SAPIENZA
UNIVERSITÀ DI ROMA

CNISM

Advances in Laser Fusion Energy

A. Schiavi, S. Atzeni, A. Marocchino

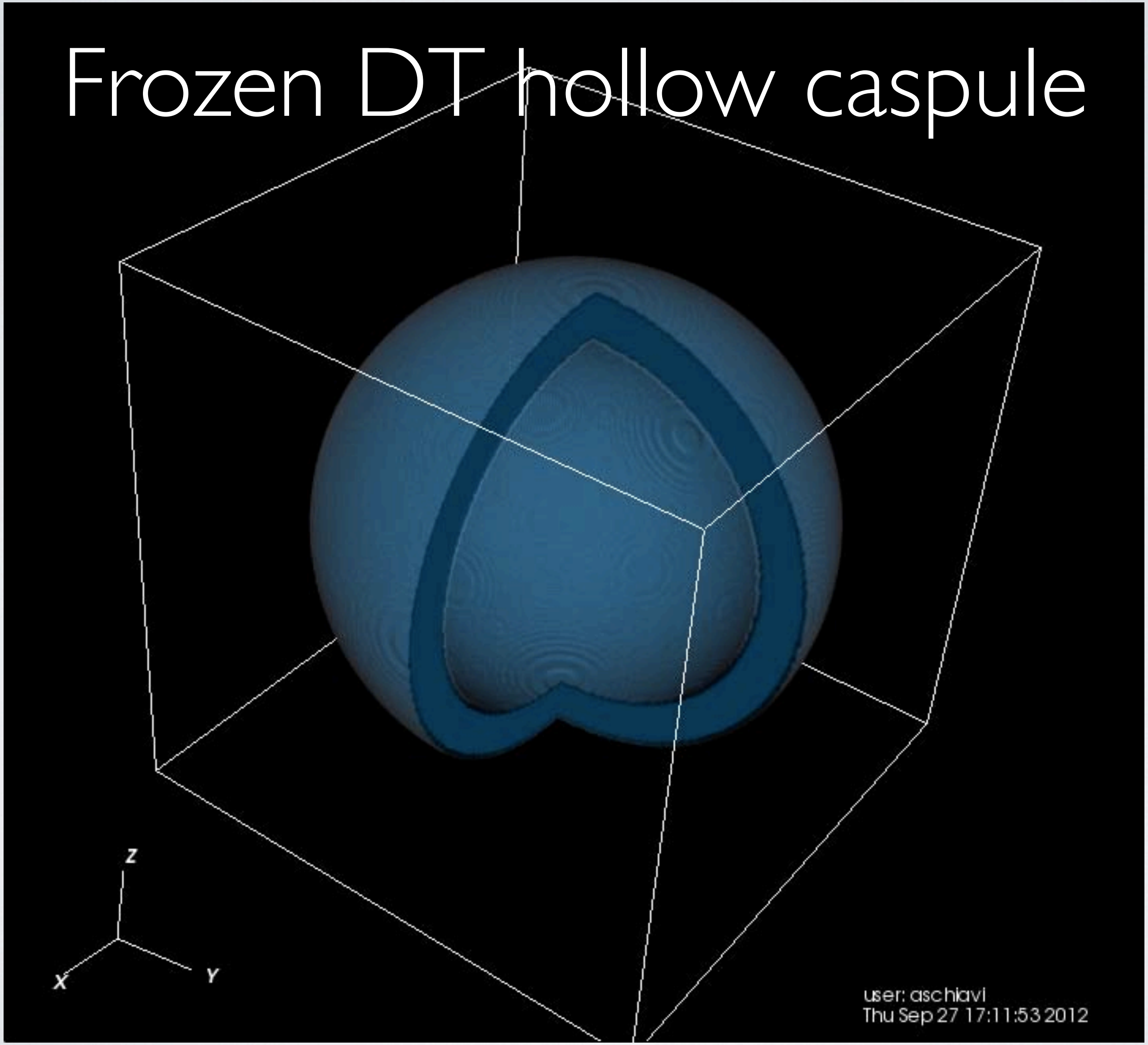
Channeling 2012, Alghero

Collaborators

- S. Atzeni and A. Marocchino, Univ. of Rome
- M. Temporal, GIFI, Univ. Pol. of Madrid
- G. Schurtz, X. Riberye, L. Hallo, CELIA, Bordeaux

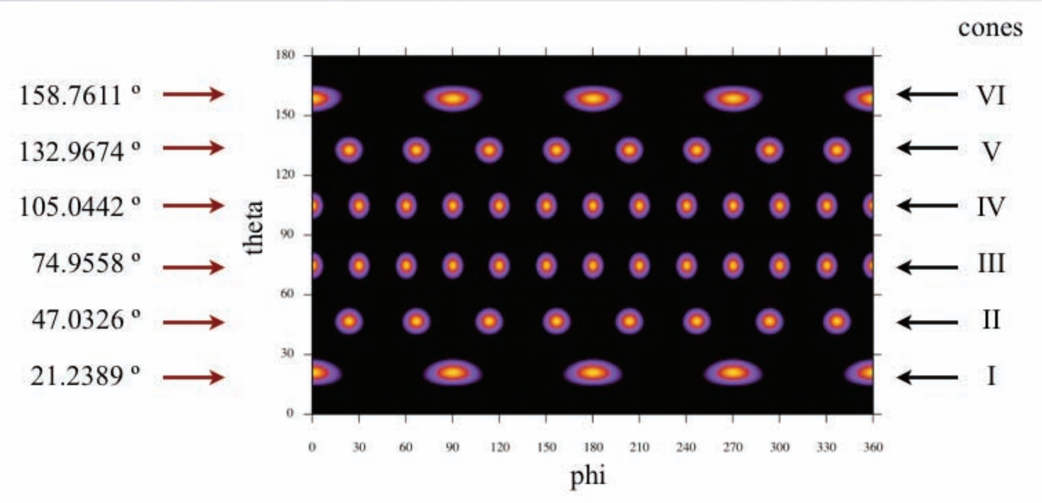
Simulations were run on the Cresco cluster at Portici

