Enabling Numerical Modeling of Extreme-Intensity Laser Produced Hot Dense Plasma

Ionization degree of silicon

Ionization wave inside a glass target driven by relativistic electrons

Yasuhiko Sentoku

Department of Physics
University of Nevada, Reno

01/07/2011@Edinburgh, UK

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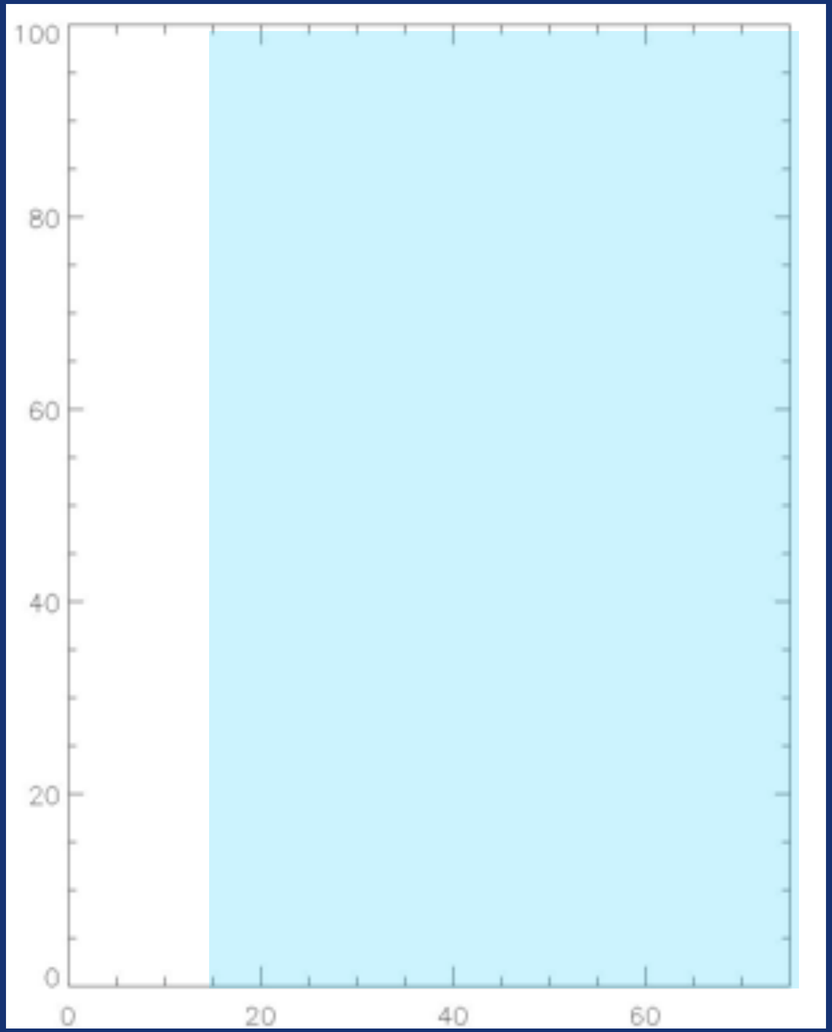

Ionization wave inside a glass target driven by relativistic electrons

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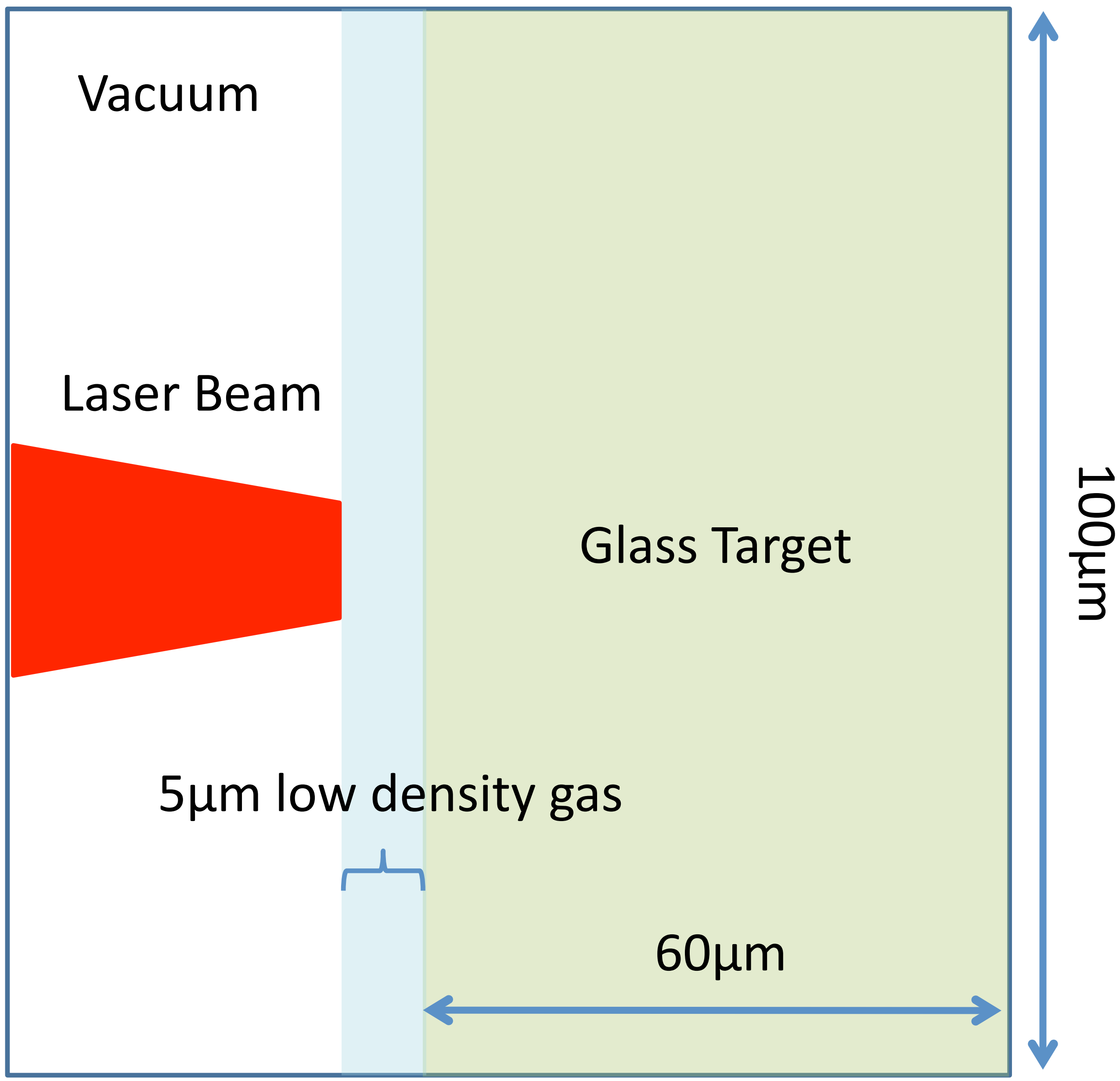
2D Simulation Parameters

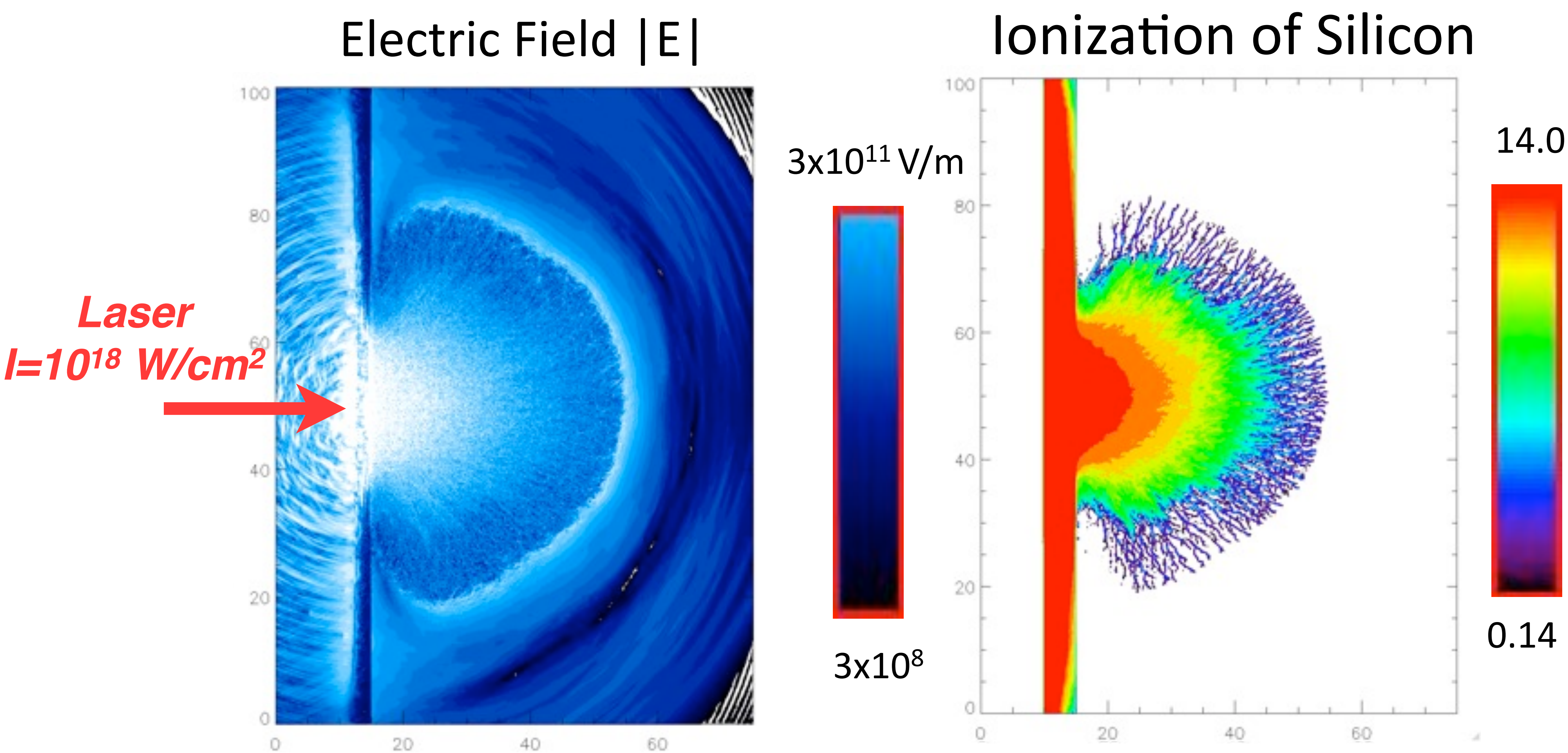
- Target
  - 60x100 µm thick solid density SiO_2
    - $N_e = 690n_c$
    - $N_{si} = 23n_c$
    - $N_{O2} = 46n_c$
  - 5 µm low density gas precursor
- Laser
  - Intensity: $5x10^{18}W/cm^2$
  - 500fs pulse length
  - 15 µm focal spot
- Code Parameters:
  - Thomas-Fermi and Saha ionization models included
  - Binary collisions included
  - 686 million particles inserted
  - 3000x4000 grids
  - Absorbing boundary condition
  - 100 CPU used
  - 1 ps total simulation duration



Simulation box geometry

Hot electron transport in insulator target

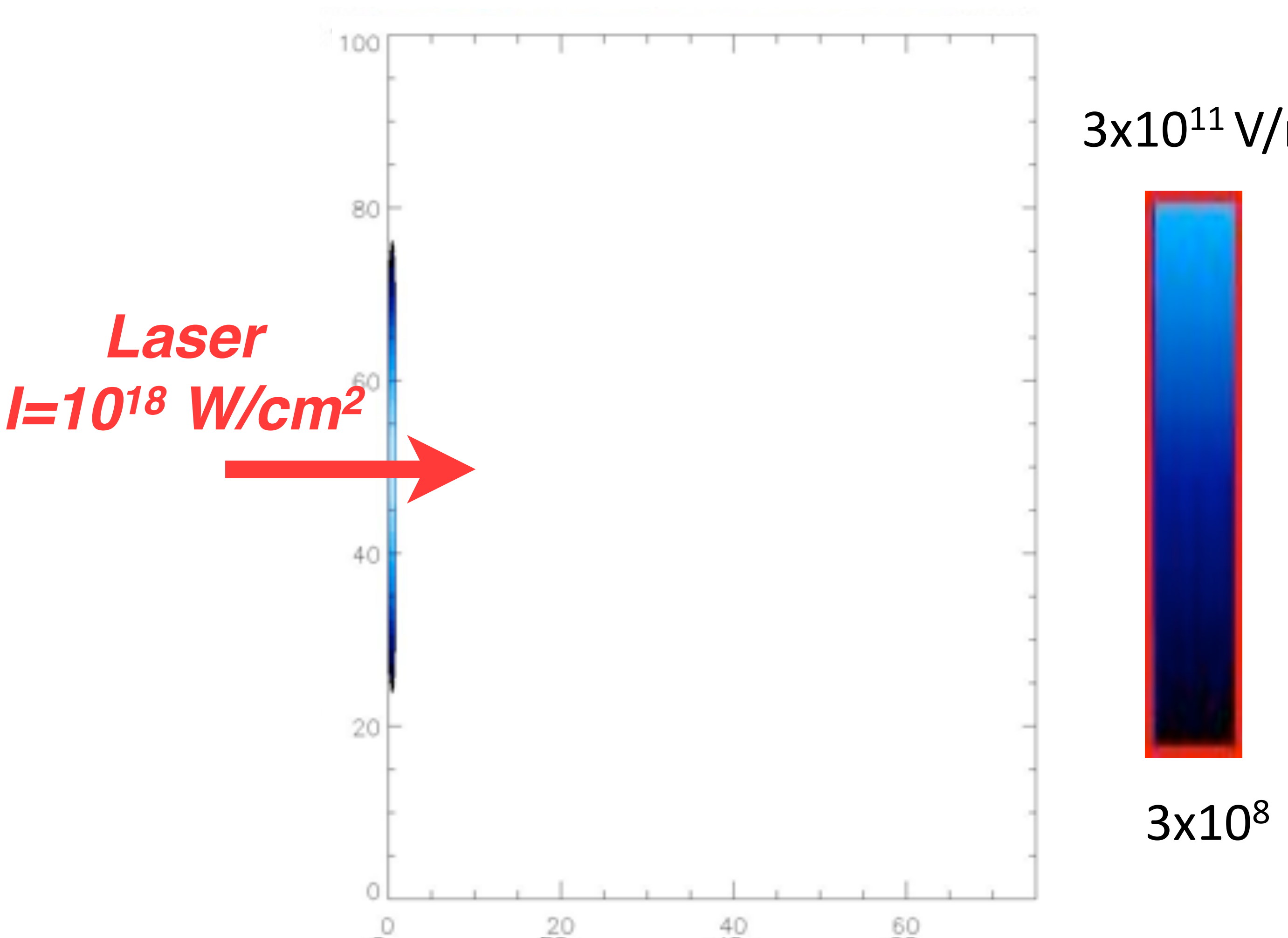
Ionization wave in silica driven by relativistic laser pulse



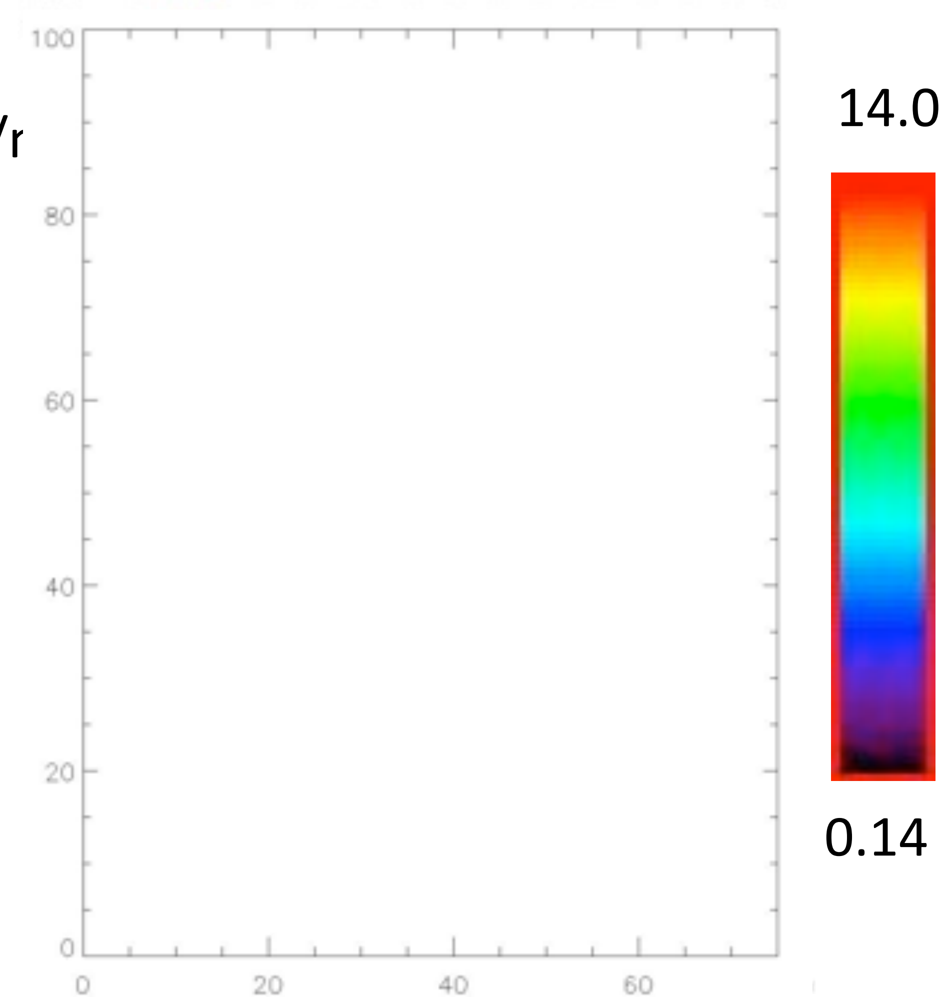
Hot electron transport in insulator target

Ionization wave in silica driven by relativistic laser pulse

Electric Field |E|

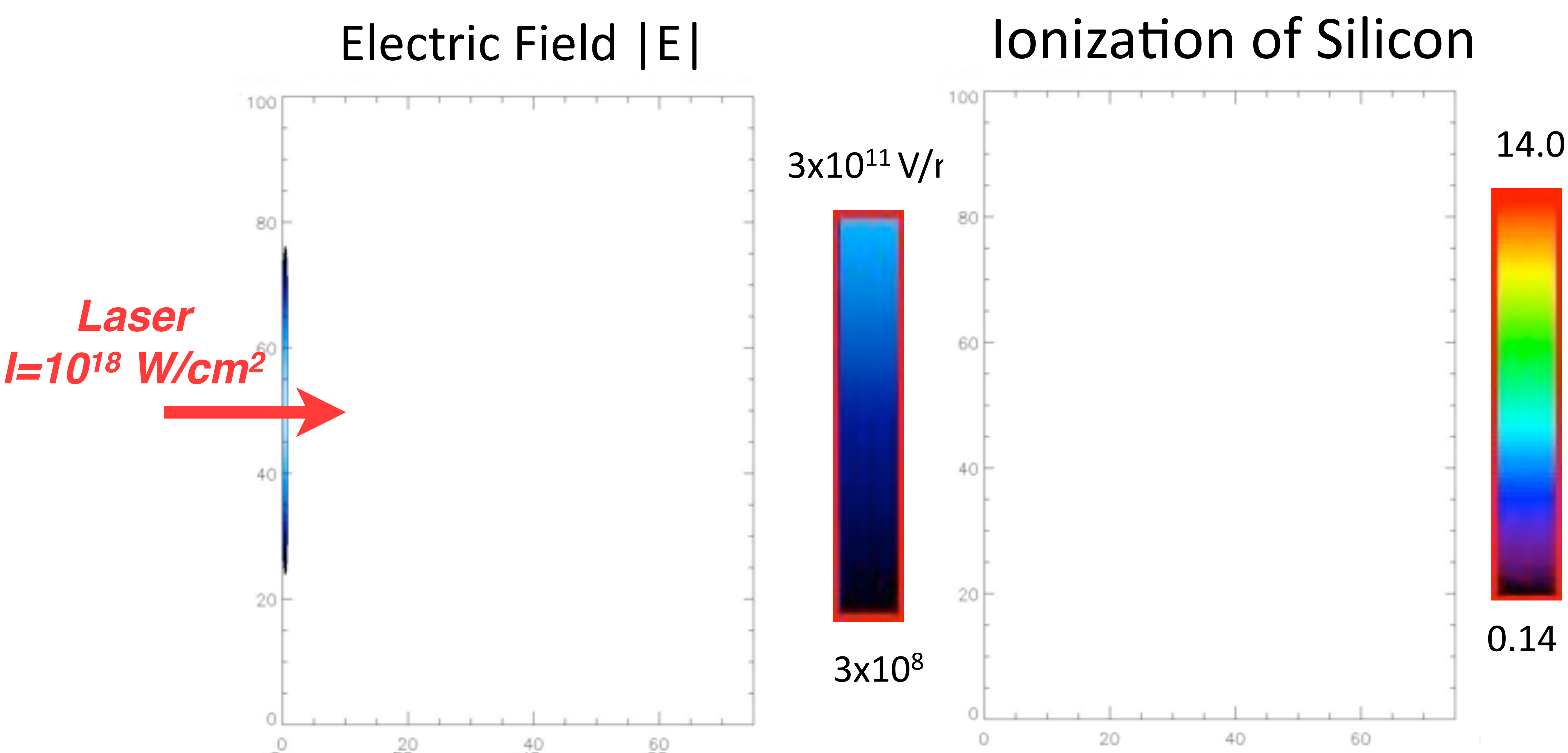


Ionization of Silicon



Hot electron transport in insulator target

Ionization wave in silica driven by relativistic laser pulse

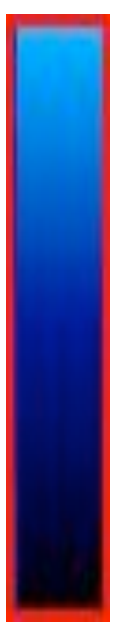


Nevada Terawatt Facility
College of Science
University of Nevada, Reno

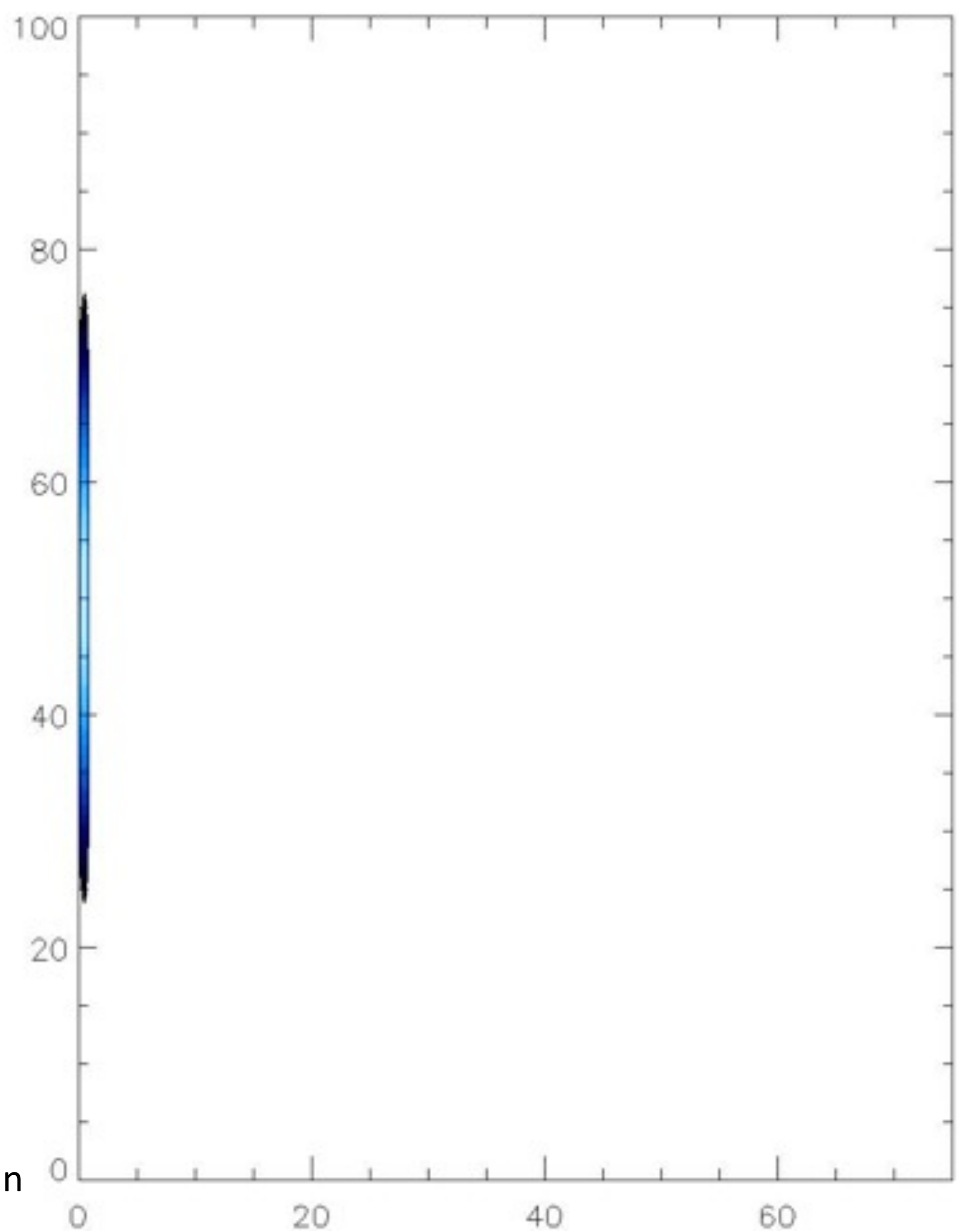
Fast Electron Beam Preceding Ionization Front

Sheath Field |E|

3×10^{11} V/m

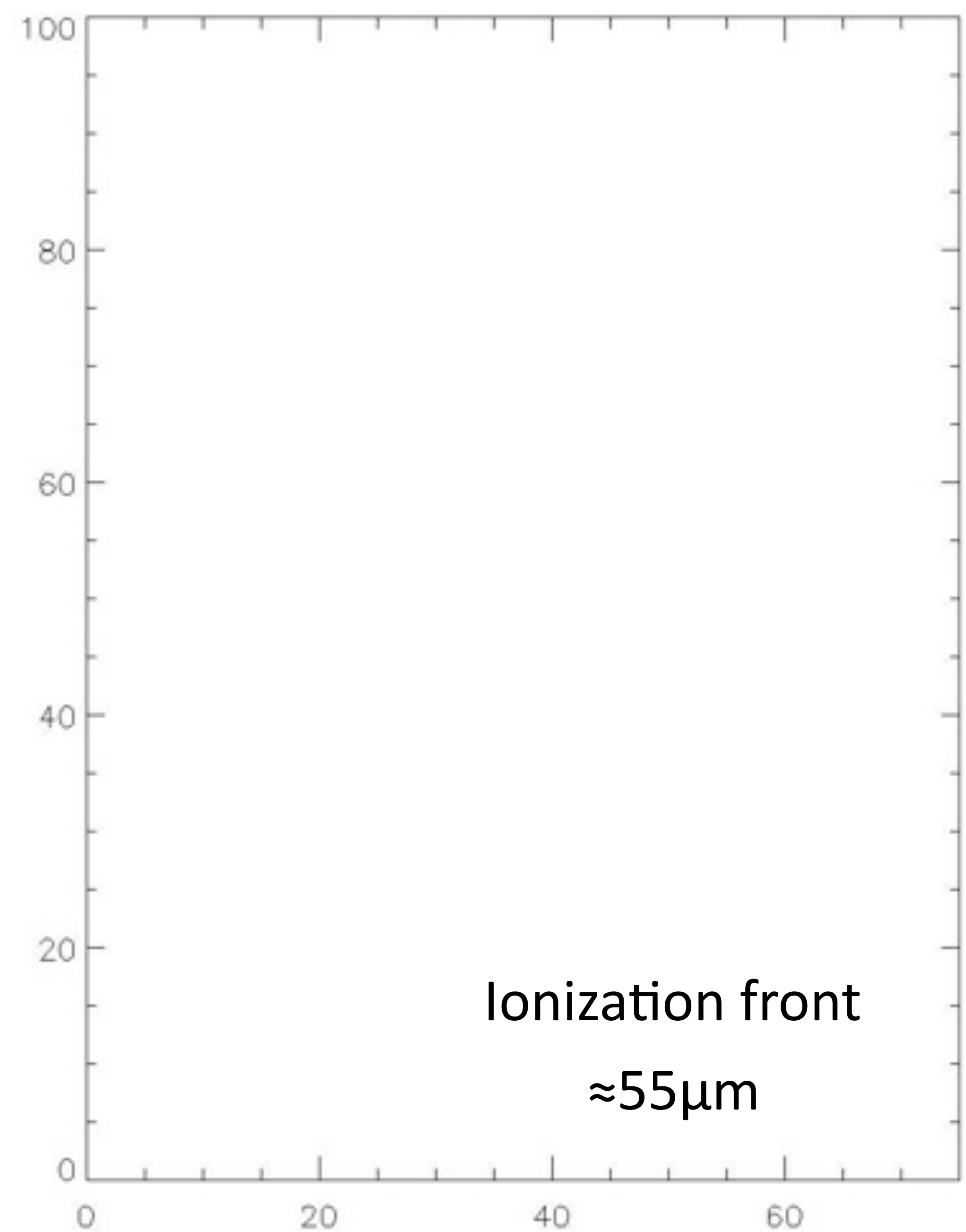


3×10^{8}

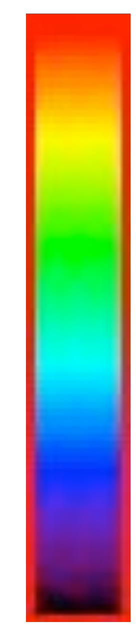


Breakdown field in silica ≈ 10^{10} V/m

Ionization of Silicon



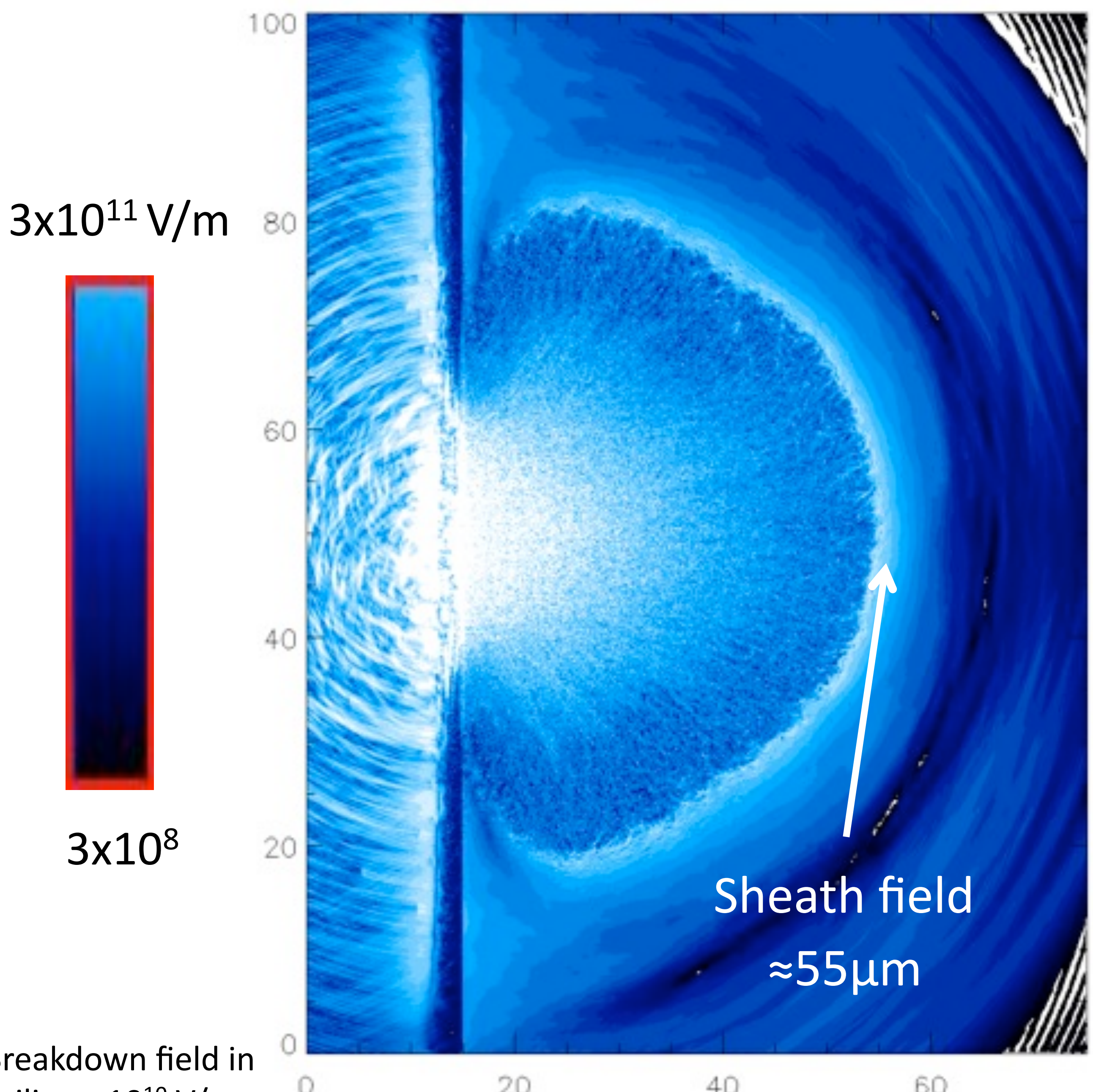
14.0



0.14

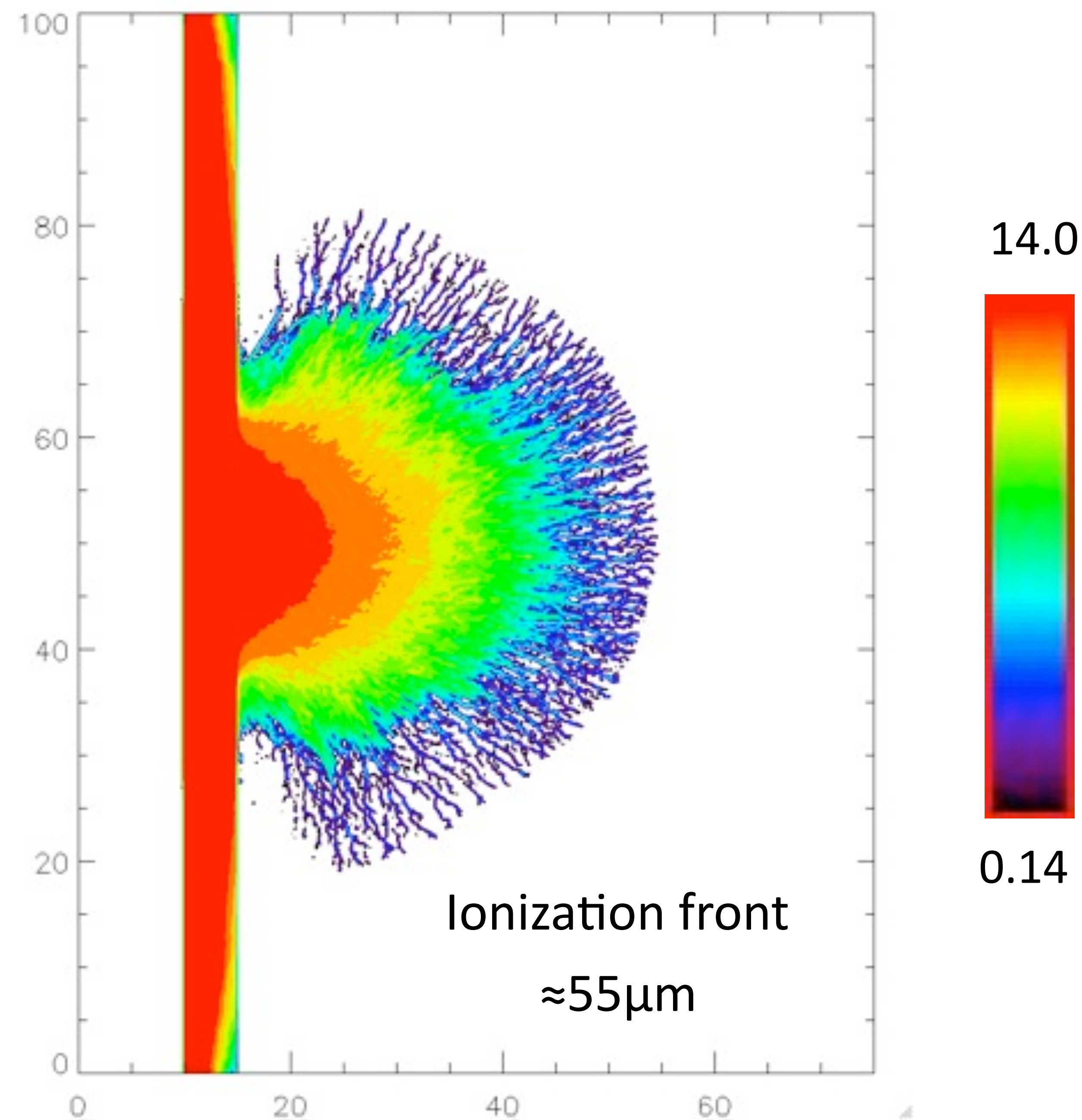
Fast Electron Beam Preceding Ionization Front

