POLITECNICO
MILANO 1863

Laser superintensi, materiali nanostrutturati, accelerazione di particelle: Il ruolo della matematica

Matteo Passoni

Milano, seminari di cultura matematica, 10 maggio 2017

Aims and outline of the seminar

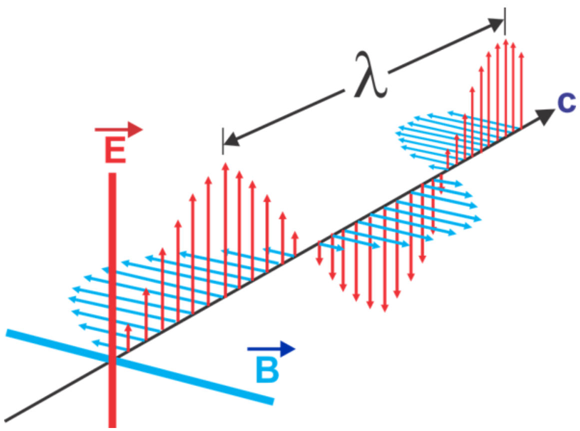
- Introduction to superintense laser-matter interaction

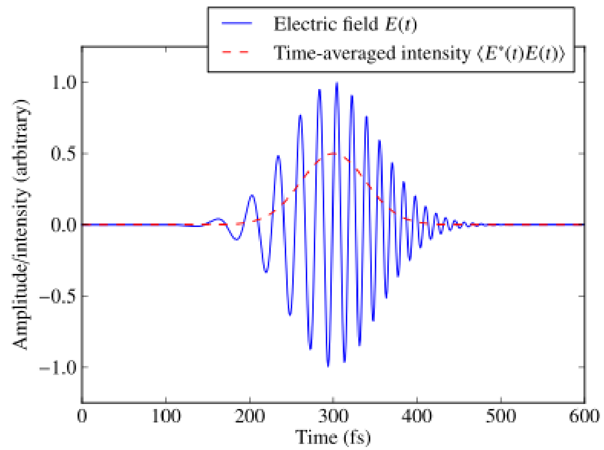
- Superintense laser-driven ion acceleration (especially using nanostructured targets)

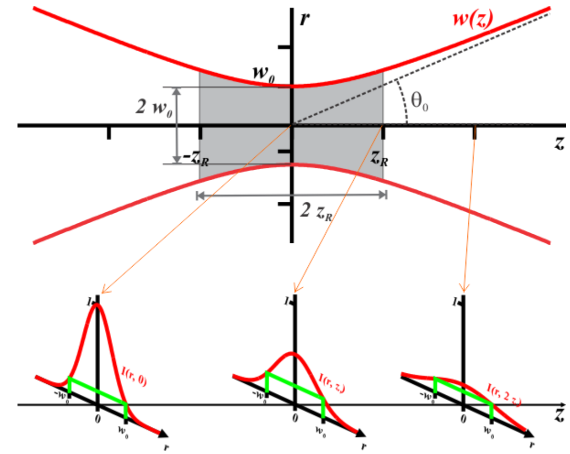
- What is the role of mathematics in all of this?

The Laser:

A revolution in the generation of electromagnetic radiation







Spatial and temporal coherence

Short pulse duration

Spatial focusing

Extremely high Intensity possible!

Electric field associated to the laser pulse:

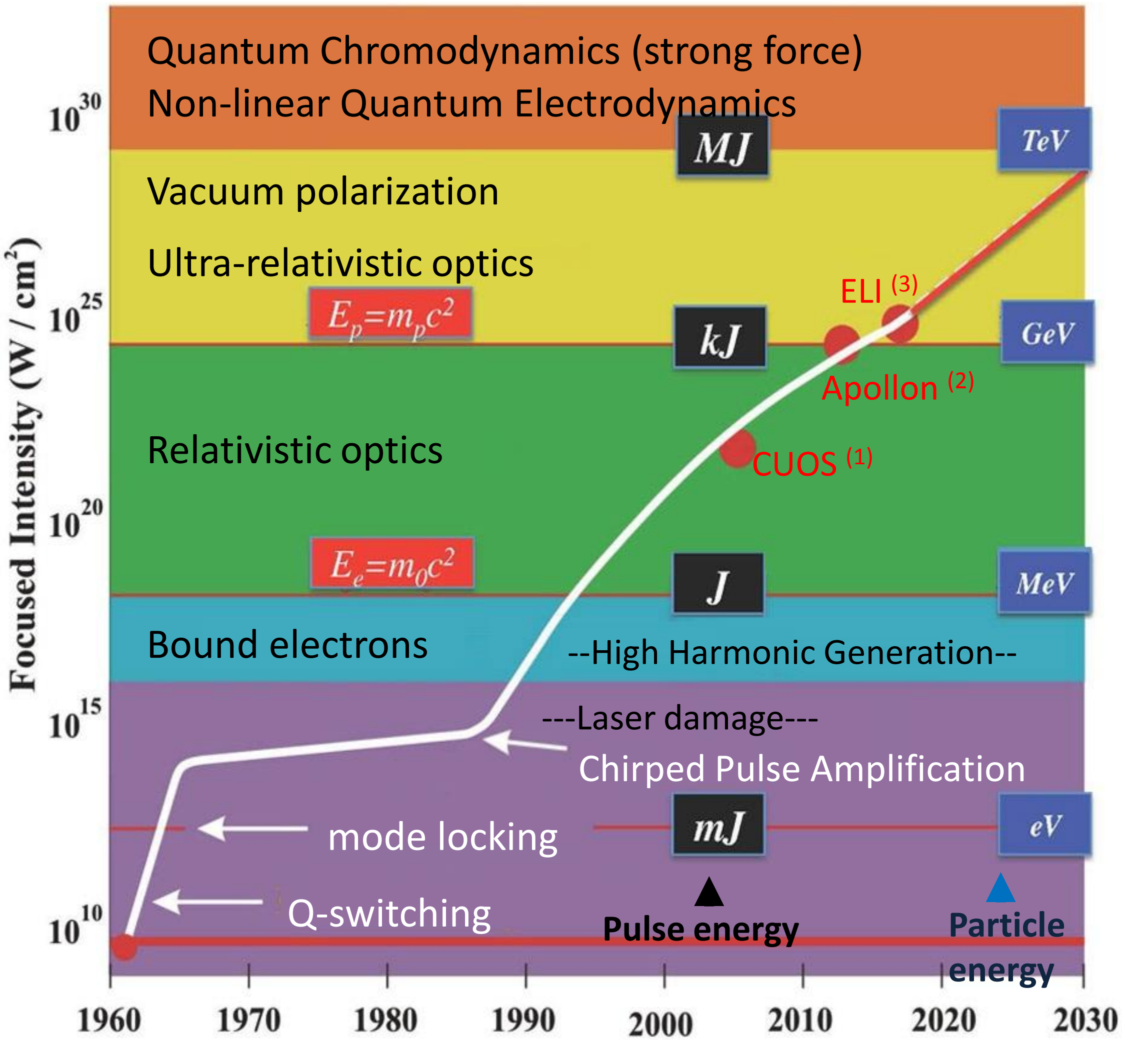
$$I = cE_{\max}^2 / 8\pi$$

$$I\left(\frac{\mathrm{W}}{\mathrm{cm}^2}\right) \approx 1.4\times10^{15} E^2\left(10^9\,\frac{\mathrm{V}}{\mathrm{cm}}\right)$$

ERC-2014-CoG No. 647554

Superintense laser-matter interaction

New physics available by progress in laser technology



(1) CUOS: Center for Ultrafast Optical Science (University Michigan)

(2) Apollon Laser, Centre Interdisciplinaire Lumière Extrême (France)

(3) Extreme Light Infastructure (EU) https://eli-laser.eu/

Important laser quantities

Typical laser parameters with Chirped Pulse Amplification (since '80s)

Laser wavelength (μm): ≈ 1 (Nd-Yag), 0.8 (Ti-Sa), ≈ 10 (CO_2)

Energy (per pulse): 10^{-1} - 10^{3} J

Pulse duration: ≈ 10 - 10^{3} fs (at λ = 1 μm, $\tau = c/\lambda$ = 3.3 fs)

Power: ≈ 100 TW - few PW (PW lines now available)

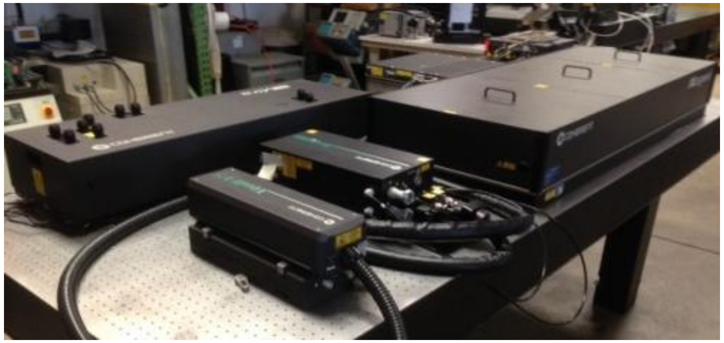
Spot size at focus: down to diffraction limit → typically ø < 10 μm

Intensity (power per unit area): 10^{18} W/cm^2 up to 10^{22} W/cm^2

From huge facilities……

Nova laser, LLNL, 1984

… to table-top systems!



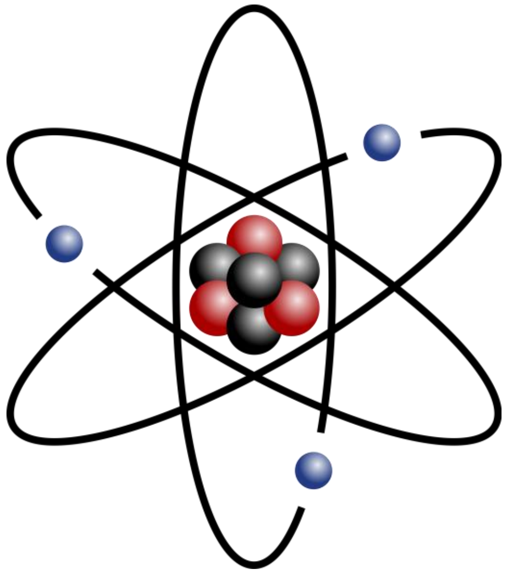
Commercial TW class laser, 2010s

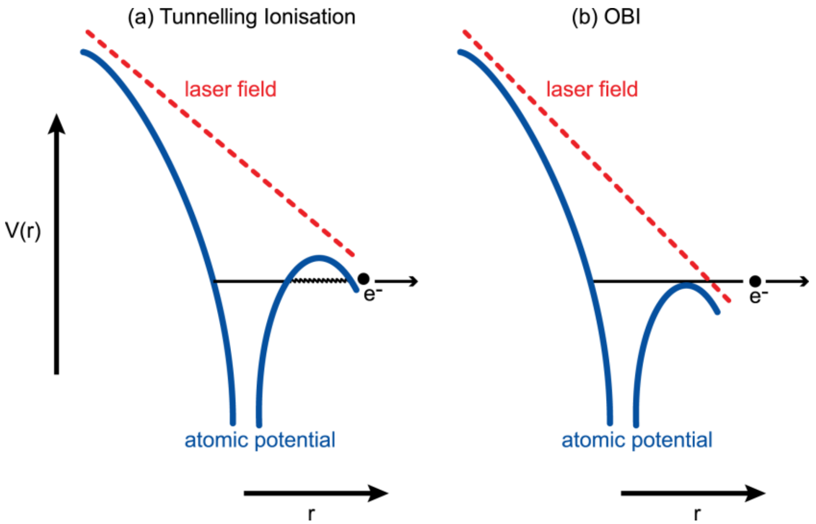
The strength of laser fields:

Laser field vs. atomic fields

Atomic field →

$$\frac{e}{a_0^2} \cong 5.15\times10^{9}\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \cong 3.6\times10^{16}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$$





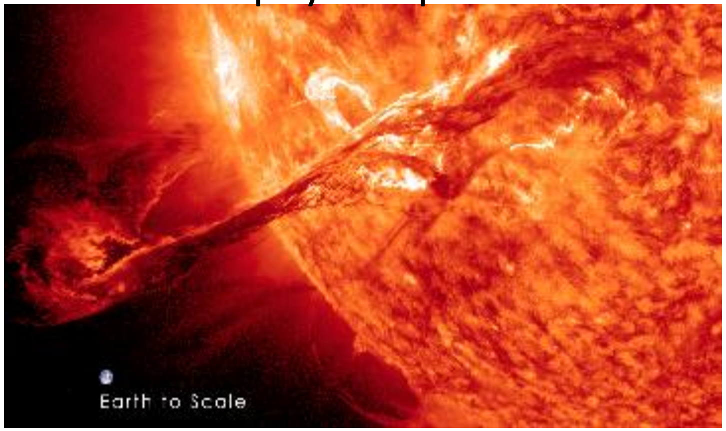
Calvert, J., Palmer, A., Litvinyuk, I., & Sang, R. (2016). Metastable noble gas atoms in strong-field ionization experiments. High Power Laser Science and Engineering

Ionization process → unbound mixture of electrons and ions → **Plasma**

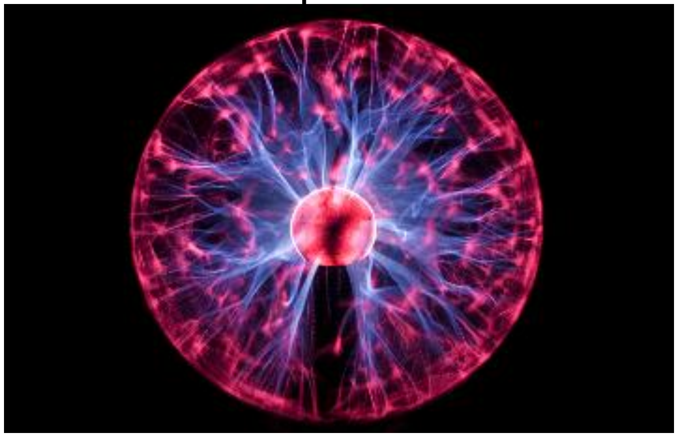
Plasma physics

99% of matter in the visible universe is in the state of plasma

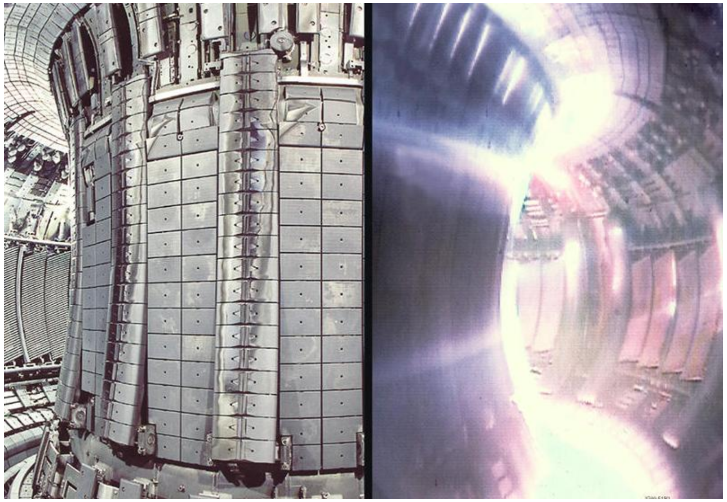
Astrophysical plasmas



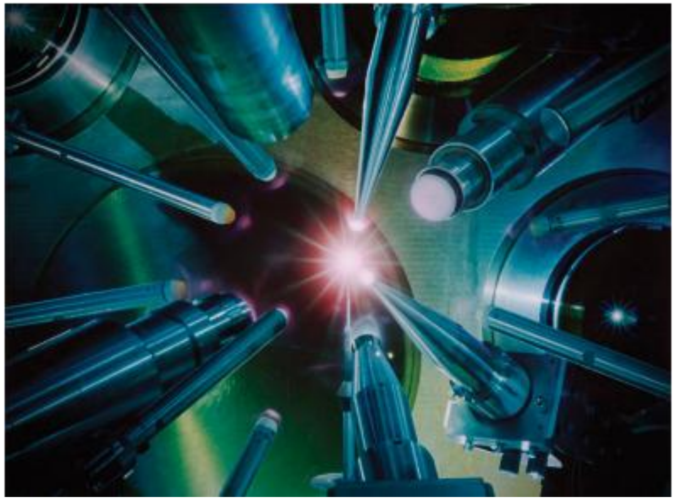
"Cold plasmas"



Magnetic fusion research

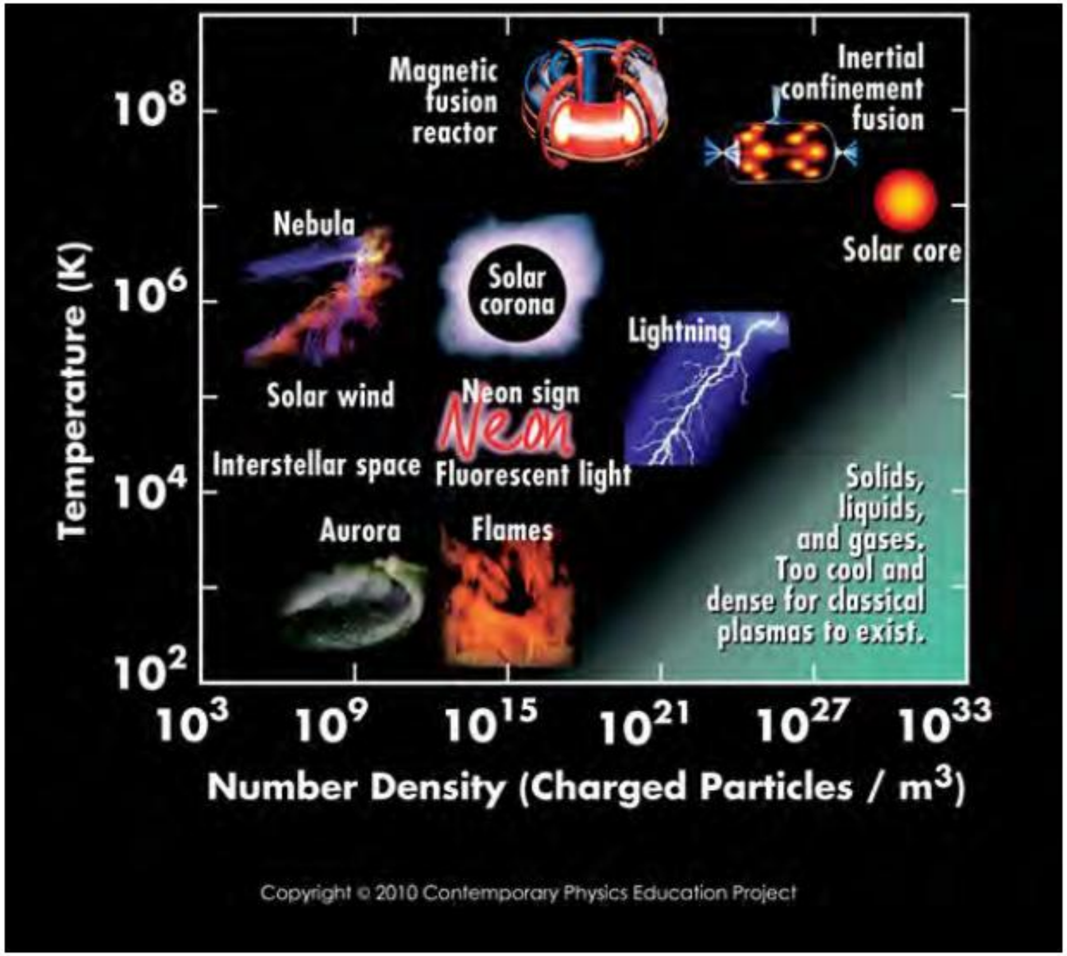


Laser-Plasma interaction



The plasma state

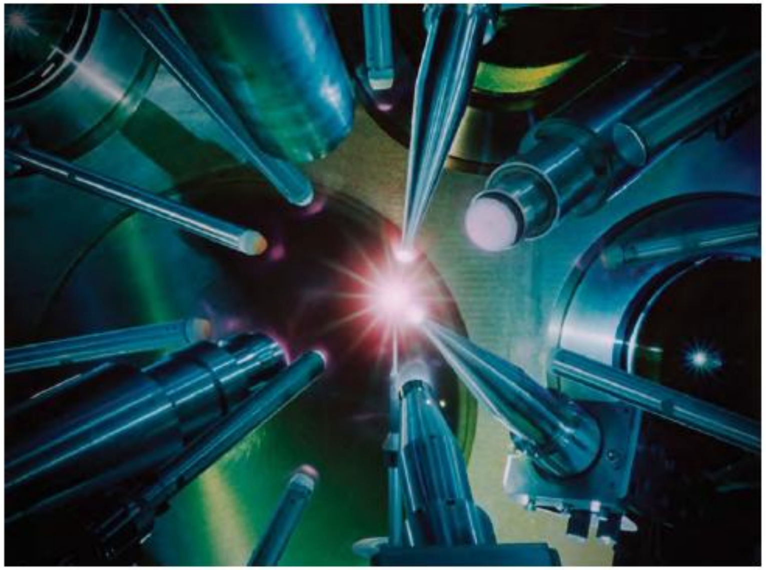
Many different plasmas exist in the universe