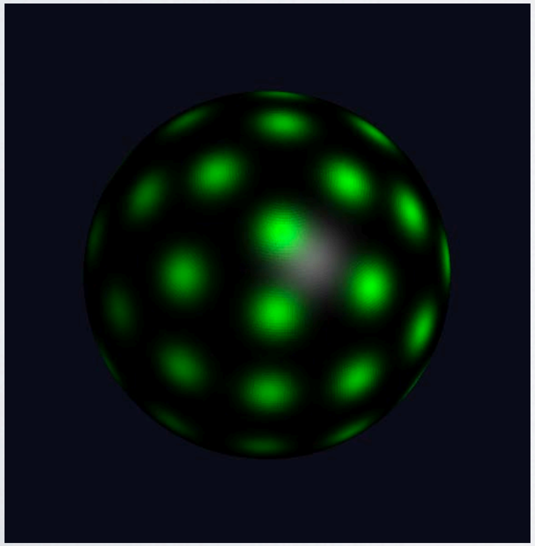
Target

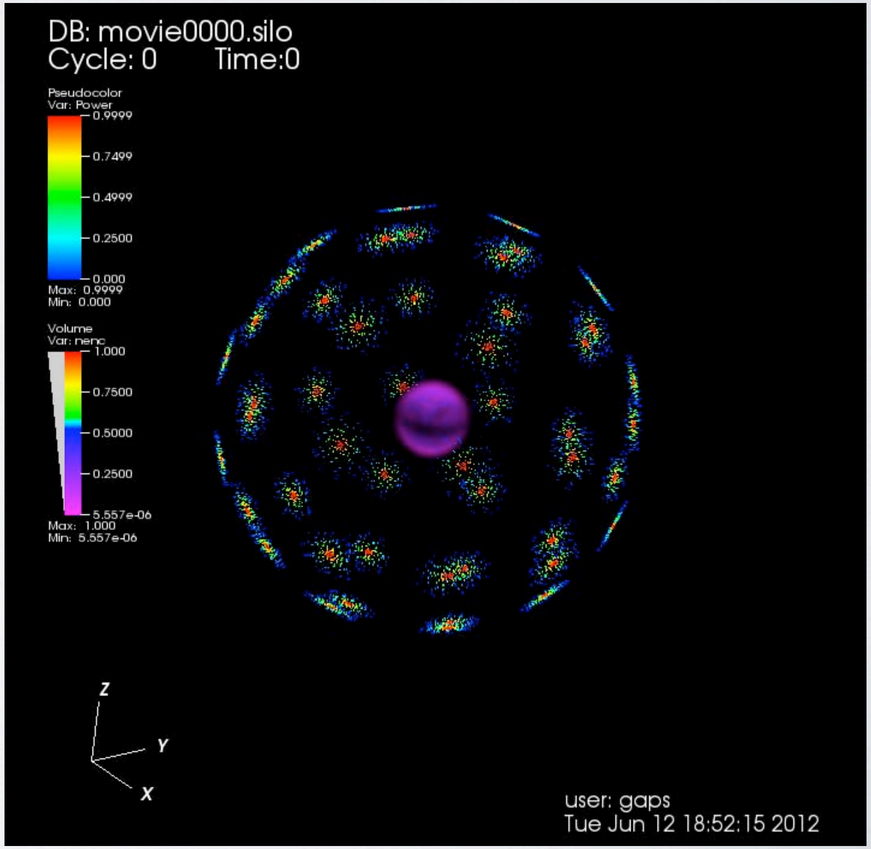

Frozen DT hollow caspule
Z
X
Y
user: aschiavi
Thu Sep 27 17:11:53 2012

Laser drive

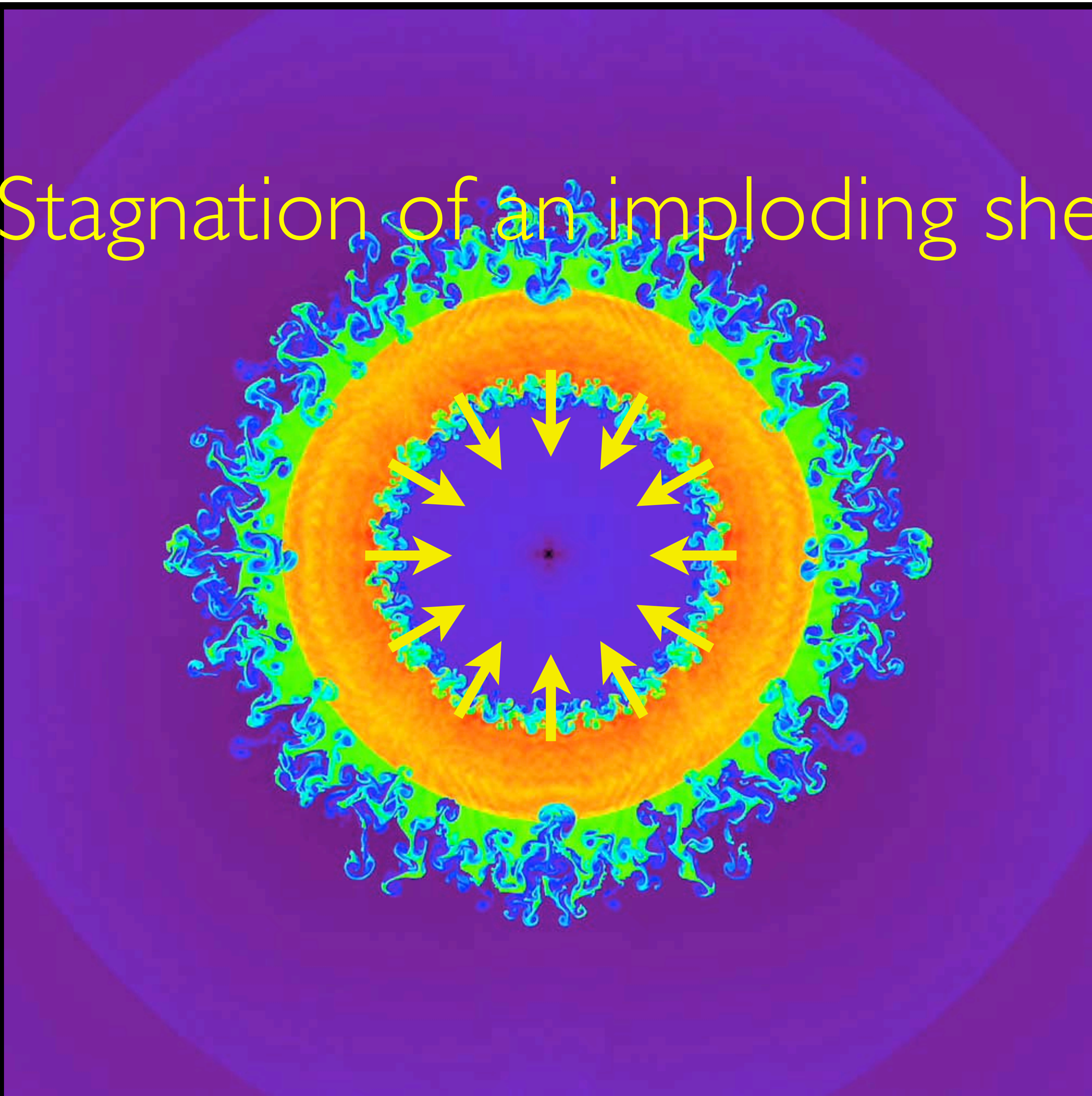
48 beam irradiation scheme





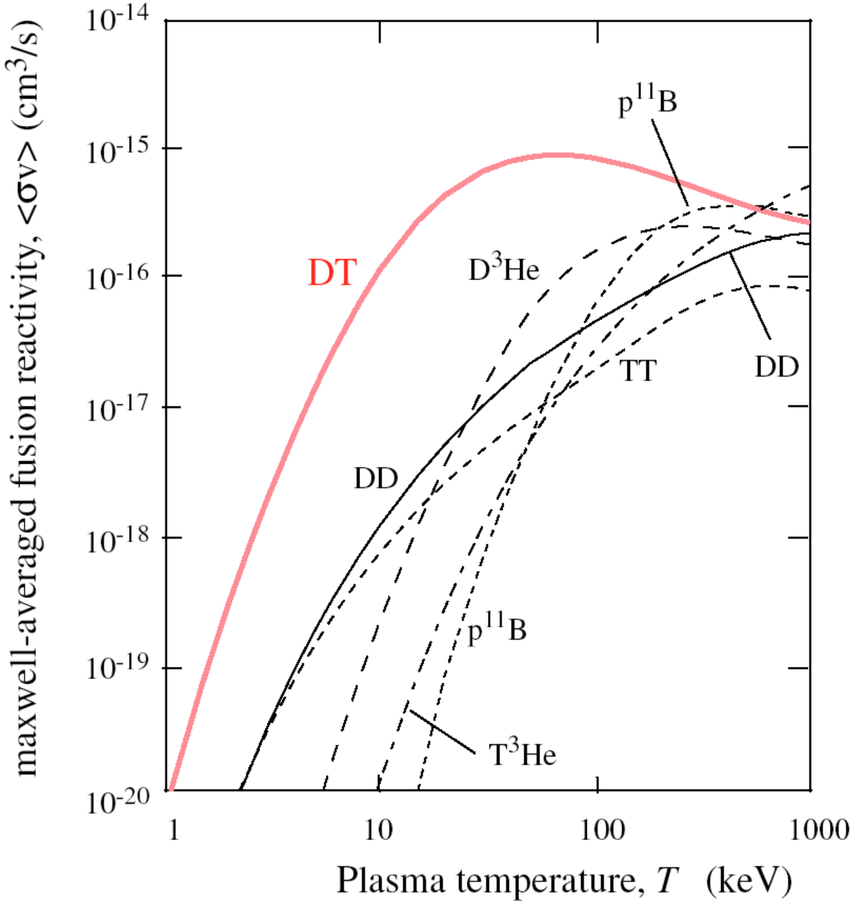


Stagnation of an imploding shell

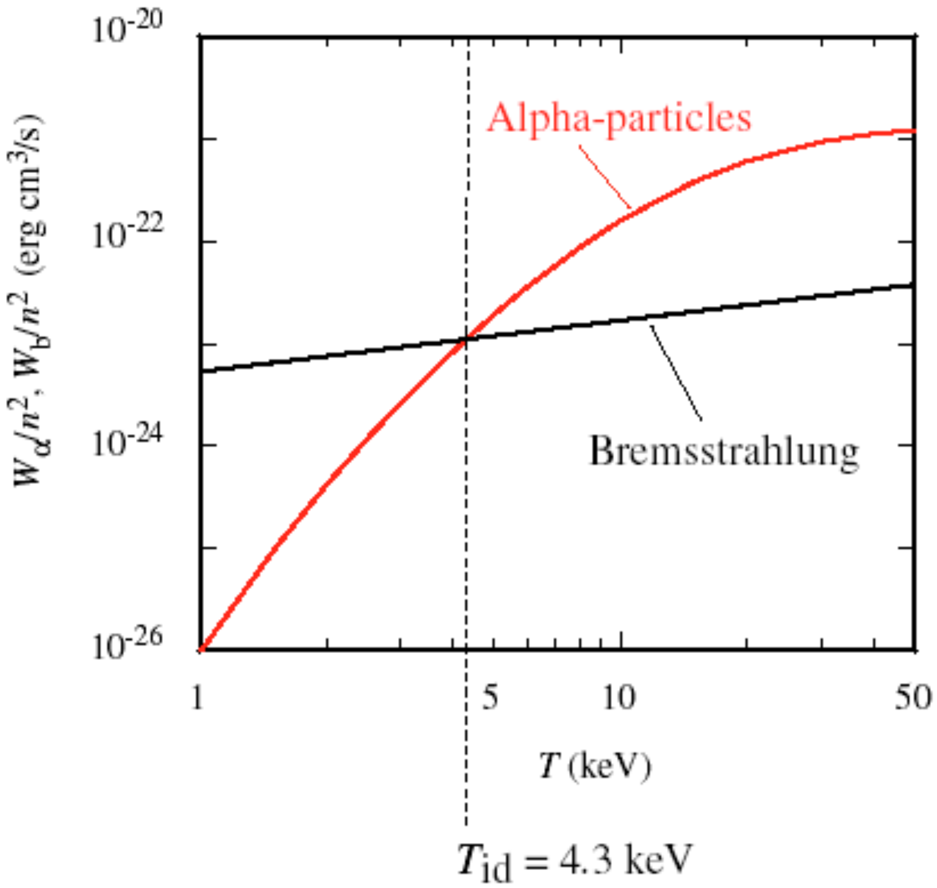


Even for the most reactive fuel, T > 5 keV to compensate for radiation losses

D + T => α + n + 17.6 MeV
has by far the largest reactivity



at 4.2 keV fusion alpha particle power exceeds bremsstrahlung power



Inertial confinement fusion (ICF)

