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Department of Energy

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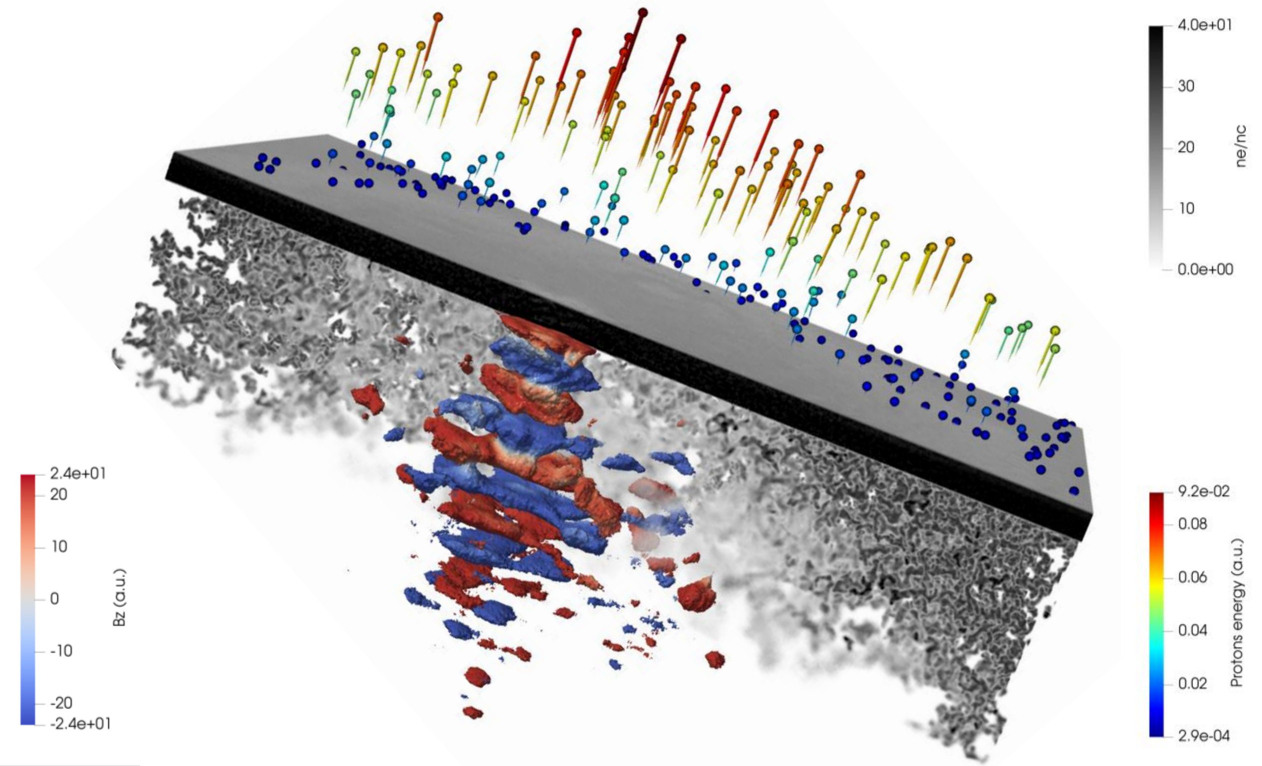


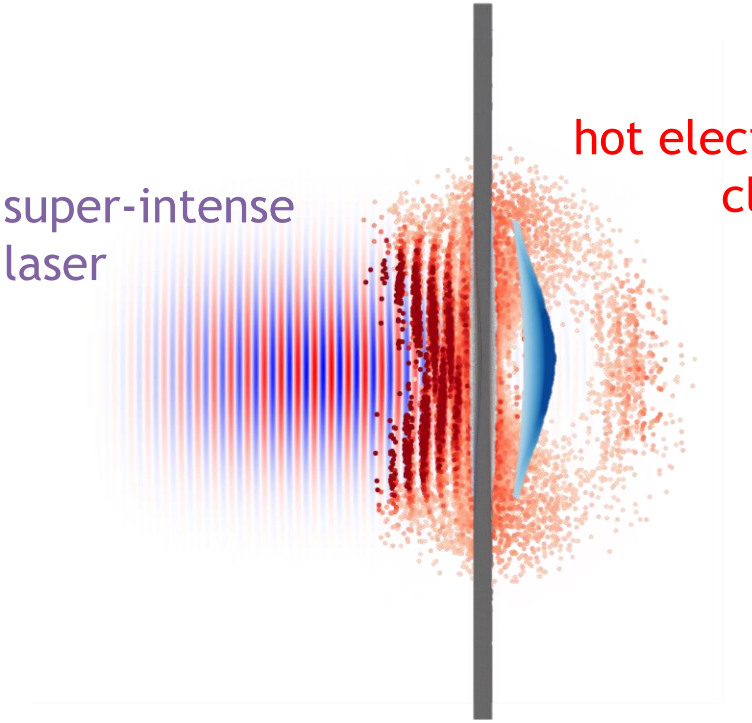
A theoretical model of laser-driven ion acceleration from near-critical double-layer targets

Andrea Pazzaglia, Luca Fedeli, Arianna Formenti, Alessandro Maffini, Matteo Passoni

Department of Energy, Politecnico di Milano, Italy

Conventional laser-driven ion acceleration

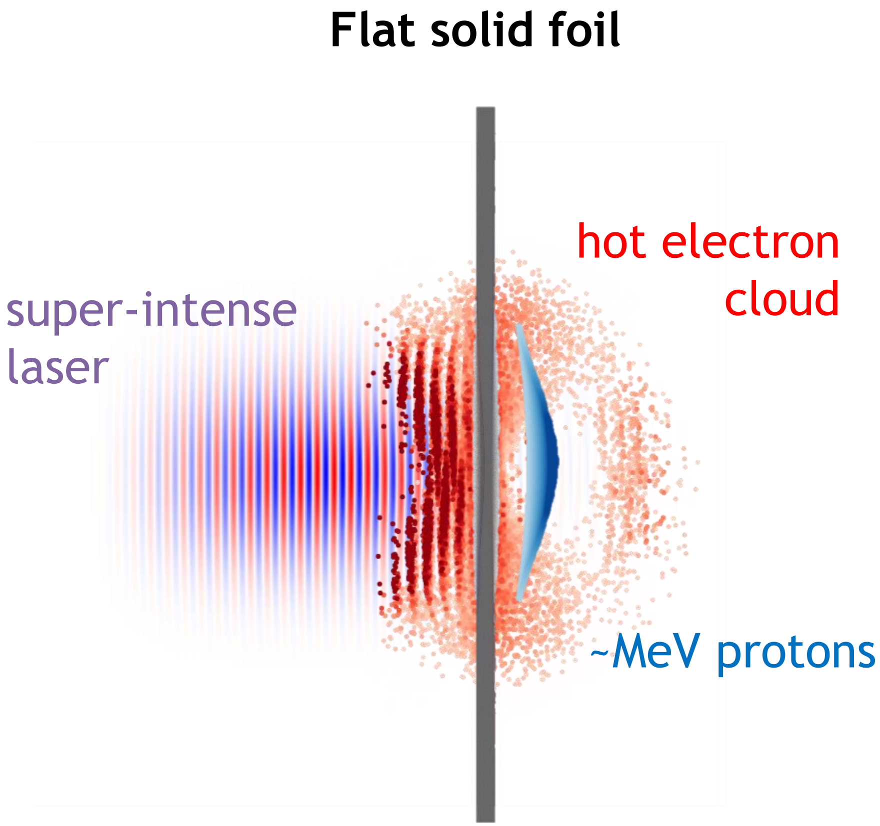
Flat solid foil



T_e → electron temperature

n_h → electron density

Conventional laser-driven ion acceleration



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n_h → electron density

quasi-static TNSA model:

$$\epsilon_p^{max} \sim T_e \left[\log\left(\frac{n_h}{\tilde{n}}\right) - 1 \right]$$

Passoni, Matteo, and M. Lontano. "*Physical review letters* 101.11 (2008): 115001.

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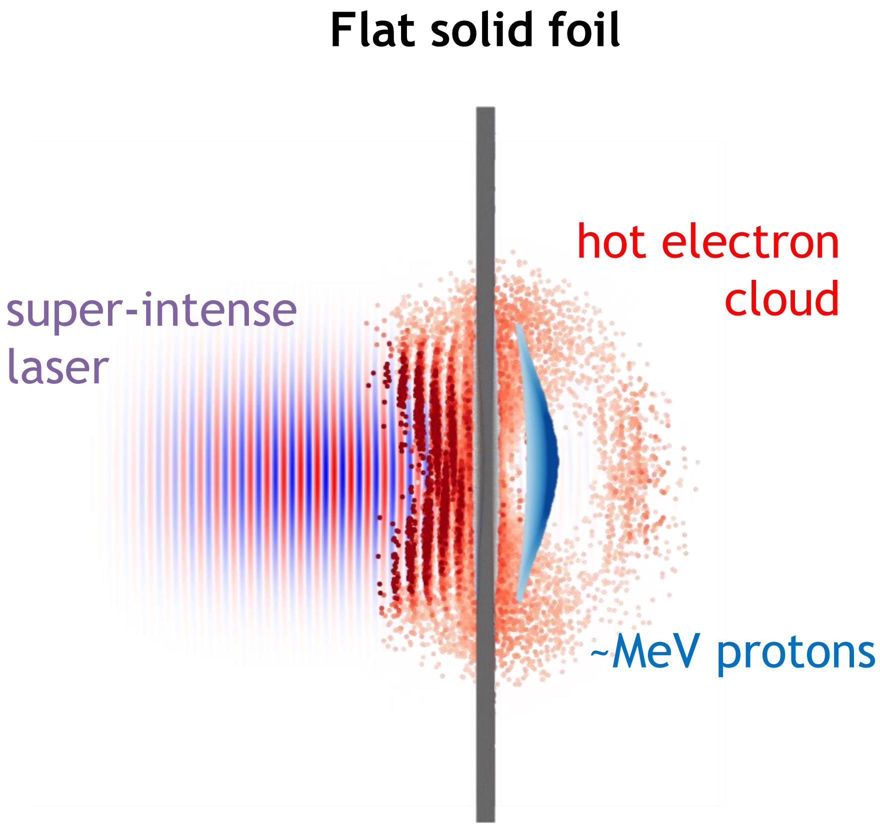

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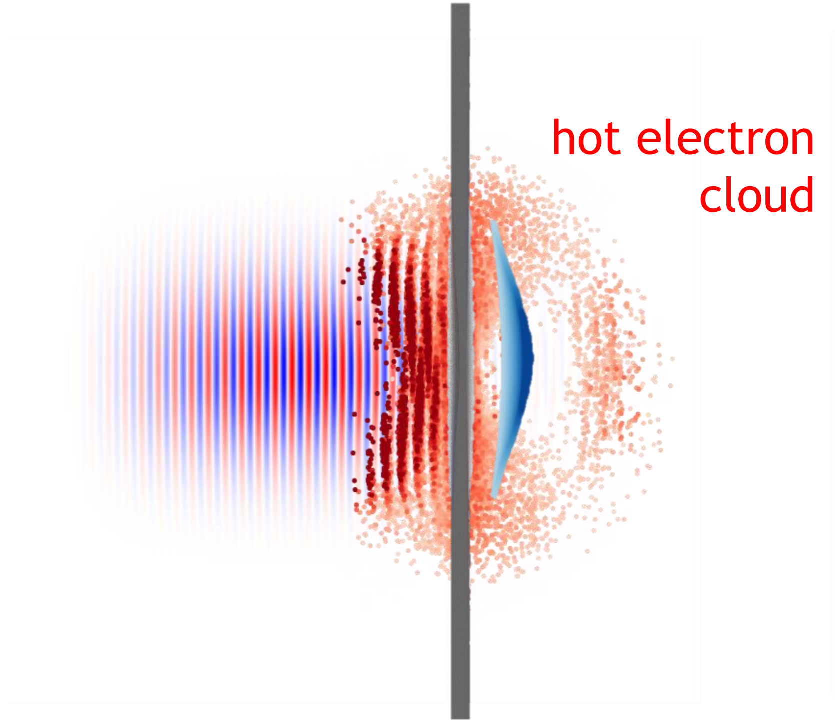
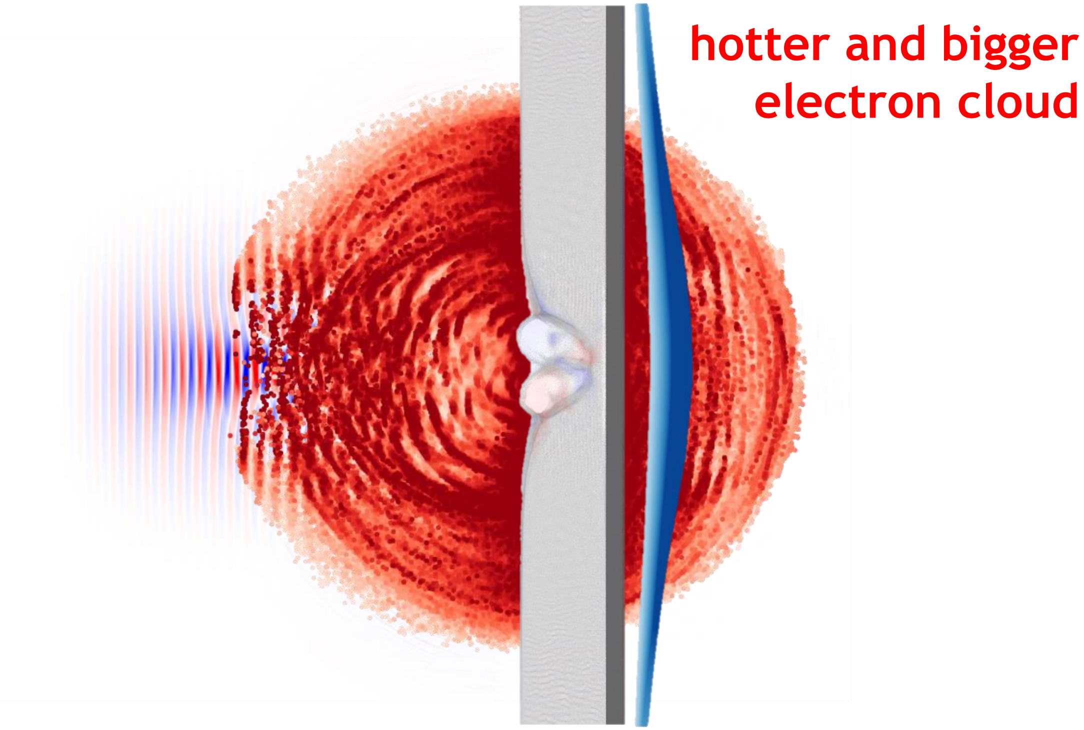
low electron conversion efficiency → **low maximum proton energy**

Acceleration with the Double-Layer Target (DLT)

Flat solid foil



<u>Near critical density layer</u>



$T_{e,DLT} > T_e$

$n_{h,DLT} > n_h$

Acceleration with the Double-Layer Target (DLT)

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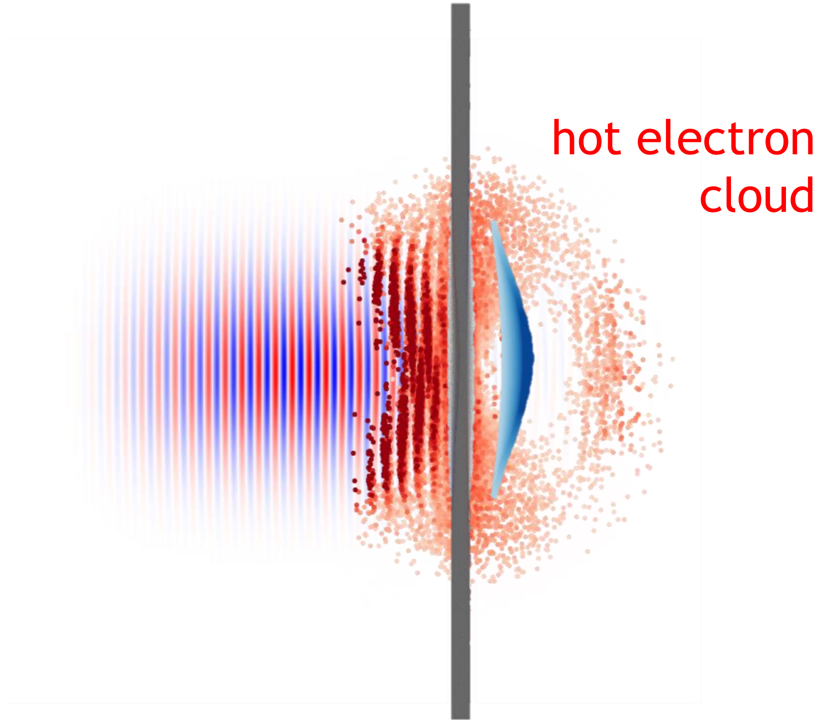

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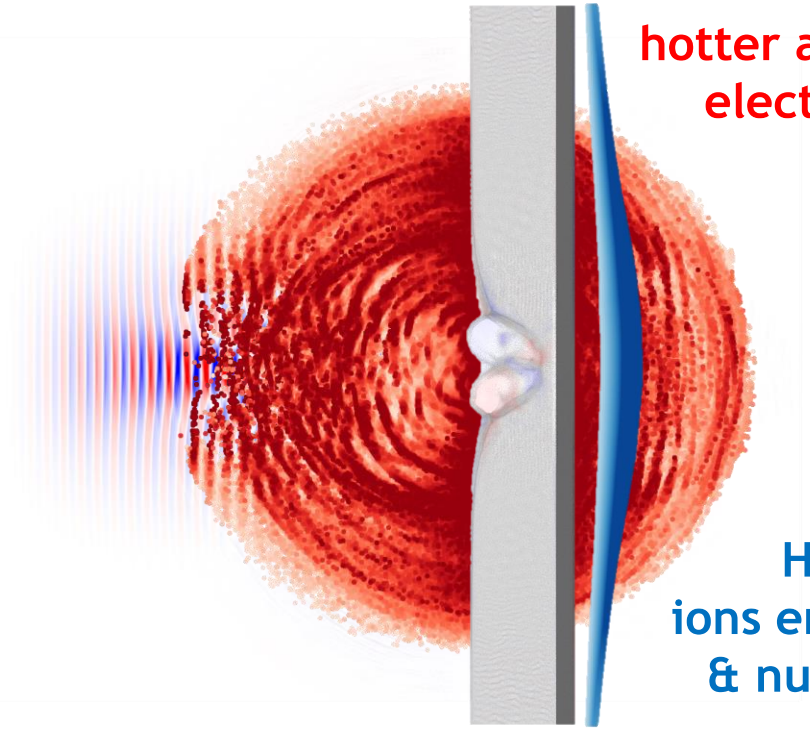


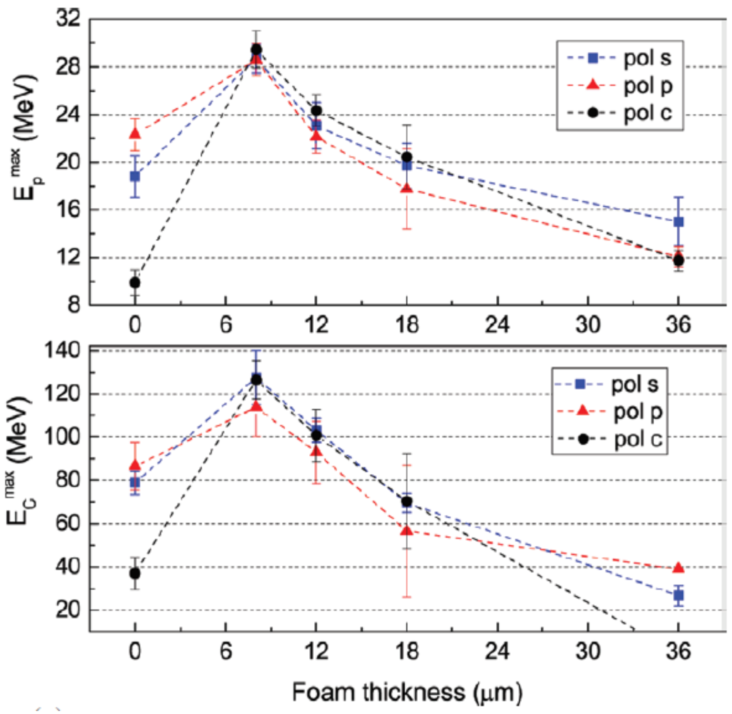
hotter and bigger electron cloud $T_{e,DLT} > T_e$ $n_{h,DLT} > n_h$

