# 2D PIC Simulations of Laser Ion Acceleration via TNSA

Zsolt Lécz, Oliver Boine-Frankenheim , Vladimir Kornilov, Thomas Weiland

**Numerical aspects in 2D PIC simulations: Laser with interacting over-dense plasma**

**11th International Computational Accelerator Physics Conference**

**ICAP'12**

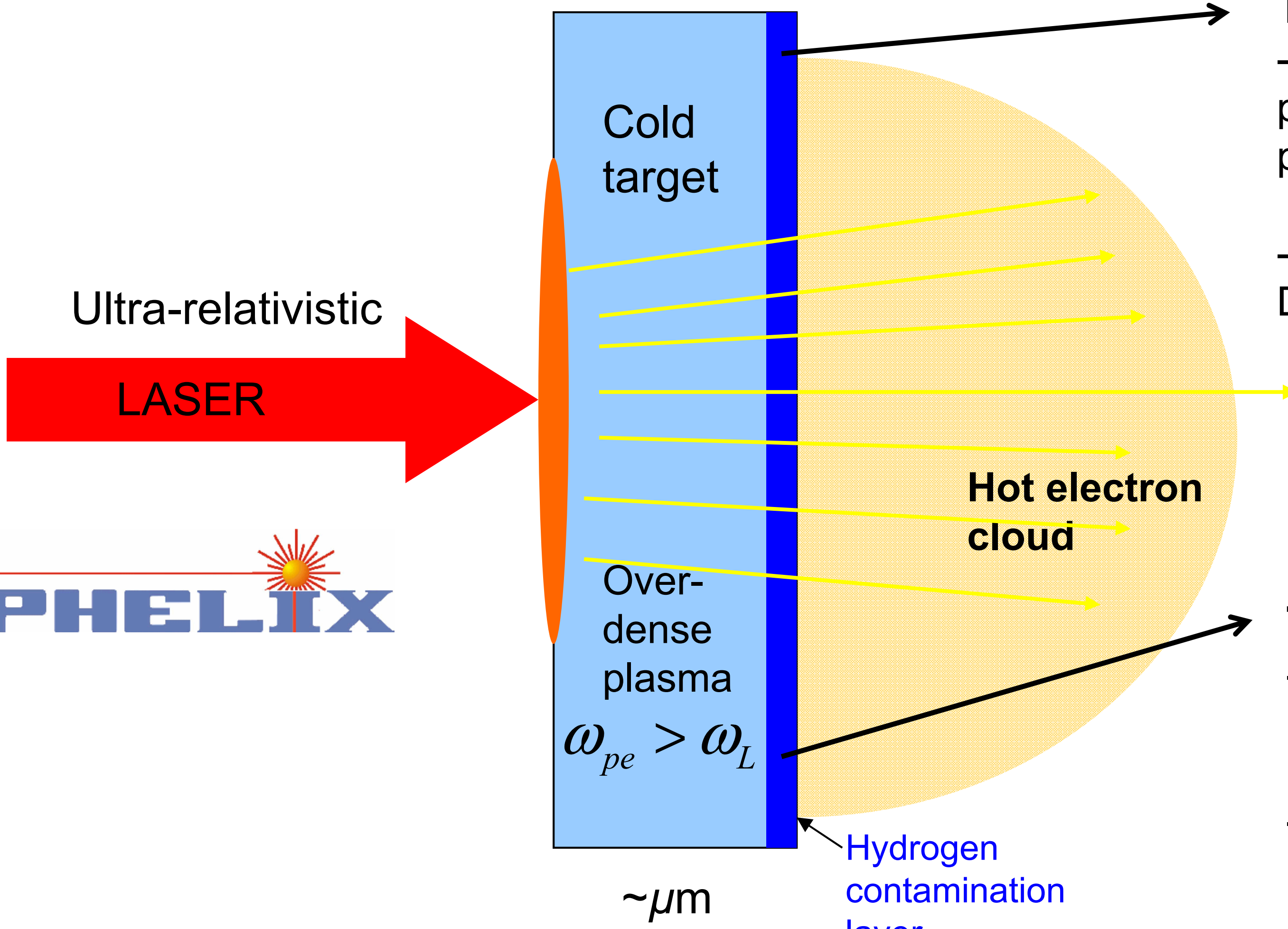
**19-24, August, 2012**
**Warnemuende**

# Outline

- Introduction: TNSA – multi-scale problem
- 3D EM PIC simulation tool
- Numerical heating of electrons
  - Without laser
  - With laser
- Results
- Conclusions

# Introduction

## **Target Normal Sheath Acceleration** (TNSA)




**Thin layer**
-Electrostatic lens, protons are test particles

-Acceleration in the Debye-sheath

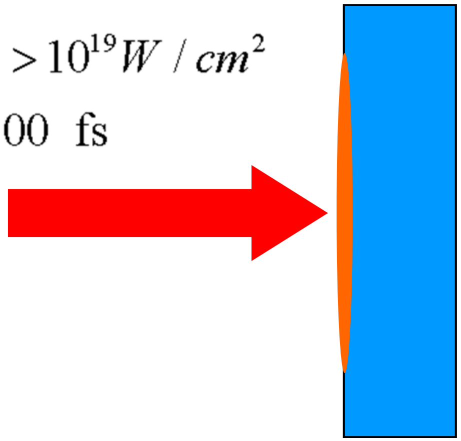
**Thick layer**
-Acceleration via plasma expansion

-Neutral proton beam

# Laser-plasma interaction

$W_L > 10^{19} W / cm^2$

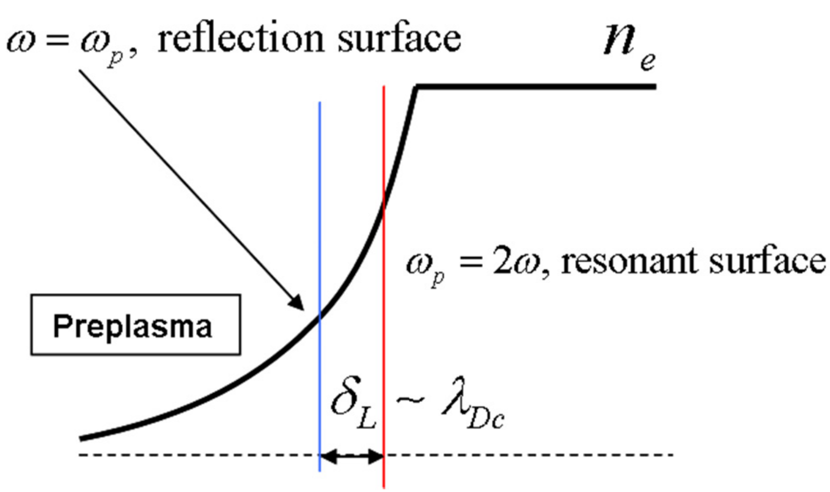
$\simeq 100$ fs



The electrons are accelerated by the **ponderomotive force**, which has the frequency: $2\omega$, where $\omega$ is the laser frequency

The laser pulse gets reflected when:

$$n_c = \frac{\varepsilon_0 m \overline{\gamma} \omega^2}{e^2} \quad (\omega = \omega_p)$$



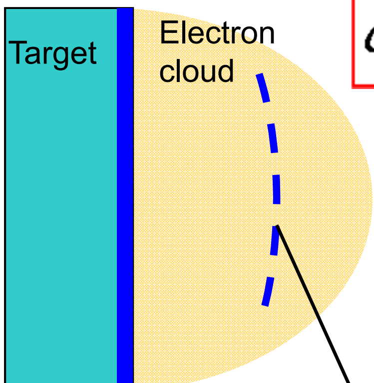

The length to be resolved:

$\delta_L$ (laser skin-depth) > $\lambda_{Dc}$ (cold electron Debye-length)

$$\delta_L = \frac{c}{\omega_p} \qquad \lambda_{Dc} = \sqrt{\frac{\varepsilon_0 T_c}{e^2 n_e}}$$

