Fundamental Issues in Fast Ignition Physics: from Relativistic Electron Generation to Proton Driven Ignition

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Introduction

A key element of **Fast Ignition** of ICF targets is the generation of a **Petawatt power beam** of **“fast” relativistic electrons** and the **transport** of the latter into a dense plasma or a solid target. The electron beam may either **drive ignition directly** or drive the acceleration of a **proton beam** which is in turn used to ignite. Both ignition scenarios involve a number of physical processes which are widely unexplored and challenging for theory and simulation.

We present theoretical and numerical investigations of several fundamental issues, including:

- **“filamentation” instabilities** of fast electrons in the “coronal” region
- **transport modeling** in solid-density matter
- **requirements for proton-driven ignition**.

Scenario of the “traditional” approach to Fast Ignition

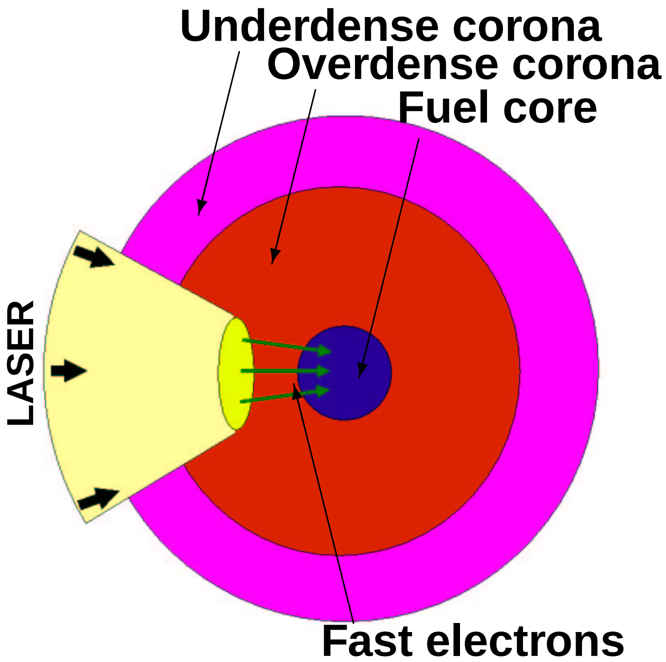
[M. Tabak et al, 1994; M. H. Key, Nature **412**, 775 (2002)]

The success of the scheme relies on the efficiency of several processes involving generation and transport of fast electrons (FE):

⇒ **laser energy conversion** into FE at the **interaction surface** (dominated by collisionless processes)

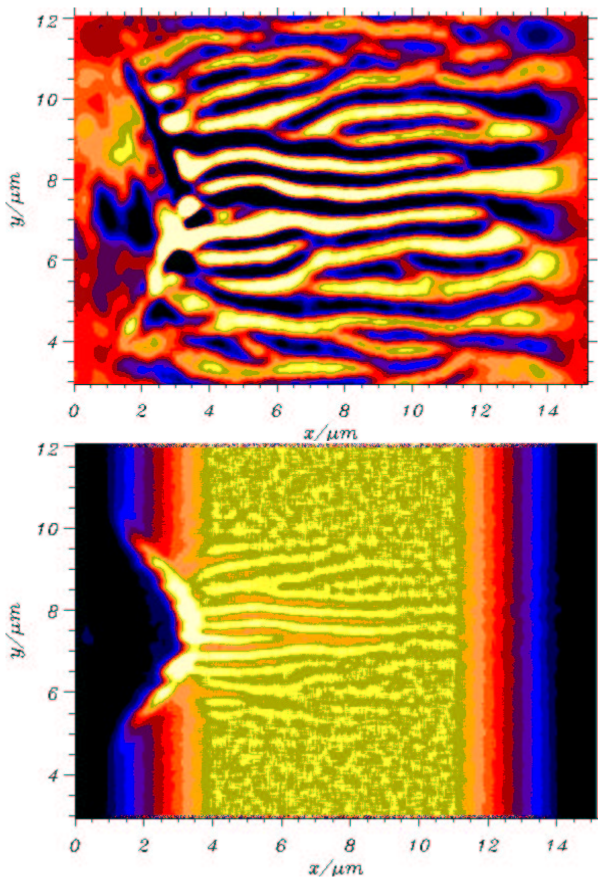
⇒ **transport of FE into the target** [affected by either **collisionless processes** (**microinstabilities**, **self-generated fields**) and by **collisions**, depending on local density and temperature]

- efficient energy deposition in the core by FE



Electron filaments in the corona: bulk or surface effect?

