High energy density physics

A focus on experiments with high power lasers

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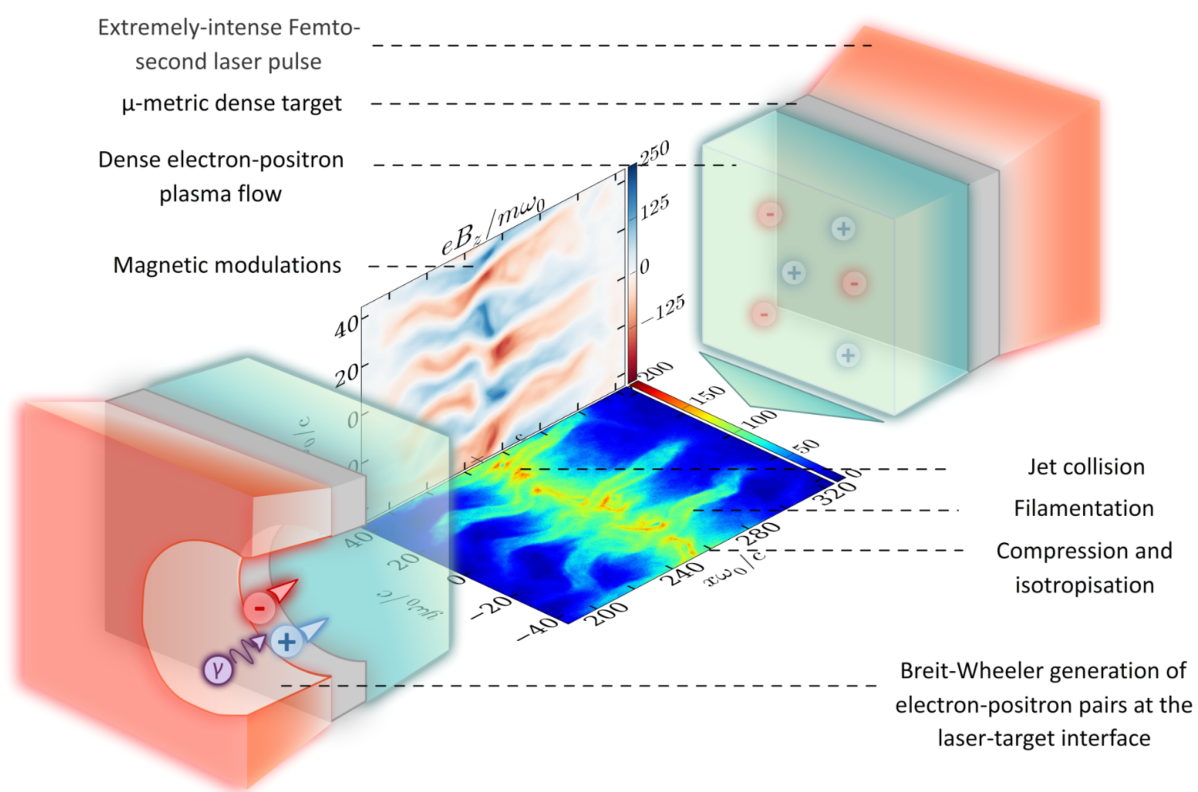

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Outline

- **What is HEDP ?**

- High power laser systems and applications

- Selected experimental studies of HEDP using high power lasers

- Conclusions and perspectives

“Definition” of High Energy Density Physics (HEDP)

Convergence of many fields into HEDP: astrophysics, condensed matter physics,....
Historically the field emerged with the declassification of fusion research and fully developed with the construction of large laser user facilities (e.g. Rochester)

High energy density matter

$\rightarrow$ energy density $\gtrsim 10^{12}$ erg cm^{-3} $= 0.1$ MJ cm^{-3} ~ 1 Mbar

However this is somewhat too restrictive and much research is also done at lower energy densities

Example

For $n_i = 10^{19}$ cm^{-3} and $T = 100$ eV ($\sim 10^6$ K) the pressure is $p \sim 2$ kbar ($\sim 2 \times 10^8$ Pa)

“Extreme matter conditions”

$\rightarrow$ matter at temperature and pressure $\ggg$ standard temperature and pressure conditions ($T \sim 300$ K and $P \sim 1$ bar)

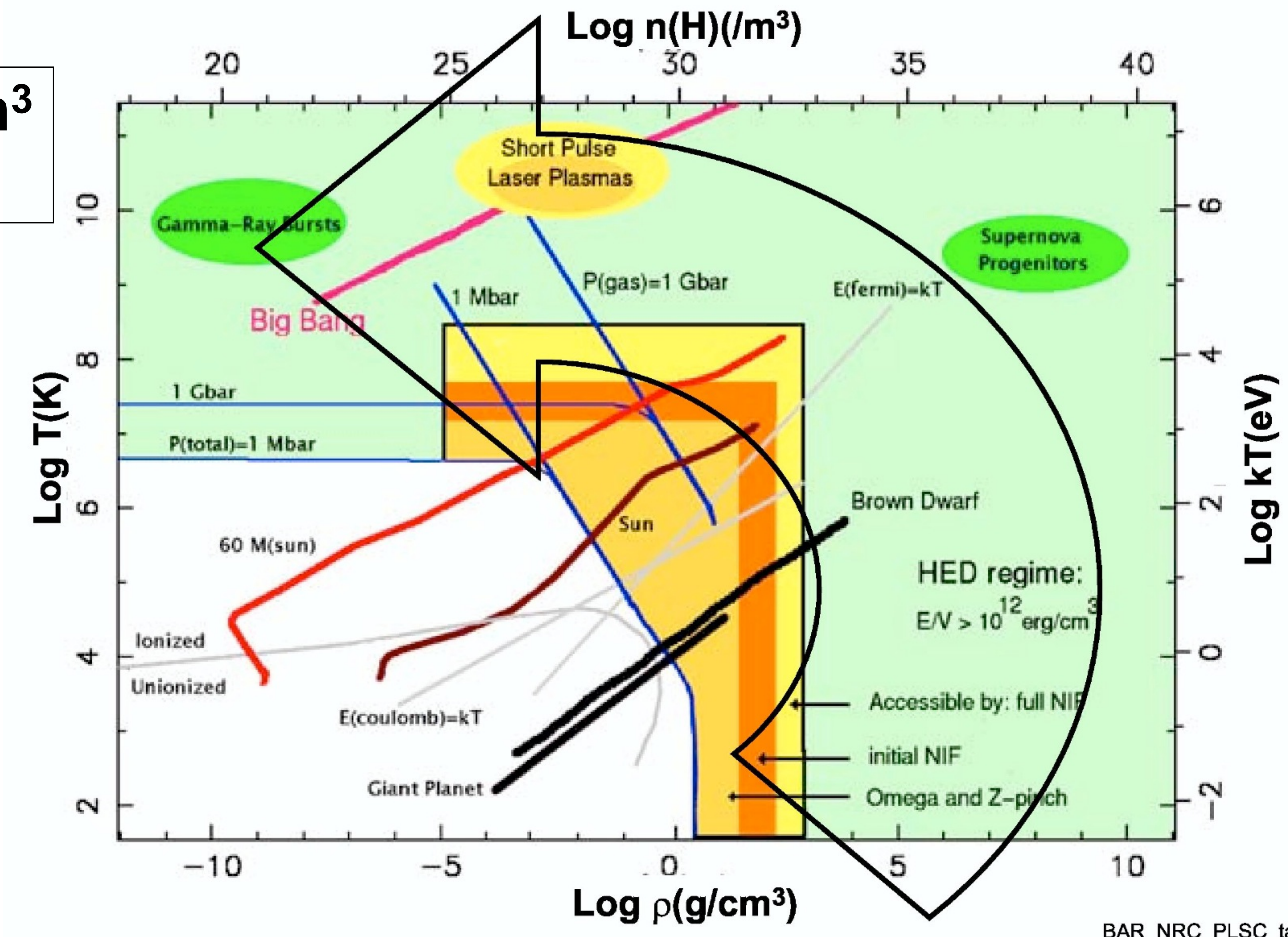
The magnetic field corresponding to a pressure of 1 Mbar is ~ 240 T

Courtesy of A. Ciardi

ICF and the High Energy Density Physics

New generation of high power lasers gives access to macroscopic volumes of hot and dense matter

***E/V* > 10^{11} J/m^3**
***P* > 1 Mbar**



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Overview: how to produce HED plasmas in the laboratory

Generating HED plasmas in the laboratory requires “a lot of energy in a small volume”. These plasmas are short lived.

