Numerical Simulations of Laser-Plasma Based Electron Acceleration

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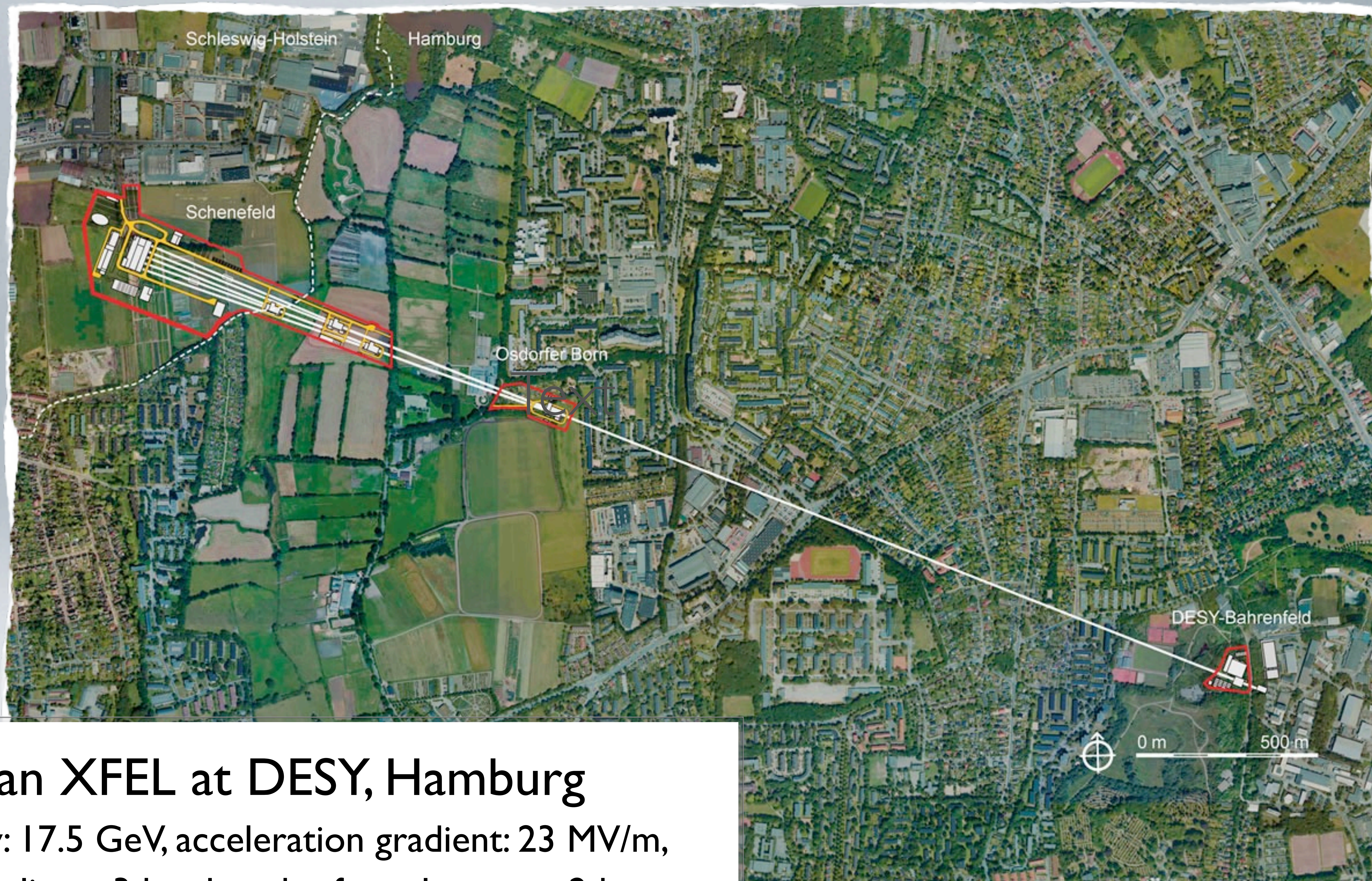
Gruppe für Plasmabeschleunigung
Universität Hamburg und DESY

Modern accelerators are large-scale machines



European XFEL at DESY, Hamburg

Electron energy: 17.5 GeV, acceleration gradient: 23 MV/m,
length of beam line: ~3 km, length of accelerator: ~2 km

Plasma accelerators allow for extreme electric fields

LOASIS TREX at LBNL, Berkeley

Laser-driven plasma accelerator for electrons with 1.0 GeV

Length: 3.3 cm, average acceleration gradient: 30 GV/m

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10^3 times larger than in conventional accelerators

Plasma accelerators allow for extreme electric fields

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

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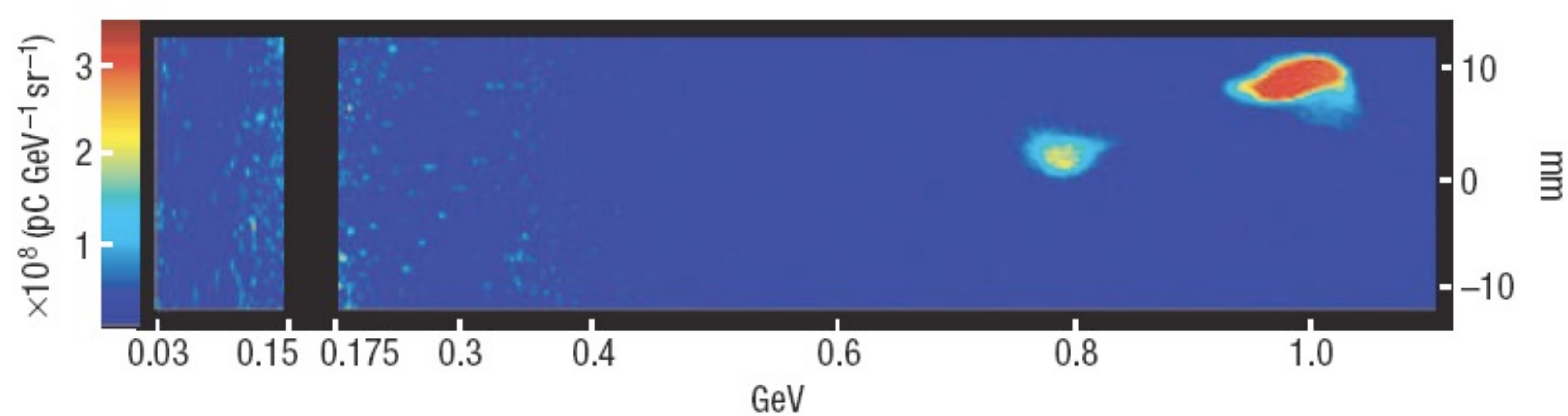
40 TW laser pulse (3×10^{18} W/cm^2) inside plasma with $n_e = 4.3\times10^{18}$ cm^{-3}

→ 30 pC of electrons at 1 GeV

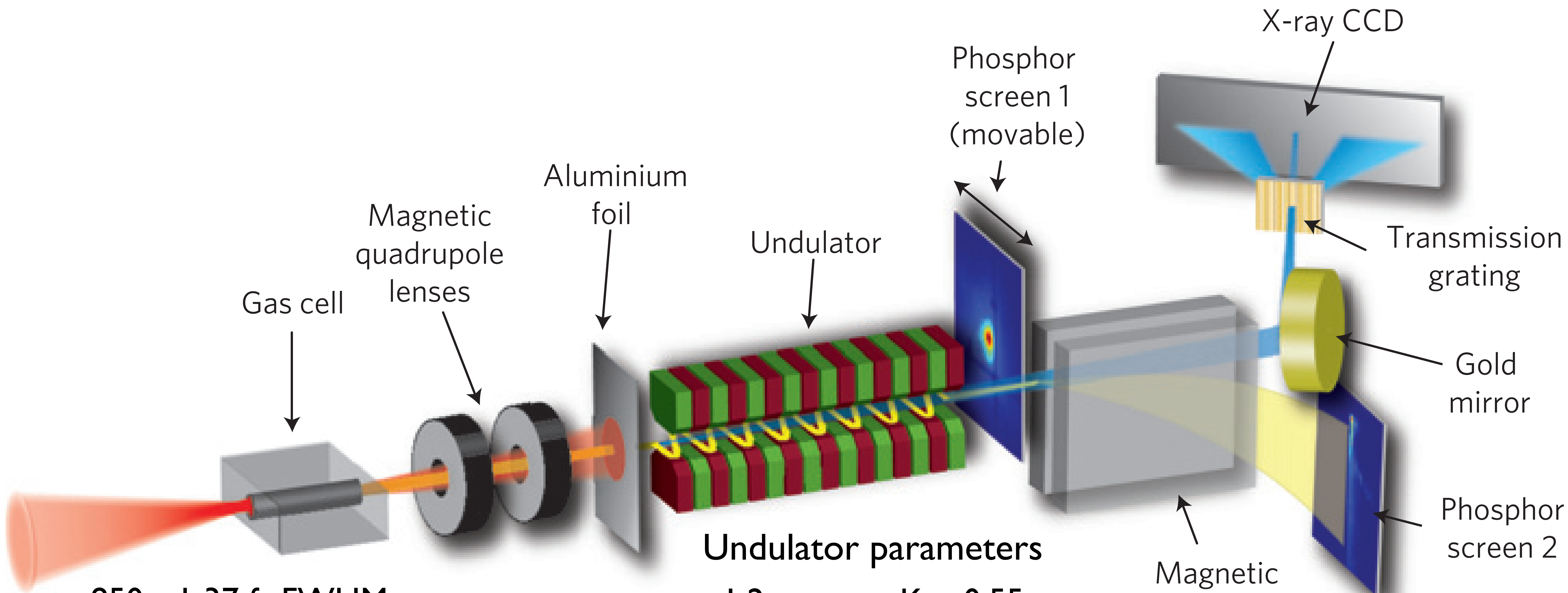
accelerated over a distance < 3 cm (with > 33 GV/m fields)



Leemans *et al.*, Nature Physics 2, 696 (2006)

Generation of soft-X-rays from an LPA driven undulator

Fuchs *et al.*, Nature Physics 5, 826 (2009)