PIC simulations show that fast electrons form **narrow current filaments** as they enter the overdense plasma [2D PIC simulations by H. Ruhl: see Mulser et al, Las. Phys. **10**, 231 (2000)].



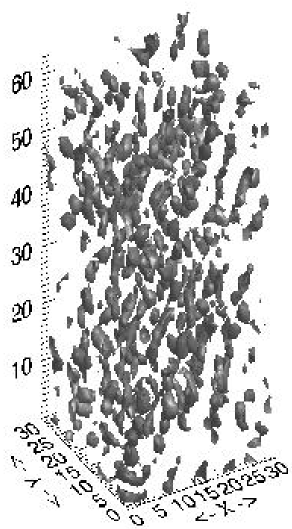
The transverse **current filamentation** (CF) or "Weibel" **instability**, driven by the **repulsion between the "fast" and the background neutralization currents** has been often invoked to explain the origin of filaments. However, **coupling to longitudinal modes** as well as **transient** and **inhomogenity effects** should be considered in this context.

An alternative picture is based on the **corrugation of the target surface** which may lead to a local **geometrical collimation** ("funnel effect") of the fast electrons [Macchi, Ruhl & Cornolti, Las. Part. Beams **18**, 375 (2000)]

3D fluid simulation of the “Weibel” current filamentation instability

Three-dimensional (3D) relativistic, collisionless fluid simulations of the CF instability have been performed. Initially **two counterstreaming, homogeneous electron beams** with zero net current, i.e. $n_1 v_1 = -n_2 v_2$, and **highly asymmetrical** ($|v_1| \gg |v_2|$) are assumed.

3D Magnetic structures are formed with typical length scales of a few $d_e = c/\omega_p$ both **in the direction of the beams** and in the perpendicular plane. **No extended filaments** in beam direction are observed. These results **agree with 3D theory** [F. Califano et al., PRE **58**, 7837 (1998)]

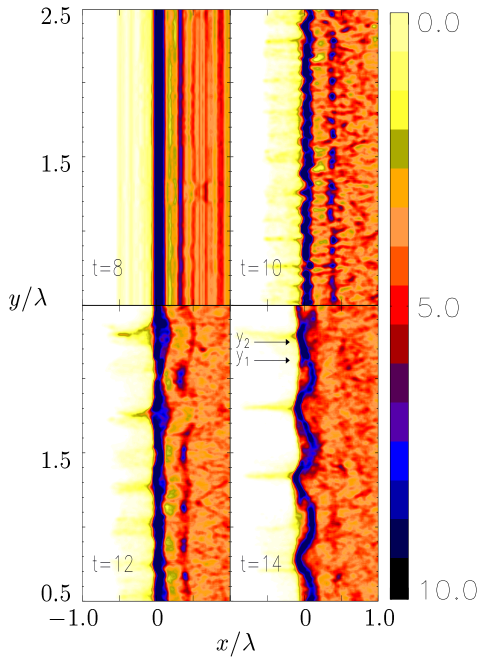


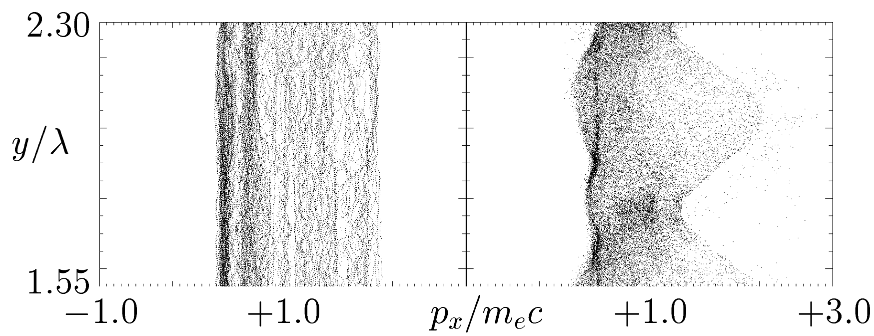
Simulation example: $n_1/n_2 = 9$, $v_1 = 0.95c$, $v_2 = -0.10556c$.
If $n_0 = n_1 + n_2 = 10^{22}$ cm^{-3} (typical of PIC simulations), the energy flux of fast electrons (1 MeV energy) is 4.6×10^{18} W cm^{-2}. Figure shows isosurfaces of A_z (vector potential component along beam direction), which is representative of the magnetic field structure because $B_z \ll (B_x, B_y)$ is found.