Pulsed-power generators – z-pinch machines [Lebedev et al., 2019] generate plasma with characteristic time-scales and volumes:
$\rightarrow \tau \gtrsim 100$ ns; vol $\gtrsim 1$ cm^{-3}

Lasers (long-pulse $\sim$ ns) can generate somewhat higher densities and temperatures but over a shorter time and over smaller volumes:
$\rightarrow \tau \lesssim 10$ ns; vol $\lesssim 1$ cm^{-3}

Heavy ion beams [Sharkov et al., 2016] can similarly generate high-energy density plasmas with:
$\rightarrow \tau \lesssim 10$ ns; vol $\lesssim 1$ cm^{-3}

Courtesy of A. Ciardi

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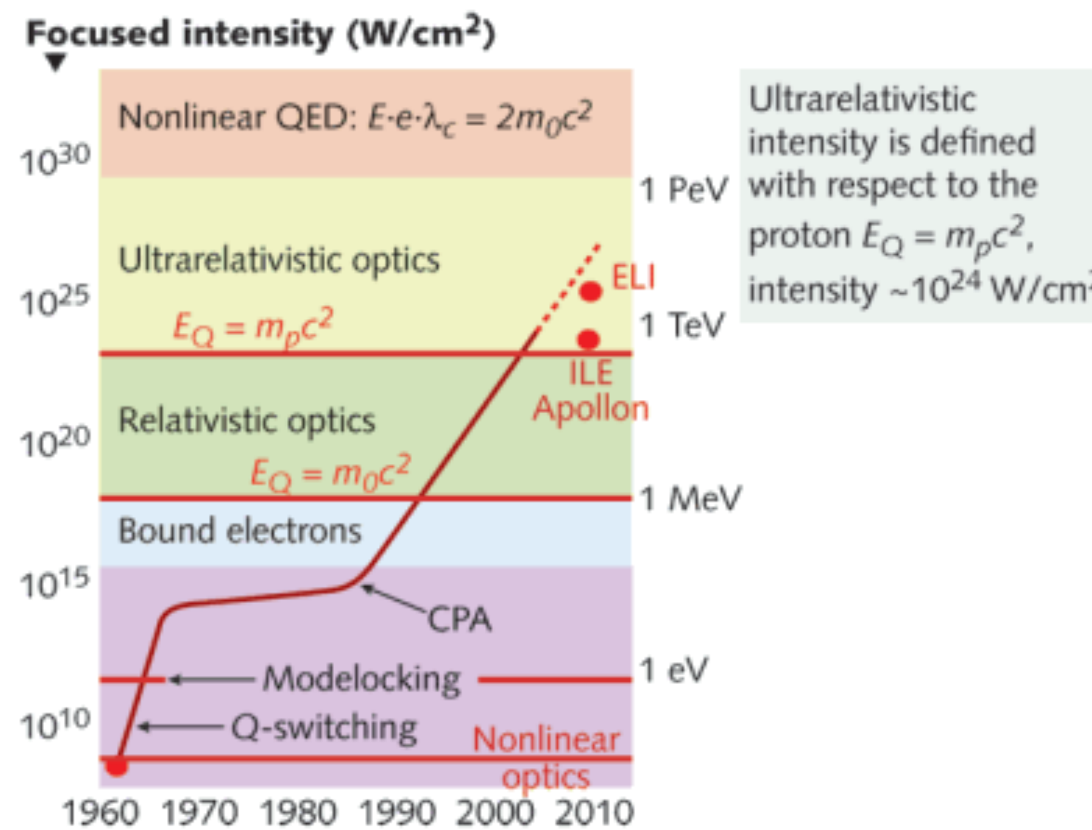
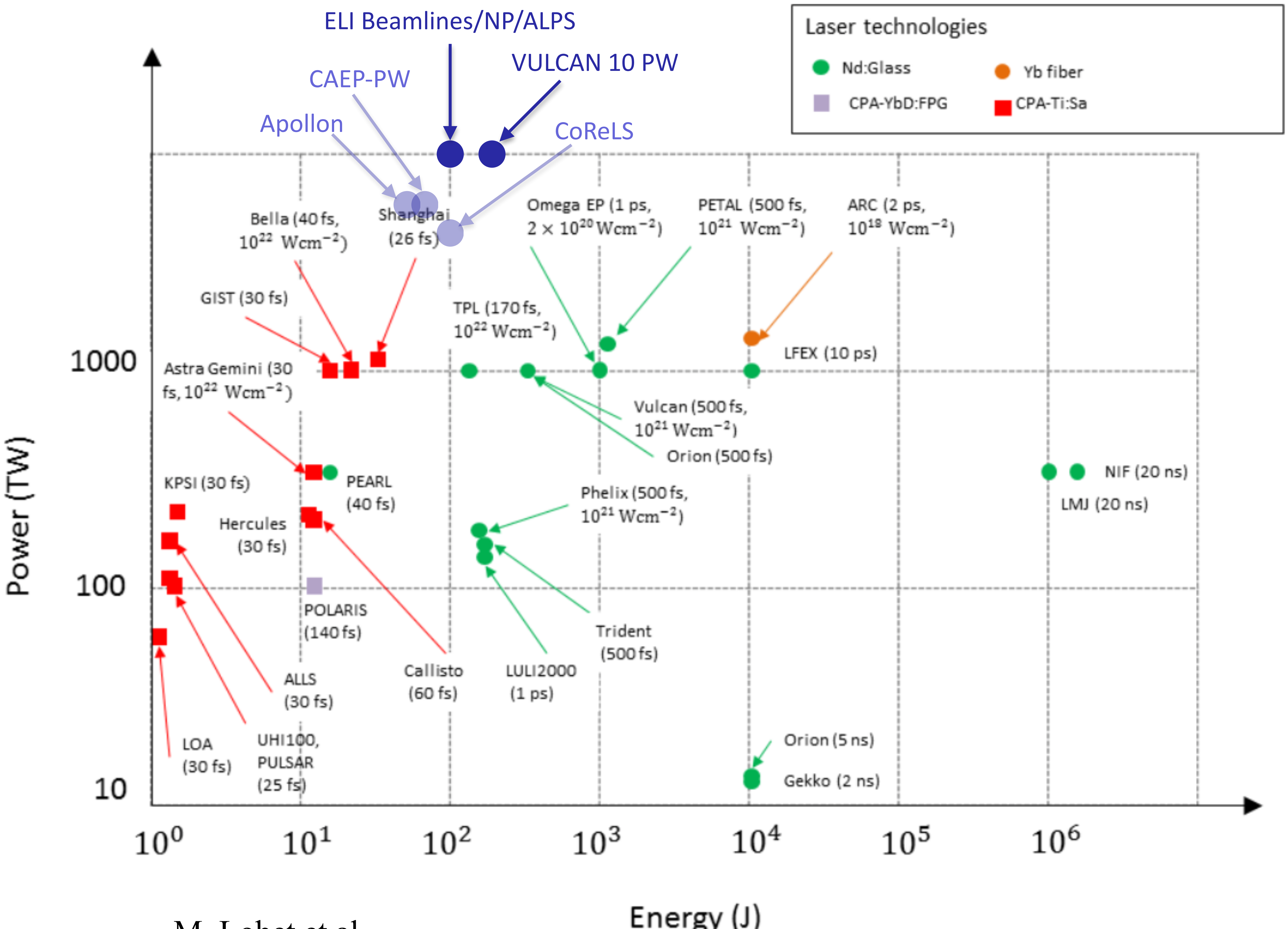
A brief history of lasers for controlled fusion
From 1962 to the present day

- **1960s:** first proposals and first experiments (USA, France, Russia)
- **1970s:** de-classification in 1971 and first steps of systematic research, multibeam lasers (Janus, Shivas, Kalmar), neutrons (1968, 10^{13} in 1988), compression (20 g/cc in 1979, 600 g/cc in 1991). Understanding of physical and technical problems (instabilities, transport)
- **1980s:** progress in power and energy: transition from CO_2 (Helios) to 3ω Nd (Nova, Phébus, Vulcan, Gekko), excimer lasers, CPA lasers
- **1990s:** instability control, smoothing, large NIF and LMJ projects, Omega laser, first PW laser, Centurion program (indirect attack), acceleration of particles
- **2000s:** NIF and LMJ lasers, new ignition schemes, applications outside the ICF (accelerators, radiography, medicine, astrophysics), new projects (ELI, HiPER)
- **2009:** construction of NIF is completed
- **After 2010:** multiplication of PW systems (Berkeley, GIST, CLPU, HZDR, INRS…)
- **2014:** construction of LMJ is completed
- **2017:** ARC and PETAL operate
- **2019:** Apollon and ELI first experiments



