Современное состояние проблемы инерциального термоядерного синтеза

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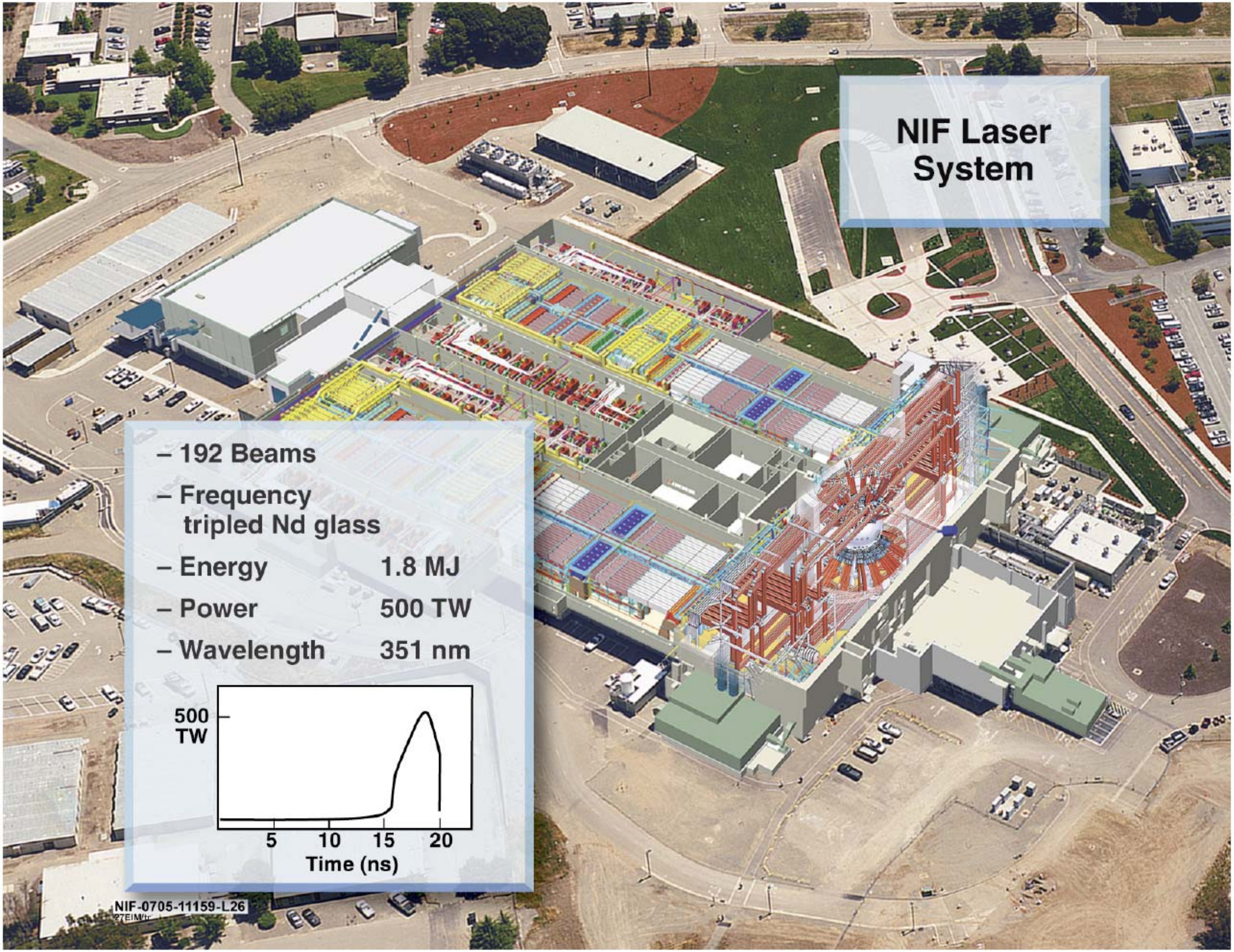
ИТЭФ, Москва, 24-25 ноября 2008

Ignition facilities

- **NIF** (Livermore, USA) is to be completed in March, 2009: ignition campaign in 2010-2011.
- **LMJ** (Bordeaux, France) is to be completed in 2010: ignition campaign in 2011-2012 (?)