Imprint effect by surface parametric instabilities

PIC simulations [1] and theory [2] show that pairs of nonlinear **electron surface waves** (ESWs) can be parametrically excited by the laser pulse. For normal incidence and s-polarization, the ESWs are driven by the $\mathbf{v} \times \mathbf{B}$ force and form a **standing wave pattern** on the target surface.

Simulations show that fast electrons are then generated predominantly at **maxima of the standing wave**. This gives an **“imprint” for electron filaments** whose size and spacing is proportional to the laser wavelength as observed in other simulations.





[1] A. Macchi et al, Phys. Rev. Lett. **87**, 205004 (2001)

[2] A. Macchi et al, Phys. Plasmas **6**, 1704 (2002)

Fast electron transport in solid-density matter

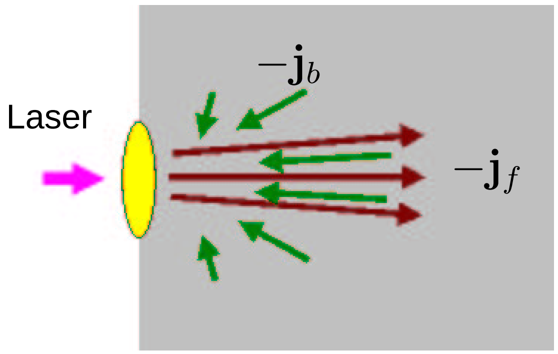
Typical transport regime in fast ignitor and laser-solid interaction experiments:

fast e^-: $n_f \approx 10^{18} - 10^{20}$cm^{-3}, $\varepsilon_f \approx 10^5 - 10^7$eV, $\tau_c > 10^{-12}$s

slow e^-: $n_b \approx 10^{23}$cm^{-3}, $\tau_c < 10^{-15}$fs (metal) produce a neutralizing "return" current $\mathbf{j}_b$:

$$\mathbf{j}_b \simeq \frac{n_b e^2}{m_e \tau_c}\mathbf{E} = \sigma \mathbf{E}$$

$|\mathbf{j}|_f \approx 10^{11} - 10^{12}$ A cm^{-2}, $I \approx 10^5 - 10^6$ A



$\longrightarrow$ self-generated $\mathbf{E}$ and $\mathbf{B}$ fields are important

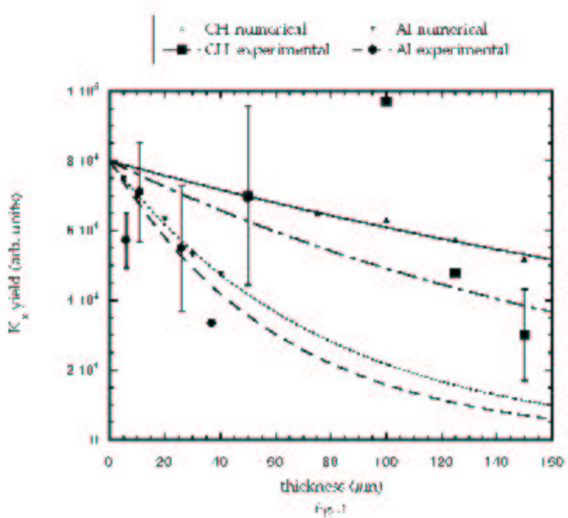
In low σ materials, $\mathbf{j}_b$ may not compensate well $\mathbf{j}_f$

$\longrightarrow$ generation of $\mathbf{E}$ fields

makes fast electron transport σ-dependent.

Experimental study of transport inhibition by self-generated fields

A first evidence of **material-dependent penetration** of fast electrons has been obtained by comparing results (from **K-shell emission** diagnostics) in **Al targets** and **Al-coated plastic targets**, so that **the spectrum of fast electrons is identical** in the two cases [1].

