SAPIENZA
UNIVERSITÀ DI ROMA

SBAI

A GPU based raytracing algorithm for DUED code

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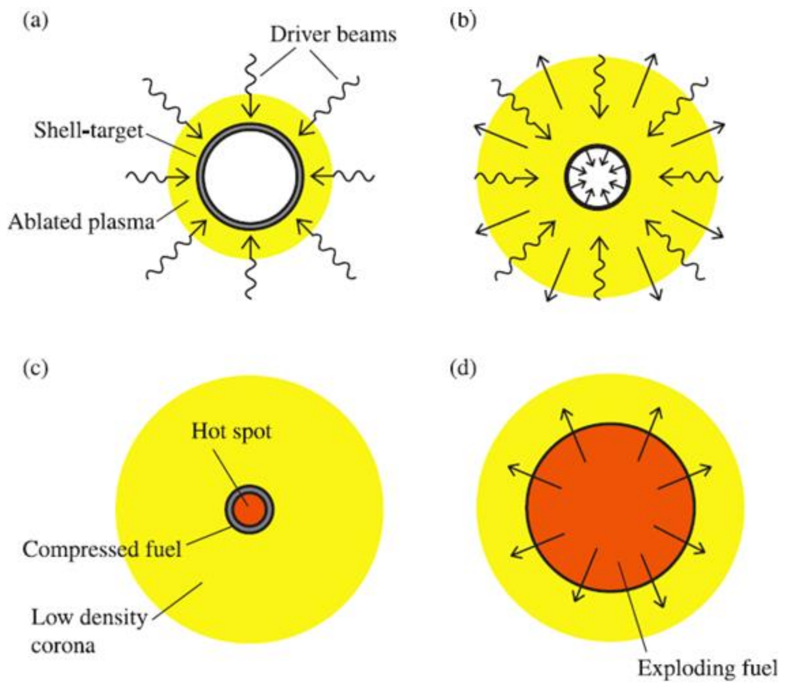
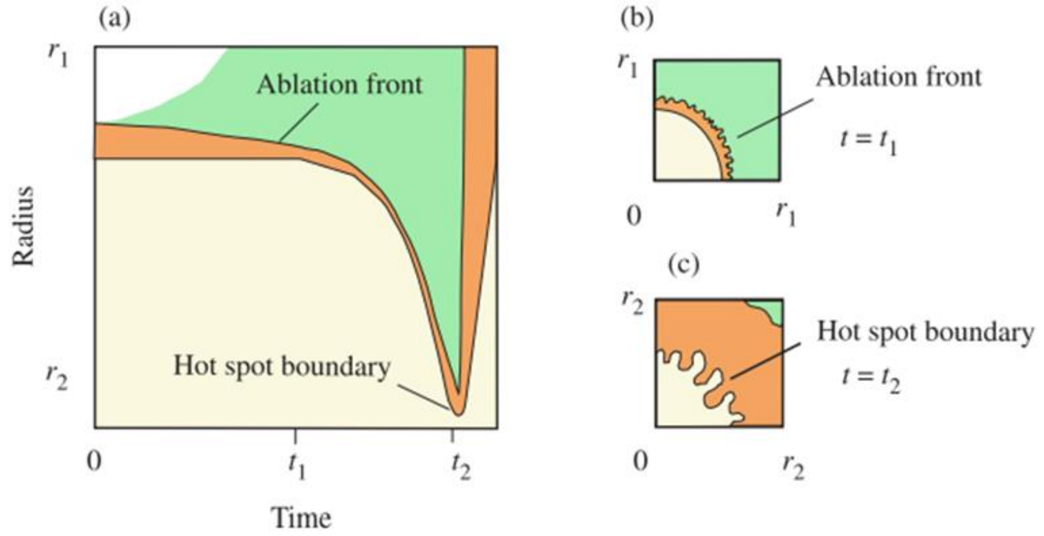
1.INTRODUCTION

[1.0] Laser-driven Inertial confinement fusion (ICF)



Four main stages:

a) Irradiation
b) Implosion driven by ablation
c) Ignition
d) Burn and explosion



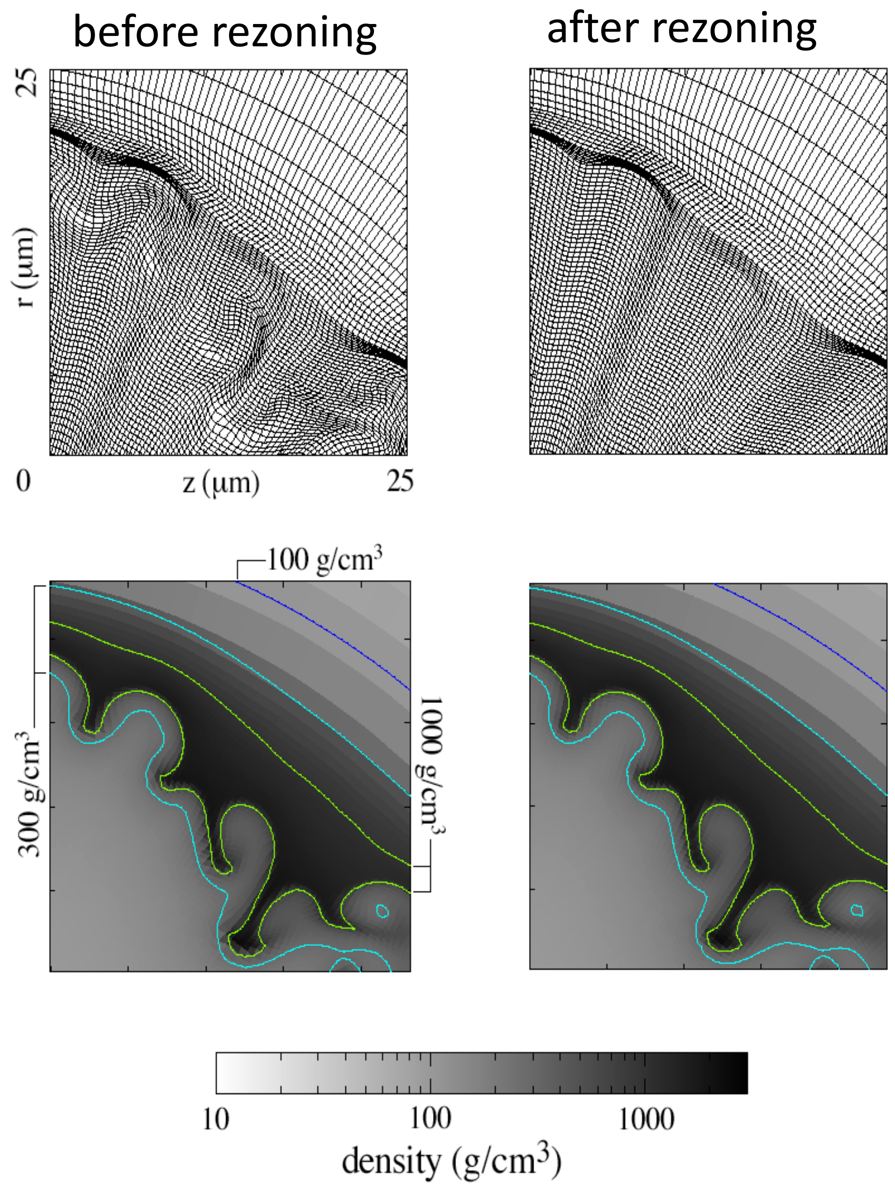
A great number of problems degrade the performance of ignition:

- Non-uniform irradiation
- Large hotspot area
- Irregular conversion of kinetic energy into internal energy

Rayleigh-Taylor instabilities

[1.1] DUED CODE

- 2D Lagrangean fluid scheme + rezoning
- 2 – temperature fluid model (ions and electrons)
- real matter equation of state
- collisional transport (flux limited conductivity, e-i exchange, viscosity (in 1D only); option for nonloncal e-transport)
- multigroup radiation diffusion with LTE (or non-LTE) opacities
- laser–plasma interaction: 1D or 2D or **3D raytracing**; inverse-bremsstrahlung absorption
- ion beam–matter interaction (binary collisions, deterministic)
- hot-electron–matter interaction (binary + collective; Monte Carlo)
- thermonuclear fusion reactions
- non-thermal fusion reactions of fusion products T(1 MeV) and 3He (0.8 MeV)
  D, T, and 3He scattered by neutrons
- fuel burn-up (D, T, 3He)
- multi-group (10–100 groups) diffusion of charged fusion products
- neutron transport (Monte Carlo):
  Elastic scattering, (n,2n), 3He(n,p)T, (n,g)
- diffusion of neutron knocked-on ions (several energy groups each)



[1] https://doi.org/10.1016/0010-4655(86)90056-1
[2] https://doi.org/10.1016/j.cpc.2005.03.036

