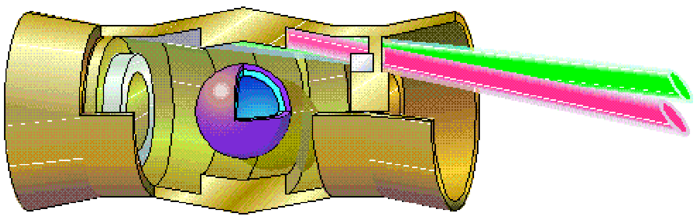
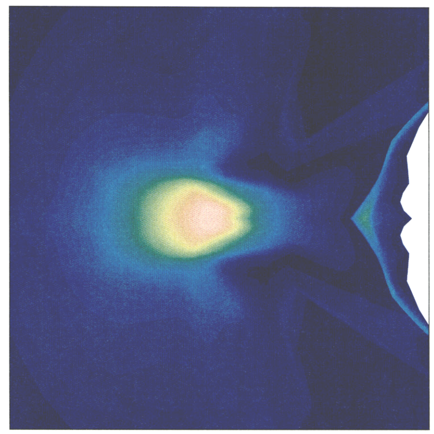
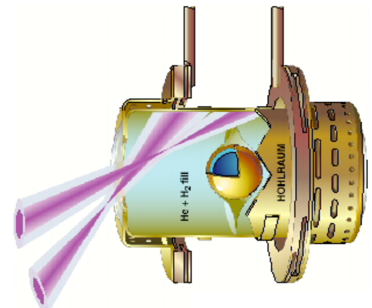
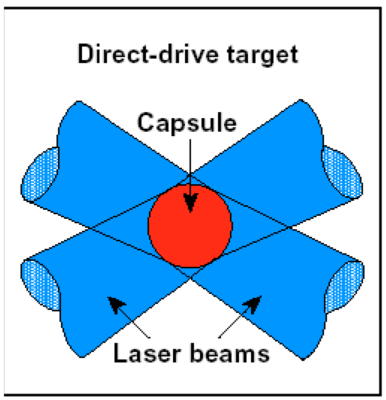
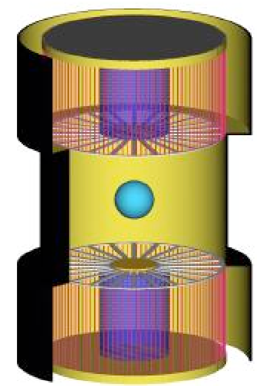
Inertial Confinement Fusion, High Energy Density Plasmas and an Energy Source on Earth











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American Association for the Advancement of Science

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We are making good progress toward achieving fusion ignition and high gain for energy applications

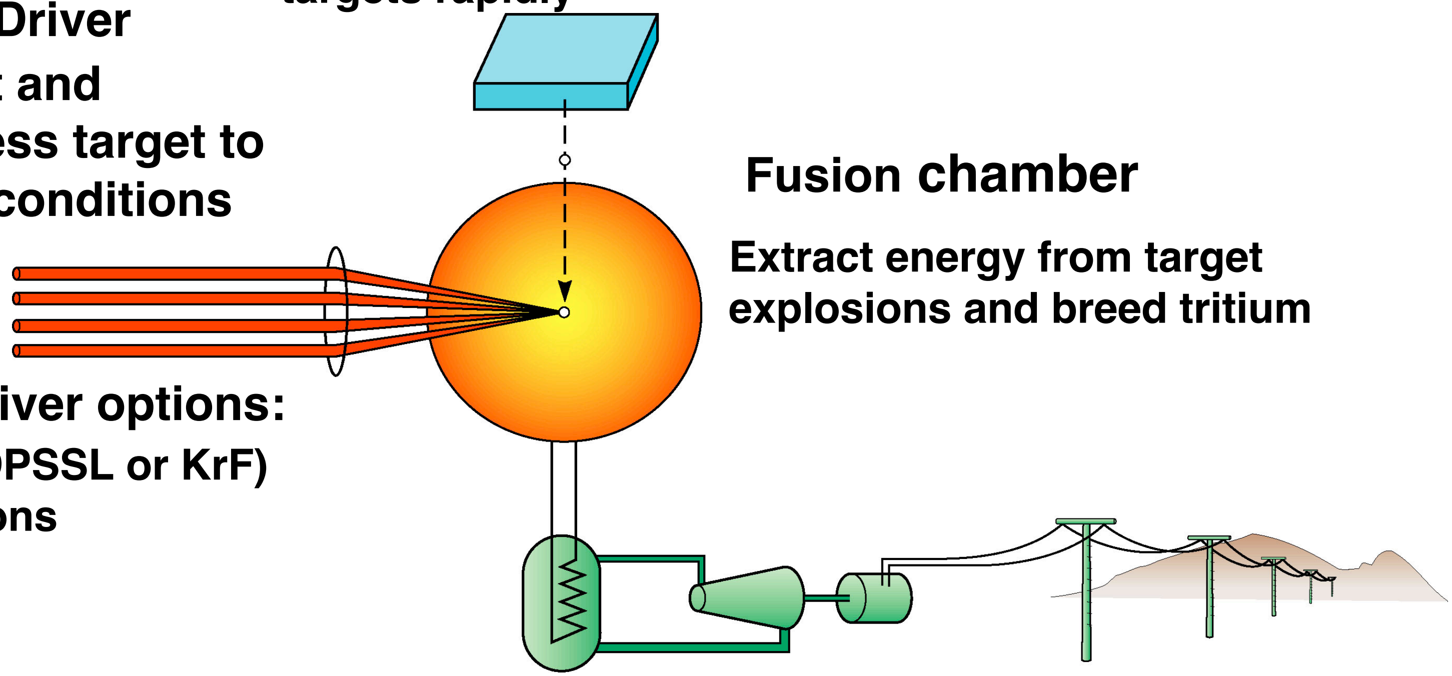
- **Recent design innovations have dramatically improved the robustness of inertial confinement fusion(ICF) targets**
- **Target designs exist that produce gain adequate for energy applications**
- **A wide variety of qualitatively different designs can be tested at the National Ignition Facility(NIF)**
- **NIF is scheduled for completion by 2009**
  - **Physics experiments have already begun**

Inertial Fusion Energy power plants have 4 parts

Target Factory
Needs to produce low cost targets rapidly

Driver
To heat and compress target to fusion conditions

Fusion chamber
Extract energy from target explosions and breed tritium



Driver options:
Laser (DPSSL or KrF)
Heavy Ions
Z-pinch

Steam plant to convert fusion heat into electricity

Target designs can be characterized by ignition method,compression method and driver