Laser pulse parameters

850 mJ, 37 fs FWHM
23 μm focus FWHM

Undulator parameters

1.2 mm gap, K = 0.55
λ_u = 5 mm, 60 periods

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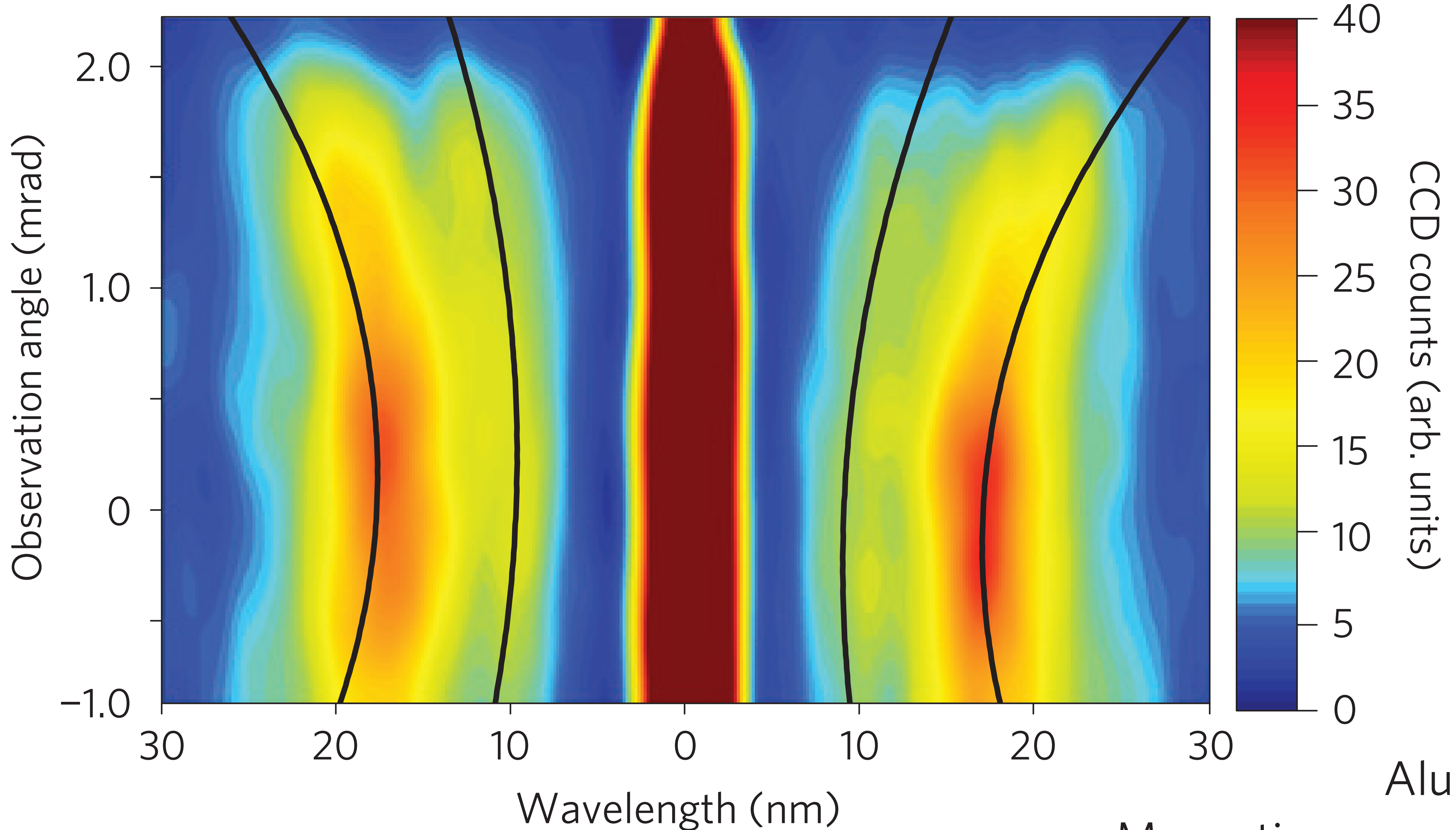
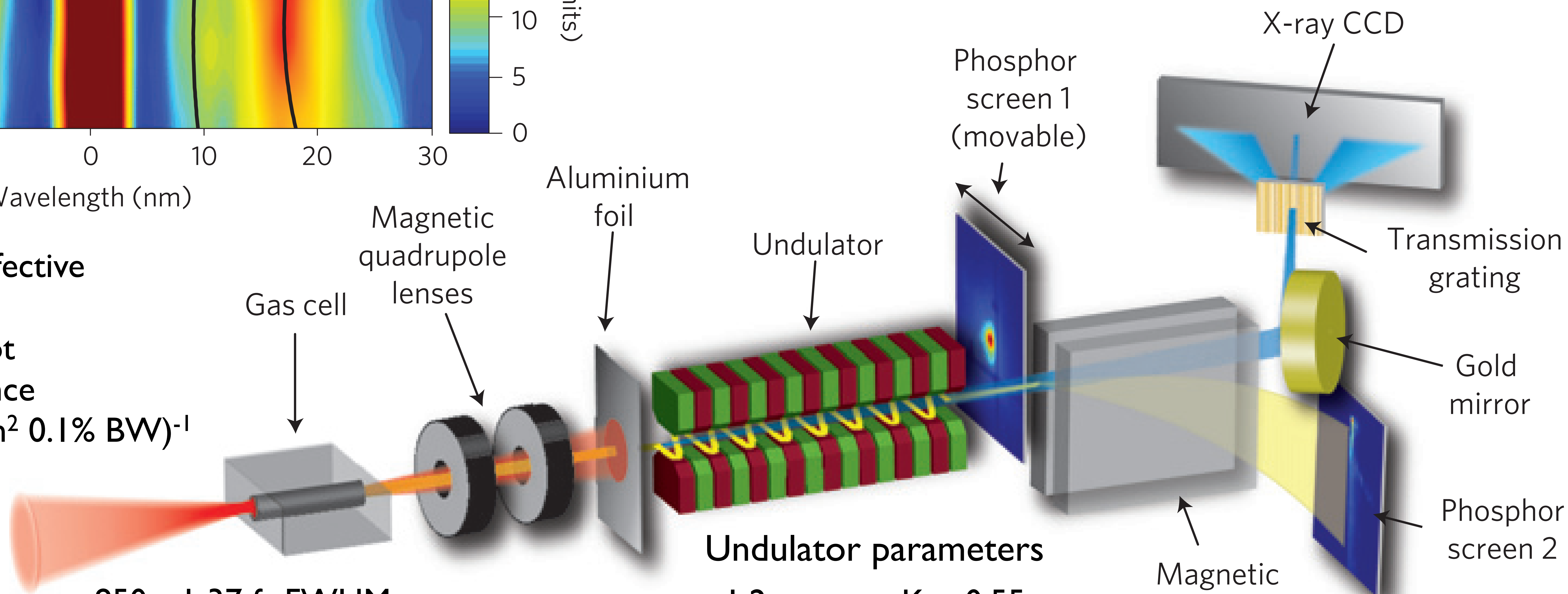


Resonance condition:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

- ~1 pC of charge in effective electron spectrum
- ~10^5 photons per shot
- Estimated peak brillance 1.3×10^{17} (s mrad^2 mm^2 0.1% BW)$^{-1}$



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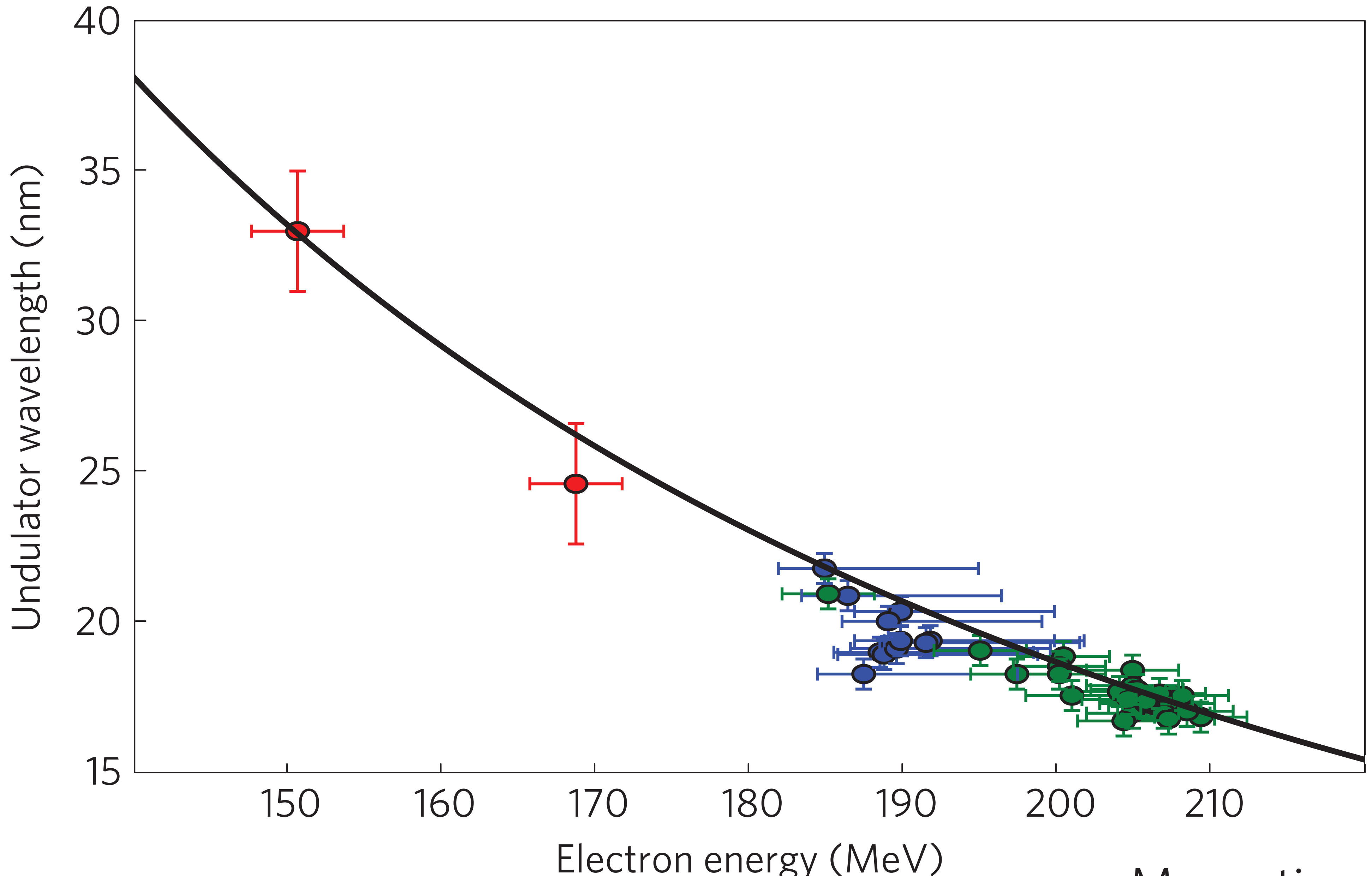

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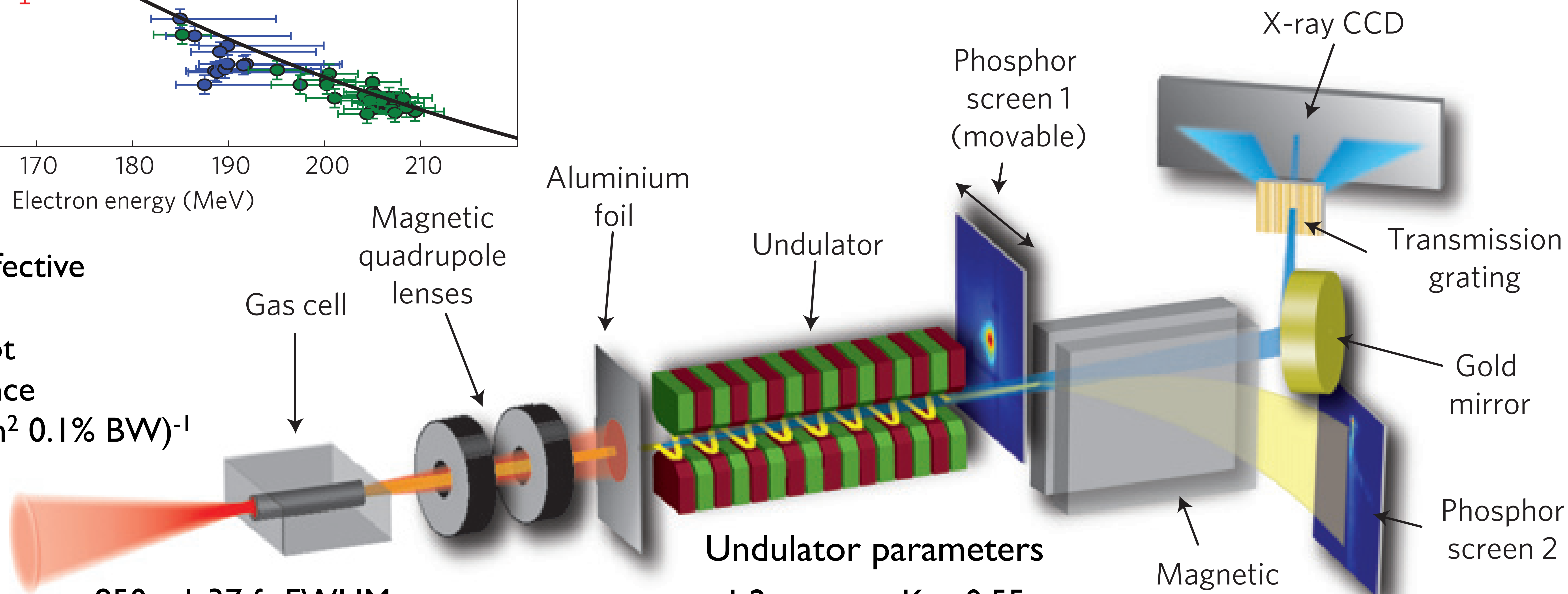

