Optimization of Ignitor Beam Properties in Proton Fast Ignition

Paul Gibbon

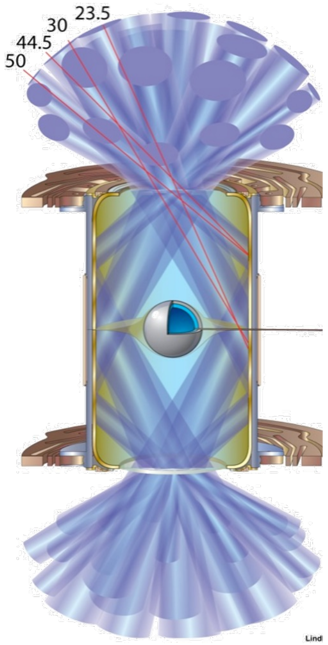
Plasma Physics Towards the Exascale Era, HiPEAC 2024, Garching, 19 January 2024

A power plant will need higher gain and higher robustness compared to NIF

Ignition milestone:
December 5th, 2022

\> 3.2 MJ fusion yield

NIF Ignition

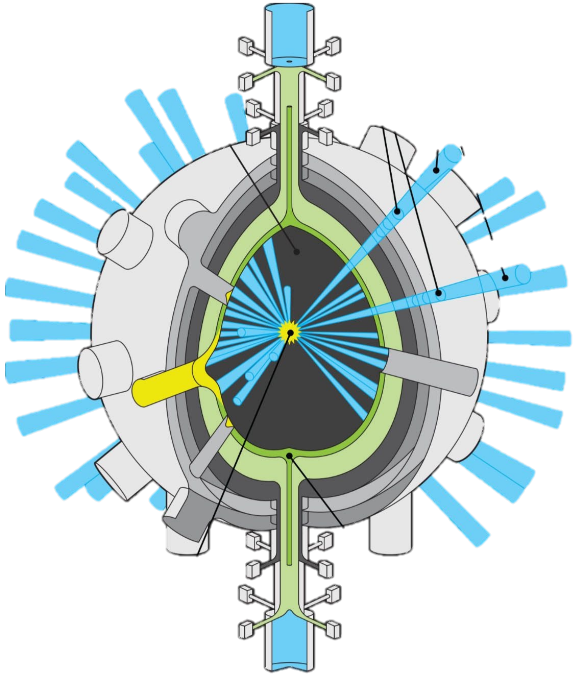


Gain ~ 2x

Single shot

Higher gain and physical robustness

Inertial Fusion Energy



Gain ~ 100x

~ 10 Hz

Focused Energy was founded in July 2021

Our goal: demonstrate commercially viable inertial fusion energy

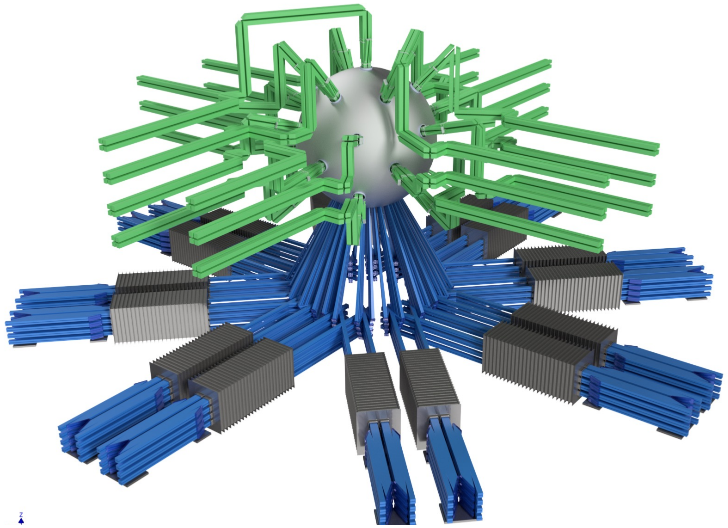
https://focused-energy.world

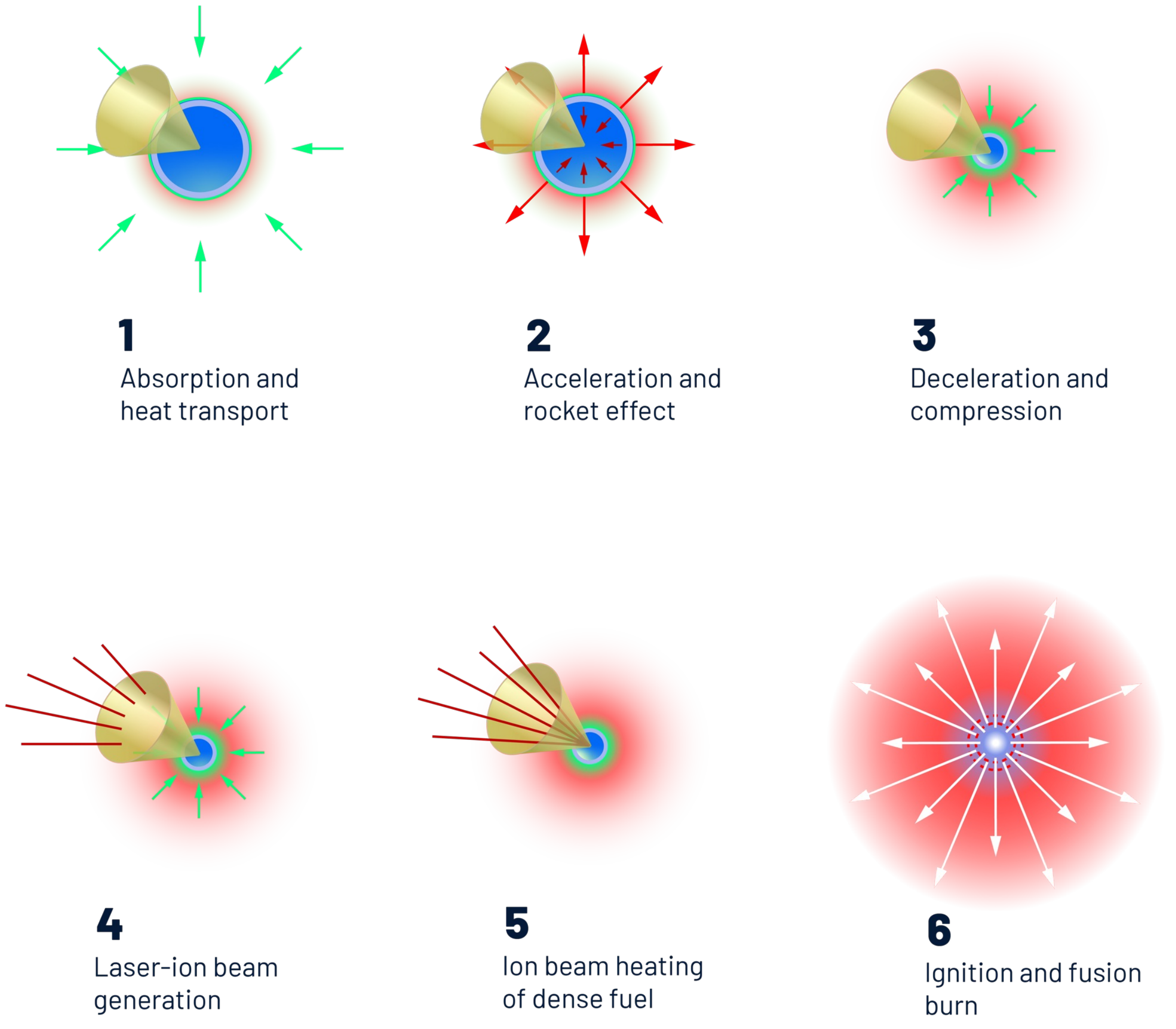
Laser-driven fusion with the Proton Fast Ignition scheme*

