US-Japan Workshop, Princeton, June 12, 2004

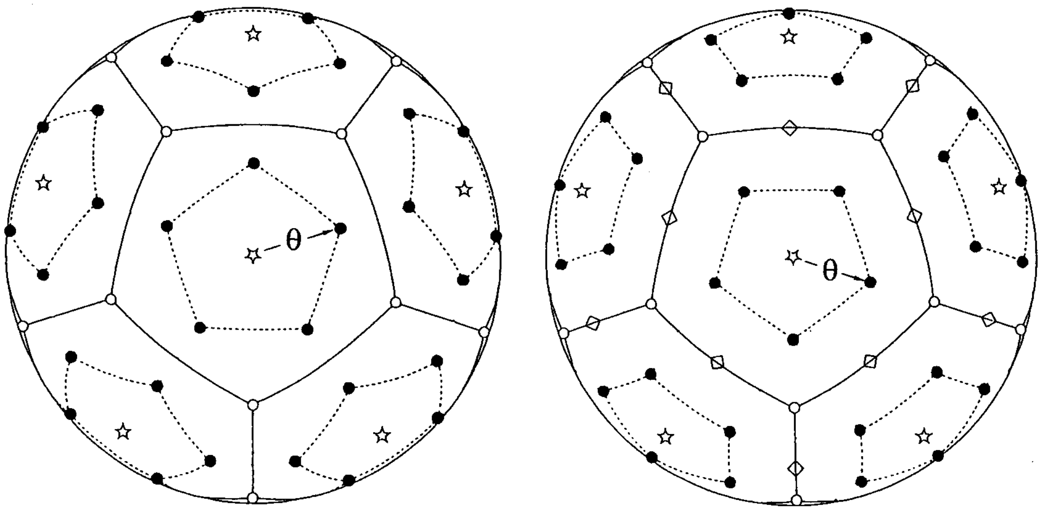
Illumination symmetry and configuration

M. Murakami

Institute of Laser Engineering, Osaka University

Various Irradiation Configurations

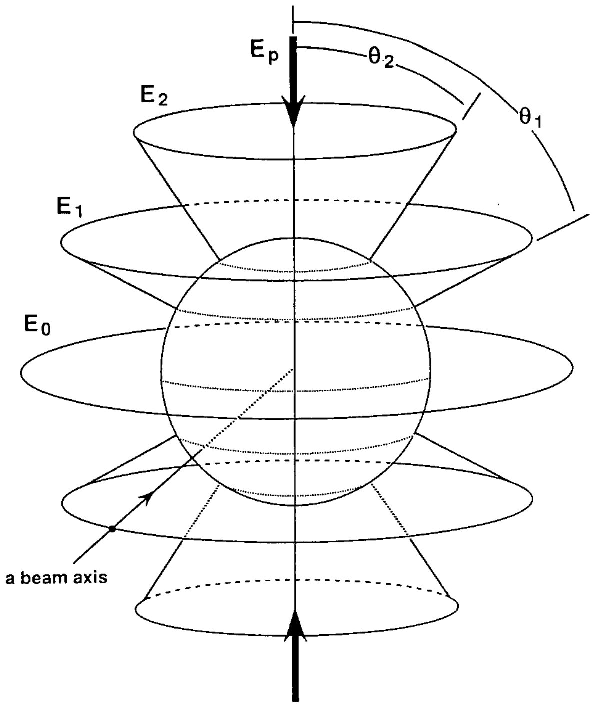
Spherical Configurations (based on Platonic Polyhedra)



(a)

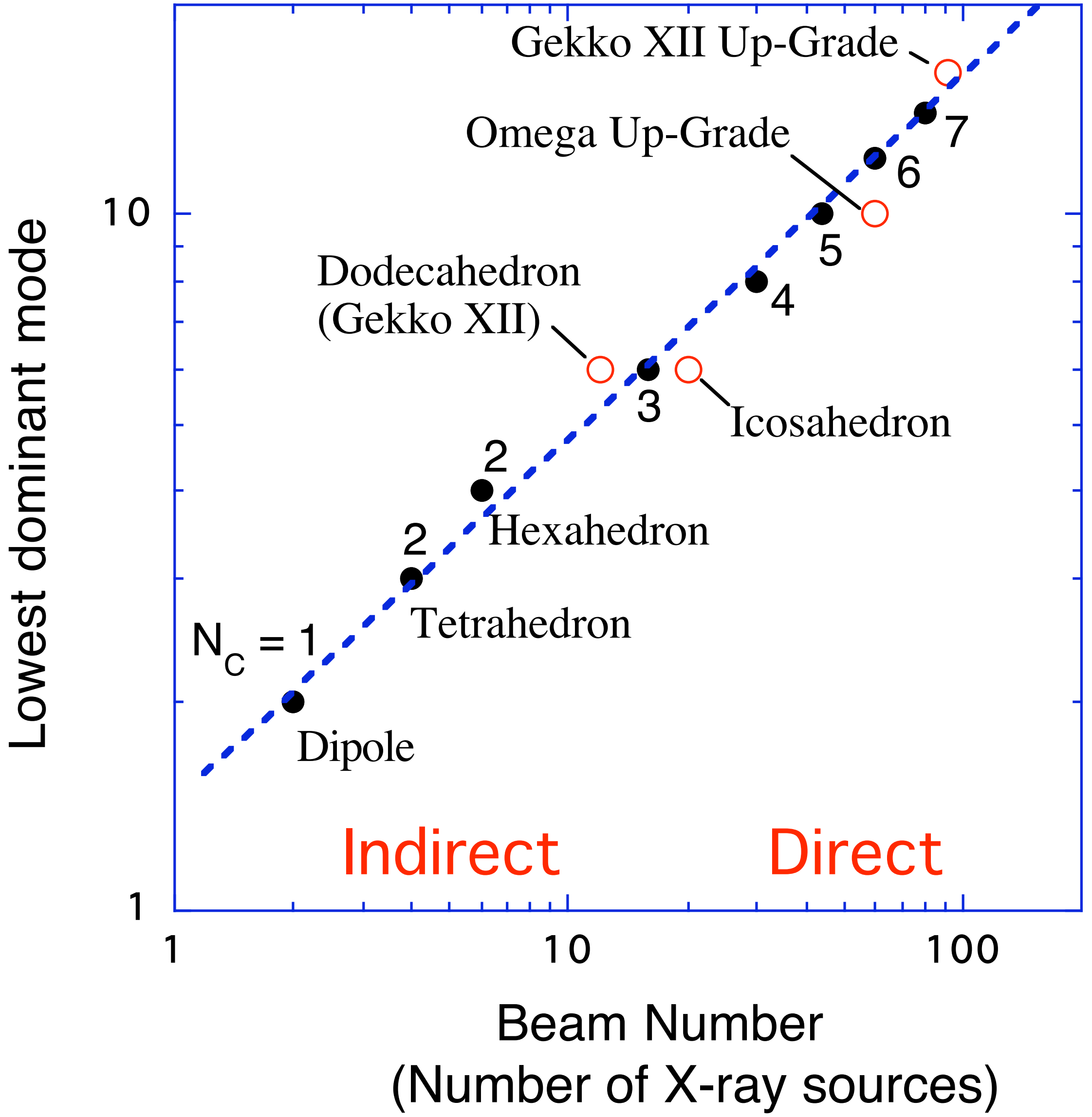
(b)