$\Delta x \propto$ nm, $\Delta t \propto$ 10 as

# Hot electron cloud

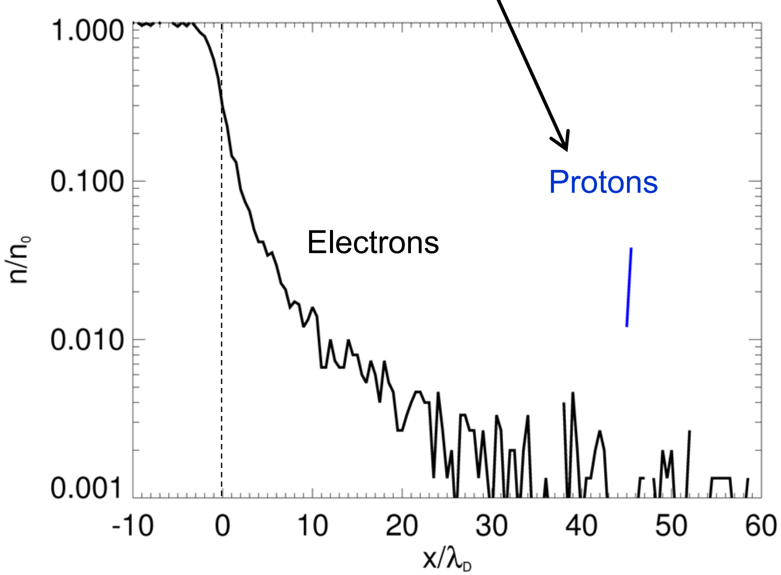


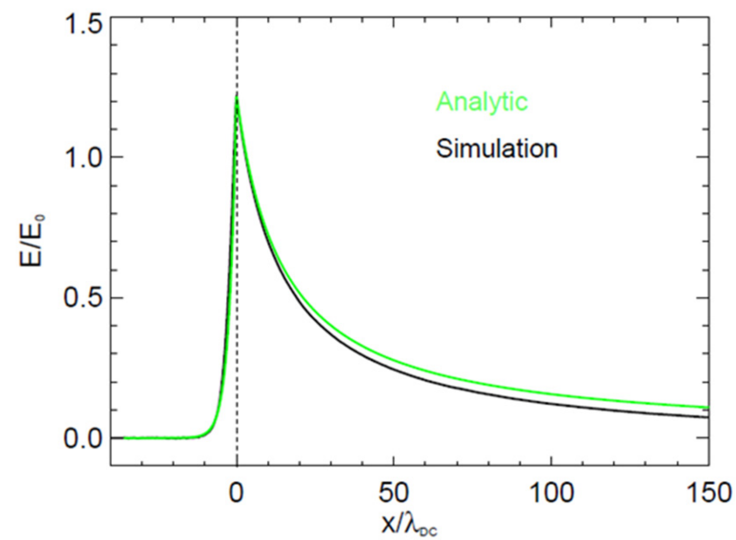

$$d \leq \lambda_{Dc}$$

$$n_h \sim \frac{n_{h0}}{x^2}$$

M. Passoni, PRL **101**, 2008

$$E_{in} \sim \exp\left(-\frac{x}{\lambda_{Dc}}\right) \quad E_{out} = \frac{2E_0}{\sqrt{2 + x/\lambda_D}} \quad E_0 = \sqrt{n_h T_h / \varepsilon_0}$$



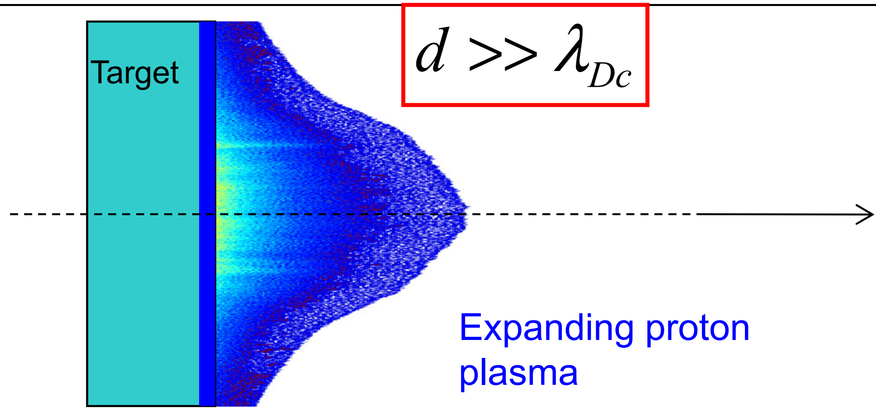




The grid-size is determined by the layer thickness and it requires high PPC (particles per cell).

# Plasma expansion



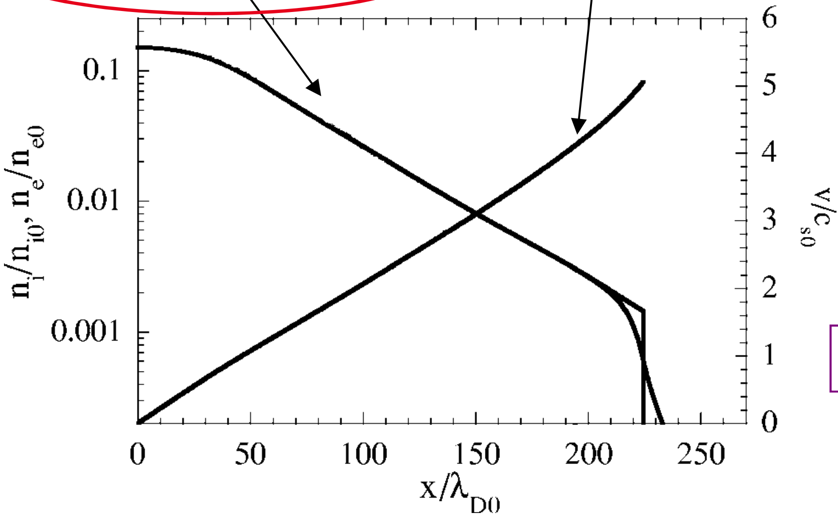
$$d \gg \lambda_{Dc}$$

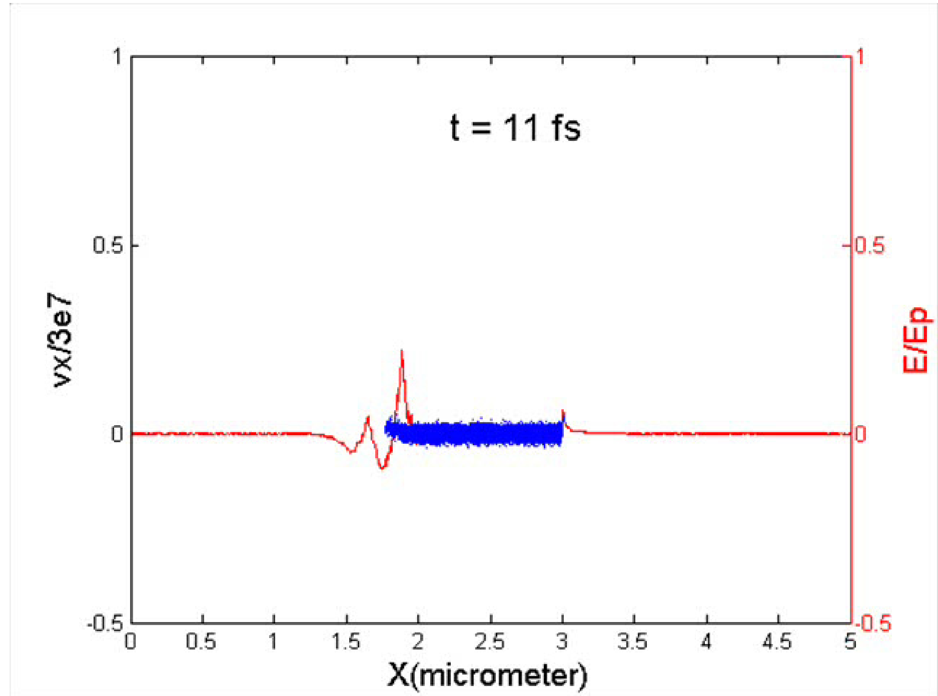



Expanding proton plasma

$$n_i = n_0 \exp[-(1 + x / C_s t)]$$

$$v_p = C_s + \frac{x}{t}, \quad C_s = \sqrt{\frac{T_h}{m_p}}$$



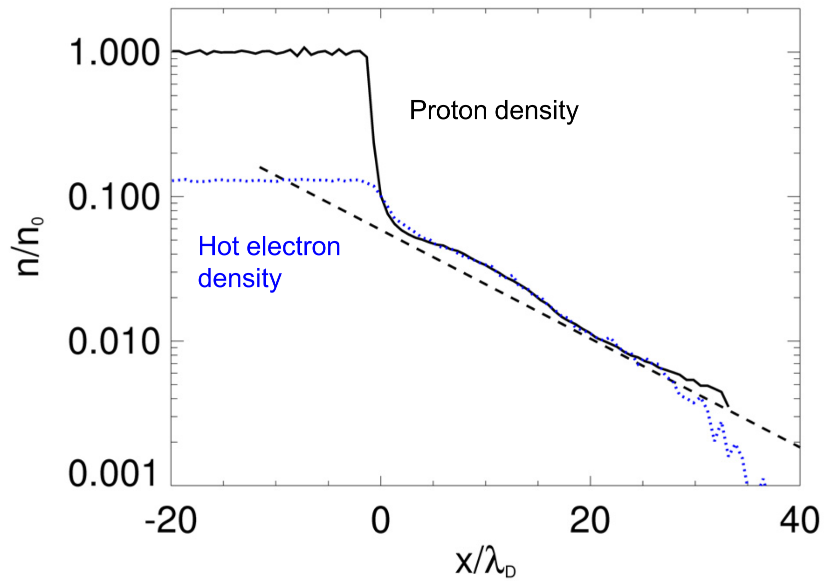




The peak electric field at the proton front:

$$E_f = \frac{2E_0}{(2 + \omega_p^2 t^2)^{1/2}}$$

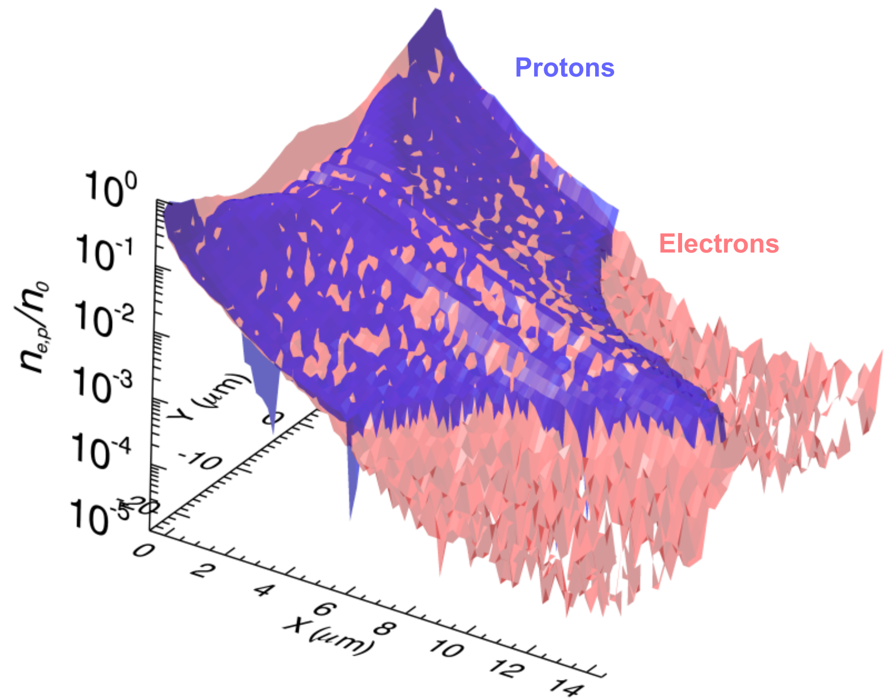
P. Mora, PRL **90,** 2003

# Time limitation




Density of the proton front:

$$\frac{n_p}{n_0} = \frac{4}{\left(\omega_p t\right)^2} \qquad \omega_p = \sqrt{\frac{n_{h0} q_e^2}{m_p \varepsilon_0}}$$




With *PPC=100* the proton density is resolved until:

$$\omega_p t = 20 \Rightarrow t \approx 200 - 300 \text{ fs}$$

# Multi-scale problem

TECHNISCHE UNIVERSITÄT DARMSTADT

Laser-plasma interaction

Target front side

$$\Delta x \simeq \lambda_{Dc}(\text{nm})$$

Plasma expansion behind the target

The electrons are still hot

$$\Delta x \simeq \lambda_{Dc} \to \lambda_{Dh}$$

Drifting cold plasma

No more acceleration

$$\Delta x > 1\ \mu\text{m}$$

**Can be 3D !**

$$\Delta t \simeq 10^{-17} s$$

$$\Delta t \simeq 10^{-17} \to 10^{-15} s$$

$$\Delta t > 10^{-14} s$$

Requires high time- and space-resolution. EM solver is used.

After the laser is off we can switch to the ES solver and to much larger grid-size.

Simulations for proton focusing, capturing and transporting to other devices.

Exponential density profile !

# Our tool: VORPAL 5.2

TECHNISCHE UNIVERSITÄT DARMSTADT

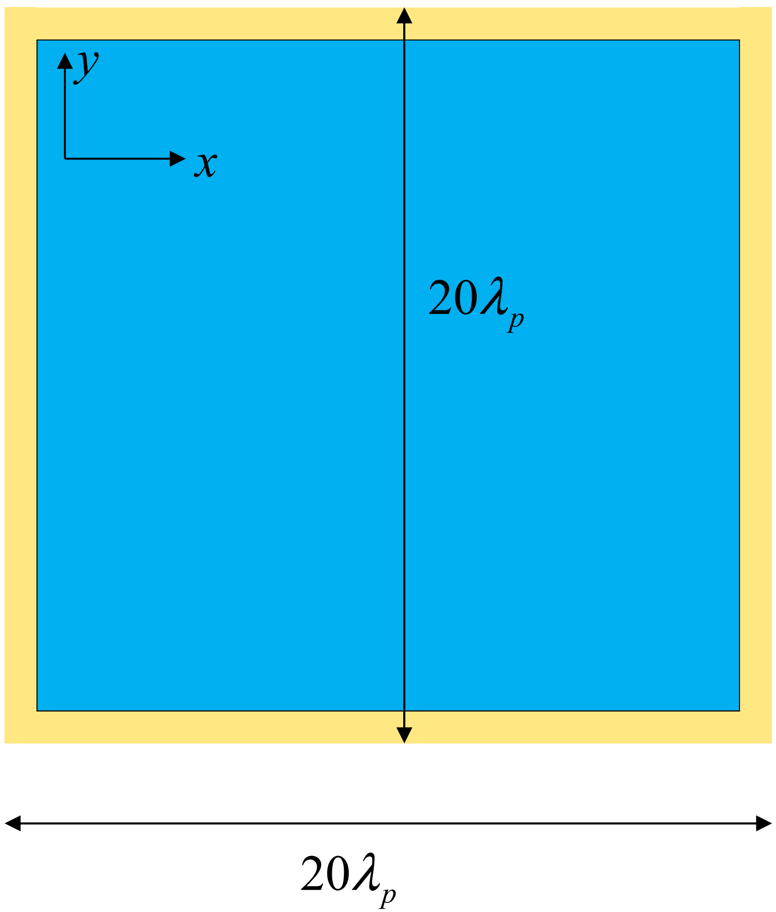
- Fully relativistic EM plasma simulation PIC code
- MPI, efficient particle loading
- Various field solvers
- User-friend, Xml-based input file editor
- Large variety of boundary conditions

▪ **Still needed:**

- Adaptive mesh for plasma simulations
- Support for cylindrical coordinate system
- (Particle loading on non-uniform grid)

# Numerical grid heating

## Without laser




Periodic boundary

Cold plasma

Plasma wave-length:

$$\lambda_p = \frac{2\pi c}{\omega_{pe}} > \lambda_D$$

$PPC$ - macroparticles per cell

$\Delta x$ - uniform grid size

# Field smoothing

$$\vec{E},\ \vec{B},\ J$$

Higher order interpolation (third order or cubic Spline)

