Effect of the proton layer thickness in the TNSA (1D)

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GSI Retreat, 10-11. Mai 2012
Hotel Haus Schönblick

A contribution to the LIGHT project.

Motivation

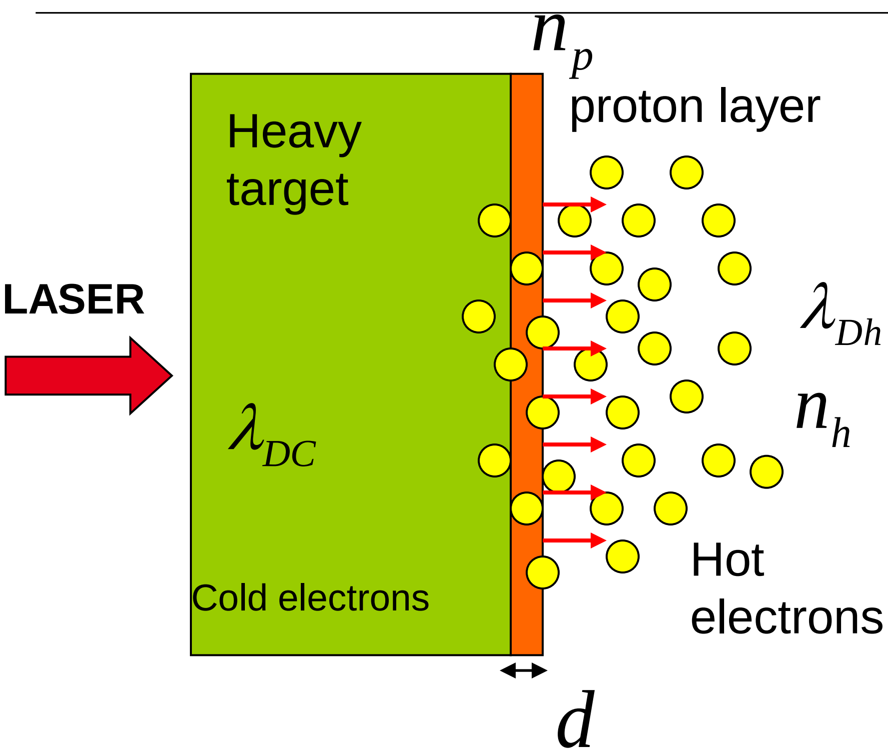
- The Target Normal Sheath Acceleration after 10 years of research is still not fully understood !
- This is the most relevant mechanism for the PHELIX laser facility at GSI, Darmstadt
- Open questions:
  - Which model can be used to interpret the experimental results?

    P. Mora, Phys Rev E **72**, 056401 (2005)

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

  - What is the distribution (density, temperature) of the co-moving neutralizing electrons?

TNSA from a double-layer target



n_h	hot electron density
n_p	proton density
λ_{DC}	cold electron Debye-length
λ_{Dh}	hot electron Debye-length
d	layer thickness

$$n_p > n_h, \quad \lambda_{Dh} > \lambda_{DC}$$

Always !

$m_i \gg m_p \longrightarrow$ The heavy ions are considered immobile!

Simulation setup

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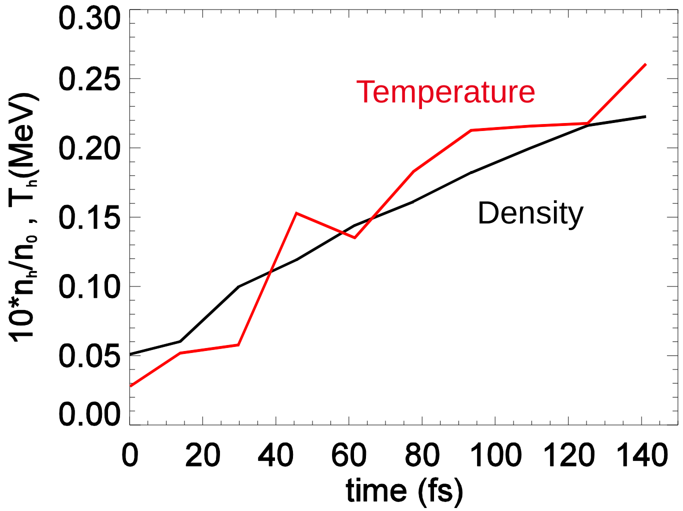
Vorpal 5.2, TechX corporation

Fully relativistic EM PIC plasma simulation code.

Laser interacting with a plasma slab →



It's difficult to define the electron parameters!

Simplification (first step):

- Plasma expansion starting with an equilibrium electron distribution.
- Only hot electrons with well-known density and temperature are included!
- 1D electrostatic solver

Easier to model and understand the basic physics!

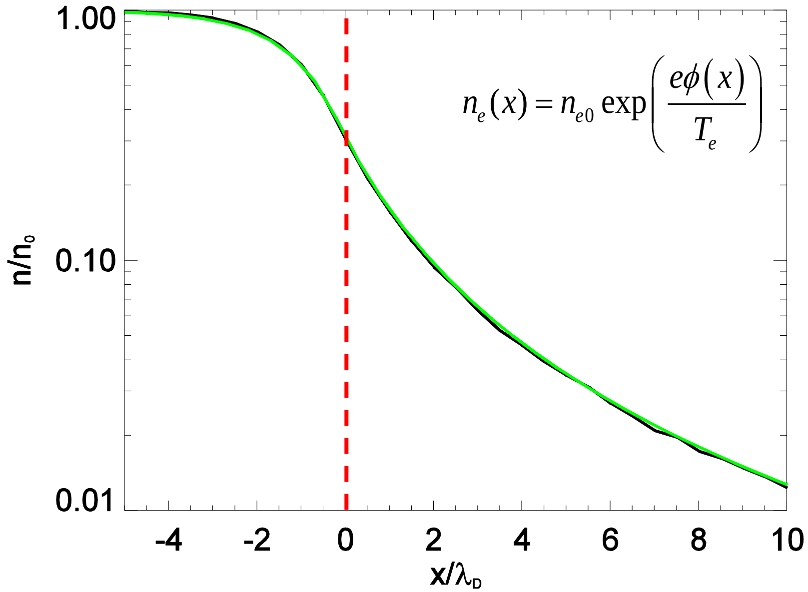
Initial conditions

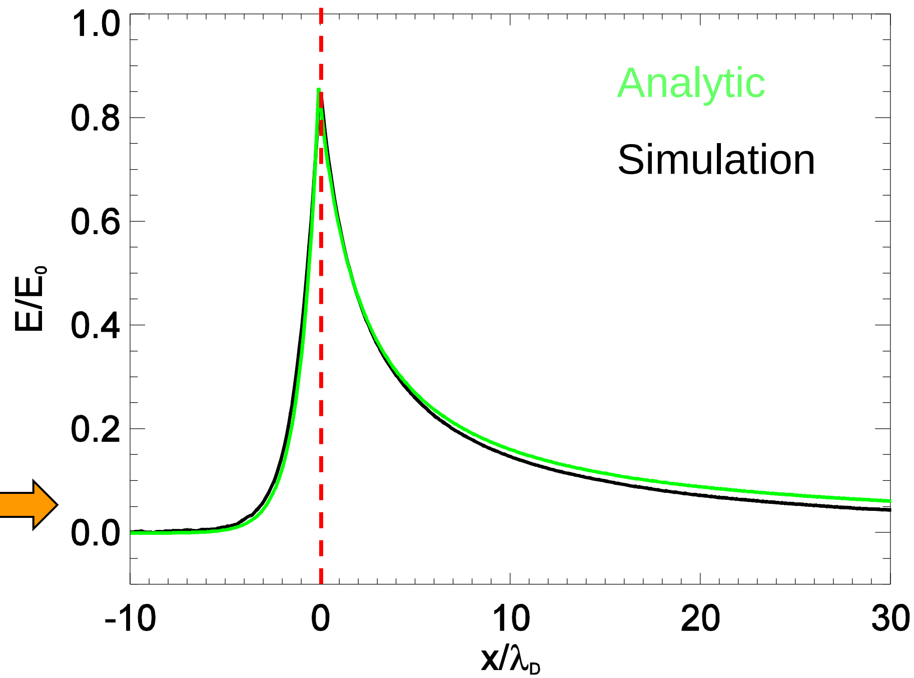
$$\frac{n_e(x)}{n_{e0}} = \begin{cases} \exp\left(-\exp\left(\sqrt{2/\mathrm{e}}(x-a)/\lambda_D\right)\right), & x < a \\ \dfrac{2}{\left(\sqrt{2\mathrm{e}}+(x-a)/\lambda_D\right)^2}, & x > a \end{cases}$$

$$\lambda_D = \left(\frac{\varepsilon_0 T_h}{e^2 n_h}\right)^{1/2}$$

$$E_0 = \sqrt{n_h T_h / \varepsilon_0}$$

If the ions are immobile the field remains unchanged forever.





