On The Role Of Non-equilibrium, Relativistic Hot Electron Population In Target Normal Sheath Acceleration

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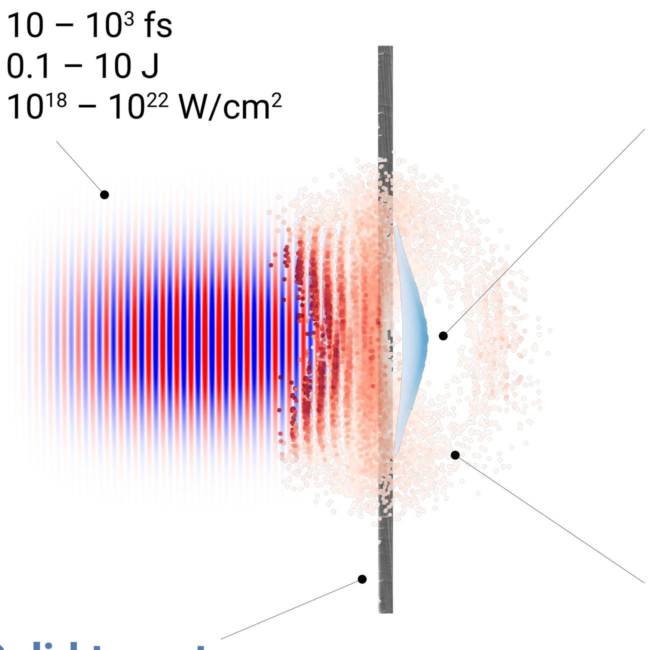
Target Normal Sheath Acceleration

Concept
- Superintense ultrashort laser → Relativistic electron population → Charge separation → Ion accelearation
- Most robust and reliable laser-driven ion acceleration scheme at present achievable laser intensities

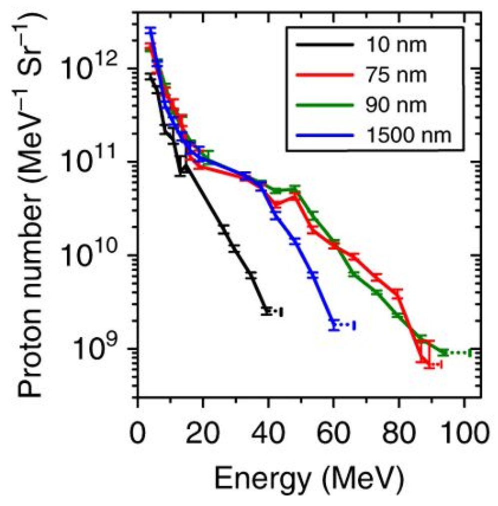
Superintense laser
- 10 – 10^3 TW
- 10 – 10^3 fs
- 0.1 – 10 J
- 10^{18} – 10^{22} W/cm²



Solid target
- 10 nm – 10 µm thickness
- Solid density
- Advanced concepts are possible

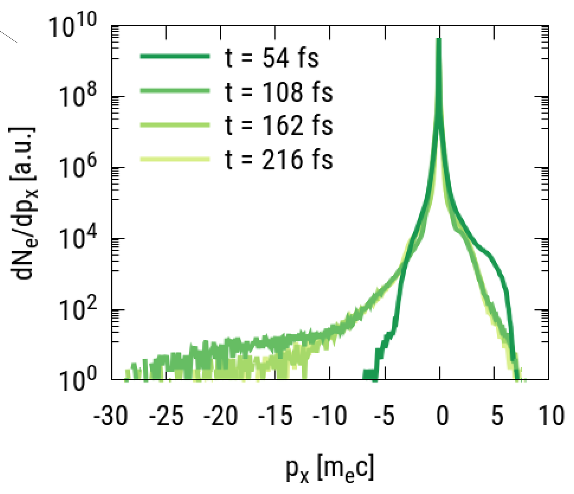
H. Daido et al., Rep. Prog. Phys. 75.5 (2012): 056401
A. Macchi et al., Rev. Mod. Phys. 85.2 (2013): 751

Accelerated ions



A. Higginson et al, Nat Comm 9.1 (2018)

Relativistic hot electrons



Applications

Today
- Proton radiography
- Ion Beam Analysis
- Radioisotope production
- Neutron generation

Tomorrow
- High Energy Physics
- QED
- Radiotherapy
- ...and much more!

