# Integrated simulations of fast ignition of inertial fusion targets

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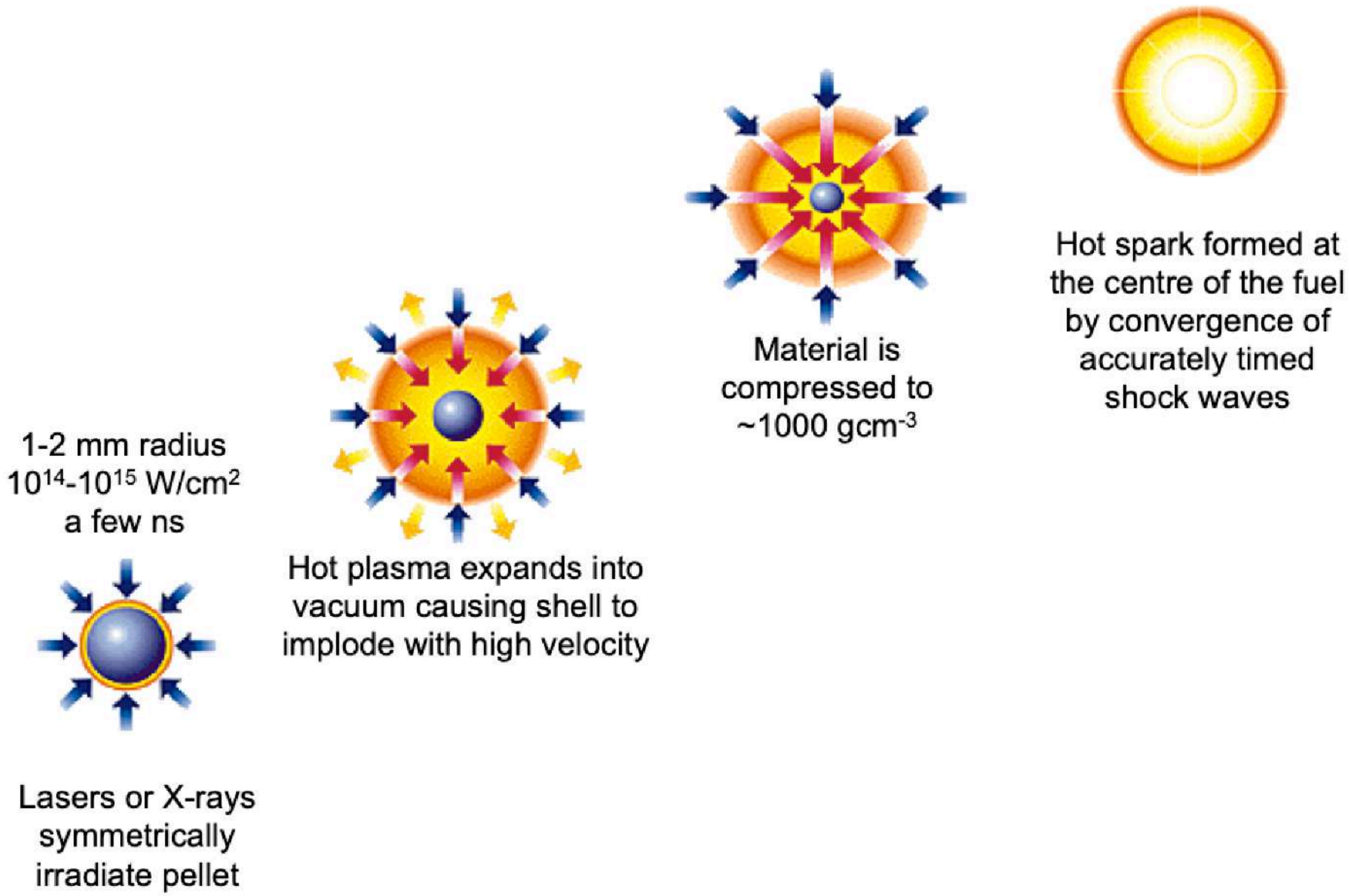
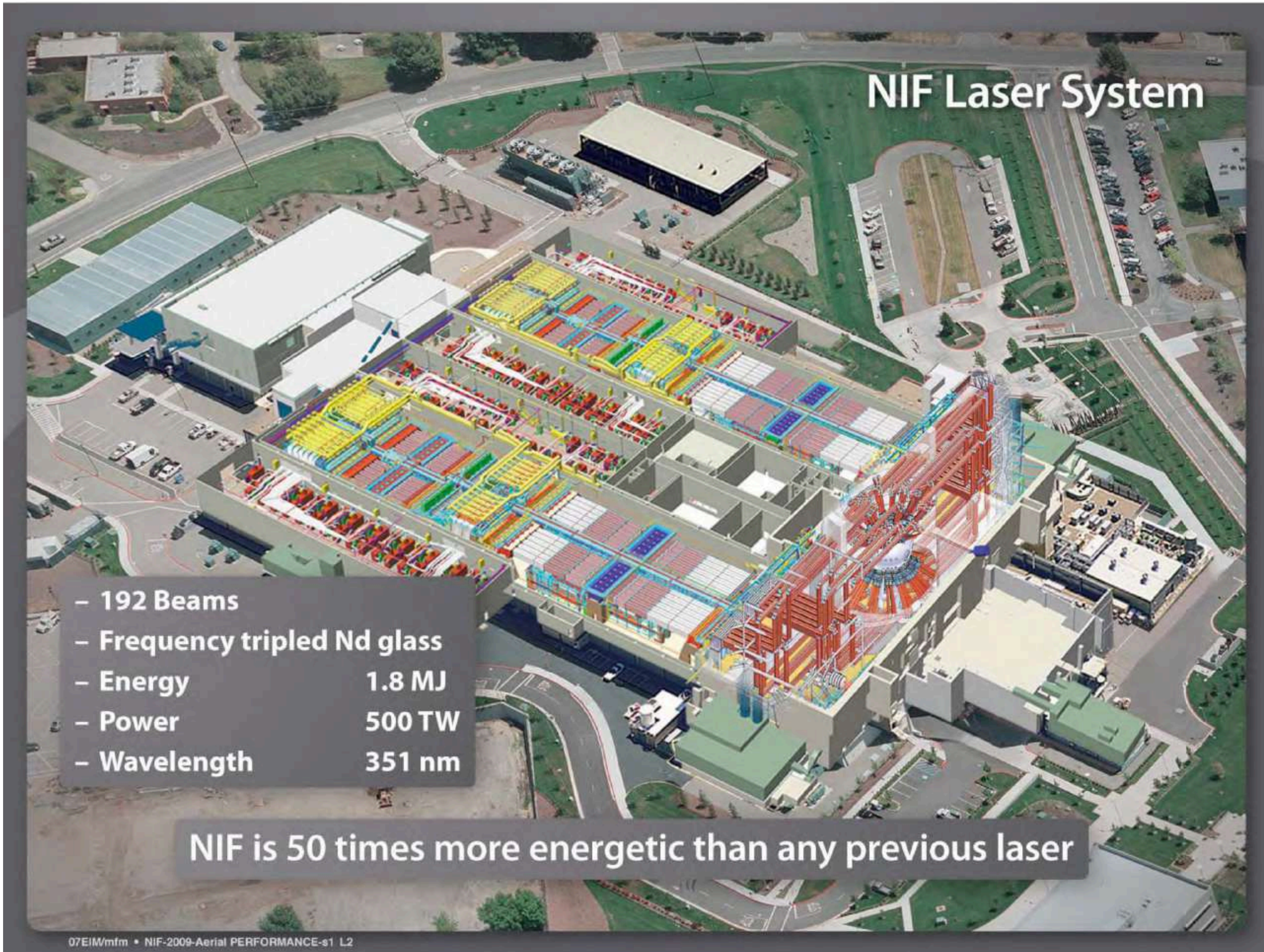
# Inertial Confinement Fusion