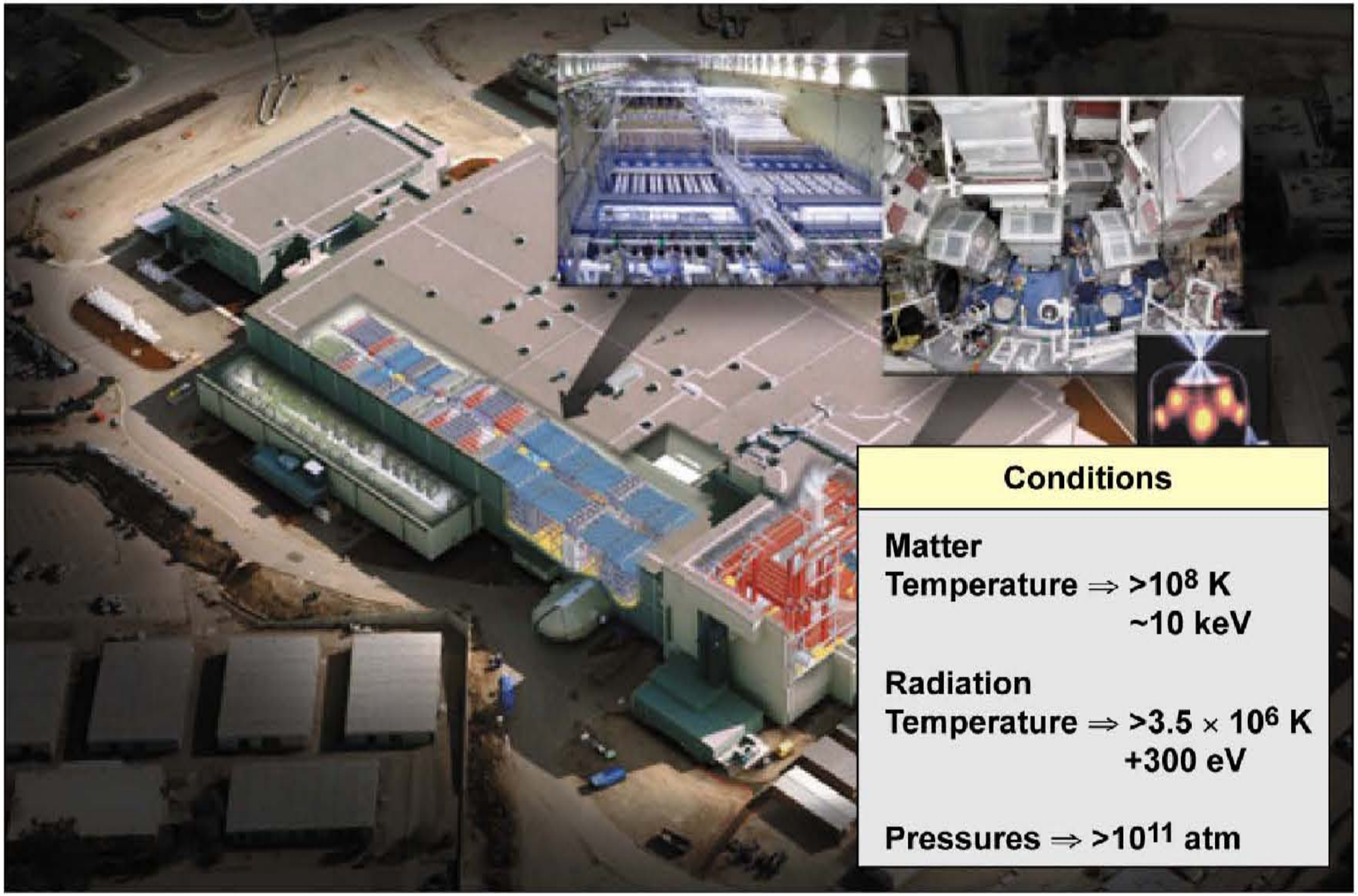
Laser facilities of power above 100 terawatts (TW) in the world as a function of their power and energy



M. Lobet et al.

The National Ignition Facility concentrates all the energy in a football stadium-sized facility into a mm^3

The National Ignition Facility



Conditions

Matter
Temperature ⇒ >10^8 K
~10 keV

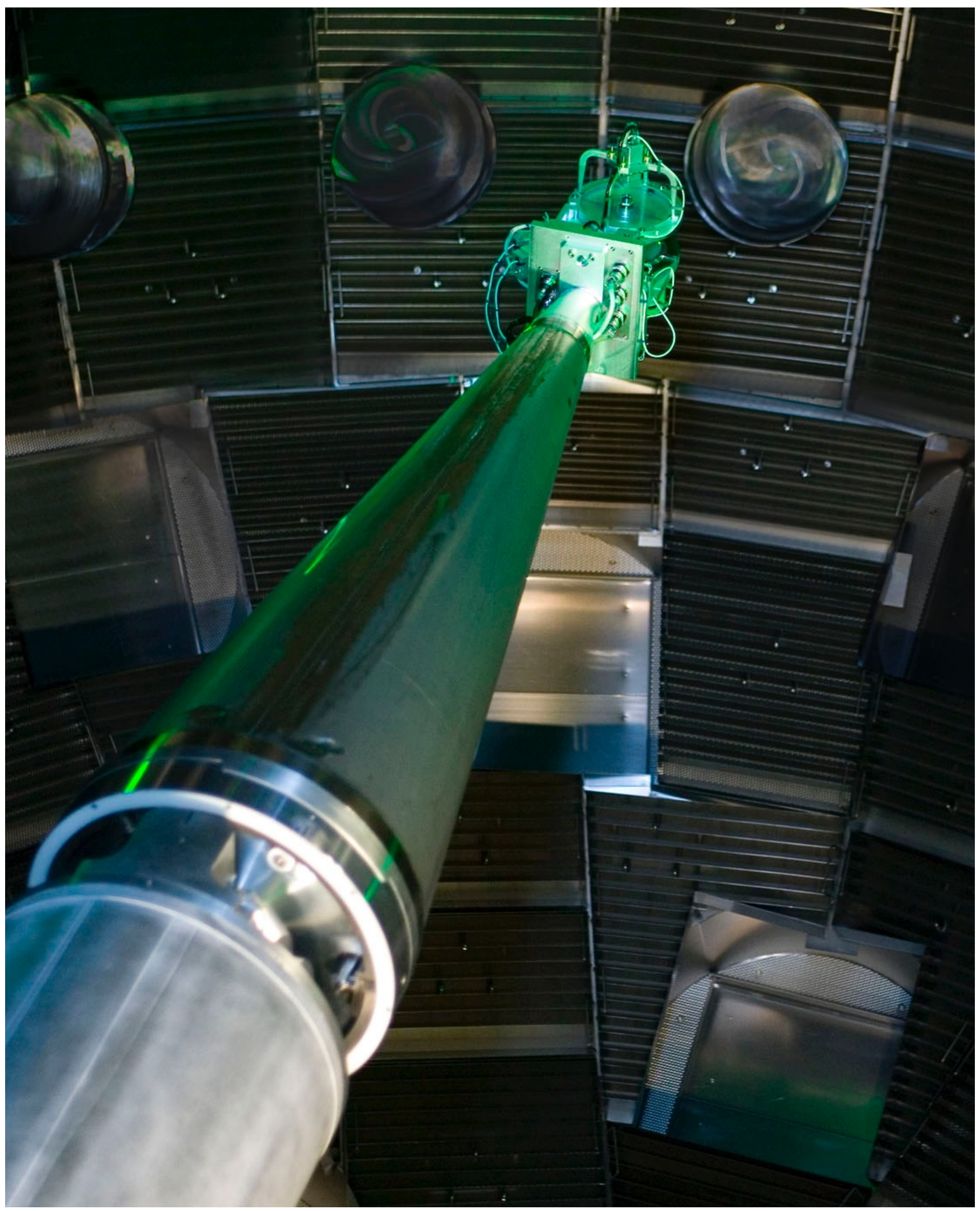
Radiation
Temperature ⇒ >3.5 × 10^6 K
+300 eV

Pressures ⇒ >10^{11} atm

March 2009 : 192 beams delivered 1.1 MJ in 3w

Photos from NIF: interaction chamber

https://lasers.llnl.gov/multimedia/photo_gallery



Inertial confinement fusion

Inertial confinement fusion aims at at generating energy via the fusion reaction: $D + T \rightarrow \alpha + n$. The thermonuclear reactions proceed without any external supply of energy (beside the initial driving), when the energy produced by fusion exceeds the energy losses.