Cylindrical Configurations



(c)

Lowest dominant mode vs Beam number



RADIATION SYMMETRIZATION IN HOHLRAUM TARGETS

- For indirect drive ICF targets, a compromise has to be found between sufficient symmetry of X-ray deposition on the capsule and high enough energy transfer to the capsule.

- However, these two requirements work against each other. Nevertheless, it could be concluded that the design space for practicable targets is real, but not large.

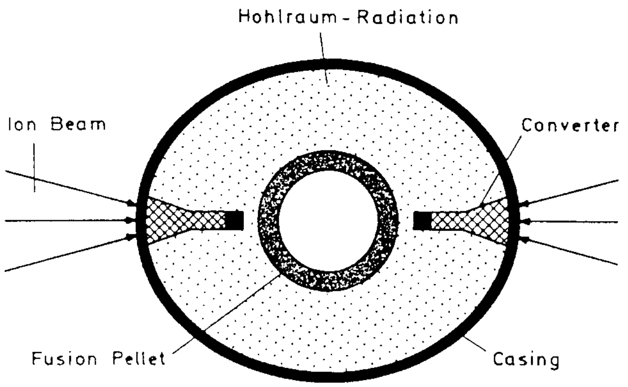
- X-ray source asymmetries can be remarkably symmetrized in a hohlraum target, the effect of which strongly depends on the three factors:

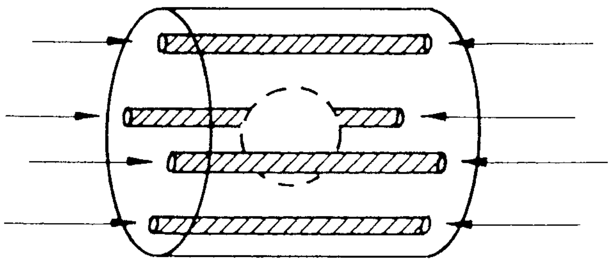
(1) target structure - how small is the capsule compared with the cavity?
(2) re-emission coefficient - how many times can photons circulate in the cavity?
(3) x-ray source configuration - how many sources are properly located in the cavity?

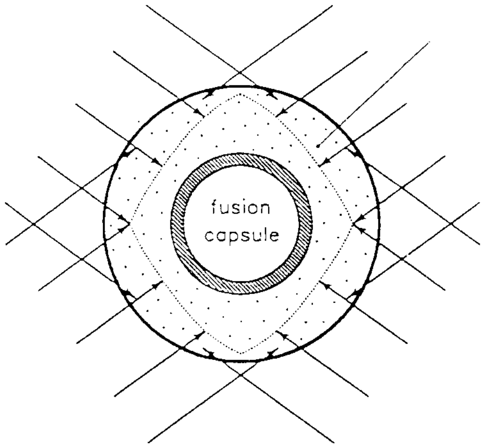
Different irradiation schemes for indirectly driven HIF

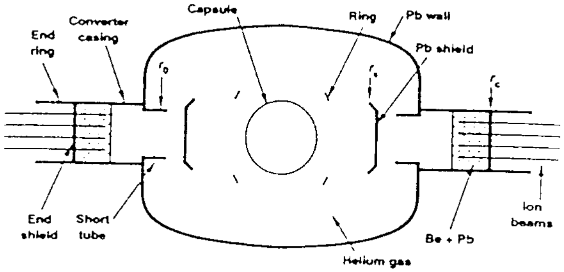
- History of designs to kill low mode asymmetries -

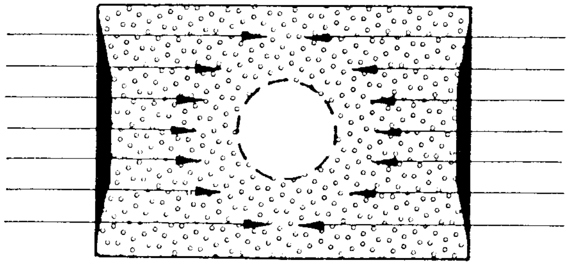
But those are for spherical fuel pellets!!