The plasma state

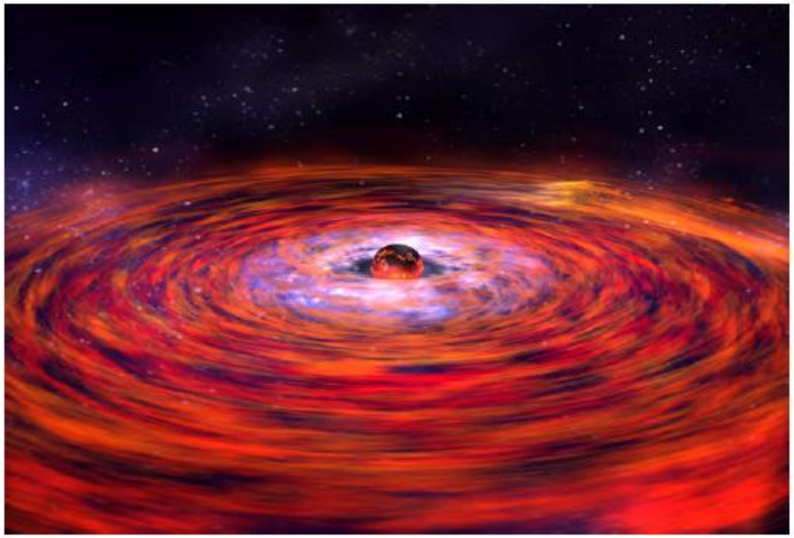
Large range of scalelenghts

ICF



~100 μm

Accretion disks

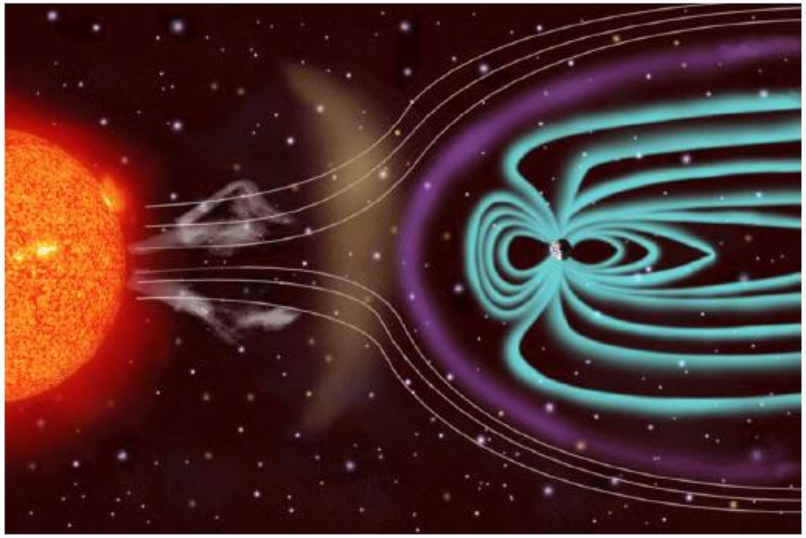


~10^5 km

The plasma state

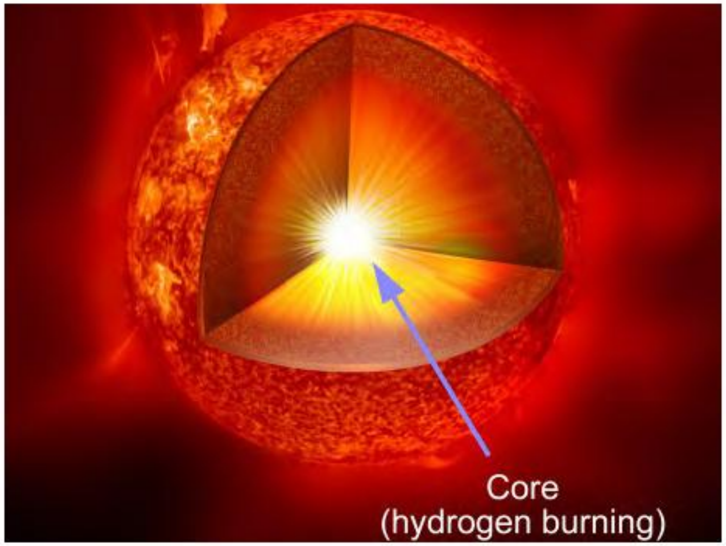
Large range of densities

Solar wind



few atoms/cm^3

Stellar core

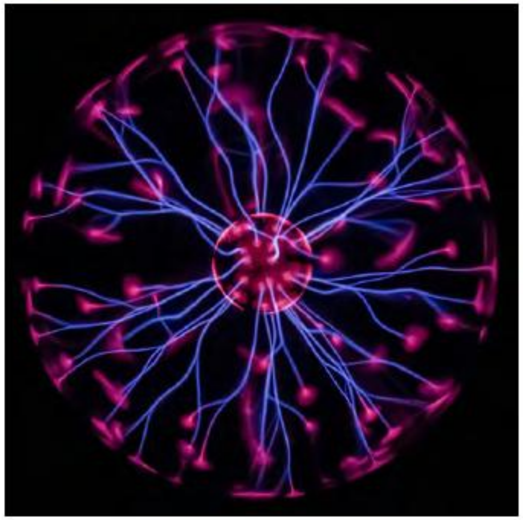


~150 g/cm^3

The plasma state

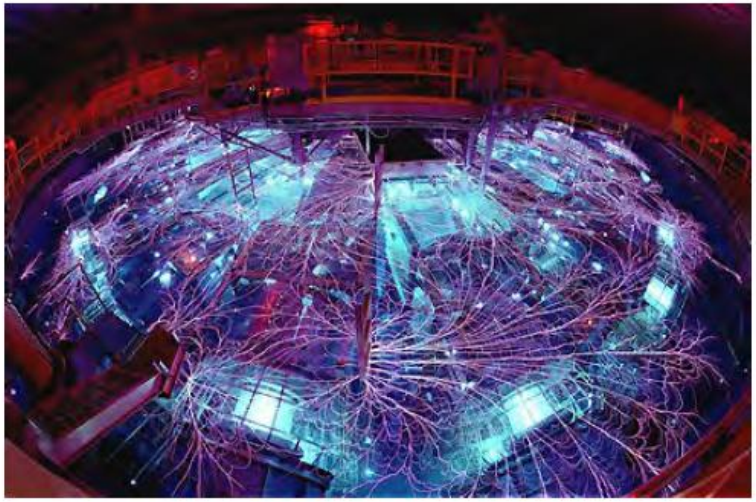
Large range of temperatures

Plasma ball



"cold plasmas"

Z-machine



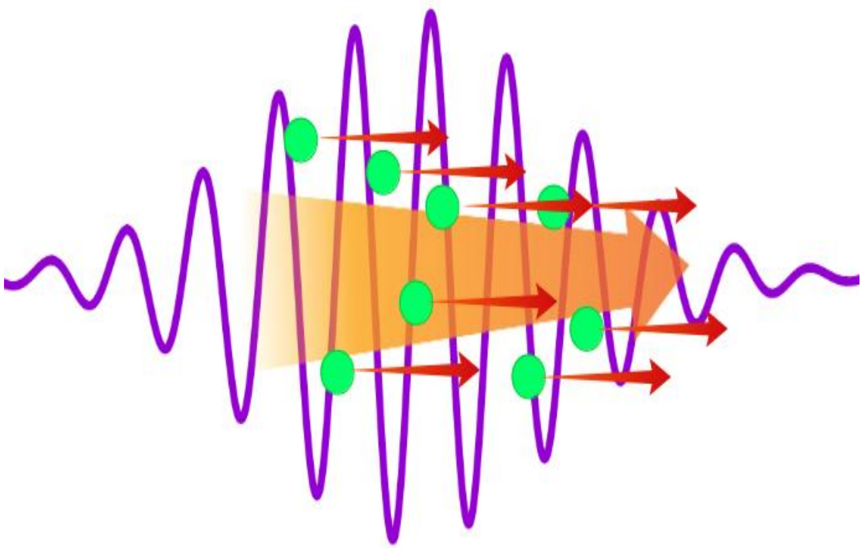
~gigakelvin

The strength of laser fields:

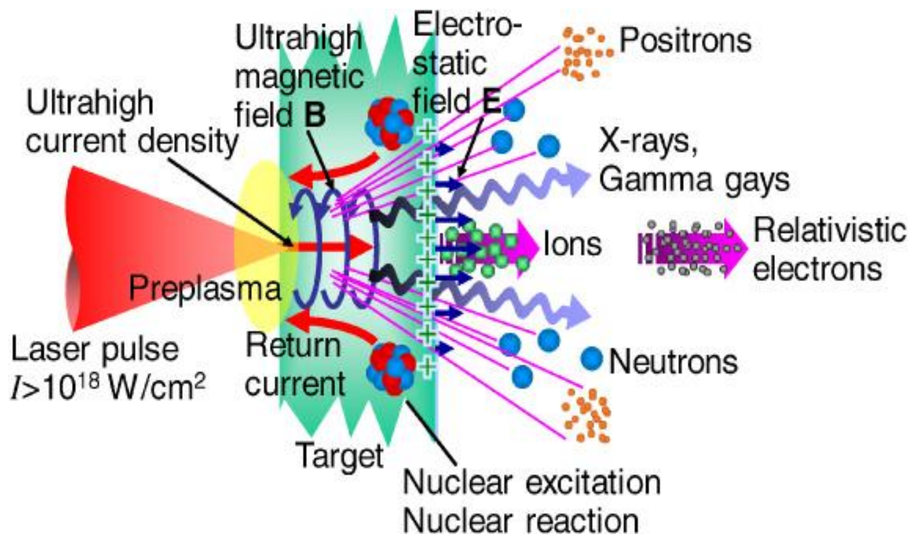
Laser field vs. "relativistic" field

Relativistic field →

$$\frac{m_e \omega c}{e} \cong \frac{3.2\times10^{10}}{\lambda(\mu\mathrm{m})}\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \cong \frac{1.4\times10^{18}}{\lambda^2(\mu\mathrm{m})}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$$



Relativistic electron momenta (p ~ mc) in one laser cycle



Hiroyuki Daido and Mamiko Nishiuchi and Alexander S Pirozhkov. Review of laser-driven ion sources and their applications , Reports on Progress in Physics 75(5), 056401 (2012)

The strength of laser fields:

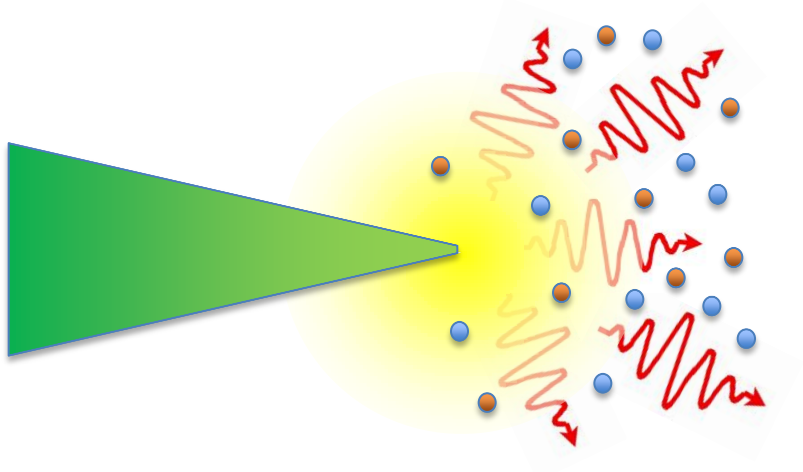
Laser field vs. "Schwinger" field

Schwinger limit

$$e E \lambda\!\!\!^{-}_C = 2 m_e c^2 \Rightarrow$$

$$E \approx 2.7 \times 10^{16} \frac{\text{V}}{\text{cm}} \Rightarrow I \approx 10^{30} \frac{\text{W}}{\text{cm}^2}$$

[Vacuum break-down: J. Schwinger, *Phys. Rev.* **82**, 664 (1951)]

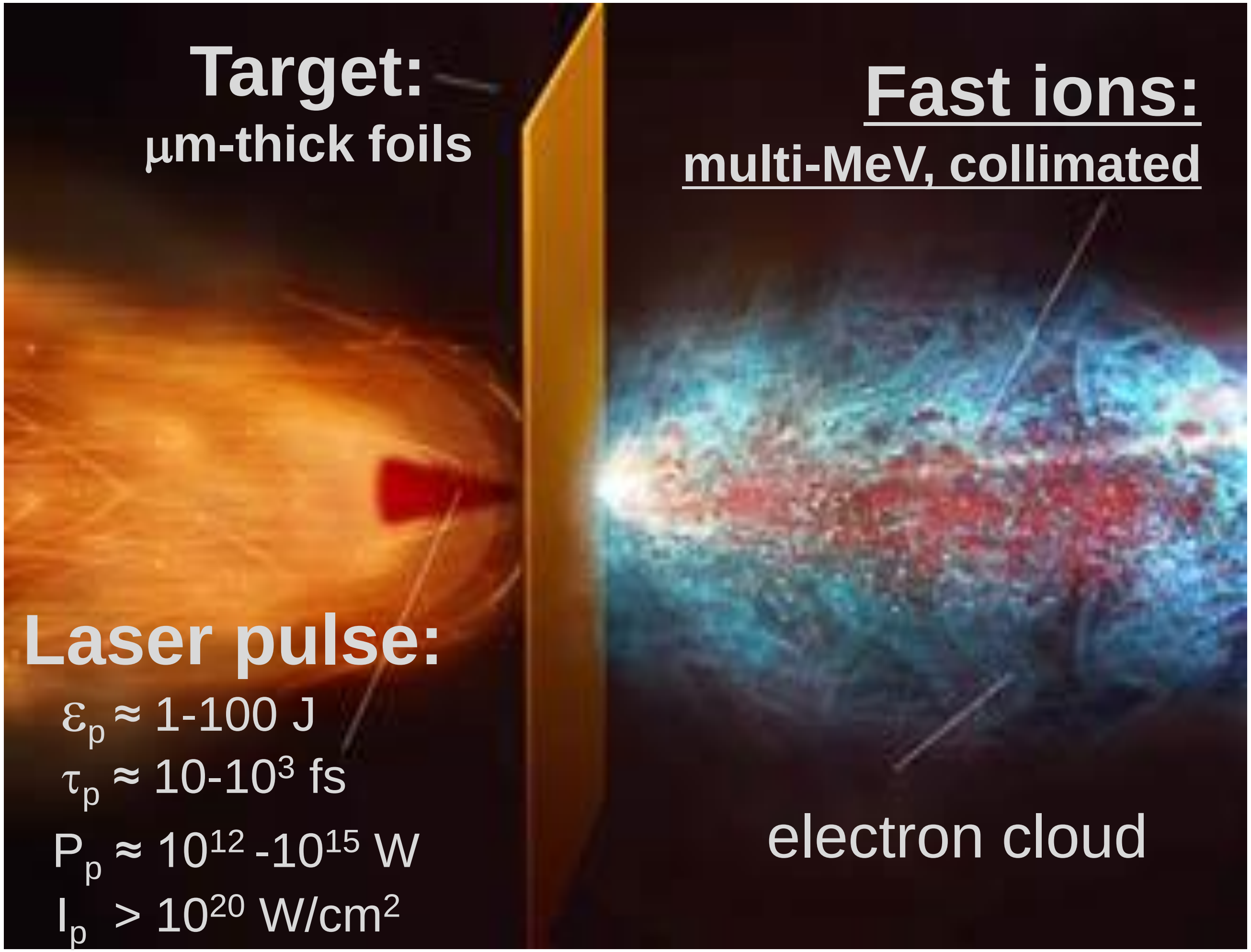


$e^+ e^-$ couples and γ photons extracted from the vacuum!

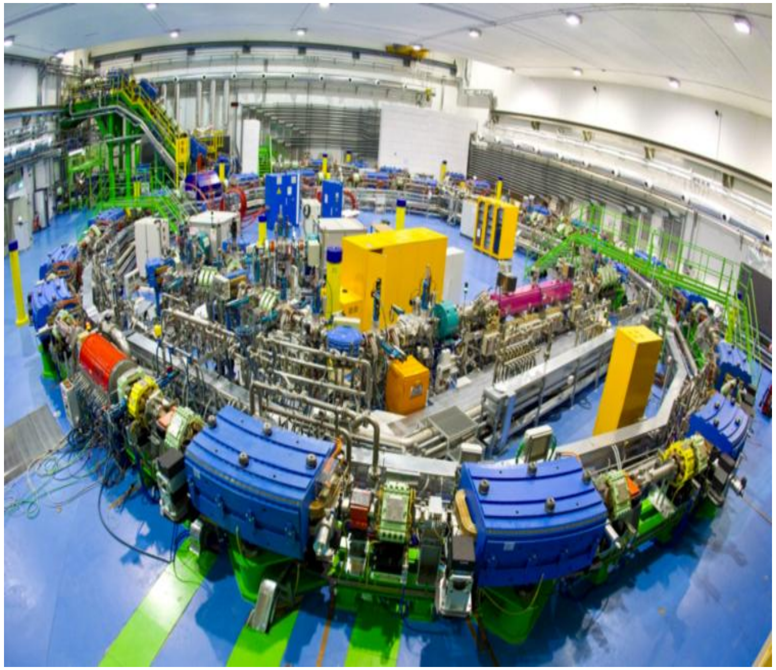
Ultimate intensity limit

Laser-driven ion acceleration

A non conventional way to accelerate heavy charged particle beams



Conventional ion accelerators:



CNAO Synchrotron (Pavia)

High-energy particle beams crucial for:

- Medicine: radiotherapy, nuclear diagnostics,…
- Material engineering: ion beam analysis, implantation
- Nuclear engineering: Inertial Confinement Fusion,…
- Basic science: particle & high energy physics,…

Laser-driven ion accelerator:

Appealing potential:

- Compactness
- Cost effectiveness
- Flexibility

Critical issues:

- Gain control of the process
- Increase efficiency/performance
- Limitation and cost of lasers

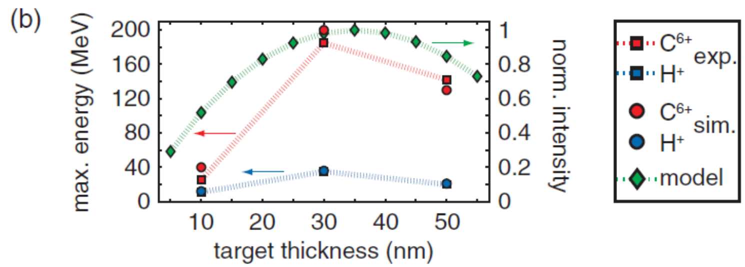
Novel targets can be the key!