Considering bremmstrahlung energy losses and heating due to the α-particles, the ignition temperature is ~ 5 keV ($\sim 5 \times 10^7$ K).

For high raction rates the DT fuel needs to be compressed $\rho \sim 300$ g cm^{-3}, over $1000\times$ its solid density.

To achieve the necessary densitites and temperature, inertial confinement fusion relies on the spherical implosion of a ~ 2 mm radius sphere of solid and vapour DT envelopped by a plastic ablator.

Laser irradation ablates the surface of the sphere and by the rocket effect drives the implosion of DT fuel. Stagnation of the imploding fuel in the centre and the conversion of kinetic energy into thermal energy ignities the DT in a hot spot. The rest of the fuel is ignited by a burn wave before the whole system disassembles.

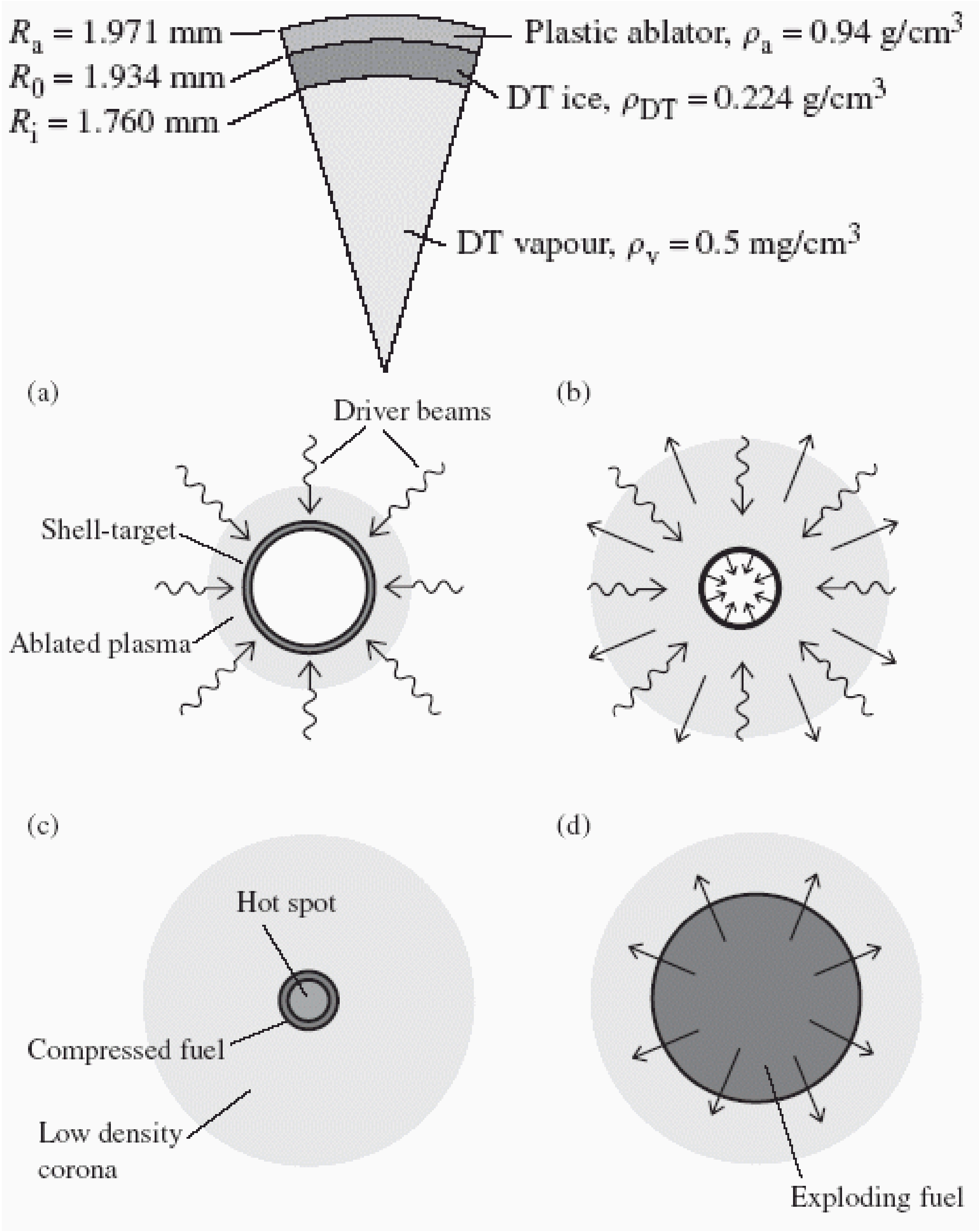


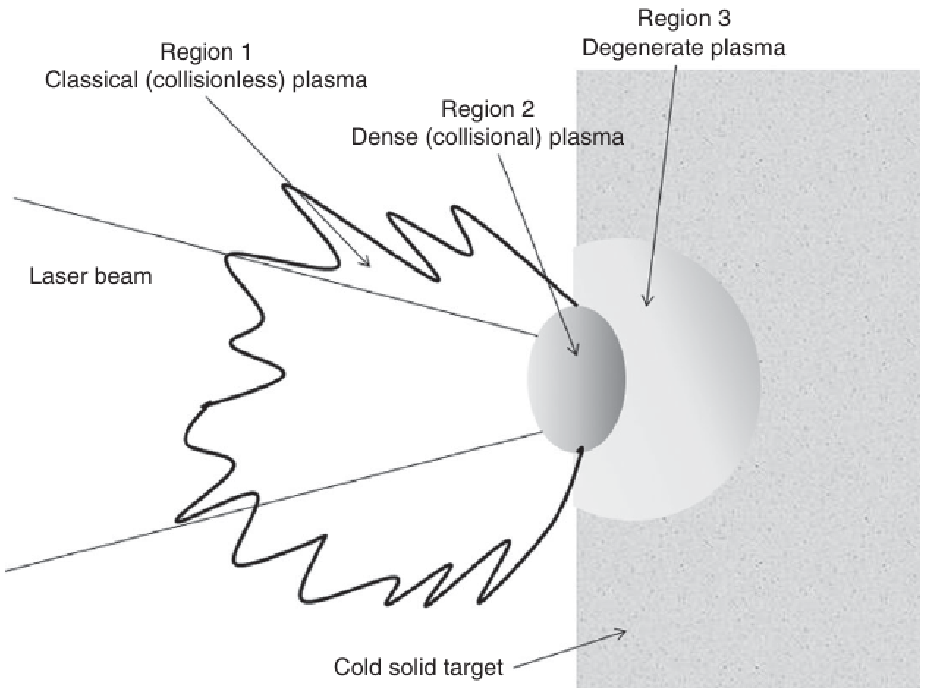
Image credit: [Atzeni and Meyer-ter Vehn, 2004]

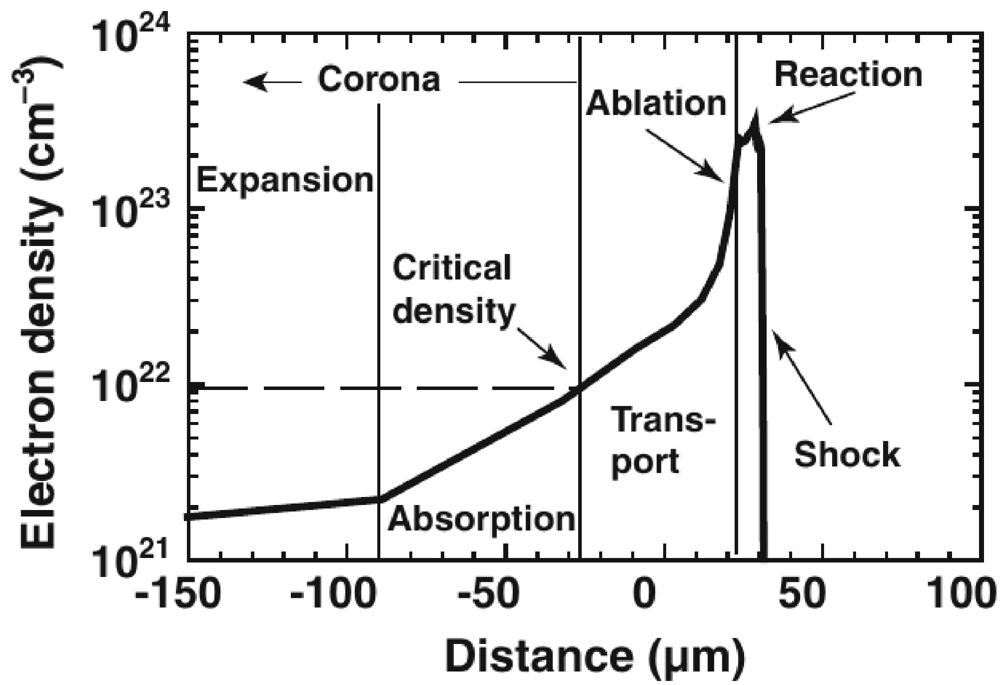
Courtesy of A. Ciardi

Laser-plasma interaction at “low-intensity”

