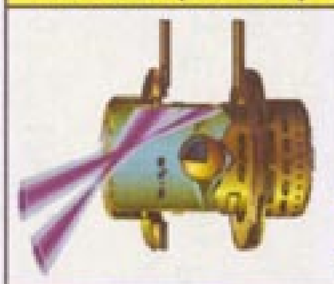
# Target Physics Issues for Inertial Fusion Energy

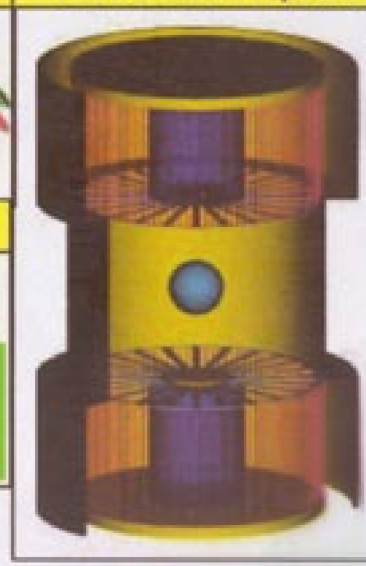
NIF laser (2x scale)

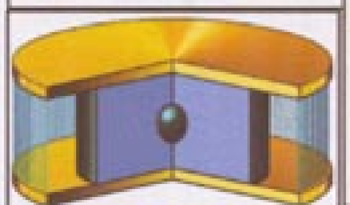


HI distributed radiator

HI hybrid target

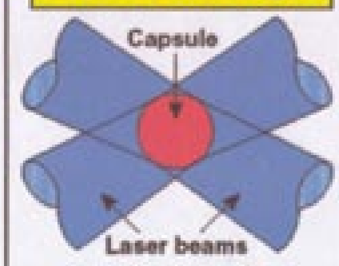
Double-ended Z-pinch





Dynamic Hohlraum

Direct drive target

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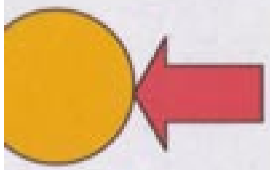
sion Summer Study
owmass,Co
ly 8,2002

Max Tabak
LLNL

Identifying Mark--

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

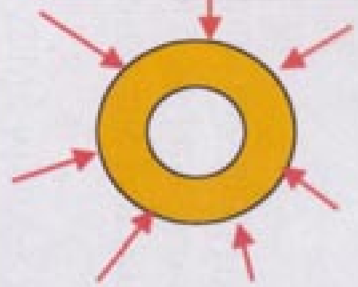
### gnition



Fast Ignition

gnition by
tagnation of
onvergent flow

### Compression



direct drive

Indirect drive

### Driver

Laser
$\eta$=5-10%

Heavy ion
Accelerator
$\eta$=15-40%

Z-pinch
$\eta$~15%

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# How do targets interface with the rest of the IFE system?

- Sets driver requirements
  - Scale and pulseshape(adiabat control) required to meet G
  - Illumination geometry and precision: symmetry control
  - Beam quality and smoothness: hydro & plasma instabilities
  - Beam brightness:convergence ratio or Fast Ignition requirement
- Sets fabrication requirement
  - Ablator/DT smoothness : residual Rayleigh-Taylor instability
  - Hohlraum design&materials: symmetry control &efficiency
- Delivers photon,neutron and debris insult to first wall and optics

**Require sufficient gain(G) q.v. $\eta G > 10$: CoE**

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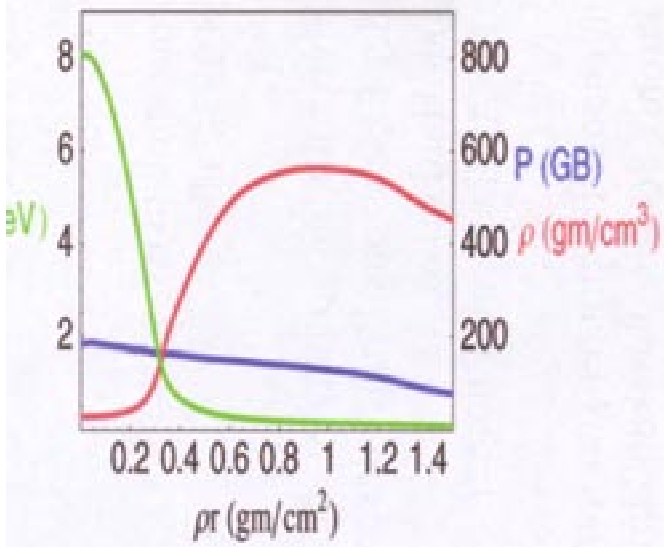
# here are several factors that control gain

- Optimal 1-D behavior
  - Entropy management by pulseshaping  and control of preheat
  - Minimum implosion velocity = v($\alpha$, Pr, E )
  - Rocket efficiency
- Hydrodynamic instability growth must be minimized to control shell breakup and  mixing of high(hotspot) and low(main fuel) entropy regions
- Implosion symmetry must to controlled so that all fuel elements stagnate simultaneously in a compact mass
- Coupling efficiency set by beam-plasma coupling and symmetry requirements

# The ignition energy can be estimated assuming an isobaric hot spot




Energy accounting:

$$E_c + E_h \sim \alpha_{stag}^{3/5} P_s^{2/5} M_c + C \frac{(\rho_h R_h)^3 T_h^3}{P_s^2}$$

optimizing over $P_s$

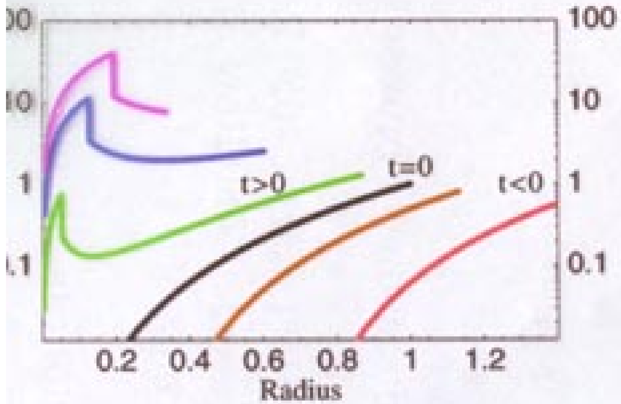
$$E_{ign} \sim \alpha_{stag}^{1/2} M_c^{5/6} \sim \alpha_{stag}^{1/2} \left( \frac{E_{ign}}{v^2} \right)^{5/6}$$

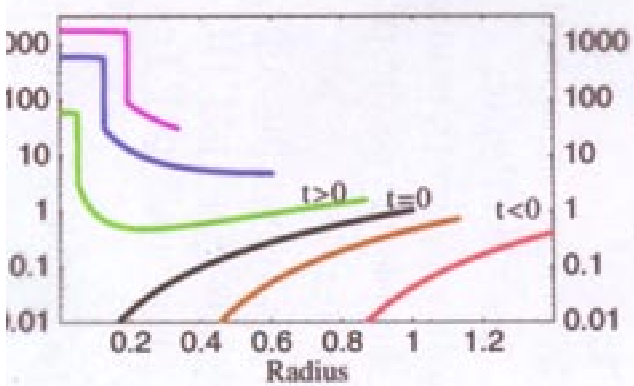
$$E_{ign} \sim \alpha_{stag}^{3}\, v^{-10}$$

tailed numerical
ulations give:

$$E_{ign}(kJ) = 2.1 \alpha_{stag}^{2.7} \left( \frac{v}{3 \cdot 10^7 \text{ cm/sec}} \right)^{-7.2}$$

## Self-similar implosions suggest the stagnation adiabat depends on $\alpha_{if}$,v,P




Meyer-ter-Vehn and Schalk found:

$$\rho_f \approx 2.4\rho_0 M^{1.5} \quad P_f \approx 3.6 P_0 M^3$$

$$\alpha_{stag} \sim \frac{P_f}{\rho_f^{5/3}} \sim \alpha_{if}\sqrt{M}$$

$$\alpha_{stag} \sim \alpha_{if}^{0.85} \mathrm{v}^{0.5} P^{-0.1}$$

From numerical simulations:

$$E_{ign}(\mathrm{kJ}) = 50.8\alpha_{if}^{1.88}\mathrm{v}^{-5.89}P^{-0}$$

v in units of $3*10^7$ cm/sec

P in units of 100MB

# he Rayleigh-Taylor instability is one of the key hysics issue facing IFE

A target will fail if the perturbation amplitude (a) equals the shell thickness ($\Delta R$).