FOCUSED ENERGY

The Proton Fast Ignition (PFI) concept comprises several distinct steps:

- long-pulse laser absorption by the plasma (1)
- fuel compression (2-3)
- short-pulse laser generation and transport of a proton beam (4-5)
- fuel ignition and burn (6)

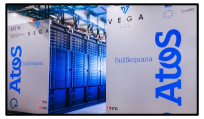




*M. Roth et al., PRL 86, 436 (2001)

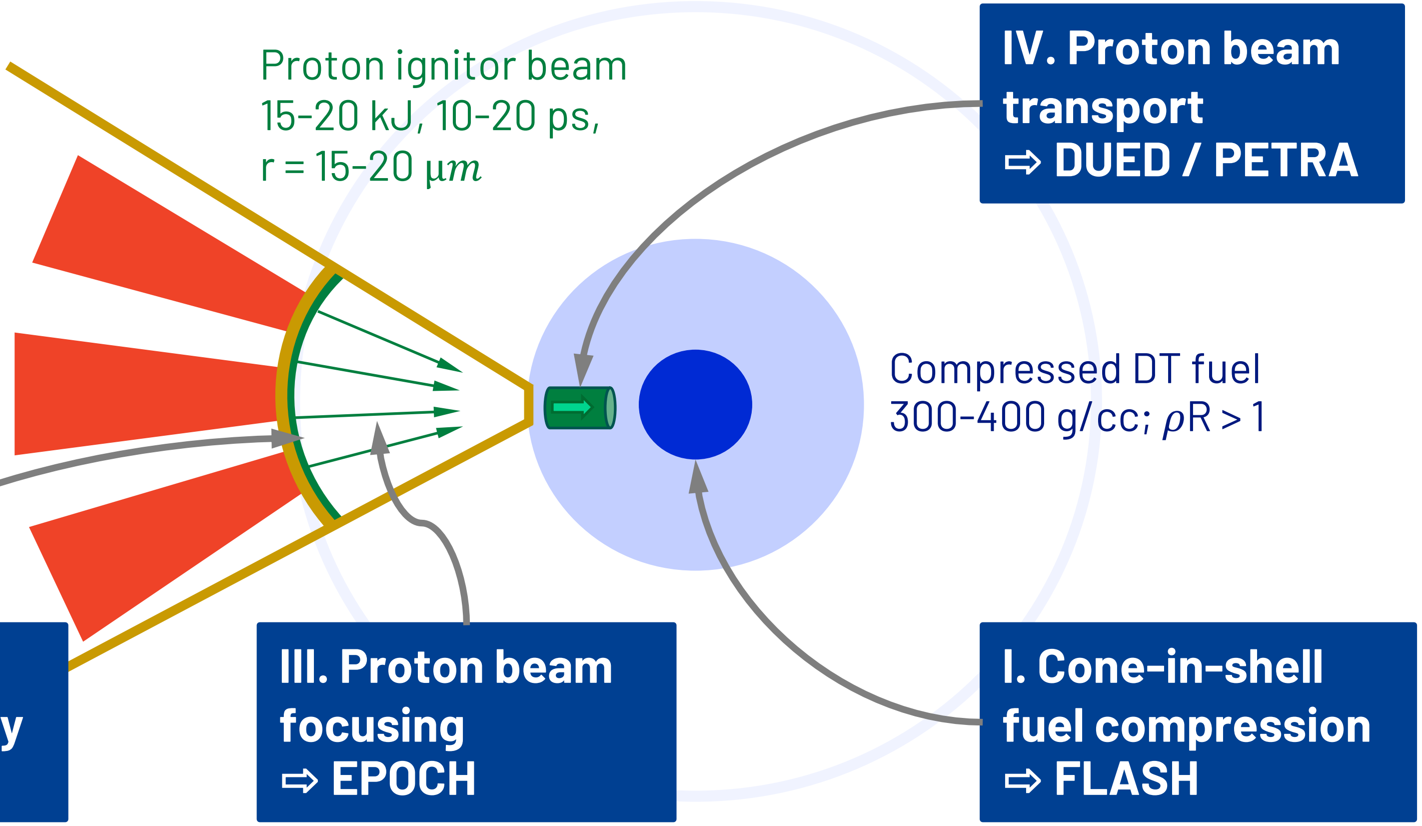
FE has successfully acquired HPC resources through EuroHPC to tackle key design challenges