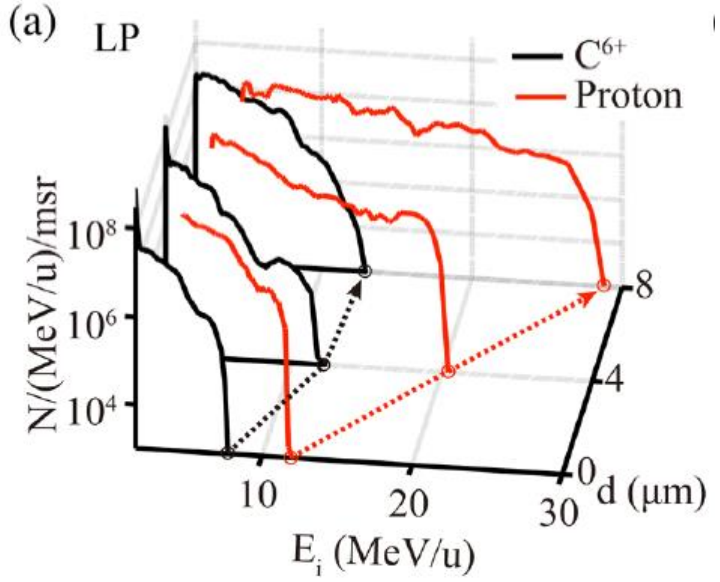
Higher ions energy & number $\epsilon_p^{max} \sim T_e \left[\log\left(\frac{n_h}{\tilde{n}}\right) - 1 \right]$

Advanced acceleration via **near-critical DLT**

Experimental evidences

Tested by independent groups:





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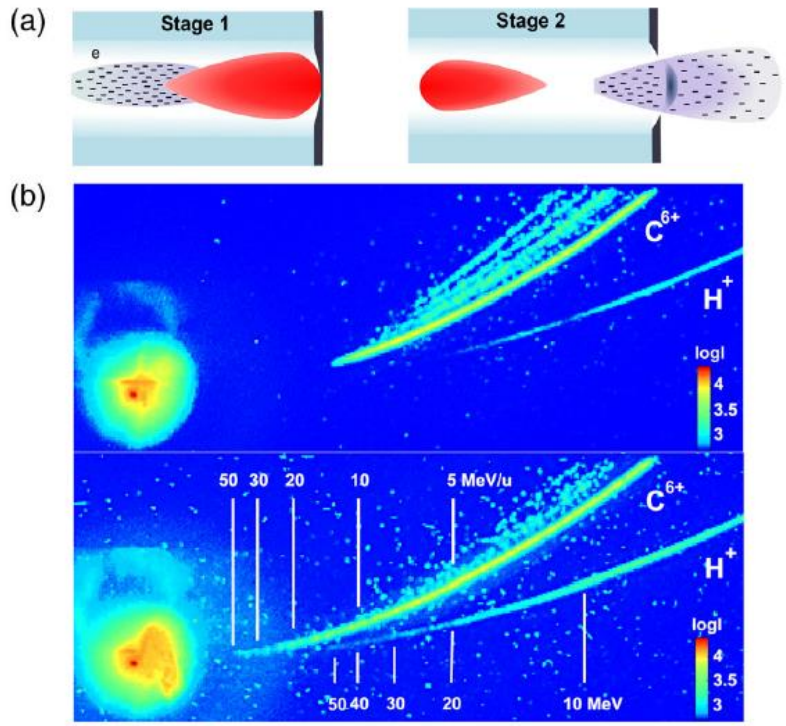

Ma, W. J., et al *Physical review letters* 122.1 (2019): 014803.

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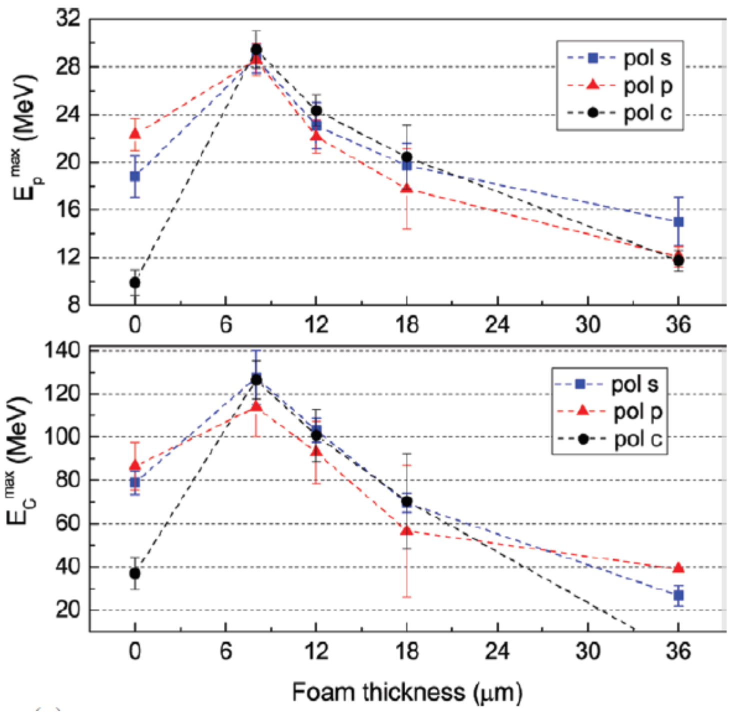

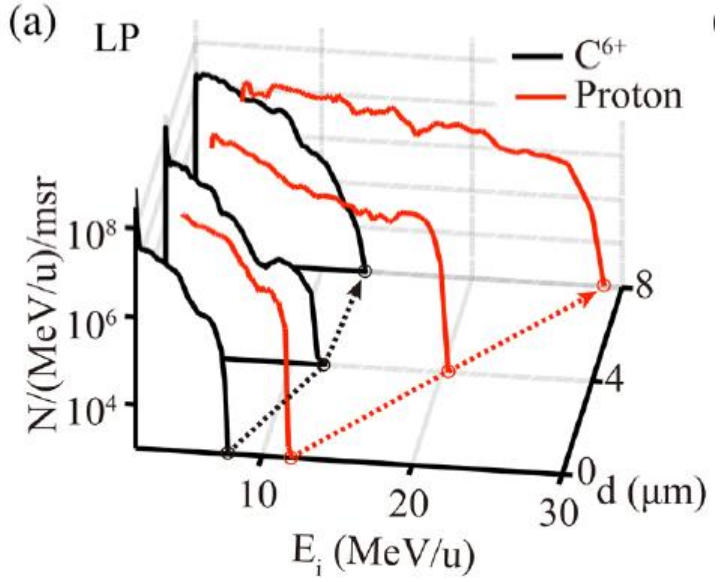

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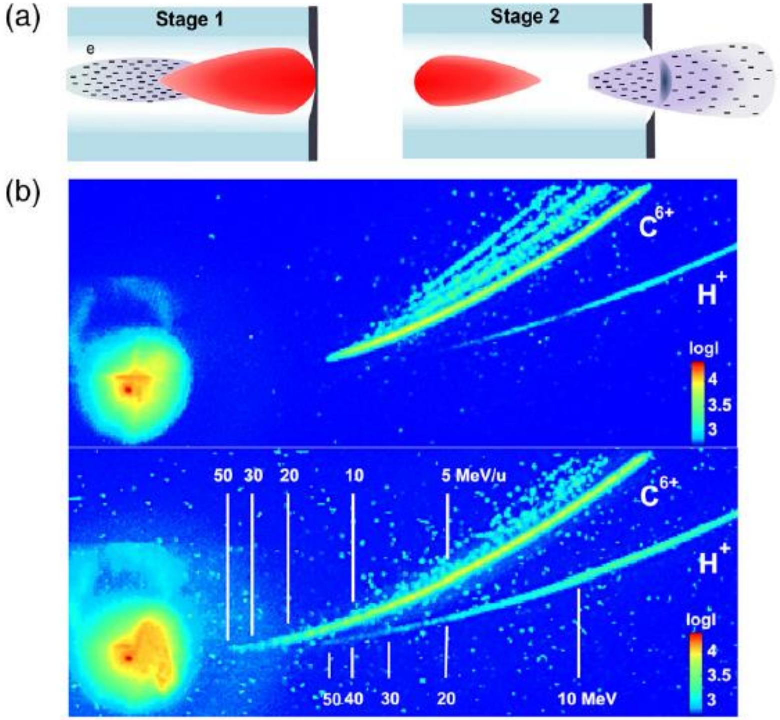

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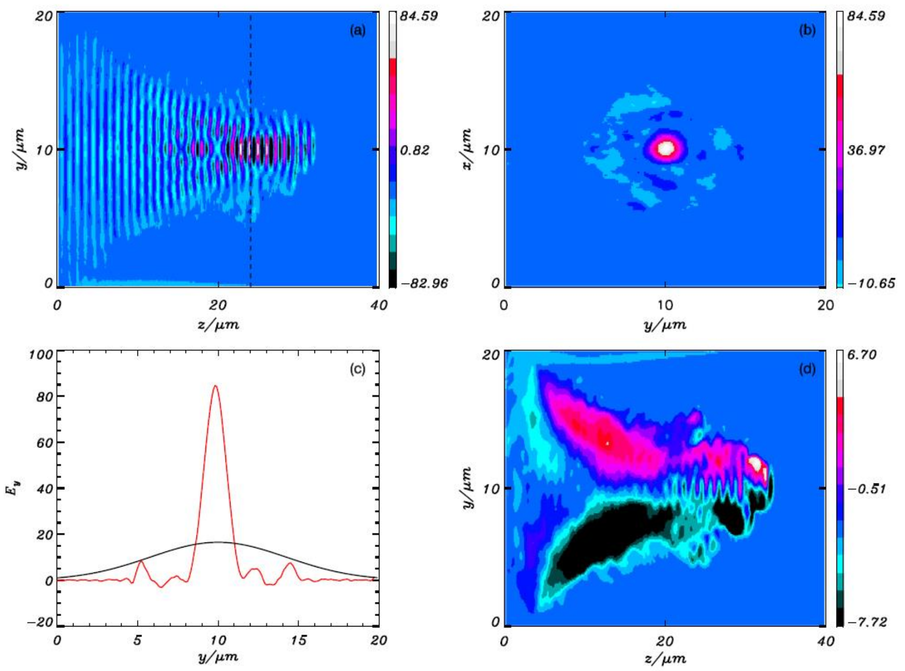
Have we achieved the best performances?

PIC simulations help to understand the interaction physics



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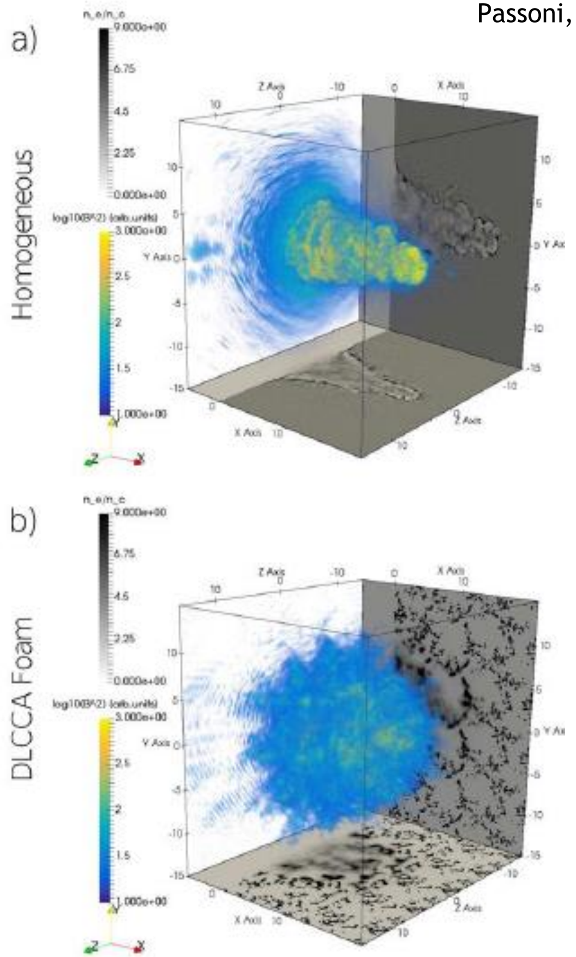

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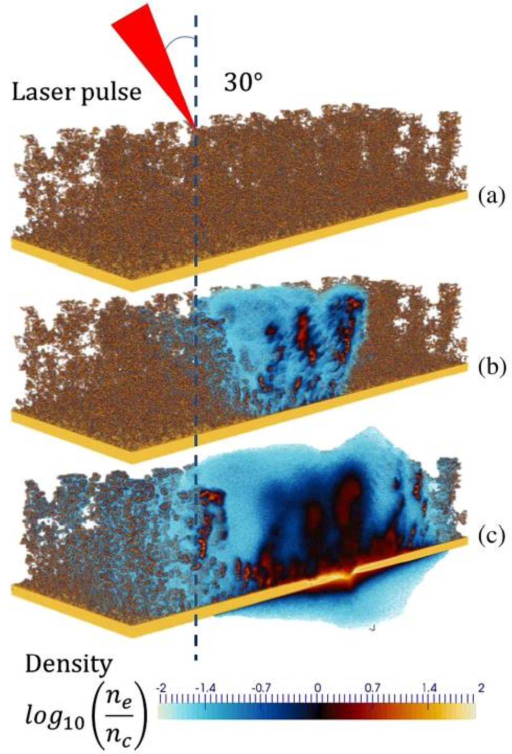

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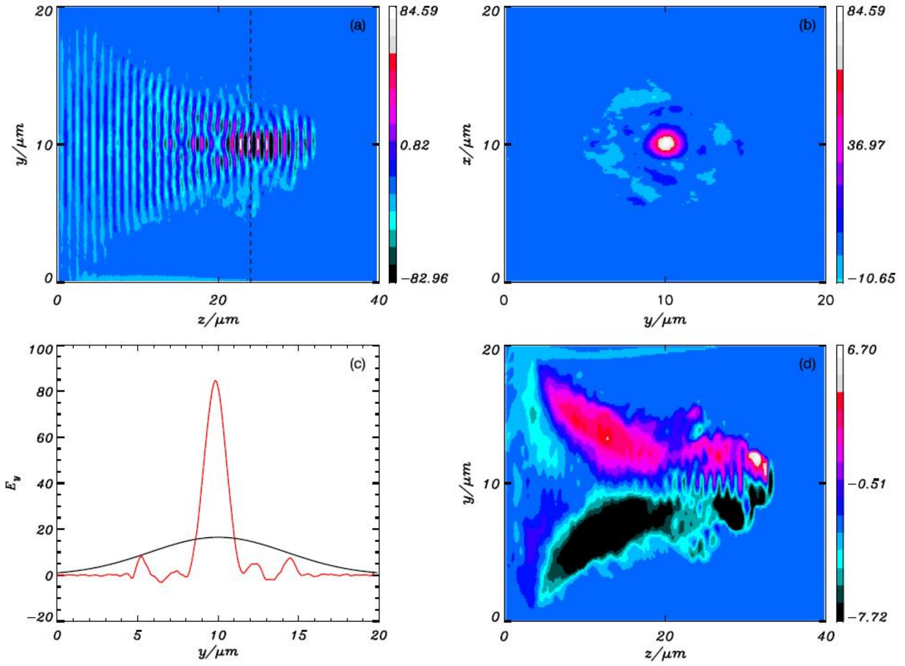

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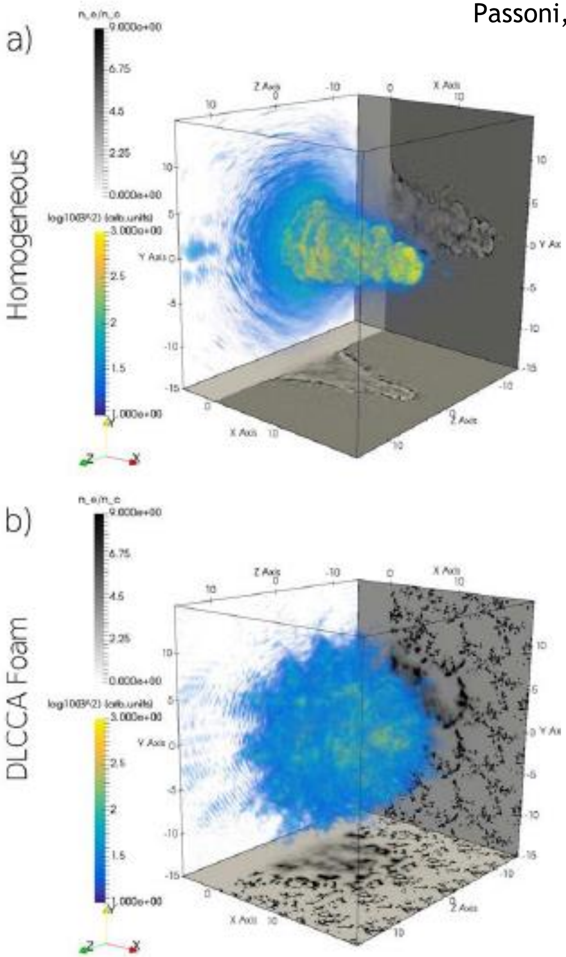