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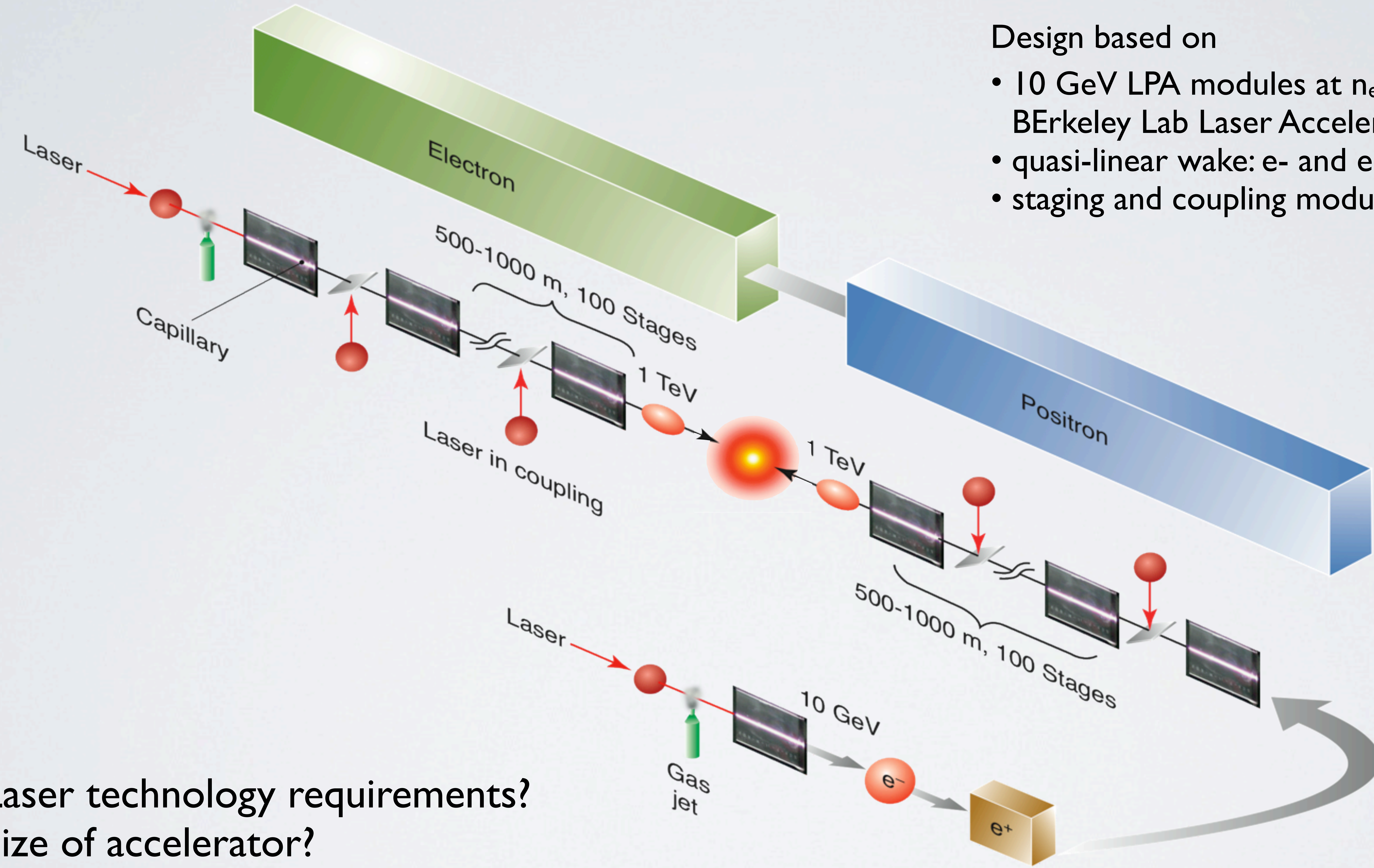
Constructing a TeV-class LPA-based linear collider



Design based on

- 10 GeV LPA modules at $n_e \approx 10^{17}$ cm^{-3} BErkeley Lab Laser Accelerator (BELLA)
- quasi-linear wake: e- and e+, wake control
- staging and coupling modules

- Laser technology requirements?
- Size of accelerator?

W. P. Leemans and E. Esarey, Physics Today (March 2009)

Laser-plasma accelerator basics

Wake excitation

Electron injection

High-intensity lasers can drive large plasma wakes

Background plasma

Laser pulse

Electron-depleted cavity

Laser pulse properties
a = 2
λ_c = 800 nm
$\Delta\tau$ = 25 fs FWHM
w_0 = 23 µm FWHM

Plasma background density
$n_p \leq 5\times10^{18}$ cm^{-3}

Run time
~500 h on 512 cores
(IBM Power 6, VIP at IPP)

osiris v2.0

INSTITUTO SUPERIOR TÉCNICO

USC

UCLA

3D particle-in-cell (PIC) simulation

Laser pulse propagates into a plasma-density ramp, electrons get trapped

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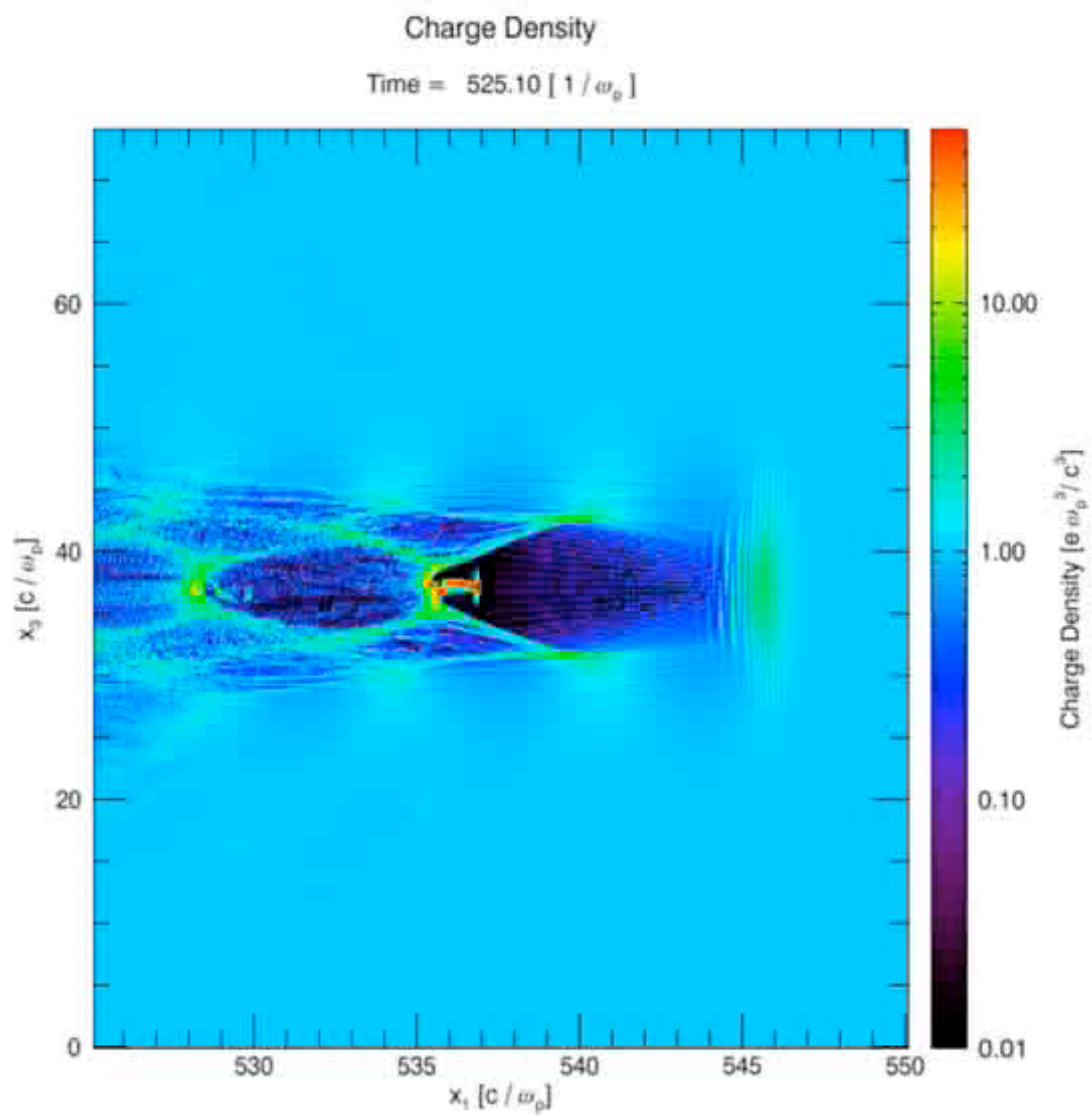


Laser pulse propagates into a plasma-density ramp, electrons get trapped

osiris v2.0

3D particle-in-cell (PIC) simulation

First computational studies at PAX: external injection

Charge density

Laser pulse properties
a_0 = 1.7
λ = 800 nm
τ = 30 fs FWHM
w = 60 μm FWHM

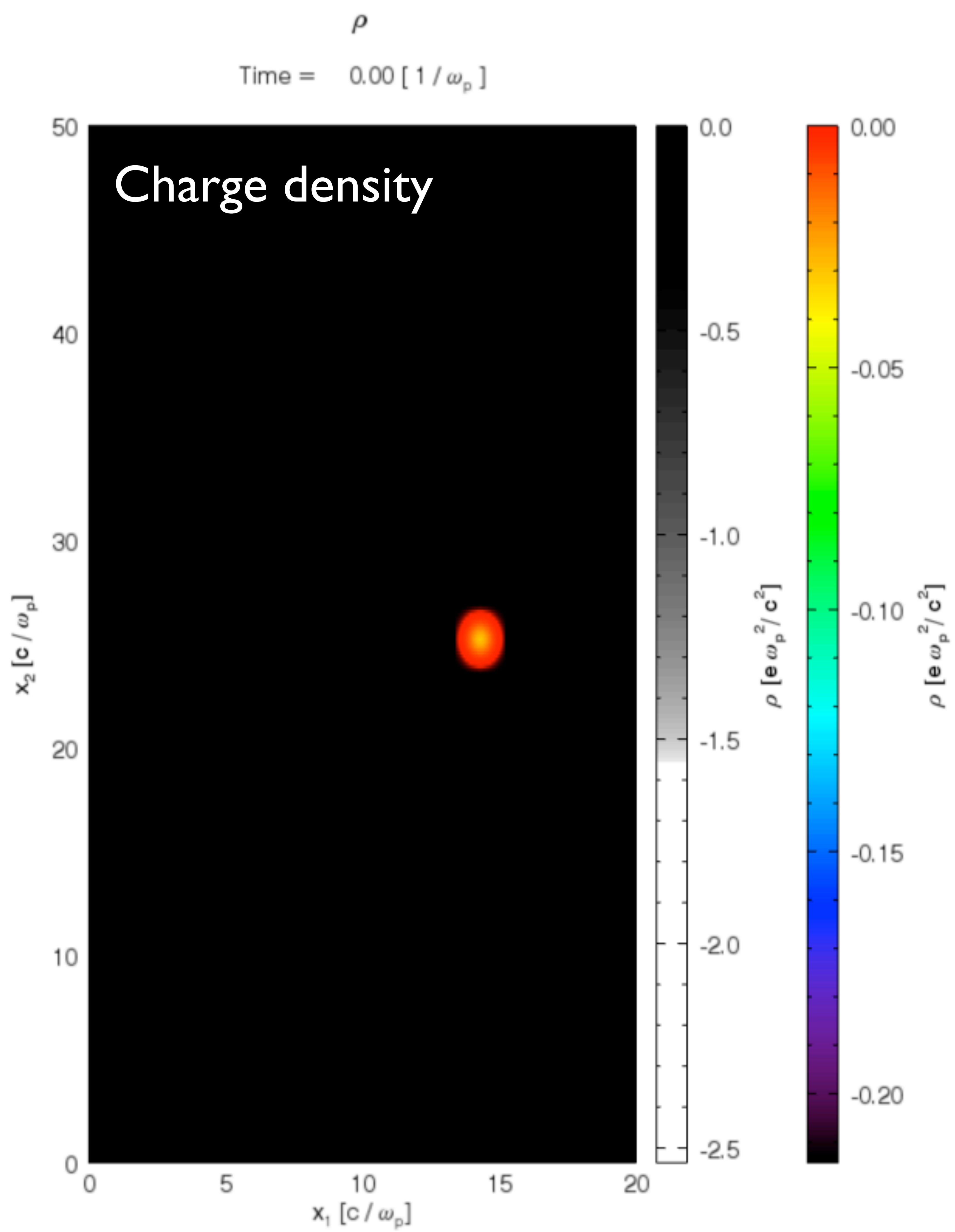
Plasma background density
n = 1×10^{17} cm^{-3}