- Fusion reactions
  from a target containing a few mg of DT fuel
  compressed to very high density (1000 times solid density)
  and heated to very high temperature

- No external confinement => fuel *confined by its own inertia*
  ($t = R/c_s$ with c_s the sound speed and
  R linear dimension of the compressed fuel)

  => confinement parameter: $\rho \boldsymbol{R}$

- Pulsed process: for energy production need to burn targets at 1 - 10 Hz

  (Target gain) * (efficiency) ≥ 10
  150 7%

Inertial Confinement Fusion

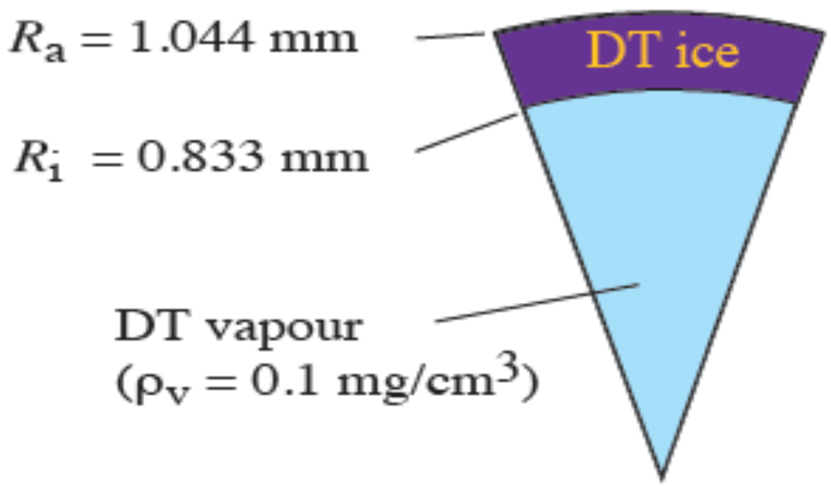
Standard approach

- **Central Ignition**

Advanced schemes

- **Fast Ignition**
- **Shock Ignition**

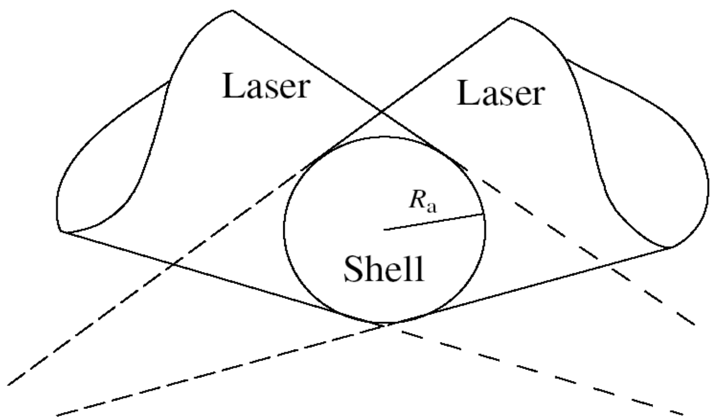
Baseline capsule



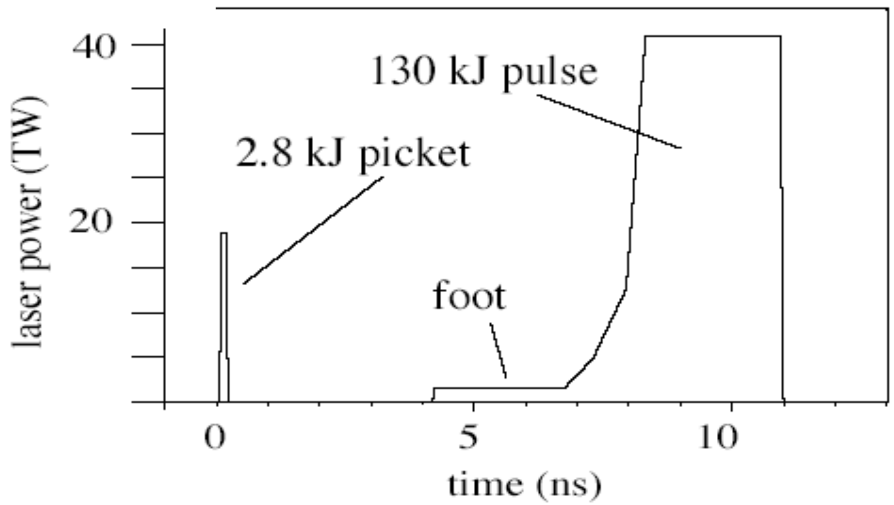
compression laser pulse

- wavelength = 0.35 μm
- focussing optics f/18
- energy = 130-180 kJ

- absorbed energy = 90-120 kJ



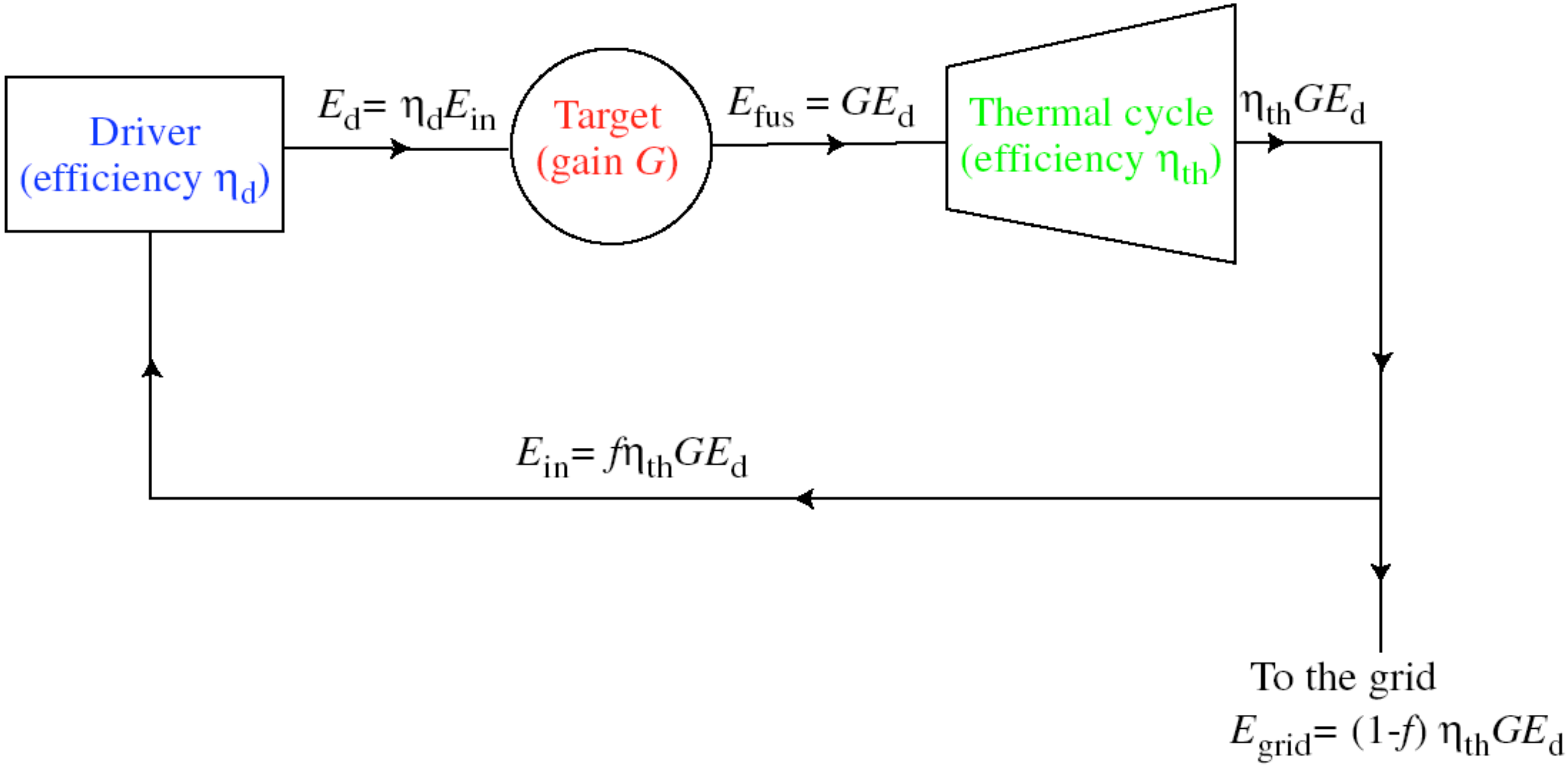
b)



ref: S. Atzeni, A. Schiavi and C. Bellei, *Phys. Plasmas*, **15**, 14052702 (2007)