Sheath Field |E|



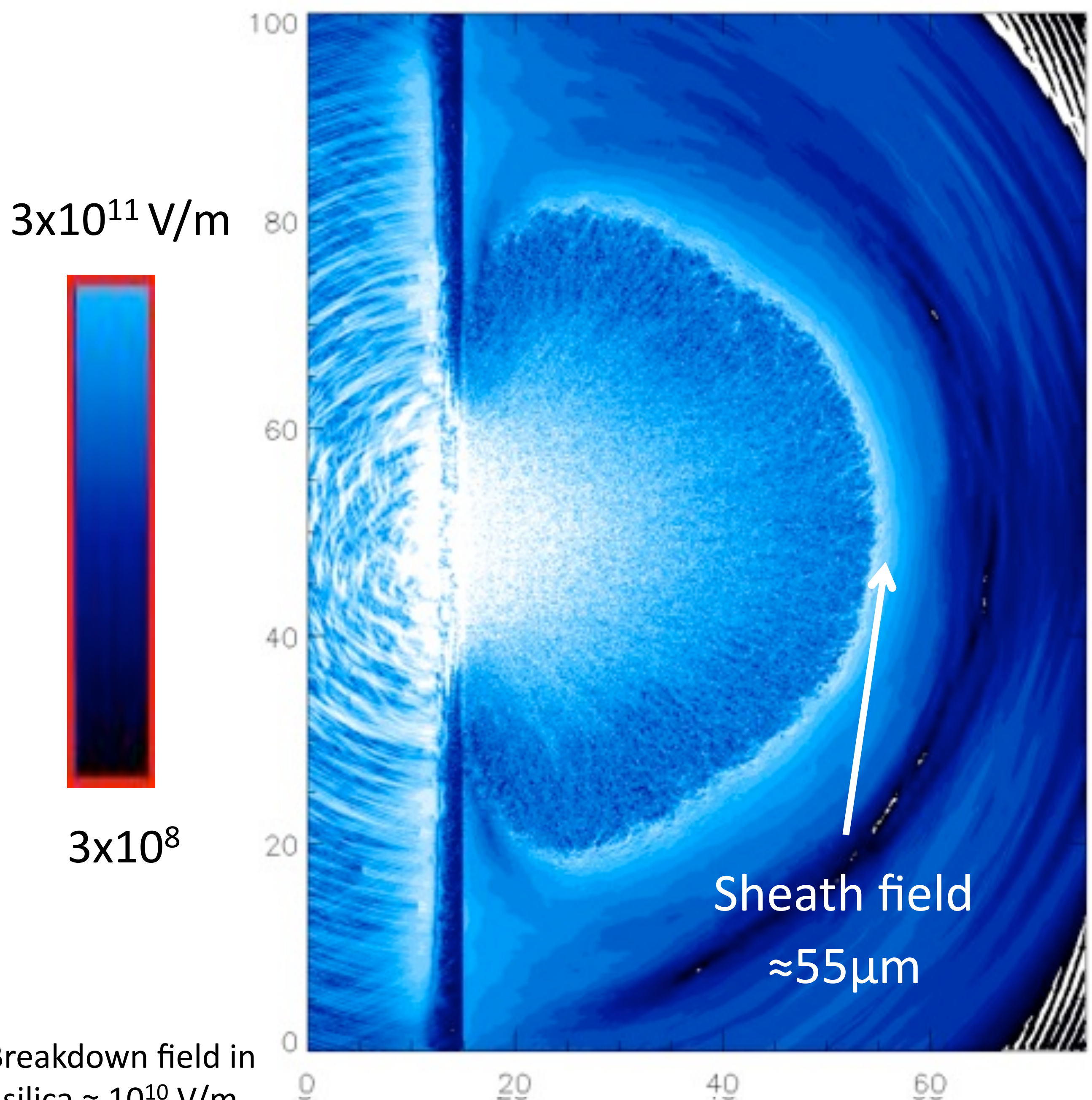
Breakdown field in silica ≈ 10^{10} V/m

Ionization of Silicon

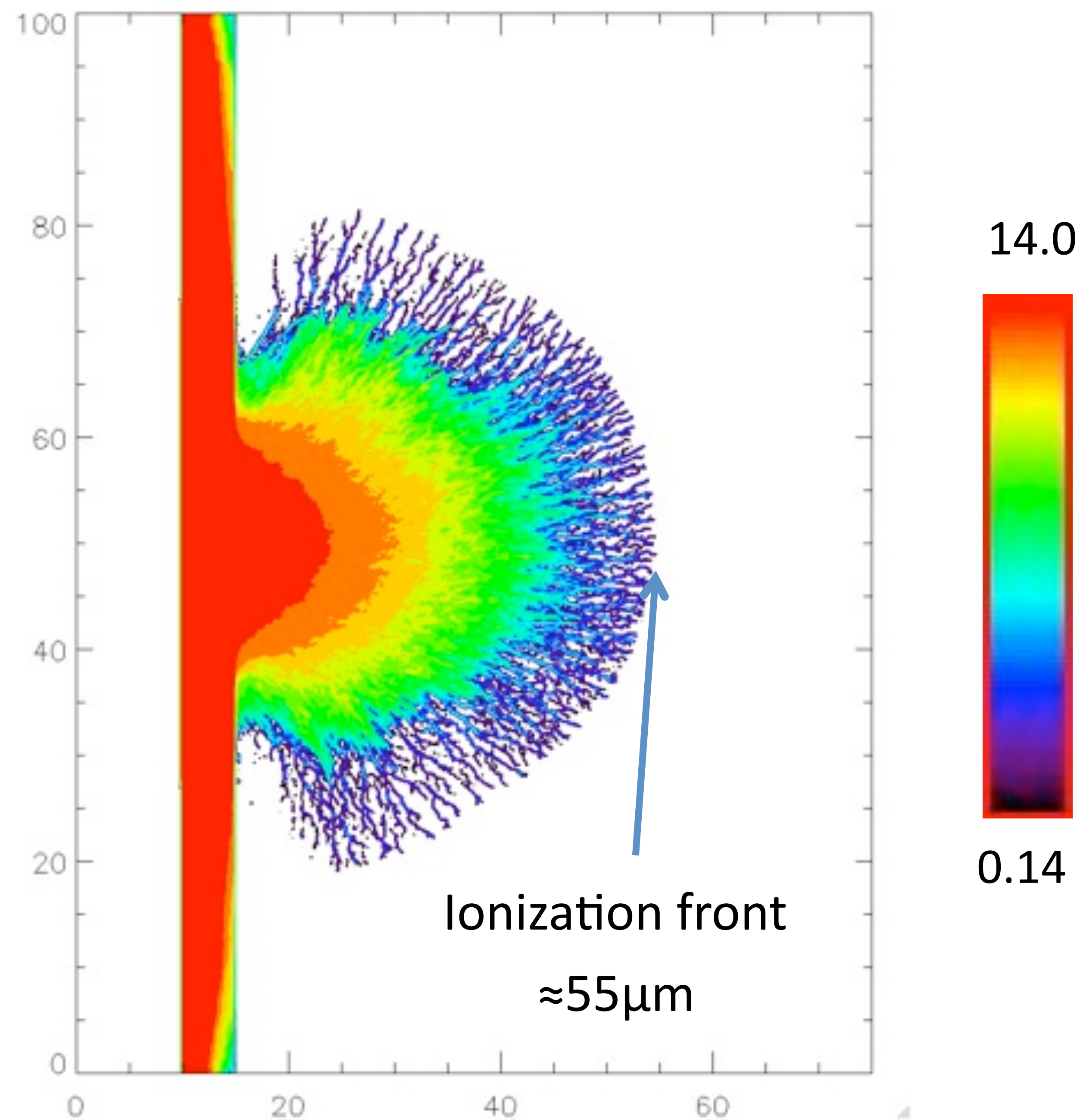


Fast Electron Beam Preceding Ionization Front

Sheath Field |E|

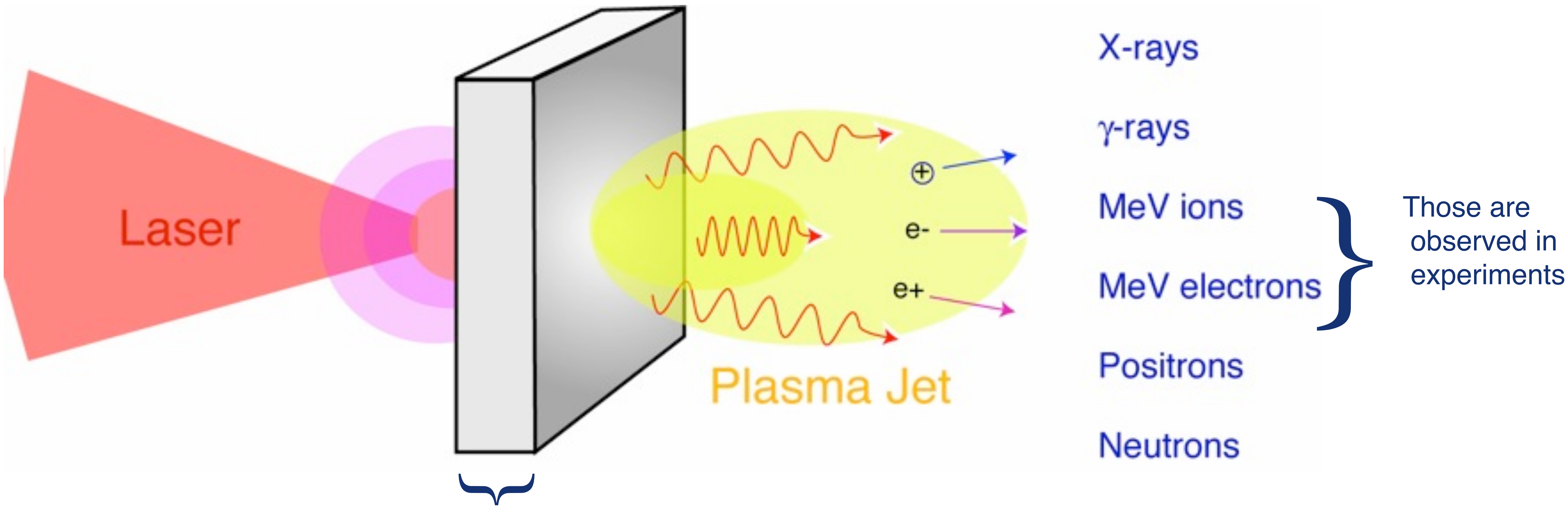


Ionization of Silicon



Breakdown field in silica ≈ 10^{10} V/m

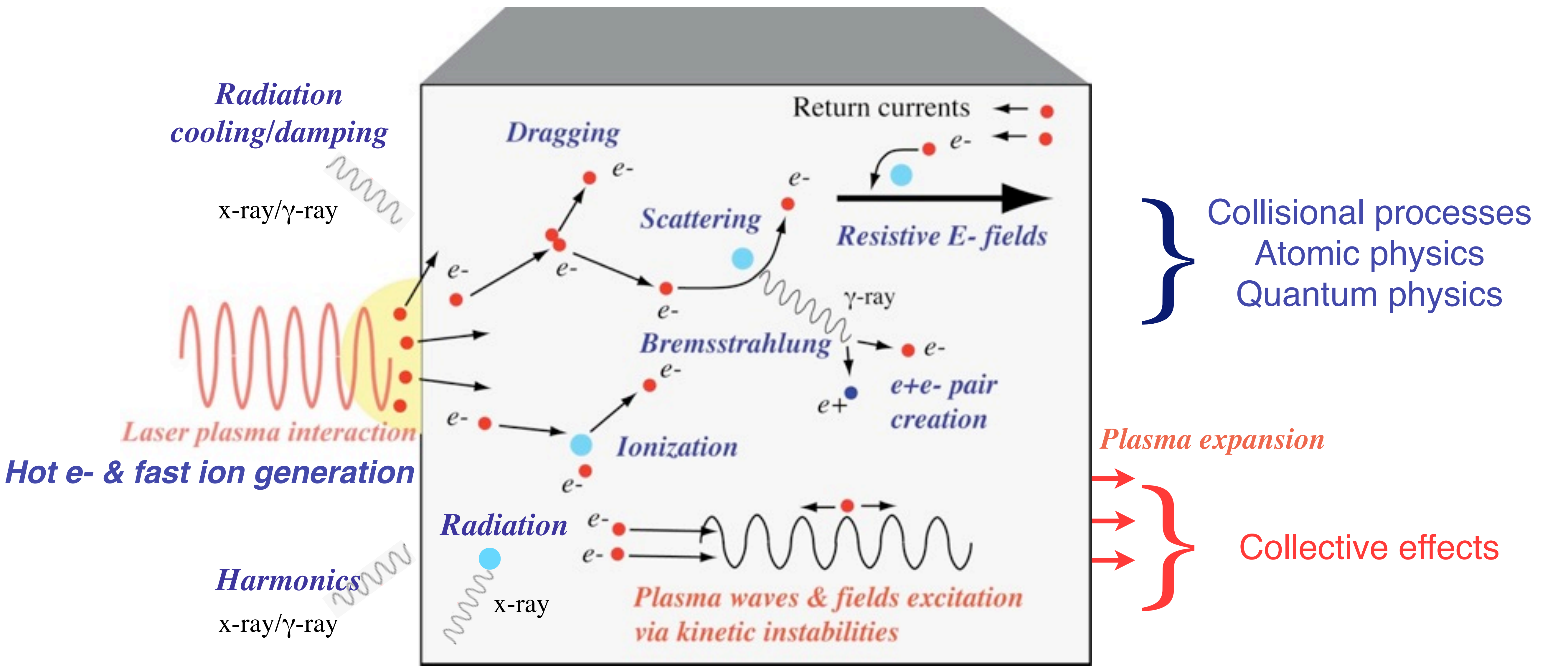
What physics is necessary in simulation to study HEDP in ultra-intense LPI?



Everything happens in less than a picosecond (10^{-12}s).
(Information is very limited in experiments...)

Summary: Physics in ultra-fast heated solid target

Plasma discharge
Kinetic instabilities and wave excitations
Collisional energy transport and target heating

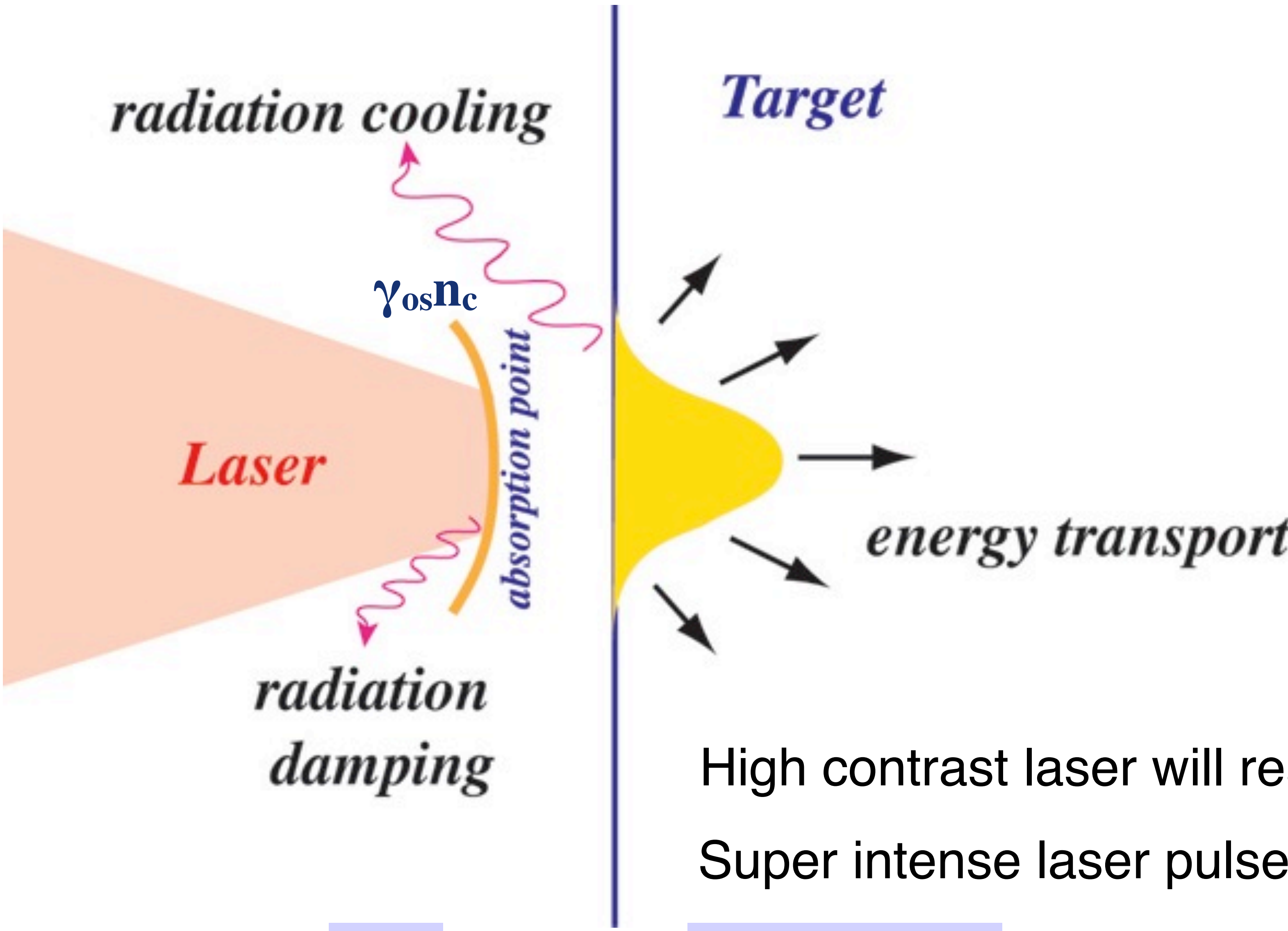


The physics in the laser isochoric heating is complicate. The collective effects and the collisional effects are competing inside the target.

We need a kinetic simulation code with the atomic physics models.

What model will be capable of simulating ultra-intense laser produced HEP plasmas?

Laser intensity will be > 10^{22} W/cm^2. **$\gamma_{os} = [1+(1+\eta)a^2/2]^{1/2} > 100$**



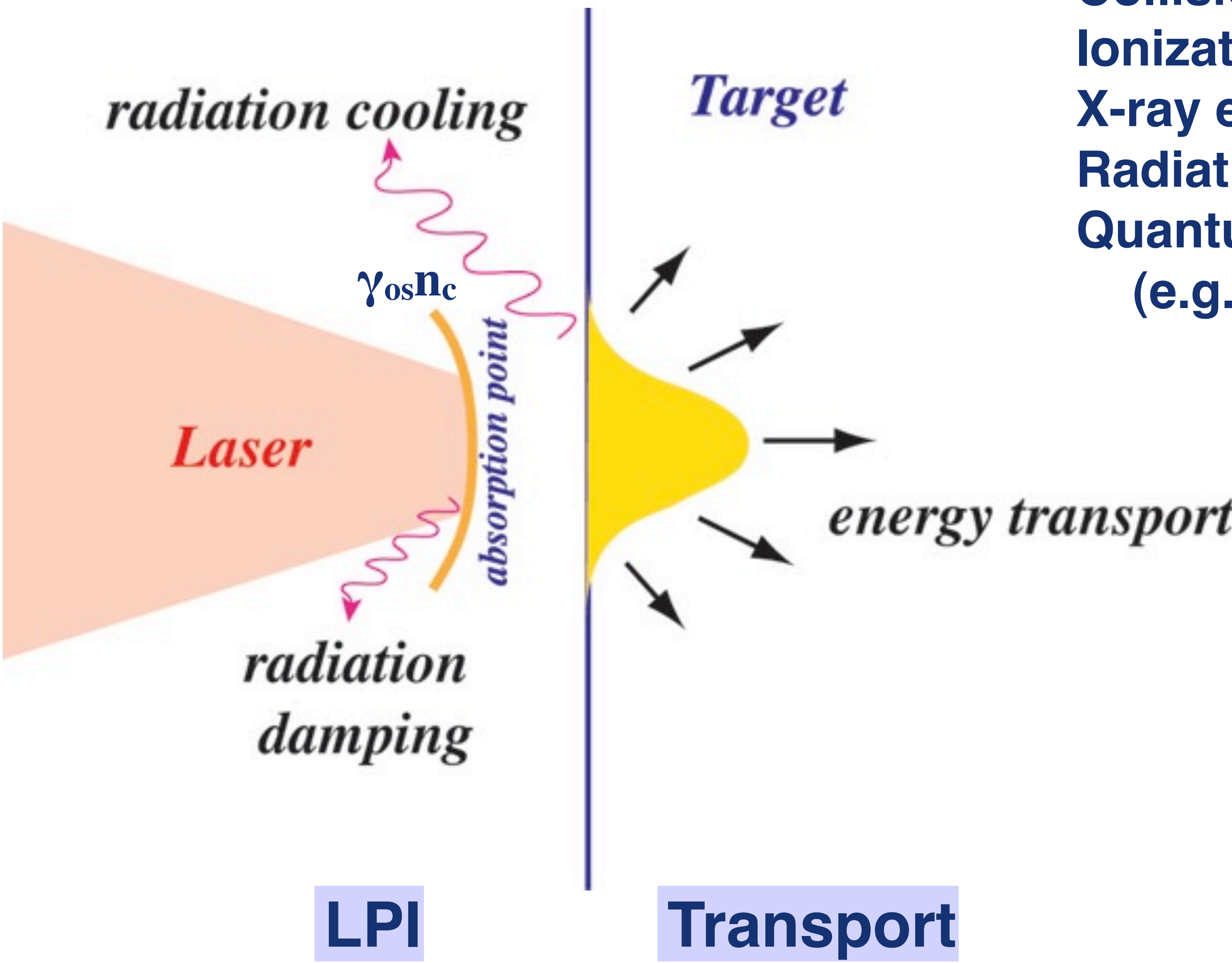
High contrast laser will realize the direct interaction.

Super intense laser pulse will directly interact on the target.

LPI **Transport**

LPI - target region will not be able to be separated. We need to solve both regions self-consistently.

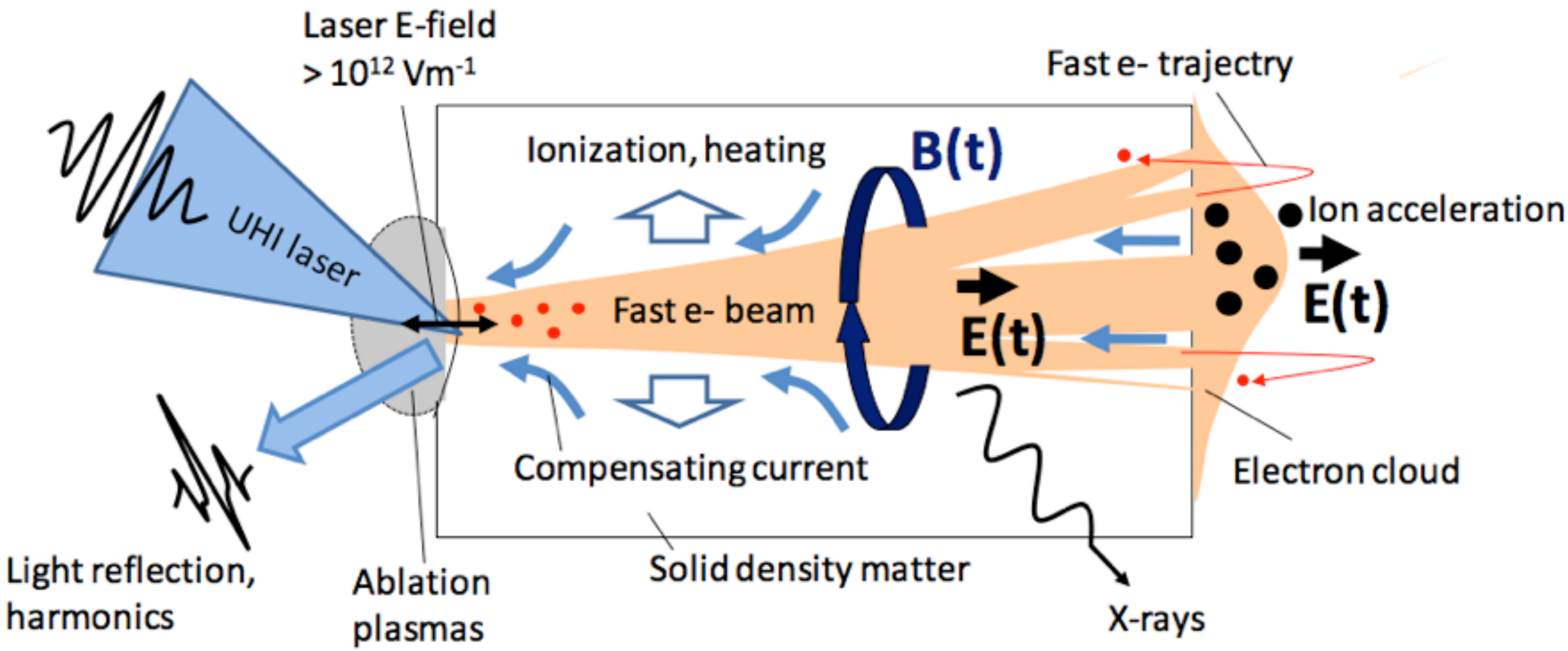
Transport region: atomic physics



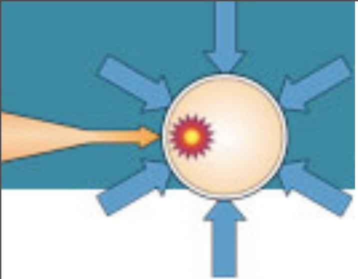
Collision (Coulomb, Elastic)
Ionization (Field, Collisional)
X-ray emission (Free, Bounded)
Radiation transport
Quantum physics
(e.g. pair creation)

Energy transport depends on resistive magnetic fields inside solid

Illustration by M. Nakatsutsumi, LULI



Resistive magnetic fields depend on how resistivity evolves during the interaction.
Correct resistivity and dynamic ionization are crucial in the modeling.
Resistive magnetic field ~ 10 - 100 MG.



Challenges in computational modeling of HEDLP by LPI

- Model requires to resolve extremely large density scales plasmas. (e.g. $10^{19} \sim 10^{26}$ cm^{-3} for Fast Ignition)
- Model requires the Coulomb collision to simulate the energy transport and heating in HEDLP. (i.e. resistive effects, scattering)
- Model requires the dynamics ionization processes since the plasma electron density and the resistivity depend on the charge state inside the target. (e.g. ultra-fast heated thin metal target by LPI)
- Model should have a strict energy conservation to avoid the numerical heating/numerical ionization in HEDLP.

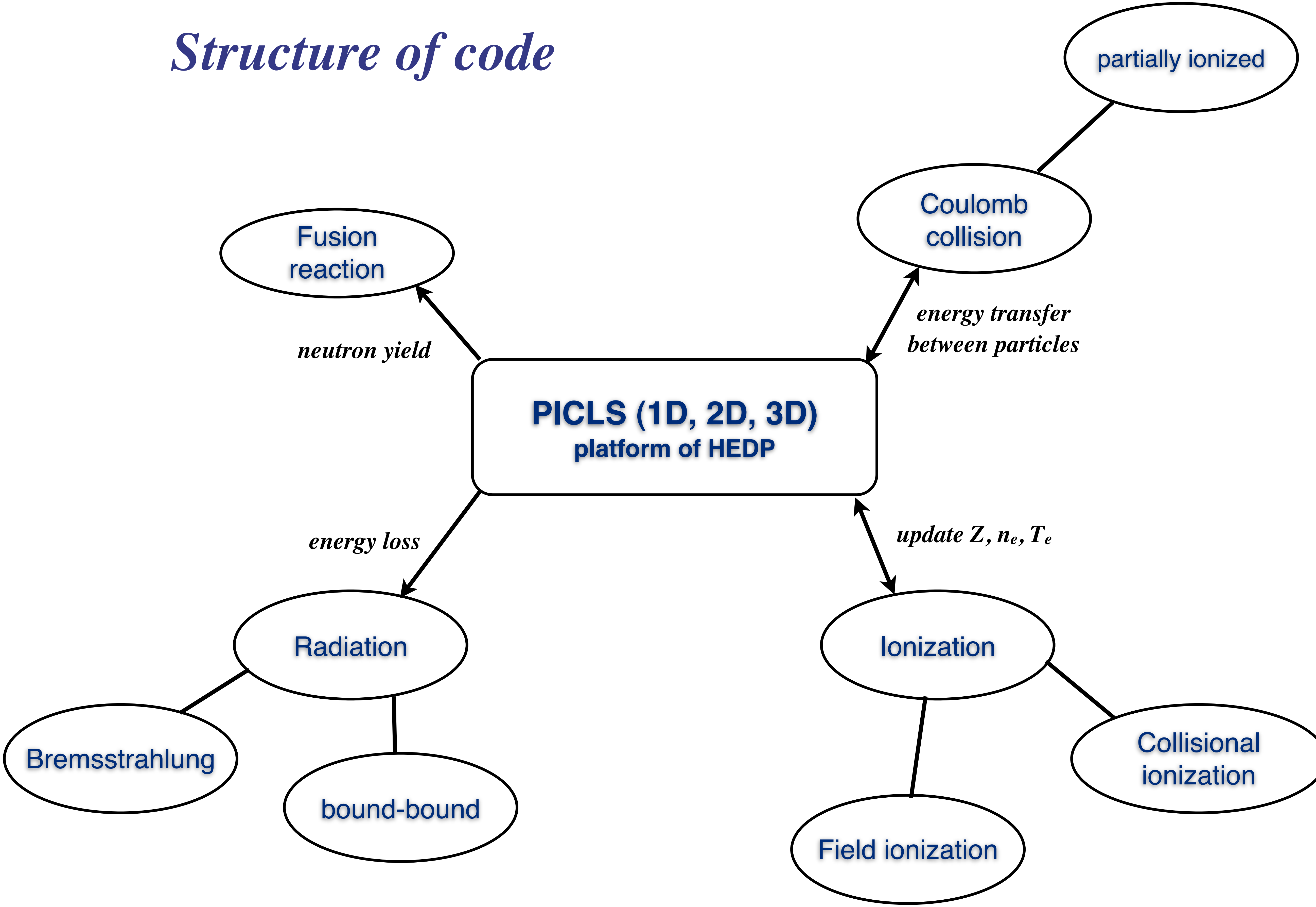
PICLS is a particle-in-cell simulation code, which is designed to solve the above issues, featuring the binary collisions among charged particles and the ionization processes.