Adding a proton layer

$\boxed{d \ll \lambda_D}$

M. Passoni, 2004

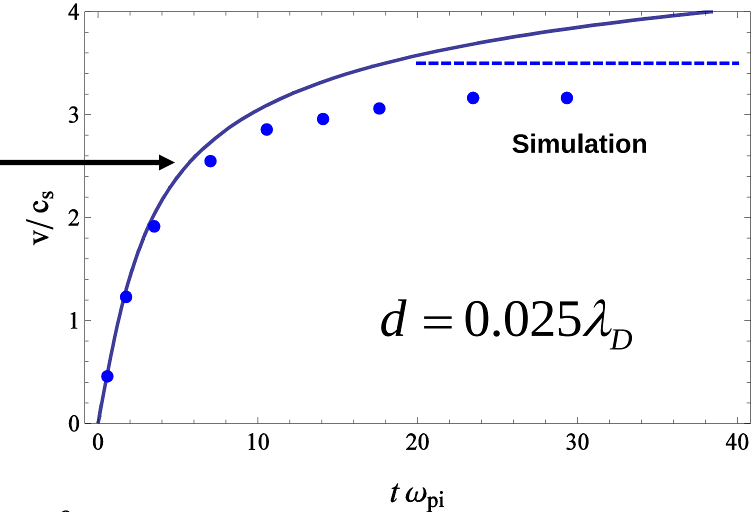
Quasi-static acceleration

$$\frac{d^2x}{dt^2} = \frac{2C_s^2}{\sqrt{2e + x/\lambda_D}}$$

$$v_f = 2C_s\sqrt{\ln\left(1+\frac{x}{\lambda_D\sqrt{2e}}\right)}$$

$$C_s = \sqrt{\frac{T_h}{m_p}}$$

$$x_{\max} \simeq 70 \Rightarrow v_{\max} \simeq 3.6 * C_s$$



$\boxed{d \gg \lambda_D}$

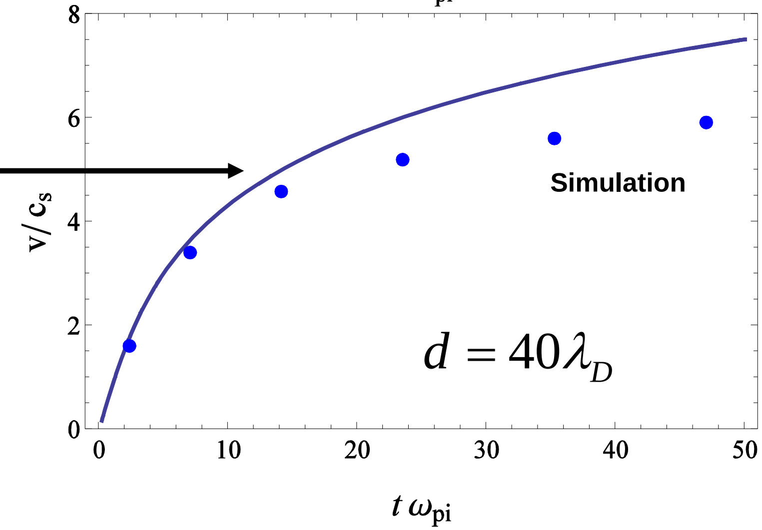
P. Mora, 2003

Isothermal expansion

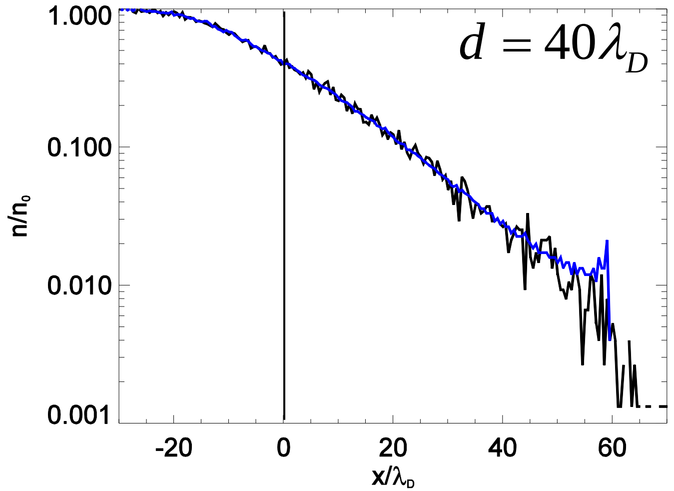
$$v_f = 2C_s \ln(\tau + \sqrt{\tau^2 + 1})$$

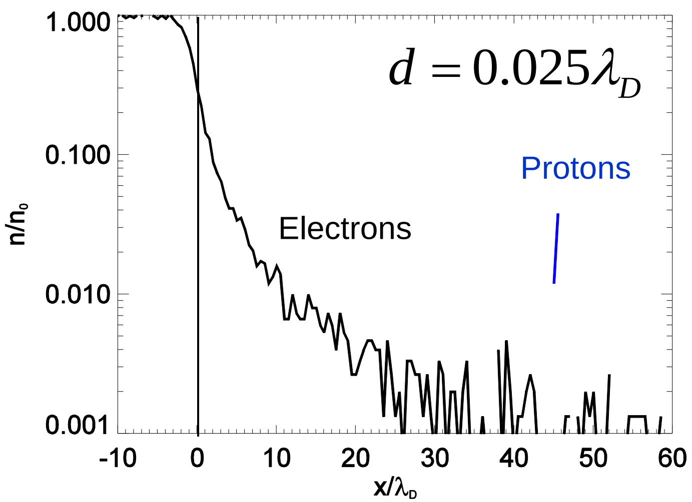
$$\tau = \frac{\omega_{pi} t}{\sqrt{2e}}$$

$$\omega_{pi} t_{acc} = \frac{L_p}{\lambda_D}$$



Quasi-static acceleration vs. Isothermal expansion

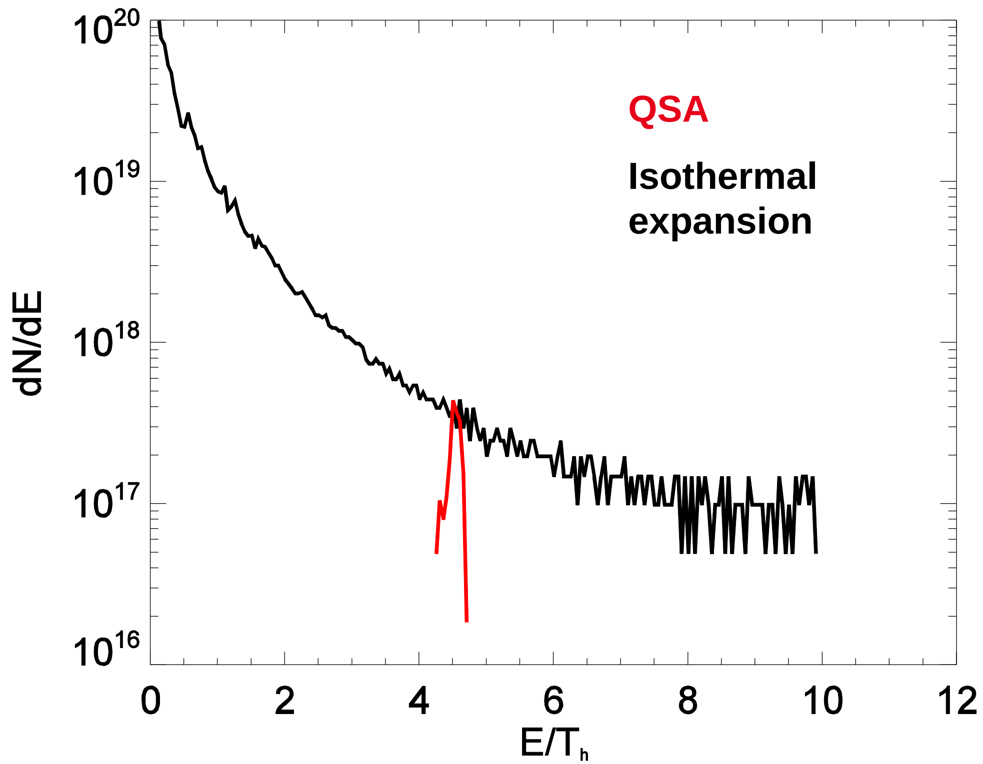




$$\omega_{pi} t = 18.8$$

P. Mora $\longrightarrow$ $E_{cutoff} = 2T_h \left[\ln(2\tau)\right]^2 \simeq 14T_h$

M. Passoni $\longrightarrow$ $E_{\max} \simeq 6T_h$



Effect of the layer thickness

Smooth transition between the two models!