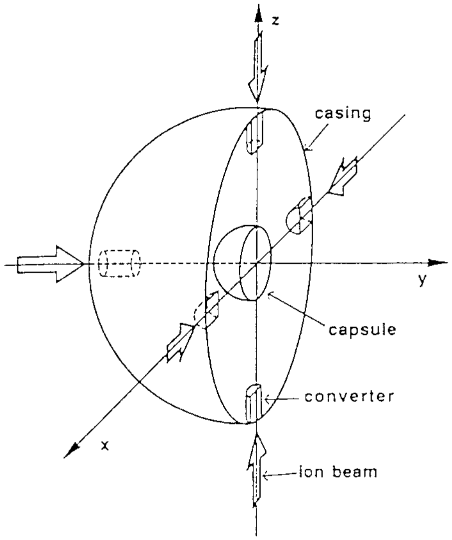












Three smoothing factors in hohlraum targets

Overlapping
smoothing factor (Ω_i)

Geometrical
smoothing factor (A)

Power imbalance

Rms nonuniformity of
X-ray irradiation on target

$$\sigma_{rms} = \left[\sum_{n=1}^{\infty} c_n^2 S_n^2 M_n^2 \left(G_n^2 + \frac{\sigma_P^2}{N_S}\right)\right]^{1/2}$$

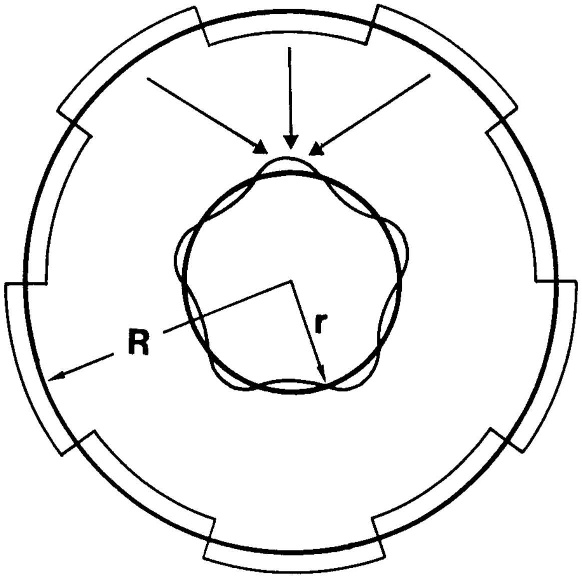
Source amplitude of nth
mode on the hohlraum wall

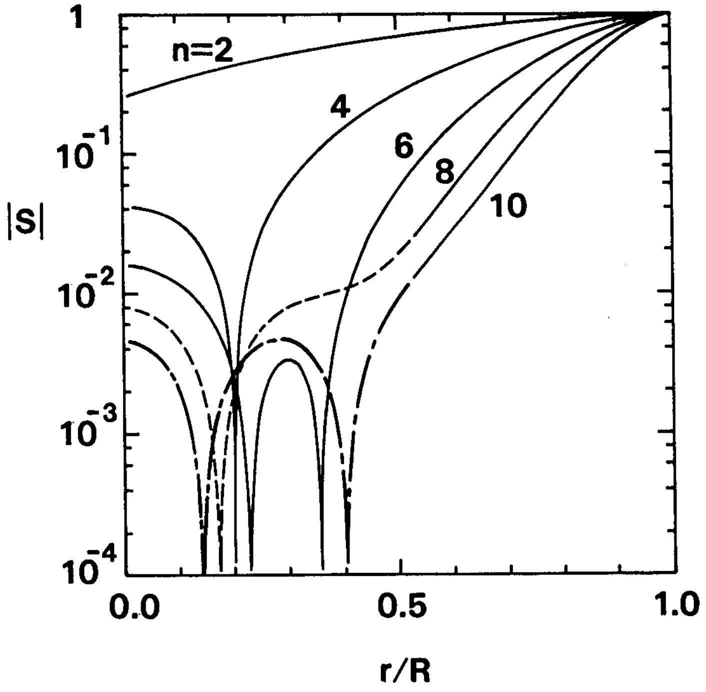
Number of X-ray sources

Multiple re-emission
smoothing factor (A, N_1, N_2)