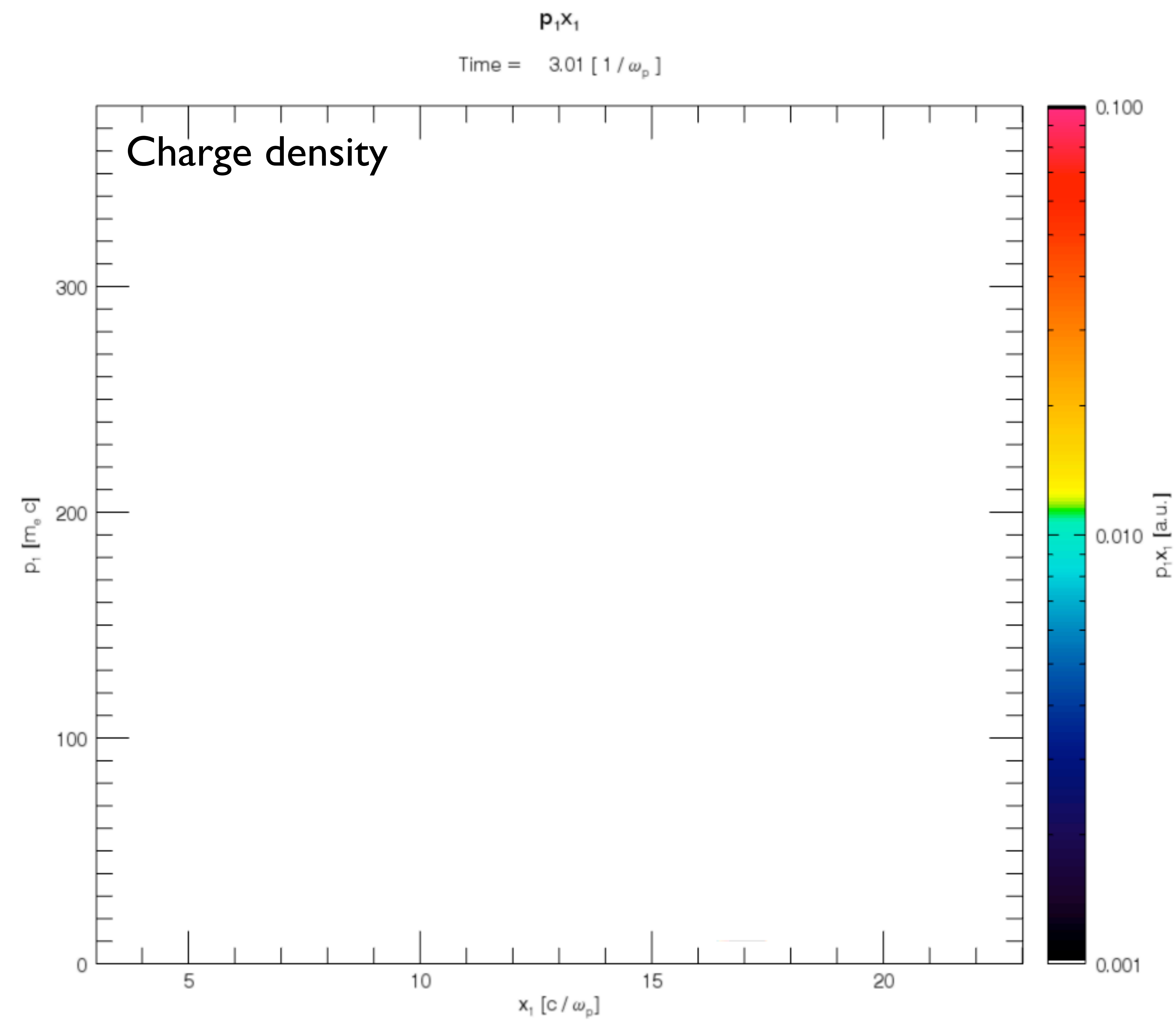
Electron beam properties
τ = 10 fs RMS
σ_{trans} = 10 μm
Q = 1 pC
E = 5 MeV
ΔE = 33 keV

Run time
~24 h on 64 cores @ PAX

…first 24 mm in 2d space

First computational studies at PAX: external injection





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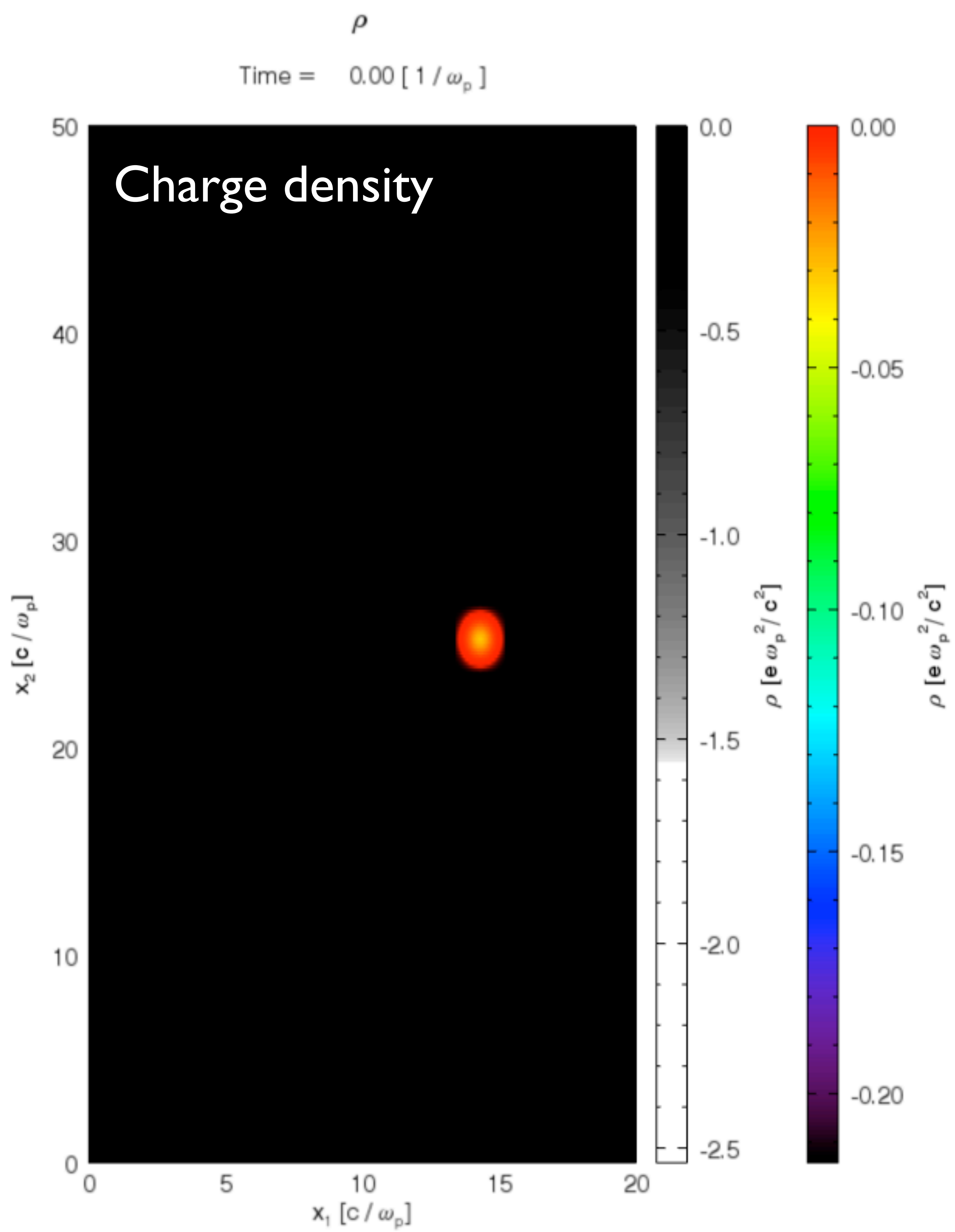
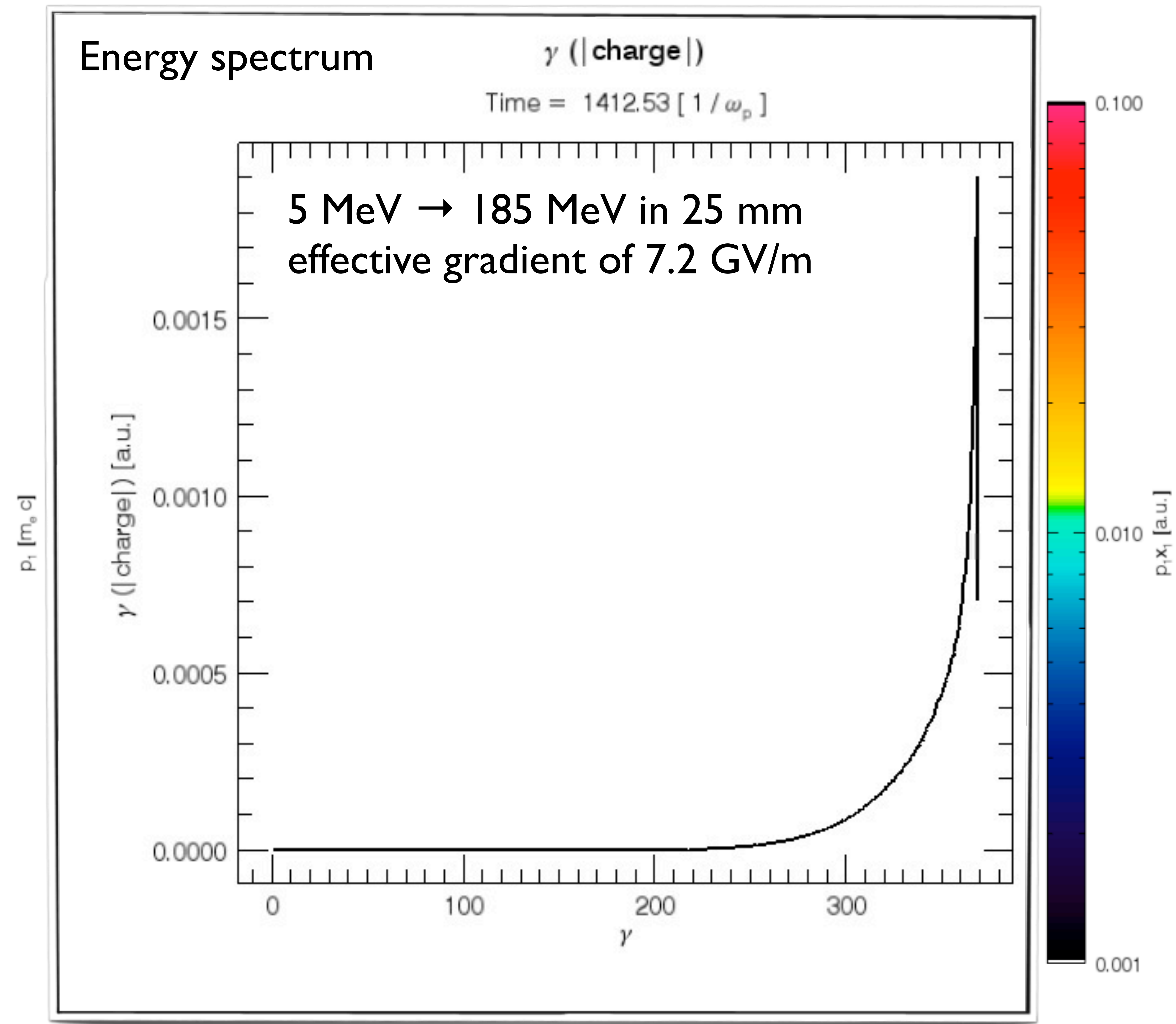




Particle in cell method in a nutshell

- Particles are combined into macro particles
- Space is divided into cells
- Macro particles move freely
- Currents, electric and magnetic fields are defined on grid points