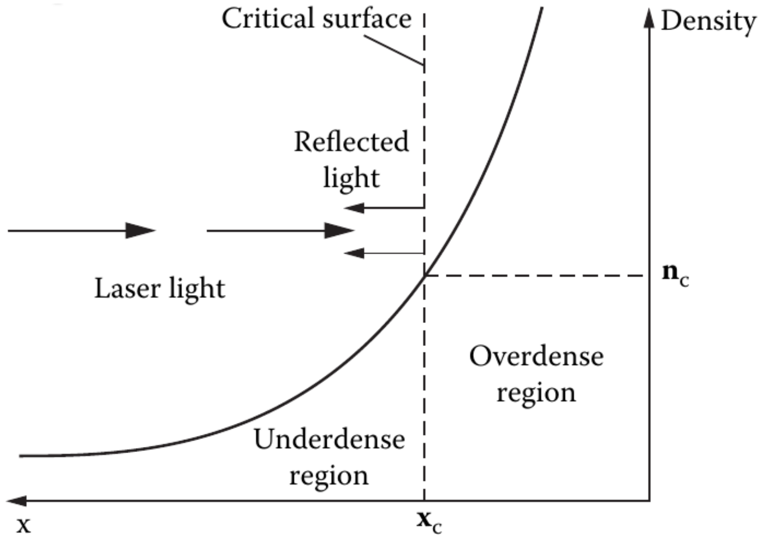
2. RAYTRACING CODE

[2.0] Laser raytracing

The laser light can only penetrate the plasma as long as the electron density is smaller than the critical density given by

$$n_c = \frac{\epsilon_0 m \omega_L^2}{e^2} = 1.1 \times 10^{21} \left(\frac{\lambda_L}{1\mu m}\right)^2 \ [cm^{-3}]$$

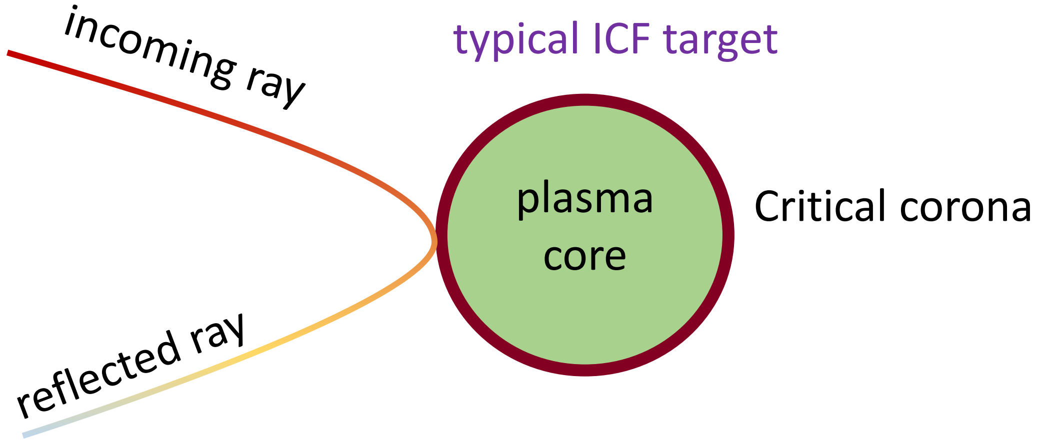
Laser pulses penetrate the plasma corona until they reach a region close to n_c . Absorption, refraction and reflection occur along the ray trajectory.



Using optical geometry approximation, the ray equation is

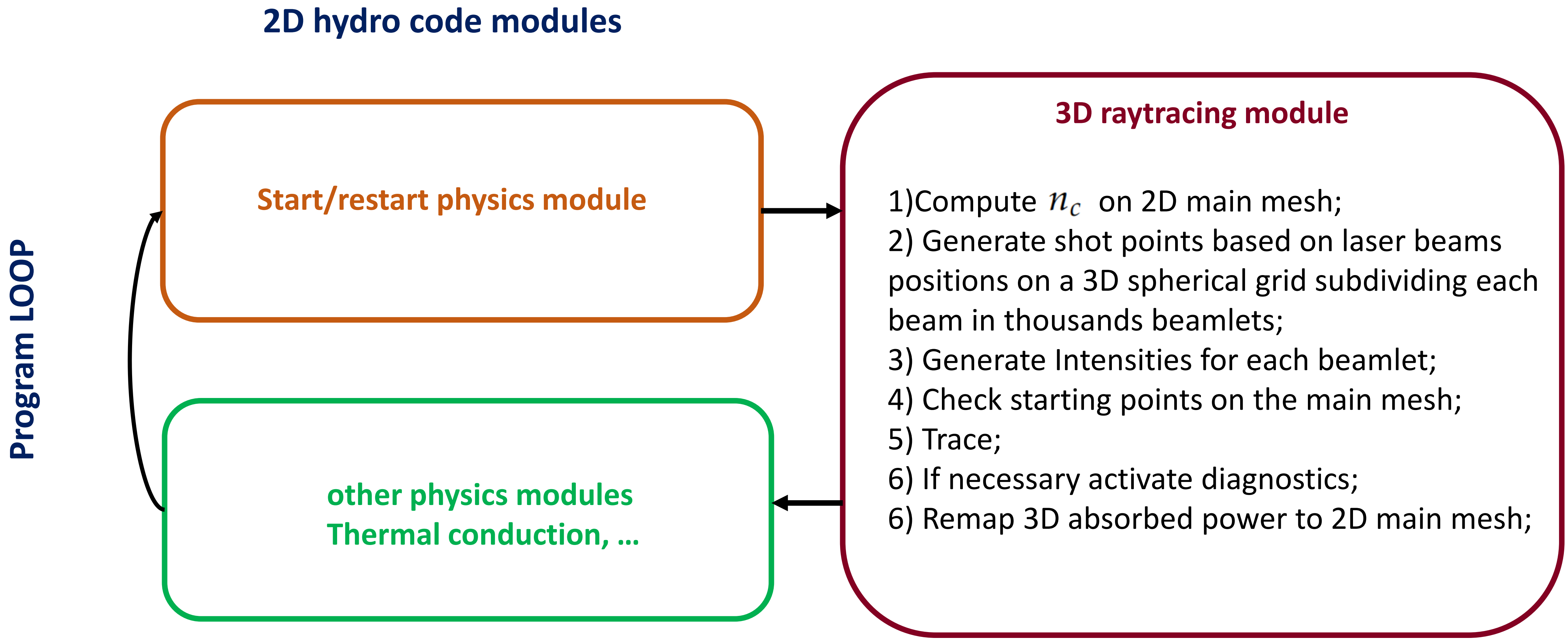
$$\frac{d^2\vec{x}}{dt^2} = \vec{\nabla}\left(-\frac{c^2}{2}\frac{n_e}{n_c}\right)$$

Solution in second order approximation: **Parabolic trajectory** characteristic of a constant force field.



[1]S. Atzeni, The Physics of Inertial Fusion
[2]W. Kruer, The Physics Of Laser Plasma Interactions
[3] S. Pfalzner, An introduction to ICF

[2.1] Main program workflow



[2.2] Our code structure

Given the large number of beamlets to be traced, the use of parallelization techniques was necessary.

Our Goal : Raytracing computational time <= Hydrodynamic computational time

Old version developed in 2010-2012 — Fortran ↔ MPI

New version developed in 2023 — Fortran ↔ C++ [communication wrapper] ↔ OpenCL™ [targeting GPUs]

[1] https://www.khronos.org/opencl/

3. CODE FEATURES

[3.0] Features: Beam static sampling

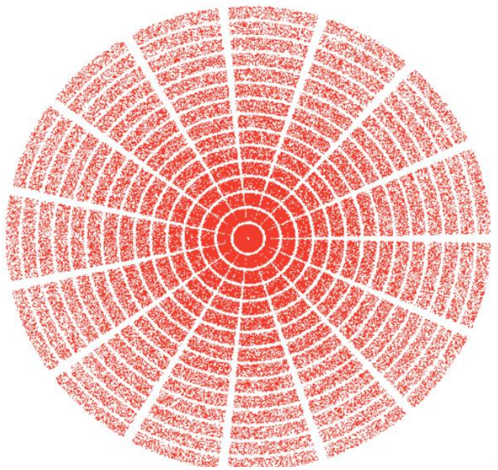
Each beam is subdivided in a large number of beamlets organized in sectors. The number of total beamlets is determined by the number of sectors.