Driver

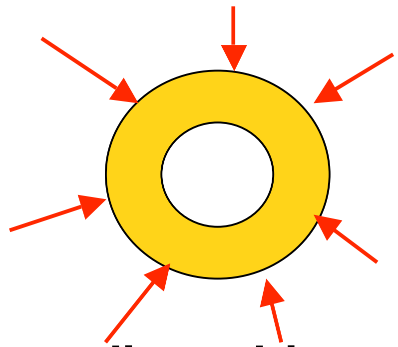
Laser
□=5-10%

Heavy ion Accelerator
□=15-40%

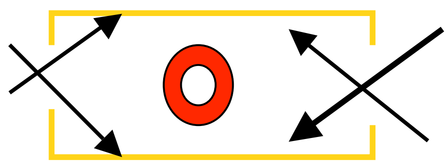
Z-pinch
□~15%

□G > 10 for energy

Compression

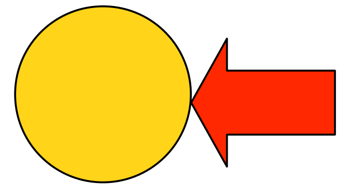


direct drive

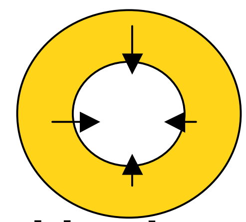


Indirect drive

Ignition



Fast Ignition



Ignition by stagnation of convergent flow

These schemes can be tested at the NIF

The inertial confinement process

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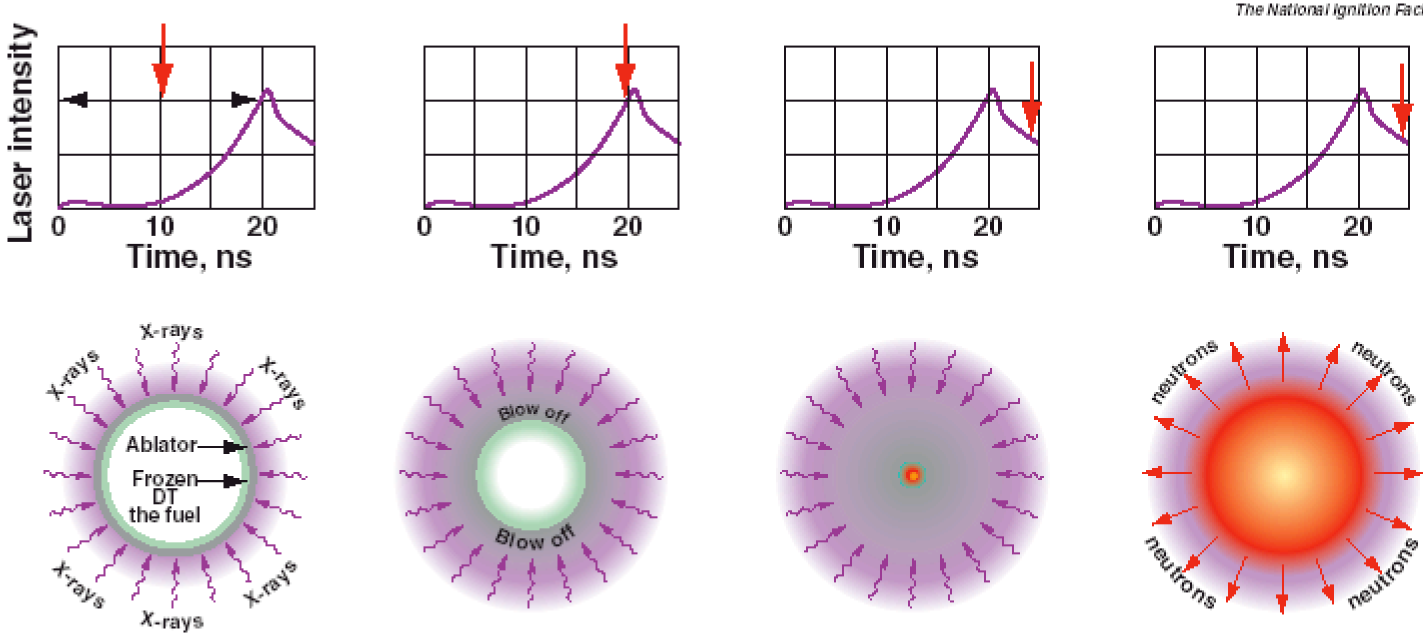


X-rays or driver beams heat ablator

Rocket reaction implodes fuel shell

Fuel shell stagnates

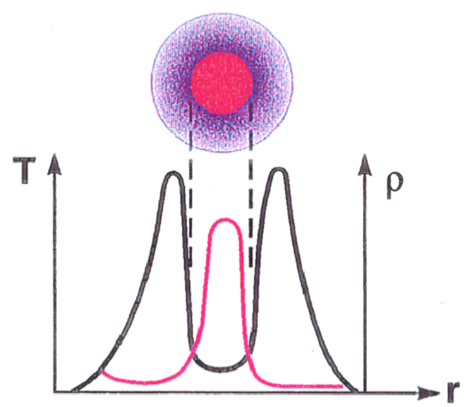
Ignition begins

Burn propagates to compressed outer fuel

Yield is produced

Technology advances had made innovative concepts possible: ultra-high brightness lasers may allow a fundamentally new method of igniting inertial fusion capsules

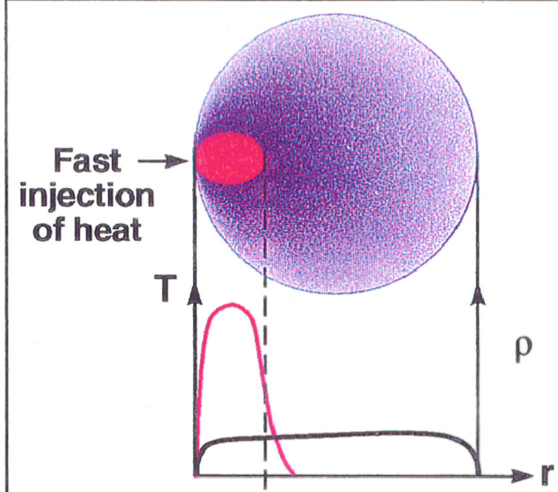
Conventional ICF



Shock heated central spot ignites a high density cold shell

$P_{HS} \approx P_c = \alpha \rho_c^{5/3}$

Fast Ignitor



Fast-e⁻ heated side spot ignites a lower density, larger uniform fuel ball $P_{HS} >> P_c$

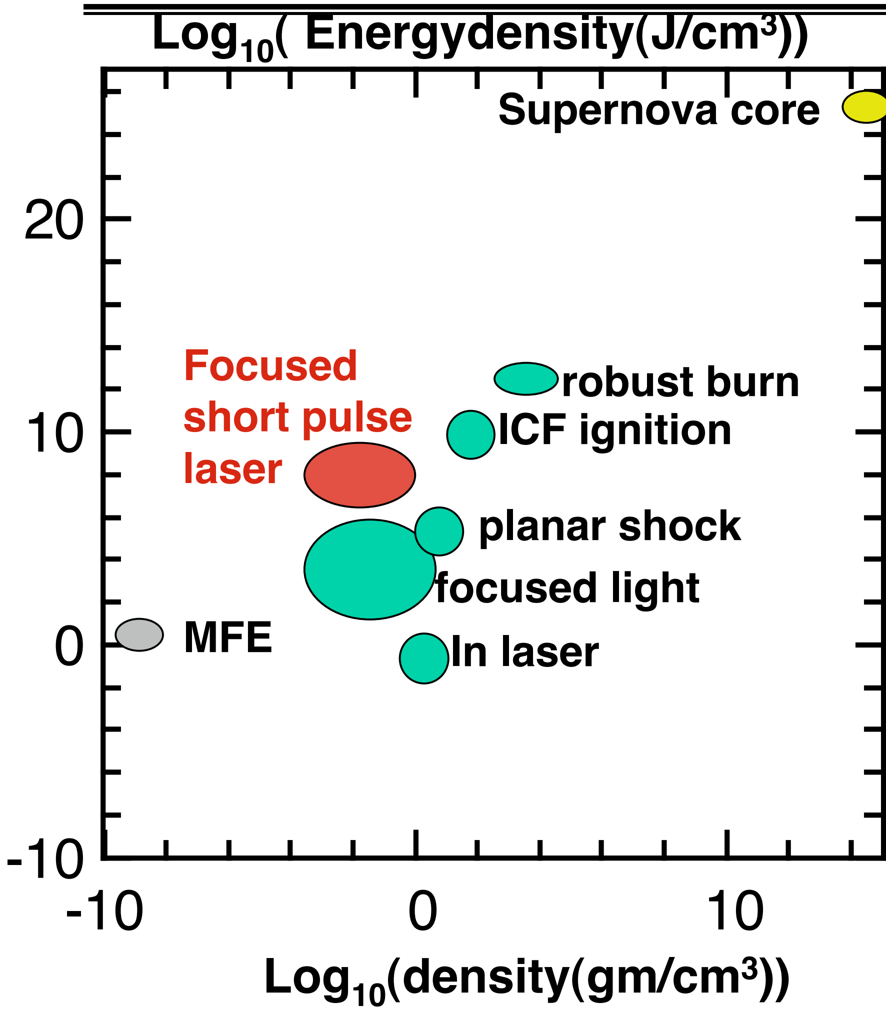
* Tabak, Hammer, Glinsky, Kruer, Wilks, Woodworth, Campbell, & Perry *Phys. Plasmas* **1**, 1626 (1994).
** H. Azechi et al., *Laser Part. Beams* **9**, 2 (1991).