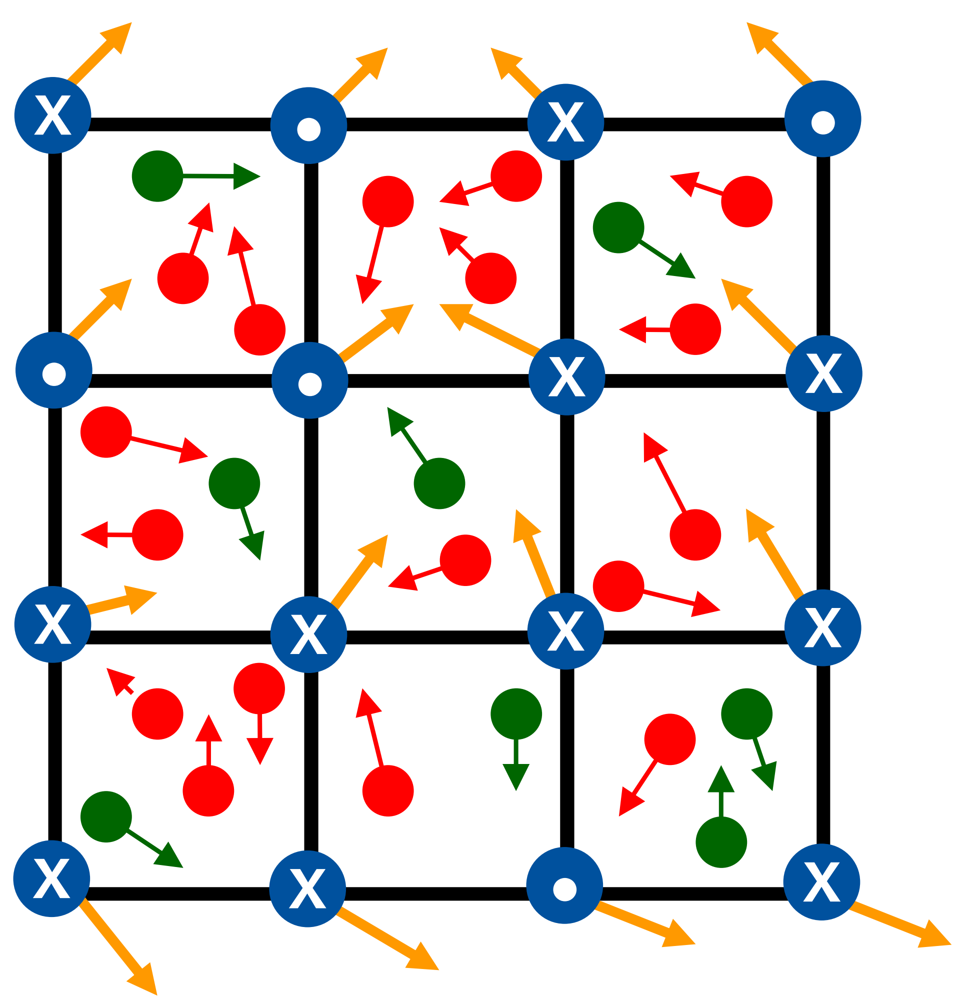
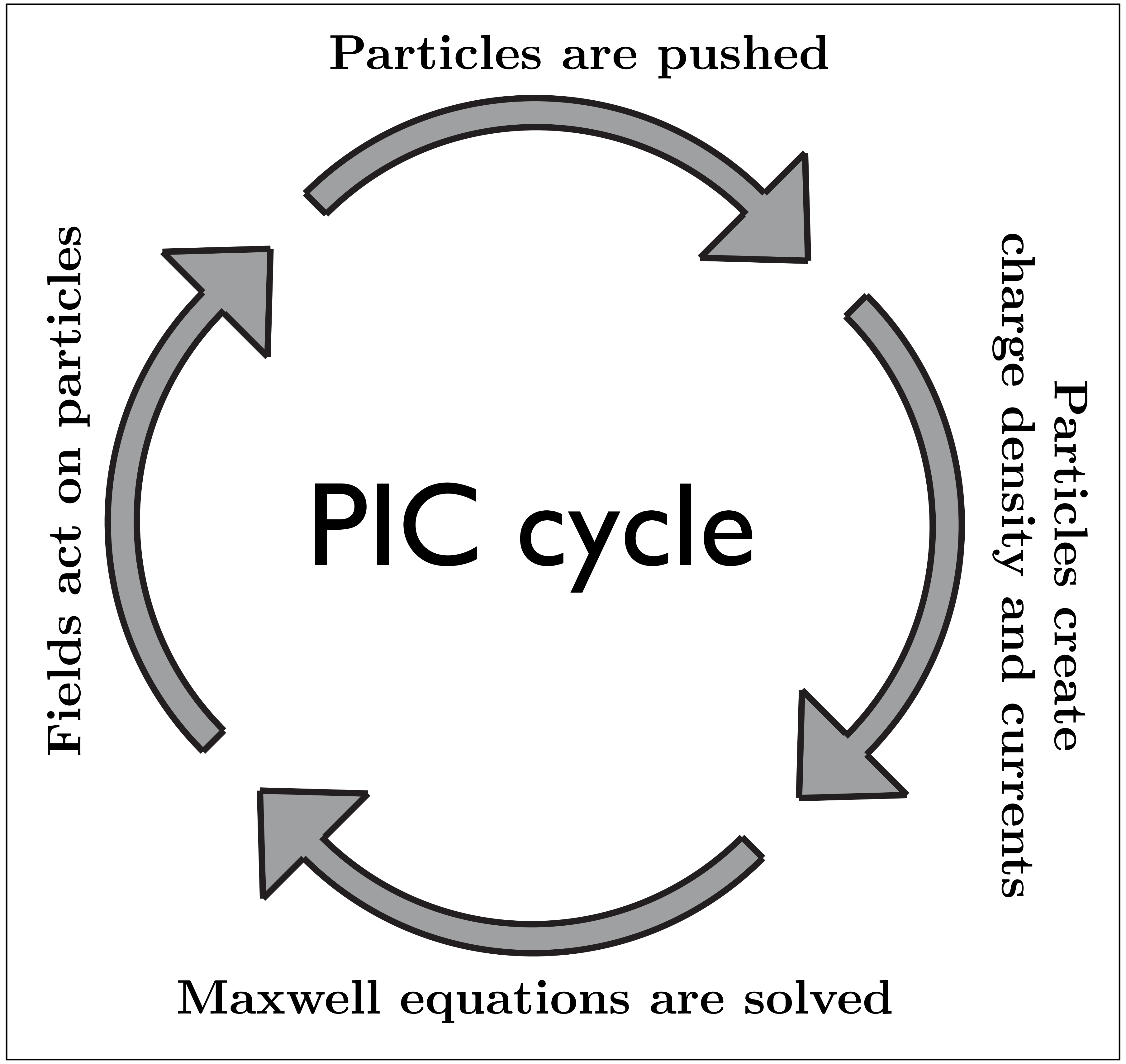


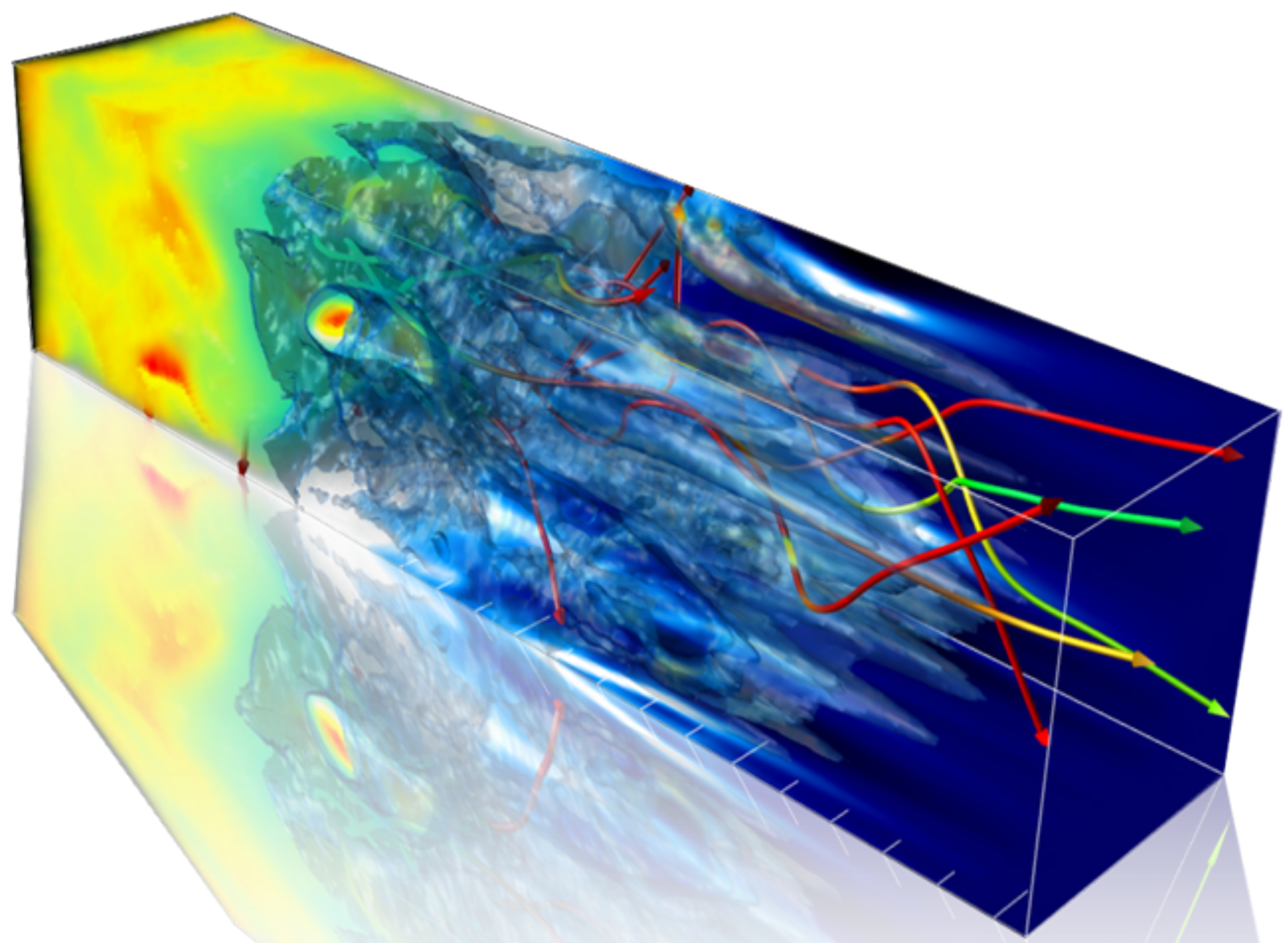
Image by René Widera, HZDR



OSIRIS 2.0

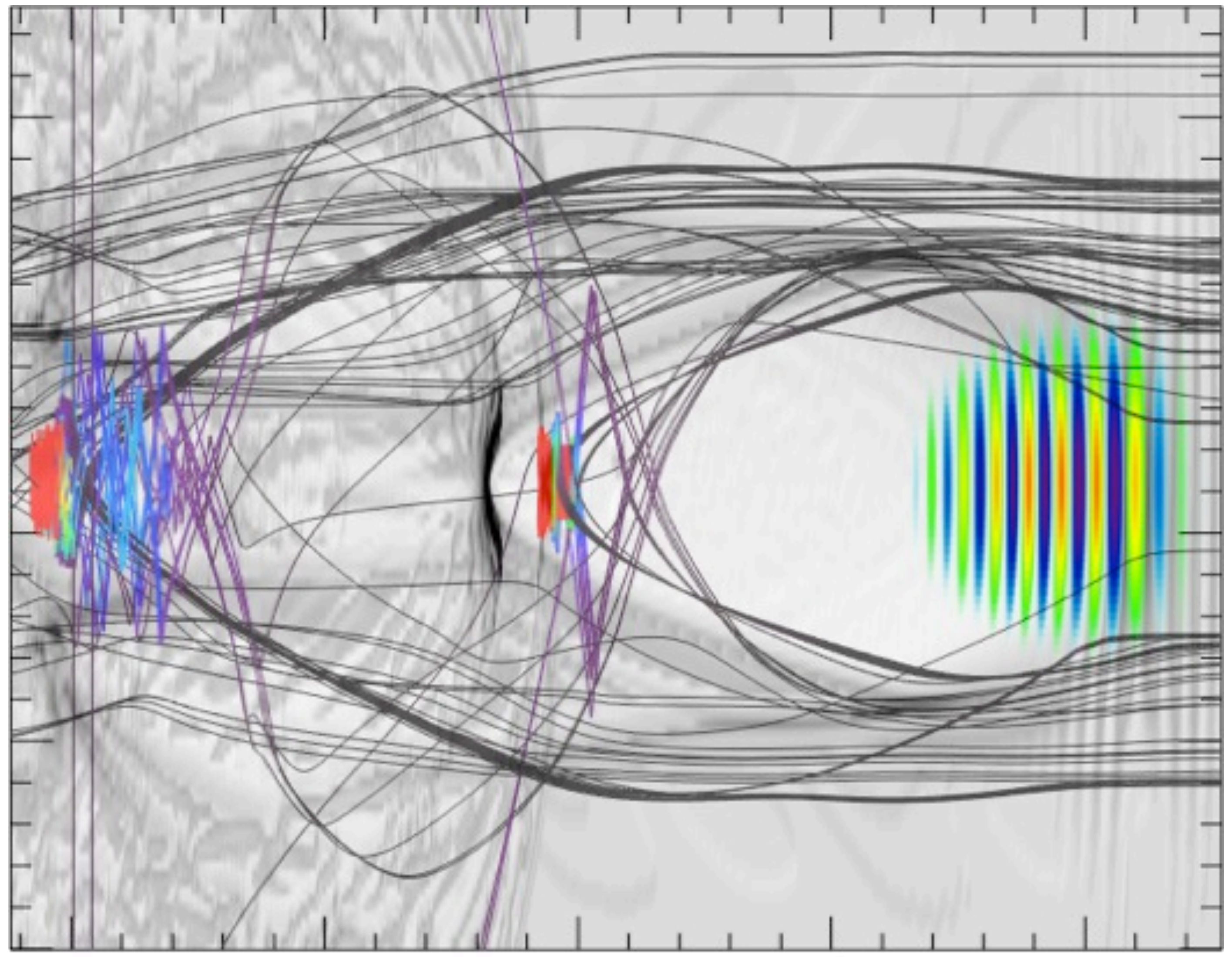
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