Isothermal model

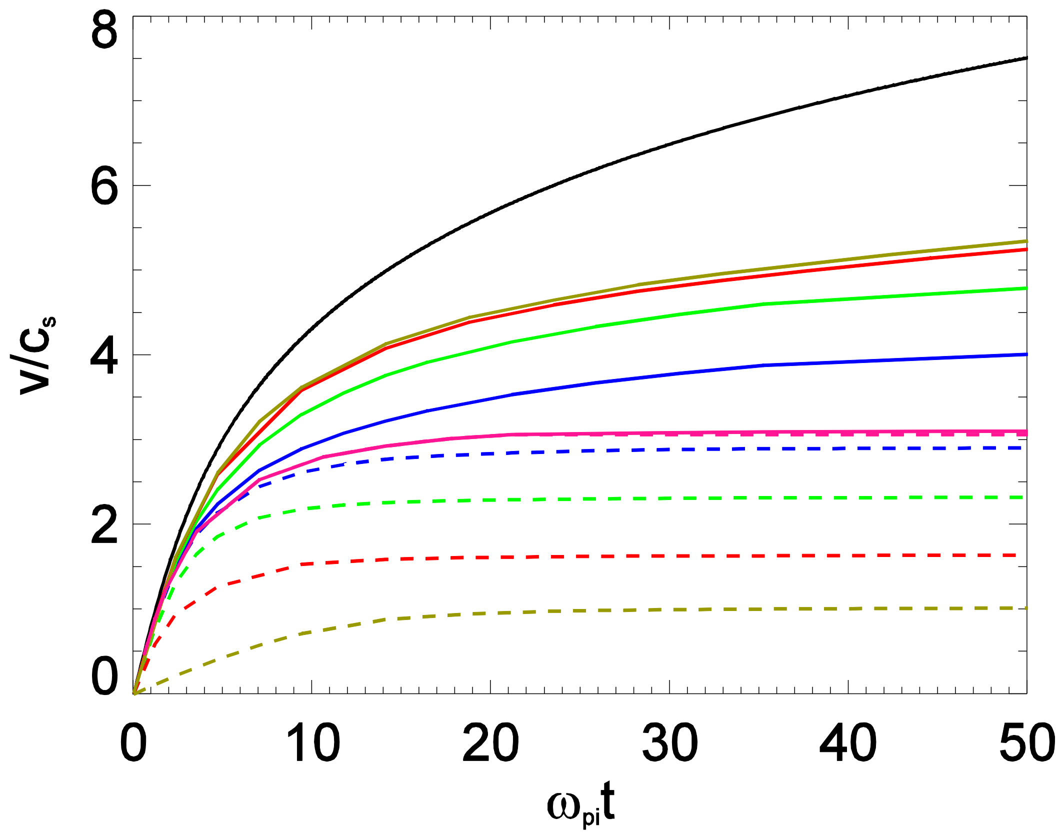
$d = 0.025\lambda_D$

$d = 0.1\lambda_D$

$d = 0.5\lambda_D$

$d = 2\lambda_D$

$d = 10\lambda_D$

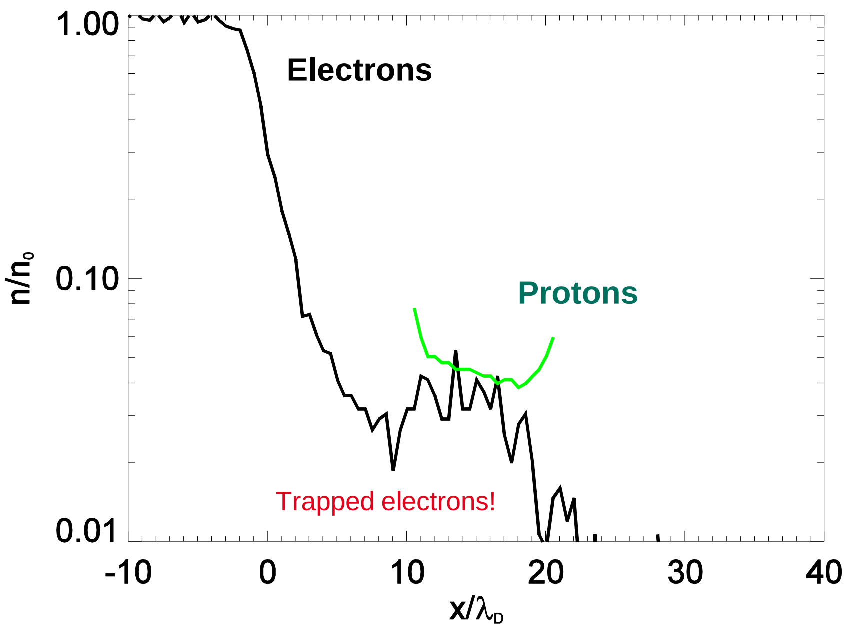


Dashed lines:

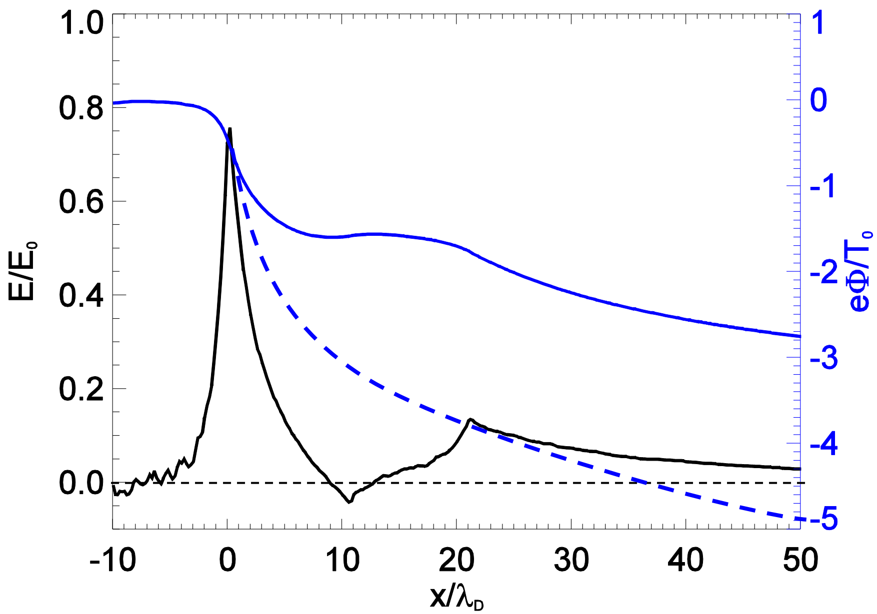
Average velocity

Intermediate regime

$$\boxed{d \approx \lambda_D}$$

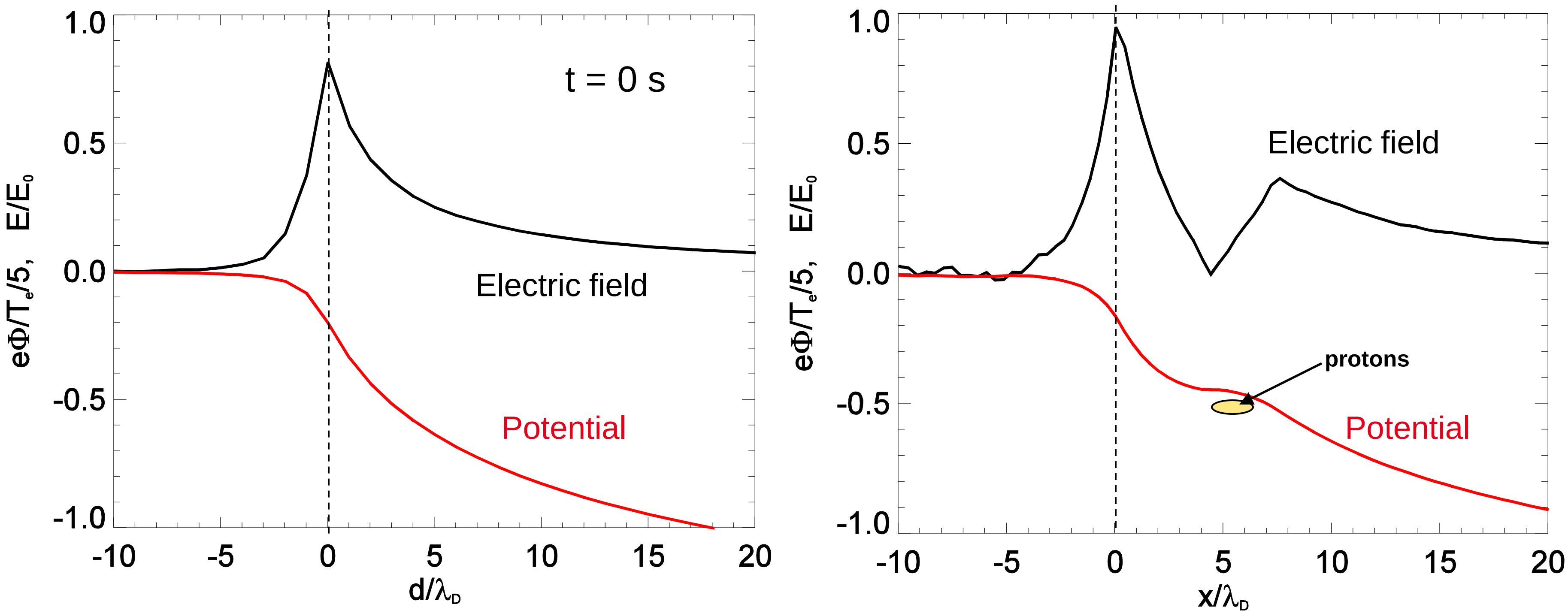


Expansion of a flying non-neutral plasma.