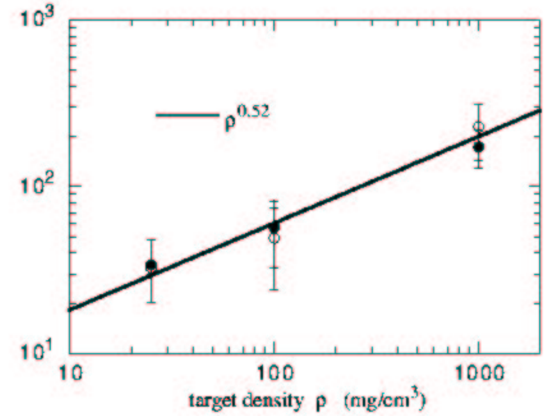


From K-shell data it is inferred that the **penetration range is much shorter in plastic than in Al** and **cannot be explained by collisional stopping** of fast electrons alone.

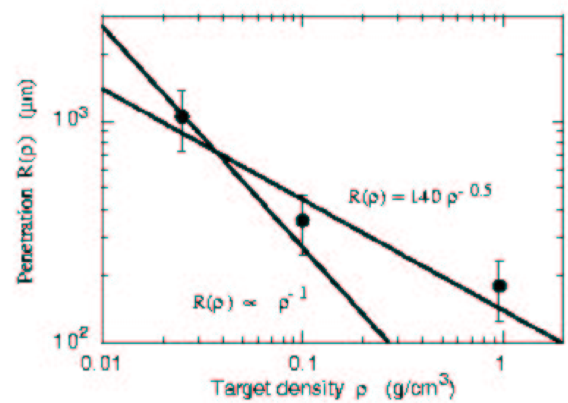
[1] F. Pisani, A. Bernardinello, D. Batani et al, Phys. Rev. E **62**, R5927 (2000)

Fast electron penetration in low-density foam targets

The K-α yield $I_{K\alpha}$ has been measured as a function of the density ρ of **plastic foam targets** with **constant mass thickness** ρd. From $I_{K\alpha}$ the **penetration range** R of fast electrons is obtained.



The deviations from the **purely collisional behavior** ($R \sim \rho^{-1}$, $I_{K\alpha} =$ cost.) indicate the effect of **self-generated fields** on fast electron transport [2].



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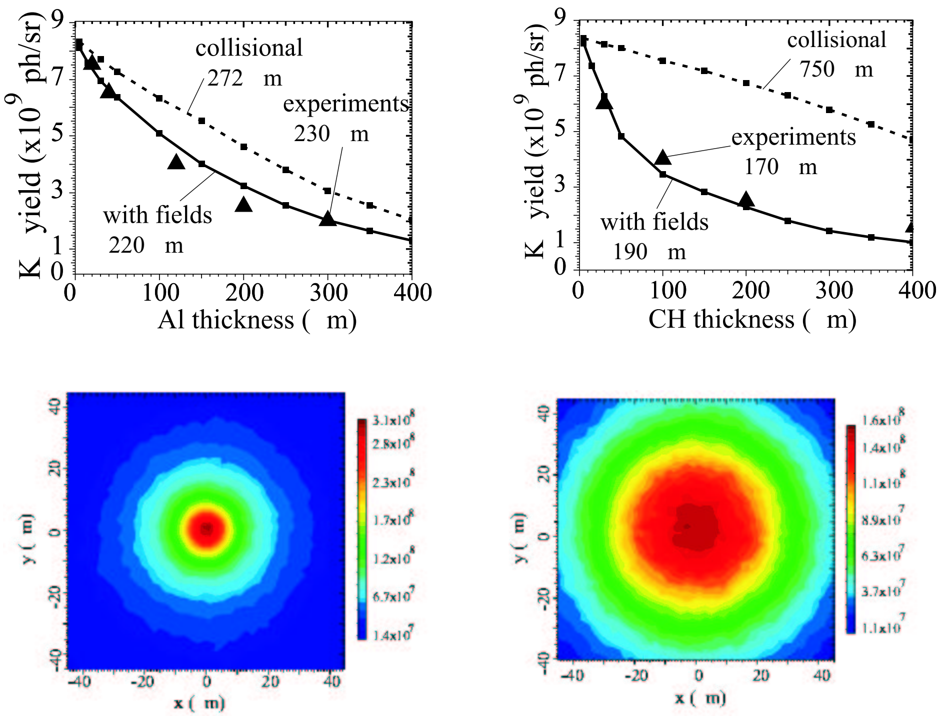
[2] D. Batani, A. Antonicci, F. Pisani et al, Phys. Rev. E **65** 066404 (2002)

Transport simulations with the PENELOPE code

The 3D Monte-Carlo electron-photon transport code PENELOPE [Beró et al, NIM B **100**, 31 (1995)] has been adapted by including **field generation** and **K-α diagnostics** [Antonicci et al. (2001)] and used to simulate the experiment by Pisani et al. Local **charge neutrality** is assumed.