Perturbations grow exponentially:

$$a_L(t) = a(t_0)e^{\gamma t}$$

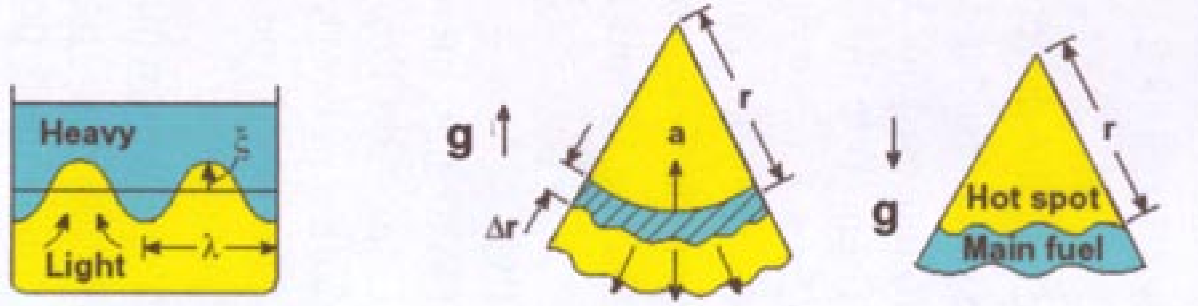
$$\gamma = \sqrt{Akg} - \beta k V_A$$

← Ablative stabilization term ($\beta k V_A$)

$$v_a = \frac{\dot{m}}{\rho_{peak}}$$

until saturation

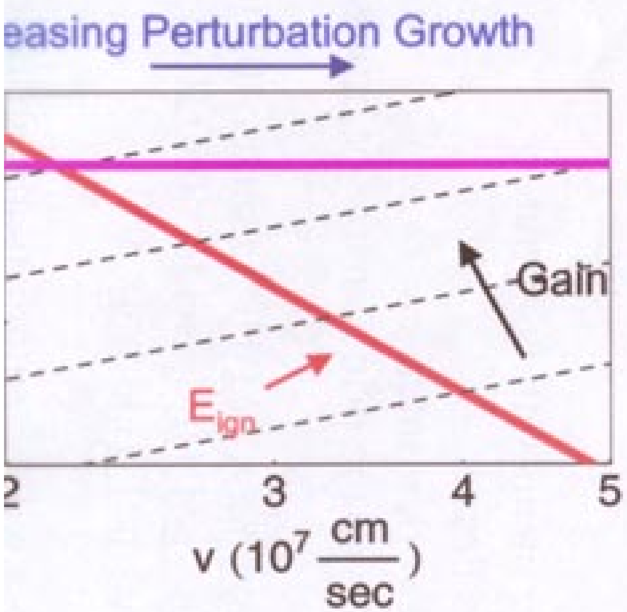
$$a(t) = a_{sat}\{1 + \log[a_L(t)/a_{sat}]\}$$




classical    acceleration    deceleration

# psule optimization involves trading off robustness versus perturbation growth

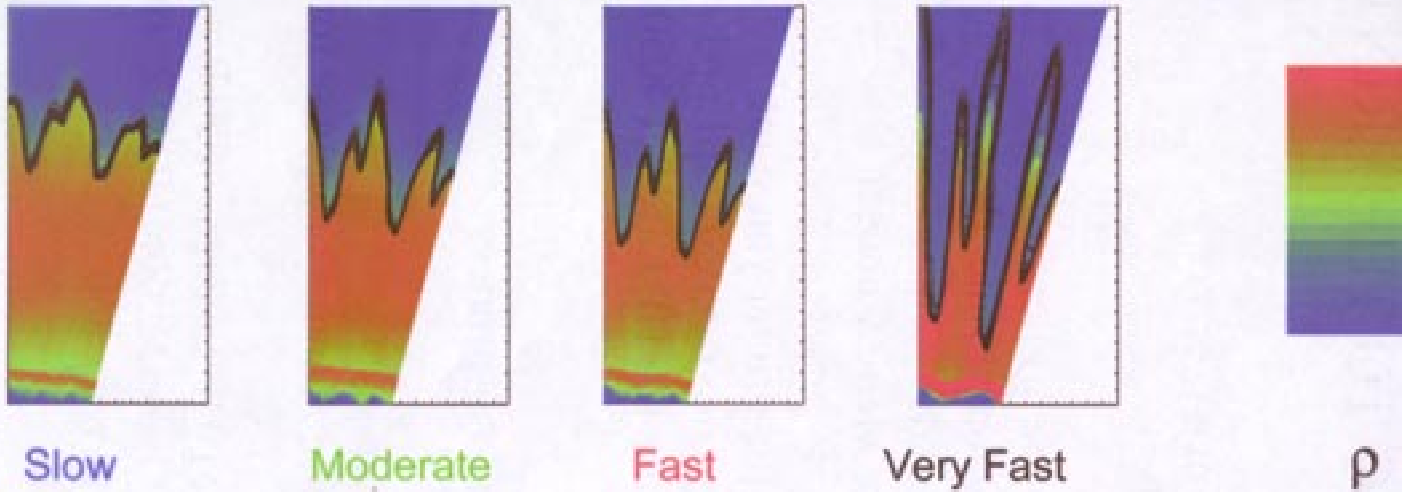
me fixed adiabat, drive pressure, and fuel energy




For fixed capsule absorbed energ
which velocity is best?

| | Low Velocity | High Velo |
|---|---|---|
| Perturbation Growth | Low | High |
| Gain | High | Low |
| Margin | Low | High |