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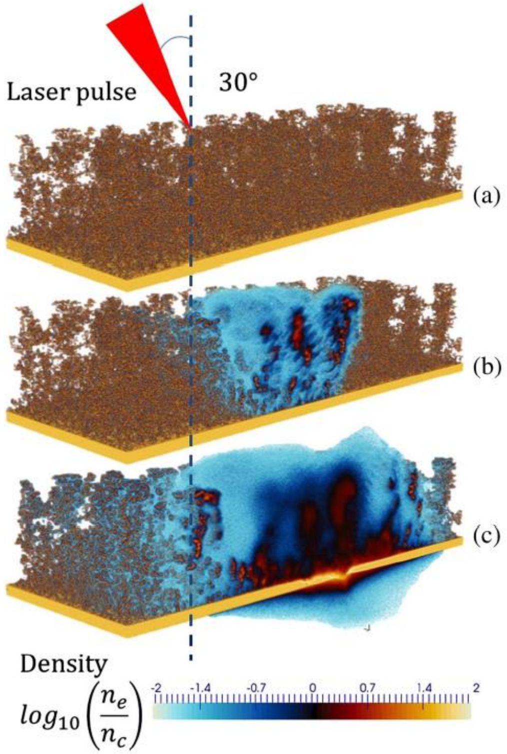
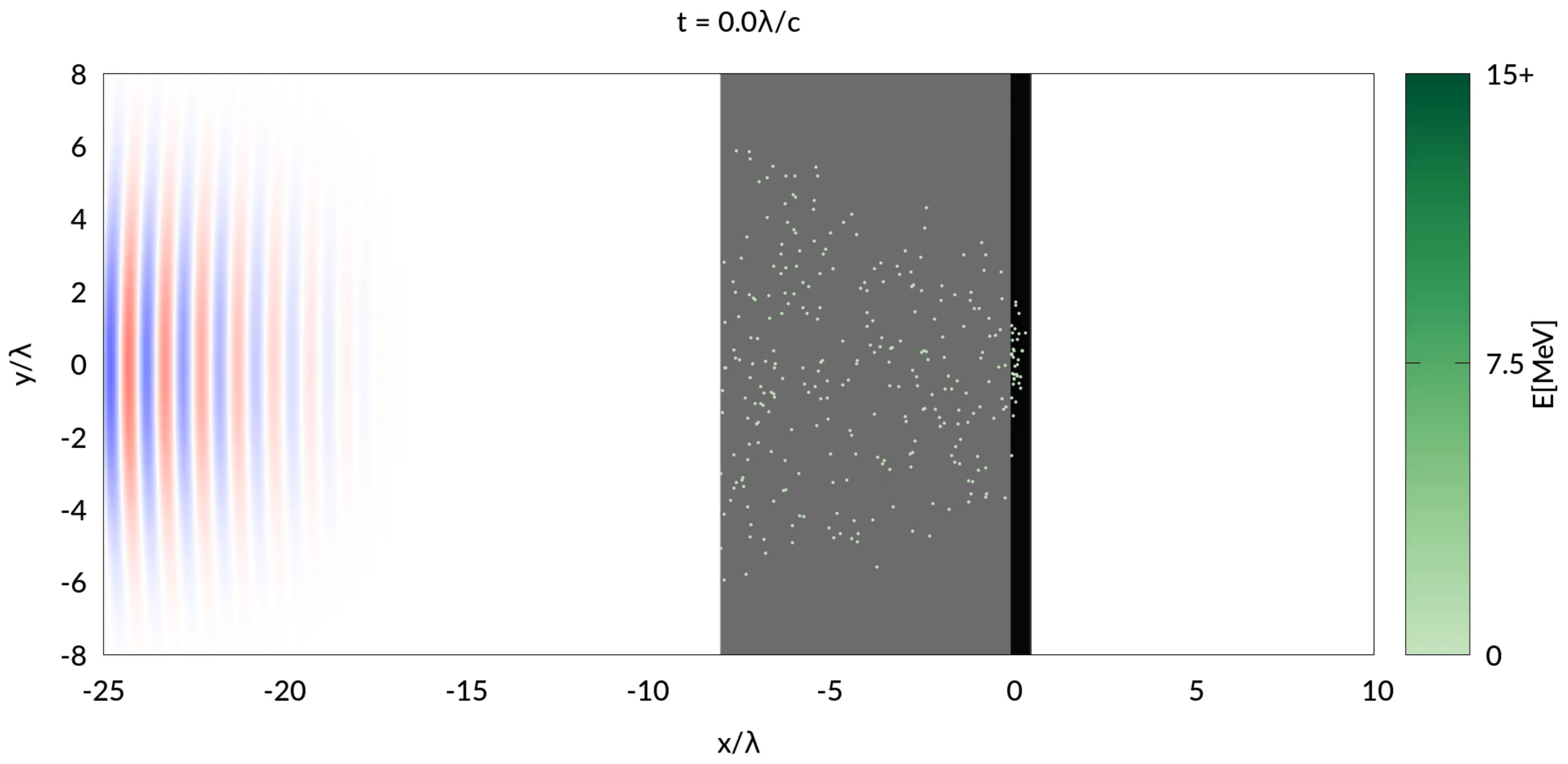


Realistic 3D PIC simulations are **computationally very expensive**

From PIC simulations to a minimal model

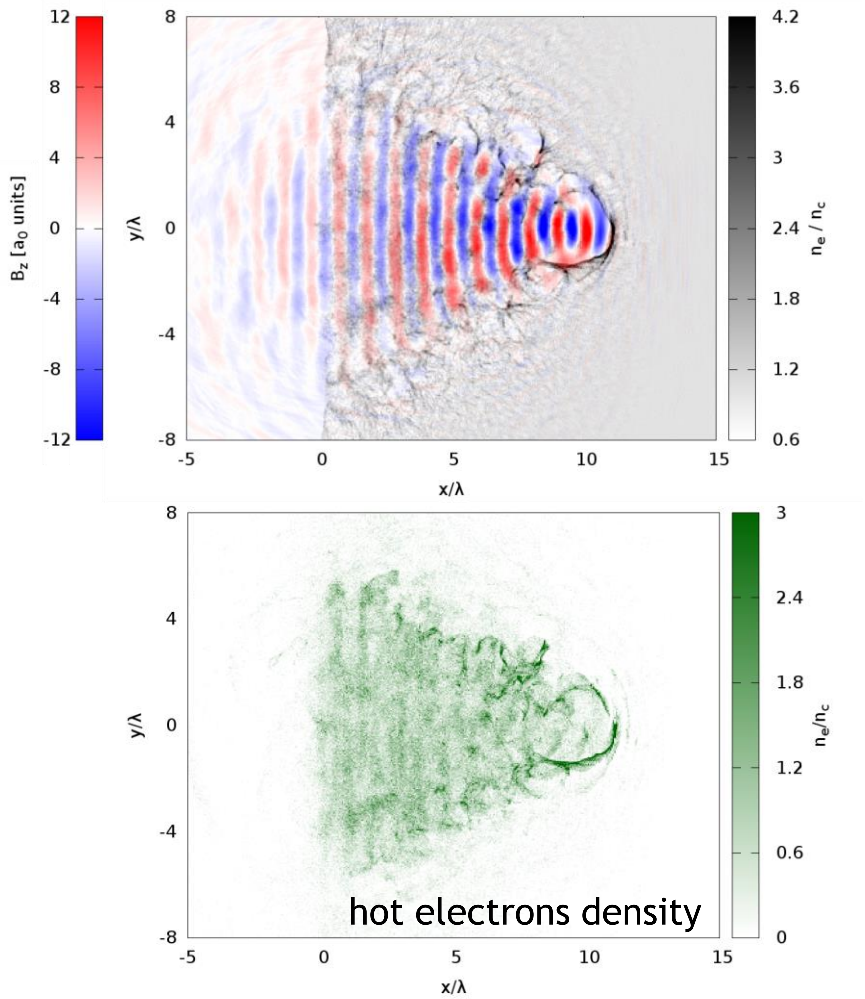


Main observed phenomena:

- Pulse drilling a channel
- Pulse self-focusing
- Hot electrons generation
- Self-generated magnetic fields

A modellistic approach is beneficial for the DLT optimization

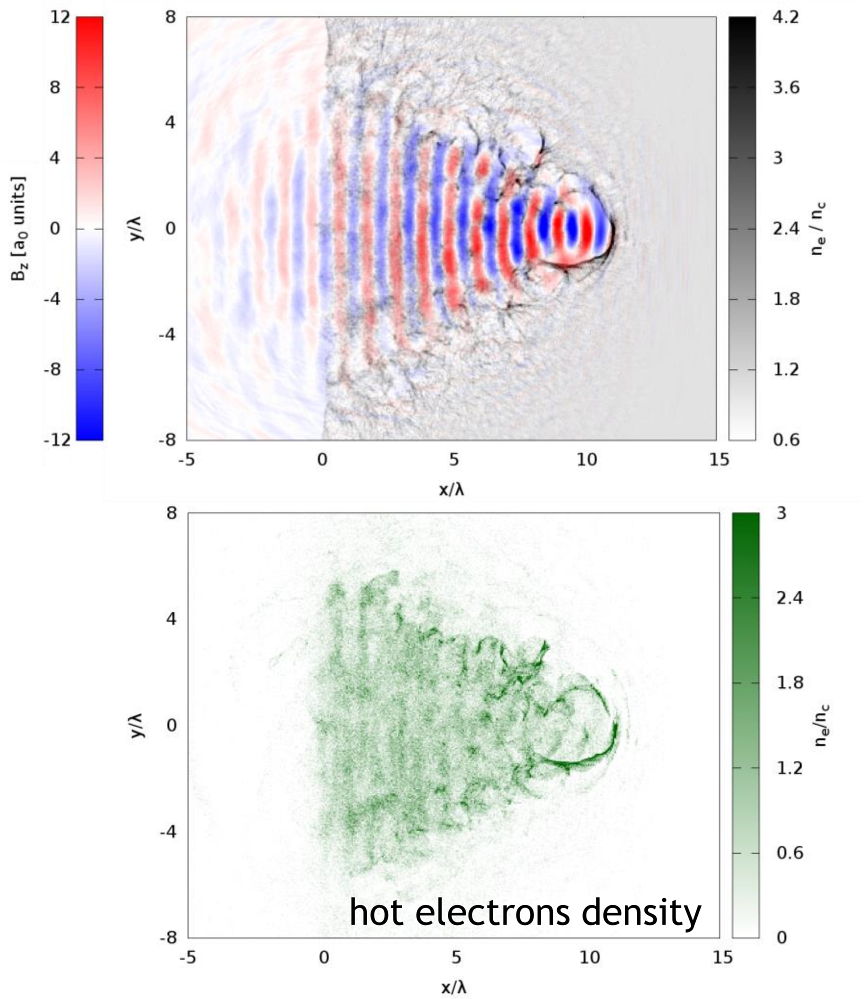
A minimal model is proposed



METHODS:

1. Theoretical model with free parameters
2. Parameters estimations with 2D/3D PIC simulations

A minimal model is proposed



METHODS:
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MODEL STEPS:
1. Laser self-focusing
2. Laser energy loss and amplification
3. Hot electrons heating
4. Ions acceleration

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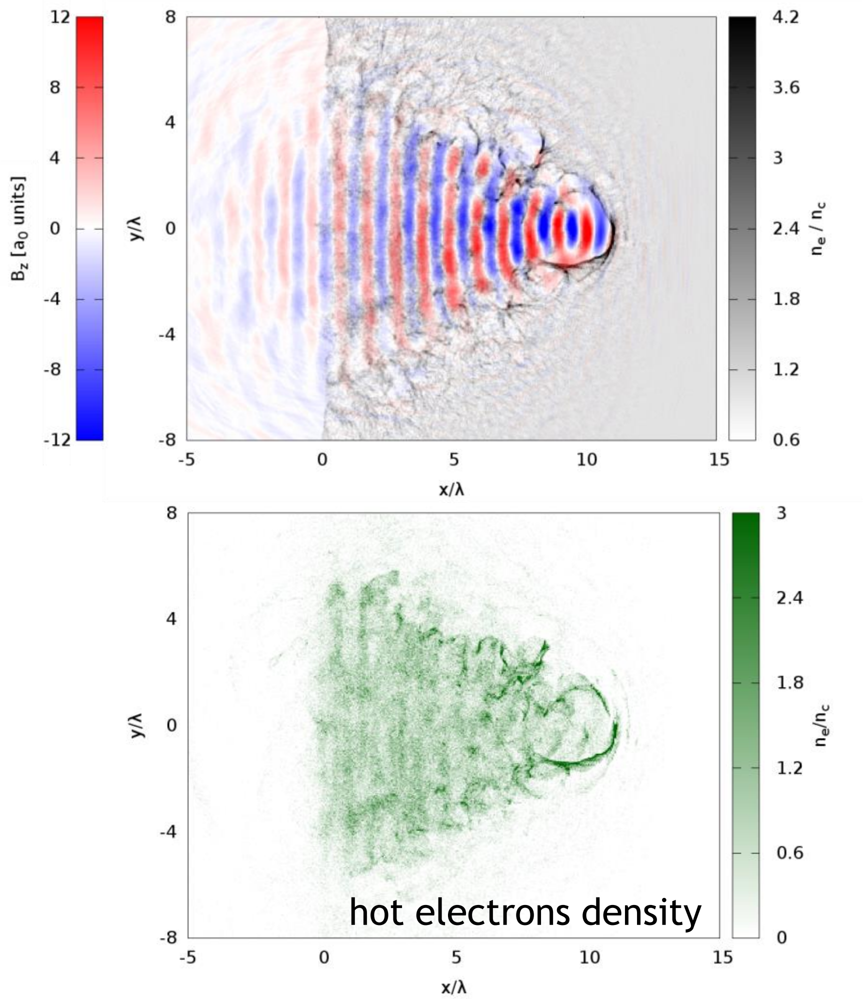

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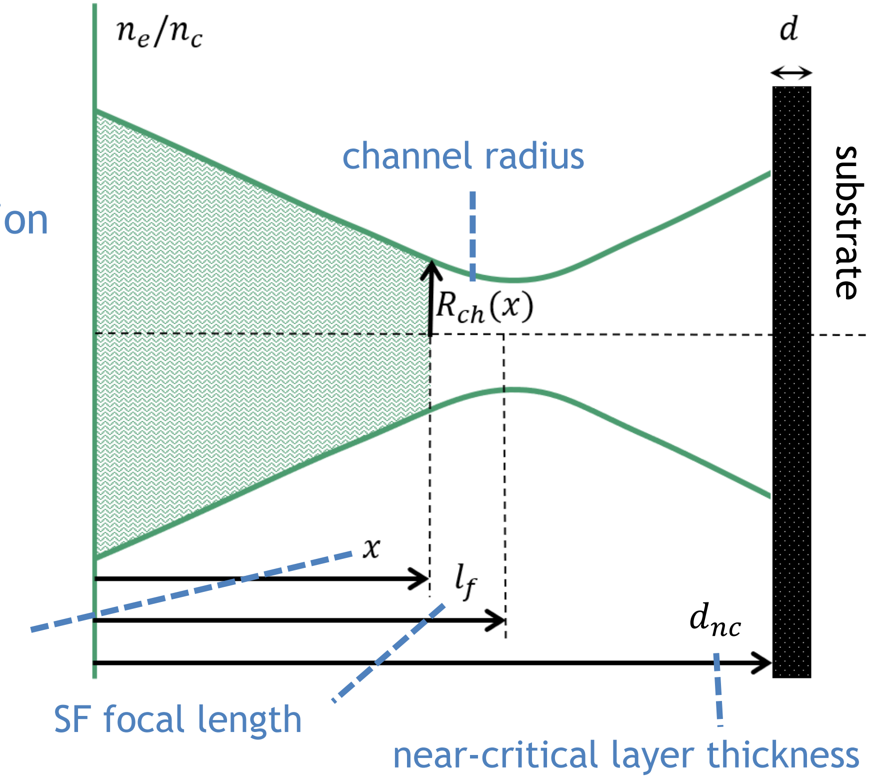
model scheme



1st step: laser propagation into a near-critical plasma

Pulse waist focuses with
a thin-lens law:

$$w(x) = w_m \sqrt{1 + \left(\frac{x - l_f}{x_R}\right)^2}$$

minimum waist

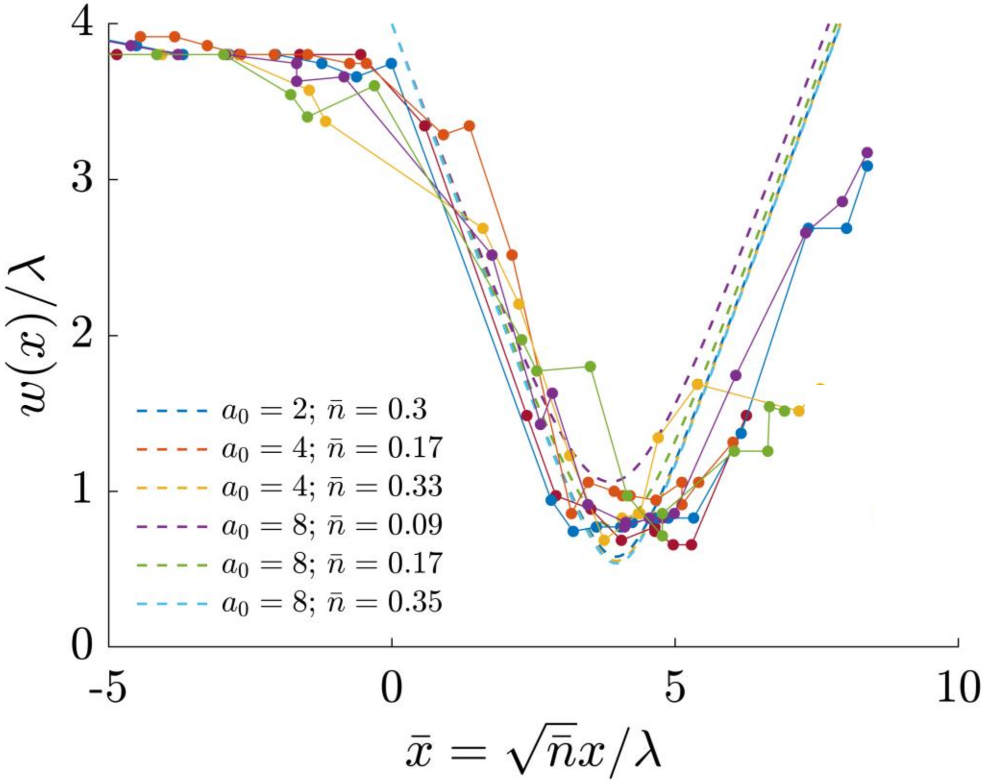
$$w_m = \frac{\lambda}{\pi}\frac{1}{\sqrt{\bar{n}}}$$

Wang, H. Y., et al. *Physical review letters* 107.26 (2011): 265002.

relativistic
transparency factor

$$\bar{n} = \frac{n_e}{\gamma n_c}$$

points → 2D PIC simulations
dashed line → model



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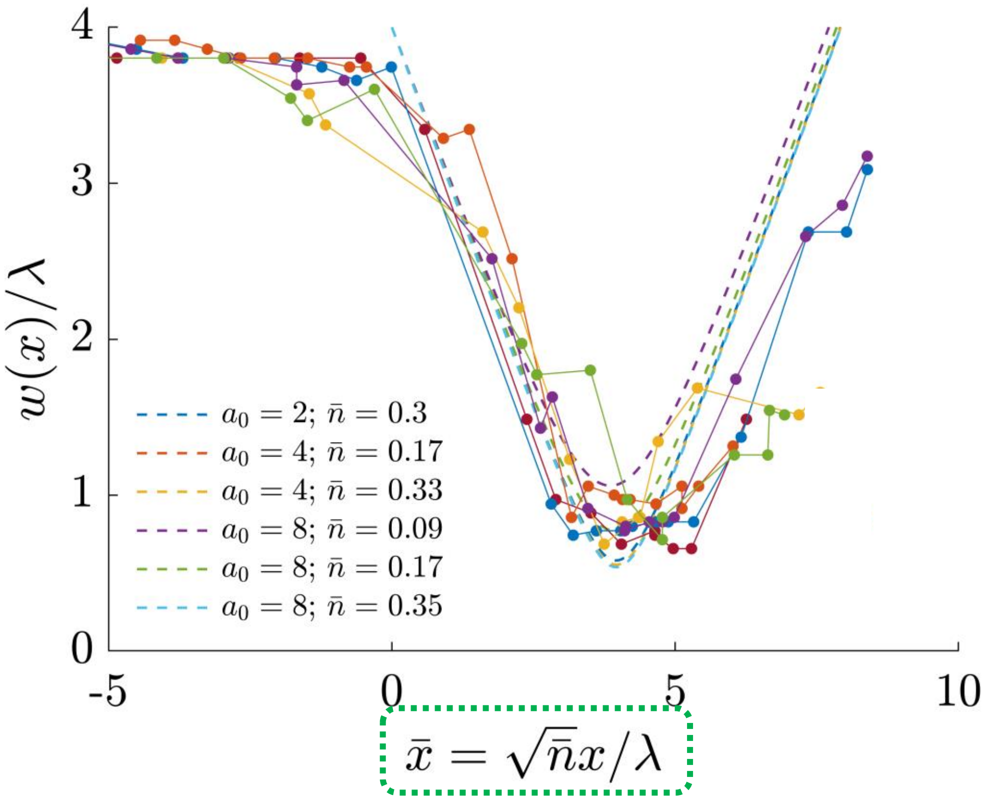