If $\square_P = 0$ □ $\square_n = c_n S_n M_n G_n$

1. Geometrical effect, S(r/R), significantly reduces higher non-uniformities

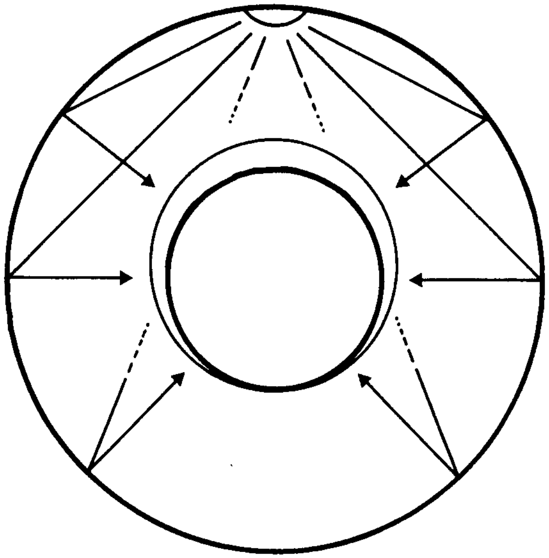


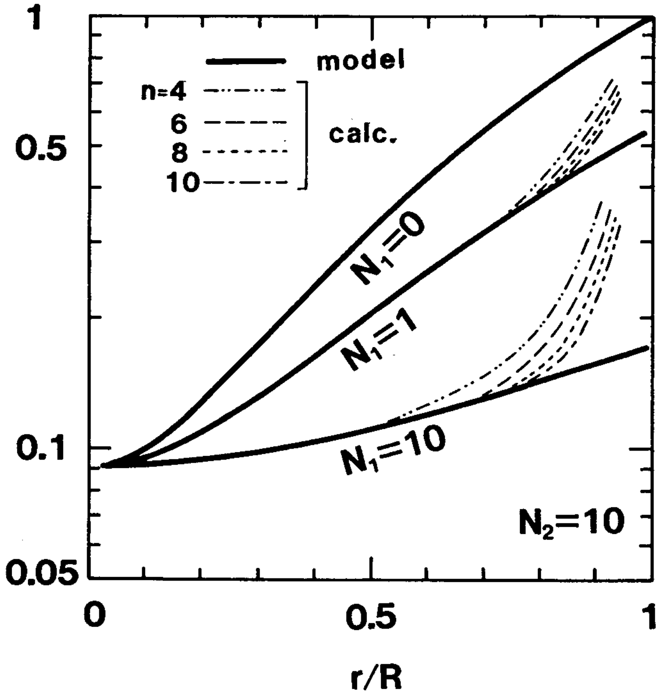


2. Multi-re-emission smoothing factor is equal to the reciprocal of average circulation number of radiation

$$M = \frac{1}{N_{cir}} = \frac{A(1+N_1)+N_2}{A(1+N_1)(1+N_2)}, \quad [A \equiv (R/r)^2]$$

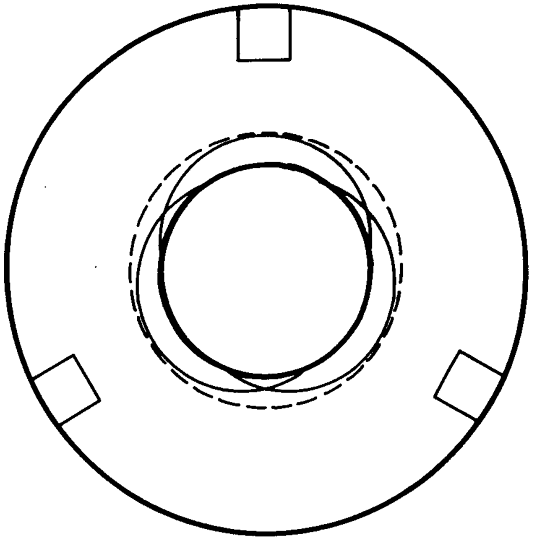
$$\Rightarrow M \to (1+N_2)^{-1} \quad \text{for} \quad A \to \infty$$