The reactor cycle:
<u>high target energy multiplication (gain)</u>
required to overcome cycle inefficiencies

$G\,\eta_D > 10$



The essential physical ingredients of ICF

(homogeneous sphere of DT, radius R, density ρ)

- COMPRESSION:

  burn fraction $\Phi = \rho R / (\rho R + 7 \text{ g/cm}^2)$

  $\Phi > 20\% \Longrightarrow \rho R > 2 \text{ g/cm}^2$

  mass $m = (4\pi/3)\rho R^3$ = few mg ==> $\rho > 200 \text{ g/cm}^3$

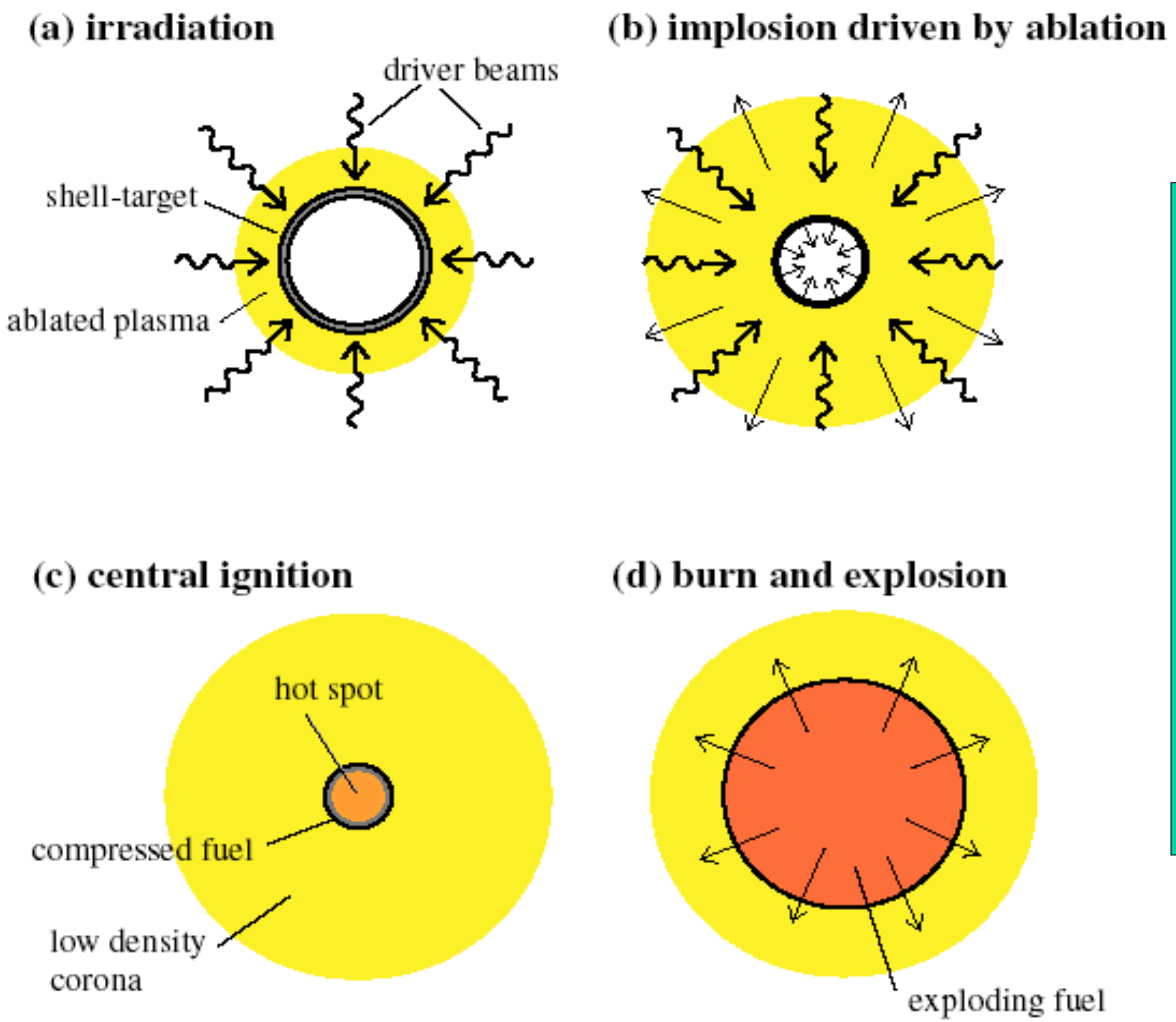
- HOT SPOT IGNITION

  do not heat the whole fuel to 5 keV

  heat to 5 – 10 keV the smallest amount of fuel capable of self heating and triggering a burn wave

the standard approach: *central ignition*

imploding fuel kinetic energy converted into internal energy and concentrated in the centre of the fuel



implosion velocity
for ignition:

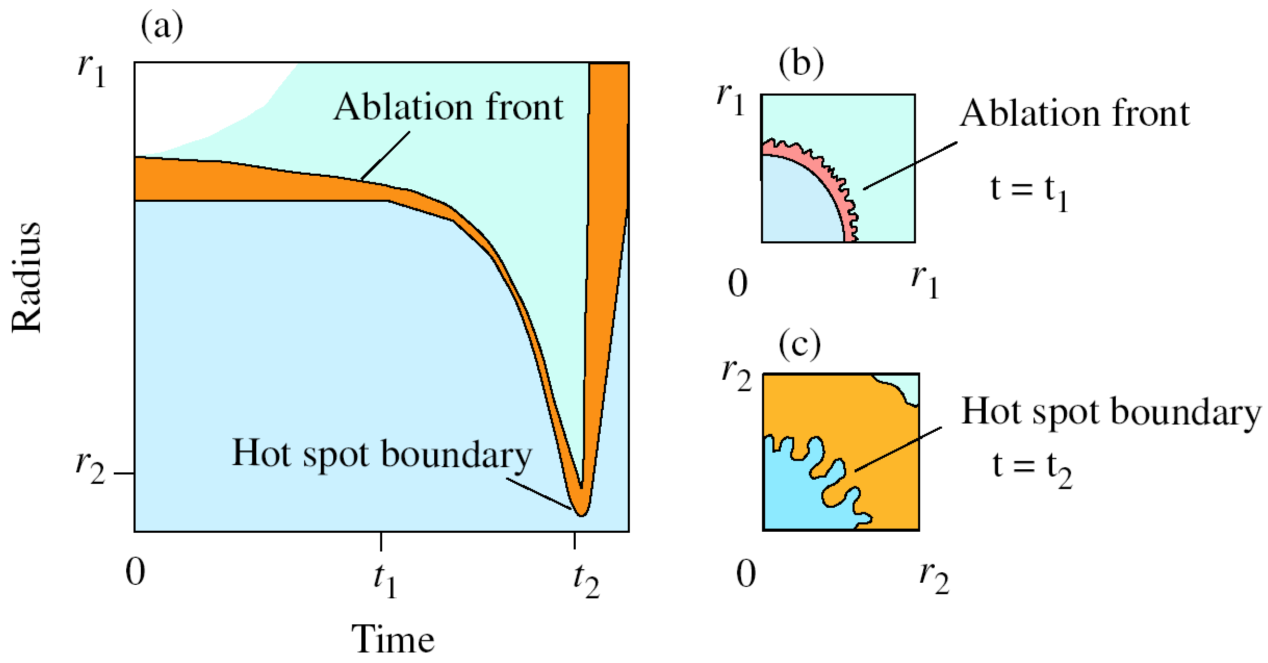
$u_{imp} > 250 – 400$ km/s

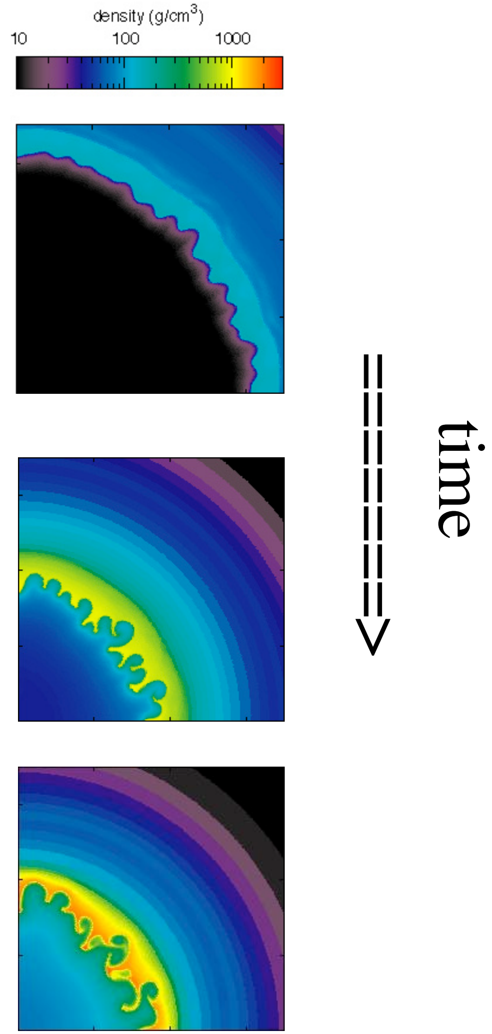
depending of the fuel mass:

$u_{imp} \propto m^{-1/8}$

(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004.)