## etailed numerical simulations with imposed rface roughness show the fastest shell is most sceptible to shell breakup



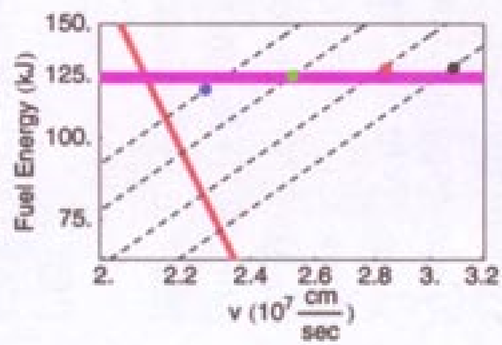


$R_{outer}$ ~2.3 mm

$E_{abs}$~900 kJ

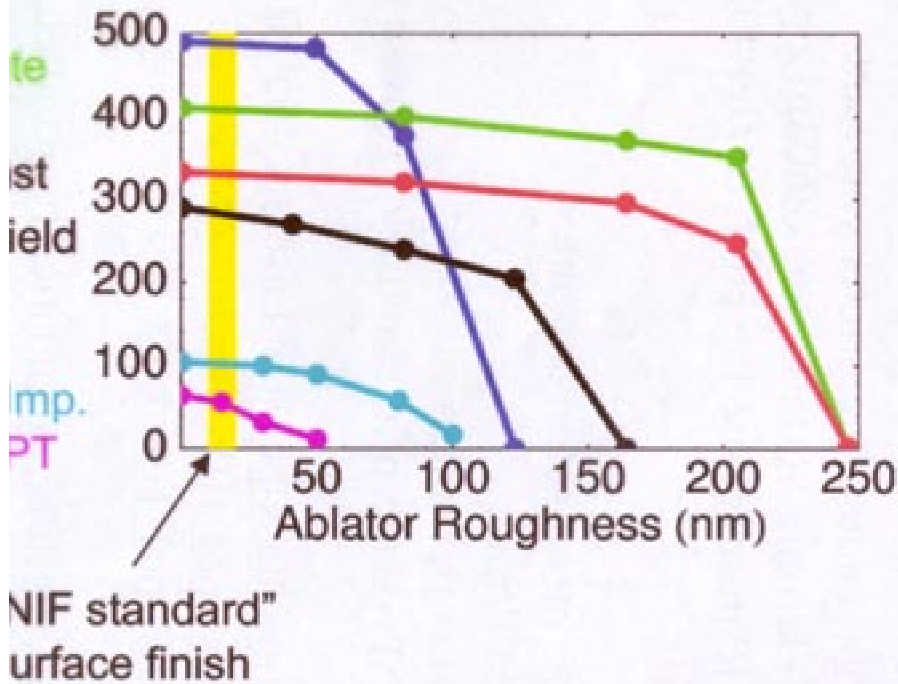
$T_{foot}$~ 80 eV

$T_{rmax}$~ 265 eV




All four capsules sta
with 8x NIF standar
ablator roughness a
standard ice roughn

# High-yield plastic capsules can tolerate ablator roughness ~10-20x NIF standard




For this configuration:

•Slow capsule fails due to
cold fuel into the hot spot

•Very Fast capsule fails d
"shell breakup"

•Moderate and Fast capsu
(Margin 1.3-1.6) are most

•Slow capsule gives highe
gain for roughness < 80nr

**NIF and High Yield Capsules show similar trade between 1-D robustness and perturbation grow**

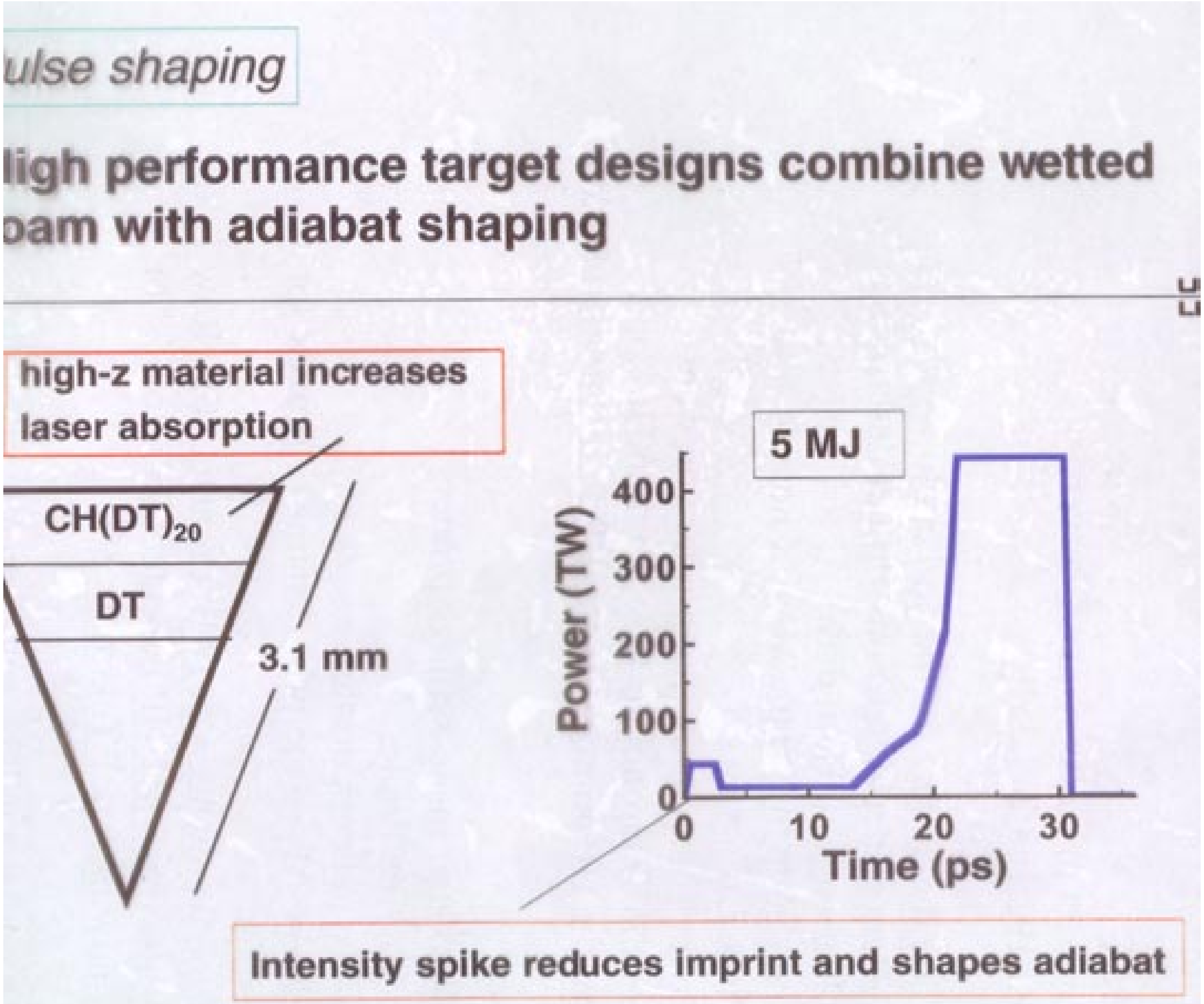
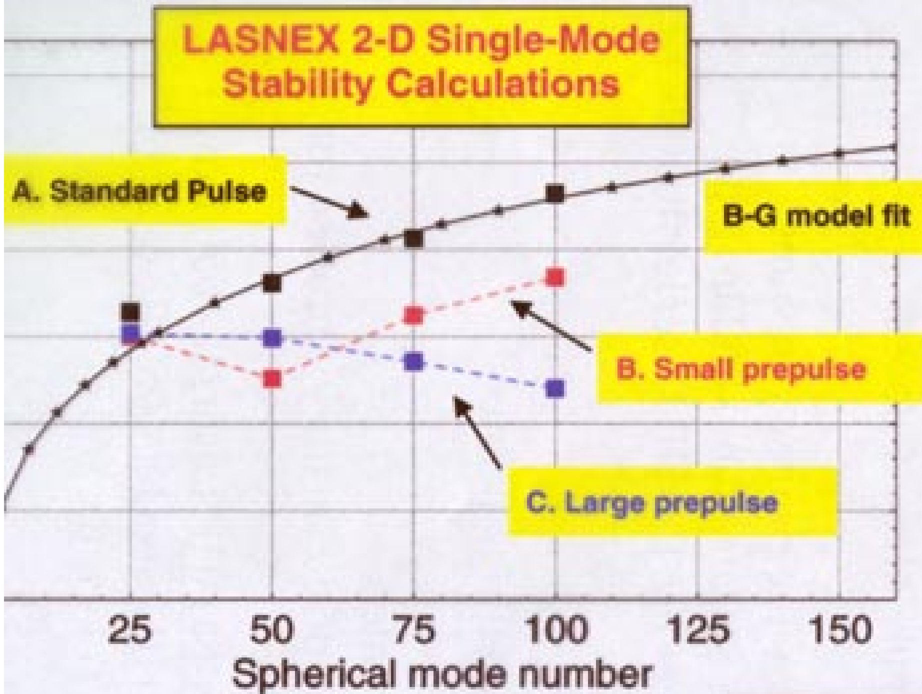
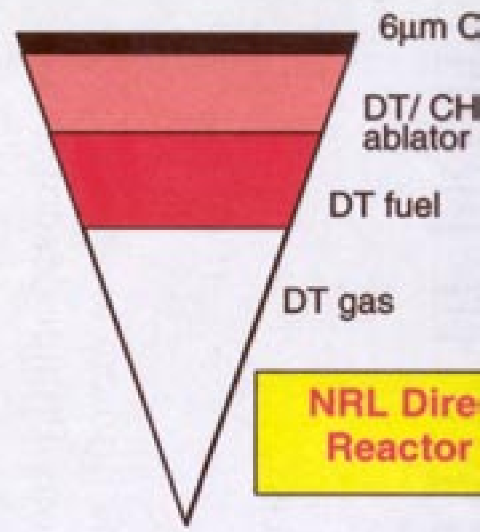
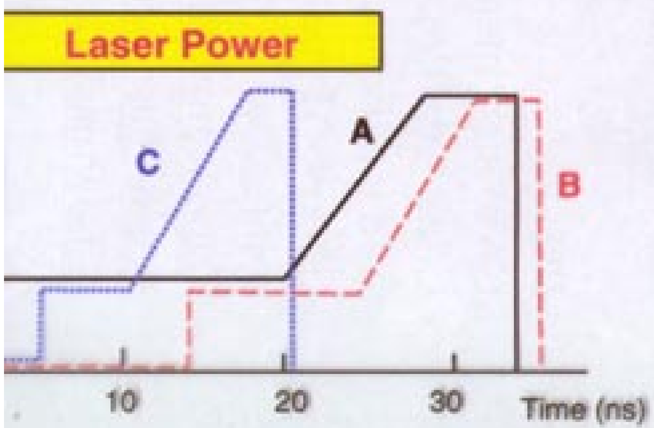