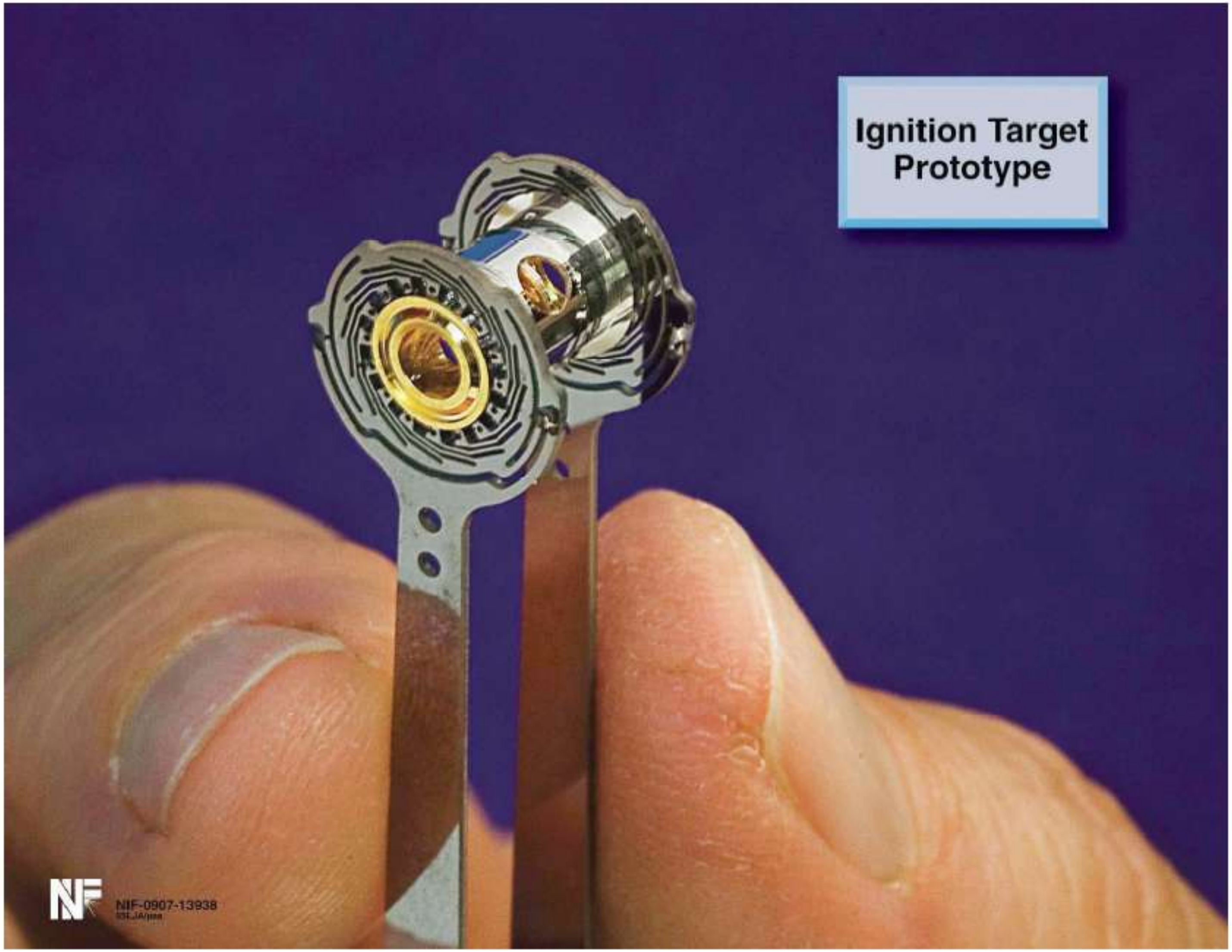


# National Ignition Facility (NIF)



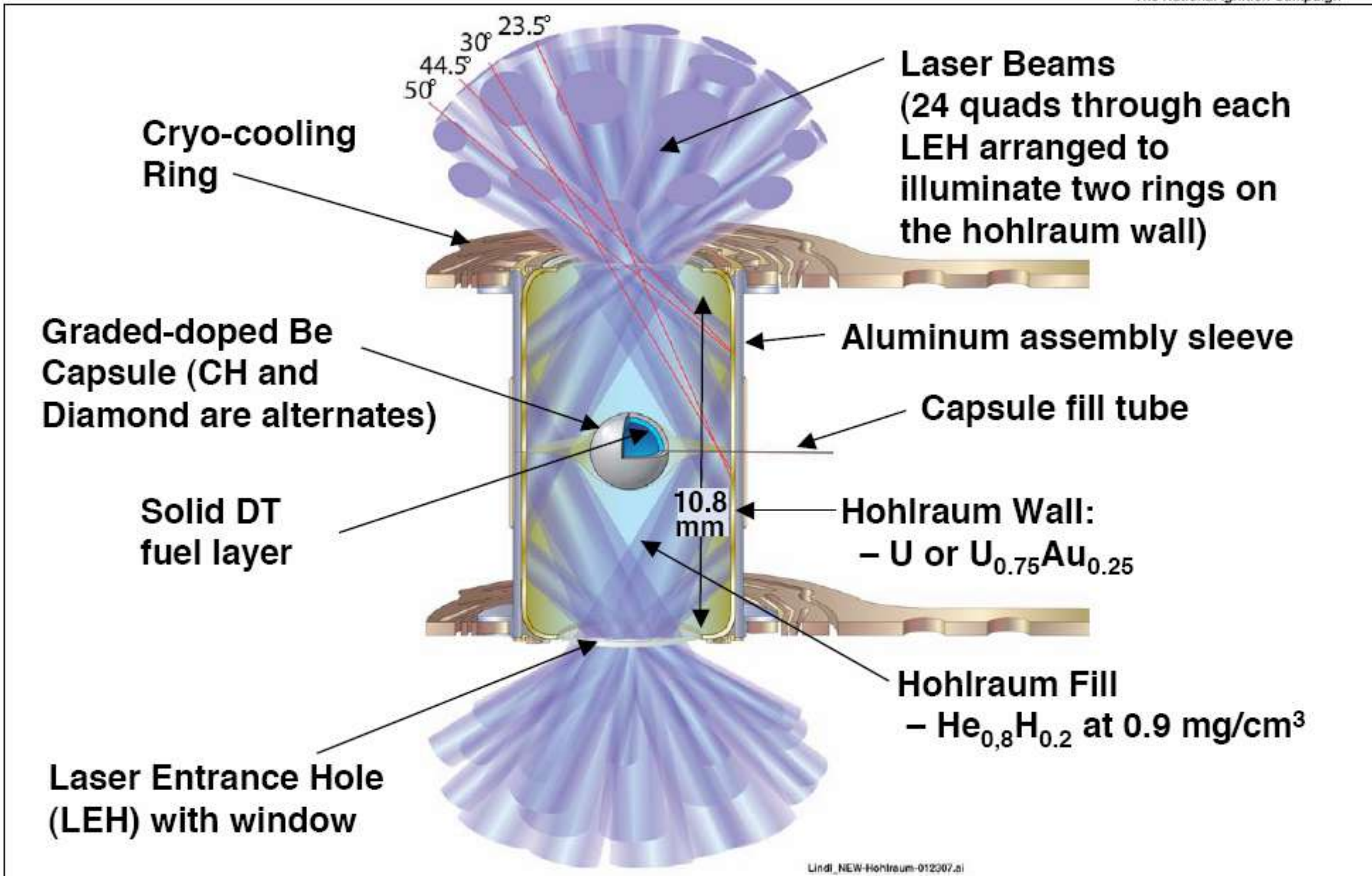
# Precision targets being developed for the NIF meet the ignition target requirements





# The NIF point design has a graded-doped, beryllium capsule in a hohlraum driven at 285 eV

NIC
The National Ignition Campaign



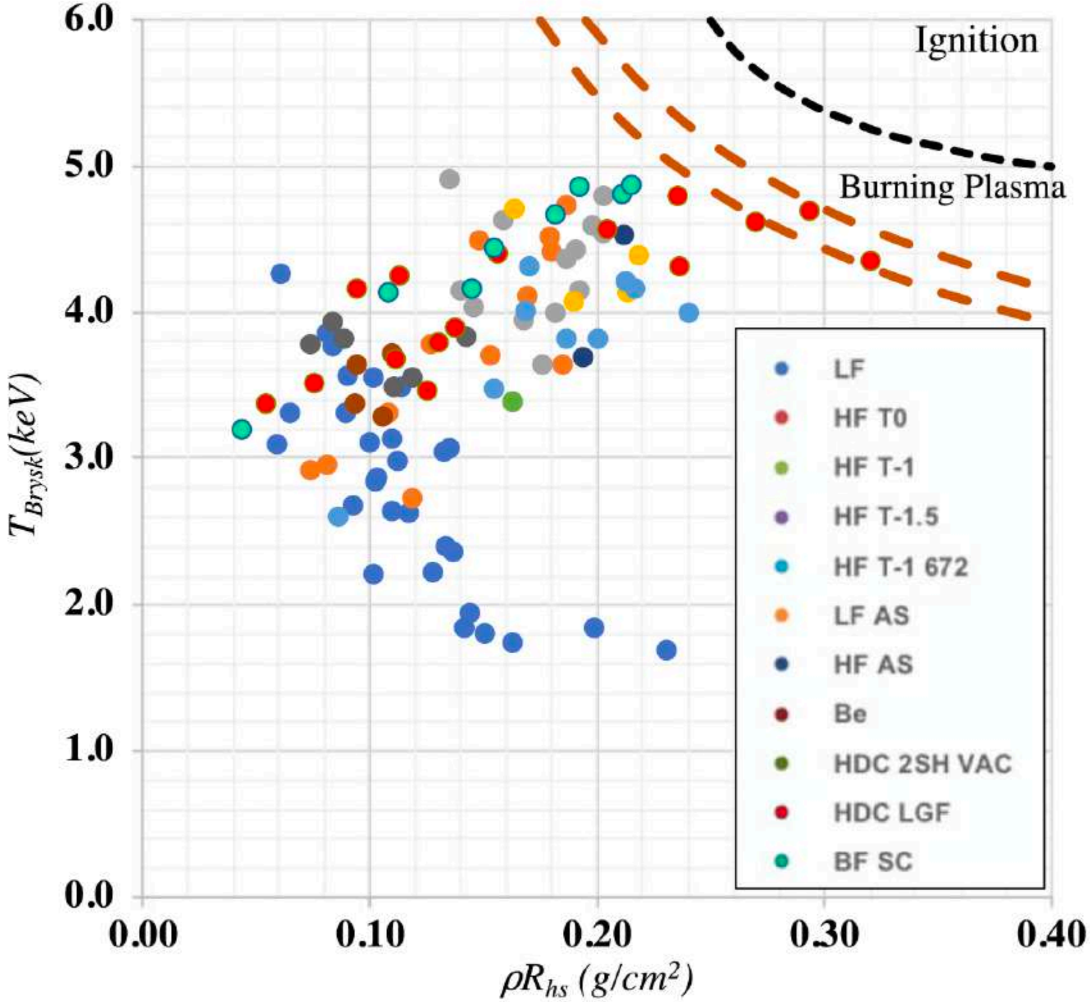
# Current status of experiments on NIF

**Best results so far:**

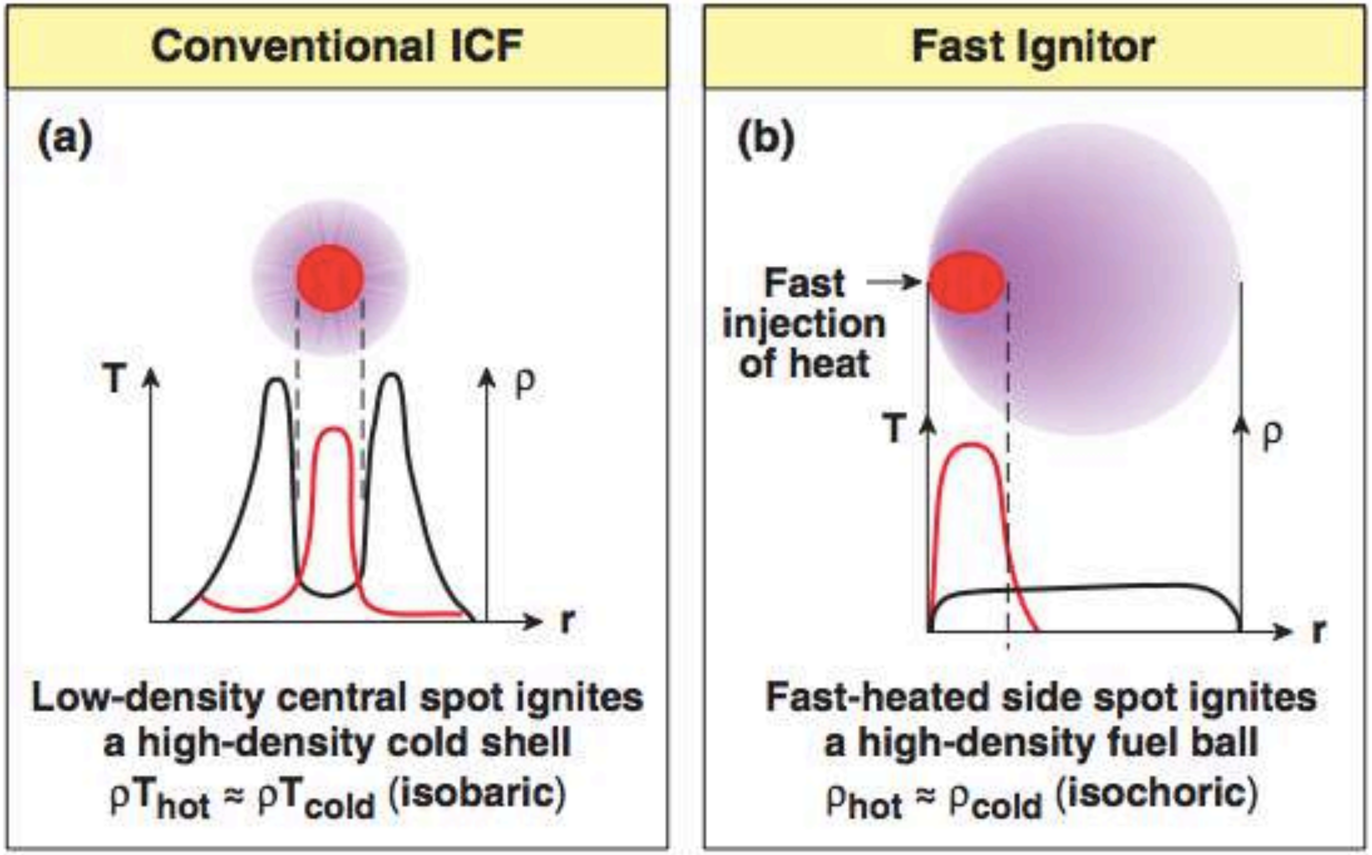
- Neutron yield: $2\times10^{16}$
- Internal DT energy: 25 kJ
- Fusion energy: ~ 55 kJ
- Inferred hot spot pressure

  ~ 350 Gbar, $\rho R_{hs}$ ~ 0.3 g/cm$^2$
- $\alpha$-particle heating regime
- Hurricane *et al*., Physics of Plasmas **26**, 052704 (2019).