PICLS

Y. Sentoku, and A. J. Kemp, "Numerical methods for particle simulations at extreme densities and temperatures", J. Comput. Phys. 227, 6846 (2008)

PICLS development had been supported by FSC (DE-FC02-04ER54789), DOE/OFES (DE-FG02-05ER54837), NTF/UNR (DOE/NSAA, DE-FC52-06NA27616).

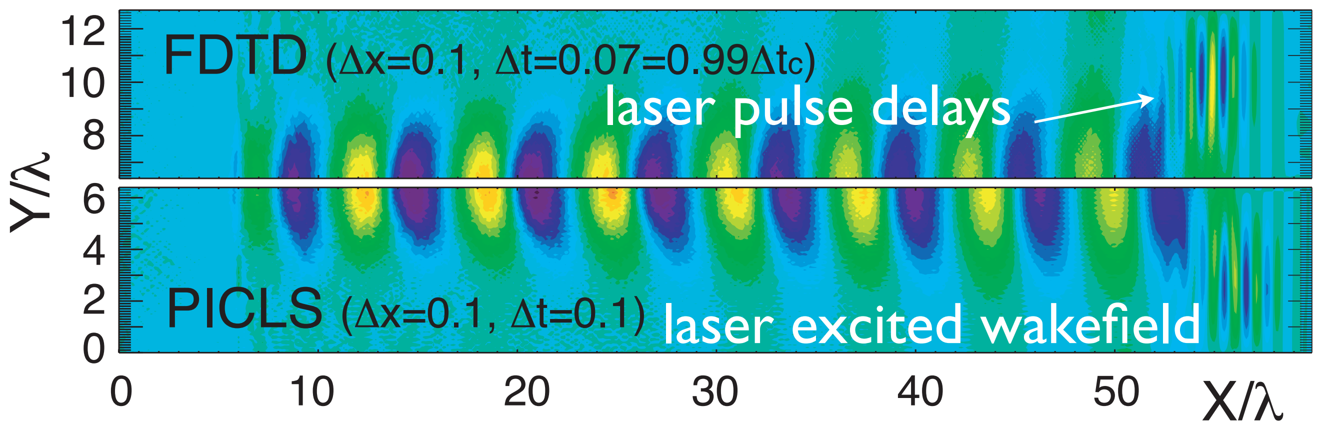
Structure of code



PICLS:

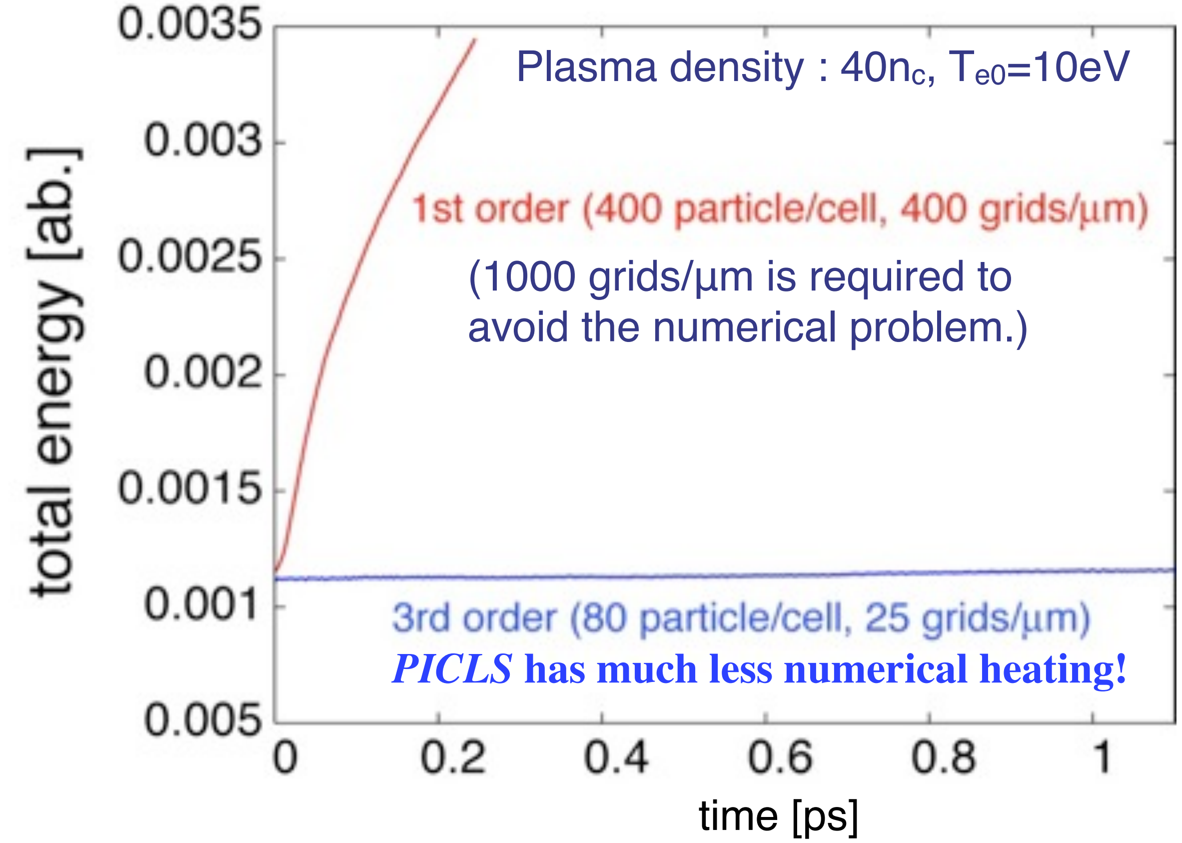
1, 2, & 3D laser plasma simulation code

I. Numerical dispersion free Maxwell solver

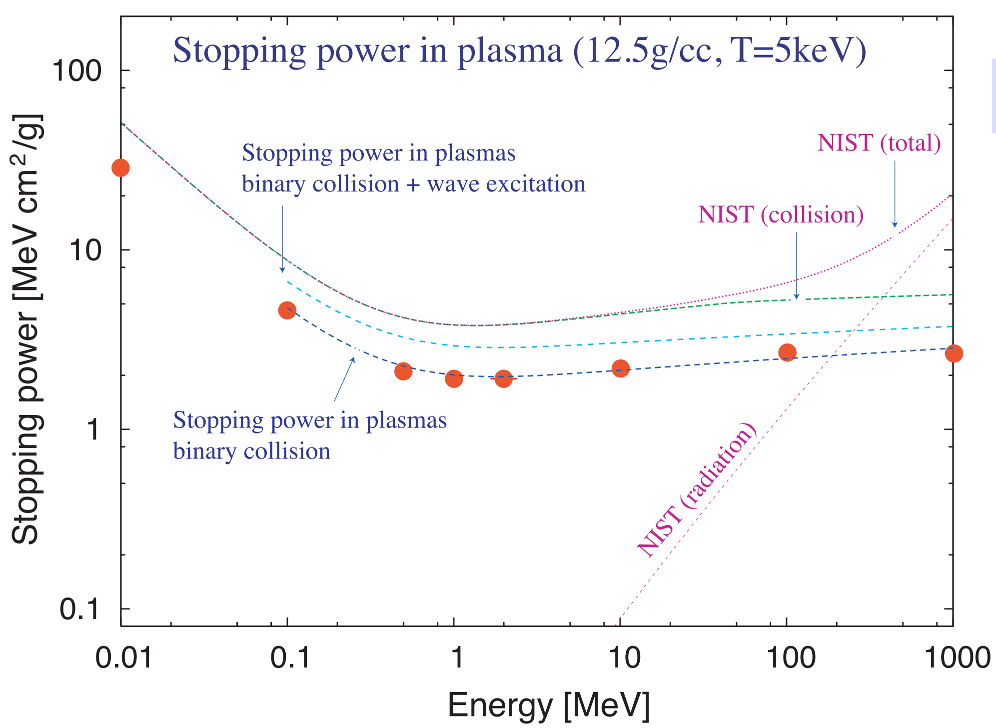


Waves delay due to the numerical diffusion in the standard scheme (FDTD). PICLS can simulate wave propagation correctly with less number of meshes (5 mesh is enough).

II. High order interpolation scheme



Adopting the high order interpolation, PICLS has much less numerical heating with even 40 times larger mesh of Debye length. Drastically reducing PIC cost.



III. Full relativistic collision model for weighted particles

- Based on Takizuka & Abe binary collision model (1977).
- Extended our early work of weakly relativistic model (Sentoku, 1998) to the full relativistic regime.
- Extended the model for weighted particle simulations.
- Verified with the theoretical prediction (stopping power, energy exchange).

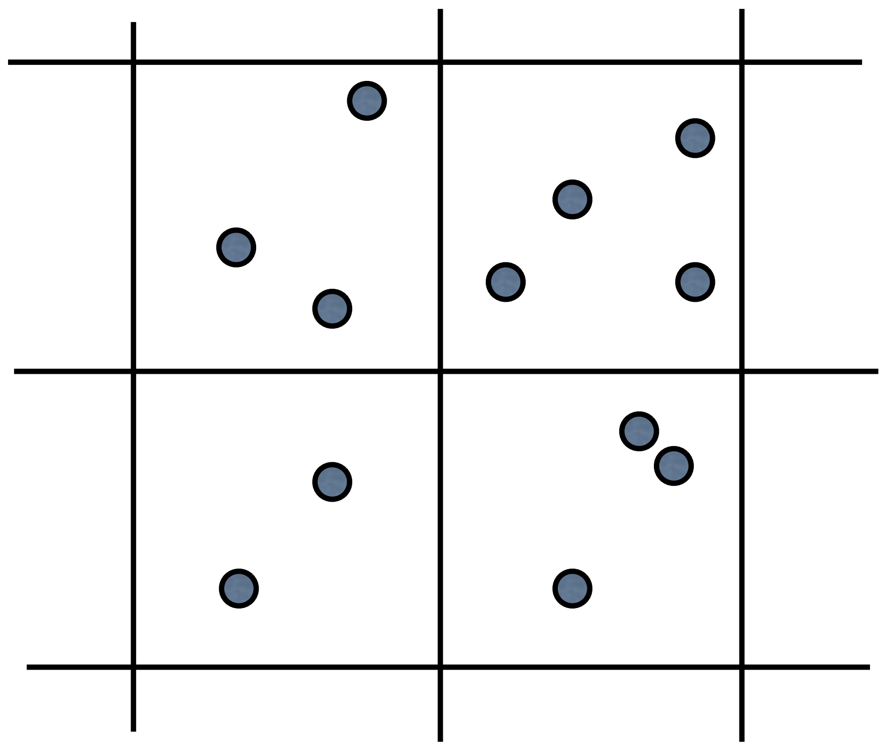
Basic equations of PIC simulation

- non-thermal & non-equilibrium plasma -

- Maxwell's equations (PDE: solved on grids)

$$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \frac{4\pi}{c}\mathbf{J}$$

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$



- Equation of particles (ODE)

$$\frac{d\mathbf{P}_i}{dt} = q_i\left(\mathbf{E}_i + \frac{\mathbf{P}_i}{m_i c \gamma_i} \times \mathbf{B}_i\right)$$

$$\frac{d\mathbf{x}_i}{dt} = \frac{\mathbf{P}_i}{m_i \gamma_i}$$

γ_i: Lorentz factor

Particle-in-Cell (PIC) simulation with Atomic processes (Monte Carlo models)

Particle Pushing

$$\frac{d\mathbf{P}_i}{dt} = q_i(\mathbf{E}_i + \frac{\mathbf{P}_i}{m_i c \gamma_i} \times \mathbf{B}_i)$$

$$\frac{d\mathbf{x}_i}{dt} = \frac{\mathbf{P}_i}{m_i \gamma_i}$$

Relativistic Coulomb collision

Ionization

Bremsstralung

Interpolation of fields to Particles

$(\mathbf{E},\mathbf{B})_j \rightarrow (\mathbf{E},\mathbf{B})_i$

Δt

Interpolation of particles to charge and current on a Grid

$(\mathbf{x}, \mathbf{v})_i \rightarrow (\varrho, \mathbf{J})_j$

Solve Maxwell equation on grids

$$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \frac{4\pi}{c}\mathbf{J}$$

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

interpolation order (nD.)

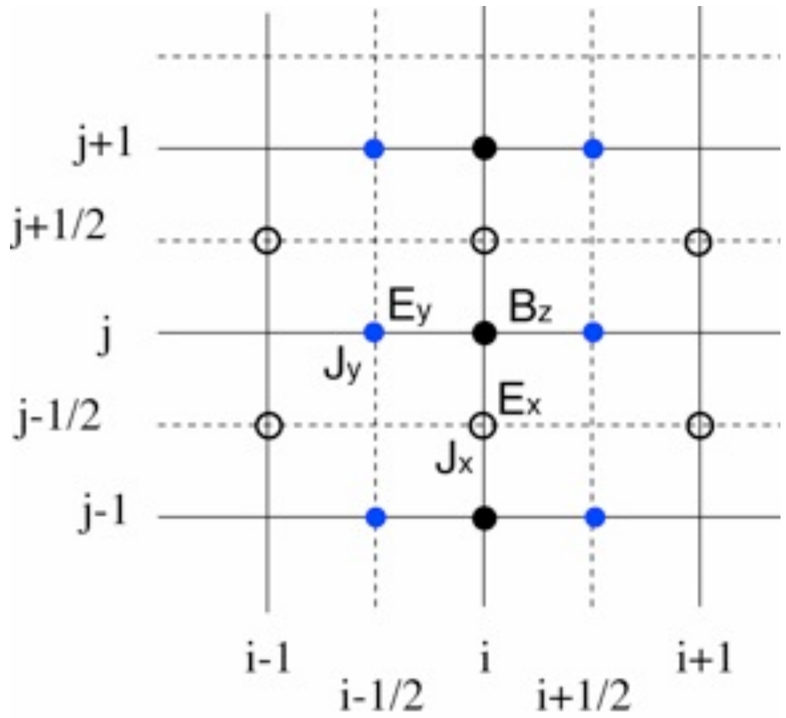
- 0th (1 grid)^n
- **1st (2 grids)^n**
- 2nd (3 grids)^n
- 3rd (4 grids)^n
- 4th (5 grids)^n

Finite Differential Time Domain method (FDTD)

Maxwell equations

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{J}$$



Definition of fields on grid

Finite differential equations

$$\frac{\mathbf{E}^{n+1} - \mathbf{E}^{n}}{\Delta t} = c\nabla \times \mathbf{B}^{n+1/2} - 4\pi \mathbf{J}^{n+1/2}$$

$$\frac{\mathbf{B}^{n+1/2} - \mathbf{B}^{n-1/2}}{\Delta t} = -c\nabla \times \mathbf{E}^{n}$$

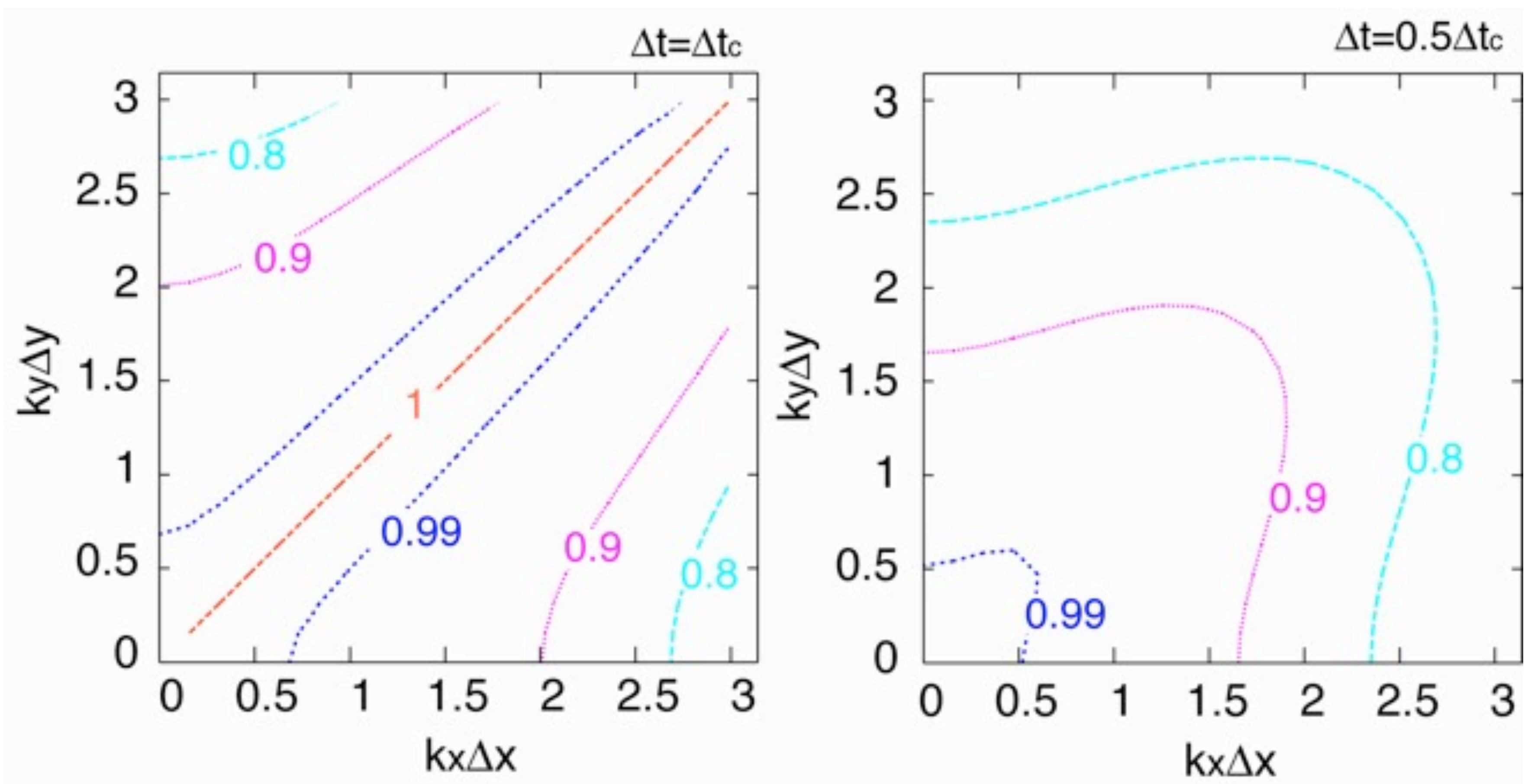
Both the space and time centered differences.

FDTD: Numerical dispersion

by inserting a plane wave $\boldsymbol{E}(\boldsymbol{x},t) = \boldsymbol{E_0} \exp[i(\mathbf{k}\bullet\boldsymbol{x} - \omega t)]$

$$\left(\frac{\sin \omega\Delta t/2}{c\Delta t}\right)^2 = \left(\frac{\sin k_x\Delta x/2}{\Delta x}\right)^2 + \left(\frac{\sin k_y\Delta y/2}{\Delta y}\right)^2$$

Obviously ω is real (stable) when $c\Delta t < c\Delta t_c \equiv \sqrt{\frac{\Delta x\Delta y}{\Delta x^2 + \Delta y^2}}$

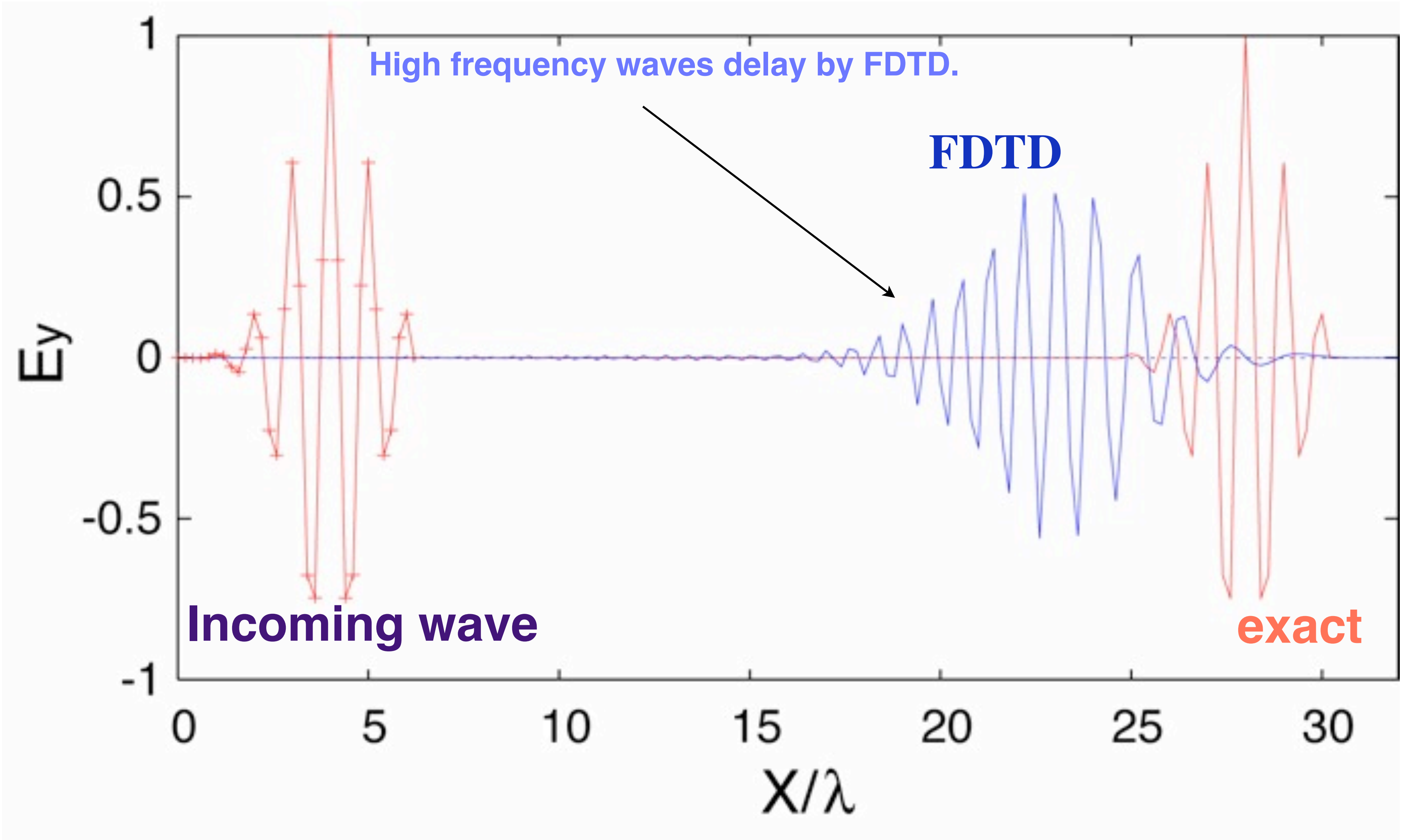


e.g.
$k_x\Delta x=0.5$
$\lambda/\Delta x\sim12$

Map of phase velocity by FDTD

FDTD: Wave propagation

$\lambda/\Delta x=5,\ \Delta t=0.7\Delta t_c$



Waves delay due to the numerical dispersion, since then a fine resolution (small grid&time-step) is necessary to simulate the laser propagation in a long (cm scale) distance.

Directional splitting (DS) method in PICLS

Maxwell equations

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{J}$$

P-pol component

$$\frac{\partial}{\partial t}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -c \\ 0 & -c & 0 \end{pmatrix}\frac{\partial}{\partial x}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & c \\ 0 & 0 & 0 \\ c & 0 & 0 \end{pmatrix}\frac{\partial}{\partial y}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} = -\begin{pmatrix} J_x \\ J_y \\ 0 \end{pmatrix}$$

Step1: x-direction

$$E_y^{\pm} = B_z \pm E_y$$

$$\frac{\partial E_y^+}{\partial t} + c\frac{\partial E_y^+}{\partial x} = -\frac{1}{2}J_y$$

$$\frac{\partial E_y^-}{\partial t} - c\frac{\partial E_y^-}{\partial x} = +\frac{1}{2}J_y$$

$$\frac{\partial}{\partial t}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -c \\ 0 & -c & 0 \end{pmatrix}\frac{\partial}{\partial x}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & c \\ 0 & 0 & 0 \\ c & 0 & 0 \end{pmatrix}\frac{\partial}{\partial y}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} = -\begin{pmatrix} J_x \\ J_y \\ 0 \end{pmatrix}$$

no d/dy for (Ey, Bz)

Step2: y-direction

$$E_x^{\pm} = B_z \mp E_x$$

$$\frac{\partial E_x^+}{\partial t} + c\frac{\partial E_x^+}{\partial y} = +\frac{1}{2}J_x$$

$$\frac{\partial E_x^-}{\partial t} - c\frac{\partial E_x^-}{\partial y} = -\frac{1}{2}J_x$$

$$\frac{\partial}{\partial t}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -c \\ 0 & -c & 0 \end{pmatrix}\frac{\partial}{\partial x}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} + \begin{pmatrix} 0 & 0 & c \\ 0 & 0 & 0 \\ c & 0 & 0 \end{pmatrix}\frac{\partial}{\partial y}\begin{pmatrix} E_x \\ E_y \\ B_z \end{pmatrix} = -\begin{pmatrix} J_x \\ J_y \\ 0 \end{pmatrix}$$

no d/dx for (Ex, Bz)

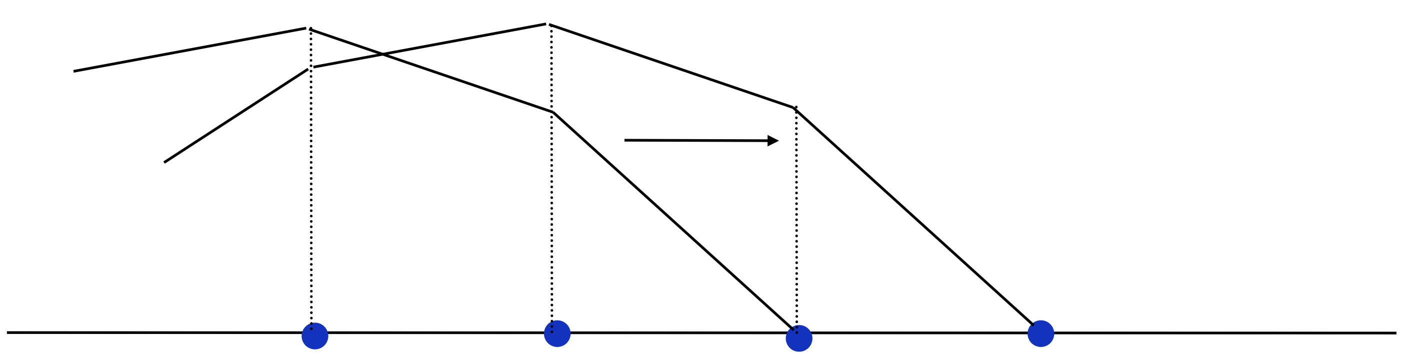
Equation of wave propagation

Equation of wave with constant velocity c (c>0)

$$\frac{\partial f}{\partial t} + c\frac{\partial f}{\partial x} = 0$$

Finite difference equation,

$$f(x_i + \Delta x, t_n + \Delta t) = f(x_i, t_n)$$



When $\Delta x = c\Delta t$, the numerical solution of this equation is very easy, just copy the grid value to the next grid.