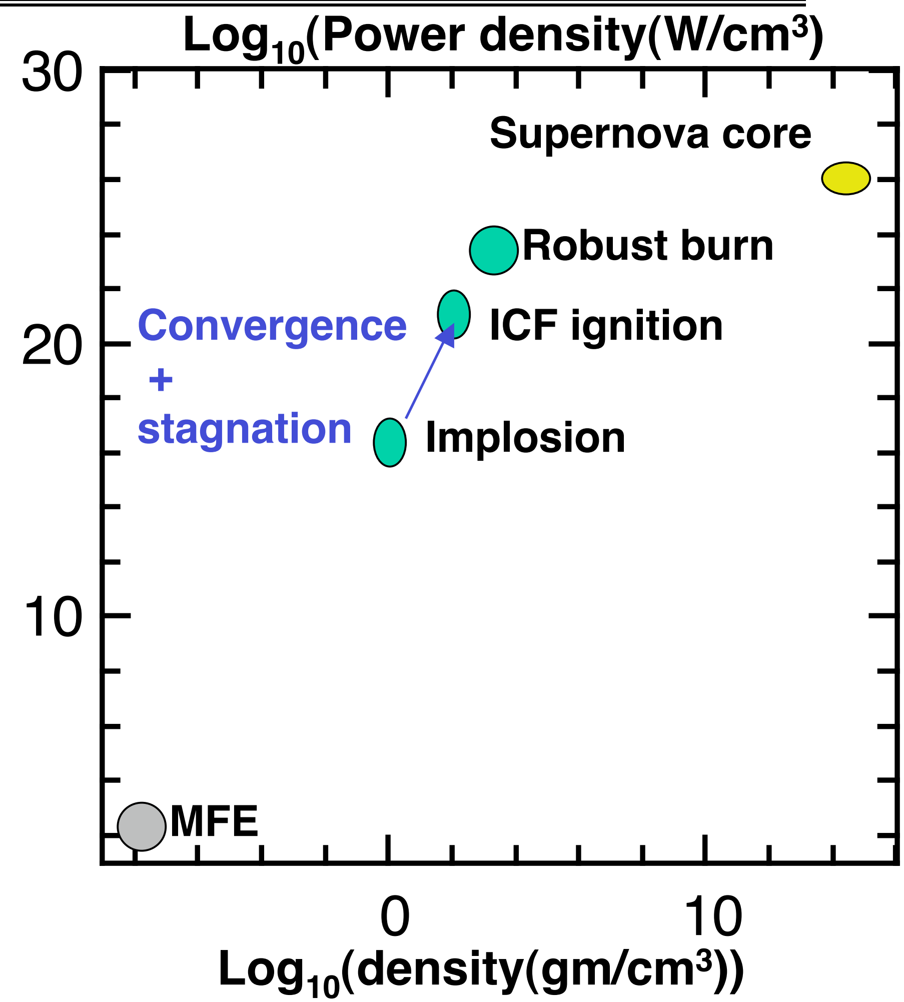
Advantages of Fast Ignitor

- Fast Ignitor implosions are less stressing: (mix, convergence, ...)
- Lower $\rho \Rightarrow$ more mass to burn ($E_c \approx \alpha\, M_c \rho_c^{2/3}$) $\Rightarrow$ Higher Gain

Significant R&D is required to explore potential of this concept

ICF ignition requires large energy and power densities





Achieving the necessary multiplication of power,energy and mass densities requires a well controlled implosion

- The fuel must be driven with a well timed sequence of weak shocks so that its entropy is minimized
- The pressure must be symmetrically applied
- Hydrodynamic instabilities must be mitigated

Implosion symmetry is an important issue for high convergence ratio targets

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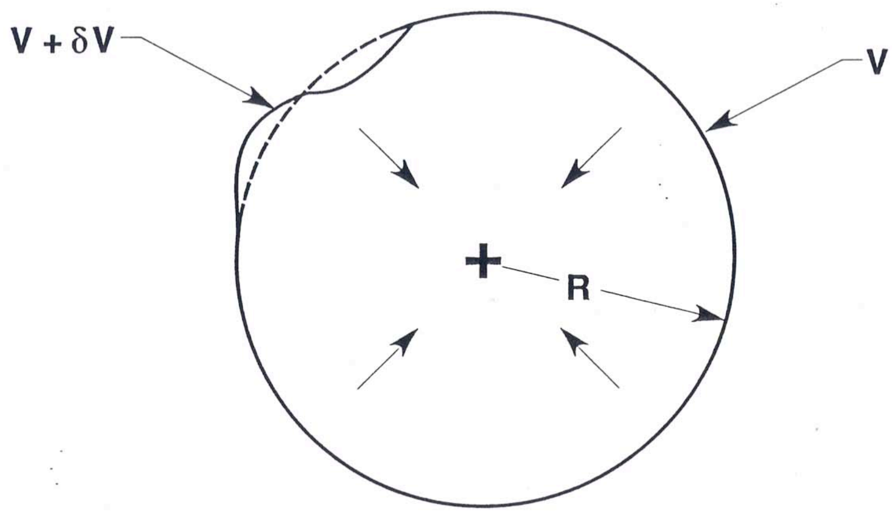
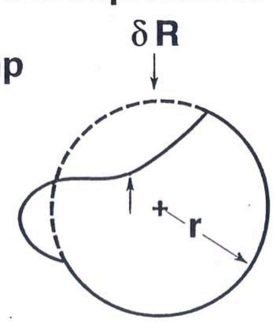
Small nonuniformity when outershell is at large radius