Understanding TNSA

3D Particle-In-Cell simulations
- Most physics included
- High computational cost

Analytical models
- Simplified picture
- Different approaches: kinetic, hydrodynamic...
- Grasp essential physics

Goal: Improve the self-consistent quasi static TNSA model

Determine model parameters from experimental quantities

Use scaling scaling laws to fix the main model parameters: n_0 , T , φ*

Include non-equilibrium features in TNSA description

Compare many scenarios that only differ by the degree of non-equilibrium

Determine model parameters from experimental quantities

Fix additional parameters
- d = thickness = 5 µm
- η = absorption efficiency = 0.1
- τ = pulse duration = 30 fs
- σ = focal spot in {5, 25 125} µm²
- E_L = laser energy in [10 mJ, 100 J]

Find "macro-quantities"

Total hot electron number and energy per unit area (← 1D model)

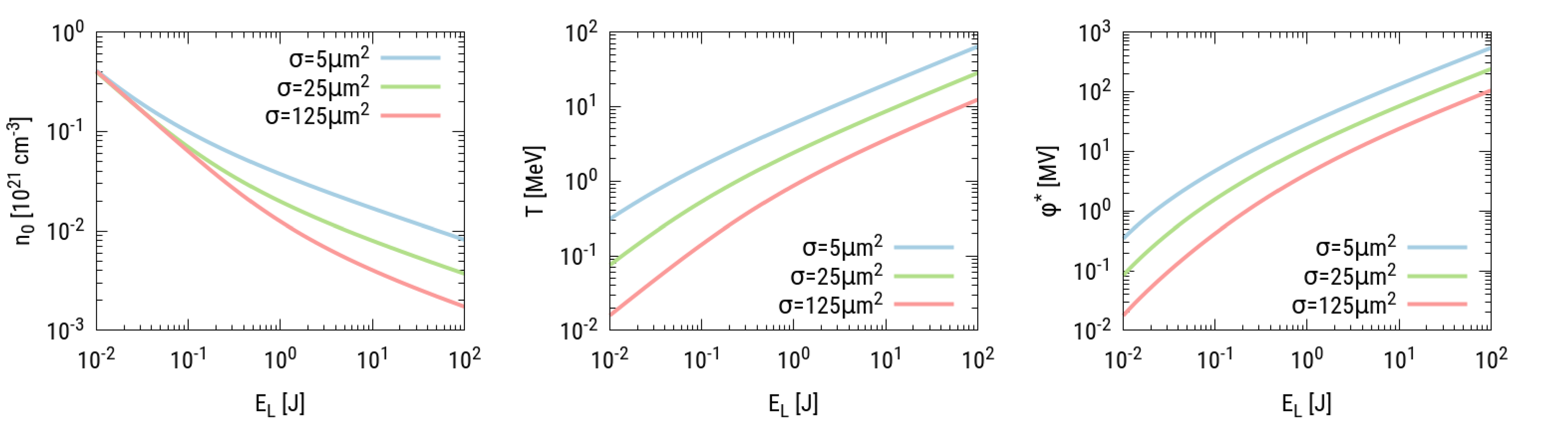
$$N_{tot} = n_0 \int_{-d}^{+\infty} e^{\frac{e\phi}{T}} dx \approx n_0 e^{e\phi^*/T} d$$

$$E_{tot} \approx n_0 e^{e\phi^*/T} d \left[T + mc^2 \left(\frac{K_0(mc^2/T)}{K_1(mc^2/T)} - 1 \right) \right]$$