FOCUSED ENERGY



HPC Vega, IZUM, Maribor **28 M core-hours***

Karolina supercomputer IT4Innovations, Ostrava **13.4 M core-hours***



EuroHPC project: EHPC-REG-2023R01-043

EuroHPC Joint Undertaking

I. Cone-in-shell simulation of DT fuel compression with FLASH

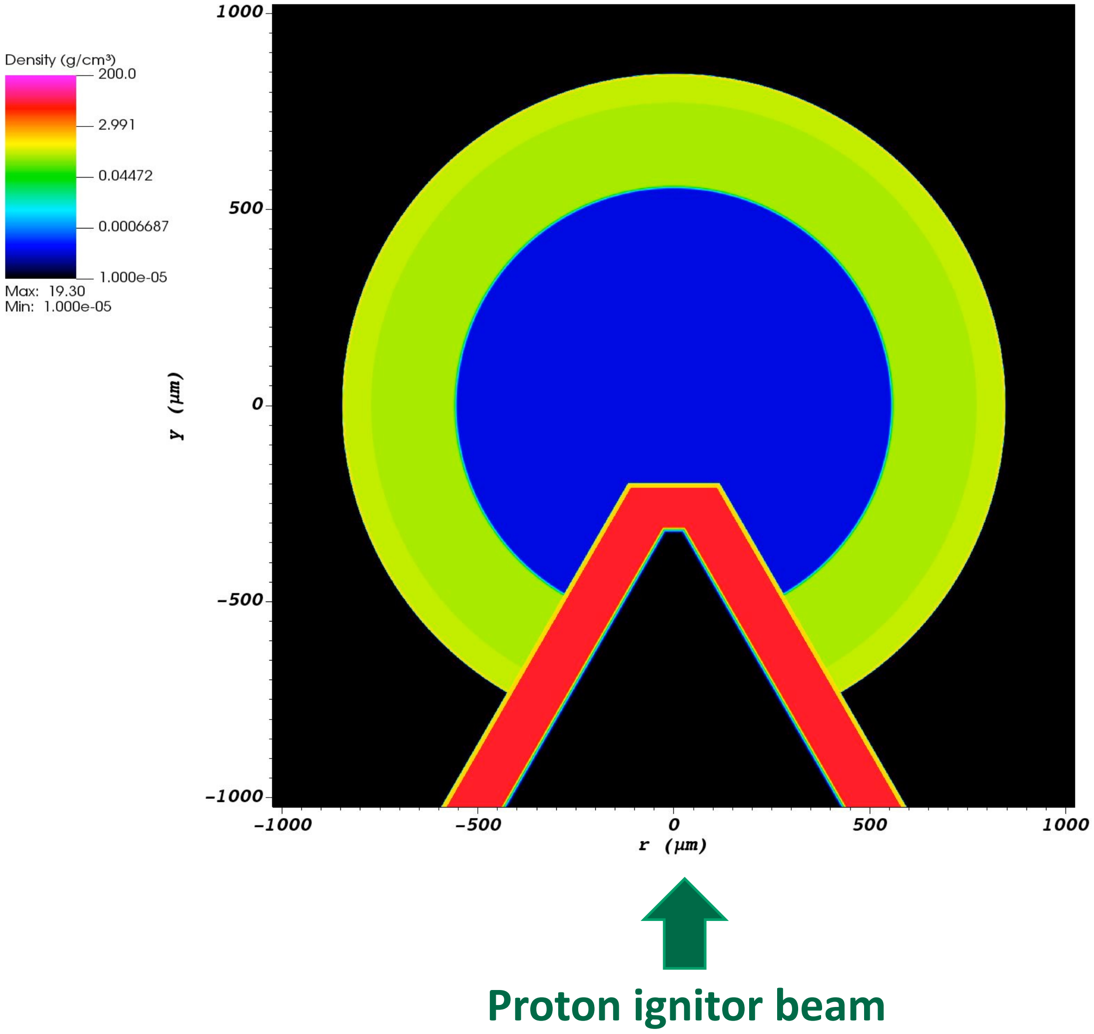
Alfonso Mateo Aguaron, Javier Honrubia (UP Madrid & FE)

Simulation details:

- 2D cylindrical geometry for hydro & laser ray-tracing
- Grid domain 1024 μm x 2048 μm; AMR with 1 μm resolution, blocksize 16x16
- Variable timestep Δt = 1.3e-13 s; 20h runtime on 512 cores

Mitigation of FLASH technical issues:

- grid remapping to remove numerical Rayleigh-Taylor instabilities
- corrected equation of state to avoid negative pressures etc.
- smoothing across material interfaces
- calibration of shock wave propagation via cross-code benchmarking with MULTI-IFE and DUED



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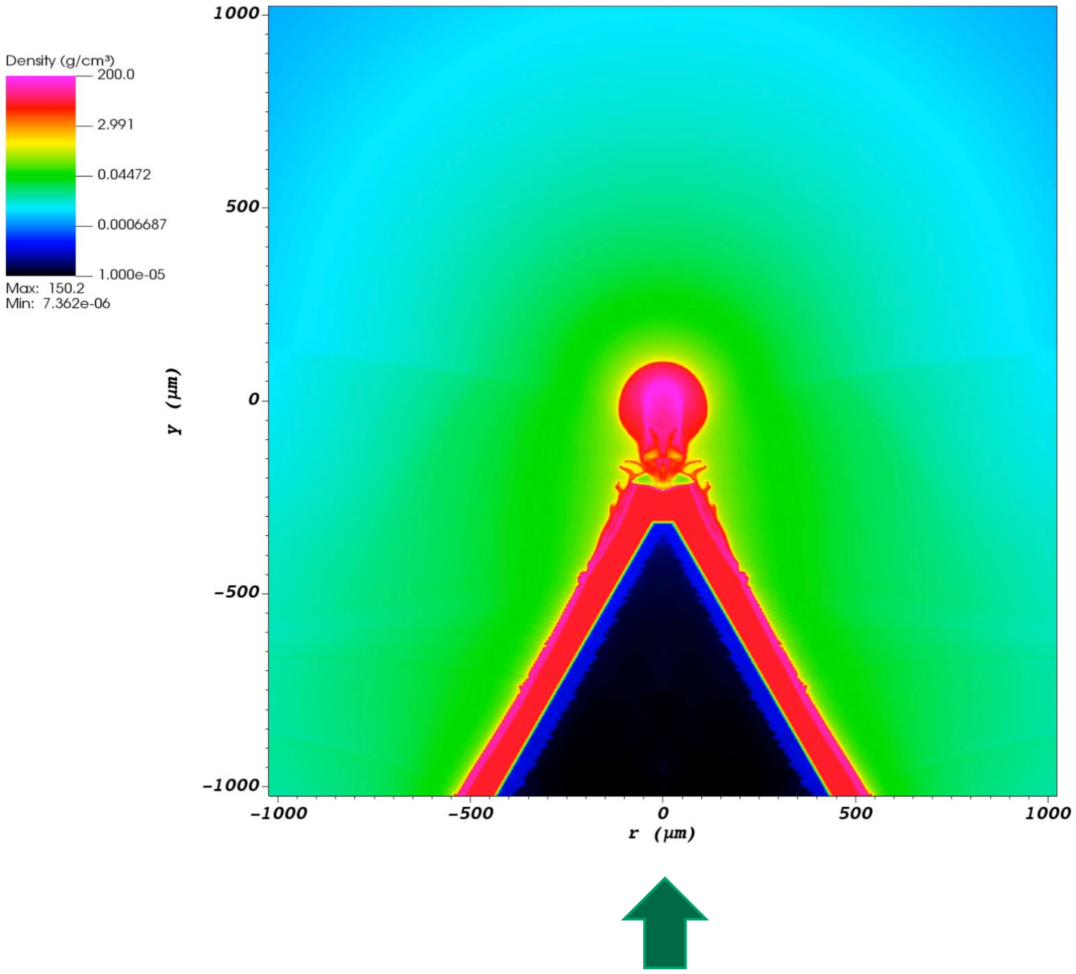