The plasma generated covers a wide range of conditions

1. Plasma plume region:
   - $\rightarrow$ rapidly expanding $v \sim 100 - 1000$ km/s
   - $\rightarrow$ low density $n \ll n_c$
   - $\rightarrow$ hot $T \gg 100$ eV
   - $\rightarrow$ semi-collisional
2. Laser absorption and energy transport region:
   - $\rightarrow$ low expansion velocity
   - $\rightarrow$ density is $n \sim n_c$ and increase rapidly
   - $\rightarrow$ temperatures are a few $\times 100$ eV
   - $\rightarrow$ collisional
3. Degenerate plasma region:
   - $\rightarrow$ solid density at a few eV
   - $\rightarrow$ collisional

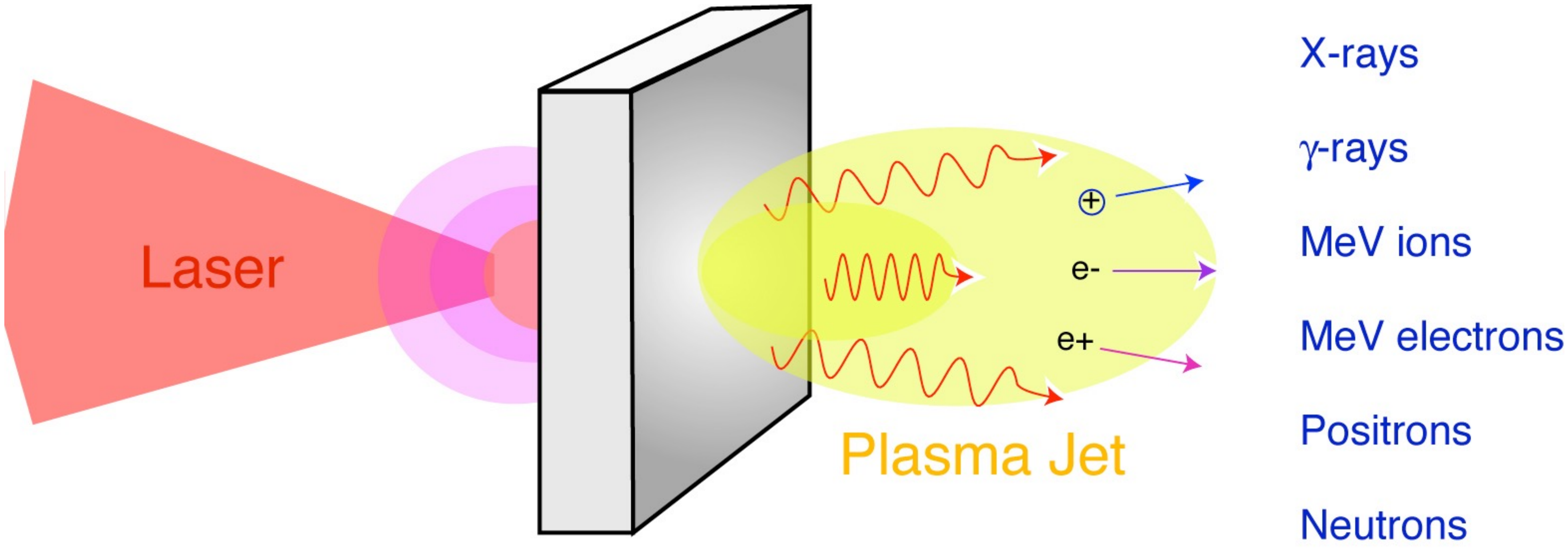




Courtesy of A. Ciardi

Image credit: [Colvin and Larsen, 2013, Drake, 2018]

Laser-plasma interaction at “high-intensity”



- Laser intensities: > 10^{18} W/cm^2
- Pulse duration: 10 fs - 10 ps
- Target: ~µm solid target, ~mm gas jet
- During the interaction: ≳TV/m electric fields, ≳110 MG magnetic fields

Plasma parameters in high power laser experiments

Velocities: 100-1000 km/s (high energy facilities), 0.1-0.3 c (high intensity facilities)

Magnetic fields: up to 100 T with non explosive coils, ~kT with laser assisted B field generation

Densities: 10^{17} cm^{-3} to 10^{24} cm^{-3} (in ICF experiments)

Temperatures: eV to 100s of eV, MeV supra thermal populations can be obtained

Maximum energies in high intensity experiments: ~9 GeV for electrons (laser-wakefield acceleration), ~100 MeV for protons and GeV C ions (with thin solid foils)

Most plasma processes can be scaled from the laboratory to other contexts using scaling laws and plasma parameters (Debye length, plasma frequency, magnetization, Mach number, Alfven Mach number, Larmor radius…).

See the lecture of S. Lebedev for diagnostics

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Laboratory astrophysics with high power lasers

Experimental astrophysics has emerged as one of the main research areas in high energy density physics

- reproduce the same physical conditions
  $\rightarrow$ microphysics: eos, opacities, ...
- reproduced "scaled" physical conditions
  $\rightarrow$ macrophysics: shocks, jets, ...

Areas of research include, but are not limited to

- The equation of state relevant to planetary interiors
- Opcities relevant to stellar interiors
- The collimation and acceleration of magnetized jets
- The turbulent amplification of magnetic fields
- The acceleration of particles at shocks
- The structure of radiative shocks
- Fluid and kinetic instabilities
- Magnetic reconnection
- ...

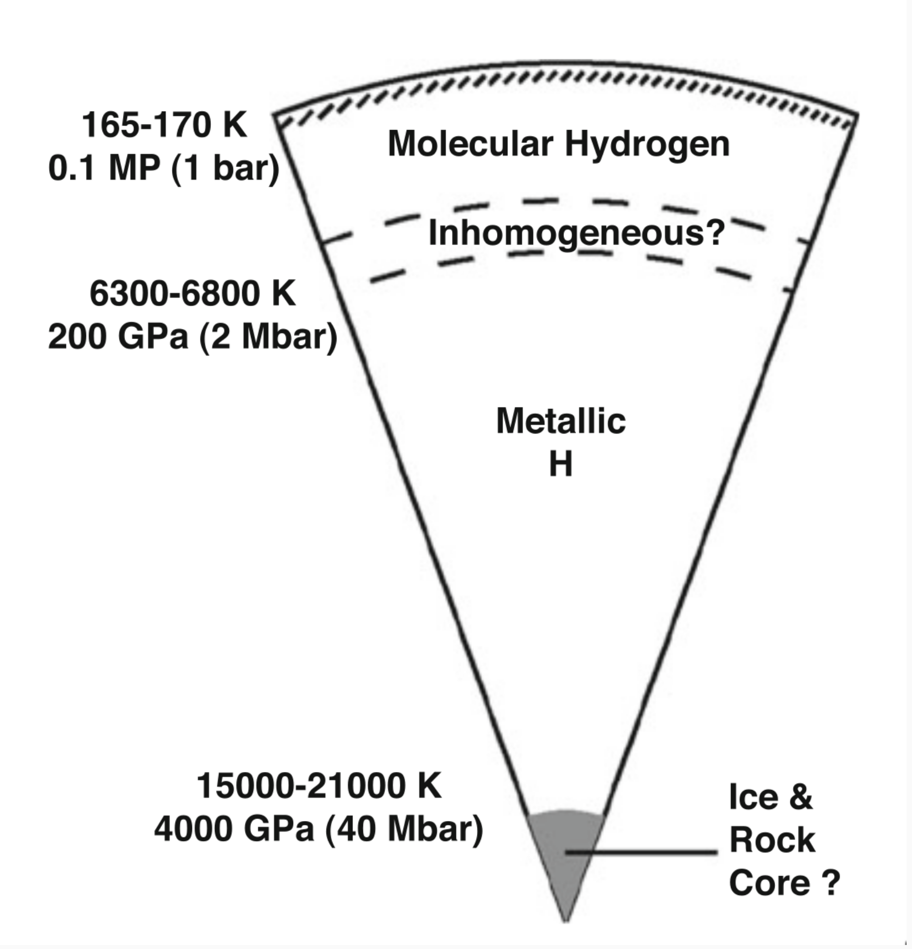


Image credit: [Drake, 2018]