Becomes magnified when shell is imploded to a very small radius

Lower peak compression, temp
Lower ρR



Typical convergence ratios >30 require δv/v ~1% so converged δR/R < 1/2

60 beams is adequate for directly driven targets

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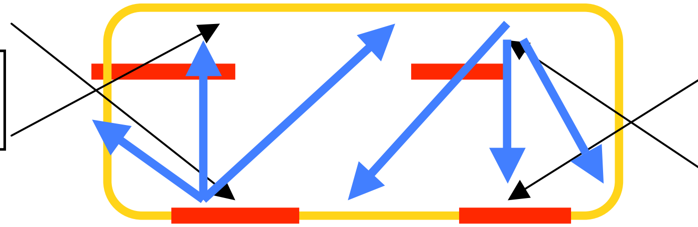
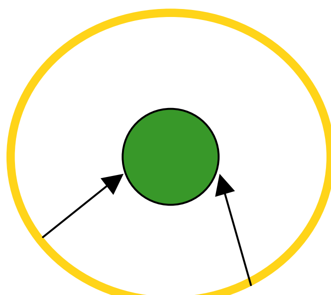
Radiation symmetry in indirectly driven targets is controlled by three factors

1

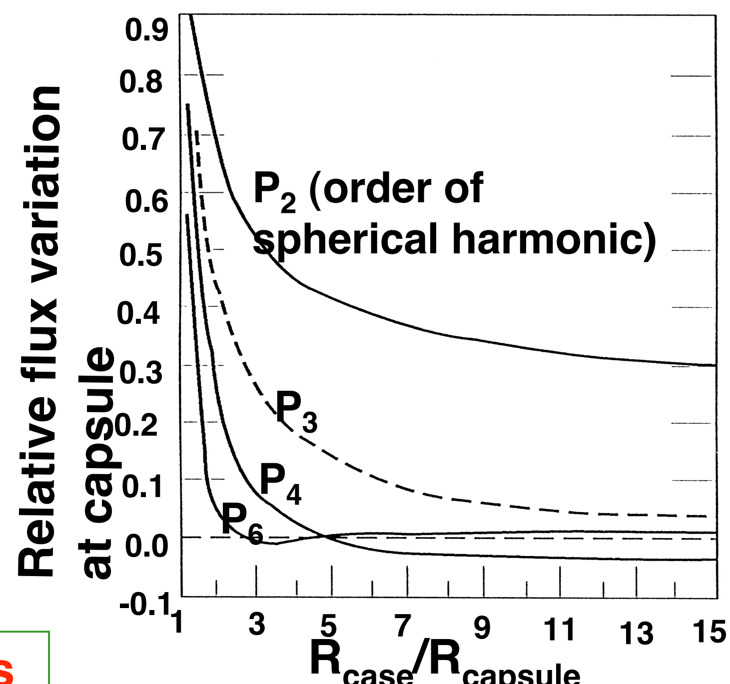


Hohlraum re-radiation smoothes wall flux by number of reemissions before absorption

2



Wall to capsule transport smoothes high l modes



3

Appropriate location of beam spots eliminates low order modes

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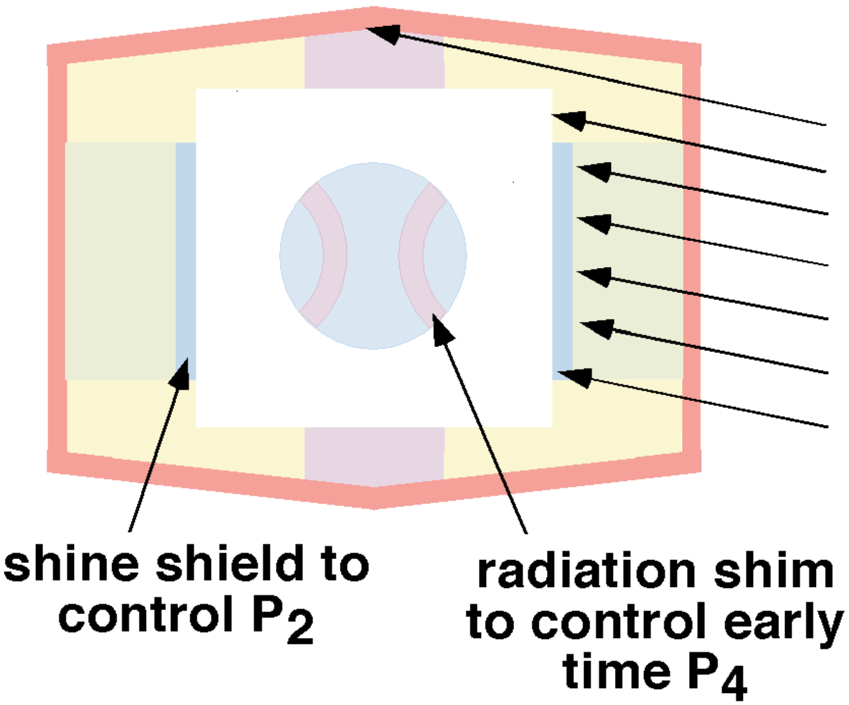
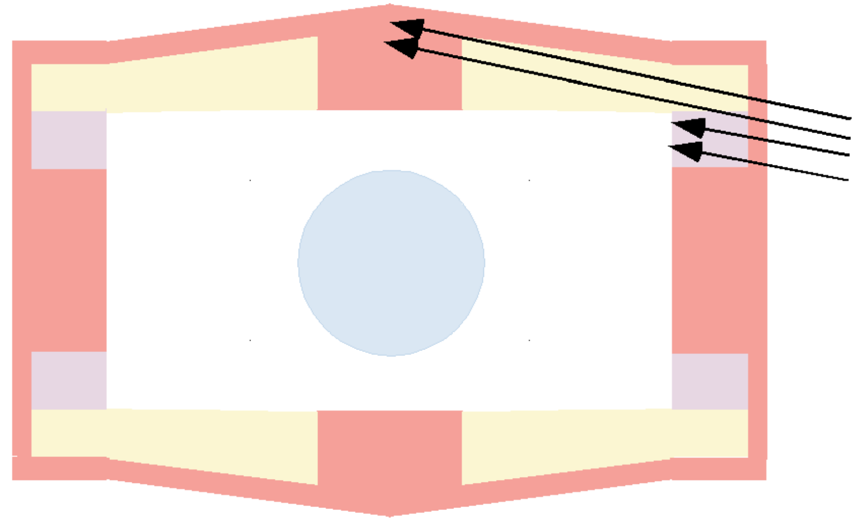
We are using internal hohlraum shields to develop distributed radiator targets with larger beam spots