Plasma Phys. Control. Fusion **61** (2019) 014033



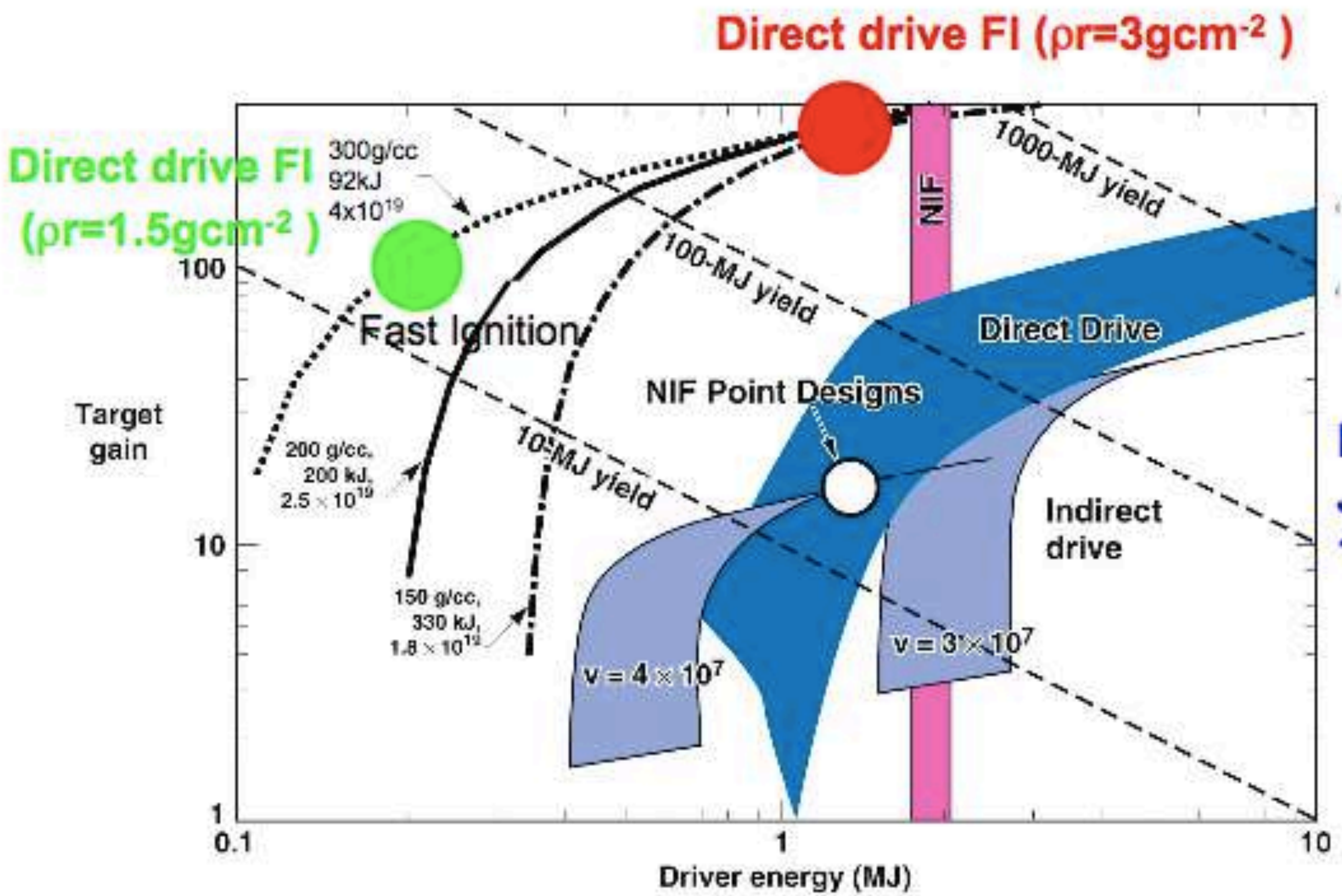
# Central ignition vs. Fast ignition



# Fast ignition can be achieved with lower drive energies

Courtesy of M. Key

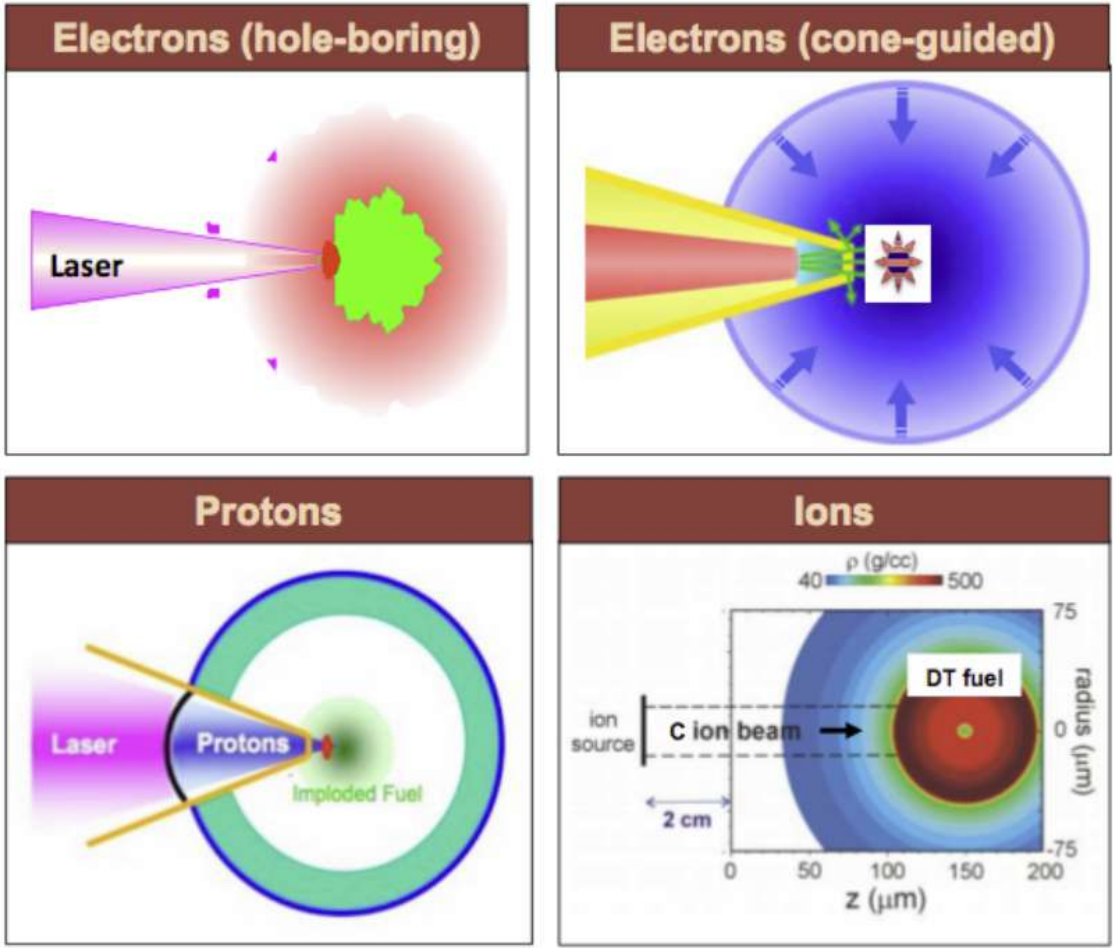
- Separation between implosion and ignition phases.




M H Key et al.
J. Fus. Energy
17, 231, (1998)

# Fast ignition schemes

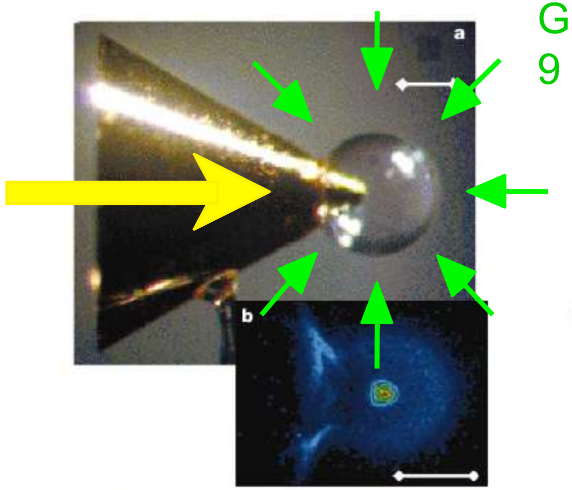
R.R. Freeman, *Fast Ignition Review*, National Academy of Sciences, March, 2011



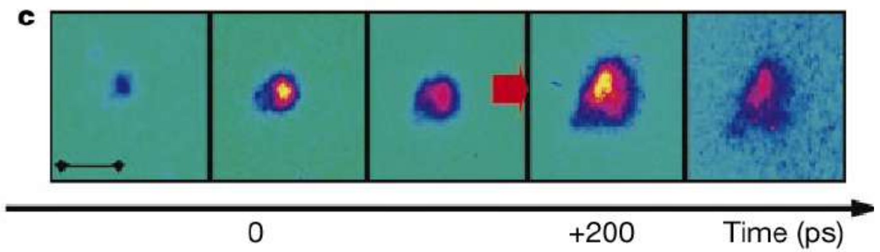
# The first integrated FI experiment was very successful

Kodama *et al*., *Nature* **412**, 798 (2001) and Kodama *et al*., Nature **418**, 933 (2002)

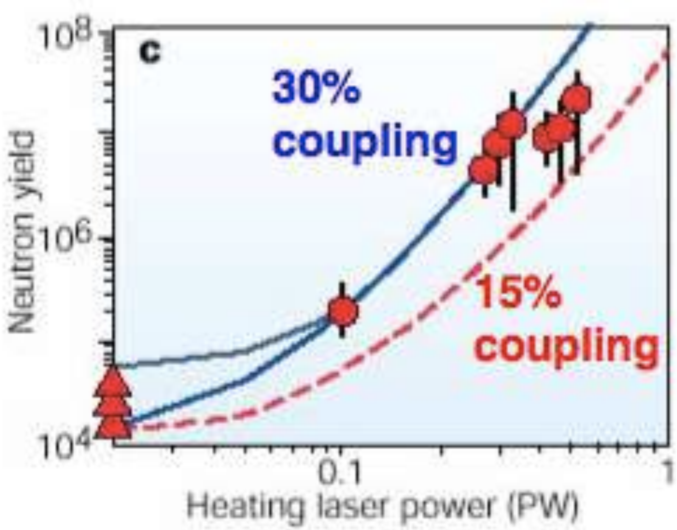
0.5 PW

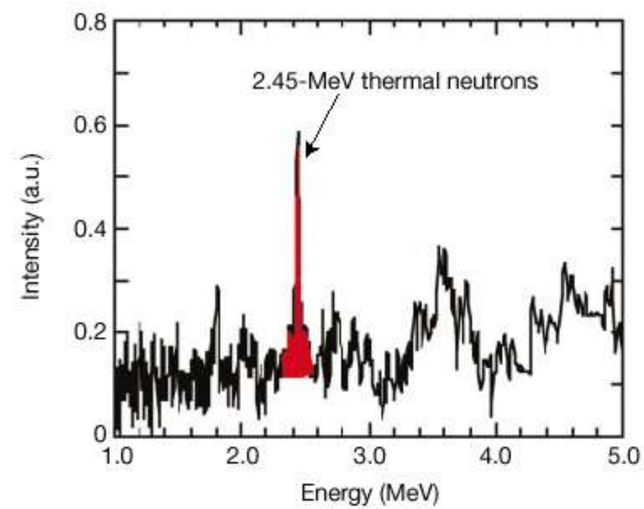



GEKKO laser
9 beams, 0.53 μm, 1.2 kJ / 1ns




**1000x** increased DD neutrons
**≈20%** coupling efficiency to imploded CD



# Our simulation work

- The research projects carried out on ***Marenostrum*** and ***Magerit*** HPC have been devoted to analyse alternative ignition schemes of inertial confinement fusion capsules with a lower ignition threshold.
- The following schemes have been explored so far:
  - **Electron-driven fast ignition** of inertial fusion targets, where an electron jet is generated by the interaction of an ultra-high intensity (UHI) laser with the cone tip. The electrons deposit their energy in the compressed core triggering the fusion reaction.
  - **Ion-driven fast ignition** the same the electron FI, but driven by UHI laser-accelerated ions.
  - **Magnetized inertial fusion targets**. Just started.
- Simulation codes used:
  - Multidimensional **Particle-In-Cell** (PIC) codes **PICLS** [Sentoku & Kemp, *JCP* **227**, 6846 (2008)] and **EPOCH** [Arber *et al.*, *PPCF* **57**, 113001 (2015)]
  - **Hybrid** code **PETRA** [Honrubia *et al.*, *Phys. Plasmas* **12**, 052708 (2005)].
  - **MHD** code **FLASH** [Fryxell *et al.*, *ApJ* **131**, 273 (2000)].

