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

- Hot electron cloud $T_e$ = electron temperature
- $n_h$ = electron density

Super-intense laser
Conventional laser-driven ion acceleration

Flat solid foil

hot electron cloud

super-intense laser

~MeV protons

\[ T_e \quad n_h \quad \text{electron temperature} \quad \text{electron density} \]

quasi-static TNSA model:

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

Passoni, Matteo, and M. Lontano. "Physical review letters 101.11 (2008): 115001."
Conventional laser-driven ion acceleration

Flat solid foil

- super-intense laser
- hot electron cloud
- ~MeV protons
- electron temperature $T_e$
- electron density $n_h$
- low electron conversion efficiency
- low maximum proton energy

Quasi-static TNSA model:

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

Passoni, Matteo, and M. Lontano. "Physical review letters 101.11 (2008): 115001."
Acceleration with the Double-Layer Target (DLT)

- Flat solid foil
  - Hot electron cloud

- Near critical density layer
  - Hotter and bigger electron cloud

\[ T_{e,DLT} > T_e \]
\[ n_{h,DLT} > n_h \]
Acceleration with the Double-Layer Target (DLT)

Flat solid foil

Near critical density layer

hotter and bigger electron cloud

$T_{e,DLT} > T_e$

$n_{h,DLT} > n_h$

Higher ions energy & number

Advanced acceleration via near-critical DLT
Experimental evidences

Tested by independent groups:

- Pazzaglia, Andrea, et al. Physical Review Accelerators and Beams 19.6 (2016): 061301.
- Prencipe, Irene, et al. Plasma Physics and Controlled Fusion 58.3 (2016): 034019.
- Passoni, Matteo, et al. Physical Review Accelerators and Beams 19.6 (2016): 061301.
- Bin, J. H., et al. Physical Review Letters 120.7 (2018): 074801.
- Ma, W. J., et al. Physical Review Letters 122.1 (2019): 014803.
Experimental evidences

Tested by independent groups:

Bin, J. H., et al. *Physical review letters* 120.7 (2018): 074801.

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

Prencipe, Irene, et al. *Plasma Physics and Controlled Fusion* 58.3 (2016): 034019.

Passoni, Matteo, et al. *Physical Review Accelerators and Beams* 19.6 (2016): 061301.

Have we achieved the best performances?
PIC simulations help to understand the interaction physics

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

Passoni, Matteo, et al. *Physical Review Accelerators and Beams* 19.6 (2016): 061301.

Fedeli, Luca, et al. *Scientific reports* 8.1 (2018): 3834.
PIC simulations help to understand the interaction physics

Realistic 3D PIC simulations are computationally very expensive

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

Fedeli, Luca, et al. Scientific reports 8.1 (2018): 3834.
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:**
1. Theoretical model with free parameters
2. Parameters estimations with 2D/3D PIC simulations

**MODEL STEPS:**
1. Laser self-focusing
2. Laser energy loss and amplification
3. Hot electrons heating
4. Ions acceleration
A minimal model is proposed

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

MODEL STEPS:
1. Laser self-focusing
2. Laser energy loss and amplification
3. Hot electrons heating
4. Ions acceleration
1\textsuperscript{st} 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

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

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

relativistic transparency factor

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

points $\rightarrow$ 2D PIC simulations
dashed line $\rightarrow$ model
1\textsuperscript{st} 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

\[ w_m = \frac{\lambda}{\pi \sqrt{n}} \]

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

relativistic transparency factor

\[ \bar{n} = \frac{n_e}{\gamma n_c} \]
1\textsuperscript{st} 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

\[ w_m = \frac{\lambda}{\pi \sqrt{n}} \]

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

relativistic transparency factor

\[ \bar{n} = \frac{n_e}{\gamma n_c} \]

The propagation is self-similar!

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

Wang, H. Y., et al. *Physical review letters* 107.26 (2011): 265002.
2\textsuperscript{nd} step: pulse energy loss and amplification

Pulse energy loss equation:

\[ d\varepsilon_p = -T_{nc}(x)n_e2R_{ch}(x)dx \]

Amplification equation:

\[ \bar{a}(x) = \frac{a(x)}{a_0} = \sqrt{\frac{\varepsilon_p(x)}{w(x)/w_0}} \]
2nd step: pulse energy loss and amplification

**Pulse energy loss equation:**

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

**Amplification equation:**

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

**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
2nd step: pulse energy loss and amplification

**Pulse energy loss equation:**
\[ d\varepsilon_p = -T_{nc}(x)n_e2R_{ch}(x)dx \]

**Electron temperature**

\[ T_{nc}(x) = C_{nc} [\gamma(x) - 1]m_e c^2 \]

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

**Amplification equation:**
\[ \tilde{a}(x) = \frac{a(x)}{a_0} = \sqrt{\frac{\varepsilon_p(x)}{w(x)/w_0}} \]

points \( \rightarrow \) 2D PIC simulations
dashed line \( \rightarrow \) model

Two free parameters: \( C_{nc} = 1.7; r_c = 2.0 \)
The energy lost by the pulse is given to the hot electrons:

\[ E_{nc}(x) = \frac{\left(1 - \bar{e}_p(x)\right) \varepsilon_p}{N_{nc}(x)} \]