Novel target is a (the?) key

Laser-ion acceleration with ultrathin (< 10^2 nm) targets

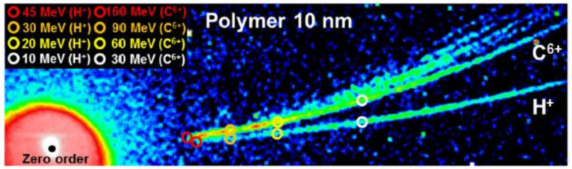
ONSET OF RELATIVISTIC TRANSPARENCY
A. Henig, *et al.*,
Phys.Rev.Lett. **103**, 045002 (2009)
(TRIDENT-Nd:glass-LANL: 40-50 J on target)

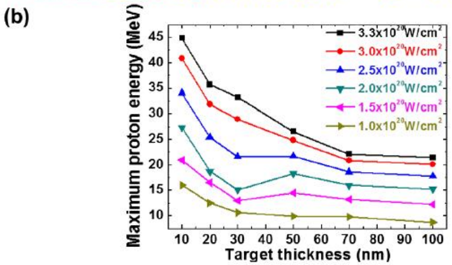
→



INCREASE OF THE MAX. ENERGY
I. J. Kim, *et al.*,
Phys.Rev.Lett. **111**, 165003 (2013)
(PULSER-Ti:Sa-GIST: < 10 J on target)

→

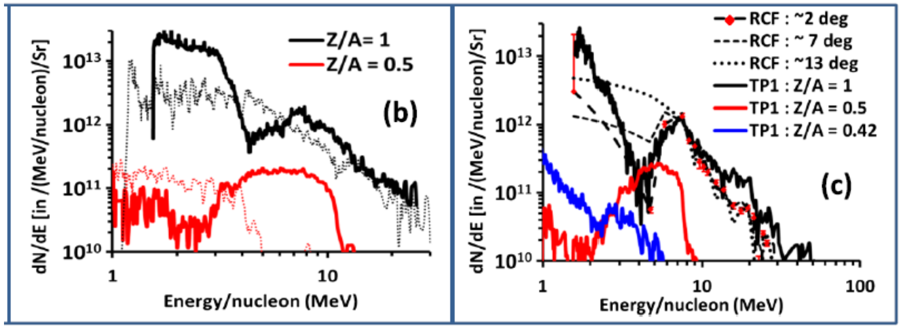




ONSET OF LIGHT SAIL-like RPA FEATURES
A. Henig, *et al.*,
Phys.Rev.Lett. **103**, 245003 (2009)
(TRIDENT-Nd:glass-LANL)

S. Kar, *et al.*,
Phys.Rev.Lett. **109**, 185006 (2012)
(VULCAN-Nd:glass-RAL: 200 J on target)

→



Novel target is a (the?) key

Laser-ion acceleration with “exotic” targets

MICRO-CONE TARGETS

S. Gaillard, *et al.*, *Phys.Plasmas* **18**, 056710 (2011) (Trident-Nd:glass-LANL) →

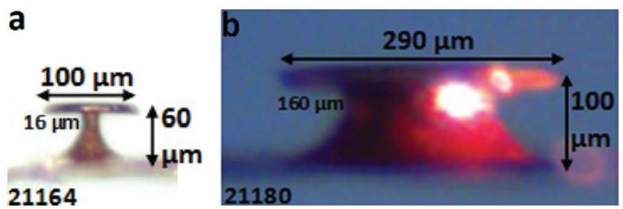
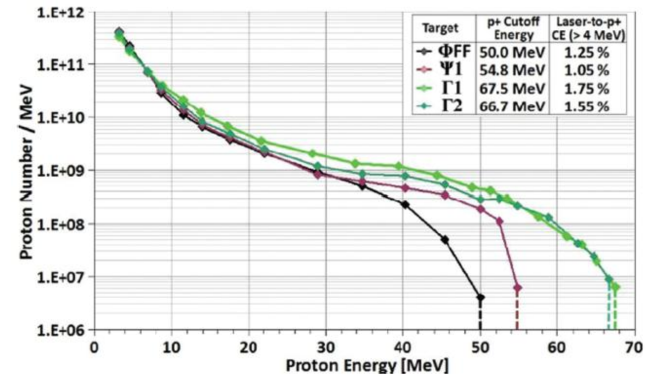


FIG. 4. (Color) Target pictures (to scale): the OD of the various necks ranged from (a) 11 μm (shot 21164) to (b) 160 μm (shot 21180).



“SNOW” TARGETS

A. Zigler, *et al.*, PRL **110**, 215004 (2013) (MBI-Ti:Sa-Berlin) →

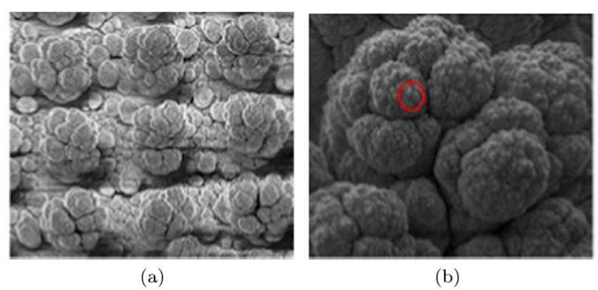
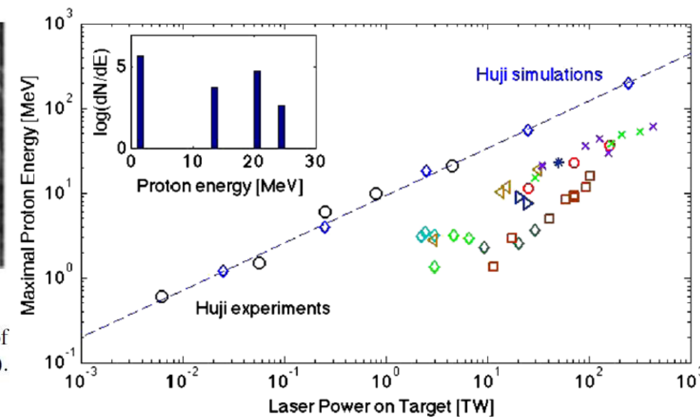


FIG. 2 (color online). Scanning electron microscope images of the snow targets. Total width shown is 1000 μ (a) and 100 μ (b). Red circle represents the laser spot.

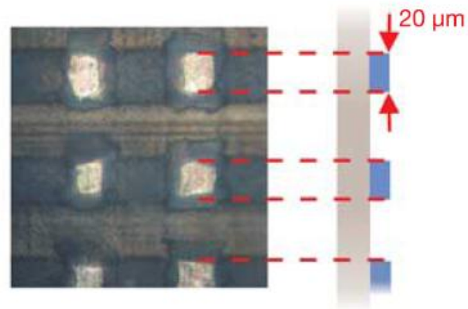


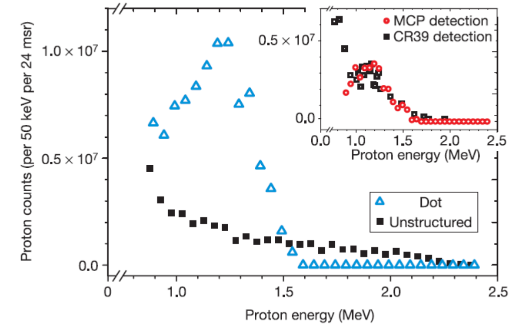
Novel target is a (the?) key

Laser-ion acceleration with micro-nanostructured targets

MICROSTRUCTURED TARGETS

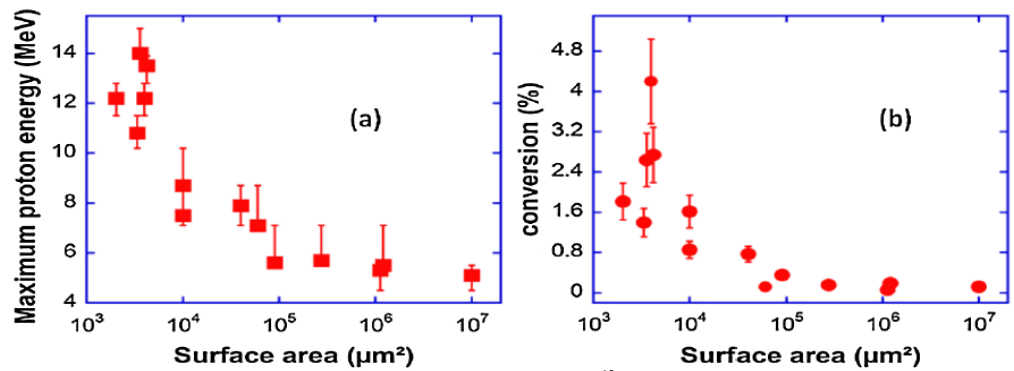
H. Schwoerer, *et al.*, *Nature* **439**, 445 (2006) (JETI-Ti:Sa-Jena) →





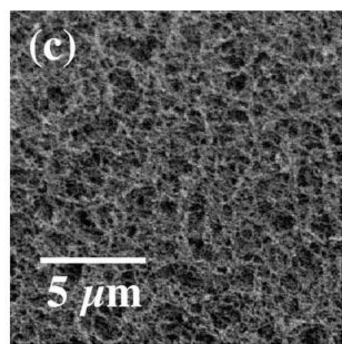
MASS LIMITED TARGETS

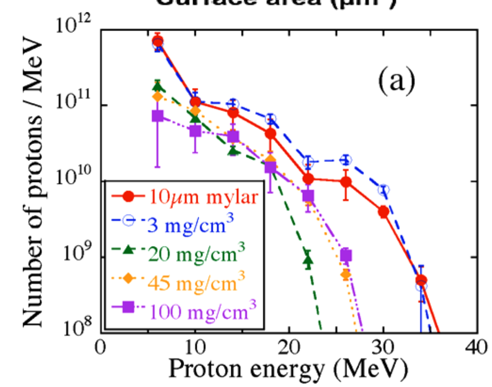
S. Buffechoux, *et al.*, *Phys.Rev.Lett.* **105**, 015005 (2010) (100TW-Nd:glass-LULI) →



LOW-DENSITY TARGETS

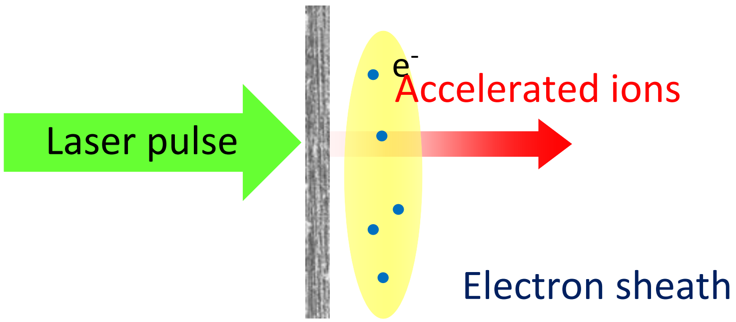
L. Willingale, *et al.*, *Phys.Rev.Lett.* **102**, 125002 (2009) (Vulcan-Nd:glass-RAL) →



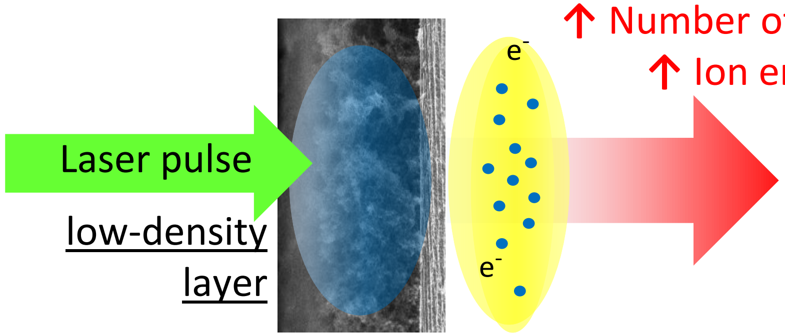


Novel target is a (the?) key

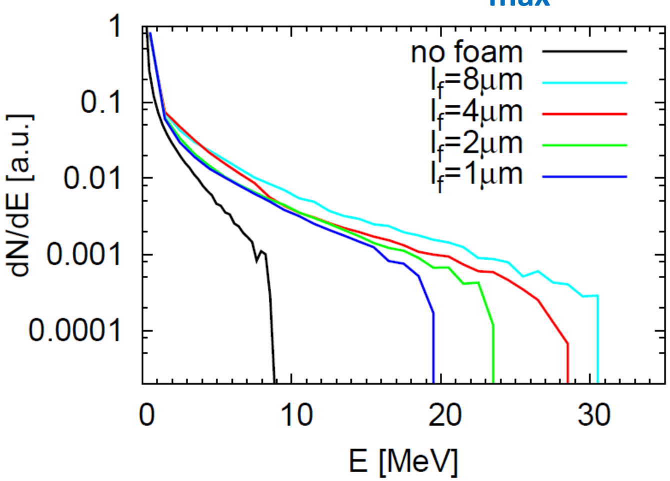
Conventional Target



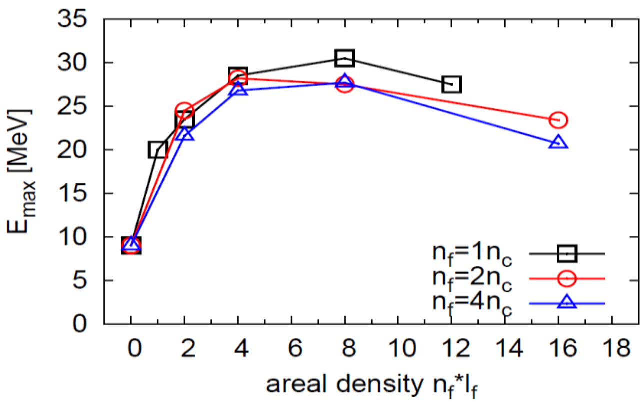
Foam-attached Target



Enhanced E_{max} !



… but foam optimization required



Quite challenging!

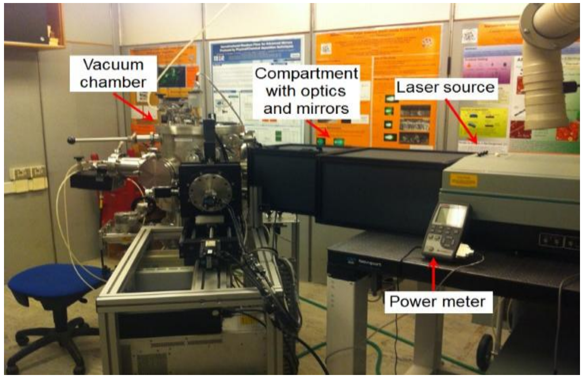
- $\rho < 10$ mg/cm^3 (for $\lambda \approx 1$ μm)
- thickness from 5 to 10s μm

Development of advanced targets

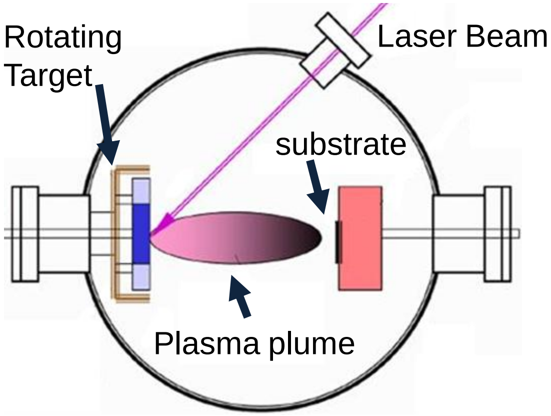
NanoLab@POLIMI facilities and infrastructures:

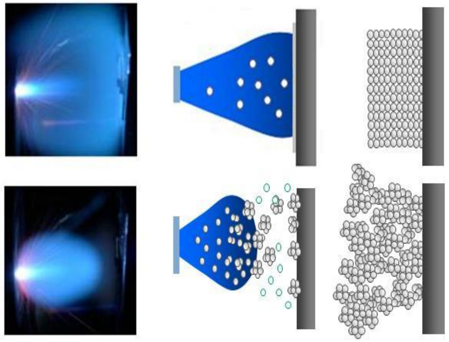
Two ns-Pulsed laser deposition (PLD) systems
Thermal treatment systems

SEM, STM, AFM microscopy
Raman & Brillouin spectroscopy

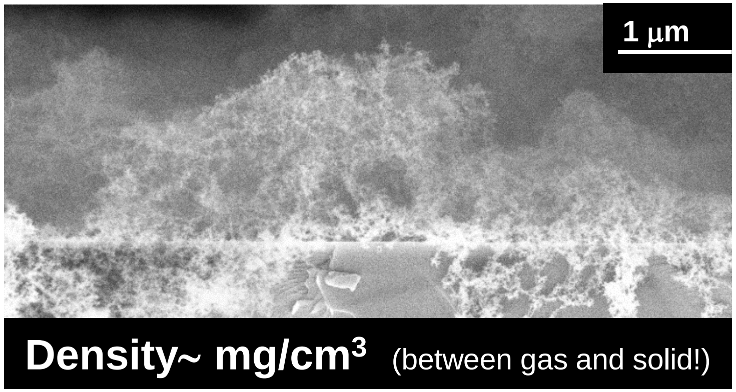


Pulsed Laser Deposition (PLD) of nanostructured targets





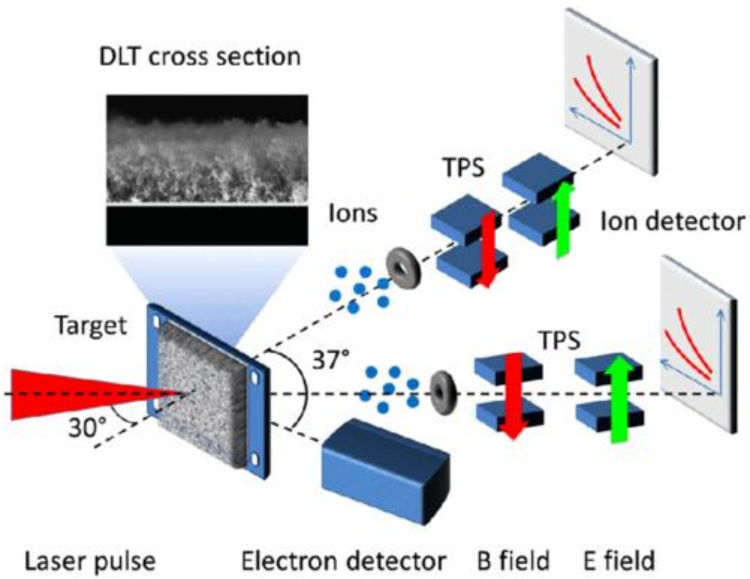
Carbon "foams"



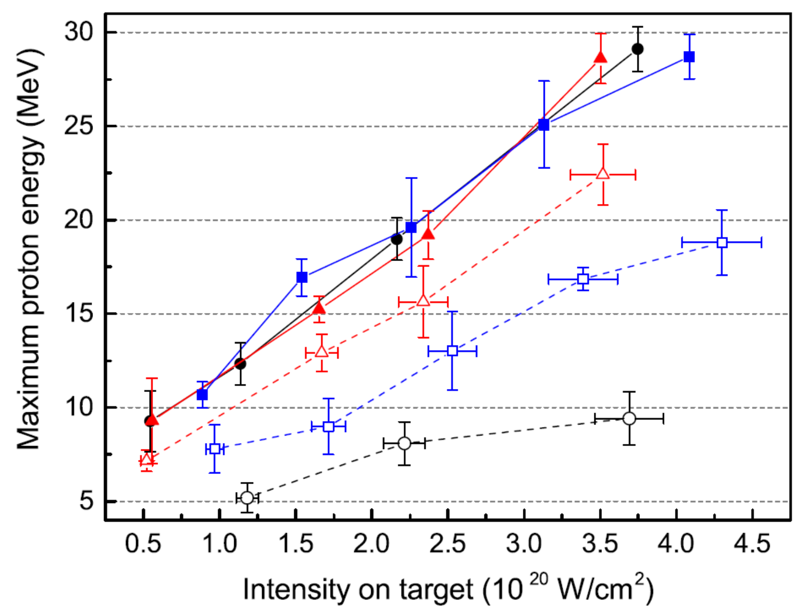
Experiments on laser facilities

Ion acceleration experiments:
- Performed at **GIST** (Rep. of Korea) in 2015-2016
- to be performed at **HZDR** (Germany) in 2017
- to be performed at **ILE** (Osaka) in 2017

Setup of an ion acceleration experiment:



Effects of advanced targets:

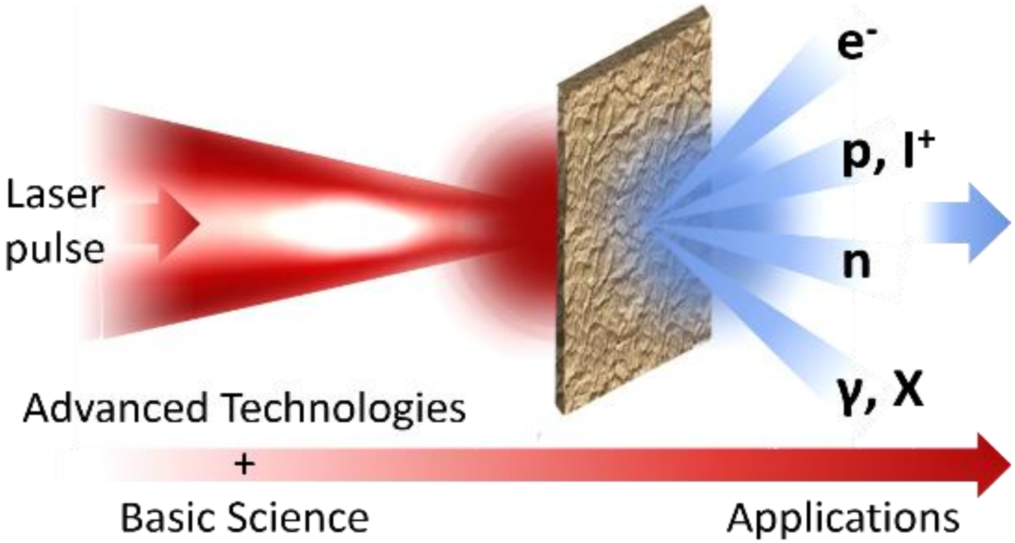


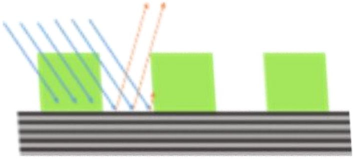
An example of application:

Material characterization & processing

- Ion beam analysis: RBS, NRA, PIXE,…
- Neutron imaging and radiography….