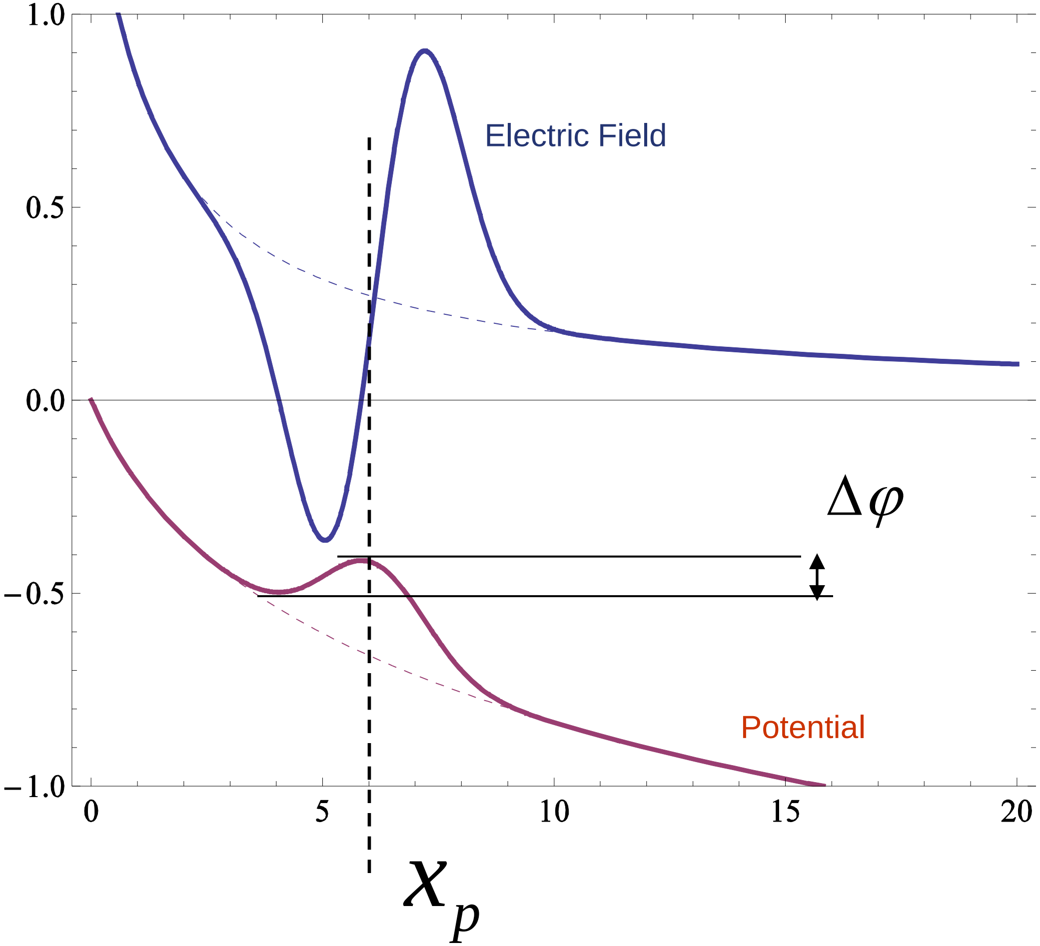
The proton bunch modifies the potential…

Deformed potential profile



Simulation !

Analytical model



Expression for the potential:

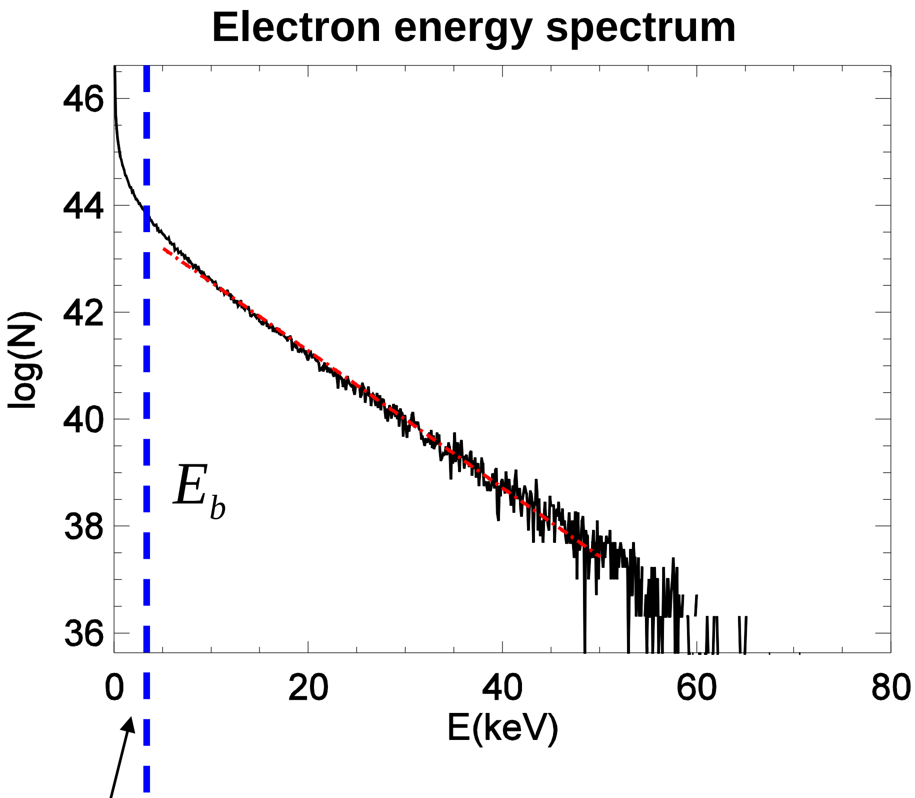
$$\frac{e\varphi(x)}{T_e} = -1 - 2\ln\left(1 + \frac{x}{\lambda_D\sqrt{2e_N}}\right) + +\sigma^2 \exp\left(-\frac{(x_p - x)}{2\sigma^2}\right)\frac{n_p}{n_h}$$

The electrons are trapped if :

$$\Delta\varphi \approx \varphi(x_t - 2\sigma) - \varphi(x_t) = E_b$$

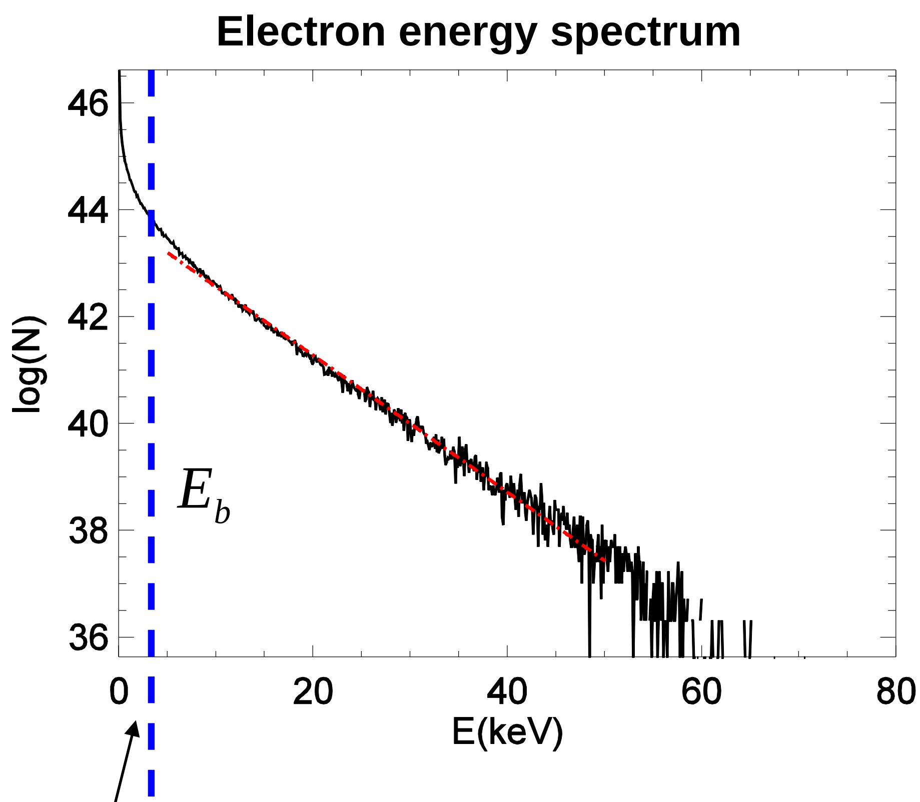
$$\Delta\varphi(x_t, \sigma) = 2\left(\frac{n_p}{n_h}\frac{d}{L_p}\right)^2$$

Numerical solution

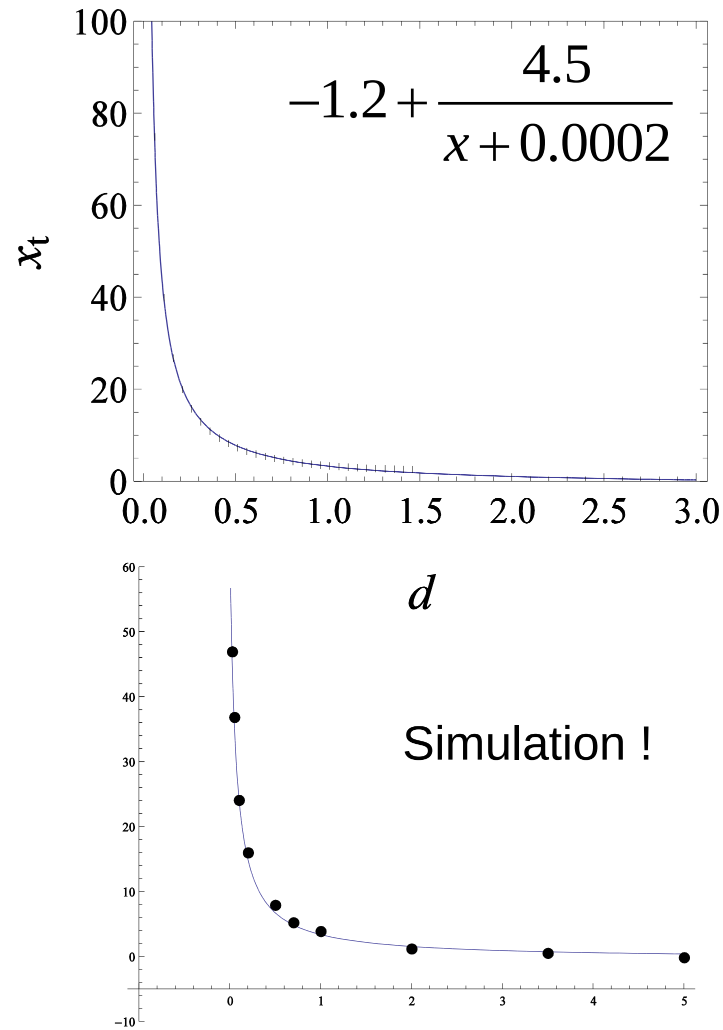


$$N_e = N_p$$

Numerical solution



$$N_e = N_p$$



Potential barrier (-drop)