Rayleigh-Taylor instability
unavoidable in inertial fusion



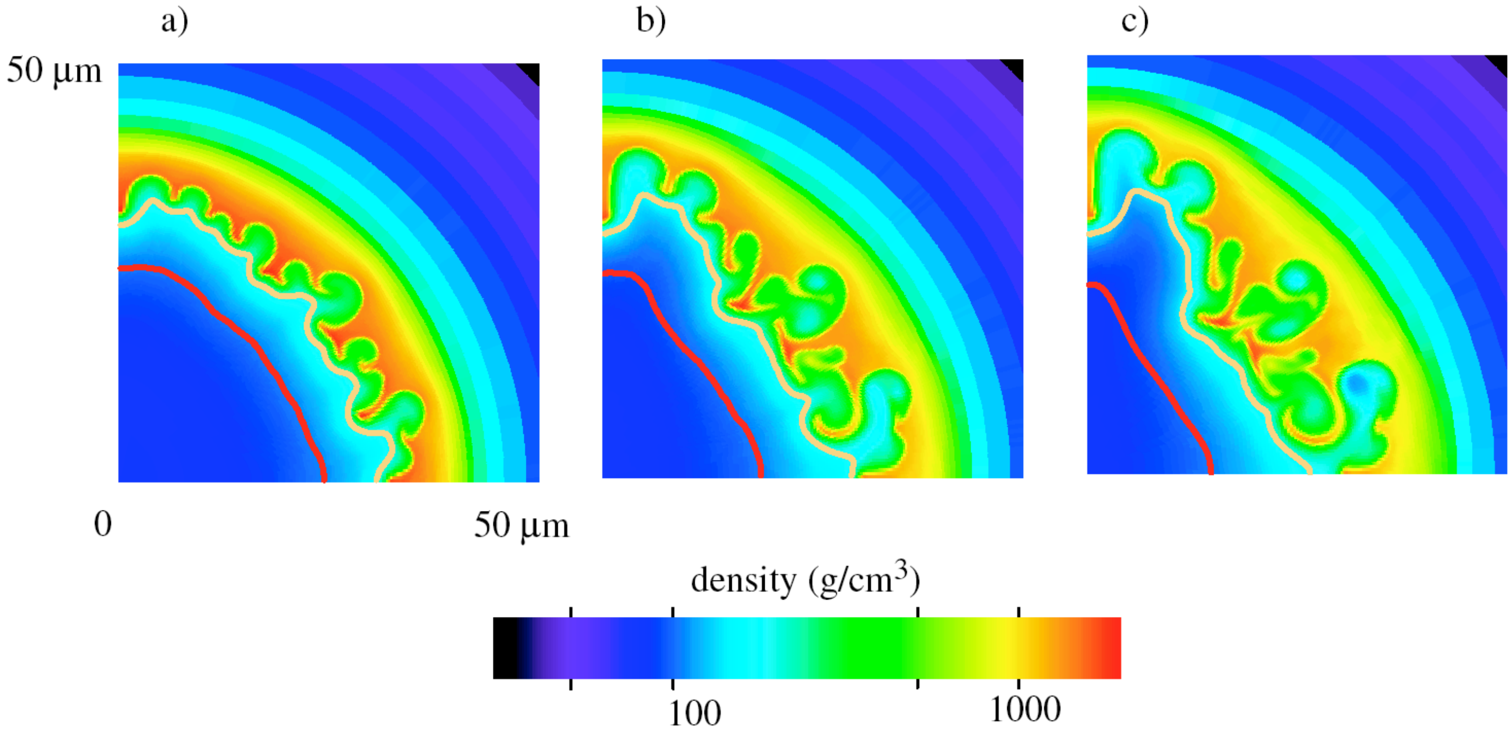


deceleration-phase instability at the hot spot boundary
(2D simulation)

Atzeni & Schiavi, PPCF 2004

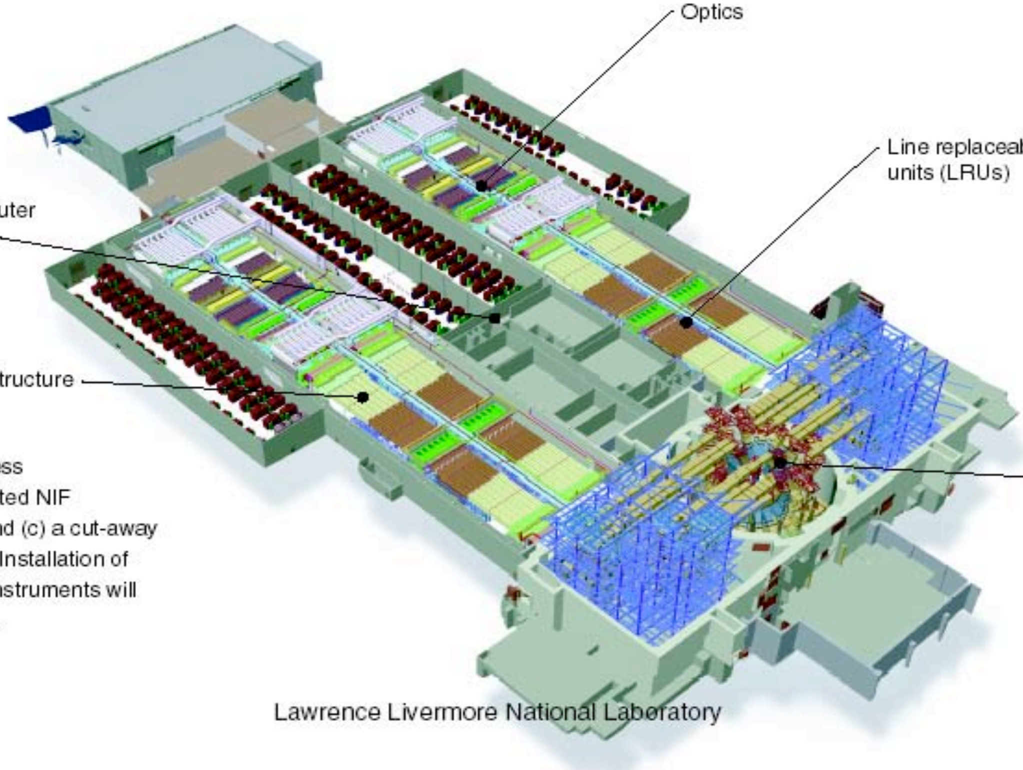
RTI limits the size of the hot spot

Below: density maps at the same time (290 ps) for cases with different perturbation amplitude:
The size of the hot spot [see the 10 keV (red) and 5 keV (orange) contours] is reduced by the penetration of the RTI spikes.