- Ion implantation
- Radiation damaging…

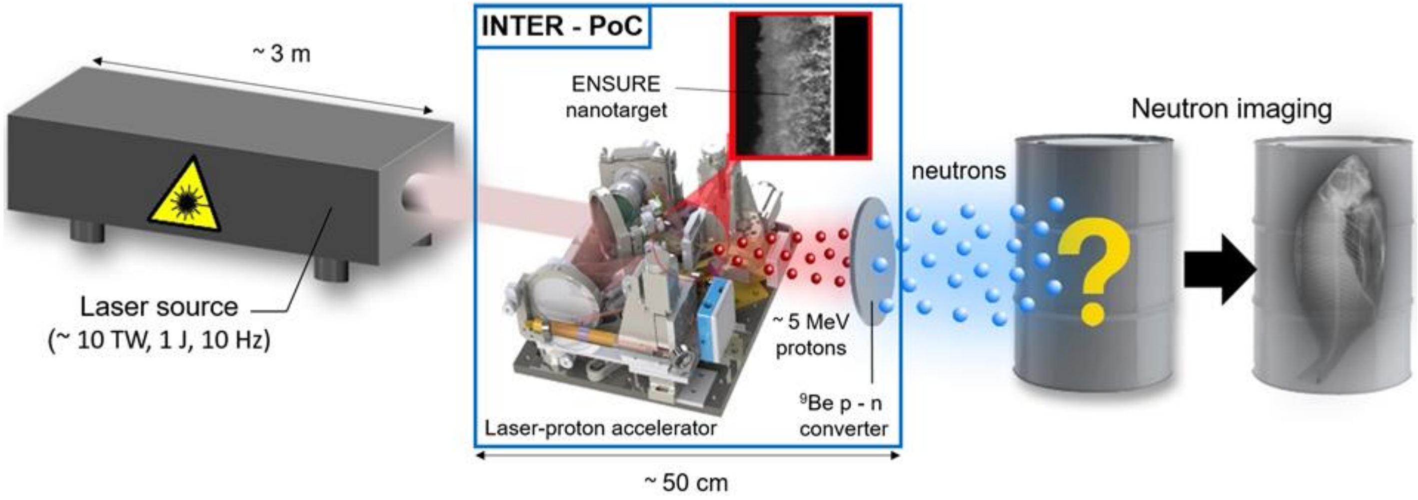




Laser-driven ion beams may *ensure* major advantages!

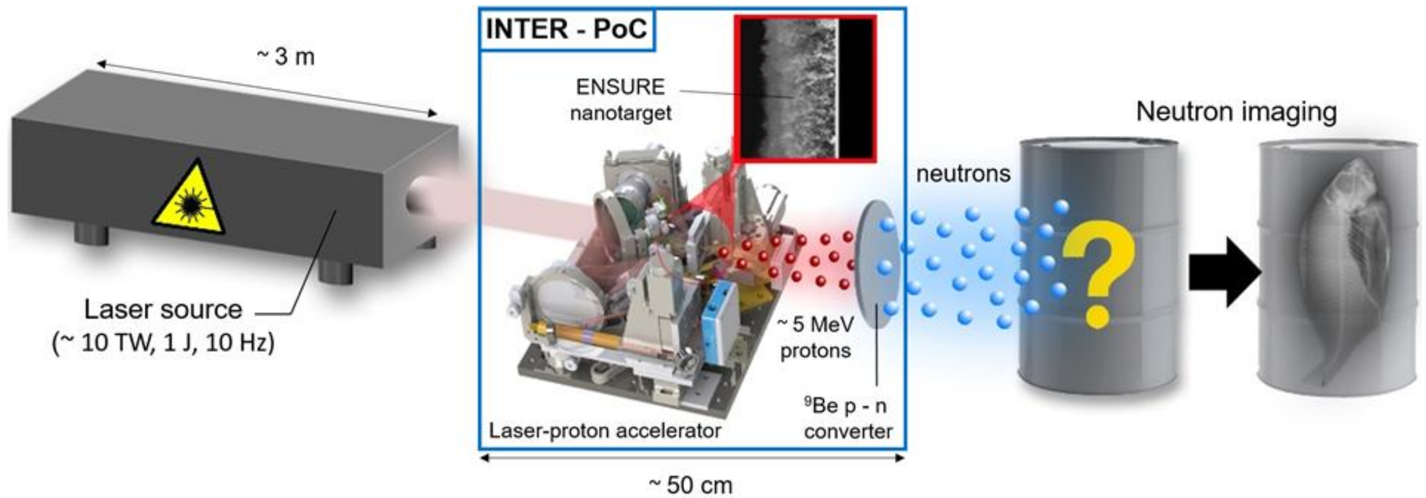
Another example of application:

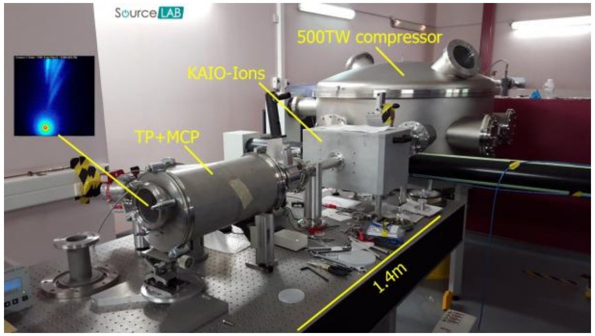
Towards a portable neutron source

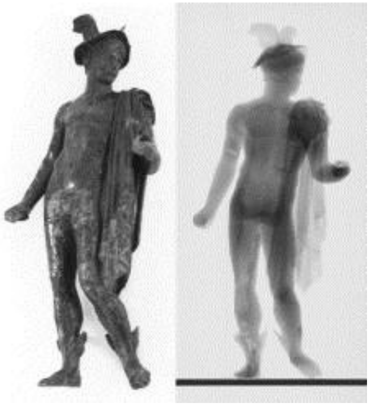


Another example of application:

Towards a portable neutron source







E. H. Lehmann et al. NIMA A 542(1-3), 68-75(2005)

Experimental: new labs @ POLIMI!

Today

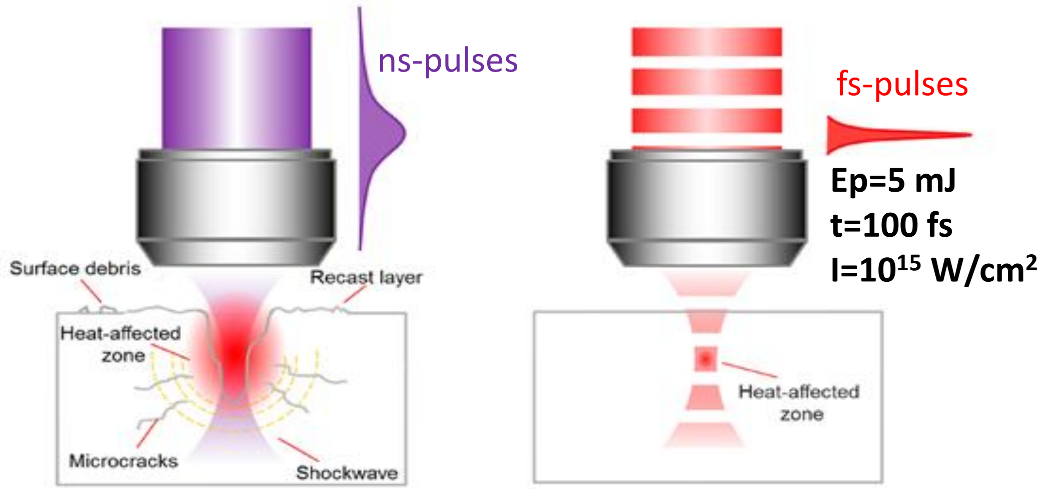
Tomorrow (within 2017)

New techniques to improve capability in **advanced target production**:

- femtosecond PLD
- HiPIMS

HiPIMS

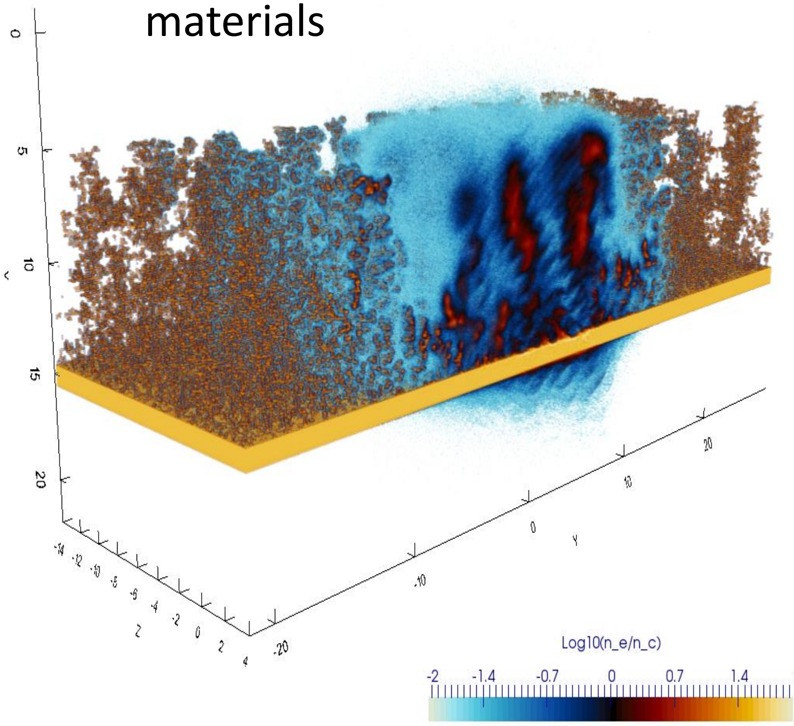
femtosecond PLD



Theoretical/numerical investigation

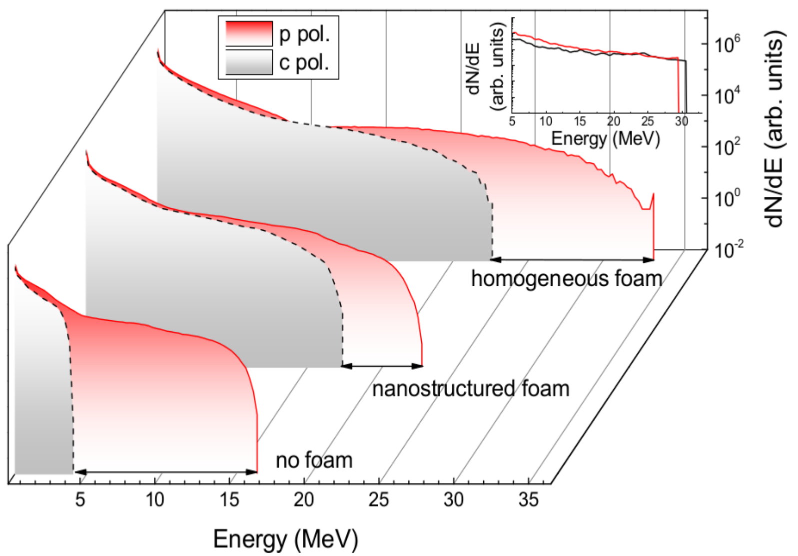
"Particle-In-Cell" simulations

- Simulation of relativistic laser interaction with nanostructured materials



High Performance computing

- 2D and 3D simulations are performed on Marconi supercomputer (CINECA, Bologna)



Energy spectra of laser-accelerated protons for linear (P) and circular (C) polarization

Theoretical models in plasma physics

Many different theoretical models to describe the plasma behavior

Microscopic → Kinetic → Fluid

Microscopic	Kinetic	Fluid
Molecular dynamics	Vlasov	Hydro
Monte-Carlo	Fokker-Planck	MHD, 2 fluids…
+ ionization, QED, nuclear reactions…		Steady state

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Theoretical models in plasma physics

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+ ionization, QED, nuclear reactions…		Steady state

The collisionless kinetic plasma model

AKA the Vlasov-Maxwell system

Vlasov equation for the distribution function

$$\partial_t f + \boldsymbol{v}\cdot\nabla_x f + q\left(\vec{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)\cdot\nabla_p f = 0$$

Maxwell's equations for the EM fields

$$\nabla\cdot\boldsymbol{E} = 4\pi\rho \qquad \nabla\times\boldsymbol{E} = -\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t}$$

$$\nabla\cdot\boldsymbol{B} = 0 \qquad \nabla\times\boldsymbol{B} = \frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} + \frac{4\pi}{c}\boldsymbol{J}$$

Coupling between matter and EM fields

$$\rho(\mathbf{r}) = \sum_a q_a \int f_a(\mathbf{r},\mathbf{p})\, d^3p$$

$$\mathbf{J}(\mathbf{r}) = \sum_a q_a \int \mathbf{v} f_a(\mathbf{r},\mathbf{p})\, d^3p$$

The collisionless kinetic plasma model

i.e. a self-consistent kinetic theory coupling matter and EM field

- A.A. Vlasov (1938): first self-consistent solution (principal value integral etc) of the linearized system

- L.D. Landau (1946): first CORRECT self-consistent solution (using Laplace transform theory etc), Landau damping (LD)…

- N.G. Van Kampen (1955): normal modes properly found adopting the theory of distribution

… …

… …

- C. Villani (2010): Fields Medal for non-linear theory of LD!

How to solve the kinetic system?

You can try with simplified analytical approaches!

An example:
a kinetic model for relativistic electromagnetic solitons in plasmas

$$f_j(W_j, \mathbf{P}_{j\perp}) = \frac{N_{0j}}{2m_j K_1(\beta_j^{-1})} \delta(\mathbf{P}_{j\perp}) \exp\left(-\frac{W_j}{T_j}\right)$$

$$W_j(\mathbf{r},t) = m_j \gamma_j + q_j \phi(\mathbf{r},t)$$
$$\mathbf{P}_j(\mathbf{r},t) = \mathbf{p}_j + q_j \mathbf{A}(\mathbf{r},t)$$
$$\gamma_j = \left(1 + \frac{p_j^2}{m_j^2}\right)^{1/2}$$

It can be shown that f_j is an exact solution of the Vlasov Eq. for:

- 1D geometry
- circular polarization for EM fields

$$N_j(\mathbf{r},t) = \int f_j(W_j, \mathbf{P}_{j\perp}) d^3\mathbf{p}_j = N_{0j} \frac{K_1(\gamma_{\perp j}\beta_j^{-1})}{K_1(\beta_j^{-1})} \gamma_{\perp j} \exp\left(-\frac{\varphi_j}{\beta_j}\right)$$

... ...

... ...

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How to solve the kinetic system?

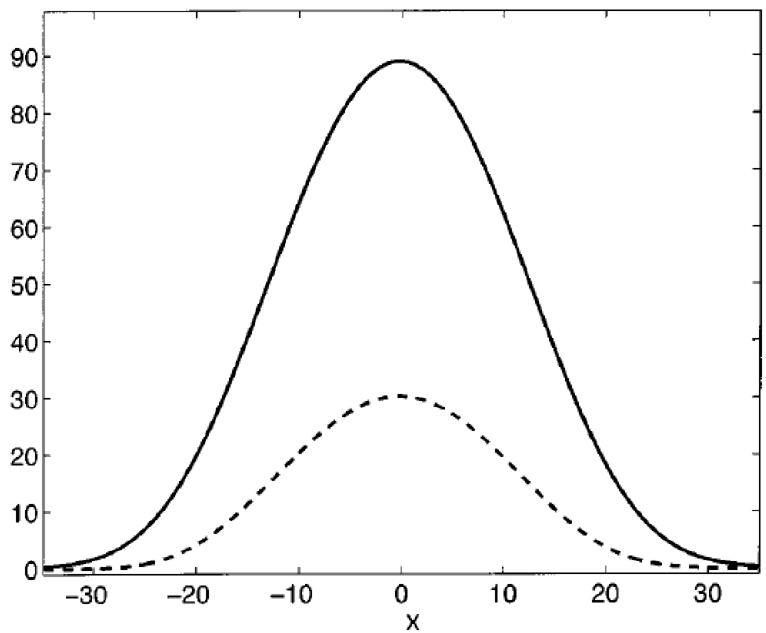
A model of relativistic electromagnetic solitons in plasmas

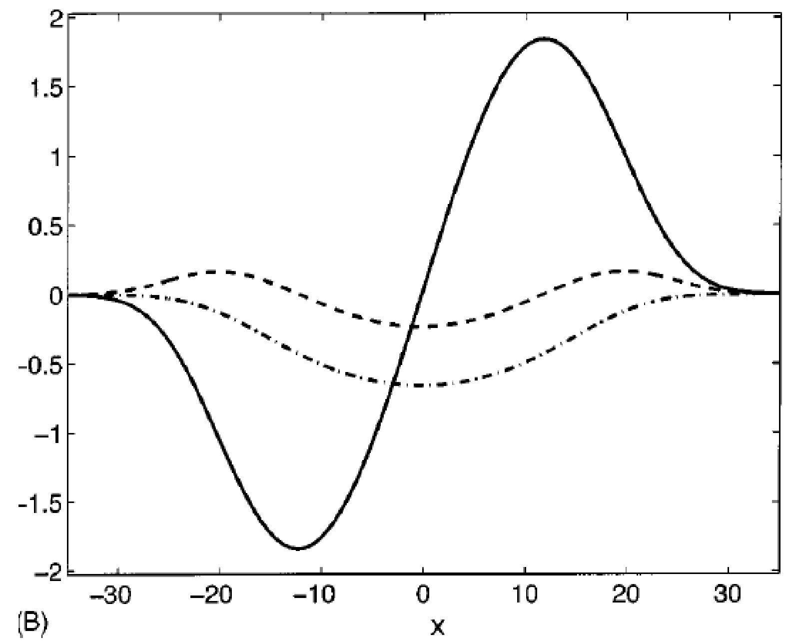
$$\mathbf{a}''_{\perp xx}-\mathbf{a}''_{\perp tt}=\mathbf{a}_\perp\left\{\frac{K_0(\sqrt{1+a_\perp^2}\lambda_e^{-1})}{K_1(\lambda_e^{-1})}\exp\left(\frac{\varphi}{\lambda_e}\right)+\rho Z\frac{K_0[\sqrt{1+\rho^2Z^2a_\perp^2}(\rho\lambda_i)^{-1}]}{K_1[(\rho\lambda_i)^{-1}]}\exp\left(-\frac{Z\varphi}{\lambda_i}\right)\right\}$$

$$e\mathbf{A}_\perp(\phi)/m_e\rightarrow\mathbf{a}_\perp(\varphi)$$

$$\varphi(a^2;\rho,\lambda_e,\lambda_i)=\left(\frac{1}{\lambda_e}+\frac{Z}{\lambda_i}\right)^{-1}\left\{\frac{1}{2}\ln\frac{1+\rho^2 Z^2}{1+a^2}+\ln\frac{K_1(\lambda_e^{-1})K_1[\sqrt{1+\rho^2Z^2a^2}/\rho\lambda_i]}{K_1(\rho^{-1}\lambda_i^{-1})K_1[\sqrt{1+a^2}/\lambda_e]}\right\}$$

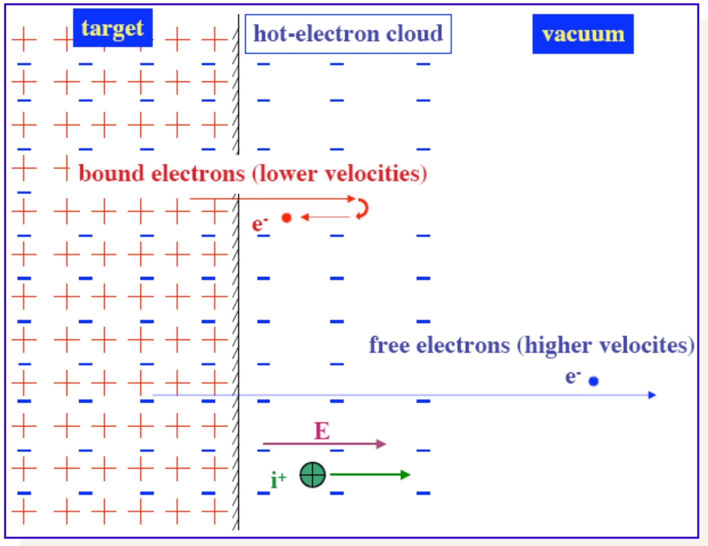
$$\frac{|N_e-ZN_i|}{N_0}\ll 1$$





How to solve the kinetic system?