Total number of electrons in the channel
The energy lost by the pulse is given to the hot electrons:

\[ E_{nc}(x) = \frac{\left(1 - \bar{e}_p(x)\right)\varepsilon_0}{N_{nc}(x)} \]

where \( N_{nc}(x) \) is the total number of electrons in the channel.
3\textsuperscript{rd} step: hot electrons heating

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

\[ E_{nc}(x) = \frac{\left(1 - \bar{\varepsilon}_p(x)\right) \varepsilon_{p0}}{N_{nc}(x)} \]

Also electrons from the substate are considered:

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

Additional free parameter: \( C_s = 0.24 \)
3rd step: hot electrons heating

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

$$E_{nc}(x) = \frac{(1 - \bar{e}_p(x)) \epsilon_p(x)}{N_{nc}(x)}$$

Total number of electrons in the channel

$$E_{nc}(x) = \frac{(1 - \bar{e}_p(x)) \epsilon_p(x)}{N_{nc}(x)}$$

Also electrons from the substate are considered:

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

Additional free parameter: $$C_s = 0.24$$
4th step: proton maximum energy estimation

Quasi-static model:

\[ \epsilon_p^{\text{max}} = E_{DLT} \left[ \log \left( \frac{n_{h,DLT}}{\bar{n}} \right) - 1 \right] \]
4th step: proton maximum energy estimation

Quasi-static model:

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

last free parameter: \( \tilde{n} = 1.3 \cdot 10^{-3} n_c \)
4th step: proton maximum energy estimation

Quasi-static model:

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

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

$$\bar{d}_{nc} = \sqrt{\bar{n}d_{nc}}/\lambda$$

$$d_{nc}^{opt} \sim w_0/\sqrt{\bar{n}}$$
The same model is solved in 3D

3D parameters:

\[ C_{nc} = 1.1 \]
\[ r_c = 2.1 \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]
The same model is solved in 3D

3D parameters:

\[ C_{nc} = 1.1 \]
\[ r_c = 2.1 \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]
The same model is solved in 3D

3D parameters:

\[ C_{nc} = 1.1 \]
\[ r_c = 2.1 \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]

optimal thickness at the SF focal length
The same model is solved in 3D

3D parameters:

\[ C_{nc} = 1.1 \]
\[ r_c = 2.1 \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]

\[ C_{nc} = \frac{1}{1.1} \]
\[ r_c = \frac{2.1}{10} \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]

\[ C_{nc} = \frac{1}{1.1} \]
\[ r_c = \frac{2.1}{10} \]
\[ C_s = 0.18 \]
\[ \bar{n} = 5 \cdot 10^{-2} n_c \]

\[ \epsilon^\text{max}_p \]

\[ d_{nc} = \sqrt{\bar{n} d_{nc}/\lambda} \]

optimal thickness at the SF focal length

optimal density??

- model \(a_0 = 4\); \(\bar{n} = 0.09\)
- model \(a_0 = 4\); \(\bar{n} = 0.17\)
- model \(a_0 = 4\); \(\bar{n} = 0.33\)
- model \(a_0 = 4\); \(\bar{n} = 0.5\)
- PIC \(a_0 = 4\); \(\bar{n} = 0.17\)
- PIC \(a_0 = 4\); \(\bar{n} = 0.33\)
- PIC \(a_0 = 4\); \(\bar{n} = 0.5\)
- PIC \(a_0 = 4\); bare target

- model \(a_0 = 4\); \(d_{nc} = 4\lambda\)
- PIC \(a_0 = 4\); \(d_{nc} = 4\lambda\)
- PIC \(a_0 = 4\); bare target
Maximum proton energy heat map

\[ a_0 = 32 \]

**Diagram:**
- Thickness \([d_{nc}/\lambda]\)
- Density \([n_e/n_c]\)
- SF focal length
- Color bar: \(\epsilon_{p_{\text{max}}}\)

**Remark:**
- Formula: \(a_0 = 32\)
Maximum proton energy heat map

\[ a_0 = 32 \]

highest energy island
Analytical solution in the ultra-relativistic case

Ultra-relativistic case \( a_0 \gg 1 \)
Analytical solution in the ultra-relativistic case

Ultra-relativistic case $\rightarrow a_0 \gg 1$

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:

$$\bar{E}_{DLT}^{opt} = \frac{3 C_{nc}}{4 C_s} \left[1 - \frac{1}{\pi} \left(\frac{\sqrt{3} C_{nc} r_c^2}{2\tau_c / \lambda}\right)^{2/3}\right]$$
Analytical solution in the ultra-relativistic case

Ultra-relativistic case $\rightarrow a_0 \gg 1$

**optimal density:**

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

**Enhancement factor:**

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

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

A minimal model is proposed

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

**MODEL STEPS:**
1. Laser self-focuses
2. Laser loses energy and is amplified
3. Hot electrons are heated
4. Ions are accelerated
Conclusions

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

- Optimal DLT realization
  - Nanostructured near-critical layer

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).

Produced by ns-PLD and fs-PLD
Future perspectives

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

M. Passoni
V. Russo
M. Zavelani-Rossi
D. Dellasega
A. Maffini
L. Fedeli
A. Pola
A. Formenti
A. Pazzaglia
F. Mirani
...and thank you for your attention!!
Realistic near-critical layer effects

Homogeneous 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!
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!

Nanostructured plasma:
- Electrons temperature $\downarrow$
- Electrons number $\uparrow$

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

lower energy expected

uniform near-critical plasma are optimal