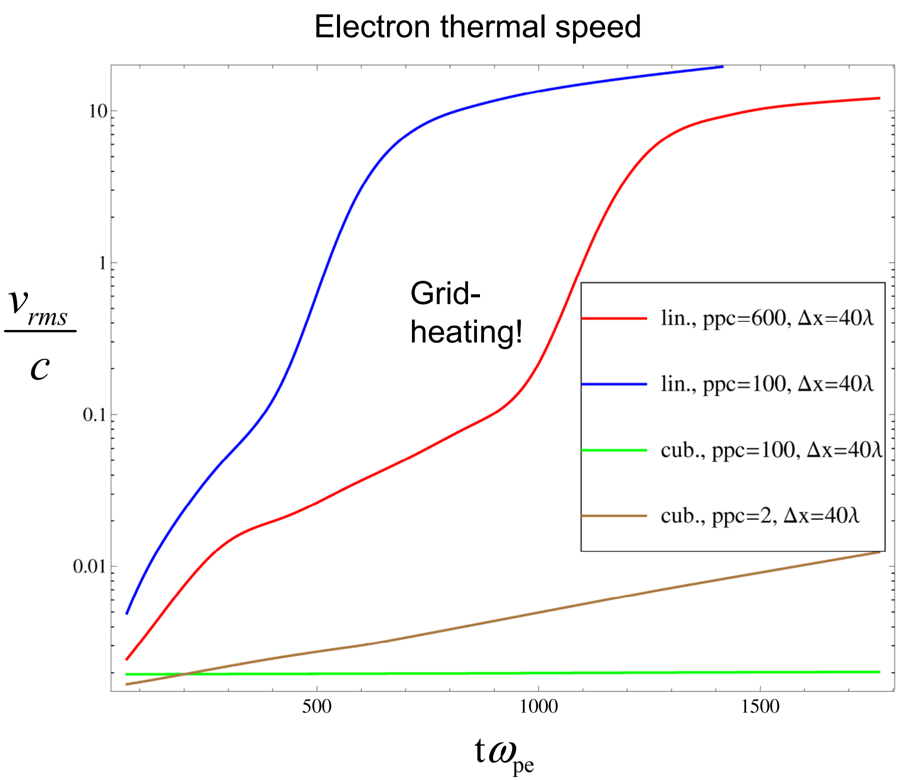
Higher order particle shape (third order or cubic weighting)

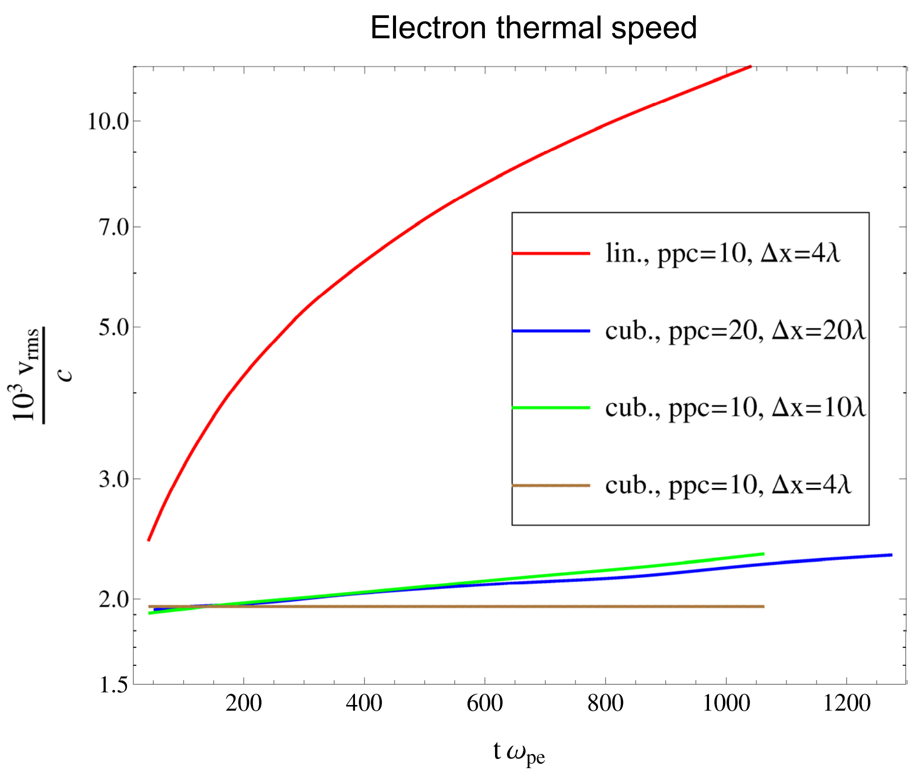
~~Digital smoothing (filter)~~

~~It is dangerous when the sharp peaks in the density have physical reason.~~

$$NGP * NGP * NGP$$

# 2D grid-heating test

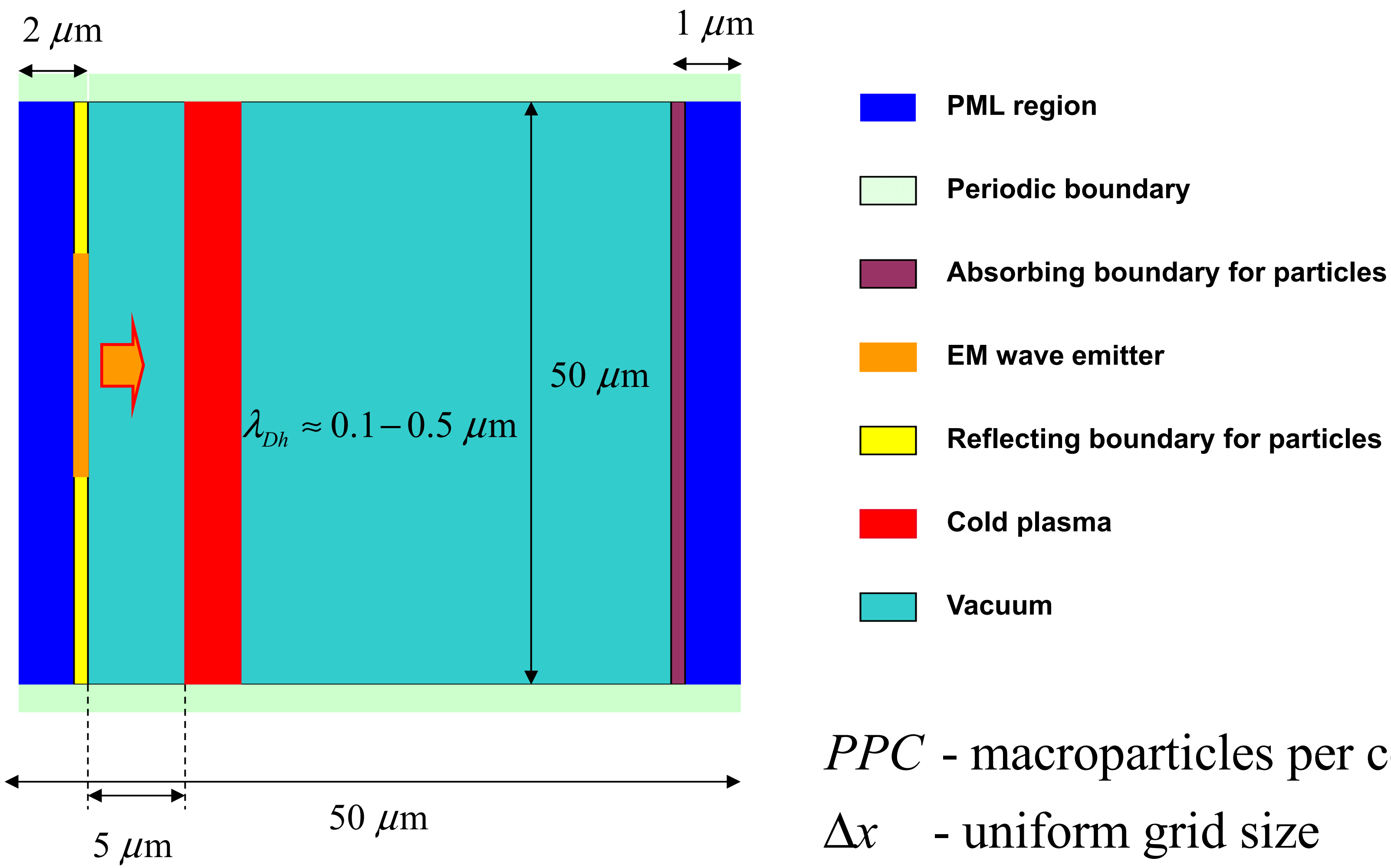



The cubic interpolation and particle shape reduces dramatically the grid heating.