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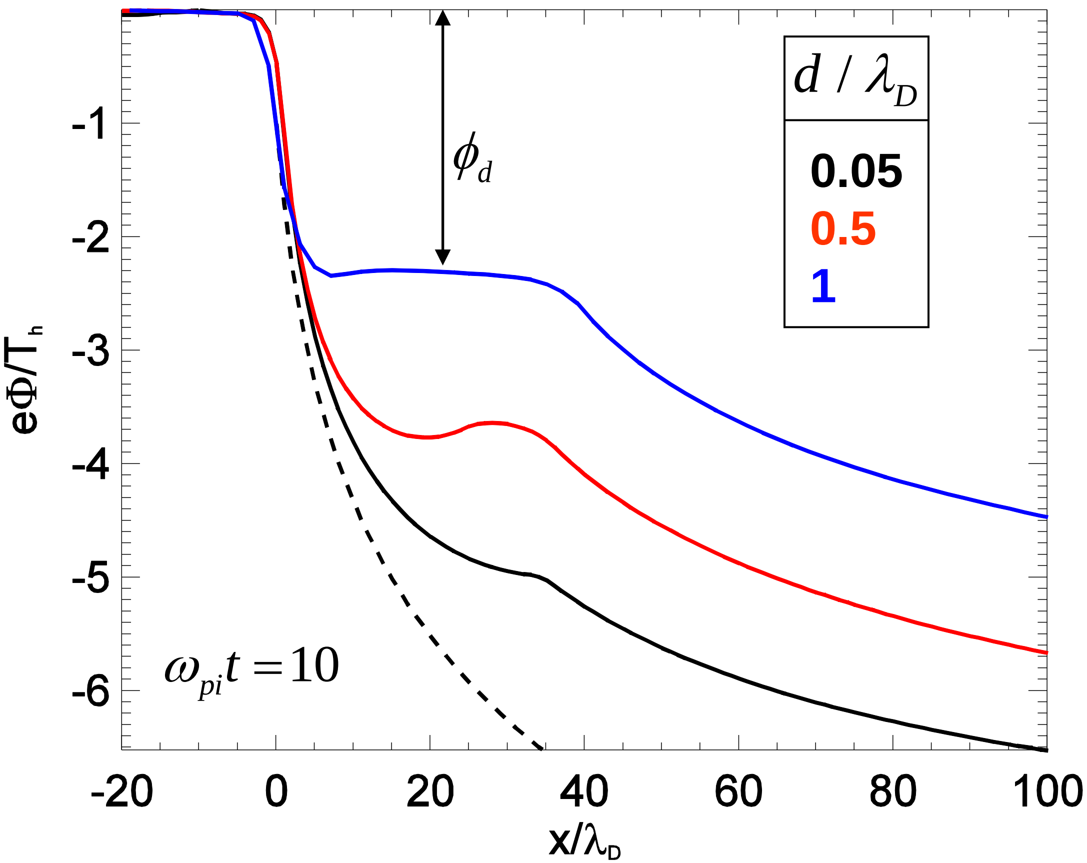
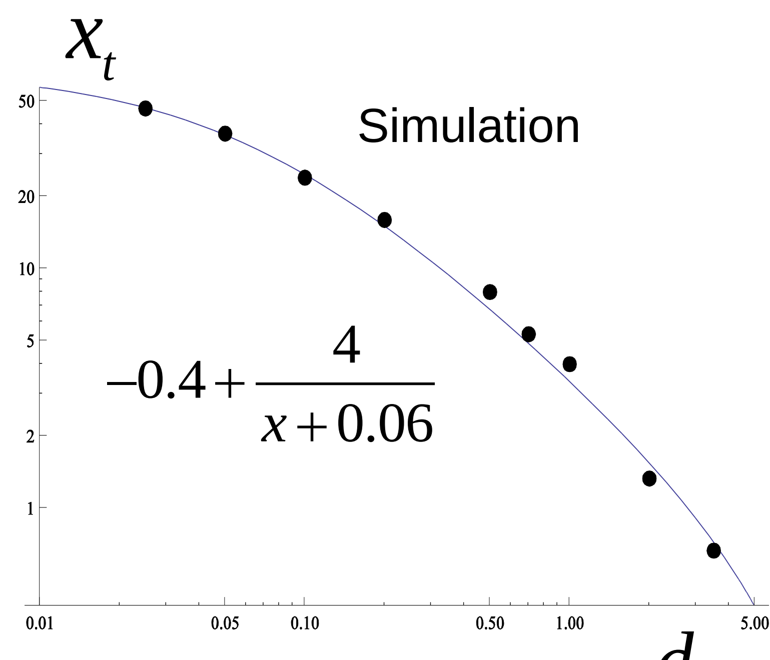
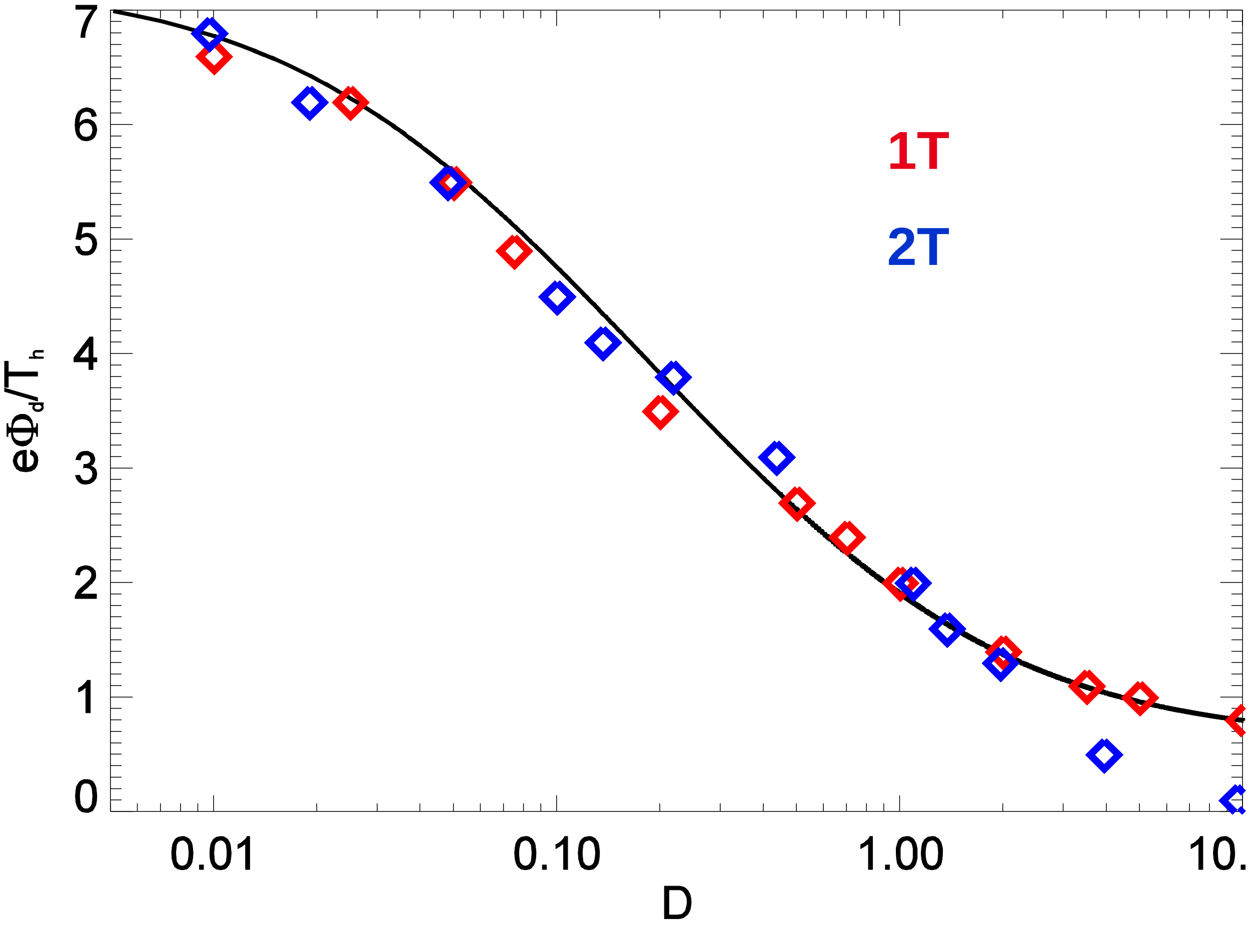


ϕ_d can be calculated from the original potential profile if we know x_t !



ϕ_B remains constant in time !

