PIC modelling of laser-solid interactions:
from ion acceleration to high fields plasmonics

Andrea Sgattoni - INO CNR Pisa **Italy**

EAAC Isola d'Elba 2015

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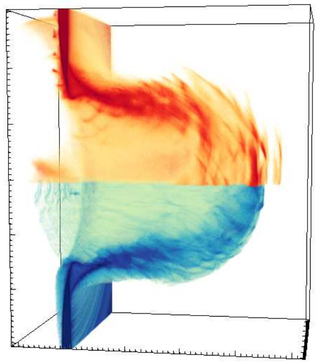
South Korea ››
- GIST Gwangju

Czech Republic ››
- Tech. University Prague

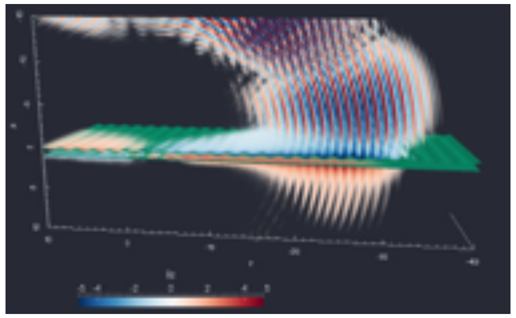
UK ››
- Queen's Univ. Belfast

PIC modelling of laser-solid interactions

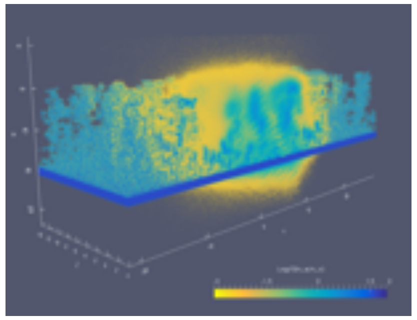
Introduction:



Ion Acceleration using thin foils:
Light-Sail acceleration



Electron Acceleration with gratings:
acceleration by relativistic surface waves



Foam Targets for ion acceleration:
enhanced TNSA

Introduction

Laser-Solid Interaction

Ion Acceleration

Electron Acceleration

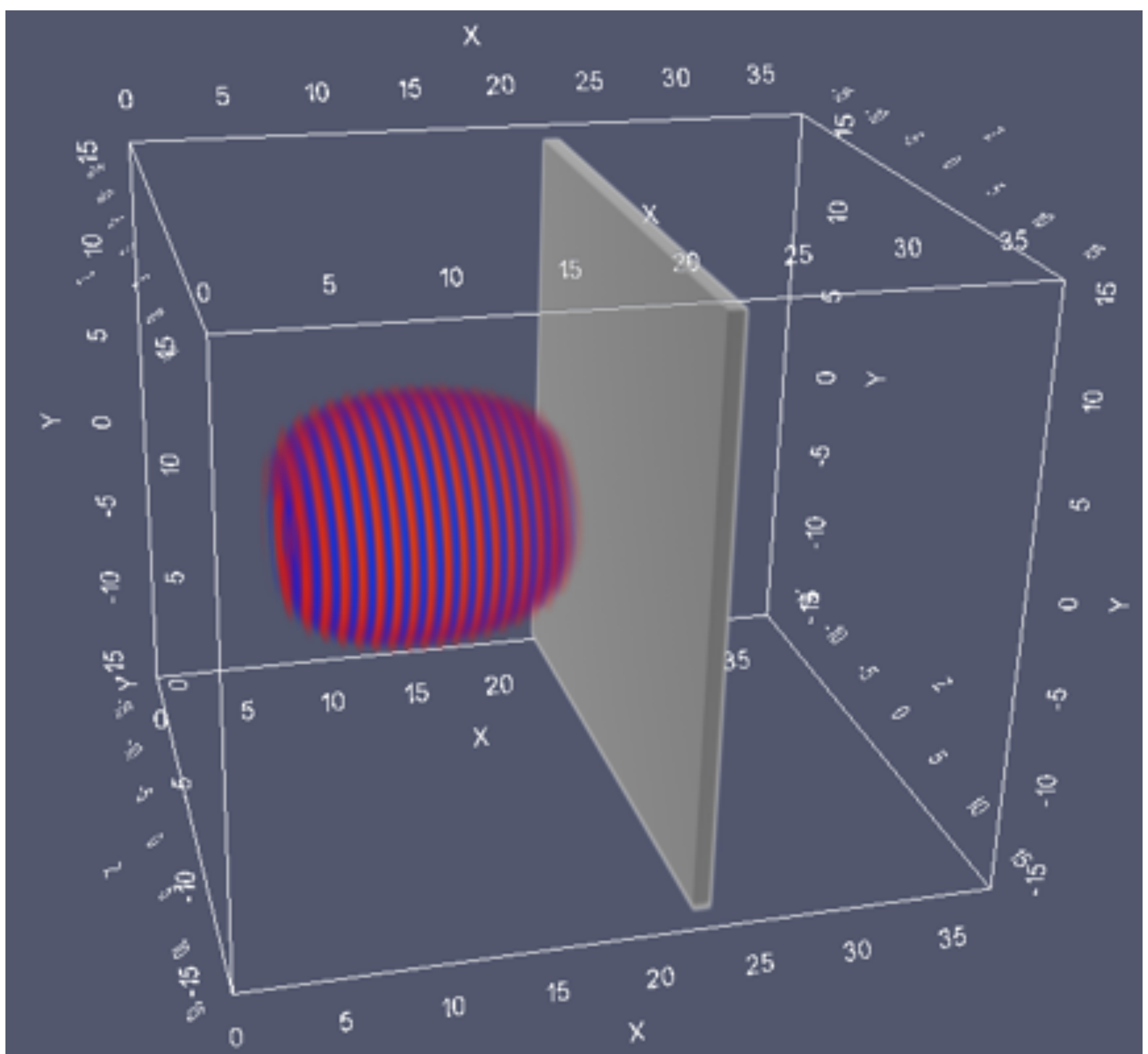
High Harmonic generation

Laser-Solid interaction

ultra-high fields and over-dense plasma

relativistic intensity laser

relativistic velocities

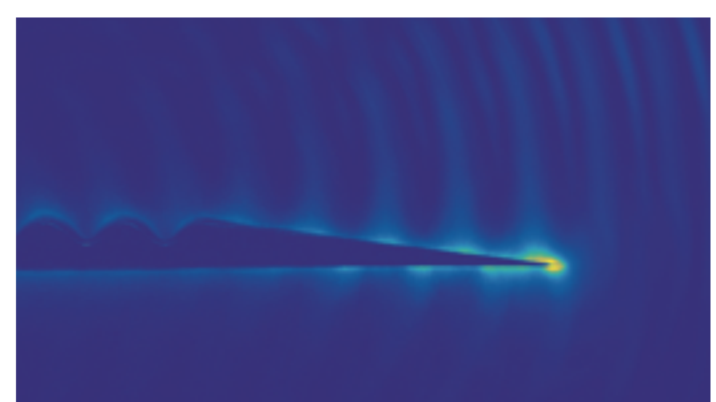


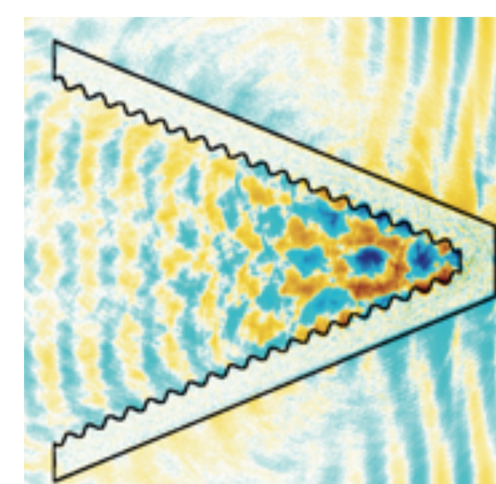
overdense plasma

skin-depth

$$l_{sd} = c/\omega_p$$

- Large box
- many particles in a small volume
- complex target structures





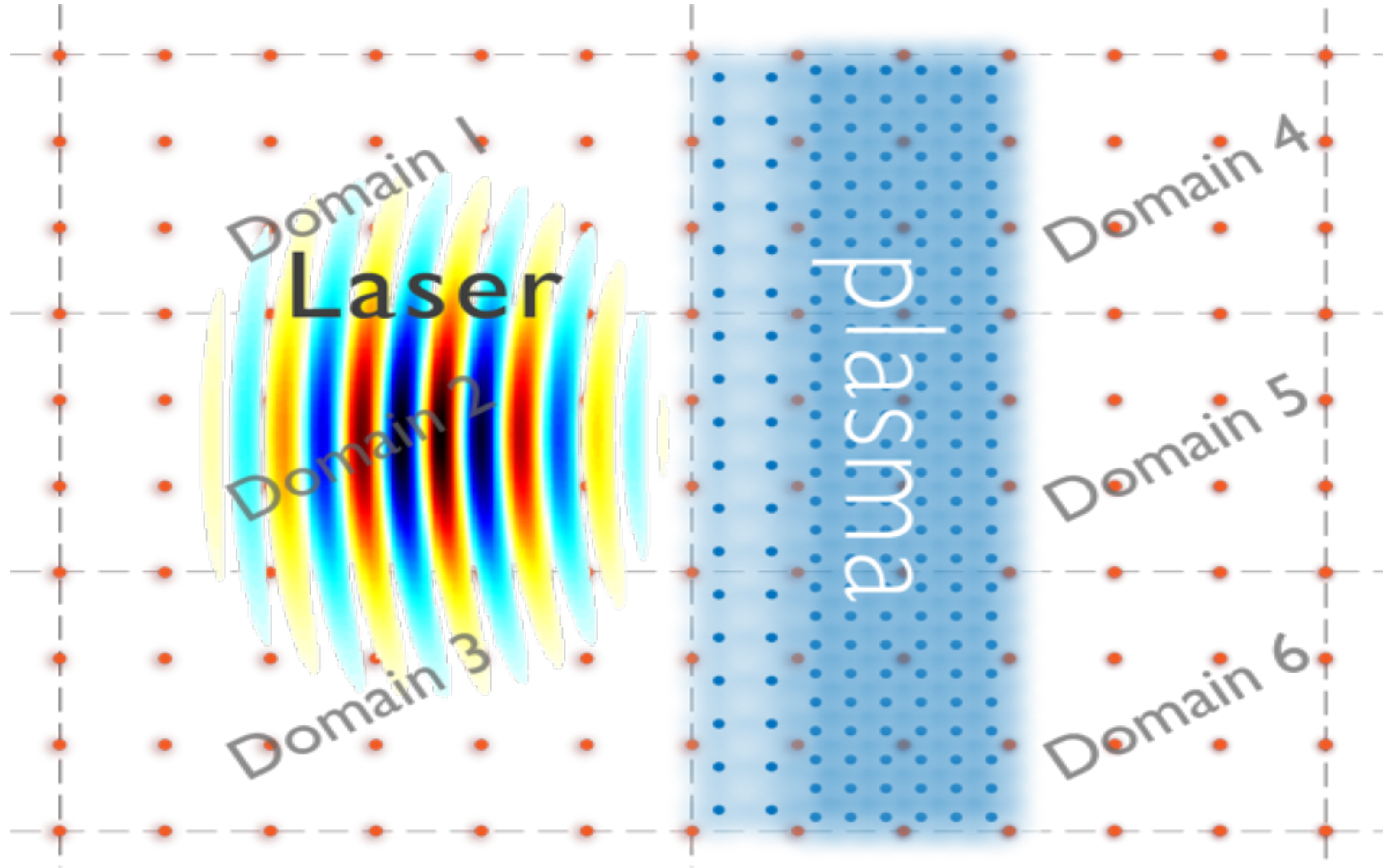
Particle In Cell

From the Maxwell -Vlasov equation to the PIC method

space discretised on a **GRID**

time steps

plasma density sampled with **numerical particles**



PICCANTE: our open source PIC

Goal: 1D-2D-3D **flexible** in-house

- ***PICCANTE*** *(italian)*: /pikˈkante/ = spicy, hot *adj.*
- 3D fully parallelized C++ MPI
- **Open source**: hosted on GitHub.com
- Started from scratch: Nov. 2013
- First production runs: Feb. 2014
- Tested up to 32k cores

thanks **GitHub** for free unlimited account

Ion acceleration using thin foils

Light-Sail acceleration

Laser driven ion acceleration

Year 2000

» Snavely et. al. PRL 85
» Maksimchuk et. al. PRL 84
» Clark et. al. PRL 84
» Wilks et. al. PoP 8 (2001)

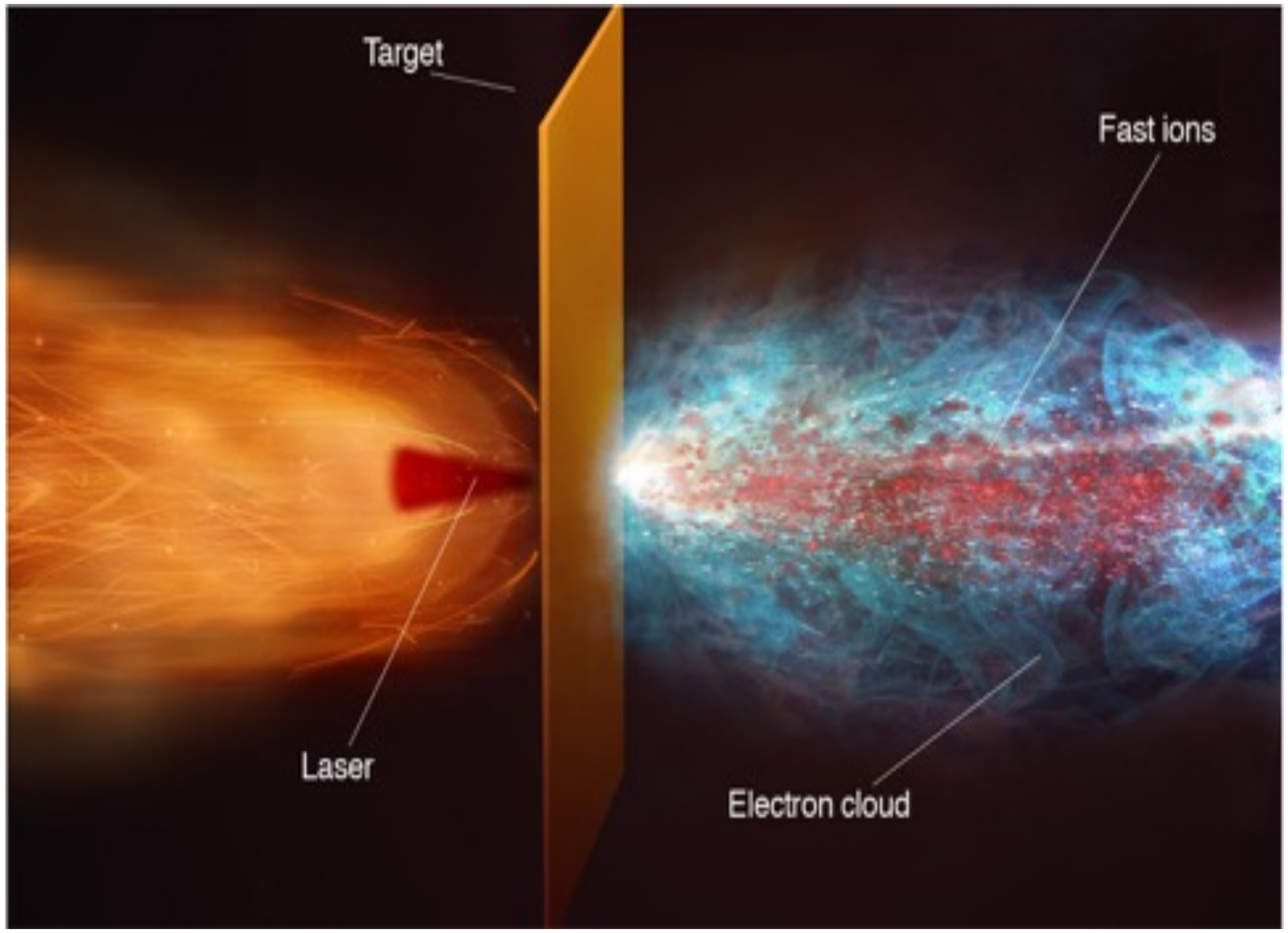
Target Normal Sheath Acceleration

» acceleration of surface contaminants

» short bunches 10s fs

» low emittance

» **exponential energy spectrum**



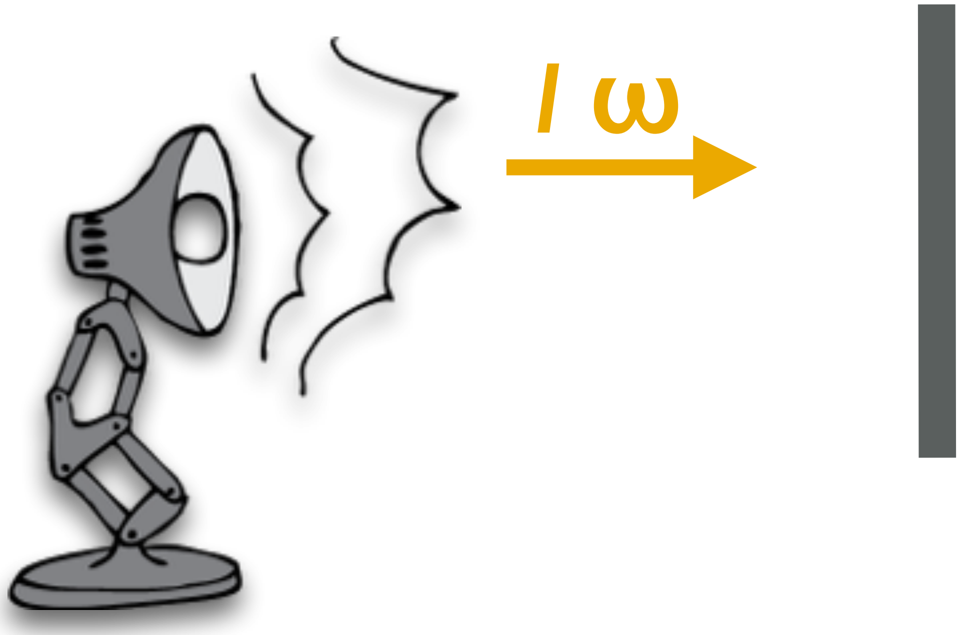
» Macchi, Borghesi, Passoni Rev. Mod. Phys 85 (2013)
» Daido, Nishiuchi, Pirozhkov, Rep. Prog. Phys. 75 (2012)

Radiation Pressure Acceleration: Light-Sail

sailing with the laser light

- ultrathin foils (10s nm) behaves like mirrors
- accelerated by the light pressure

$$P = \frac{2I}{c}$$



T. Esirkepov, et al. PRL., **92** (2004)
APL Robinson et al, NJP, **10** (2009)

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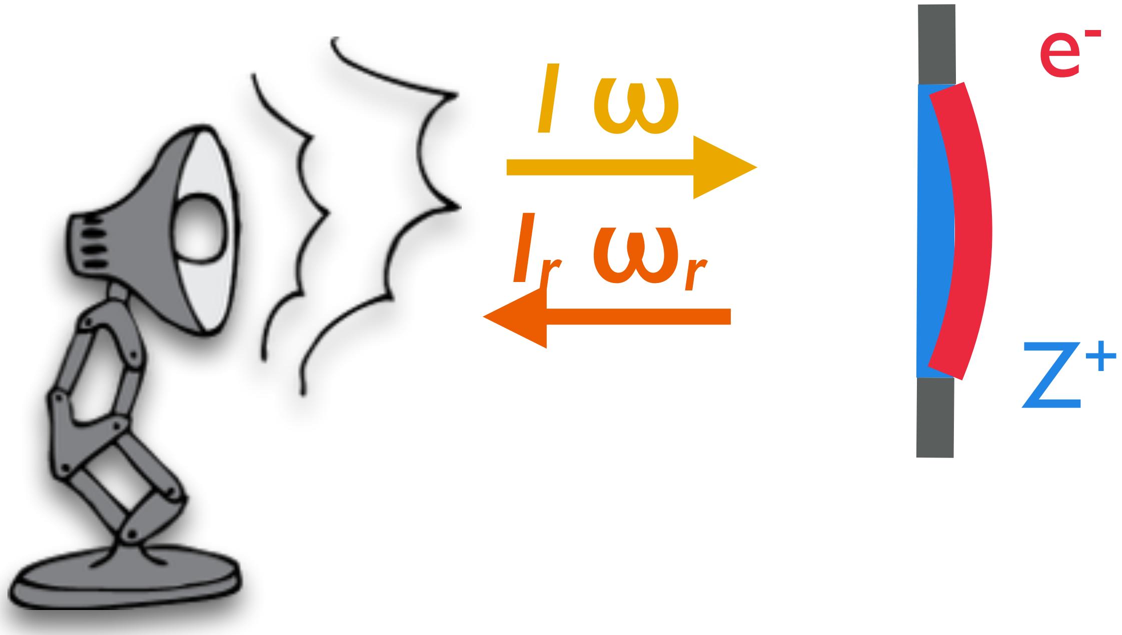

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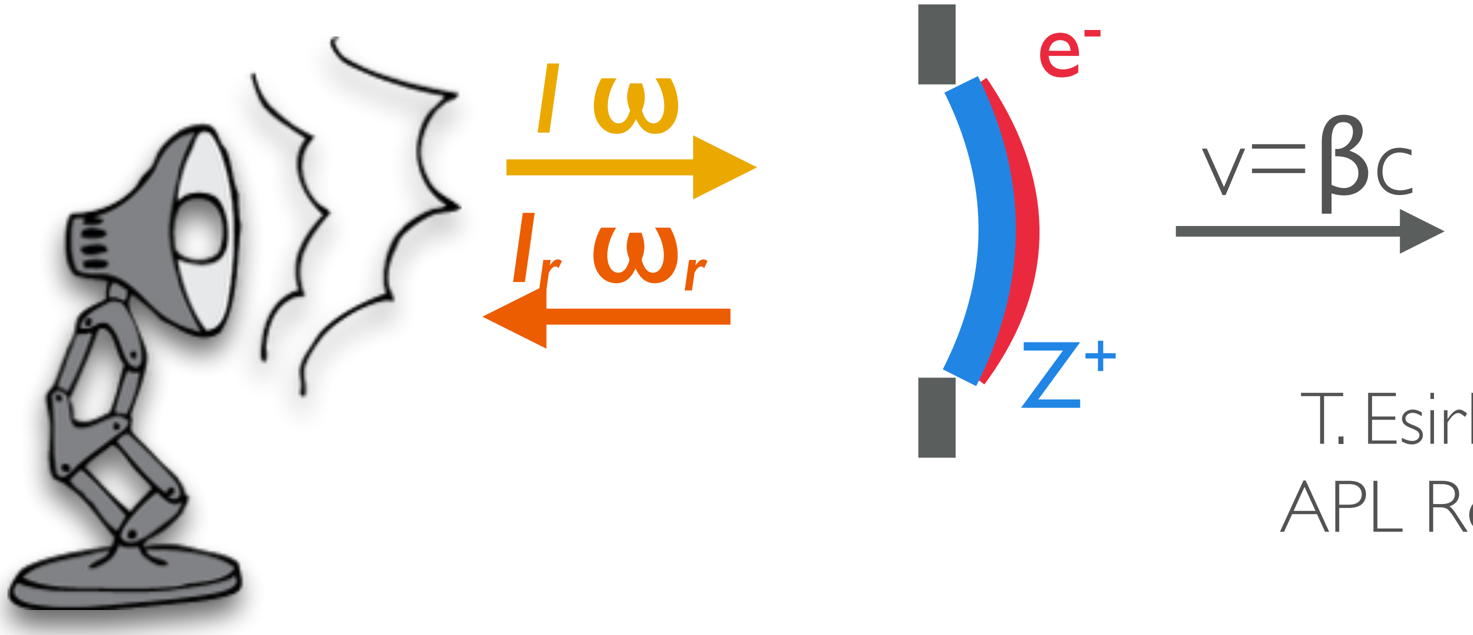


T. Esirkepov, et al. PRL., **92** (2004)
APL Robinson et al, NJP, **10** (2009)

good

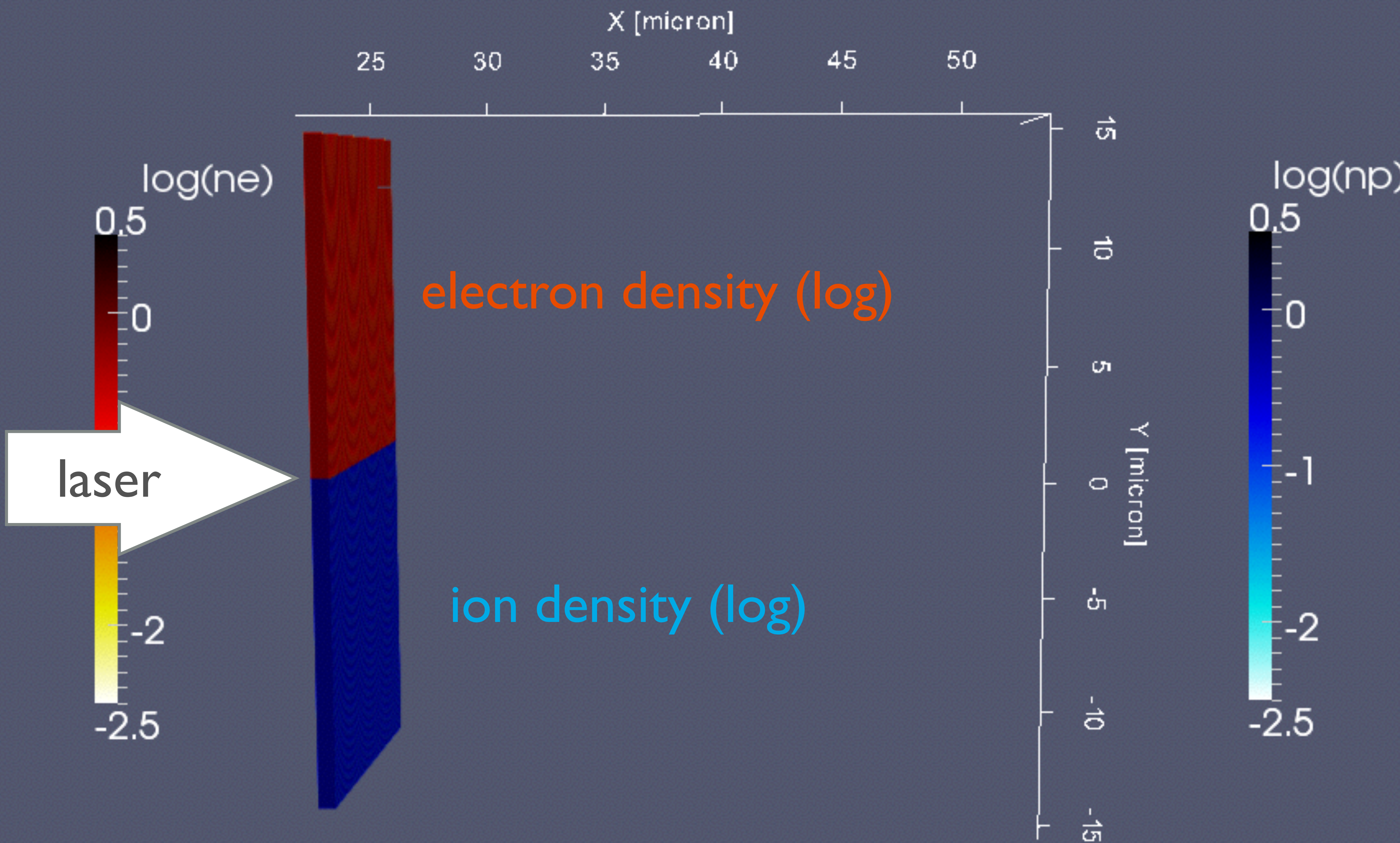
narrower energy spread: acceleration of the bulk of the target
better scaling than TNSA: $E_{max} \sim I$ vs. $\sim I^{1/2}$

critical

light polarisation: circular is preferred
target integrity: heating, target disassembly, instabilities