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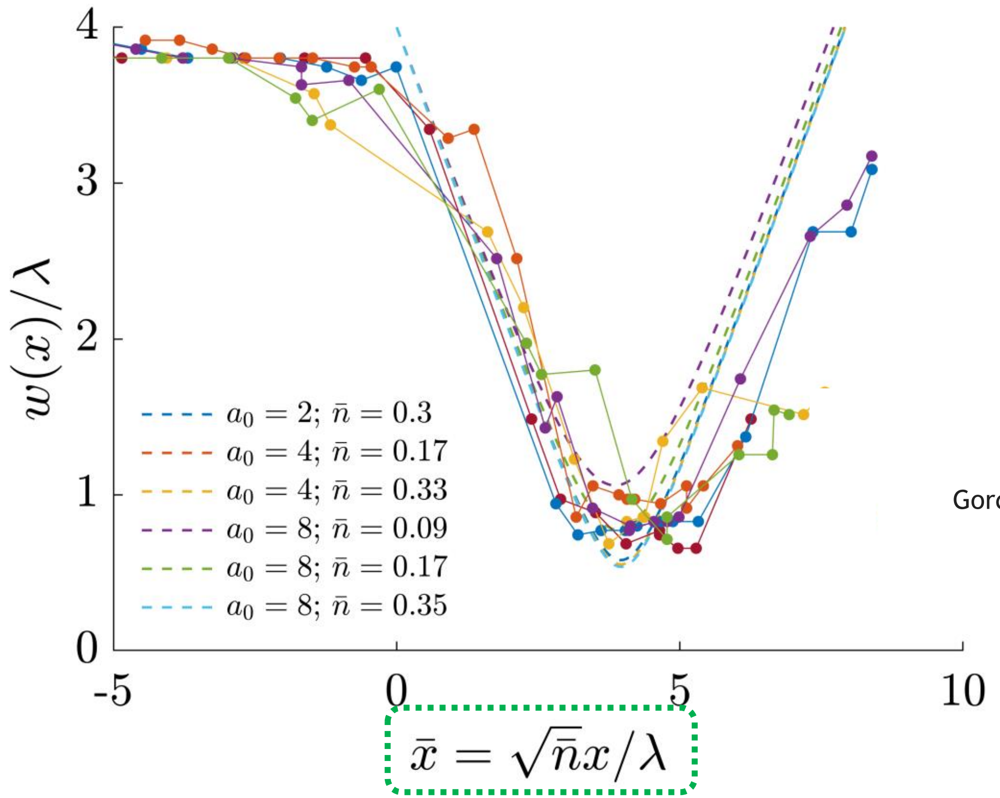

thin-lens law can be written as:

$$w(\bar{x}) \sim \lambda \sqrt{\frac{1}{\pi^2 \bar{n}} + \left(\bar{x} - \frac{w_0}{\lambda}\right)^2}$$

$$\boldsymbol{\bar{x} = \sqrt{\bar{n}}\, x/\lambda}$$

The propagation is self-similar!

Gordienko, S., and A. Pukhov. *Physics of Plasmas* 12.4 (2005): 043109.

2^{nd} step: pulse energy loss and amplification

pulse energy loss equation: ⟷ coupled with ⟷ amplification equation:

$$d\varepsilon_p = -T_{nc}(x) n_e 2 R_{ch}(x) dx$$

$$\bar{a}(x) = \frac{a(x)}{a_0} = \sqrt{\frac{\overline{\varepsilon_p}(x)}{w(x)/w_0}}$$

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2^{nd} step: pulse energy loss and amplification

pulse energy loss equation: ←→ amplification equation:

coupled with

$$d\varepsilon_p = -T_{nc}(x) n_e 2 R_{ch}(x) dx$$

electron temperature $T_{nc}(x) = C_{nc}[\gamma(x) - 1] m_e c^2$ corrected ponderomotive scaling

Cialfi, Lorenzo, Luca Fedeli, and Matteo Passoni. *Physical Review E* 94.5 (2016): 053201.

channel radius $R_{ch}(x) = r_c w(x)$ proportional to pulse waist

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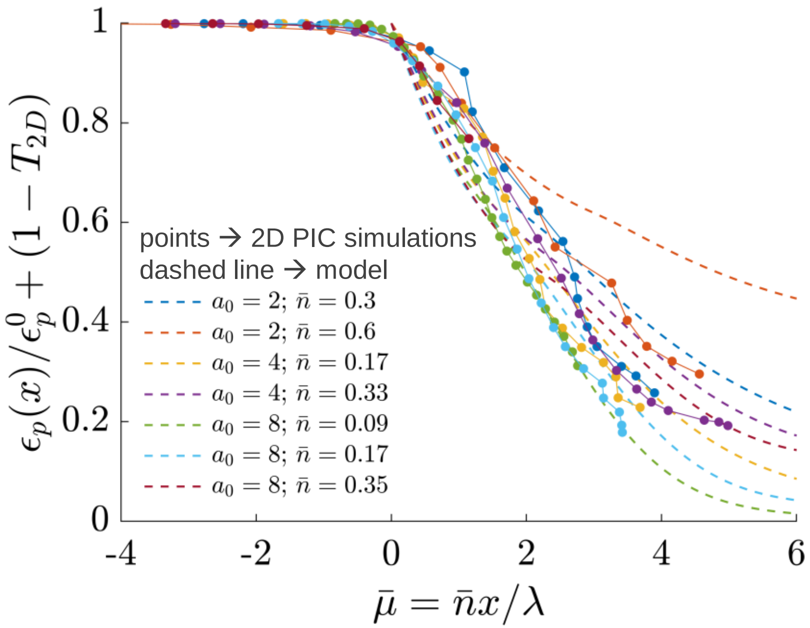

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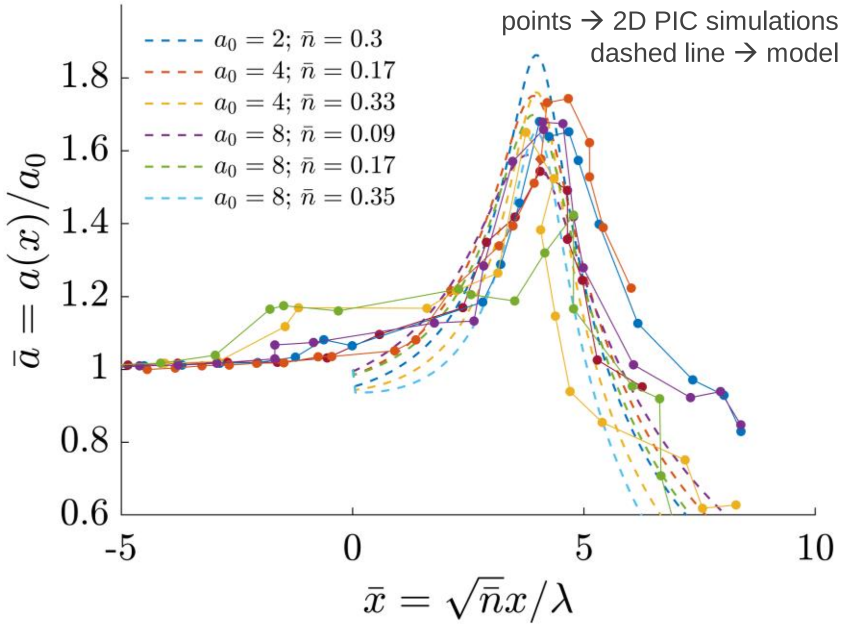

Two free parameters: $C_{nc} = 1.7; r_c = 2.0$

3^{rd} step: hot electrons heating

The energy lost by the pulse is given to the hot electrons:

$$E_{nc}(x) = \frac{\left(1 - \overline{\varepsilon_p}(x)\right)\varepsilon_{p0}}{N_{nc}(x)}$$

$N_{nc}(x)$ → Total number of electrons in the channel

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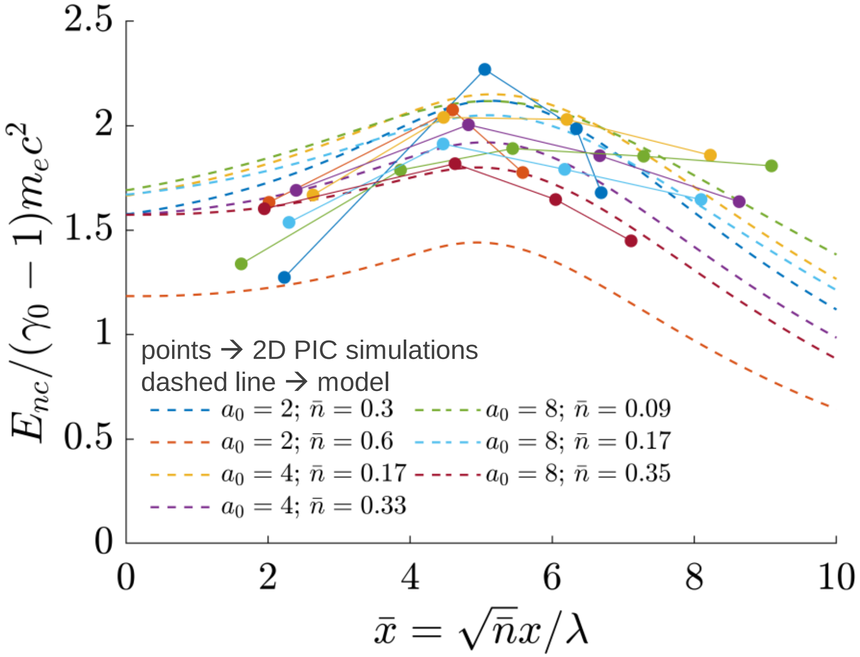

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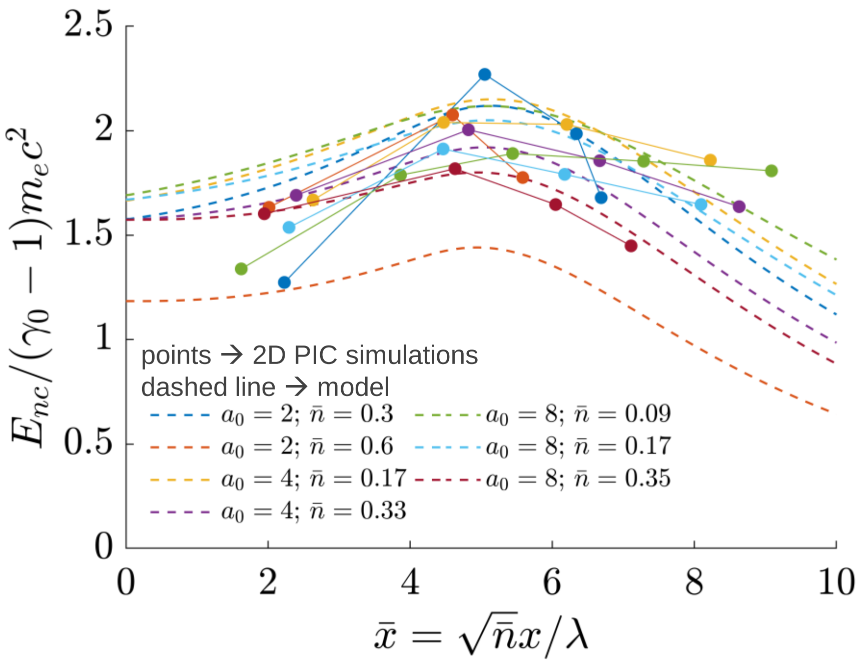
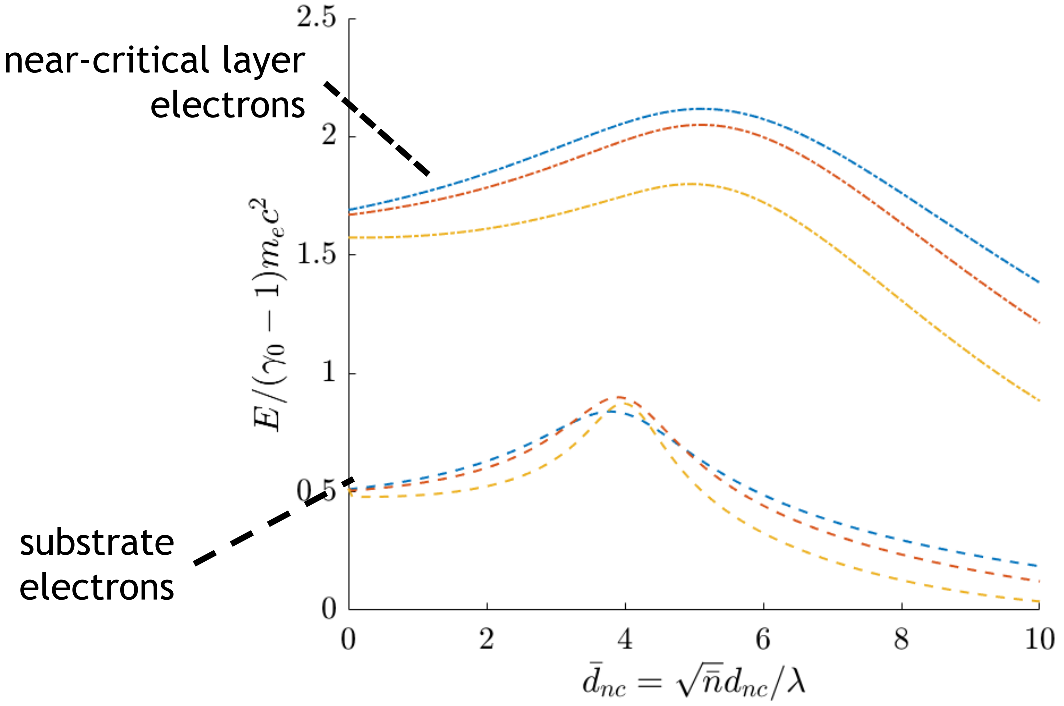


Also electrons from the substate are considered:

$$E_s(d_{nc}) = C_s[\gamma(d_{nc}) - 1]m_e c^2$$



Additional free parameter: $\boldsymbol{C_s = 0.24}$

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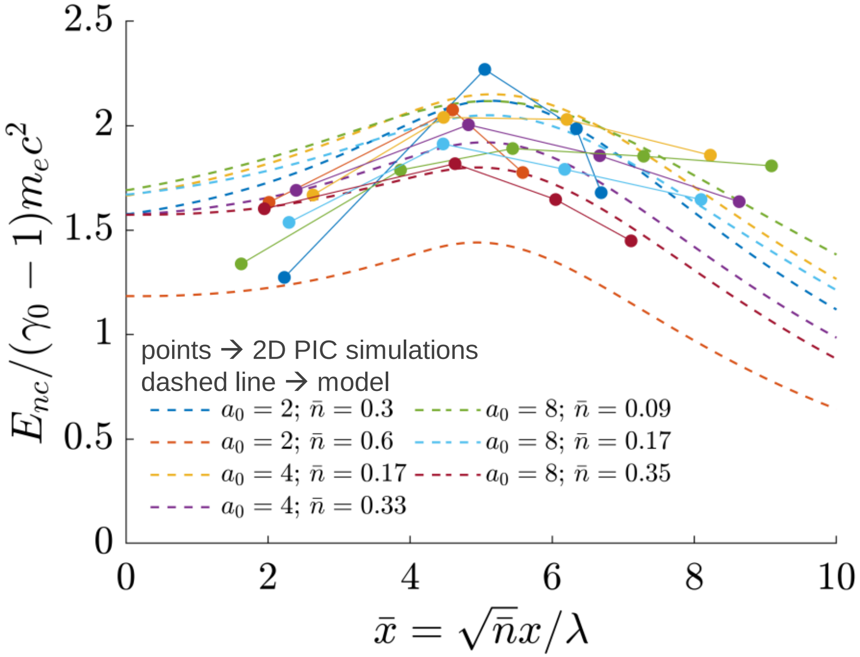

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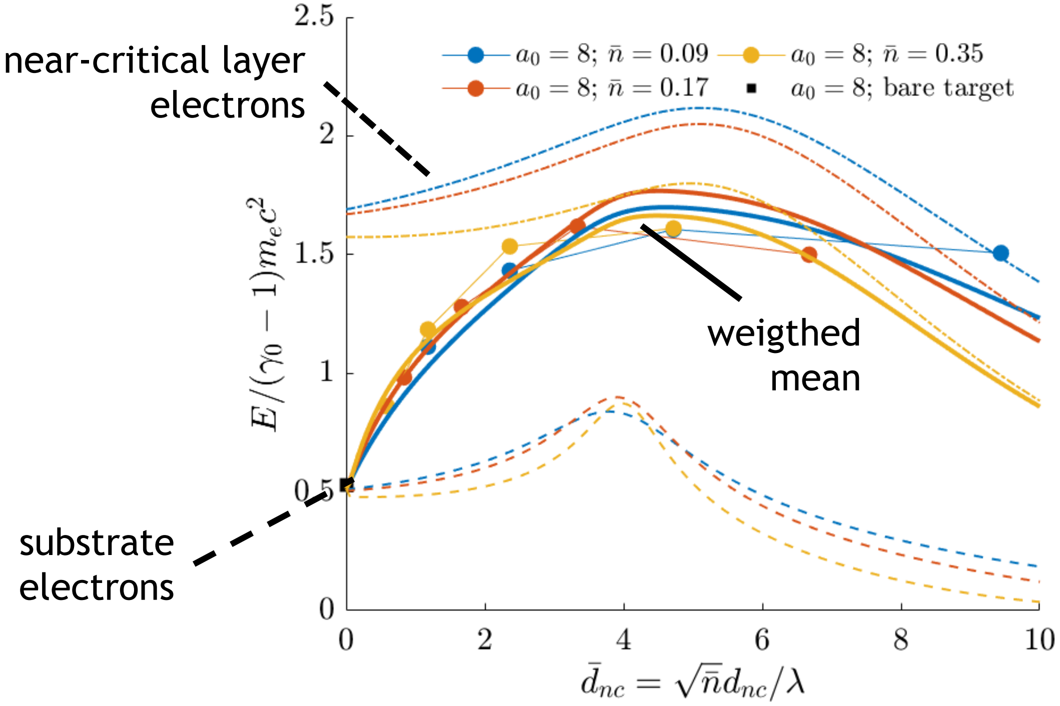

Additional free parameter: $C_s = 0.24$

4^{th} step: proton maximum energy estimation

Quasi-static model:

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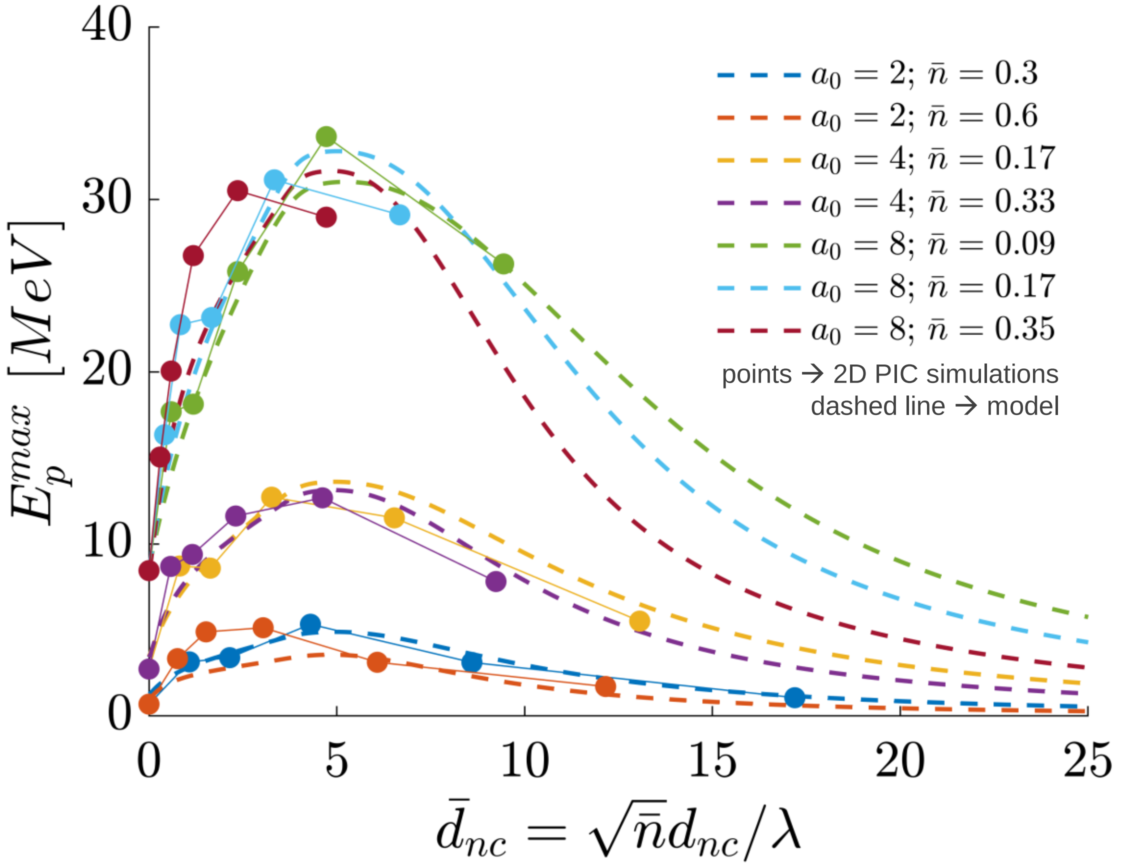
4th step: proton maximum energy estimation

Quasi-static model:

$$\epsilon_p^{max} = E_{DLT}\left[\log\left(\frac{n_{h,DLT}}{\tilde{n}}\right) - 1\right]$$

last free parameter: $\tilde{n} = 1.3 \cdot 10^{-3} n_c$



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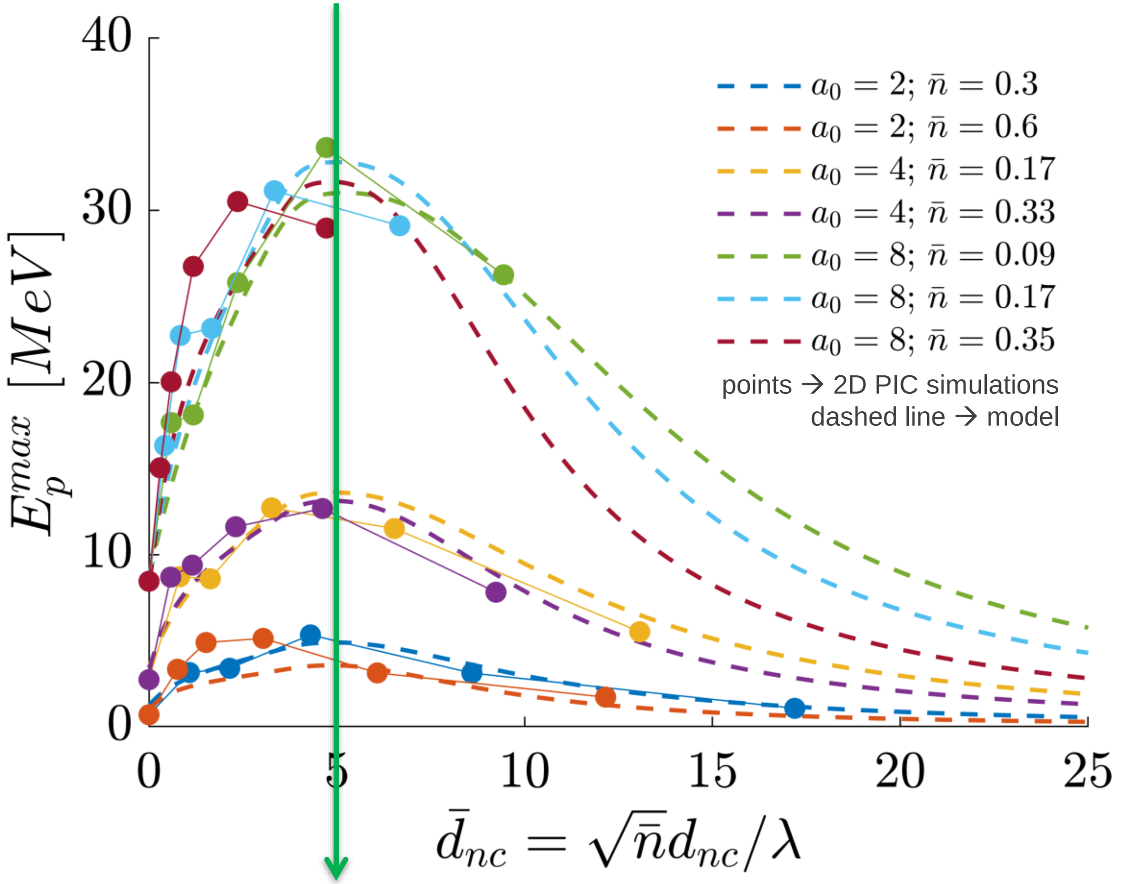


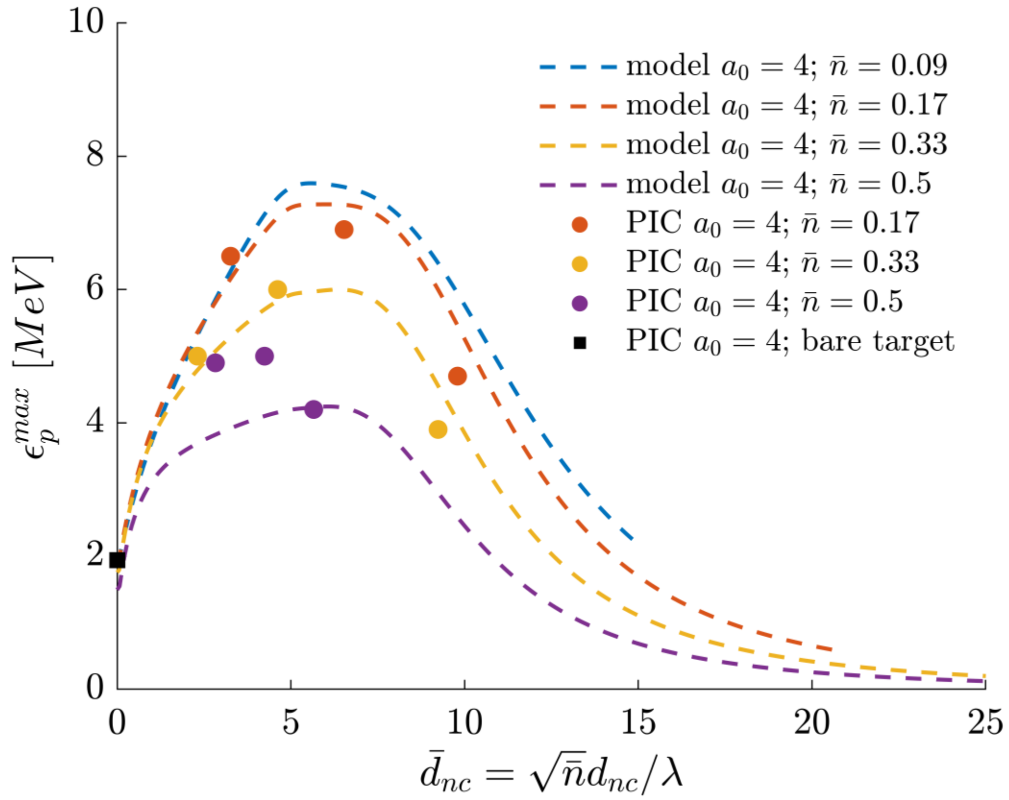
optimal thickness at the SF focal length

$$d_{nc}^{opt} \sim w_0/\sqrt{\bar{n}}$$

The same model is solved in 3D

3D parameters:

$C_{nc} = 1.1$
$r_c = 2.1$
$C_s = 0.18$
$\tilde{n} = 5 \cdot 10^{-2} n_c$



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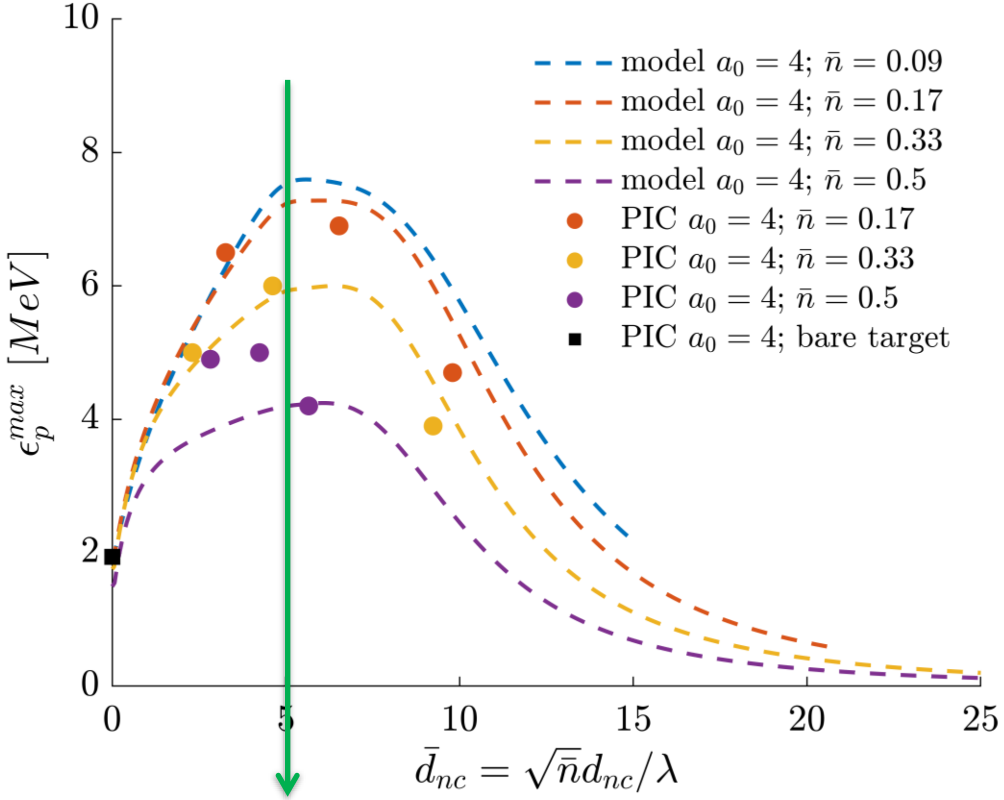

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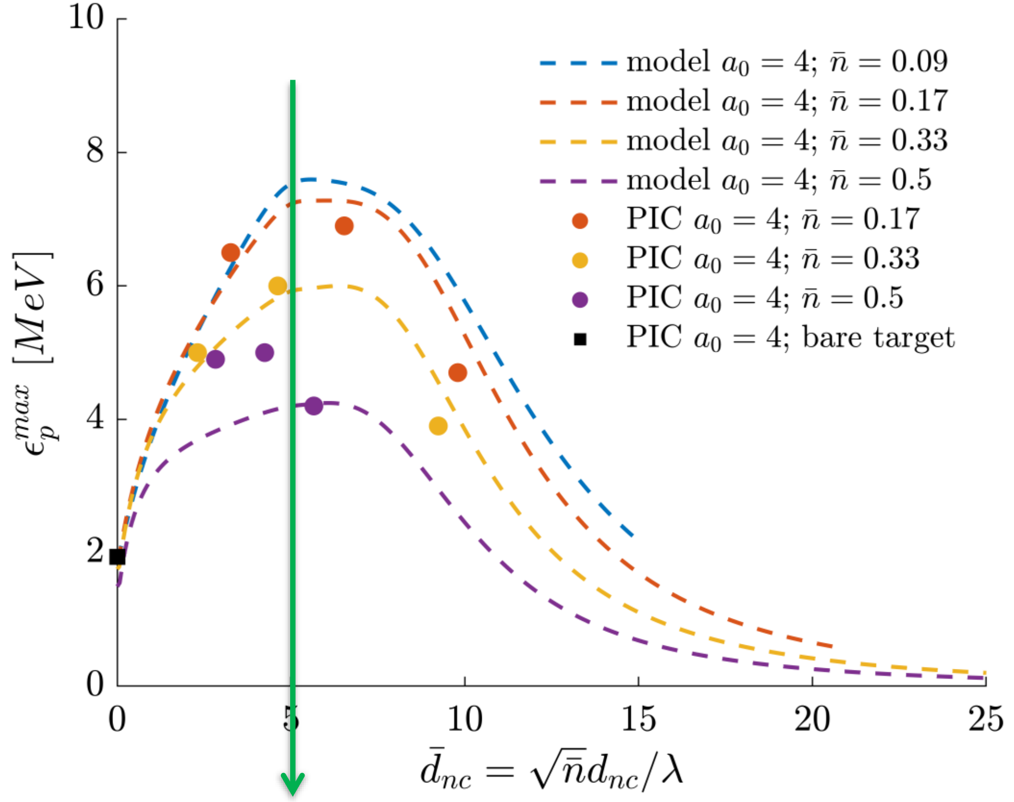