Courtesy of A. Ciardi

Laboratory model of an accretion column

Experiments

ELFIE 100 TW laser (LULI, Ecole Polytechnique)

- energy 40 J (I_{max} ~ 1.6 x 10^{13} W cm^{-2})
- pulse duration 0.6 ns
- laser wavelength 1.057 μm
- focal spot diameter ~ 700 μm

Laboratory modelling

GORGON: single fluid, 2-T, 3D resistive MHD

- laser transport
- anisotropic thermal conduction
- optically thin radiative losses
- computational "vacuum"

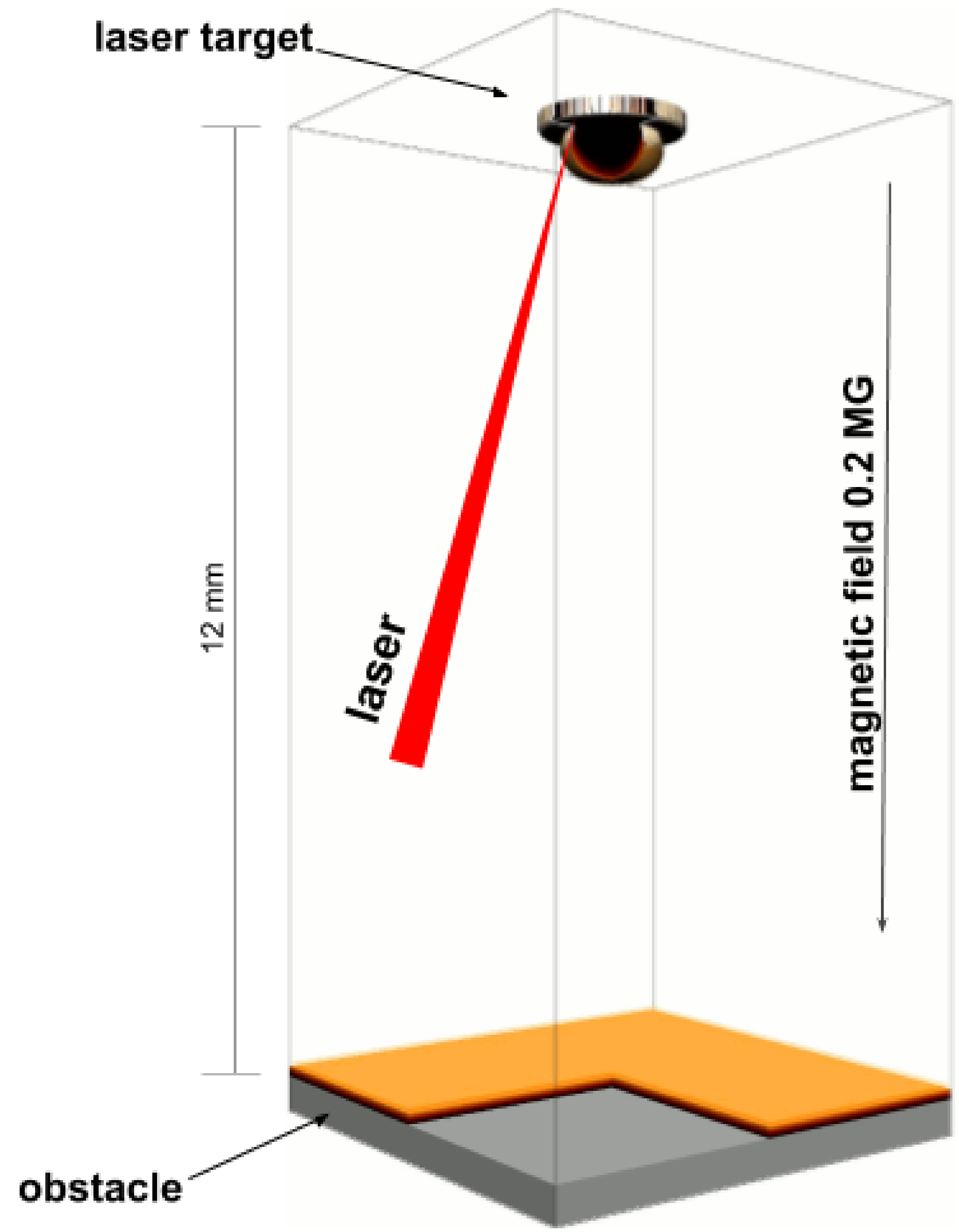
Astrophysical modelling

PLUTO: single fluid, 1-T, 2D MHD

[Mignone+ 2007]

- anisotropic thermal conduction
- optically thin radiative losses

Revet et al. Science Advances 2017

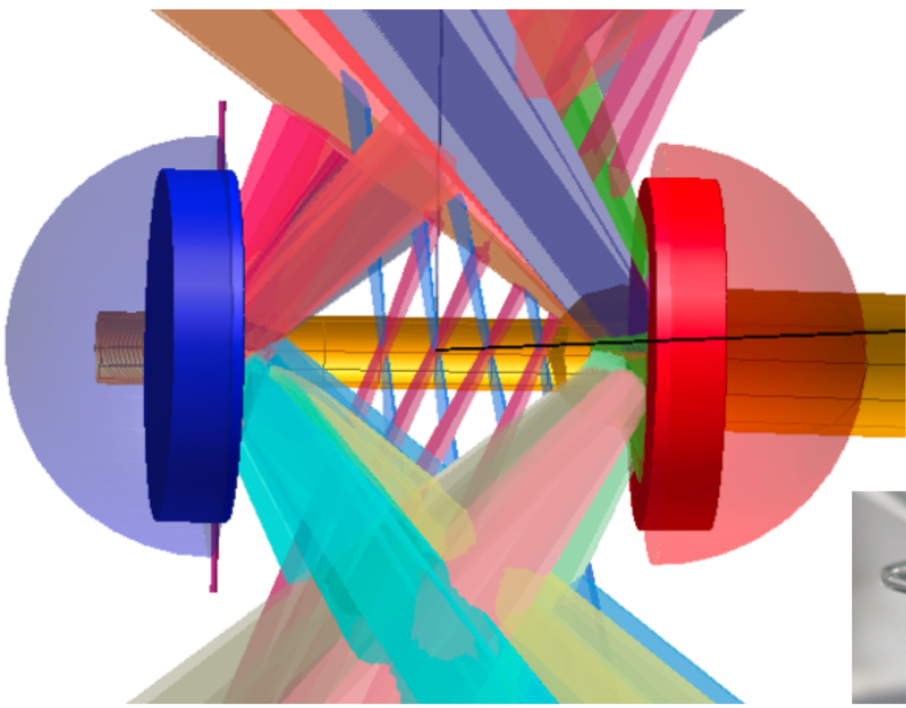


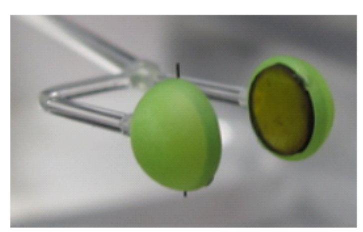
Shock formation expected to be within the reach of the National Ignition Facility