Another example: analytical theory of laser-driven ion acceleration



$$f_e(x,p) = \frac{\tilde{n}}{2mcK_1\left(\frac{mc^2}{T}\right)} \exp\left(-\frac{\varepsilon(x,p)}{T_e}\right)$$

only the density of "trapped" e$^-$ enters Poisson eq.; integrating over $\varepsilon < 0$ we get the trapped e$^-$ density $n_{tr}(\phi(\mathbf{r}))$

$$n_{tr}(\mathbf{r}) = \int_{\varepsilon(\mathbf{r},\mathbf{p})\leq 0} f_e(\mathbf{r},\mathbf{p})\, d^3p$$

$$\begin{cases} \nabla^2\varphi = N_{tr}(\varphi) \quad \varphi = \dfrac{e\phi}{T_e},\ N_{tr} = \dfrac{n_{tr}}{\tilde{n}} \\ \varepsilon(\mathbf{r},\mathbf{p}) \leq 0 \Rightarrow |\mathbf{p}| \leq p_{max}(\mathbf{r}) \end{cases}$$

$$\varepsilon(x,p) = mc^2(\gamma - 1) - e\phi(x) \leq 0$$

$$p^2 \leq p_{max}^2 \equiv m^2c^2\left[\left(\frac{e\phi}{mc^2}\right)^2 + \frac{2e\phi}{mc^2}\right]$$

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}\xi^2} = \mathrm{e}^{\varphi}\int_0^{\beta(\varphi)} \mathrm{e}^{-\sqrt{p^2+\zeta^2}}\,\mathrm{d}p - \frac{(Z_{\mathrm{H}}n_{0\mathrm{H}} - n_{0\mathrm{c}})}{\tilde{n}}\zeta K_1(\zeta) H(-\xi)$$

How to solve the kinetic system?

Another example: analytical theory of laser-driven ion acceleration

$$\int_{\varphi(0)}^{\varphi(\xi)} \frac{d\varphi'}{\left(e^{\varphi'} I(\varphi') - e^{-\zeta}\beta\right)^{1/2}} = -\sqrt{2}\xi$$

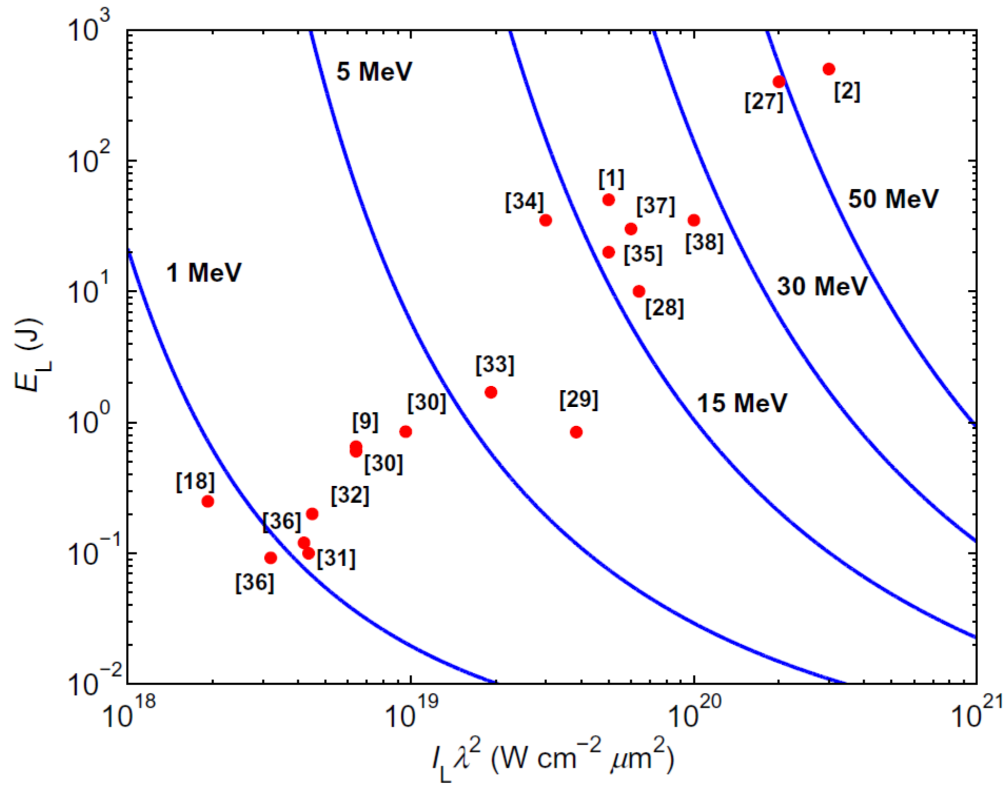
$$I(\varphi) = \int_0^{\beta} e^{-\sqrt{\zeta^2+p^2}}\,dp$$

$$\beta = \sqrt{(\varphi+\zeta)^2 - \zeta^2}$$

$$\zeta = mc^2/T$$

$\xi = x/\lambda_D$ (λ_D from $\tilde{n}$)

$$\varphi_0 = \varphi(\xi = 0)$$

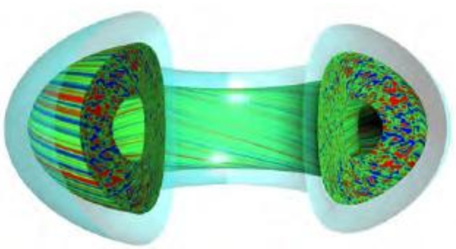


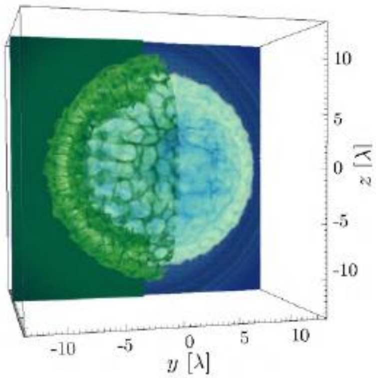
How to solve the kinetic system?

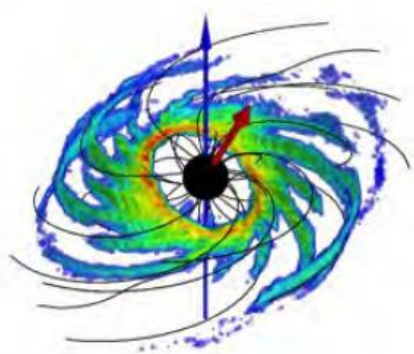
Develop and exploit suitable numerical approaches!

Frequently analytical calculations are not enough to study a complex system

We need simulations to:







Design experiments

Understand experiments and observations

Study phenoma beyond our reach

Simulations of the kinetic system

Vlasov vs Particle In Cell (PIC) codes

Vlasov equation for the distribution function

Two radically different strategies:
Vlasov codes
PIC codes

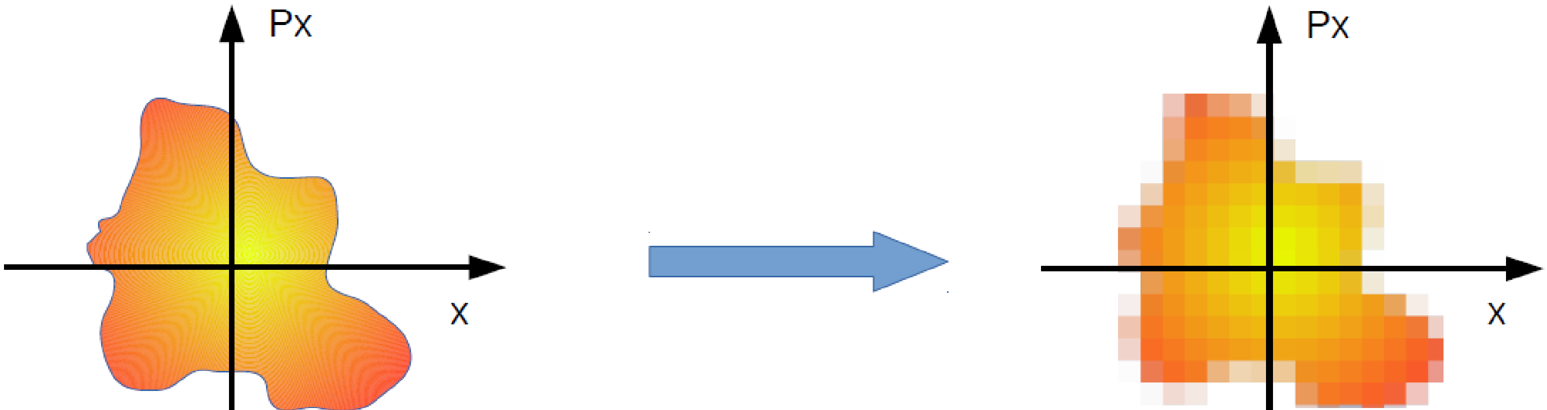
Maxwell equations for the EM fields

Maxwell equations are solved on a grid. Many solvers.

Simulations of the kinetic system

Vlasov codes

The distribution function is discretized on a grid



$$\partial_t f + \vec{v} \cdot \nabla_{\vec{x}} f + q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) \cdot \nabla_{\vec{p}} f = 0$$

At each time-step the distribution function is evolved according to Vlasov equation

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Simulations of the kinetic system

Vlasov codes

Very good to describe phenomena involving small populations and have low numerical noise

Non trivial extension to 2D3V and 3D3V in the relativistic case

Require a lot of computational resources in more than 1 spatial dimension

A 3D3V simulation with 1000 points in each coordinate means 10^{18} cells, which would require **~8ExaBytes** of RAM to store the distribution function!

Simulations of the kinetic system

PIC codes

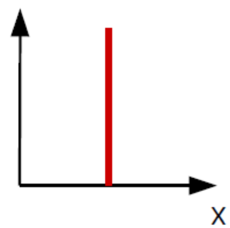
$$\partial_t F + \boldsymbol{v} \cdot \nabla_x F + q\left(\vec{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right) \cdot \nabla_p F = 0$$

$$F(\boldsymbol{x}, \boldsymbol{p}, t) = \sum_i \delta(\boldsymbol{x} - \boldsymbol{x}_i(t))\,\delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

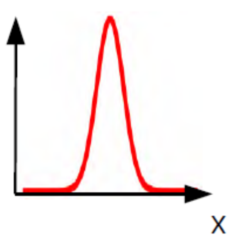
$$\frac{d\boldsymbol{x}_i}{dt} = \frac{\boldsymbol{p}_i}{\gamma m}$$

$$\frac{d\boldsymbol{p}_i}{dt} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}_i}{c} \times \boldsymbol{B}\right)$$

We replace Dirac delta-functions with shape-functions



$$F(\boldsymbol{x}, \boldsymbol{p}, t) = \sum_i \delta(\boldsymbol{x} - \boldsymbol{x}_i(t))\,\delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$



$$F(\boldsymbol{x}, \boldsymbol{p}, t) = \sum_i S(\boldsymbol{x} - \boldsymbol{x}_i(t))\,\delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

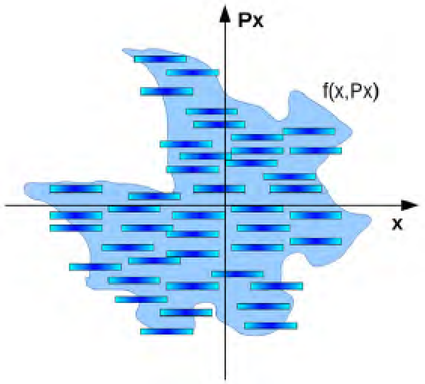
Simulations of the kinetic system

PIC codes

Vlasov equation

$$\partial_t f + \mathbf{v}\cdot\nabla_x f + q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\nabla_p f = 0$$

We approximate the distribution function



$$f(\mathbf{x},\mathbf{p},t) \approx \sum_i S(\mathbf{x}-\mathbf{x}_i(t))\,\delta(\mathbf{p}-\mathbf{p}_i(t))$$

We obtain equations of motion for the macroparticles

$$\frac{d\,\mathbf{x}_i}{dt} = \frac{\mathbf{p}_i}{\gamma m} \qquad \frac{d\,\mathbf{p}_i}{dt} = \int d\mathbf{q}\left(\mathbf{E} + \frac{\mathbf{v}_i}{c}\times\mathbf{B}\right) S(\mathbf{q}-\mathbf{x}_i(t))$$

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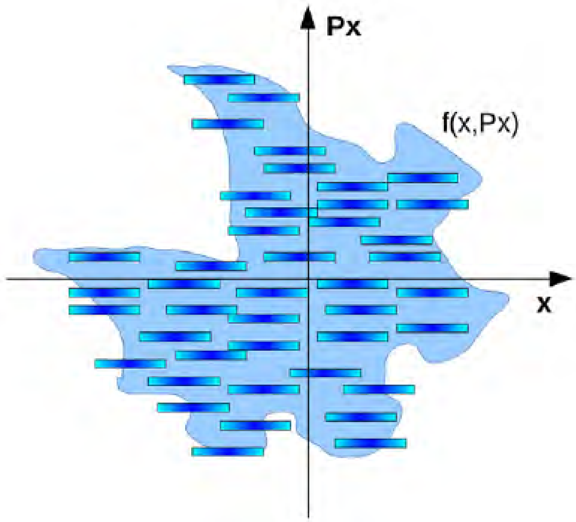
Simulations of the kinetic system

PIC codes

Vlasov equation (+Maxwell eq.)

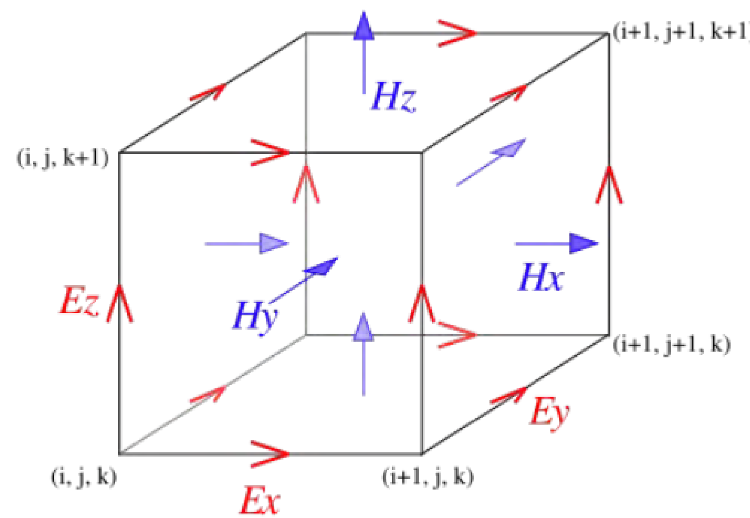
$$\partial_t f + \mathbf{v}\cdot\nabla_x f + q\left(\vec{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\nabla_p f = 0$$

Macroparticles



$$f(\mathbf{x},\mathbf{p},t) \approx \sum_i S(\mathbf{x}-\mathbf{x}_i(t))\,\delta(\mathbf{p}-\mathbf{p}_i(t))$$

EM fields on a grid



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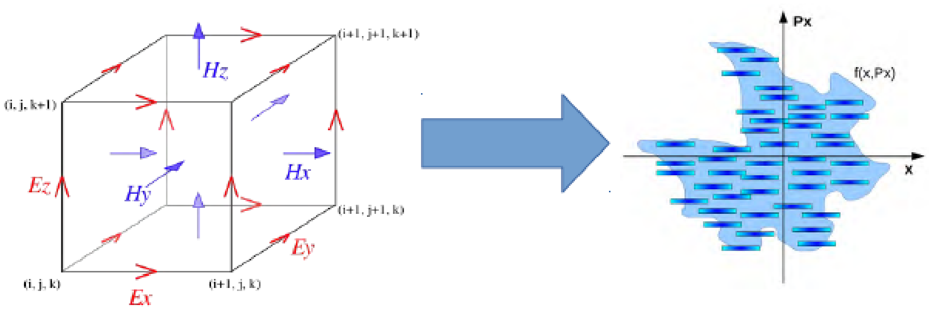
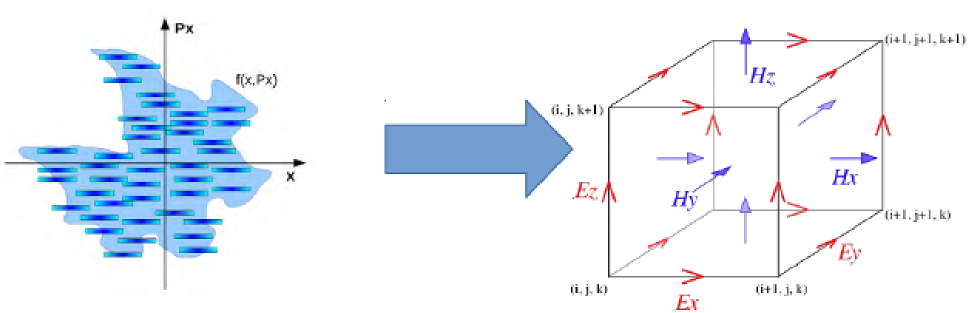
Simulations of the kinetic system