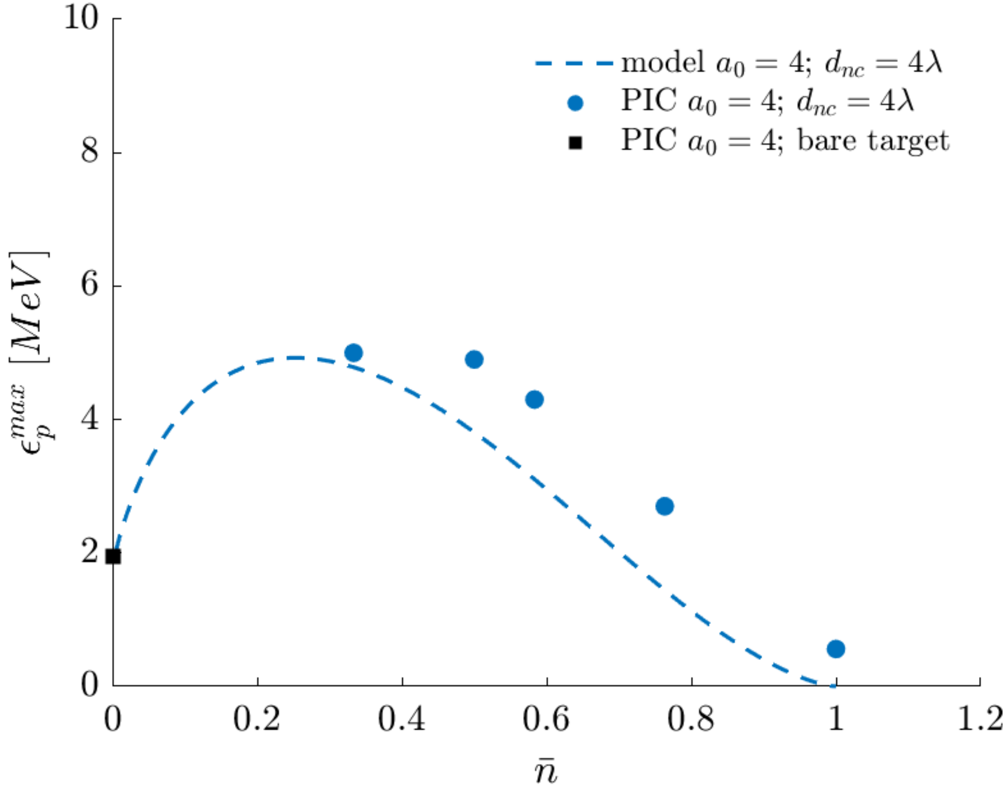

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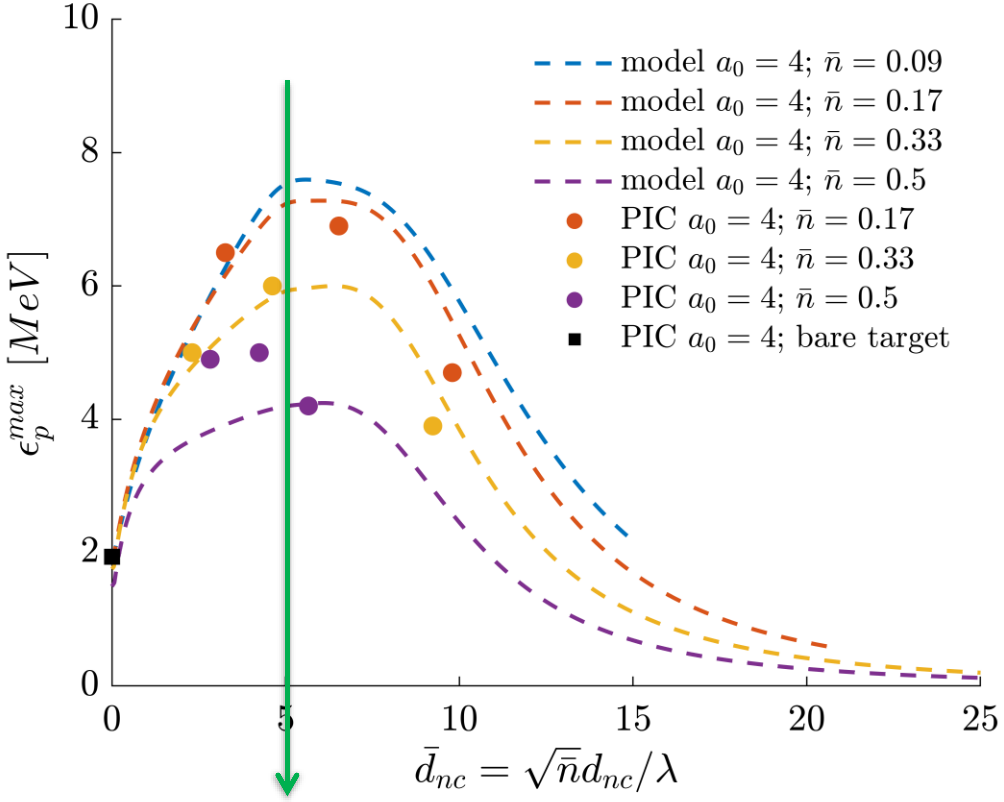
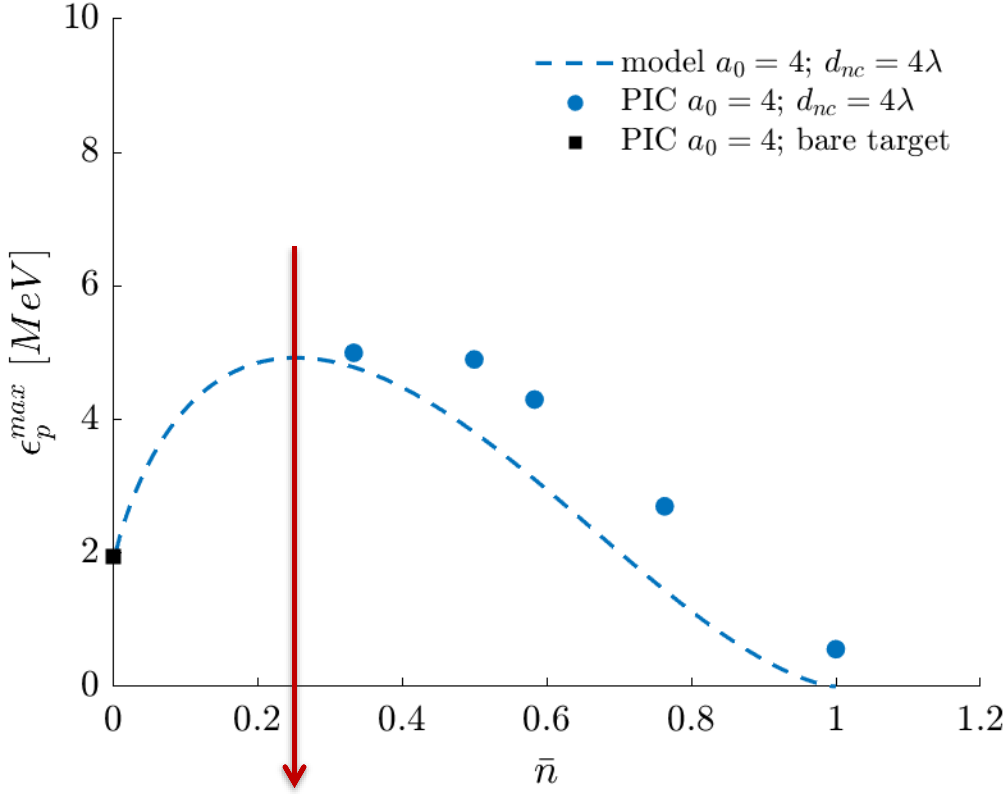
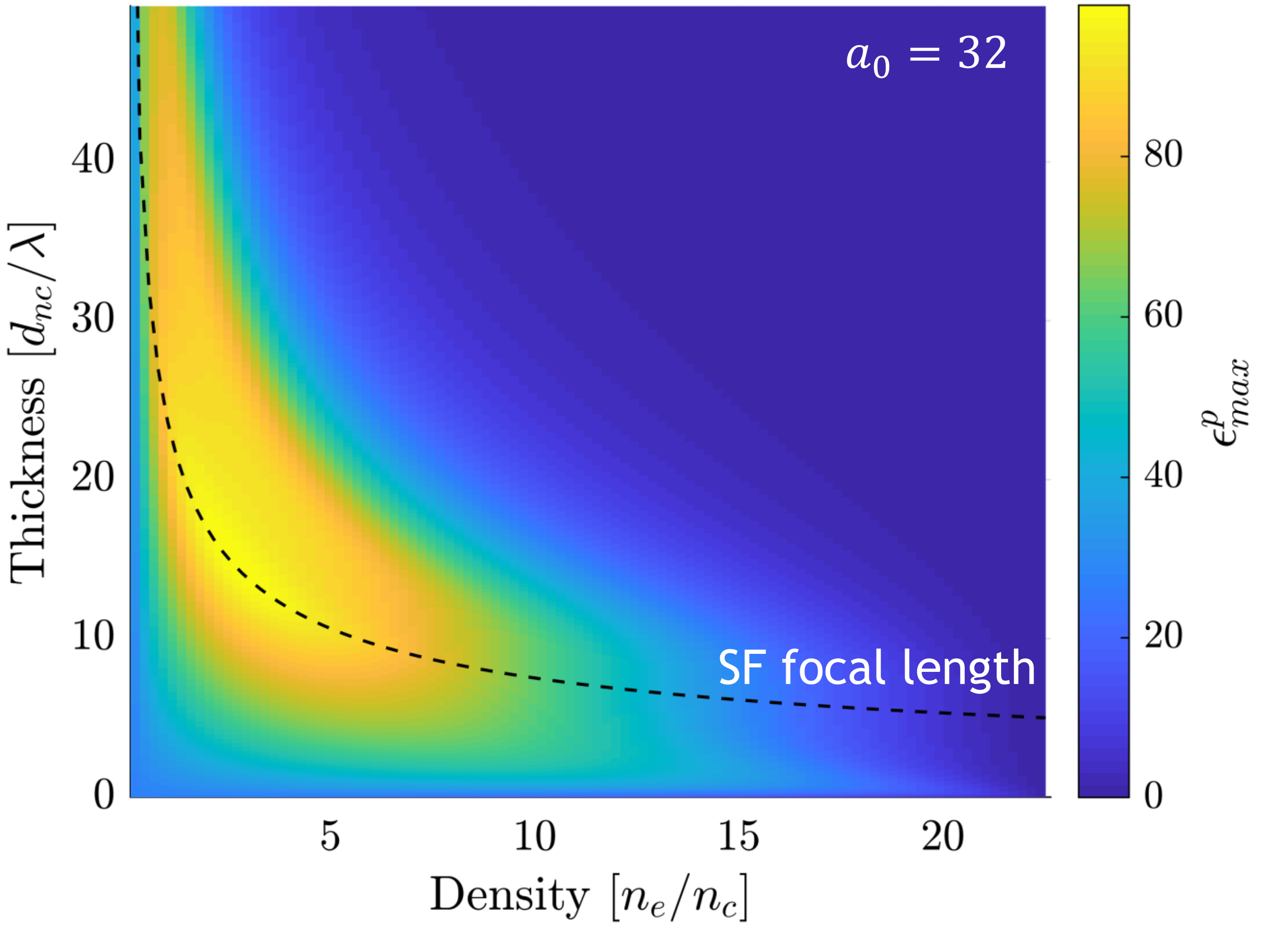




optimal thickness at the SF focal length

optimal density??

Maximum proton energy heat map



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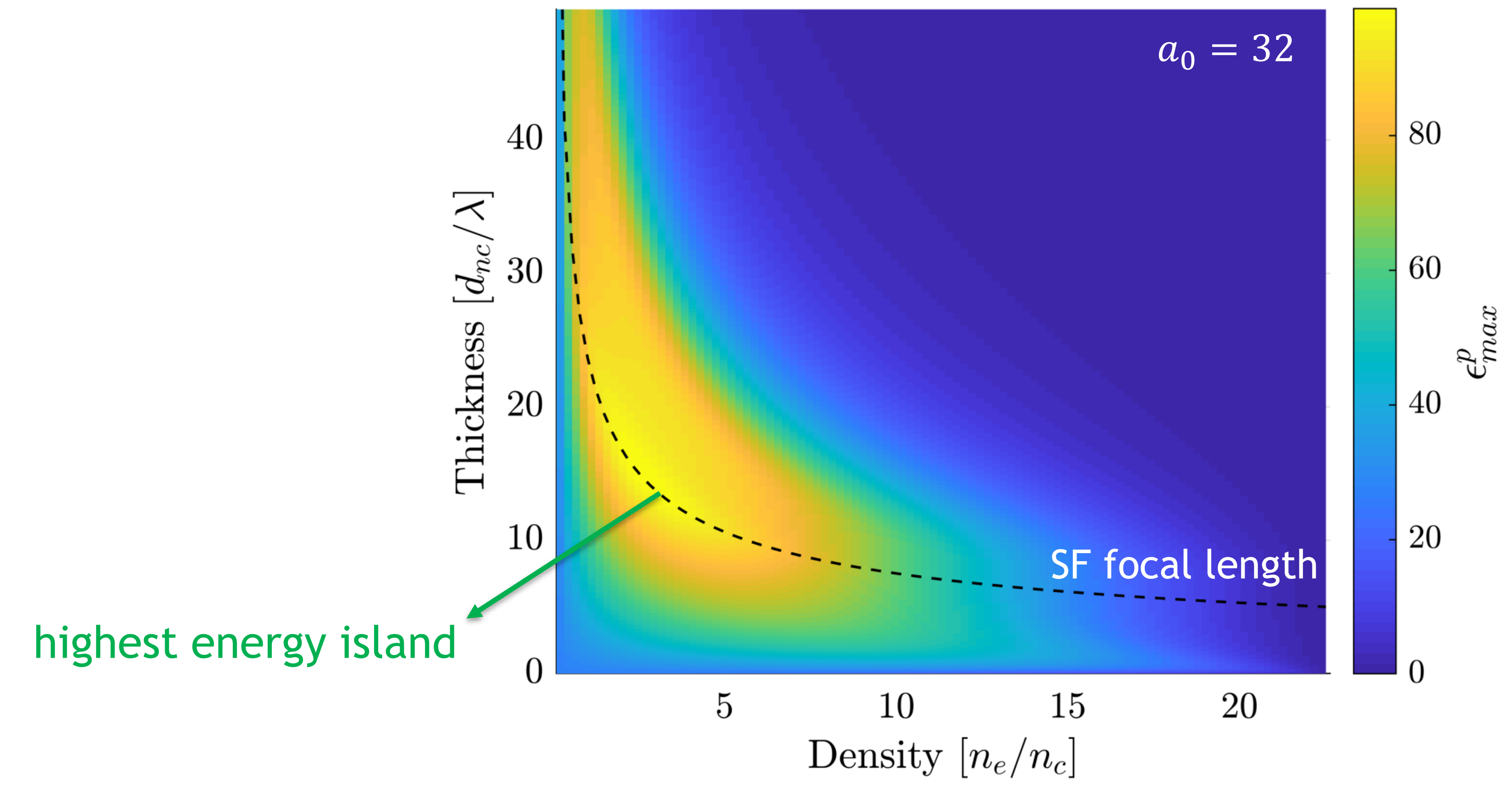
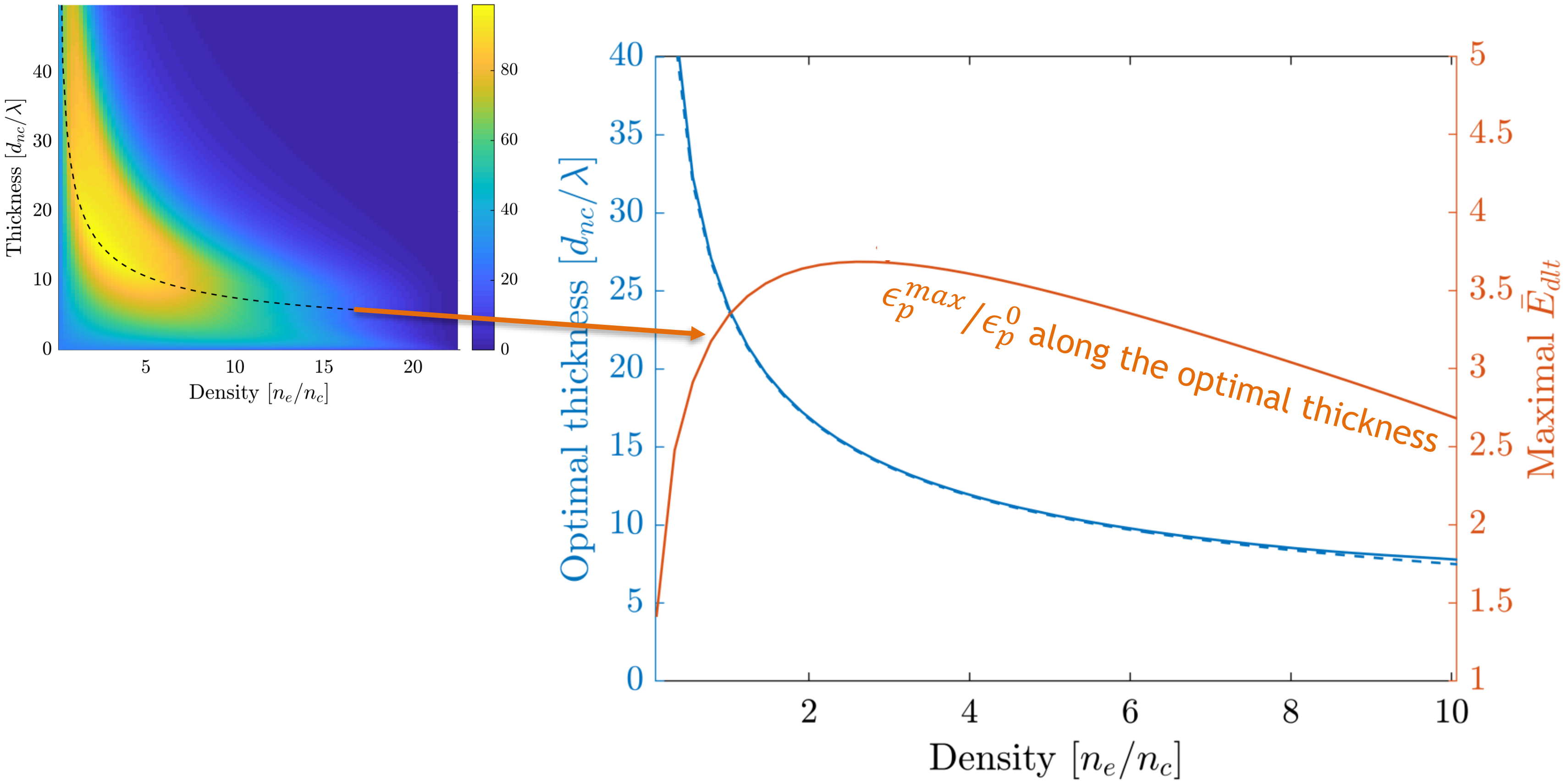
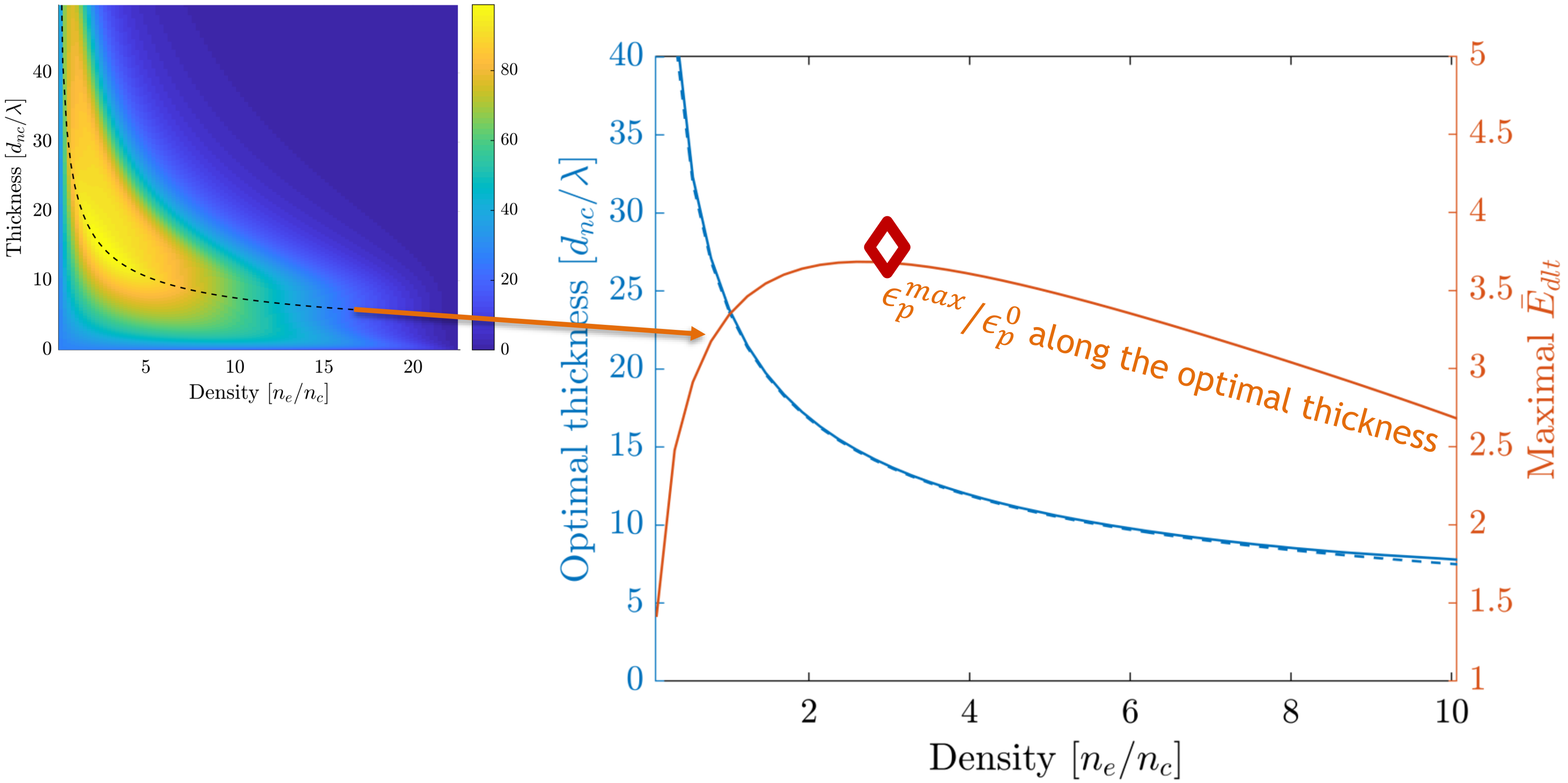


Analytical solution in the ultra-relativistic case



Ultra-relativistic case → $a_0 \gg 1$

Analytical solution in the ultra-relativistic case



Ultra-relativistic case → $a_0 \gg 1$

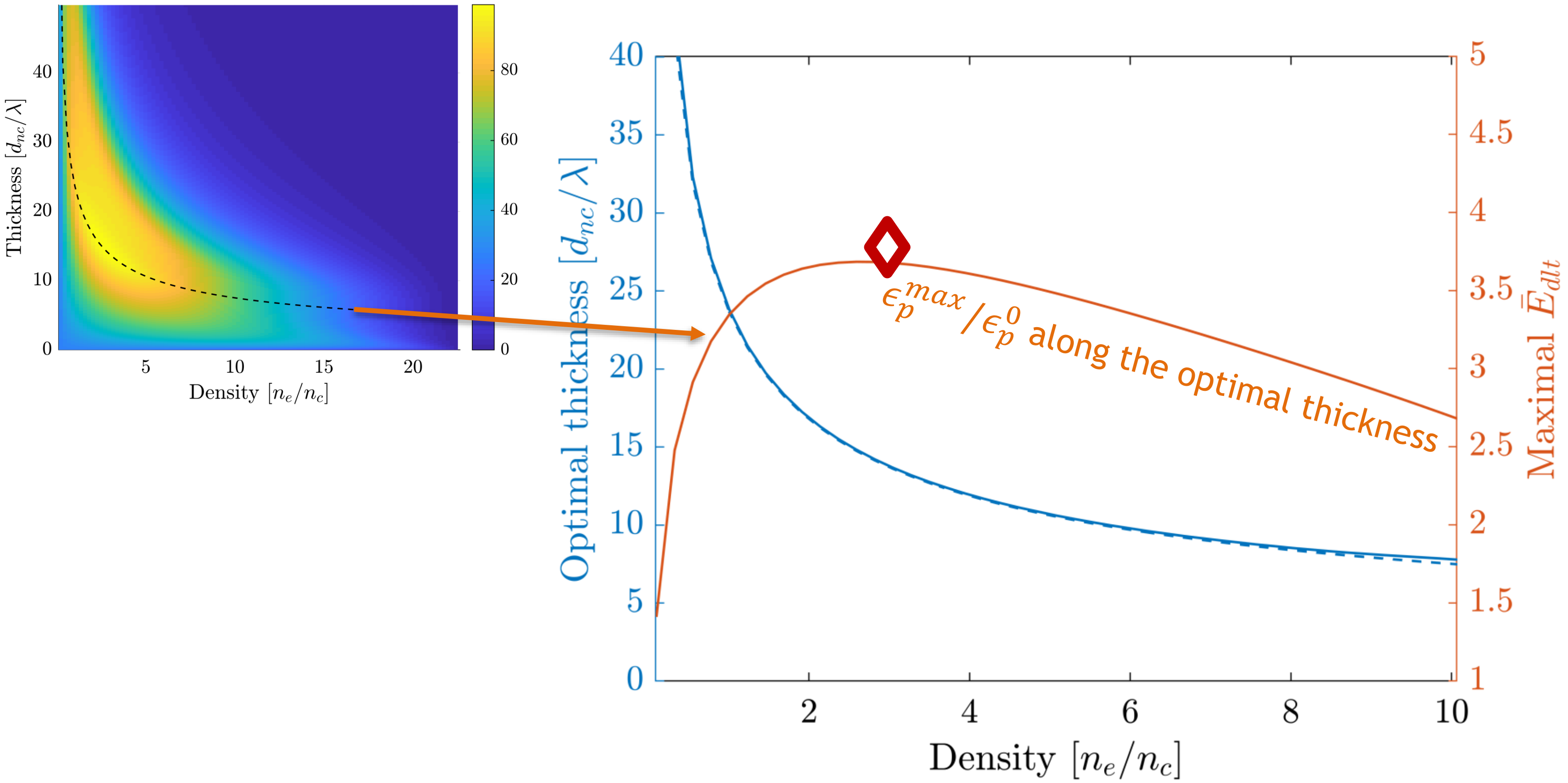
optimal density:

$$\bar{n}^{opt} = \frac{\lambda^2}{\pi w_0^2}\left(\frac{12\sqrt{2}\tau c/\lambda}{r_c^2 C_{nc}}\right)^{2/3}$$