DS: Calculate the numerical dispersion

Step1: x-direction

$$E_y^{n+1} = E_{y0}\exp[k_x x_i + k_y y_j - \omega(t_n + \Delta t)]$$

$$= \frac{B_{z0} + E_{y0}}{2}\exp[k_x(x_i - \Delta x) + k_y y_j - \omega(t_n)] - \frac{1}{2}J_{y,i-1/2,j}$$

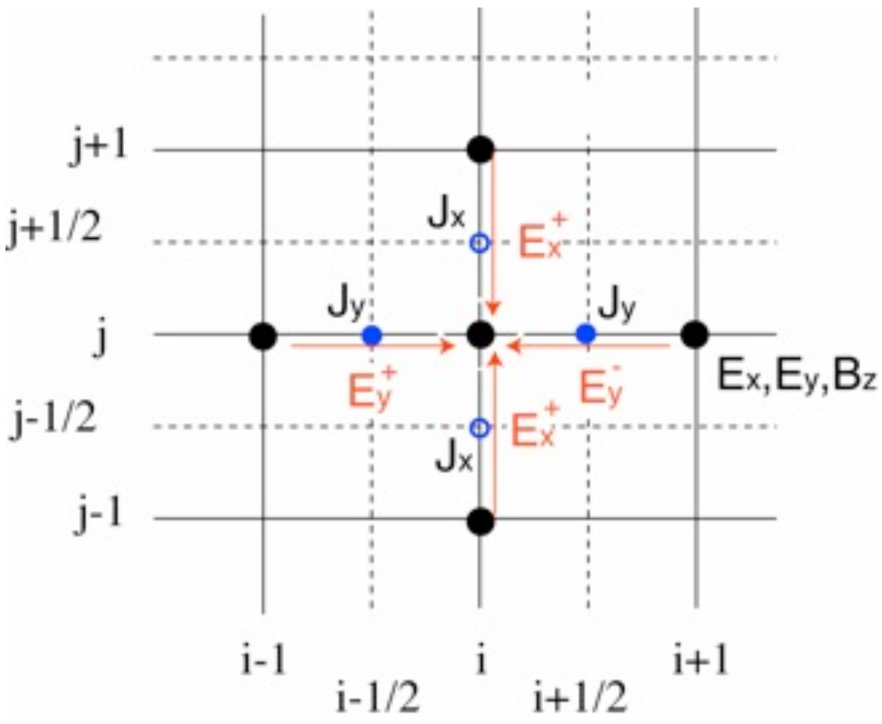
$$-\frac{B_{z0} - E_{y0}}{2}\exp[k_x(x_i + \Delta x) + k_y y_j - \omega(t_n)] - \frac{1}{2}J_{y,i+1/2,j}$$

$$B_z^{n*} = B_{z0}\exp[k_x x_i + k_y y_j - \omega(t_n^*)]$$

t_n*: transient time

$$= \frac{B_{z0} + E_{y0}}{2}\exp[k_x(x_i - \Delta x) + k_y y_j - \omega(t_n)] - \frac{1}{2}J_{y,i-1/2,j}$$

$$+\frac{B_{z0} + E_{y0}}{2}\exp[k_x(x_i + \Delta x) + k_y y_j - \omega(t_n)] + \frac{1}{2}J_{y,i+1/2,j}$$



Step2: y-direction

$$E_x^{n+1} = E_{x0}\exp[k_x x_i + k_y y_j - \omega(t_n + \Delta t)]$$

$$= -\frac{B_{z0}}{2}\exp[k_x x_i + k_y(y_j - \Delta y) - \omega(t_n^*)] + \frac{E_{x0}}{2}\exp[k_x x_i + k_y(y_j - \Delta y) - \omega(t_n)] - \frac{1}{2}J_{x,i,j-1/2}$$

$$+\frac{B_{z0}}{2}\exp[k_x x_i + k_y(y_j + \Delta y) - \omega(t_n^*)] + \frac{E_{x0}}{2}\exp[k_x x_i + k_y(y_j + \Delta y) - \omega(t_n)] - \frac{1}{2}J_{y,i,j+1/2}$$

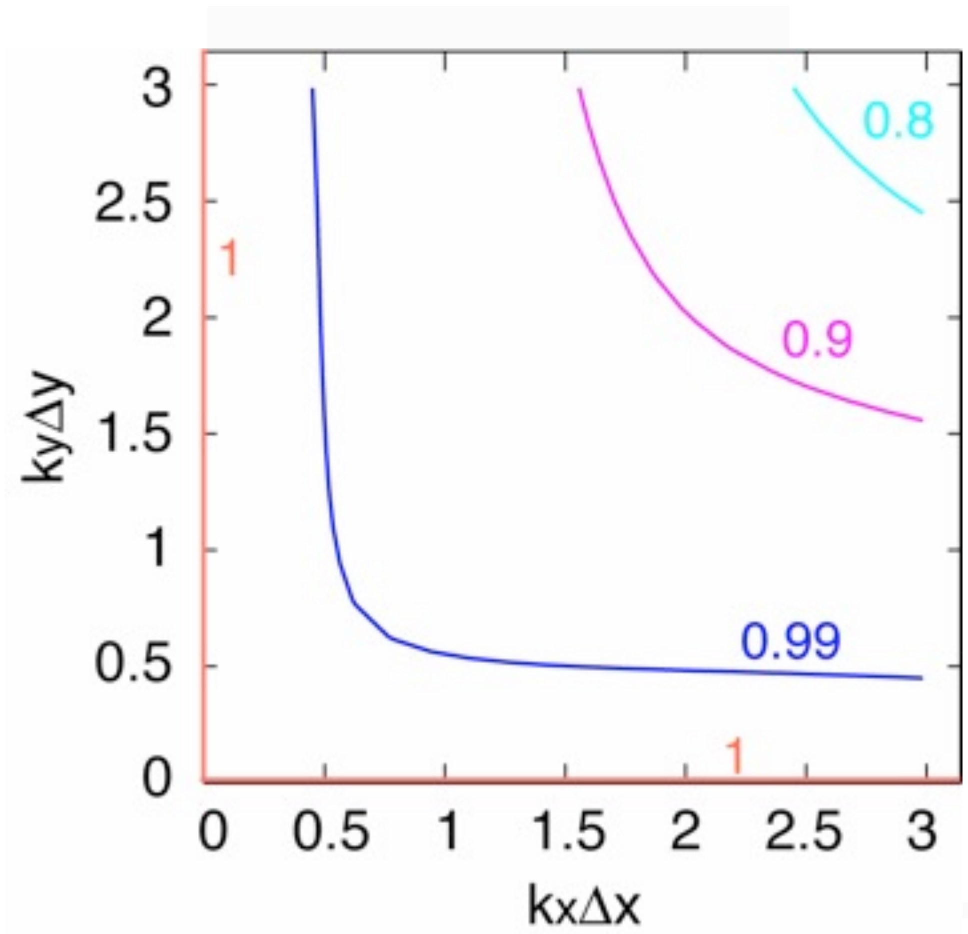
$$B_z^{n+1} = B_{z0}\exp[k_x x_i + k_y y_j - \omega(t_n + \Delta t)]$$

$$= \frac{B_{z0}}{2}\exp[k_x x_i + k_y(y_j - \Delta y) - \omega(t_n^*)] - \frac{E_{x0}}{2}\exp[k_x x_i + k_y(y_j - \Delta y) - \omega(t_n)] + \frac{1}{2}J_{x,i,j-1/2}$$

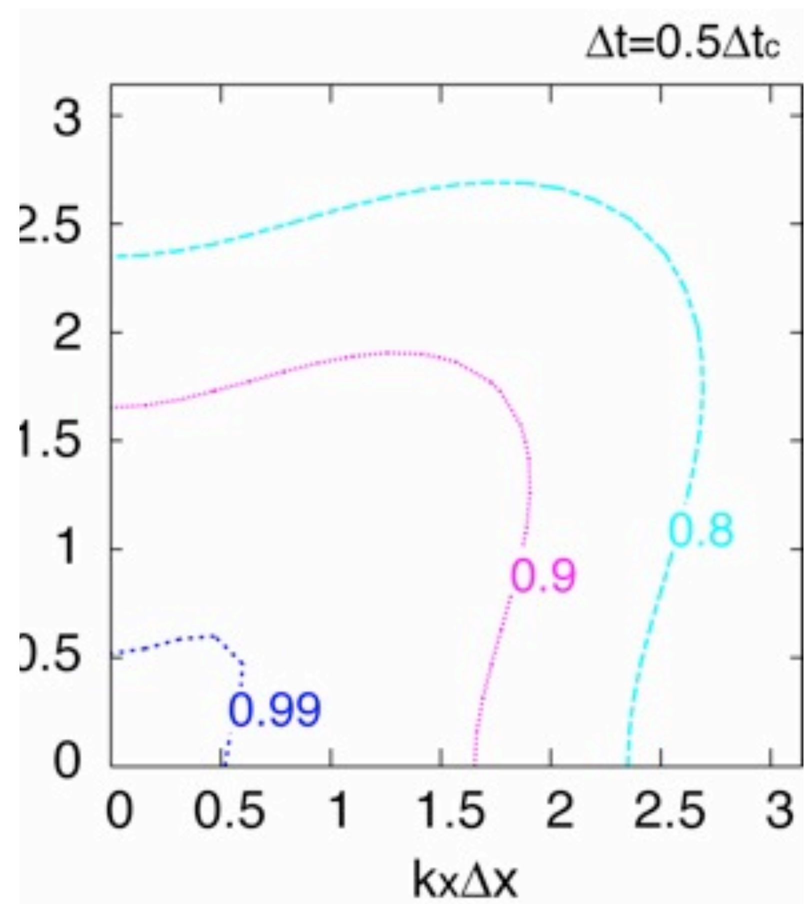
$$+\frac{B_{z0}}{2}\exp[k_x x_i + k_y(y_j + \Delta y) - \omega(t_n^*)] + \frac{E_{x0}}{2}\exp[k_x x_i + k_y(y_j + \Delta y) - \omega(t_n)] - \frac{1}{2}J_{y,i,j+1/2}$$

DS: Numerical dispersion

$$\cos\omega\Delta t = \frac{1}{2}\left(-1 + \cos k_x\Delta x \cos k_y\Delta y + \cos k_x\Delta x + \cos k_y\Delta y\right)$$



Map of phase velocity by DS

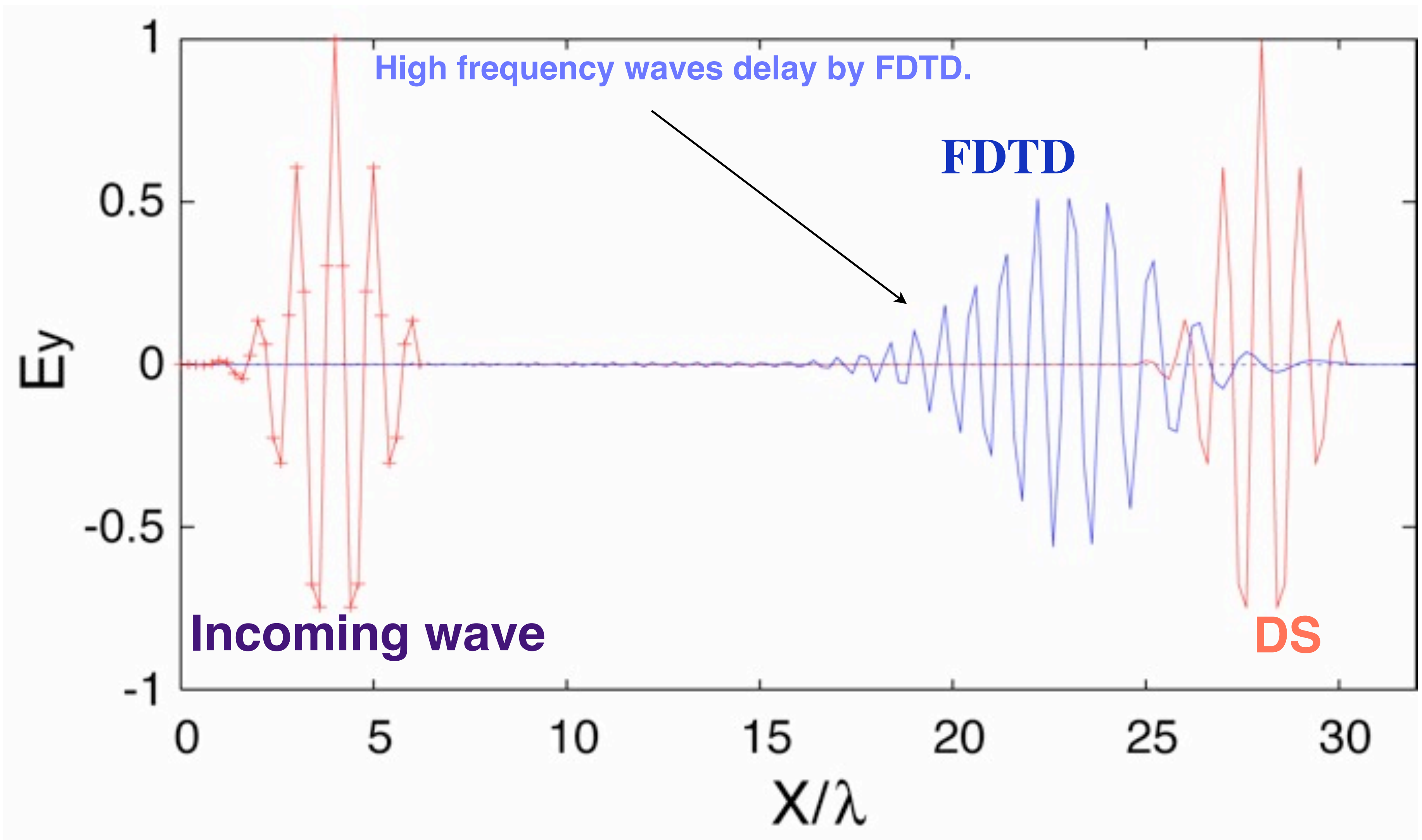


Map of phase velocity by FDTD

NO numerical dispersion along the grids.

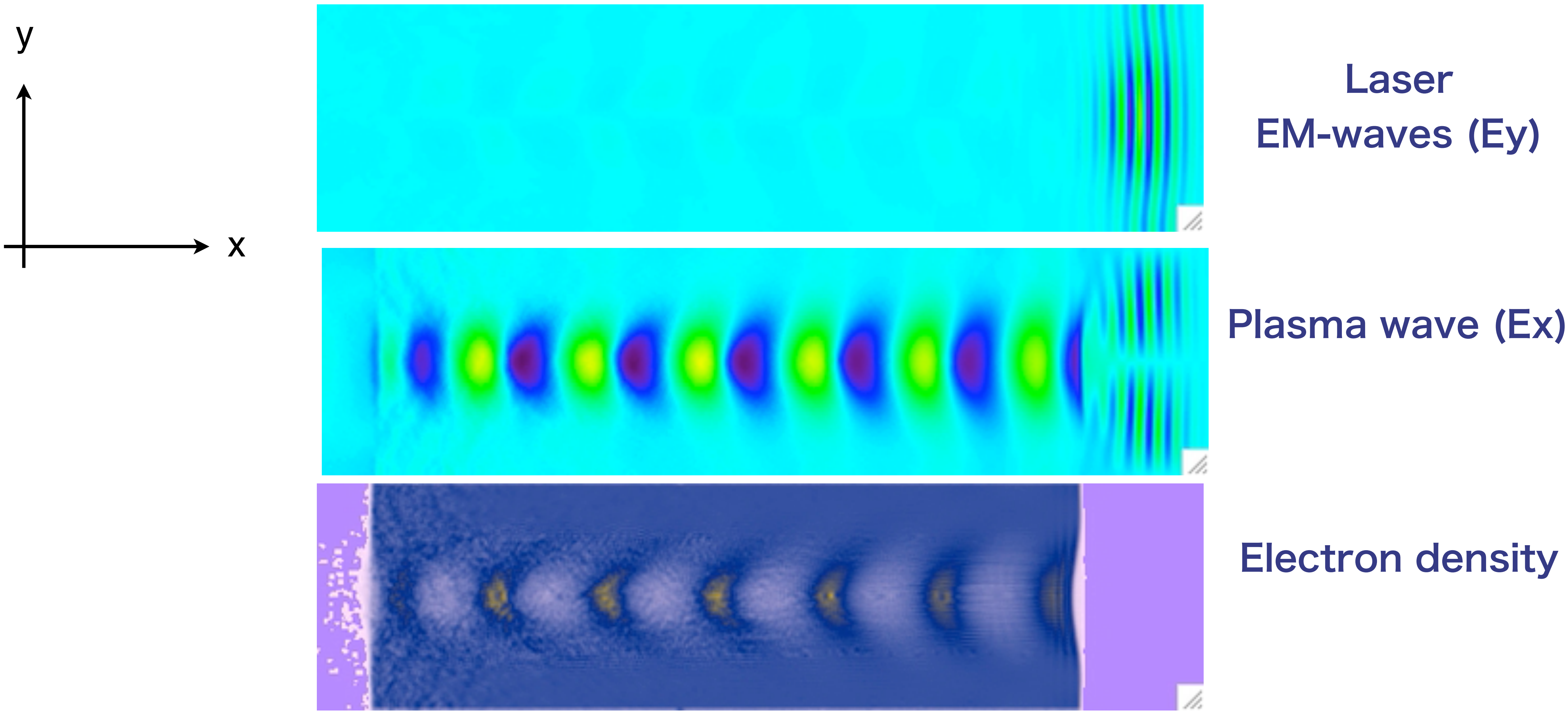
FDTD: Wave propagation

$\lambda/\Delta x=5$, $\Delta t=0.7\Delta t_c$



Waves delay due to the numerical dispersion, since then a fine resolution (small grid&time-step) is necessary to simulate the laser propagation in a long (cm scale) distance.

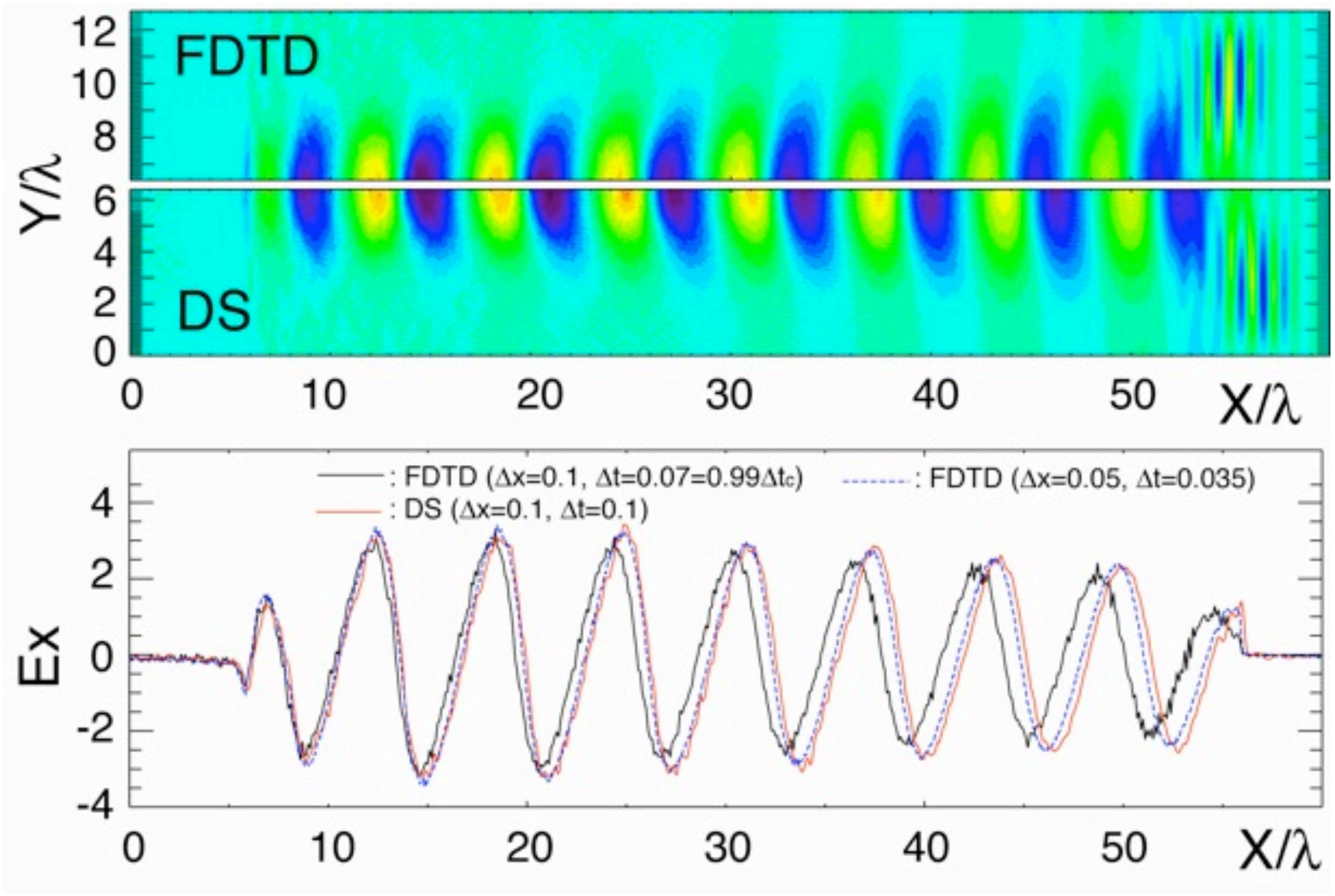
Wakefield simulation by PIC



PIC solves the Maxwell equations and kinetic equations of charged particles.

Test II: Wake fields

Laser: a = 1, pulse length = 5λ



DS:
300x128 mesh

10 mesh is quite enough for one laser wavelength with the DS scheme.
The FDTD needs two times more meshes in one direction.

numerical modeling of hot dense plasma is challenging due to large scale both in time and space

e.g.
- fast ignition in inertial confinement fusion (ICF)
  time scale ~ ps, spatial scale ~ 100 μm

time step ~ $1/\omega_p$ ~ 0.01 fs → simulation time scale ~ ps
mesh size $\propto T_e^{1/2}/\omega_p$ ~ 0.001 μm → simulation scale 100 um

time step will be $>10^5$
number of mesh will be $\sim 10^{5 \times N_D}$
impossible by current computers!!

Can we extend grid size greater than debye length without having numerical heating?

High order interpolation to extend grid size ~ plasma skin length >> Debye length

Extend grid size beyond Debye length
- reduce numerical heating by high order interpolation -

Time evolution of system energy of thermal plasma

demonstration (1d)

- *internal energy evolution* -

Plasma: solid density ($40n_c$),

T_{e0}=10eV (without a laser pulse)

To resolve the above plasma with standard PIC simulation,

1000 grids/μm resolution

is required to suppress

the numerical heating!

Extend grid size beyond Debye length

- reduce numerical heating by high order interpolation -

demonstration (1d)

- *internal energy evolution* -

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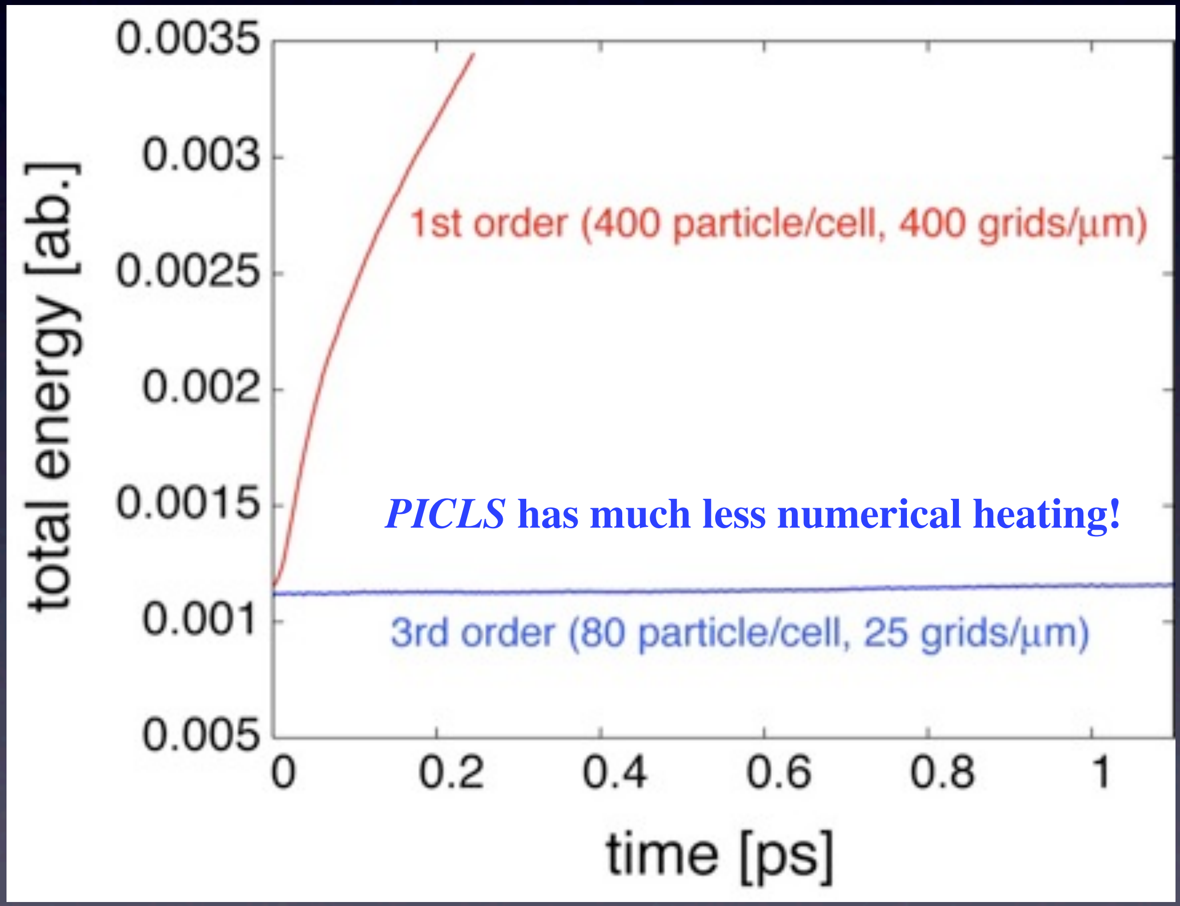
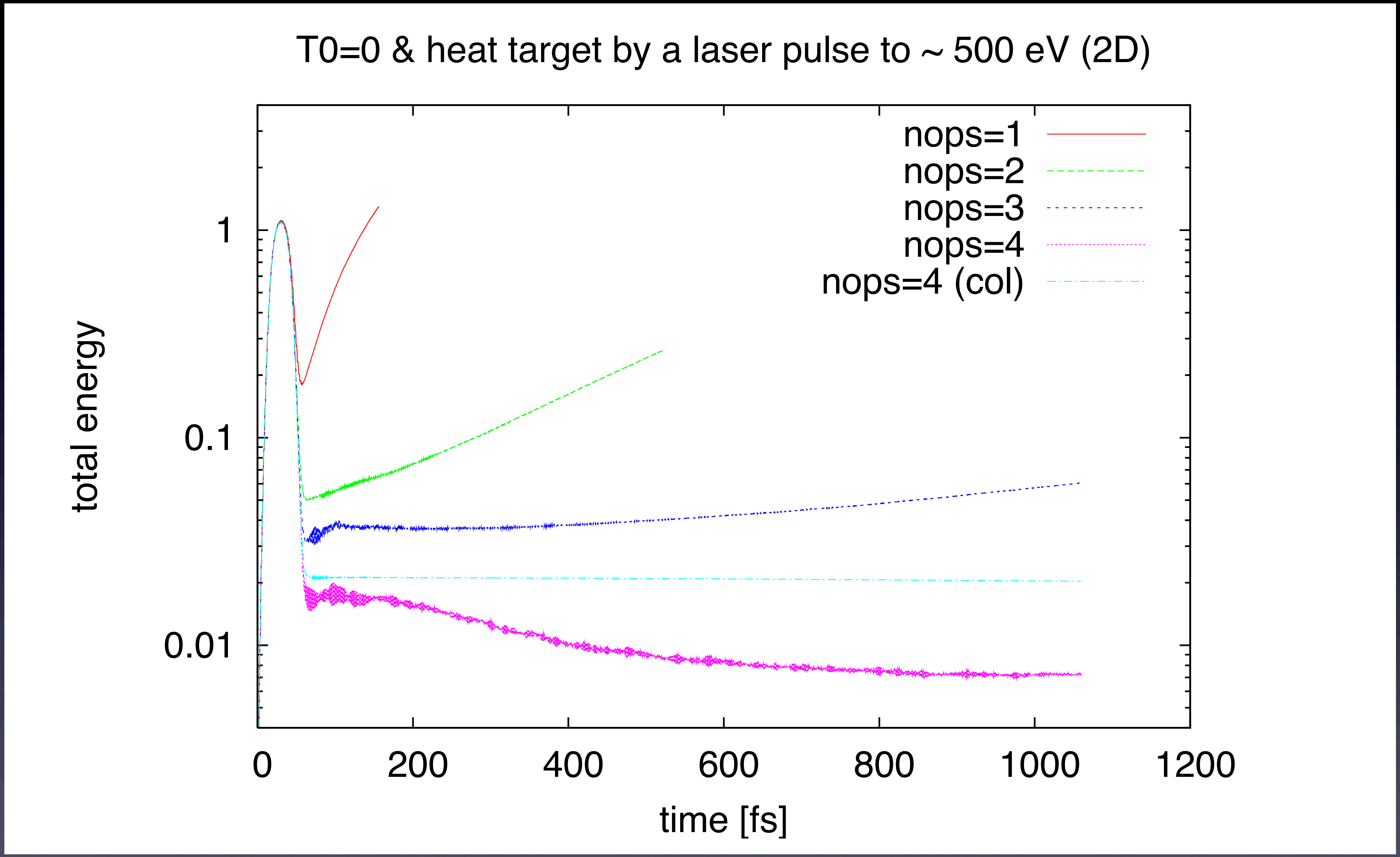


4 order magnitude less computational cost in 2D!!

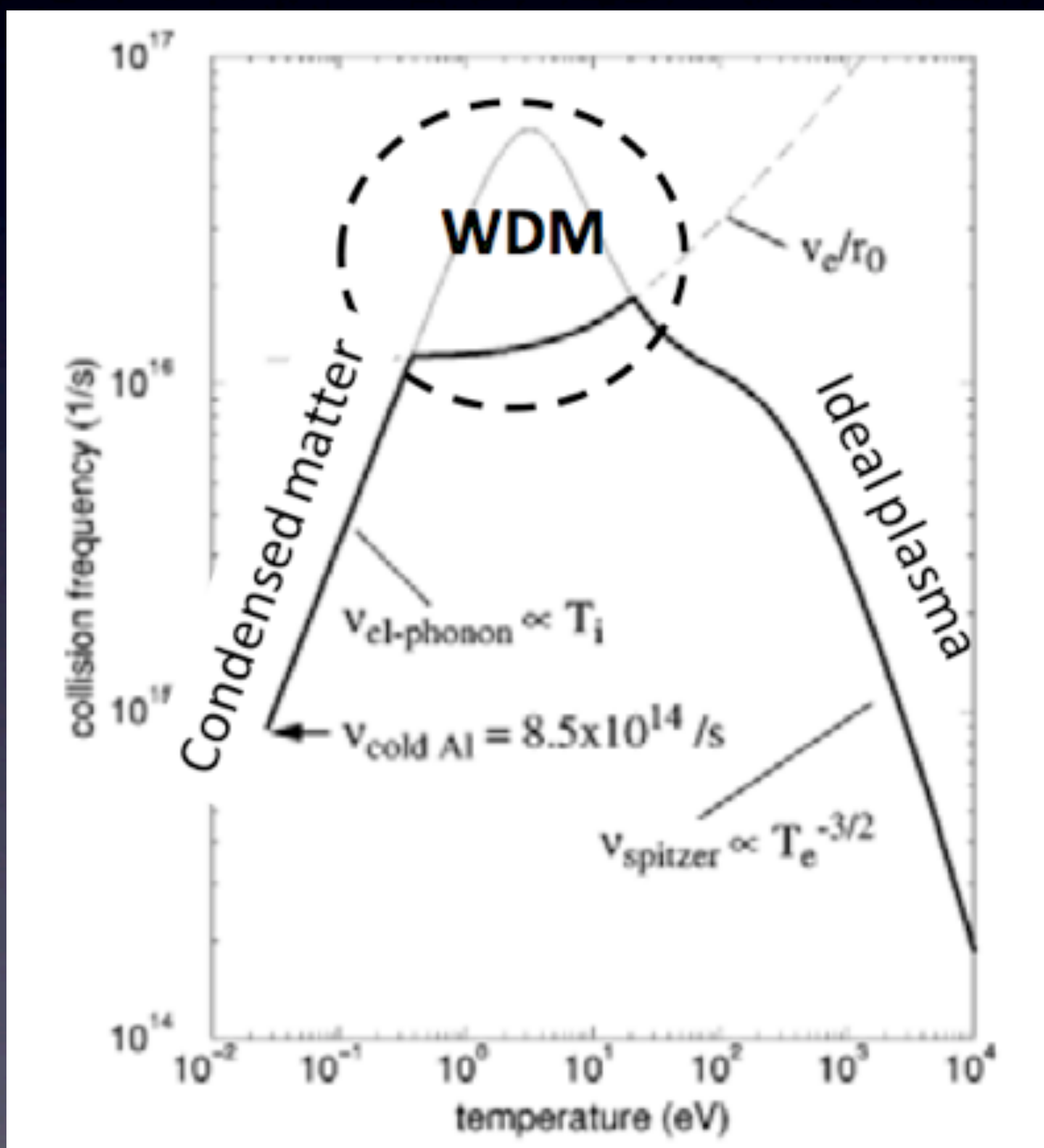
Long time stability with high order interpolation
- demonstration by 2D PIC -



Time evolution of thin plasma after short pulse irradiation

target $40n_c$, thickness 2 um, box:10um x 6um
a=2, 30 fs, np=10, Δx=1um/25

Relativistic collision model for weighted particles



$$\nu_{\alpha\beta} = \frac{4\pi(e_\alpha e_\beta)^2 n_1 L}{p_{\text{rel}}^2 v_{\text{rel}}}$$

Collision frequency in Spitzer regime

$$\frac{T_0}{m_e c^2} = \left(\frac{\sqrt{2}\pi^{3/2}\hbar^3 n_h}{m_e^{3/2}}\right)^{2/3}$$

T_0: transition temperature from Spitzer regime to degenerate regime

$$\nu_{\alpha\beta} = \frac{4 m_e Z e^4 L}{3\pi\hbar^3}$$

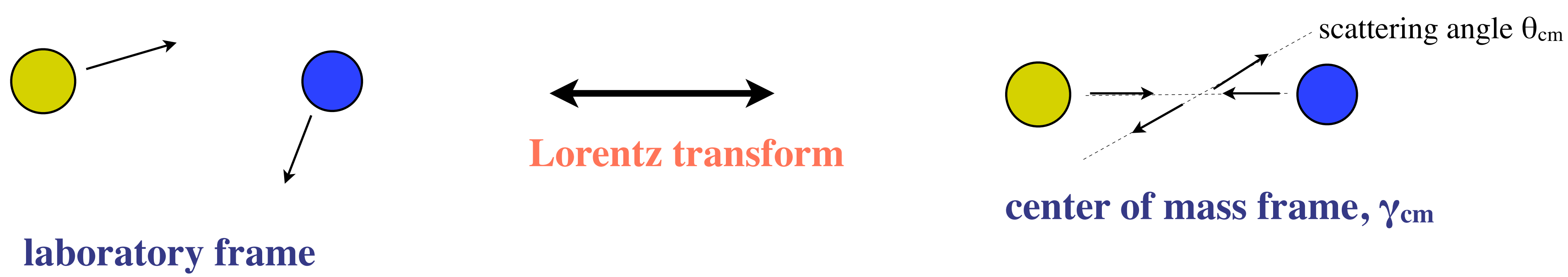
Collision frequency in degenerate regime

Y.T. Lee, R.M. More, Phys. Fluids 27 (1984) 1273.

Y. Sentoku and A. J. Kemp, J. Comp. Phys. **227**, 6846 (2008).

Full relativistic kinematic of energy transfer in collision

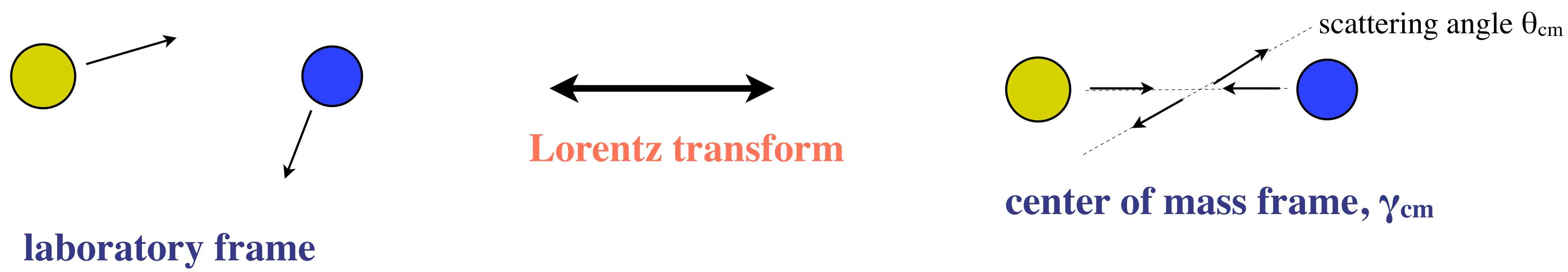
Binary collision model (Takizuka & Abe, J. Comp. Phys., 1977)
Weakly relativistic collision model (Sentoku et al., J. Phys. Soc. Jpn, 1998)



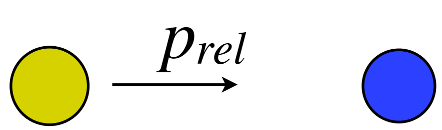
Perfect energy and momentum conservation!