Atzeni & Schiavi, PPCF 2004

Laser NIF

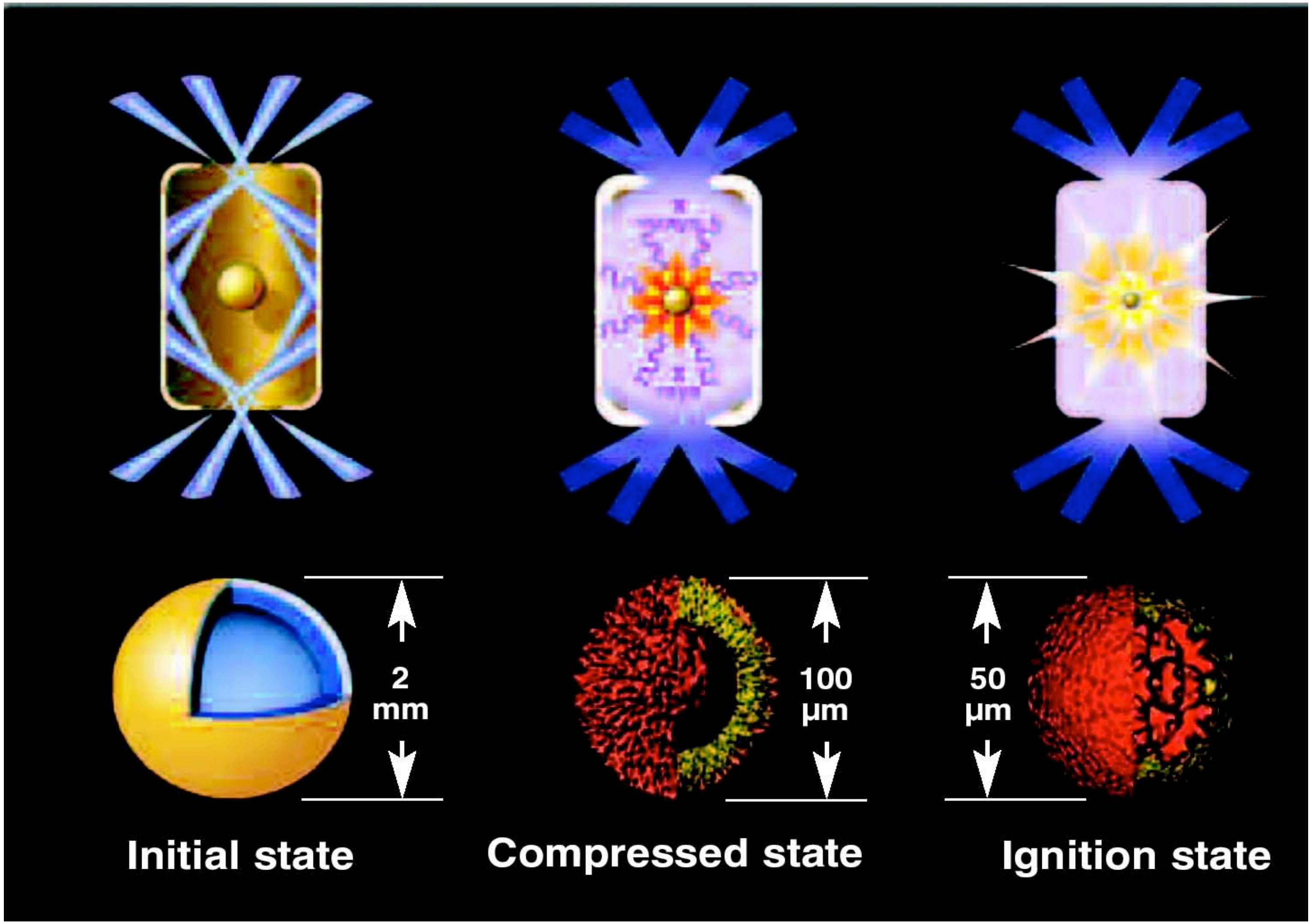


(a) Construction progress in 1997, (b) the completed NIF conventional facility, and (c) a cut-away showing NIF's interior. Installation of optics and diagnostic instruments will continue through 2008.

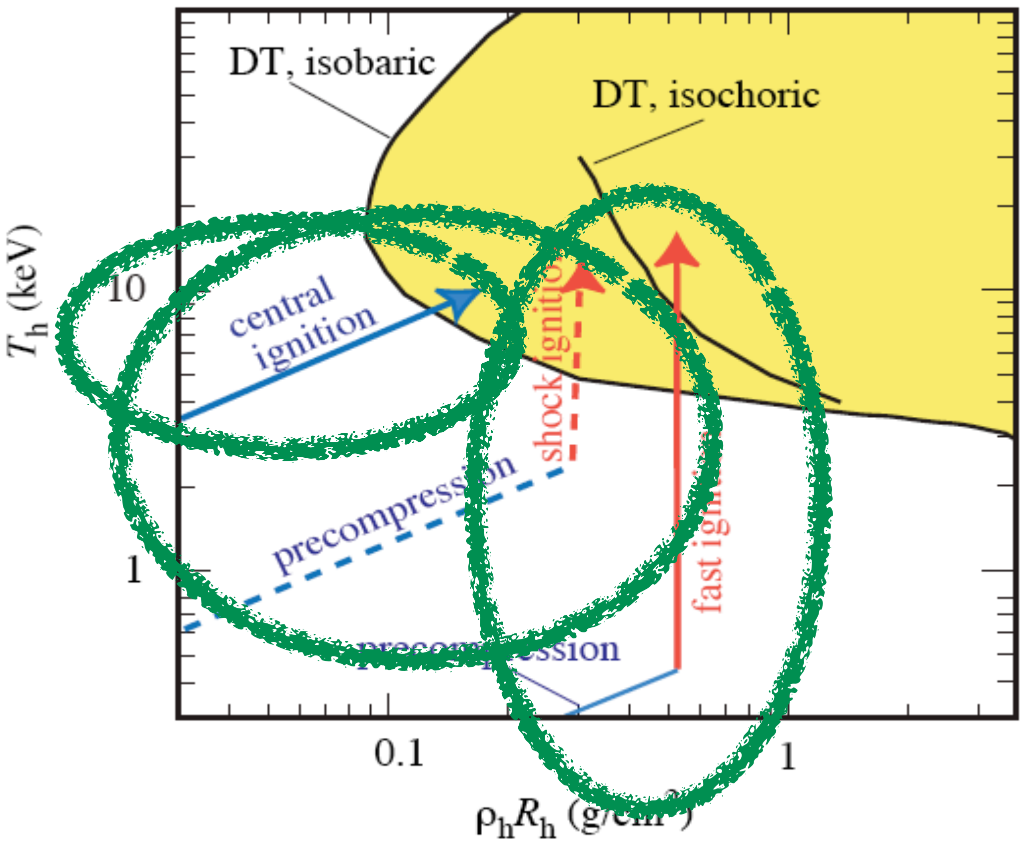
Lawrence Livermore National Laboratory

3D simulation of a NIF ignition experiment

S. Haan et al., *NF* 44, S171 (2004), courtesy of LLNL



Alternative routes to ignition: separate compression & heating

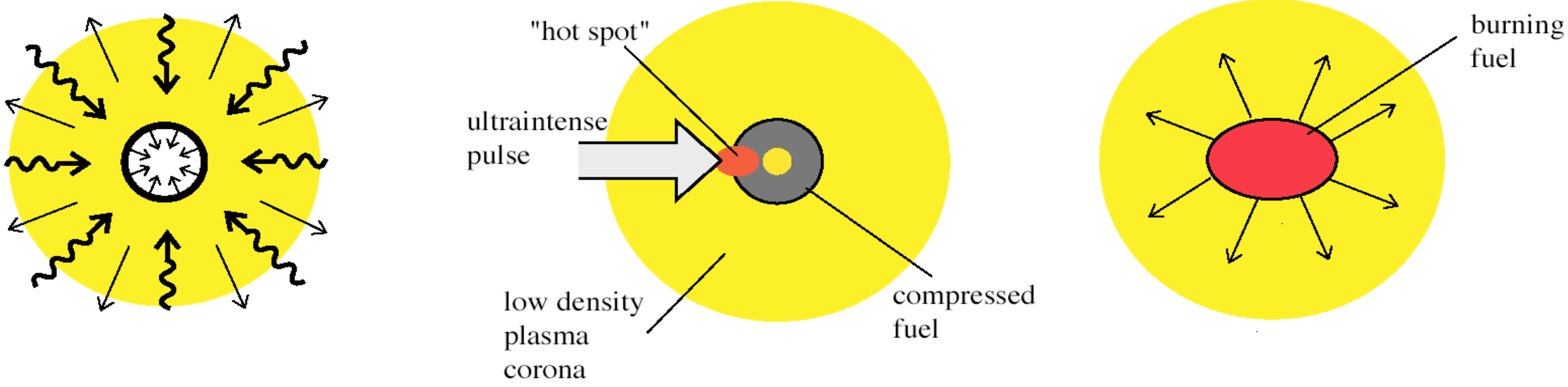


Fast ignitor

(a) and (b) symmetric irradiation and implosion

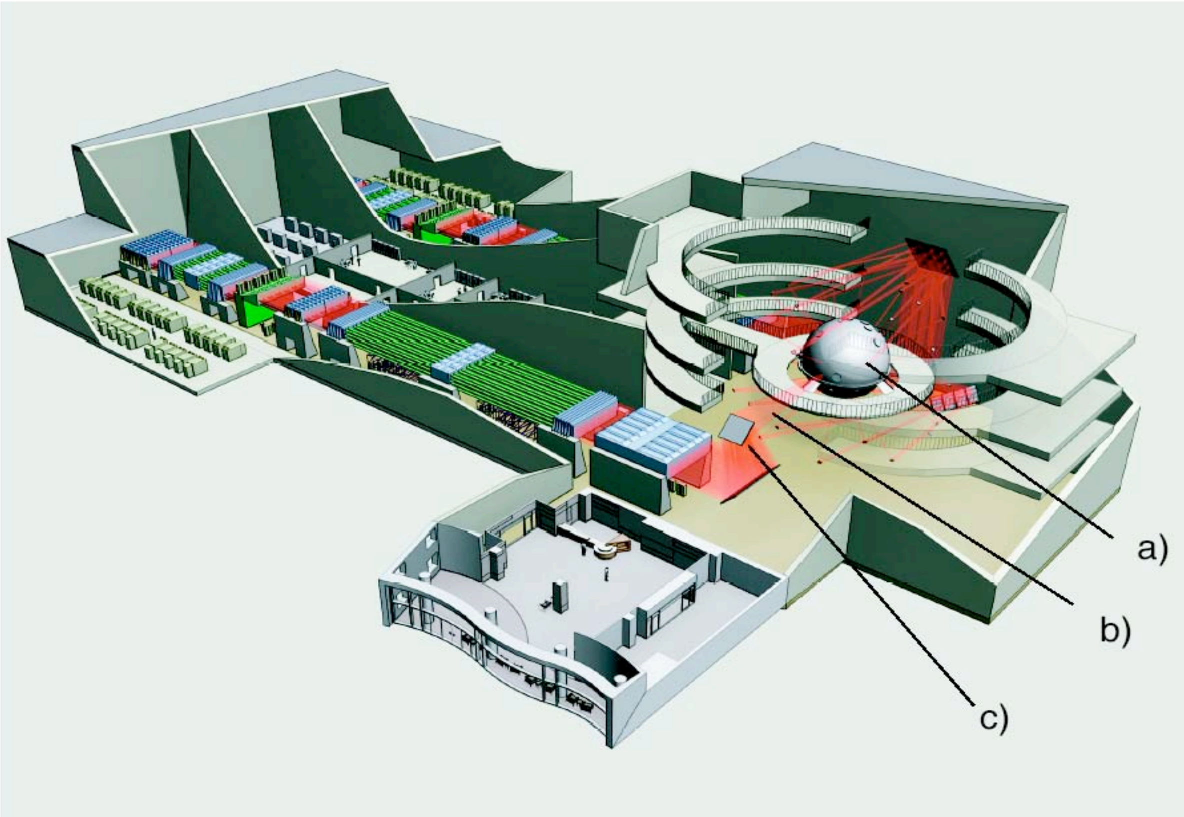
(c) hot spot generation by an ultraintense pulse