Enhancement factor:

$$\bar{E}_{DLT}^{opt} = \frac{3C_{nc}}{4C_s}\left[1 - \frac{1}{\pi}\left(\frac{\sqrt{3}C_{nc}r_c^2}{2\tau c/\lambda}\right)^{2/3}\right]$$

Analytical solution in the ultra-relativistic case



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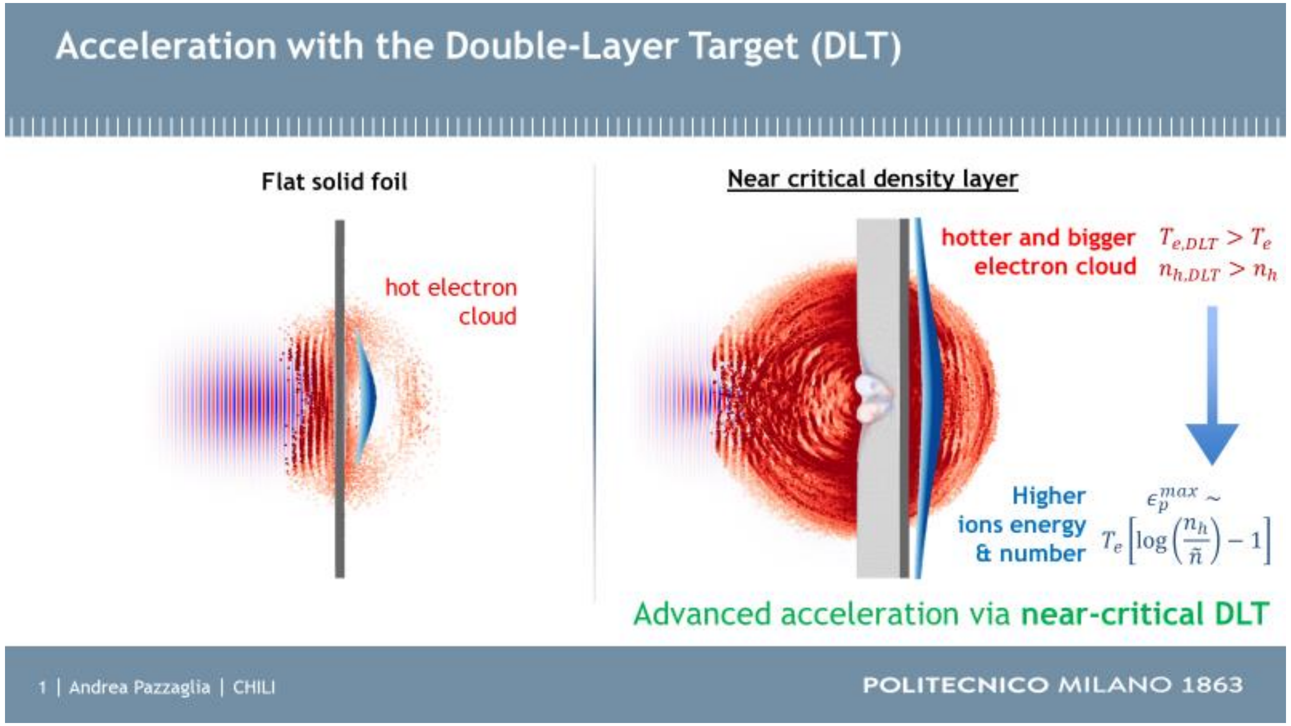
enhancement factors higher than ones reported in the literature

Conclusions

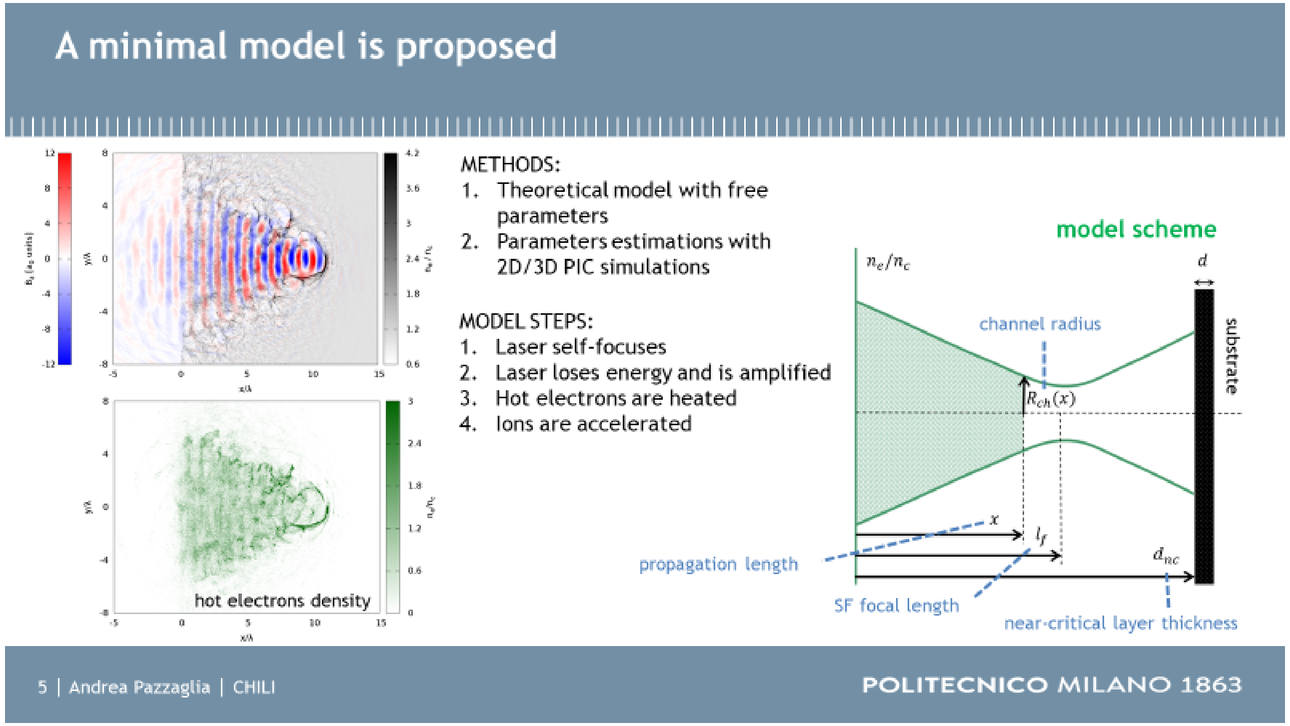
- Advanced TNSA via near-critical double-layer target



Conclusions

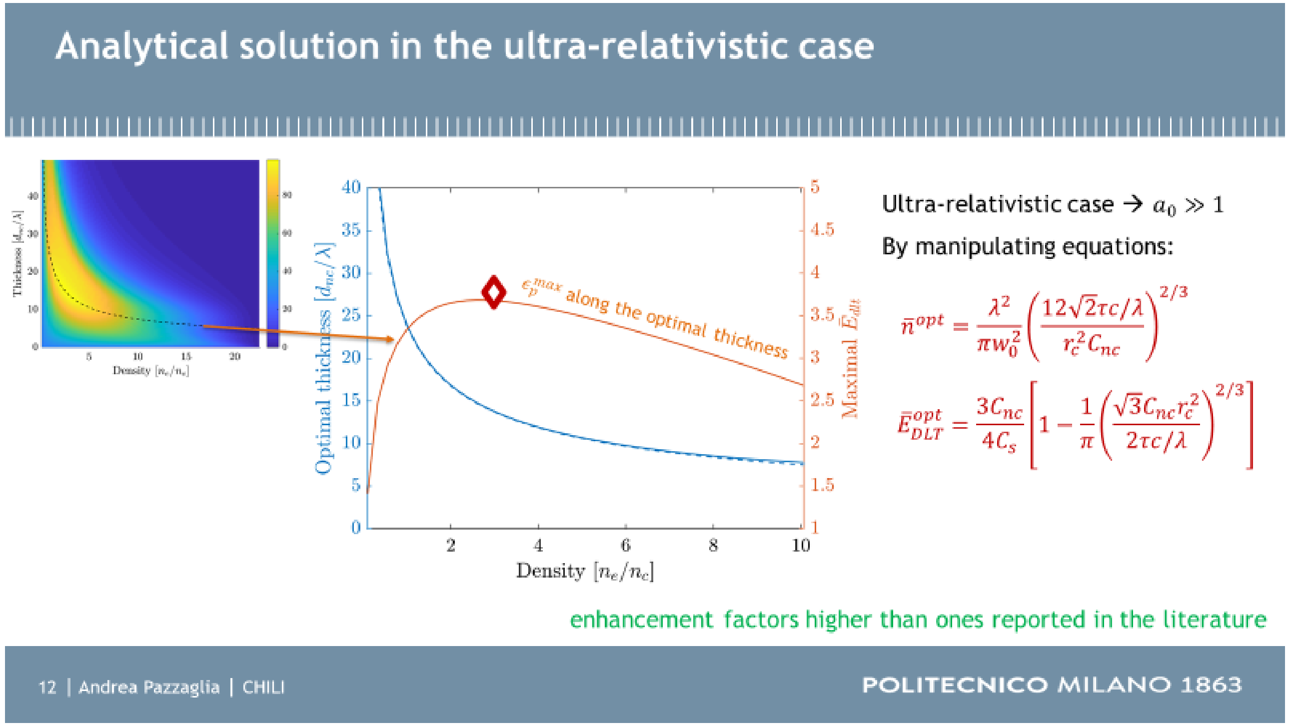
- Advanced TNSA via near-critical double-layer target

- Modelization of proton acceleration with DLT



Conclusions

- Advanced TNSA via near-critical double-layer target
- Modelization of proton acceleration with DLT
- Optimal DLT parameters

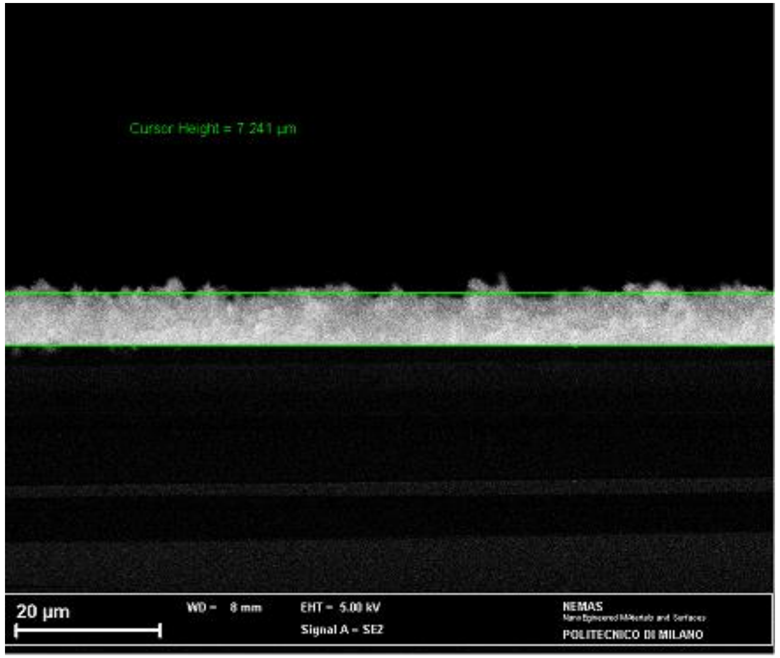


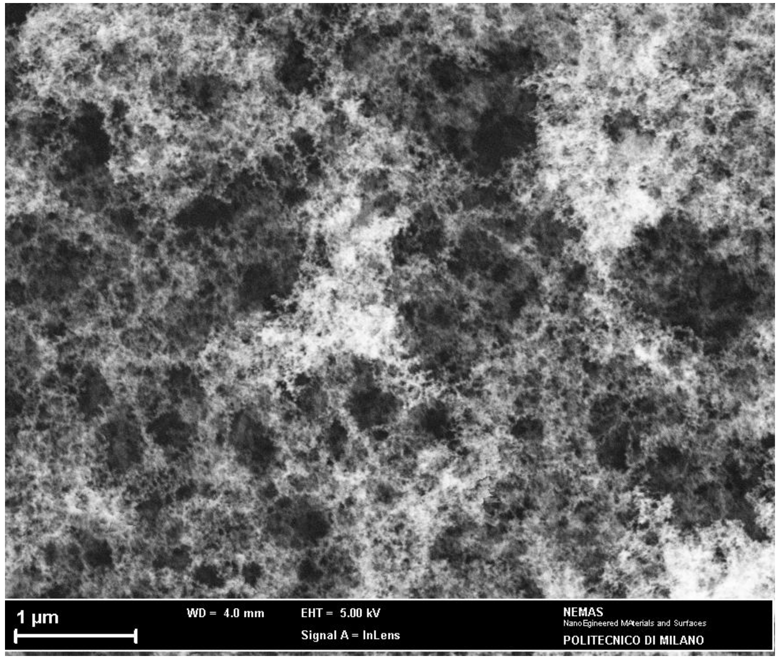
Future perspectives

Zani, Alessandro, et al. *Carbon* 56 (2013): 358-365.
Maffini, A., et al. *Physical Review Materials* 3.8 (2019): 083404.
Passoni, Matteo, et al. *Plasma Physics and Controlled Fusion* (2019).

- Optimal DLT realization
    - ❖ Nanostructured near-critical layer

Produced by ns-PLD and fs-PLD

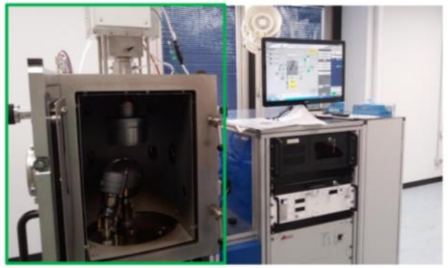




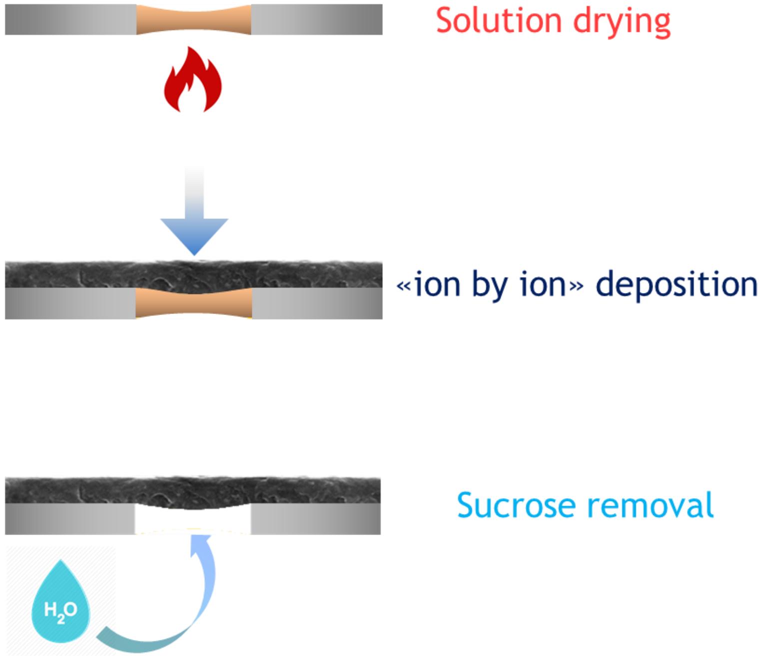
Future perspectives

- Optimal DLT realization
  - ❖ Nanostructured near-critical layer
  - ❖ Substrate production

High Power Impulse Magnetron Sputtering (HiPIMS)



Sucrose + water

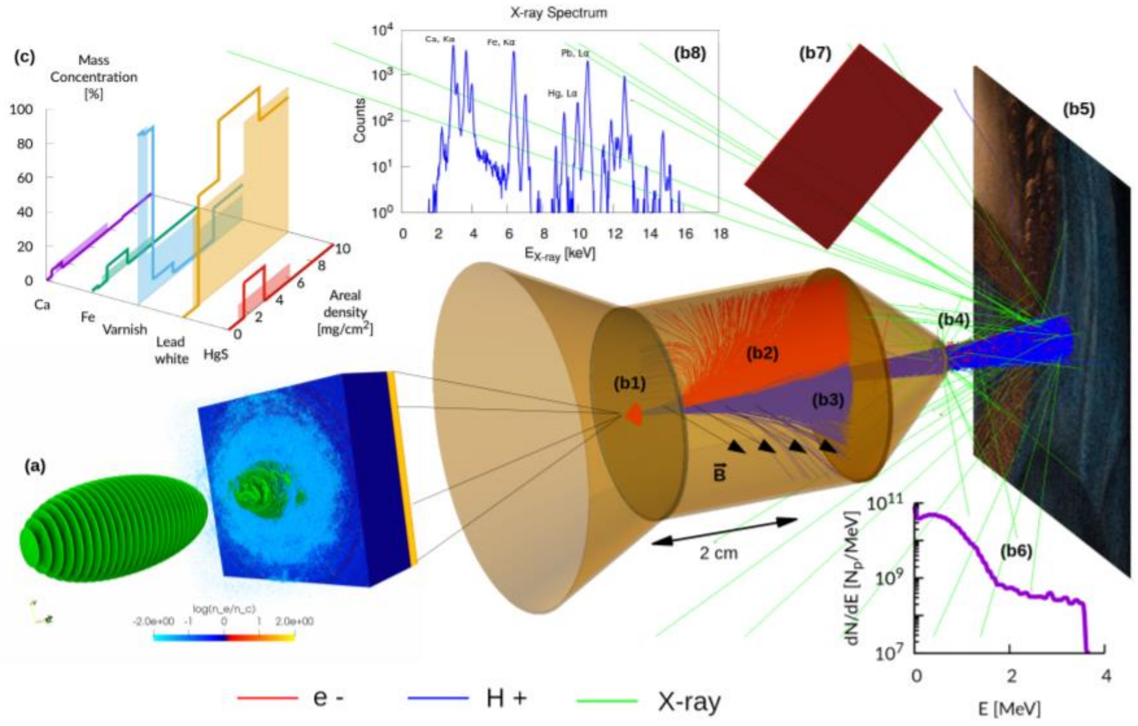


Future perspectives

- Optimal DLT realization
  - ❖ Nanostructured near-critical layer
  - ❖ Substrate production