PIC codes



EM field to particles

“Easy”: we interpolate using the shape function



Particles to EM fields

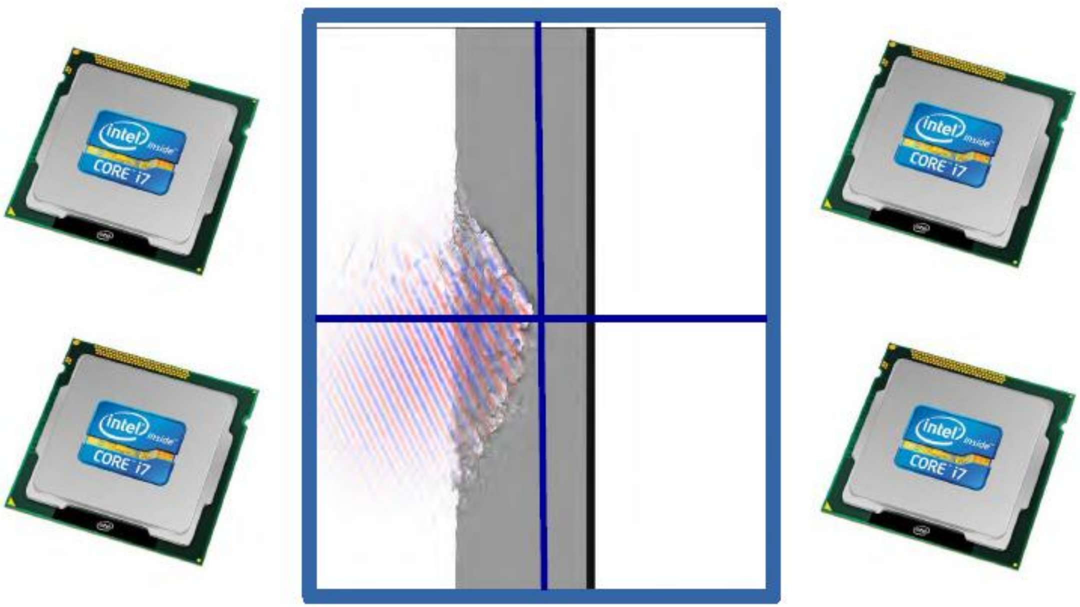
Few choices for **current deposition**

Simulations of the kinetic system

PIC codes

PIC codes can be parallelized rather naturally

We can slice the simulation domain



Each task simulates particles and fields in a given region

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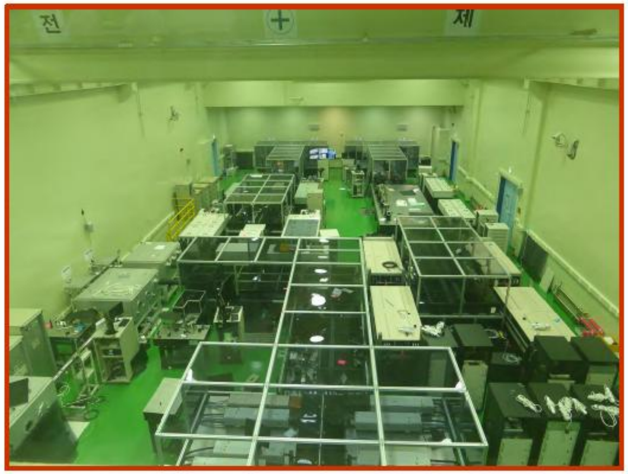
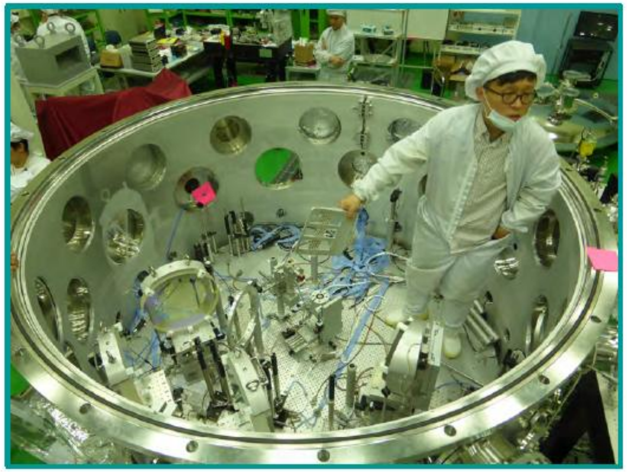
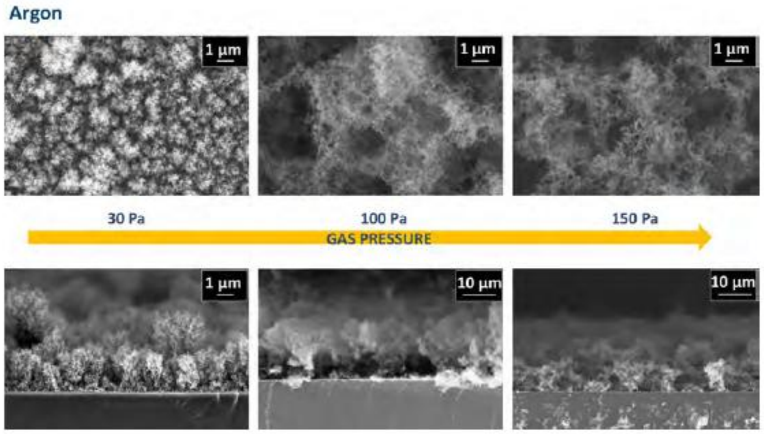
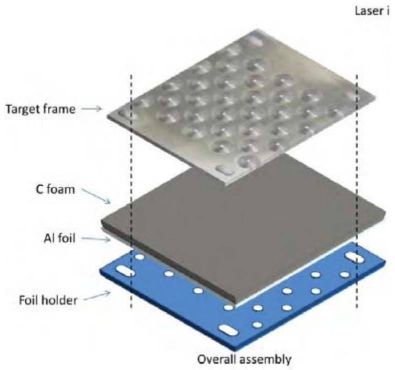
Ion acceleration with foam-based targets

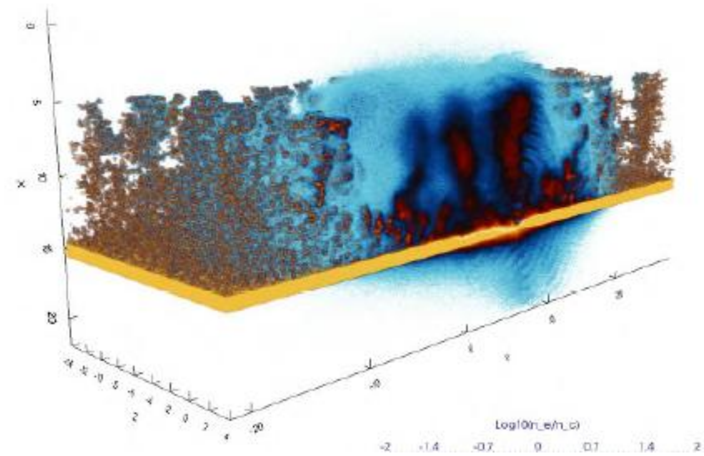
Target preparation, experiments on laser facilities and…simulations!











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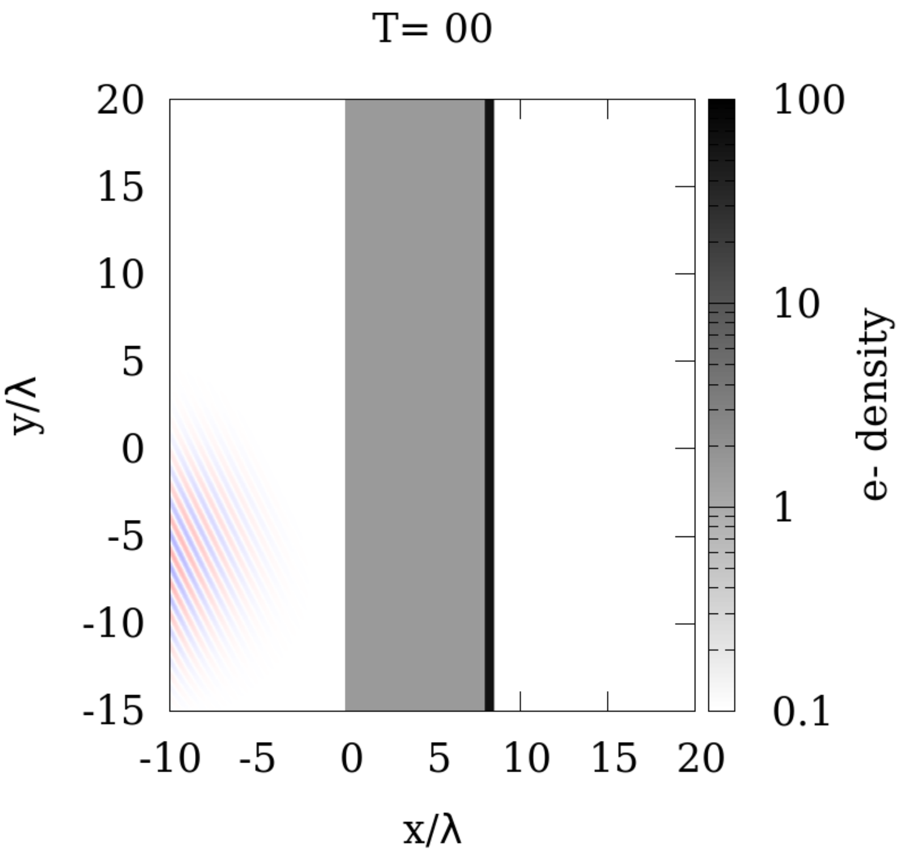
Ion acceleration with foam-based targets

Example of a 2D PIC simulation with a uniform low-density plasma



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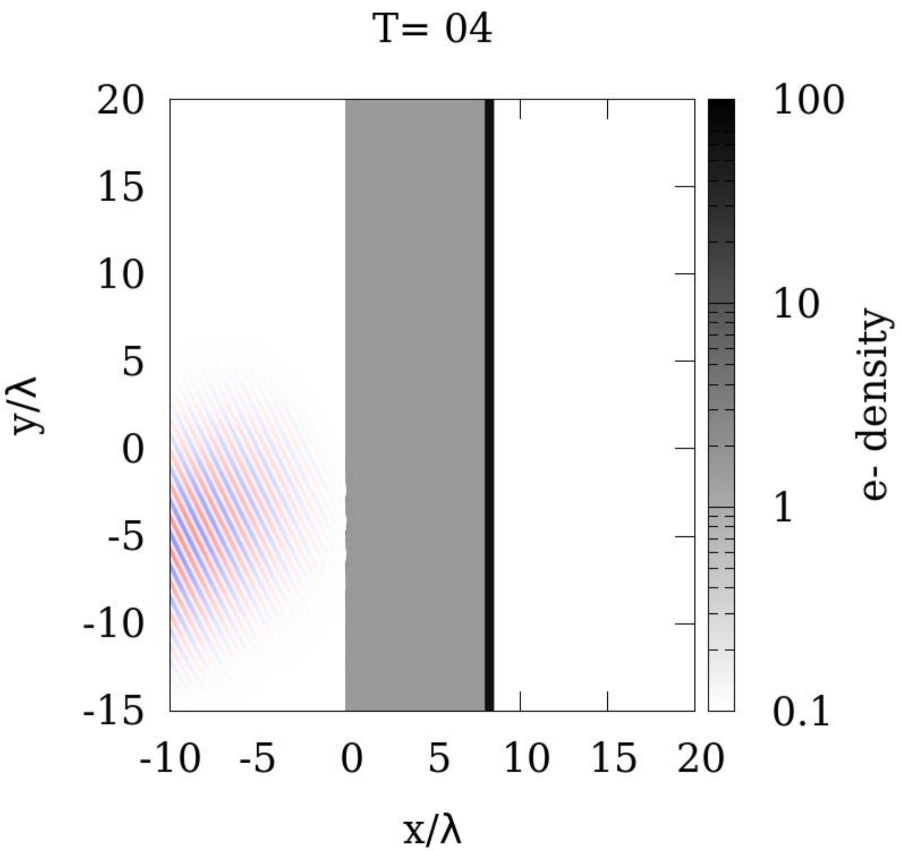

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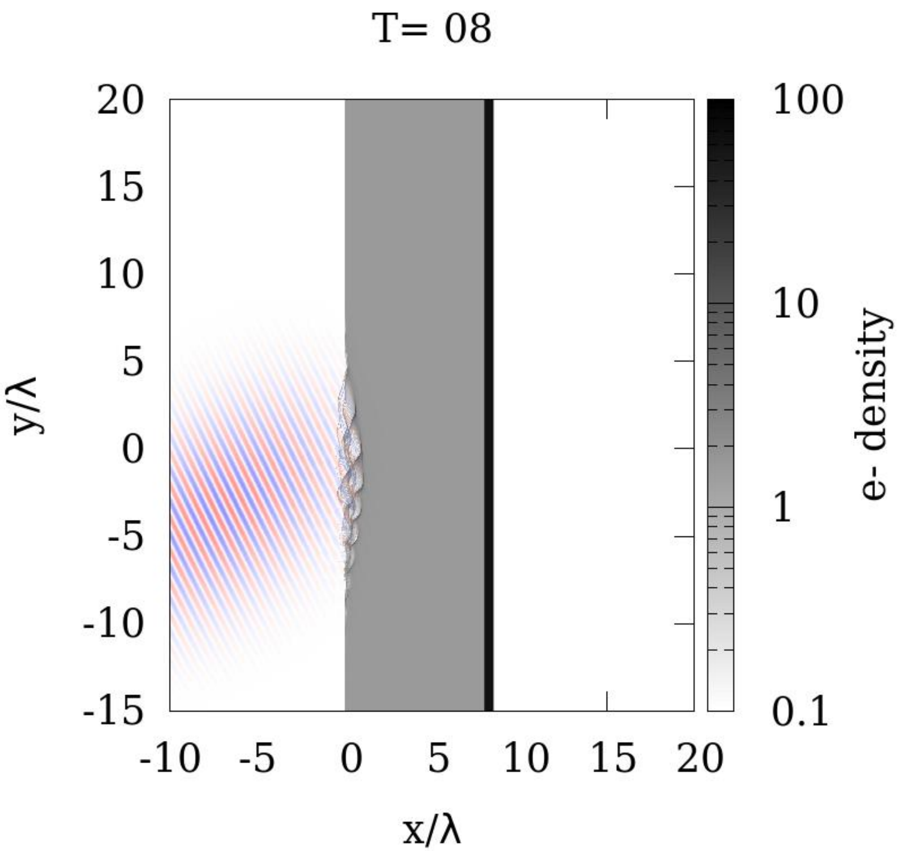

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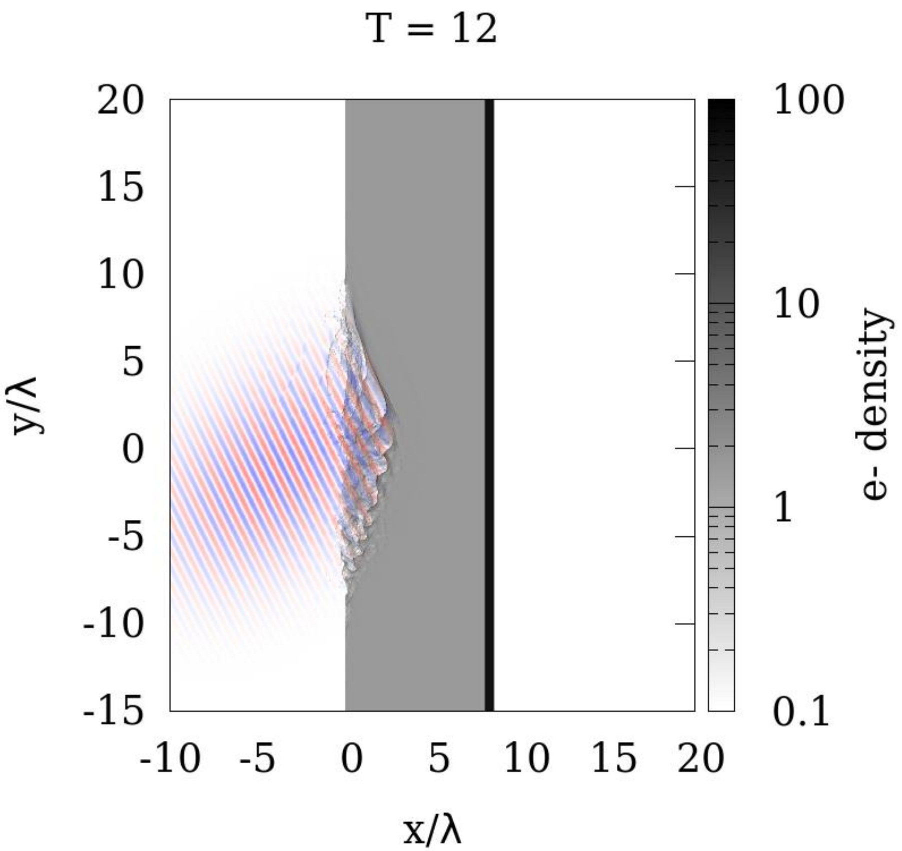

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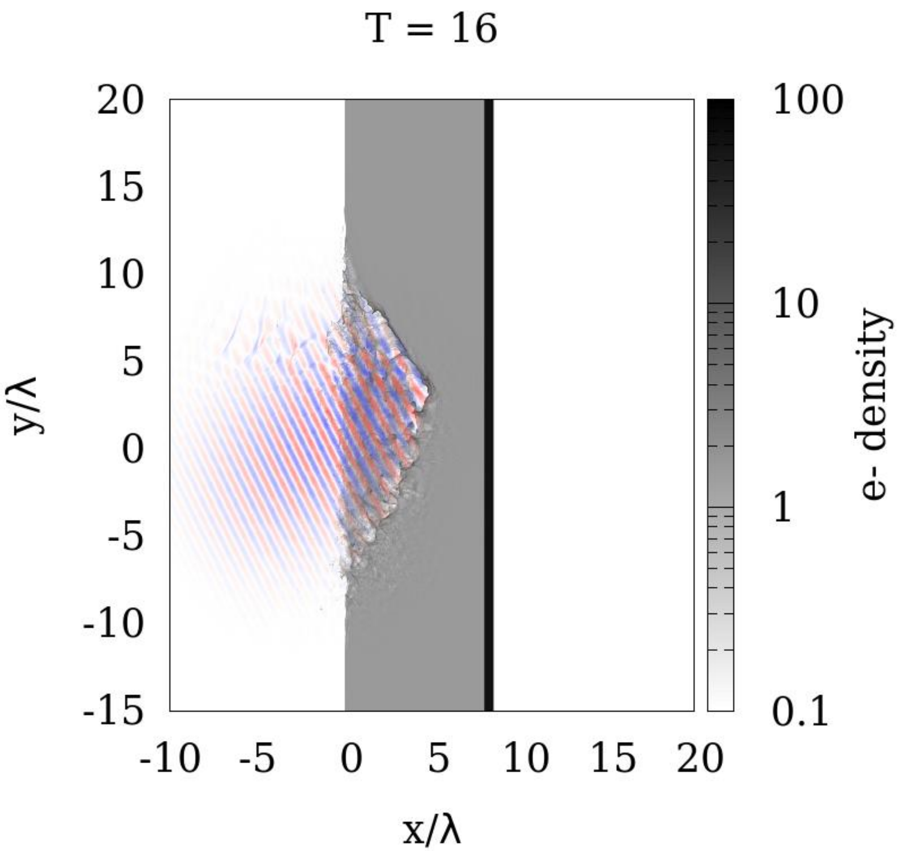

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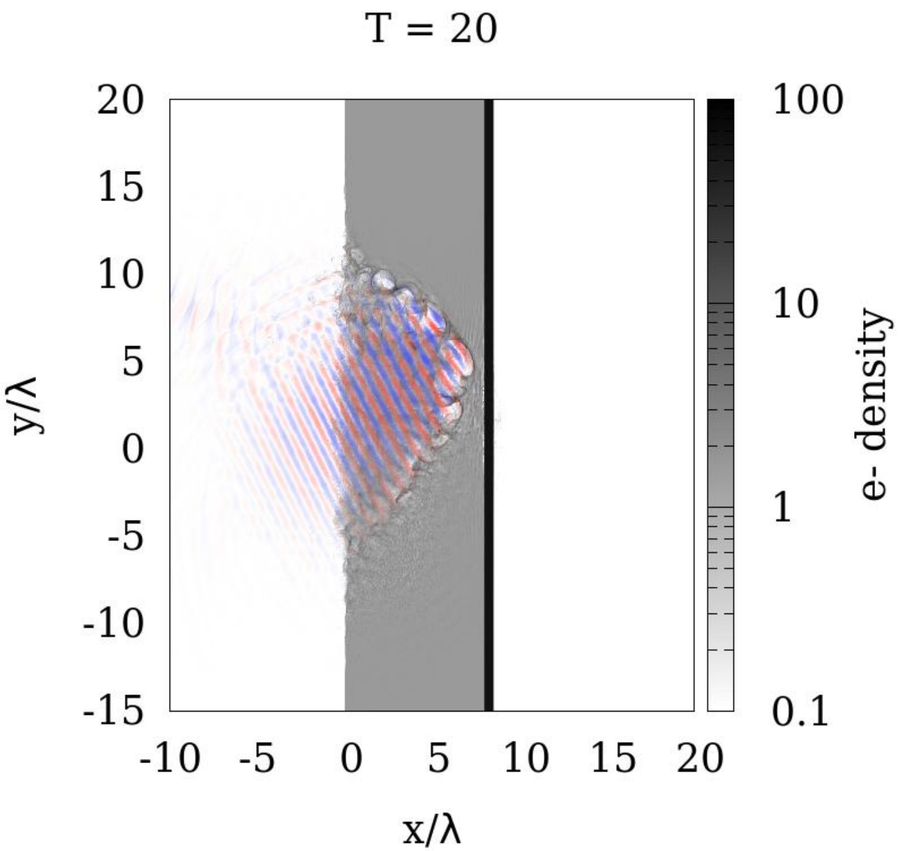