ulse shaping
ligh performance target designs combine wetted
oam with adiabat shaping
high-z material increases
laser absorption
CH(DT)20
DT
3.1 mm
5 MJ
Power (TW)
400
300
200
100
0
0
10
20
30
Time (ps)
Intensity spike reduces imprint and shapes adiabat

Fig. 1

## ing the Laser Pulse Offers Large Improvements n Stability for the Same Direct Drive Target



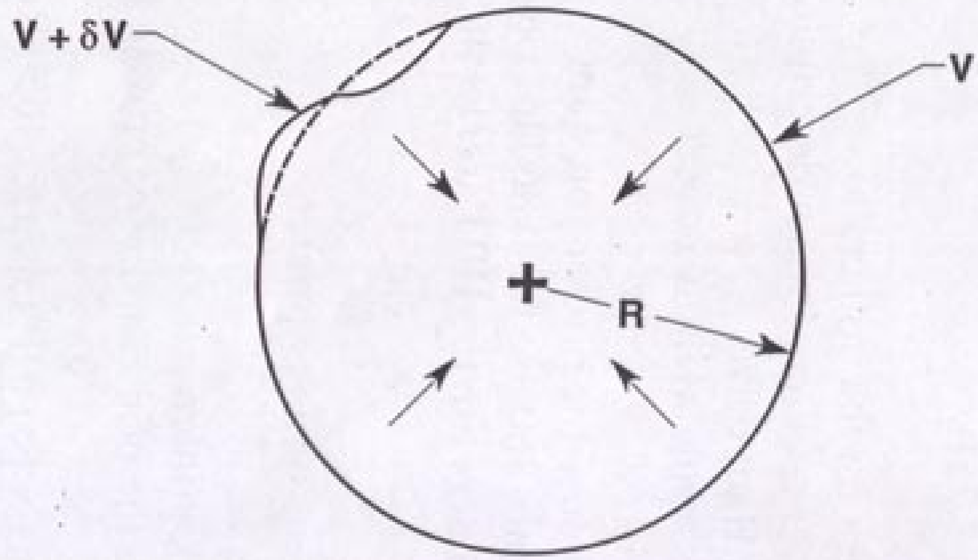




| Pulse Shape | Laser (MJ) | Yield (MJ) | Gain | M<br>Breal |
|---|---|---|---|---|
| A. Standard | 2.4 | 430 | 180 | |
| B. Small prepulse (small "picket) | 2.5 | 420 | 170 | |
| C. Large prepulse (large "picket") | 3.1 | 360 | 110 | |

*With contributions from A. Schmitt (NRL), R. Be* nmetry

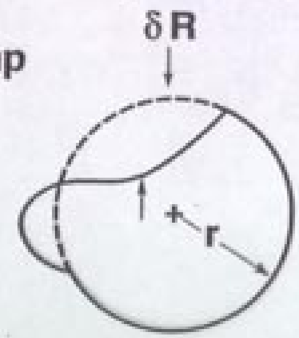
# losion symmetry is an important issue for ı convergence-ratio targets