Full relativistic kinematic of energy transfer in collision

Binary collision model (Takizuka & Abe, J. Comp. Phys., 1977)
Weakly relativistic collision model (Sentoku et al., J. Phys. Soc. Jpn, 1998)



evaluate the collision frequency on the one particle at rest frame.



one particle at rest frame

$$\nu_{\alpha\beta} = \frac{4\pi (e_\alpha e_\beta)^2 n_l L}{p_{rel}^2 v_{rel}}$$

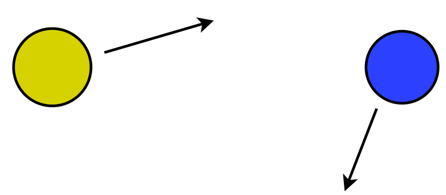
$$L = \ln(\lambda_D p_{rel} / \hbar)$$

$$\langle \tan^2 \theta_L / 2 \rangle = \nu_{\alpha\beta} \Delta t$$

Perfect energy and momentum conservation!

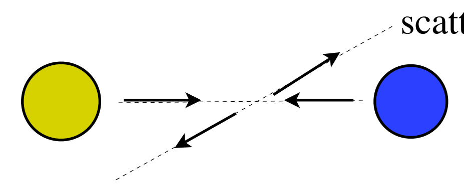
Full relativistic kinematic of energy transfer in collision

Binary collision model (Takizuka & Abe, J. Comp. Phys., 1977)
Weakly relativistic collision model (Sentoku et al., J. Phys. Soc. Jpn, 1998)



laboratory frame

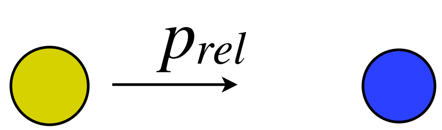
Lorentz transform



center of mass frame, γ_{cm}

$$\tan\theta_{cm} = \frac{\sin\theta_L}{\gamma_{cm}(\cos\theta_L - \beta_{cm}/\beta)}$$

evaluate the collision frequency on the one particle at rest frame.



one particle at rest frame

$$\nu_{\alpha\beta} = \frac{4\pi(e_\alpha e_\beta)^2 n_l L}{p_{rel}^2 v_{rel}}$$

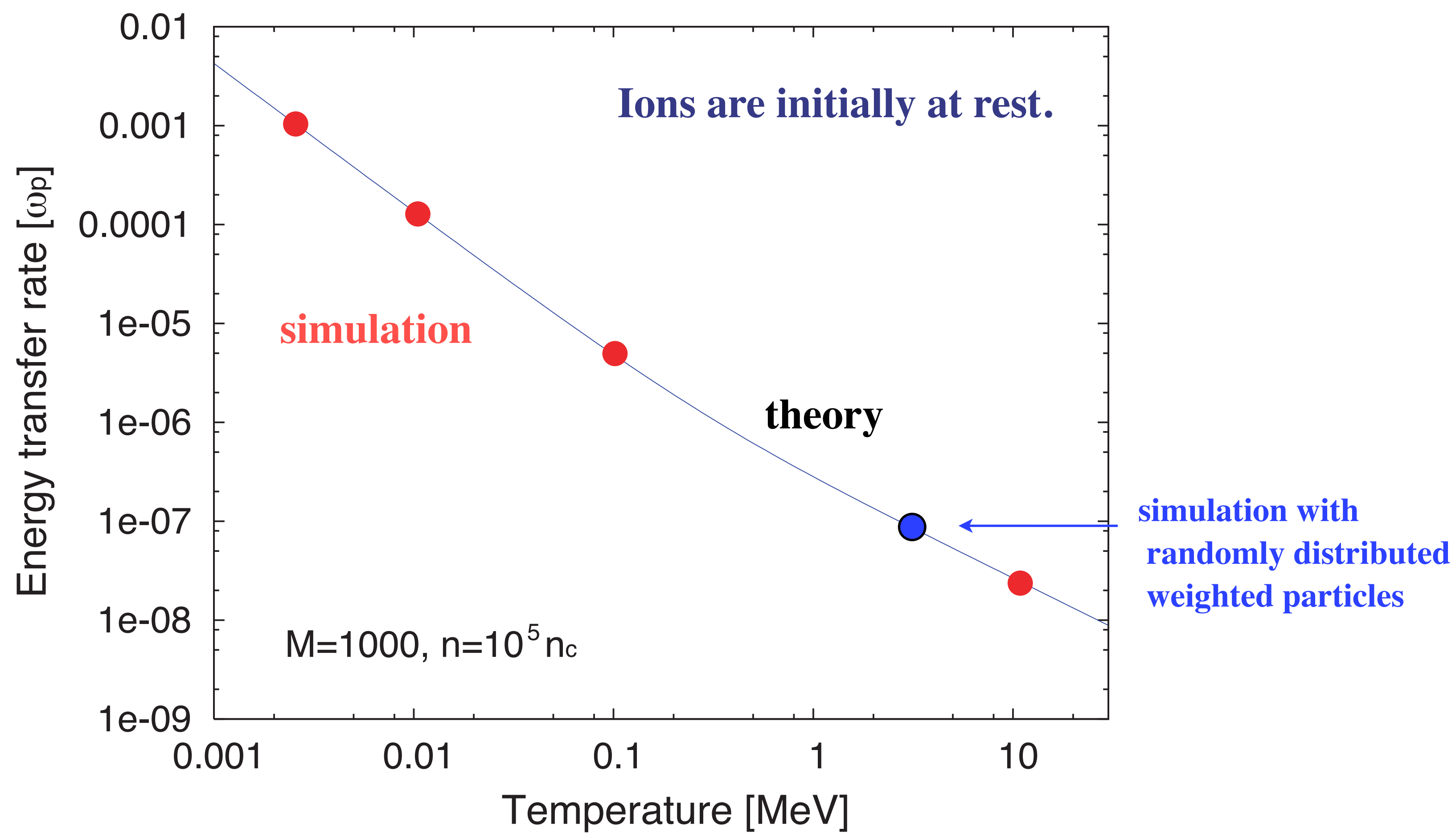
$$L = \ln(\lambda_D p_{rel}/\hbar)$$

$$\langle \tan^2\theta_L/2 \rangle = \nu_{\alpha\beta}\Delta t$$

Lorentz transform

Perfect energy and momentum conservation!

Energy transfer rate from hot electrons to ions
- test simulation of relativistic collision model -

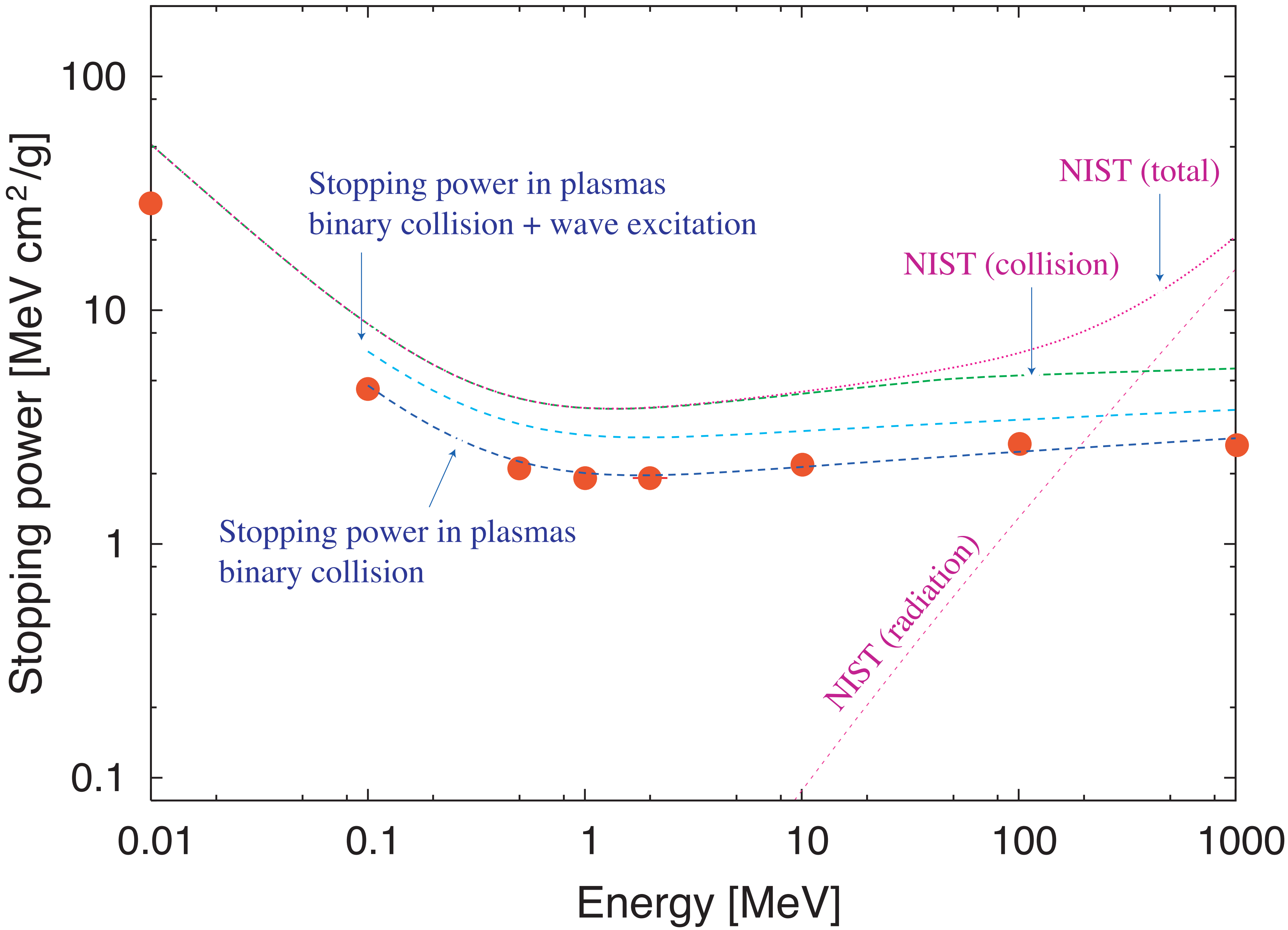


theory
(Lifshitz, 1981)

$$\frac{d(E_i/E_e)}{dt} = \frac{8\pi z^2 e^4 nL}{Mm_e c^3(\gamma - 1)}$$

Electron stopping power in hydrogen plasma
- test simulation of e-e collision -

UNIVERSITY OF NEVADA RENO
Nevada Terawatt Facility

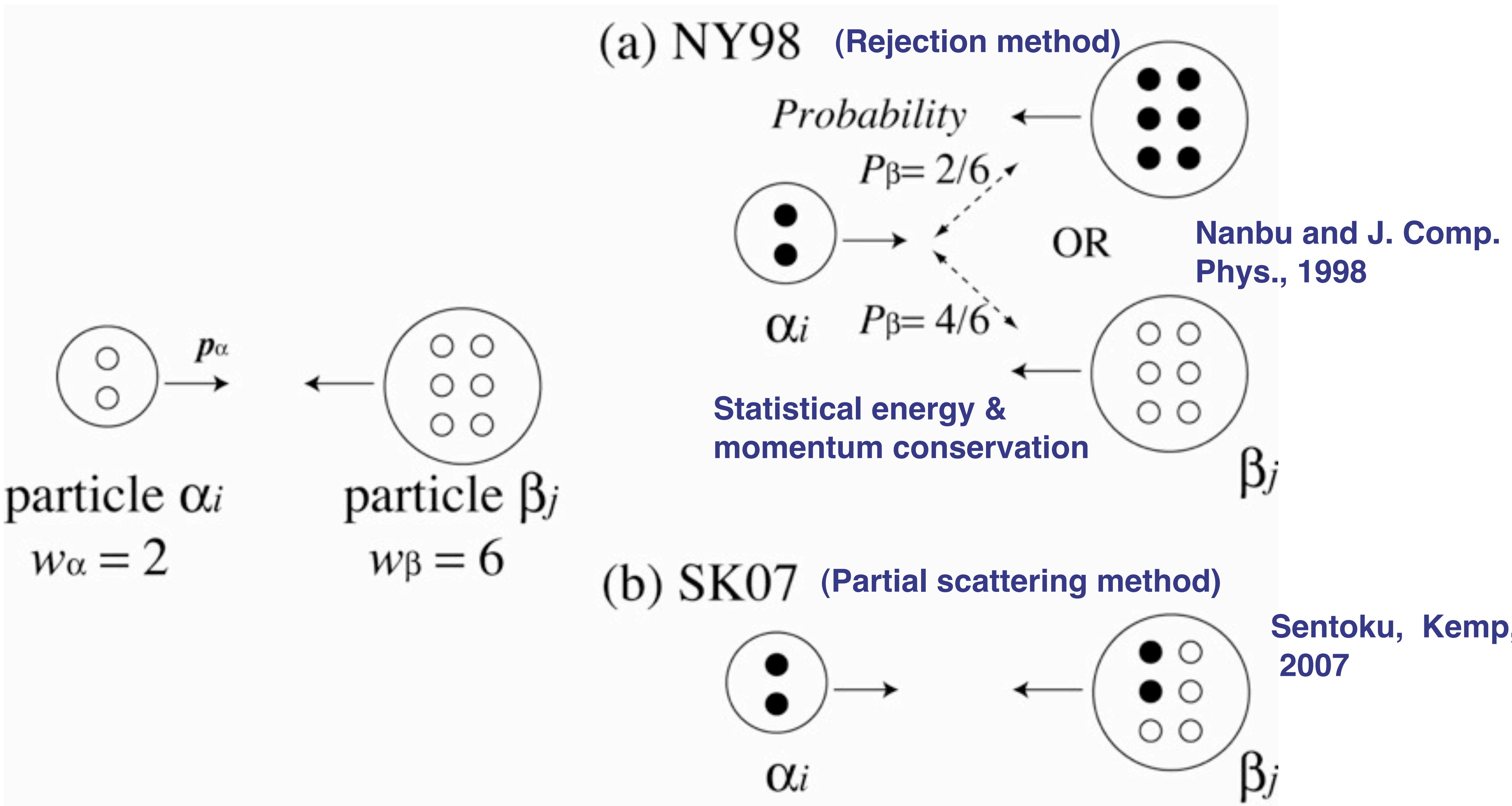


Plasma
12.5g/cc
T=5keV

NIST database: electron stopping power in hydrogen gas

Collision model of weighted particles in PICLS

- Rejection method & Partial scattering method -



particle β energy

$$\epsilon_\beta^{after} = \epsilon_\beta^{before} \cdot (1 - P_\beta) + \epsilon_\beta^{scattered} \cdot P_\beta,$$

particle β momentum

$$\mathbf{p}_\beta^{after} = \mathbf{p}_\beta^{before} \cdot (1 - P_\beta) + \mathbf{p}_\beta^{scattered} \cdot P_\beta.$$

$$\mathbf{p}_\beta^{final} = \mathbf{p}_\beta^{after} + \Delta\mathbf{p}_{\beta\perp}.$$

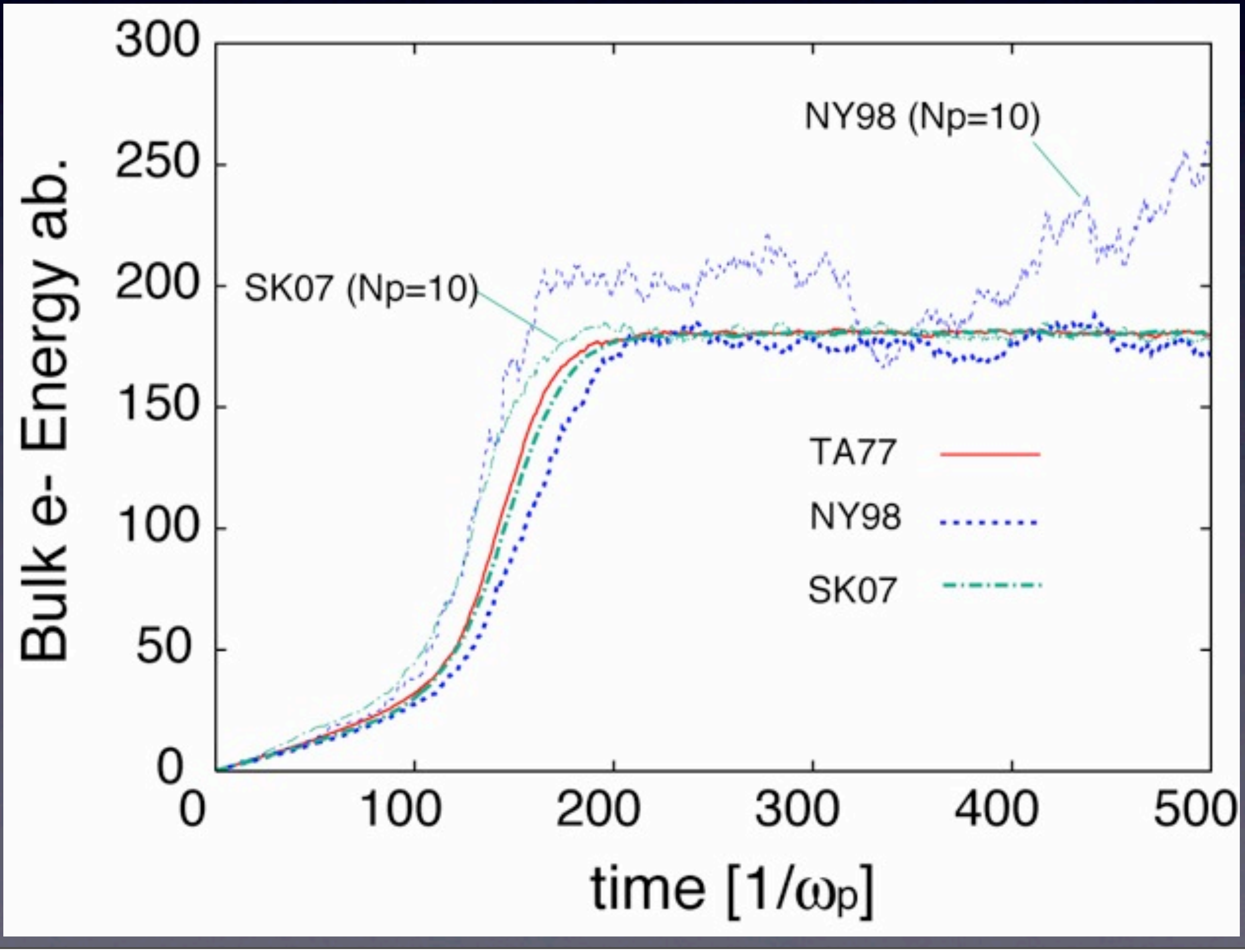
$\Delta p_{\beta\perp}$: random vector

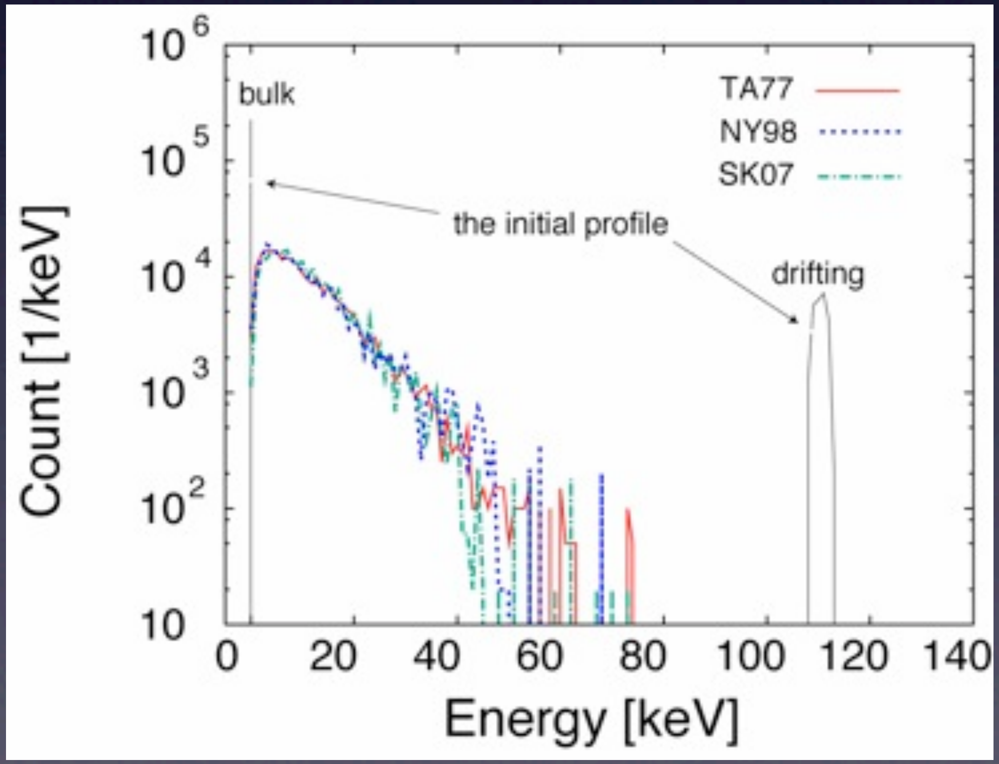
Scale up momentum to conserve energy by adding a random vector.
Perfect energy conservation & statistical momentum conservation

Beam relaxation: benchmark of weighted particle collision model

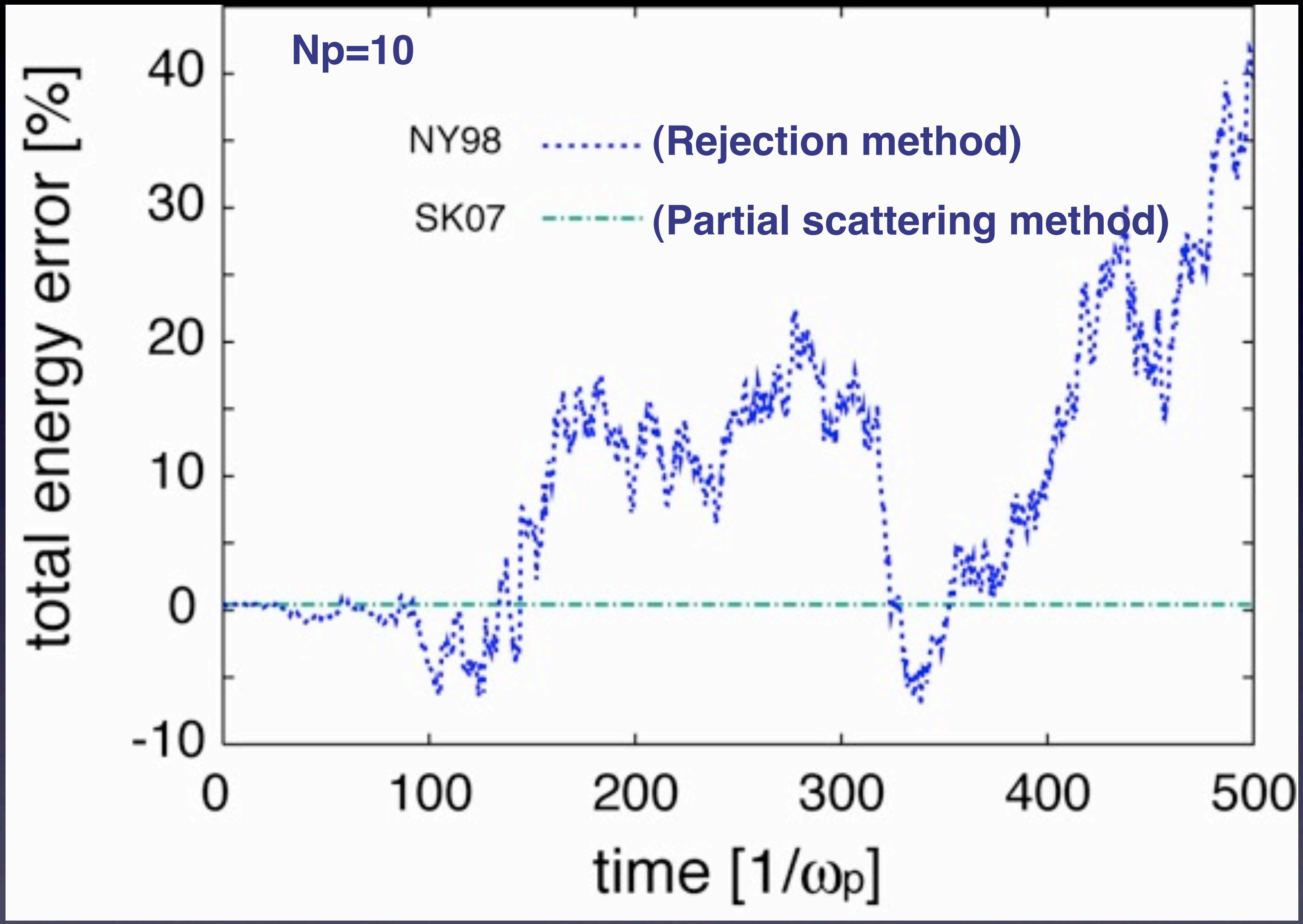
Bulk e- 90%
Beam e- 10% with $p_{drift}=0.7m_ec$
$n=10^{25}$ 1/cm^3
e-e collision

case A (TA77): uniform weighted particle, 500/cell (bulk 450, beam 50)
case B (NY98): weighted 250/cell (bulk 125, beam 125)
case C (SK07): weighted 250/cell (bulk 125, beam 125)





Rejection method has serious energy violation with small number of particle



Partial scattering method has a perfect energy conservation with small particles.

ionization

Field ionization
Collisional ionization (equilibrium model)
Collision for partially ionized plasmas

Field ionization in PICLS
- Tunneling ionization model -

Ionization Rate
(Landau and Lifshitz, Quantum Mechanics)

$$W[E(t)] = 4\omega_a \left(\frac{\varepsilon_i}{\varepsilon_h}\right)^{5/2} \frac{E_a}{E(t)} \exp\left[-\frac{2}{3}\left(\frac{\varepsilon_i}{\varepsilon_h}\right)^{3/2} \frac{E_a}{E(t)}\right]$$

ε_i : ionization potential
ε_h : potential of hydrogen (13.6eV)

$$\omega_a = \frac{m_e e^4}{\hbar^3} \qquad E_a = \frac{m^2 e^5}{\hbar^4}$$

- We use the ADK formula to calculate the ionization rate W(E). Ionization probability R=1-exp[-W(E)Δt], E is the electric field.
- Condition of ionization: R > random number [0-1].
- The new electron has the same weight and position as the ionized ion. It is created with no momentum.

$$j_{ion}^{(i)} = \frac{U_p^{eV}}{|E_{norm}|^2 \Delta t} E^{(i)}$$

Ionization current

Field calculation

Field ionization and calculation of the ionization current

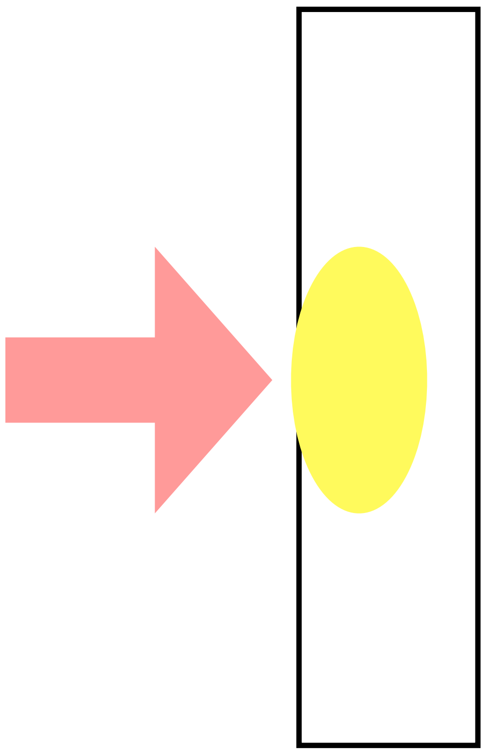
Particle movement

Current calculation

S. Kato, Y. Kishimoto, and J. Koga, Phys. Plasmas ***5****, 292 (1998).*

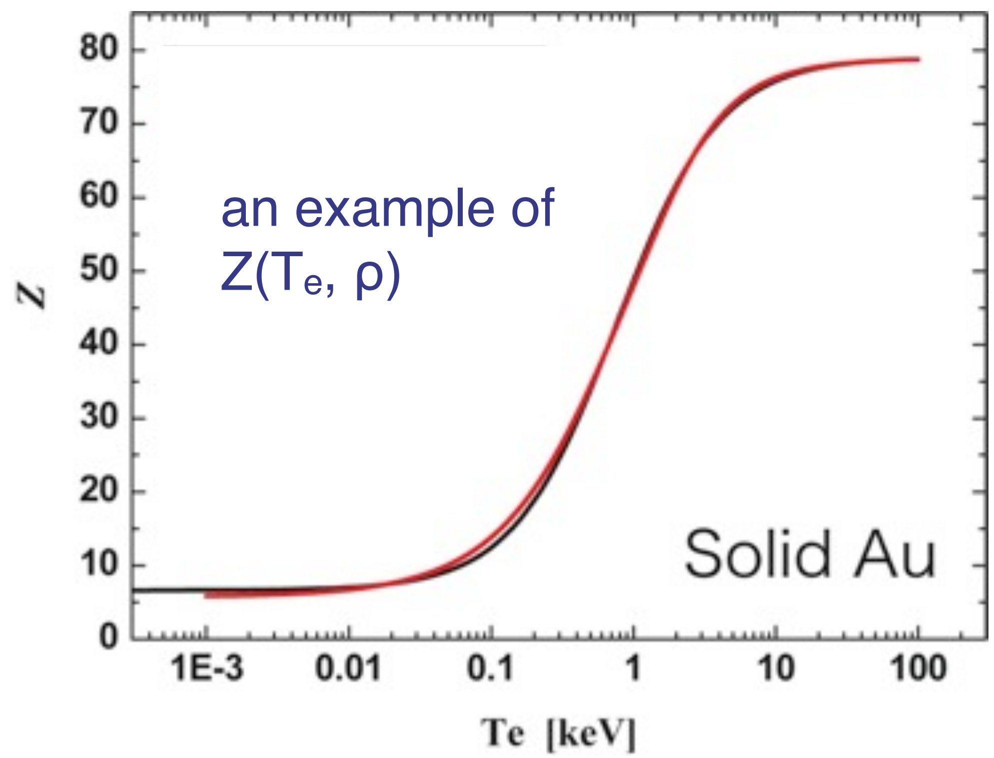
Ionization model in PICLS

- Thomas Fermi model (equilibrium model) -

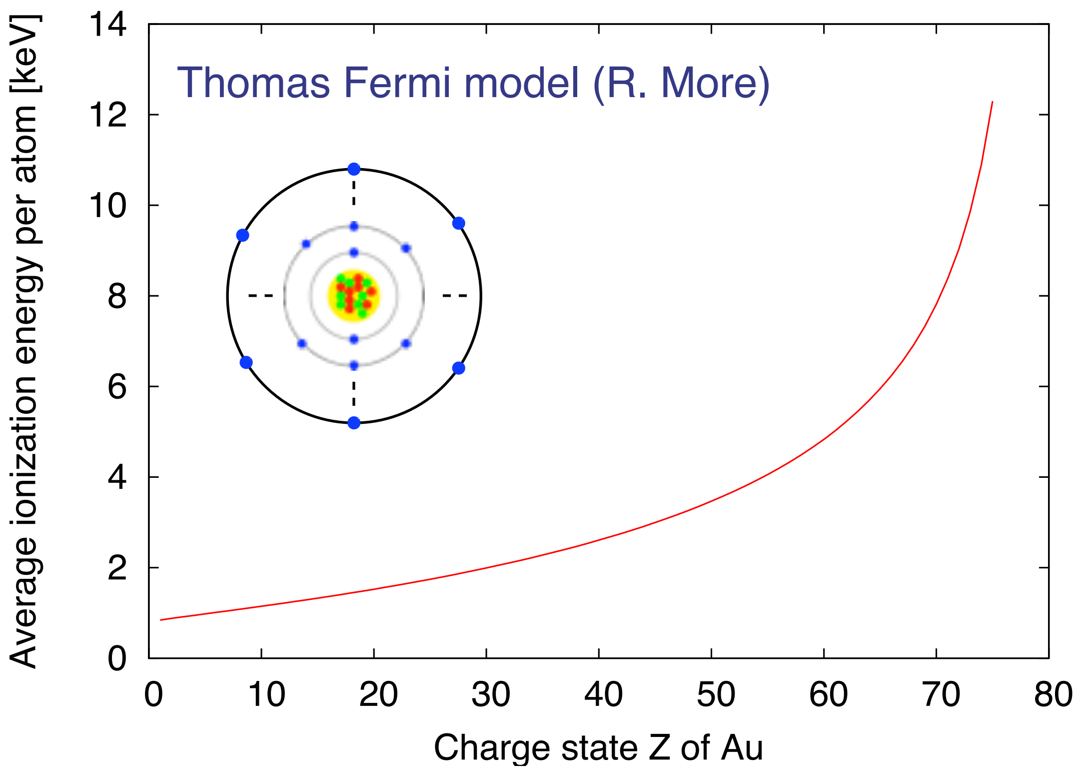


Bulk electrons are heated up by hot electrons via collisional or collective processes.