4096x1720x1720 grid points 10 billion particles

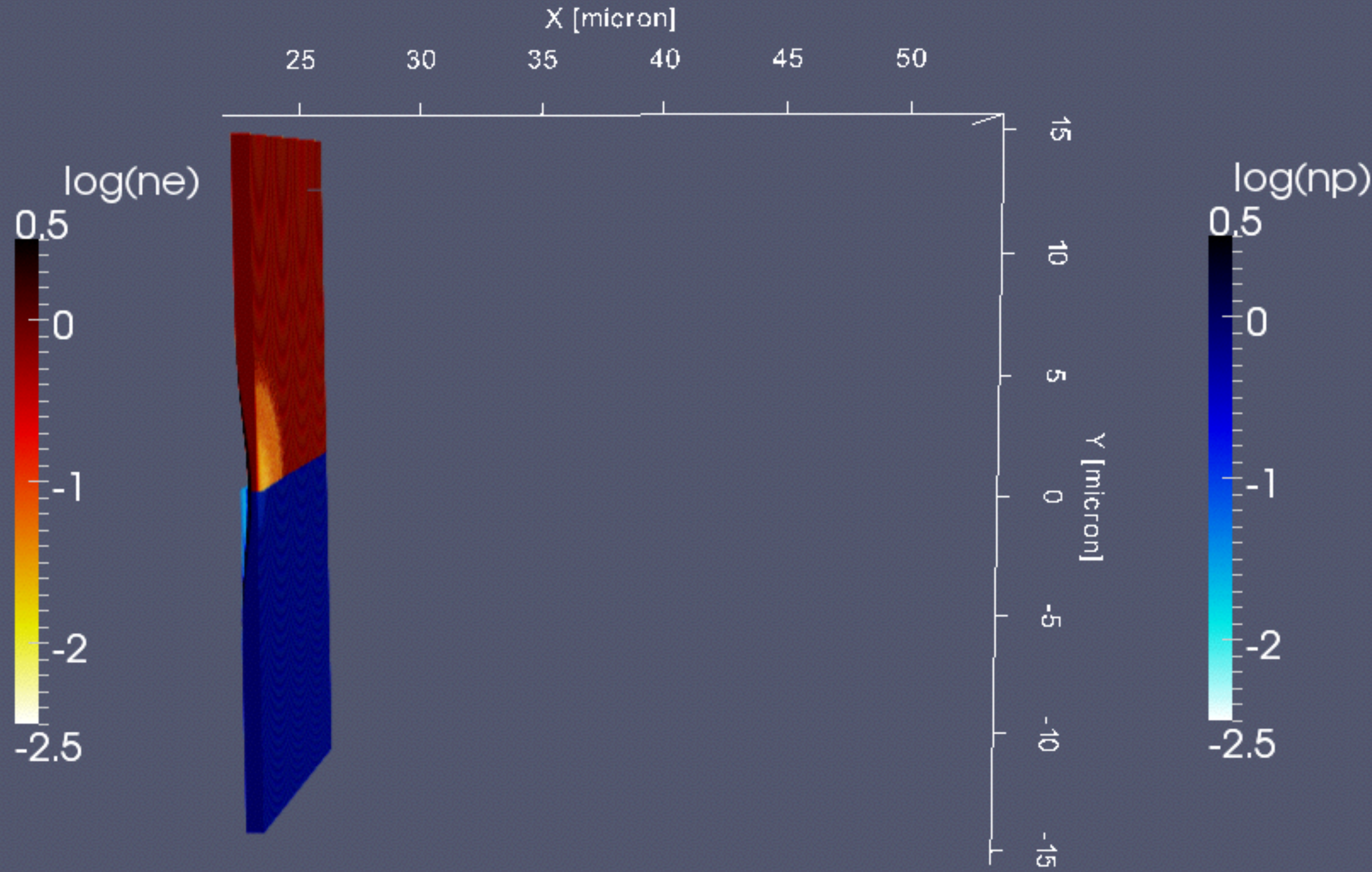
$t = 0$ fs



CP laser: $I=1.7\cdot 10^{23} W/cm_2$ $w_0=3{,}5\mu m$ $\tau=24fs$ $\lambda=0{,}8\mu m$

e-p plasma: $d=0{,}8\mu m$ $n_e=64n_c$

$t = 16{,}6$ fs



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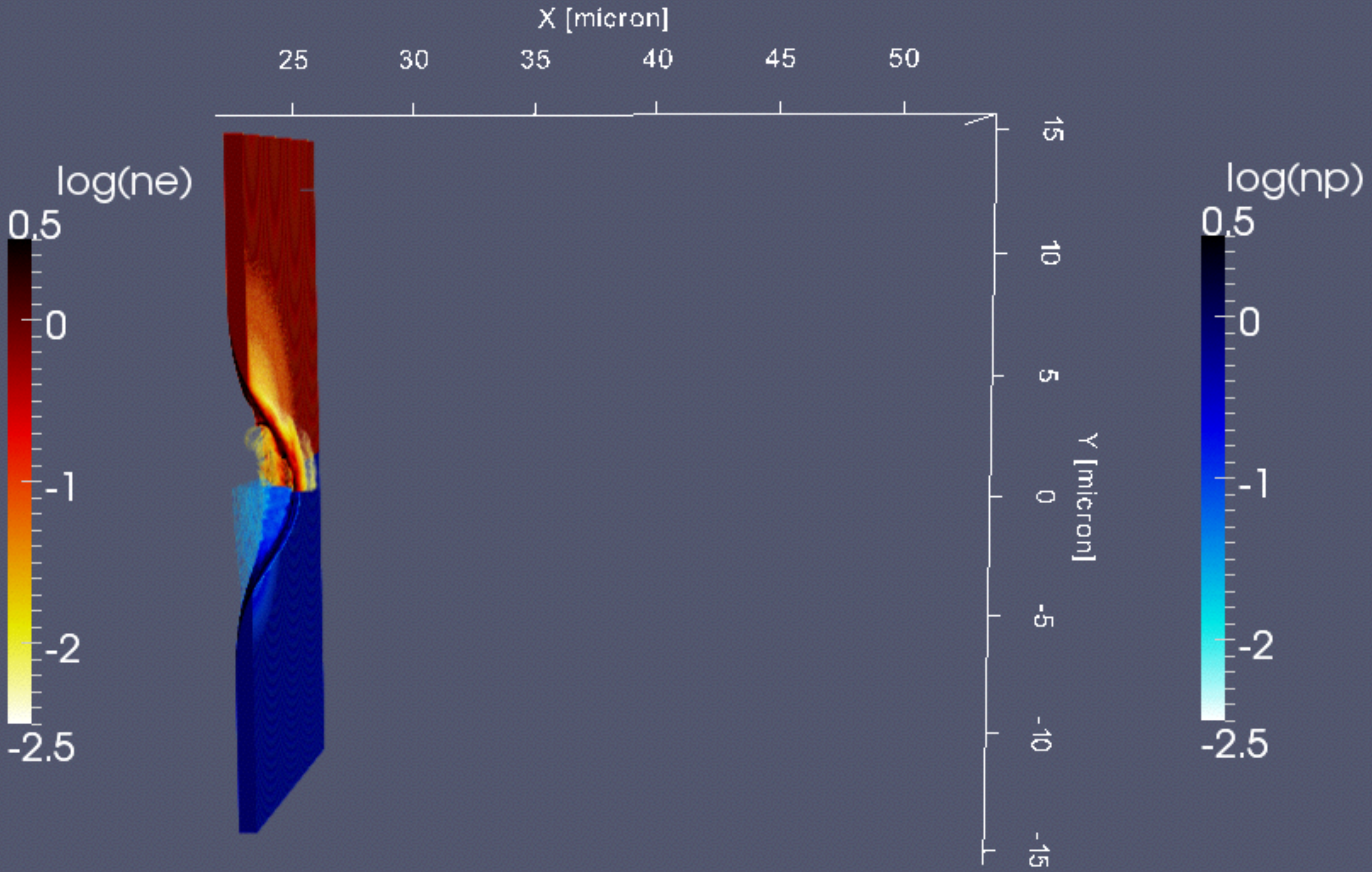
e-p plasma: $d = 0{,}8\,\mu m$ $n_e = 64 n_c$

$t = 33{,}3$ fs



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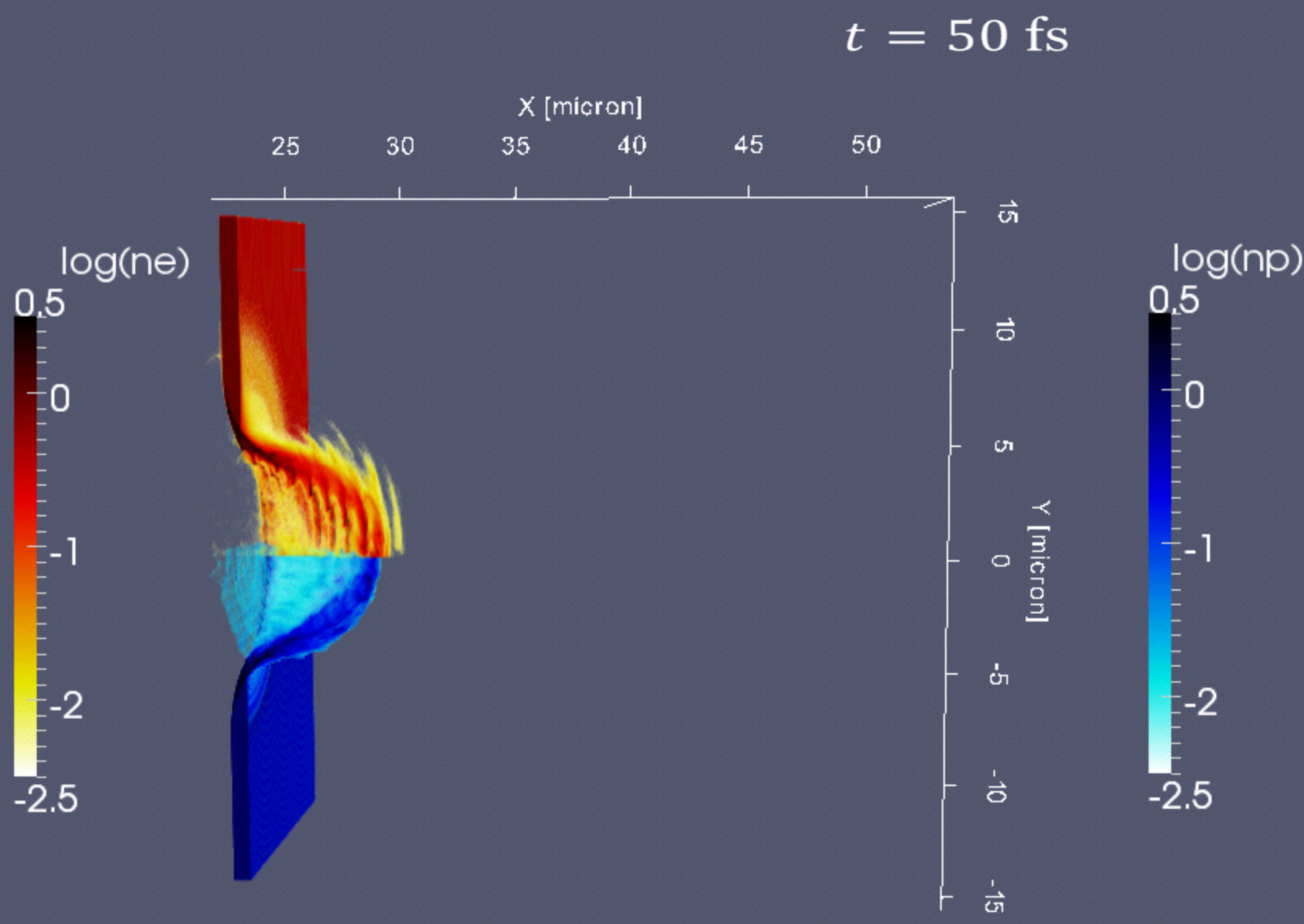
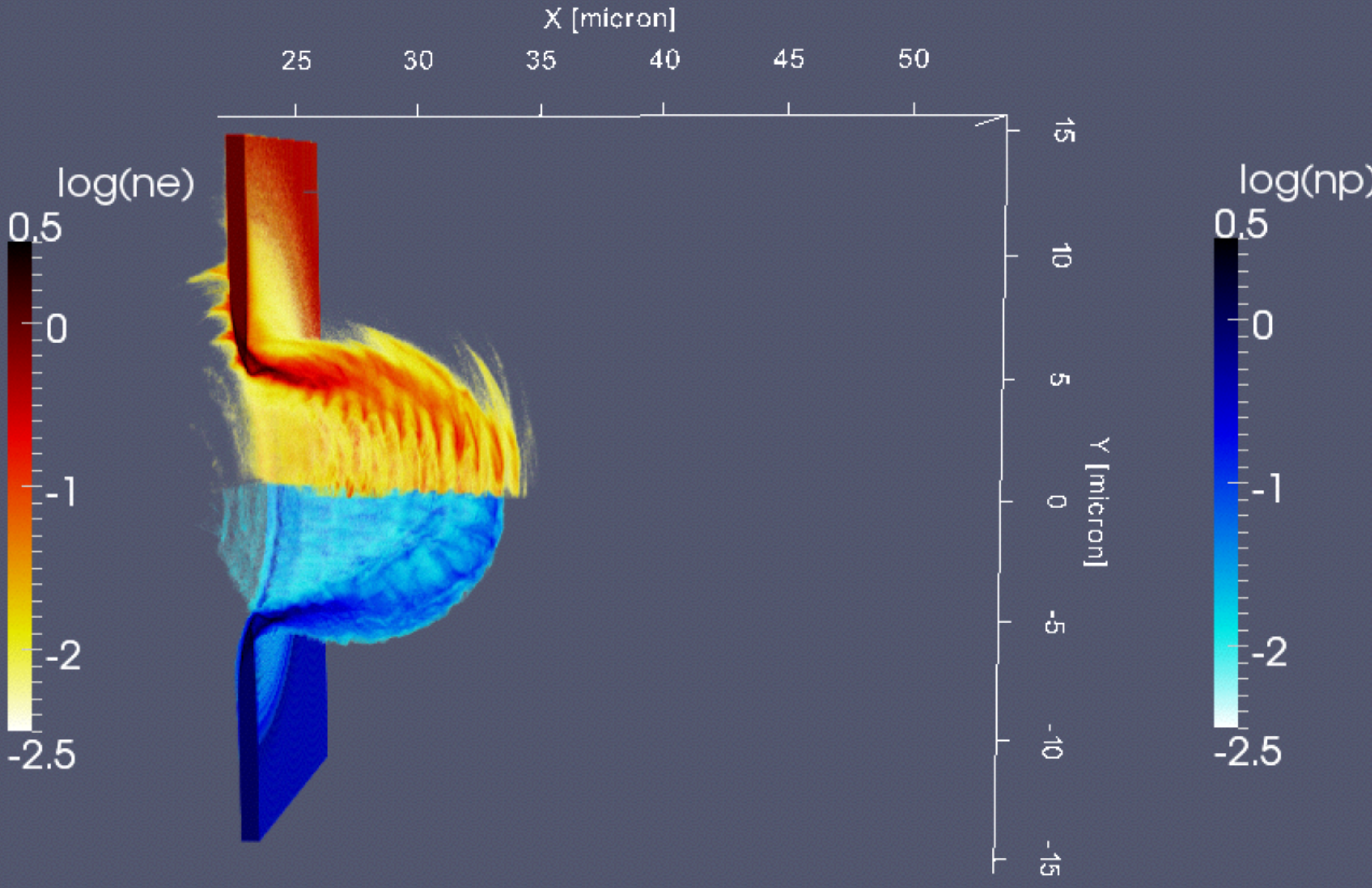


CP laser: $I = 1.7 \cdot 10^{23} W/cm_2$ $w_0 = 3{,}5\mu m$ $\tau = 24 fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $d = 0{,}8\mu m$ $n_e = 64 n_c$

$t = 66{,}6$ fs



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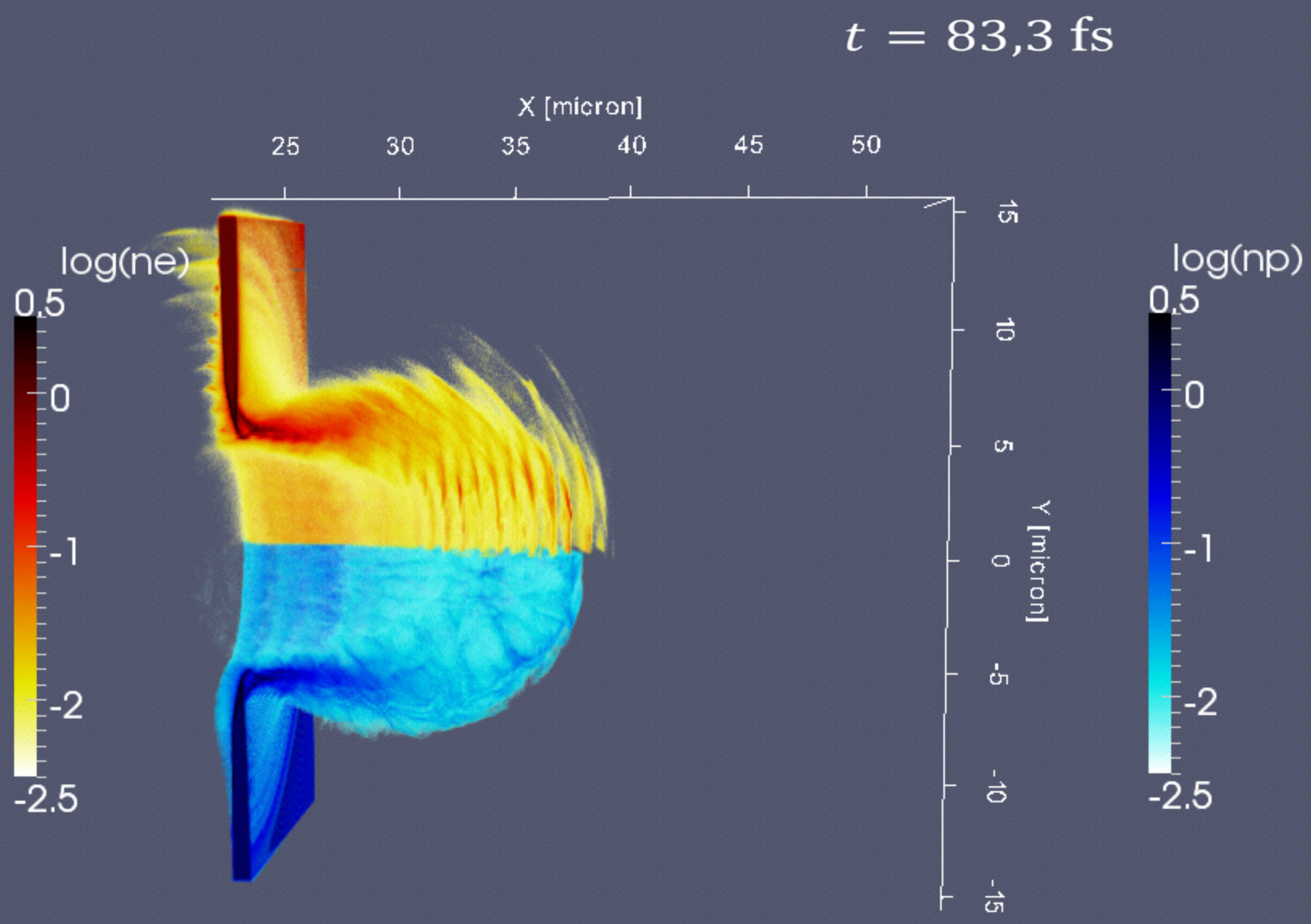

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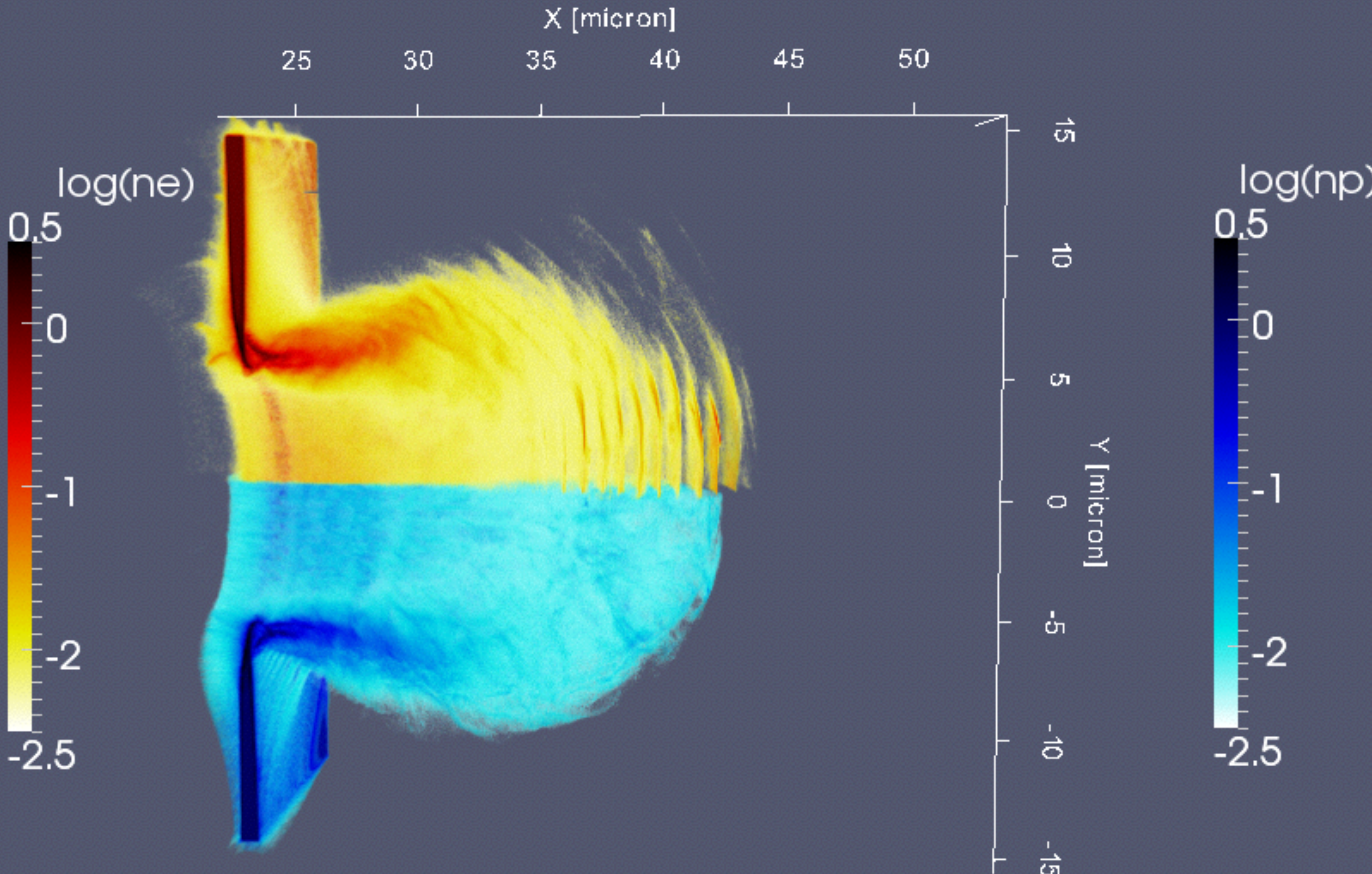
e-p plasma: $d=0{,}8\mu m$ $n_e=64n_c$

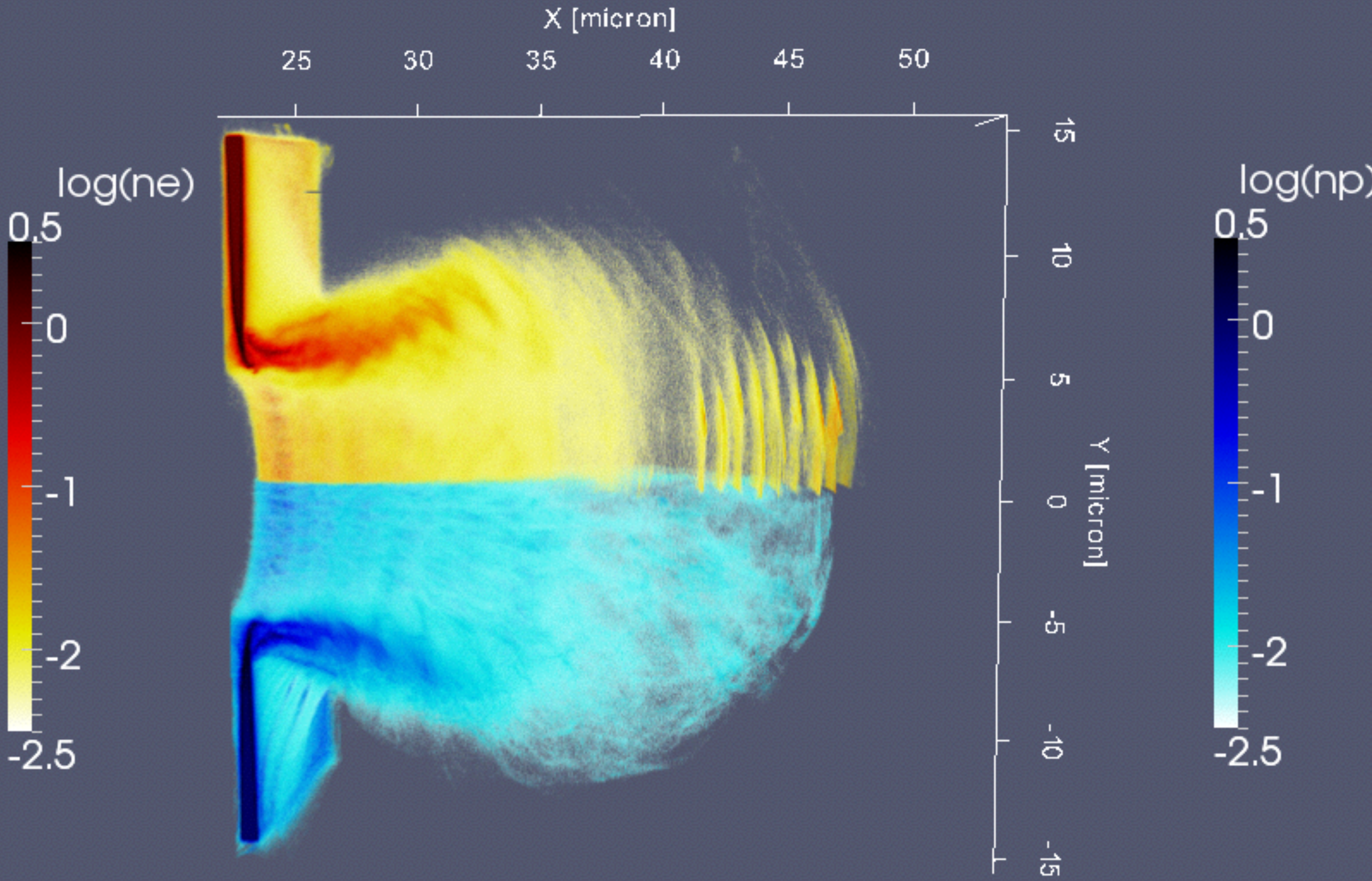
$t = 100$ fs



CP laser: $I = 1.7 \cdot 10^{23}$ W/cm_2 w_0=3,5μm τ=24fs λ=0,8μm

e-p plasma: d=0,8μm $n_e = 64 n_c$

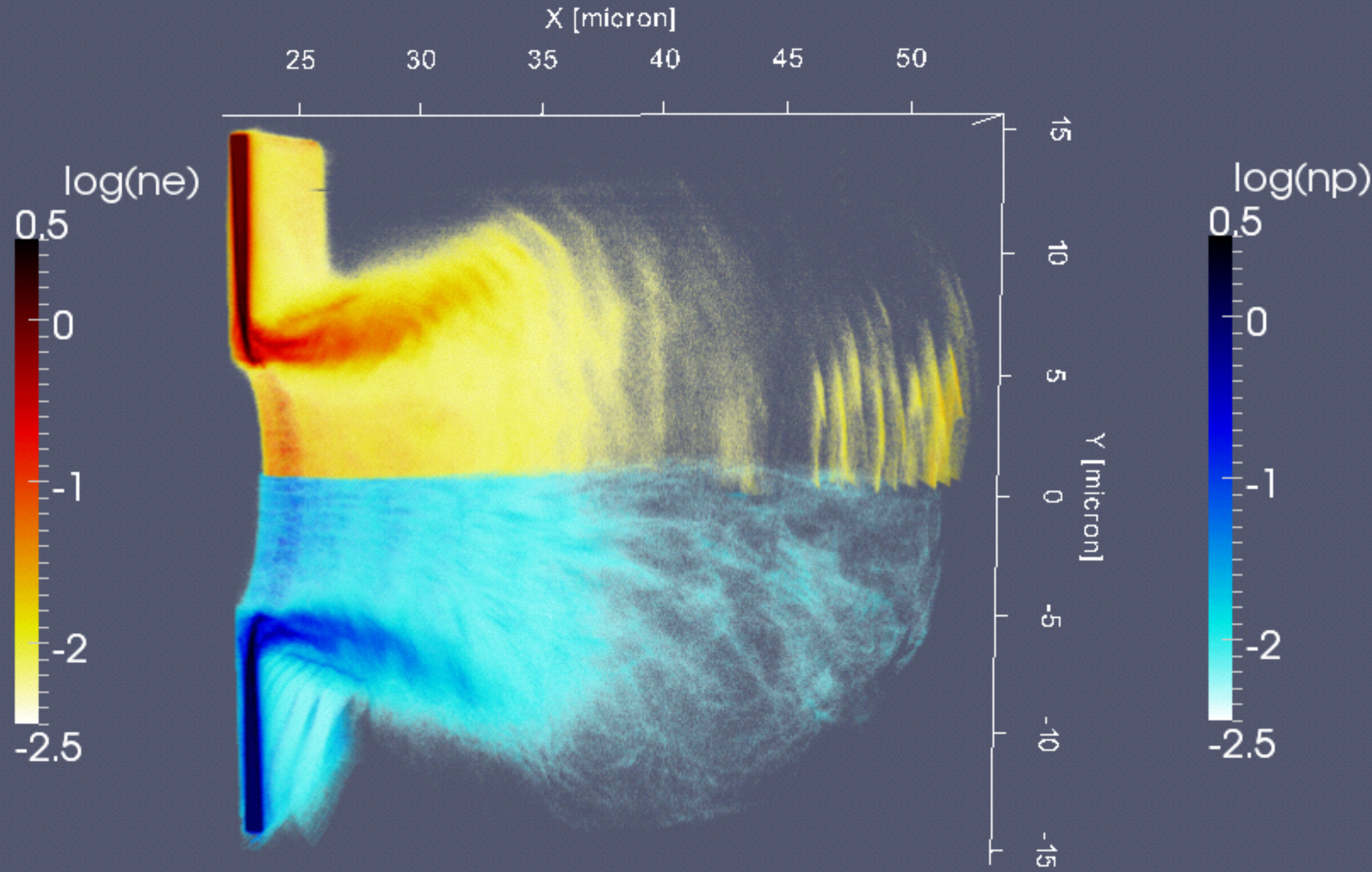
$t = 116$ fs



CP laser: $I=1.7 \cdot 10^{23} W/cm_2$ $w_0=3{,}5\mu m$ $\tau=24fs$ $\lambda=0{,}8\mu m$

e-p plasma: $d=0{,}8\mu m$ $n_e=64n_c$

$t = 133$ fs



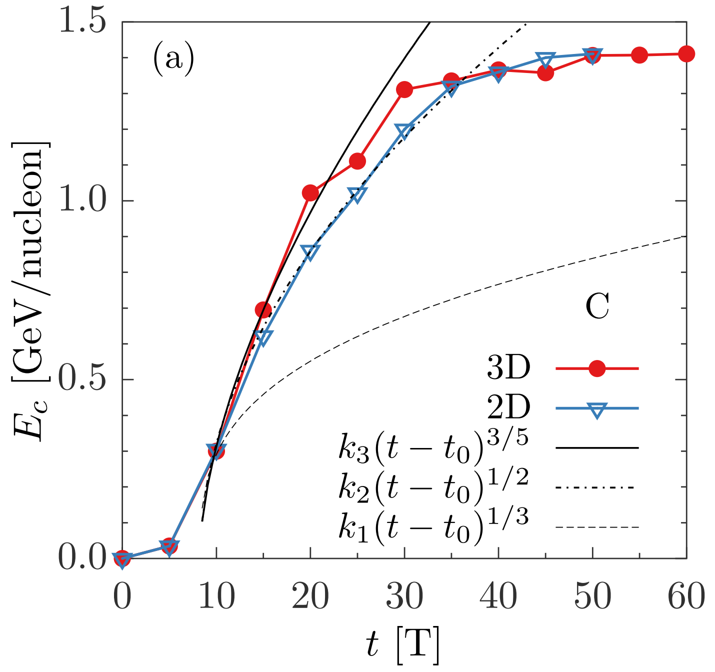
CP laser: $I=1.7 \cdot 10^{23}$W/cm$_2$ w_0=3,5µm τ=24fs λ=0,8µm

e-p plasma: d=0,8µm $n_e=64n_c$

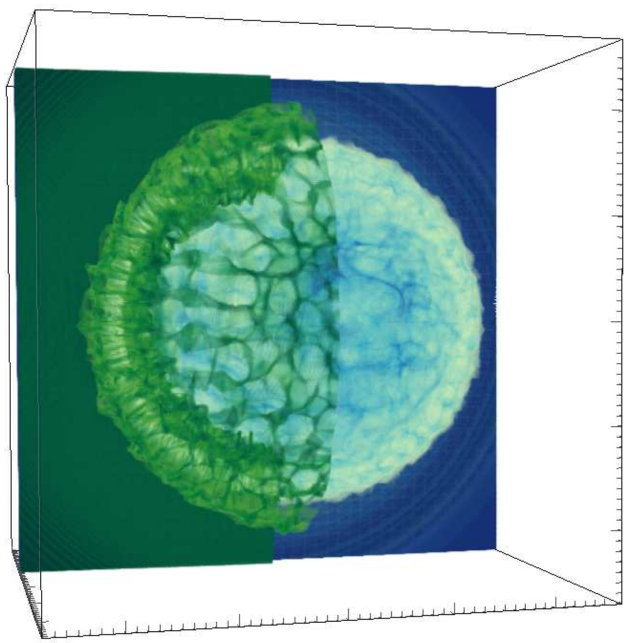
3D PIC simulations of Light Sail acceleration