Small nonuniformity when outershell is at large radius




ecomes magnified when shell is imploded to a very small radius

wer peak compression, temp
wer ρR

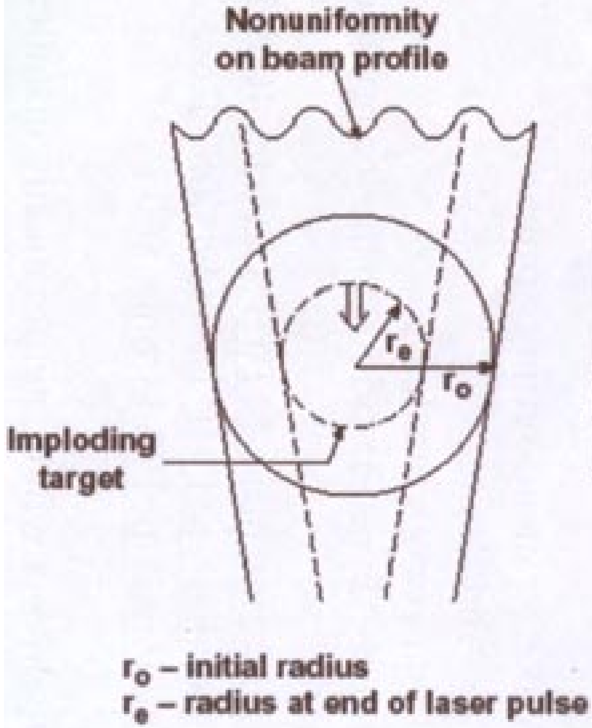


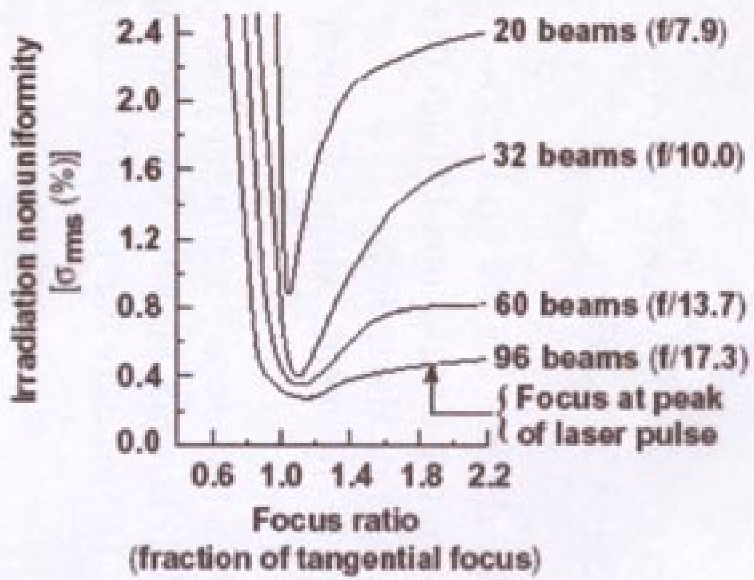

$$\delta R = (\delta V)t \sim \delta V \frac{R}{V} < 1/2\ r$$

$$\therefore\ \frac{\delta R}{r} = \left(\frac{\delta V}{V}\right) \frac{R}{r} < 1/2$$

$$\therefore\ \frac{\delta V}{V} < 1/2\ \frac{r}{R} < 1/2\ (\text{conv. ratio})$$

## A sufficient number of beams provide adequate long-wavelength uniformity throughout the implosion

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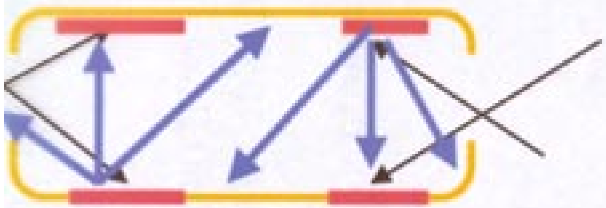
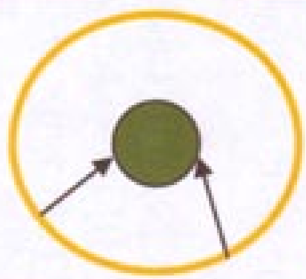
# adiation symmetry in indirectly driven targets is ntrolled by three factors

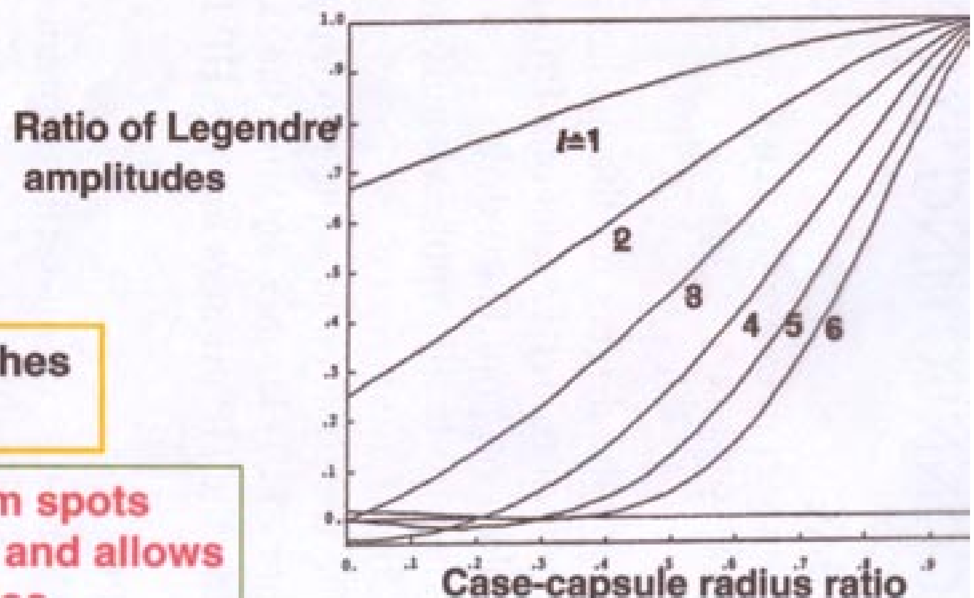


Hohlraum re-radiation smoothes wall temperature by factor $1/(1-\alpha)$



to ball transport smoothes
*l* modes

opriate location of beam spots
nates low order modes and allows
l case-capsule area ratios

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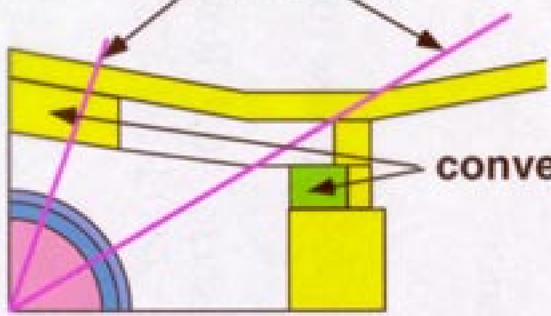
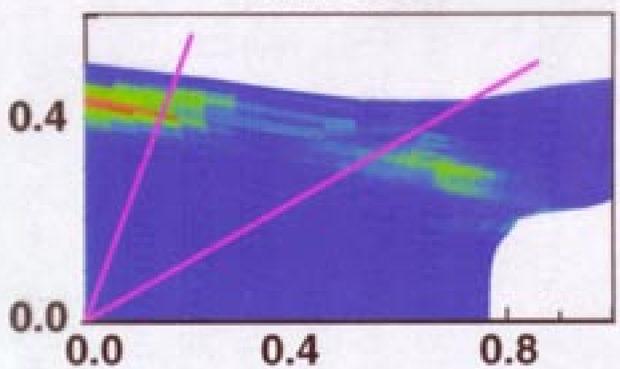
# For the heavy ion distributed radiator target, symmetry is achieved by depositing most of the energy near the zeros of $P_4$




Deposited energy density at 28 nsec

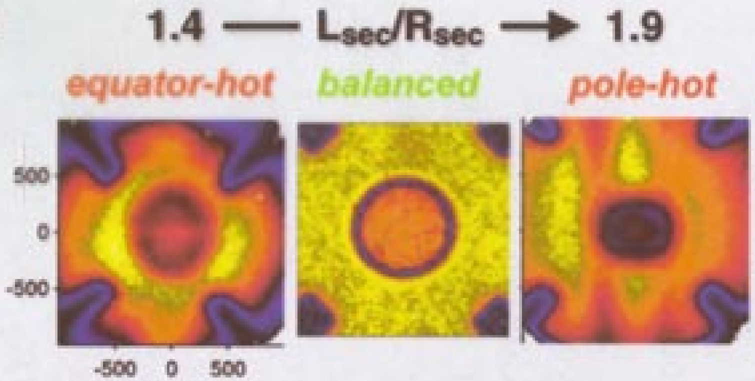


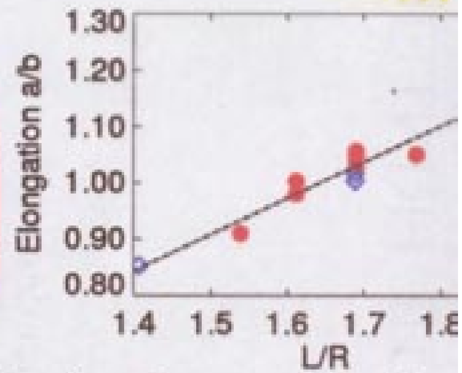

- For a spherical hohlraum, sources with Gaussian weights located at the zeros of $P_4$ causes all moments from $P_1$ to $P_7$ to be zero
- Converters are placed near the zeros of $P_4$ so that most of the energy is deposited there
- Converter densities are adjusted so that $P_2$ is small