(d) burn



- Scheme: M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
- Ignition mechanism: S. Atzeni, Jpn. J. Appl. Phys. 34, 1980 (1995)
- Ignition requirements: S. Atzeni, Phys. Plasmas 6, 3316 (1999);
  S. Atzeni and M. Tabak, Plasma Phys. Controll. Fusion 47, B769 (2005)

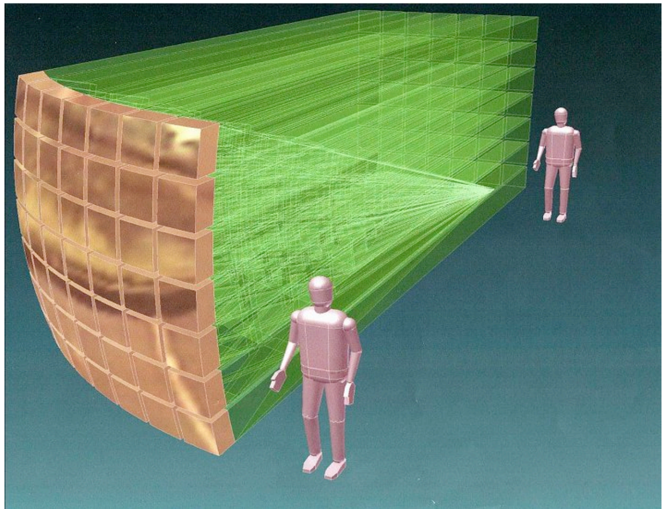
testing fast ignition at minimum energy



artist's view

70kJ, 10psec, 1ω, 2ω or 3ω

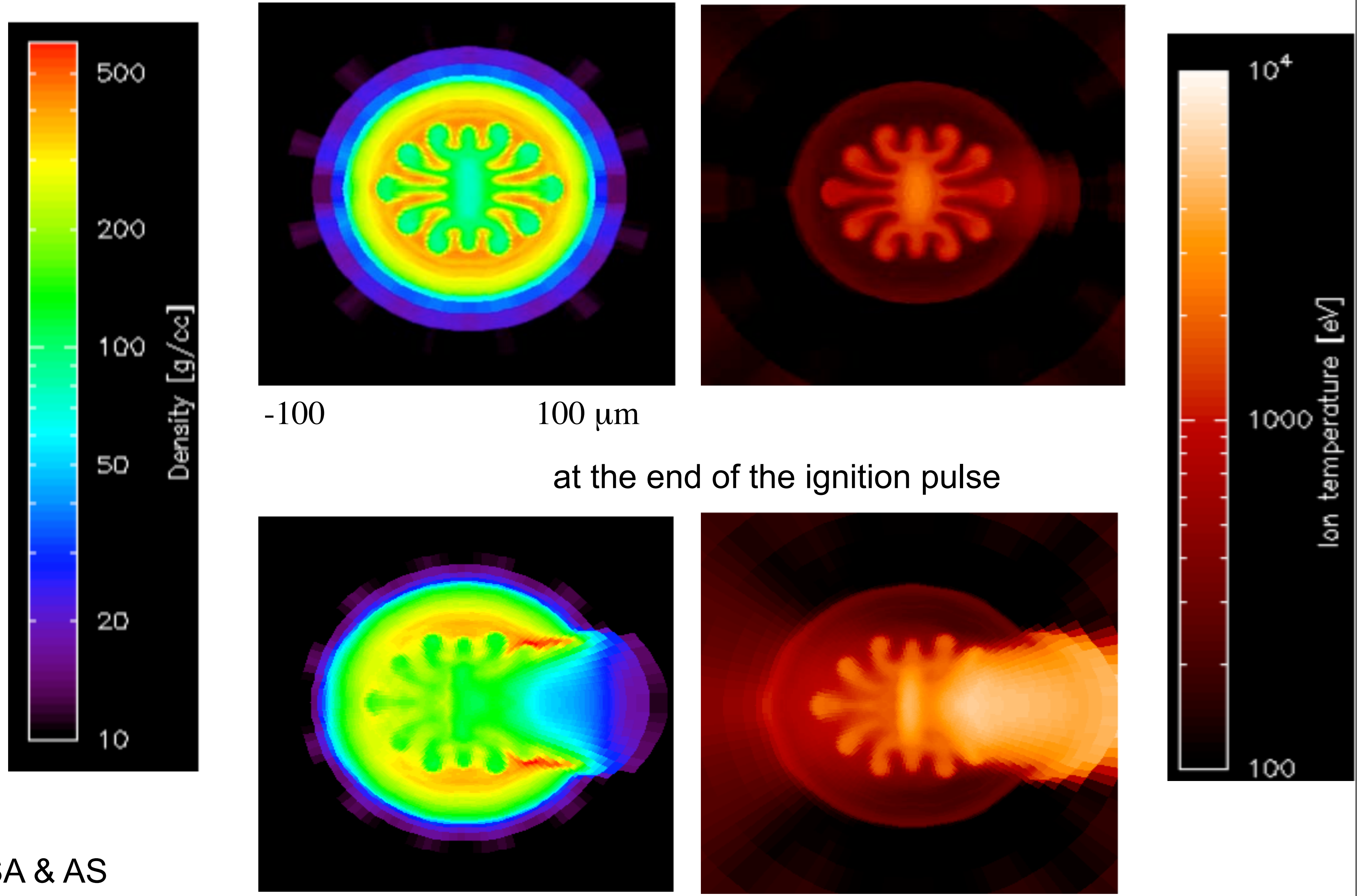
c)



a)

200-300kJ, 5nsec, 3ω

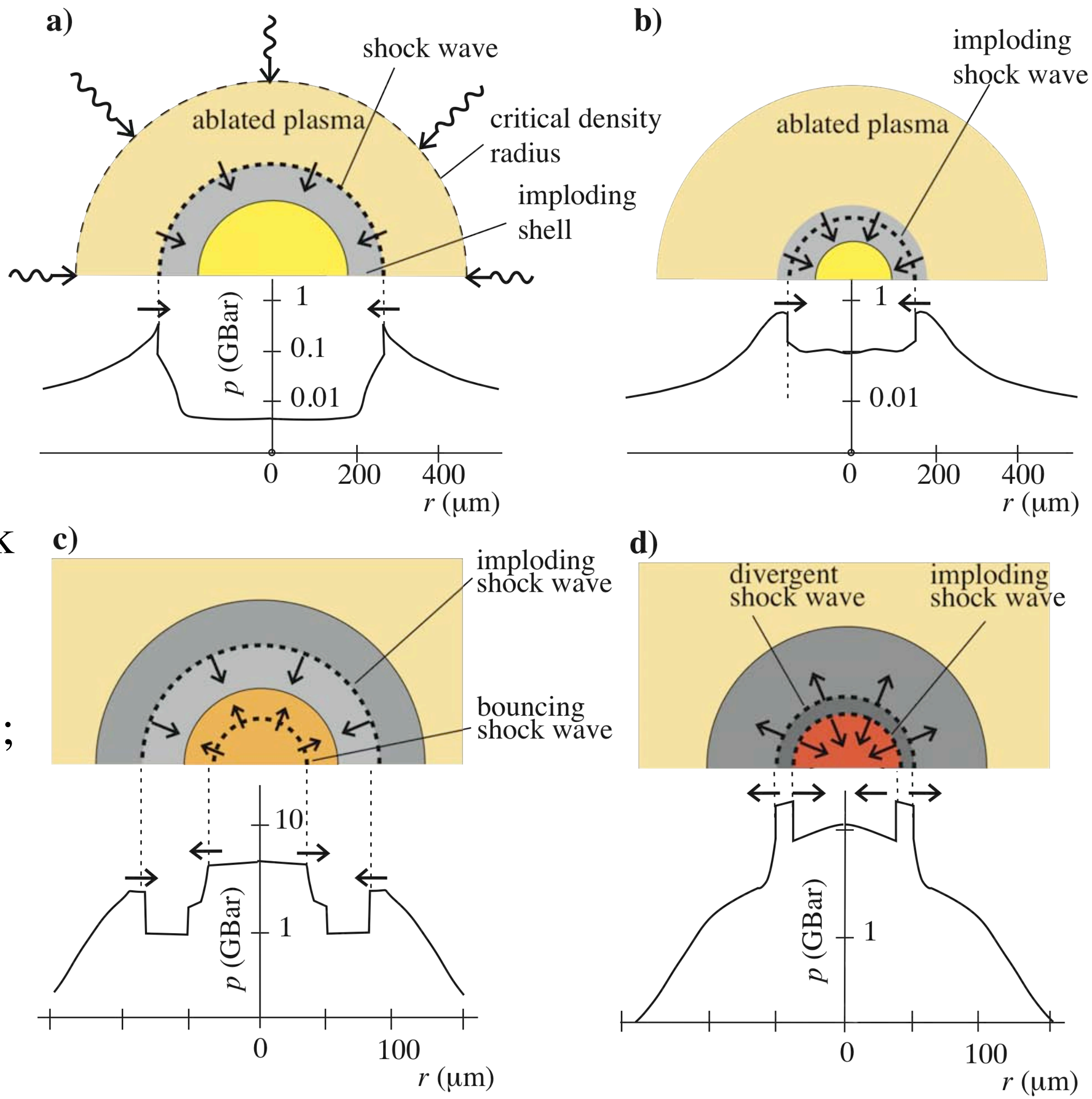
t = 11.450 ns; 1 ps after start of ignition pulse



