_e = n_c$

Nanostructured foam



Random spheres
$R_s = 10\ nm\ n_e = 100\ n_c$
Average density: n_e=n_c

Interaction with foam attached targets



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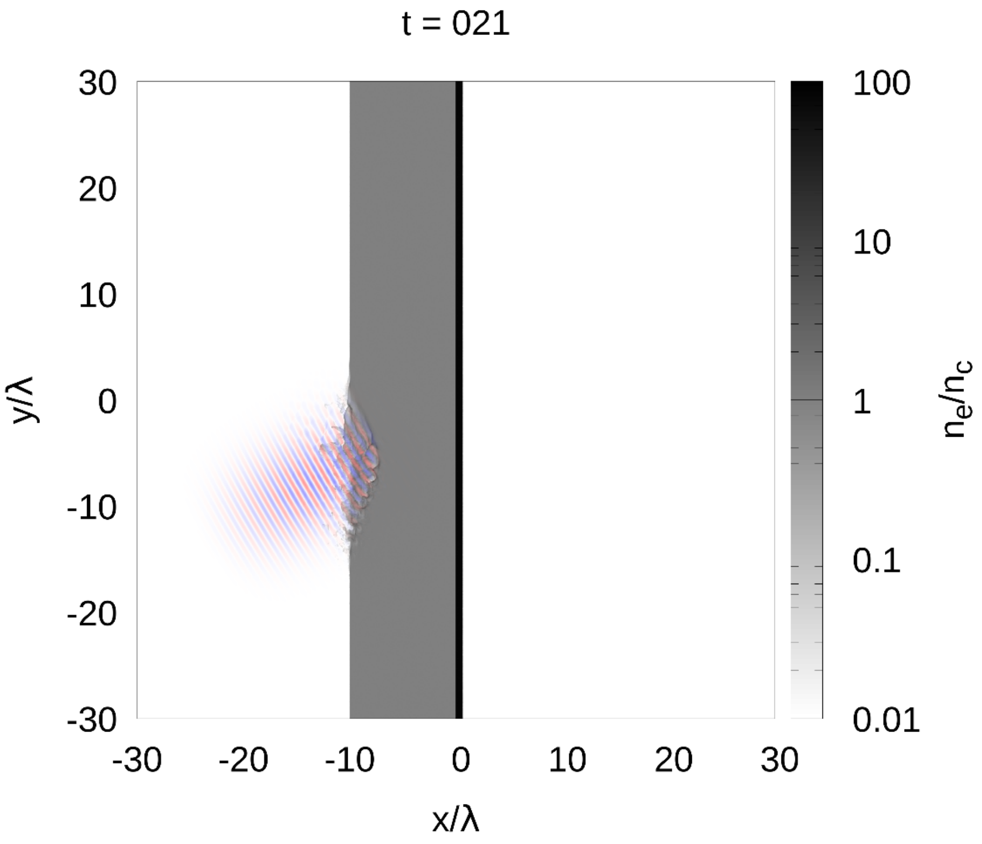

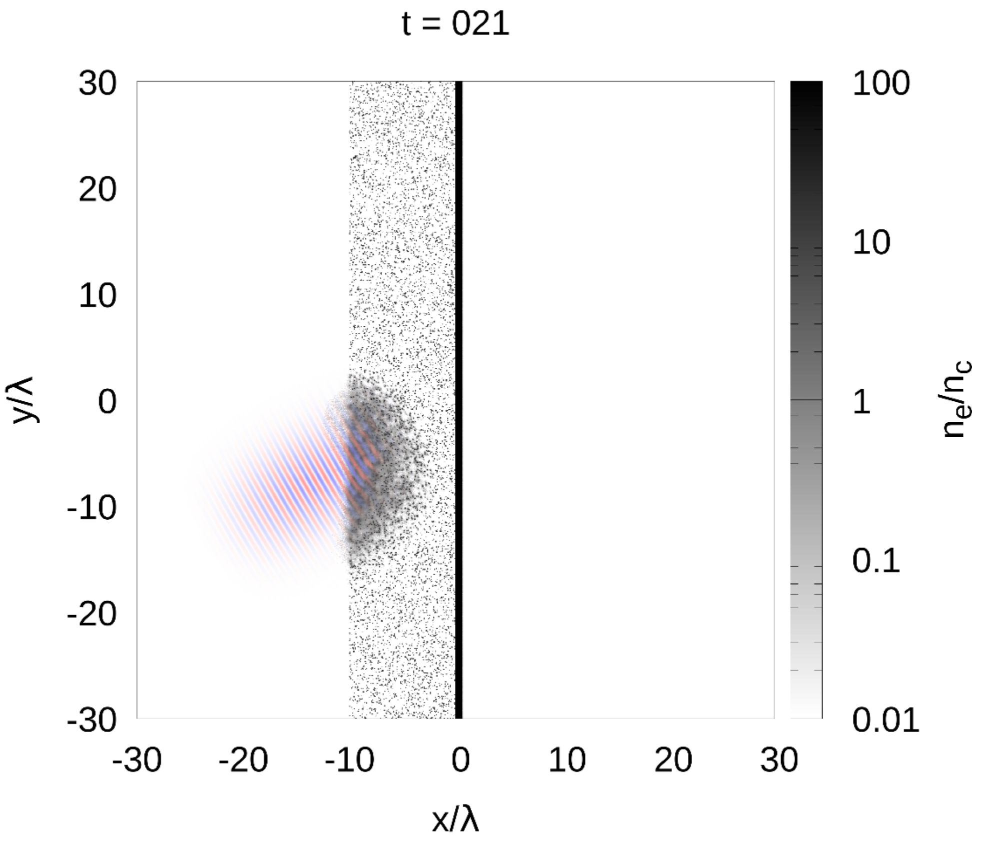

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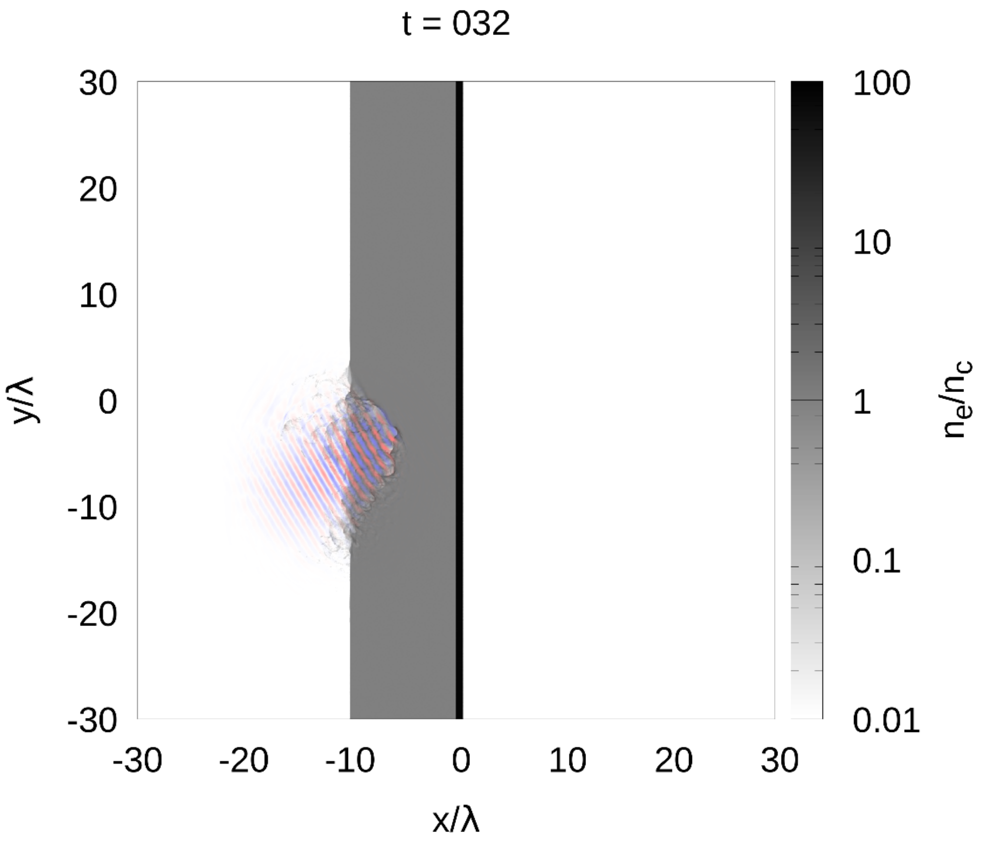

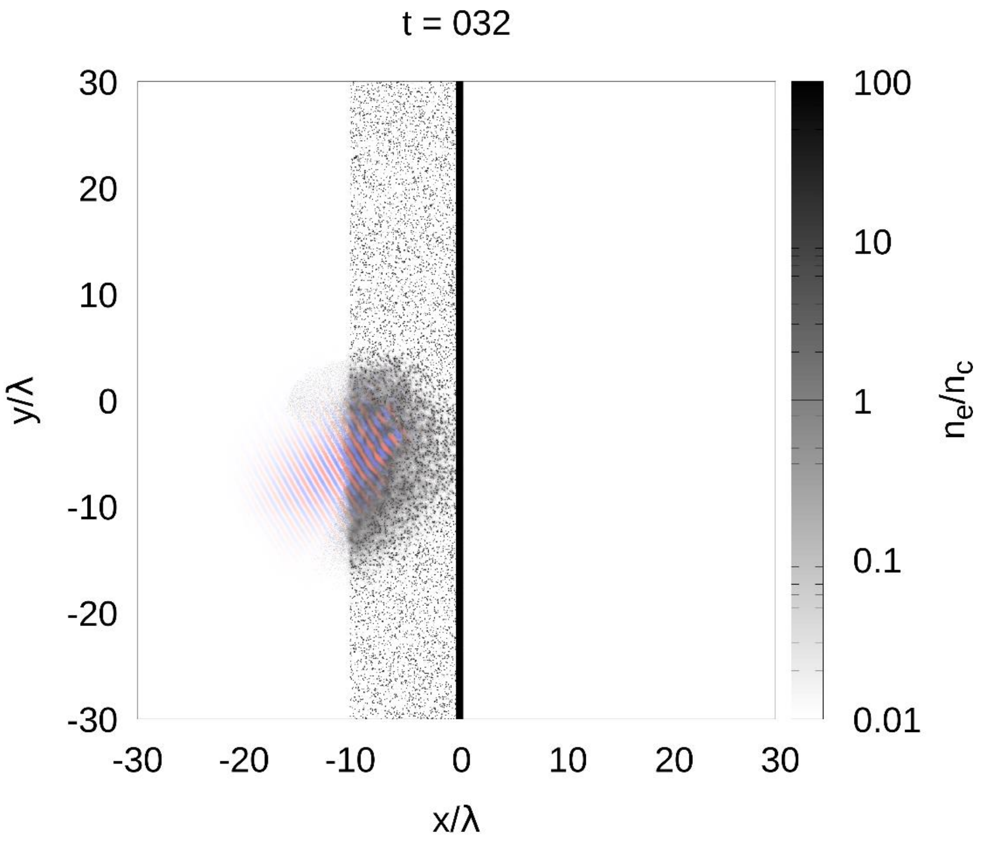

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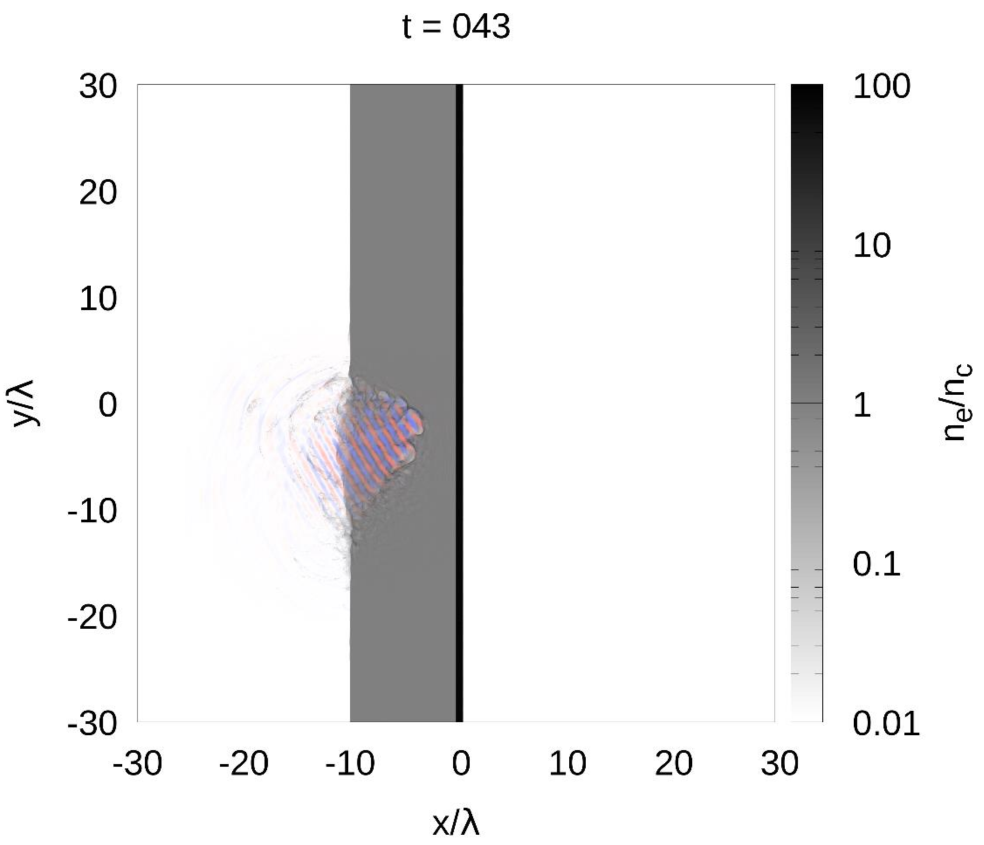