original distributed radiator target

Beam spot: 3.8 mm x 5.4 mm
Effective radius: 4.5 mm

6.7 MJ beam energy
Gain = 58

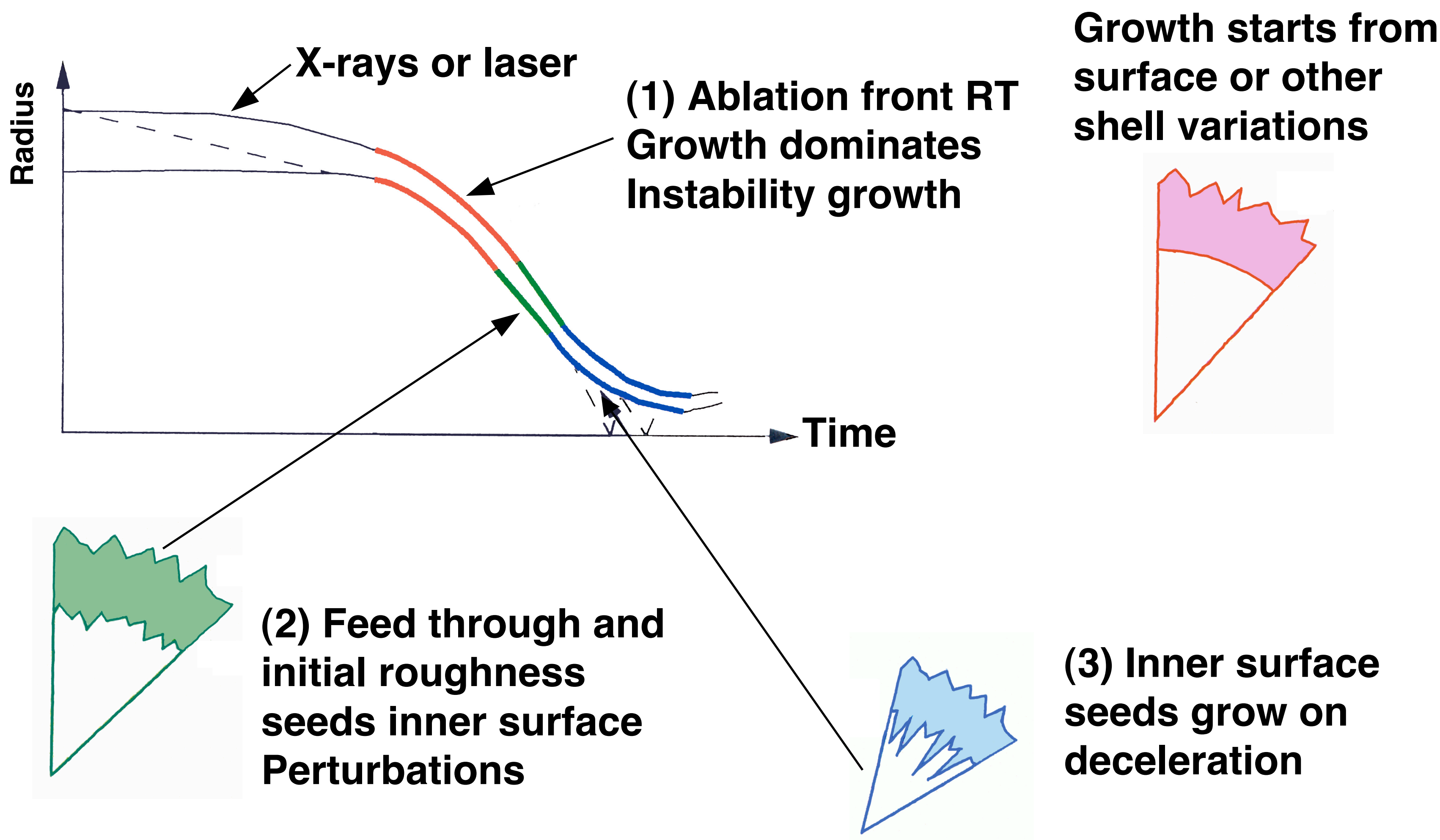
Beam spot: 1.8 mm x 4.1 mm
Effective radius: 2.7 mm

5.9 MJ beam energy
Gain = 68

66% increase in beam radius with a 14% increase in beam energy

Callahan-Miller 7/00

The ablation front hydrodynamic instability can destroy an imploding shell



Hydrodynamic instabilities can be mitigated by design choices

- Appropriate choice of ablator materials
- Appropriate choice of pulse shape

New designs using Be with graded Cu dopant are spectacularly robust

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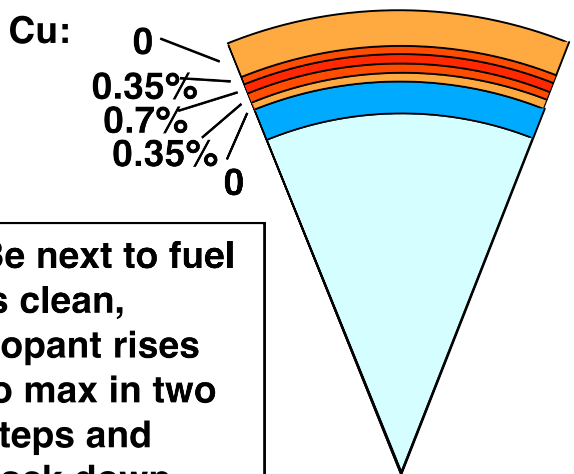
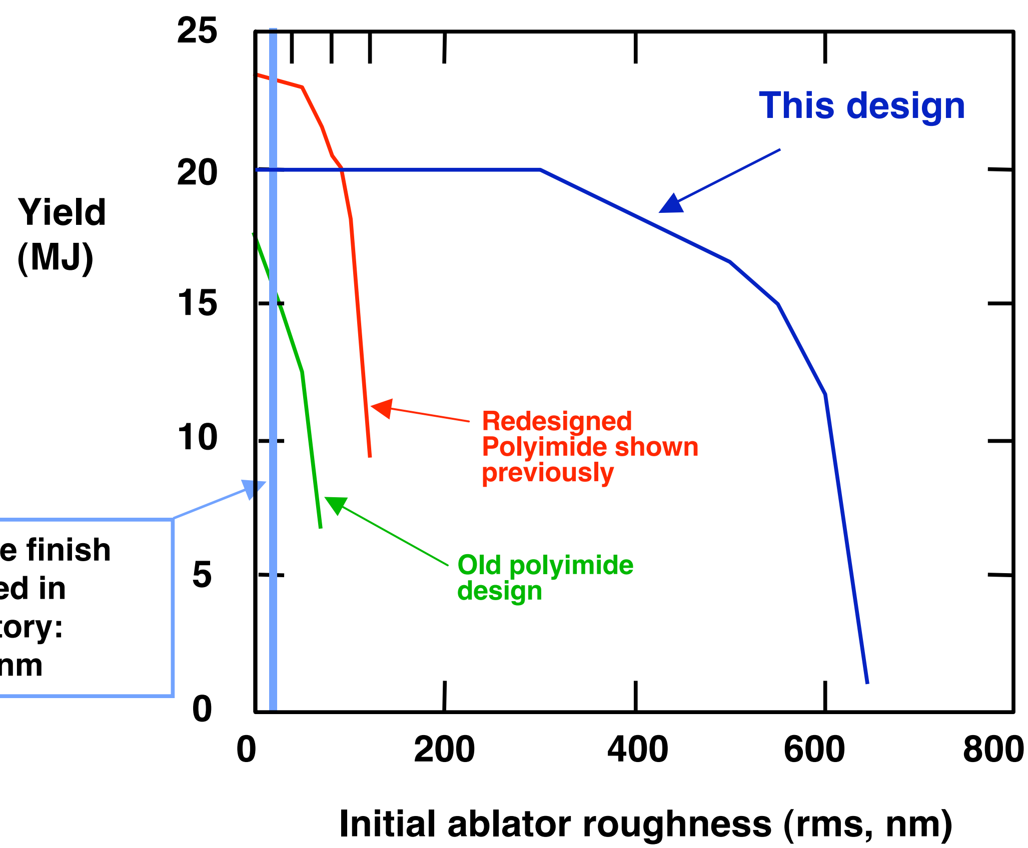