allahan 6/02

## emonstrating capsule symmetry control is a gh priority for near-term experiments on Z

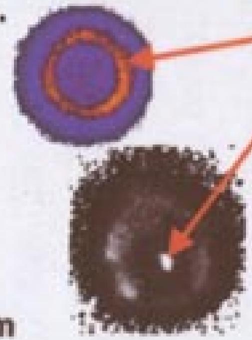
ouble-Pinch Hohlraum



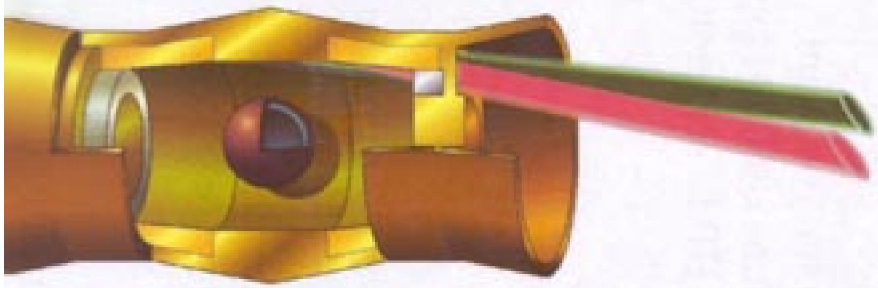

- *Symmetry control via hohlraum design (e.g. $L_{sec}$ variation)*
- *Agreement with viewfactor-RHD + integrated calculations*
- *Optimum length symmetry is close to scaled HY requiremen*

namic Hohlraum

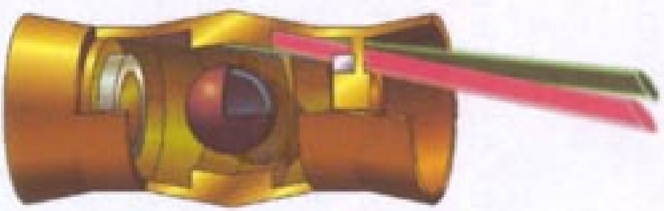
- *Shock emission width consistent with low pinch R*
- *End-on core x-ray images + spectra, side-on plann*
- *Foam dopants, radiation burnthrough shielding, a converter shaping for pole-equator asymmetry*

## ing a smaller hohlraum allows us to trade f coupling efficiency and symmetry



Coupling efficiency: 17%
Gain: 66
Driver Energy: 5.9 MJ

lohlraum dimensions reduced by
6% but driving the same capsule



Coupling efficiency: 27%
Gain: 130
Driver Energy: 3.3 MJ

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# eam plasma coupling seems acceptable but udies continue

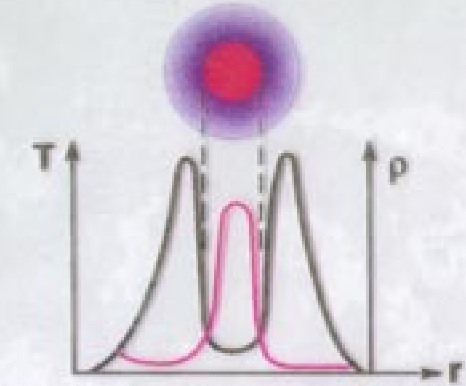
- Laser coupling efficiency 70%(direct drive)-90%(indirect drive or zooming)
  - Study SBS in hohlraums
- Filamentation can change location of laser energy deposition,affecting symmetry and driving other instabilities
- Raman scattering can lead to hot,preheating electrons but levels seem to be acceptable

- Ion beam stopping power has 20% theoretical uncertainties
  - Plasma target experiments beginning
  - By varying target designs we can accommodate factor 2-3 uncertainty

## nnology advances had made innovative concepts sible: ultra-high brightness lasers may allow a lamentally new method of igniting inertial fusion capsul