See the lecture of A. Spitkovsky

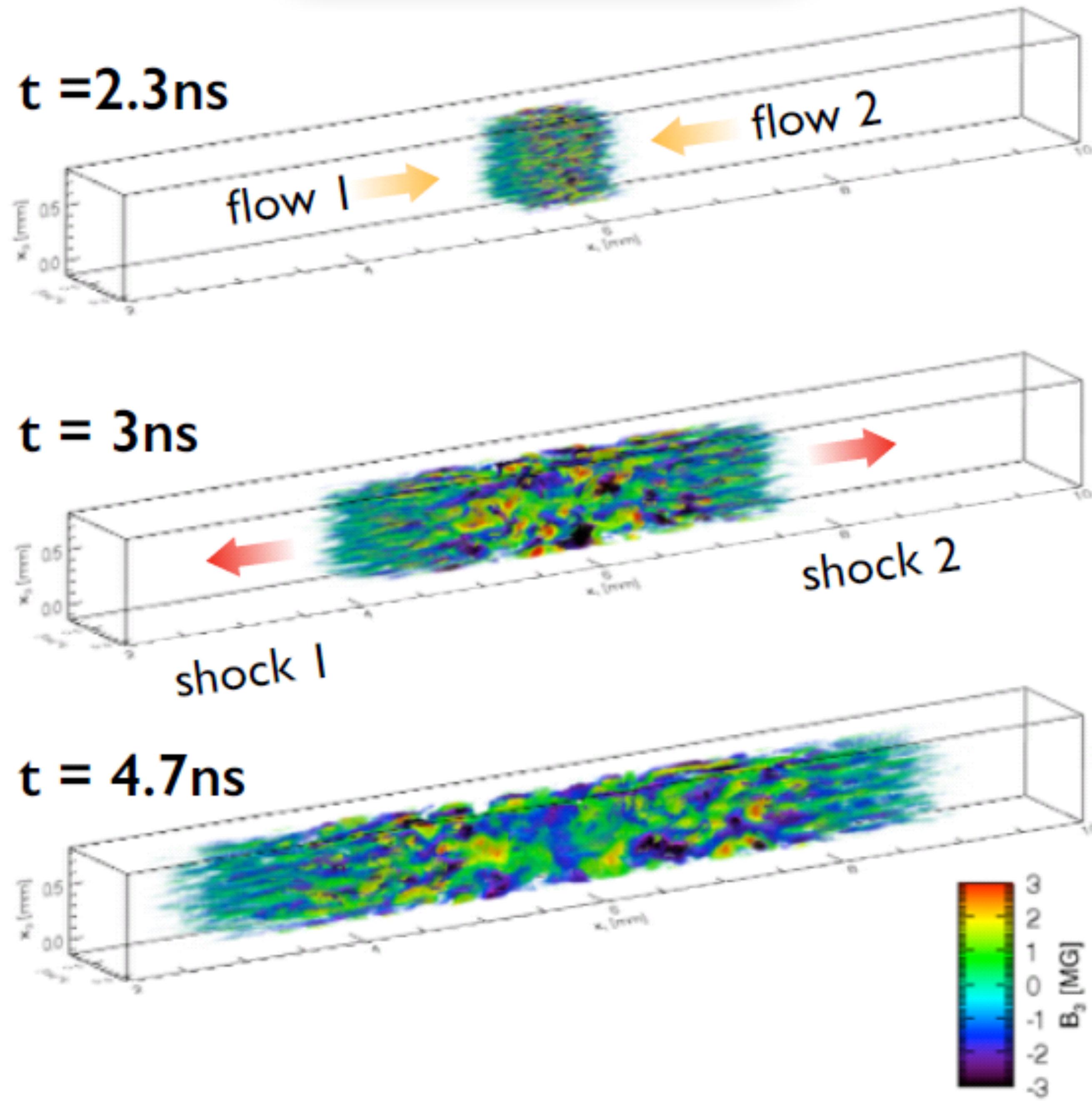
NIF target design[1]

150 - 250 kJ per target
6 mm apart
Fe/Ni (0.1%) doped CD/CH foils





3D PIC (OSIRIS) simulation[1]



- Larger plasma densities ($\sim 2 \times 10^{20}$ cm^{-3}) are expected $\Rightarrow$ longer effective interaction length ($\sim 500c/\omega_{pi}$), yet instability development may be affected by Coulomb collisions.
- PIC simulations performed with 'heavy' electrons ($m_{e,PIC} = 28m_e$) to reduce computing time.

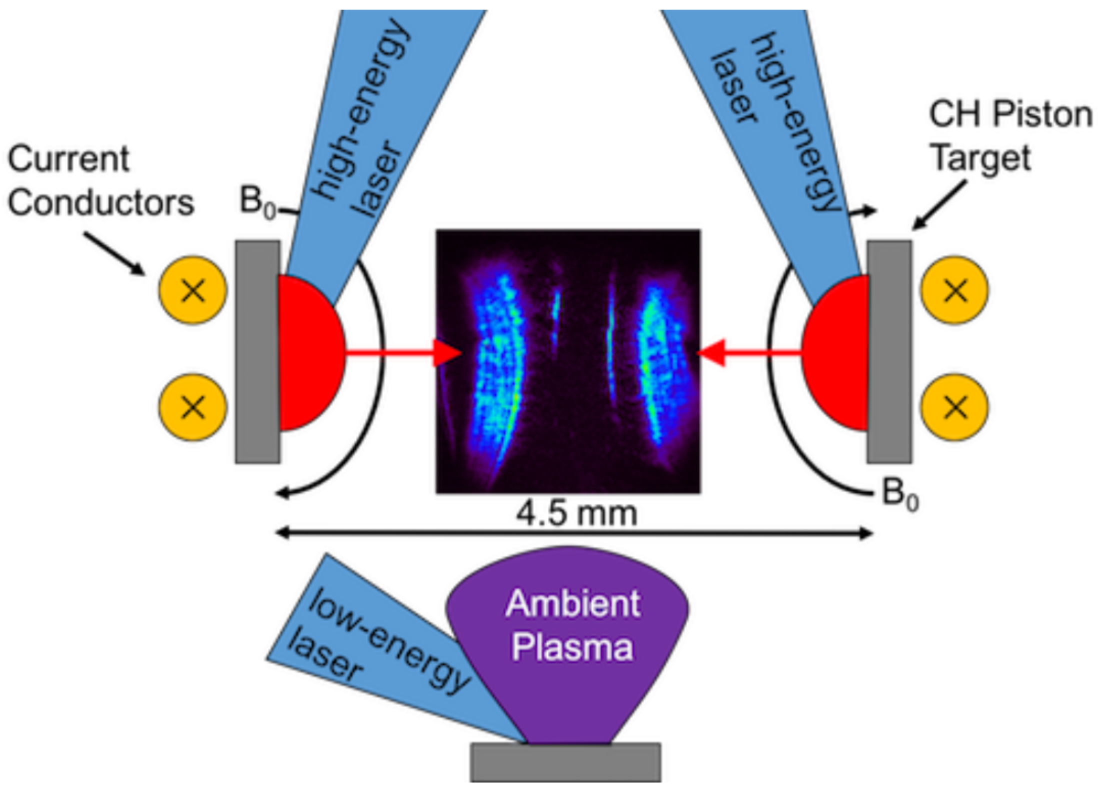
[1]F. Fiuza, NIF/JLF Users Meeting 2015

Courtesy of Laurent Gremillet

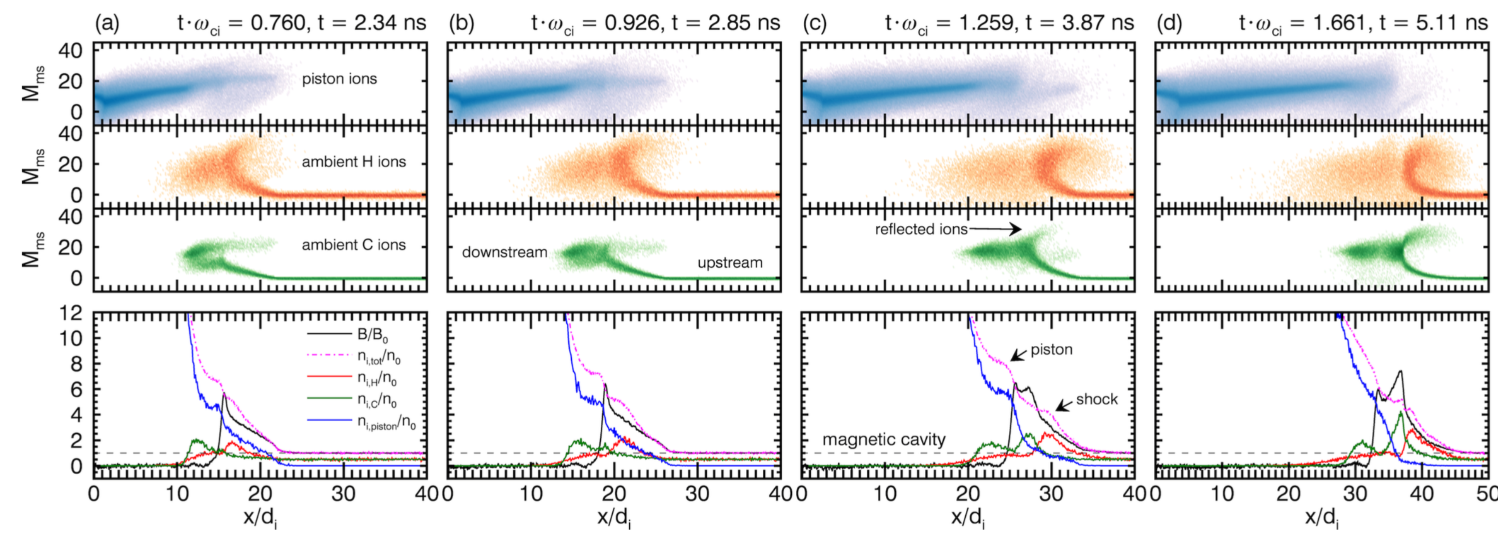
Experiments on the generation and Evolution of High-Mach Number, Laser-Driven Magnetized Collisionless Shocks in the Laboratory