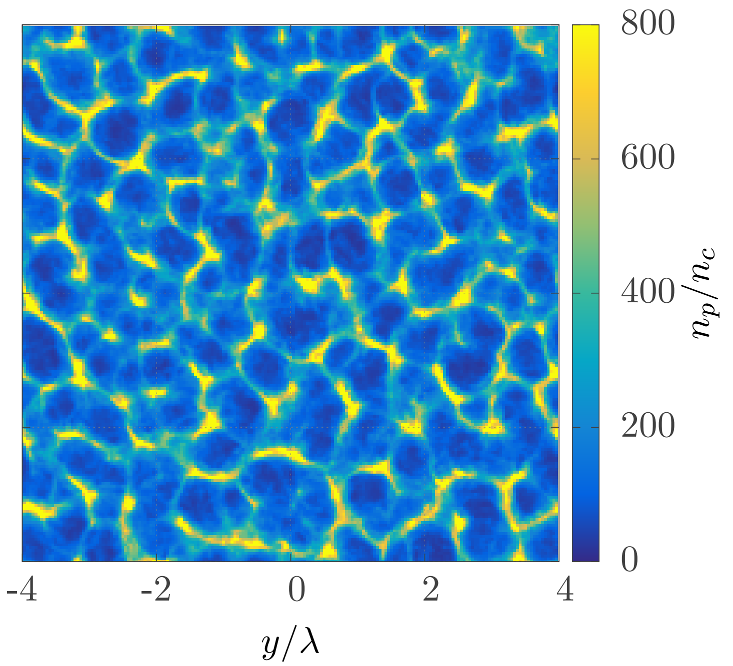
- » interaction followed until transparency
- » **acceleration in 3D is faster than 2D** in agreement with analytical model

Sgattoni et. al. APL 105 (2014)



Rayleigh Taylor Instability:
net-like structures





S. I. Abarzhi, PRE 59 (1999)
Sgattoni et. al. PRE 91 (2015)
B. Eliasson NJP 17 (2015) Pegoraro, Bulanov, PRL (2007)

Light-Sail @ GEMINI (RAL) UK

group of Borghesi at Queen's University Belfast

- **Very high contrast** (10^{12})
- **control polarisation**
- **ultrathin carbon targets** 10-100nm
- **normal incidence**

τ=40fs, λ=0.8μm, E=6.5J, FWHM~4μm, $I \sim 3 \cdot 10^{20}$W/cm^2

Talk by Clare Scullion (WG2 today 15:00)

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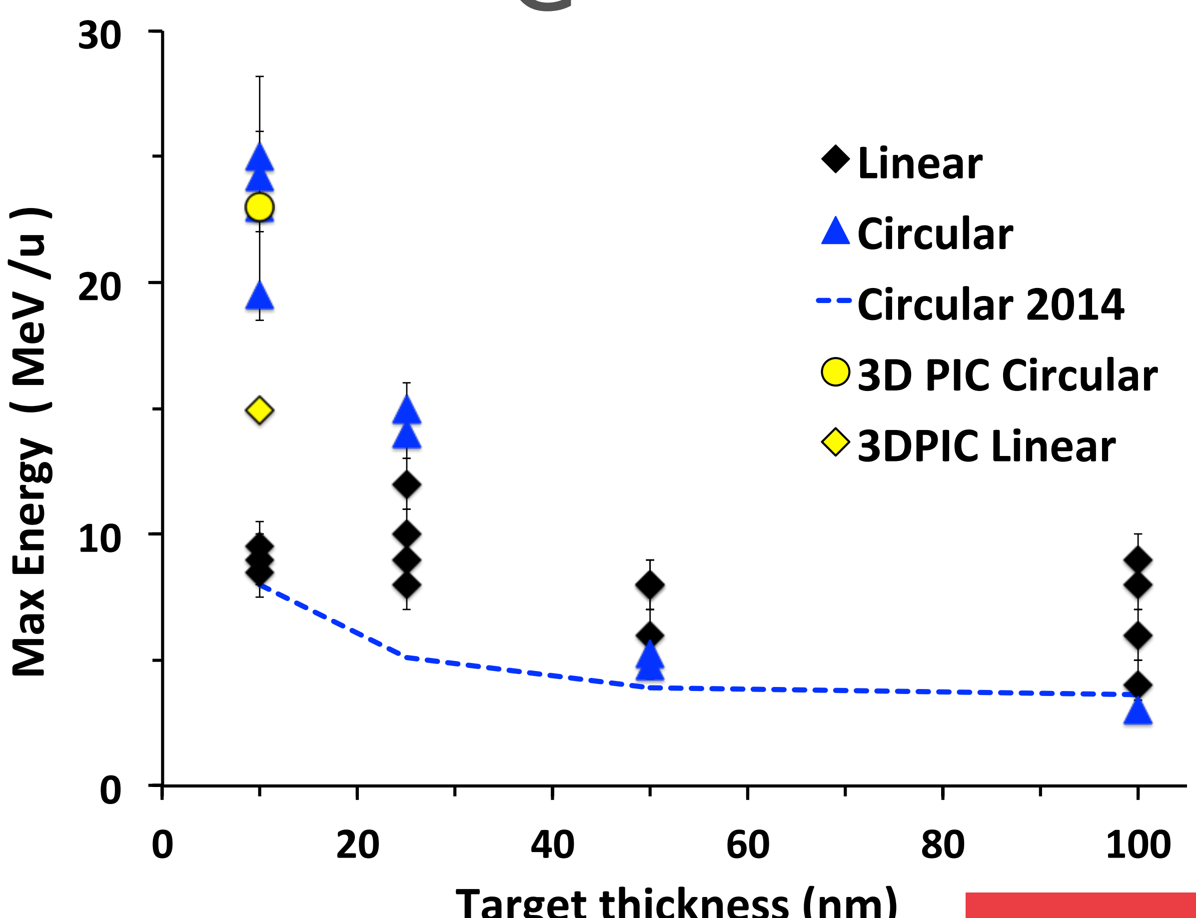
C^{6+}



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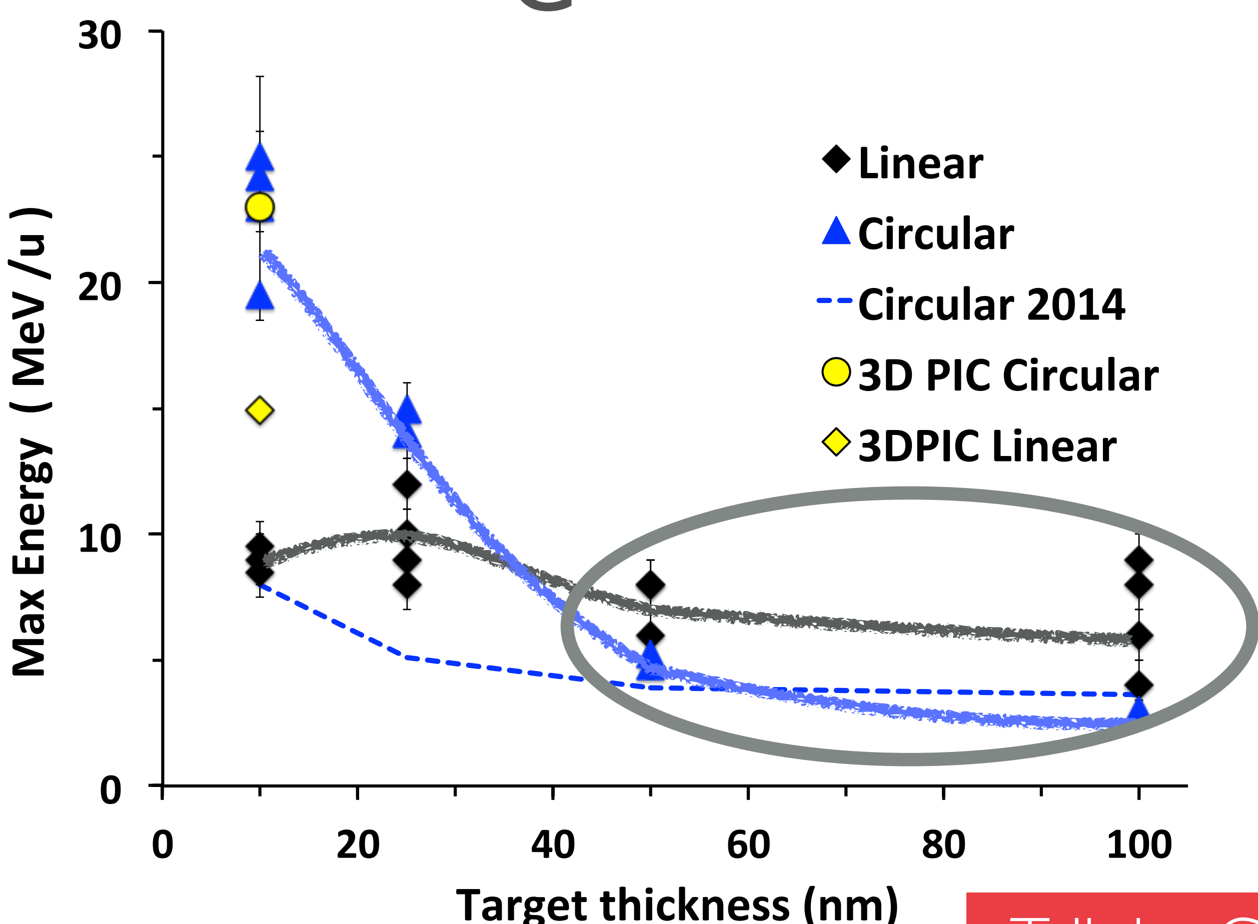

- **for "thick target"**
  linear pol. is better than circular

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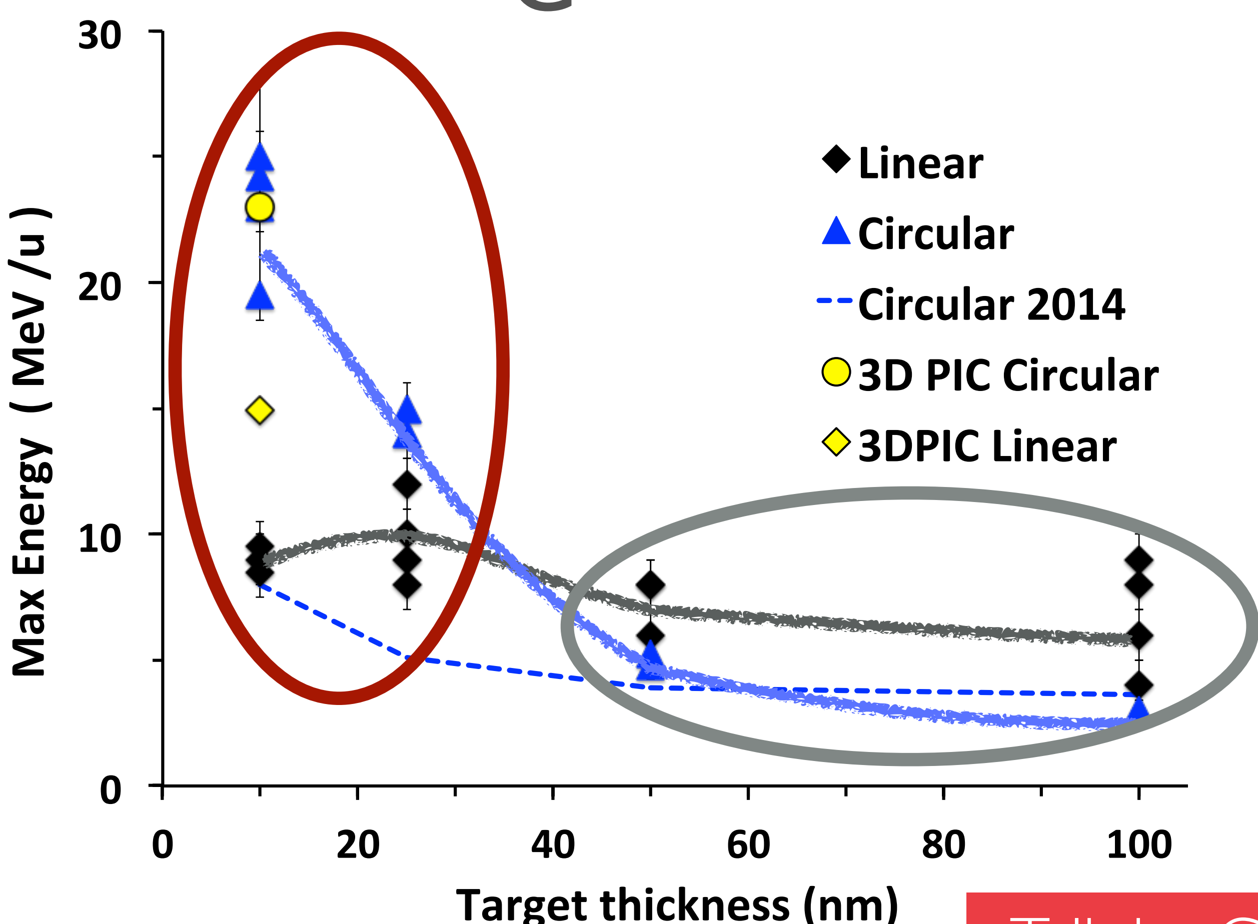
C^{6+}



- **for "thick target" linear pol. is better than circular**
- for thin target **circular pol is best**
- Light-Sail dominates for the thinnest targets

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group of Borghesi at Queen's University Belfast

- **Very high contrast** (10^{12})
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- **ultrathin carbon targets** 10-100nm
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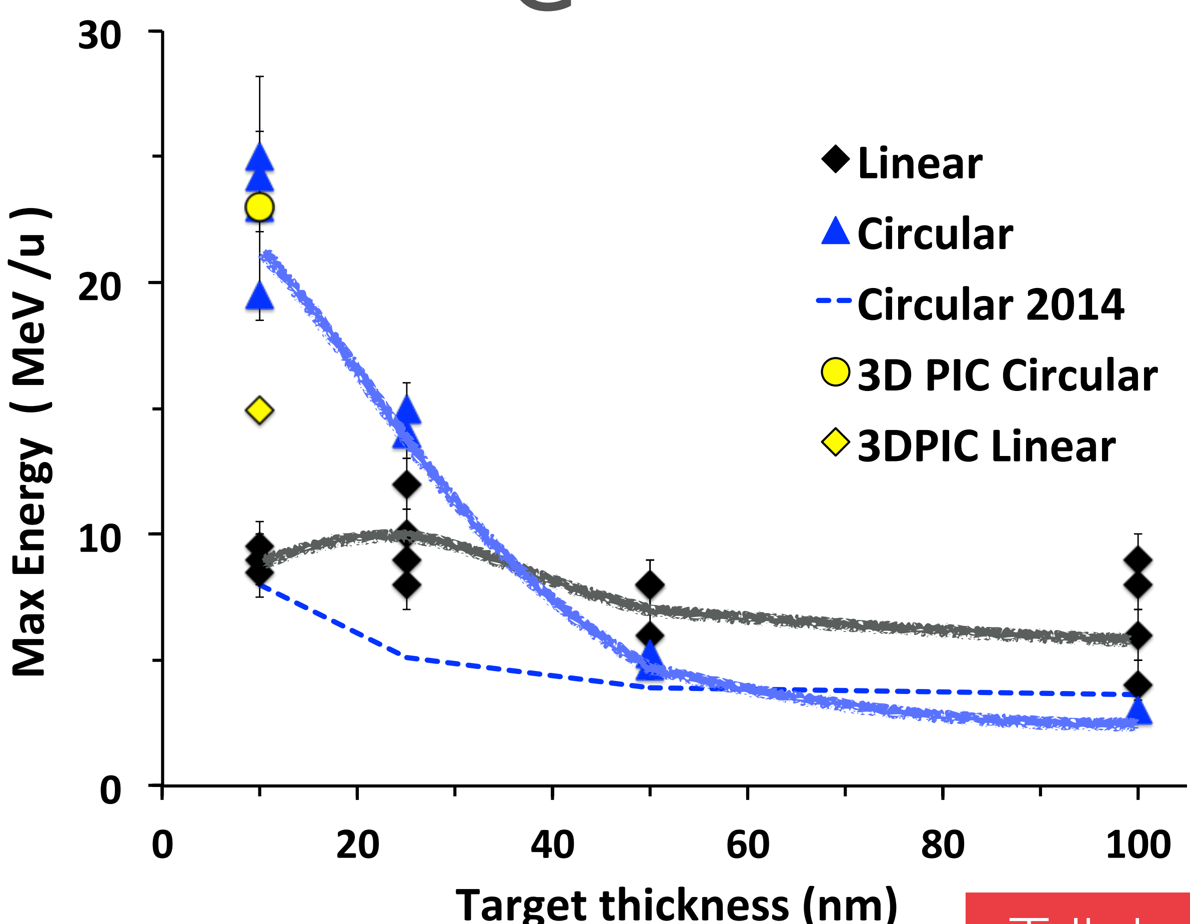
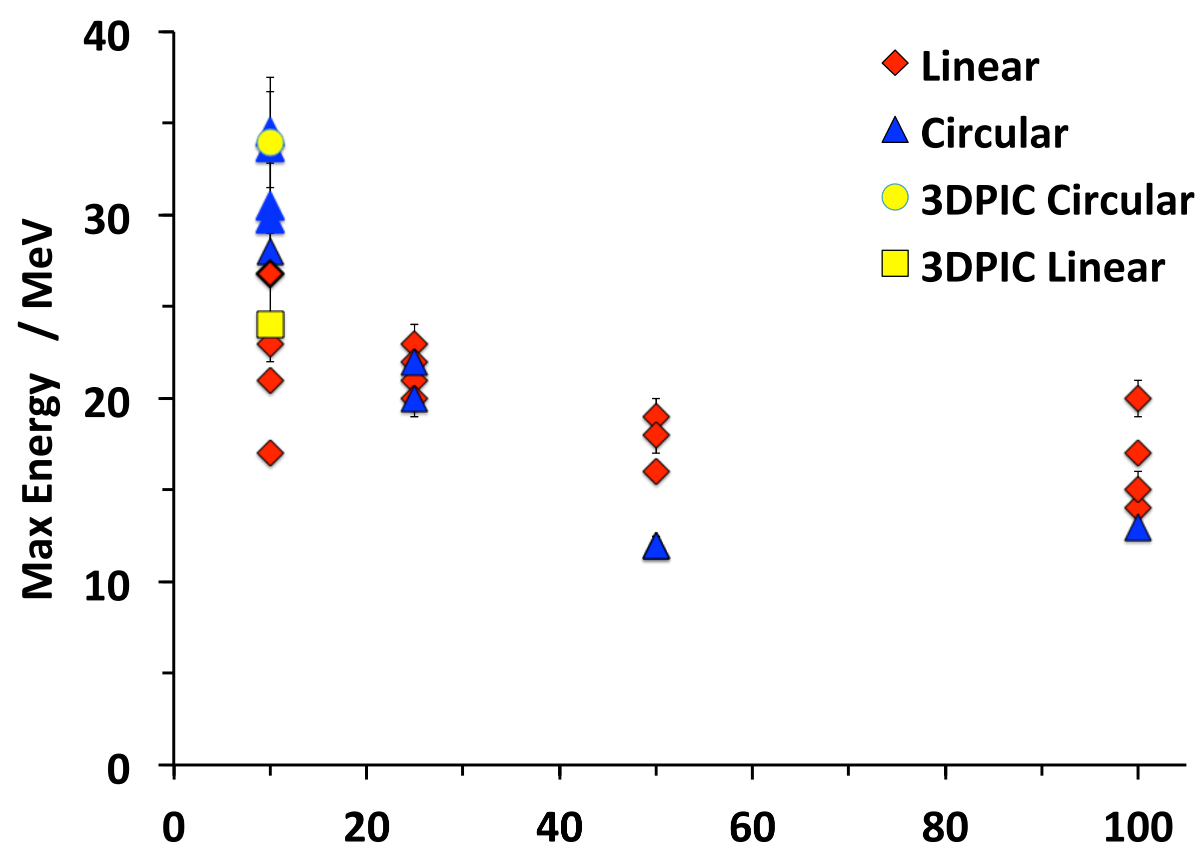
τ=40fs, λ=0.8µm, E=6.5J,   FWHM~4µm, I~$3\cdot10^{20}$W/cm^2

C^{6+}



H^+



Talk by Clare Scullion (WG2 today 15:00)

Light-Sail @ GEMINI (RAL) UK

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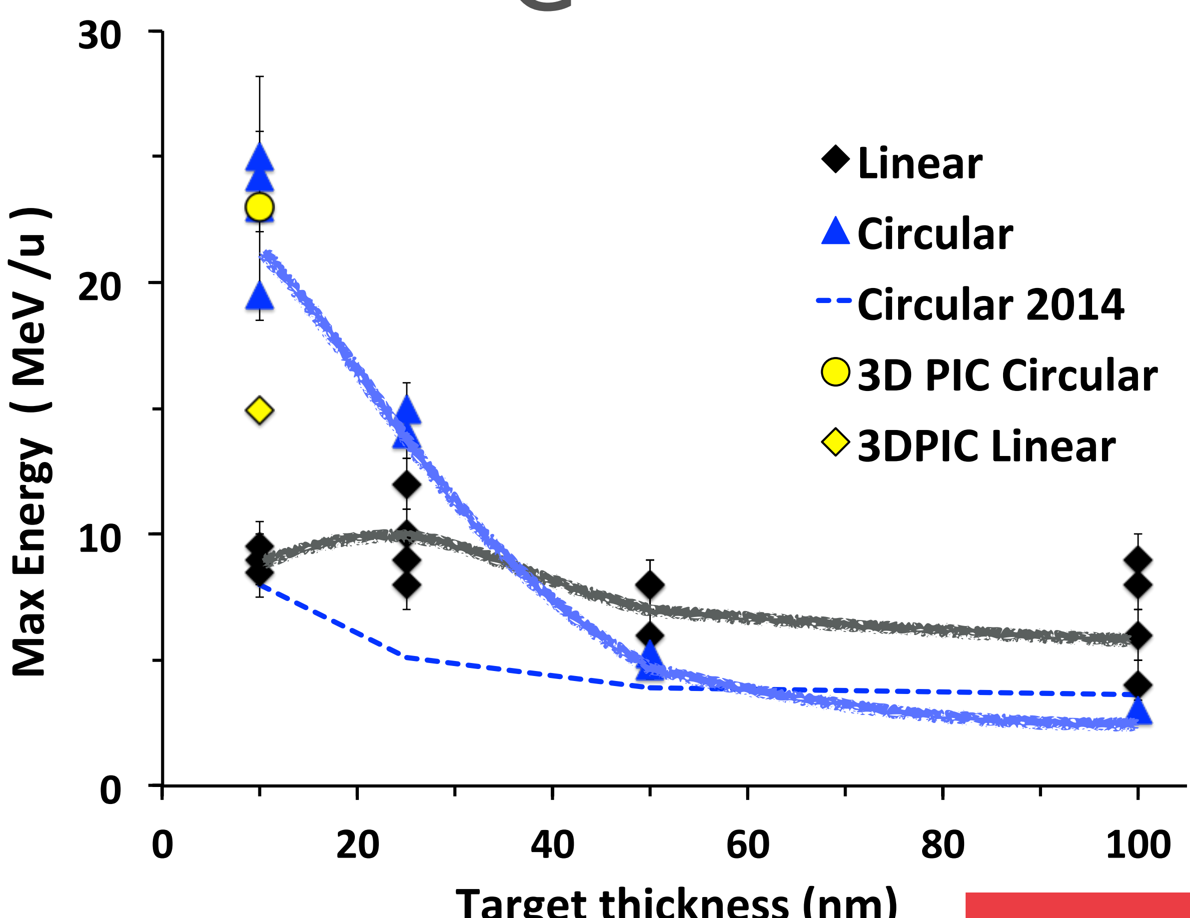
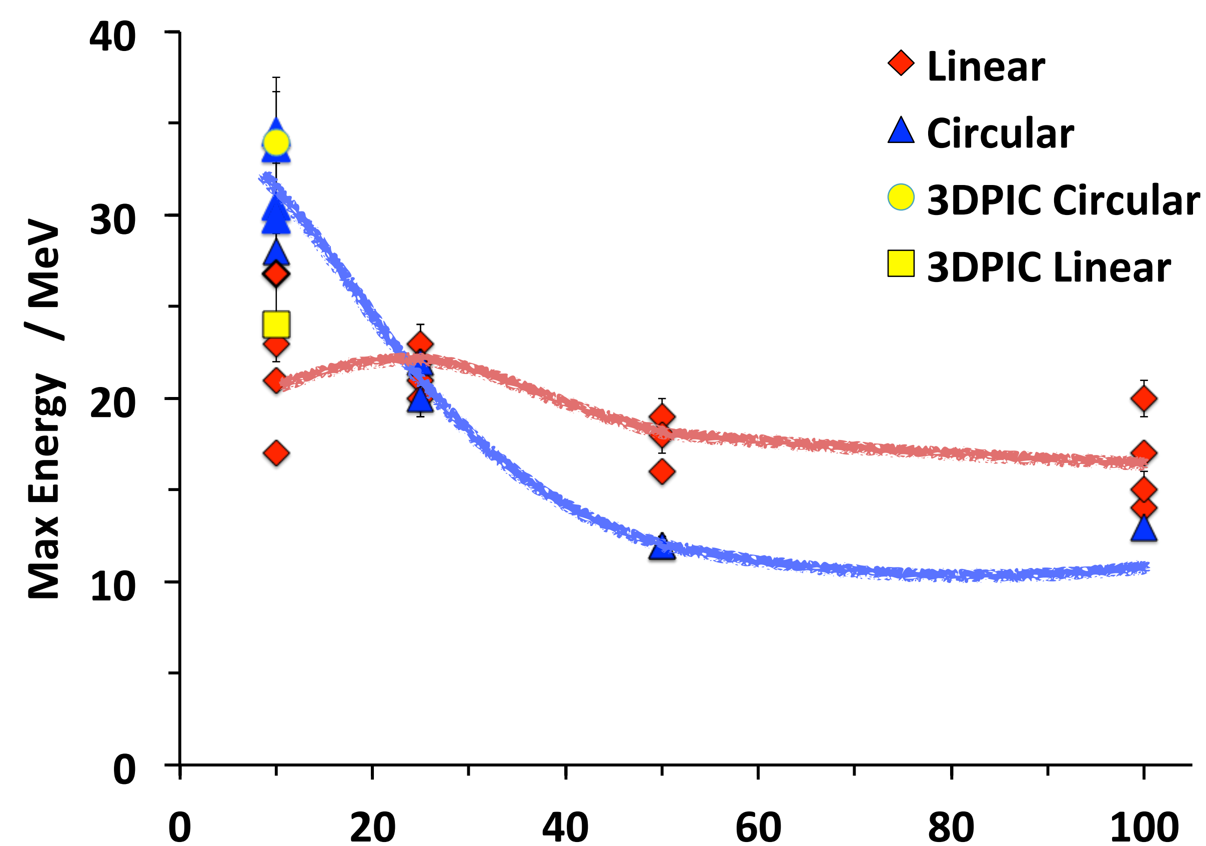
C^{6+}