Be next to fuel is clean, dopant rises to max in two steps and back down again



CH surface finish achieved in laboratory: 20±5 nm

For short wavelength RT, this capsule can tolerate a roughness 30 times greater than typical CH capsules produced in the laboratory =>IFE targets driven with low intensity laser or ion beams

Baseline ignition target has been redesigned using 3D code Hydra, and simulated with full asymmetry + capsule perturbations

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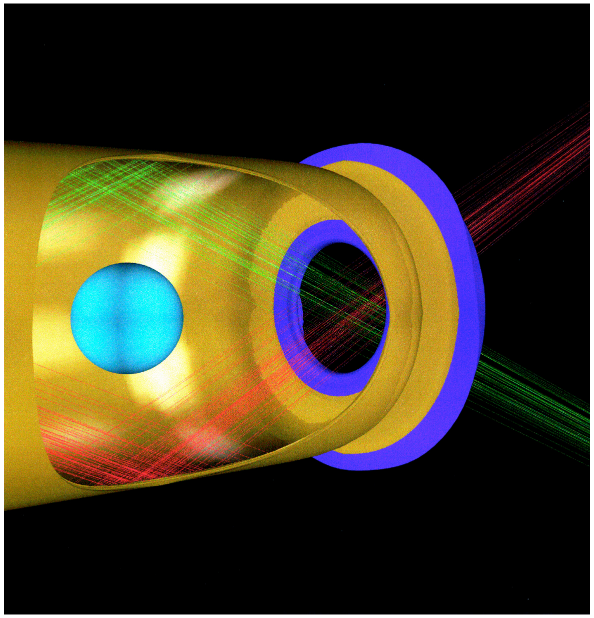
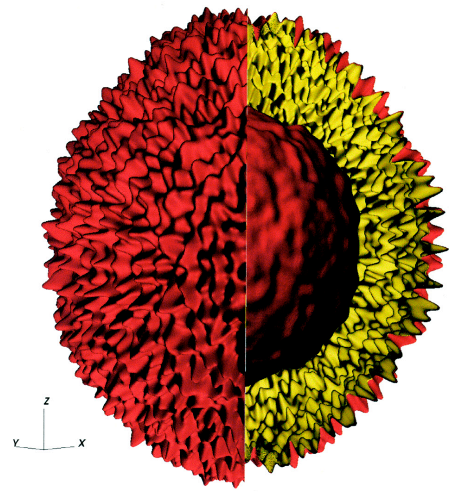
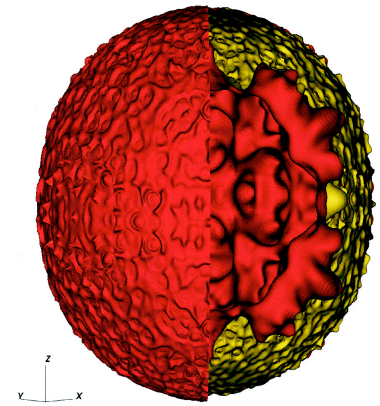




140 ps before ignition time, 60 g/cc density isosurface



Ignition time, 400 g/cc density isosurface (not to scale)

Hohlraum simulations use 15 million Monte Carlo photons,

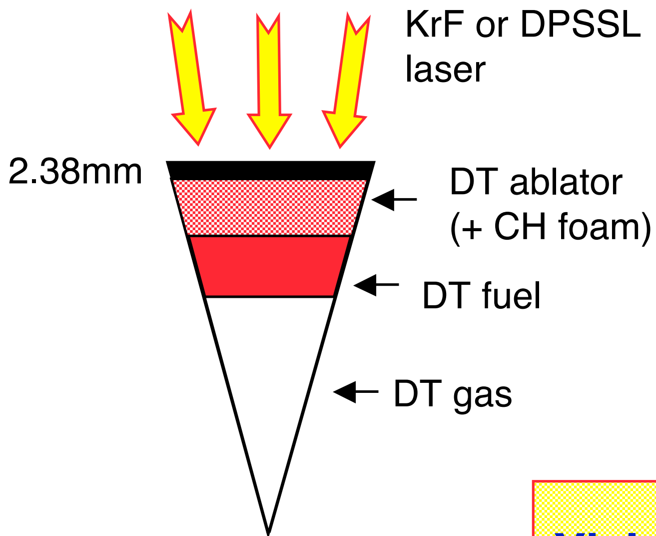
1200 rays/beam laser raytrace

NLTE, Arbitrary Lagrange Eulerian grid motion

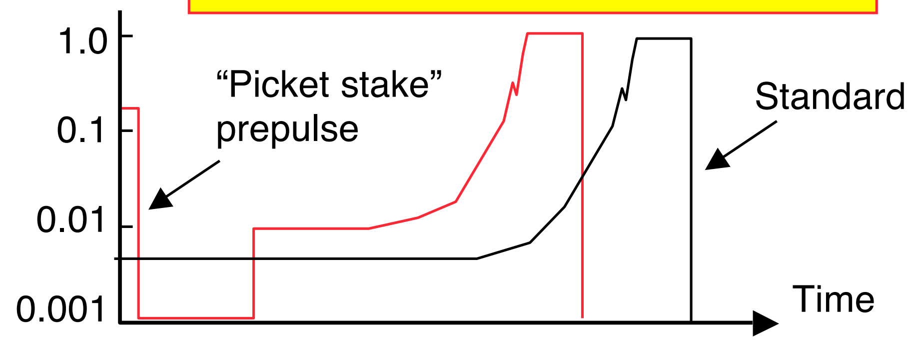
Hohlraum redesigned — LEH liner, gas fill, cone-to-cone ratio, pointing

Capsule simulations use 12.8 million zones, 120 processors. Include intrinsic drive asymmetry, full spectrum of contributing capsule perturbations $l \geq 2$. Yield 22 MJ (versus clean 24 MJ)

Through Innovative Laser Pulse Shaping we have Significantly Improved the Stability of High-Gain Direct-Drive Targets for Inertial Fusion Energy



Laser Power Pulse Shape



Yield ***350MJ***

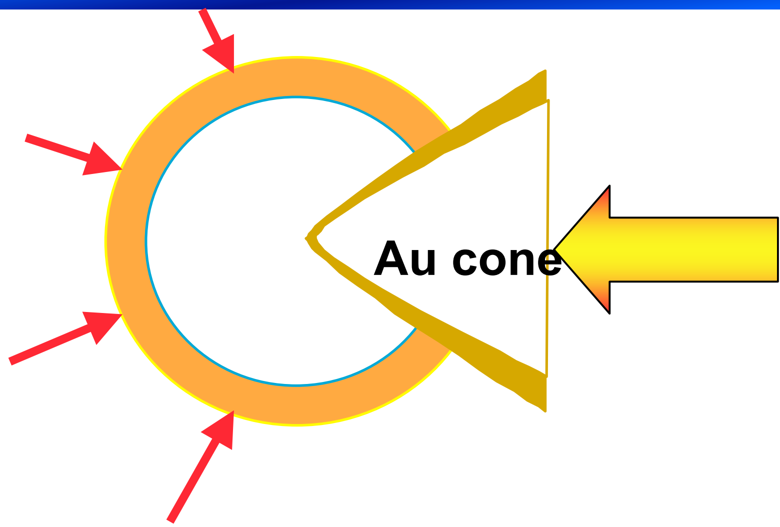
E_{laser} ***2.9MJ***

Gain ***120***

Shell breakup fraction:

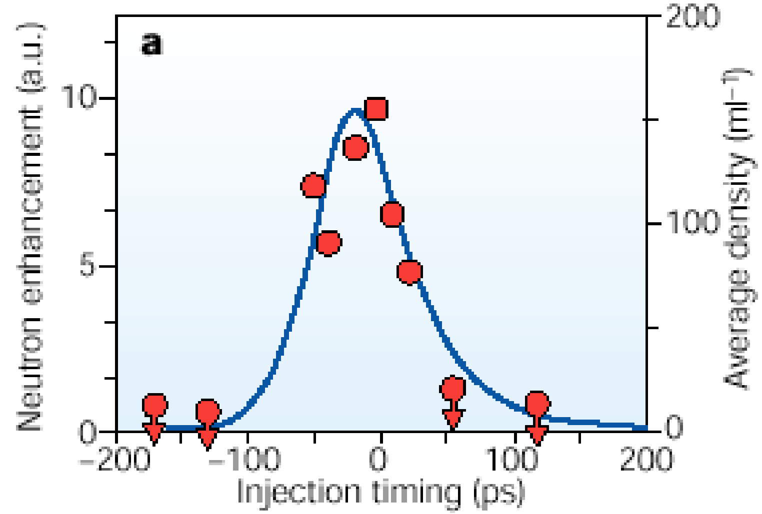
- ***Standard pulse ~1.8***
- ***Picket pulse ~0.15***

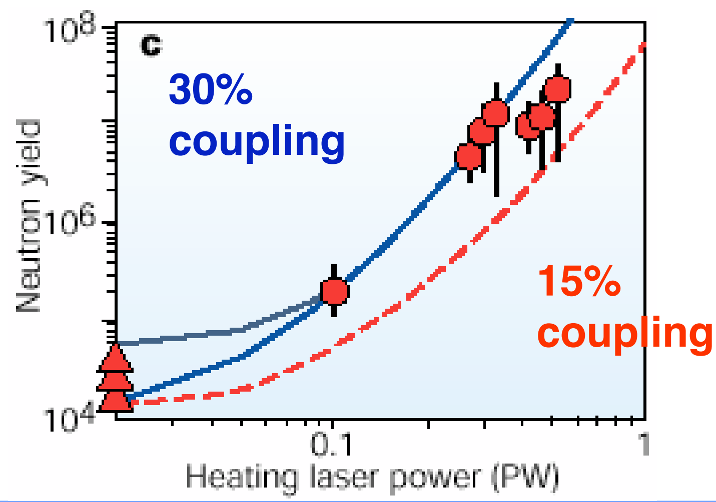
Fast Ignition results from ILE,Osaka are encouraging



Light propagates down cone axis and couples near tip producing relativistic electrons

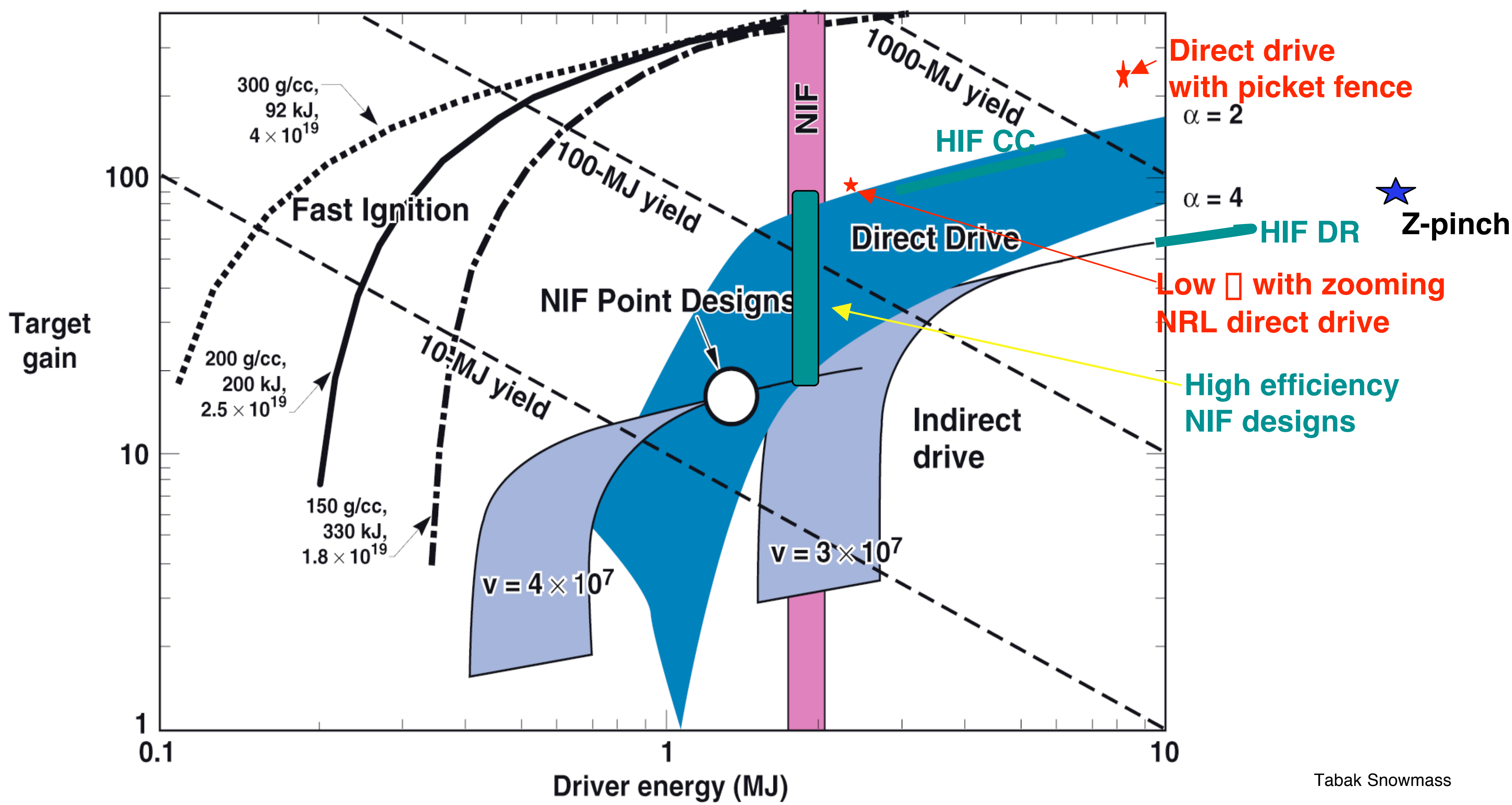
Electrons couple to compressed fuel





Infer 15-25% coupling efficiency from laser to compressed fuel!