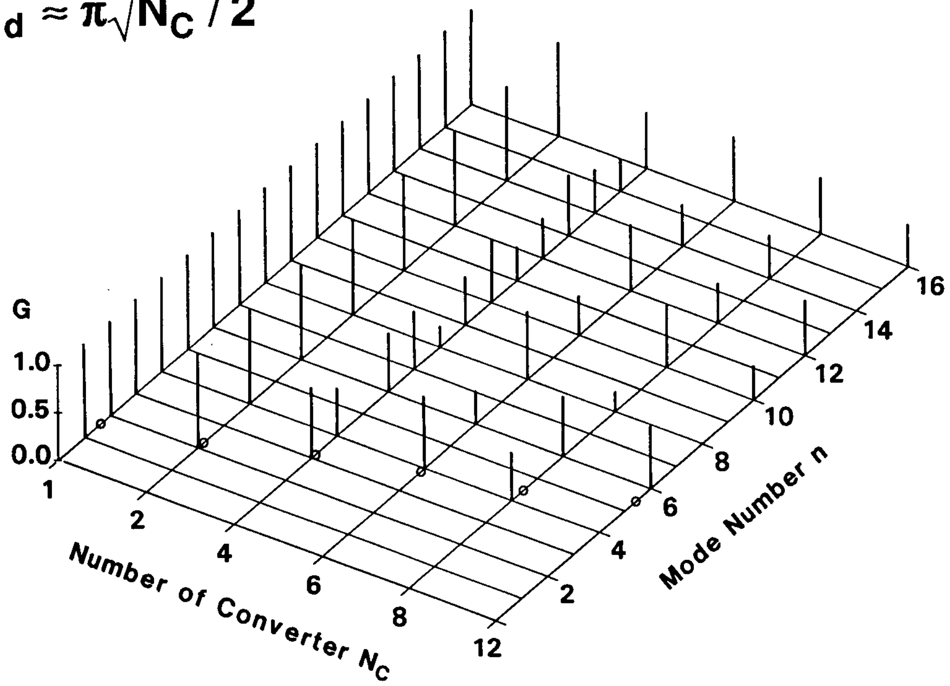




3. Overlapping effect in use of multiple converters automatically kills lower non-uniformities

lowest dominant mode: $\mathbf{n_d} \approx \pi\sqrt{\mathbf{N_C}/2}$

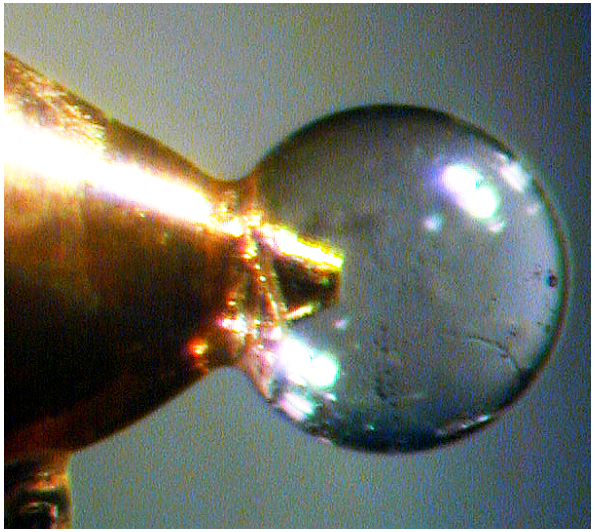




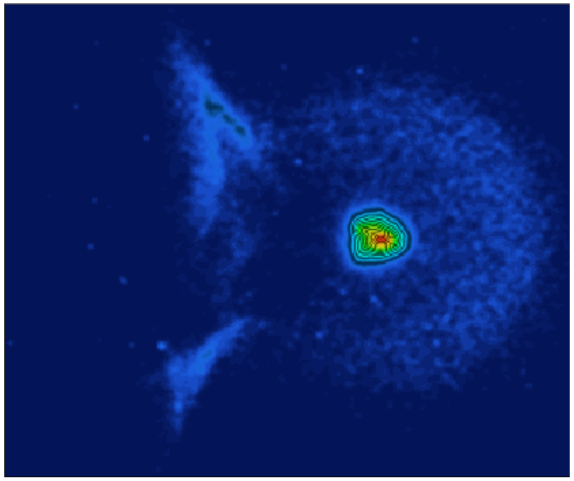
$$G_n = \left[\sum_{j=1}^{N_B} \sum_{k=1}^{N_B} P_{\mathbf{n}}(\hat{\Omega}_j \cdot \hat{\Omega}_k)\bar{I}_j \bar{I}_k \Big/ I_T^2 \right]^{1/2}$$

Efficiently compressed core can be generated even by nonuniform implosion

Cone shell target



X-ray image of the compressed fuel plasma



Those experimental results have been published in Nature (2001 & 2003).

Numerical simulation of cone-guided implosion using 2D radiation-hydro simulation code “PINOCO”

PINOCO

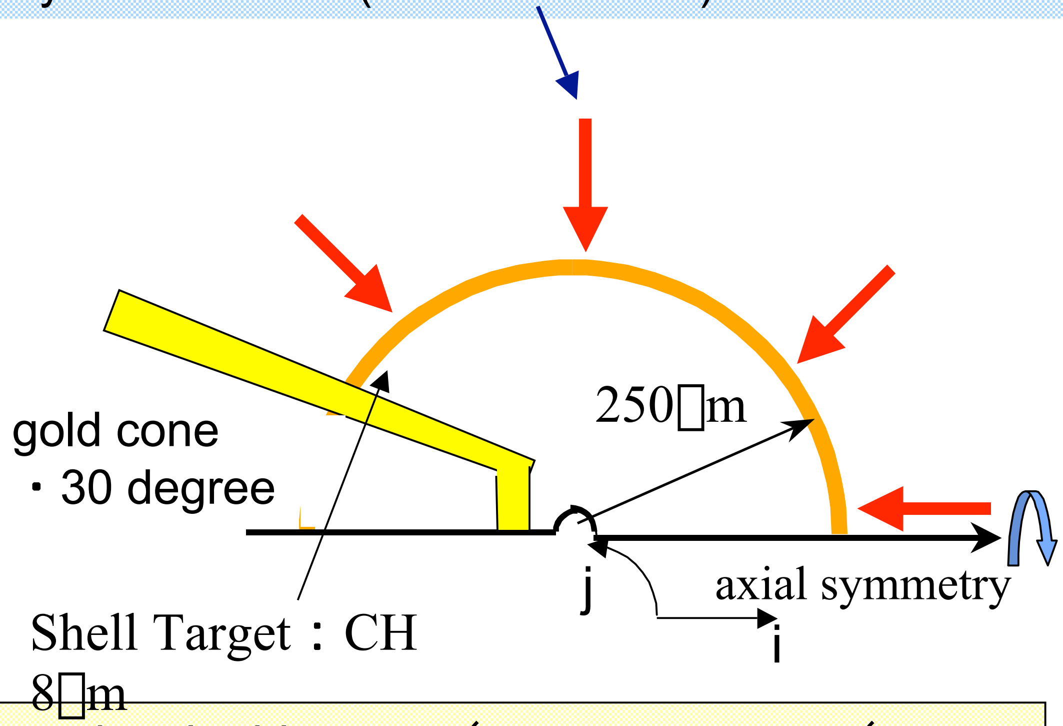
- 2 temperature plasma
  - Hydro ALE-CIP method
- Thermal transport
  - flux limited type Spiter-Harm
  - Implicit (9 point-ILUBCG)
- Radiation transport
  - multi-group diffusion approximation
  - Implicit (9 point-ILUBCG)
  - Opacity, Emissivity (LTE, CRE)
- Laser energy
  - 1-D ray-trace
- EOS
  - Tomas-Fermi
  - Cowan

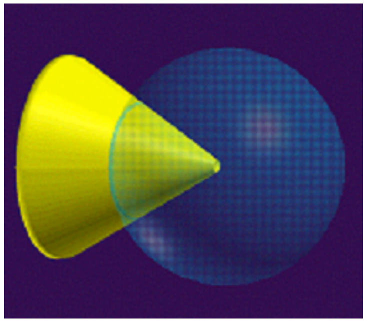
Laser condition

Wavelength ：0.53mm

Energy ： 6kJ (Gaussian, on target, center focused)

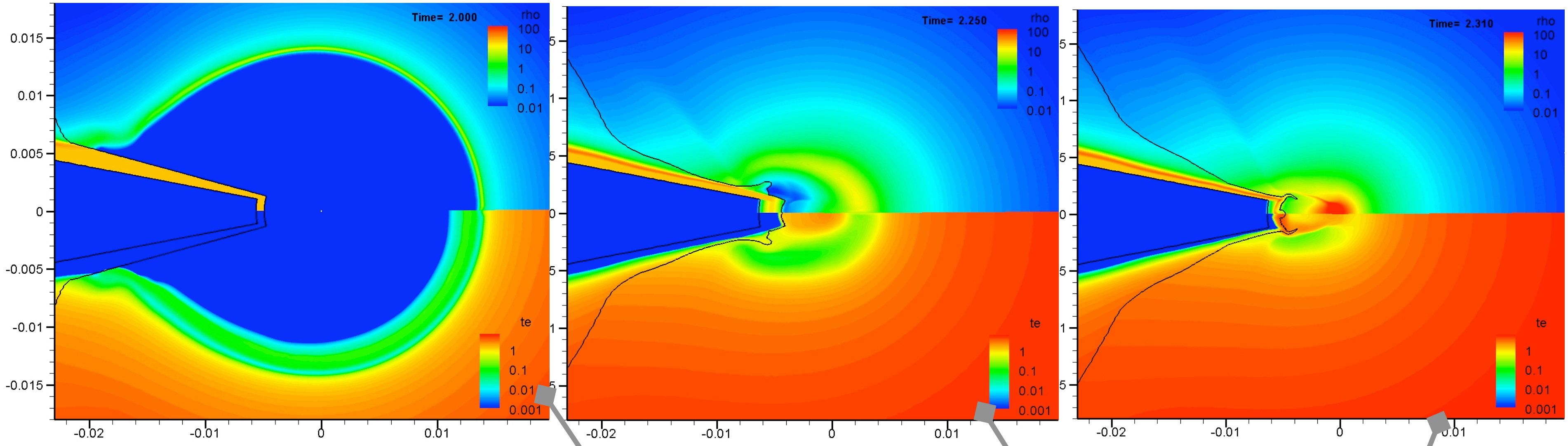
Ray-trace： 1 - D (radial direction)





