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Multi-scale simulations of proton-driven fast ignition of inertial fusion targets

Paul Gibbon, FusionHPC Workshop
Barcelona 29-30 November 2023

The National Ignition Facility shots that changed the game

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Laser-driven fusion has been successfully achieved and scientifically validated

1 August 8th, 2021

NIF validated the **fundamental science** of Inertial Fusion Energy (IFE) by demonstrating a **propagating burn wave**

>1.3 MJ of fusion yield was produced

70% conversion of laser energy to fusion energy

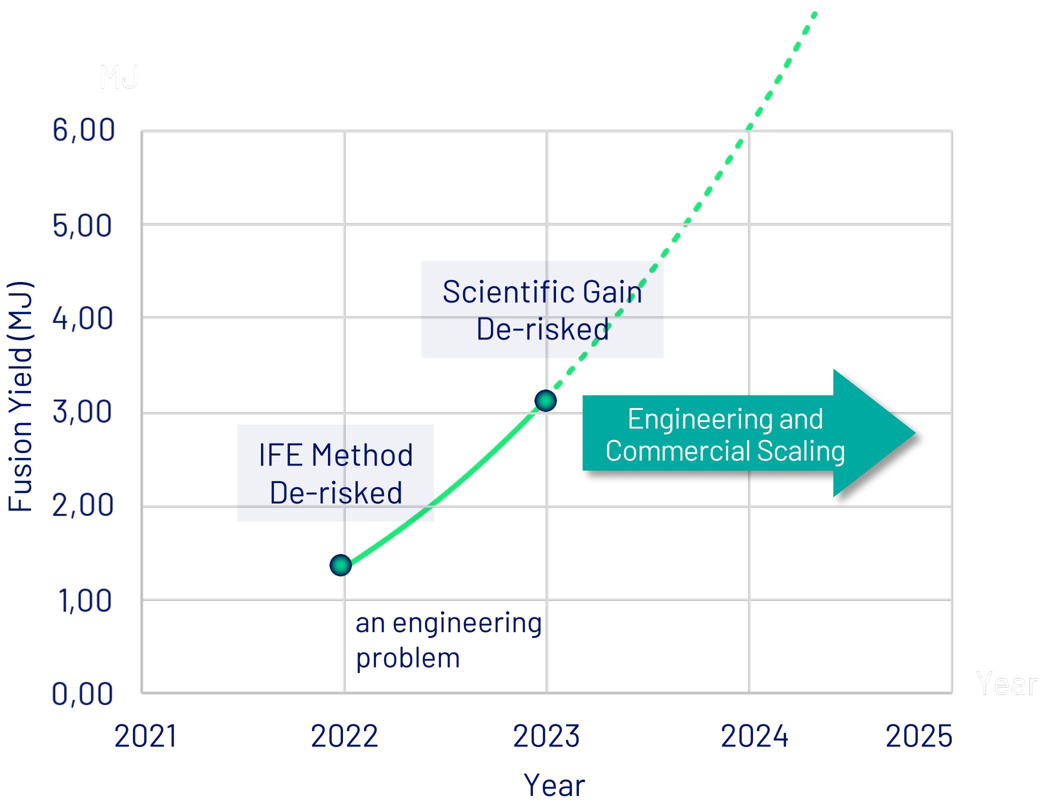
2 December 5th, 2022

NIF validated the commercial viability of IFE by achieving net energy gain **(fusion energy/laser energy >1)**

>3.2 MJ of fusion yield was produced

160% conversion of laser energy to fusion energy

Fusion is now an engineering and commercial scale-up problem



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

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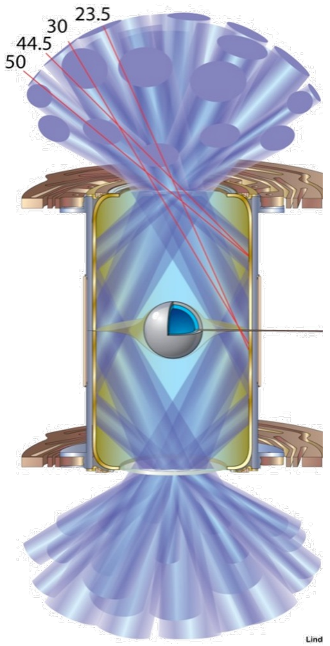
NIF Ignition

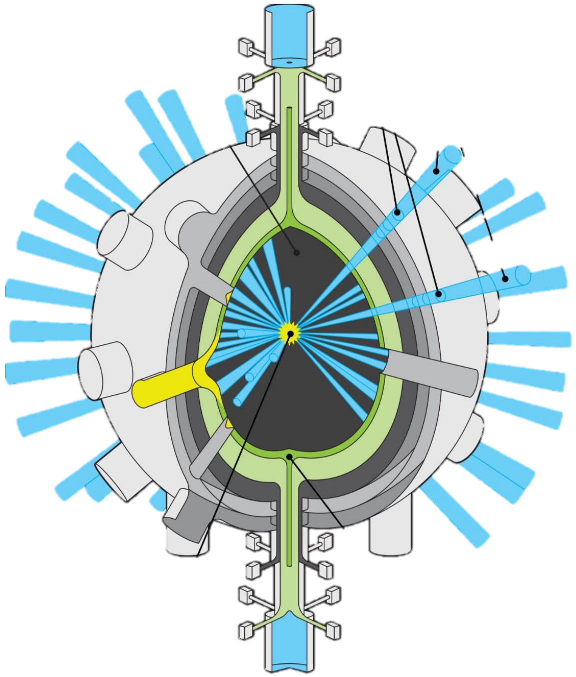


Gain ~ 2x

Single shot

Higher gain and physical robustness

Inertial Fusion Energy



Gain ~ 100x

10 Hz

IFE power plant: we need a target gain of ~ 100 at 10 Hz

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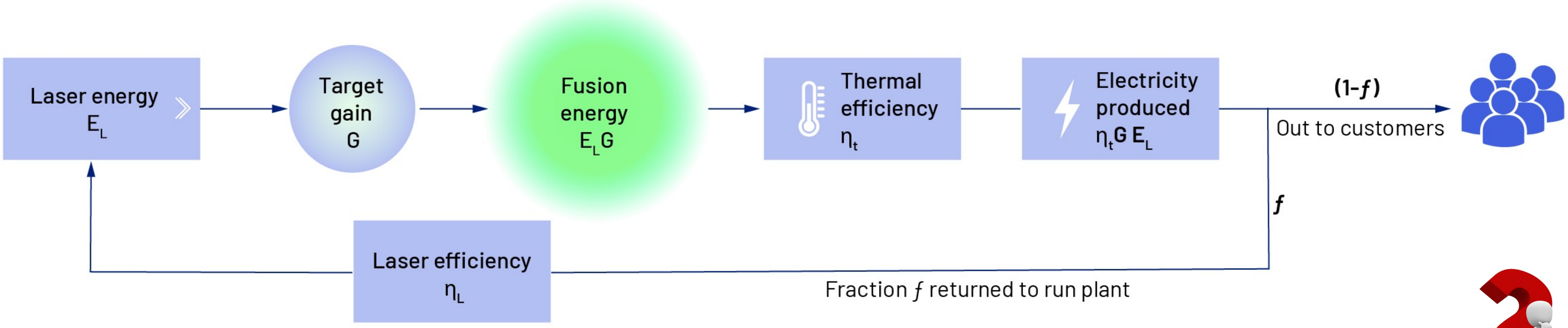

How do we achieve this?