$$Sectors = N\phi \times N\theta$$

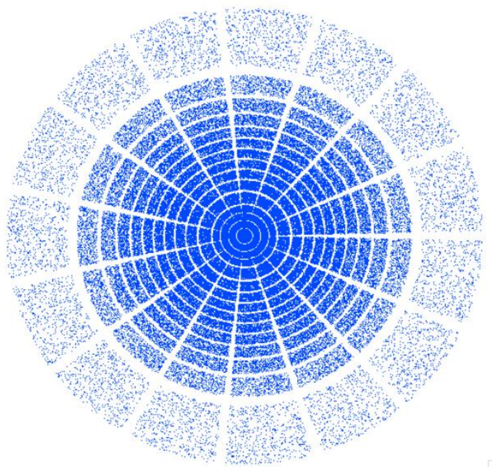
Spatial intensity distribution of each beamlet is given by

$$I(r) = I_0\, e^{-\left(\frac{r}{w}\right)^m}$$

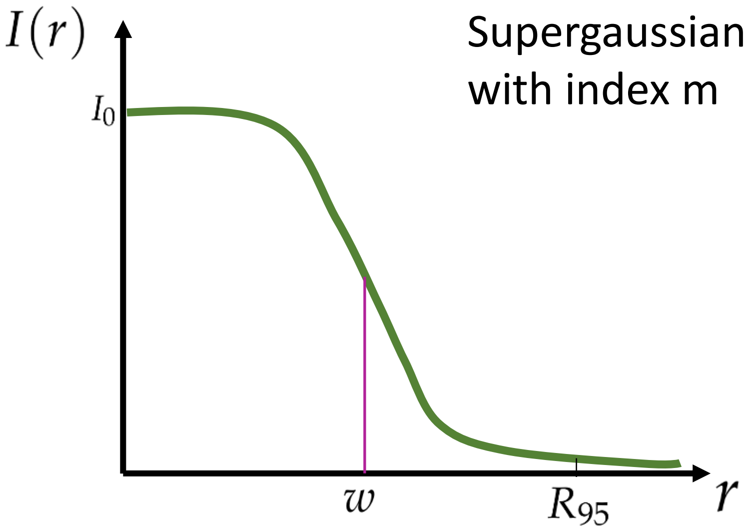
Uniform along r



Using CDF along r



One ray per sector

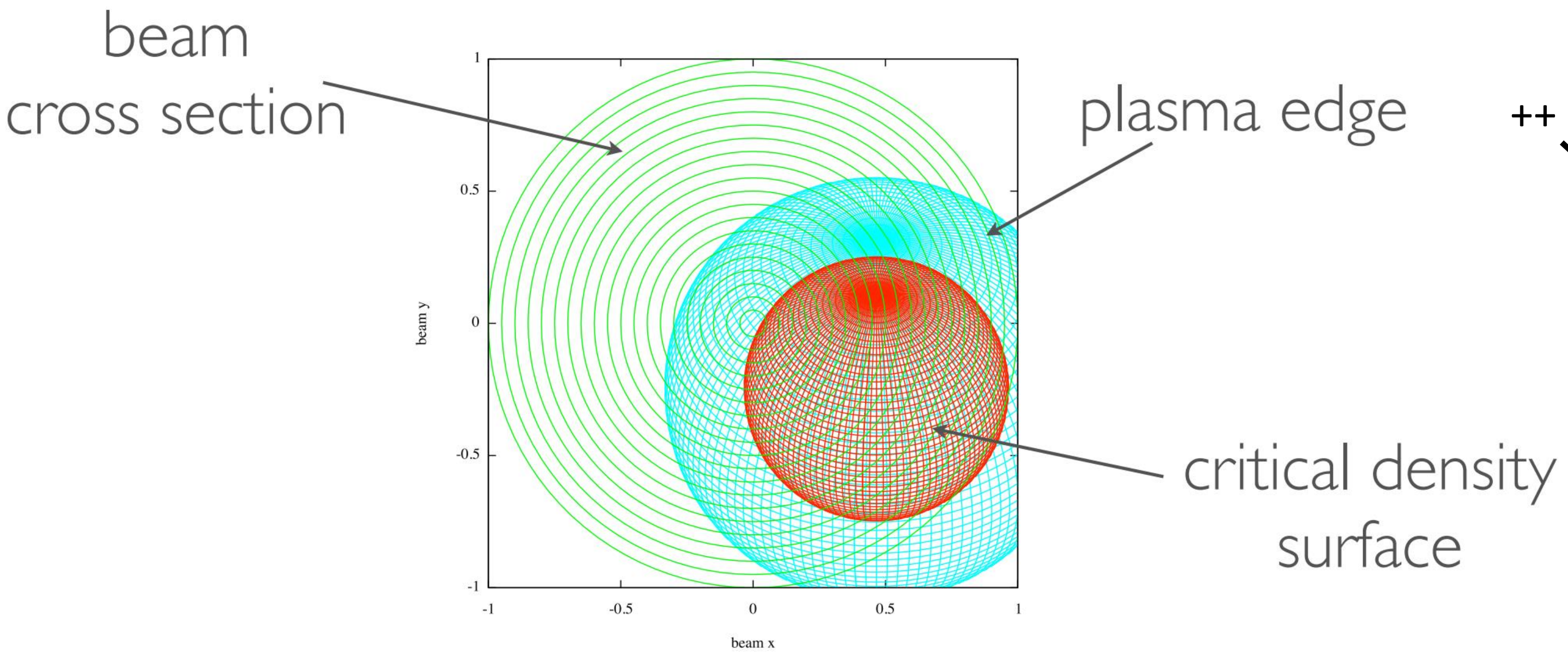


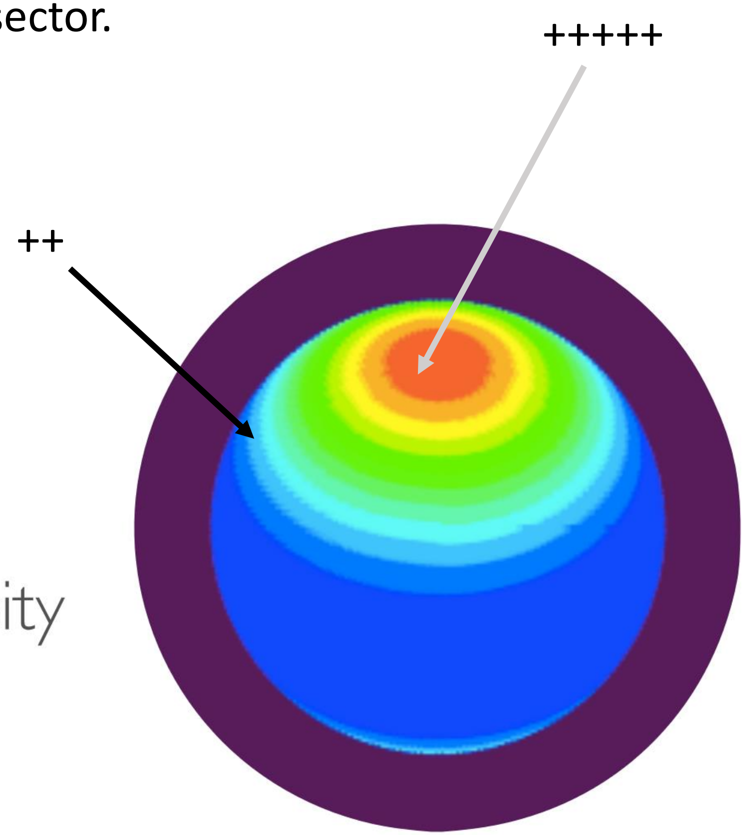
Supergaussian with index m

[3.1] Features: Beam dynamic sampling (Oversampling)

During compression/expansion of the target the critical region compresses/expands. We need to increase beam sampling inside the plasma and close to the critical density.

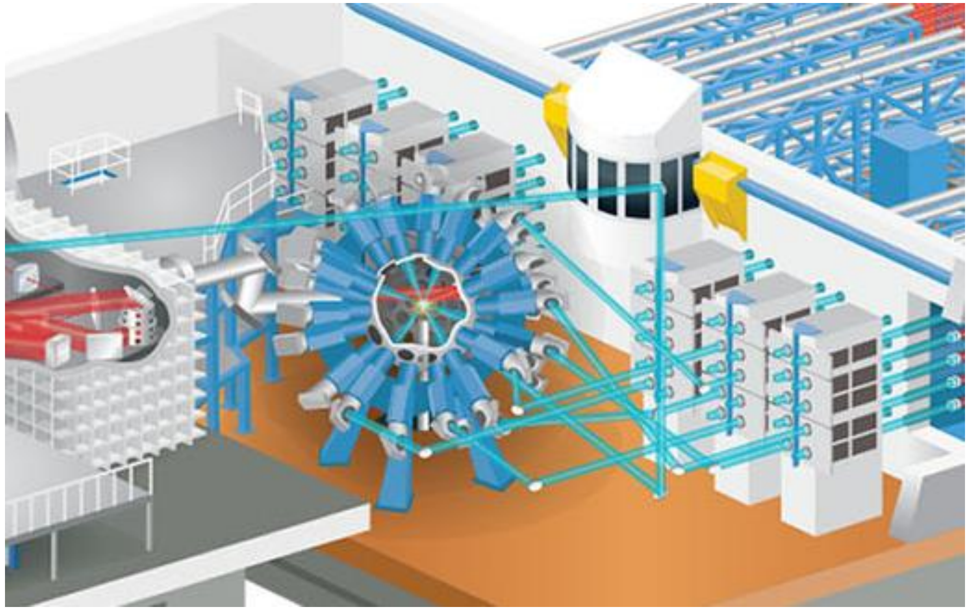
Solution: increase (with a proper function) the number of beamlets in each sector.