# Convergence study

With laser, cubic interpolation

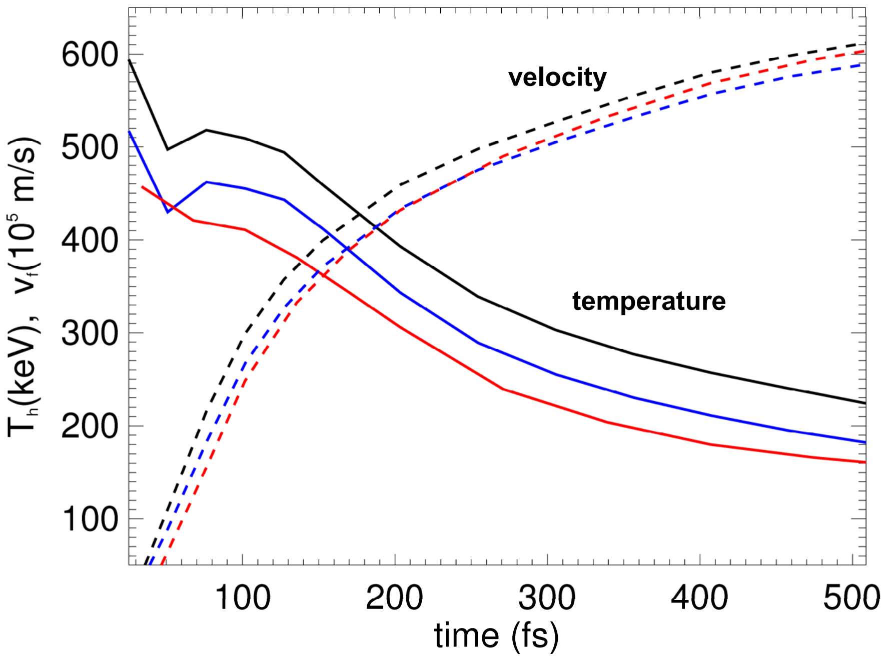



$PPC$ - macroparticles per cell

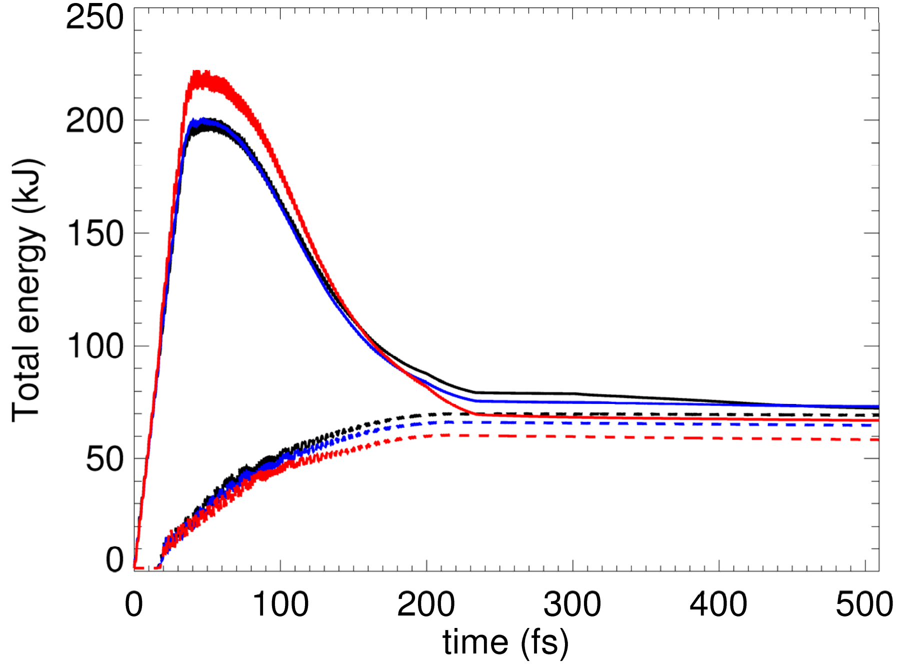
$\Delta x$ - uniform grid size

# Results, same PPC

Hot electron temperature and proton front velocity




Total energy of the system




$\Delta x = 5\lambda_{Dc}, PPC = 50$

$\Delta x = 10\lambda_{Dc}, PPC = 50$

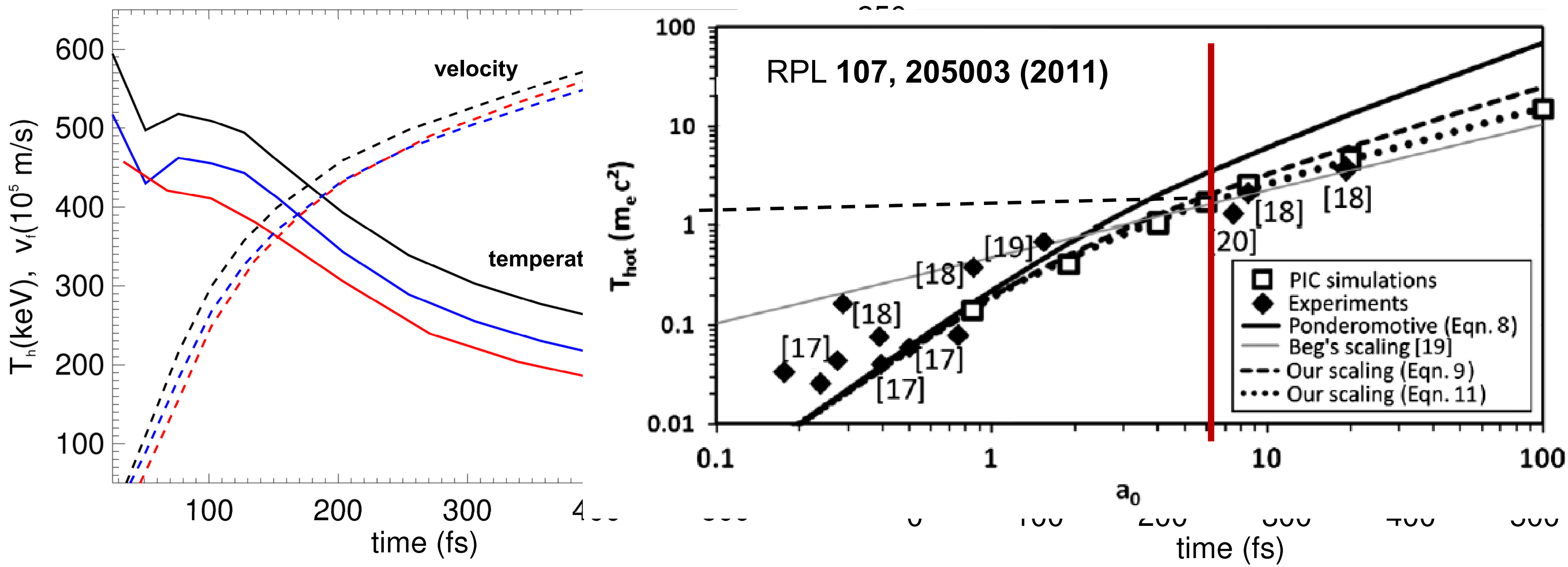
$\Delta x = 20\lambda_{Dc}, PPC = 50$

The dashed line is the total energy of particles.

# Results, same PPC

Hot electron temperature and proton front velocity

Total energy of the system




$\Delta x = 5\lambda_{Dc}, PPC = 50$

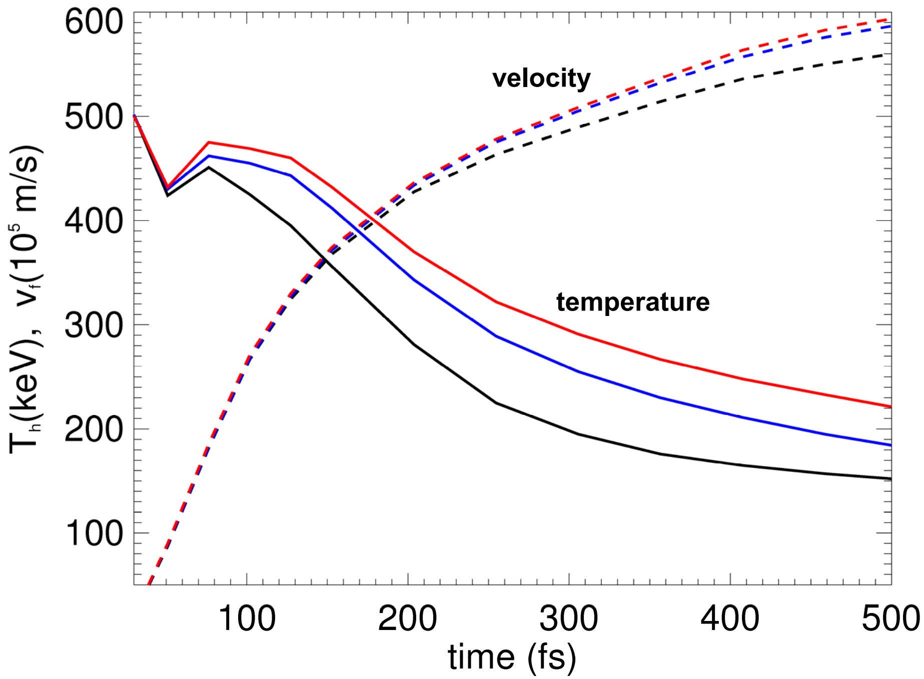
$\Delta x = 10\lambda_{Dc}, PPC = 50$

$\Delta x = 20\lambda_{Dc}, PPC = 50$

The dashed line is the total energy of particles.