- Energy to run the laser is E_L/η_L
- Energy produced is $E_L . G . \eta_t$
- If we keep recirculating power frac. to less than 25%, then $\eta_L \eta_t G > 4$
- If $\eta_{th} \approx 0.4$, then, $\eta_L . G > 10$
- If $\eta_L \approx 0.1$, then, $\boldsymbol{G > 100}$
- For ~ 750 MW out to the grid, then repetition rate needs to be about **10 Hz** for 2.5 MJ laser

Focused Energy was founded in July 2021

Our goal: demonstrate commercially viable inertial fusion energy

FE's strategy is based on the Proton Fast Ignition concept *

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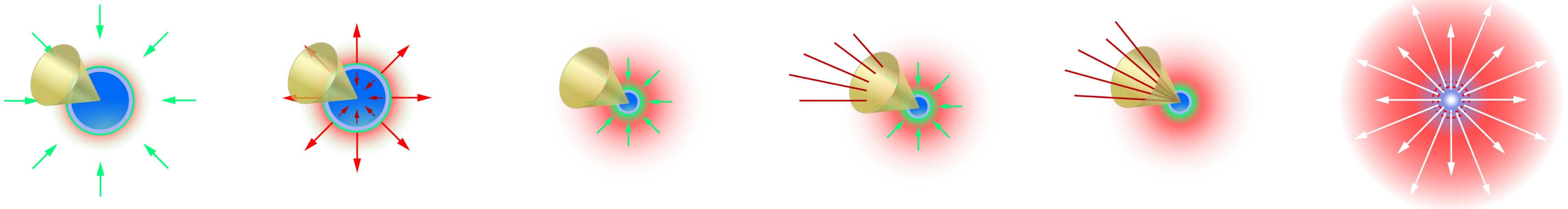


1 Absorption and heat transport

2 Acceleration and rocket effect

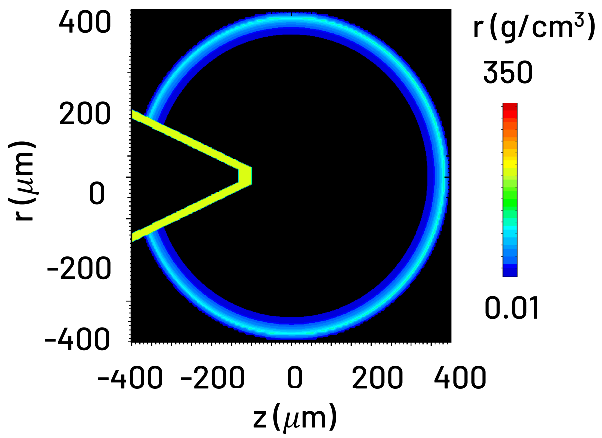
3 Deceleration and compression

4 Laser-ion beam generation

5 Ion beam heating of dense fuel

6 Ignition and fusion burn

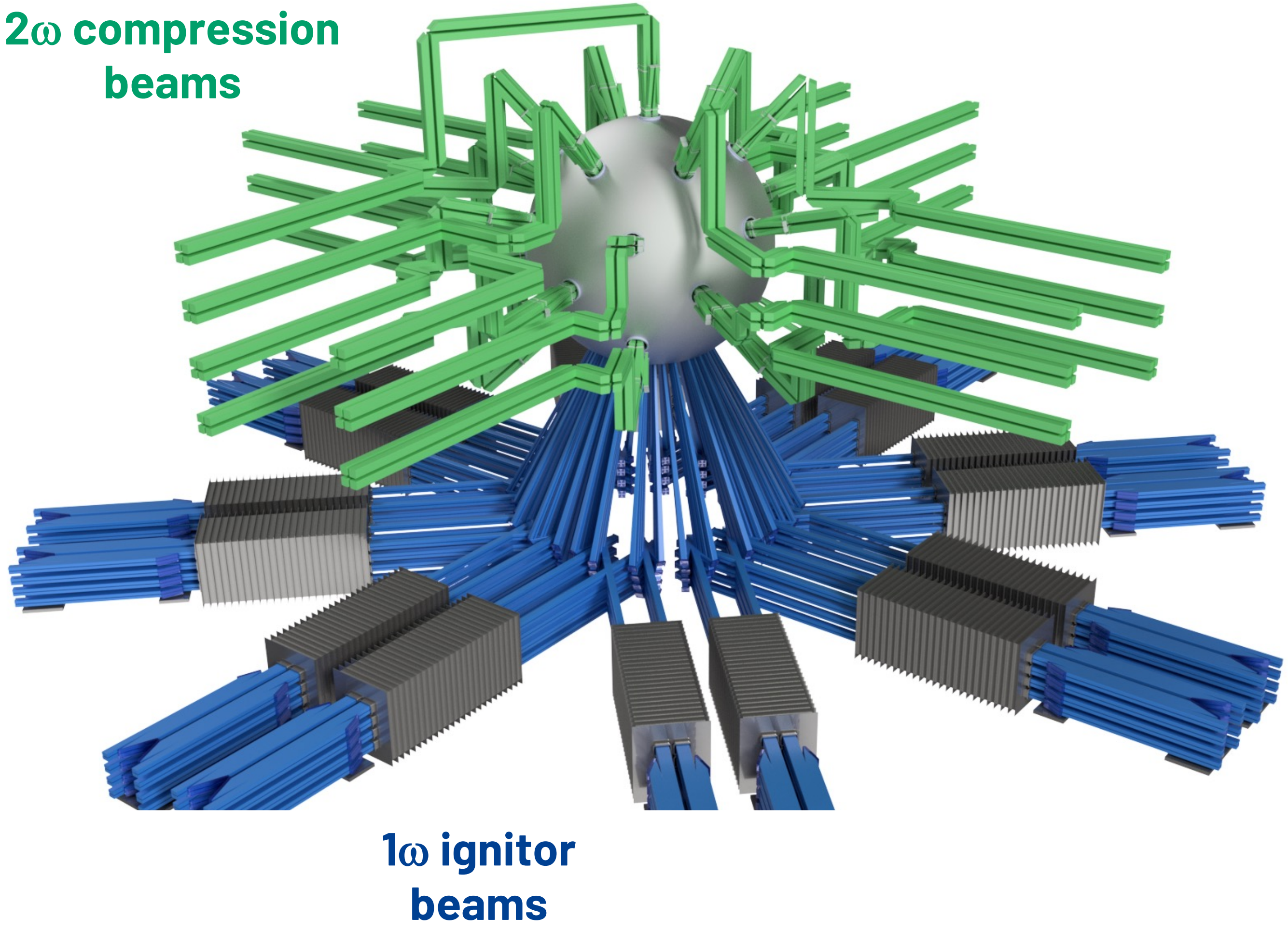
Compression (1–3) **Heating** (4–5) **Ignition** (6)



- Two sets of lasers are needed with different requirements for compression and heating
- Physics of compression and ignition largely understood, but needs verifying at scale

**M. Roth et al., Phys. Rev. Lett. 86, 436 (2001)*

A sub-scale implosion facility will provide a key de-risking step towards a Fusion Power Plant



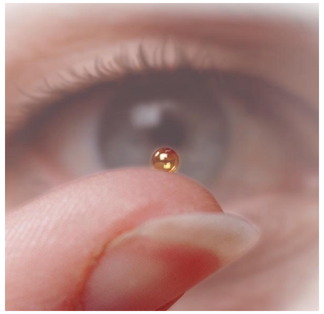
Phase I

- 30 kJ (LP) + 6 kJ (SP) beams based on liquid-cooled flashlamps (shot/5 min)
- DT wetted foam targets
- Capability for 100+ shots/day

Phase II

- Upgrade with additional 30 kJ (LP) + 6 kJ (SP) diode-pumped beams (10 Hz)
- Target injector and tracking, beam steering for 10 Hz operation
- Integrated de-risking at sub-scale

Target physics design

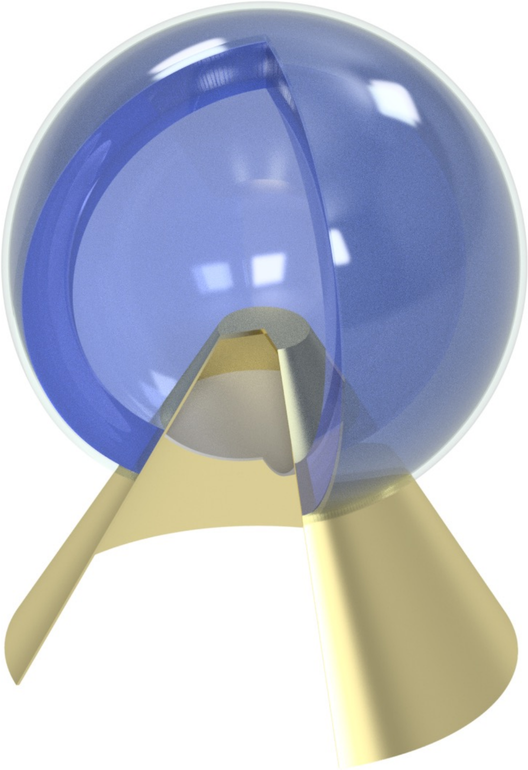


Compression requirements

- 2.5 g DT fuel ⇒ 200 MJ yields
- Laser energy (total) < 2 MJ
- $\rho > 300$ g/cm^3, $\rho R > 2.5$ g/cm^2