Find main parameters

$$\begin{cases} E_L = \dfrac{\sigma}{\eta} E_{tot} & \text{laser energy conversion into hot electron energy} \\ T = m_e c^2 \left(\sqrt{1 + \dfrac{a_0^2}{2}} - 1 \right) & \text{ponderomotive scaling} \\ \dfrac{\varphi^*}{T} = 4.8 + 0.8 \log(E_L[J]) & \text{empirical scaling from M. Passoni PRL (2008)} \end{cases}$$

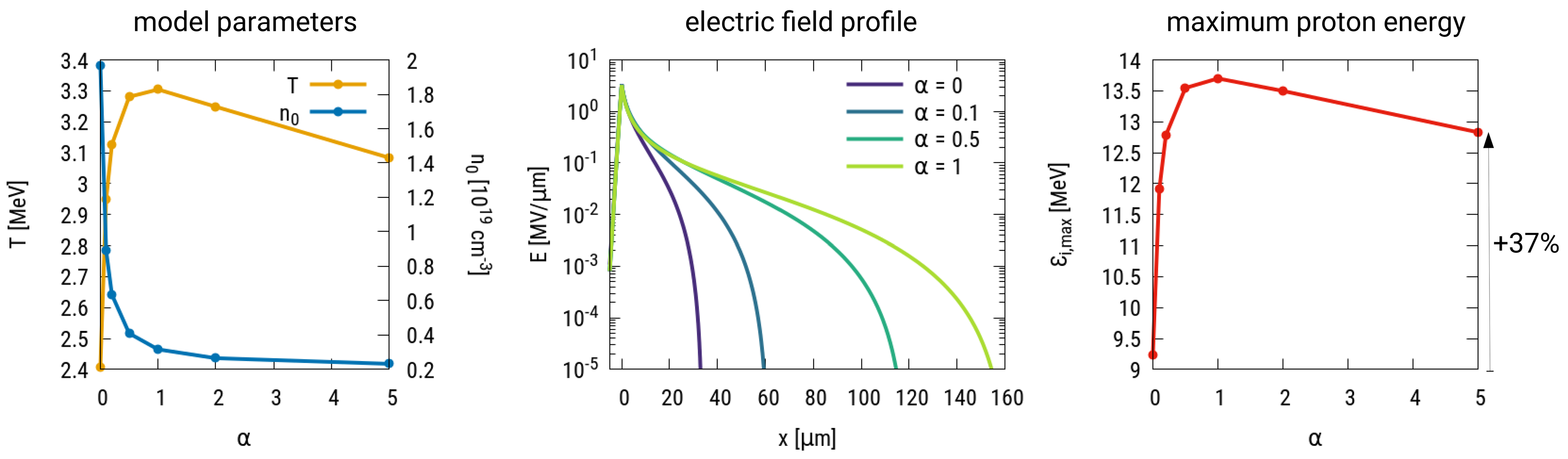
→ given E_L we can find physically significant values for n_0 , T , φ*



Results for increasing non-equilibrium

Same laser: E_L = 1J → same T/φ* ~ 4.8
Same total number: N_{tot} ~ 1.25 x 10^{10} e⁻/µm²
Same energy of hot electrons: E_{tot} ~ 4 x 10^{-3} J/µm²

- d = 5 µm
- η = 0.1
- τ = 30 fs
- σ = 25 µm²



Self-consistent quasi-static TNSA model

Framework
- Kinetic description of hot electrons
- 1D1D phase space ↔ (x, p)
- Time independent
- Frozen ions and cold electrons

M. Passoni et al., Phys. Rev. Lett. 101.11 (2008): 115001
M. Passoni et al., New J. Phys. 12.4 (2010): 045012.

Hot electrons distribution: Maxwell-Jüttner

$$f(x,p) = \frac{n_0}{2m_e c K_1(m_e c^2/T)} \exp\left[-\frac{m_e c^2 \gamma(p)}{T} \right], \qquad \gamma(p) = \sqrt{1 + \frac{p^2}{m_e^2 c^2}}$$