Analytical (fit) expression

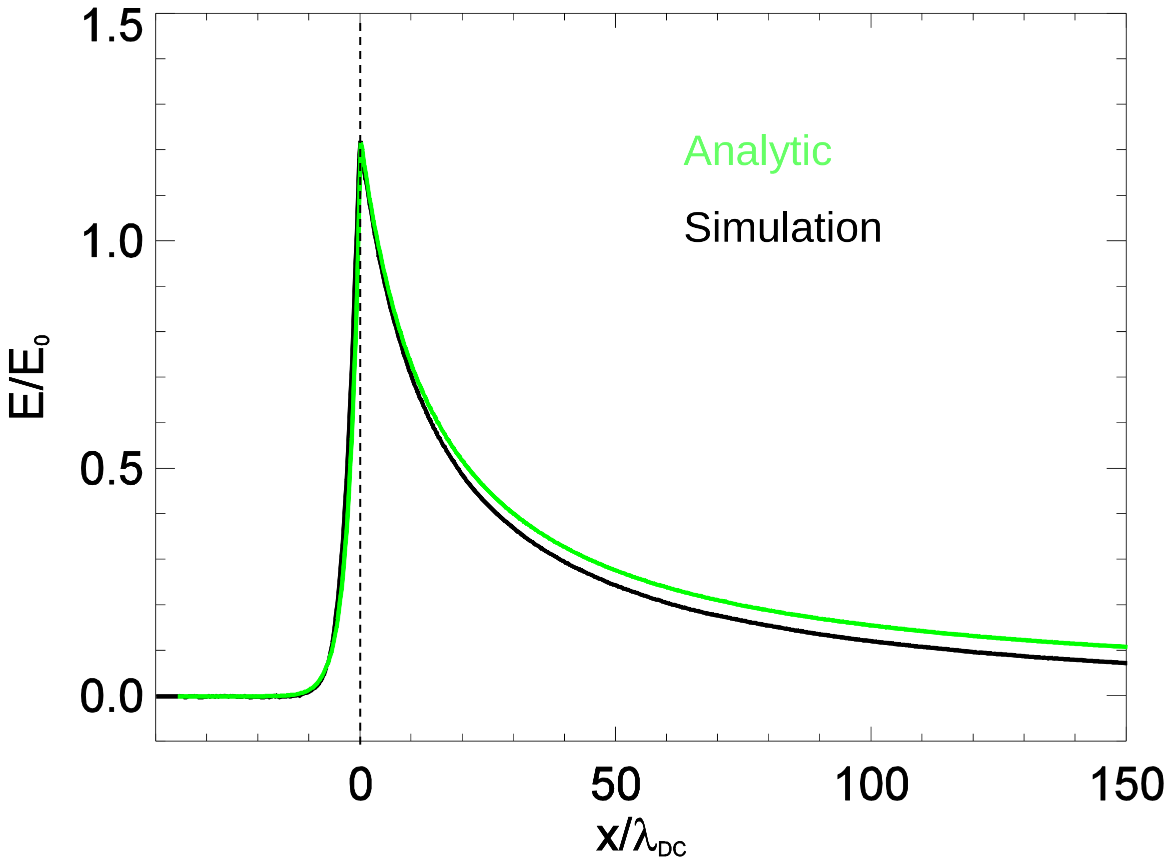


$$\frac{e\phi_d(D)}{T_e} = 1 + 2\ln\left(1 + \frac{x_t(D)}{\sqrt{2e}\lambda_D}\right)$$

$$\frac{x_t(D)}{\lambda_D} = -0.4 + \frac{1.8}{D + 0.025}$$

$$D = r\frac{d}{\lambda_D} = \sqrt{1 + \frac{n_c T_h}{n_h T_c}}\frac{d}{\lambda_D}$$

Two-temperature plasma



The scale length of the penetrated electric field is smaller.