# Results, same grid

Hot electron temperature and proton front velocity

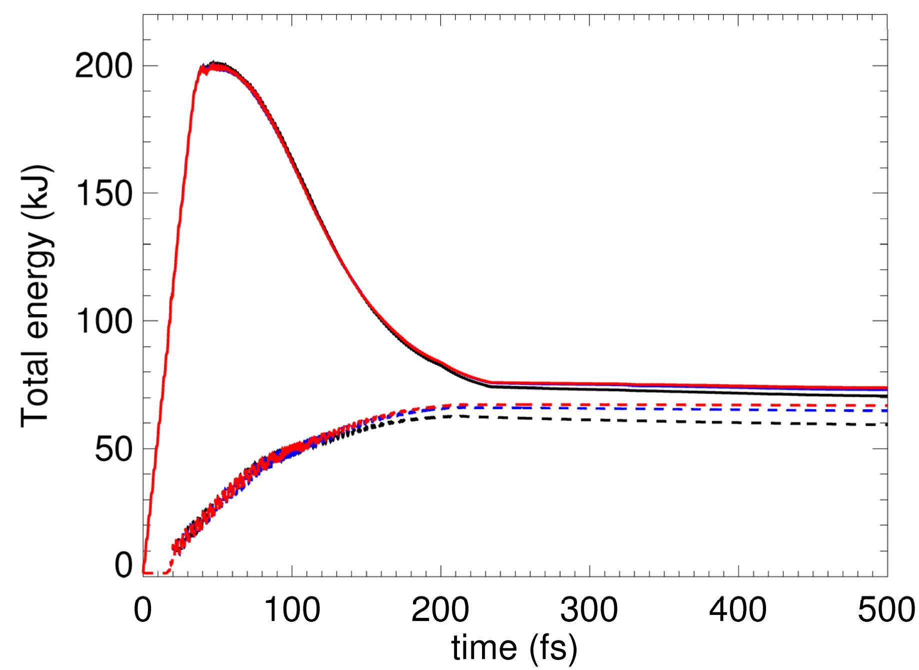



$\Delta x = 10\lambda_{Dc}, PPC = 20$

$\Delta x = 10\lambda_{Dc}, PPC = 50$

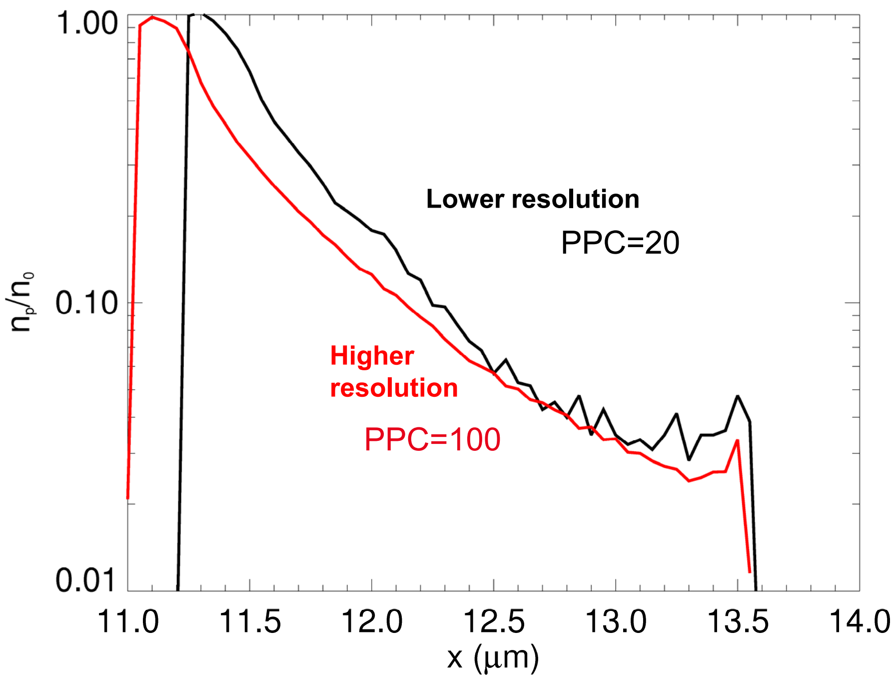
$\Delta x = 10\lambda_{Dc}, PPC = 100$

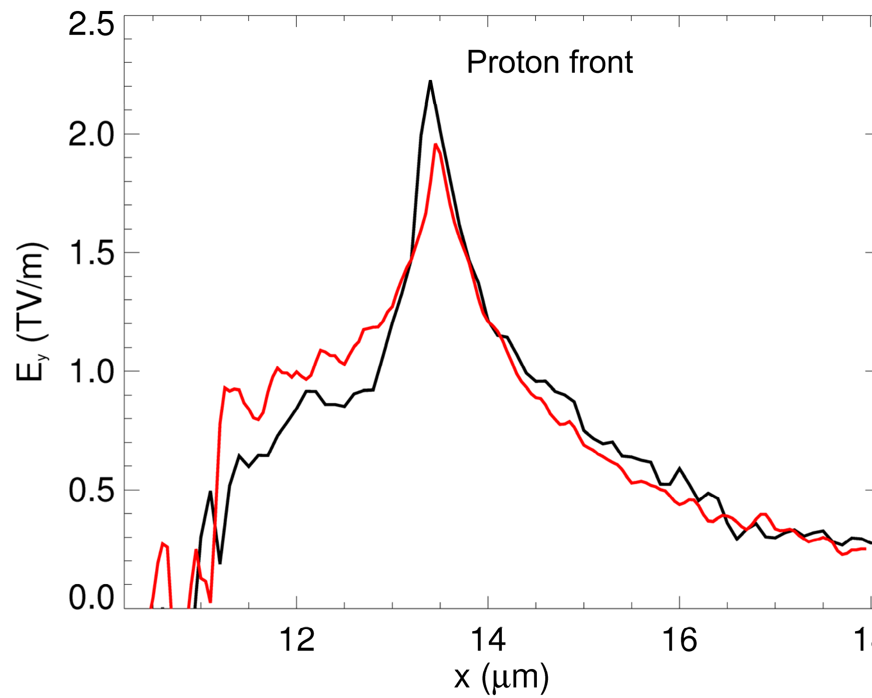
Total energy of the system




The dashed line is the total energy of particles.

# Fields and density on axis




Higher macro-charge results in a higher charge-separation field!

# Performance

For the correct hot electron generation the laser skin depth at the front side has to be resolved.

$$\delta_L \simeq 10 \cdot \lambda_{Dc}$$

The optimal grid size: $\Delta x = 5 \cdot \lambda_{Dc}$ → No grid-heating and the laser skin-depth is resolved.

<u>Example</u>: $\lambda_{Dc} = 4 \text{ nm}$ →

Total number of cells:

$$2500 \times 2500$$

Total number of particles (if ppc=50):

$$N / species \approx 12.5 \text{ million}$$

Total number of time steps:

**~10000**

The usual run time on 32 nodes:

1-2 day(s)

# Possibilities for speed-up

$$\Delta x \sim \lambda_{Dc} \sim \sqrt{\frac{T_c}{n_0}}$$

$$T_c \ll T_h \sim I_{laser}^{1/2}$$

The laser intensity must be increased!

$$(\lambda_{Dc} \ll \lambda_{laser})$$

$$n_0 > n_c \sim \omega^2$$

The laser wave-length must be increased!