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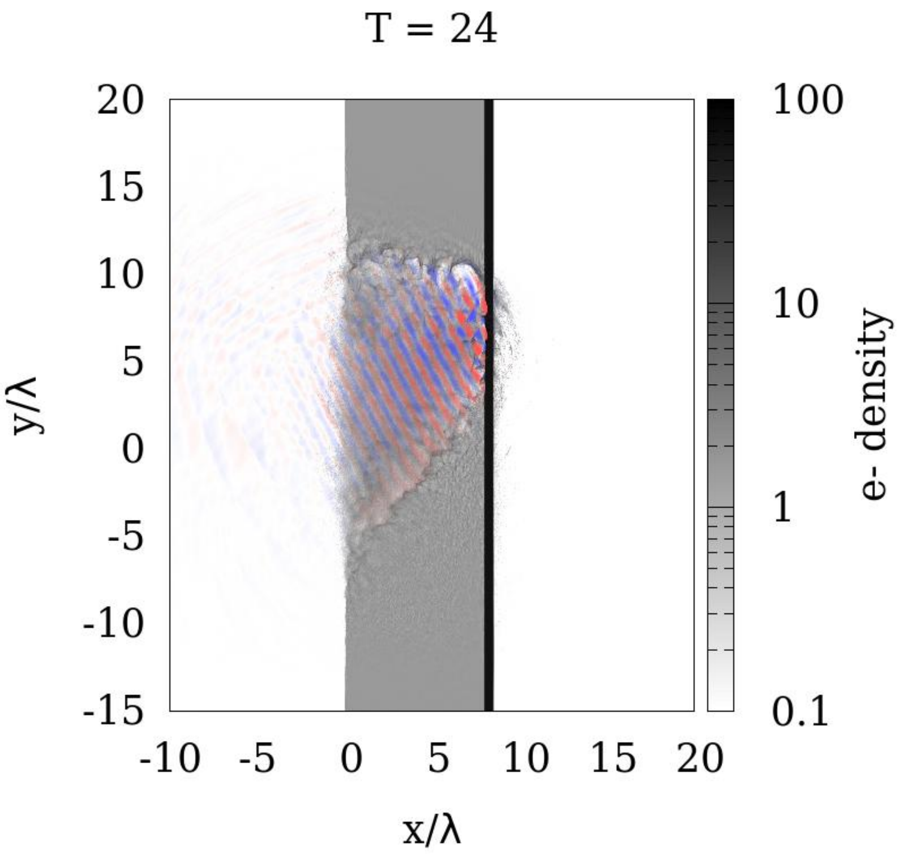

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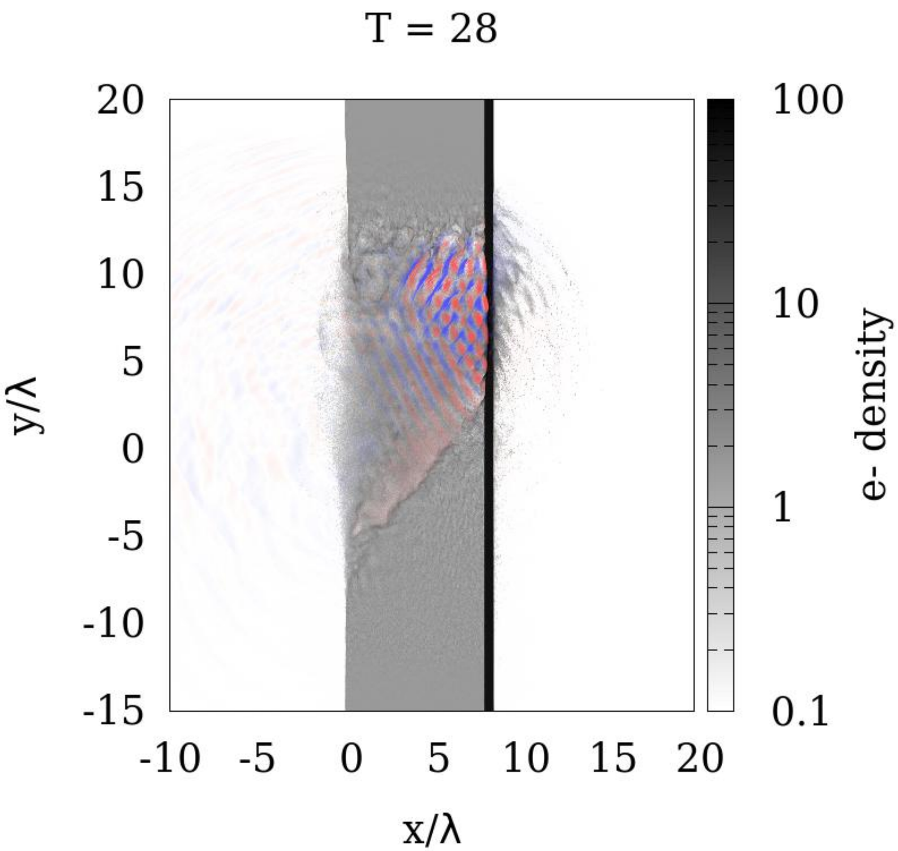

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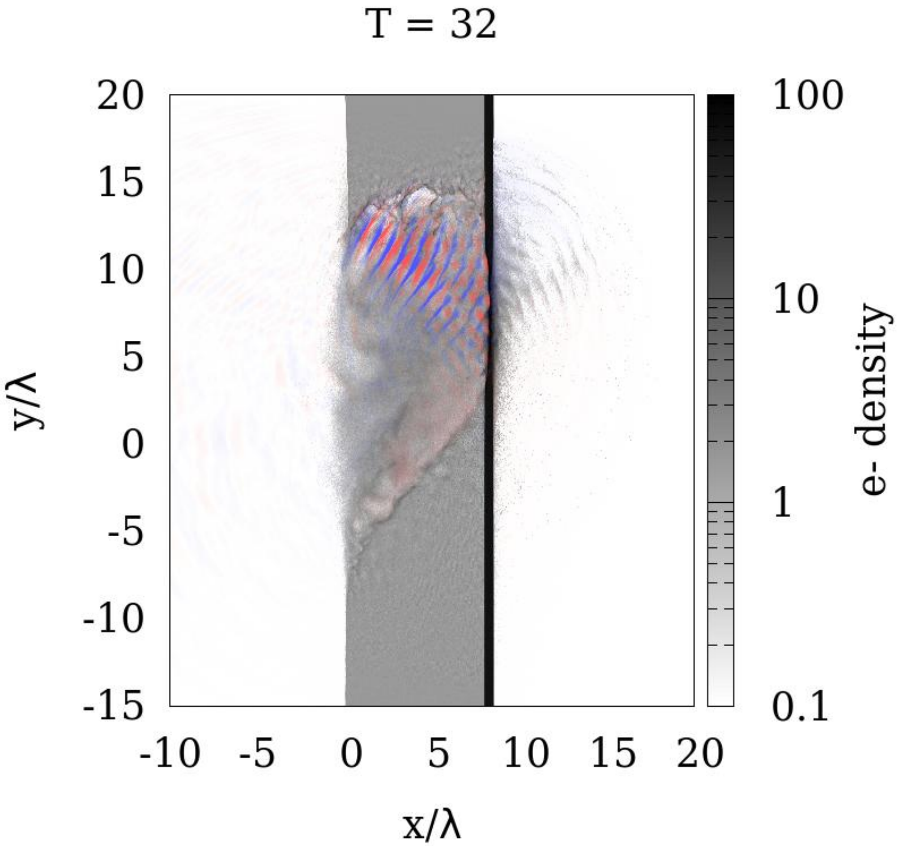

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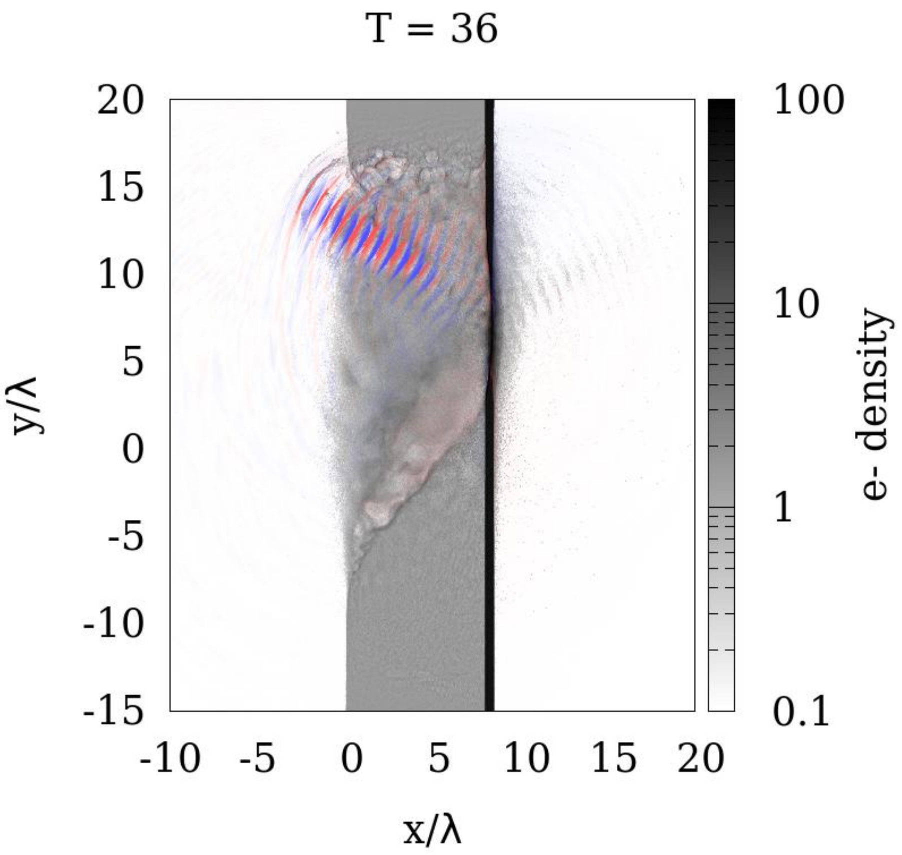

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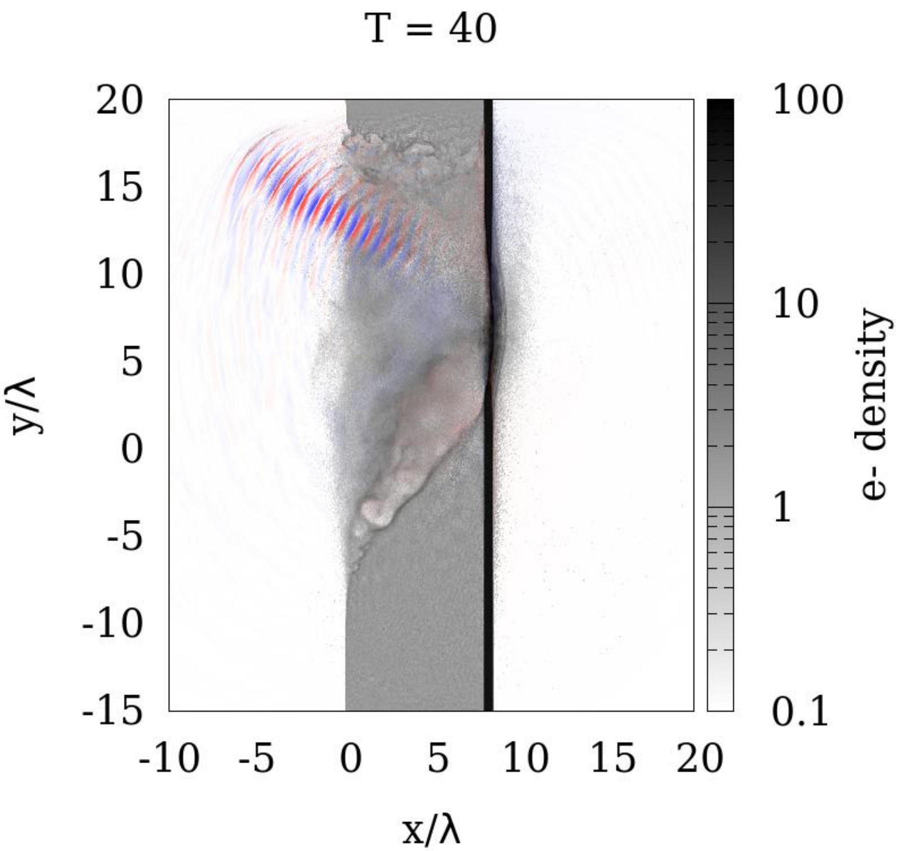
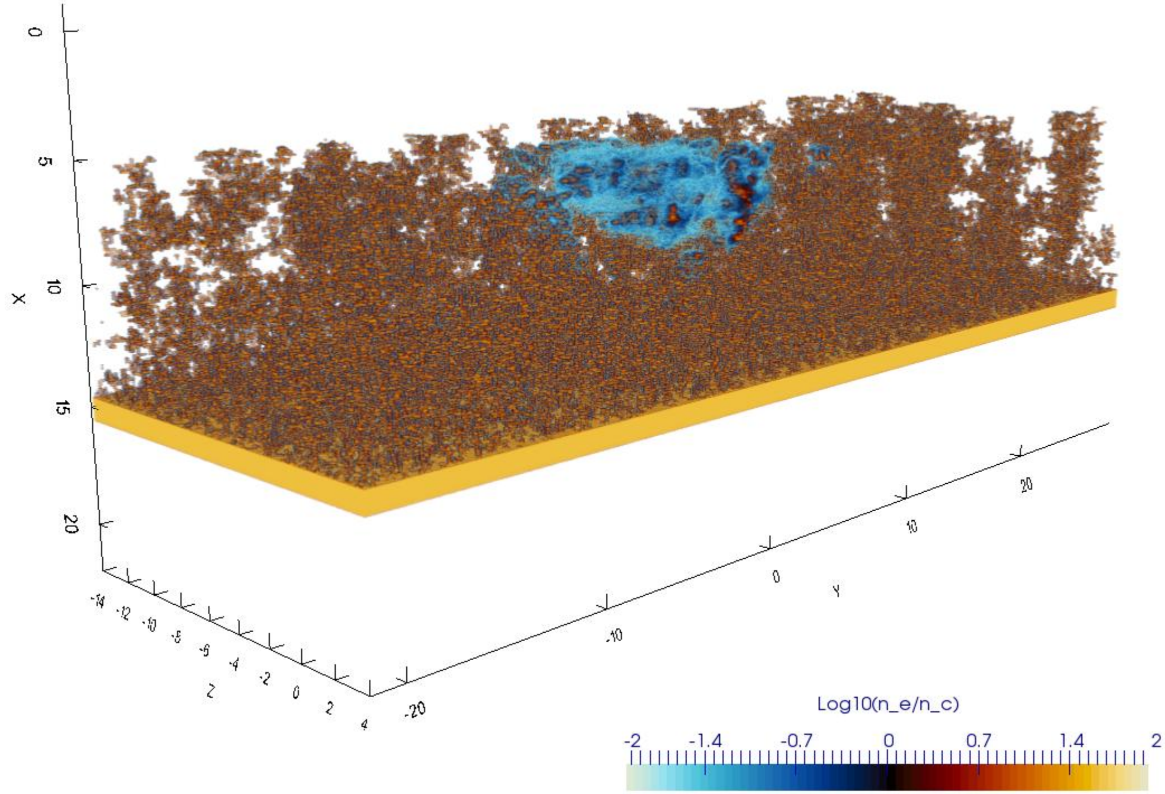


Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

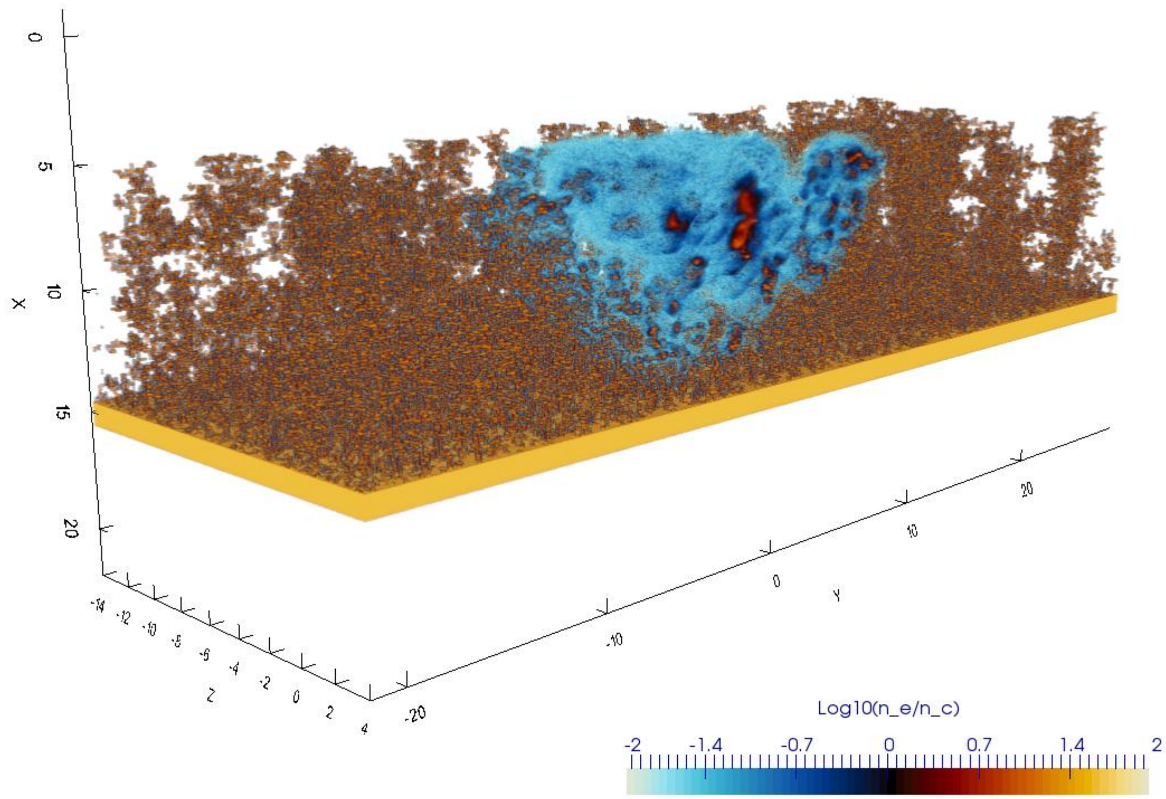
T = 08 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

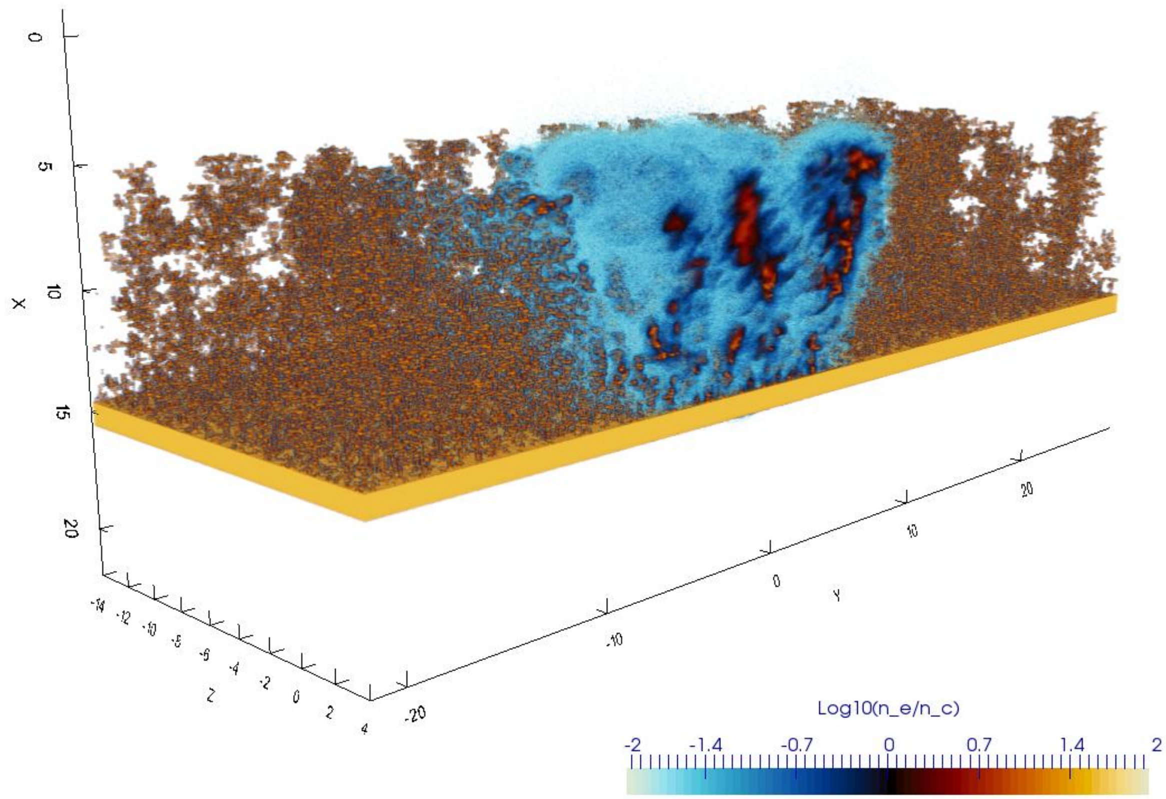
T = 12 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