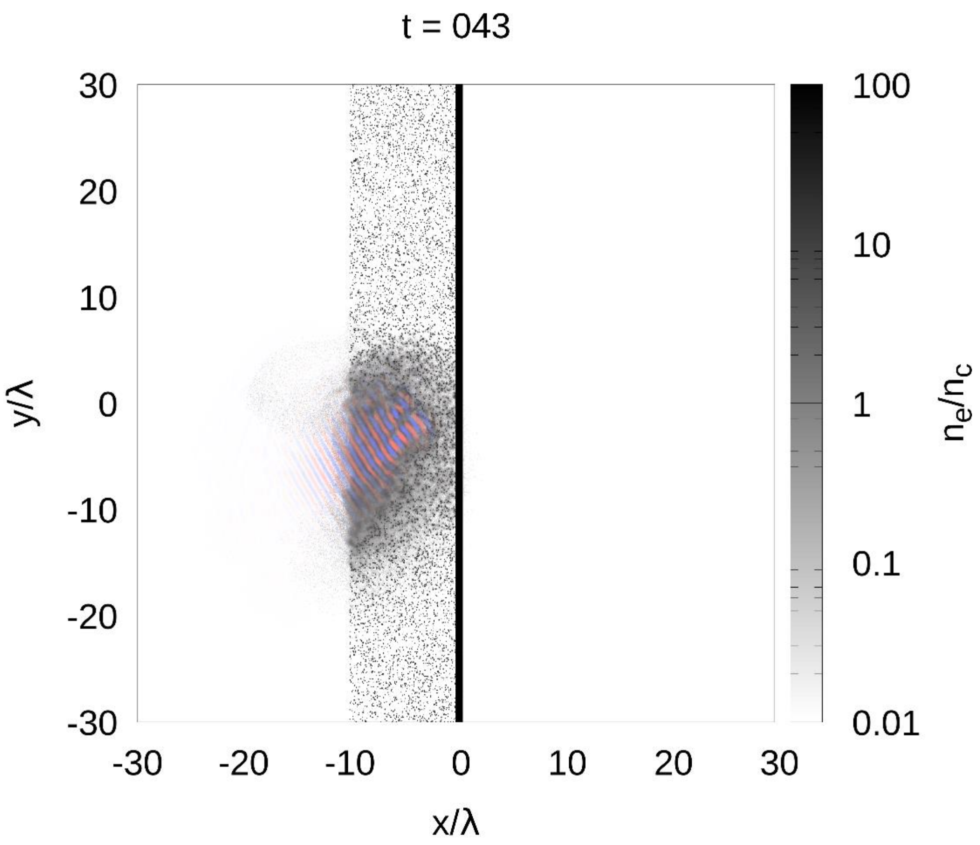

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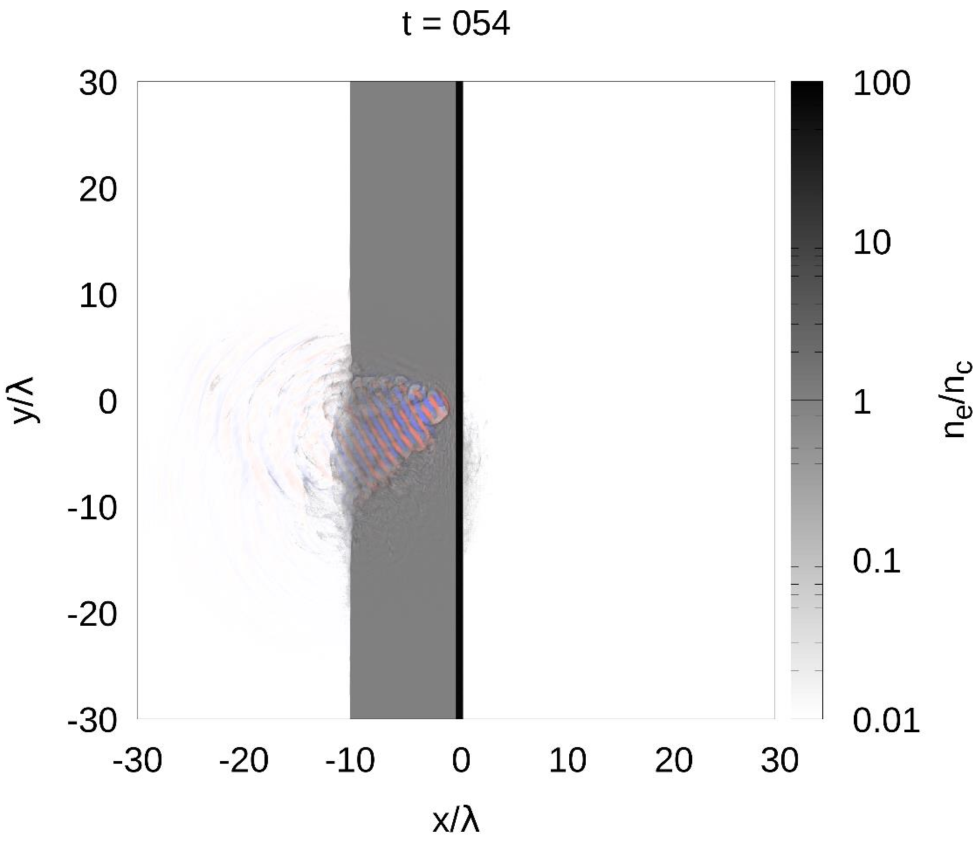