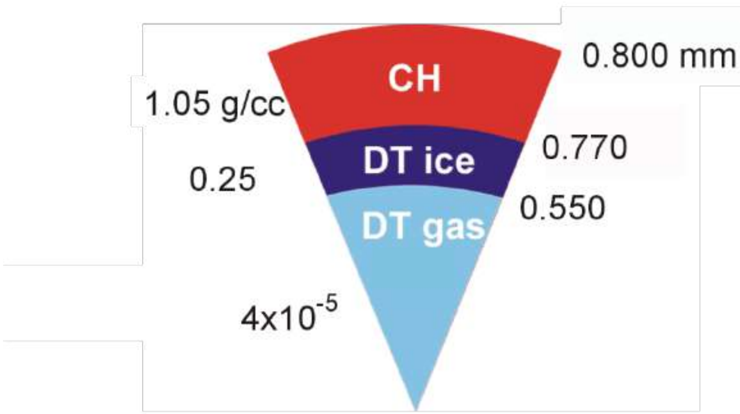
# Fast ignition target simulation

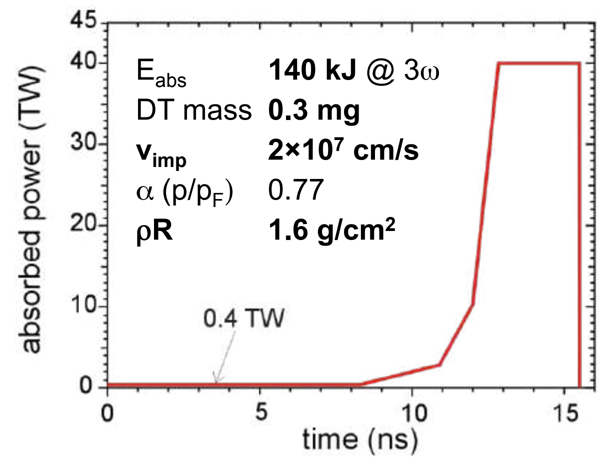
- Multidimensional **radiation-hydrodynamic** simulations for fast ignition (FI) target design, including laser pulse shaping.
  - Implosion symmetry is not as crucial as in central ignition targets.
  - FI targets are much less prone to hydrodynamic instabilities.
  - Laser pulse intensities around $10^{14}$ W/cm$^2$ with ns duration.
- **Electron or ion acceleration** by ultra-high intensity lasers.
  - Kinetic PIC simulations are used to determine the initial distribution function of electron and ion beams.
  - Fully relativistic multidimensional PIC codes.
  - Coupling of the PIC results with the fast ignition simulations.
  - Laser pulse intensities around $10^{20}$ W/cm$^2$ with ps duration.
- **Transport and energy deposition** of laser-driven electron and ion beams.
  - 2D/3D hybrid-PIC simulations including self-generated, resistive fields (collective effects, resistive Weibel instability,…).
  - Coupling with radiation-hydrodynamic codes including ignition physics.

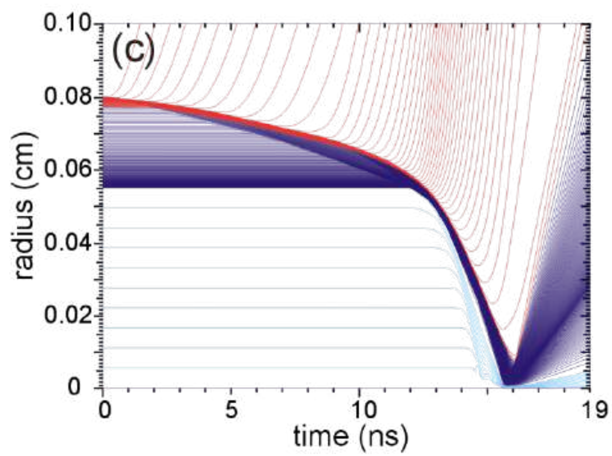
# Hydrodynamics of target implosion

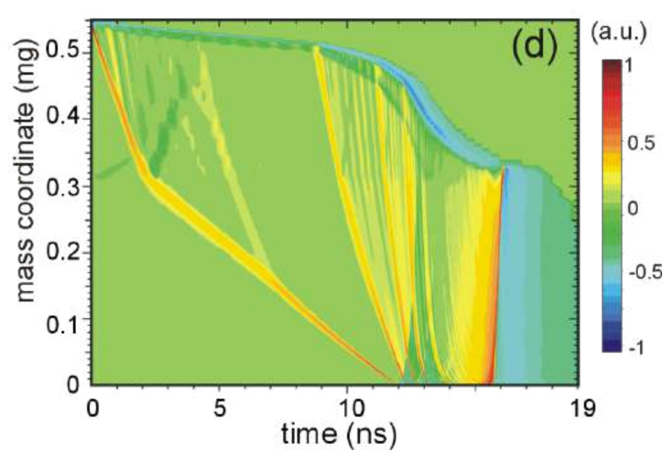
# 1D Hydrodynamic simulations

- Multigroup radiation-hydrodynamic model with laser energy deposition .
- Hundreds of spatial cells, 100 energy groups, 12 angular intervals.
- Execution time: tens of minutes with a single processor.



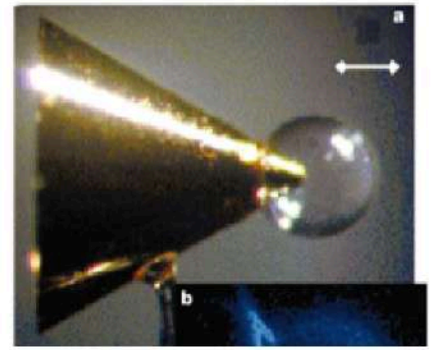



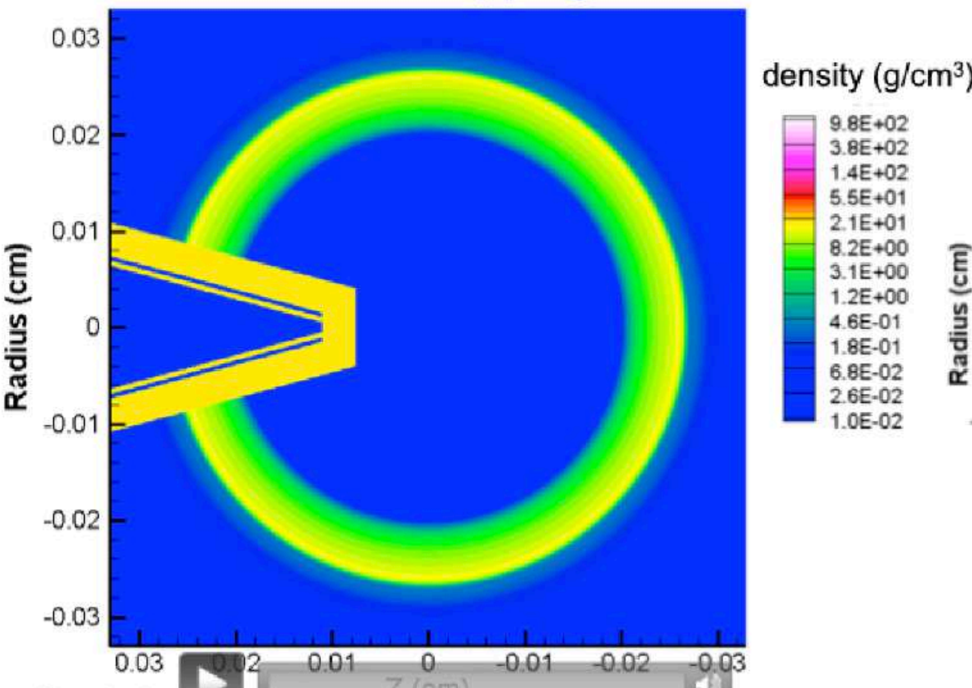



# 2D Hydro cone-target simulations

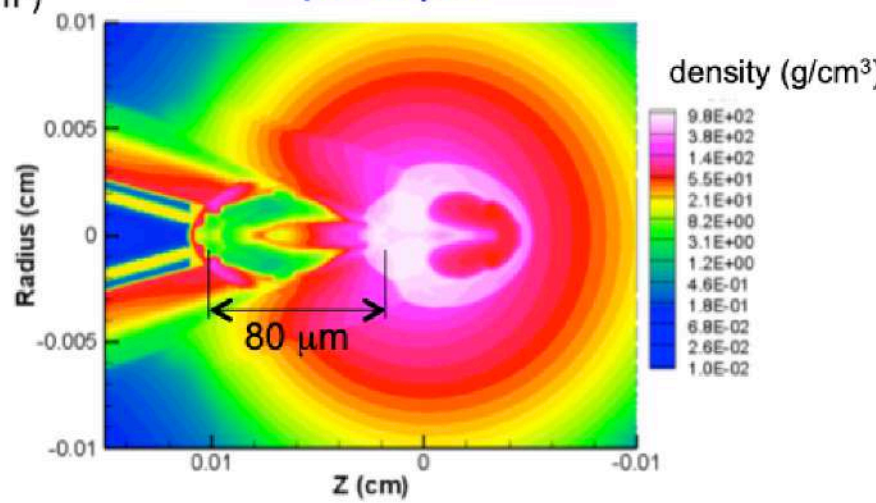
- Multigroup radiation-hydrodynamics model with ray-tracing laser energy deposition.
- $1.5\times10^5$ spatial cells, 20 energy groups, $S_8$ angular approximation.
- Execution time: a few hours with a single processor.