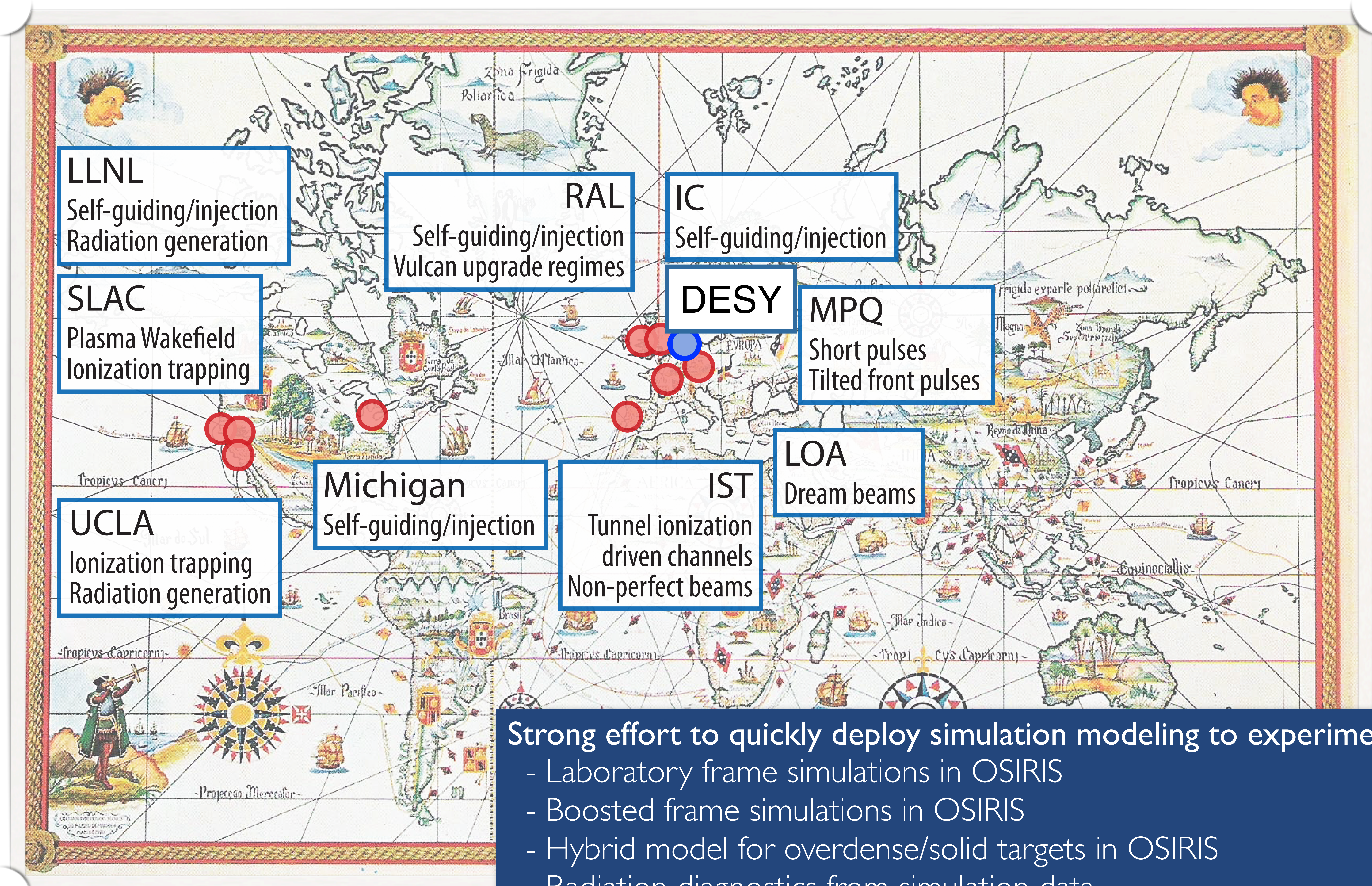
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/



New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

OSIRIS has been used to model many experiments



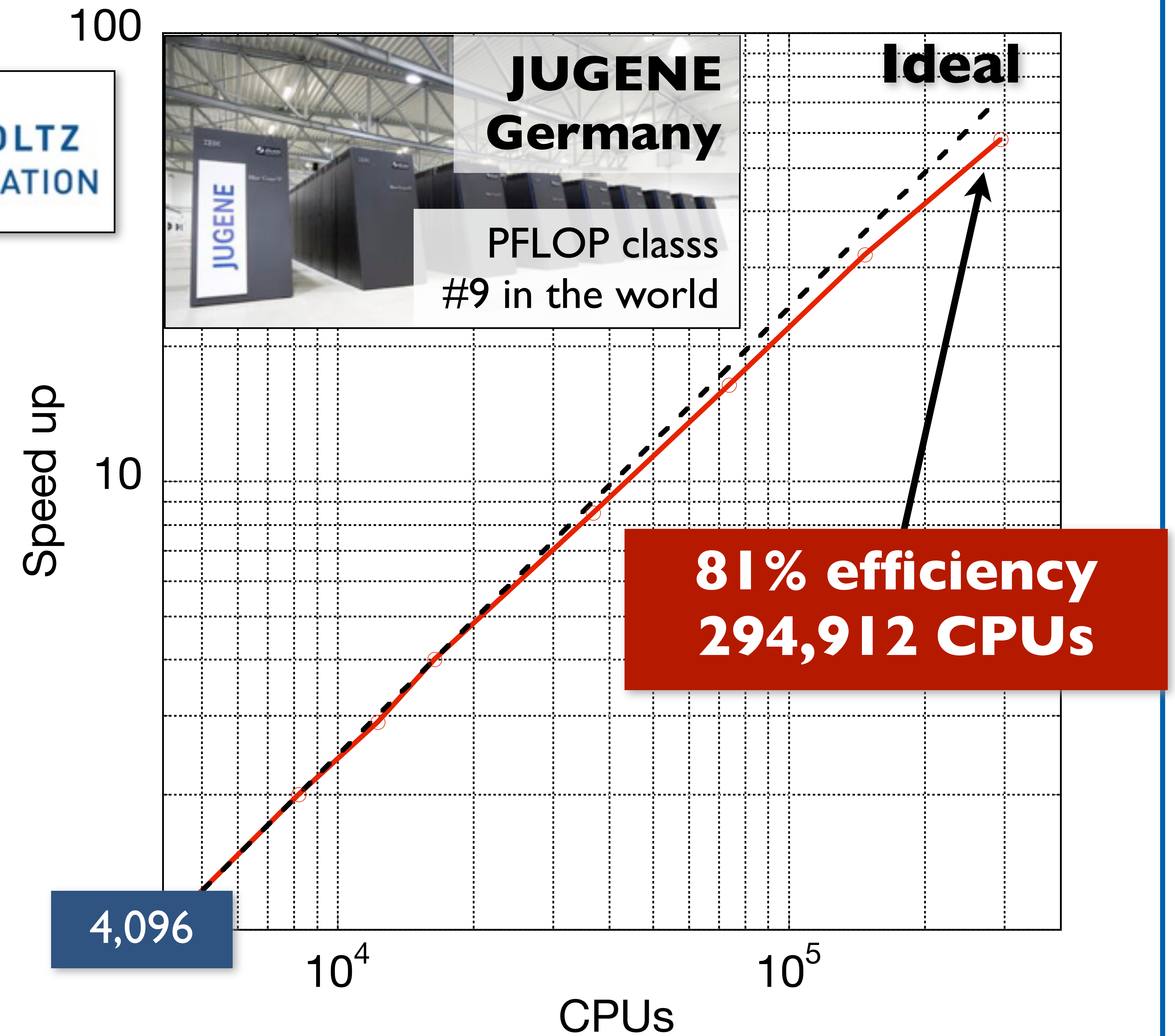
Strong effort to quickly deploy simulation modeling to experimental teams

- Laboratory frame simulations in OSIRIS
- Boosted frame simulations in OSIRIS
- Hybrid model for overdense/solid targets in OSIRIS
- Radiation diagnostics from simulation data

Optimize scalability and tap new hardware features

OSIRIS strong scaling up to ~300k CPUs

HELMHOLTZ ASSOCIATION



- ✱Spatial domain decomposition
- ✱Local field solver
- ✱Minimal communication
- ✱Dynamic Load Balancing

New hardware features

SIMD units

tailored code already in production

Power SOURCE · intel Core 2 Extreme inside · AMD Opteron 64

GPUs

CUDA development (test PIC code)

NVIDIA · GRAPHICS BY ATI

Typical hardware and CPU time requirements

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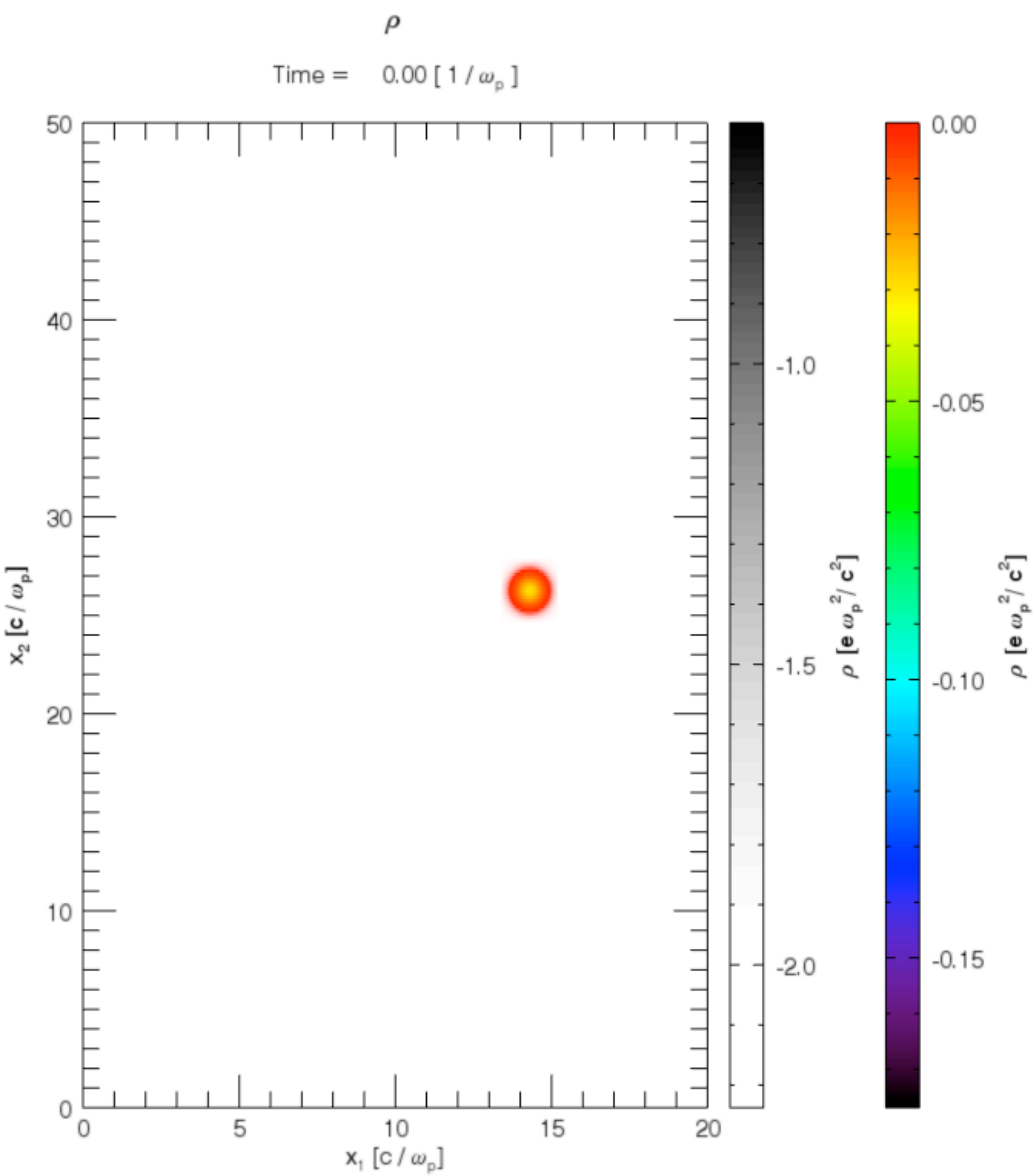