Compression design

- CH ablator, DT-wetted foam, with clean inner DT ice or liquid
- $E_{LP} \sim 1.5$ MJ at $\lambda_{LP} = 0.5\mu m$
- 24-48 beam ports
- LPI mitigation techniques
  ⇨ laser and target design



Ignitor requirements*

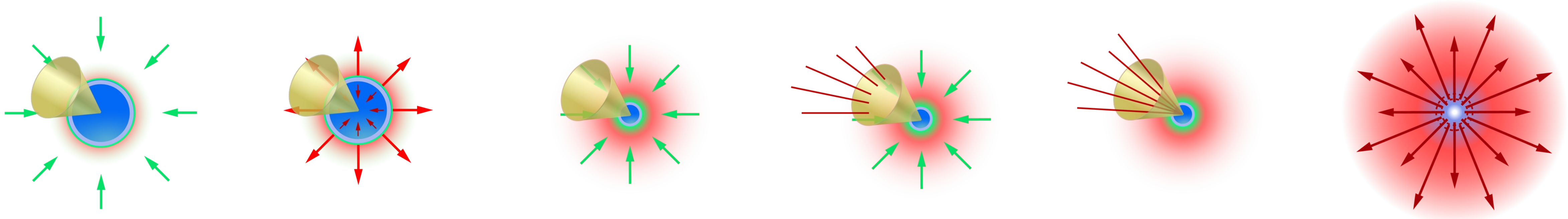
- ~ 20 kJ proton beam energy @T_p~10 MeV
- ~ 20 µm focal radius
- < 20 ps pulse duration

Ignitor design

- Maximise conversion efficiency:
  ⇨ foil composition and dimensions, laser pulse shaping
- Maximise focusability:
  ⇨ foil shape, laser irradiation profile, cone design to tailor E- & B-fields

*Atzeni et al., *Nucl. Fusion* **42**, L1–L4 (2002)

PFI modelling requirements: a fusion Exascale Challenge!



1 Absorption and heat transport

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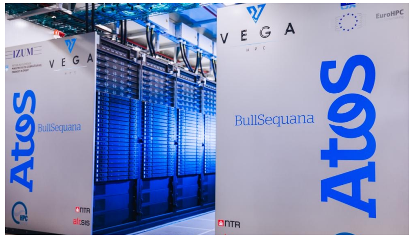
- 1 → 2D/3D wave-fluid & PIC
- 2, 3 → 1D/2D/3D radiation-hydrodynamics
- 4 → 2D/3D particle-in-cell (PIC)
- 5, 6 → 2D/3D hybrid particle transport + rad-hydro

- Length scales: *nanometres -> millimetres*
- Time scales: *femtoseconds -> nanoseconds*

HPC access through GCS and EuroHPC is helping FE to tackle these computational challenges