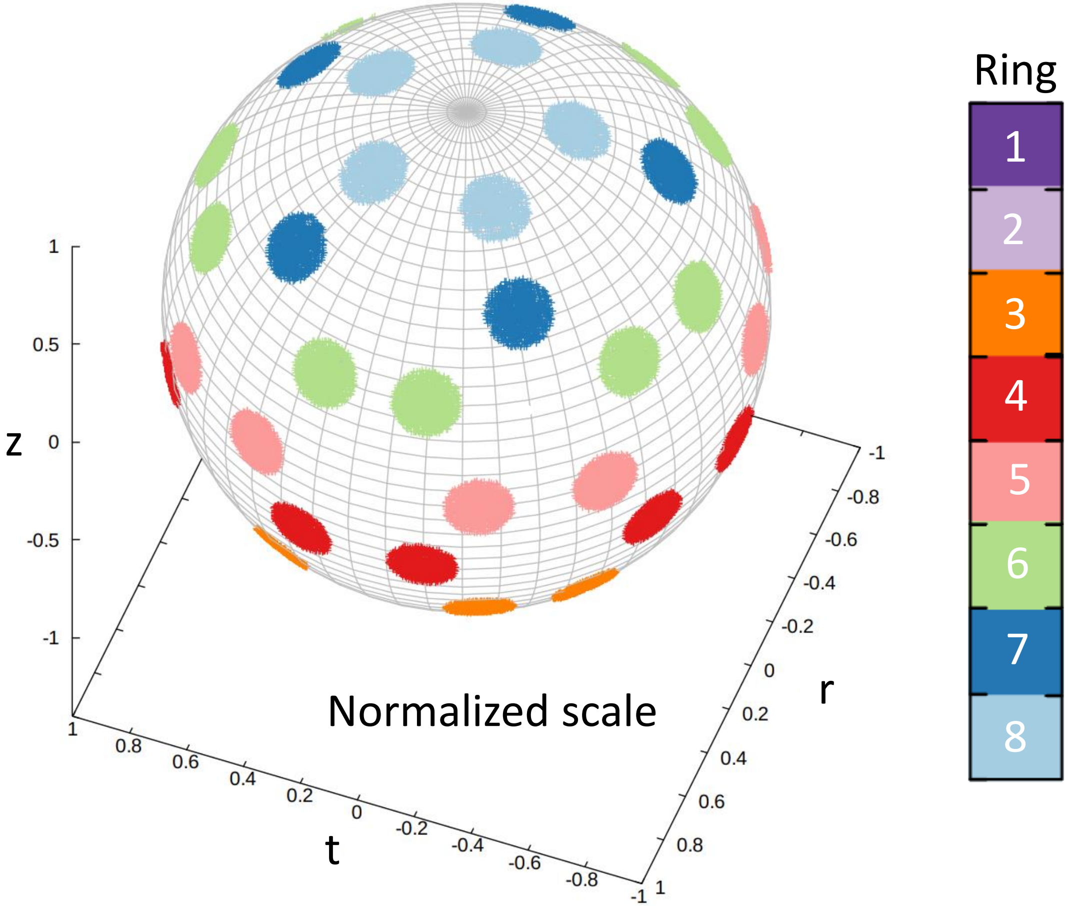




Best combination: CFD+ Oversampling

[3.2] features: full beam pointing (example for Omega laser 60)





Advantages:
- full geometry;
- can apply power imbalances on each beam;
- mispointing.

-Disadvantages:
- complex input;
- big amount of beamlets to be traced.

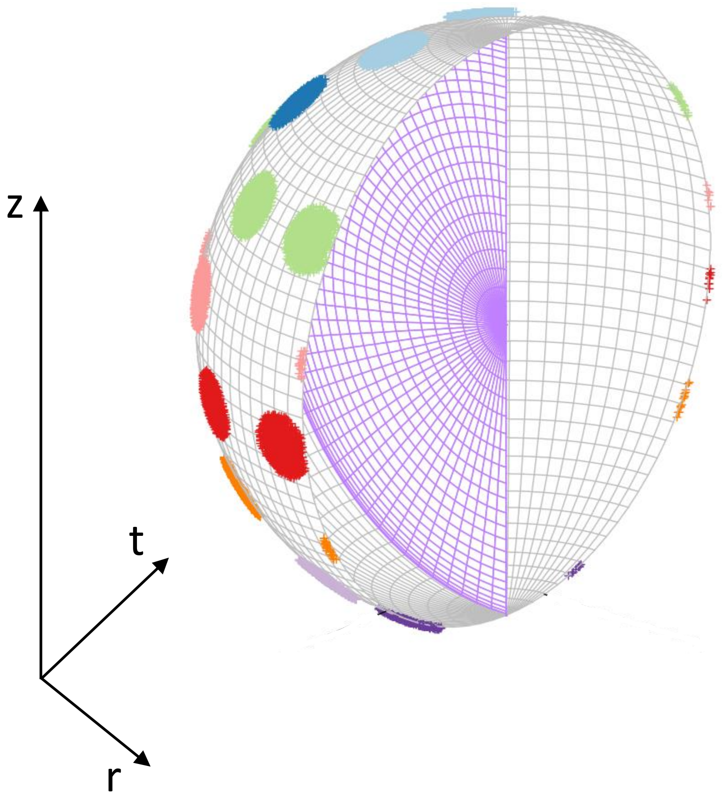
[1] https://www.lle.rochester.edu/omega-laser-facility-2/omega-laser-system/

[3.3] Features: Packing multiple beams

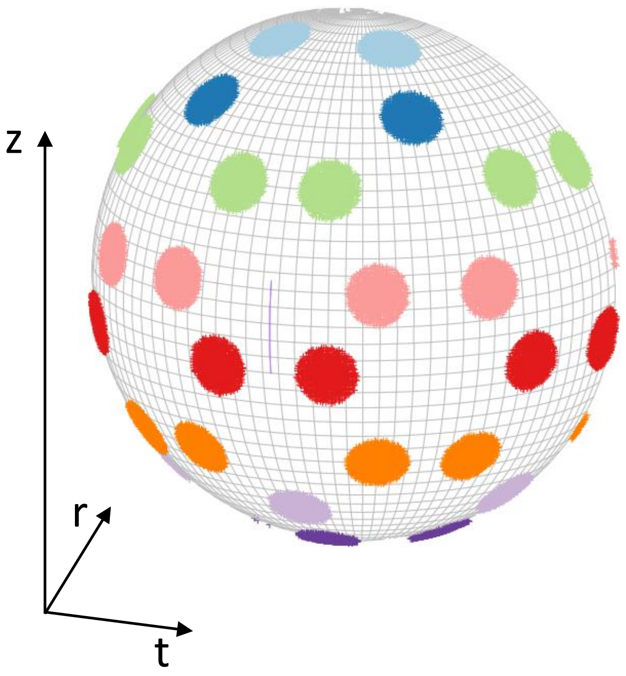
Advantages:
- easy input data;
- good statistics with less number of beamlets.

Disadvantages:
- cannot apply power imbalance for each beam.

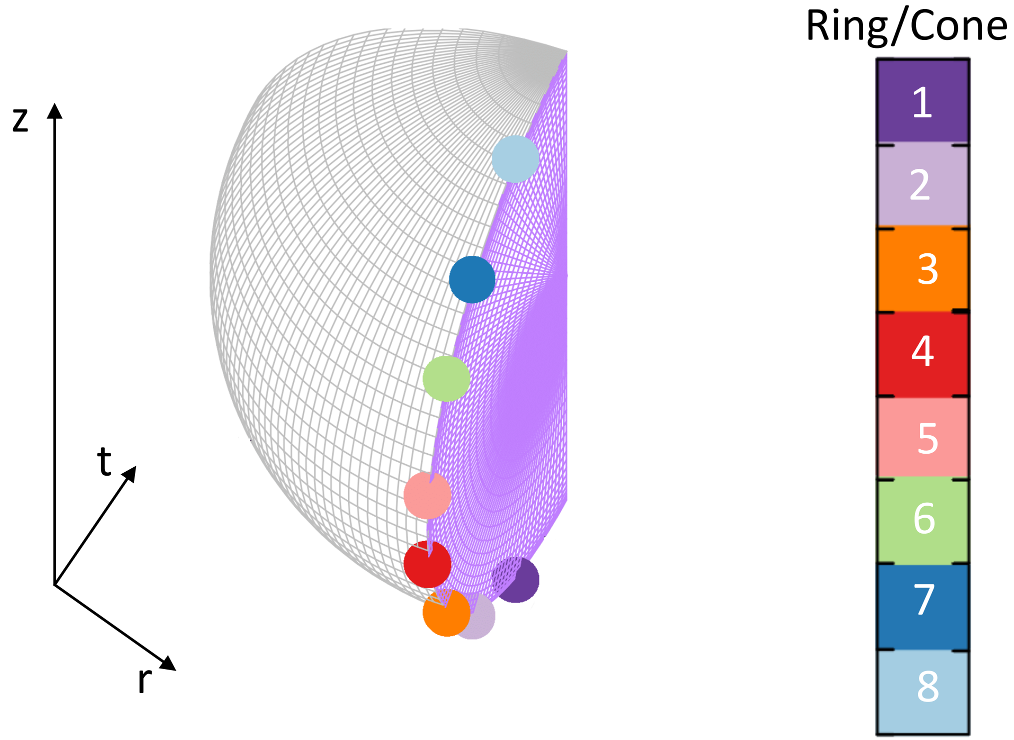
What takes place along the direction of the azimuth of the raytracing grid is hidden to the hydro mesh.