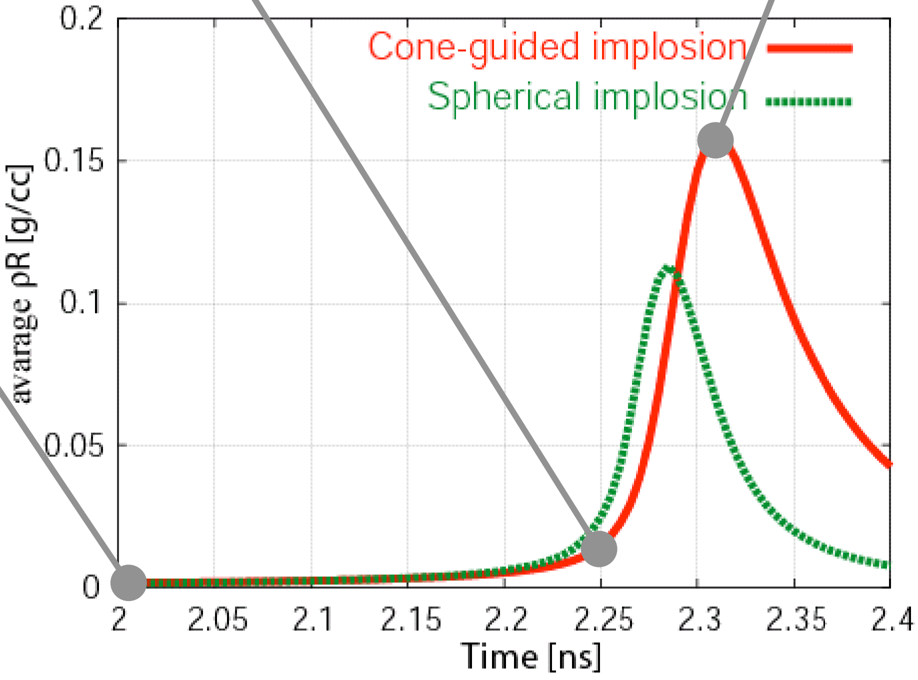
computational grids：300 （i- direction) x 280 （j - direction）

time dependence of angular average ρR in gold cone-guided implosion (GXII scale CH target)



In the spherical implosion, the shell target was rebound after the maximum compression at 2.285 ns.

In non-spherical implosion case, however, the shell continued to be imploded due to the shifted hot spot. As the result, the average ρR reached maximum at 2.310 ns, and the value becomes 40% larger than that of the spherical case.



So far we have long pursued such a illumination system that a critical rule-of-thumb root-mean-square non-uniformity is set around 1 %.

However, the experimental and simulation results on asymmetric implosions press us to alter the uniformity criterion that we have stuck to.

This in turn implies that the impact ignition target may allow us different illumination condition and beam options beyond standard parameters.