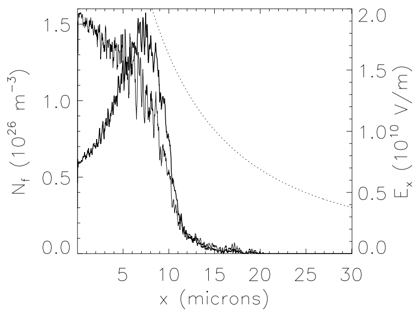


The **penetration range** of fast electrons is affected by **self-generated fields**; the effect is **stronger in CH** (low conductivity).

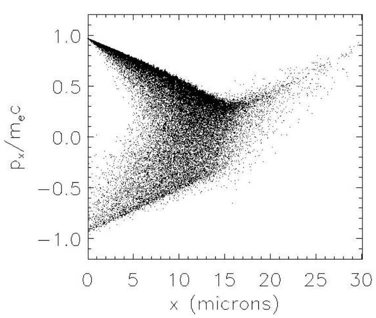
The comparison of simulations for Al targets **with (left)** and **without (right) fields included** show **self-collimation** of the fast electron beam in the first case.

Simulations of transport inhibition by electrostatic fields

To address the importance of **electrostatic (ES) fields** in low-σ materials, a new hybrid code with **charge separation effects included** is under development. Preliminary results in 1D are reported for an Al isothermal plasma ($T_e = 100$ eV), fast electrons with 200 keV energy, beam intensity 3.6×10^{17} W cm^{-2}. Profiles of fast electron density and ES field and the (x-p_x) phase space plot are shown at $t = 100$ fs.



Surface charges generate a strong back-holding ES "capacitor" field (thin line). The density profile (thick) is very different from that obtained from Bell's formula (dotted) [Bell et al., PPCF **39**, 653 (1997)].



Phase space plots show that most of the electrons are reflected back by the ES field, with only a small number penetrating deep into the target. Broadening in momentum space is due to Coulomb collisions.

Proton acceleration by fast electrons in solid targets

The **electric field** $E_b \approx -j_f/\sigma$ generated into the target bulk slows down fast electrons and **accelerates ions**, in particular **hydrogen ions** which are present also in **metallic targets as impurities**.

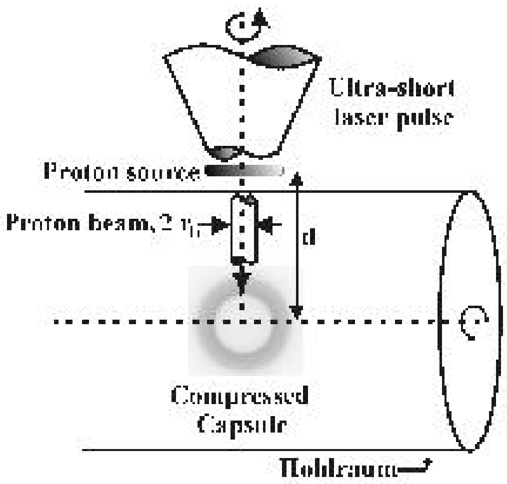
In addition, hydrogen ions **can be accelerated efficiently at the target back surface** by **fast electrons escaping the target** and forming a “Debye” sheath with density n_d, with an electric field

$$E_s \approx 2\sqrt{\pi m_e c^2(\gamma_f - 1)n_d}$$

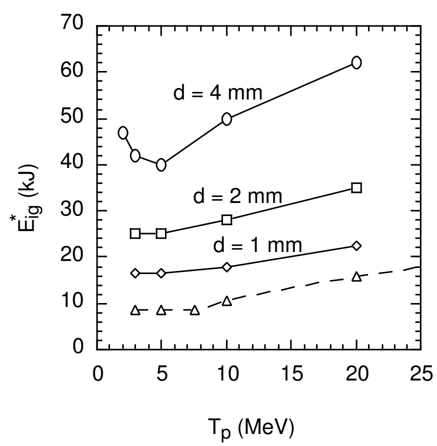
The **energy of protons** from the back surface is about **one half of the fast electron energy** (e.g. a few MeV) with a laser energy **conversion efficiency** into protons **up to a few percent**.