The heating is calculated by the collisional PIC.



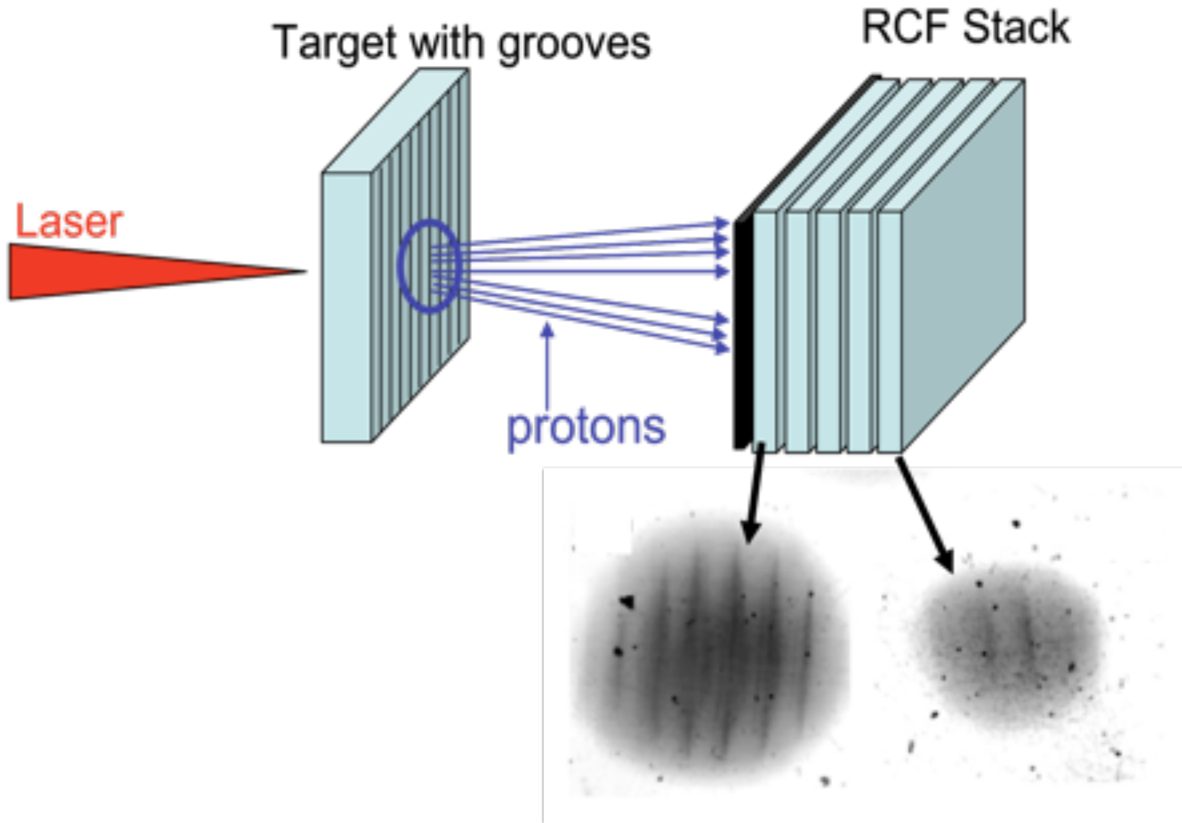
1) Average charge state is calculated as function of bulk electron temperature T_e and local mass density ρ. The function $Z(T_e, \rho)$ is obtained by fitting the EOS database.



2) After the ionization is done, new electrons are born, and the bulk electrons will lose the ionization energy (by shrinking momenta to conserve energy).

The field ionization is also implemented for the insulator target.

Proton Image as result of MA current transport in Al, Cu, and Au targets



What makes a modulated transport?
1. instabilities at the interface?
2. modulation inside target?
3. instabilities at the vacuum interface

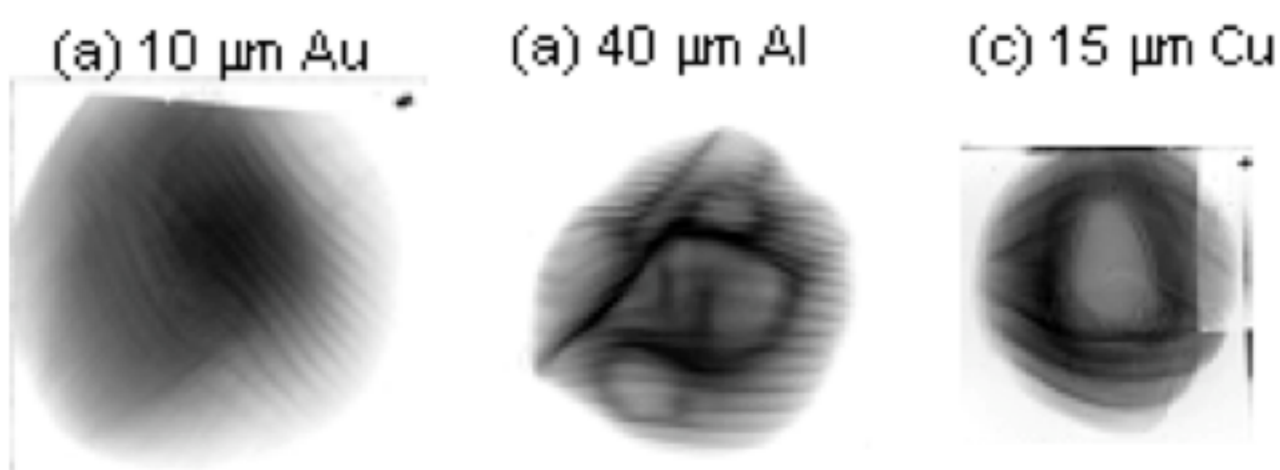
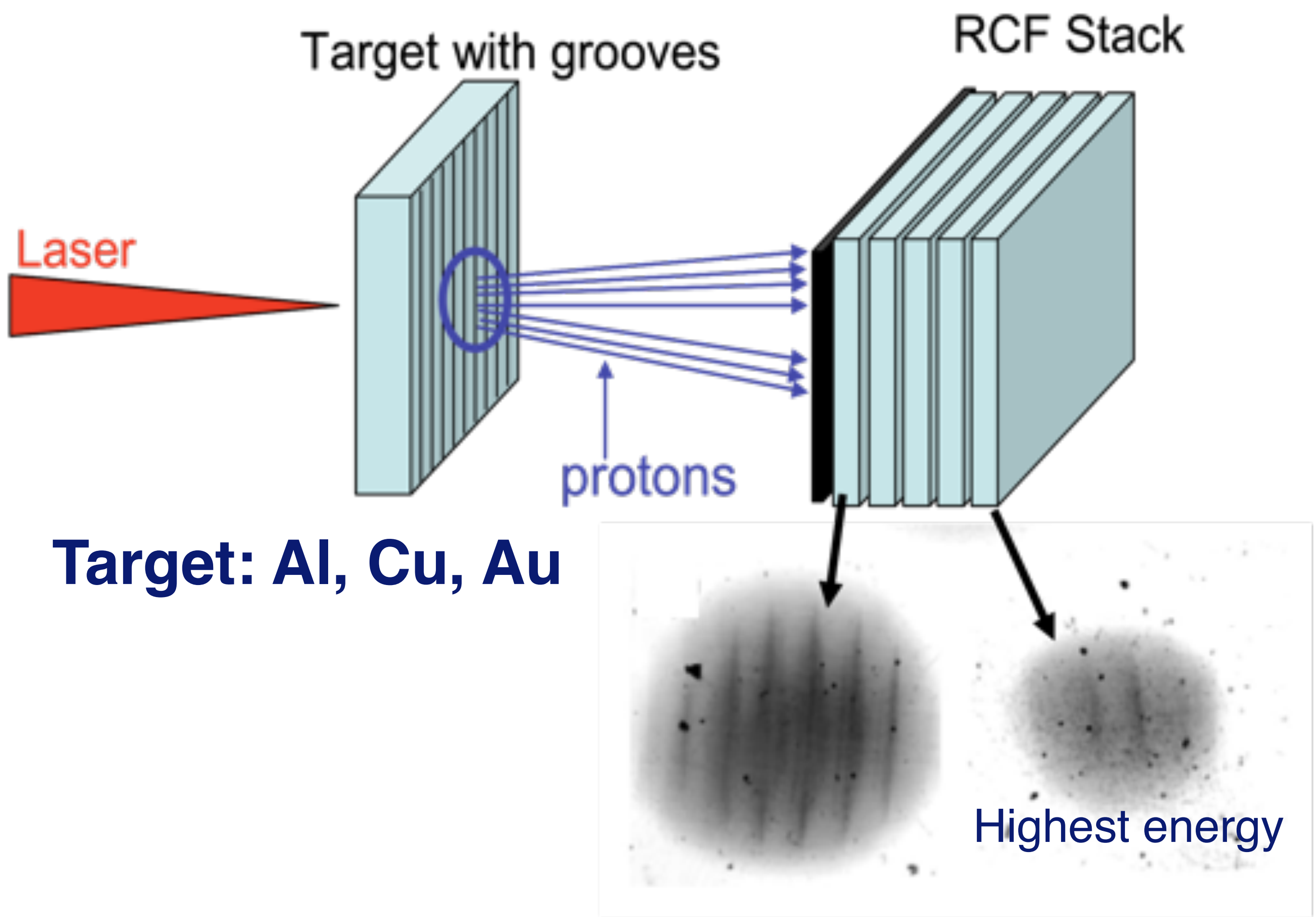


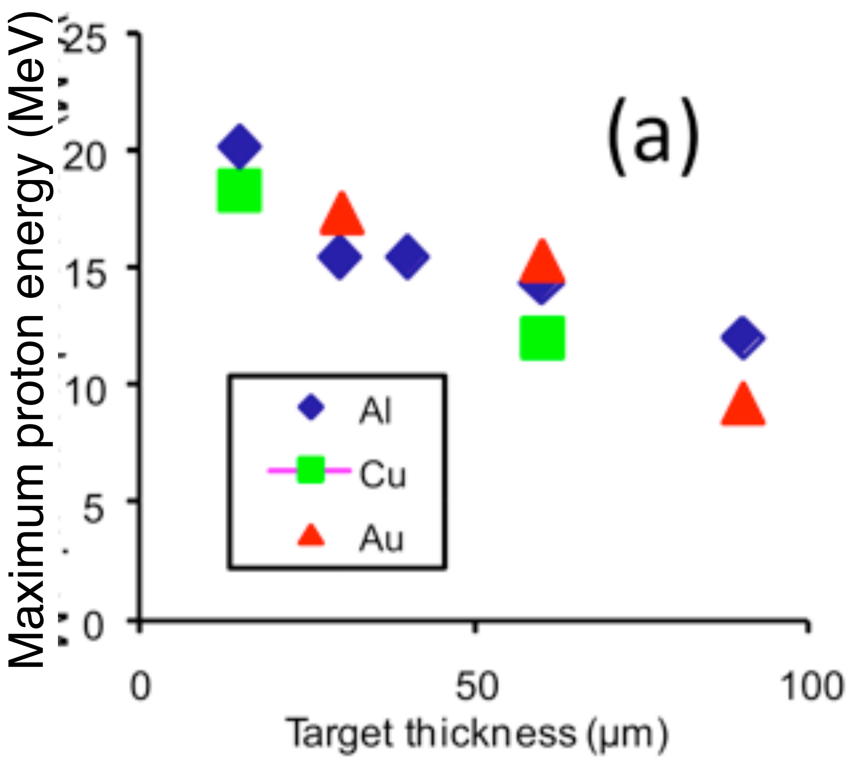
Figure:
Proton angular distributions at 6 MeV for different target materials, Au, Al Cu.
by J. Fuchs, LULI

LULI Experiment

Laser: $I=6x10^{19}$ W/cm^2
duration=350fs, spot=8um

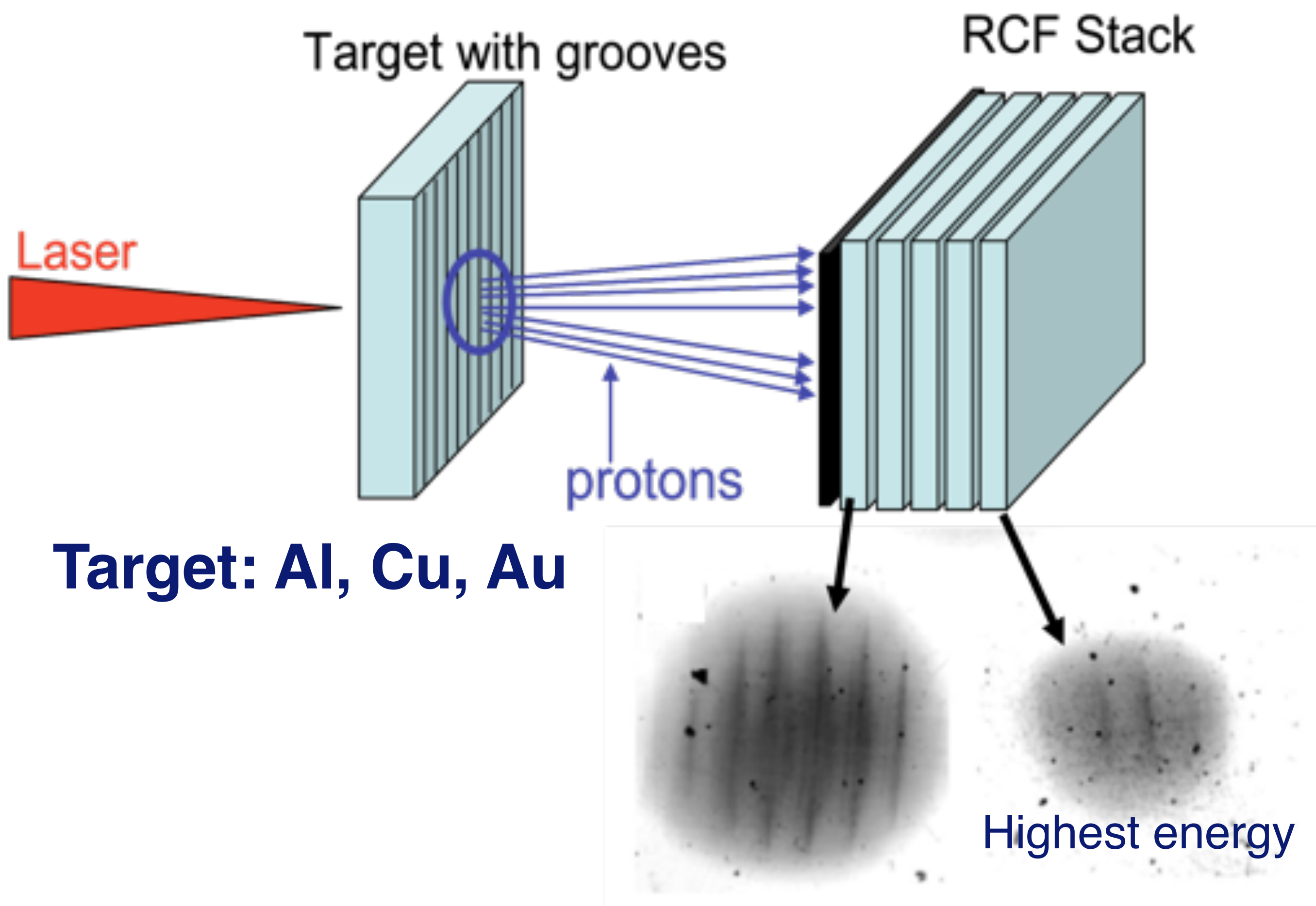


Target: Al, Cu, Au

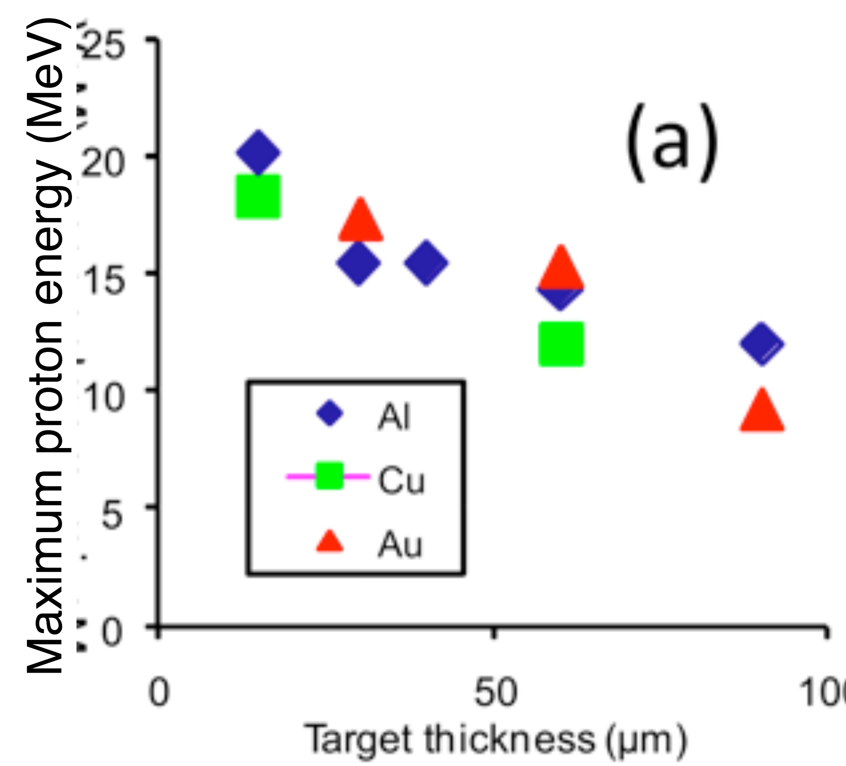


LULI Experiment

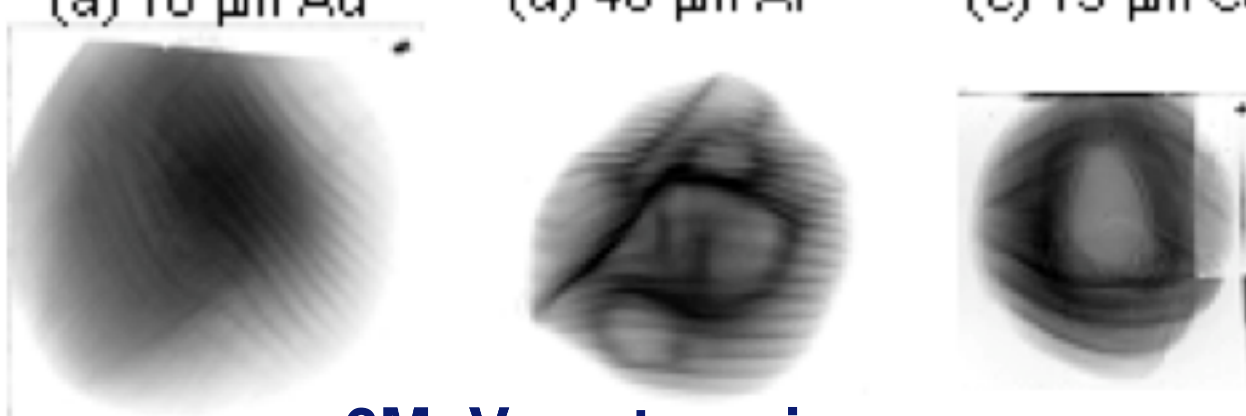
Laser: I=6×10^{19} W/cm^2
duration=350fs, spot=8um



Target: Al, Cu, Au



(a) 10 μm Au (a) 40 μm Al (c) 15 μm Cu



6MeV protons image

Benchmark 2D Code with Collsion&Ionization - MA current transport in Al, Cu, and Au targets-

PICLS2d
Ionization: Thomas-Fermi model
Collision : Relativistic binary collision

Laser: I=6×10^{19} W/cm^2 (P-pol, λ=1μm)
duration=350fs, spot=8um **LULI Laser**

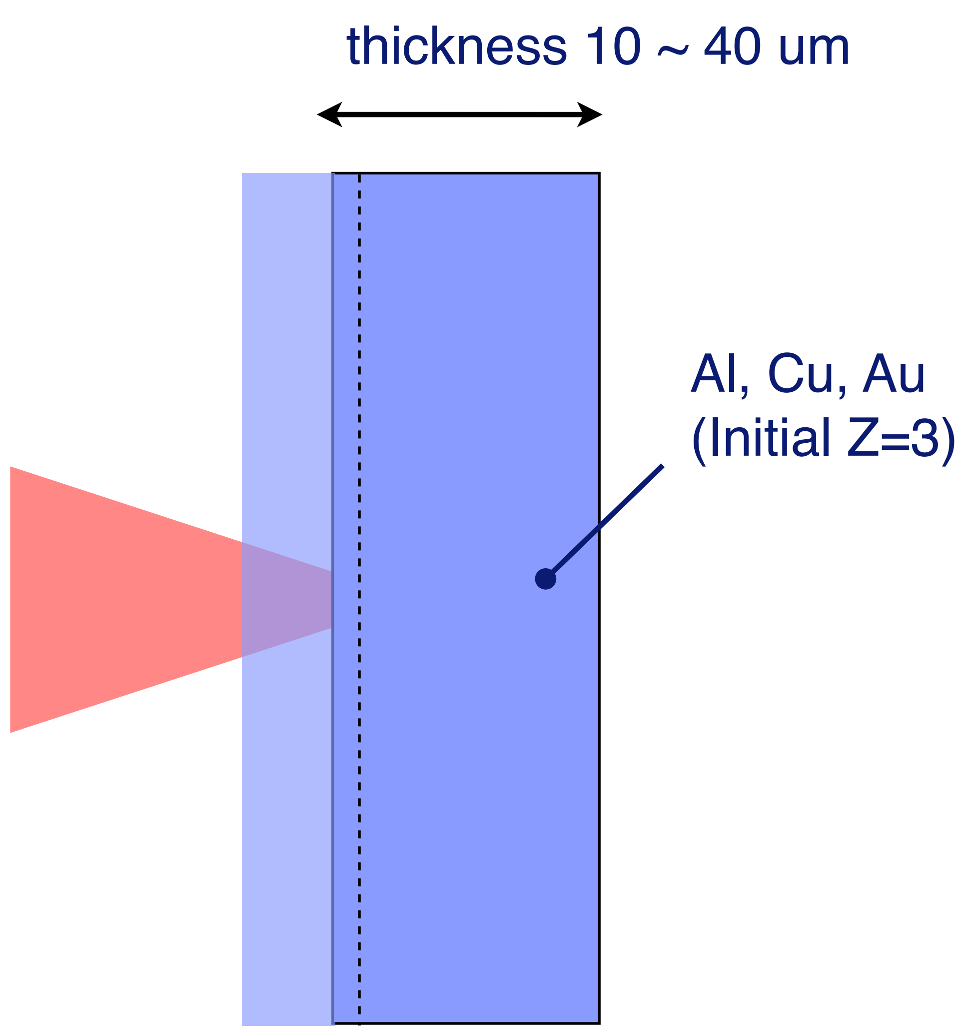
Target:
Al, Cu, Au thin foil (Initial Z=3)
+ small pre-plasma

	mass,	Z	ion dens.	e- dens.
Au:	197M_p	79	50nc	3950n_c
Cu:	64M_p	29	50n_c	1450n_c
Al :	27M_p	13	50n_c	650n_c

n_c: critical density of 1um laser (10^{21} 1/cm^3)

Time step $\Delta t = \tau/50$, Grid size $\Delta x=\lambda/50$

Same parameters with the LULI experiment.



Resistive magnetic fields has two source terms

Resistive field

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} = \eta \mathbf{J}$$

η: resistivity

$$\eta \propto \frac{Ze^2}{T^{3/2}}$$

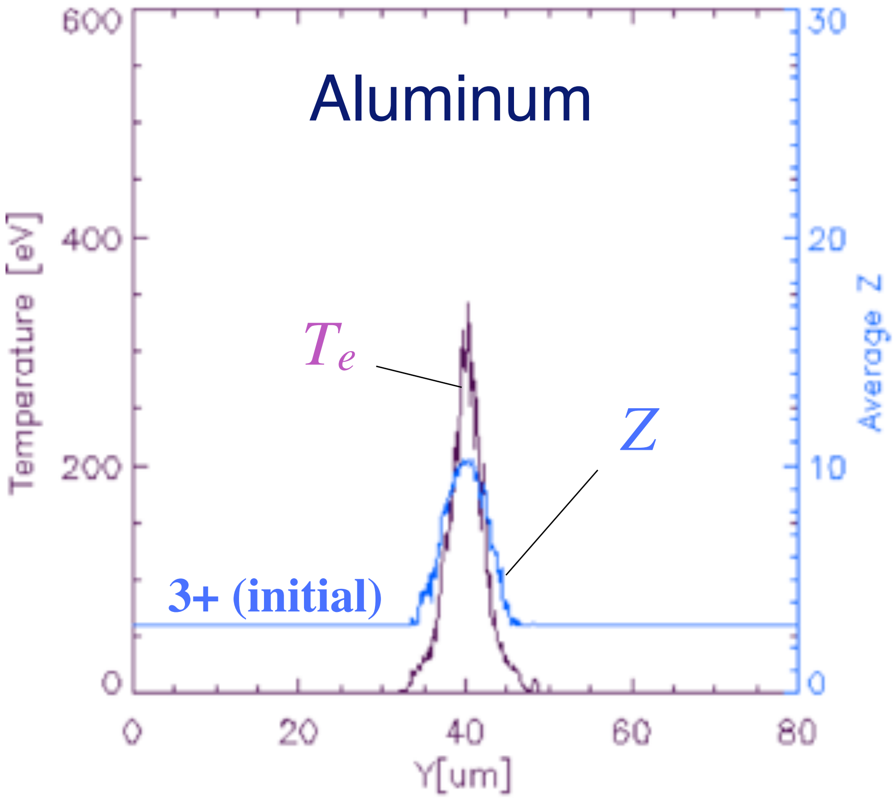
$$\frac{\partial \mathbf{B}}{\partial t} = -\left(\underbrace{\eta \nabla \times \mathbf{J}}_{\text{Current term}} + \underbrace{\nabla \eta \times \mathbf{J}}_{\text{Resistivity term}}\right)$$

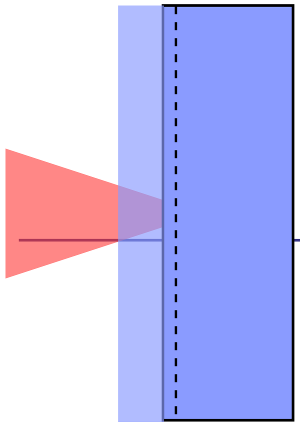
Current term **Resistivity term**

Resistivity term is a minor term in fixed Z case.

Resistivity evolution in ionizing target
- competition between heating and cooling -

Temperature and average Z distribution inside 1um at t=80fs





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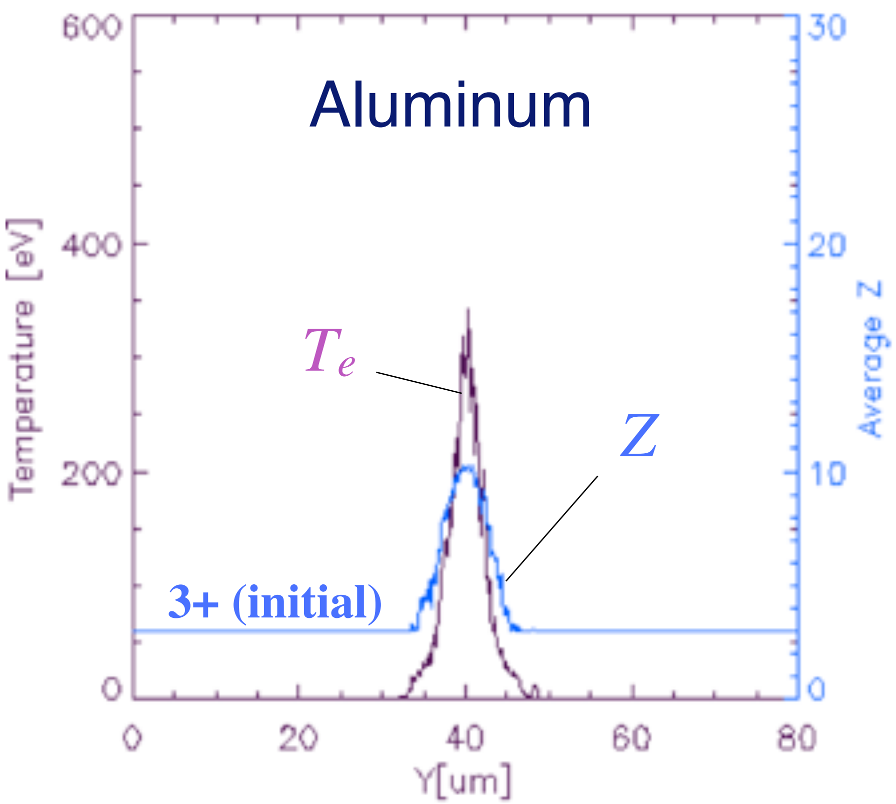
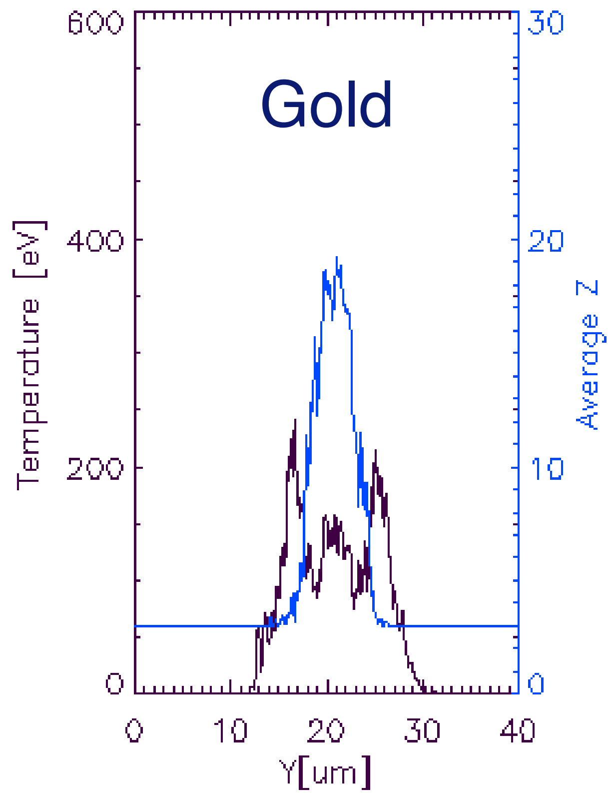
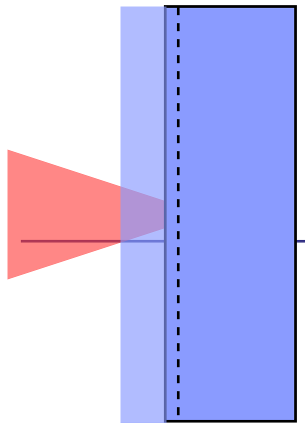