Proton ignitor beam

II. Proton beam conversion efficiency (CE) modelling

Valeria Ospina-Bohorquez

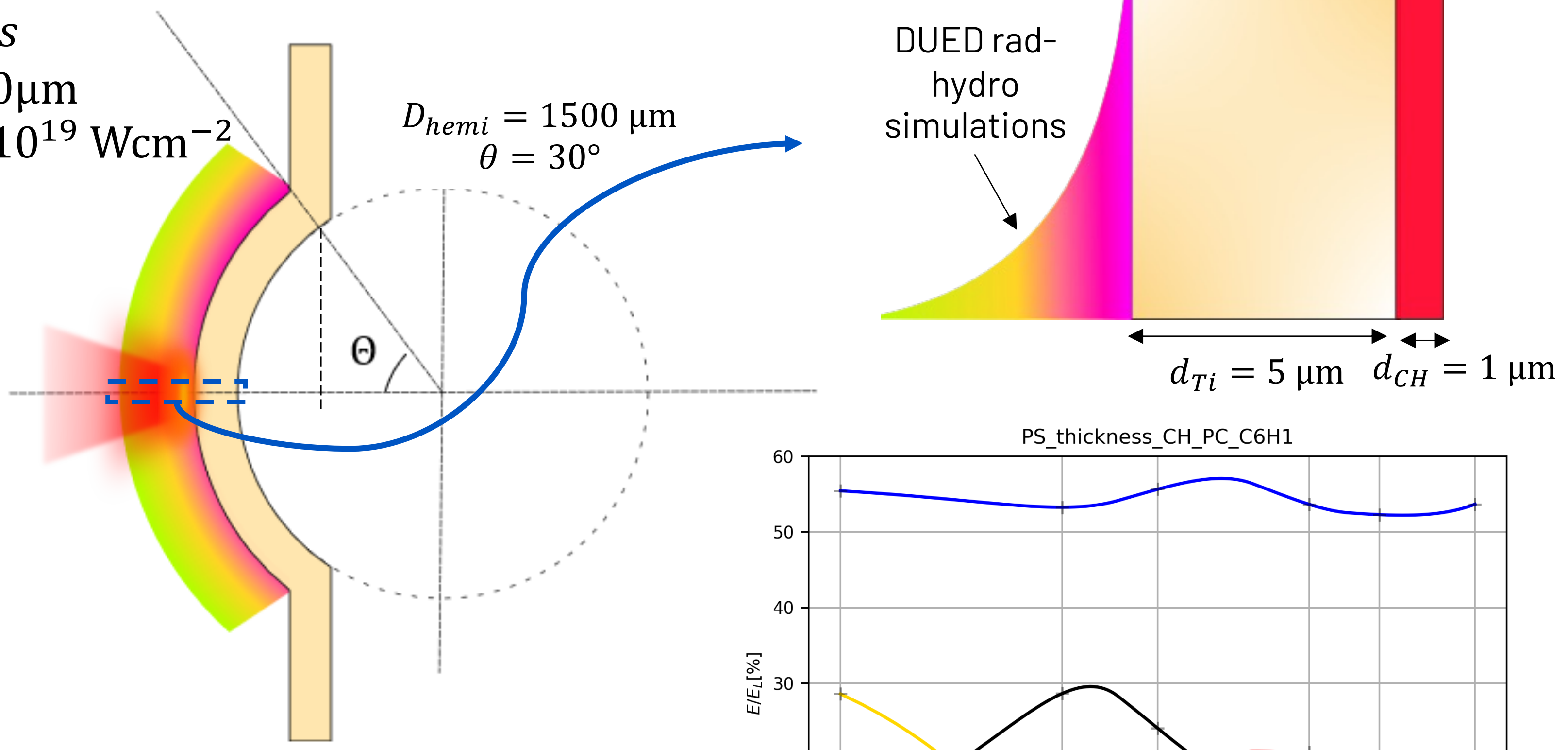
Laser parameters:

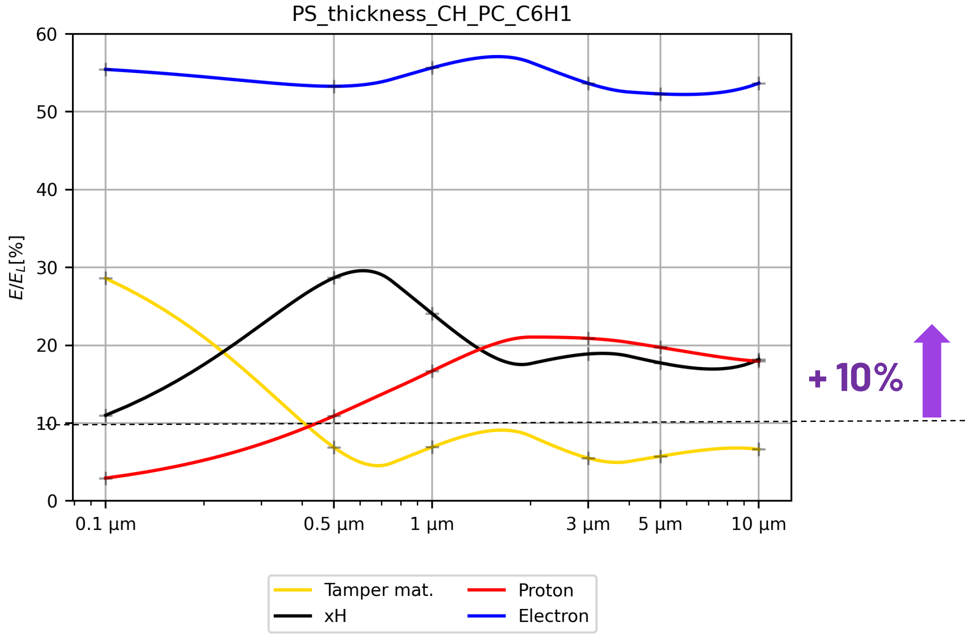
- intensity
- contrast
- duration, shape
- spot size, distribution
- wavelength?