We could think of «reduce» beams with same zenith but different azimuth into beams with 0 azimuth (main meridian) and original zenith angle.



The new beams are called *cones*.
The total energy is preserved.

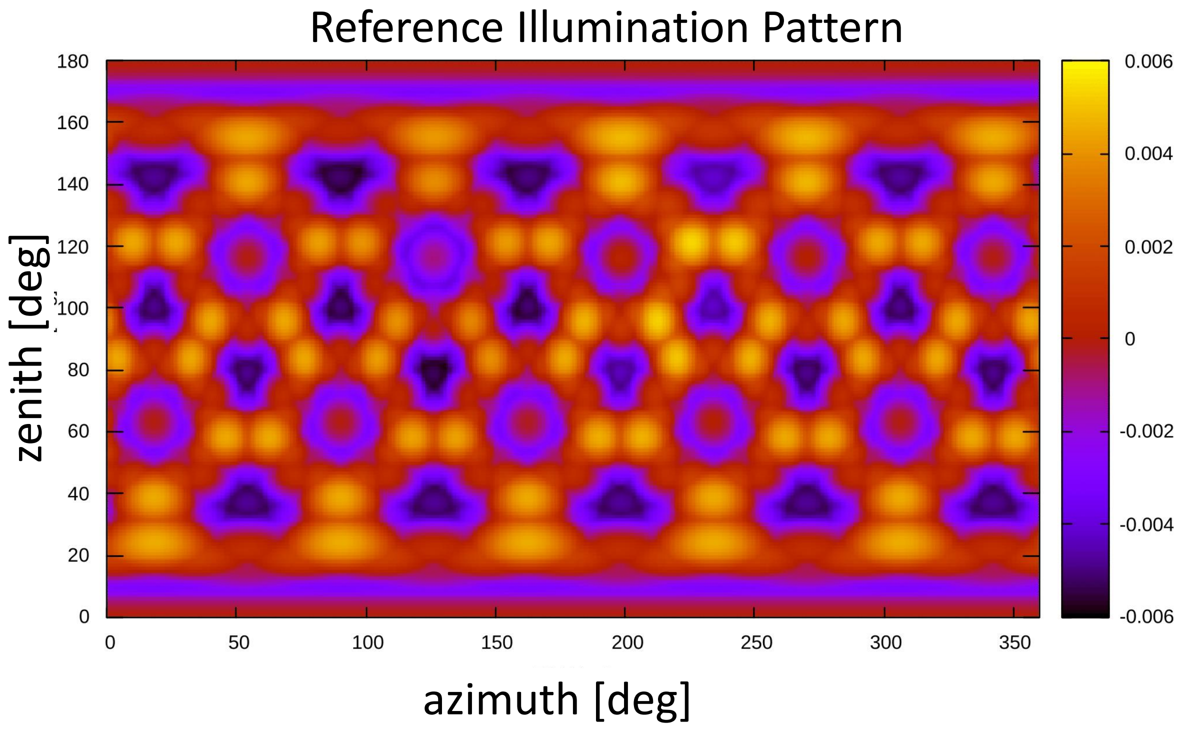


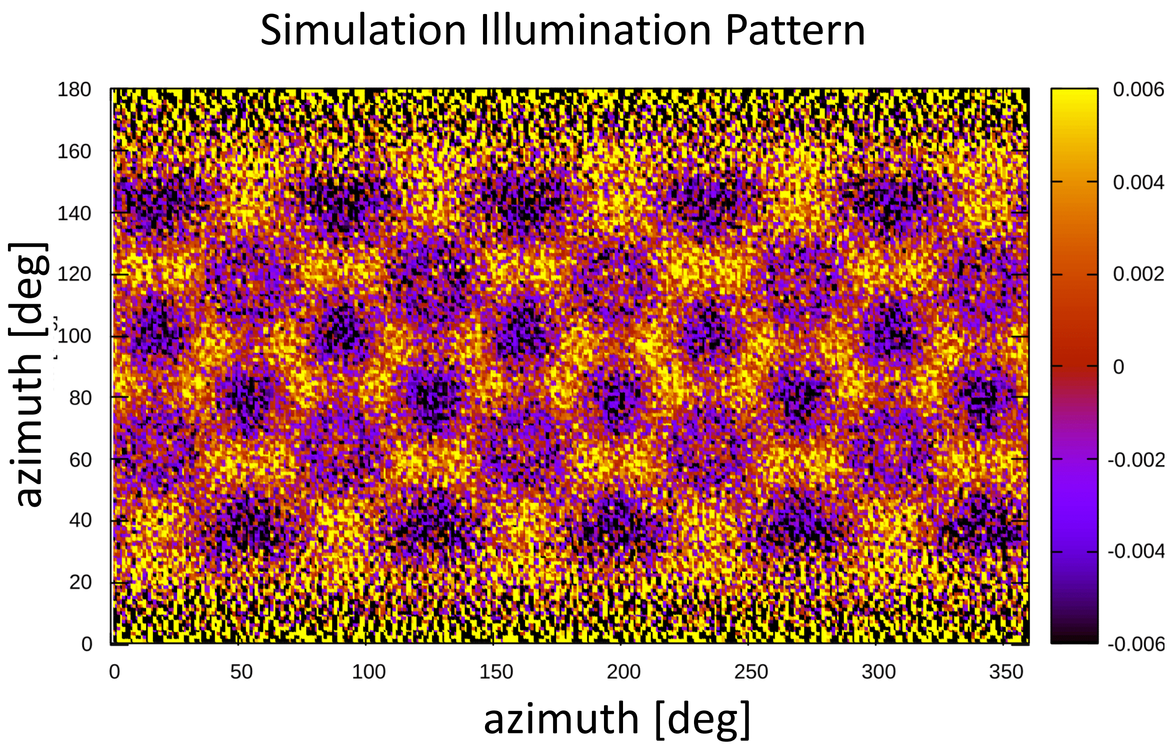
4. CODE DETAILS

All the graphs presented in the next slides are based on simulations of a spherical target, with radius 320 µm, made of plastic foam. This target is the basis of an experimental campaign conducted at the Omega Laser of the University of Rochester USA for a new target concept. More details at

[1] https://link.aps.org/doi/10.1103/PhysRevLett.131.015102

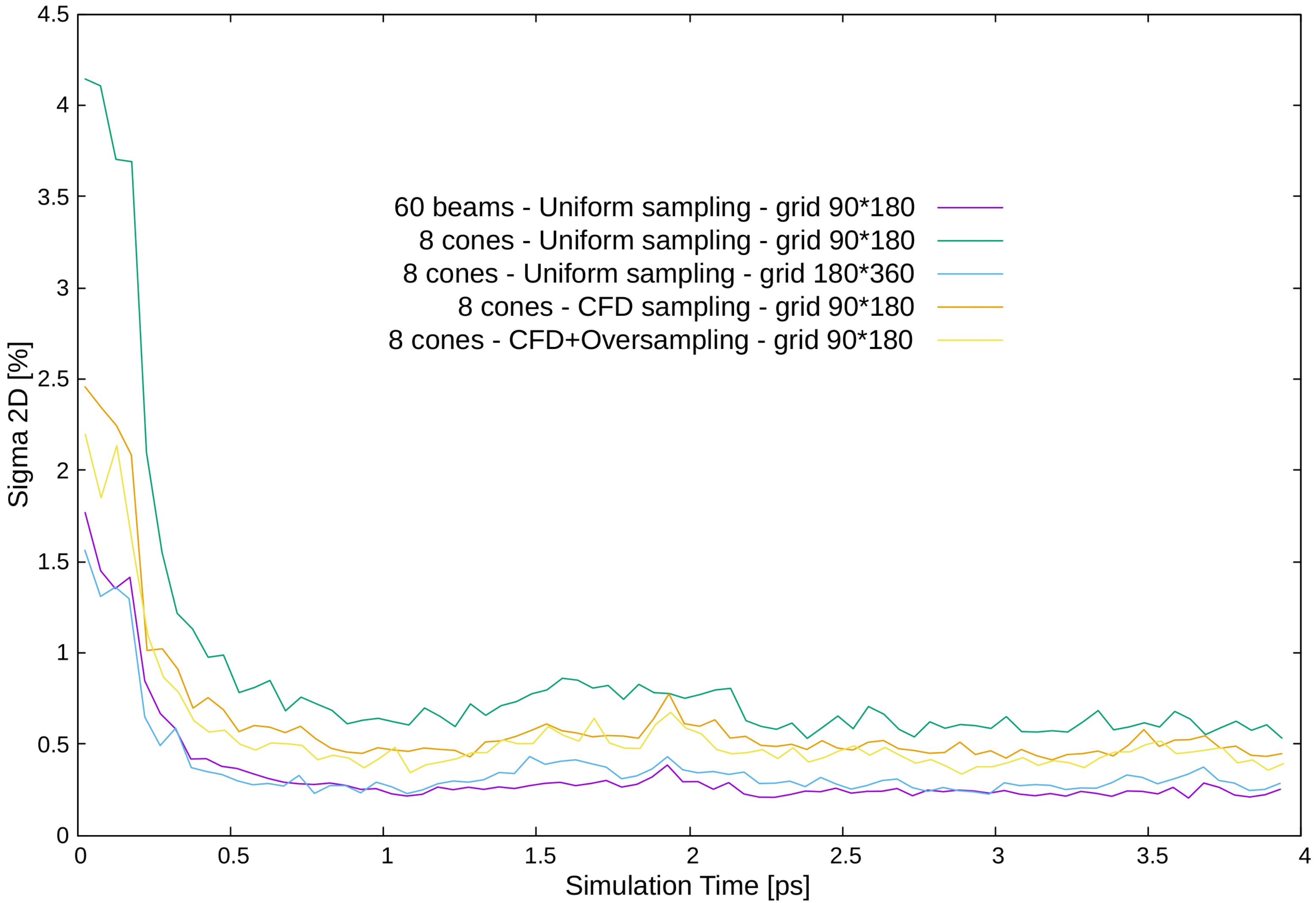
[4.0] Details: Illumination pattern (omega 60)





non-uniformity irradiation (sigma)