| Conventional ICF | Fast Ignitor |
| --- | --- |

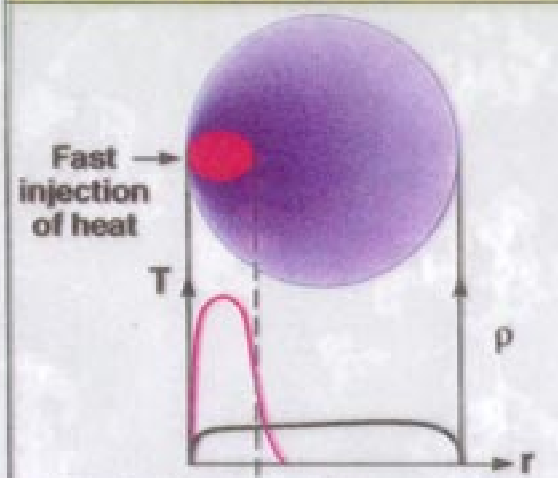
**Conventional ICF**




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 $P_{HS} >> P_c$

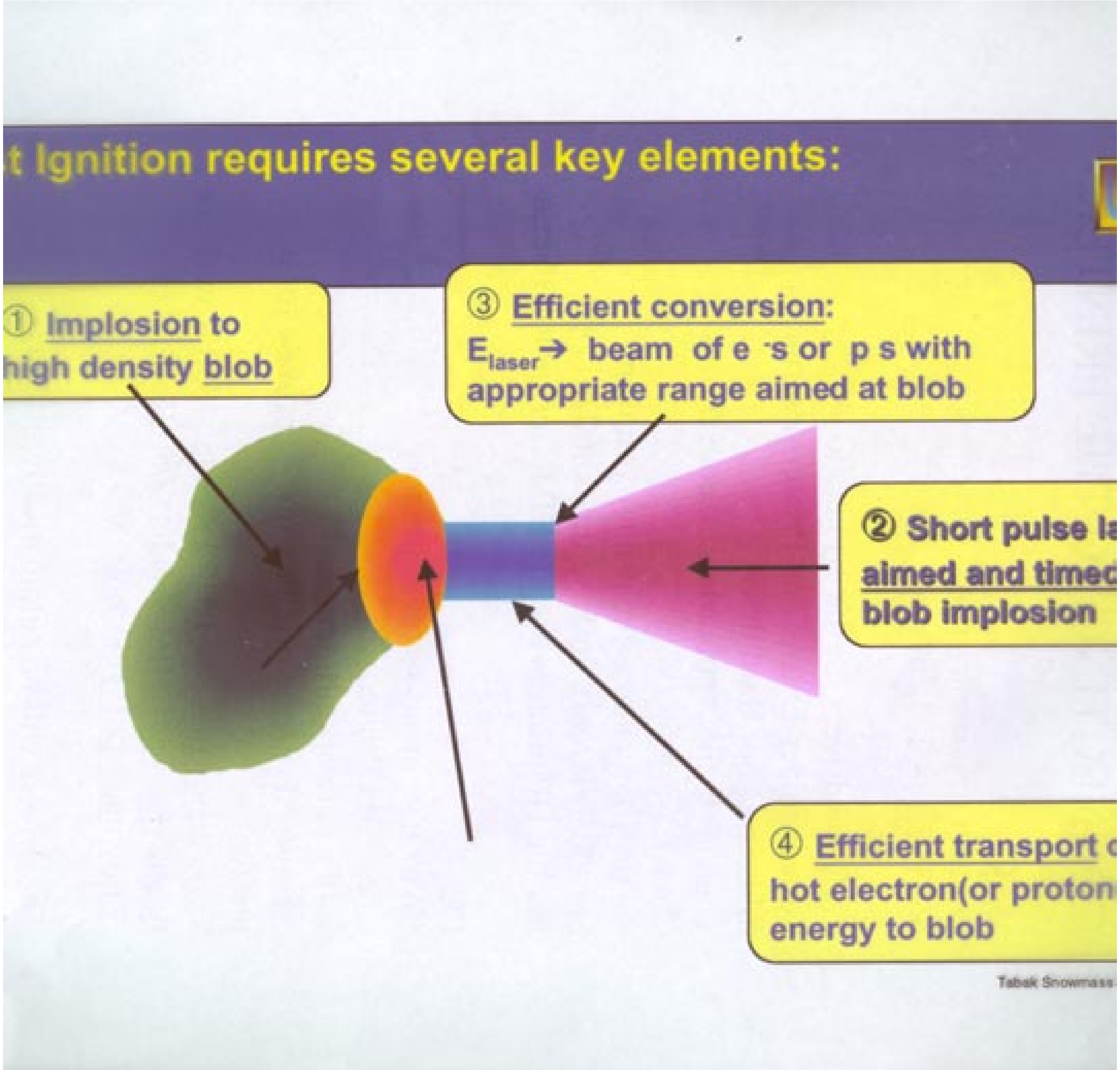
* Tabak, Hammer, Glinsky, Kruer, Wilks, Woodworth, Campbell, & Perry *Phys. Plasmas* **1**, 1626 (1994).

** 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**


t Ignition requires several key elements:
① Implosion to
high density blob
③ Efficient conversion:
E laser→ beam of e ⁻s or p s with
appropriate range aimed at blob
② Short pulse la
aimed and timed
blob implosion
④ Efficient transport o
hot electron(or proton
energy to blob
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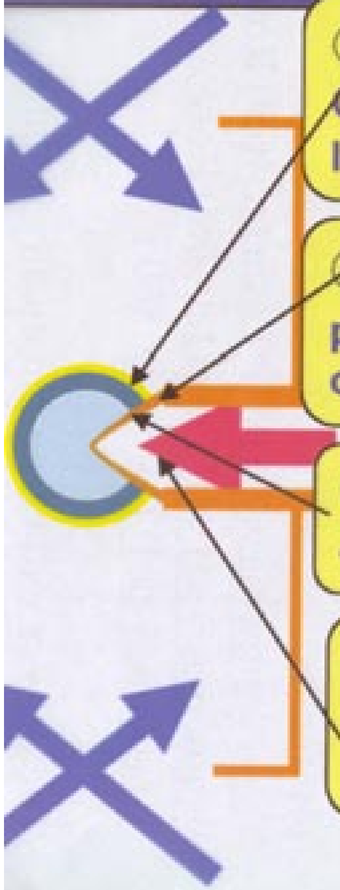
# -focussed scheme provides
# t of the key FI elements.



① Low aspect ratio capsule: Get hi ρ blob with relatively low drive symmetry

②④ Cone provides pointing & puts deposition of laser v. close to hi ρ blob

③ $E_{laser}$ → hots at surface, ~50% conversion (exp t)