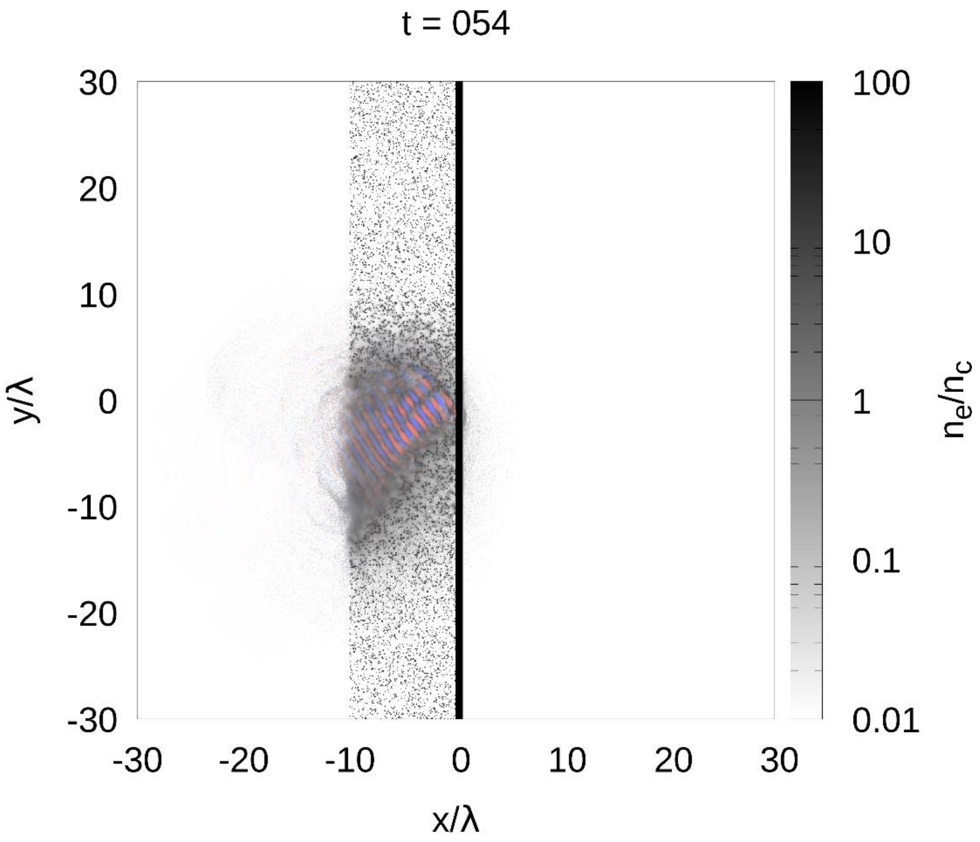

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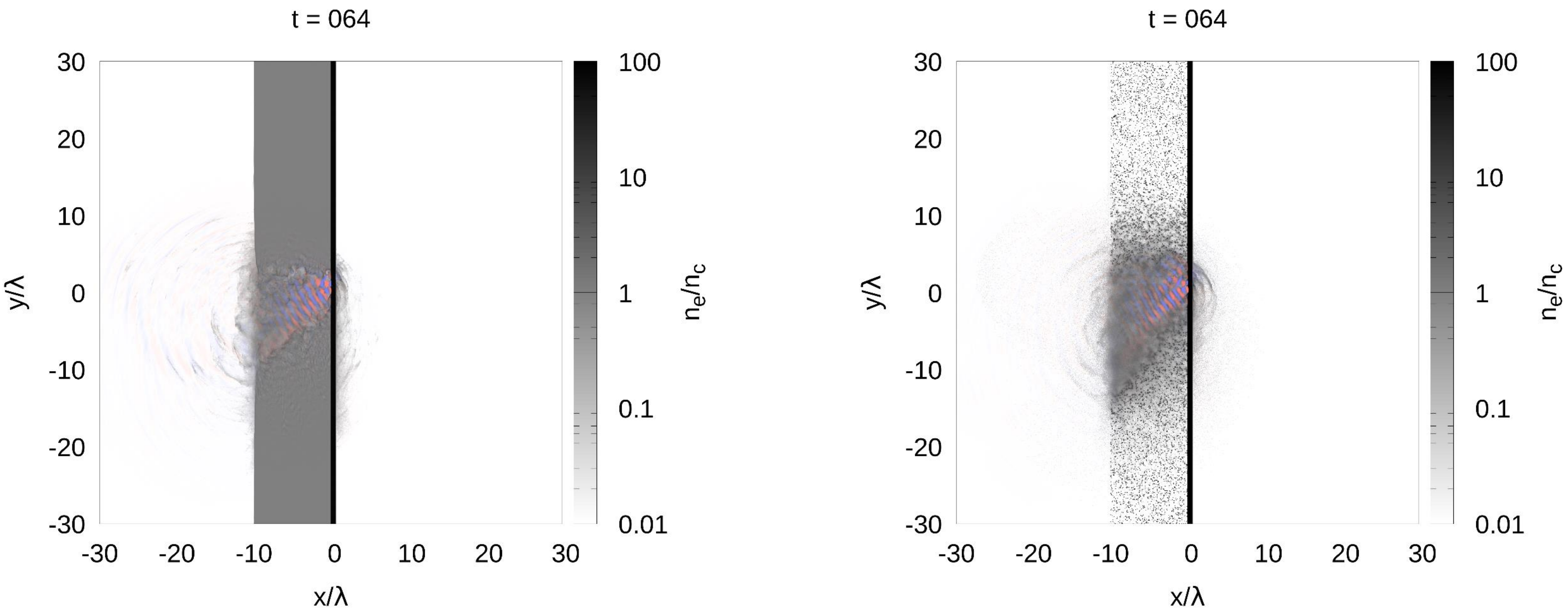
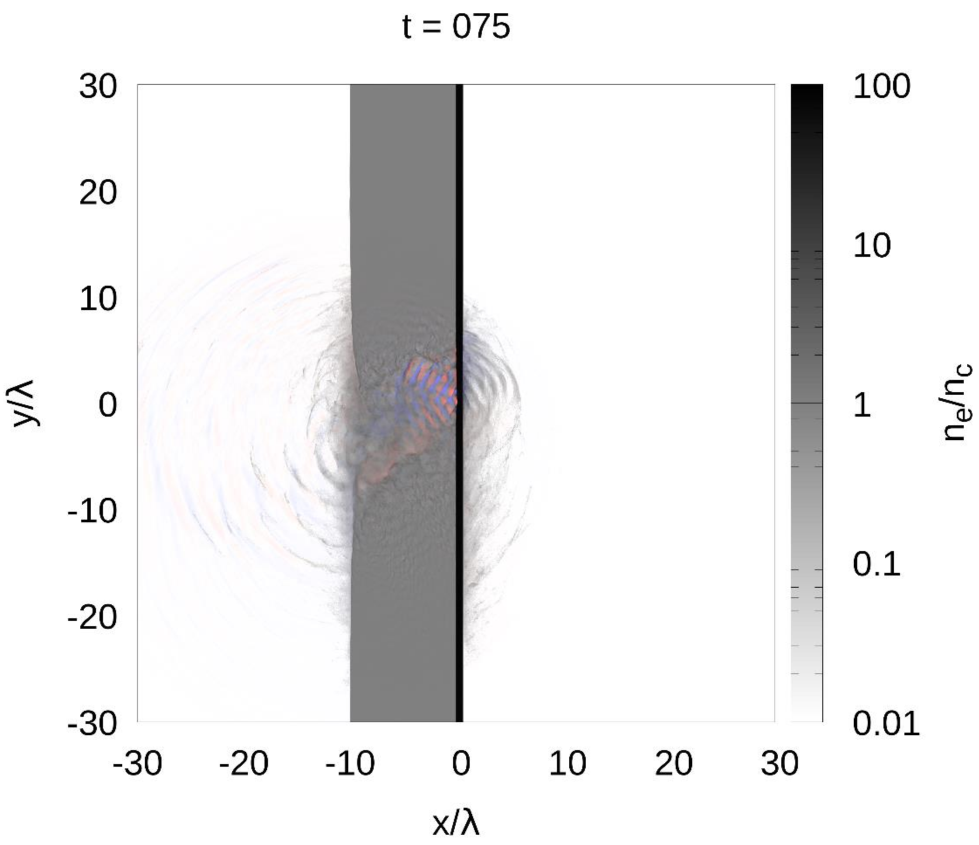
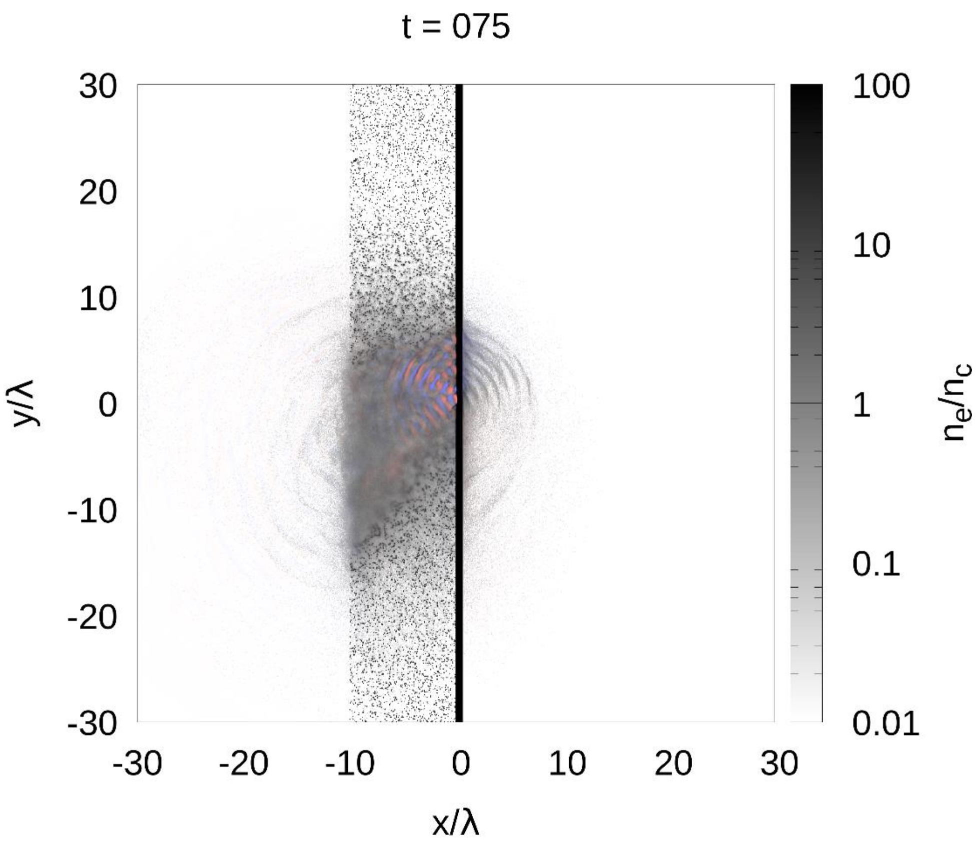
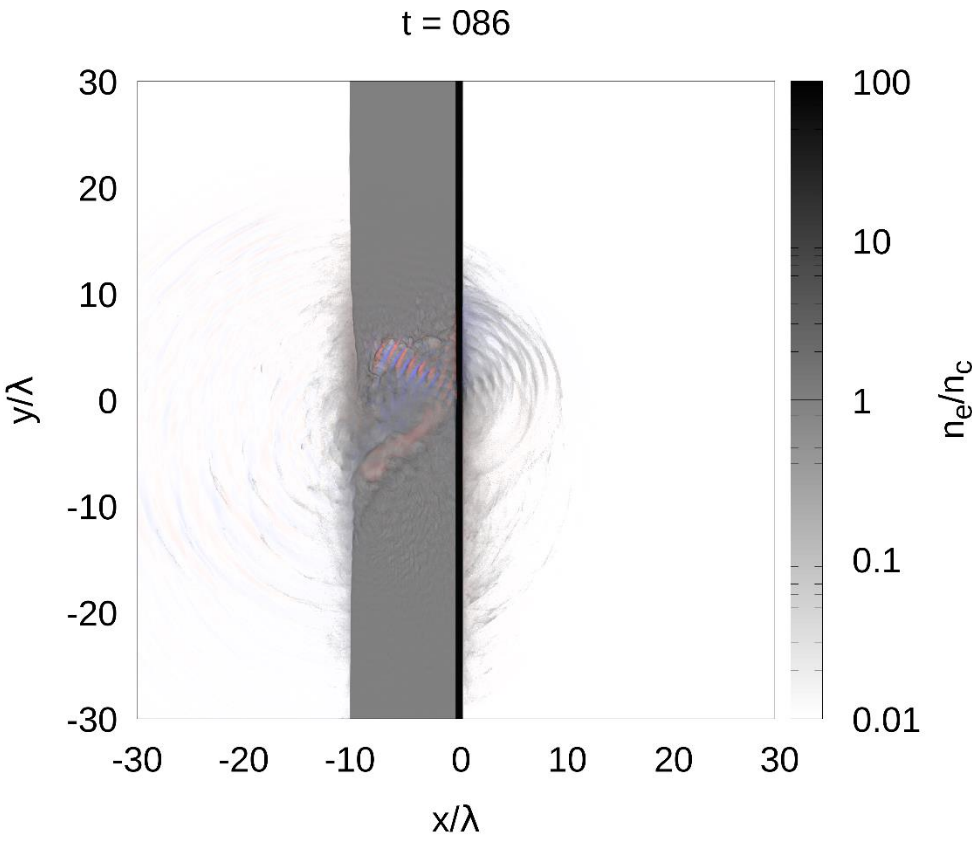