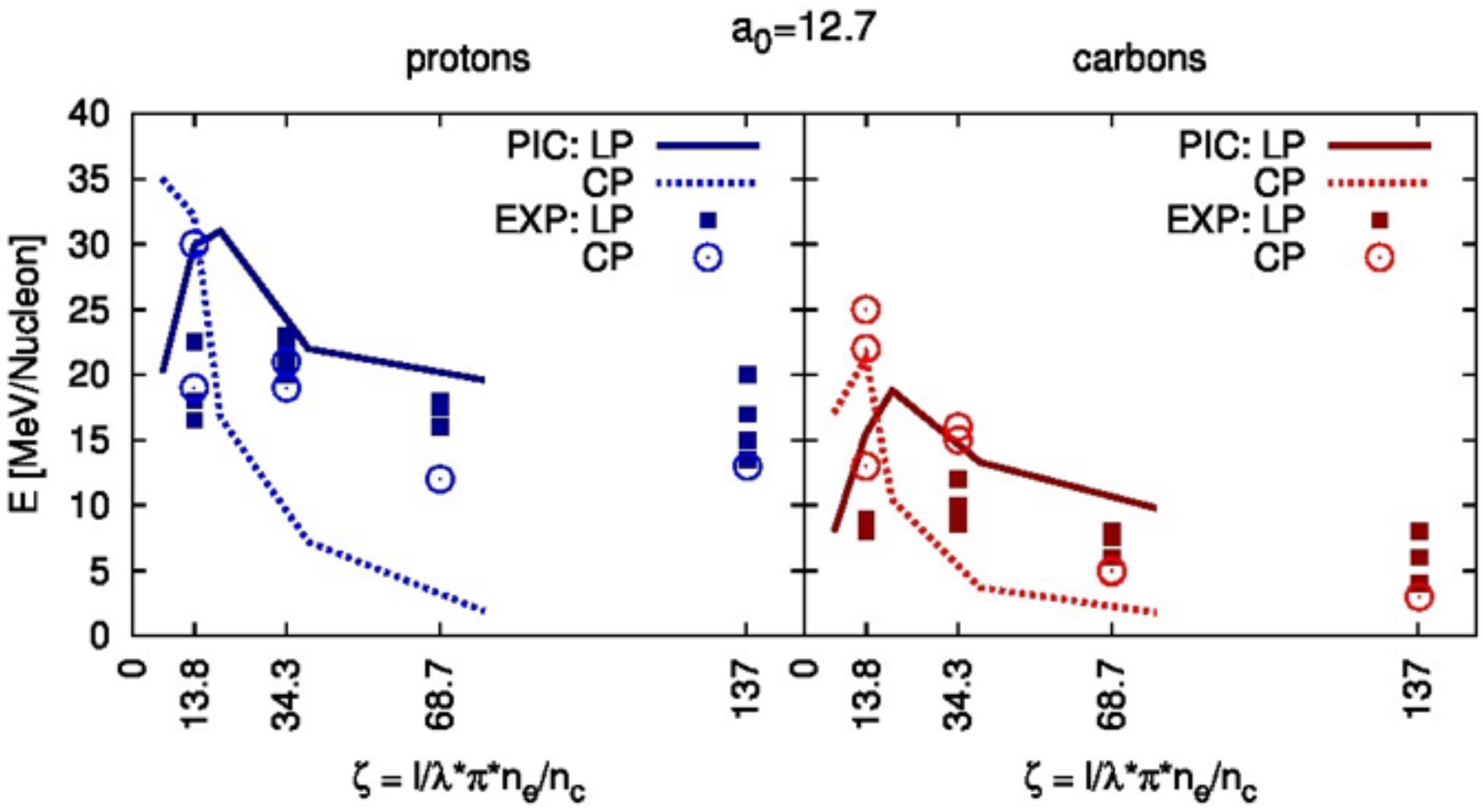


H^{+}



Talk by Clare Scullion (WG2 today 15:00)

2D simulations



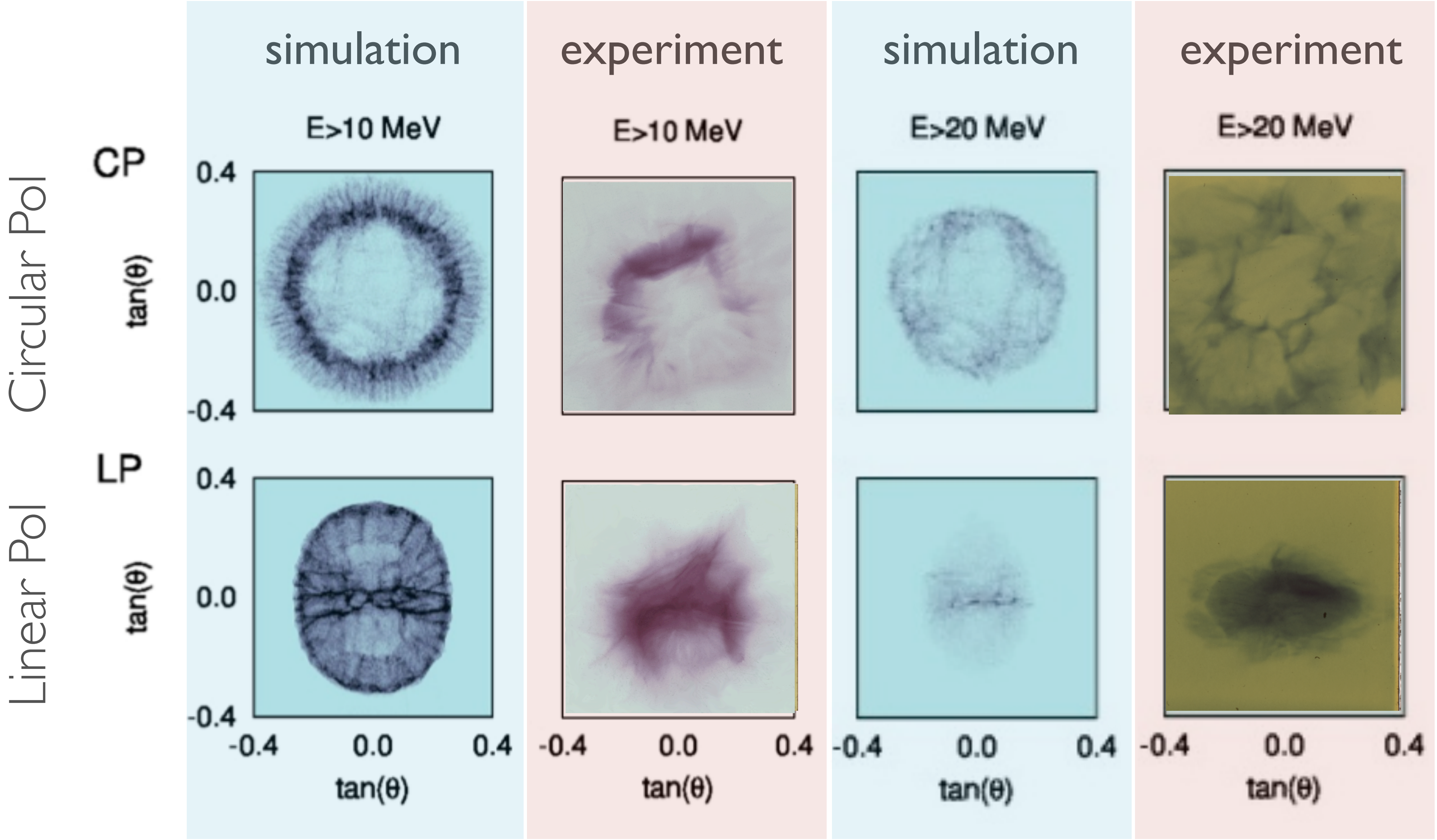
For the thinnest targets

linear-pol: electron heating leads to **transparency**

circular-pol: target stays opaque and accelerated by **radiation pressure**

Light Sail experiment (Gemini) vs. 3D PIC

τ=40fs, λ=0.8µm, E=6.5J, FWHM~4µm, I~3 · 10^{20}W/cm^2



Talk by Clare Scullion (WG2 today 15:00)

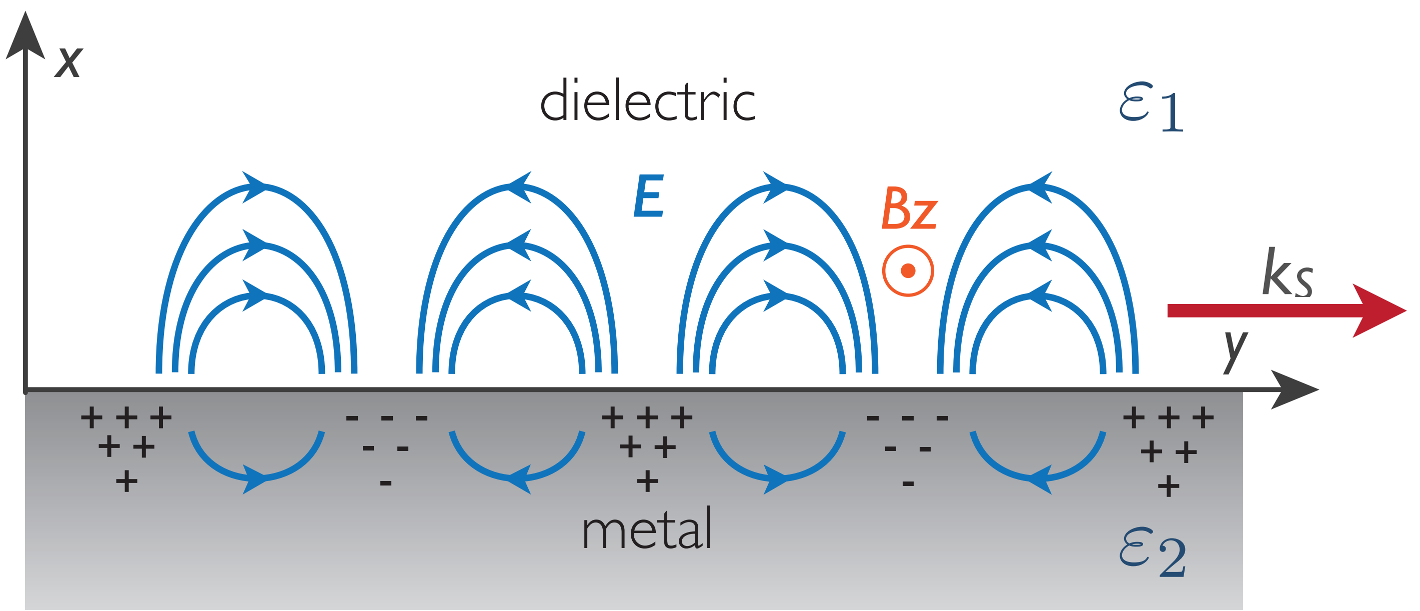
Electron acceleration using grating targets

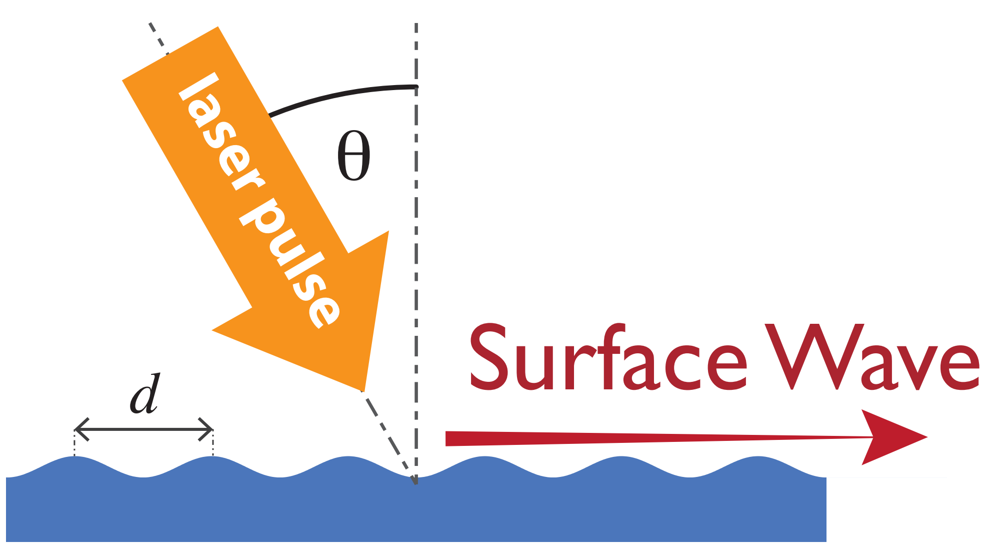
acceleration by relativistic surface waves

Surface waves excitation using grating

collective e- oscillation
at the surface of a metal
or a plasma

$$k_{SW}(\omega) = \frac{\omega}{c}\sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}}$$

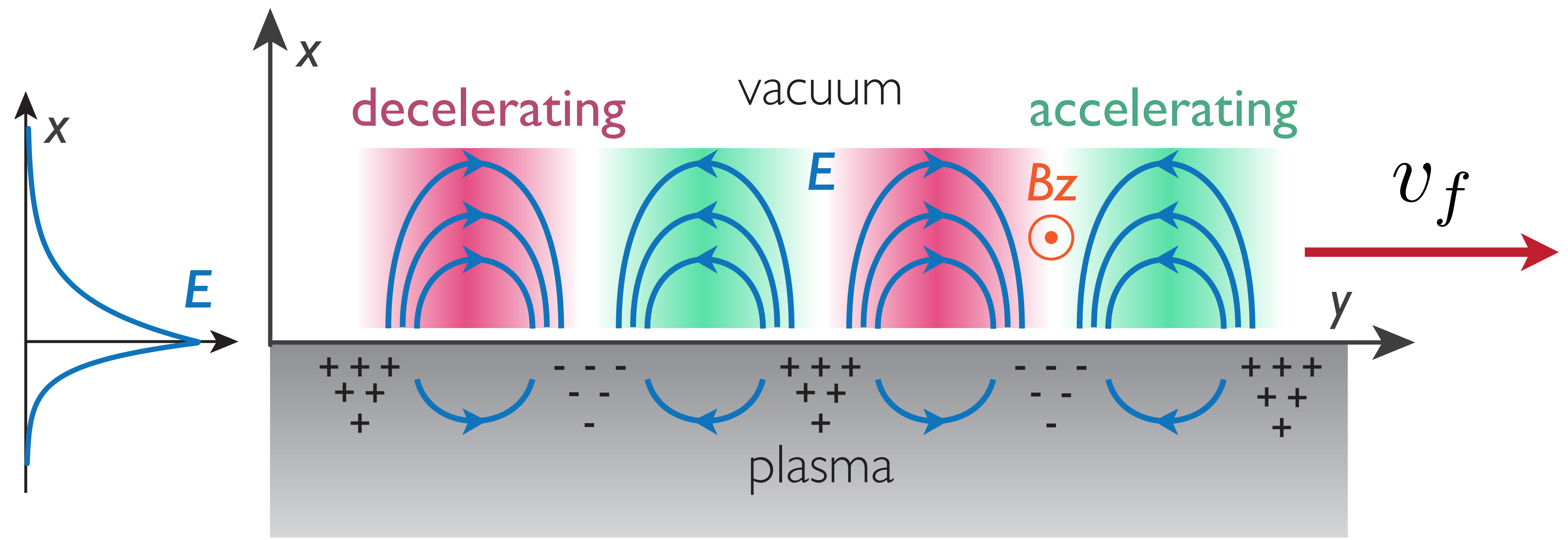




can be excited by a laser on a grating

$$\omega_L \sin(\theta) = k_{\mathrm{SW}}(\omega_L) \pm nq$$

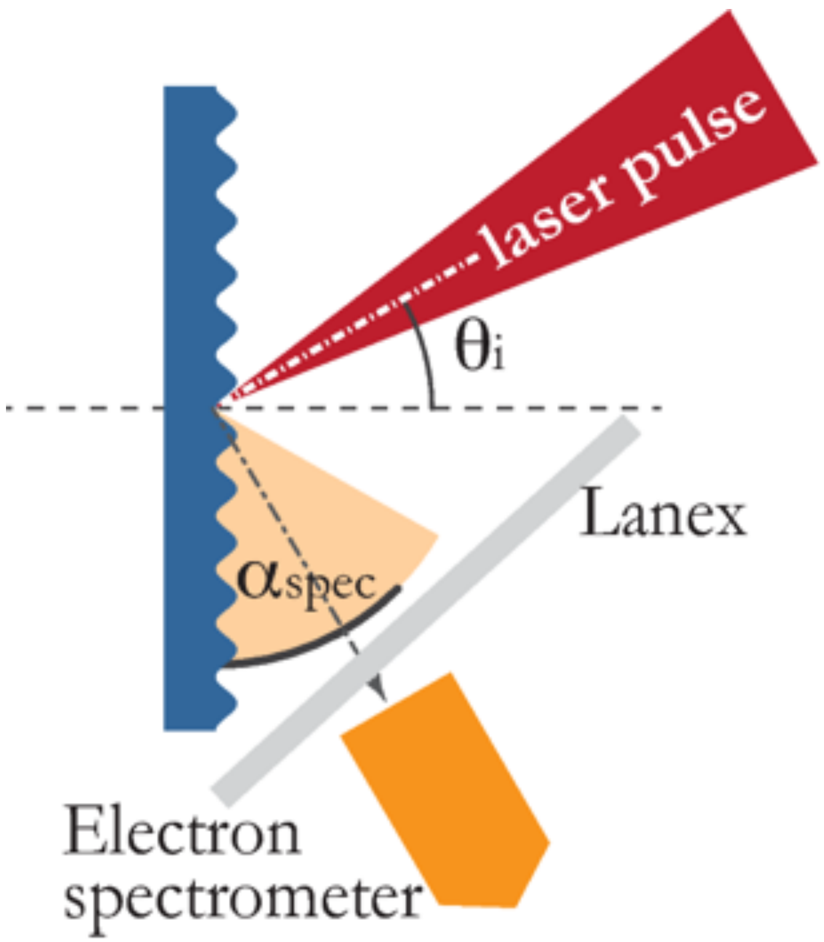
Electron acceleration by **relativistic** SW



electrons can phase-lock with SW
and be accelerated

C. Riconda et. al. Phys. Plasmas 22, 073103 (2015)

Experiment
@ SLIC CEA-Saclay France (group of T. Ceccotti)



Laser:

UHI100 laser at CEA Saclay - France

P-polarised, contrast 10^{12}

$$I \sim 5 \cdot 10^{19} \mathrm{W/cm}^2$$

$\tau \sim 25\mathrm{fs}$

$\lambda \sim 0,8\mu\mathrm{m}$

$w_0 \sim 4\mu\mathrm{m}$

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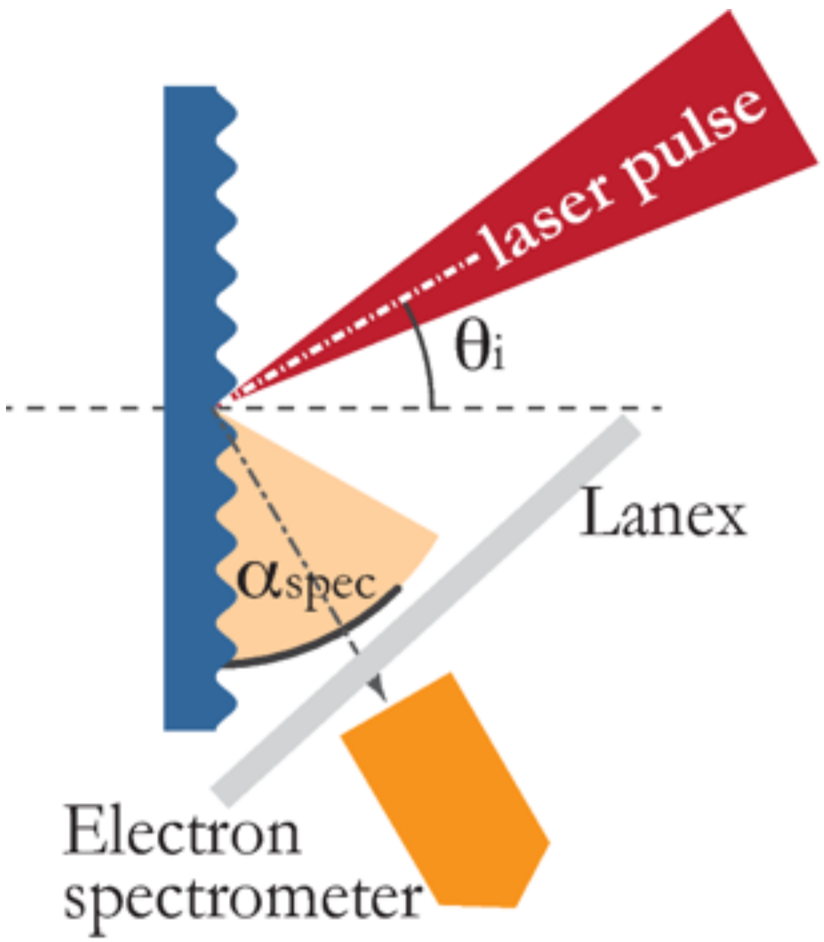

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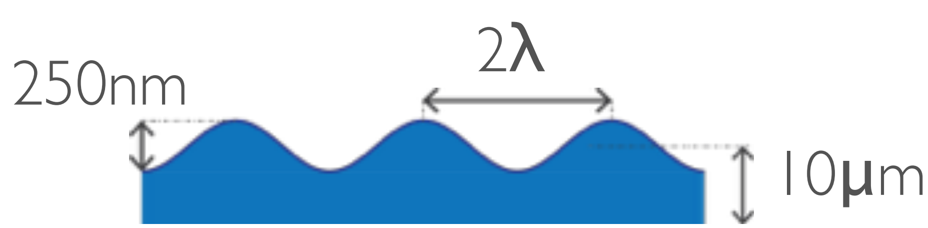
Mylar Targets

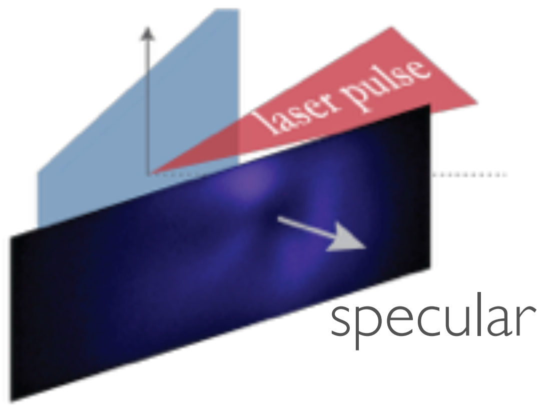


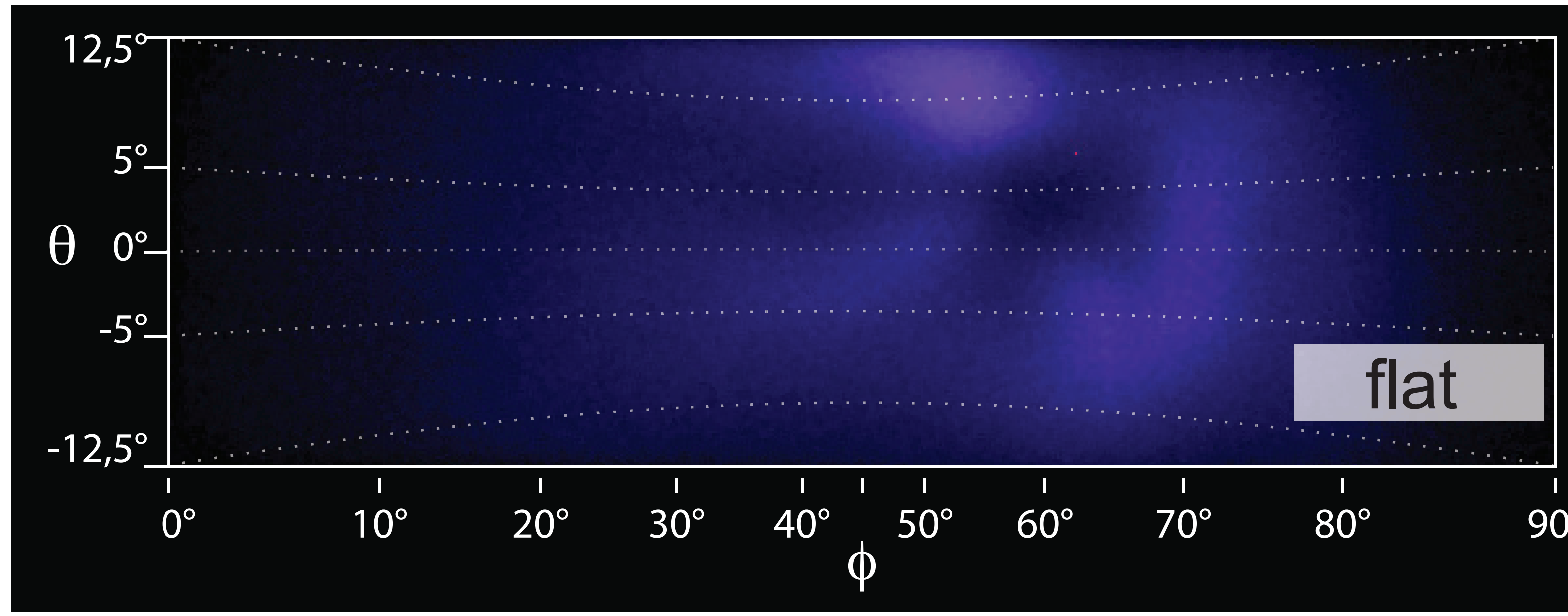
$$\theta_{\mathrm{res.}} = 30^\circ$$

Electron emission from the front side

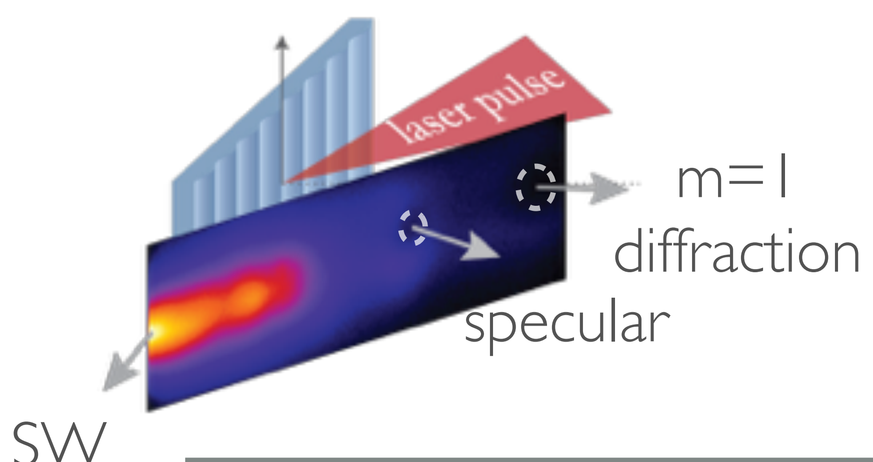
E>1.5MeV

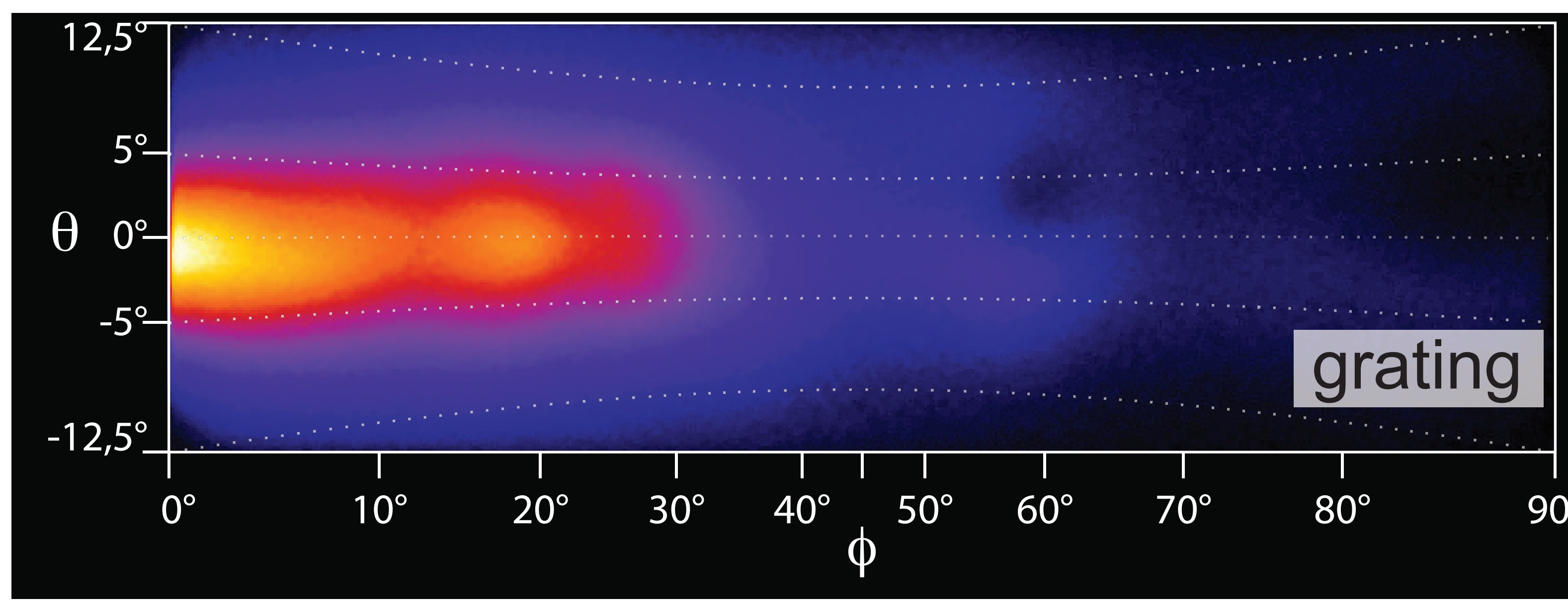
Flat target:





Grating @ resonance





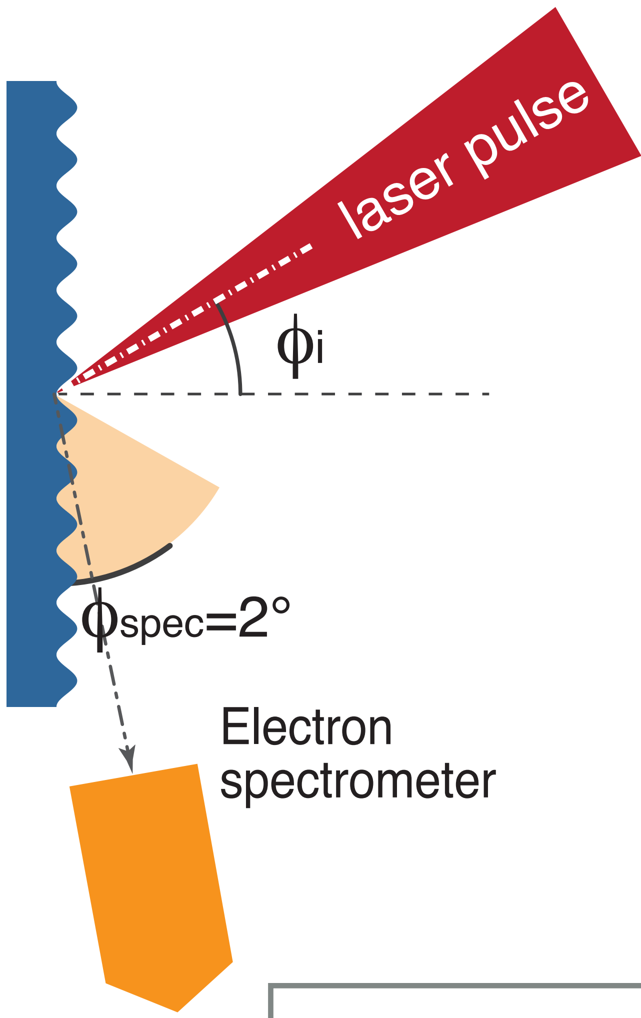
» **narrow** emission along the **surface**

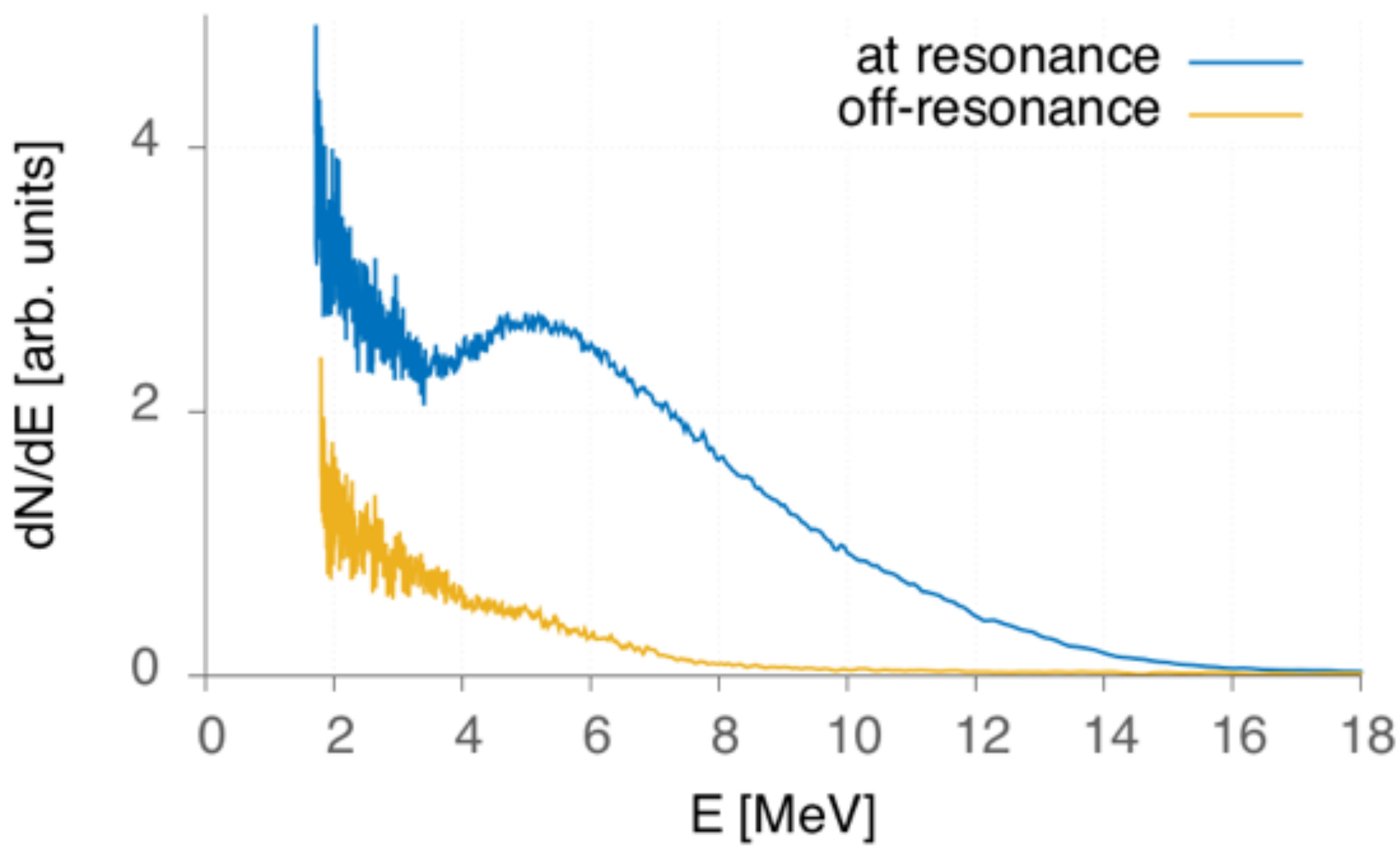
» with grating **10x higher flux:** **>100pC in ~100mrad**

Electron spectrometer: **grating** targets

$\phi_{\text{res.}} = 30°$

spectrometer kept at ϕ_{spec}~2°



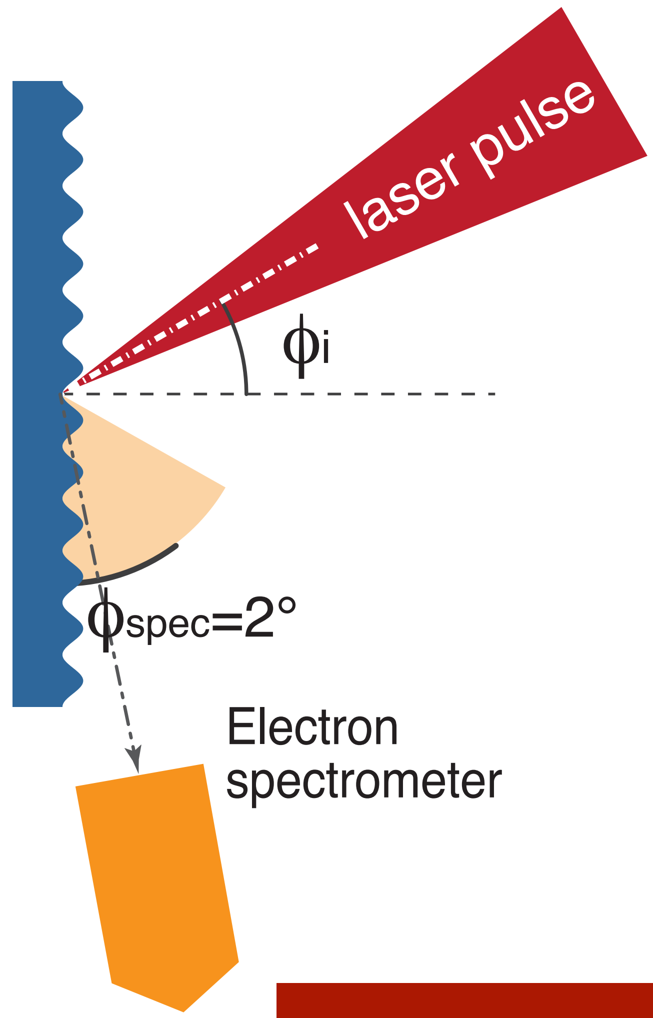


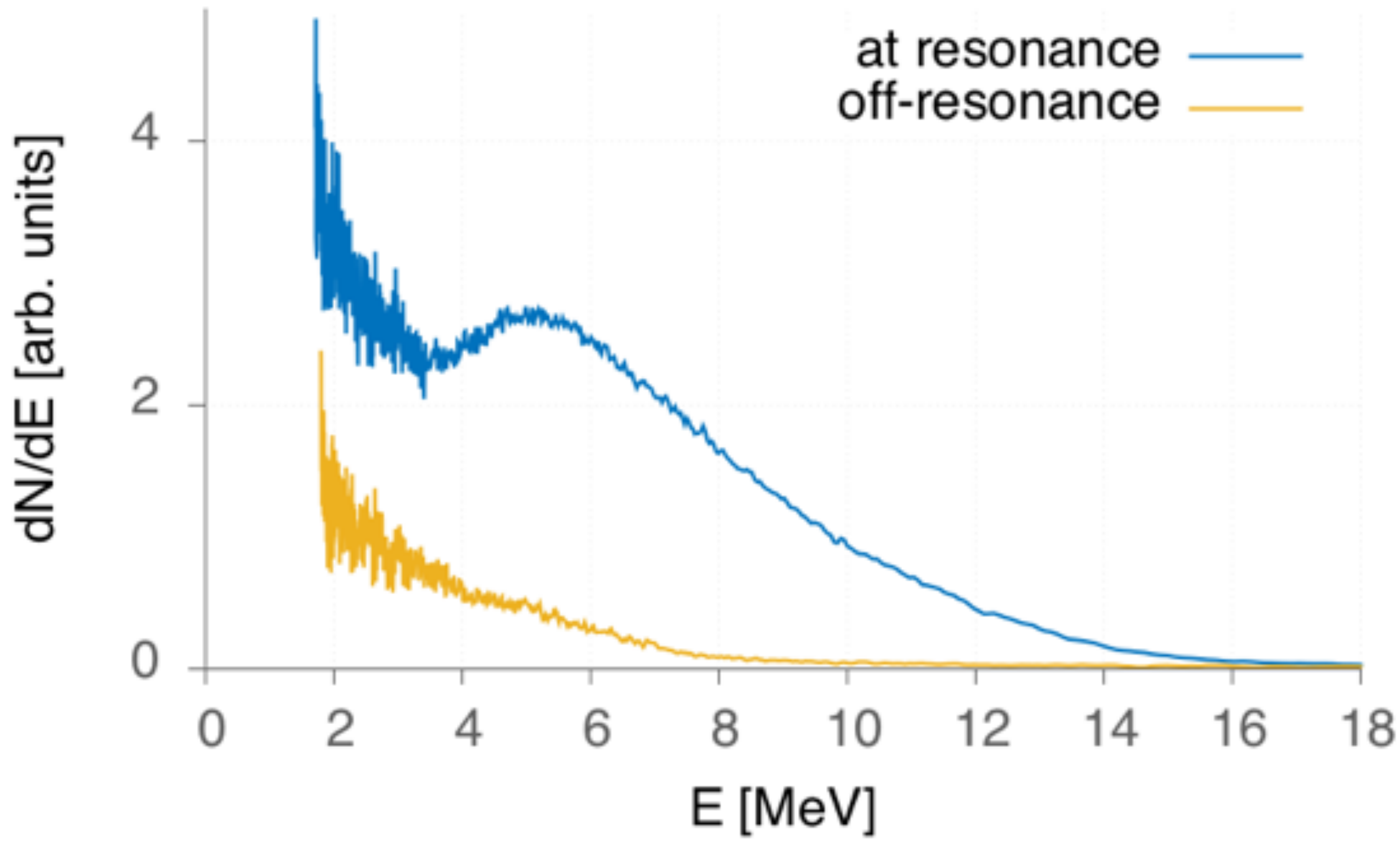
» **non-thermal** spectrum
» **peak at 6-10 MeV**
» **high energy**
»small signal out res.

Electron spectrometer: **grating** targets

$\phi_{res.} = 30°$

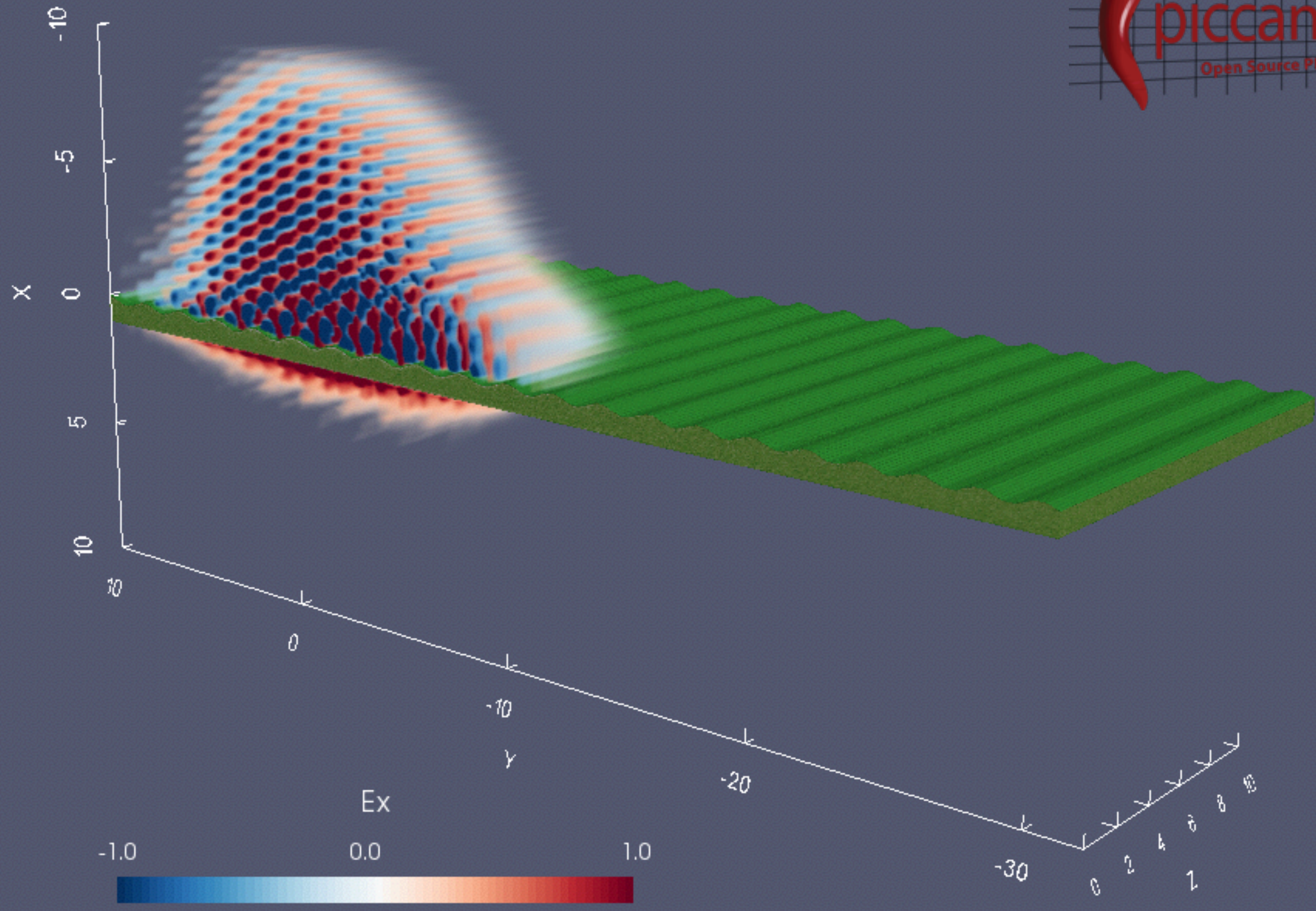
spectrometer kept at ϕ_{spec}~2°

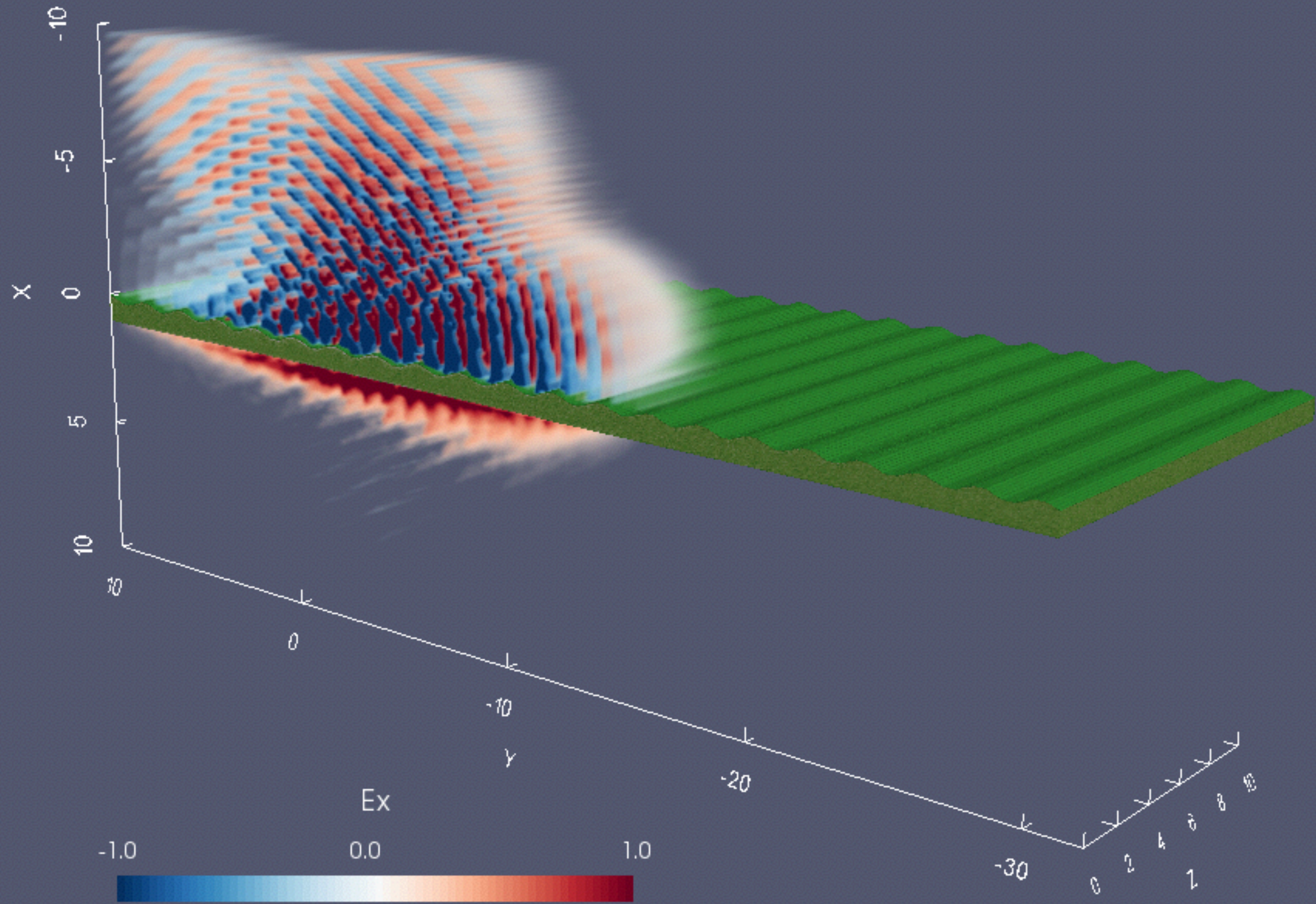




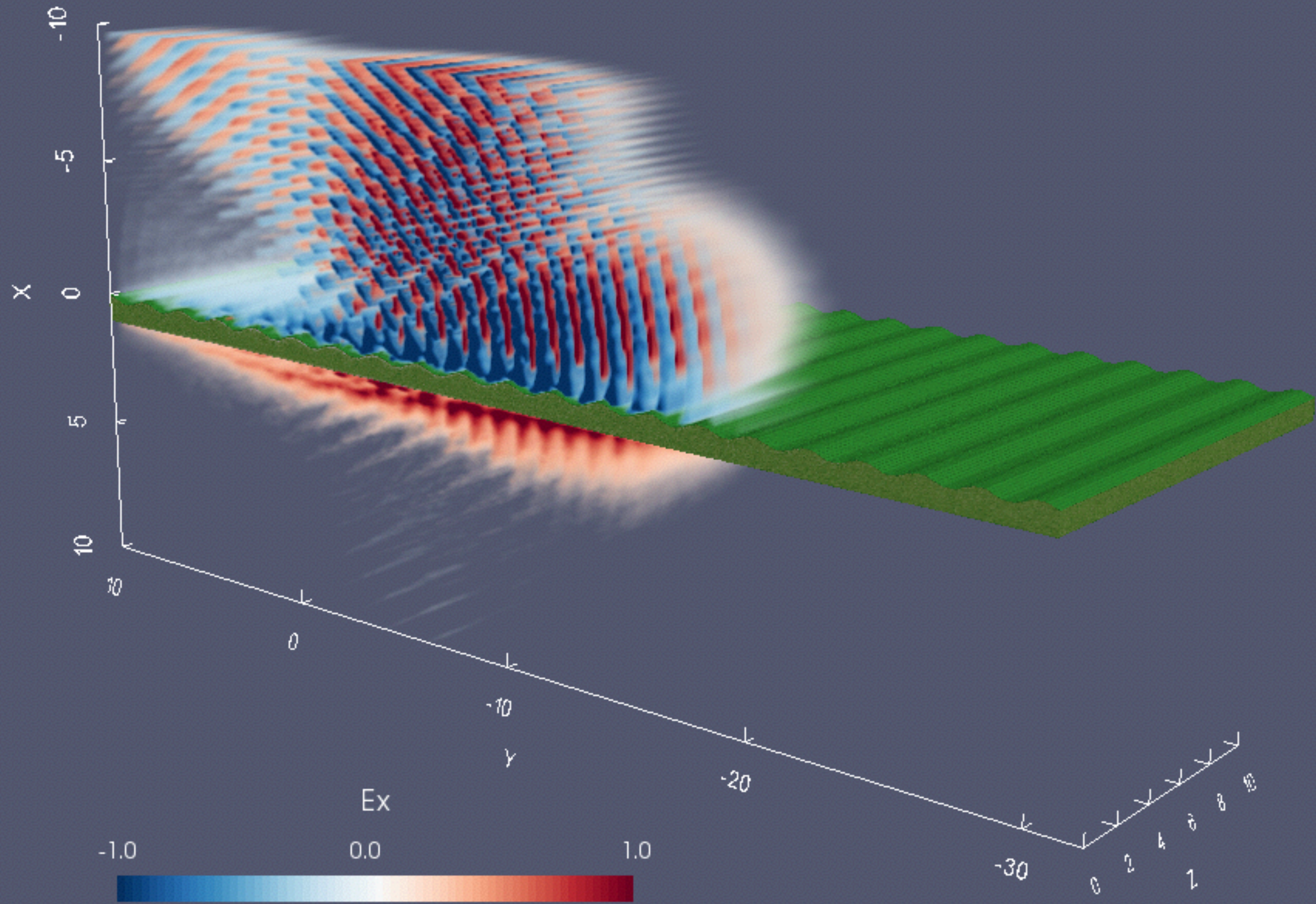
Similar results obtained with grating for different angle of resonance!!! ϕ_{res}=15° or 45°

piccante
Open Source PIC Code

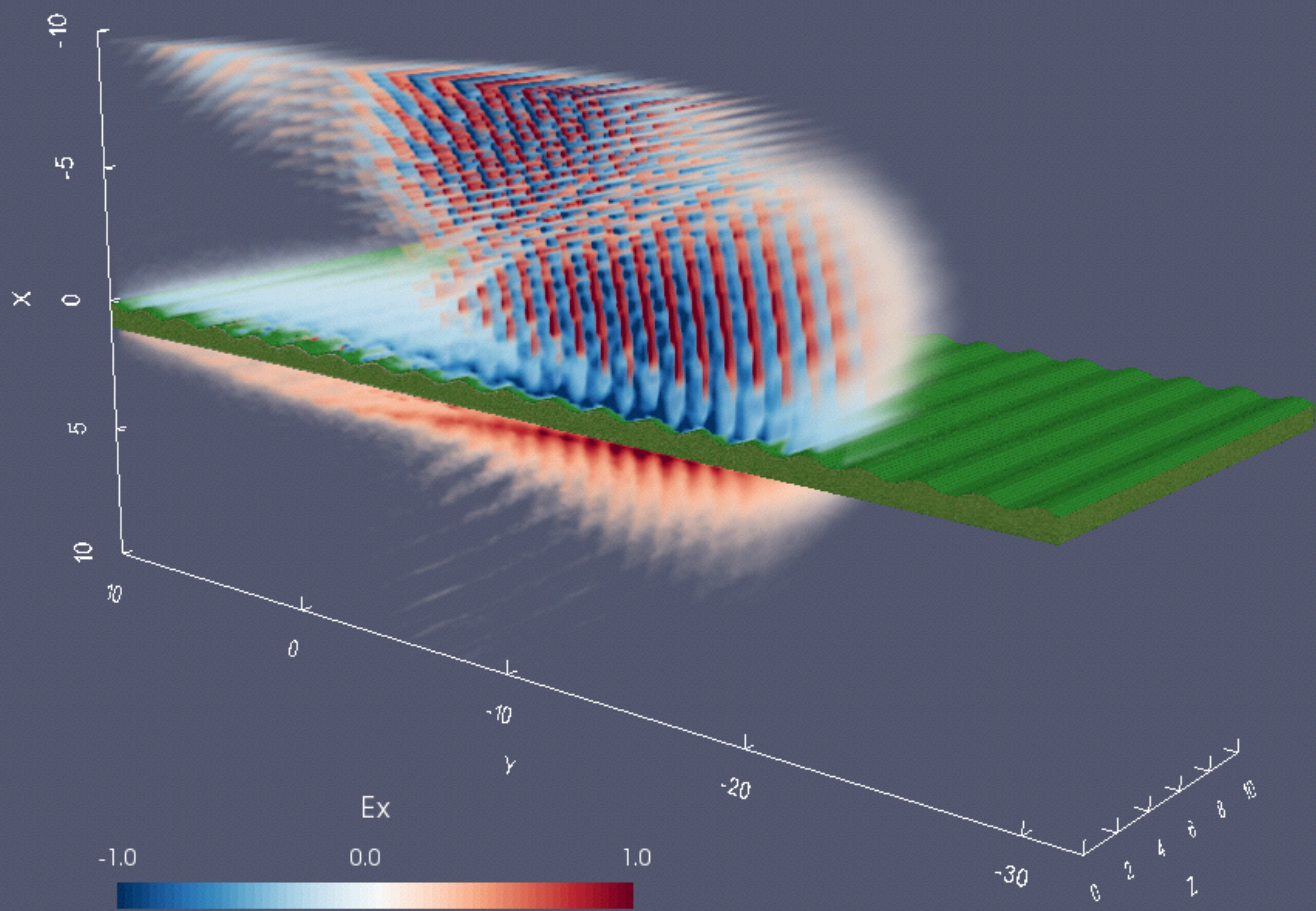




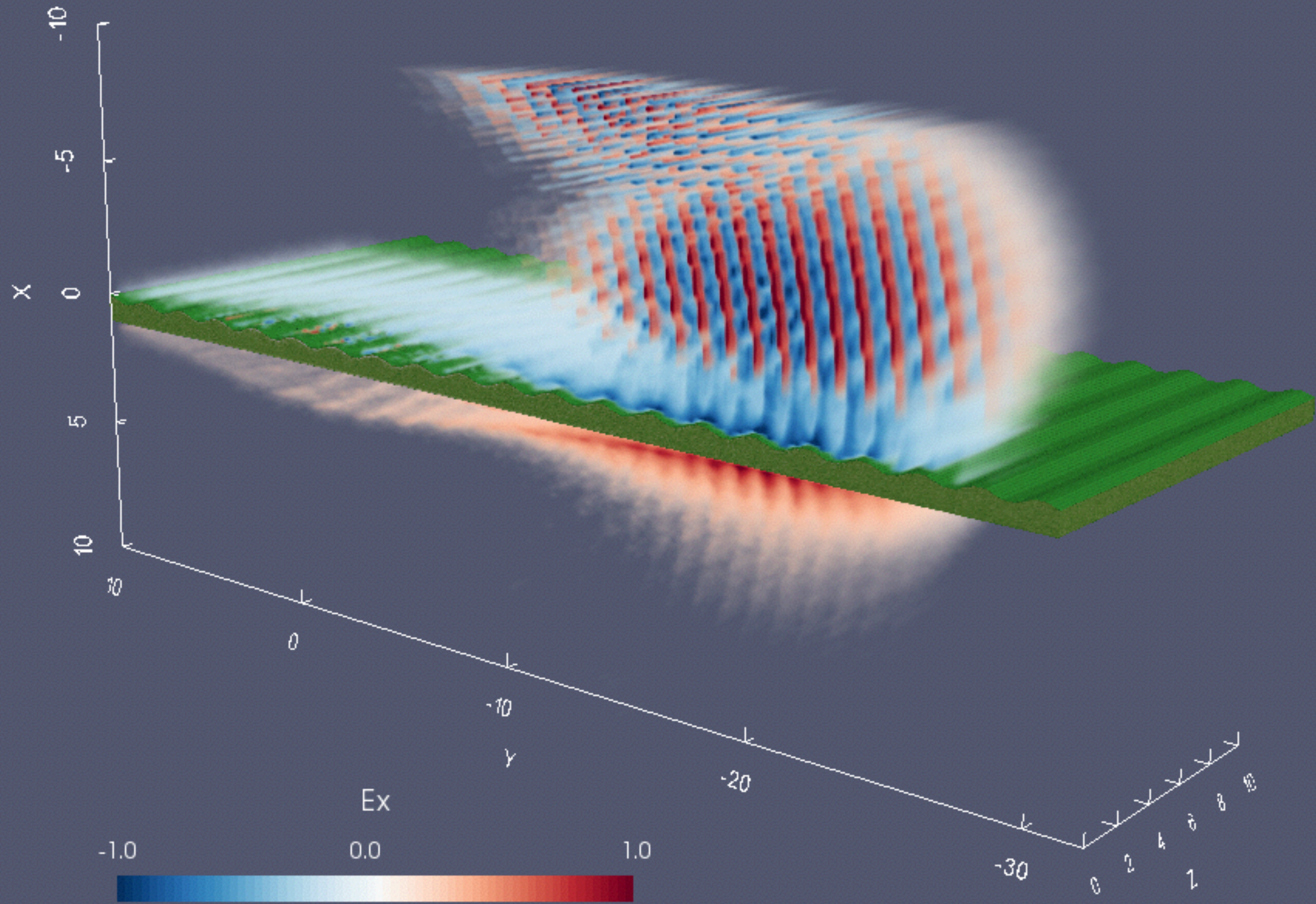
X
-10
-5
0
5
10
Y
10
0
-10
-20
-30
Z
0
2
4
6
8
10
Ex
-1.0
0.0
1.0