Only trapped electrons build up the accelerating field

$$n_{trap}(x) = \int_{-p_{cutoff}}^{+p_{cutoff}} f(x,p) \mathrm{d}p, \qquad p_{cutoff} = m_e c \sqrt{\left(\frac{\varphi(x)}{m_e c^2} + 1 \right)^2 - 1}$$

Self-consistent Poisson equation

$$\begin{cases} \Delta\varphi = 4\pi e (n_{trap}(x) - n_{trap}(x^*)) & \text{if } x \le 0 \\ \Delta\varphi = 4\pi e n_{trap}(x) & \text{if } x > 0 \\ BC \to \exists x^* : \varphi(x^*) = \varphi^* & \longrightarrow \max \varphi(x) = \varphi^* \end{cases}$$

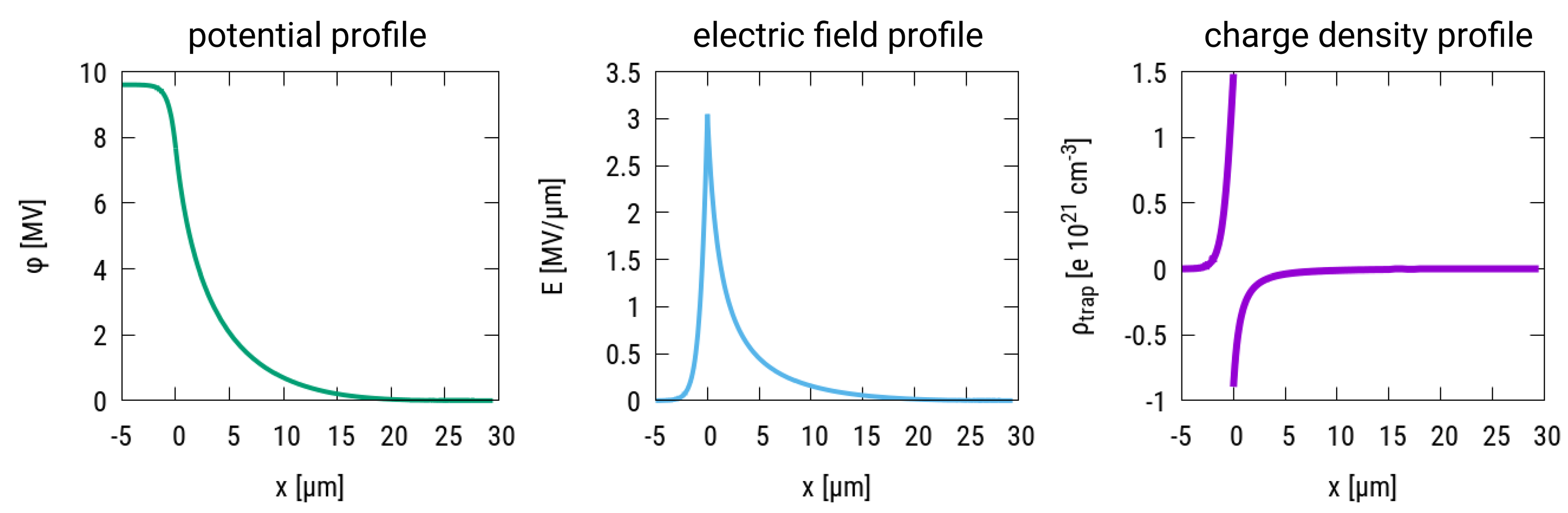
Accelerated ions, maximum energy

$$\mathcal{E}_{i,max} = Ze\varphi_0 = Ze\varphi(x=0)$$

- strong nonlinearity
- 3 main parameters: n_0 , T , φ*
- f(x,p) at equilibrium

An example

n_0 = 2 x 10^{19} cm⁻³, T = 2 MeV, φ*= 10 MV



Include non-equilibrium features in TNSA description

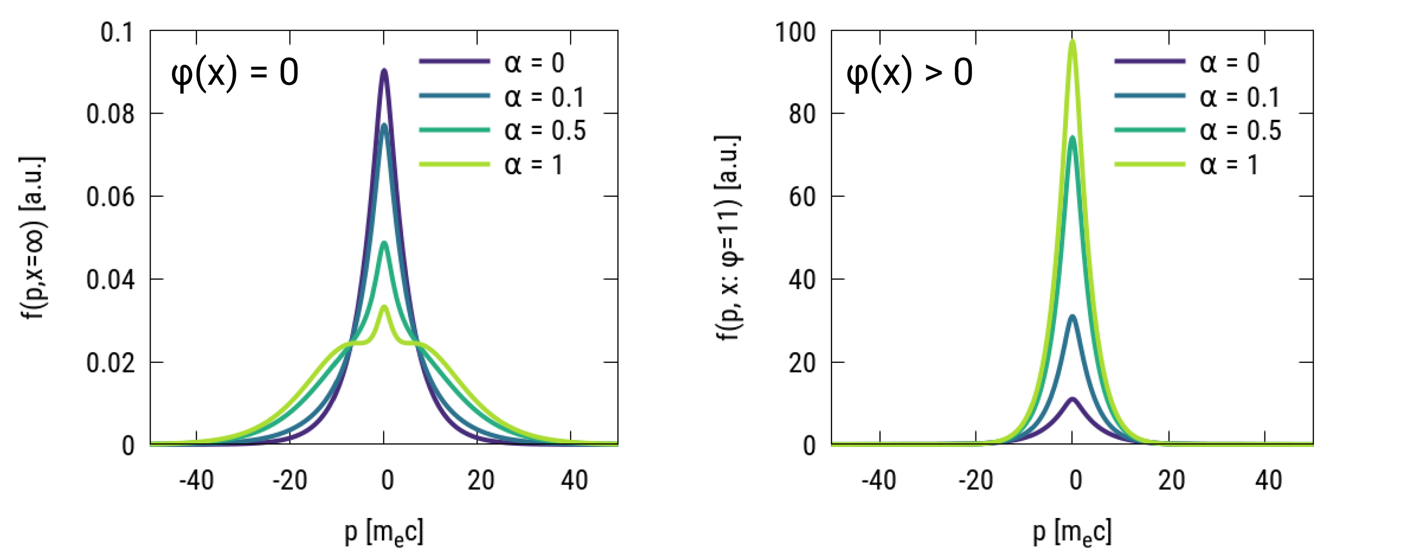
Build a relativistic distribution function solution of Vlasov equation

- Cairns distribution function for space plasmas R. A. Cairns et al. , Geophys. Res. Lett. 22.20 (1995): 2709-2712
- A non-relativistic version proposed for TNSA A. Bahache et al., Phys. Plasmas 24.8 (2017): 083102