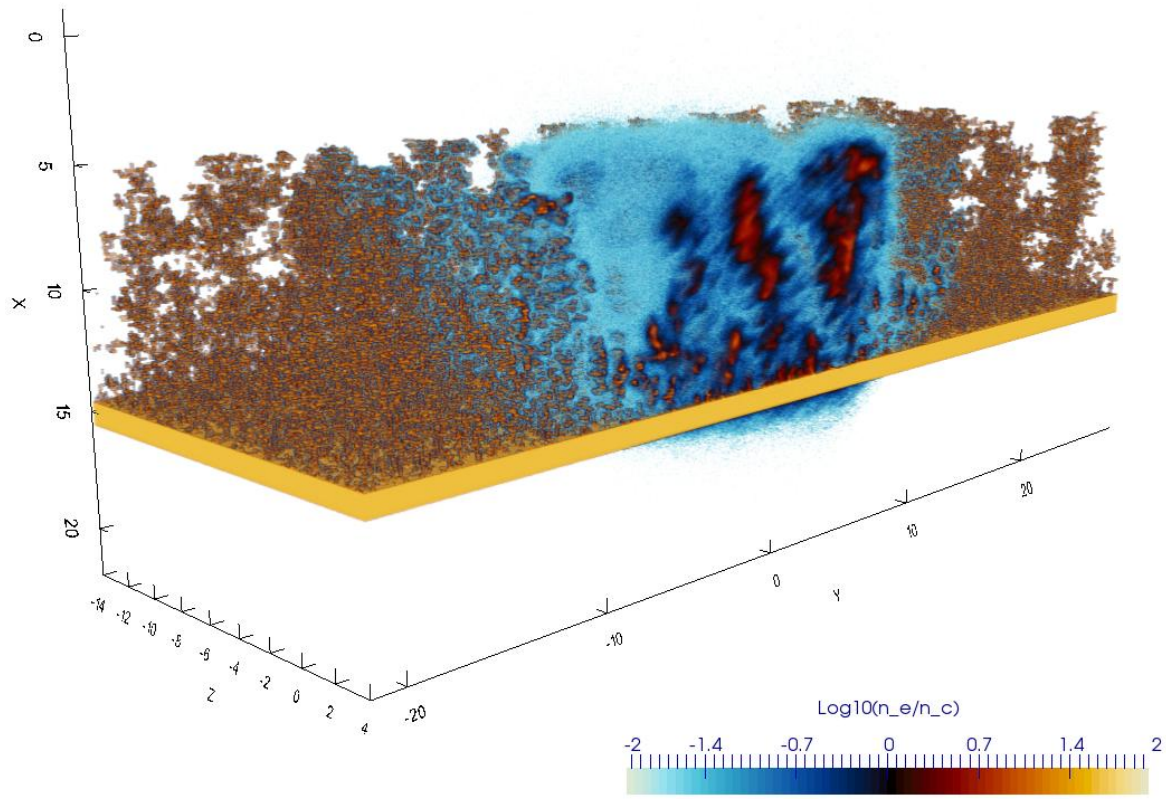
T = 16 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

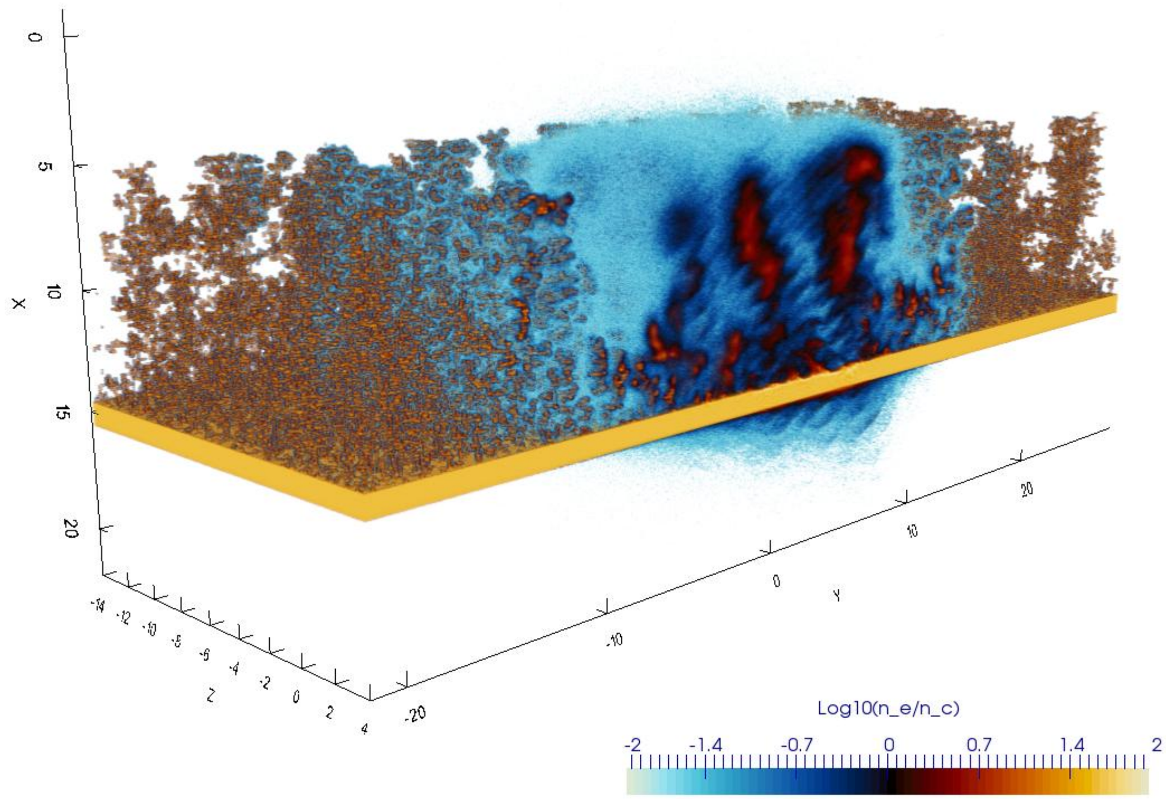
T = 20 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

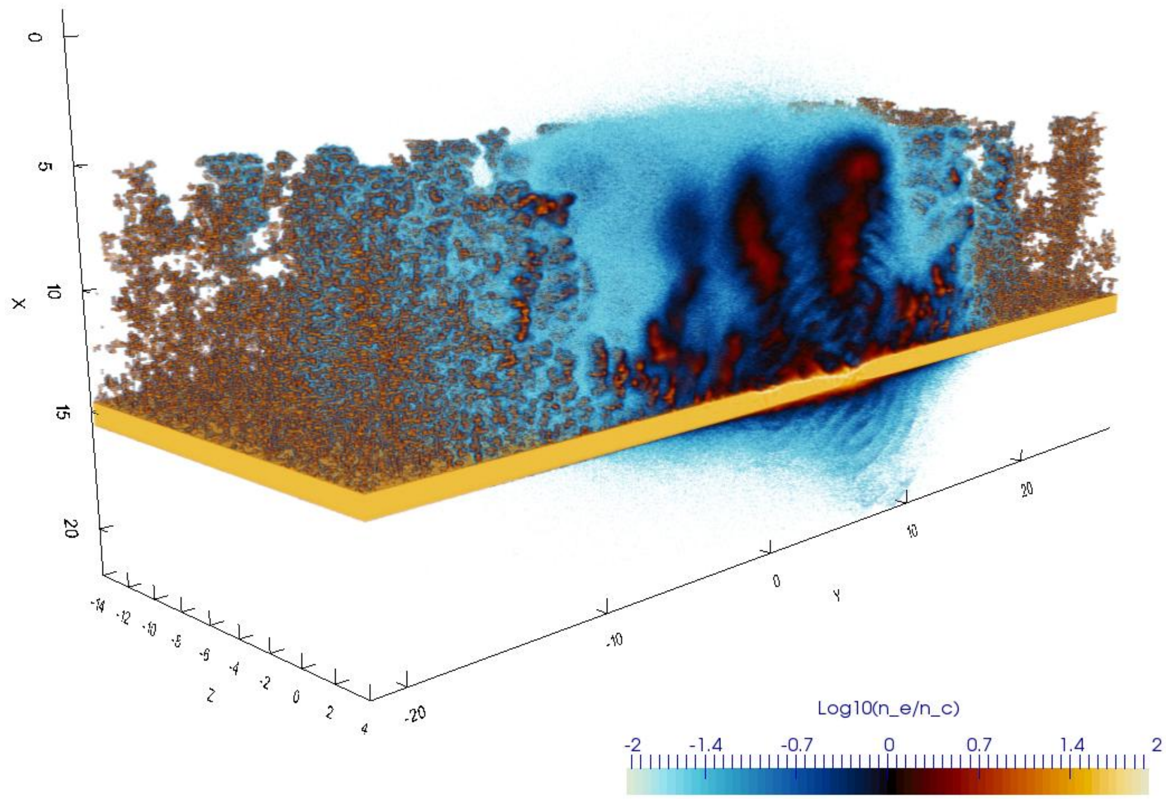
T = 24 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

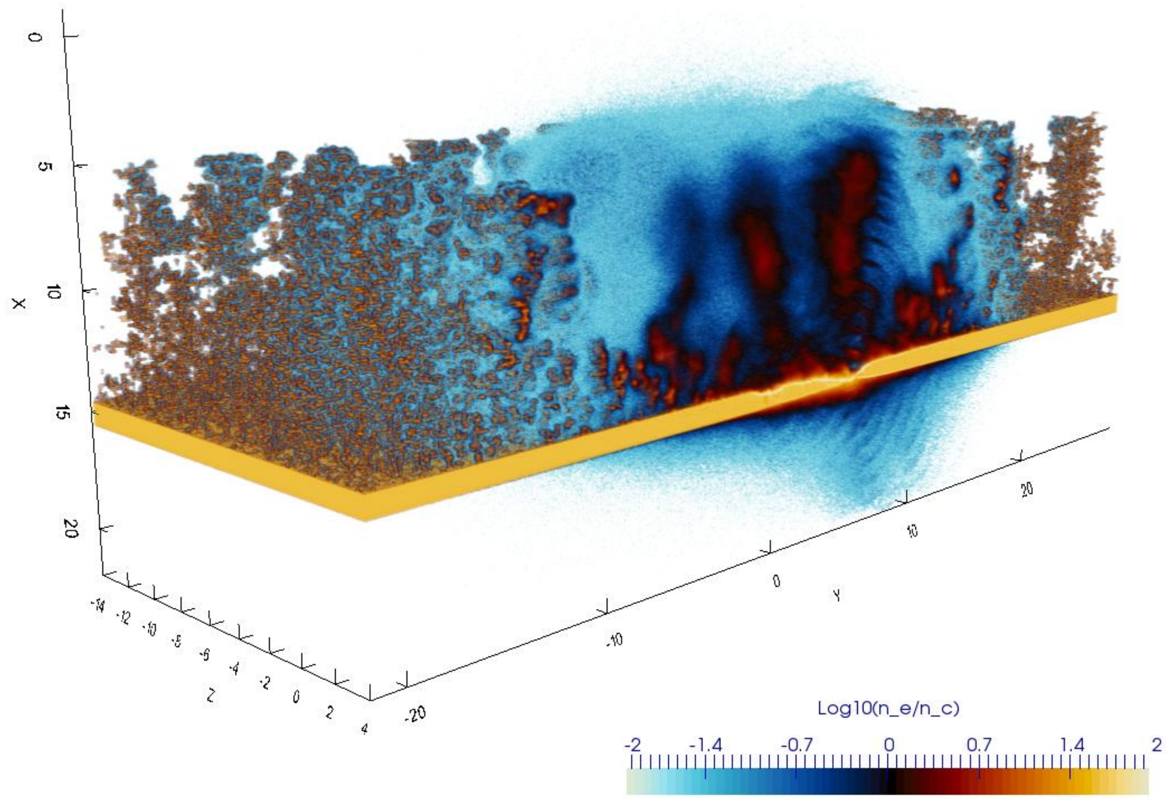
T = 28 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

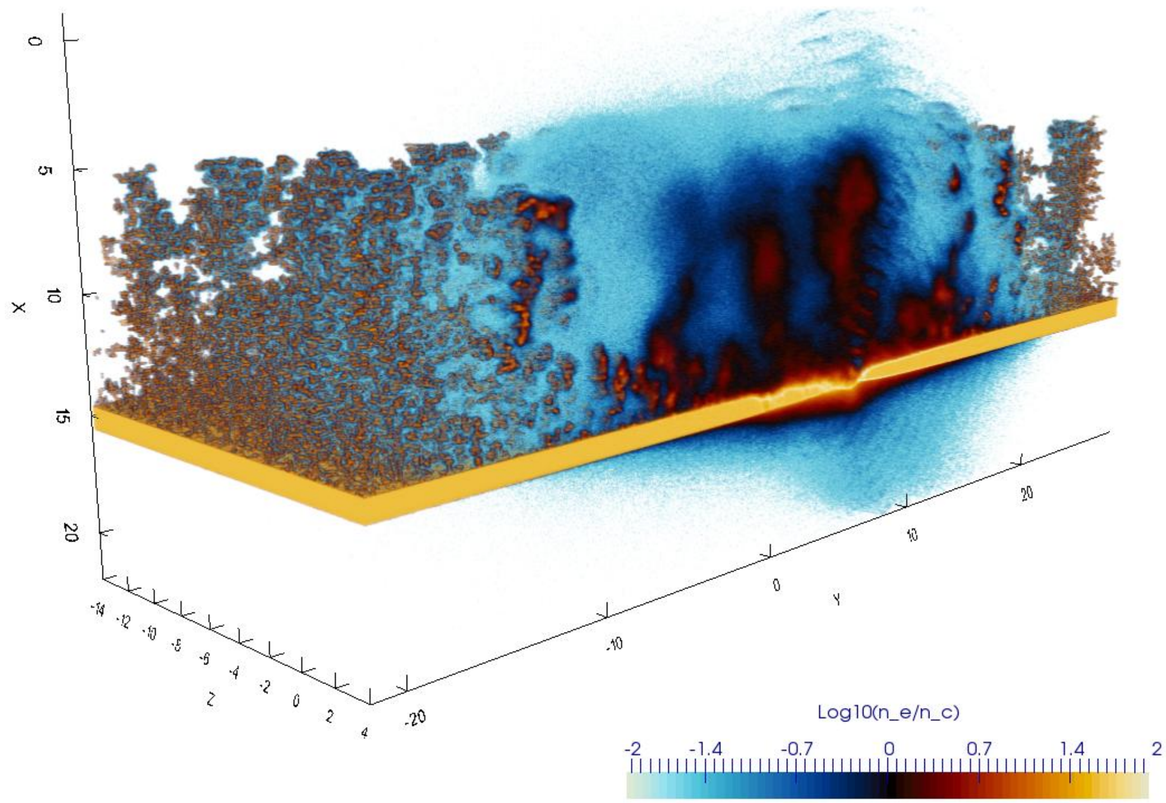
T = 32 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

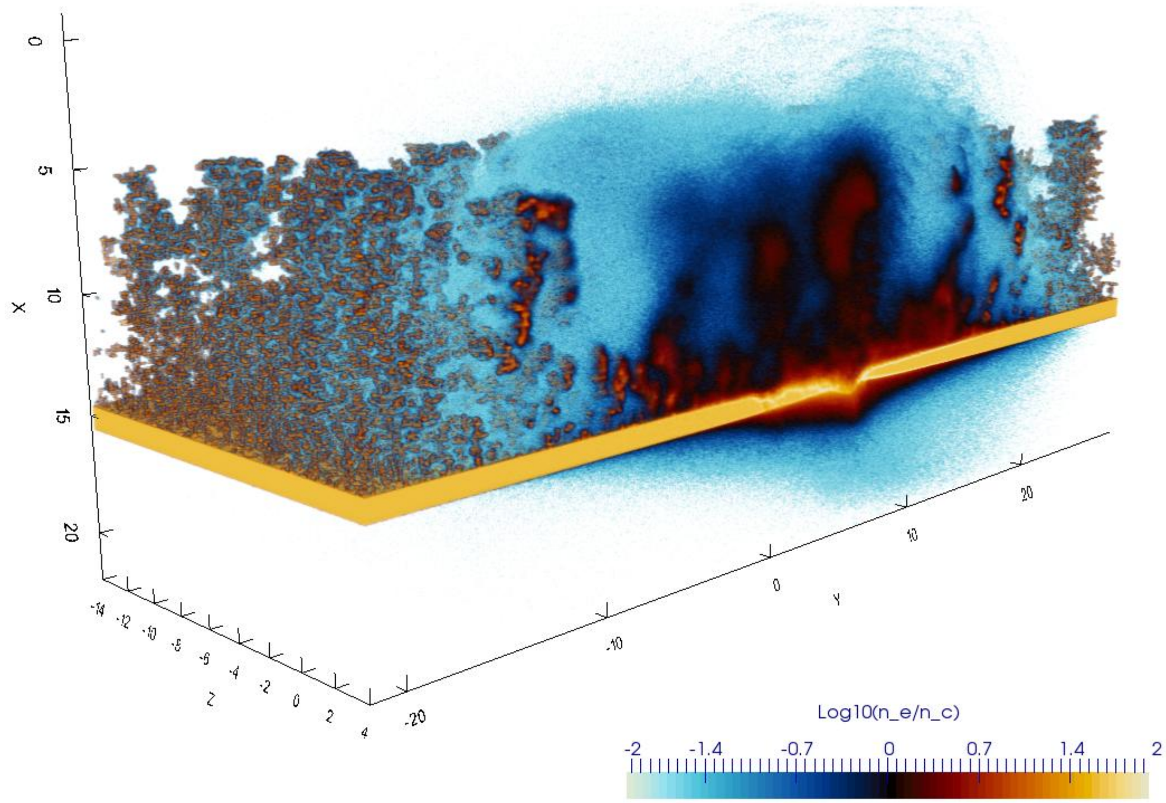
T = 36 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

T = 40 tp



Conclusions

- Mathematics is very important in modeling many aspects of laser-plasma interaction physics

- This is especially true for superintense laser-driven ion acceleration using nanostructured targets

- We have just mentioned one example! Many others exist, e.g.:
    - Fluid theories
    - Additional physics (ionization, collisions, QED, …)
    - Mathematical description of materials under irradiation, secondary radiation sources (analytical, MonteCarlo, …), …

Special thanks to…

The ERC-ENSURE (and ERC-INTER) team!

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Associate professor,
Principal investigator

Margherita Zavelani Rossi
Associate professor

+ support from NanoLab

Valeria Russo
Researcher

David Dellasega
Post-doc

Alessandro Maffini
Post-doc

Luca Fedeli
Post-doc

3 PhD students

Lorenzo

Arianna

Andrea

1 Master's student

Francesco

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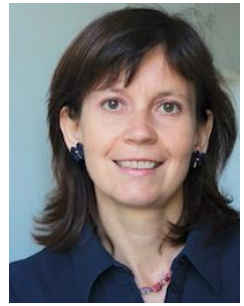

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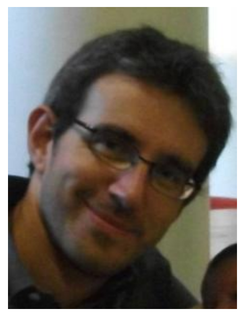

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Thanks for your attention!

ENSURE

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