Implosion and compression after remapping




Density map at the time of peak ρR



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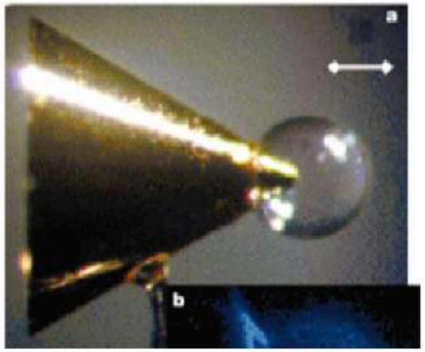


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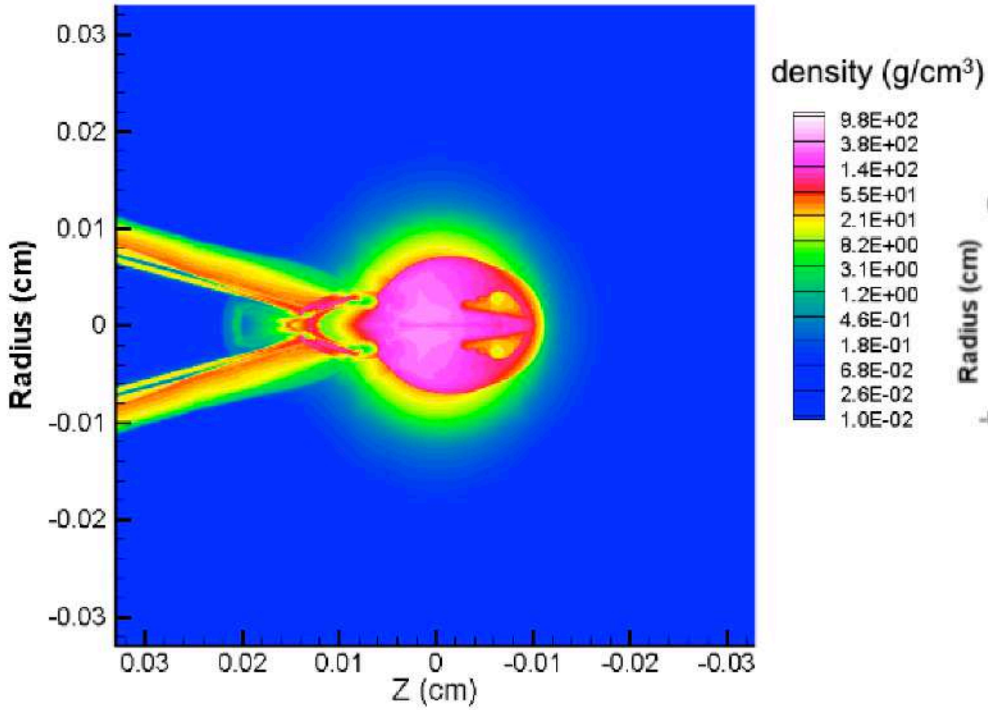


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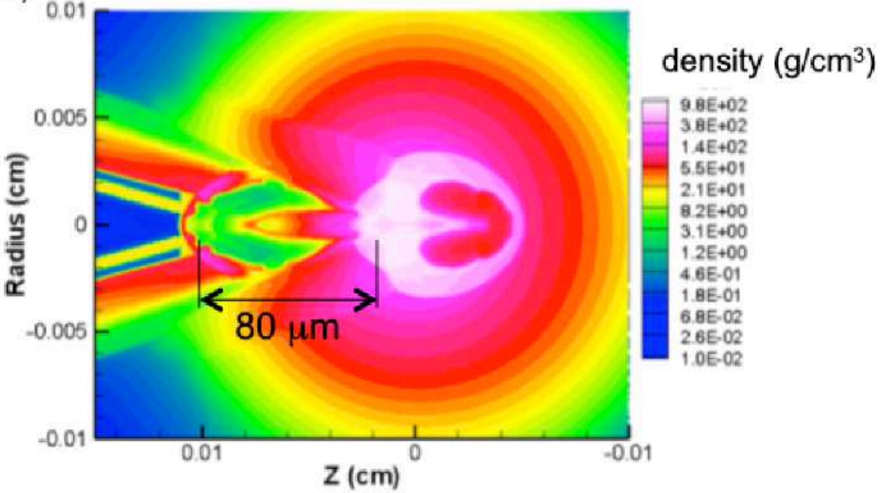


# Electron and ion acceleration by ultra-high intensity lasers

# 2D PIC simulations

- **Target:**

  Length (x) = 130 μm, width (y) = 90 μm.

  Grid: 4550 x 3150 = 14.3×106 cells (35 cells per laser wavelength).

  Particle number = ~ $1.5\times10^{9}$ electrons + ions.

- **Boundary conditions for particles and fields:**

  x : laser and thermal

  y : periodic

- **Computing time on MareNostrum 4**

  Number of PE: 1100

  Execution time: 24 h

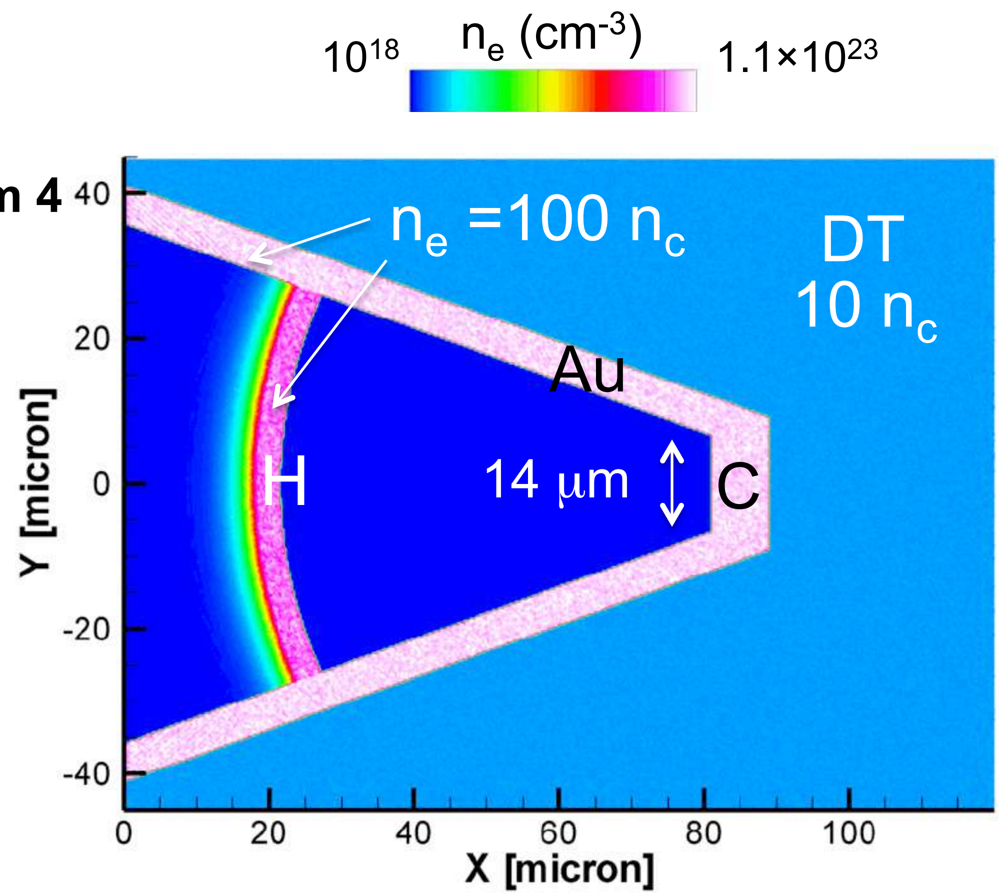
- **Laser**

  Wavelength λ = 1.06 μm.

  Peak intensity $I_0 = 10^{20}\ W/cm^2$.

  Spatial profile: Super-Gaussian,
  FWHM = 55 μm.

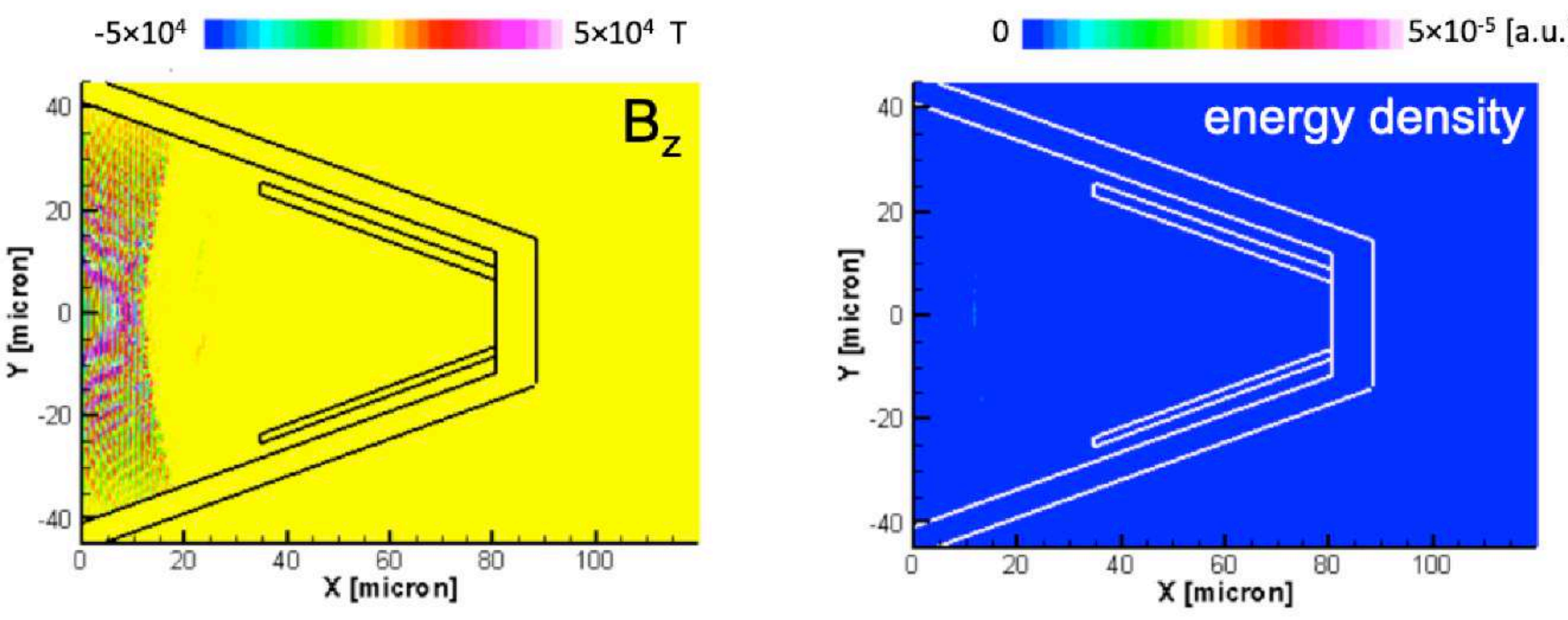
  Temporal profile: Gaussian,
  FWHM = 1 ps.



# Example of laser-driven electron acceleration in a double cone

- B-field generated by the currents flowing along the cone outer wall are 'confined' in the gap between the two walls.
- The B-fields at the cone tip are reduced substantially compared with the single wall cones. Even the low energy protons are well collimated.
- The divergence half-angle in this case is about 10 - 15º (HWHM) depending on the proton energy.

**Laser intensity $I_{l,max} = 10^{20}$ W/cm²**



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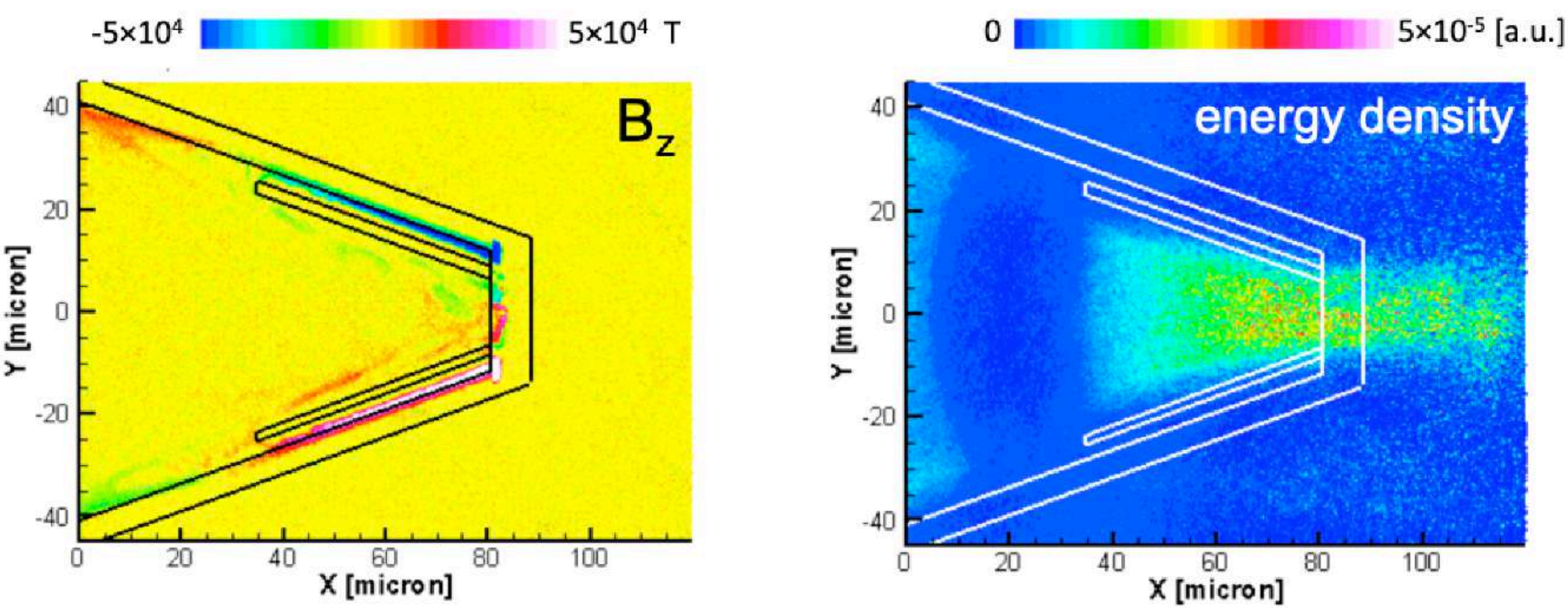