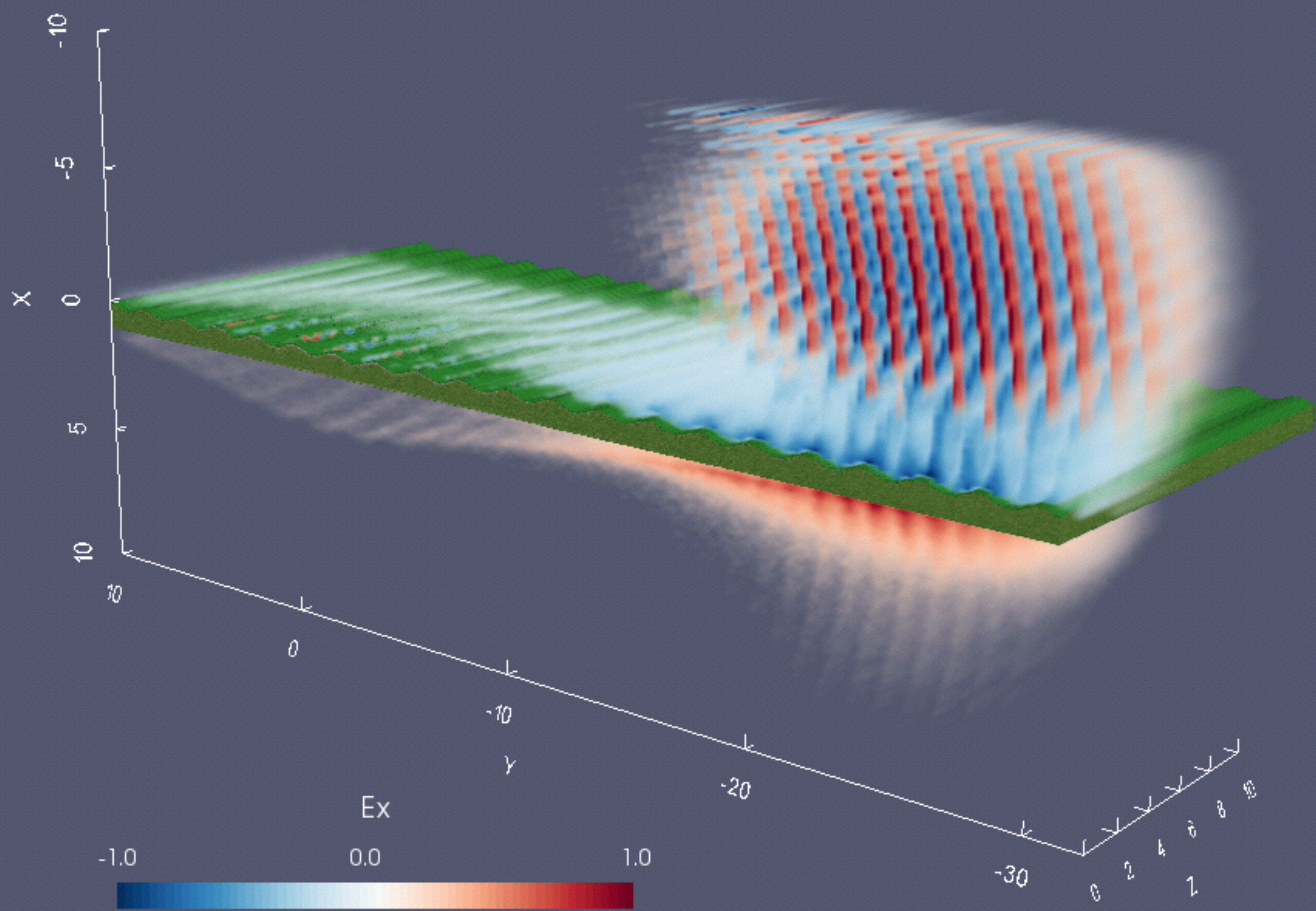
X
-10
-5
0
5
10
Y
10
0
-10
-20
-30
Z
0
2
4
6
8
10
Ex
-1.0
0.0
1.0



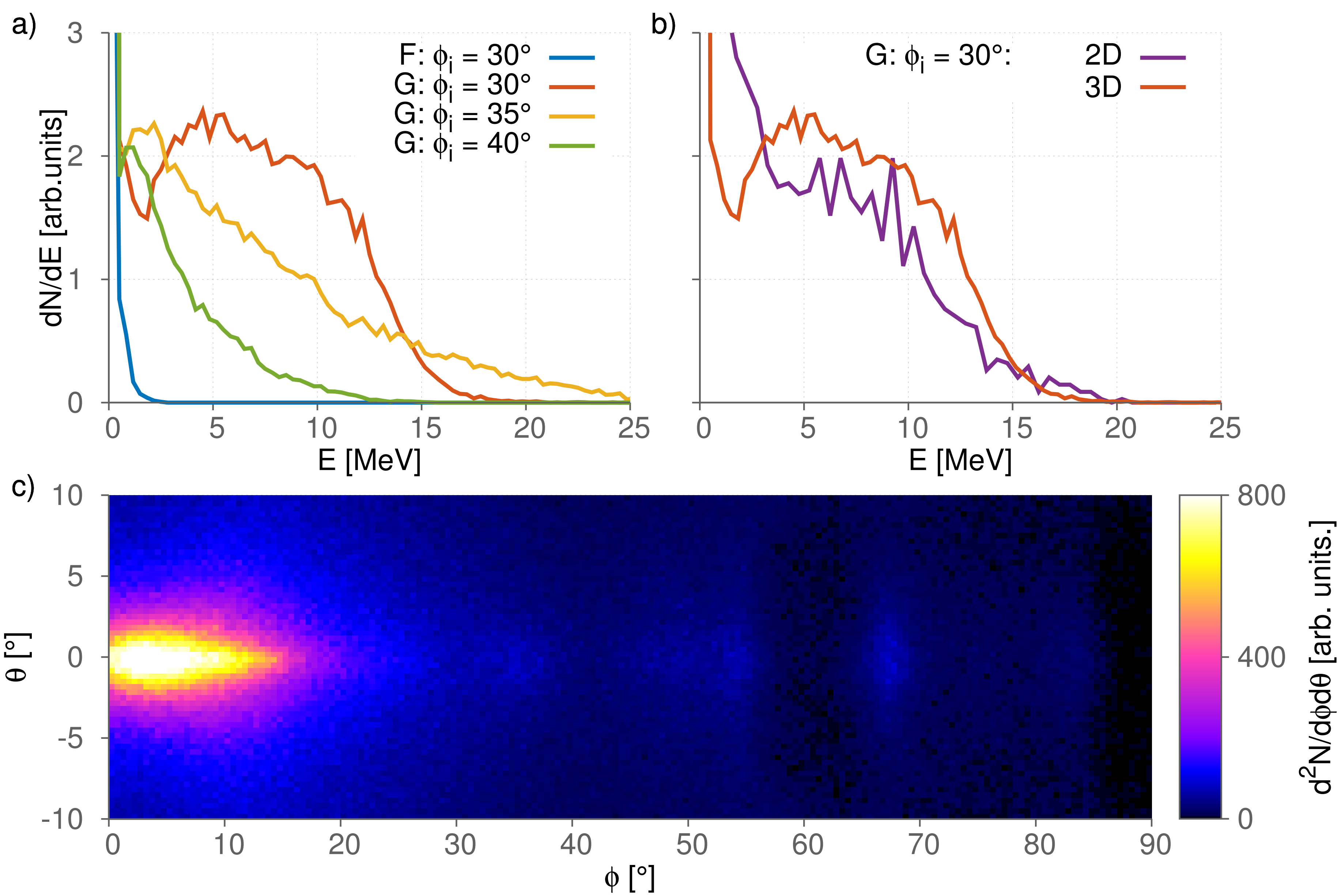
X
-10
-5
0
5
10
Y
10
0
-10
-20
-30
Z
0
2
4
6
8
10
Ex
-1.0
0.0
1.0



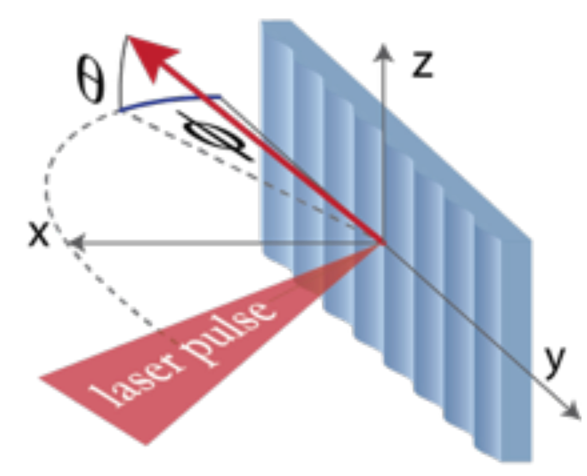
-10
-5
X
0
5
10
10
0
-10
Y
-20
-30
0
2
4
6
8
10
Z
Ex
-1.0
0.0
1.0


-10
-5
X 0
5
10
10
0
-10
Y
-20
-30
0 2 4 6 8 10
Z
Ex
-1.0
0.0
1.0

3D simulations



at ϕ=2° Θ=0°

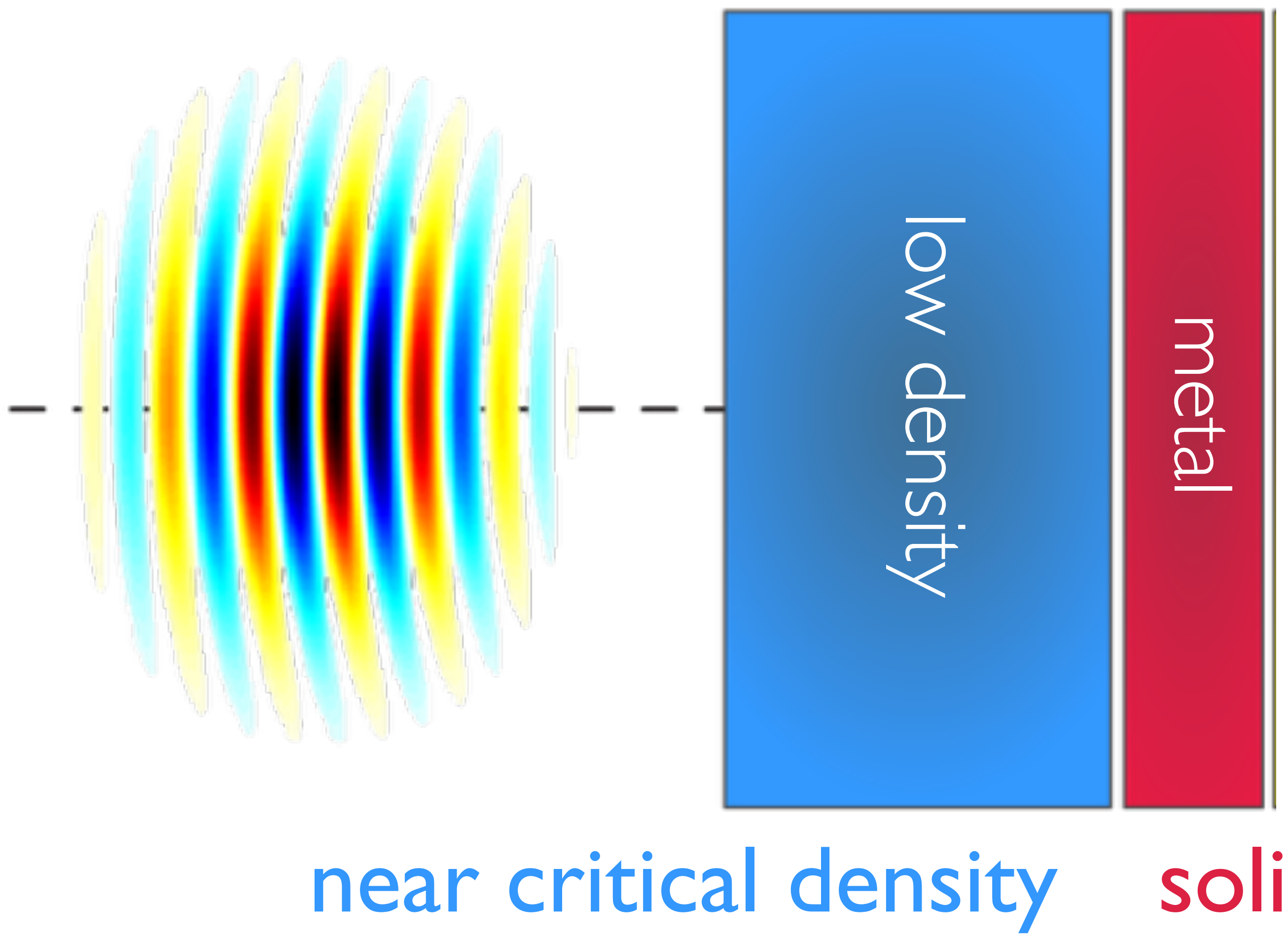


Only the 3D simulation reproduces correctly the ***e-spectra***

Targets for enhanced TNSA

thin solid foils with a thick low density foam layer

2 Layer target for enhanced TNSA



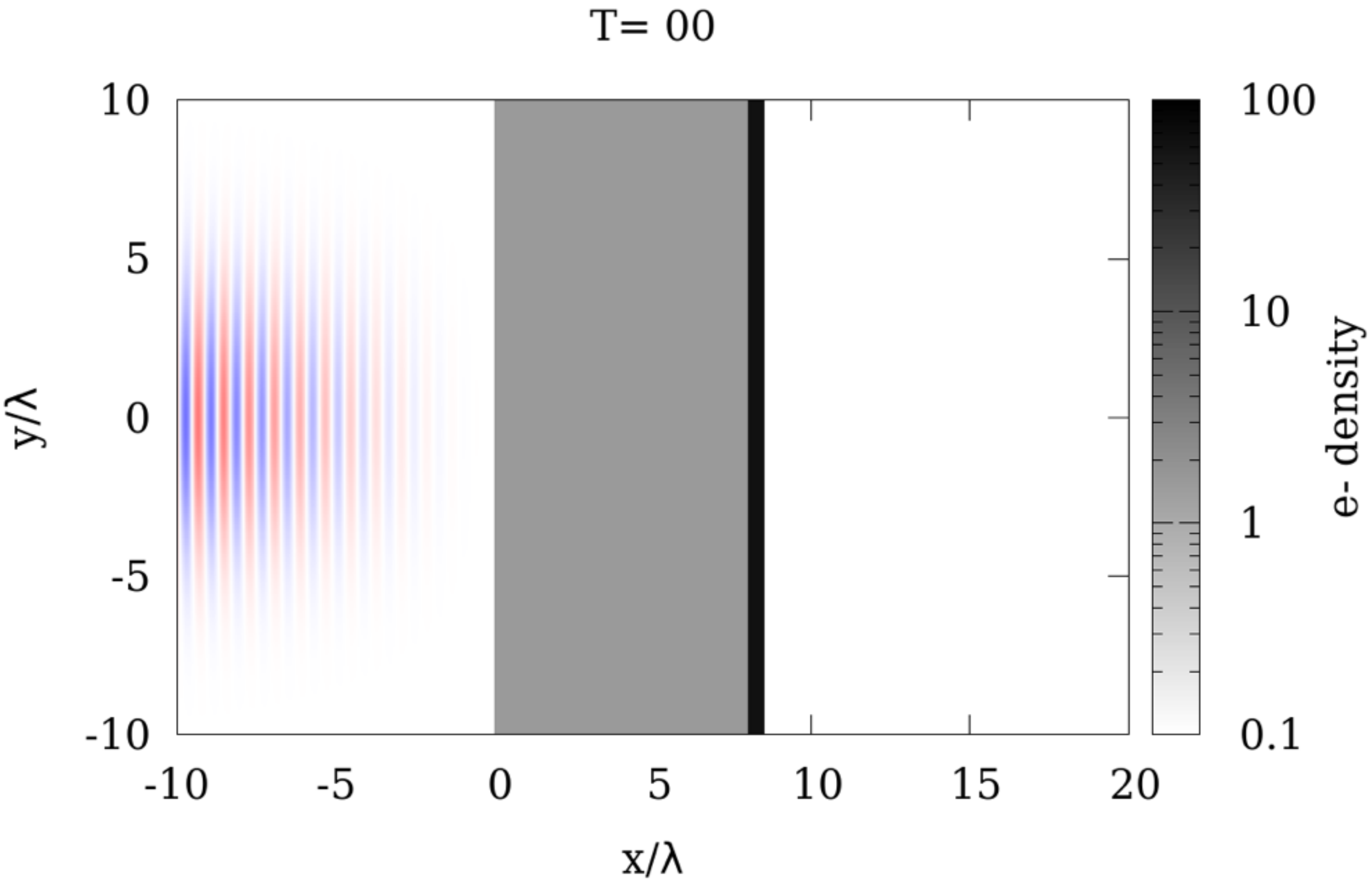
- High energy absorption
- High electron temperature
- Enhanced proton acceleration

Nakamura et. al. PoP **17**, (2010)

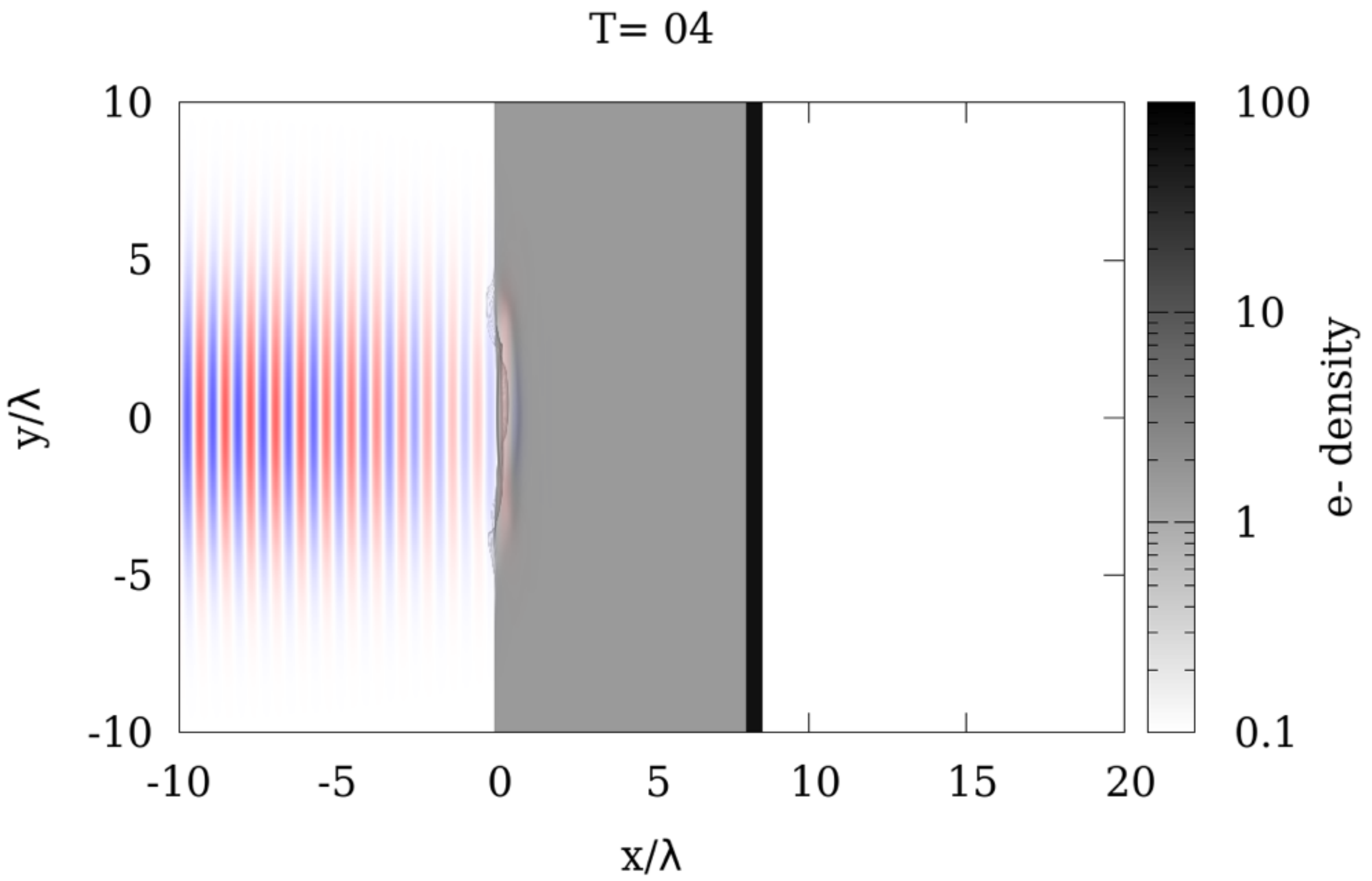
Passoni et. al. PPCF 56(2014)

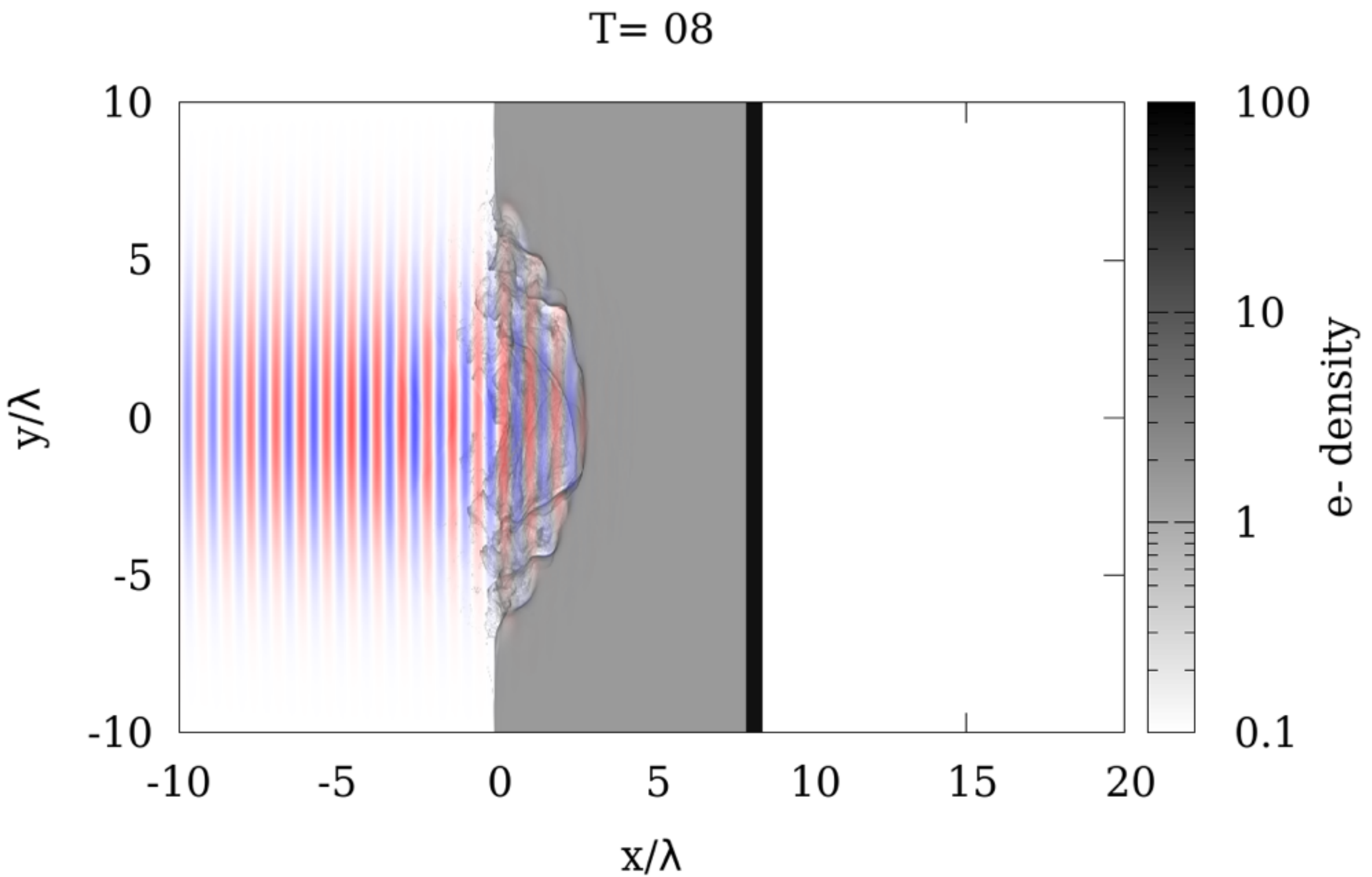
Sgattoni et. al. PRE **85** (2012)

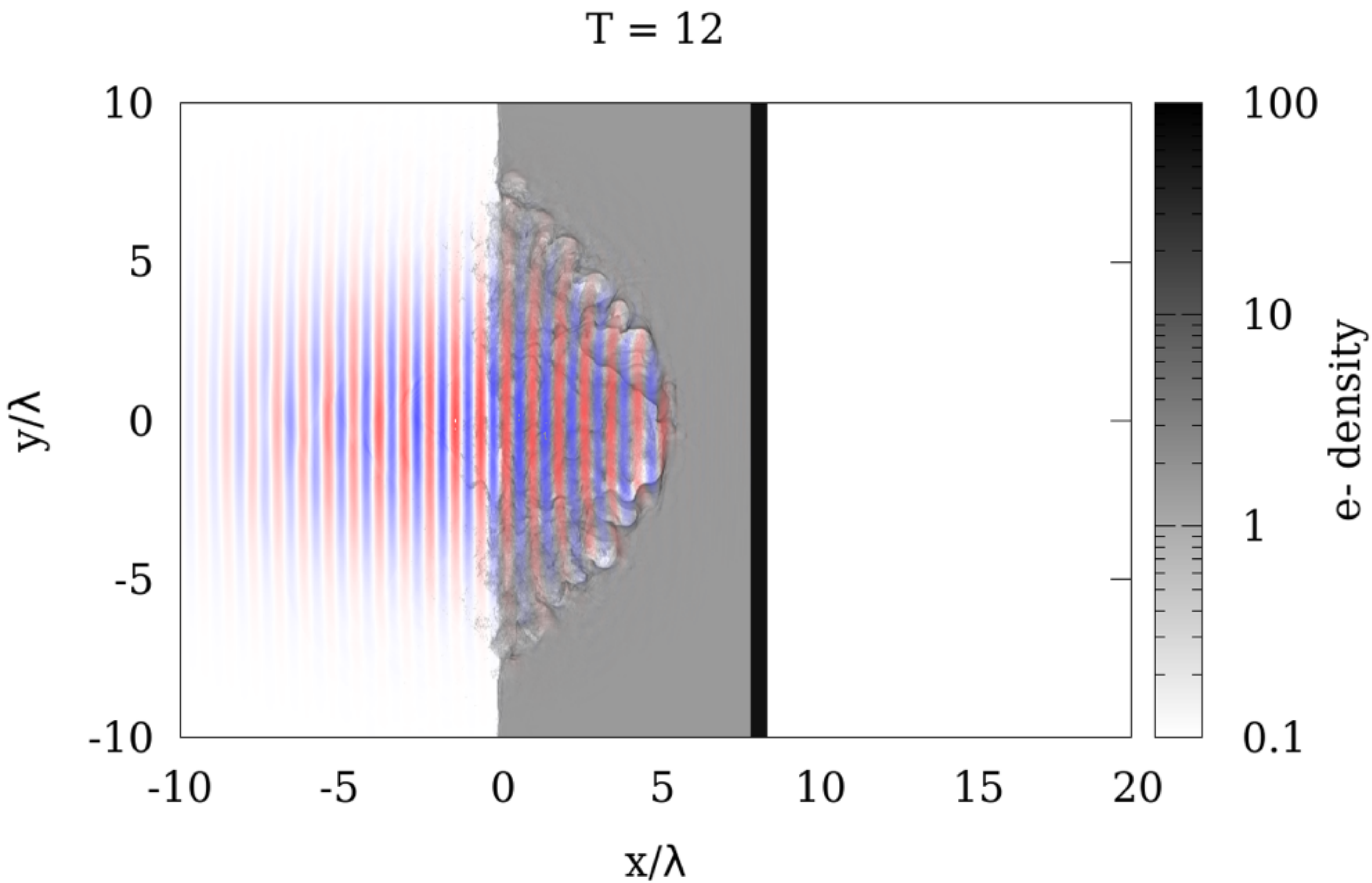
J. H. Bin, et. al. PRL **115**(2015)