HPC Vega, IZUM, Maribor

28 M core-hours*

Karolina supercomputer
IT4Innovations, Ostrava

13.4 M core-hours*

GCS
Gauss Centre for Supercomputing

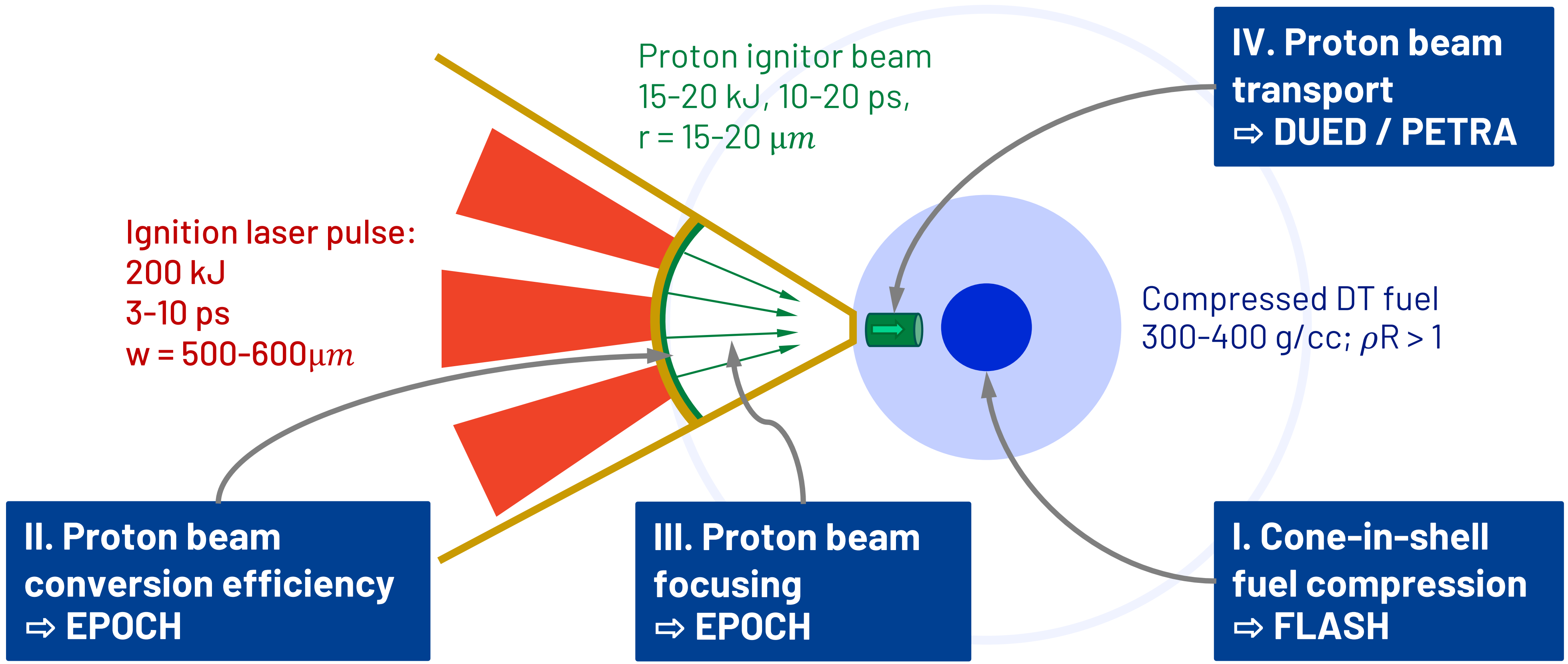
JUWELS, Jülich
Supercomputing Centre

15 M core-hours

**EuroHPC* Joint Undertaking

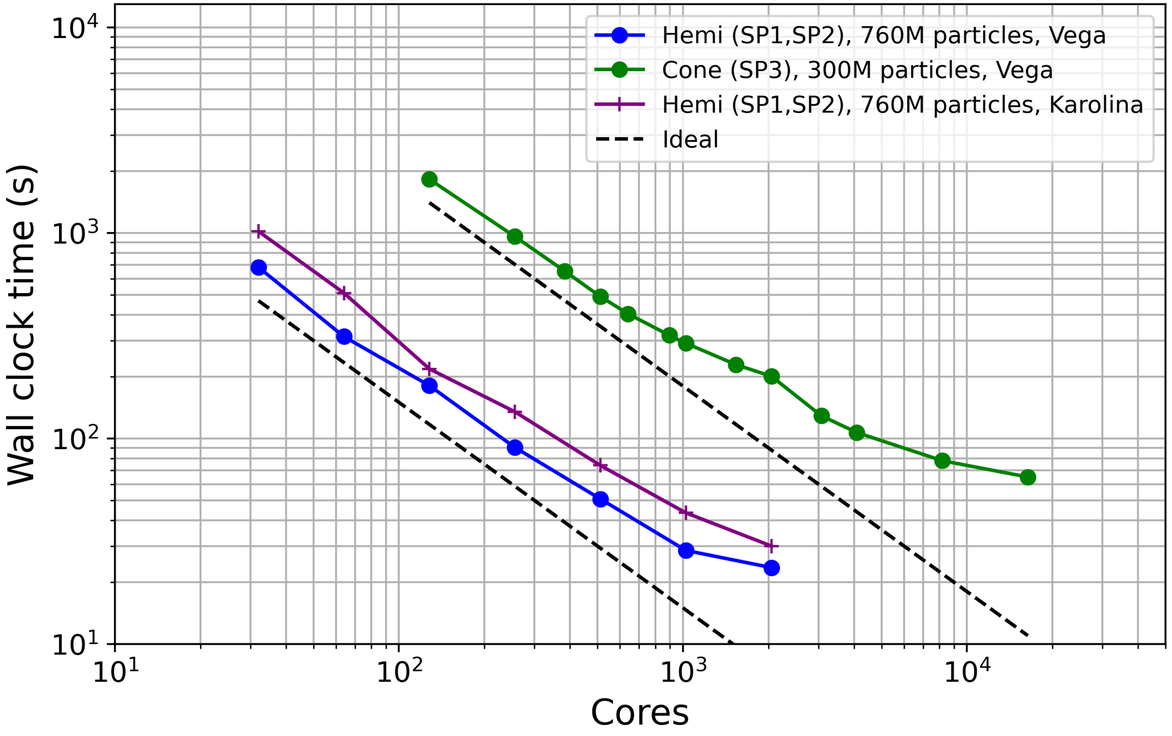
EuroHPC project: EHPC-REG-2023R01-043

EuroHPC & GCS projects: compression symmetry and physics of proton ignitor beam generation

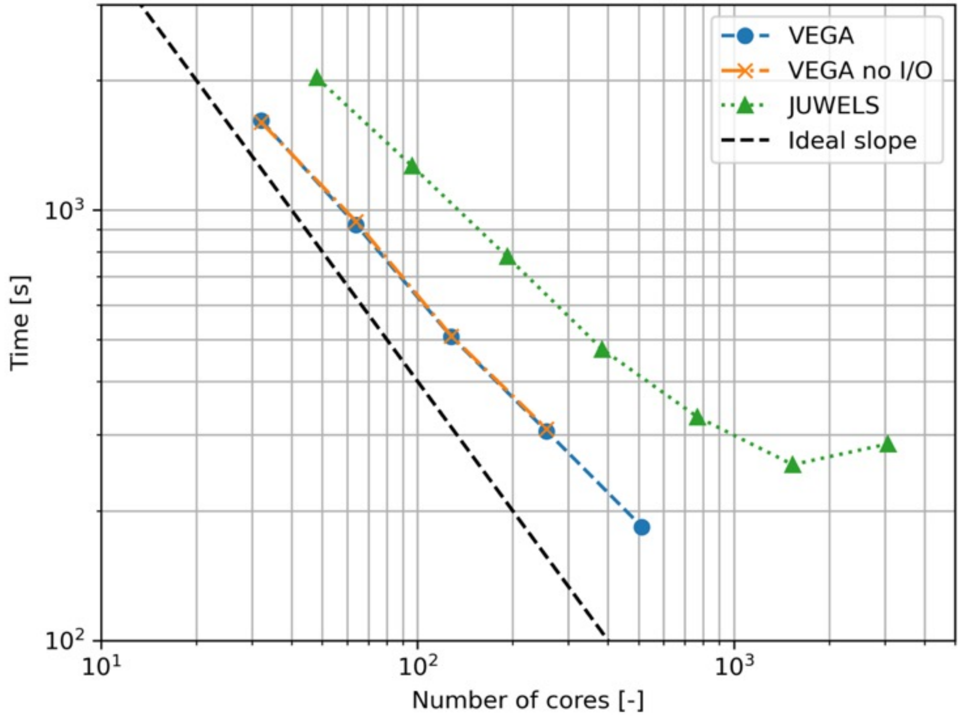


Performance of EPOCH and FLASH codes on Vega & Karolina

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



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



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

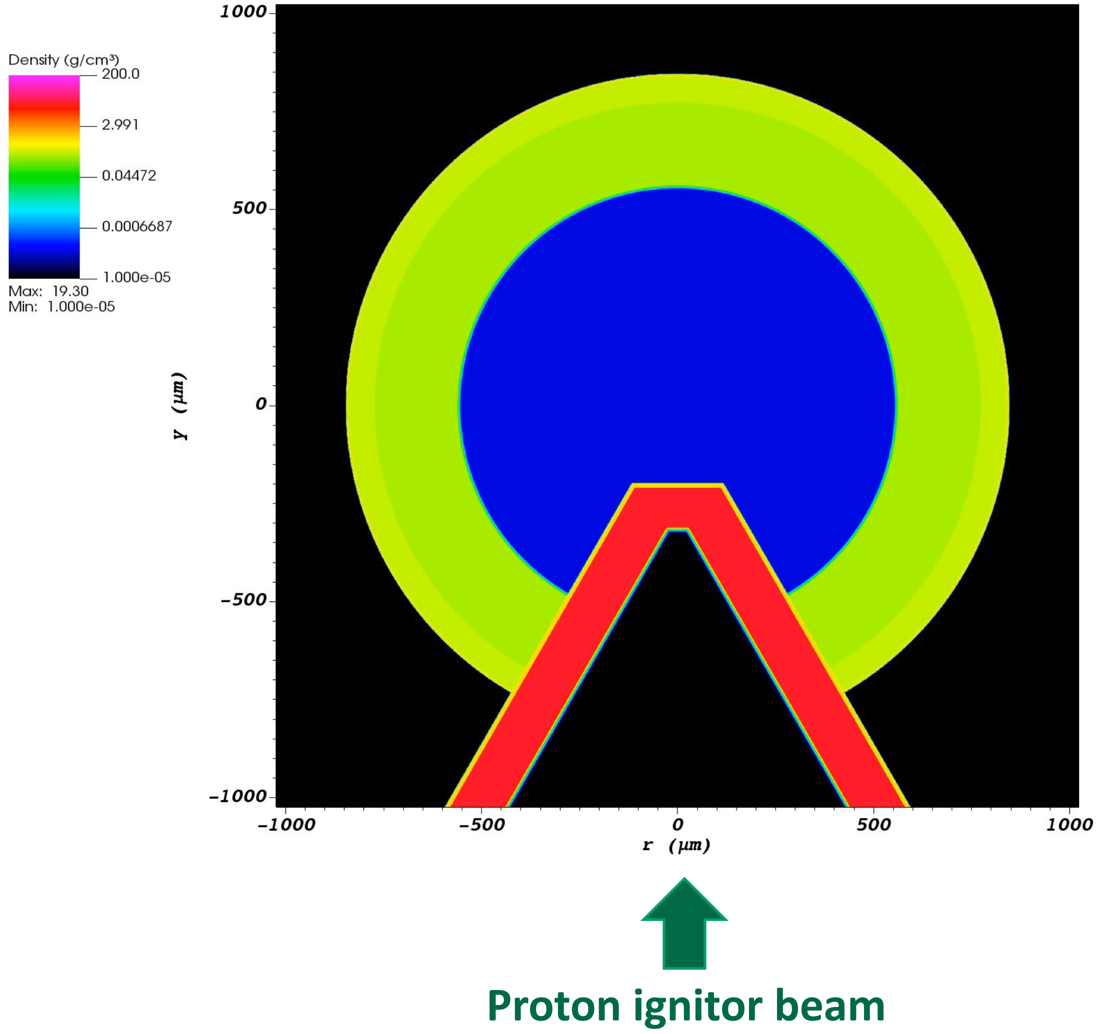
Alfonso Mateo Aguaron, Javier Honrubia (UP Madrid & FE)

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 EOS to avoid negative pressures etc.
- smoothing across material interfaces
- calibration of shock wave propagation via cross-code benchmarking with MULTI-IFE and DUED