# Integrated simulations of fast ignition driven by electrons and ions

# Hybrid-PIC simulation code

- **Kinetic** (**PIC**) description of fast electrons and a **fluid** description of the background plasma.
- **EM** fields are obtained from simplified Maxwell equations:

$$\mathbf{E} = \eta\, \mathbf{j}_{\text{return}} - \frac{\nabla p}{e\, n_{ep}} - \mathbf{v}_{ep} \times \mathbf{B} - e^{-1}\beta \cdot \nabla T_e$$

$$\mathbf{j}_{\text{fast}} + \mathbf{j}_{\text{return}} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

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

$\eta$ = plasma resistivity

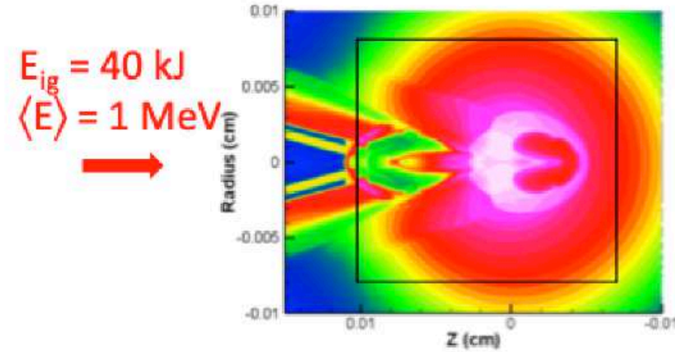
unknowns

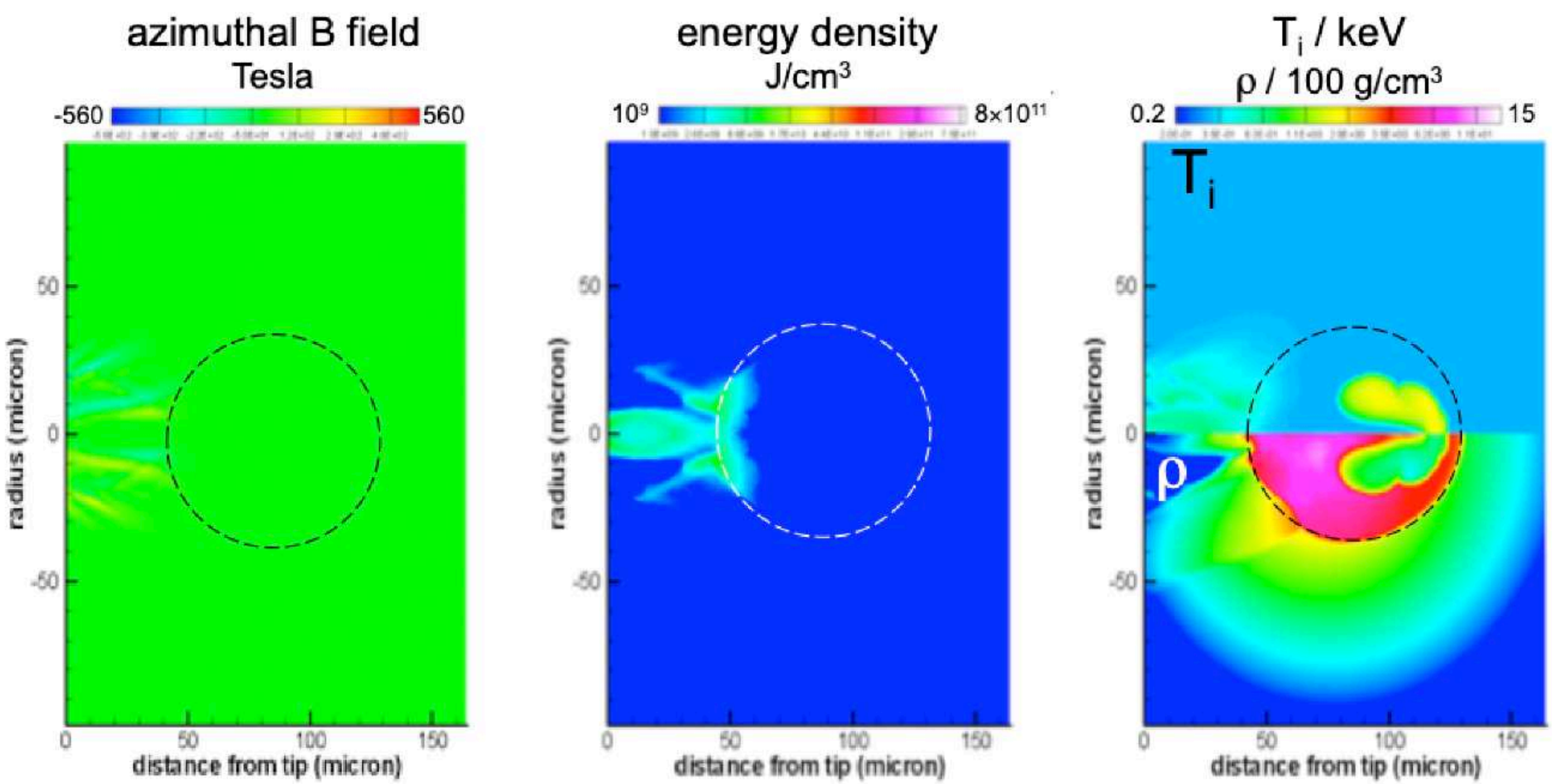
$j_{return}$, **E and B**

- Thermal conduction by flux-limited diffusion.
- Plasma ionization, electron and ion temperatures obtained from tabular EOS (SESAME, QEOS).
- 2D Eulerian hydrodynamics including:
  - $S_n$ radiation transport (angular dependence).
  - Fusion reactions and $\alpha$–particle transport (neutron in progress).

# e-driven fast ignition simulations

- 2D/3D hybrid simulations coupled to 2D hydro and multigroup radiation transport.
- $3\times10^6$ cells, $10^7$ particles injected, 10 energy groups for thermal radiation transport.
- Computing time: 12 hours, 128 PE.



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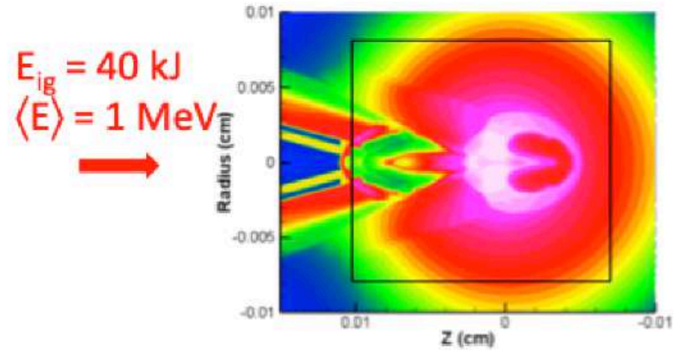
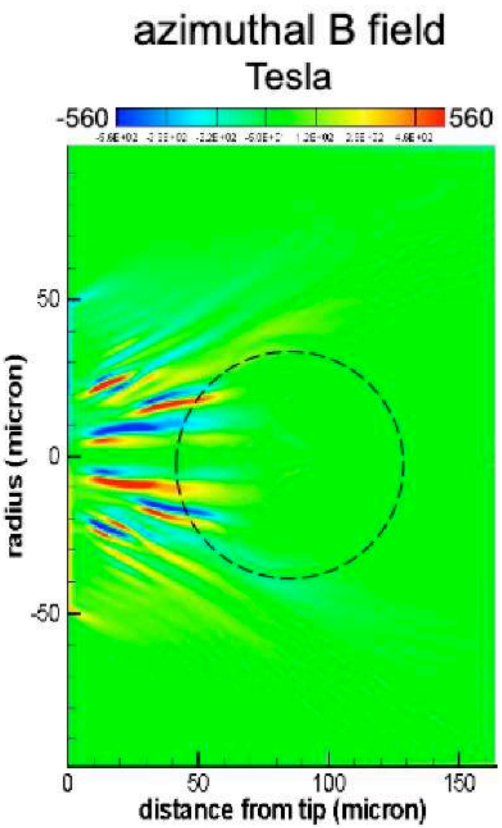
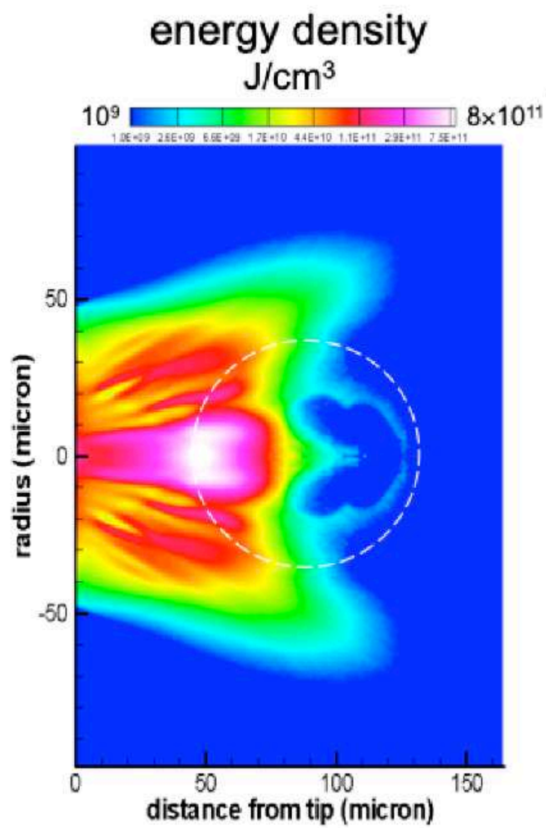
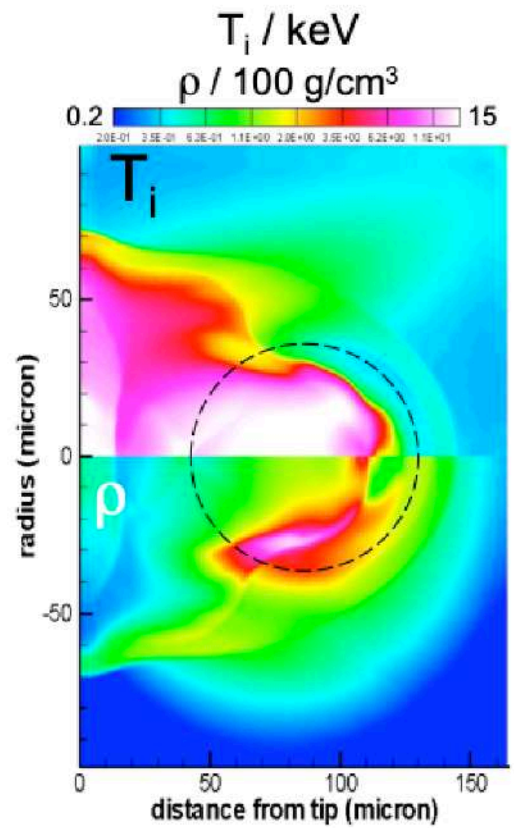