$\tau_L = 3\,ps$
$\sigma_L = 300\mu m$
$I_L = 3\times10^{19}\ \mathrm{Wcm^{-2}}$

Target parameters:

- substrate thickness
- proton layer thickness
- proton layer composition (LiH, CH_n, ErH_3 …)

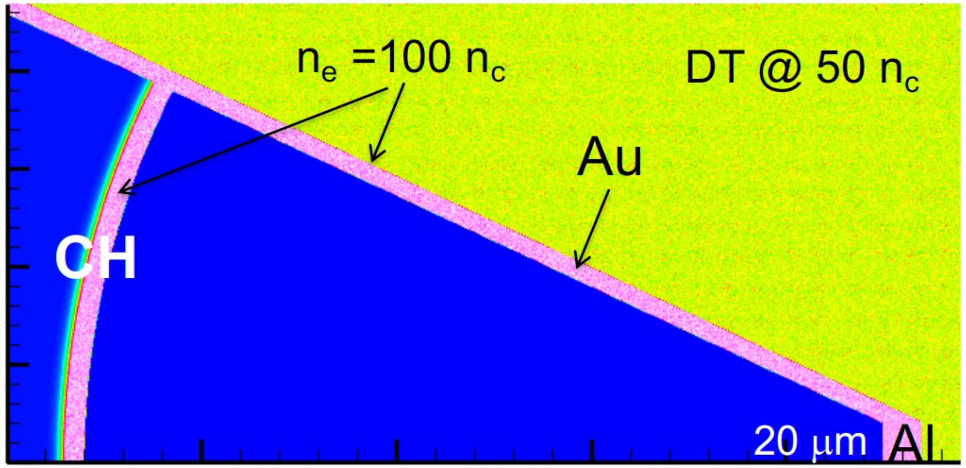


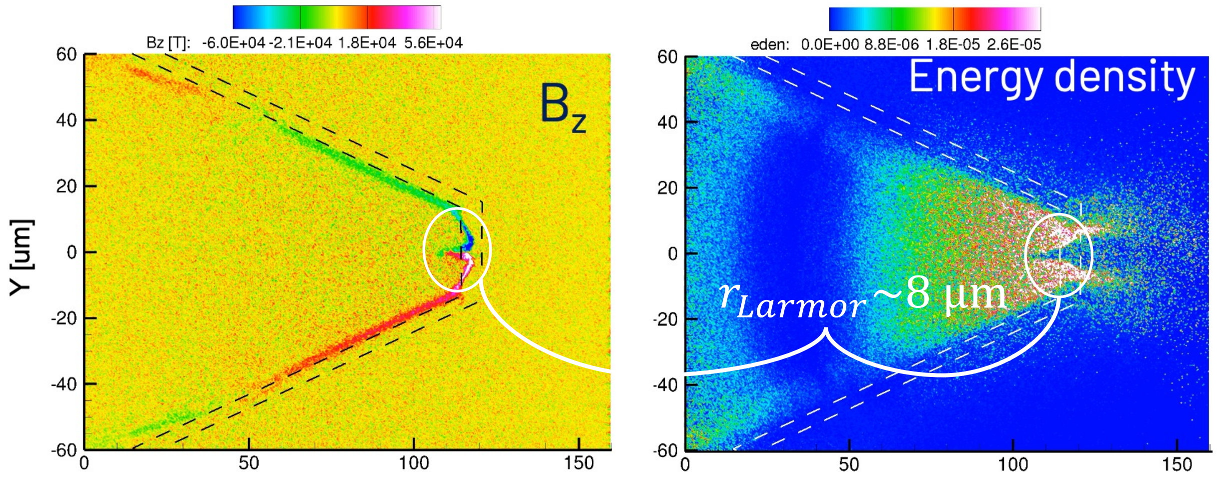


- *At today's prices, each 1% improvement in CE translates to saving of ~ $50M in the ignitor laser system!*

III. Proton beam focusing with 'integrated' cone targets*

Javier Honrubia





Multiple effects of cone wall and DT fuel plasma:

- Strong *return currents* through cone walls and from DT plasma replenish foil electrons and suppress sheath field, reducing proton conversion efficiency
- Magnetic fields generated near cone tip cause strong proton *beam defocusing*
- Mitigation measures: reduced laser intensity, double cone walls, heavy ions
- **Does the cone-tip B-field & defocusing effect still persist for mm-scale cones?**

Honrubia, Morace and Murakami, MRE **2, 28 (2017)*
*Recent expt: King et al., PPCF **66** 015001 (2024)*

Putting the pieces together for ignition (mm-) scale targets

Novel features:

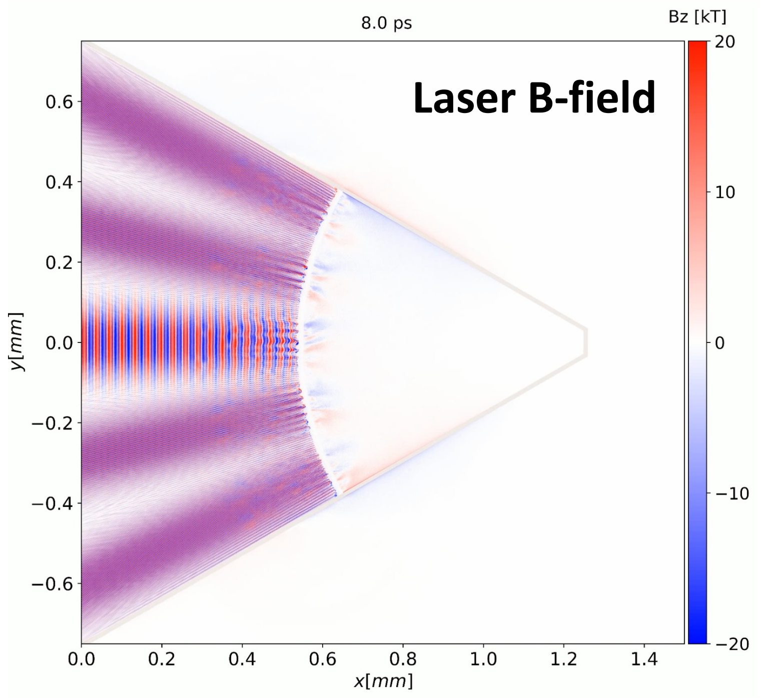
- Multi-beam laser irradiation in mm-scale cone geometry:
  5 x $I_L = 3.0 \times 10^{19}$ Wcm^{-2}; $\lambda = 1\ \mu m$; $\tau_L = 3$ps; $\sigma_{FW} = 100\ \mu m$
- Utilize 'best of' parametric target scans: rad-hydro computed pre-plasma, laser profile, foil composition & dimensions