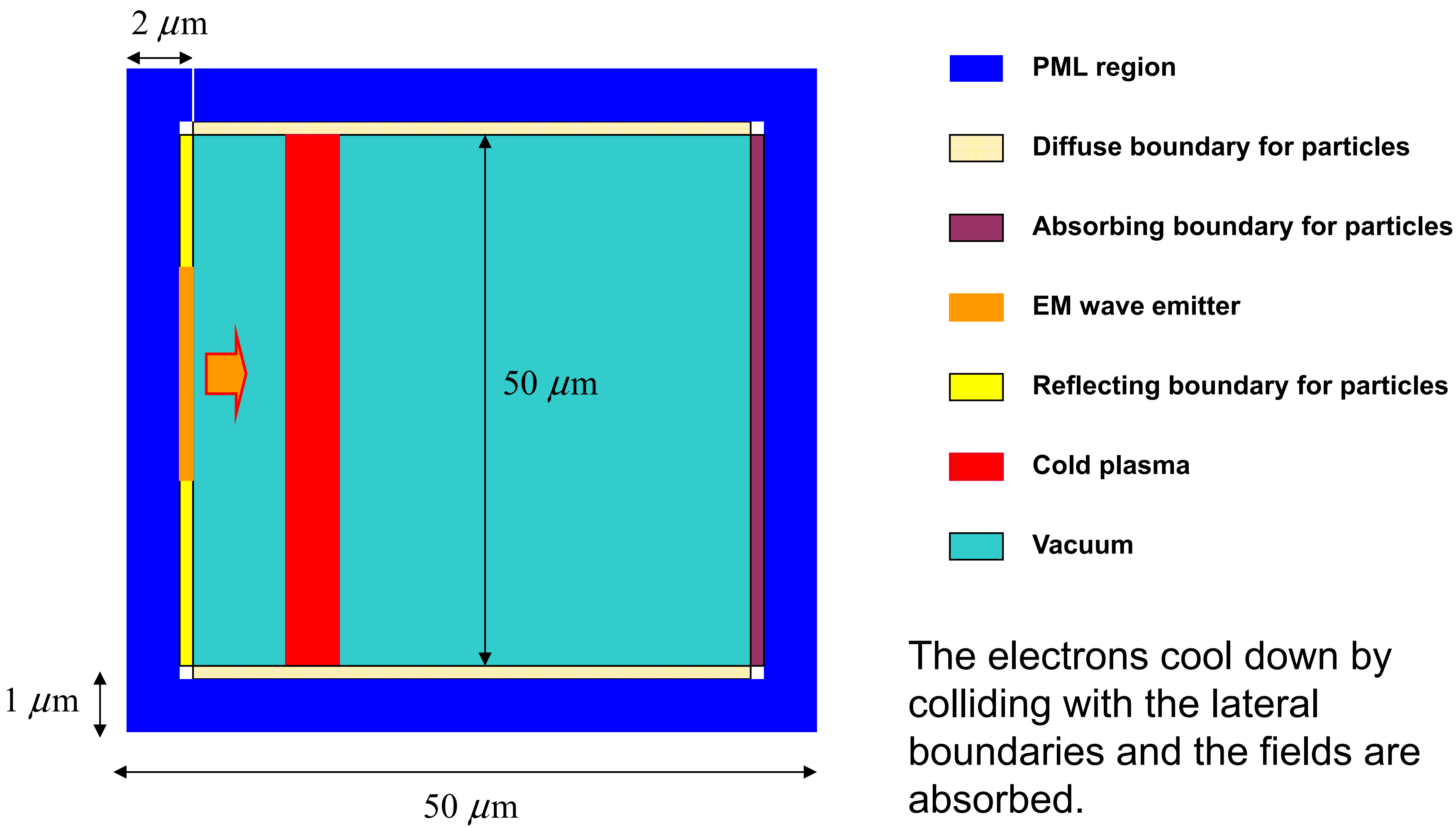
Different laser absorption !?

In our case: $T_{init} = 3 - 6\ \mathrm{keV}$

$\lambda_{laser} = 1\ \mu\mathrm{m}$

**OR GPU !**

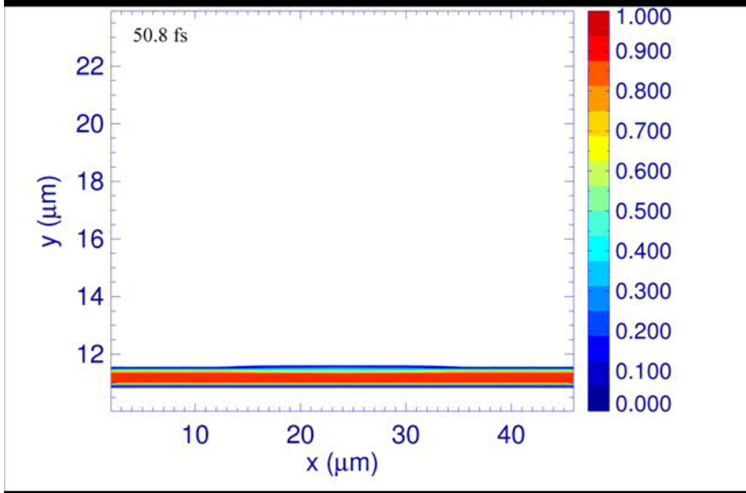
# Infinite space

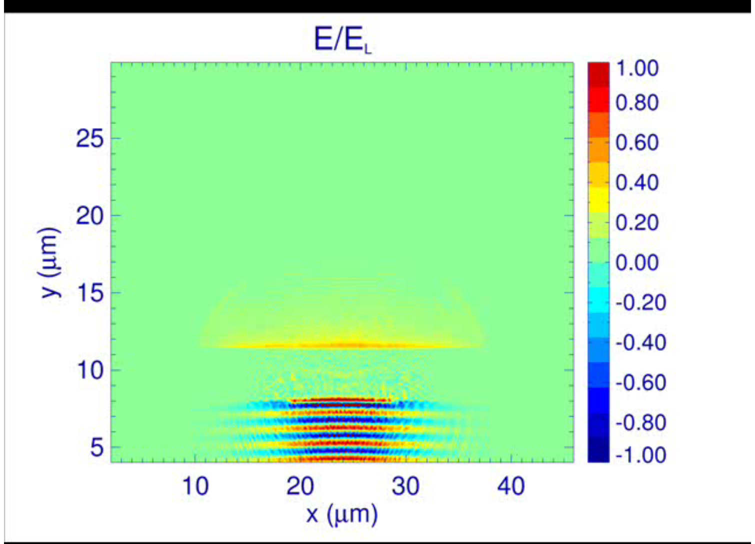



The electrons cool down by colliding with the lateral boundaries and the fields are absorbed.