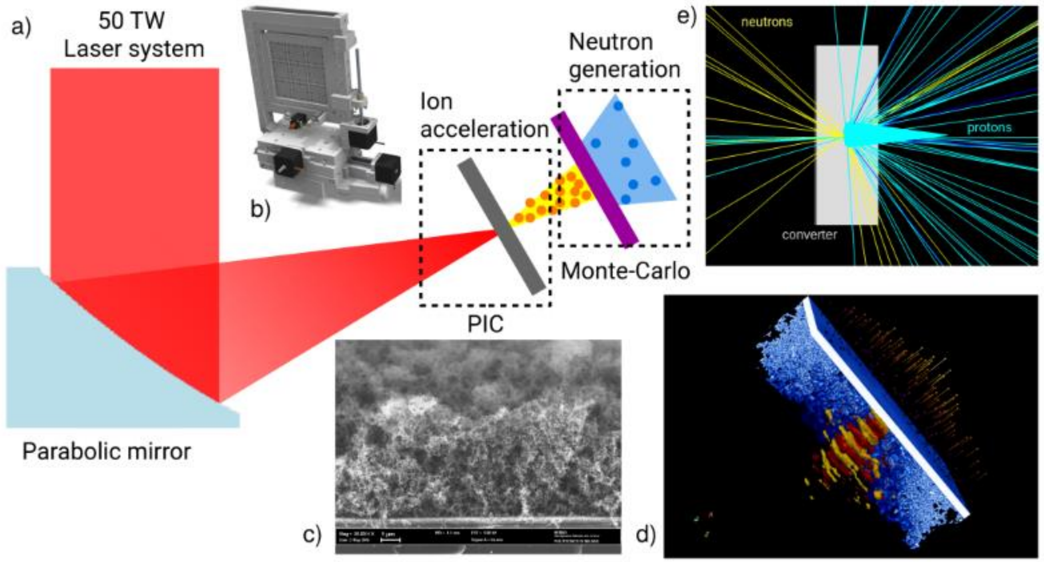
- Applications
  - ❖ Ion Beam Analysis

Passoni M., Fedeli L and Mirani F. Superintense Laser-driven Ion Beam Analysis (2019). *Scientific Reports*



Future perspectives

- Optimal DLT realization
  - ❖ Nanostructured near-critical layer
  - ❖ Substrate production
- Applications
  - ❖ Ion Beam Analysis
  - ❖ Neutron & Radioisotopes production



Fedeli L. et al. *New Journal of Physics* Under review

A. Tentori Master's thesis, Politecnico di Milano, Italy (2018)

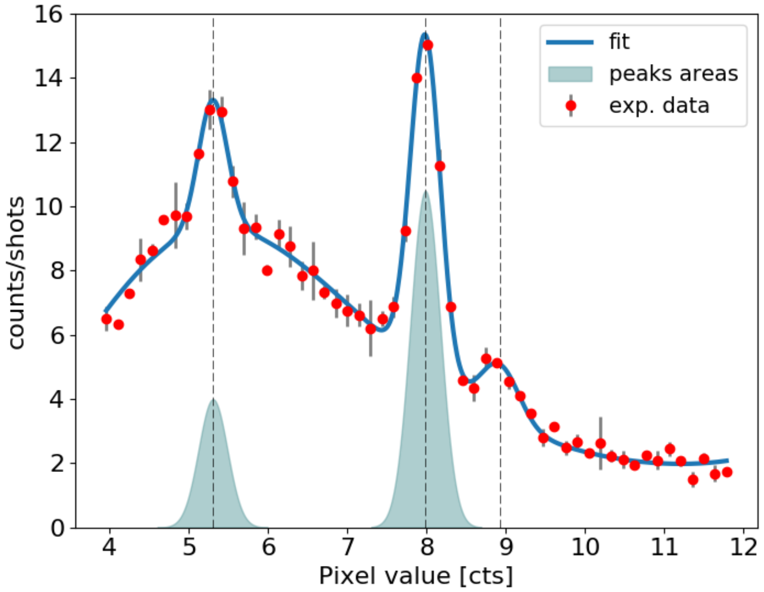
F. Arioli Master's thesis, Politecnico di Milano, Italy (2019)

A. Giovannelli Master's thesis, Politecnico di Milano, Italy (2019)

Future perspectives

- Optimal DLT realization
  - ❖ Nanostructured near-critical layer
  - ❖ Substrate production

- Applications
  - ❖ Ion Beam Analysis
  - ❖ Neutron & Radioisotopes production
  - ❖ Dedicated experiments



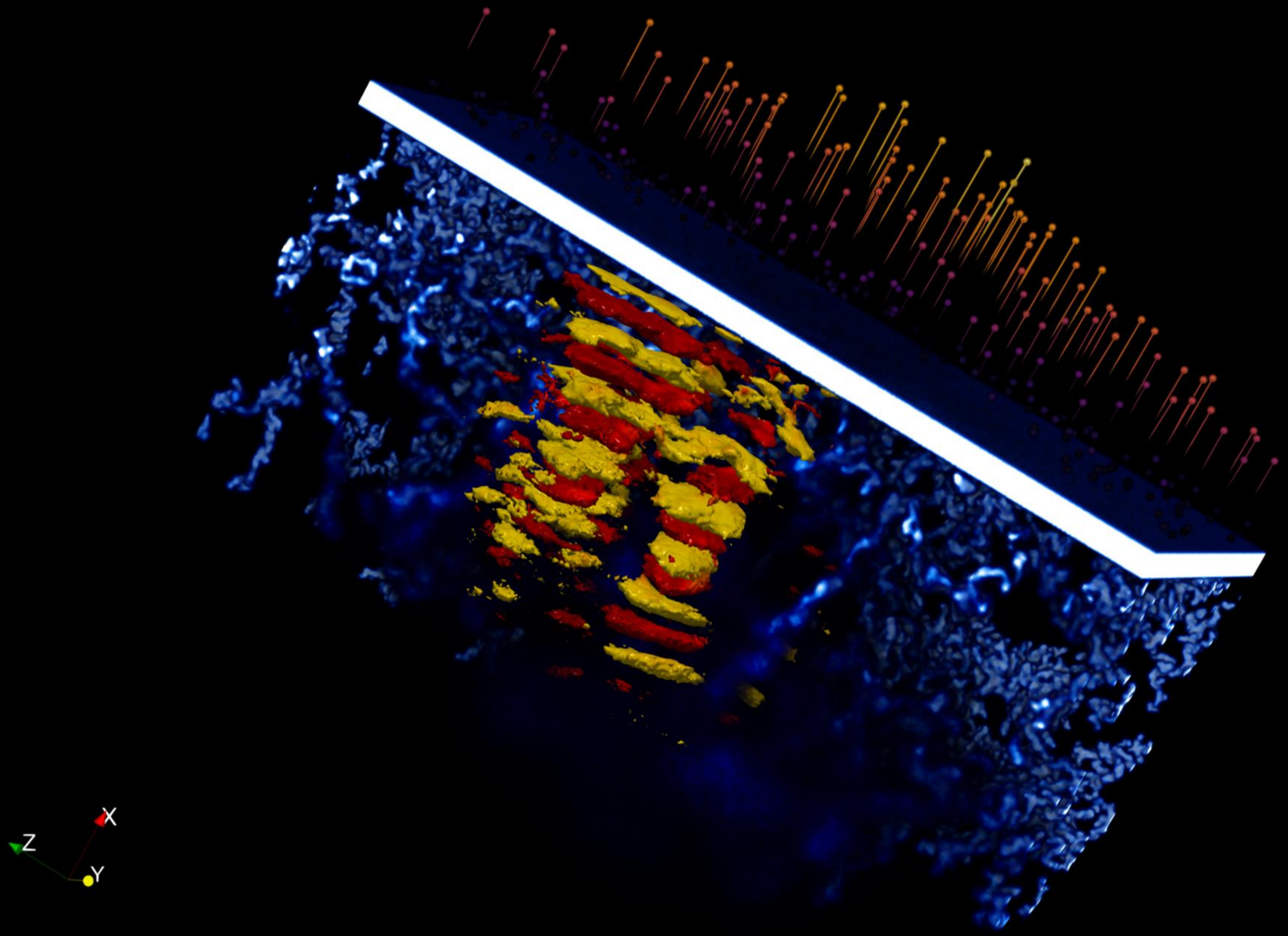
CLPU

Acknowledgments

POLITECNICO MILANO 1863

NanoLab

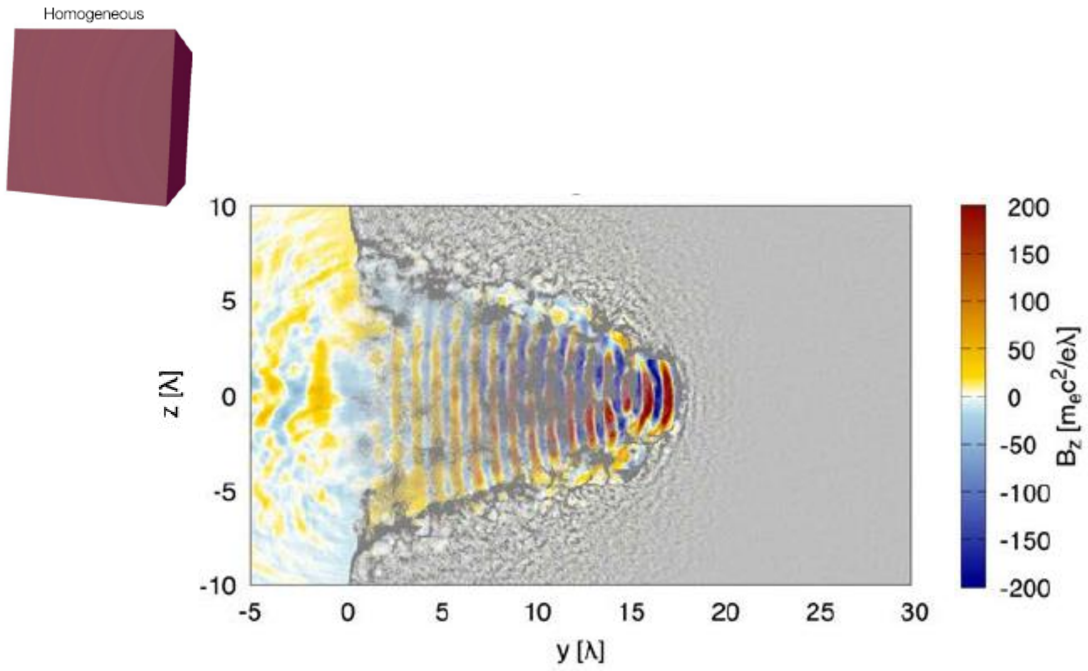
erc ERC-2014-CoG No. 647554 ENSURE



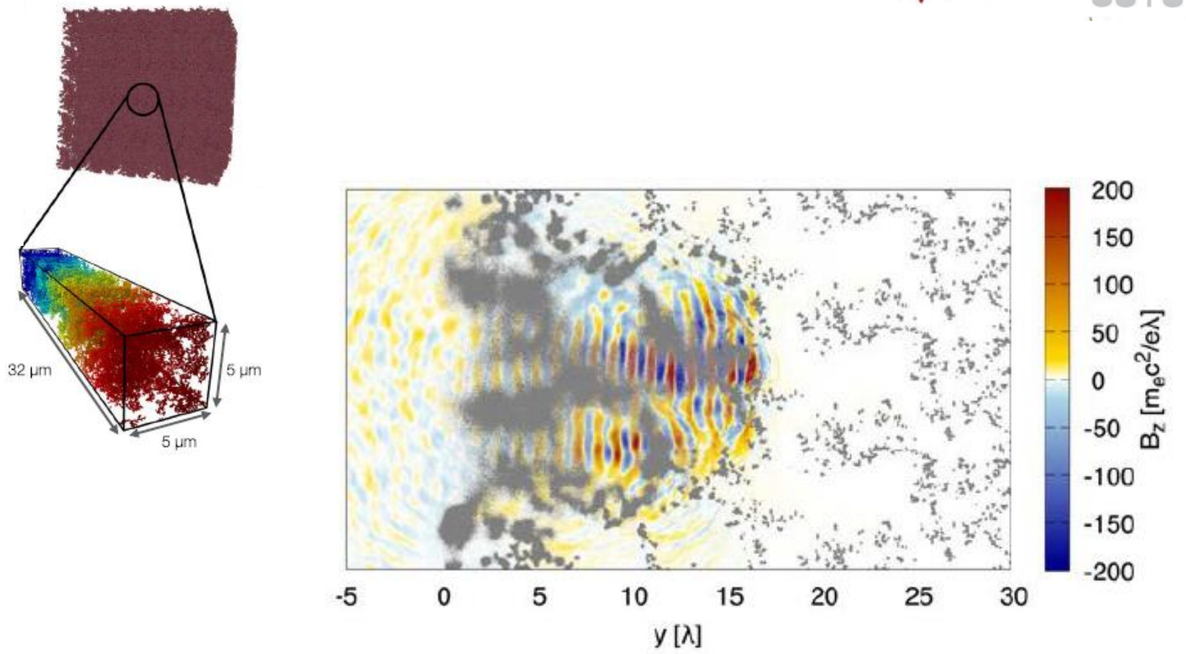
...and thank you for your attention!!

Realistic near-critical layer effects

Homogeneus near-critical plasma



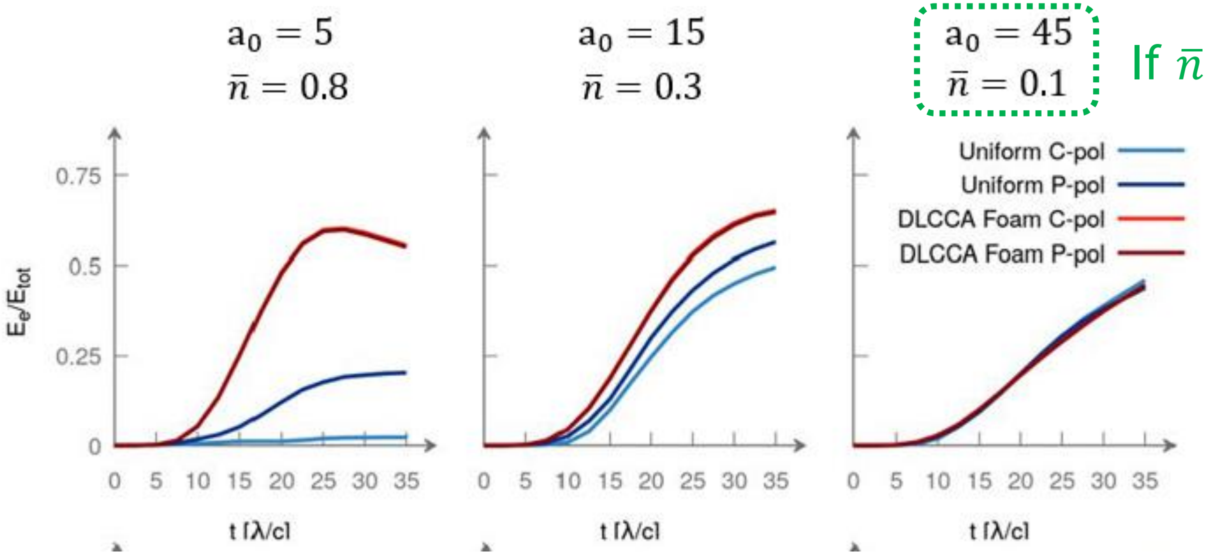
Nanostructured near-critical plasma



Fedeli, L., Formenti, A., Cialfi, L., Pazzaglia, A., & Passoni, M. (2018). Ultra-intense laser interaction with nanostructured near-critical plasmas. *Scientific reports*, *8*(1), 3834.

3D PIC simulations show evident differences

Differences in pulse energy loss and electron heating



If $\bar{n} \ll 1$ the energy loss is similar

the model previsions are valid in this regime!

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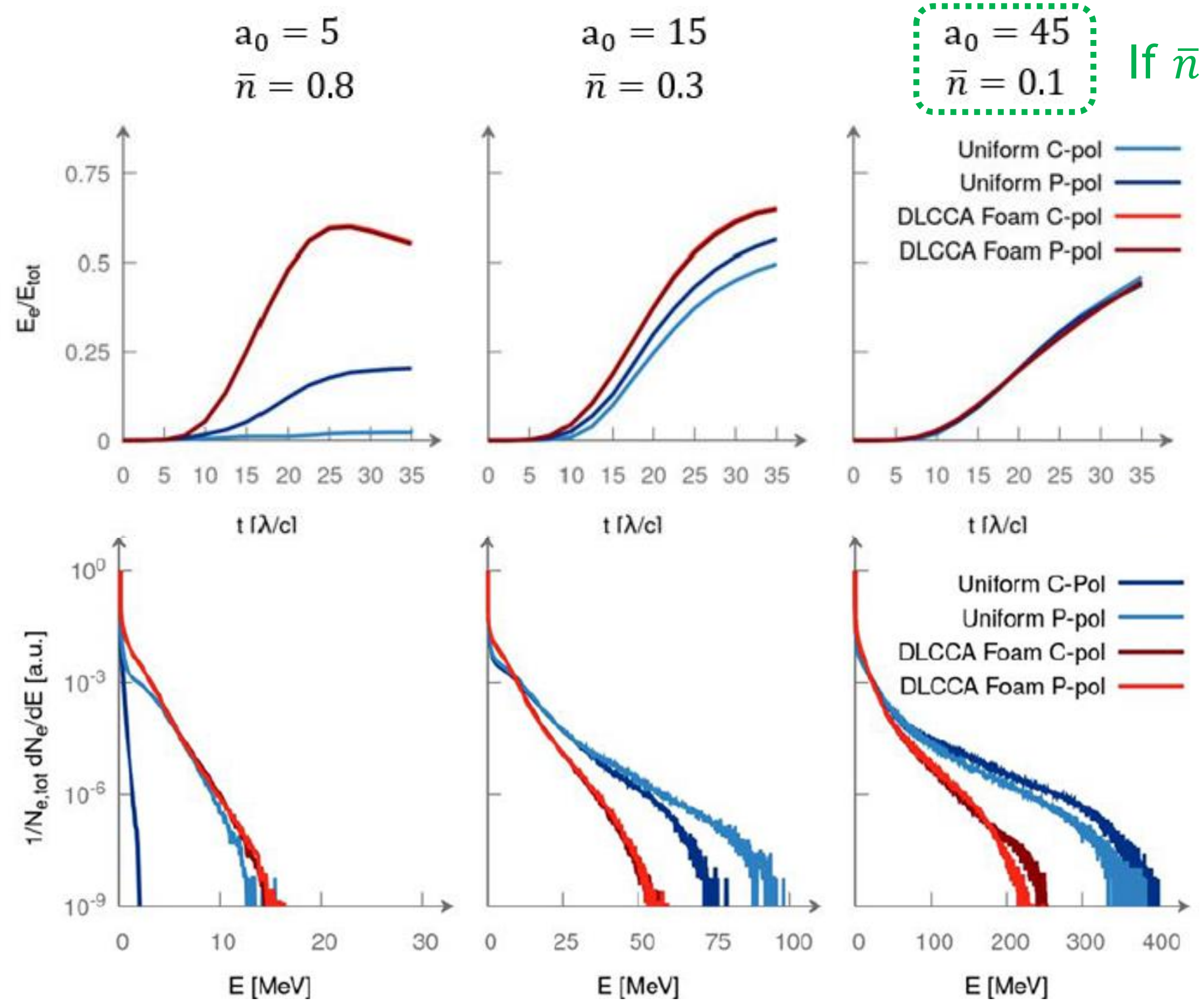

If $\bar{n} \ll 1$ the energy loss is similar

the model previsions are valid in this regime!

Nanostructured plasma:

- Electrons temperature ↓
- Electrons number ↑

$$\epsilon_p^{max} = T_{DLT}\left[\log\left(\frac{n_{h,DLT}}{\tilde{n}}\right) - 1\right]$$

→ lower energy expected

uniform near-critical plasma are optimal