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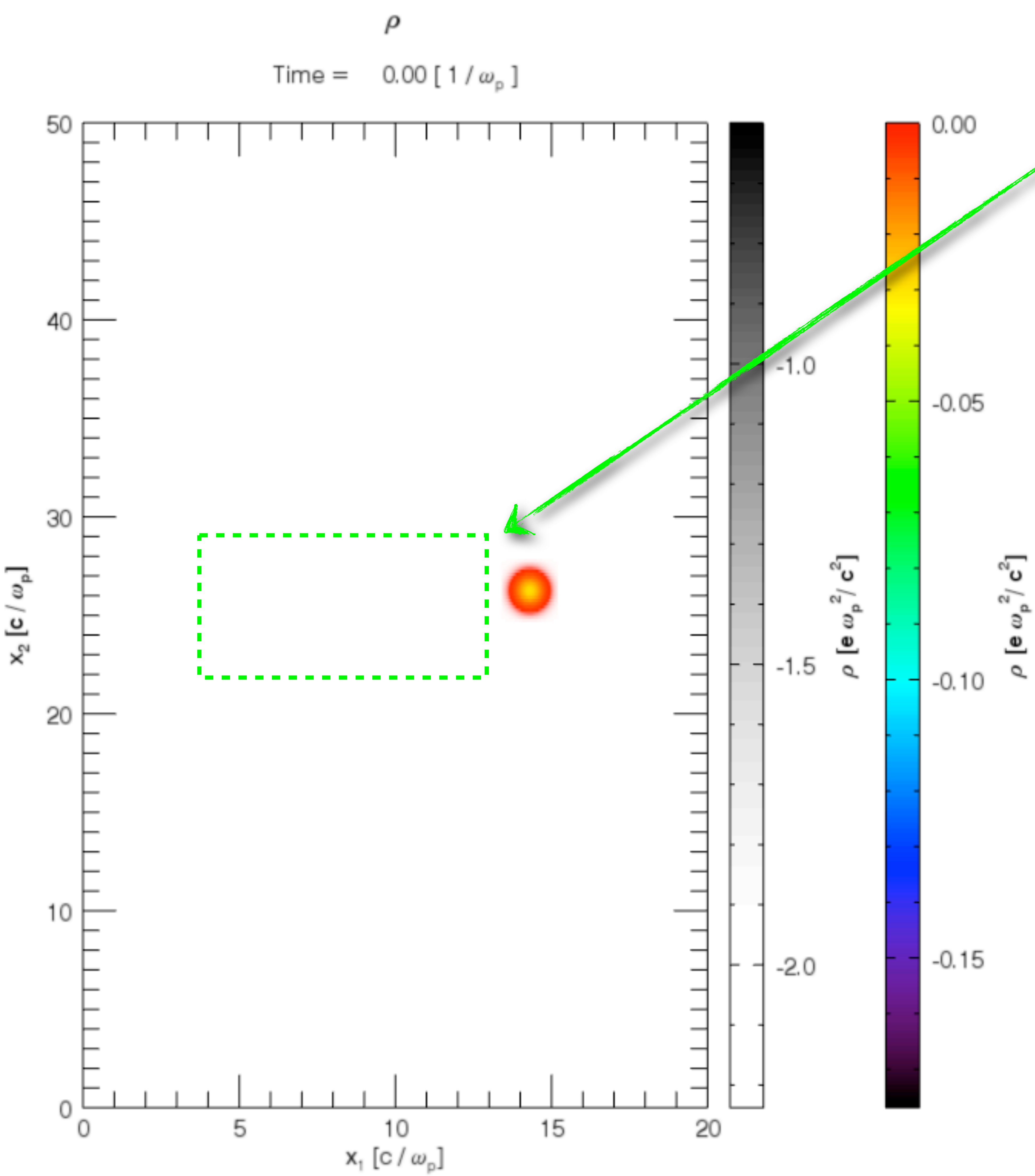
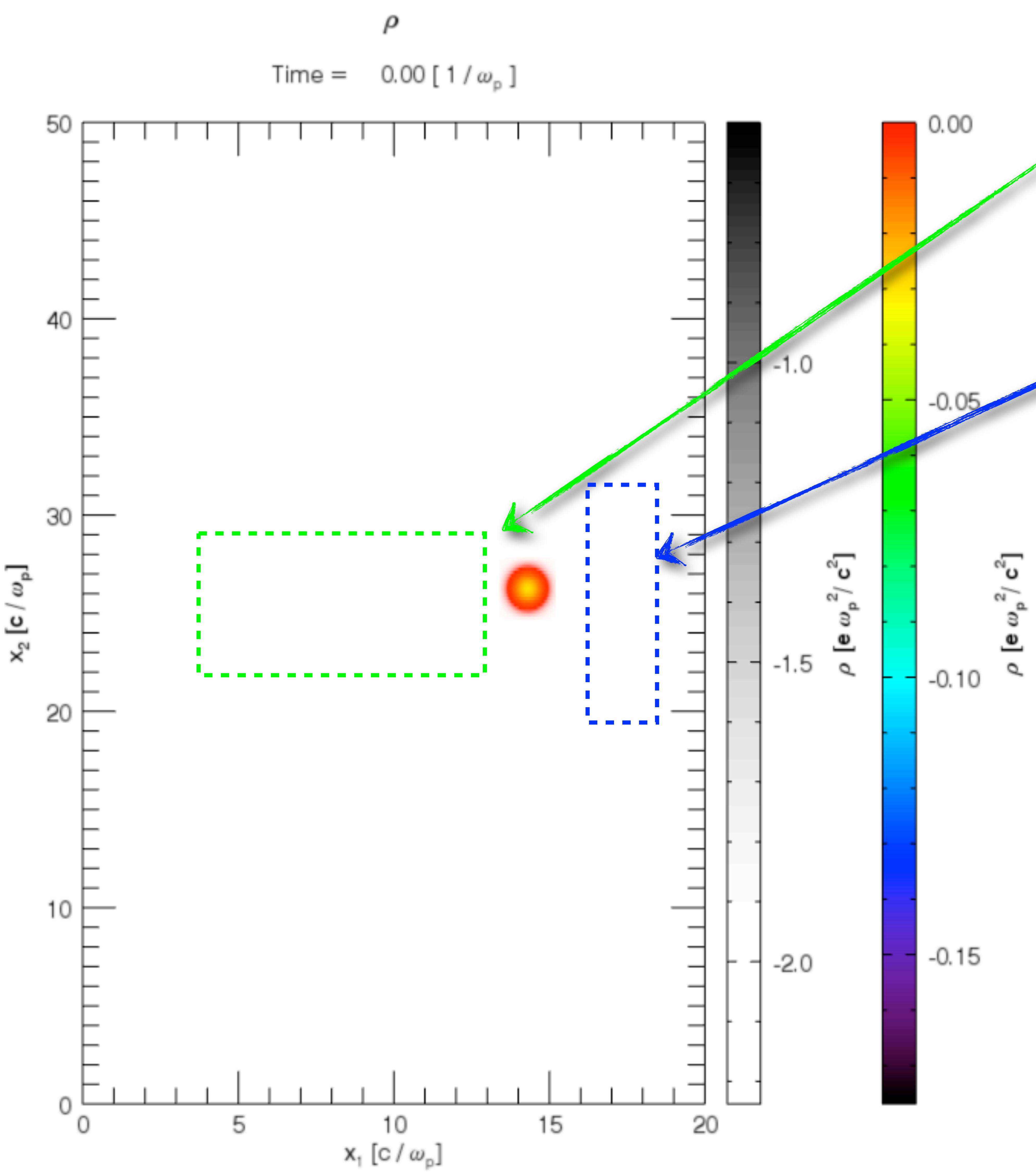


Plasma wave sets transverse resolution and box size

wavelength must be resolved and fit into box

Typical hardware and CPU time requirements



Plasma wave sets transverse resolution and box size
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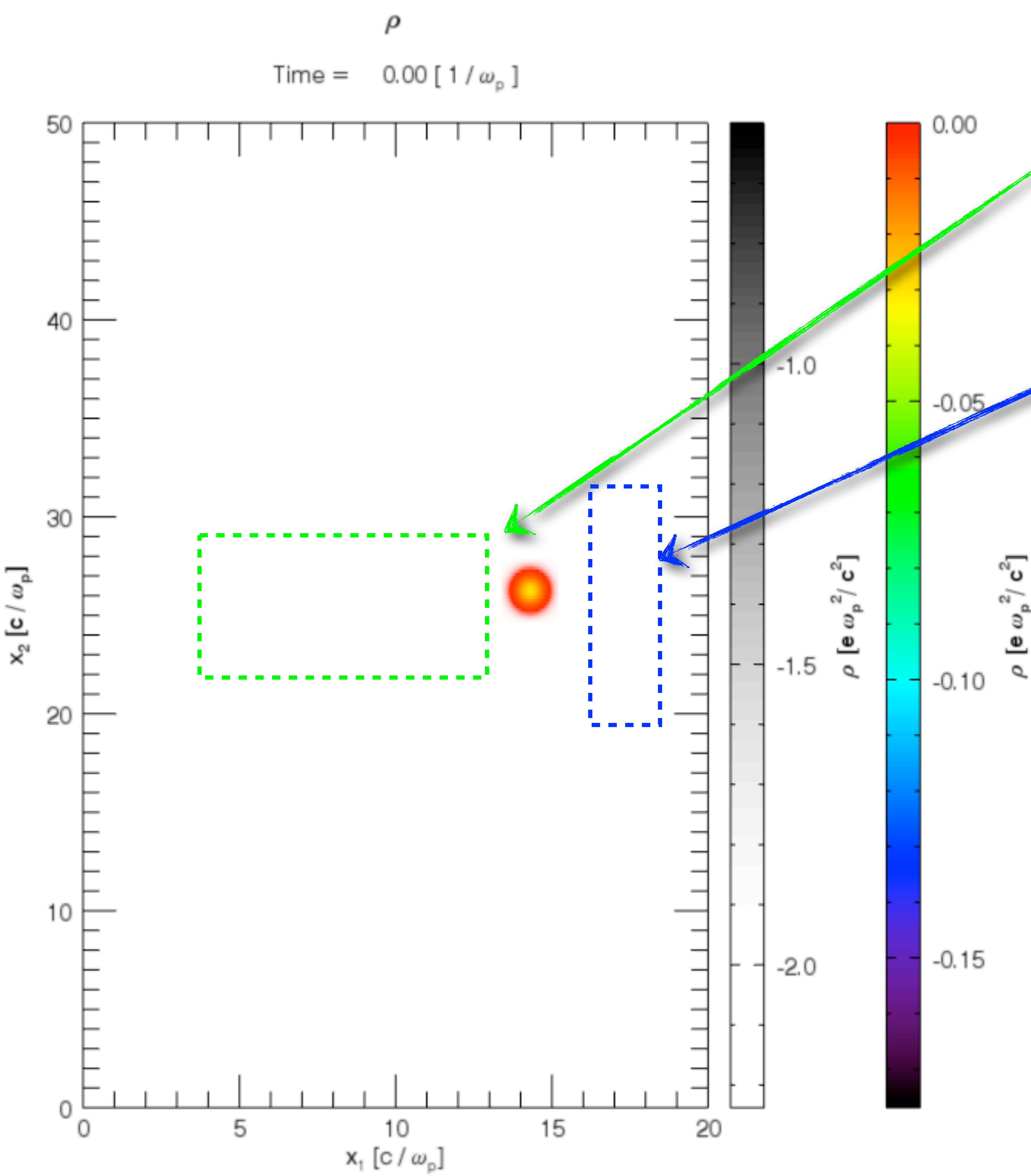
Laser pulse sets longitudinal resolution
wavelength must be resolved

Typical hardware and CPU time requirements



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↓

Typical number of grid points: 10^3 (1d), 10^6 (2d), 10^9 (3d)
and macro particles: 10^5 (1d), 10^7 (2d), 10^9 (3d)