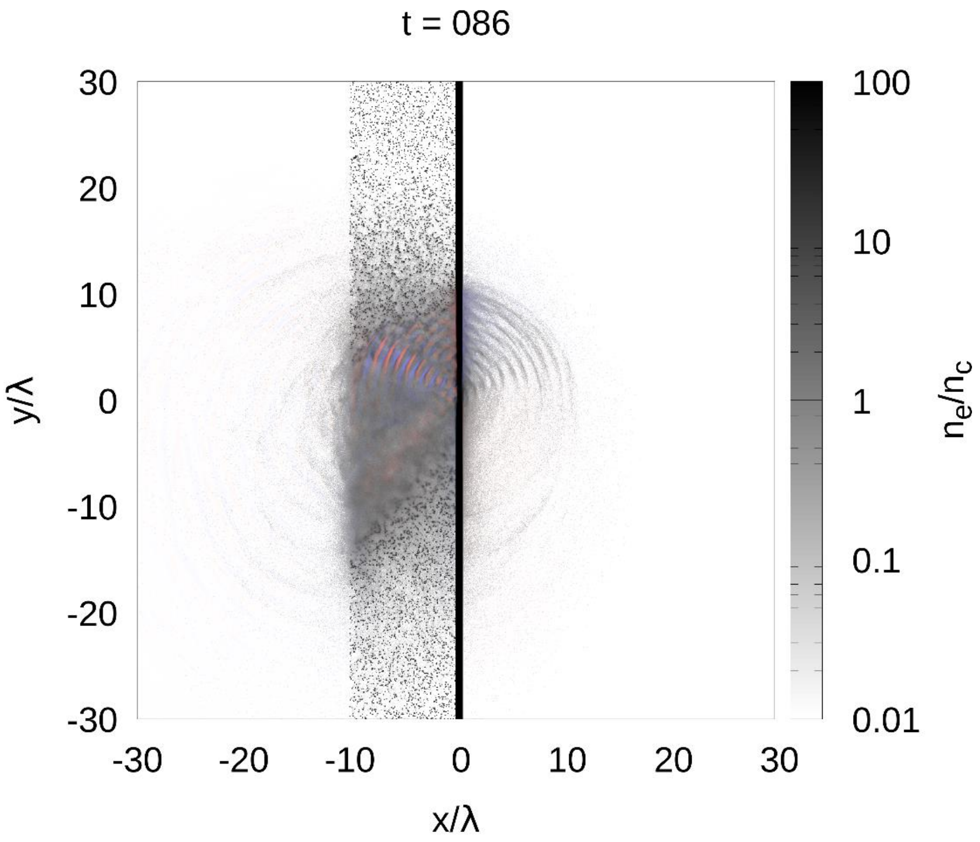
Interaction with foam attached targets



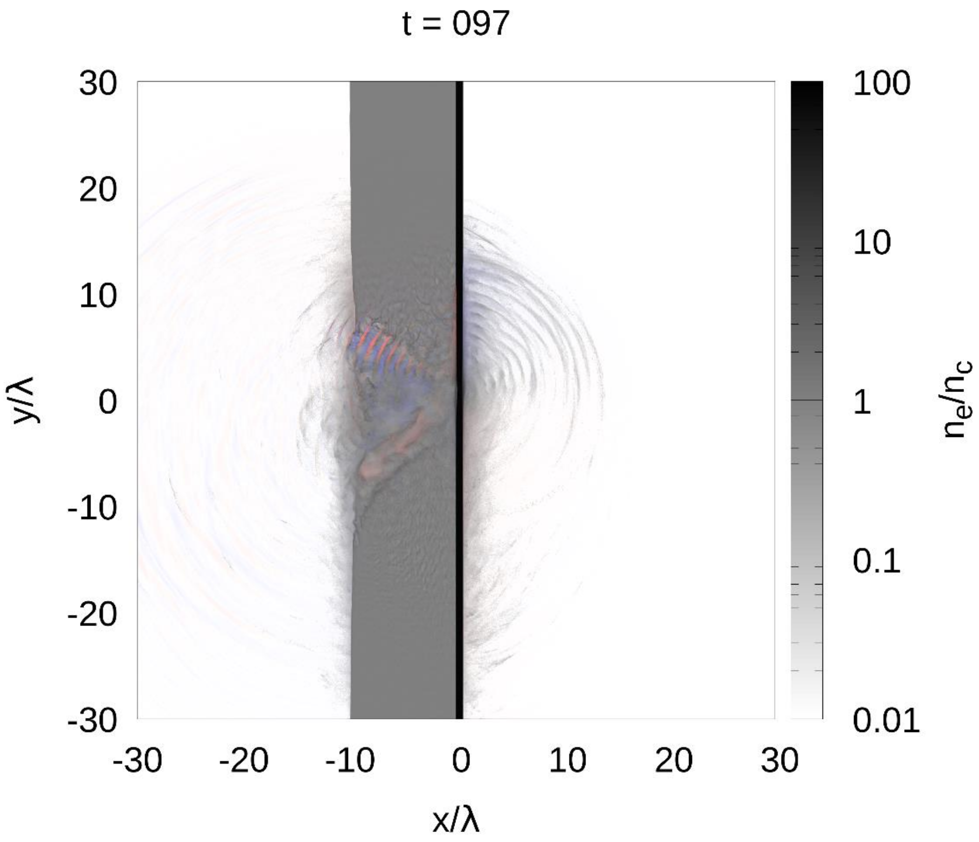


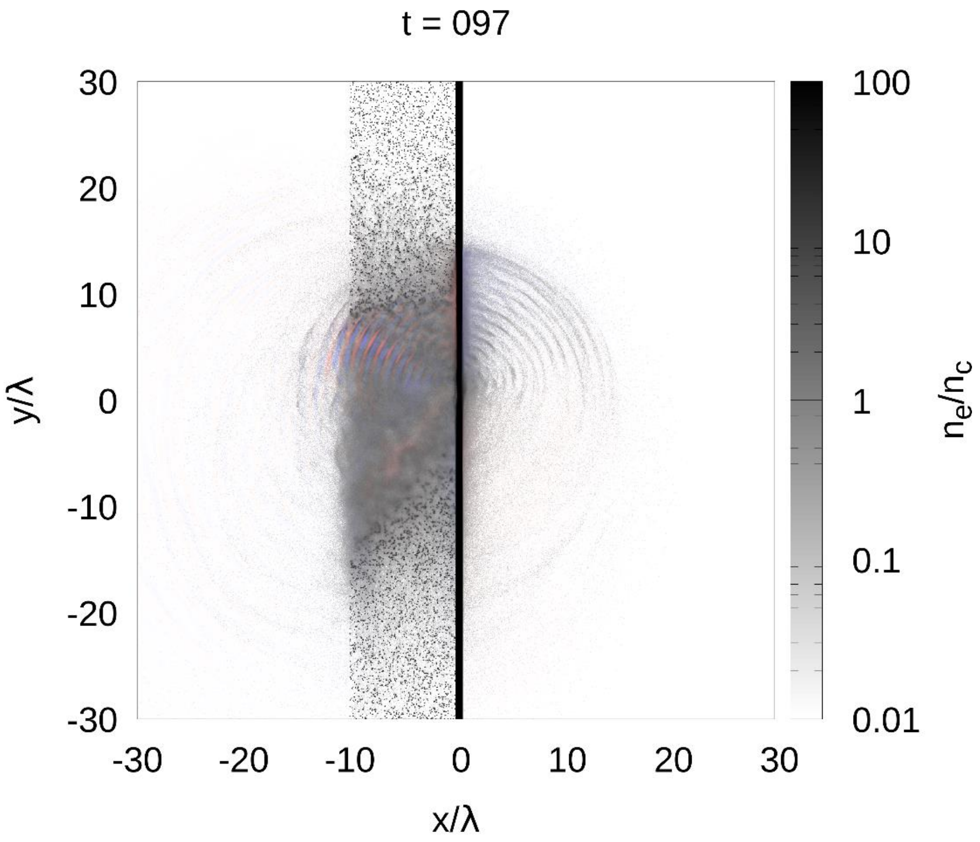
Interaction with foam attached targets



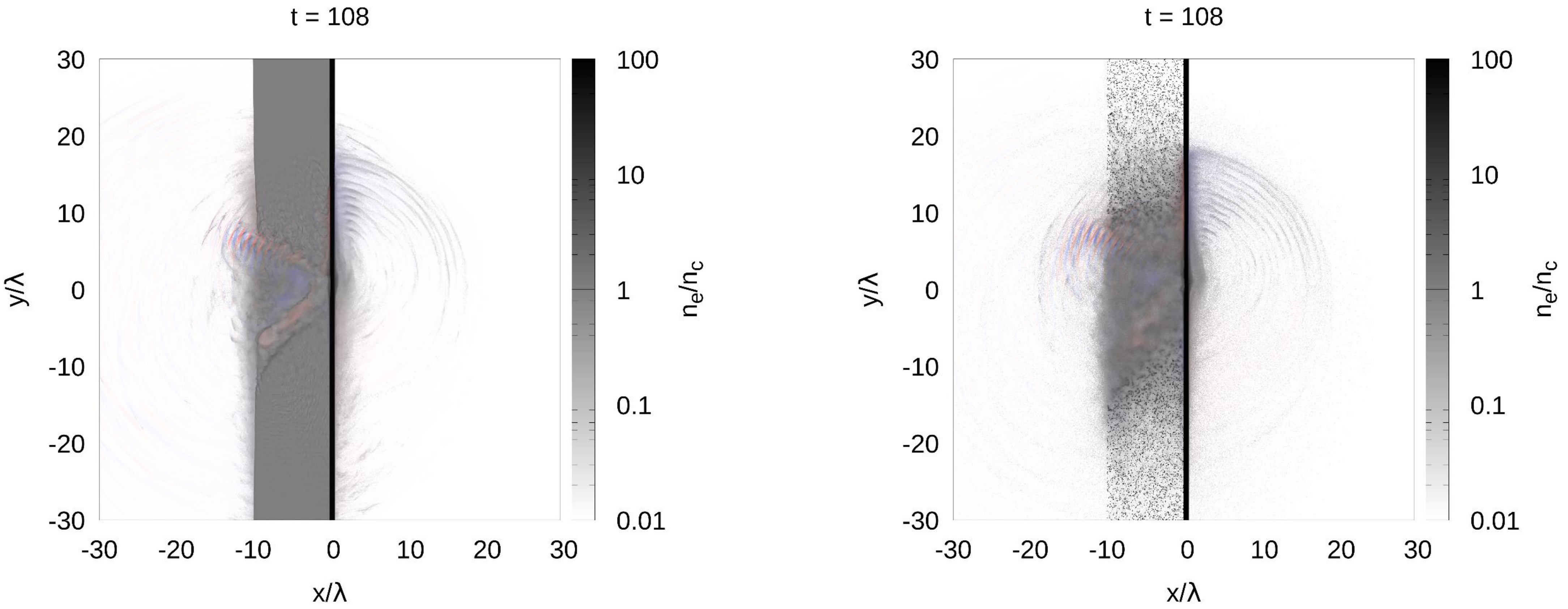


Interaction with foam attached targets

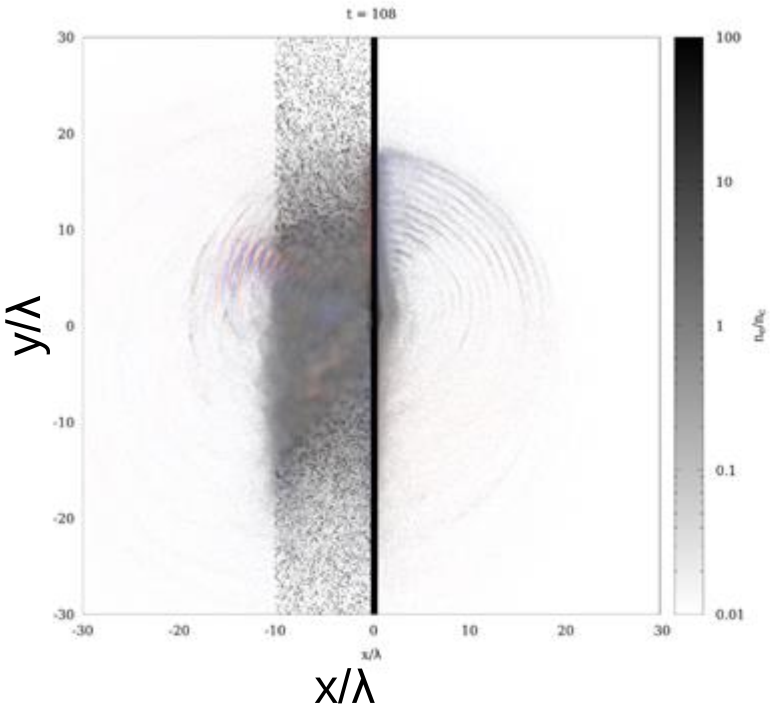


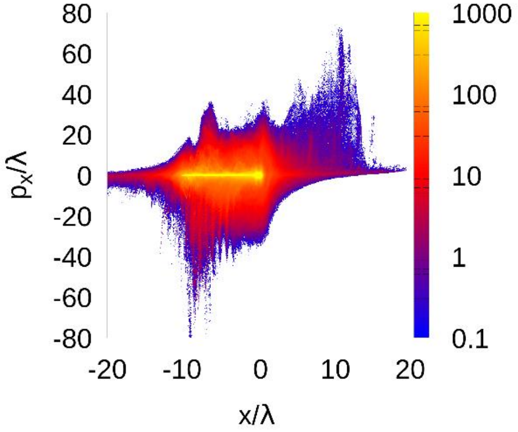


Interaction with foam attached targets



Electron heating in foam attached targets

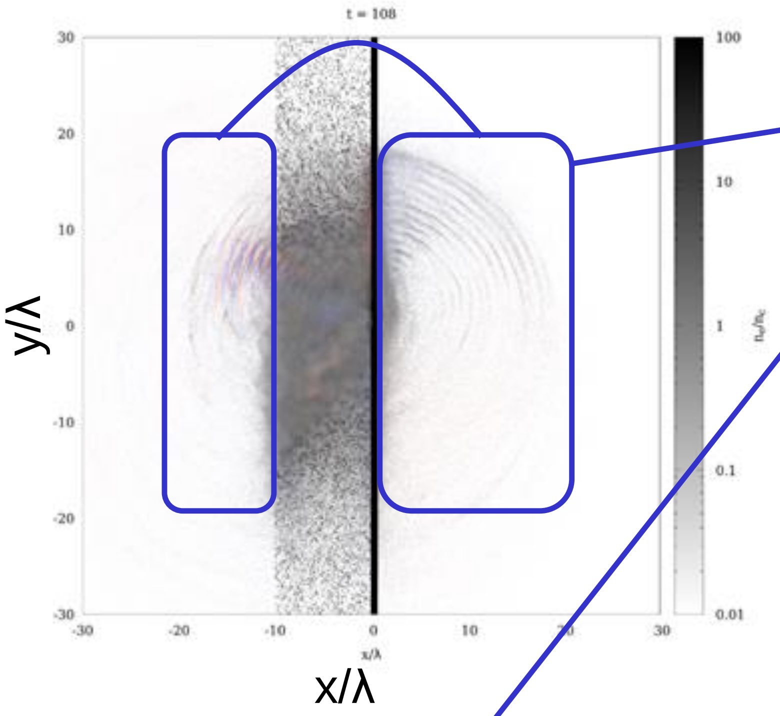


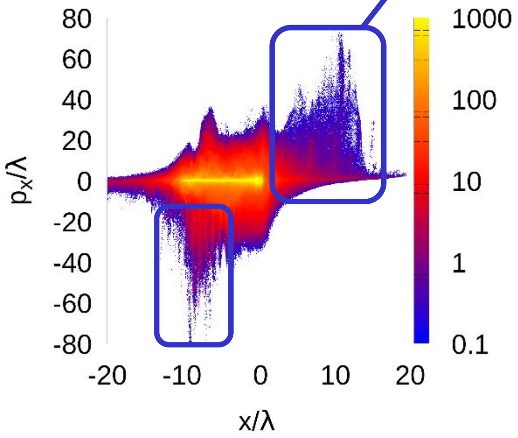


Two populations:

- Fast escaping electrons
- Confined electrons

Electron heating in foam attached targets





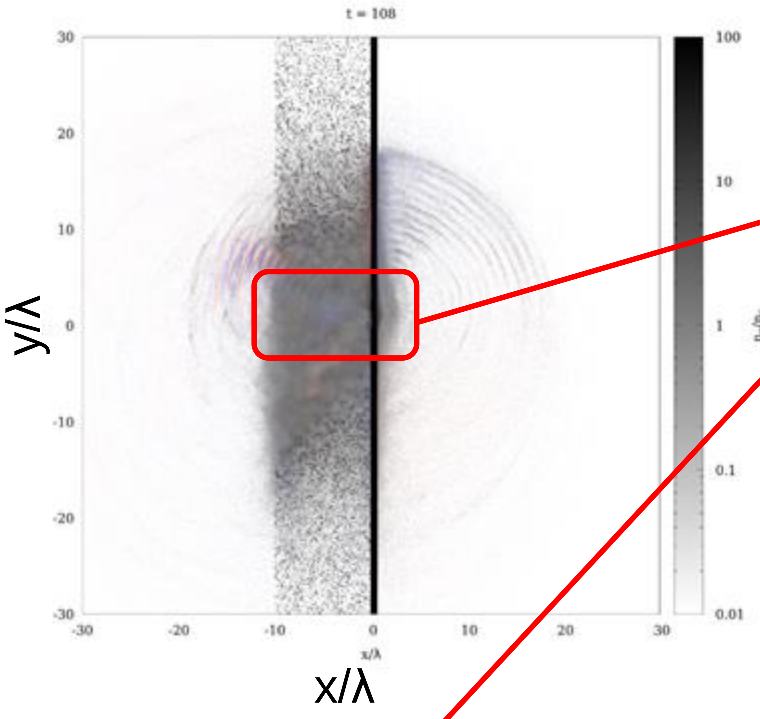
Two populations:

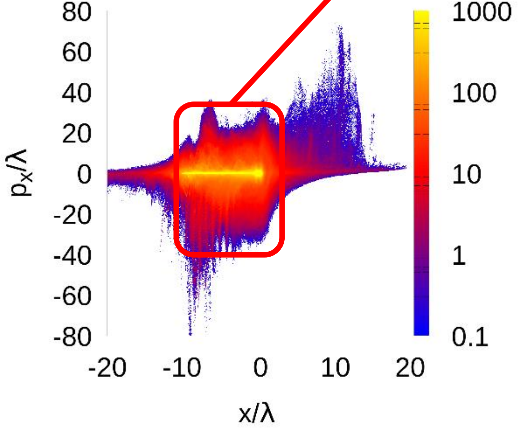
- Fast escaping electrons
- Confined electrons

Fast electrons

- Prompt escape (t < 100fs)
- p_{max} α a_0^2

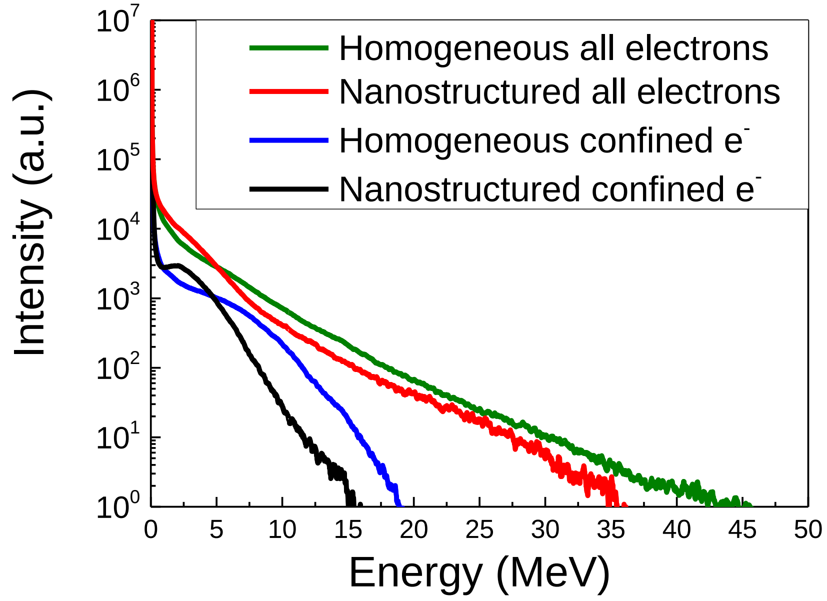
Electron heating in foam attached targets





Two populations:

- Fast escaping electrons
- Confined electrons



Confined electrons:

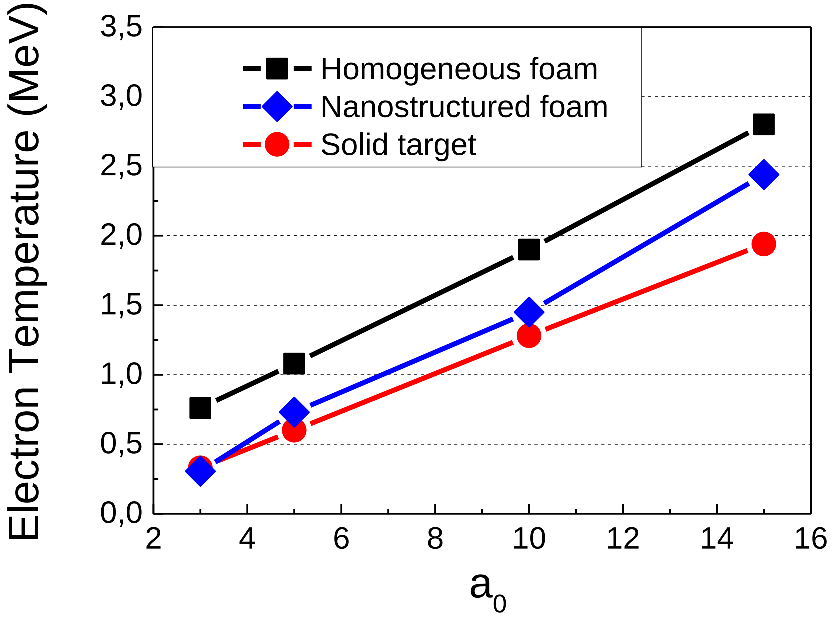
- More energetic than solid foil e^-
- Spectrum dependant to the nanostructure
- Long confinement time (> 100 fs)

Hp: **confined** electrons → enhanched TNSA

Temperature scaling and benchmark

Hp: ponderomotive heated confined electrons

$$T_e = C_3 T_{pond} + C_4$$

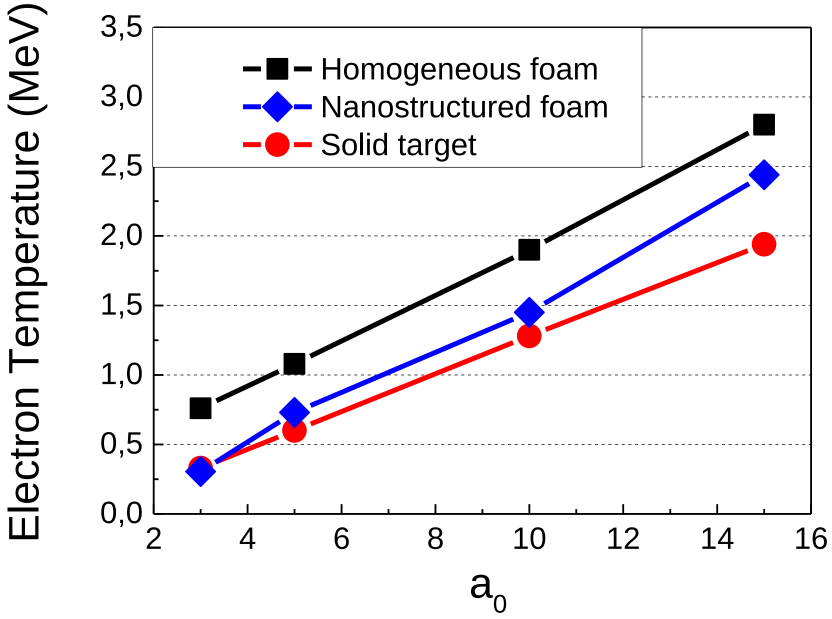


- Electron heating dependant to the target nanostructure
- Nanostructure → lower electron temperature

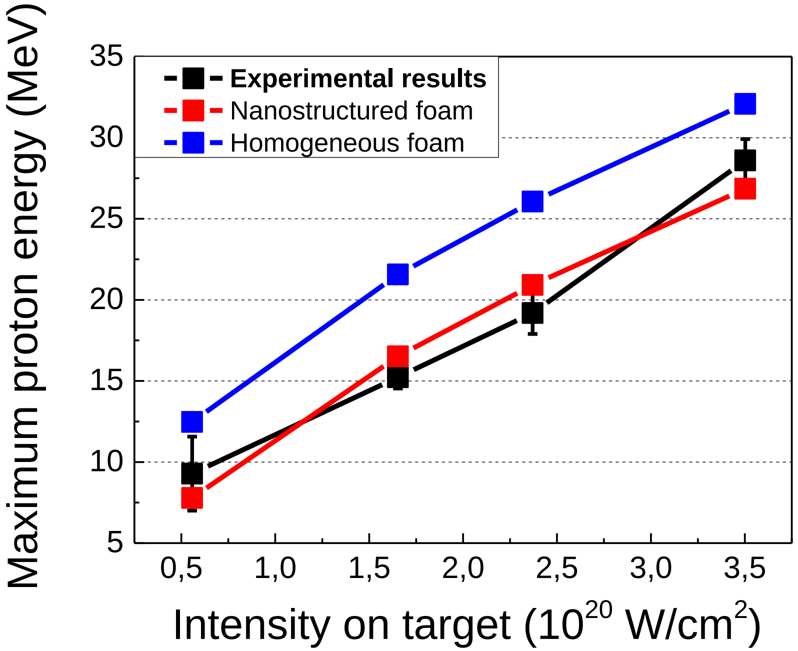
Temperature scaling and benchmark

Hp: ponderomotive heated confined electrons

$$T_e = C_3 T_{pond} + C_4$$



Experimental results and benchmarks



- Electron heating dependant to the target nanostructure
- Nanostructure → lower electron temperature

Conclusion and future perspectives

Interaction with over-dense plasma:

- Brunel effect and jxB heating → combined heating
- Ponderomotive scaling over-estimates electron temperture in this regime
- Very good agreement with TNSA experiments

Interaction with near-critical plasma:

- Production of fast-escaping and confined electrons
- TNSA should be due to the confined electrons
- Nanostructure is a key parameter in laser-matter interaction

Future prespectives:

I. Numerical 3D campaign with foam attached targets
II. More realistic nanostructure design
III. Theoretical model for ponderomotive heating in near critical targets

Pubblished works

Recent works

I. L Cialfi, L Fedeli and M Passoni, **Electron heating in sub-picosecond laser interaction with over-dense and near-critical plasmas**, submitted.

II. M Passoni, A Sgattoni, I Prencipe, et al., **Toward high-energy laserdriven ion beams: Nanostructured double-layer targets**, Physical Review Accelerators and Beams 19, 061301 (2016).

III. I Prencipe, A Sgattoni, M Passoni et al., **Development of foam-based layered targets for laser-driven ion beam production**, Plasma Physics and Controlled Fusion 58, 034019 (2016).

European Research Council

Thank you for your attention

Sub picosecond ultra-intense lasers

Laser parameters considered:
I > $10^{19}\ {}^{W}/_{cm^2}$
Pulse duration (FWHM) < 100 fs
Focal spot ~ µm
P > 100 TW
Pulse energy > J

Example: CoReLS, IBS (Gwangju, S. Korea)

Laser wavelenght: 800 nm (Ti:Sapphire)
$0.5\ \cdot 10^{20}\ {}^{W}/_{cm^2}$< I < $4.2 \cdot 10^{20}\ {}^{W}/_{cm^2}$
Pulse duration (FWHM) < 30 fs
Focal spot = 5 µm
1 < Energy on target > 7.5 J

I. **Matter ionization** → Laser- plasma interaction

II. **Critical density**

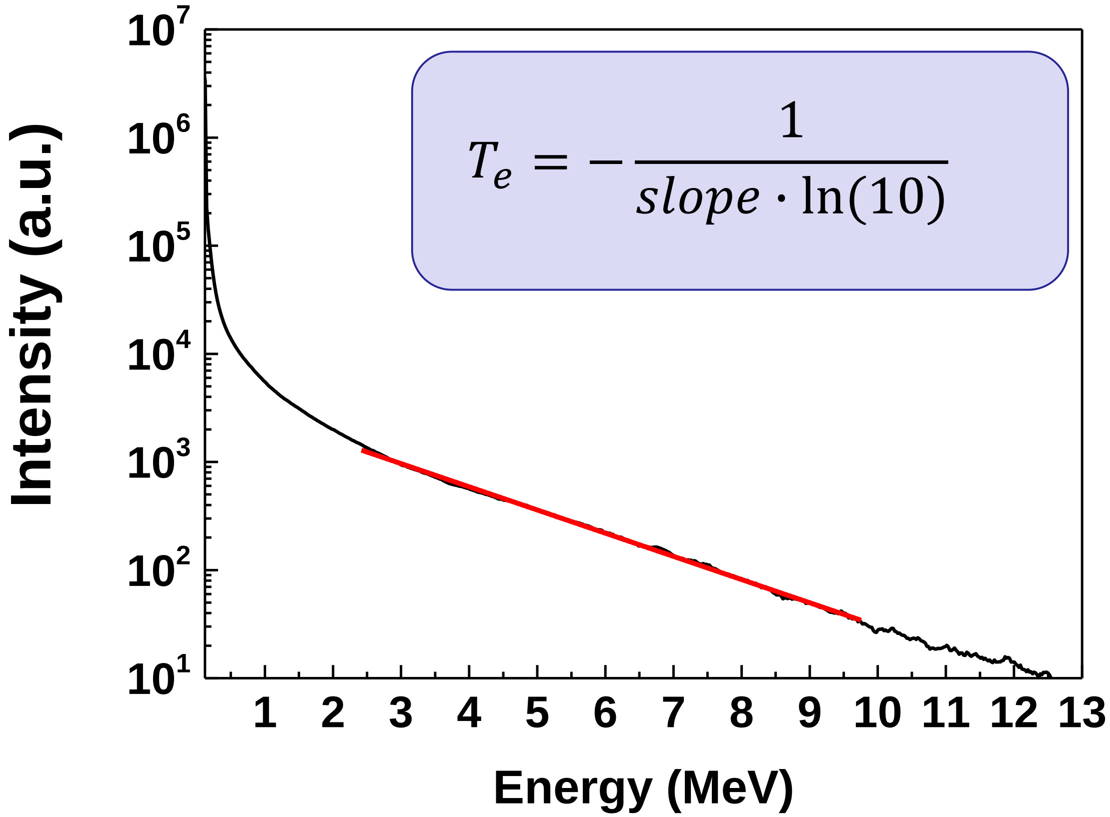
$n_c = \gamma \frac{m_e \omega^2}{4\pi e^2}$ for Ti:Saphire $n_c \sim {}^{mg}/_{cm^2}$
→ $\mathrm{n} > n_c$: Over dense plasma
→ $\mathrm{n} < n_c$: Under dense plasma

Relativistic transparency I↑→ n_c↓

III. **Skin depth**

$\lambda_{sd} = c\gamma/\omega_{pe} \quad (\sim 10 - 50\ \ nm)$

Electron temperature estimation

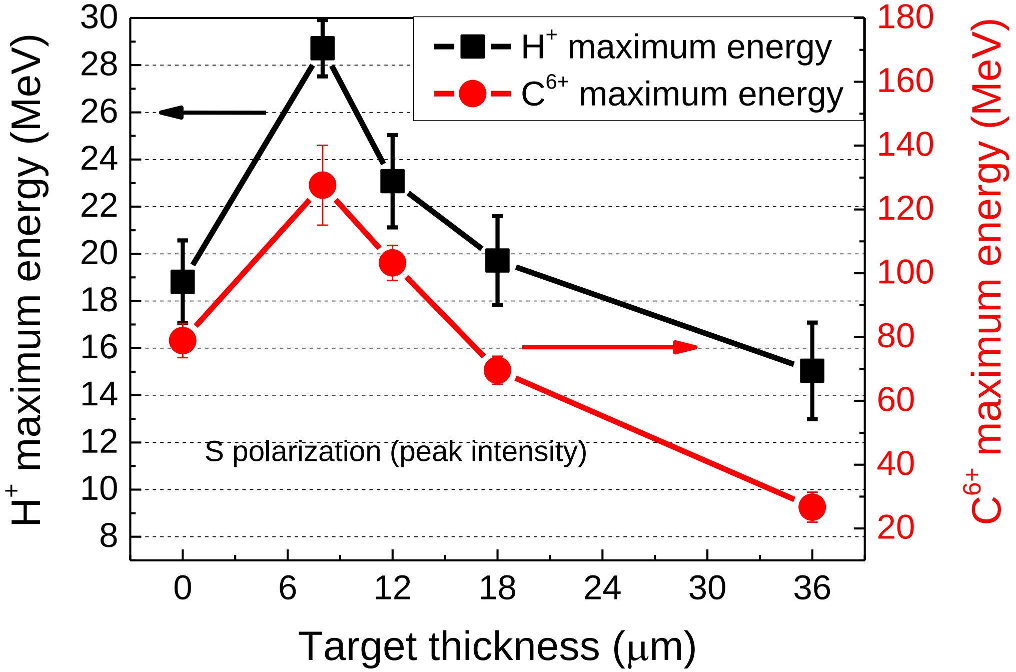


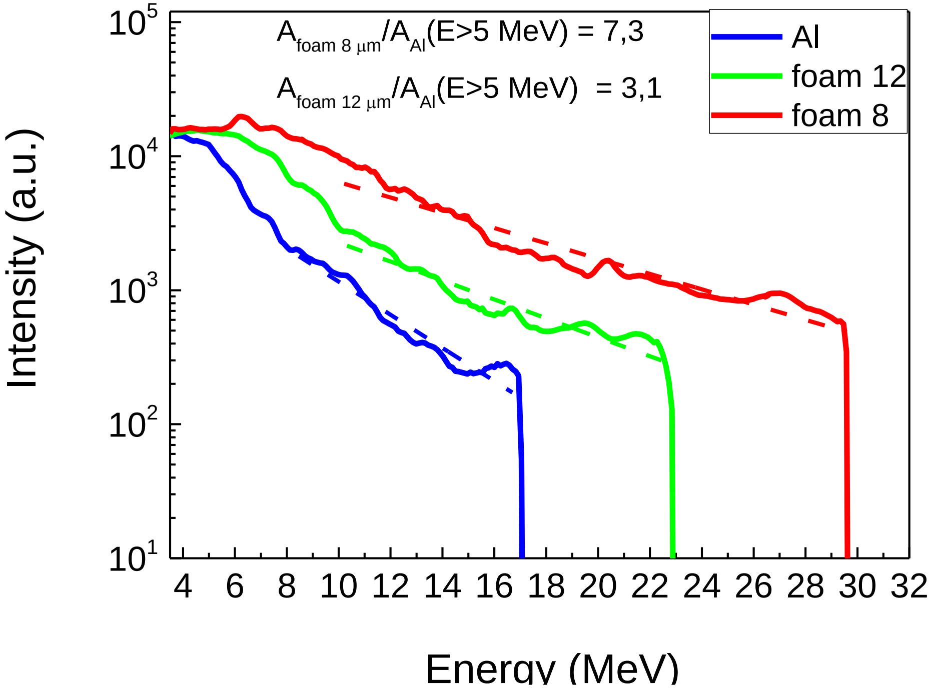
$$T_e = -\frac{1}{slope \cdot \ln(10)}$$