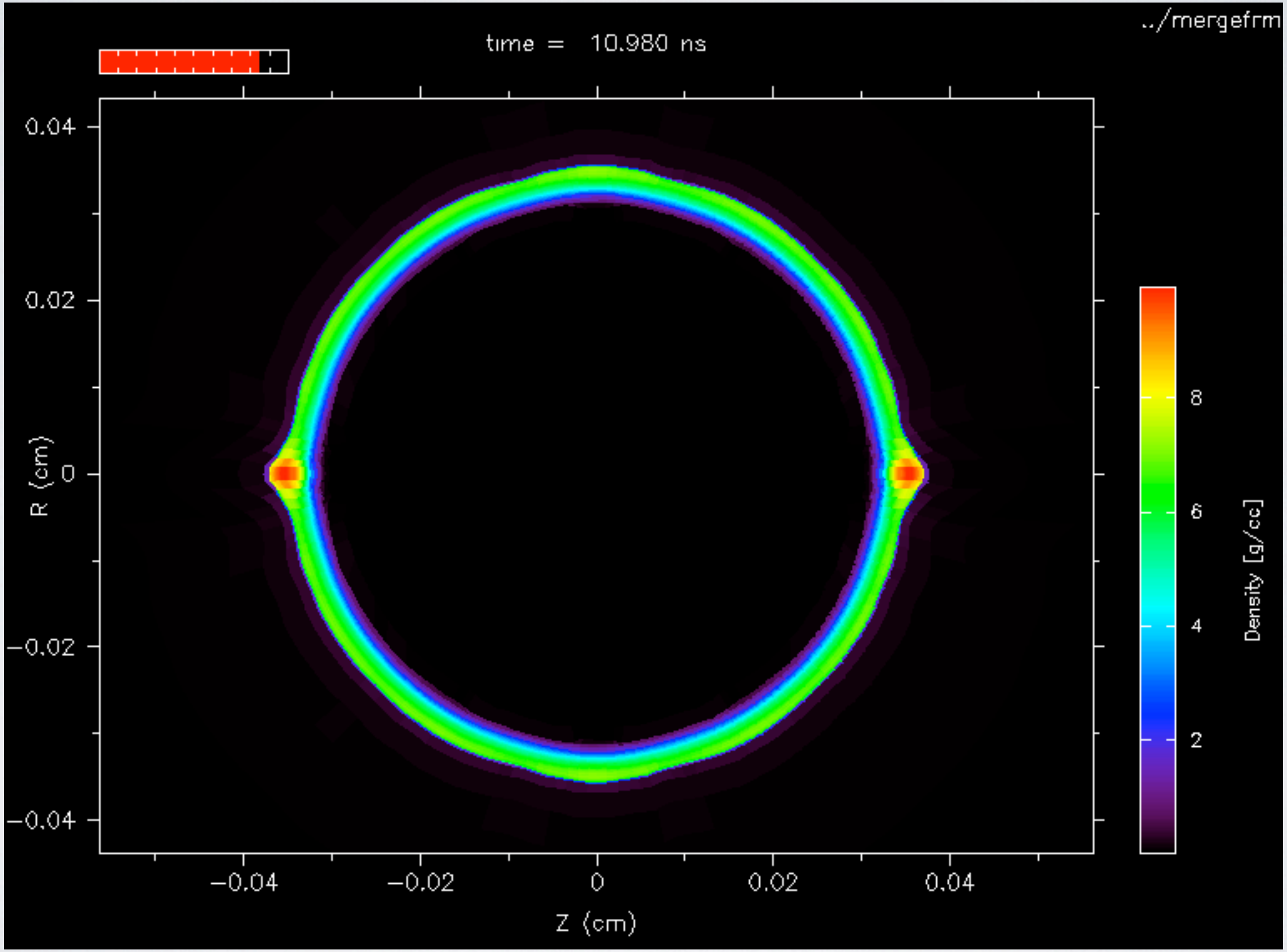
SA & AS

Shock ignition: pressure amplification

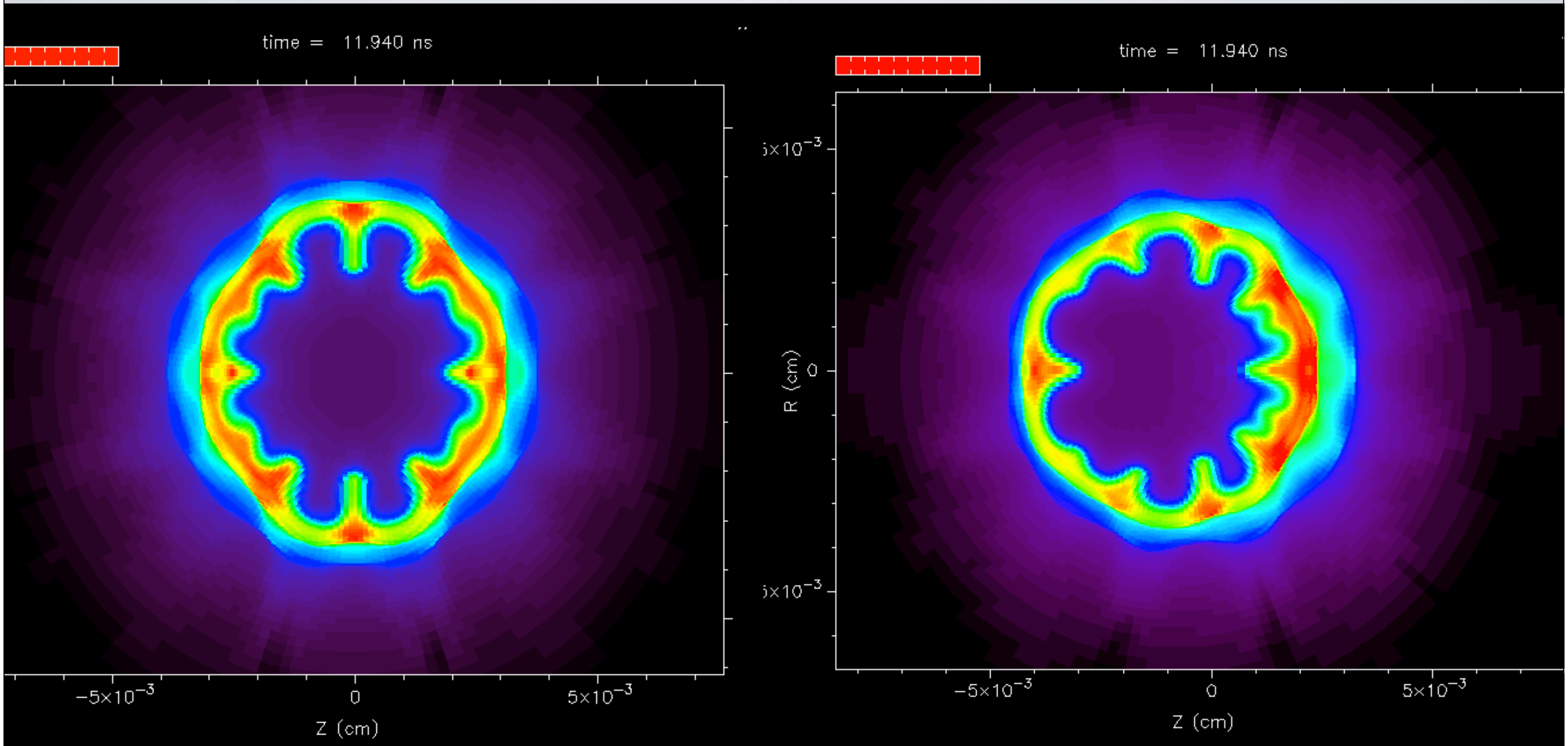
a) pulse generates imploding shock
b) imploding shock amplified as it converges
c) imploding shock progresses, while shock bounces from center
d) the two shocks collide, and launch new shocks; the imploding shock heats the hot spot



2D fluid implosion with 3D raytracing



Target displacement 1% (10 μm)



TP=0% TP=1%

ICF STATUS

- Central ignition: confirmation of proof-of-principle expected from NIF
- Advanced ignition schemes are promising, but with technological and physical issues still to be addressed
- Fusion reactor: needs high gain, high repetition rate
- Critical issues shared with MCF: tritium breading, material damage