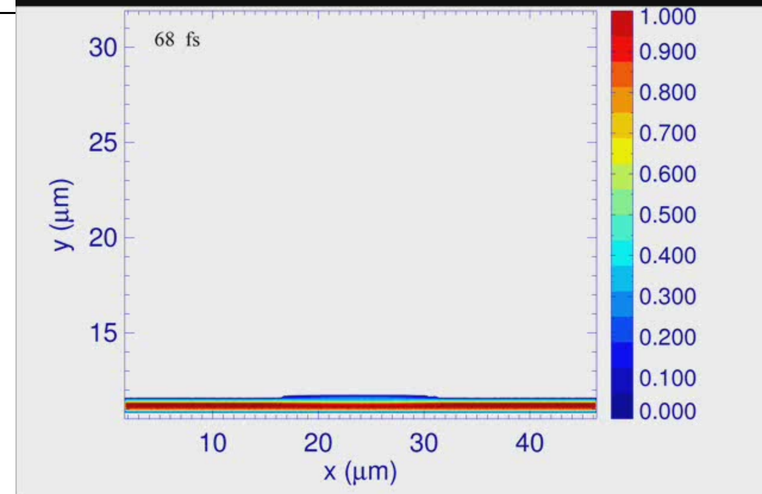
# Example: fields and density

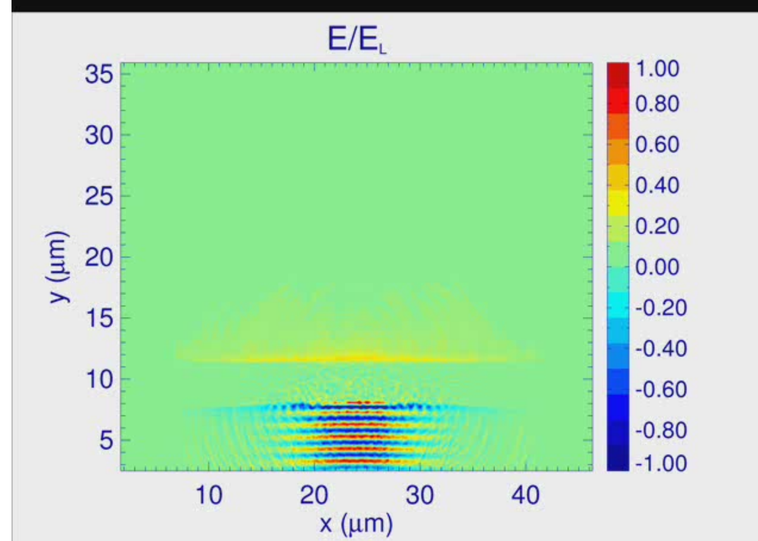
$\Delta x = 5\lambda_D, \quad PPC = 50$




$\Delta x = 20\lambda_D, \quad PPC = 50$



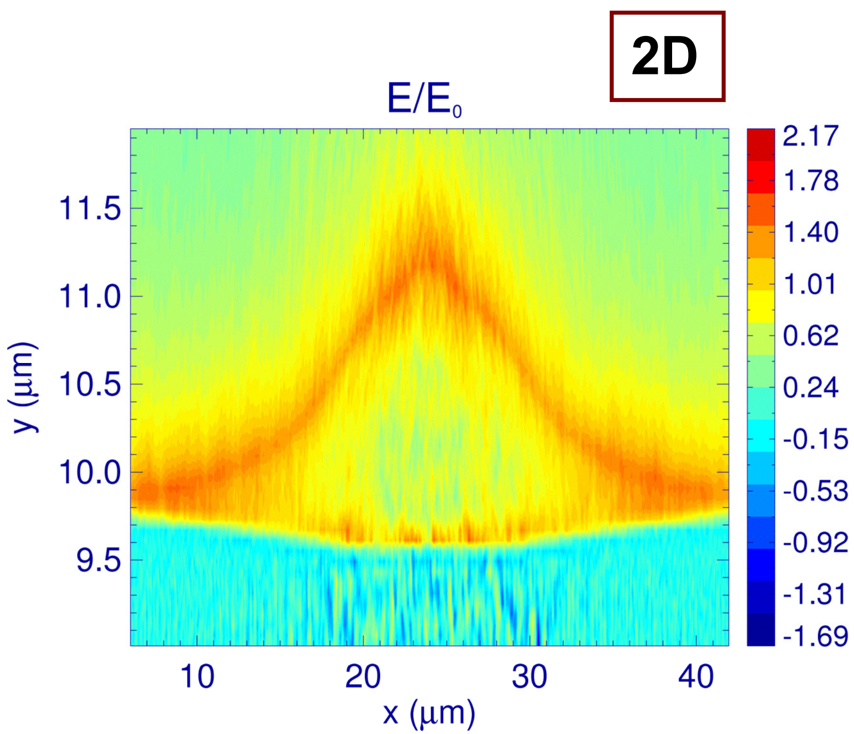



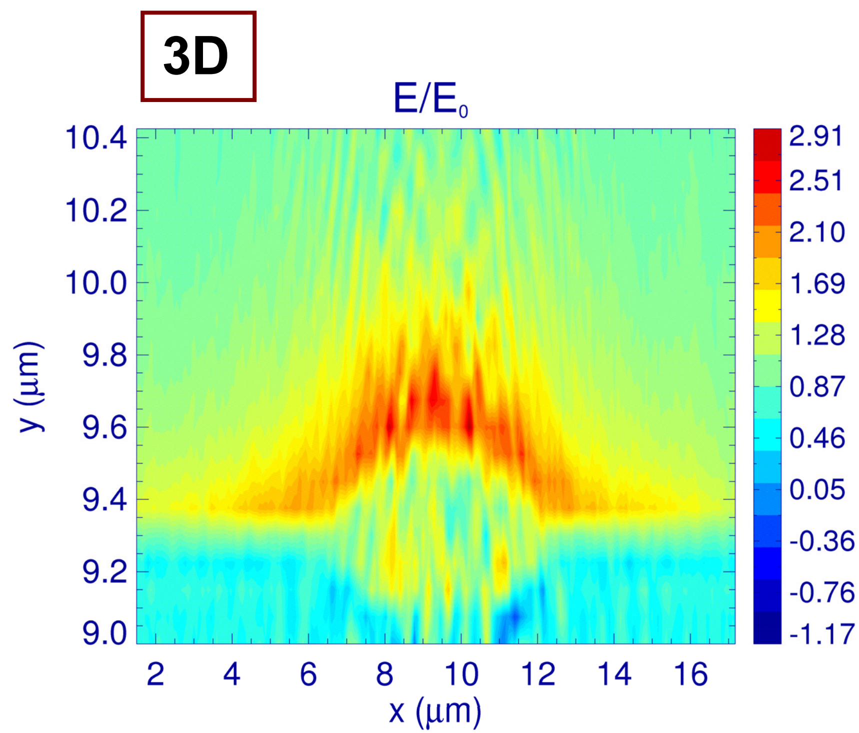
# Differences between 2D and 3D

The 2D simulation gives realistic results only close to the axis of symmetry of the laser pulse!

The hot electron density should be inversely proportional to the distance from the middle point.

$$n_h \sim \frac{1}{r}$$



# Conclusions

- Higher order (3rd) particle shapes and field interpolation eliminates the grid heating even if the physical scales are not resolved

- Optimal simulation parameters
  - Grid size: 5-10 cold electron Debye length
  - Macro-particle number per cell:  50-100 or more

- The planar XY geometry is not enough for the correct plasma expansion
  - 3D simulation requires large computing power and long time
  - Cylindrical coordinate system (2D) – under investigation

# Thank you for your attention!

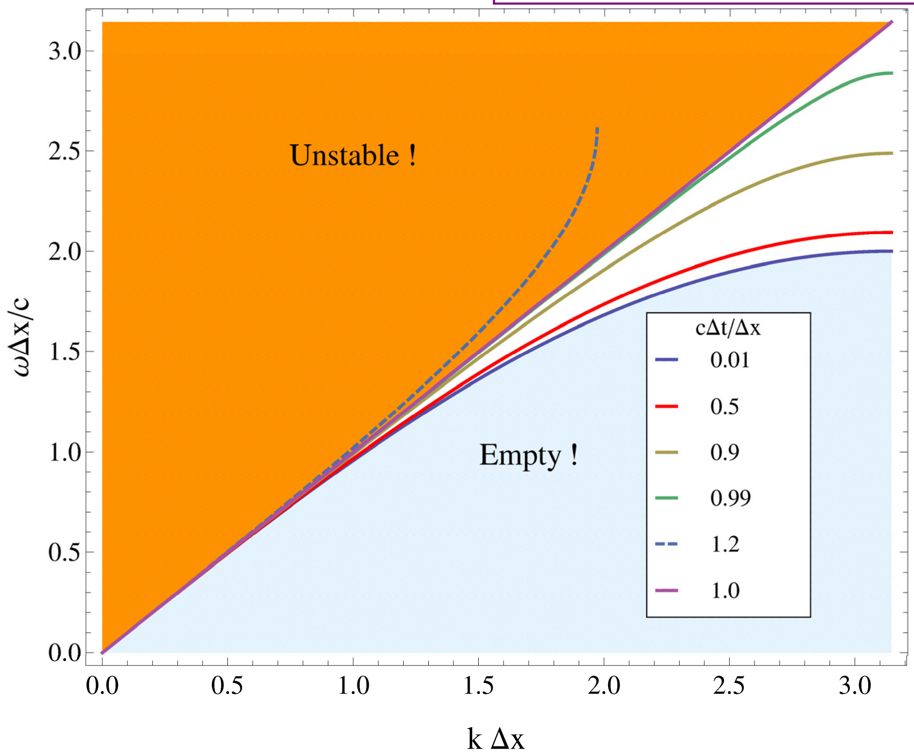
# Cherenkov radiation

$$\boxed{1 > (c\Delta t)^2 \left( \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right)} \Rightarrow \frac{\omega}{k} \le c$$

$$\Delta x = 4\lambda_{Dc}$$

$$PPC = 50$$

C. K. Birdsall, 1991




Total energy of electrons over time