Acceleration experiment @ PULSER I GIST

Role of target properties (s-polarization, full power)

- **nearcritical foam thickness**: Al (0.75 µm) + foam (6.8 mg/cm³, **0-36 µm**)





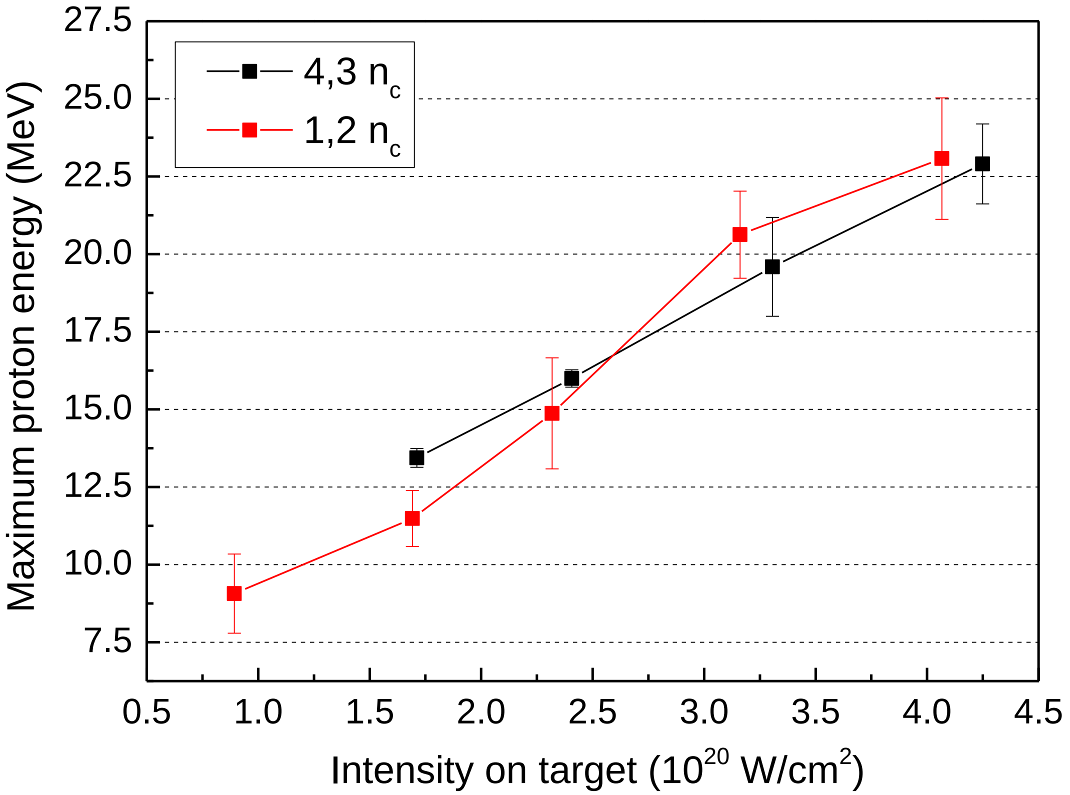
- ↑ E_{max} protons: 30 MeV
  [vs 18 MeV (s), 22 MeV (p)]
- ↑ E_{max} C^{6+}: 130-140 MeV
  [vs 80 MeV (s), --- MeV (p)]

- ↑ proton temperature 7.3 MeV
  (vs 3.5 MeV for Al)
- ↑ number of protons
  (gain factor 7.3 above 5 MeV (vs s))

Acceleration experiment @ PULSER I GIST

Role of target properties (s-polarization, full power)

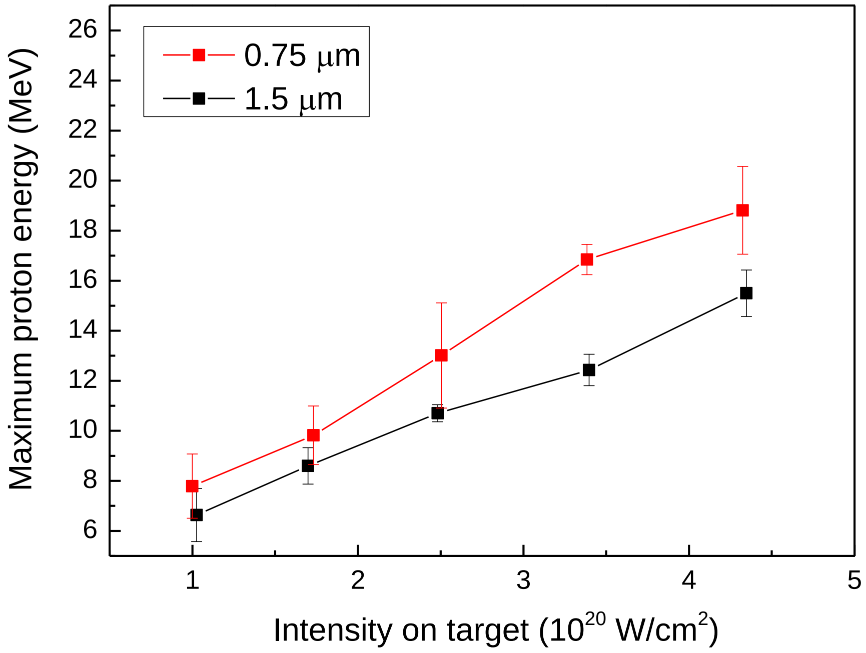
- **foam density**: Al (0.75 µm) + foam (**6.8 – 25 mg/cm³**, 12 µm)



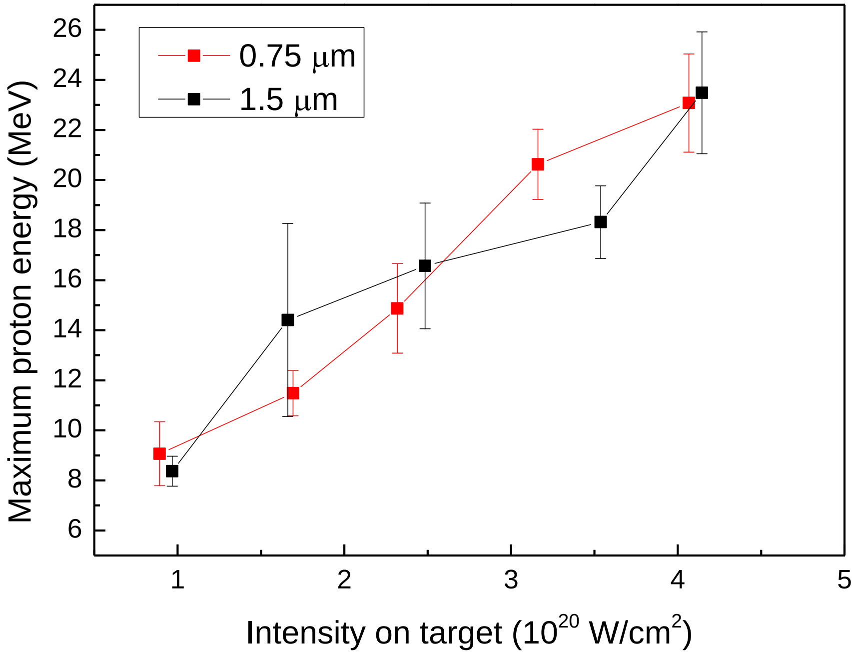
Acceleration experiment @ PULSER I GIST

Role of target properties (s-polarization, full power)

- **substrate thickness**: Al (**0.75 and 1.5 µm**) + foam (6.8 mg/cm^3, 12 µm)

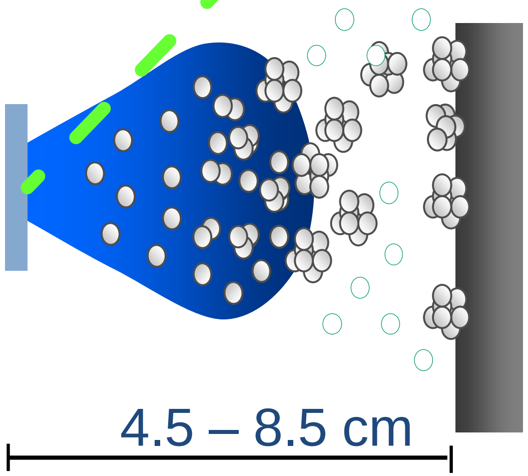


Bare Al targets



Foam-attached targets

Foam attached targets: production



BUFFER GAS
Ar/He 0-1000 Pa

LASER BEAM
532 nm 0.8 J cm^{-2}
5-7 ns 10 Hz

PYROLITIC GRAPHITE TARGET

SUBSTRATE
Si <100>
Al (0.7-12 µm)
C (3 nm)