[4.1] 2D Illumination non-uniformity (sigma)



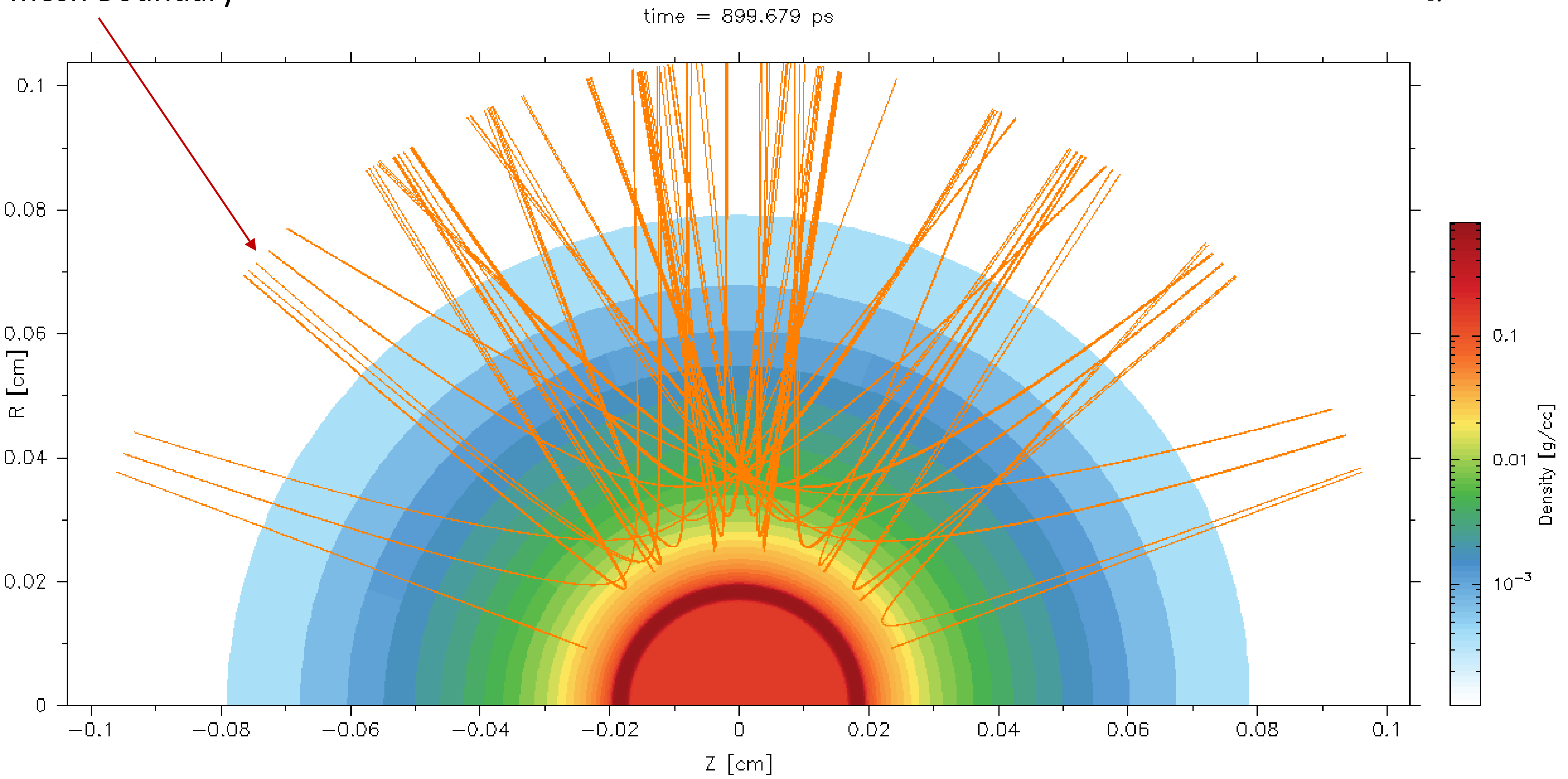
Expected 0.25%

Total beamlets to trace:
972000
129600
514.400
129600
≈129600

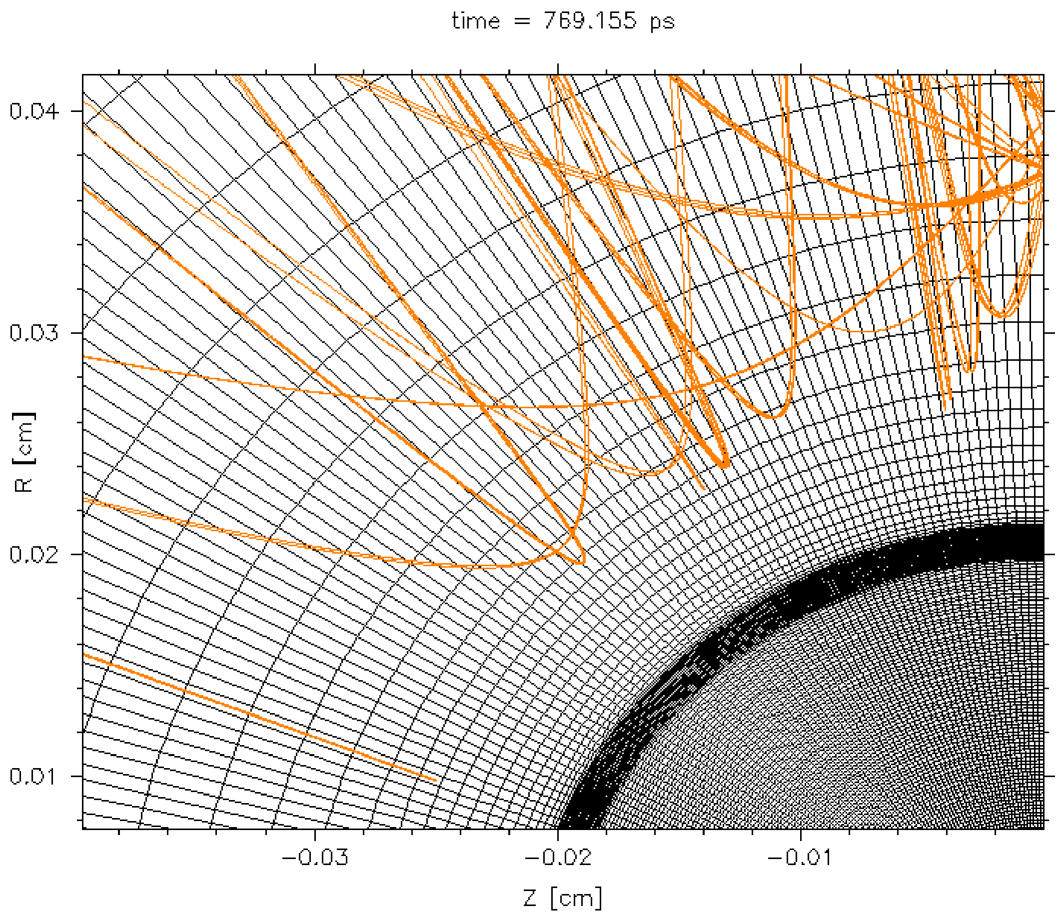
[4.2] Details: Ray trajectories projected onto 2D hydro mesh