II. Proton beam conversion efficiency (CE) modelling

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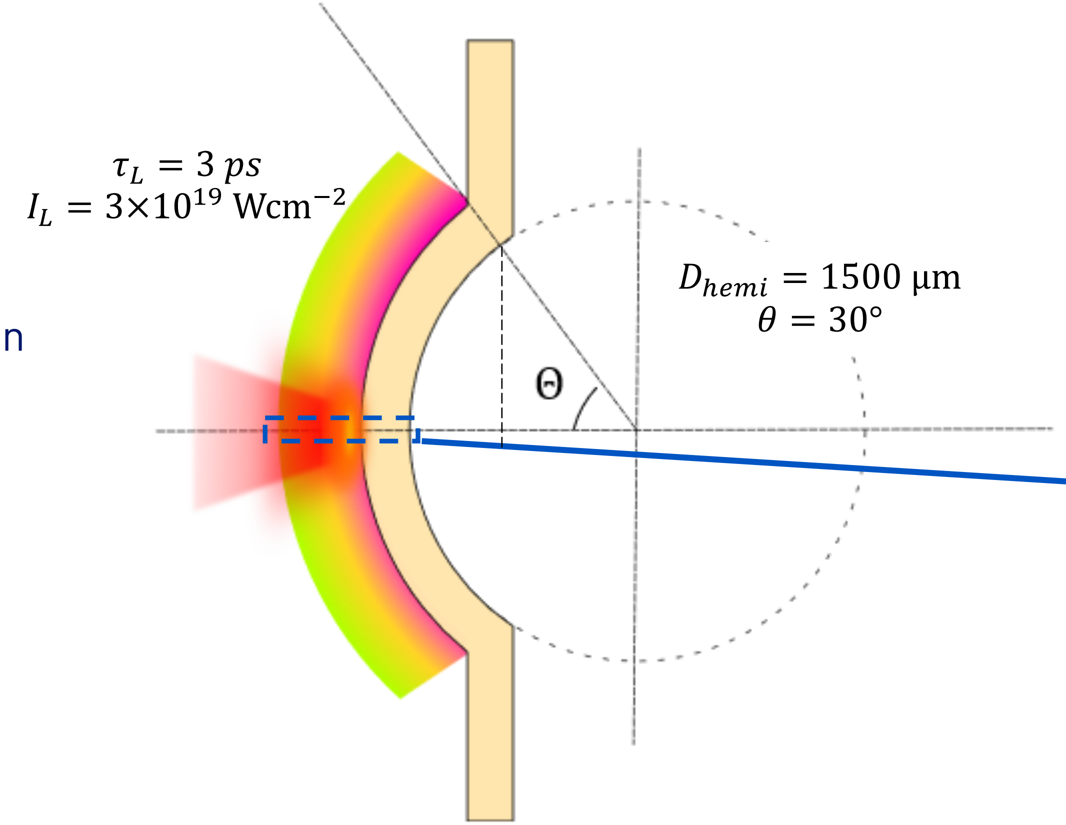
Valeria Ospina-Bohorquez

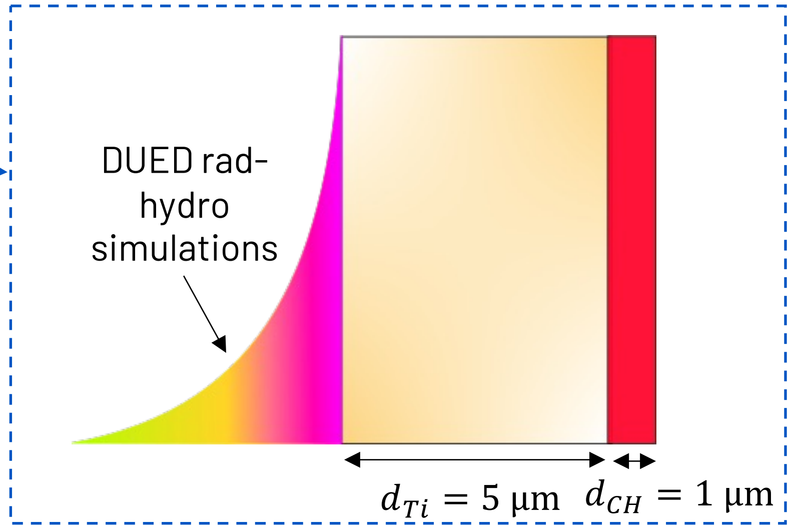
Laser parameters:

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



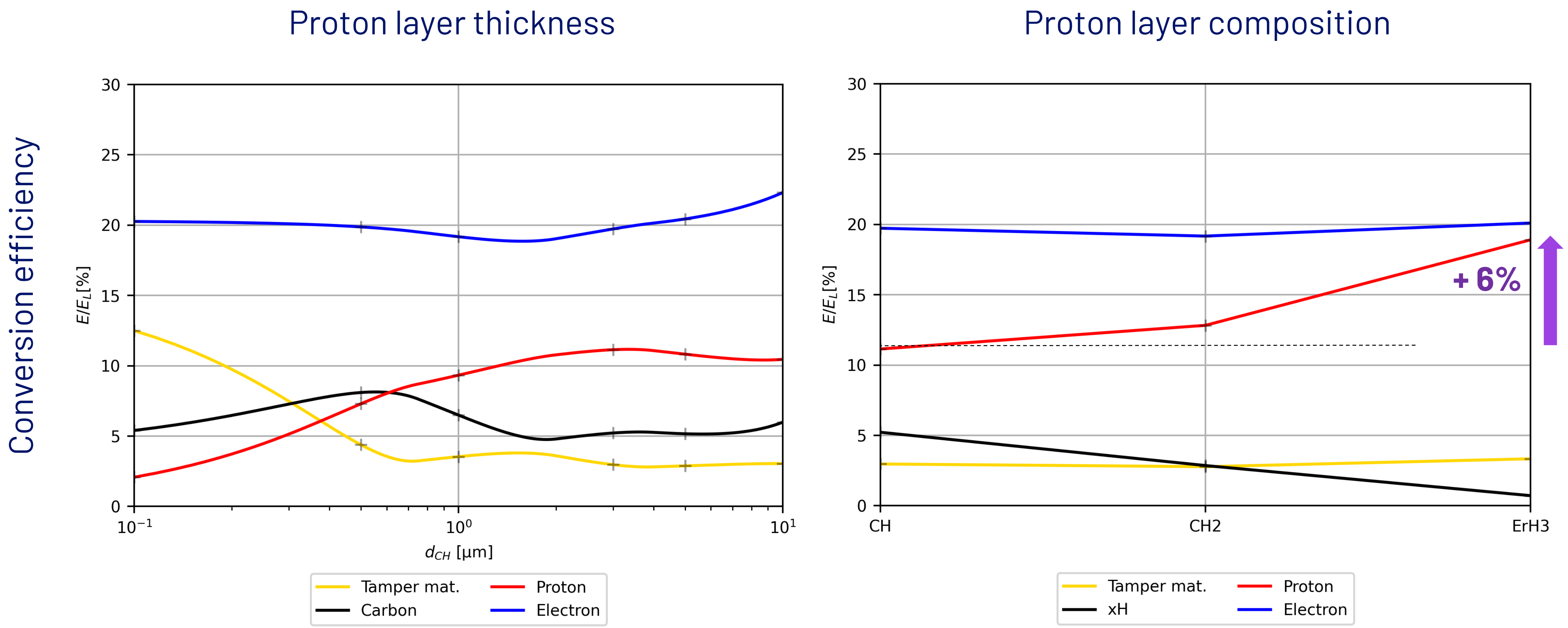
Target parameters:

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



*M.E. Foord et al., J. Appl. Phys. **103** 056106 (2008)