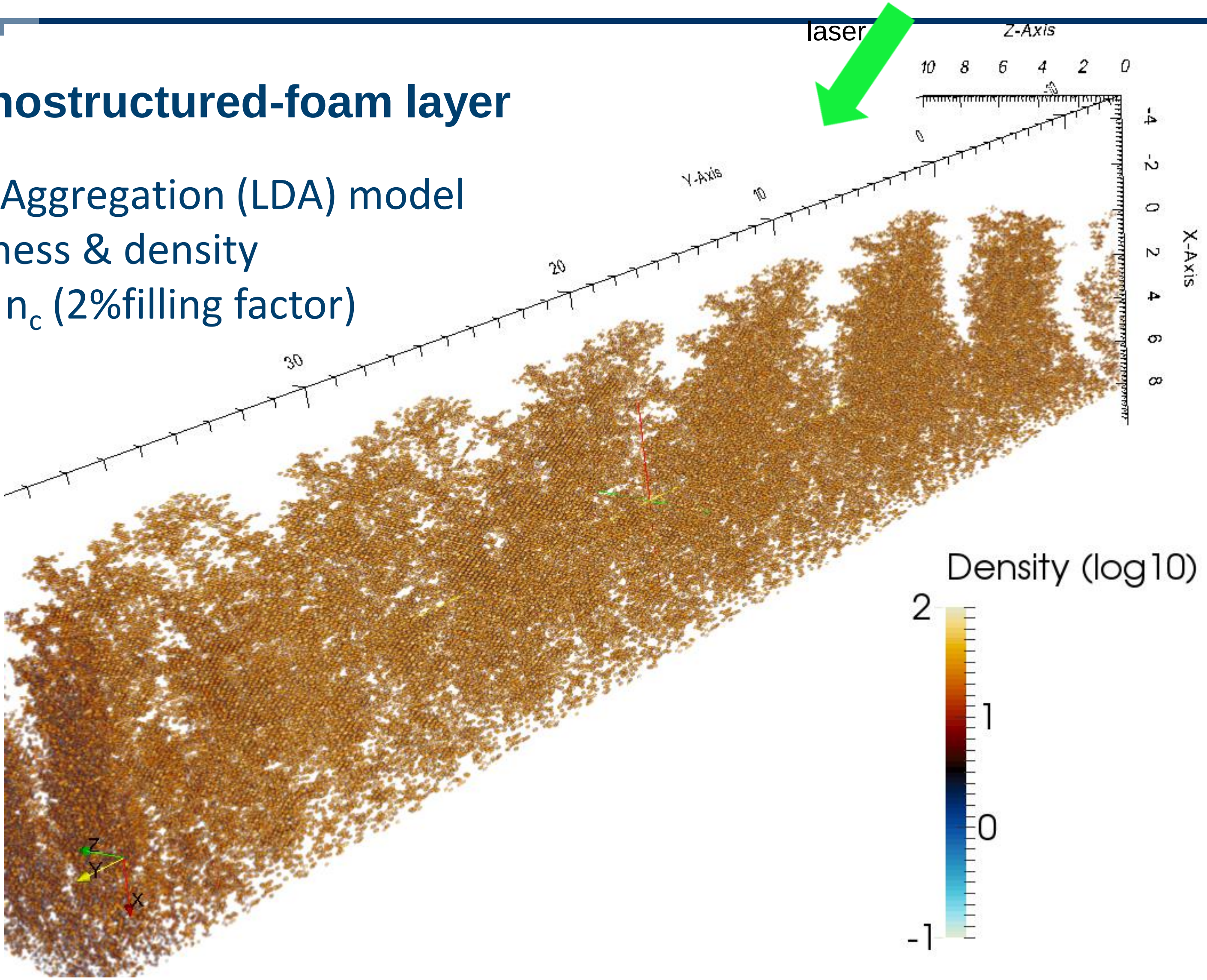
4.5 – 8.5 cm

A. Zani *et al.*, Carbon, **56** 358 (2013); I. Prencipe *et al.*, J. Phys. Conf. Ser., (2015)

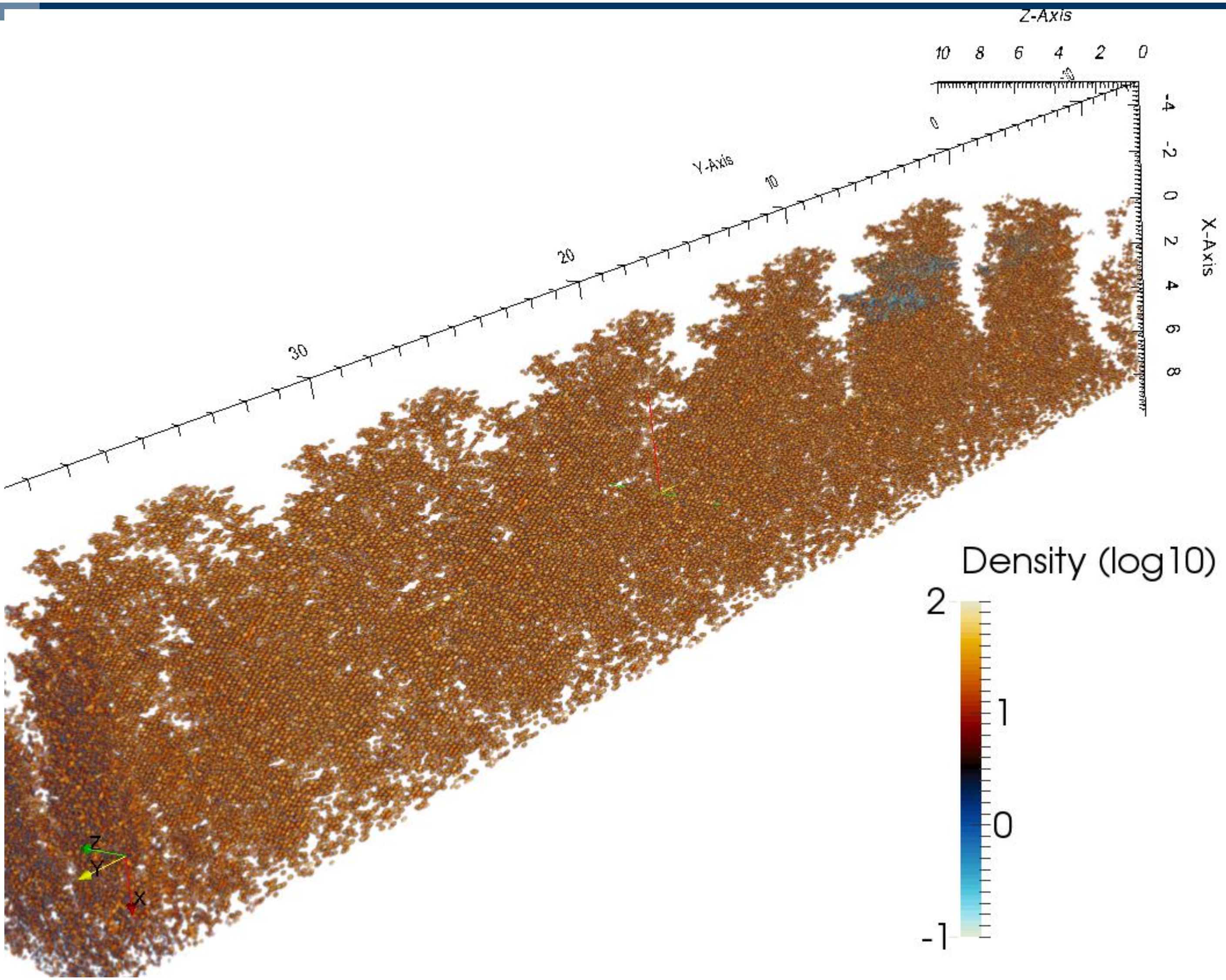
3D-PIC simulations of the experiment

More realistic: nanostructured-foam layer

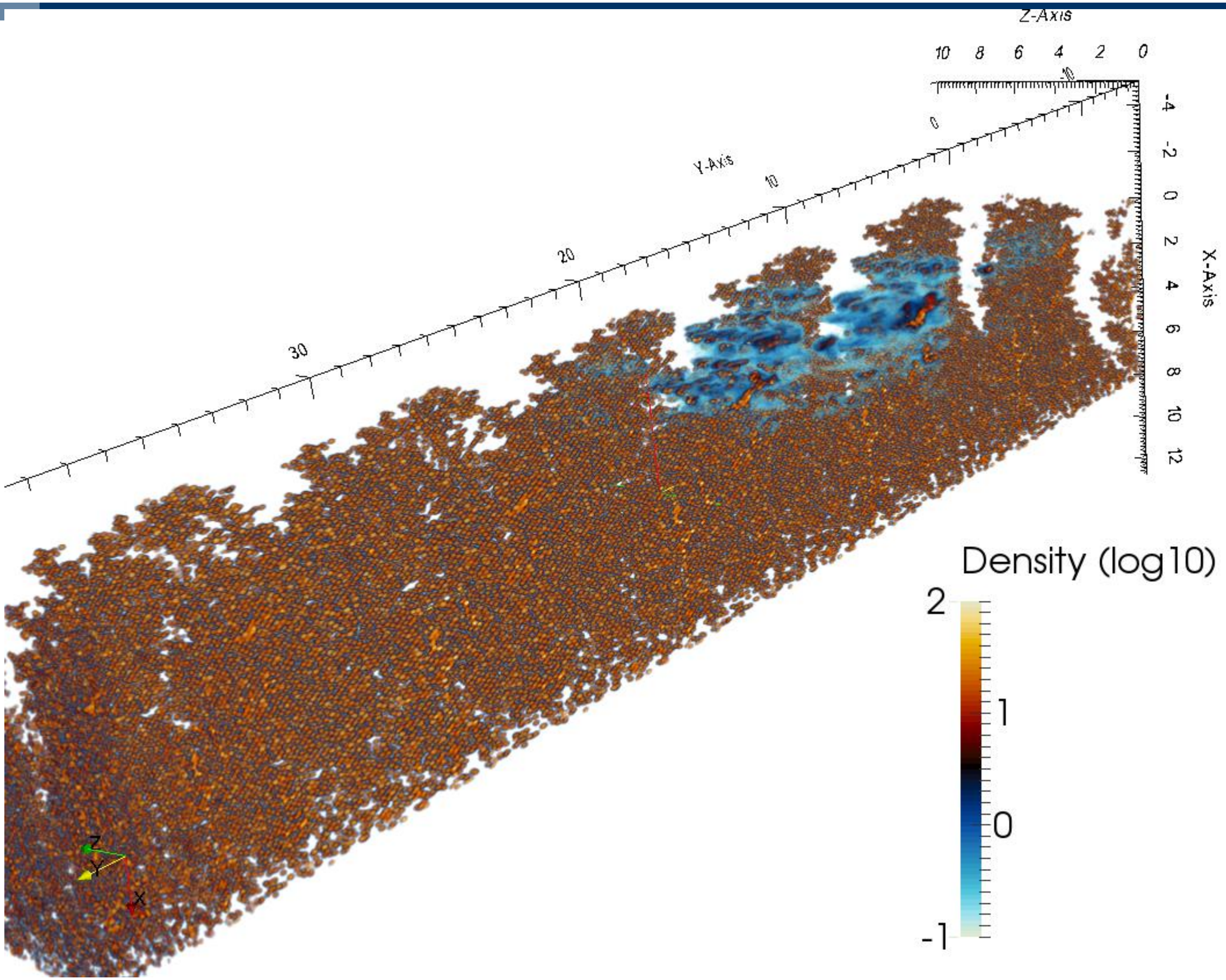
- Limited Diffusion Aggregation (LDA) model
- same mean thickness & density
- nanoparticles: 50 n_c (2%filling factor)



3D-PIC simulations of the experiment



3D-PIC simulations of the experiment



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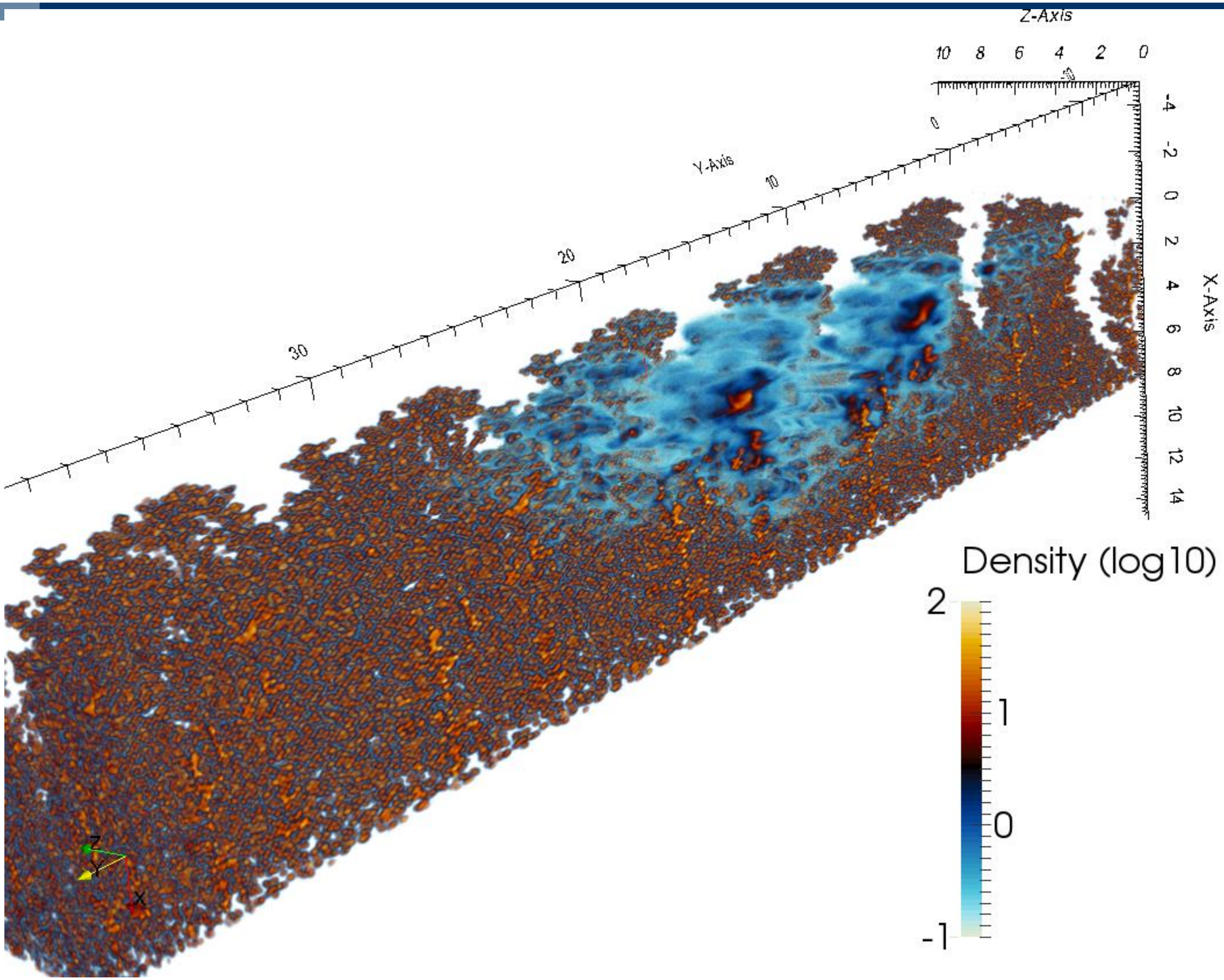