Hydro mesh Boundary

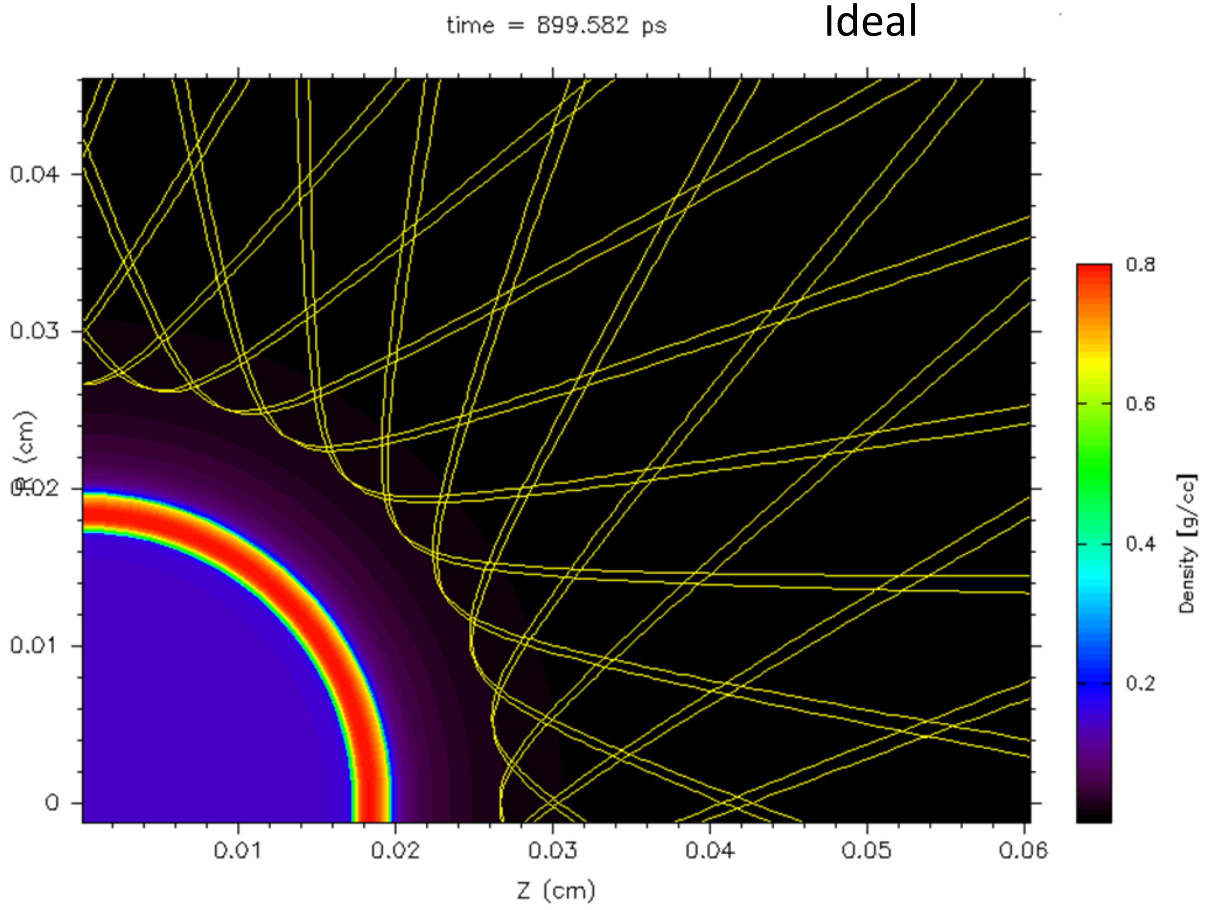
[plot of 100 rays]



[4.3] Details: 3D versus 2D raytracing (trajectories)

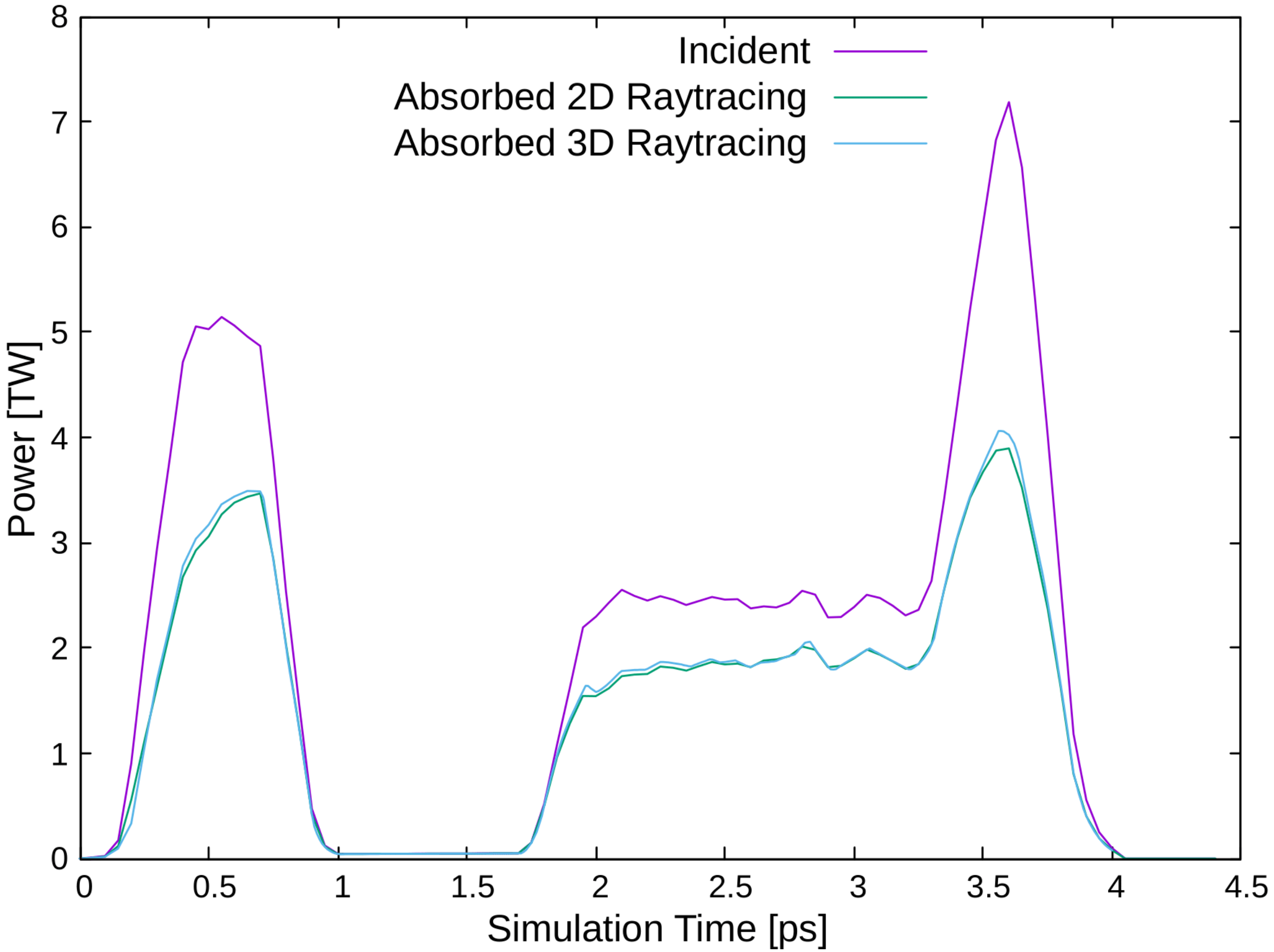


2D Hydro + 3D Raytracing



1D Hydro + 2D Raytracing

[4.4] Details: 3D vs 2D raytracing (Absorbed Power)



3D raytracing laser absorbed energy is slightly less than the ideal 2D raytracing case as expected.