- We propose a fully relativistic Cairns-like distribution function, solution of Vlasov equation

$$f(x,p) = \frac{n_0}{N(T,\alpha)} \left\{ 1 + \alpha \left[\frac{m_e c^2(\gamma(p) - 1) - e\varphi(x)}{T} \right]^2 \right\} \exp\left[-\frac{m_e c^2 \gamma(p) + e\varphi(x)}{T} \right]$$

Can't depend on φ

Only non-equilibrium parameter
- α =0 → Maxwell-Jüttner
- ↑α → ↑non-equilibrium



Make fair comparisons to asses the role of non-equilibrium features

$$\frac{\partial N_{tot}}{\partial \alpha} \neq 0, \qquad \frac{\partial E_{tot}}{\partial \alpha} \neq 0 \longrightarrow$$ The "macro-quantities" vary with α

Procedure
- pick E_L → find N_{tot} and E_{tot} at equilibrium → find n_0 , T , φ* at equilibrium
- we assume the same T/φ* ratio ∀ α
- pick α > 0 → find adjusted values of n_0 , T , φ* such that N_{tot} and E_{tot} are the same
- ∀ α solve TNSA model with new parameters

Conclusions

Determination of model parameters → with physical scaling laws
Inclusion of non-equilibrium features → definition of a suitable distribution function
Results → non-equilibrium features do have a role
→ ∃ optimal non-equilibrium parameter for ion maximum energy

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