These features make these laser-accelerated protons **extremely interesting for applications**. In the following a study of their application in the **fast ignition of ICF targets** is investigated.

Study of fast ignition by laser-generated proton beams



The requirements for fast ignition by protons are studied by means of **analytical modeling** and **2D radiation-hydro-nuclear simulations** to obtain the **minimum proton beam energy** E_{ig} for ignition as a function of **fuel density** ρ, **proton beam temperature** T_p and **source-to-fuel distance** d.



For homogeneous precompressed fuel spheres,

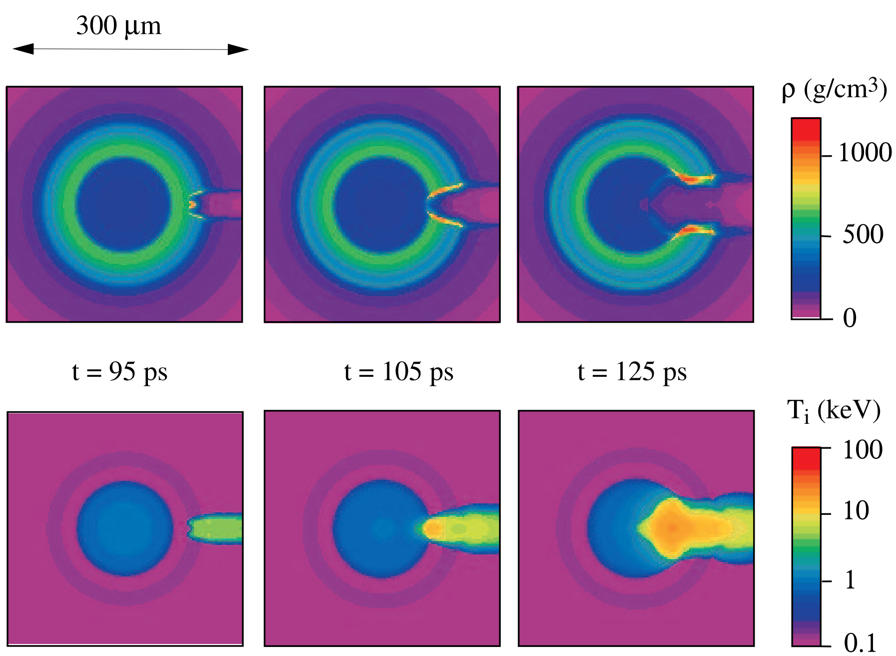
$d = 1 - 4$mm, $T_p \simeq 5$ MeV,

$$\boxed{E_{ign} = 90(d/1\text{mm})^{0.7}/(\rho/[100\text{g/cm}^3])^{1.3}\text{kJ.}}$$

E_{ign} is **larger than earlier estimates** due to effects related to **beam velocity dispersion** and **reduced plasma stopping power** at high temperatures.

S. Atzeni, M. Temporal and J. J. Honrubia, *Nucl. Fusion* **42**, L1 (2002)

2D simulations of ignition by protons and fuel burn



The interaction of the proton beam with a pre-compressed DT fuel capsule has been incorporated in the DUED radiation-hydrodynamic code.

From the simulations an **energy gain** $\boxed{G \approx 200}$ **is obtained**, confirming the potential of the scheme for energy production. Appropriate target design (e.g. **cone-guided targets**) may reduce d and require an energy $\boxed{E_{ign} \simeq 10 \text{ kJ}}$ for ignition.

M. Temporal, J. J. Honrubia and S. Atzeni, *Phys. Plasmas* **9**, 3098 (2002).

Perspectives for future work

- **Understanding current filamentation**: study transient and inhomogeneity effects in Weibel-like instabilities, go deeper into the imprint effect of surface waves.
- **Improving models of fast electron transport:** account for electrostatic effects and conductivity changes due to ionization.
- **Integration of transport and fusion codes**: evaluating the energy transport flux by electrons and protons to give as an input to burn simulations.
- **Different schemes of fast ignition**: simulation of alternative target design, test of “coronal” ignition [S. Hain and P. Mulser, PRL **86**, 1015 (2001)].

Acknowledgments

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