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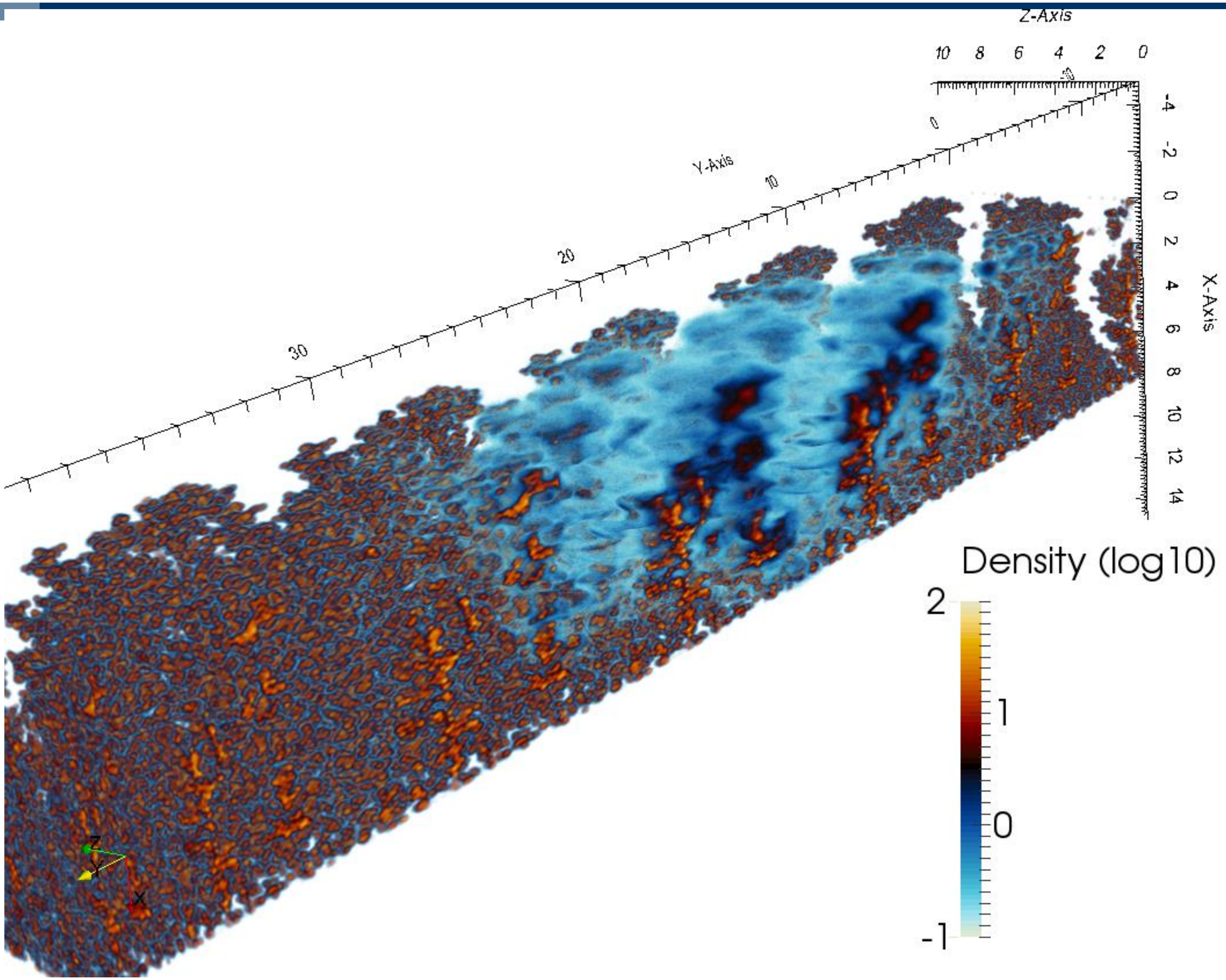

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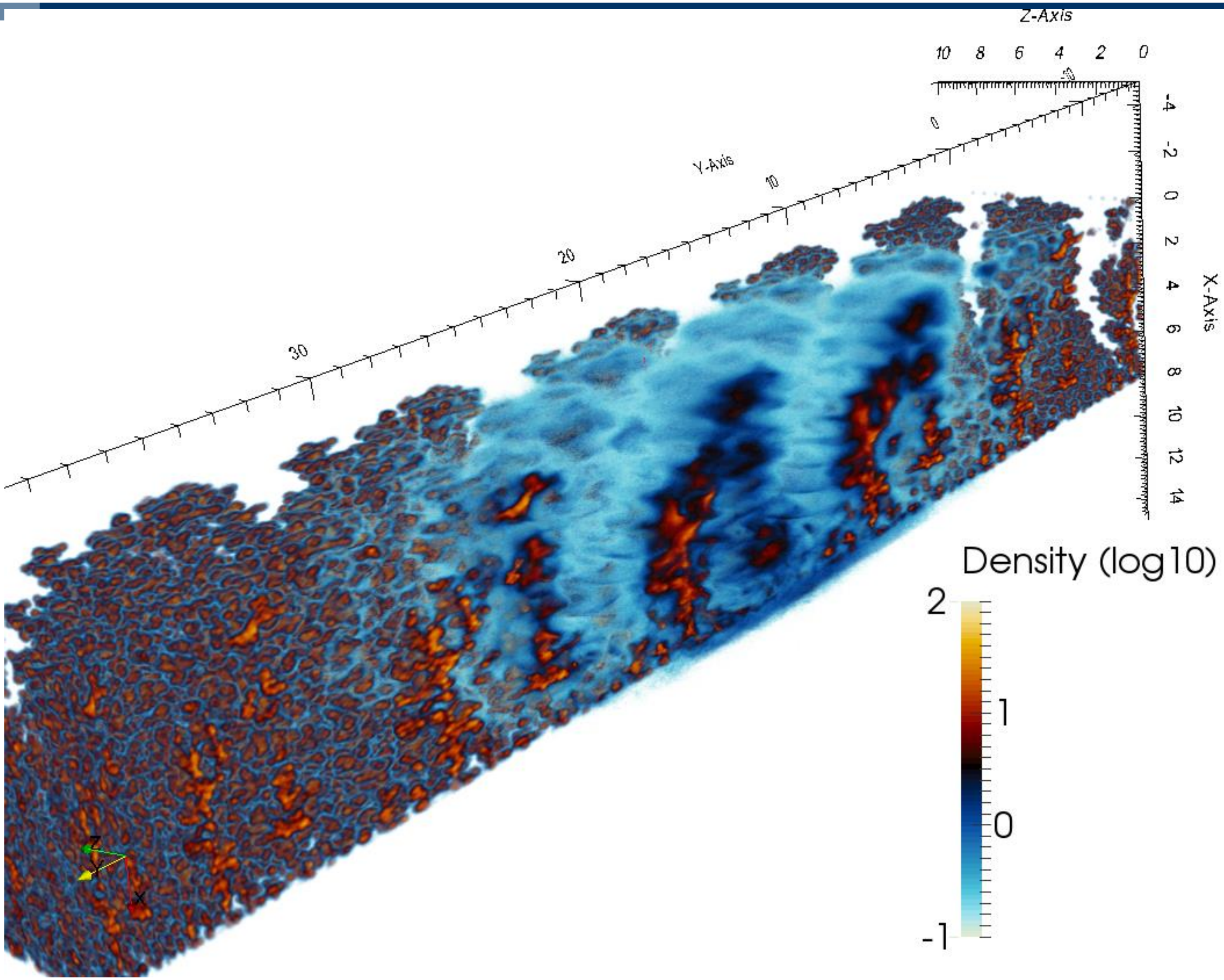

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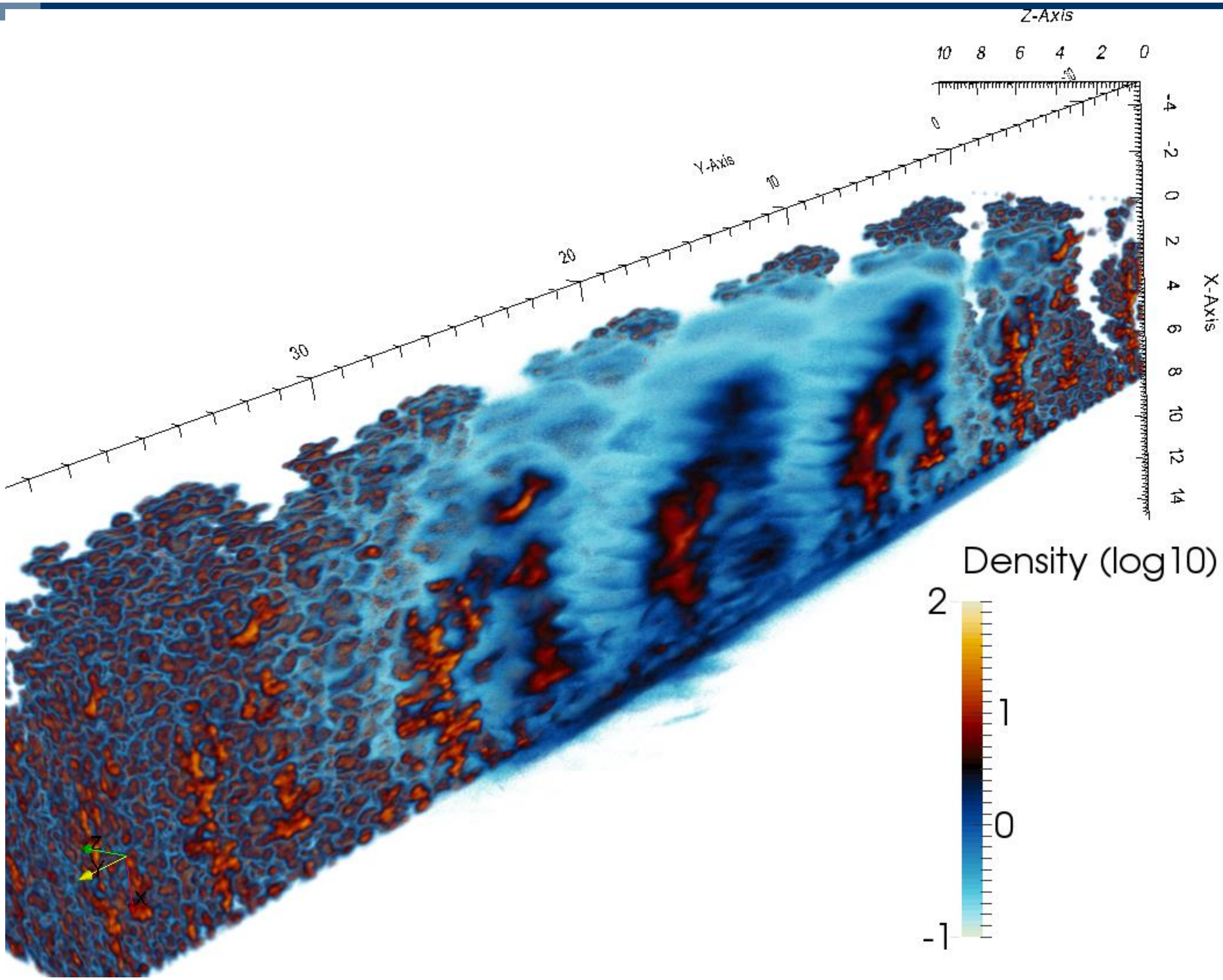

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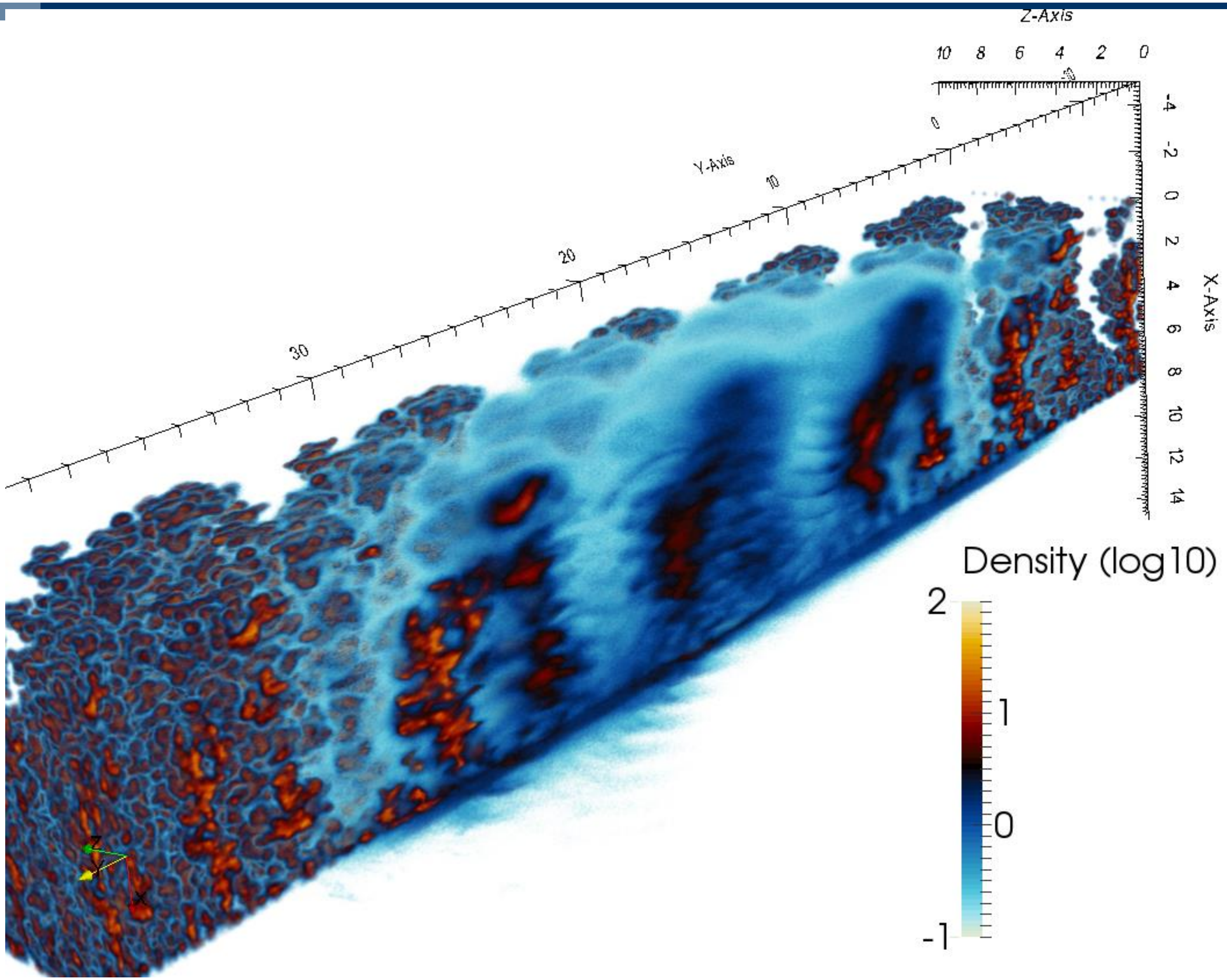

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