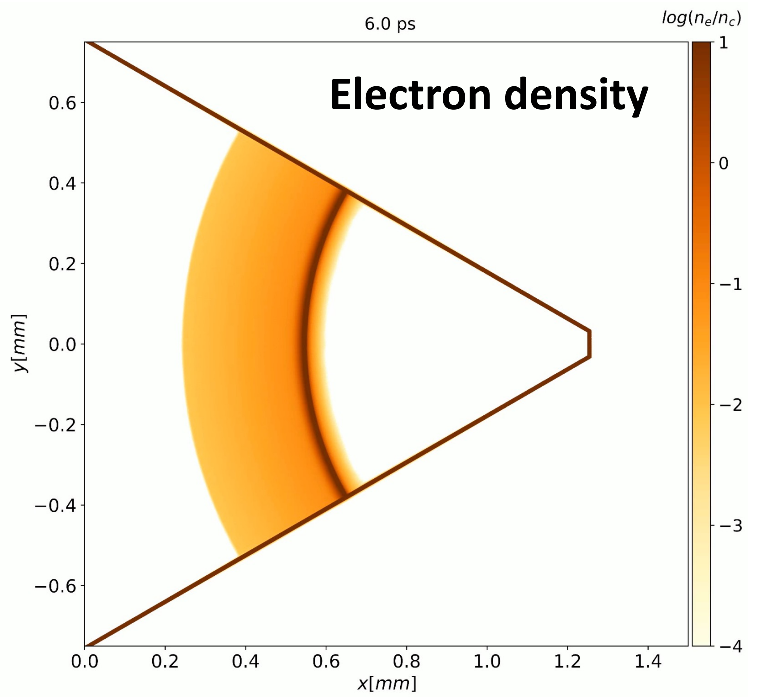
Numerics:

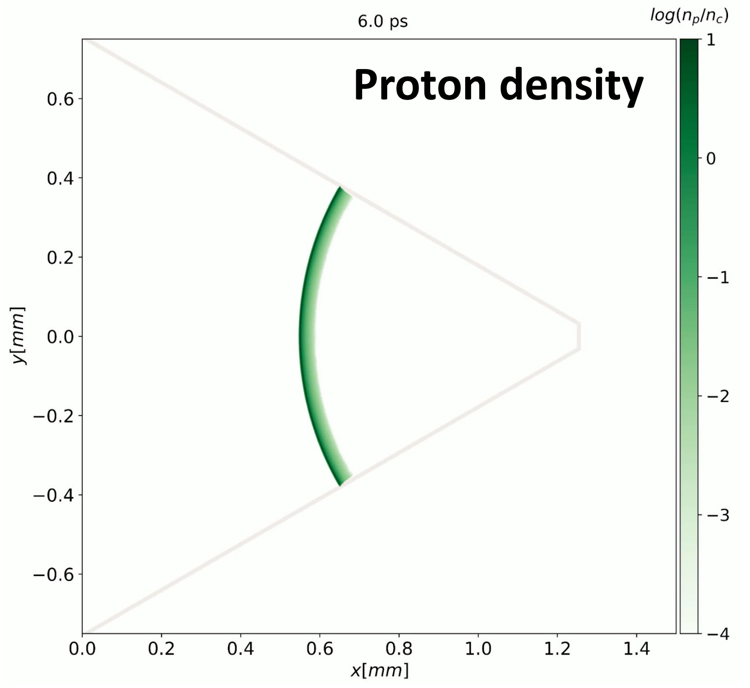
- 30k x 30k = 9 x 10^8 grid points; $\Delta x = \lambda_L/20$
- 2 x 10^9 particles
- 48h on 3k cores of Vega

Future refinements:

- collisions, ionization, wall isolation, 3D!







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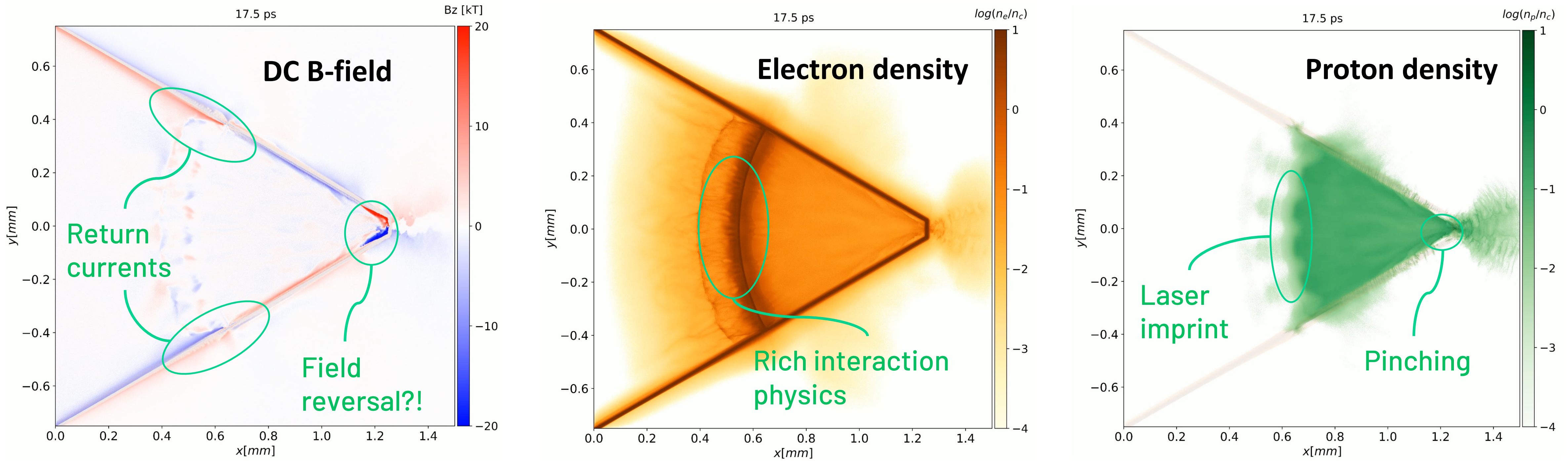


IV. Proton beam divergence leads to higher ignition threshold

Javier Honrubia

PETRA hybrid code*:

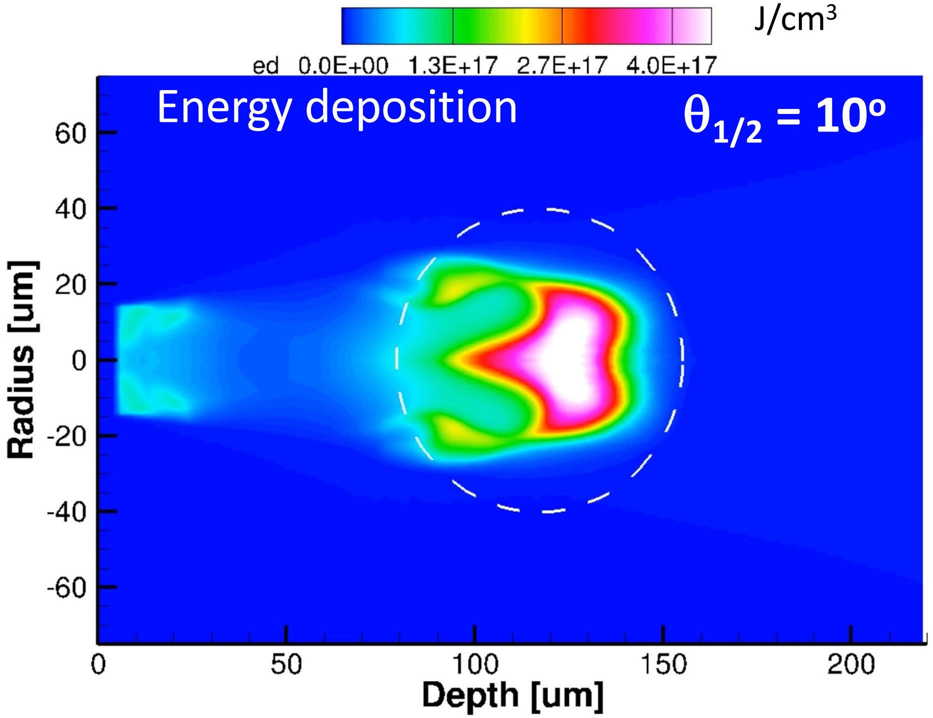
TNSA proton beam with T_p = 5 MeV transported into **imploded DT**

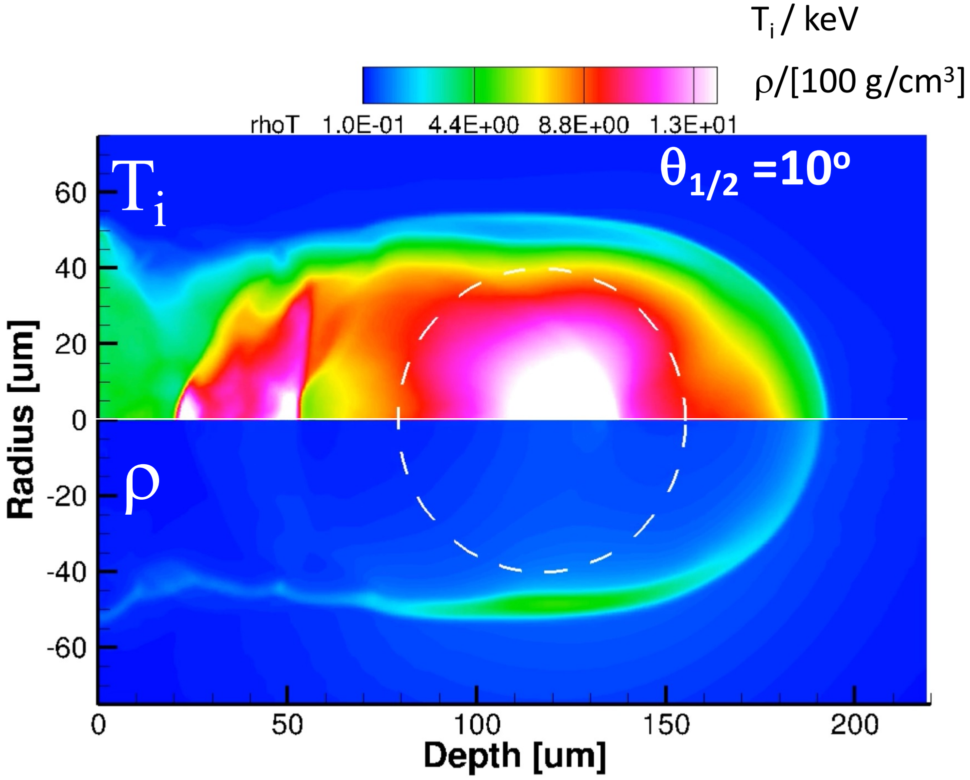
ρ_{max} = 512 g/cm³

standoff distance = 1 mm

E_{ig} = 18 kJ , $\theta_{1/2}$ = 0°

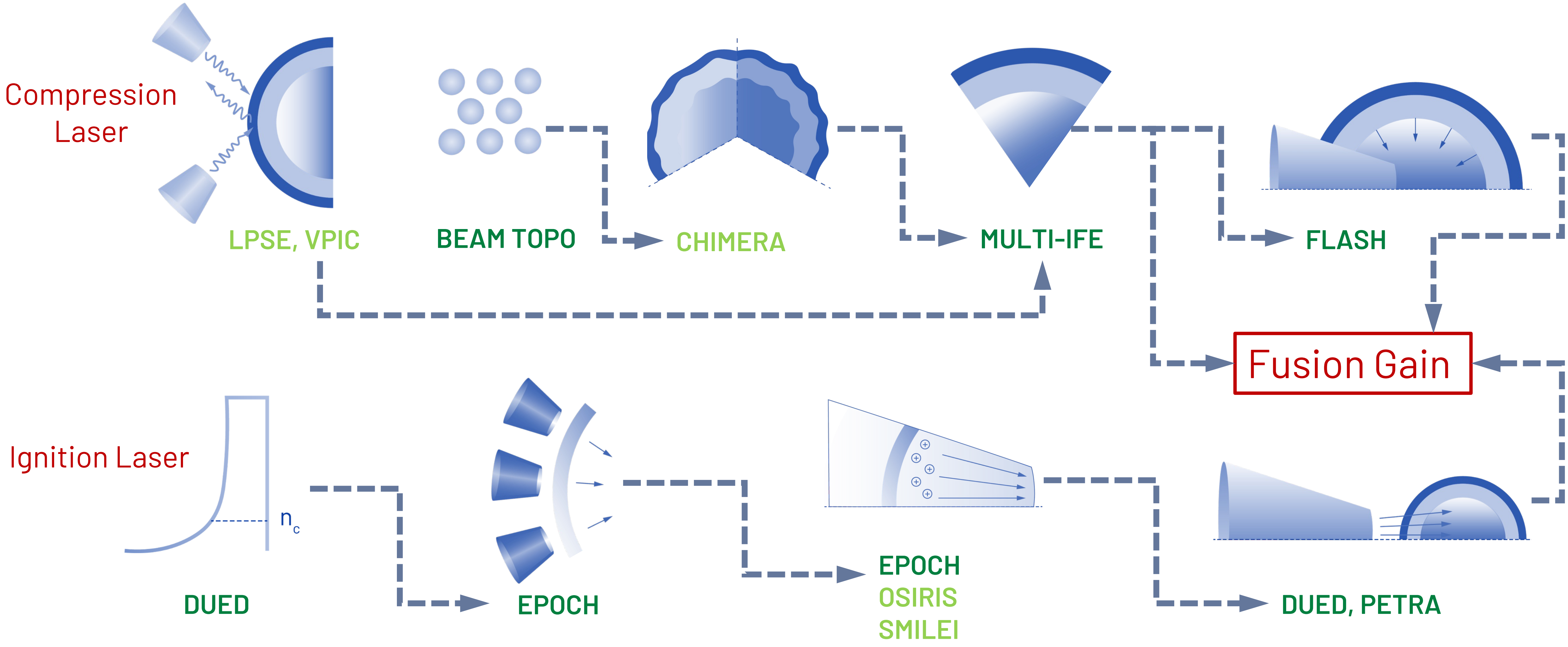
E_{ig} = 27 kJ , $\theta_{1/2}$ = 10°





*See, eg: Honrubia and Murakami, Phys. Plasmas **22**, 012703 (2015)