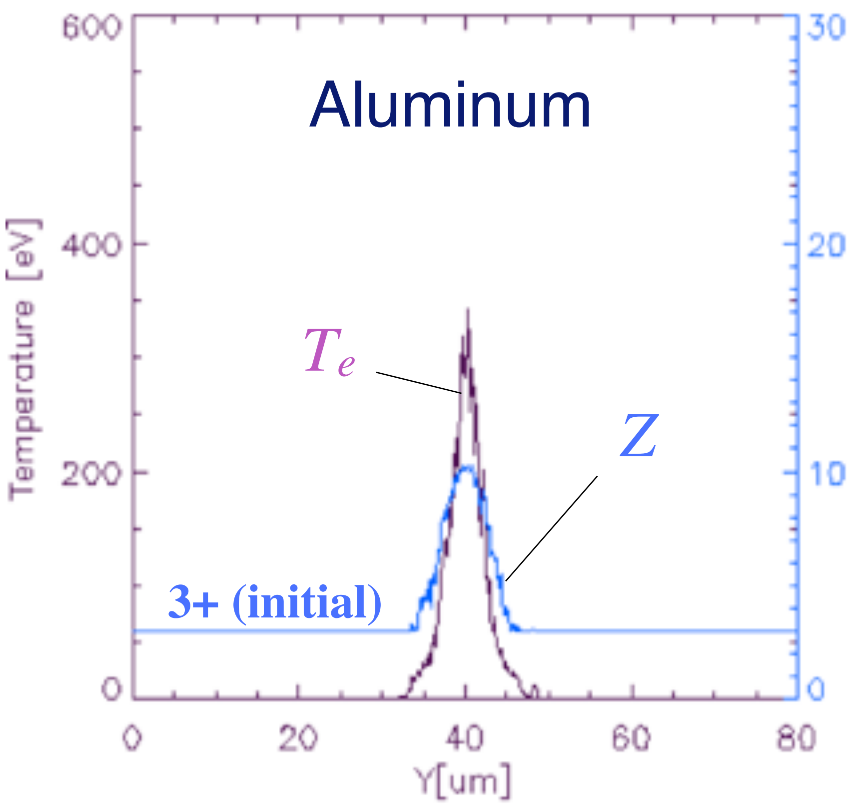


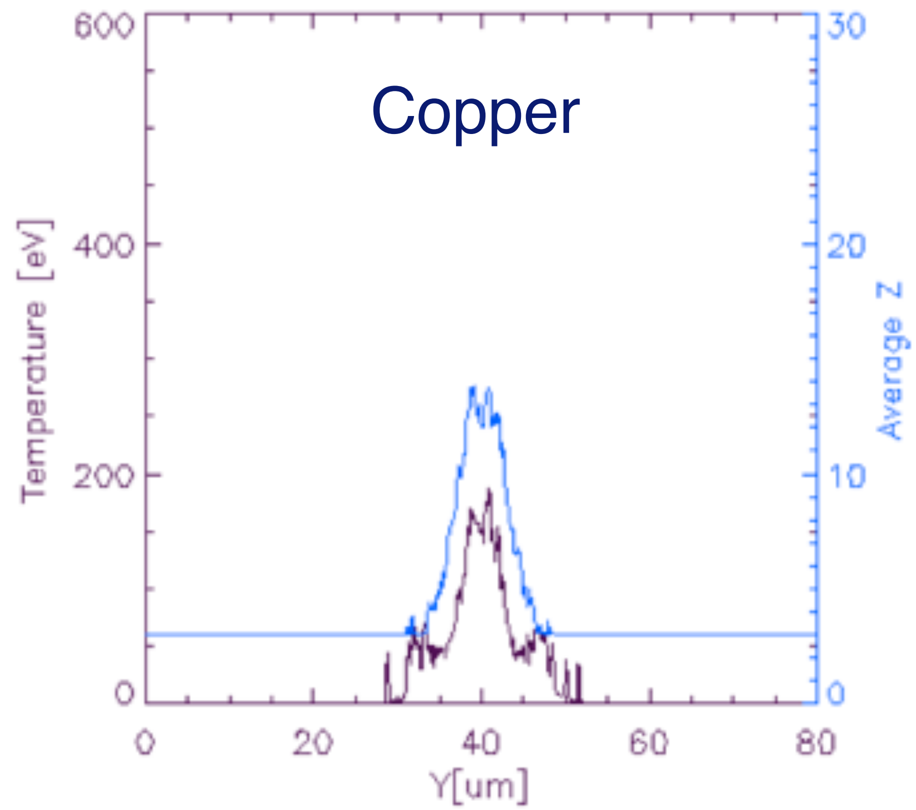
ionization consumes
local energy

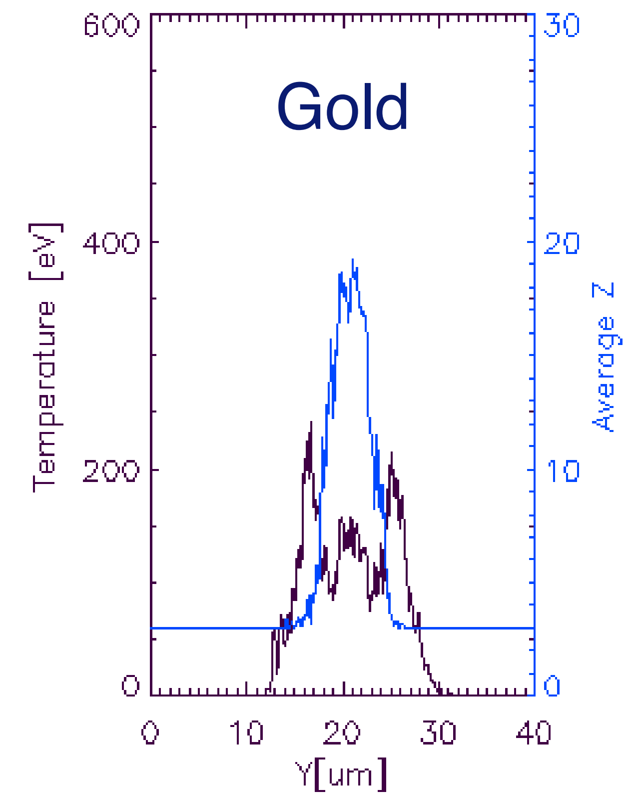


Resistivity evolution in ionizing target
- competition between heating and cooling -

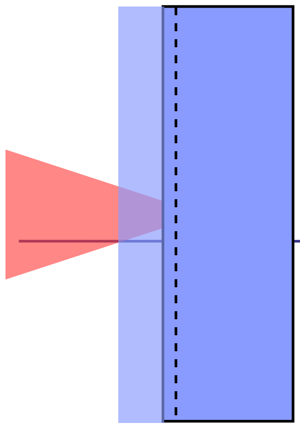
Temperature and average Z distribution inside 1um at t=80fs





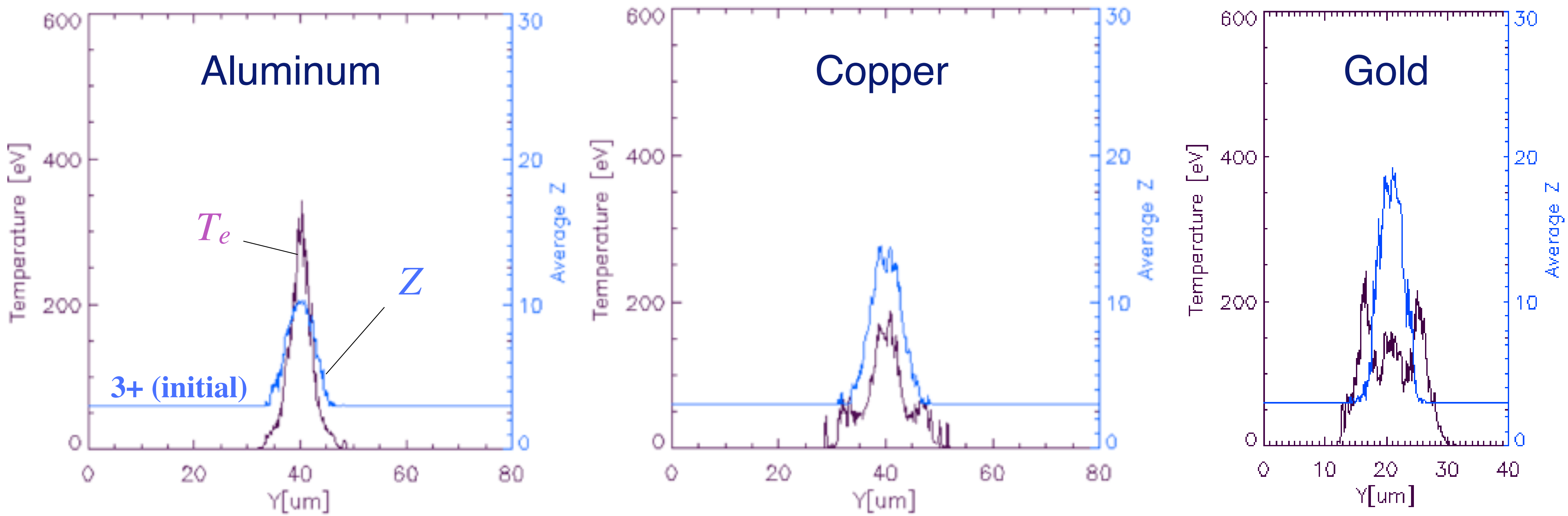


ionization consumes
local energy

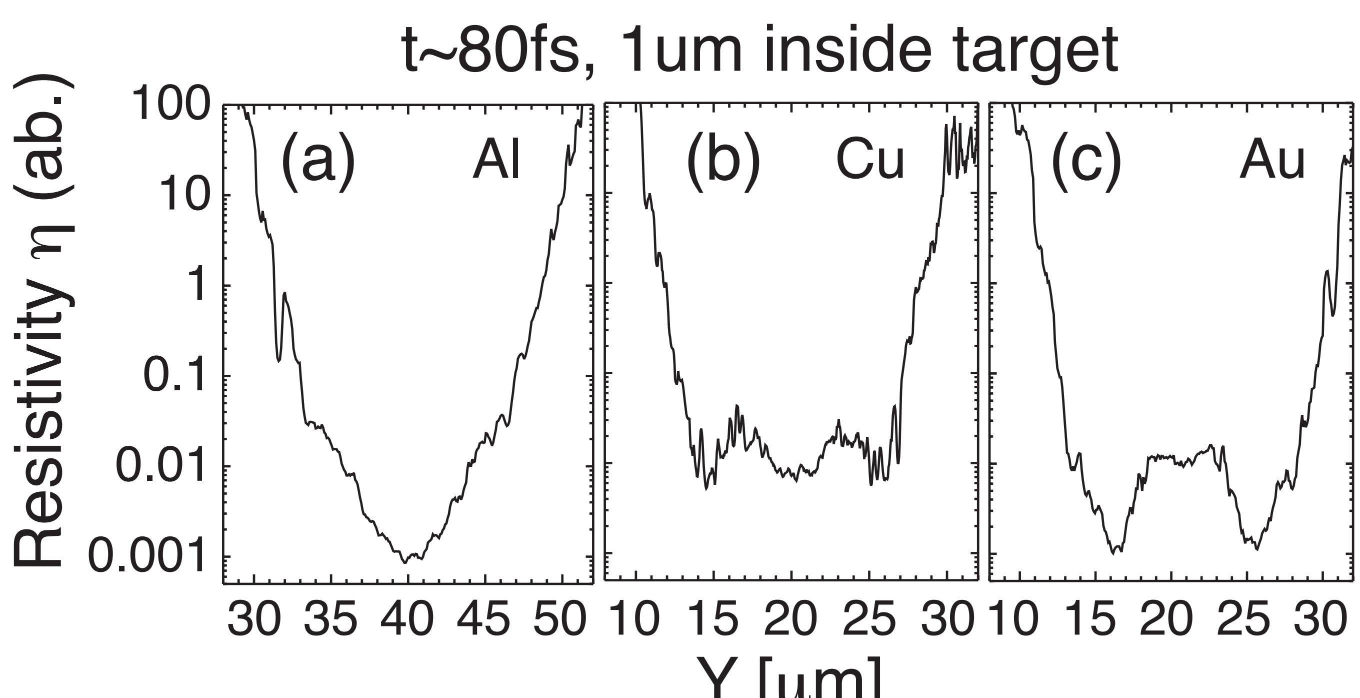


Resistivity evolution in ionizing target - competition between heating and cooling -

Temperature and average Z distribution inside 1um at t=80fs



$$\eta \propto \frac{Ze^2}{T^{3/2}}$$



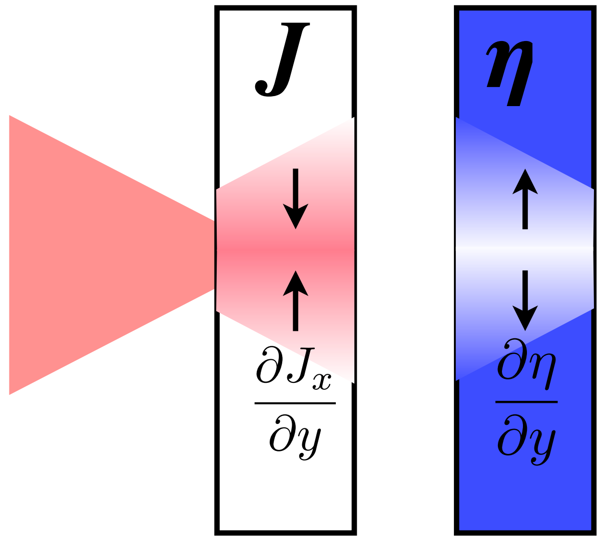
ionization consumes local energy

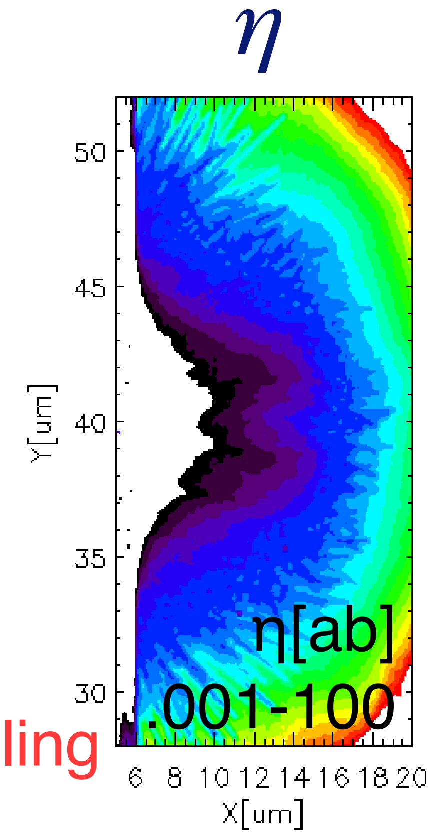
Resistive magnetic fields evolution in high Z target - competition between heating and cooling (ionization) -

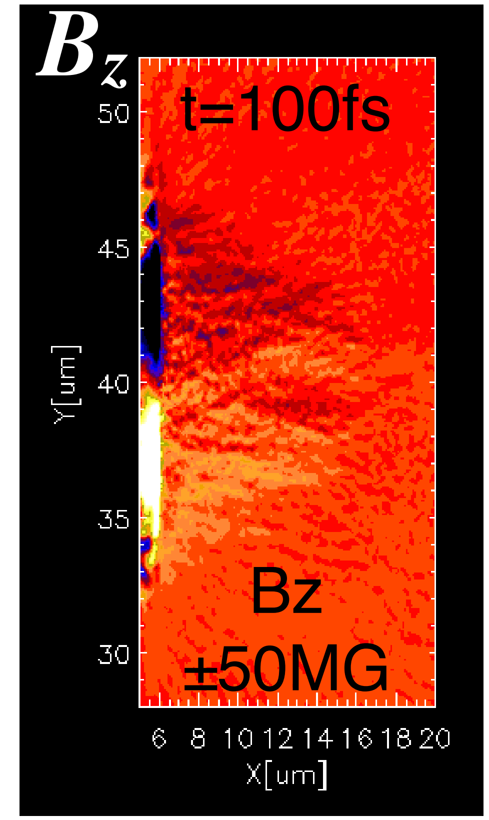
Resistive B-field (B_z)

$$\frac{\partial B_z}{\partial t} = \left(\eta \frac{\partial J_x}{\partial y} + \frac{\partial \eta}{\partial y} J_x\right)$$

Aluminum







Current term
∇×J dominant
(1st term)

heating > ionization cooling

Resistivity

$$\eta \propto \frac{Ze^2}{T^{3/2}}$$

Resistive magnetic fields evolution in high Z target
- competition between heating and cooling (ionization) -

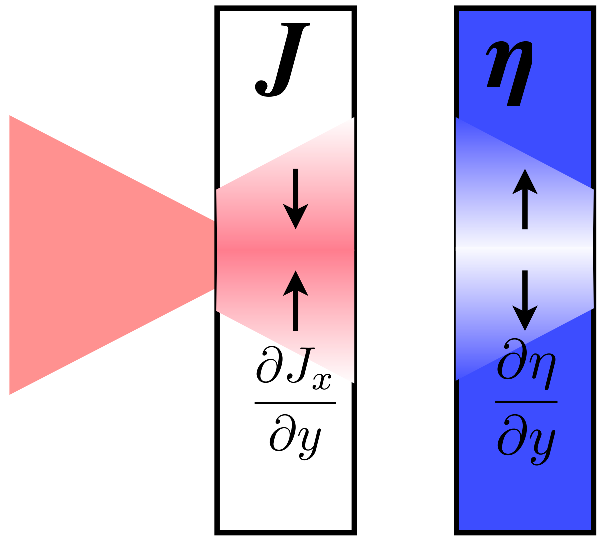
Resistive B-field (B_z)

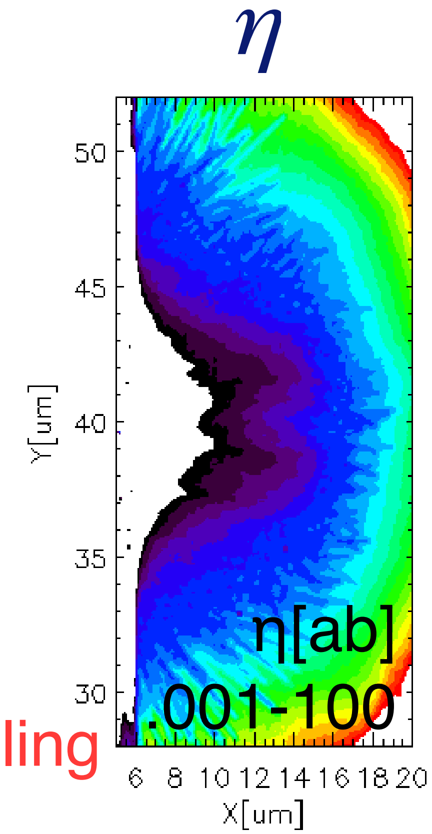
$$\frac{\partial B_z}{\partial t} = \left(\eta \frac{\partial J_x}{\partial y} + \frac{\partial \eta}{\partial y} J_x \right)$$

Resistivity

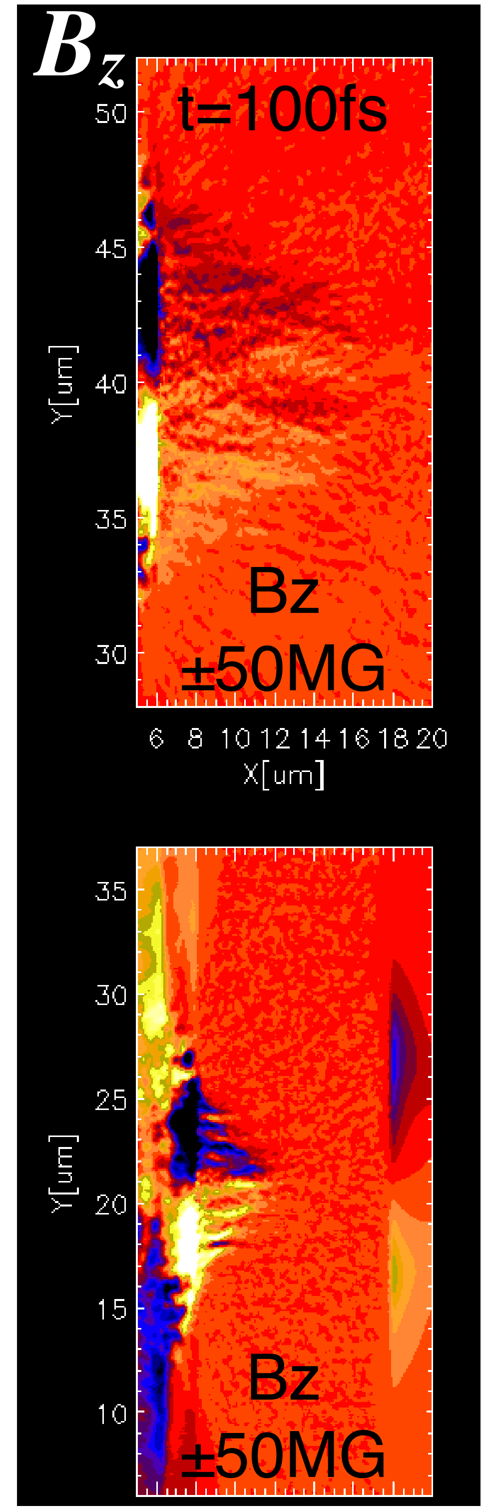
$$\eta \propto \frac{Ze^2}{T^{3/2}}$$

Aluminum



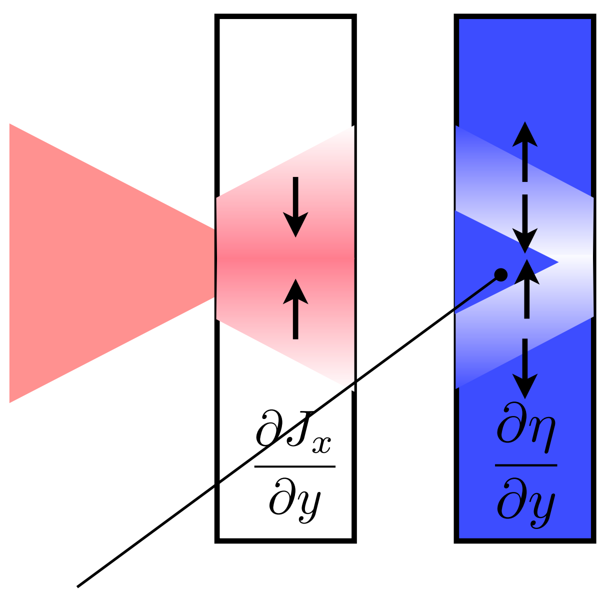


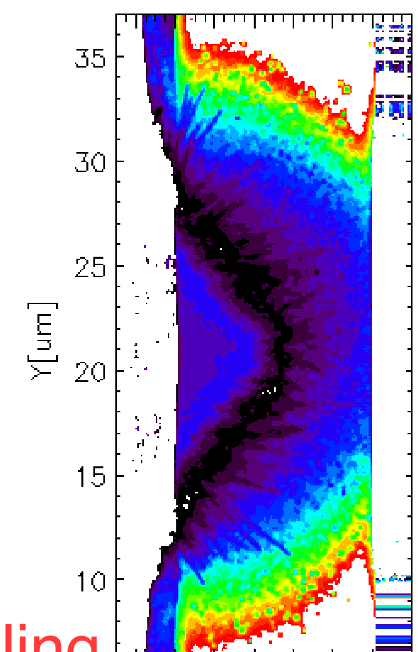
heating > ionization cooling



Current term
∇×J dominant
(1st term)

Gold





Resistivity term
∇η dominant
(2nd term)

heating < ionization cooling

Resistivity η drops by bulk heating, however η recovers in high Z target due to local cooling via ionization. Strong B fields grow in the ionization wave (slower than fast e-).

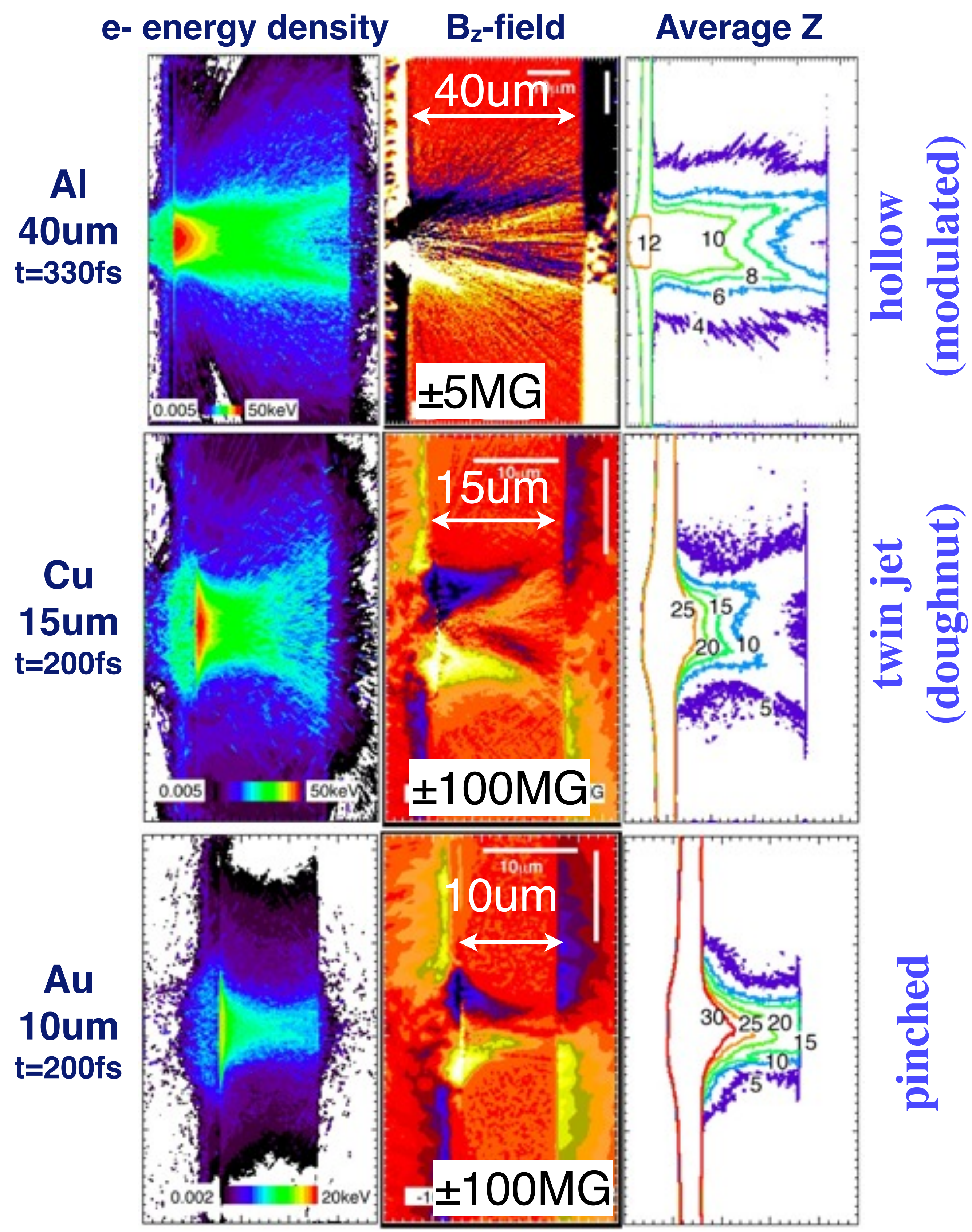
Ionization affects the resistivity inside target and excites 100MG resistive magnetic fields in Au & Cu

Resistive B-field

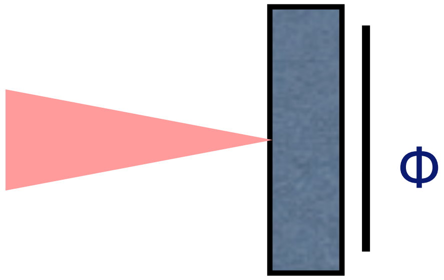
$$\frac{\partial \mathbf{B}}{\partial t} = -\left(\eta \nabla \times \mathbf{J} + \nabla \eta \times \mathbf{J}\right)$$

- Al target: ∇×J term is dominant. Resistive magnetic fields is ~ 5MG. Modulated.
- Au target: ∇η term is dominant. Strong resistive magnetic fields ~ 100MG. Single channel.
- Cu target: η has a twin peak distribution. Strong resistive fields like gold, but twin channel (2D), would be hollow (3D) pattern.

The cyclotron frequency will become ~ ω_0 (laser frequency) under 100MG B-field. The fine resolution of sub-micron, sub-femtosecond is required!



Pattern of sheath is consistent with the proton image observed in different material, Al, Cu, and Au in LULI exp.



Laser: $I=6\times10^{19}$ W/cm^2 (P-pol)
duration=350fs, spot=8um

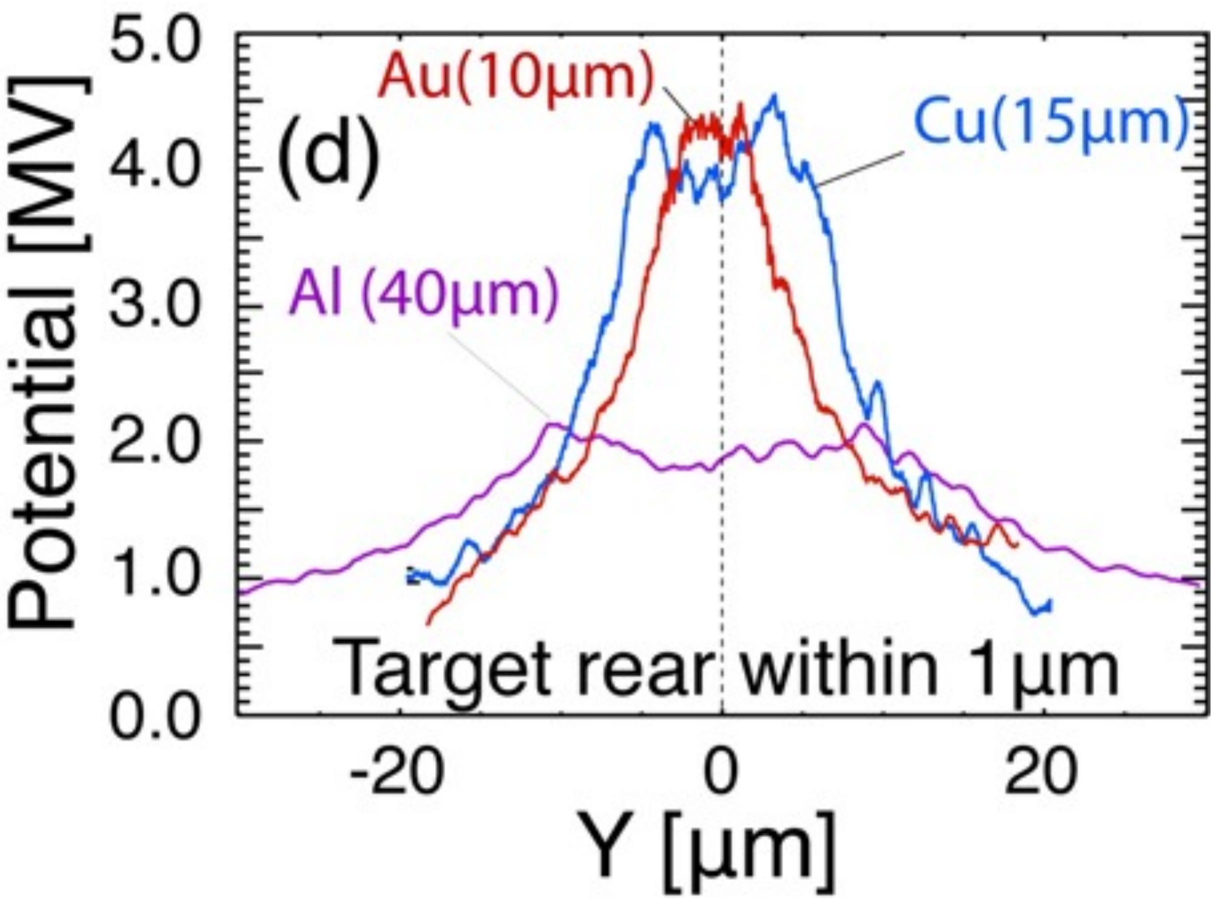
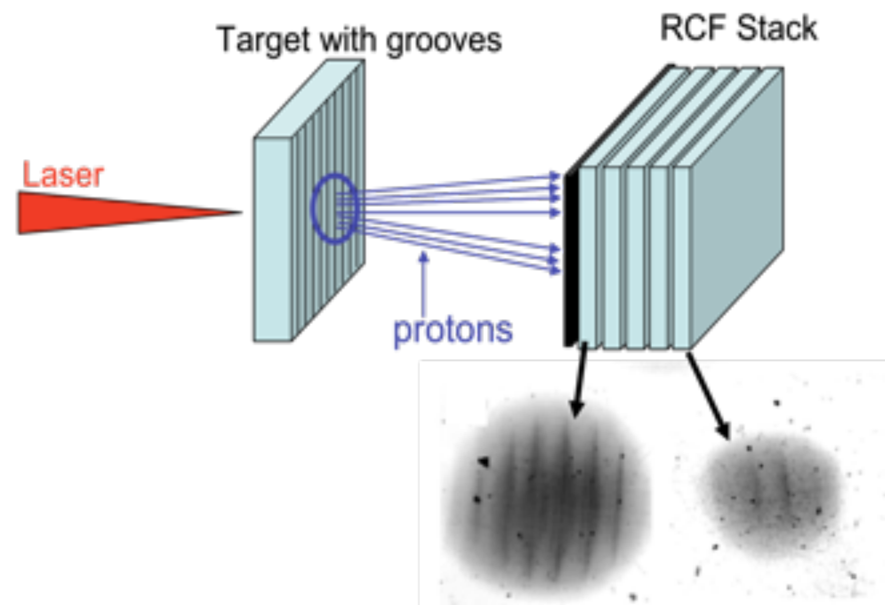


Fig. Electrostatic potential at the target rear in 1um. Plots observed at the time when the sheath potential has the maximum, and time-averaged during 100 fs.