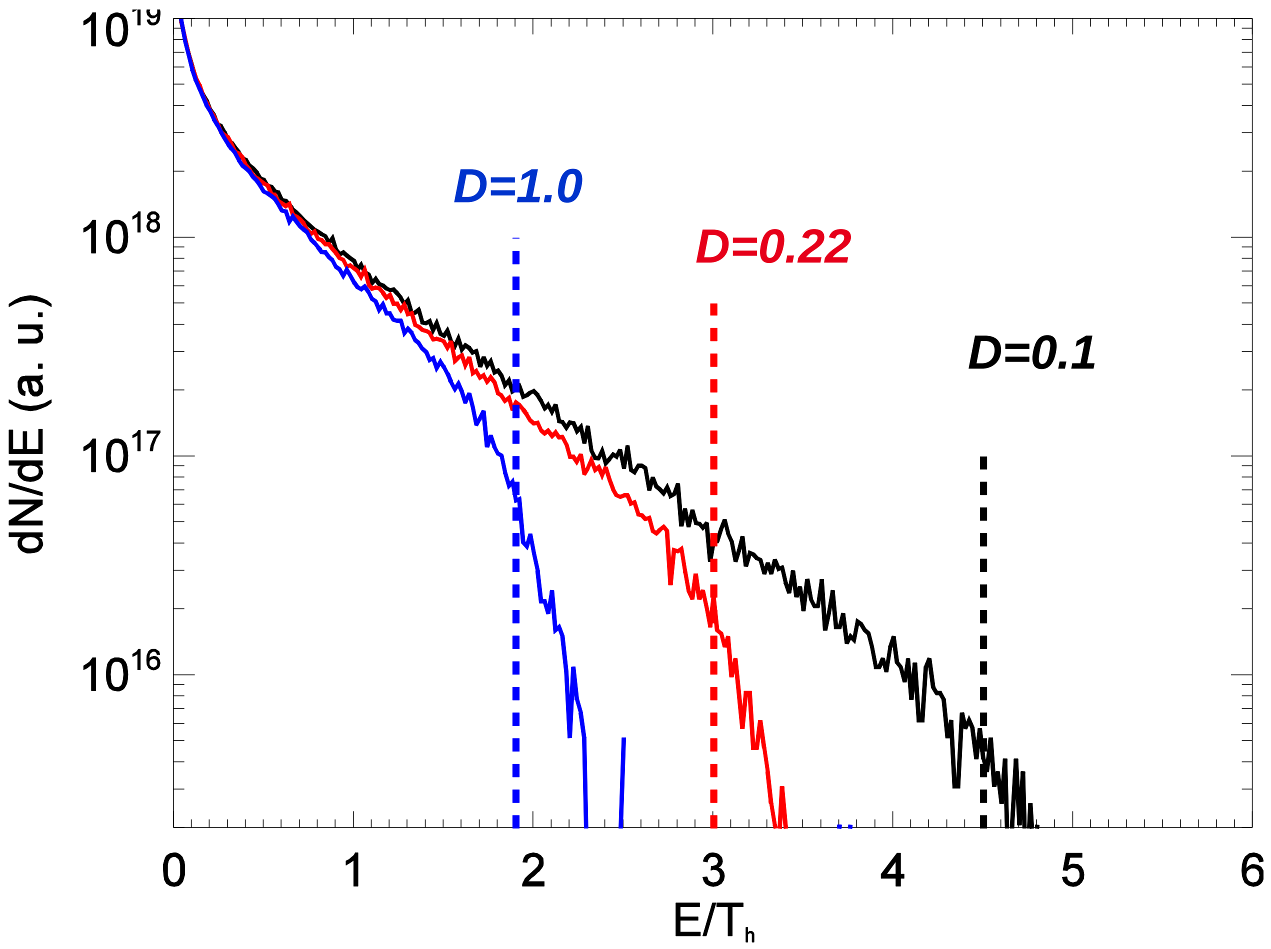
$$x < 0$$

$$\frac{E_{in}}{E_0} \sim \exp\left(\frac{x}{\lambda_D / r}\right)$$

$$r = \sqrt{1 + \frac{n_c T_h}{n_h T_c}}$$

$$\frac{n_c}{n_h} = 3 \qquad \frac{T_c}{T_h} = 0.05$$

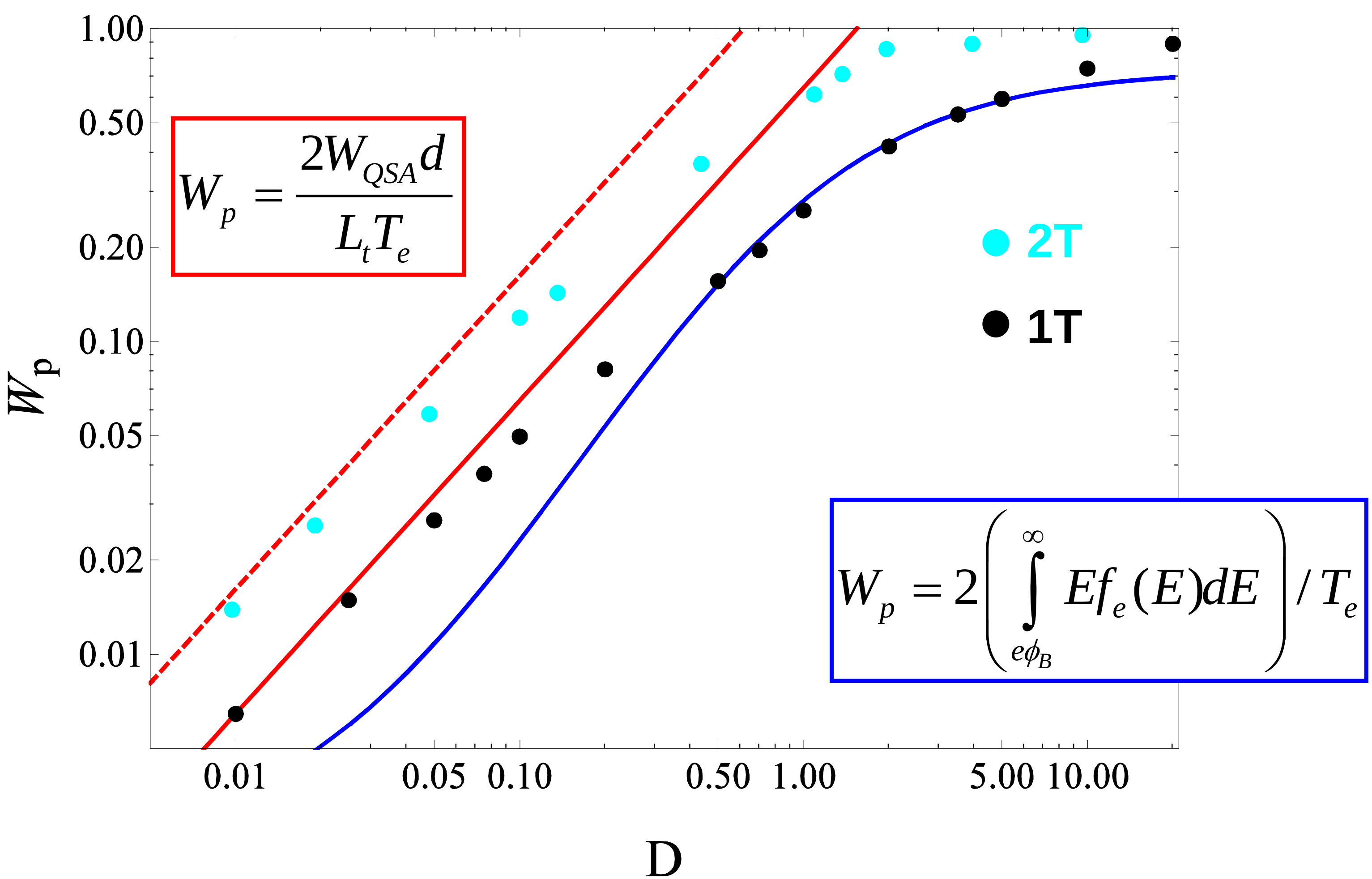
Final electron spectrum



Electrons with higher energy than the potential-drop contribute to the acceleration.

Energy transfer

Final proton energy over the initial total energy of electrons.



Proton energy spectrum

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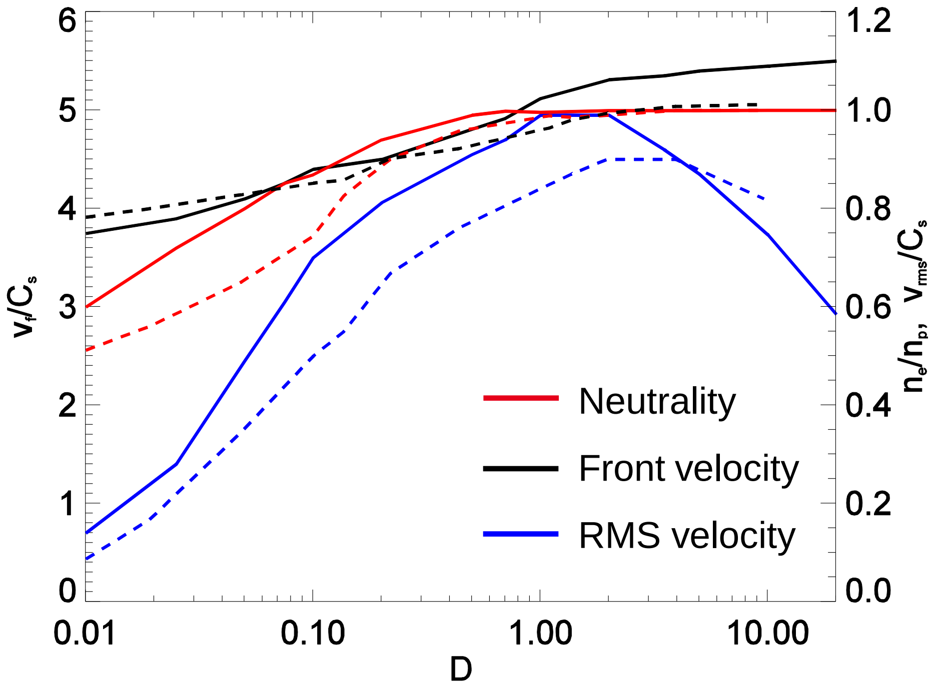
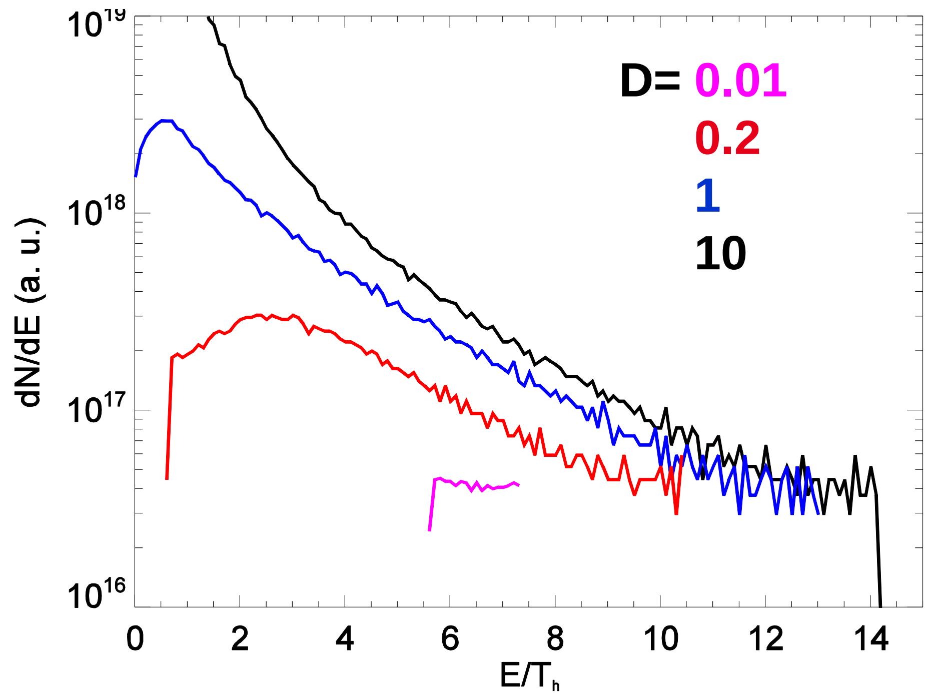


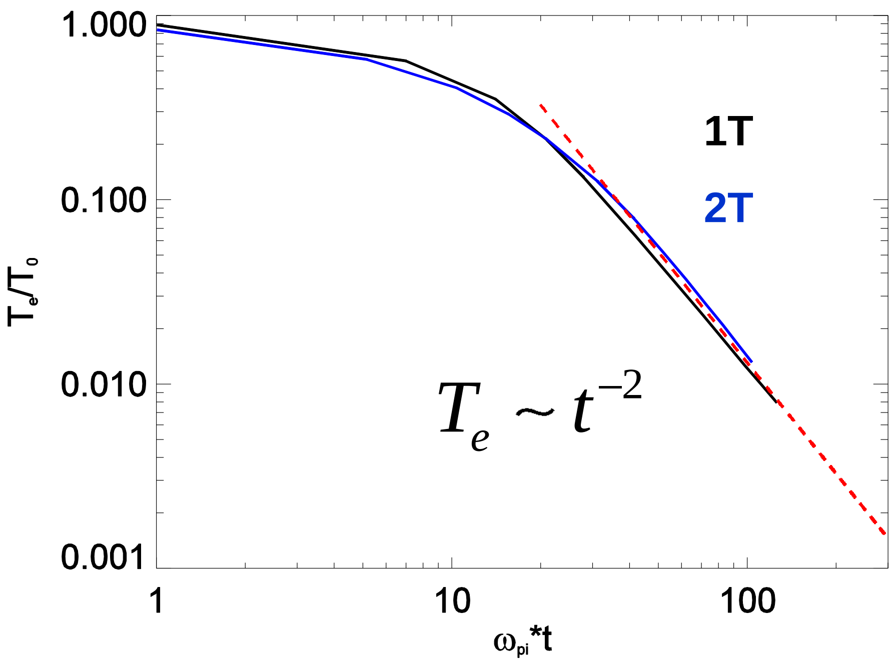


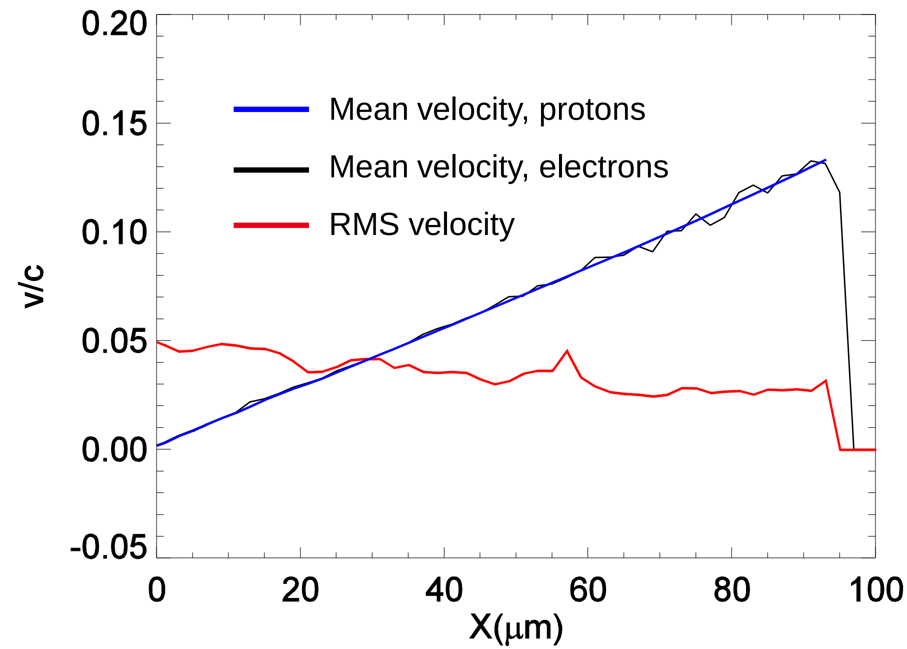
Full line – 1T

Dashed line – 2T

Smooth transition between the two models: quasi-static acceleration and isothermal expansion