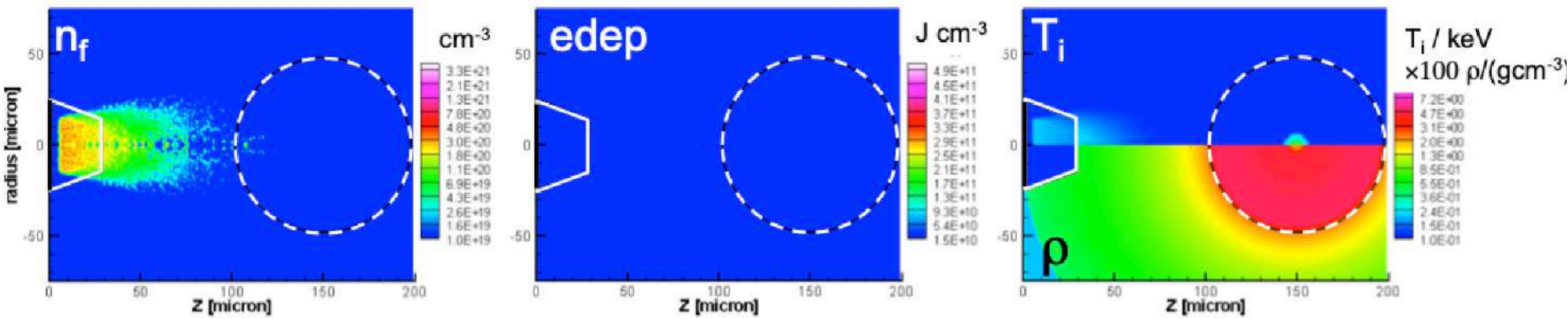



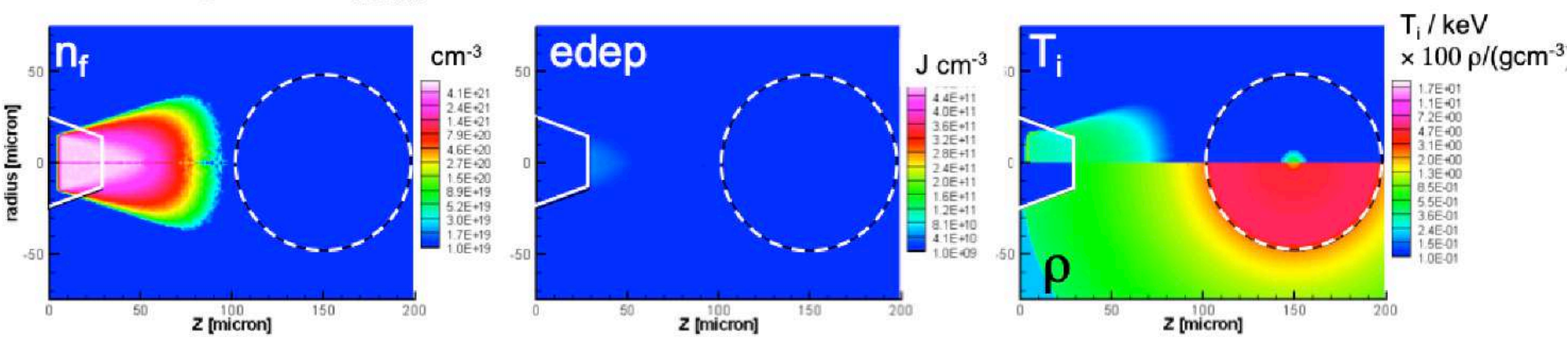



# Ion-driven fast ignition

- Ideal imploded superGaussian (m = 4) density distribution with $\rho_{max}$ = 400 g/cm$^3$.
- Carbon ions, Maxwellian distribution with $T_C$ = 200 MeV, 20º divergence, $E_{beam}$ = 51 kJ.




- Carbon ions, quasi-monoenergetic with ‹E›= 650 MeV, δE/E = 0.125, 20º divergence, $E_{beam}$ = 35 kJ.



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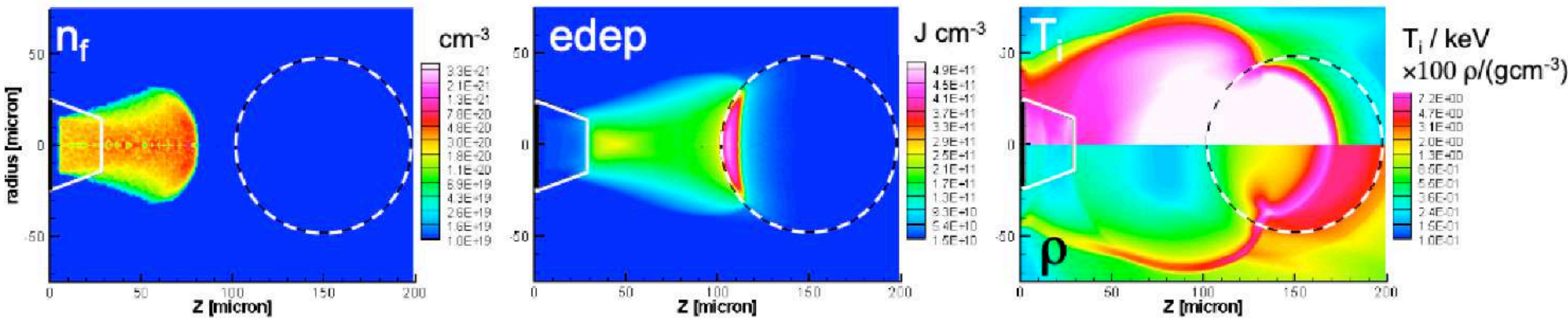


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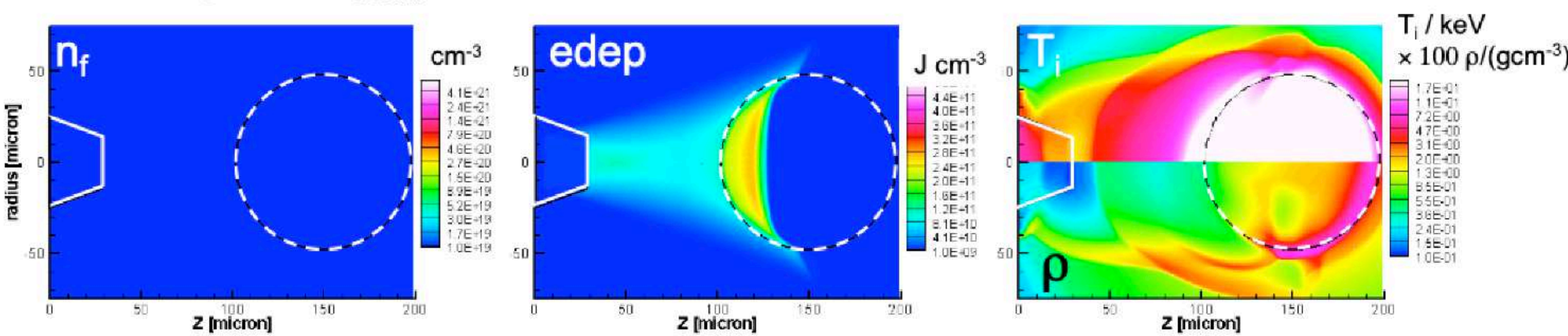
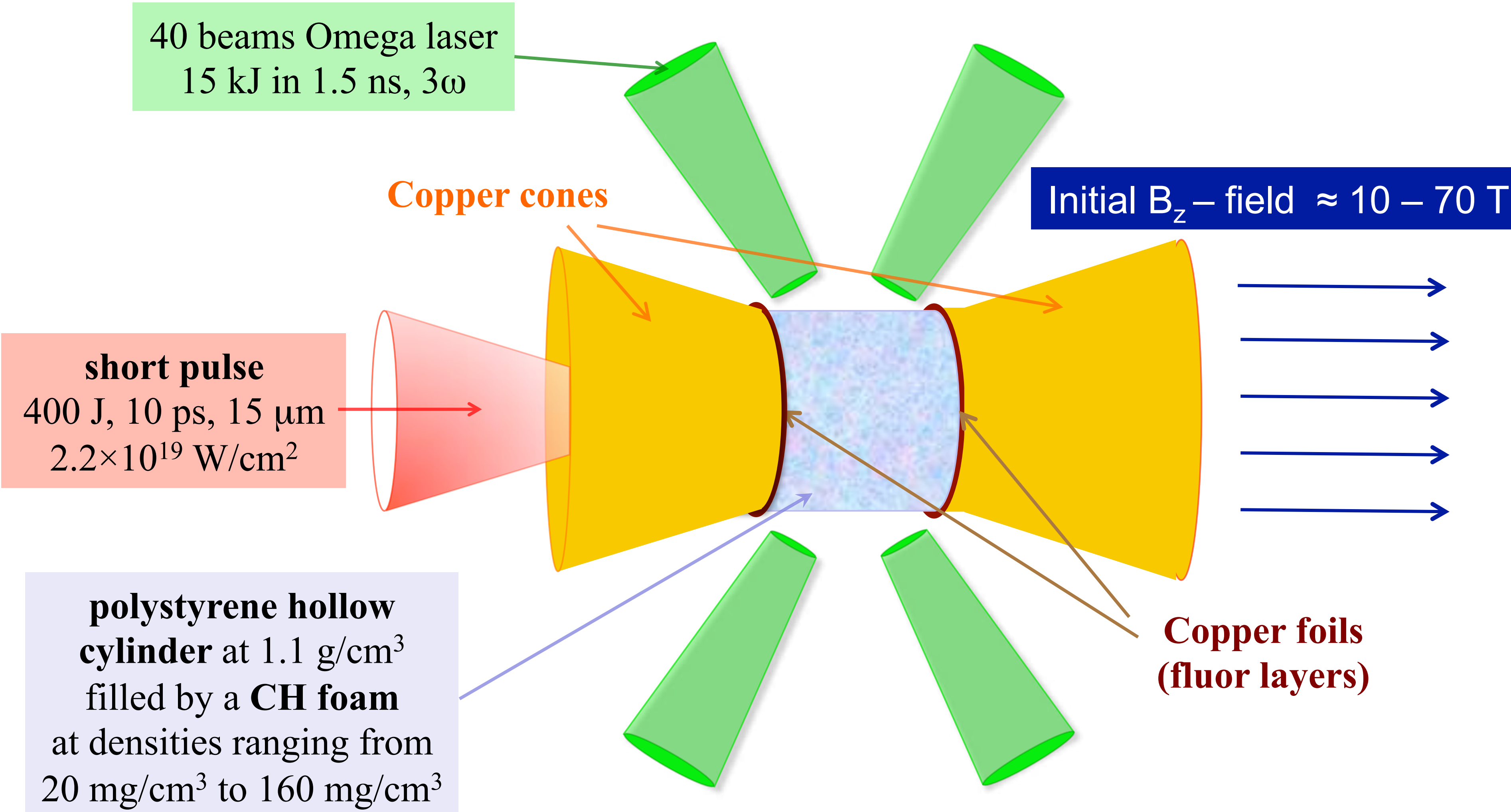