Towards an integrated PFI model framework (⟶ Digital Twin)

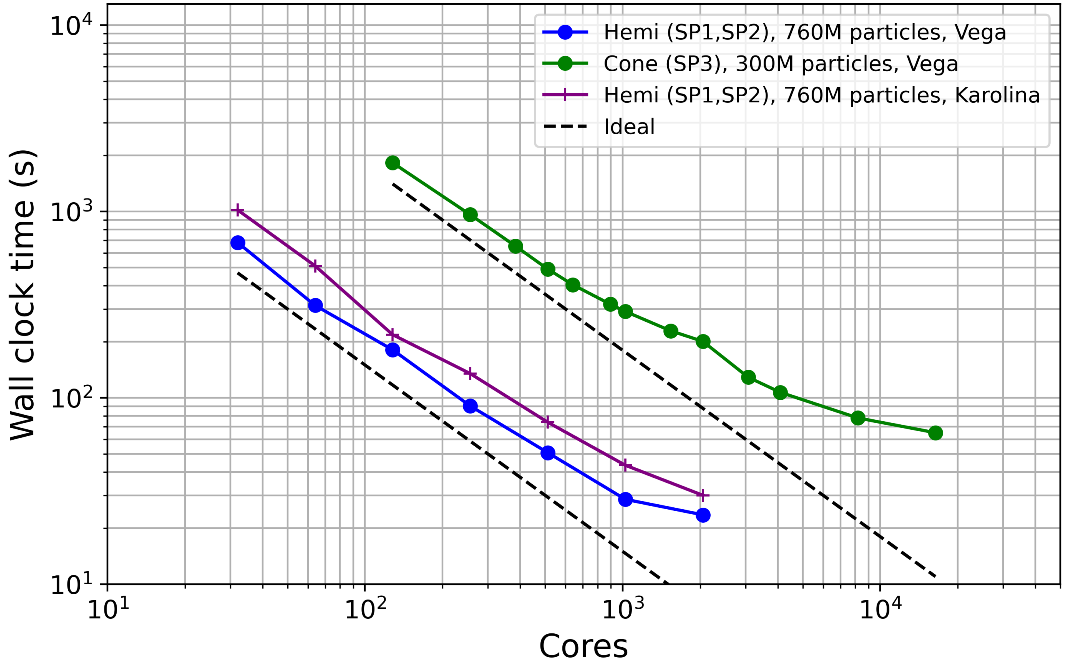


- FE/Open source
- Cooperation

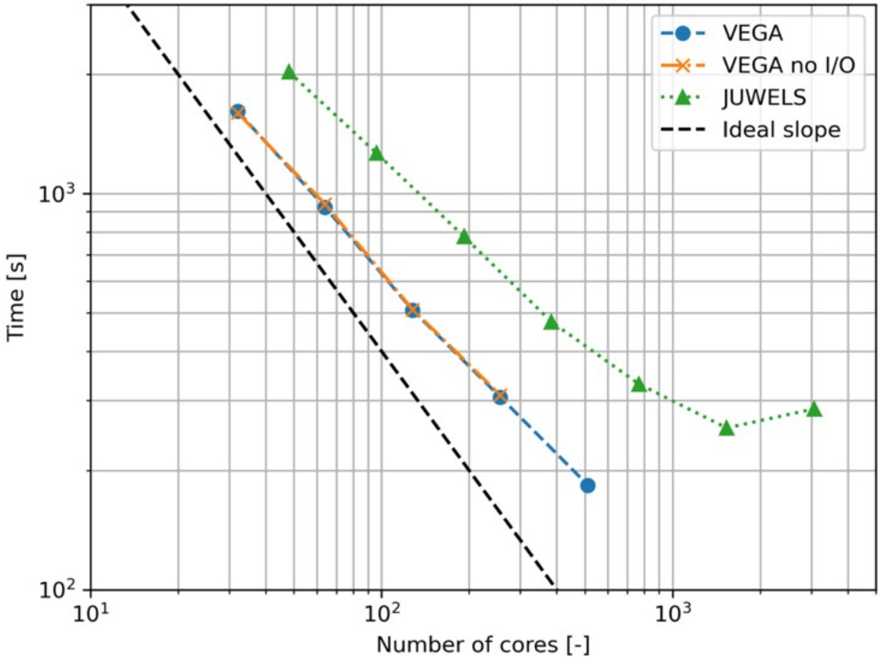
Performance of EPOCH and FLASH codes on Vega & Karolina

EPOCH

T. Arber et al., PPCF ***57****, 113001 (2015)*



B. Fryxel et al., Ap J. ***131****, 273 (2000)*



- Both codes exhibit good weak scaling, so feasible to run with 10^{10} particles/grid points on $>10^4$ cores
- CPU, MPI only (OpenMP possible). Evaluating PIC codes SMILEI, WARP-X for GPU, parallel I/O capability

Summary

- **Progress on key open physics questions of Proton Fast Ignition:**
  - Isochoric compression of DT fuel capsule with inserted cone
  - Strategies for enhancing proton beam conversion efficiency in PFI regime
  - Proton beam focusing in full-scale cone targets: control of return currents
  - Ignition threshold of compressed DT fuel: sensitivity to beam properties

- (Pre-) exascale computing resources (100s of millions of core-h/y) will play a vital role in de-risking inertial fusion power plant design

- Future sub-scale, high repetition-rate experimental facilities will enable quantitative calibration and refinement of models

Thanks to …

EuroHPC JU for awarding this project access ***EHPC-REG-2023R01-043*** hosted by VEGA, Maribor and KAROLINA, Ostrava

and

The Focused Energy Science Team:

J. J. Honrubia, V. Ospina-Bohorquez, A. Mateo-Aguaron, S. Atzeni, M. Brönner, X. Vaisseau, D. Callahan, W. Theobald, P. Patel, M. Roth