Parametric scans of CE with 1D surrogate PIC model



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

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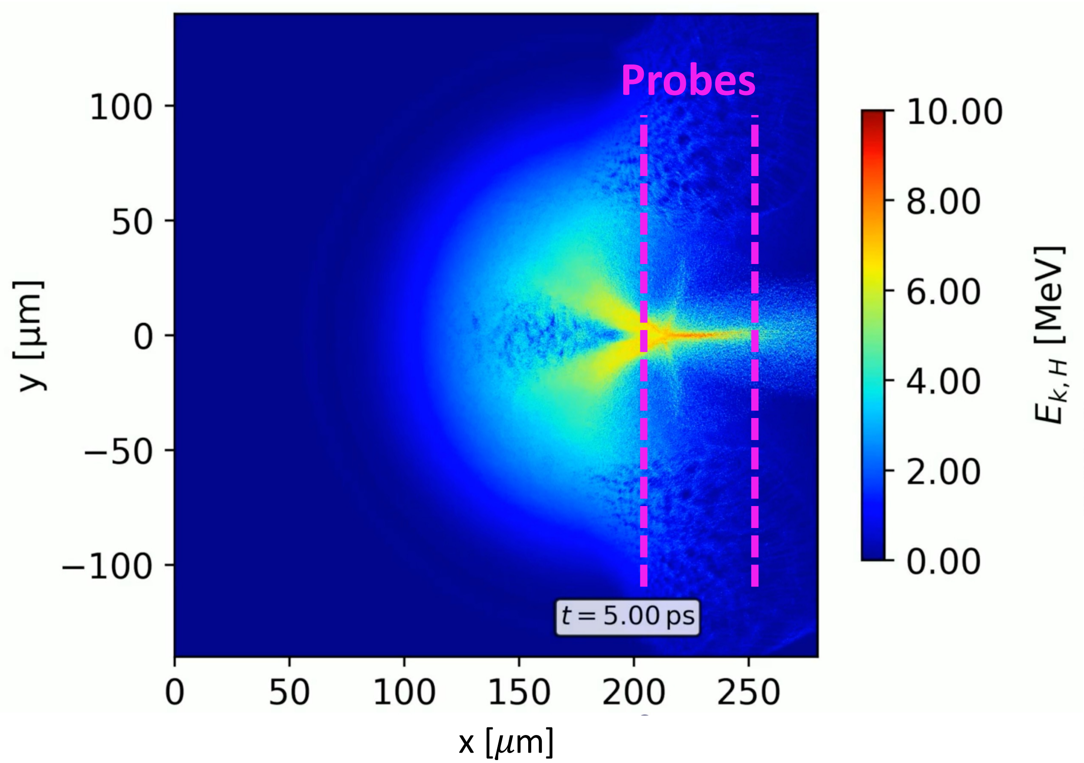
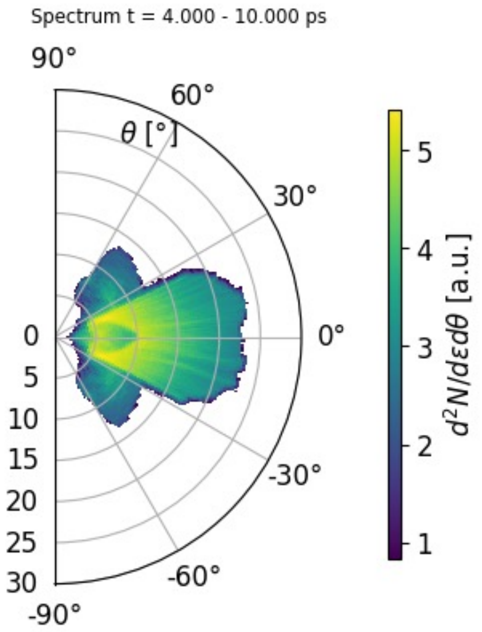
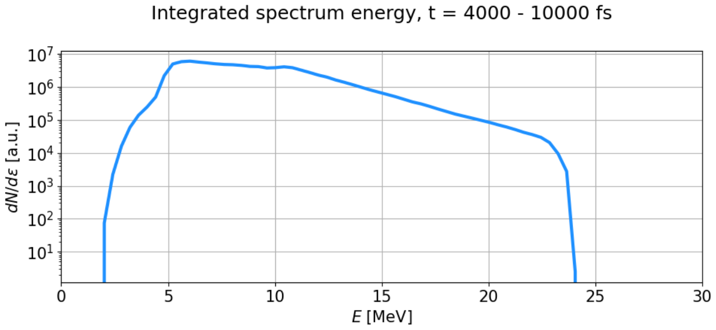
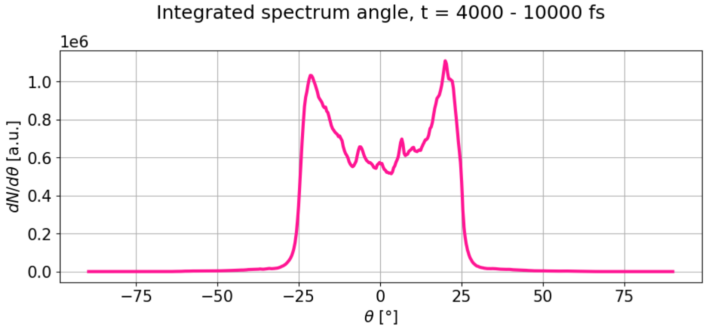
2-D simulations with diagnostic probes to characterize proton beam





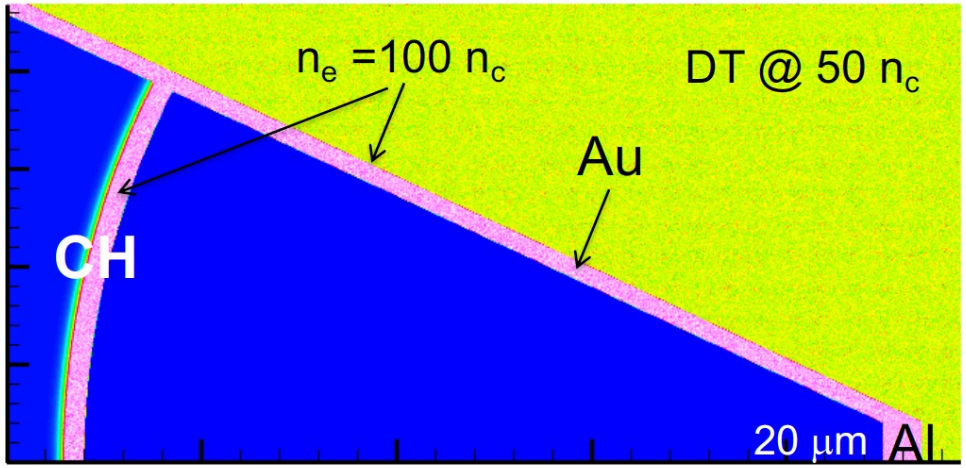


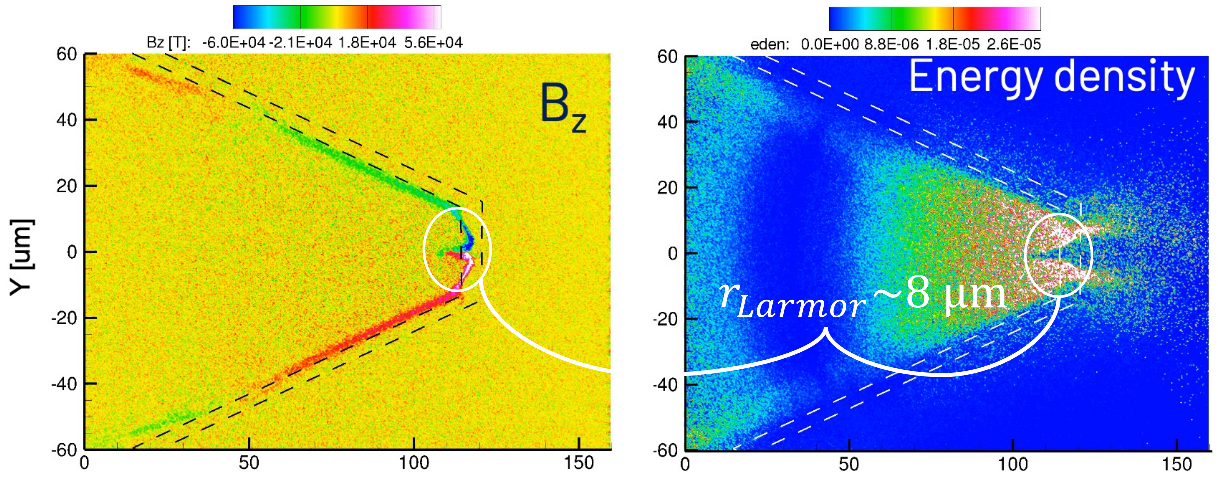


- Experimental campaign on proton focusing planned in spring 2024 at Colorado State University (LaserNetUS Program)

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-scale targets

Novel features:

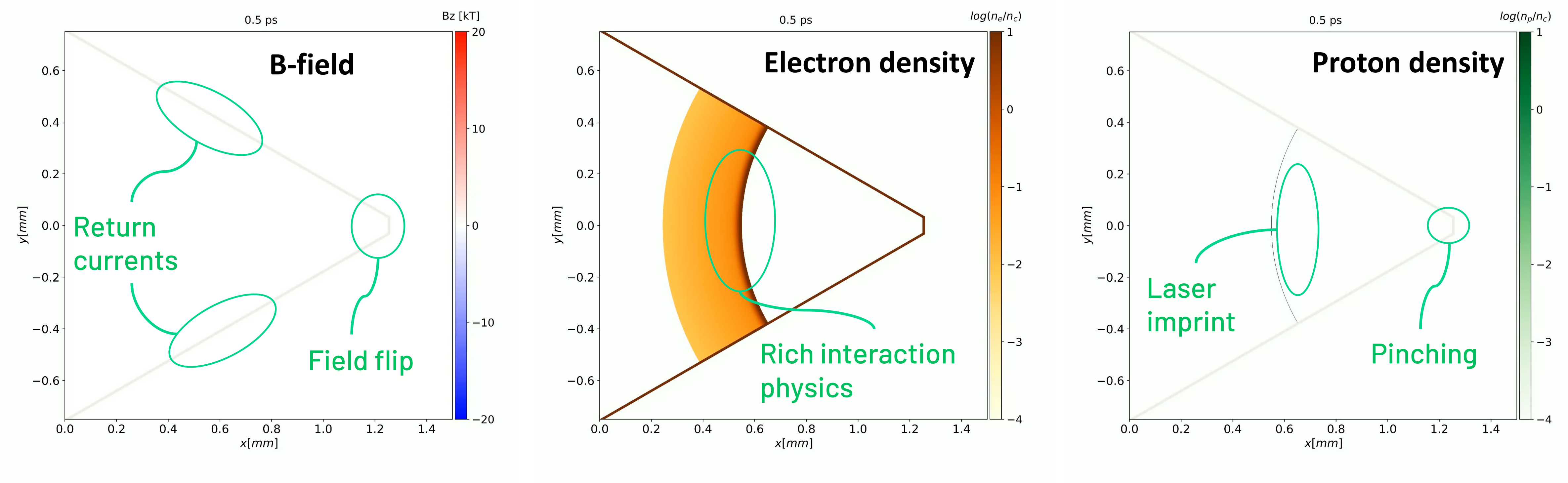
- Multi-beam laser irradiation in mm-scale cone geometry:
  5 x $I_L = 3.0 \times 10^{19}$ Wcm^{-2}; $\lambda = 1\ \mu m$; τ_L = 3ps; $\sigma_{FW} = 100\ \mu m$
- Utilize 'best of' parametric target scans: rad-hydro computed pre-plasma, laser profile, foil composition & dimensions

Numerics:

- 30k x 30k = 9 x 10^8 grid points; $\Delta x = \lambda_L/20$
- 2 x 10^9 particles
- 36h on 3k cores of Vega

Future refinements:

- collisions, ionization, wall isolation, 3D!



IV. Heating of imploded fuel capsule: ignition threshold

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Stefano Atzeni

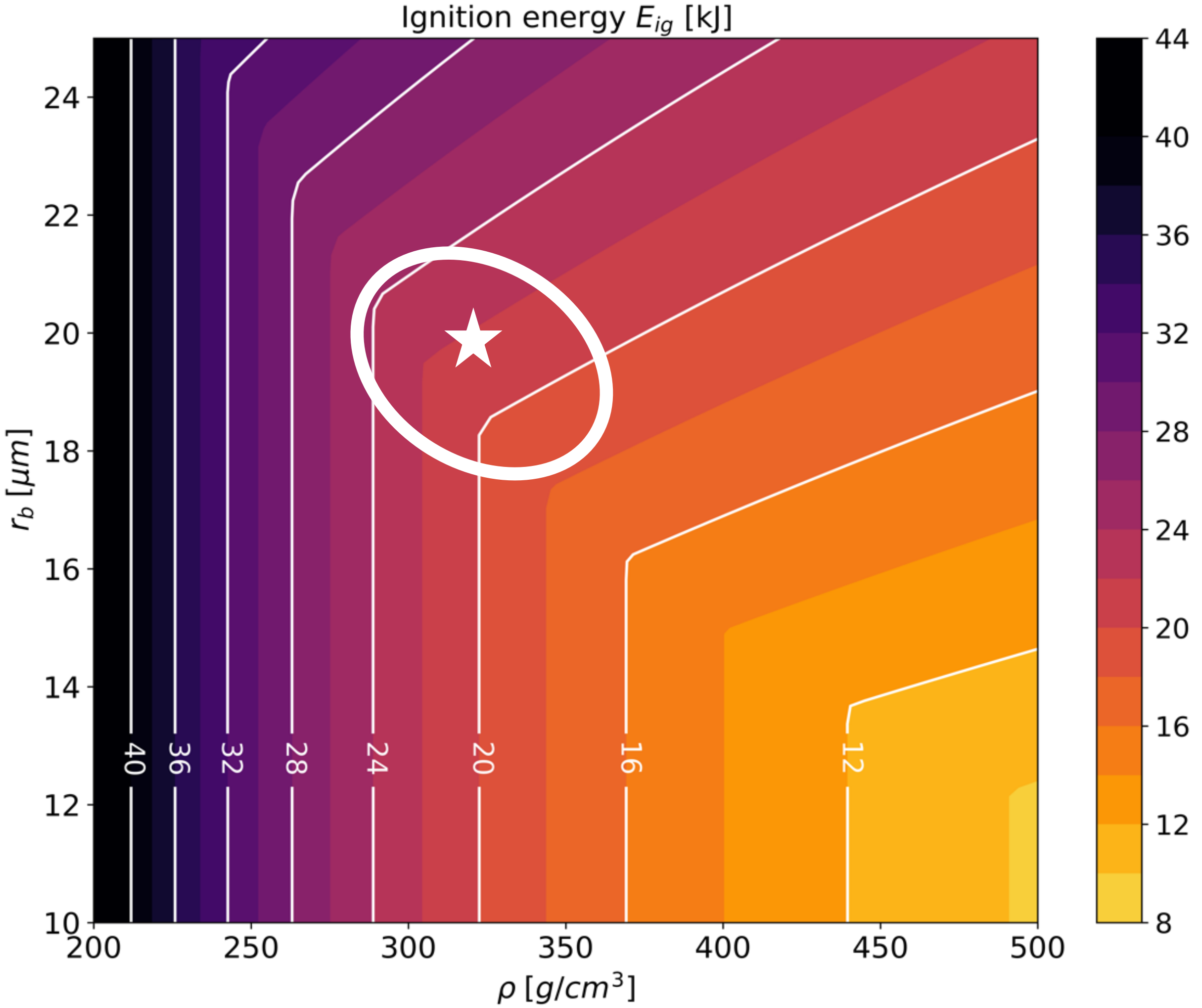
Empirical scaling*:

DT fuel density — Proton beam radius

$$E_{ig}^{*}[\text{kJ}] \approx 25.3 \left(\frac{\rho}{300\ \text{g/cc}}\right)^{-1.65} \times \max\left(0.9; \frac{r_b}{1.1 r_{opt}}\right)^{1.1}$$

with $r_{opt} \approx 20 \left(\frac{\rho}{300\ \text{g/cc}}\right)^{-0.97}$

- Determined from many 100s of transport calculations using hybrid radiation-hydro code DUED



*revised from: Atzeni et al., Nucl. Fusion **42**, L1–L4 (2002)

Proton beam divergence leads to higher ignition threshold

Javier Honrubia

PETRA hybrid code*:

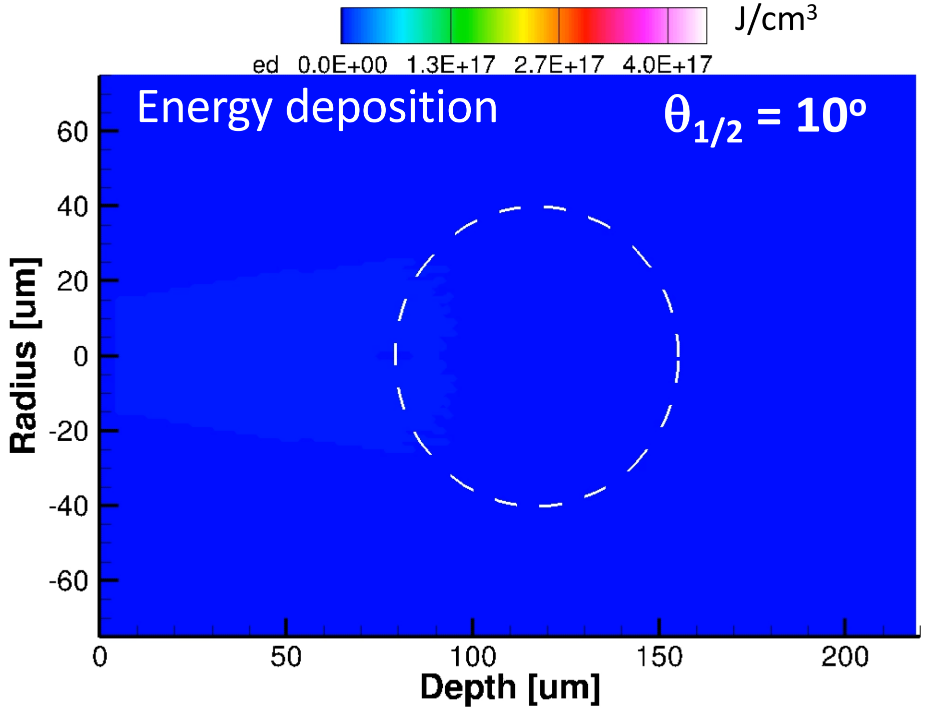
TNSA proton beam with T_p = 5 MeV transported into **imploded DT**

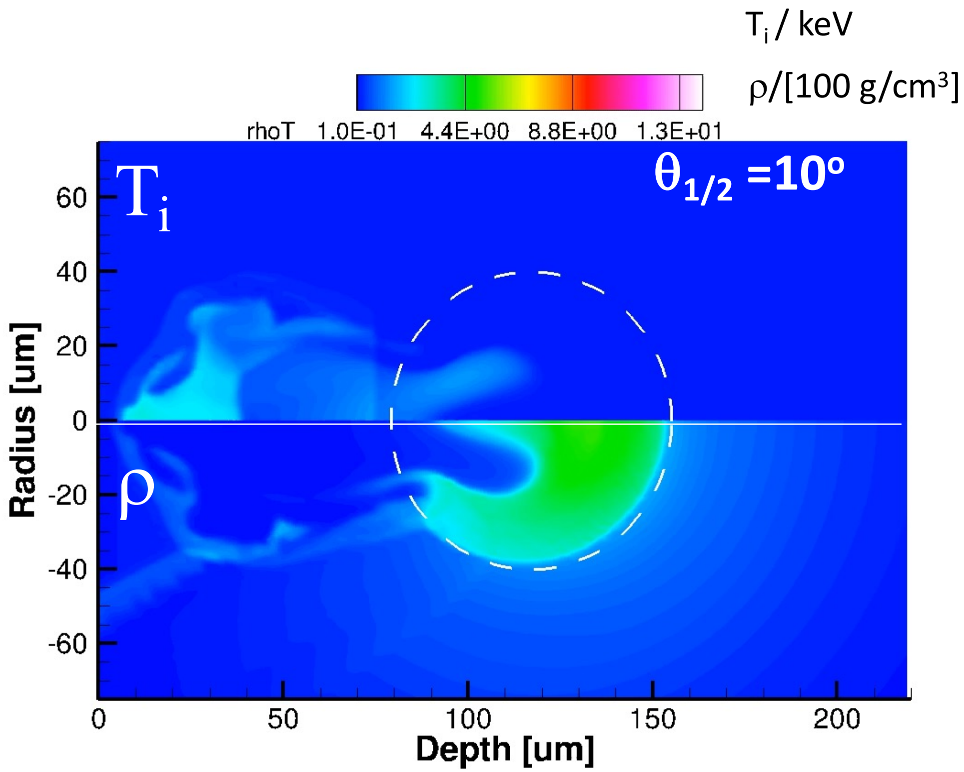
ρ_{max} = 512 g/cm^3

standoff distance = 1 mm

E_{ig} = 18 kJ , $\theta_{1/2}$ = 0°

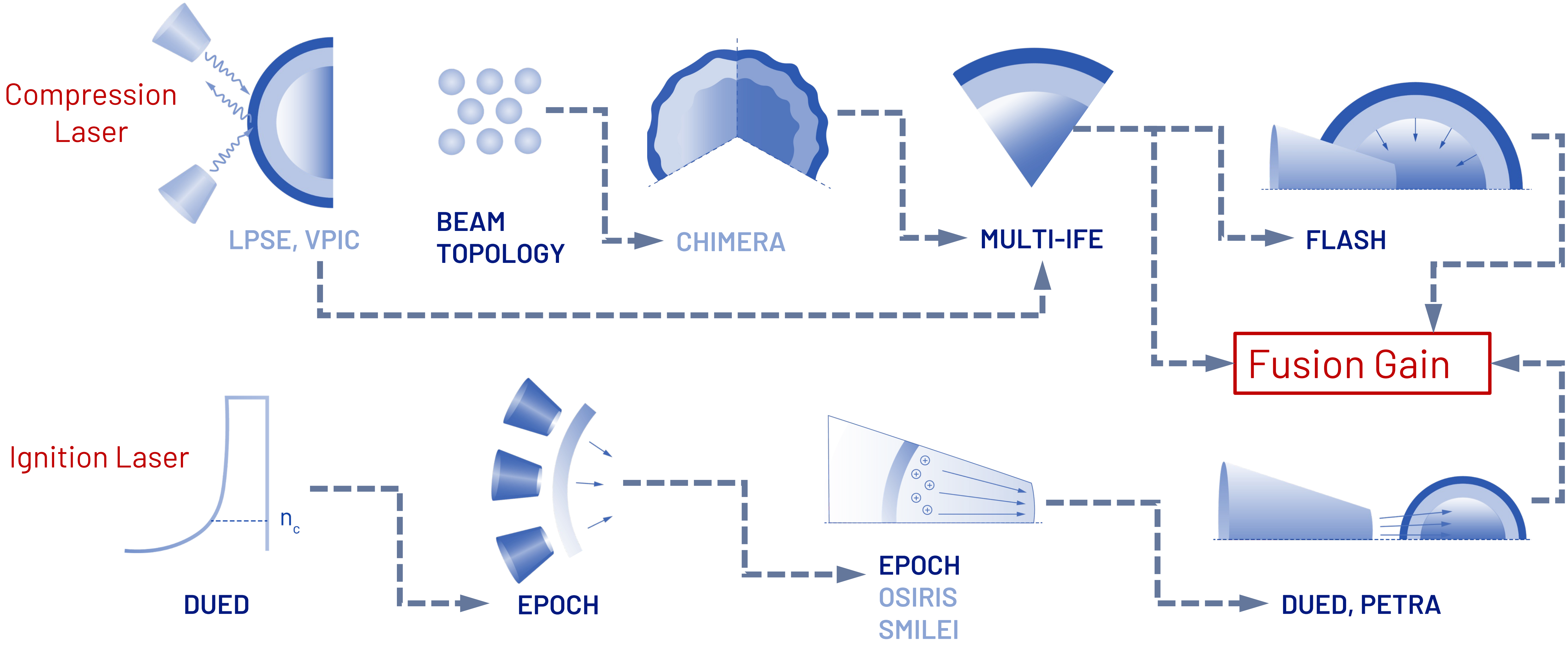
E_{ig} = 27 kJ , $\theta_{1/2}$ = 10°





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

Towards an integrated PFI model framework



- FE/Open code
- Cooperation

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Summary

- **Early progress on key open physics questions of Proton Fast Ignition:**
  - Isochoric compression of DT fuel capsule with inserted cone
  - Strategies identified for optimal proton beam conversion efficiency
  - Proton beam focusing in full-scale cone targets: control of return currents
  - Heating and ignition of compressed DT fuel: sensitivity to beam properties

- (Pre-) exascale computing resources (100s of millions of core-h) 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 computing time project award ***EHPC-REG-2023R01-043*** hosted by VEGA, Maribor and KAROLINA, Ostrava

Gauss Centre for Supercomputing for computing time on JUWELS (Jülich Supercomputing Centre) under the project **PROFIS**

and

The Focused Energy Science Team:
J. J. Honrubia, V. Ospina-Bohorquez, A. Mateo-Aguaron, S. Atzeni, M. Brönner, L. Savino, X. Vaisseau, D. Callahan, W. Theobald, P. Patel, M. Roth