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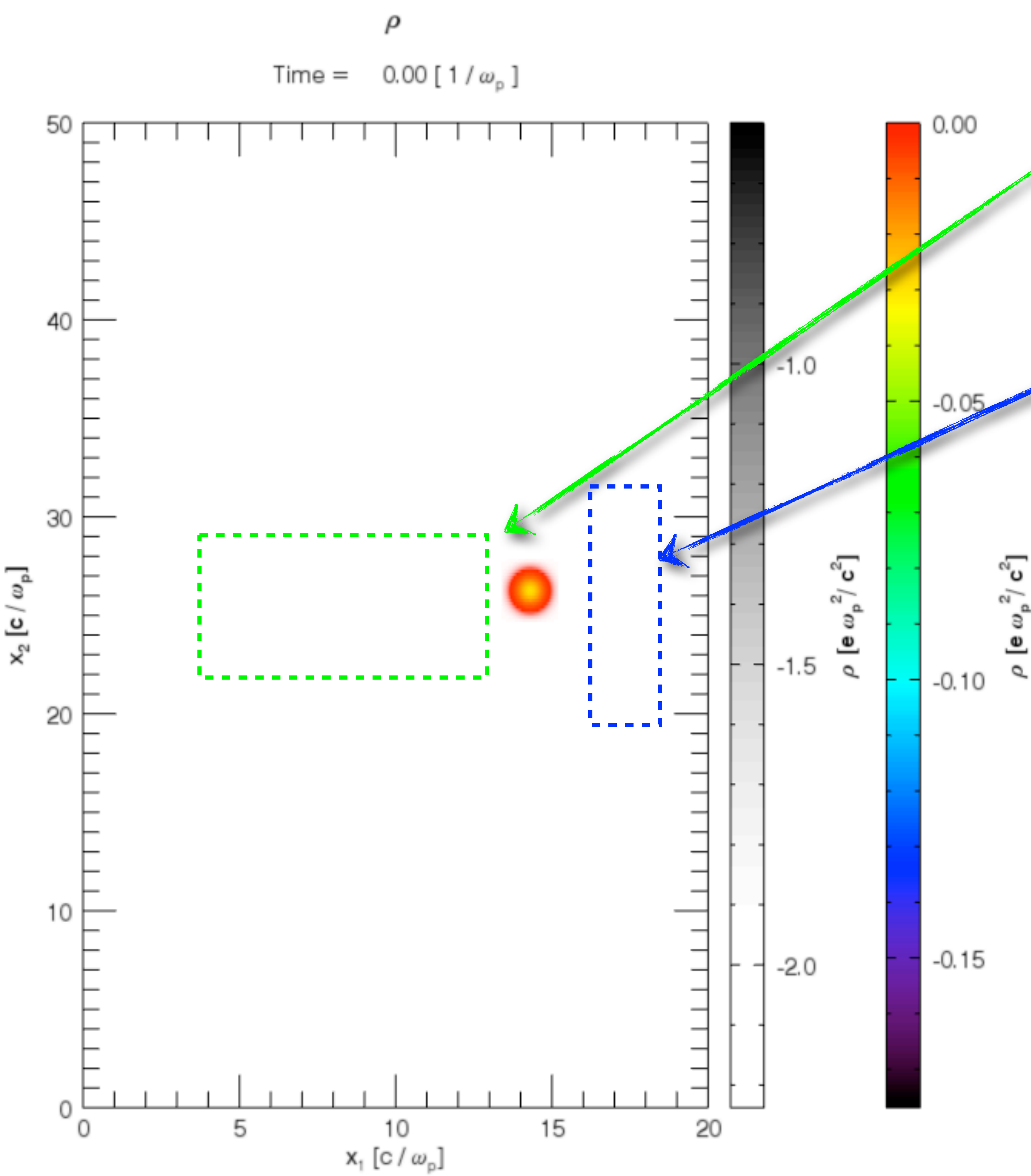

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RAM requirements: 50 MB (1d), 5 GB (2d), 100 GB (3d)

Calculation time (on current Intel CPUs):
20 CPU h / mm (1d), 250 CPU h / mm (2d), 10000 CPU h / mm (3d)

e.g. for 20 mm simulation distance:
4 days on quad core PC (1d),
2 days on 128 core PAX blade (2d),
8 days on the full 1024 core PAX cluster (3d)

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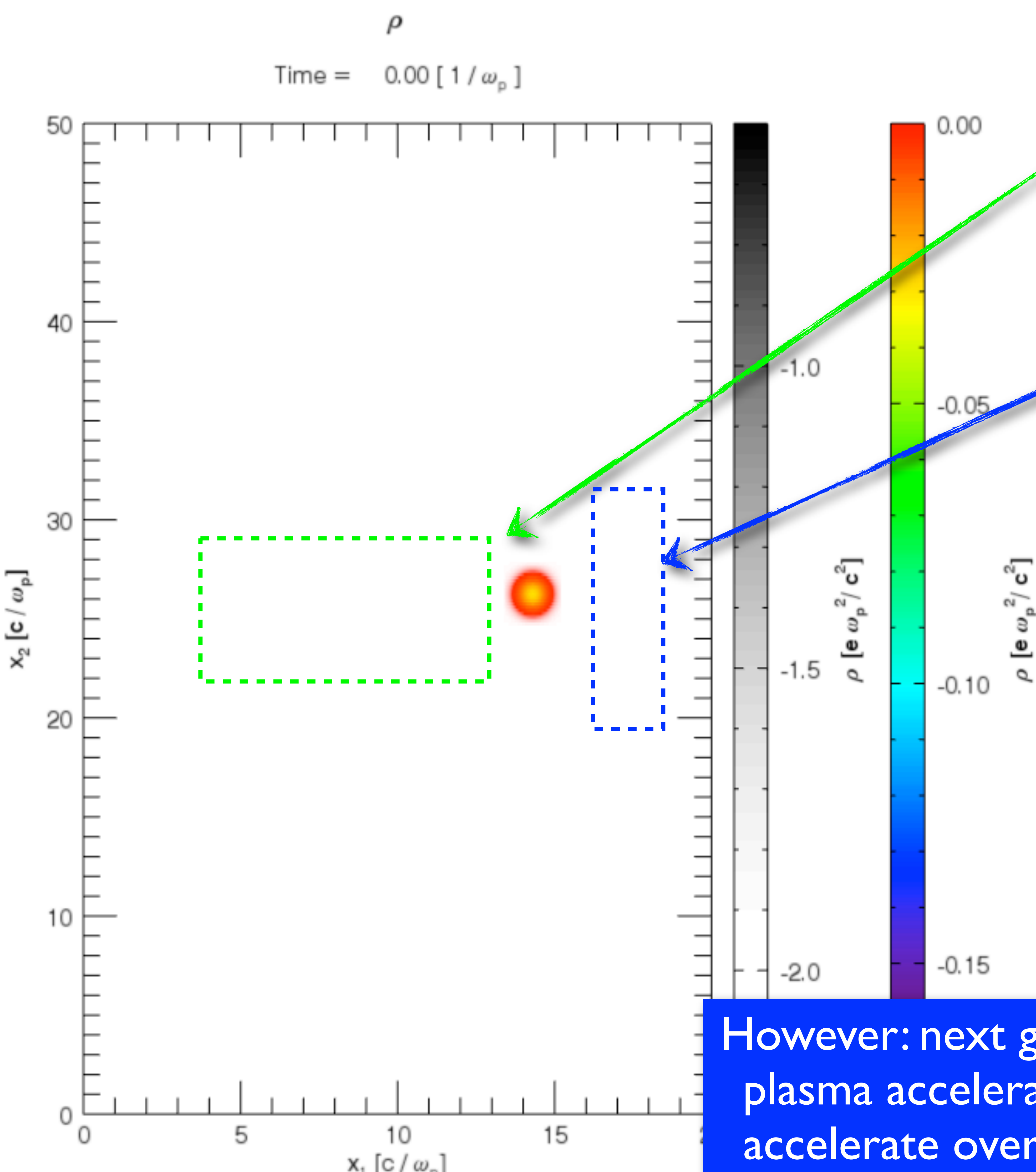

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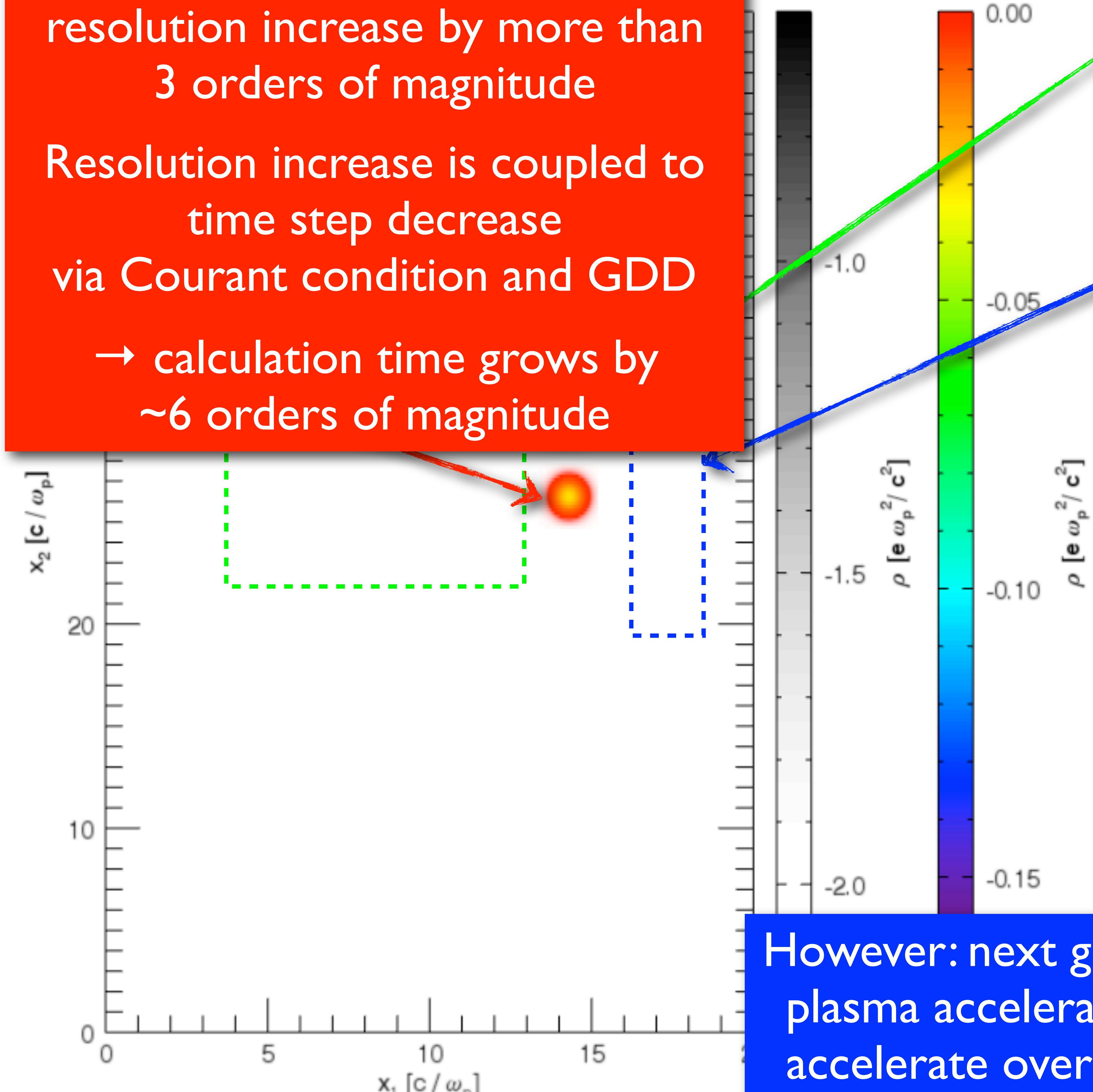
However: next generation plasma accelerators will accelerate over meters!

Typical hardware and CPU time requirements

Accurate propagation treatment of emitted synchrotron light requires resolution increase by more than 3 orders of magnitude

Resolution increase is coupled to time step decrease via Courant condition and GDD

→ calculation time grows by ~6 orders of magnitude



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Summary

- Laser-plasma based acceleration is a promising technique to realize compact, extremely high-gradient particle accelerators
- PIC simulations are used to prepare first plasma acceleration experiments at DESY
- Parameter studies are performed in 2 spatial dimensions for e.g. external beam injection into a wakefield
- Full featured 3d simulations are numerically expensive, but indispensable tools for a complete understanding of the involved processes
- Simulations of next generation laser-plasma accelerators will be able to utilize orders of magnitude more computing power than available today


Thank you for your attention!