Advantages of Impact Ignition

(1) Simple Physics

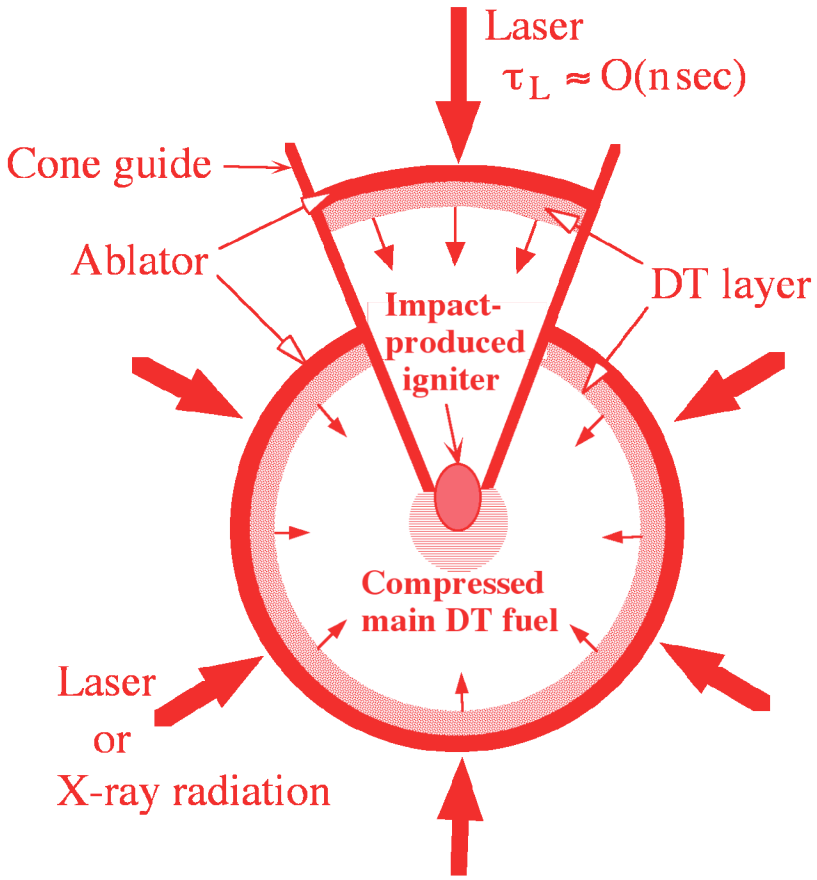
(2) High Efficiency

(3) High Robustness

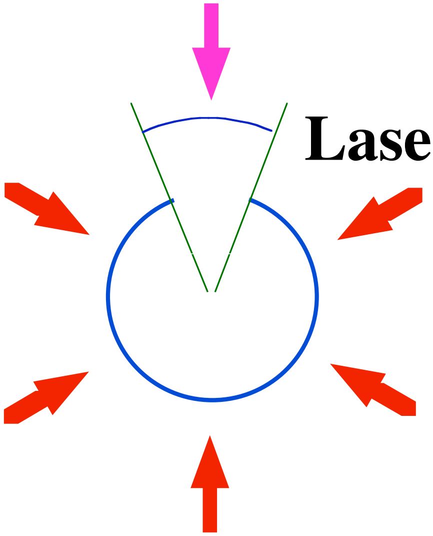
(4) High Gain

(5) Low Cost

(6) No need for PW Laser

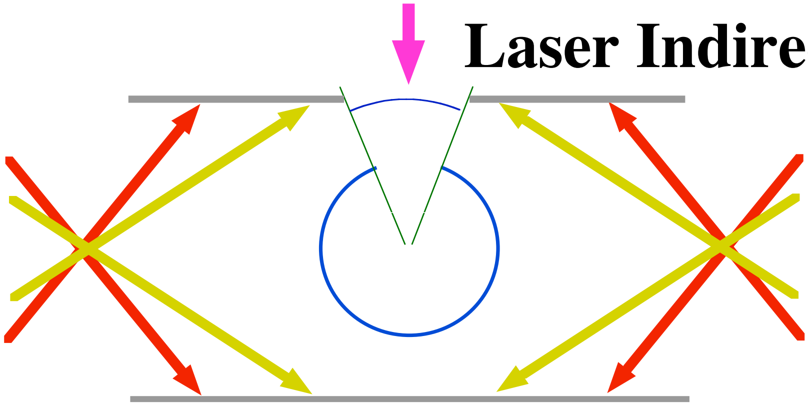


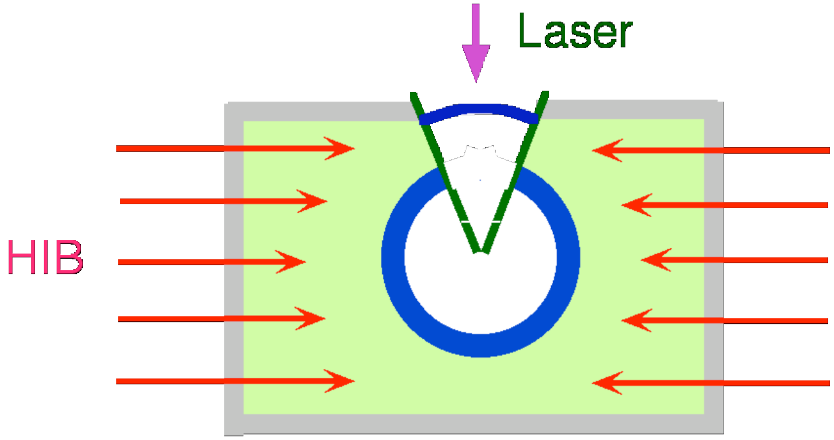
Impact Ignition can be designed in other illumination schemes