Target designs with varying degrees of risk provide adequate gain for all driver concepts



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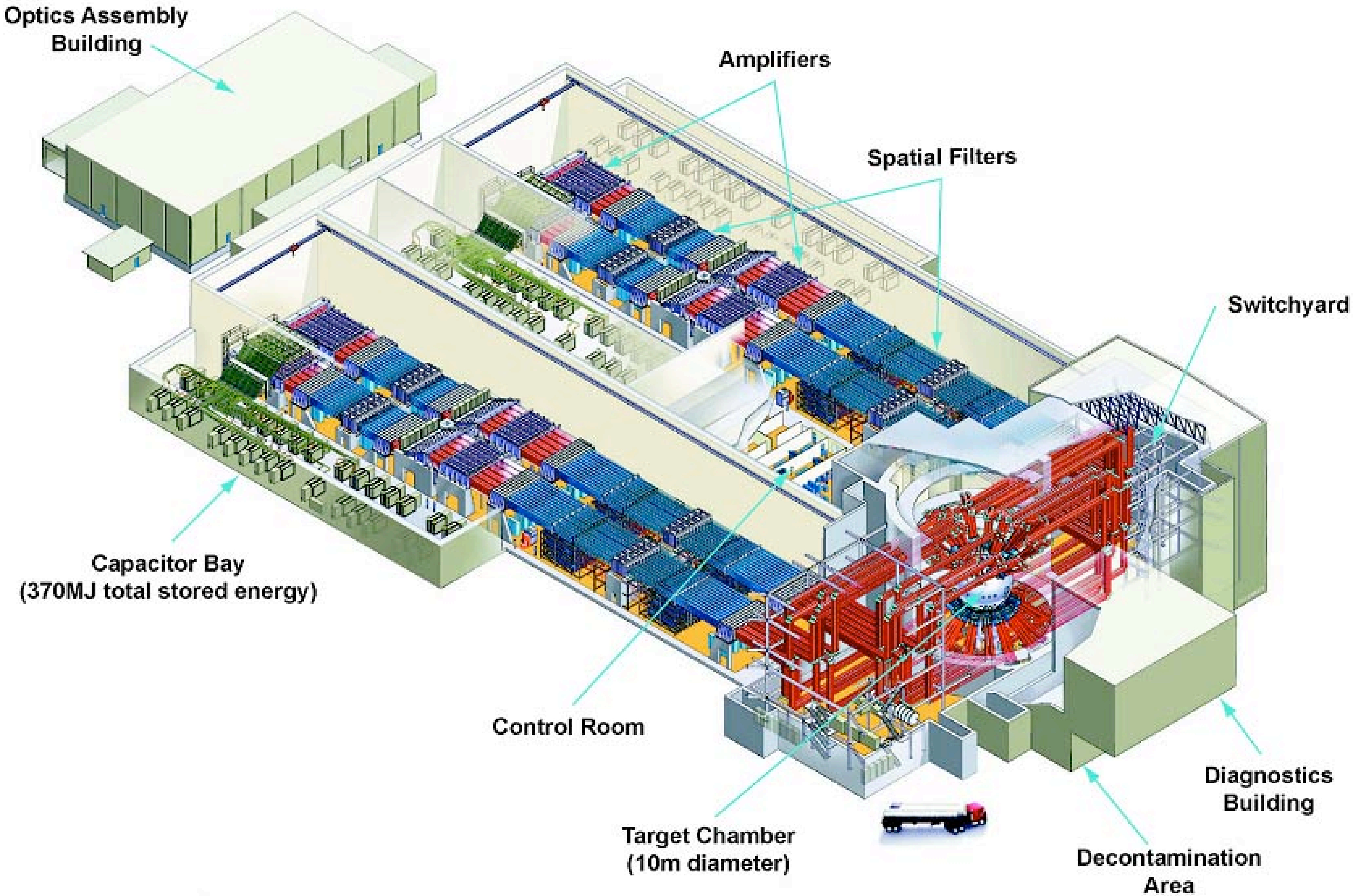
The National Ignition Facility (NIF), a nominally 1.8MJ/500TW blue laser being built at Livermore, meets the requirements for ignition

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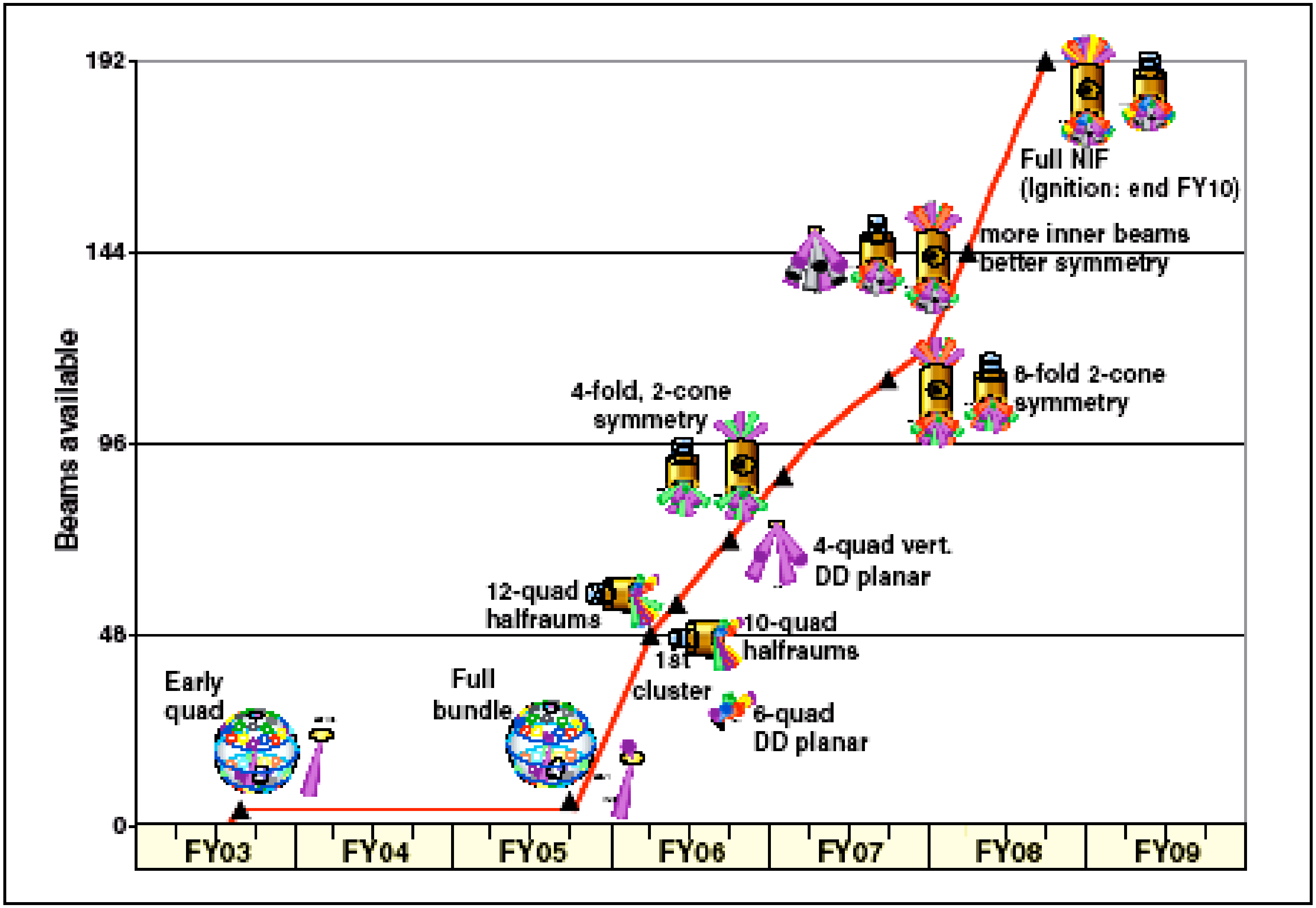
Support infrastructure is completed in laser Bay 1

Planned deployment of additional NIF laser beams

The National Ignition Facility



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