Schaeffer et al. arXiv:1610.06533

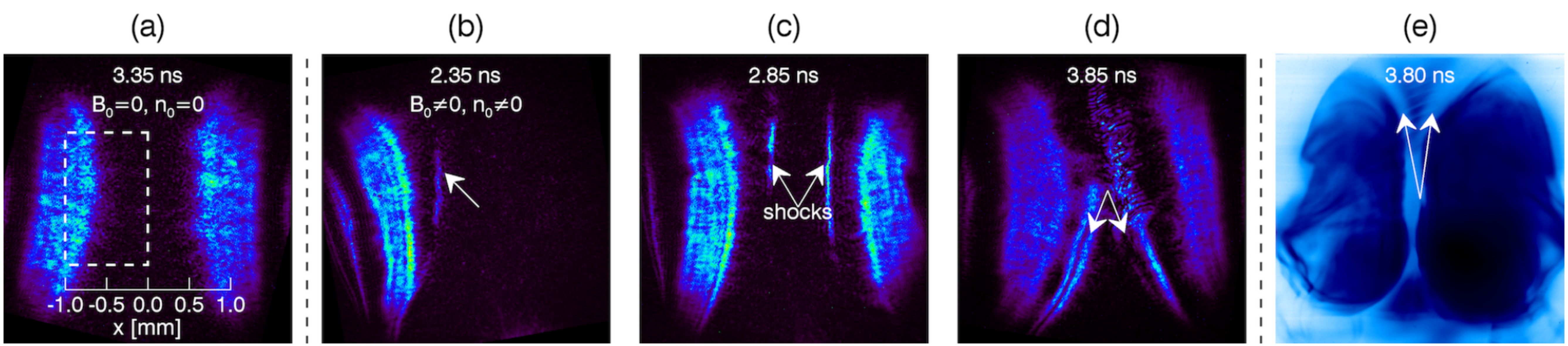
PRINCETON UNIVERSITY



Experimental setup. An external magnetic field (B_0 = 8 T) in an anti-parallel geometry was applied by pulsing current through conductors located behind opposing plastic (CH) piston targets.



Results from 2D particle-in-cell simulations that show the formation of a high-Mach number, magnetized collisionless shock



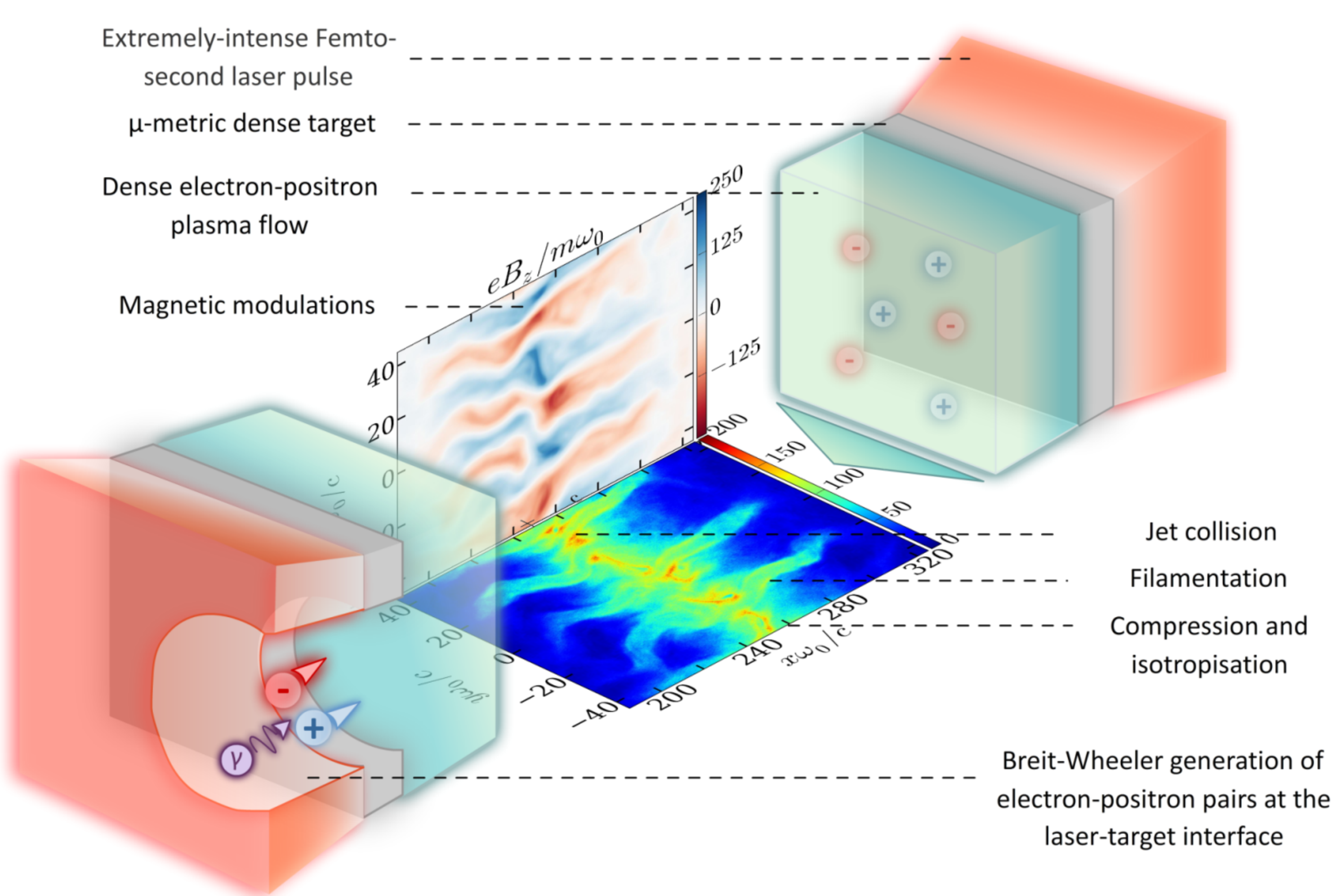
Refractive and proton radiographic images of collisionless shock evolution

Two-target configuration for the study of the Weibel instability in colliding e⁻e⁺ jets

Could be transposed to e⁻p plasma collisions using low density targets

- High laser intensity necessary to generate sufficiently dense pair plasmas
- Large focal spot necessary to minimize transverse spreading of pair plasma and generate many filaments

⇒ Total laser energy > 200 kJ



CALDER PIC Simulation

- **Laser:** plane wave, wavelength $\lambda_0 = 1\ \mu\mathrm{m}$, Gaussian profile of $125\omega_0^{-1}$ (65 fs) FWHM, linear polarization, amplitude $a_0 = 800$ $(I \sim 8.9 \times 10^{23}\ \mathrm{Wcm^{-2}})$
- **Target:** fully-ionized Al^{13+} slab of $32c\omega_0^{-1}$ ($5\ \mu m$) thickness + preplasma of $12.5c\omega_0^{-1}$ ($2\ \mu m$) thickness

M. Lobet et al. PRL 2015

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Conclusions and perspectives

• Steady progress in the development of high power laser systems and their applications.

• Laboratory astrophysics experiments on high power lasers are still in their infancy but with progresses in diagnostics and simulations they should allow to test a large variety of astrophysical models.

• With the construction of UHI laser facilities it should be possible to produce pair plasmas and extreme magnetic fields in the laboratory (see the lecture of T. Grismayer).