Electron cooling



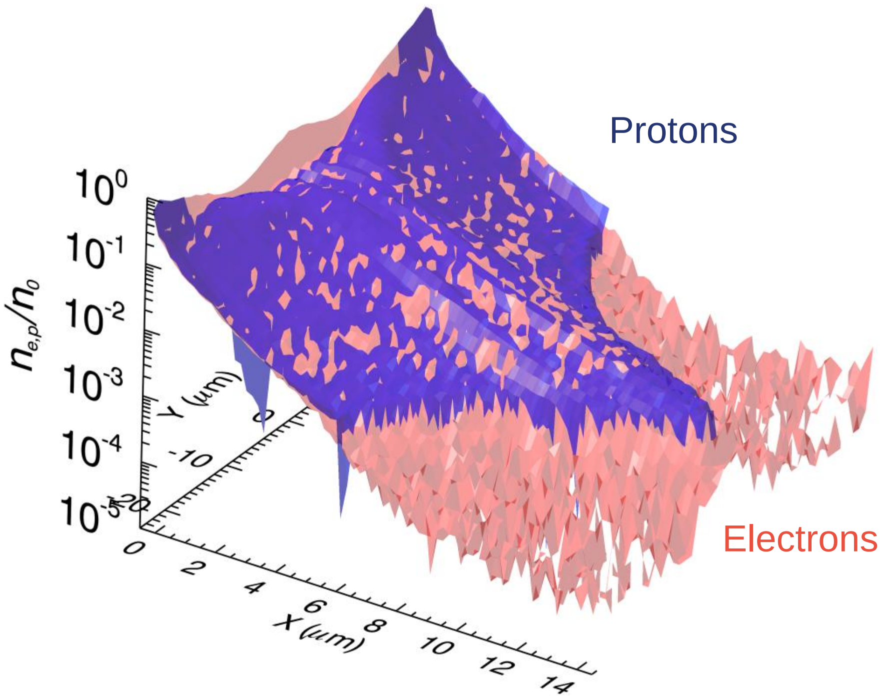


The electrons are co-moving and cold !

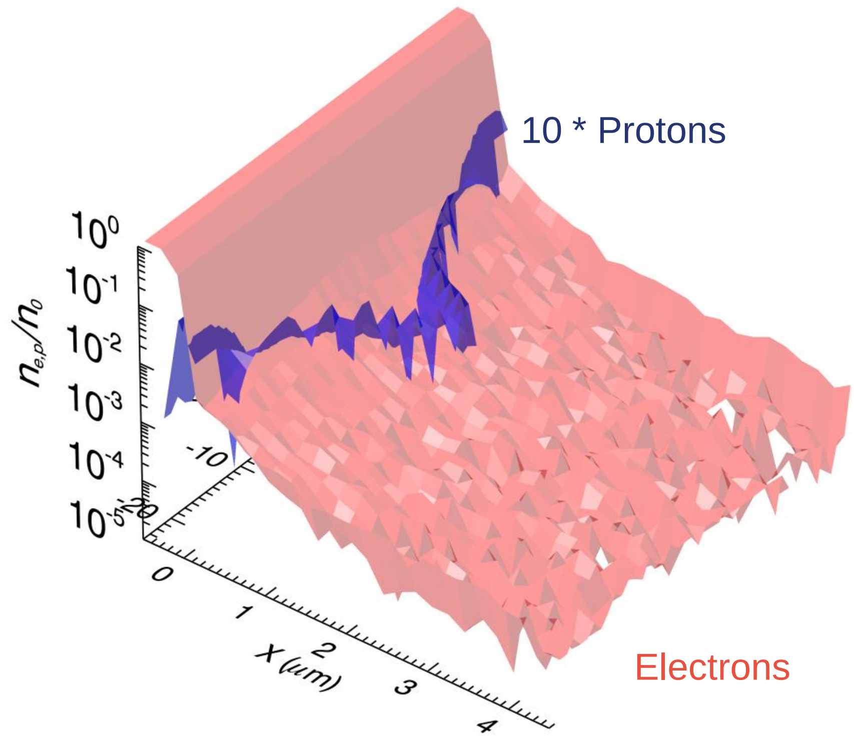
The scaling low valid in 2D as well !

2D results, density

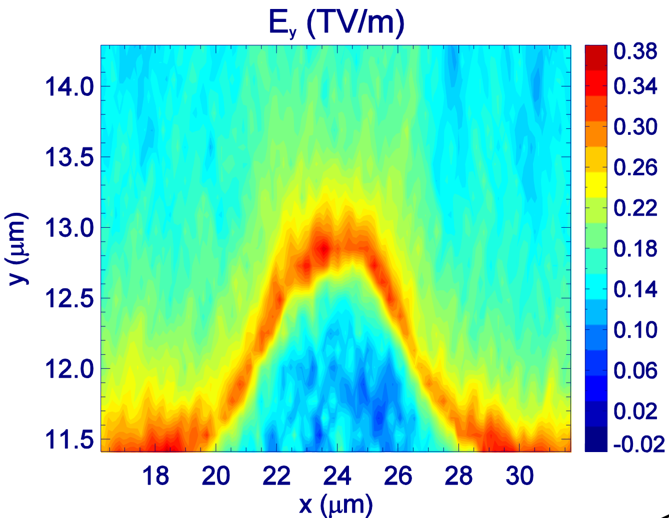
Thick layer



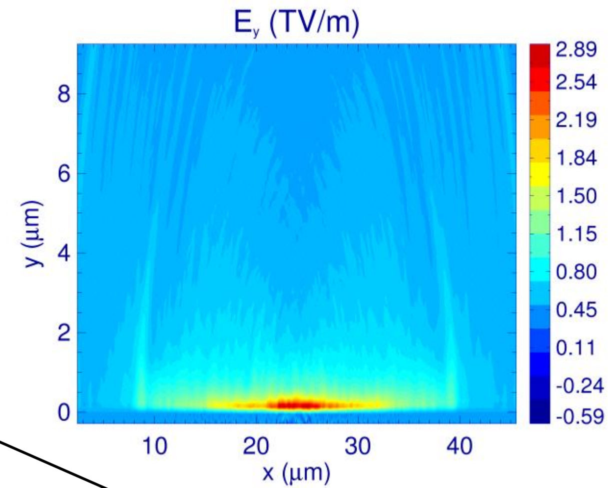
Mono-layer



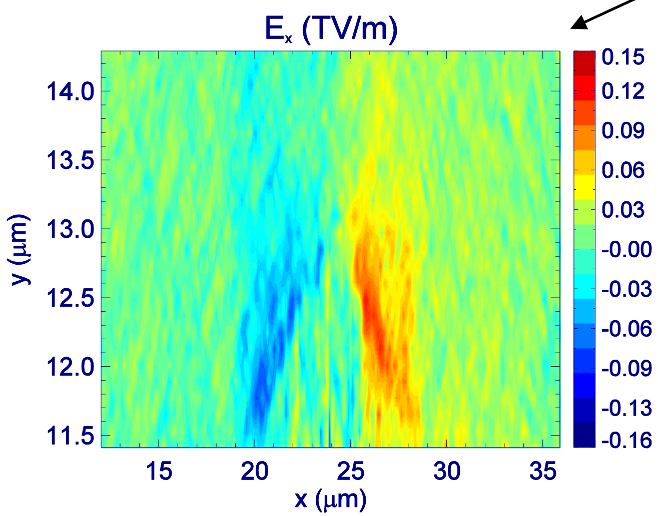
2D results, electric field



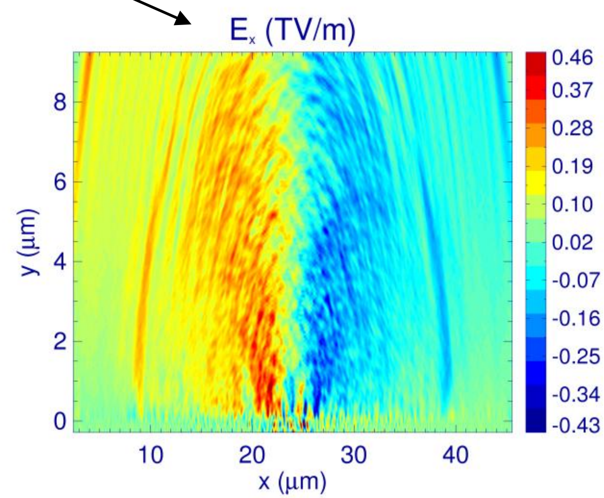
Longitudinal fields



Different focusing !



Transversal fields



Conclusions, outlook

- The simulations show good agreement with the analytical models in the extreme cases : D<<1, D>>1
- An analytical fit could be found to explain the energy conversion from electrons to protons
- There is no exact border between the two models

Outlook

- ➢ Test the energy conversion model with 1D laser-plasma interaction simulations
- ➢ Perform the same parameter-scan in 2D
- ➢ Study the effect of layer thickness on the divergence

Thank you for your attention!