# Implosion of magnetized targets.
# MHD simulations

# MHD simulations: cylindrical target for B-field amplification



# Magnetized cylindrical target

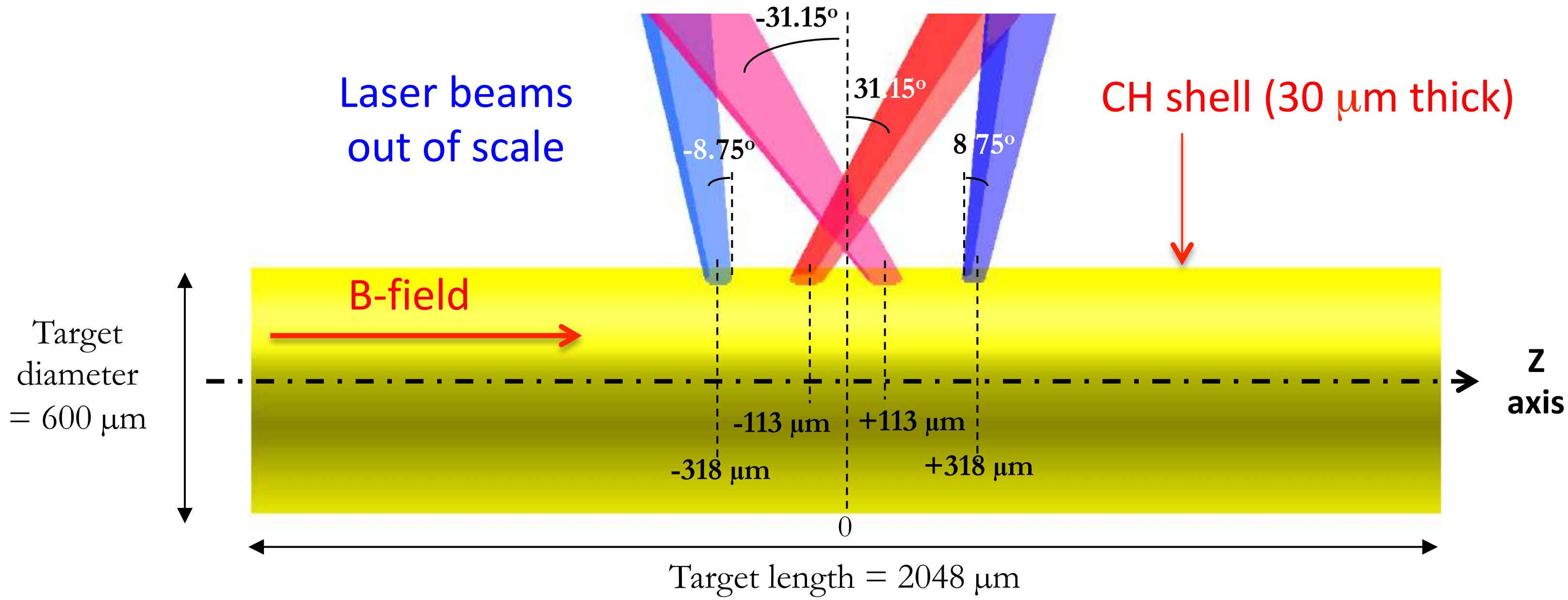
## Target data

- Target radius = 300 μm.
- CH shell thickness = 30 μm.
- CH shell density = 1.1 g/cm³.
- CH foam density = 20 – 160 mg/cm³.
- Initial B-field = 10 – 70 T **(generated by MIFEDS or laser-driven coils)**.

## Laser data

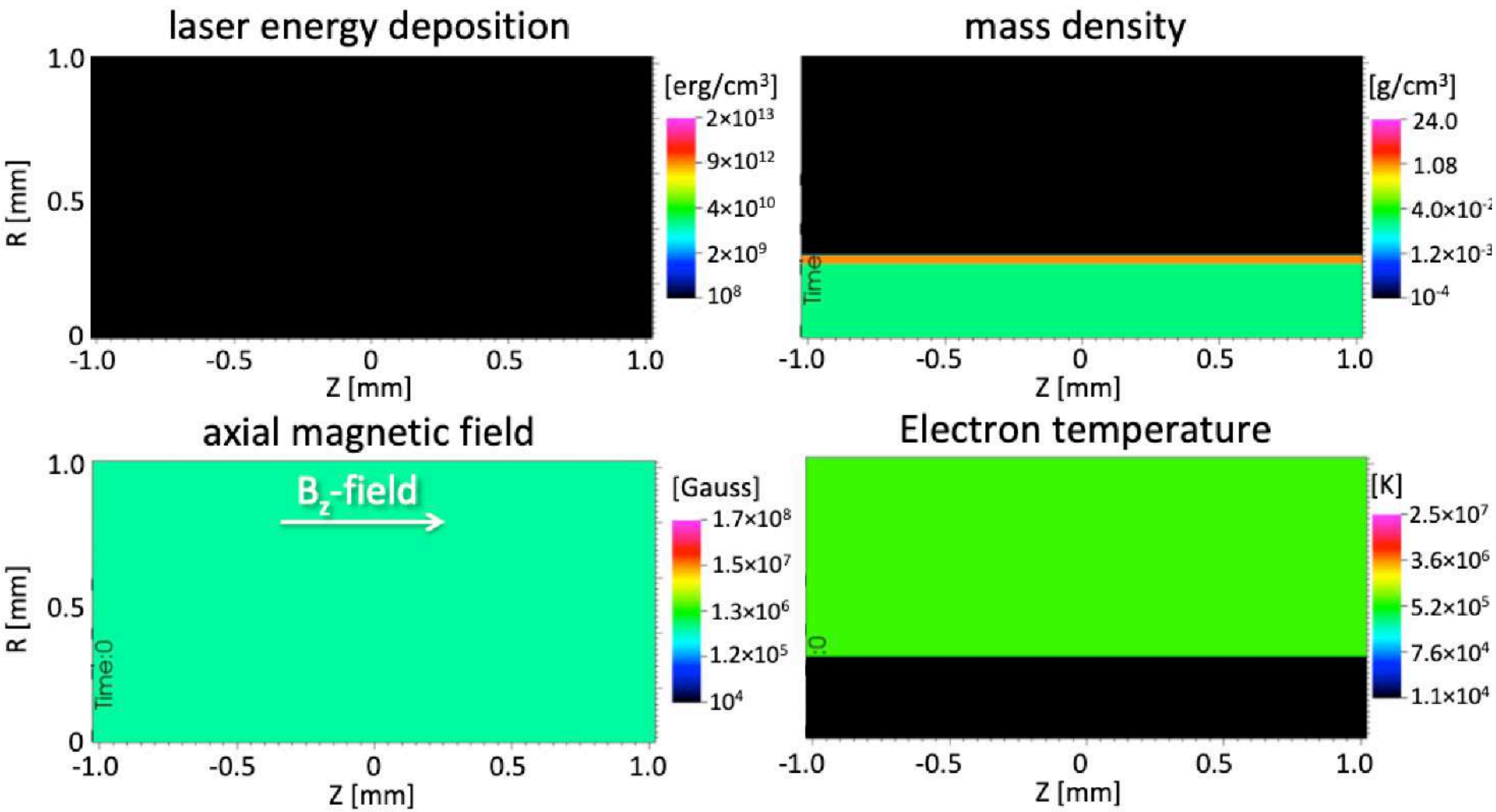
- 40 beams focused on 290 μm spot.
- Illumination length about 1 mm.
- Mean intensity on target = $3.8\times10^{14}$ W/cm².
- The energy of the laser pulse is 15.2 kJ with a duration of 1.5 ns.

## Laser illumination scheme at Omega mini-MagLIF



# 2D implosion simulation (FLASH)

- Uniform compression.
- Multigroup radiation transport. Important hot spot radiation cooling.
- $B_z$-field is amplified from the initial 50 T to about 17 kT at stagnation (×340).



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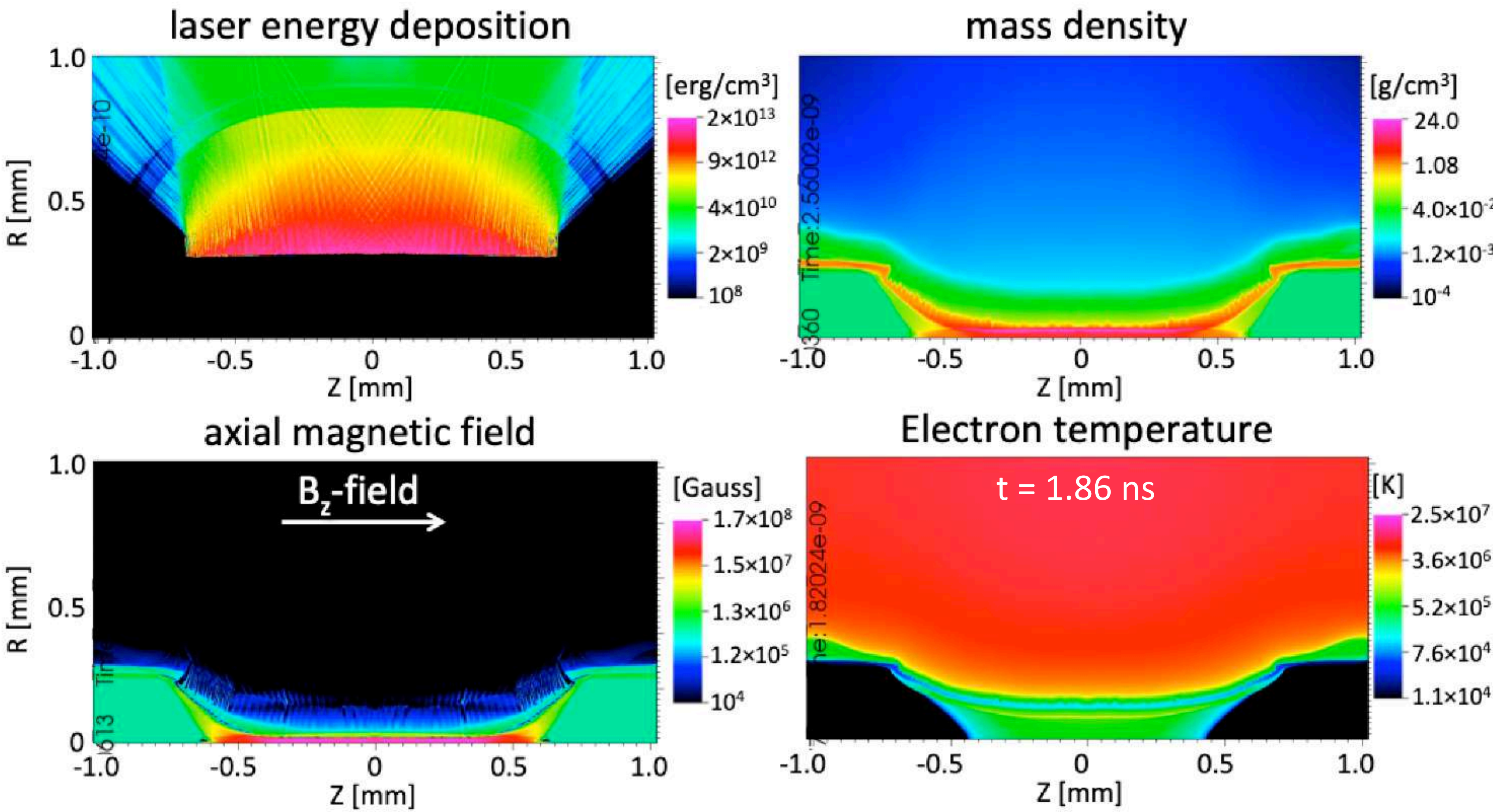

# Summary

- Hydrodynamic, PIC and hybrid simulations have proven to be very useful for target design and interpretation of experiments.
- *MareNostrum* and *Magerit* HPC allowed us to carry out realistic simulations, competitive with those performed at the large scale facilities.
- We plan to continue studying ignition alternative schemes, such as *fast ignition*, *shock ignition* and *magnetized inertial confinement fusion*.
- Those new schemes will be analyzed in close contact with experiments and within the context of the **EUROfusion** projects '***Towards inertial fusion energy***' and '***Preparation and Realization of European Shock Ignition Experiments***'.

# Thanks for your attention!