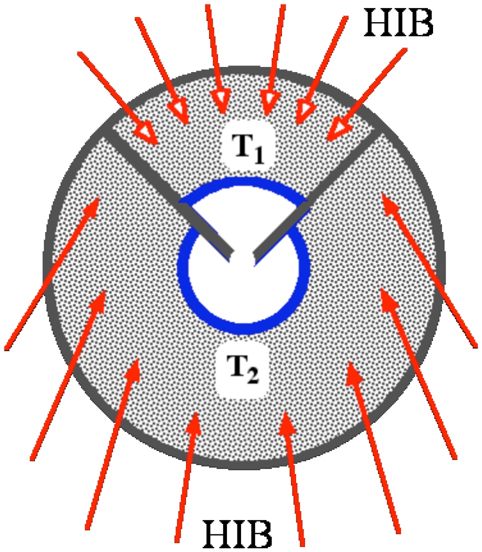


Laser Direct

Laser Indirect







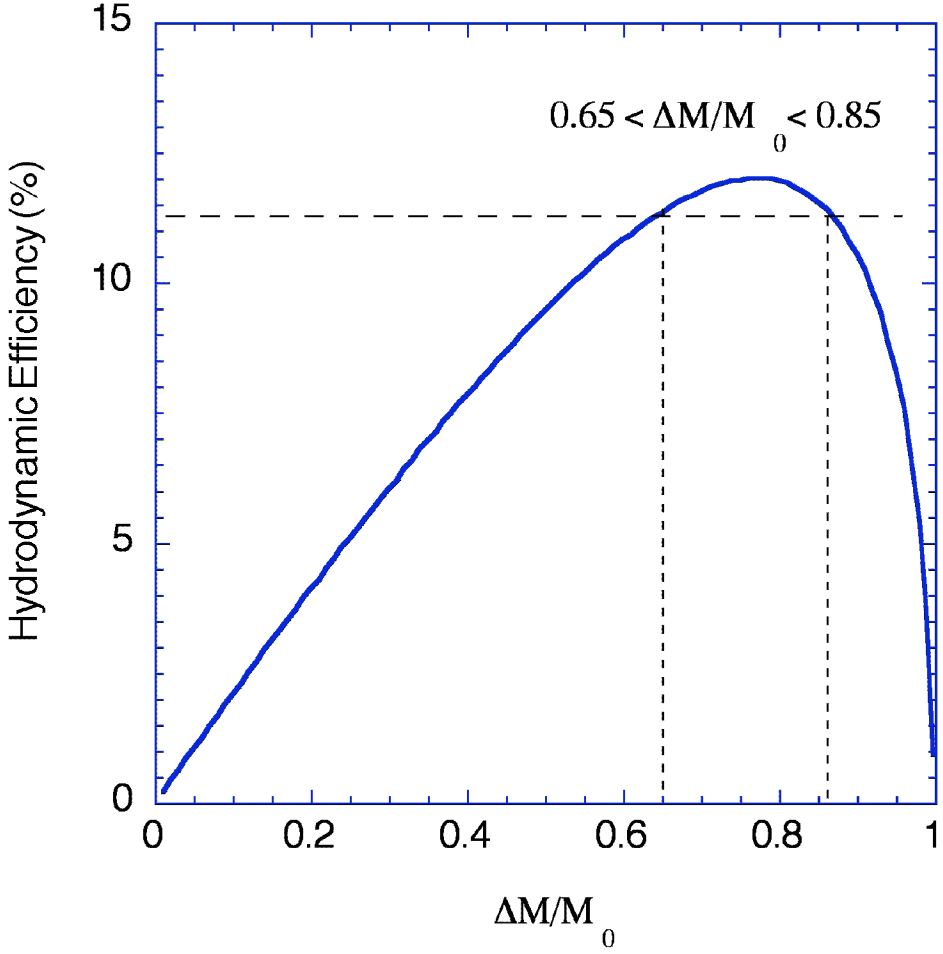
HIB Indirect

β

β

Hydrodynamic Efficiency

$$\eta_h = \eta_{h\,max}\, f(\tilde{M}) \qquad f(\tilde{M}) = \frac{99}{14}\,\frac{\tilde{M}\,\ln^2 \tilde{M}}{5(1-\tilde{M}) + M\,\ln \tilde{M}}$$



Scaling laws for laser-driven ablation

- Mass density at the sonic point: $\rho_{C-J} \approx \rho_{crt}$
- Energy balance: $\eta_a I_L \approx 4\rho_{C-J} u_{C-J}^3$

$\Downarrow$

$$\rho_{CJ}\,(\mathrm{g/cm^3}) = 3.7 \times 10^{-3} \lambda_L^{-2}$$

$$c_{CJ}\,(\mathrm{cm/sec}) = 8.8 \times 10^{7} (I_{a15} \lambda^2)^{1/3}$$

$$\dot{m}\,(\mathrm{g/cm^2 \cdot sec}) = 3.3 \times 10^{5}\,(I_{a15} \lambda_L^{-4})^{1/3}$$

$$P_a\,(\mathrm{Mbar}) = 43\,(I_{a15}\, \lambda_L^{-1})^{2/3}$$

Design Window for Laser and Target Parameters

$0.95 \square \square_h / \square_{h\,max} \square 1$ || $0.15 \sqcap \tilde{M} \sqcap 0.35$

$0.97 \square \square \square 1.9$

$0.085 \square I_{a15} \square_L^2 \square 0.50$

$\square_L = 0.35 \square m$ || $0.69 \square I_{a15} \square 4.1$

$68 \square P_a (Mbar) \square 220$

$3.0 \square \square_a (g/cm^3) \square 6.0 \quad (\square_s = 5)$

High isentrope suppresses Rayleigh-Taylor Instability

$$\gamma_{RT} = \sqrt{kg/(1+kL)} \approx 3kv_a$$

Under constant acceleration for $R_0 \geq R \geq R_0/2$

$$\Gamma \equiv \int \gamma_{RT}\,dt = \sqrt{\ell/(1+\varepsilon\ell\Delta R/R)} \approx 3\ell(R/\Delta R)(1-\tilde{M})$$

$$\ell = 2\pi R/\Delta R$$

$$\Gamma = \ln 10^3$$

| |

$$R/\Delta R \approx 95$$

$$171\alpha_s^{-3/5} \leq R/\Delta R \leq 387\alpha_s^{-3/5}$$

| |

$$\boxed{3 \leq \alpha_s \leq 6}$$

In indirect scheme, it is hard to achieve high implosion velocities for the ignitor shell

Implosion velocity: $v_{imp} = \square c_{C\square J} \ln (M_0 / M)$

Sound speed: $c_{C\square J} = \sqrt{\dfrac{(Z+1)k_B T}{Am_p}}$

If we assume $T = 300\,\mathrm{eV}, \quad \square \square 1.5, \quad (Z+1)/A \square 1/2$

Remaining mass:

$v_{imp} = 3 \square 10^7\,\mathrm{cm/s} \quad \square \quad M/M_0 = 19.0\%$ Feasible

$v_{imp} = 6 \square 10^7\,\mathrm{cm/s} \quad \square \quad M/M_0 = 3.5\%$ Very hard*!*

Direct drive for the igniter shell has much higher potential to achieve Impact Ignition than indirect drive

Advantages:

(1) Laser pulse shape and irradiation timing can be rather freely designed.
(2) With high specific deposition power, the exhaust velocity and thus the implosion velocity is quite controllable.
(3) Experiment can be conducted under orthodox laser systems (Gekko XII) with no special know-how for the target fabrication and optical design and operation.

Summary

- A totally new ignition scheme, Impact Ignition, has been proposed.
- Impact Ignition has very attractive features.
- Major breakthrouh expected in future experiments is to demonstrate high implosion velocities at low isentropes.