⑤ Laser spot size & pulse length tuned to give hot e s with optimum range

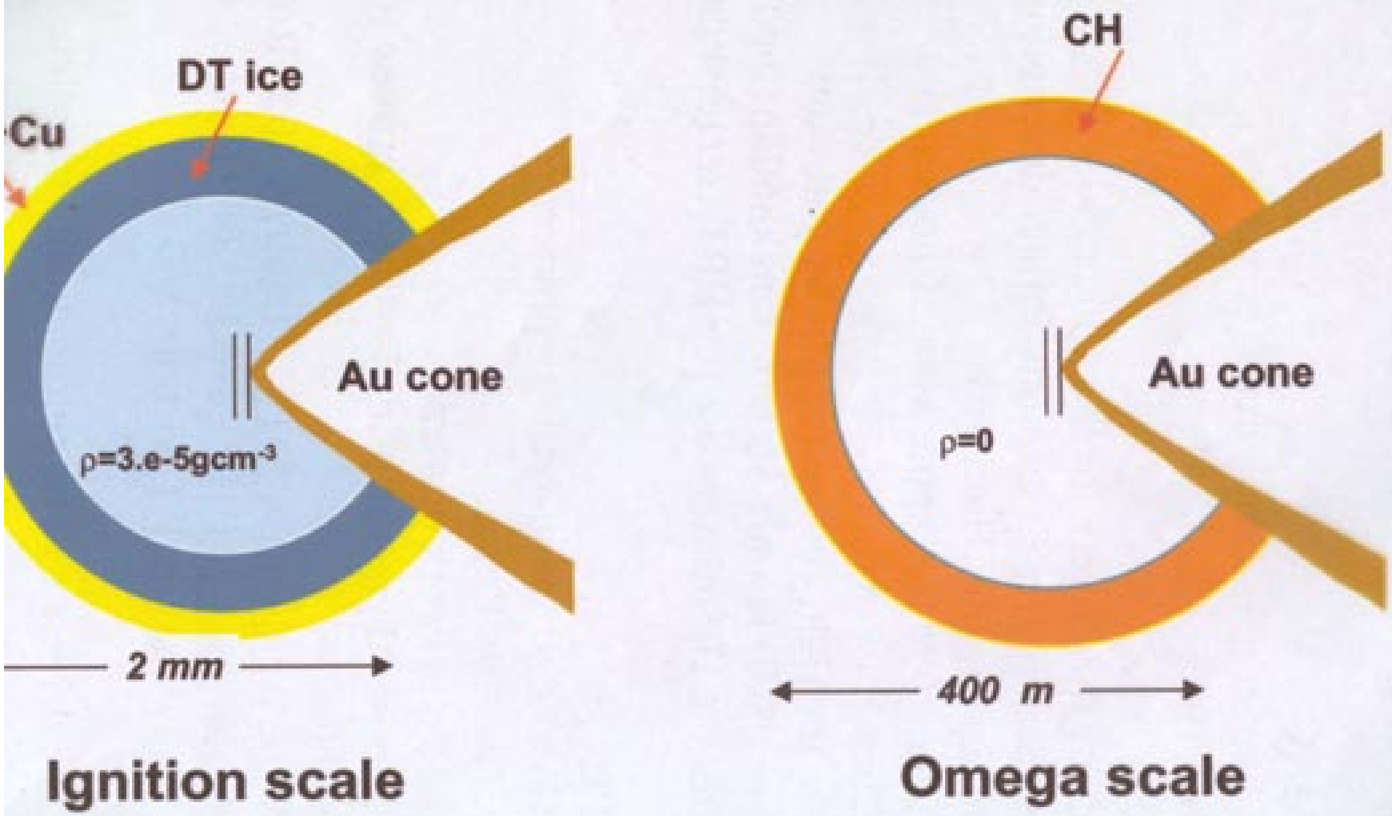
**Other options:**

Direct drive

Use produced proton beam as intermediary

Without cone: Ponderomotive hole boring throug coronal plasma

## nega experiments tested cone-focus concept for
## t ignition at 1/5 scale

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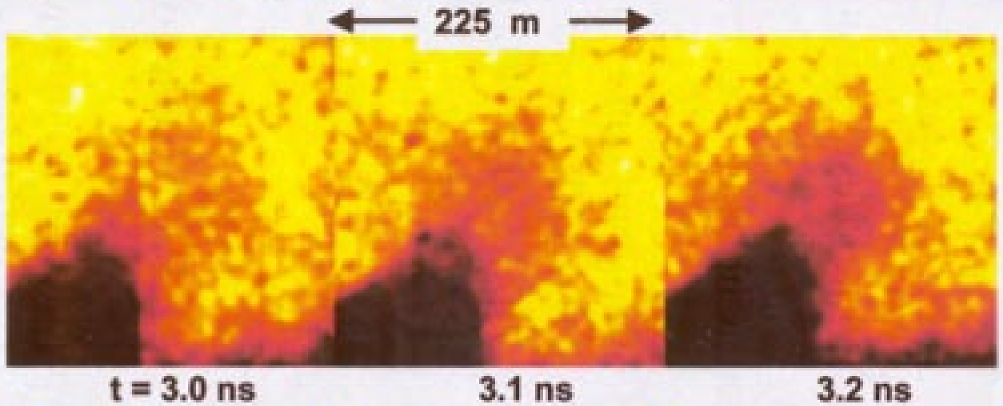
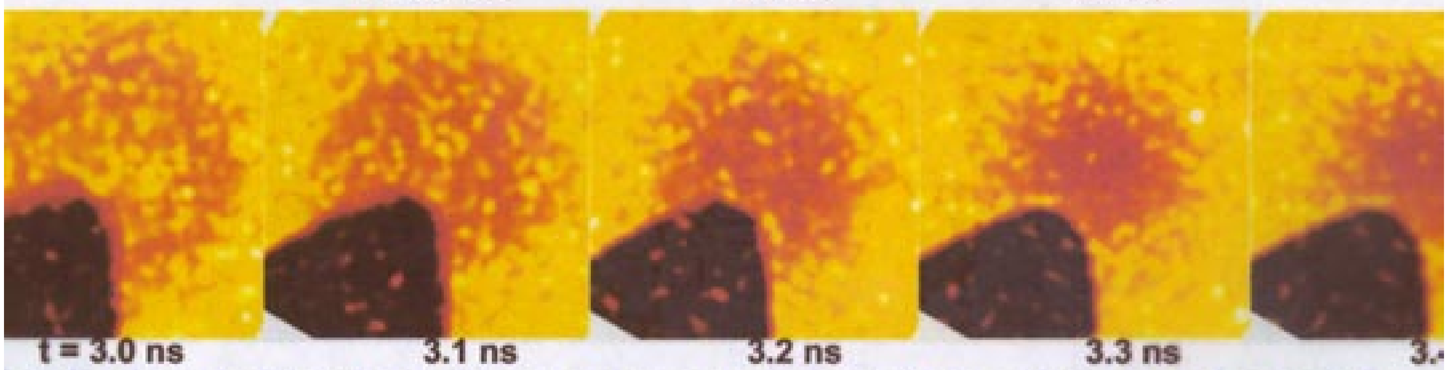
# acklit images (@8 keV) show convergence of one-focussed targets was very similar to rediction — with perhaps a small time offset.

xperiment



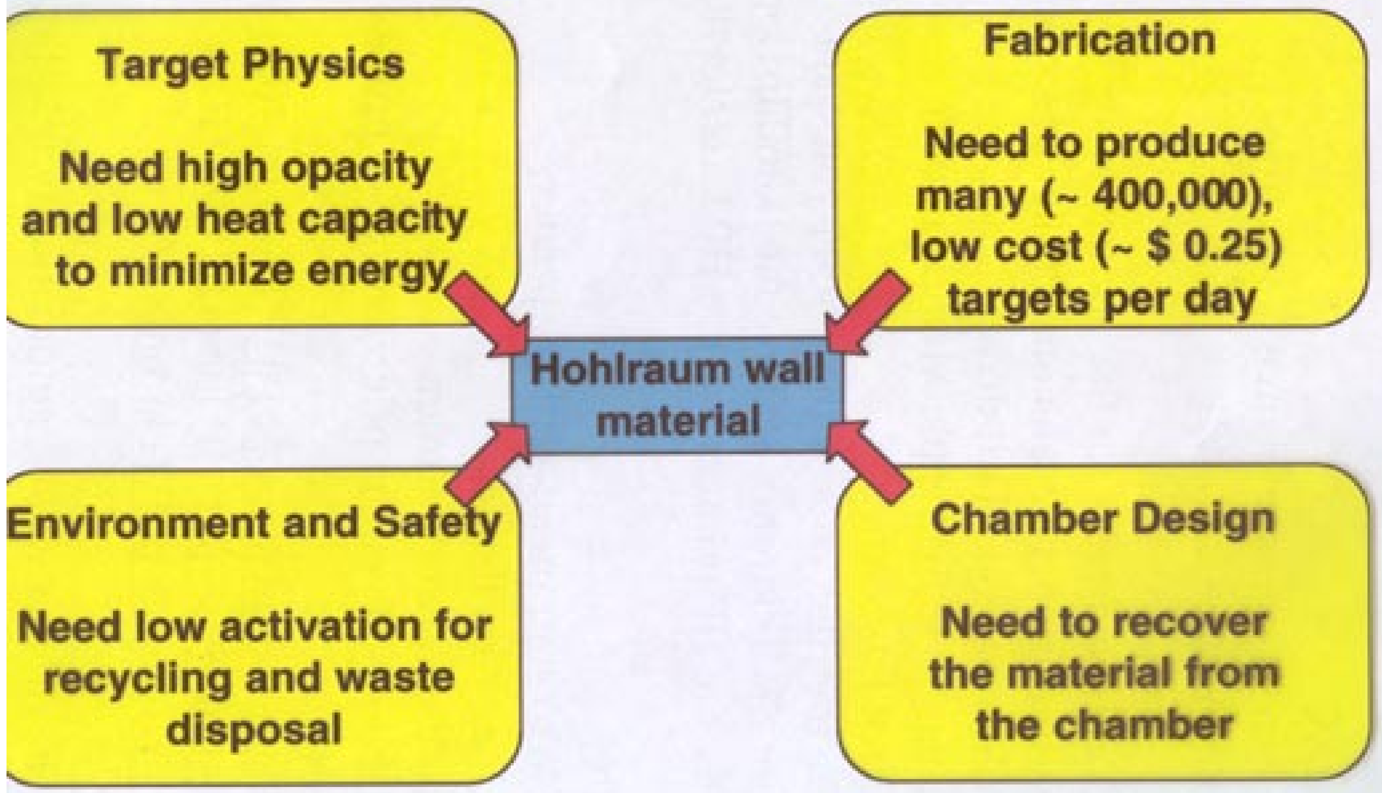

rediction (with pixelation, noise, and smoothing like exp. images)

*mparison shows some exp. evidence for gold entrainment near tip o*

Tabak S

eactor issues

## he hohlraum wall material must atisfy constraints from four areas

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## arget designs with varying degrees of risk rovide adequate gain for all driver concepts