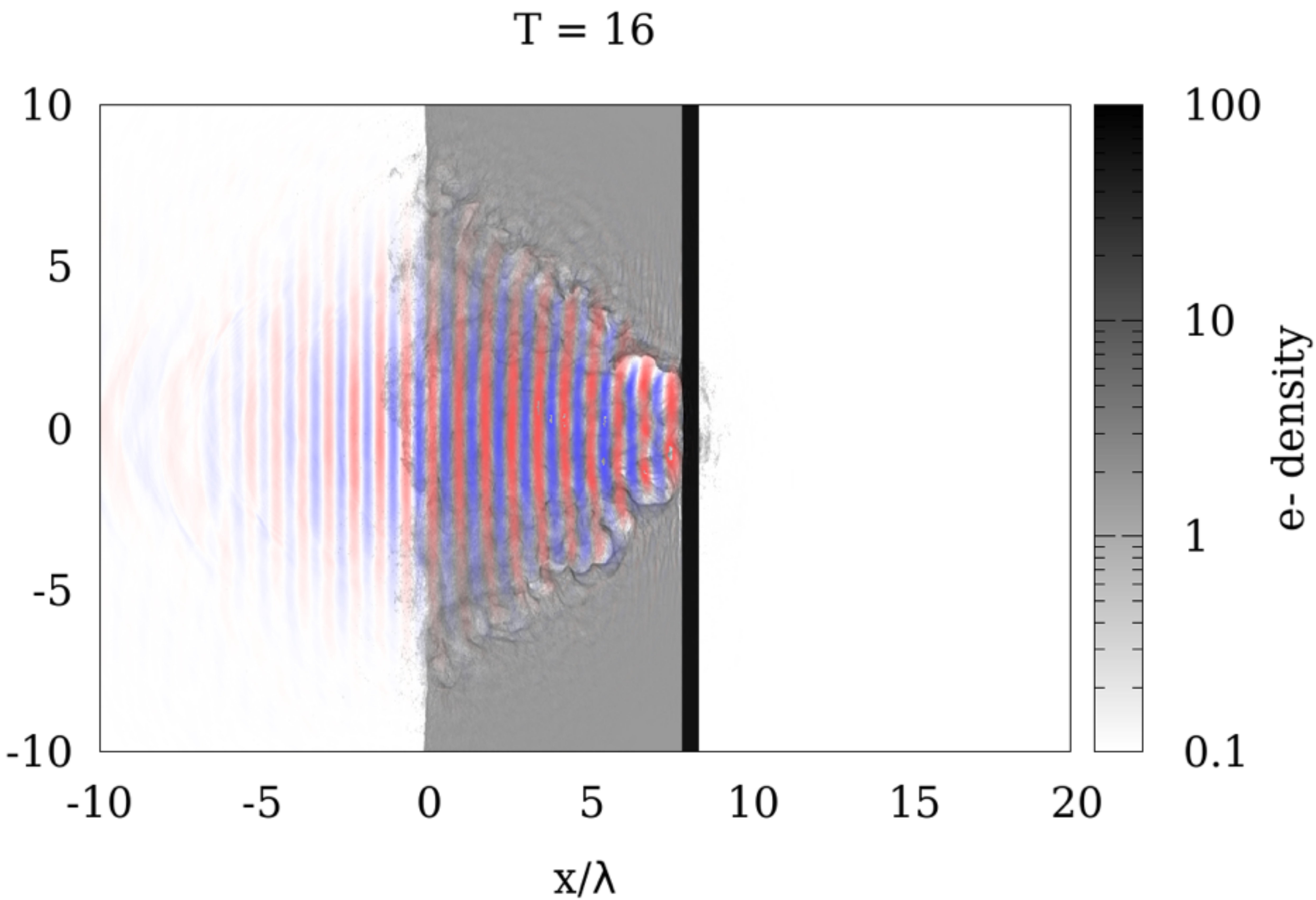


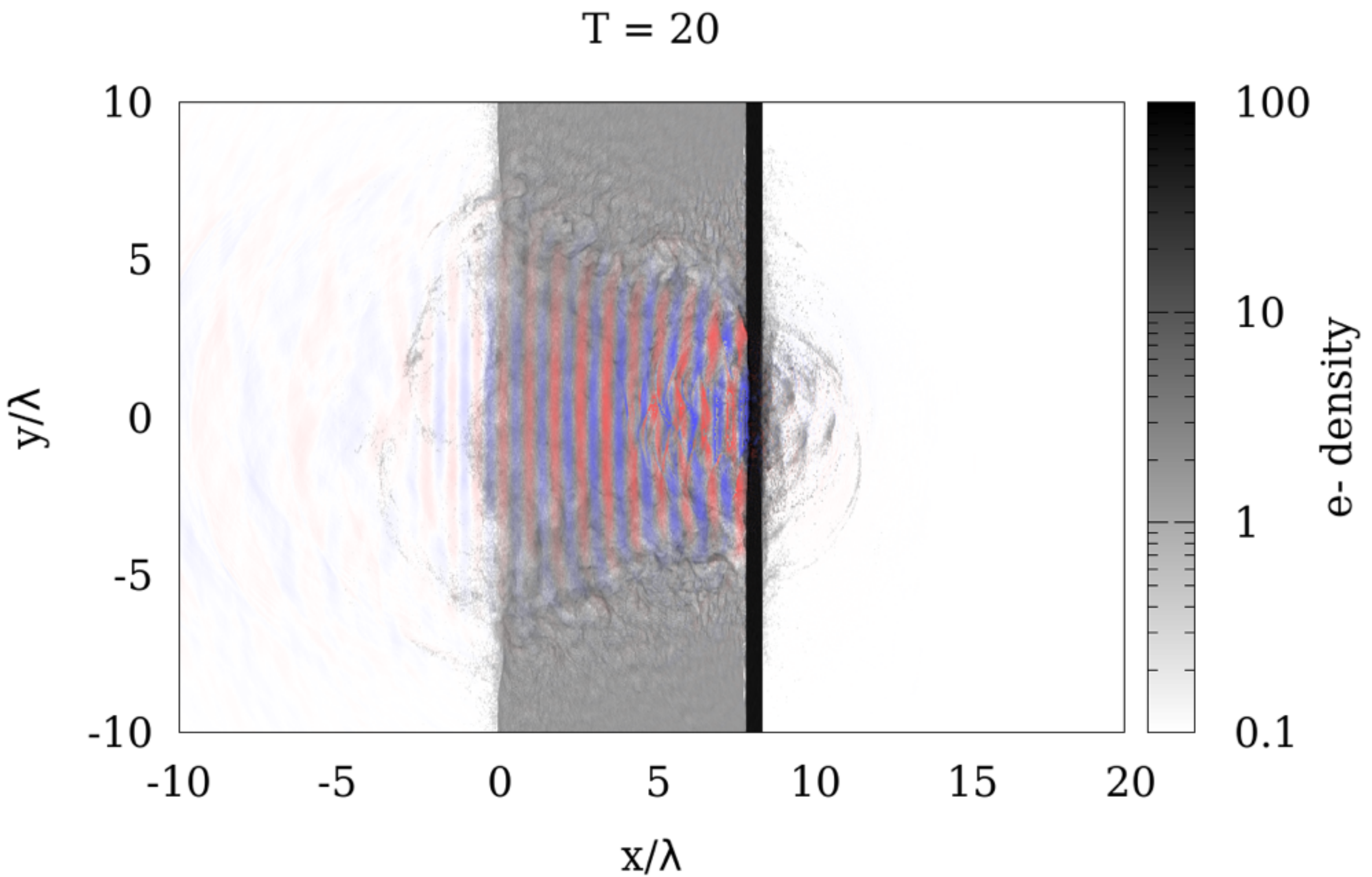
T= 00
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

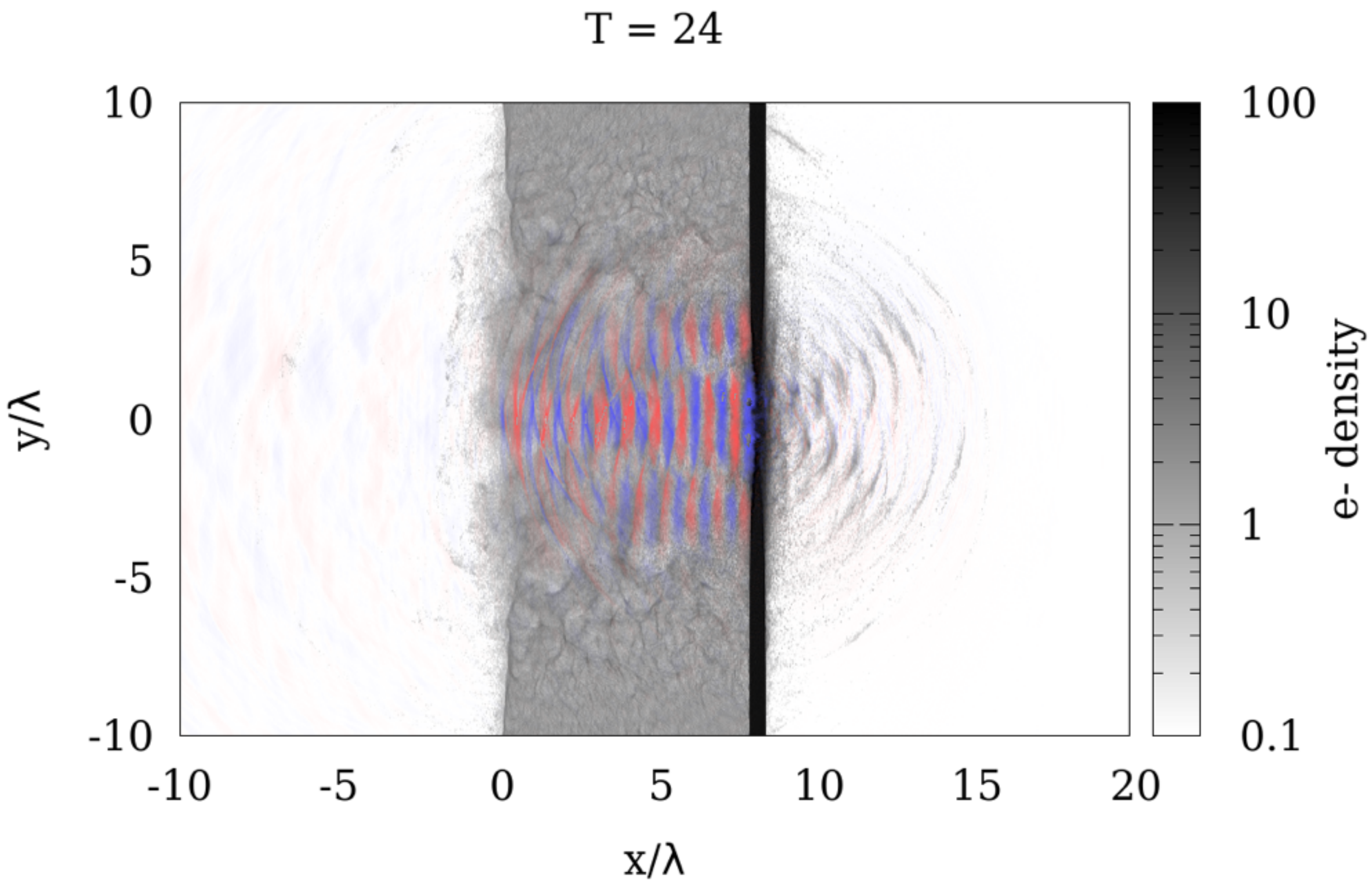

T= 04
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

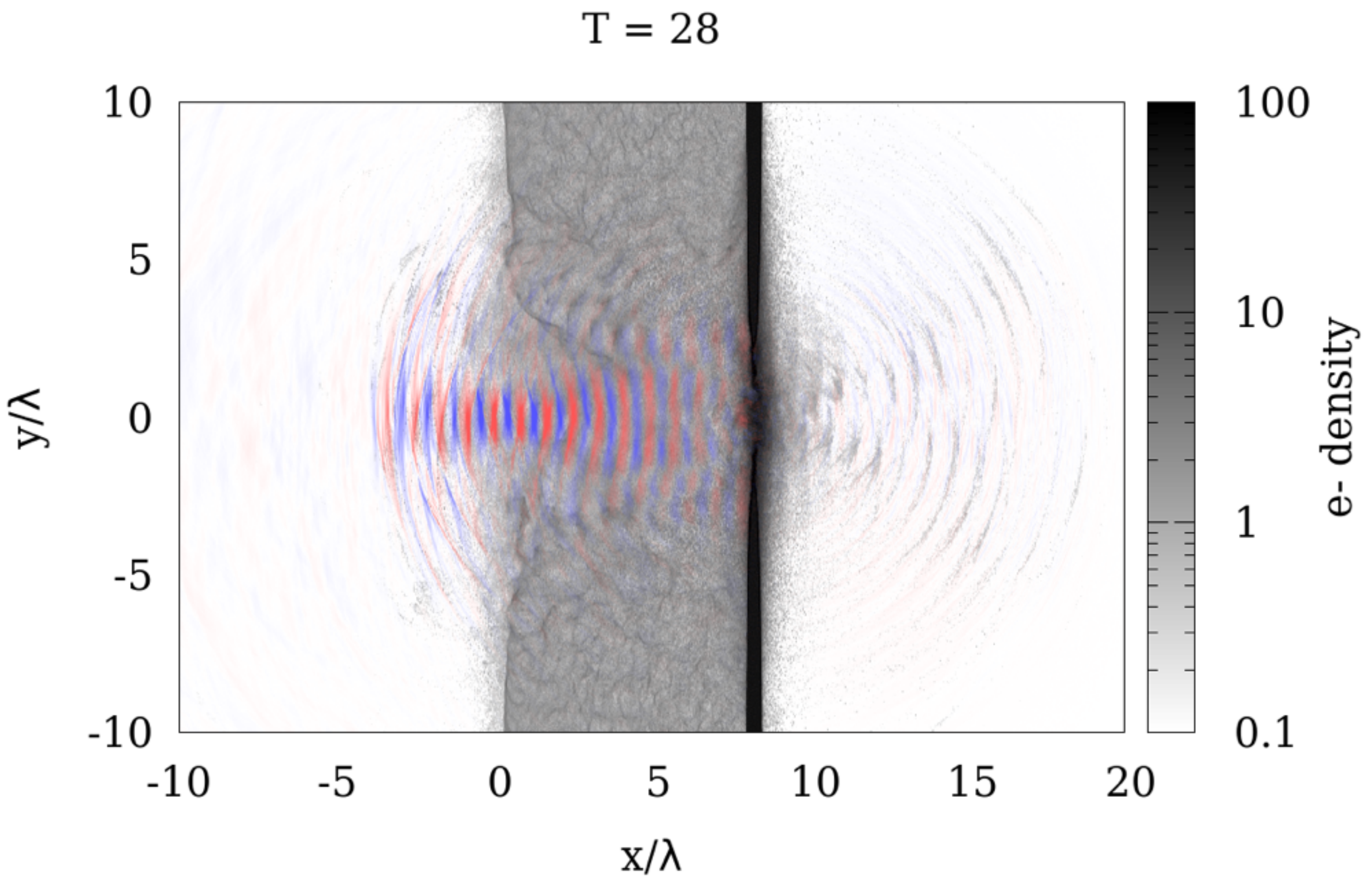

T= 08
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density


T = 12
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

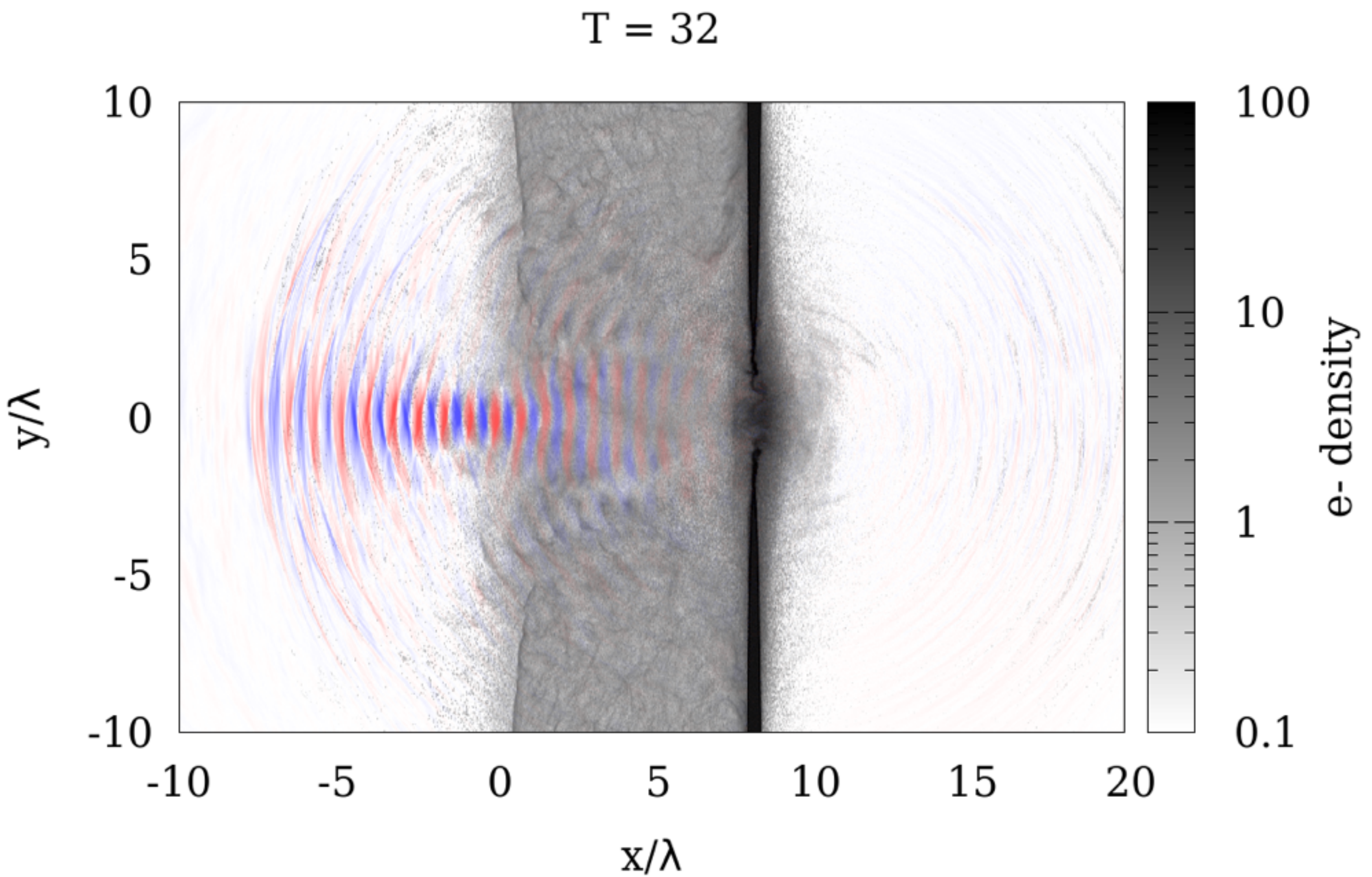

T = 16
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density


T = 20
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density


T = 24
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

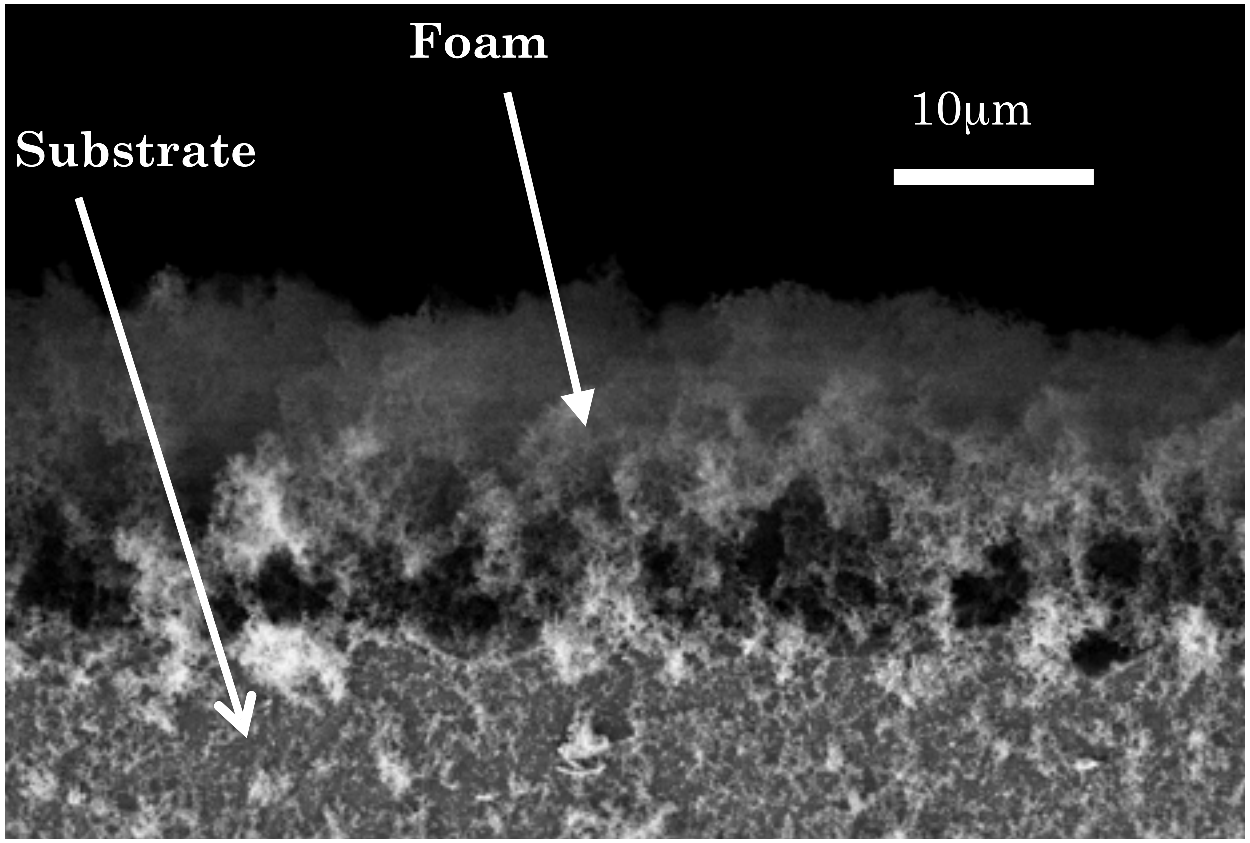


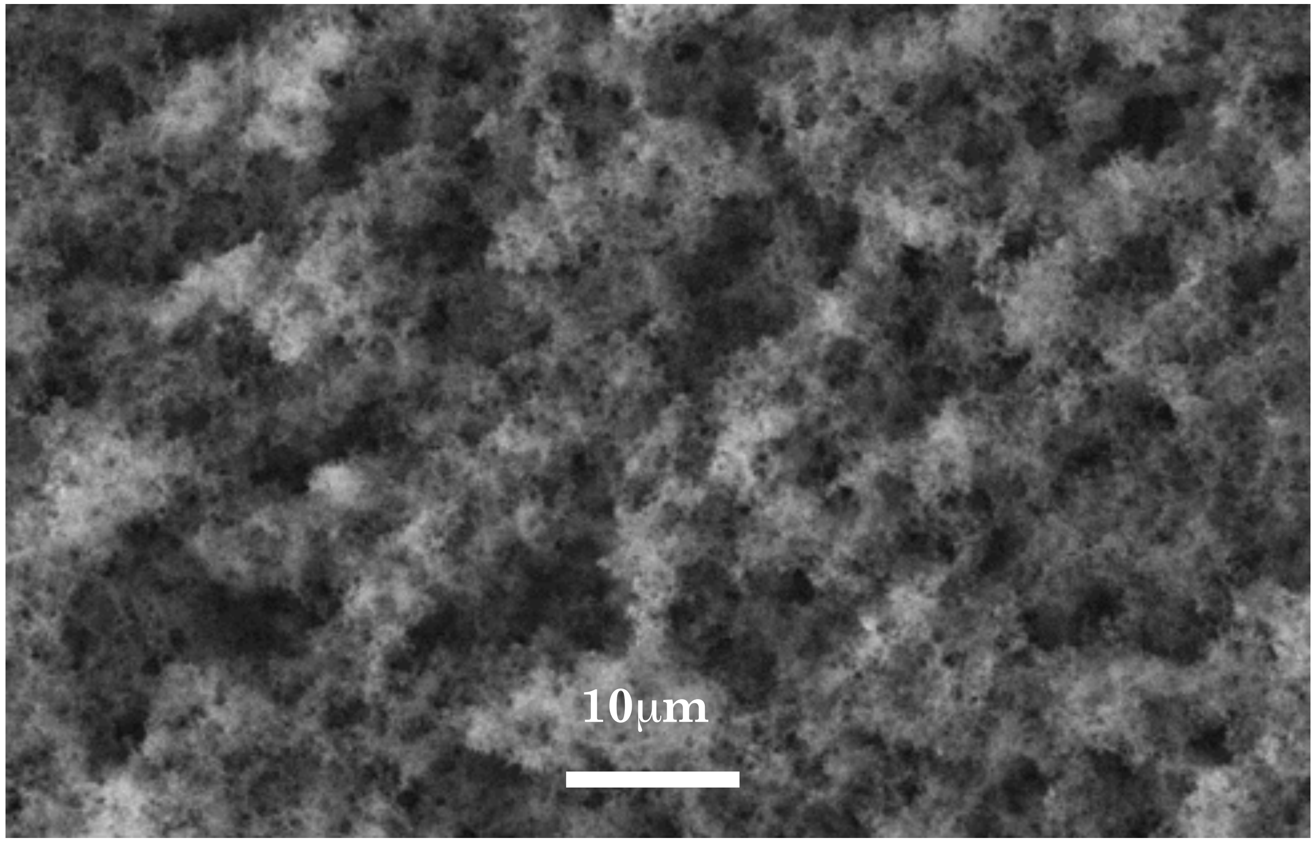
T = 28
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

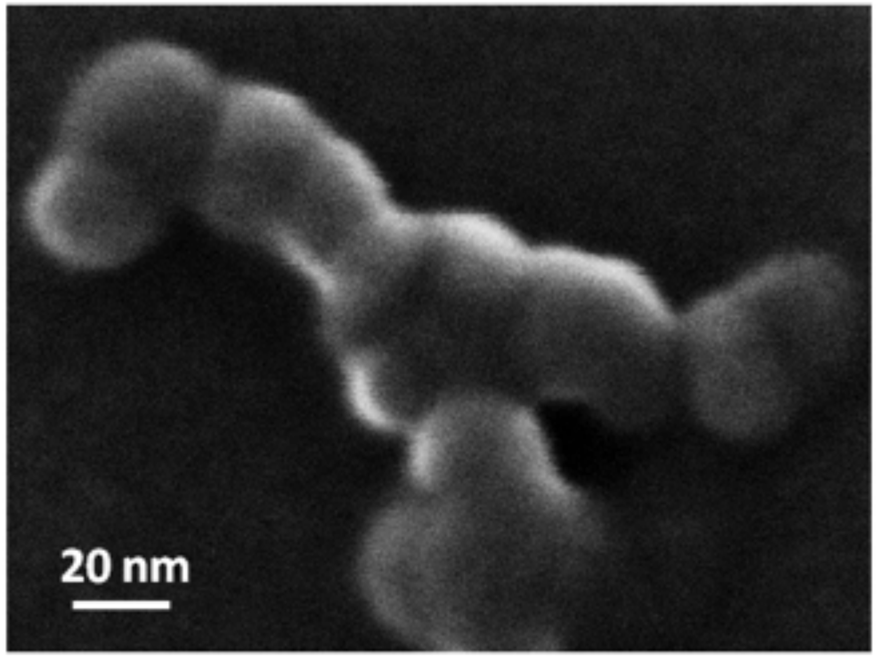

T = 32
10
5
0
-5
-10
y/λ
-10
-5
0
5
10
15
20
x/λ
100
10
1
0.1
e- density

Pulsed Laser Deposition

group of Passoni @ Politecnico di Milano







- Pulsed Laser Deposition (PLD)
  - **Carbon** "foam" grown solid foils
  - 5~10mg/cm3

Zani et al, Carbon **56** (2013)

experiment @ GIST Gwangju South Korea

Proton maximum Energy @ GIST

30 fs, spot 4μm $5 \cdot 10^{20}$W/cm², incidence 30°

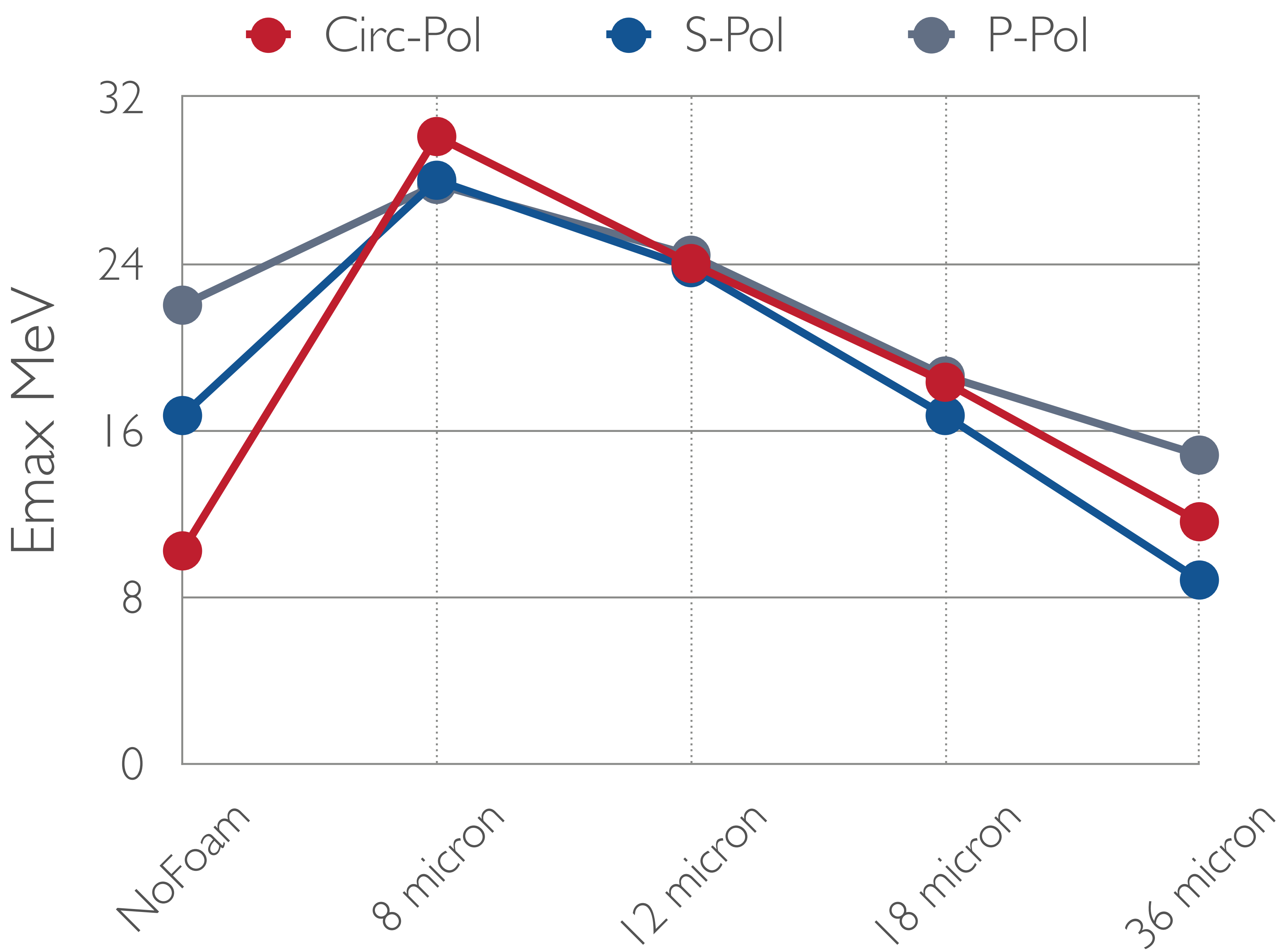
targets:

Al 0,75μm

+

C foam 6,8 mg/cm³
» 8μm
» 12μm
» 18μm
» 36μm

(Nov 2014)

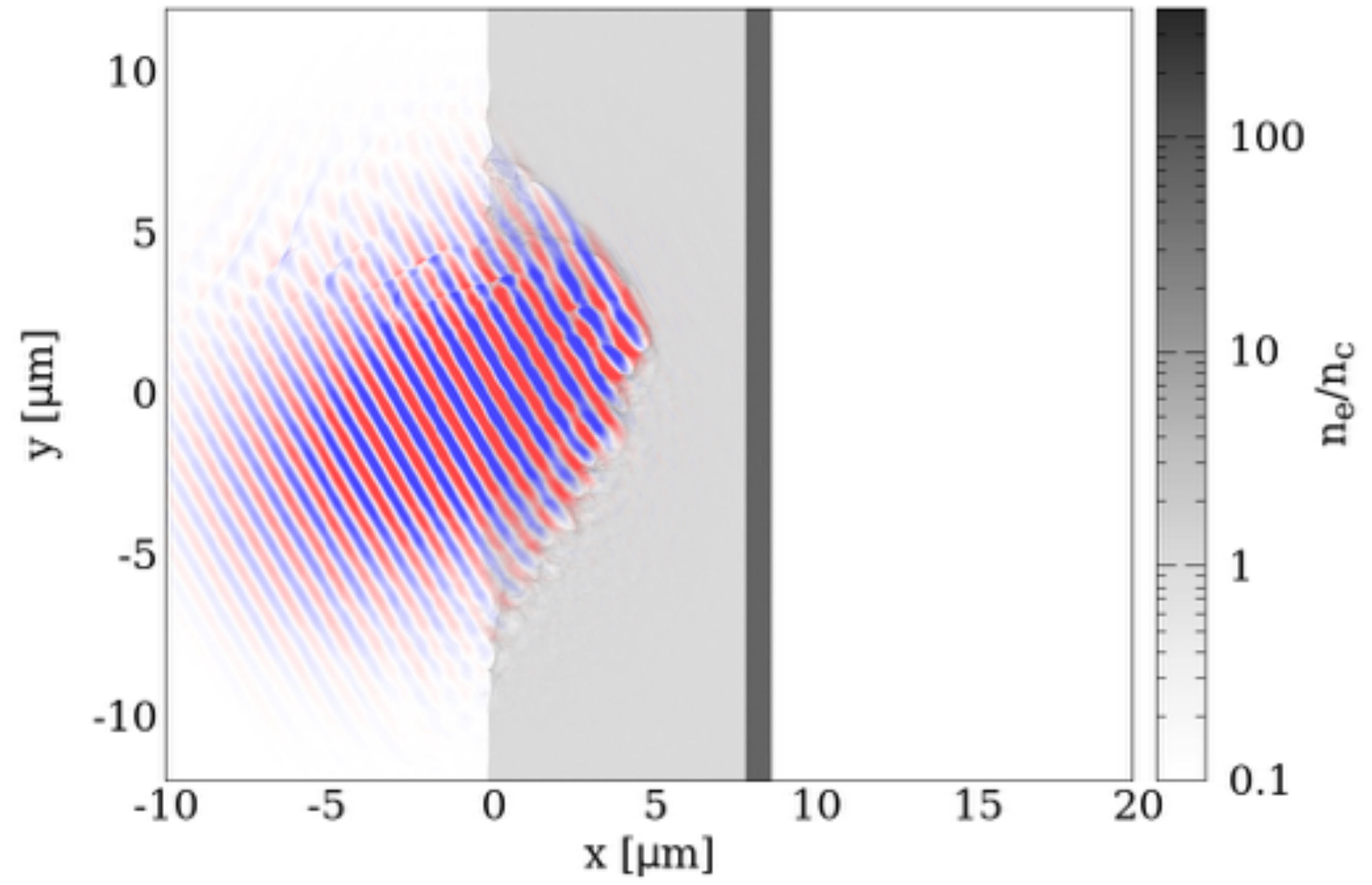


2D simulations

Energy scaling is not comparable with experiments

Huge difference between polarisations

Not predictive!



Foam layer as aggregate of cluster

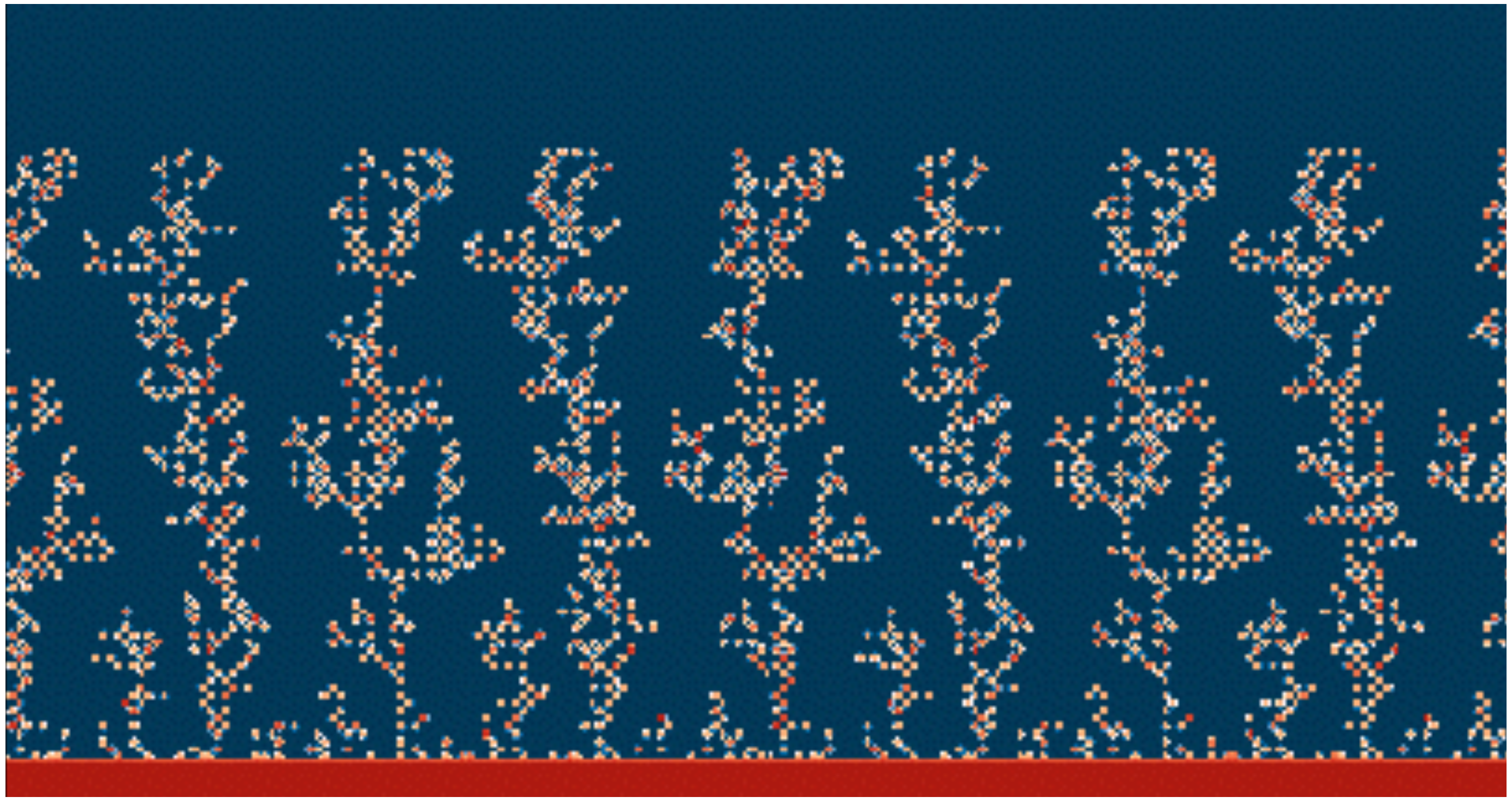
work in progress

DLA

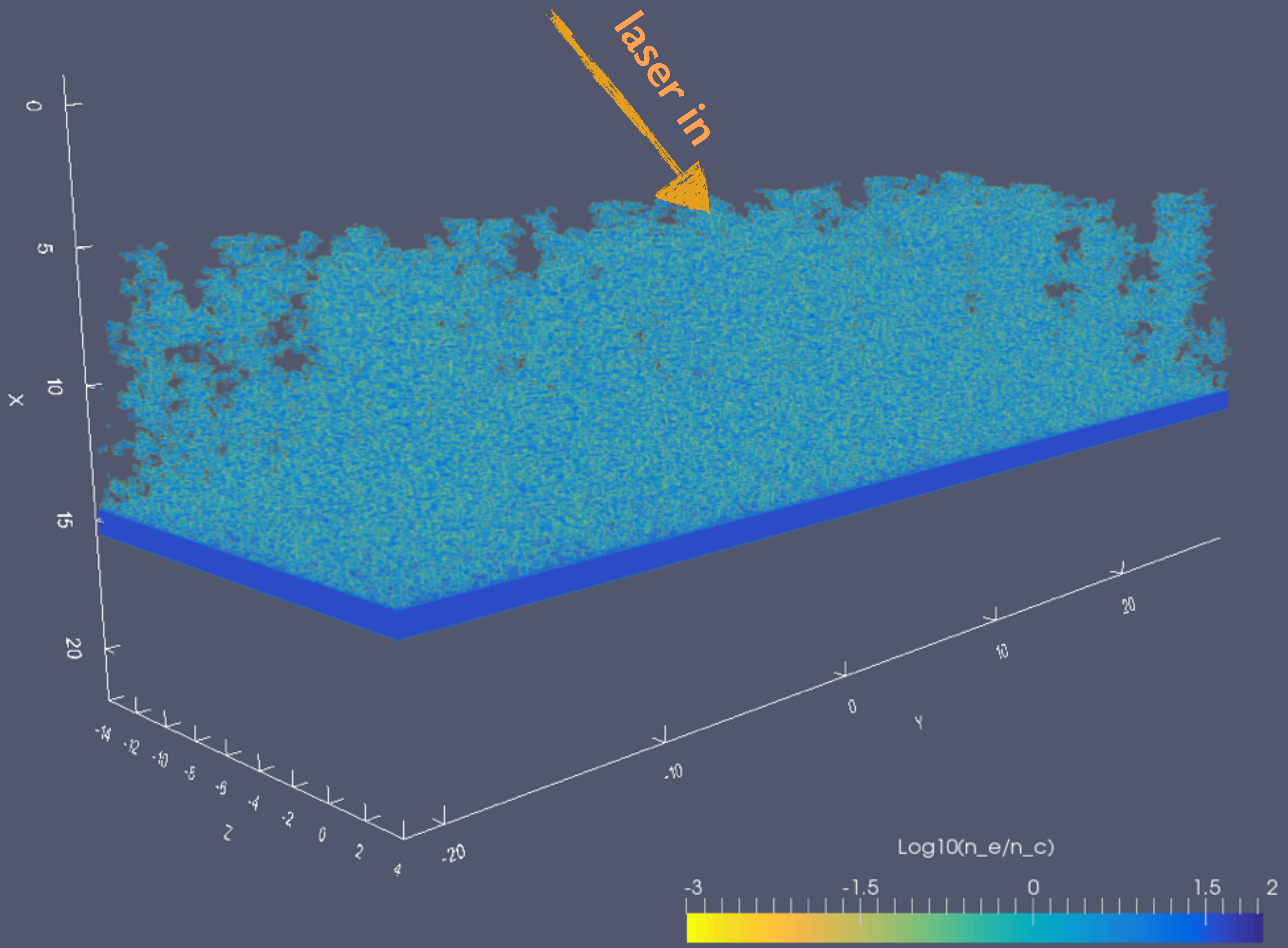
Diffusion Limited Aggregation ✤
algorithm for "growing" fractal structures *Brownian trees*

foam

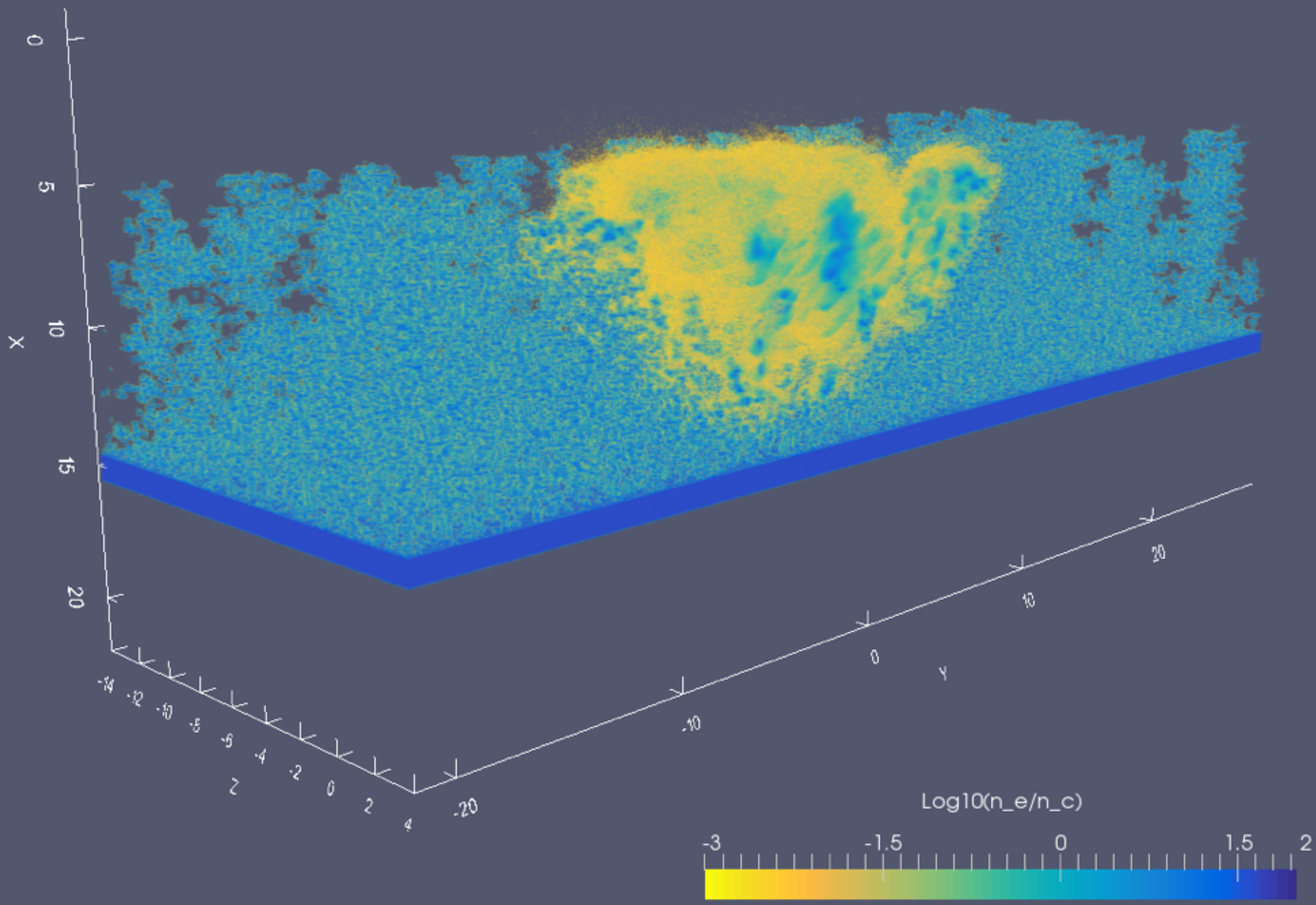
dense clusters $n \sim 50 n_c$
average density $n \sim 1 n_c$

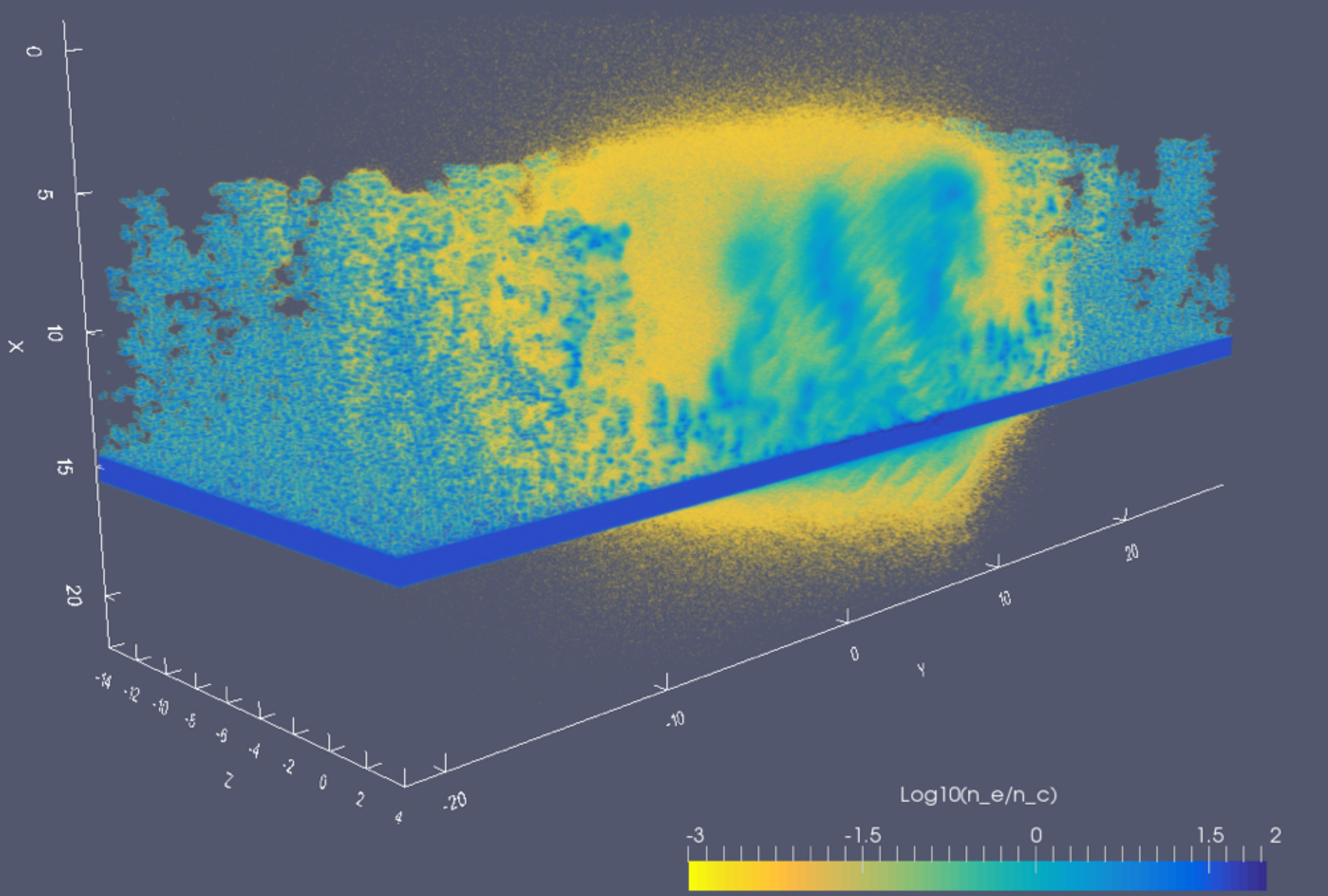


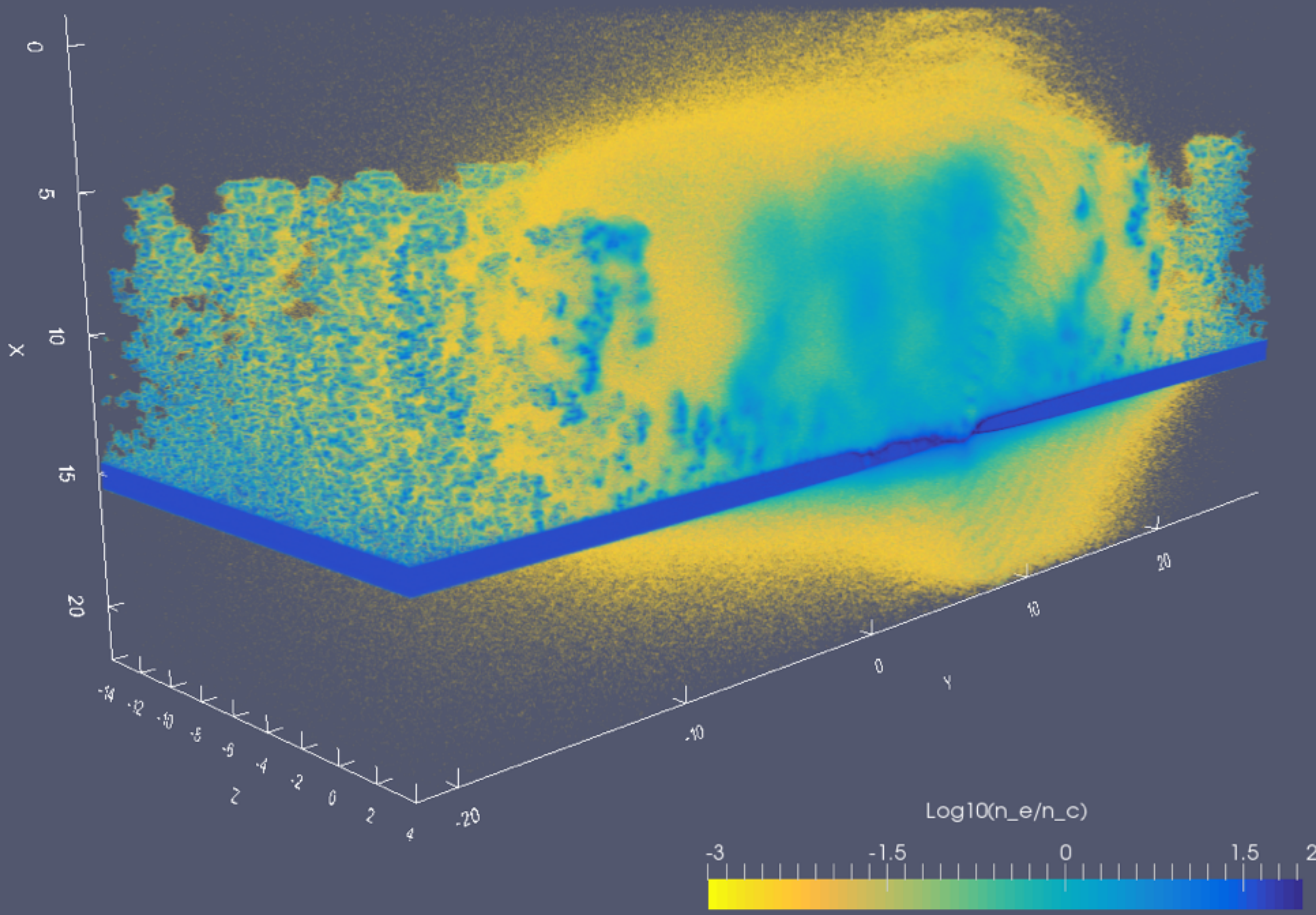
✤T. A. Witten Jr, L. M. Sander, Phys. Rev. Lett. 47, 1400 (1981)



laser in
X
0
5
10
15
20
Y
-20
-10
0
10
20
Log10(n_e/n_c)
-3
-1.5
0
1.5
2

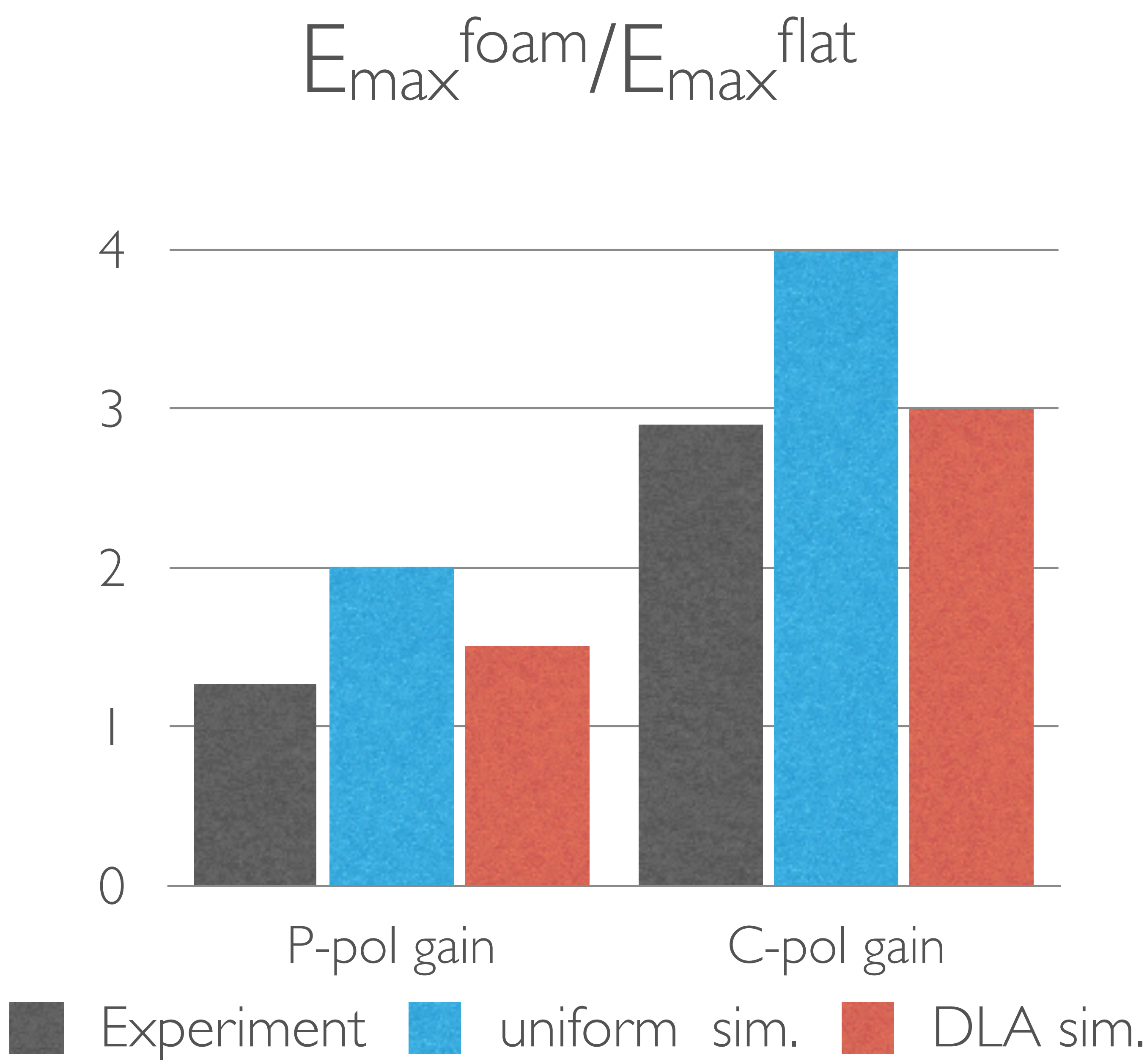

X
0
5
10
15
20
Y
-20
-10
0
10
20
Z
-14
-12
-10
-8
-6
-4
-2
0
2
4
Log10(n_e/n_c)
-3
-1.5
0
1.5
2


X
0
5
10
15
20
Z
-14
-12
-10
-8
-6
-4
-2
0
2
4
Y
-20
-10
0
10
20
Log10(n_e/n_c)
-3
-1.5
0
1.5
2



X
0
5
10
15
20
Y
-20
-10
0
10
20
-14
-12
-10
-8
-6
-4
-2
0
2
4
Z
Log10(n_e/n_c)
-3
-1.5
0
1.5
2

Emax gain with vs. without foam



20-30% underestimation of the max. ion energy but…

DLA Foam seems to catch the features of the interaction better than uniform foam

… more work to come

Conclusions

PIC

Light-Sail acceleration under same interaction conditions
Circular Pol better than Linear Pol

PIC

Electron acceleration by surface waves:
multi MeV non-thermal e-bunches

3D PIC simulations can be quantitatively predictive also for laser-solid interaction… if used wisely

2D simulations rarely give quantitative estimations and should be used with the support of few 3D runs

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Ministero dell'Istruzione, dell'Università e della Ricerca

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thank you