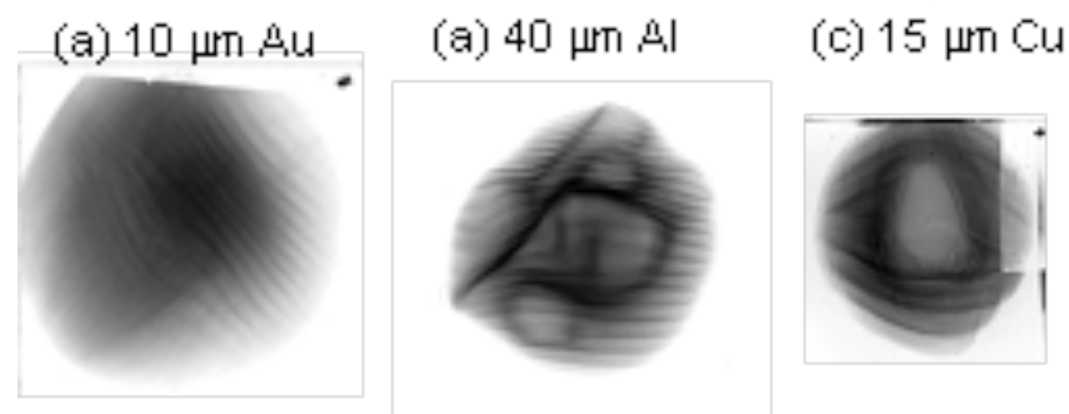


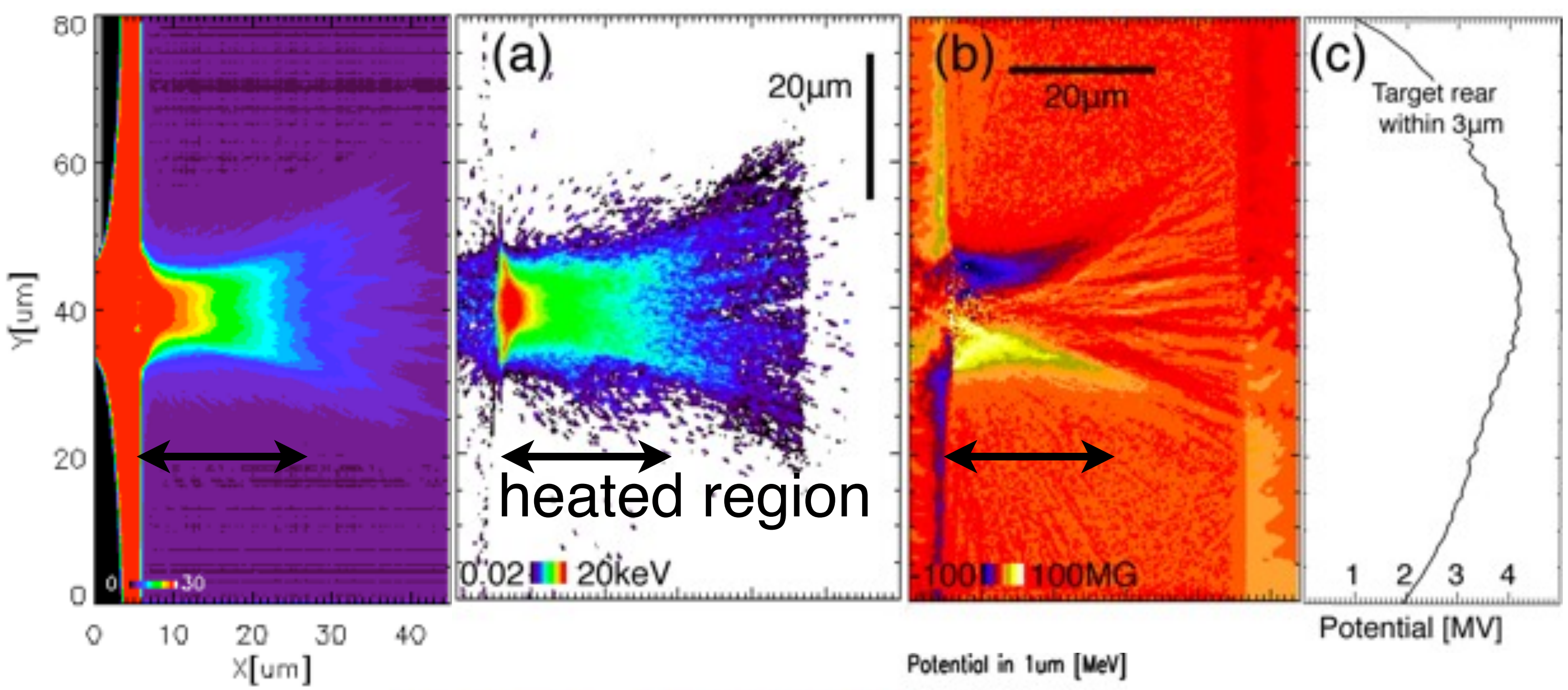
Fig. 6MeV proton images from different material target.

Proton has a smooth image from thicker Cu target

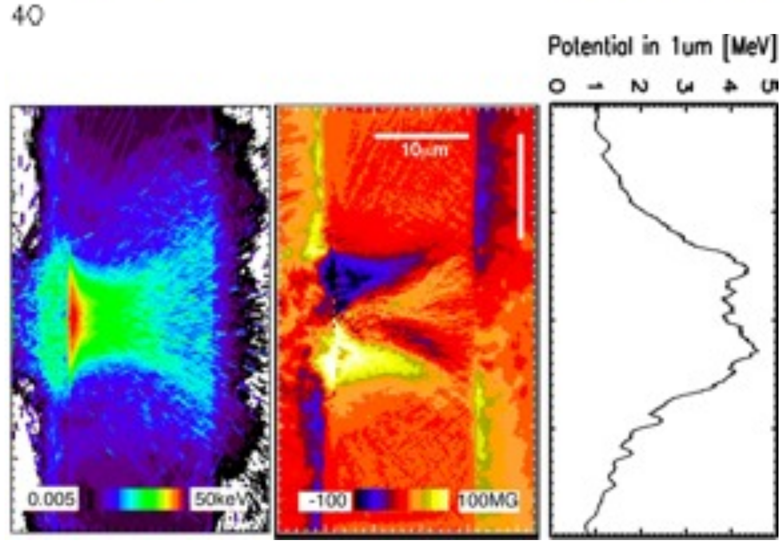
Laser: I=6x10^{19} W/cm^2 (P-pol)
duration=350fs, spot=8um

Average Z | **e- energy density** | **B_z-field** | **Potential profile at rear**

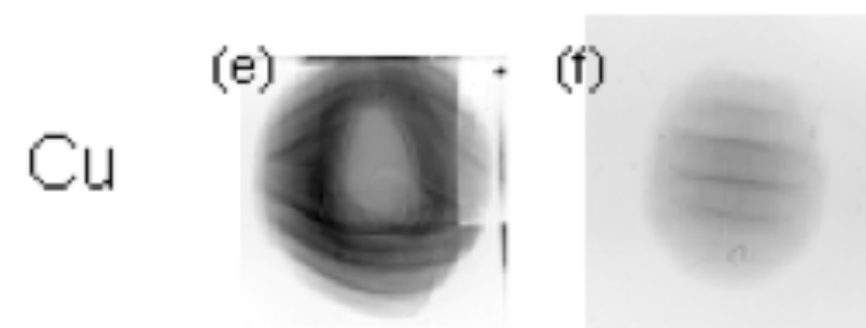
Cu 40um
t=370fs



Cu 15um
t=200fs



Cu 15um | **Cu 40um**

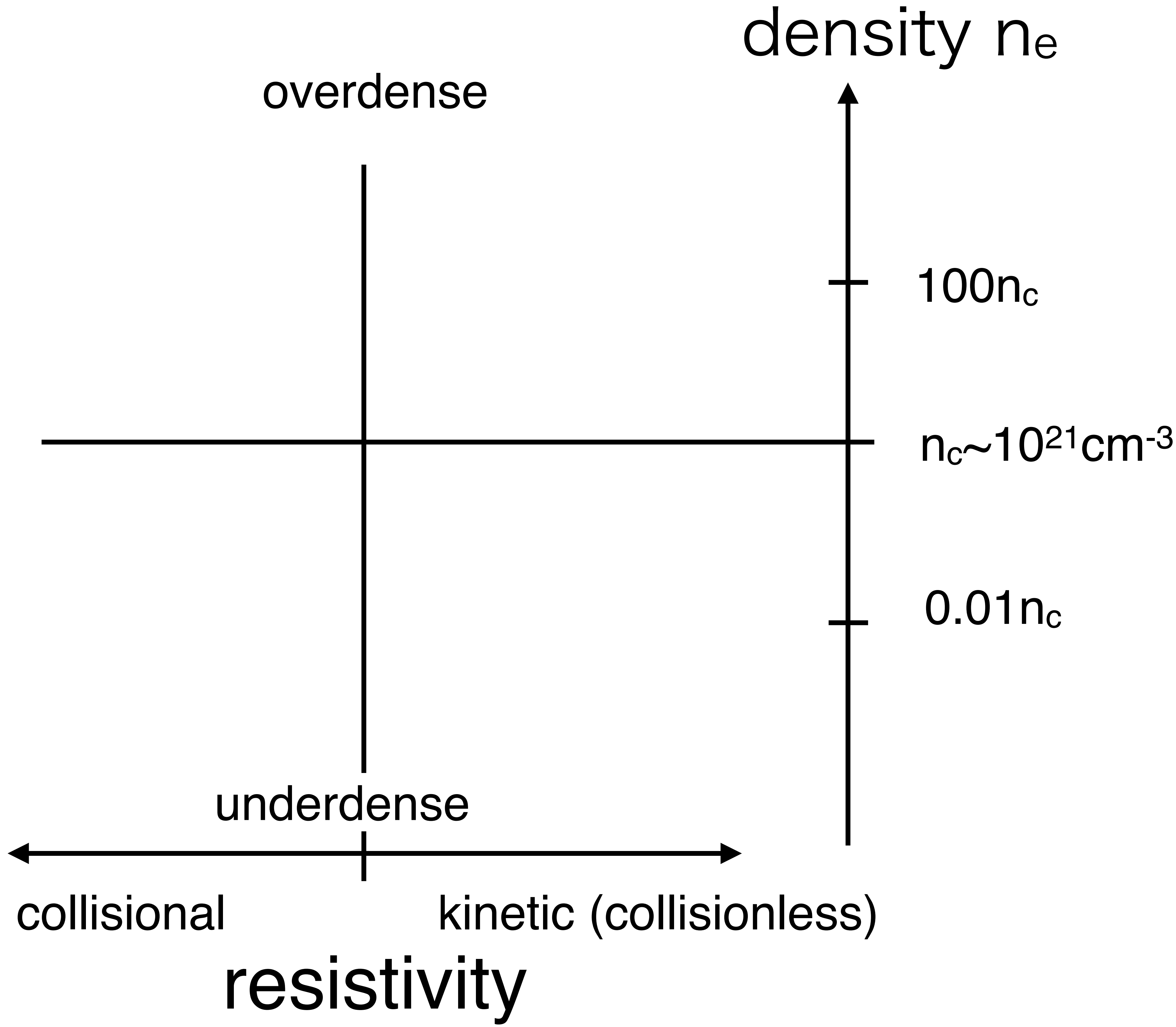


Ionization driven resistive magnetic fields extend only in the heated region (propagation speed ~ 0.15c, heat diffusion velocity). MeV electrons, which go beyond the strong B fields, are spraying and make a smooth potential at the target rear.

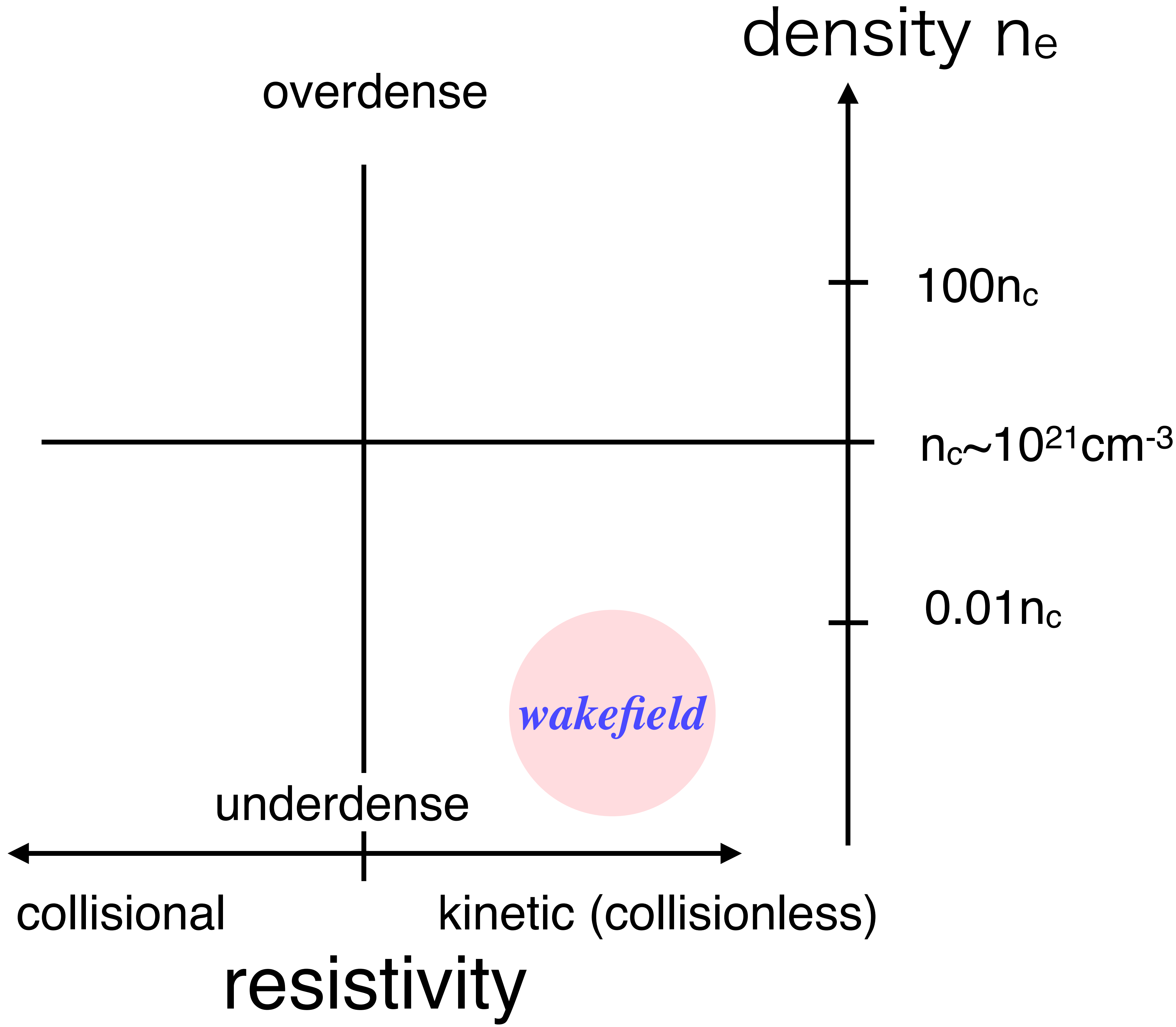
Summary

- We had studied the MA current transport in high conductive target by collisional/ionization PICLS code.
- We found that the current term ($\nabla\times J$) is dominant in low Z target (Al) as a source term of resistive magnetic fields. While the resistivity term ($\nabla\eta$) plays an important role, and produces extremely strong B-fields (~0.1gigagauss) in high Z target (Cu, Au). Important to include ionization in Cu&Au targets.
- The resistive magnetic field structure depends on the resistivity evolution in the heated region. The Cu target has a twin jets (hollow) structure, and the Au has a single channel under the current experiment/simulation conditions.
- Hot electron transport is affected by the strong resistive B fields, and it makes modulation in the sheath potential at target rear, which is recorded in the MeV proton image. PICLS shows a consistent potential profile with the proton images for Al, Cu, and Au targets.

Is your plasma kinetic or collisional?



Is your plasma kinetic or collisional?



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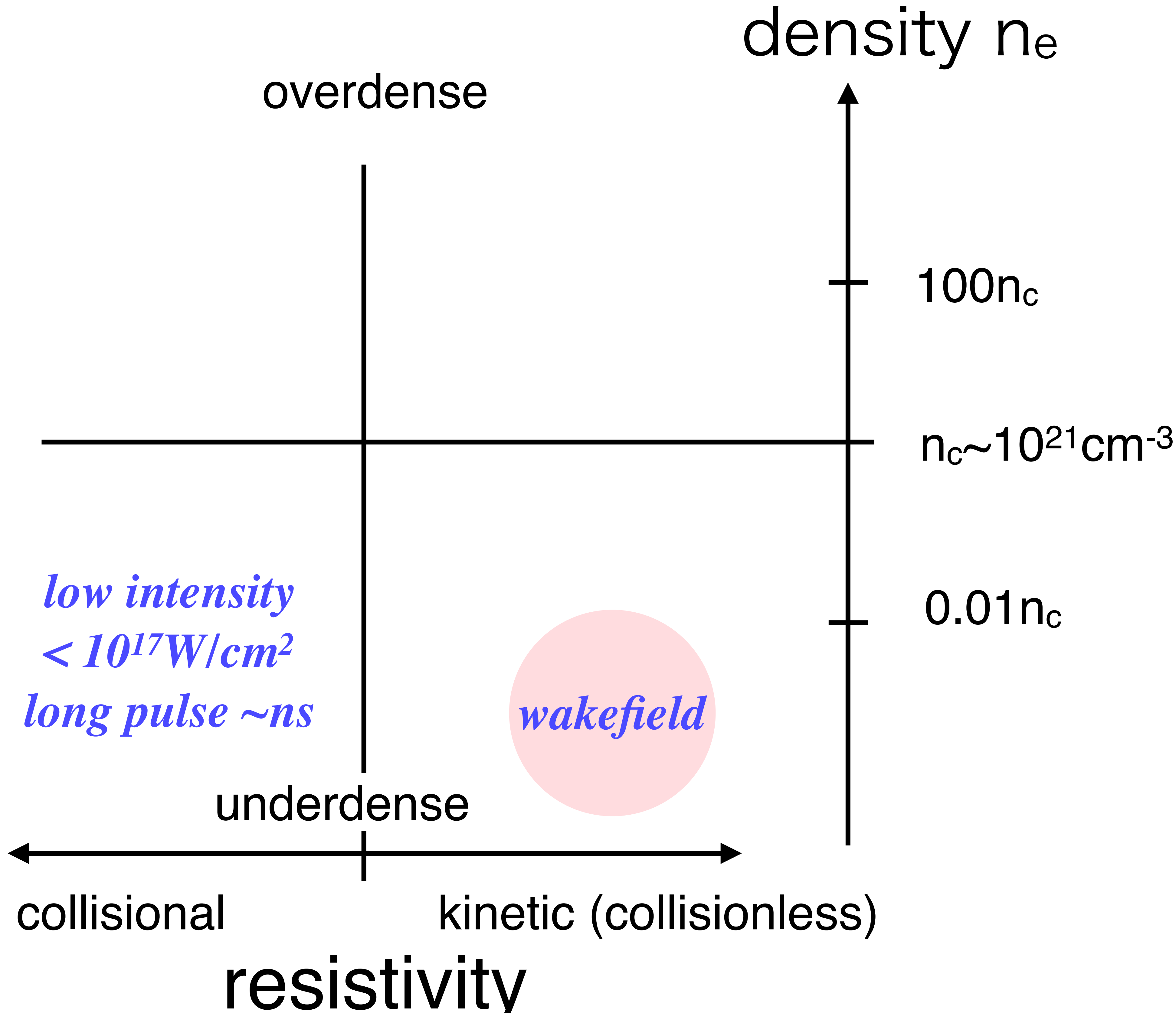

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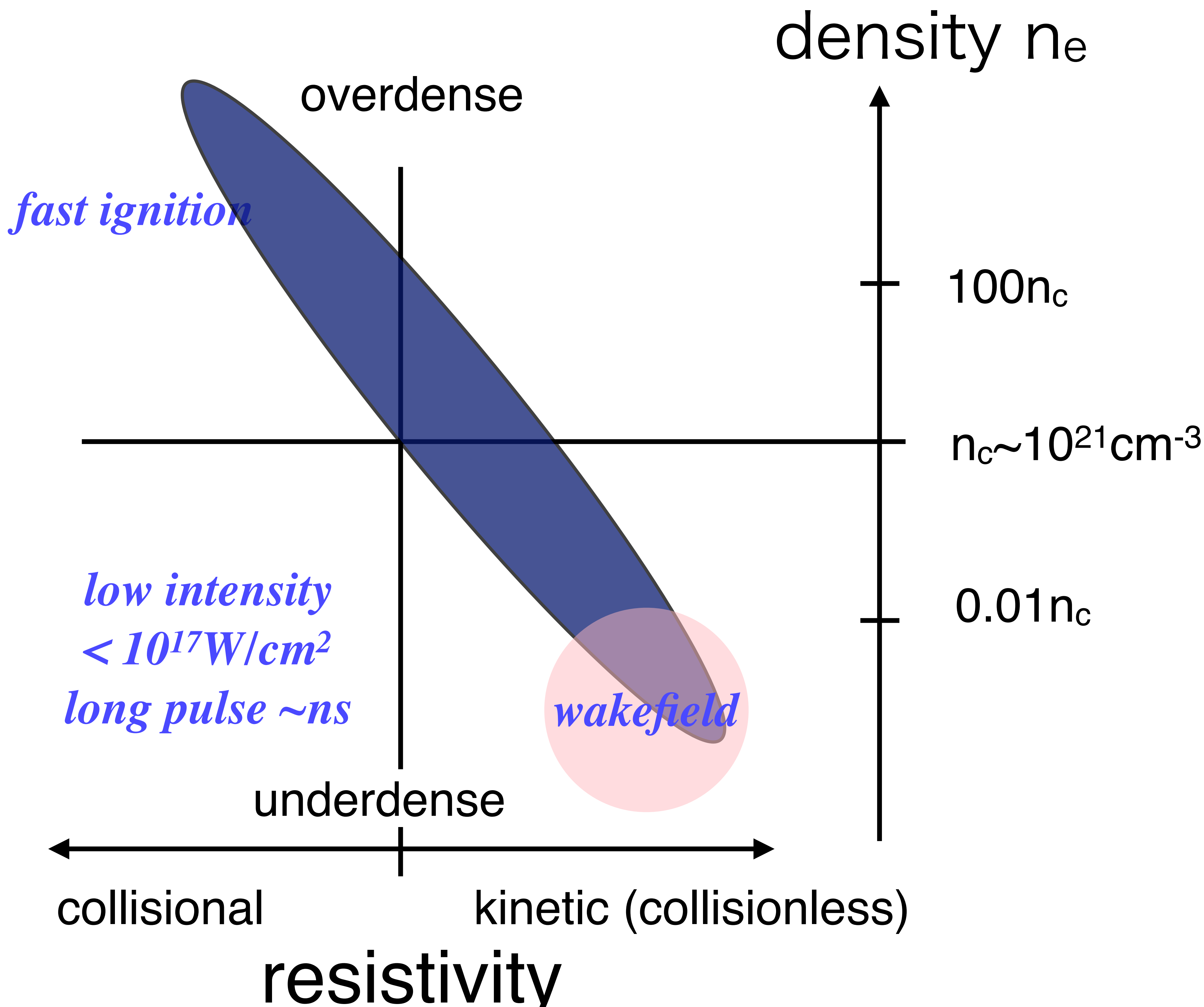

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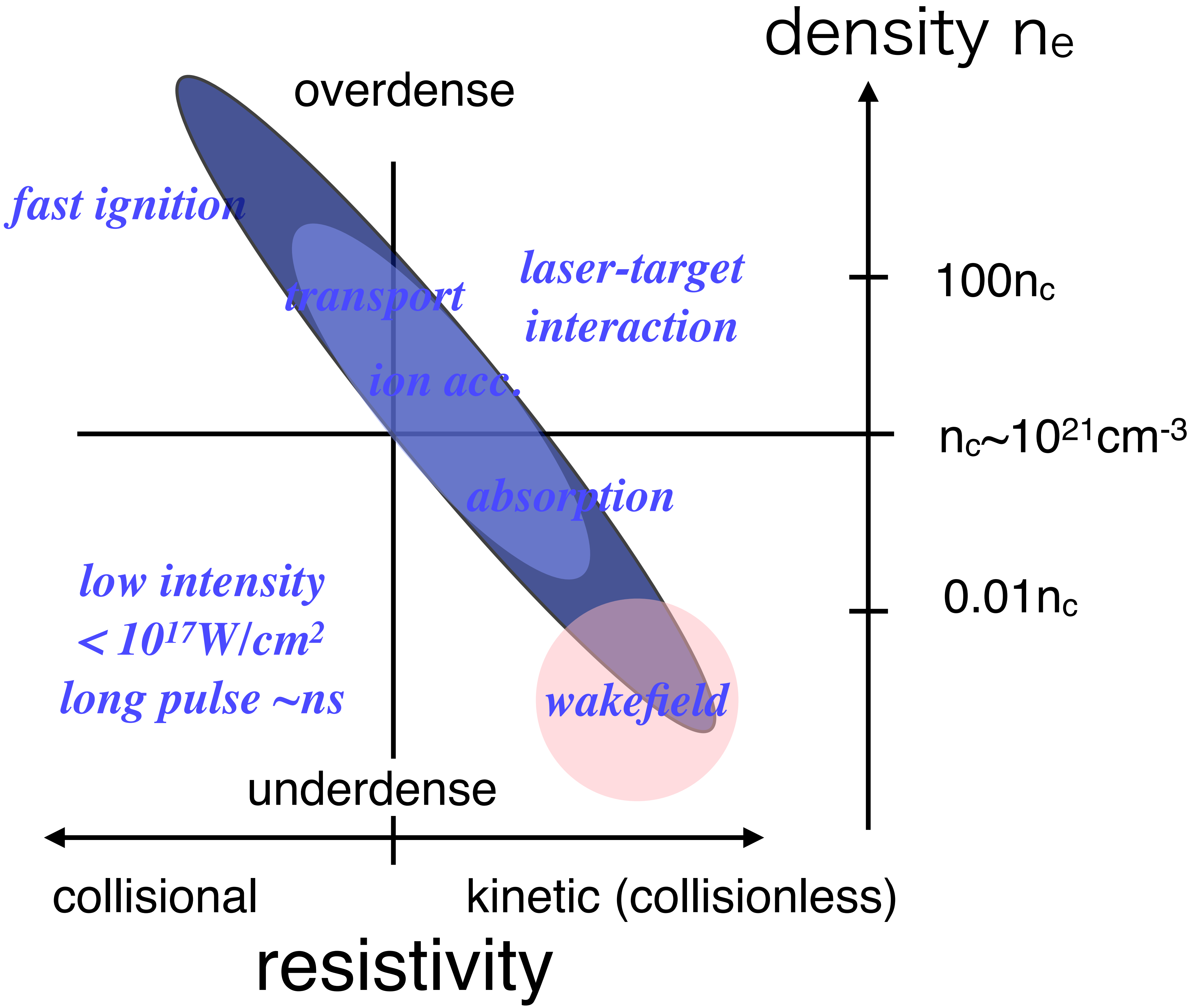

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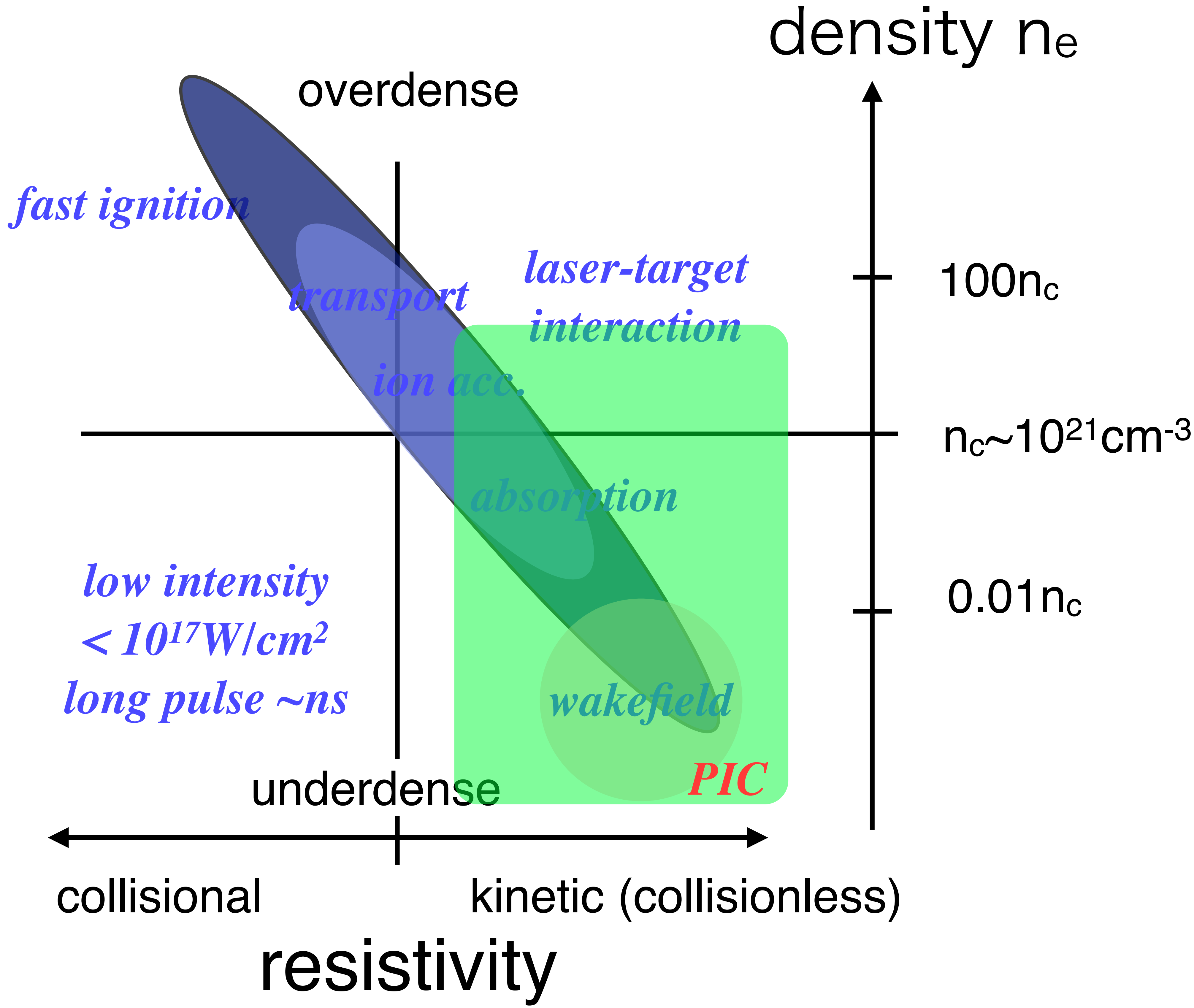

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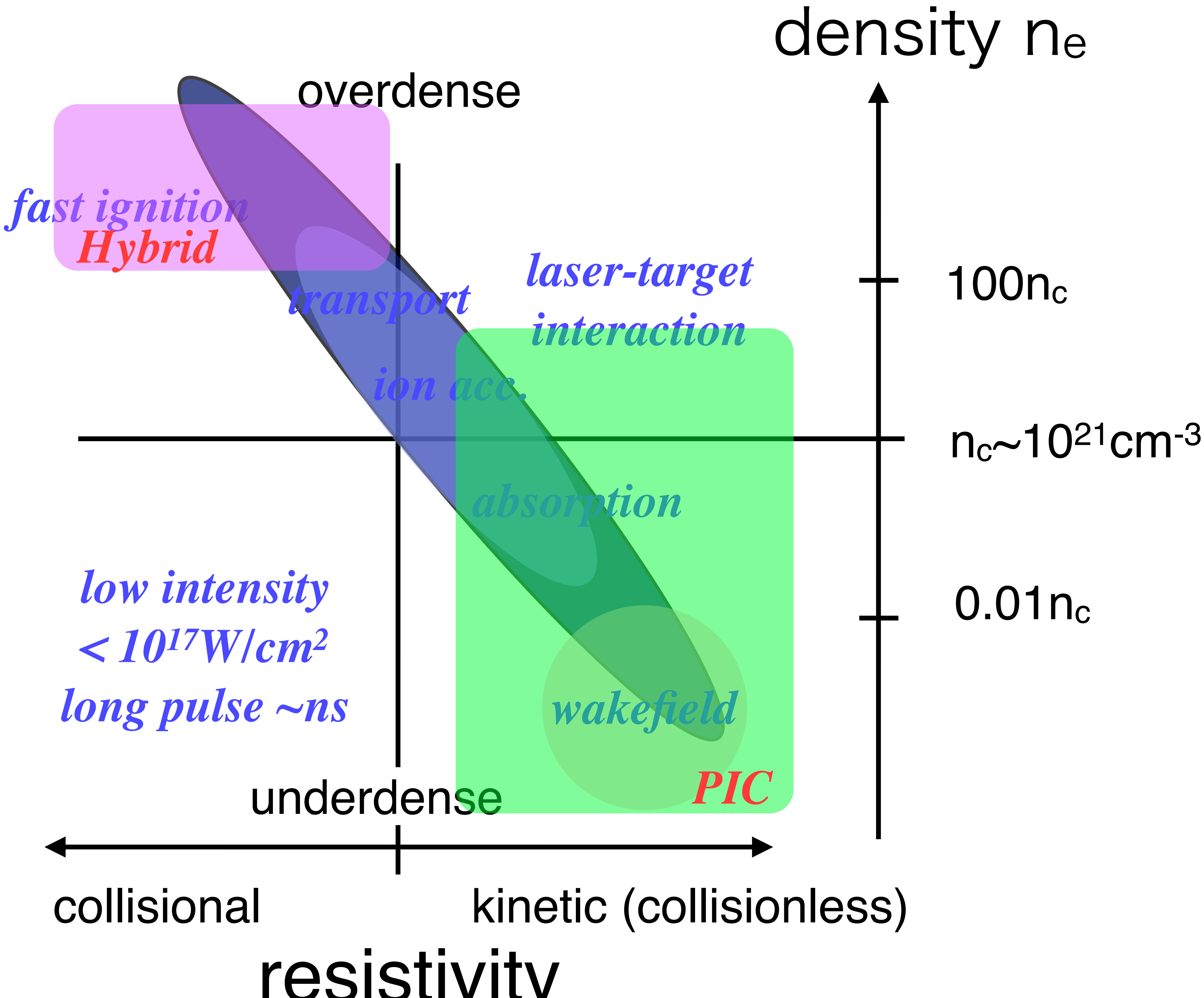

Is your plasma kinetic or collisional?