5. CODE PERFORMANCE

[5.0] Our test benches

1

Workstation

AMD Threadripper 5955WX
16c/32t
«Zen3» architecture

AMD Radeon VII
3840 CU
FP32 13.5 TFLOPS
FP64 3.4 TFLOFS
«Vega 20» architecture

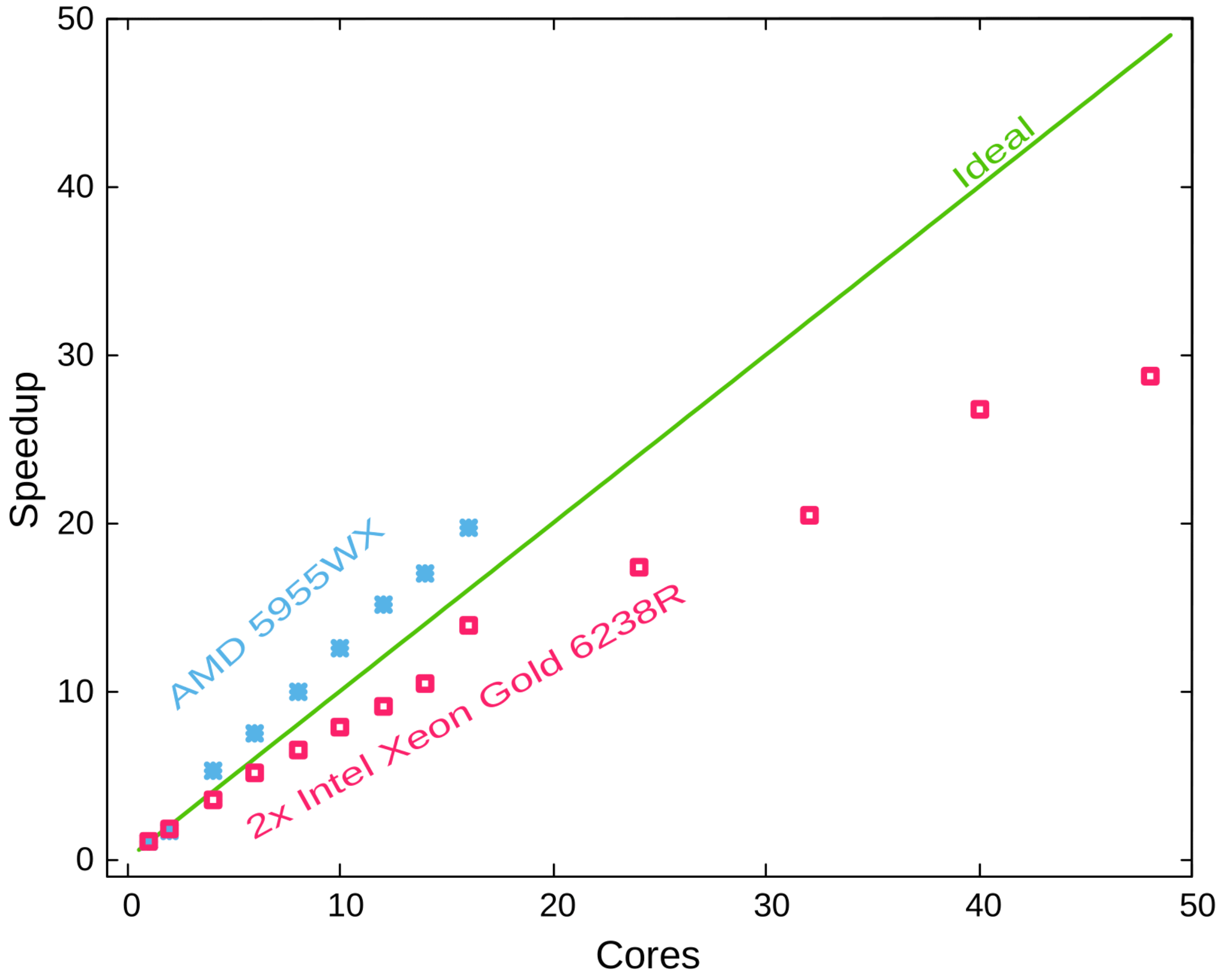
2

Server

Intel Xeon Gold 6238R
28c/56t
«Cascade Lake» architecture
2 sockets

Thanks to SBAM group of SBAI department at Sapienza University

[5.1] Performance



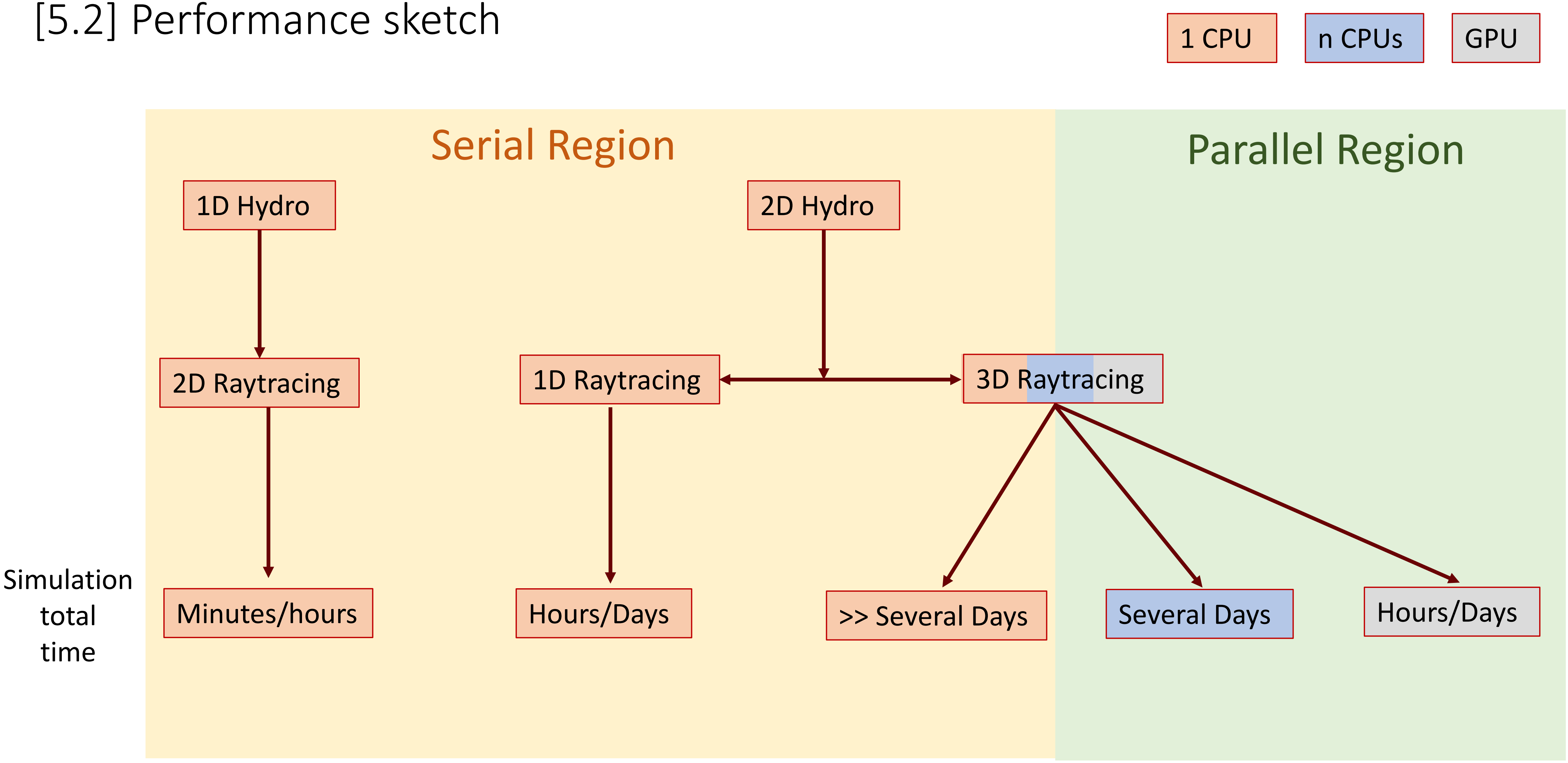
CPU:

- A cluster with more than 100+ CPU cores is required
- Large cache CPUs improve the overall performances
- Not suitable for daily simulations.

GPU:

- Simulation with one AMD Radeon VII GPU is **200x** faster than cpu serial simulation (AMD 5955WX)
- Higher values may be reached with more GPUs
- On-demand simulations without queueing
- Cross vendor compatibility (Nvidia/AMD/Intel)

[5.2] Performance sketch



6. CONCLUSIONS

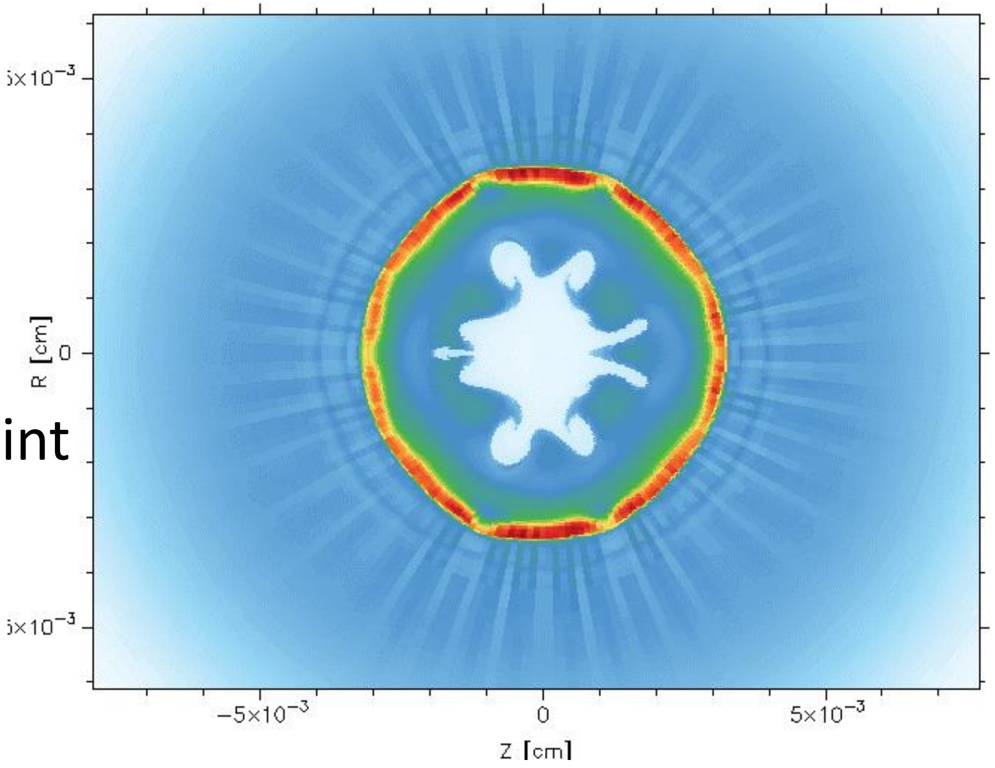
[6.0] Conclusions

Key points:

- Faster simulations with fully 3D raytracing are now possible
- Power imbalance and mispositioning with 3D raytracing are taken into account
- More realistic 2D hydrodynamic simulations

Work in progress:

- drive multiple GPUs to increase performance and maximize statistics when simulating full geometry.
- Simulation of OMEGA experiments in which laser imprint leads to strong instability during the implosion.



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