NIF Laser System
– 192 Beams
– Frequency tripled Nd glass
– Energy 1.8 MJ
– Power 500 TW
– Wavelength 351 nm
500 TW
5
10
15
20
Time (ns)
NIF-0705-11159-L26

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The beampath infrastructure for all 192 beams is complete and the first four beams have been activated for experiments

NIF Target Chamber upper hemisphere

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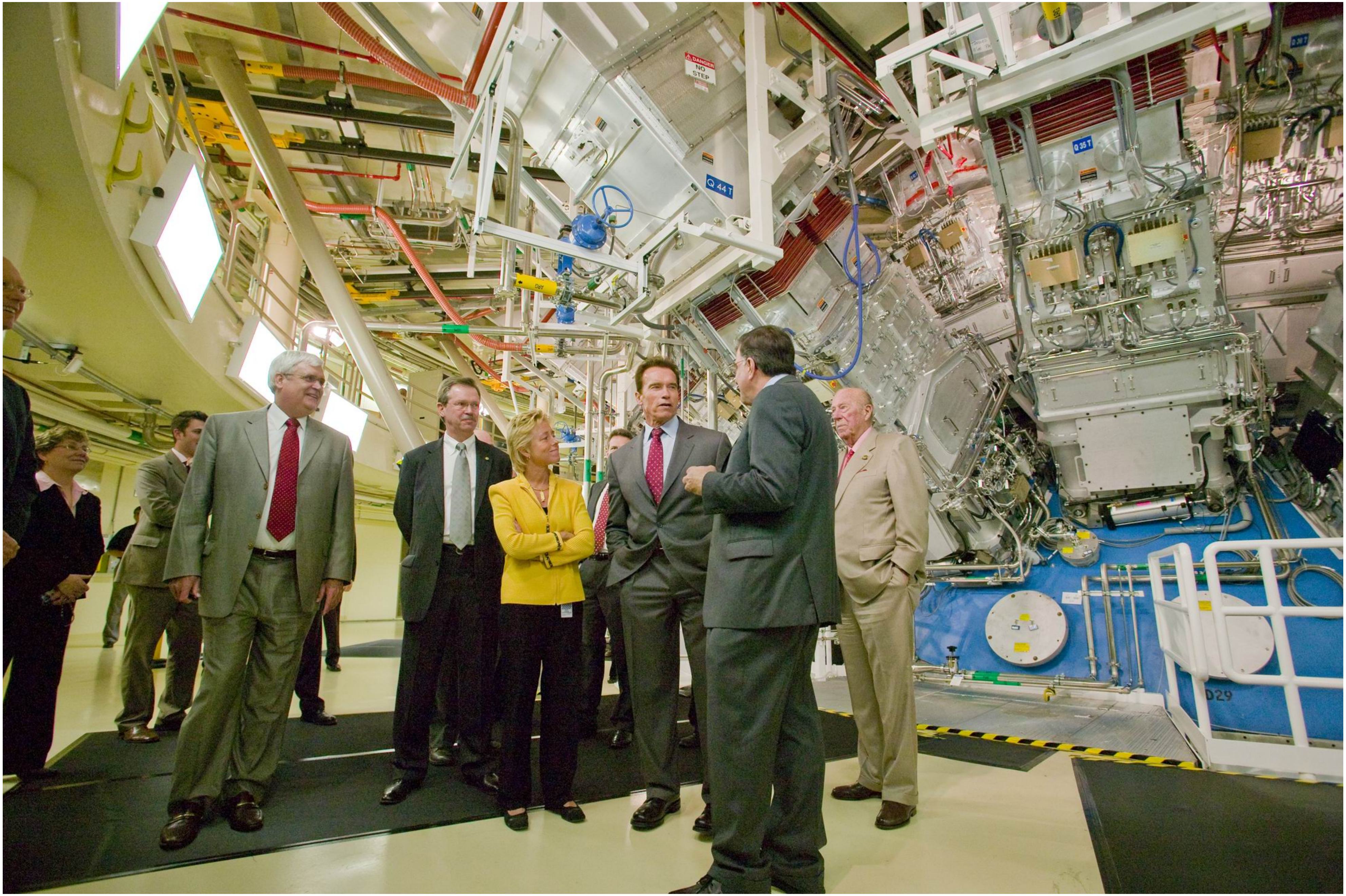
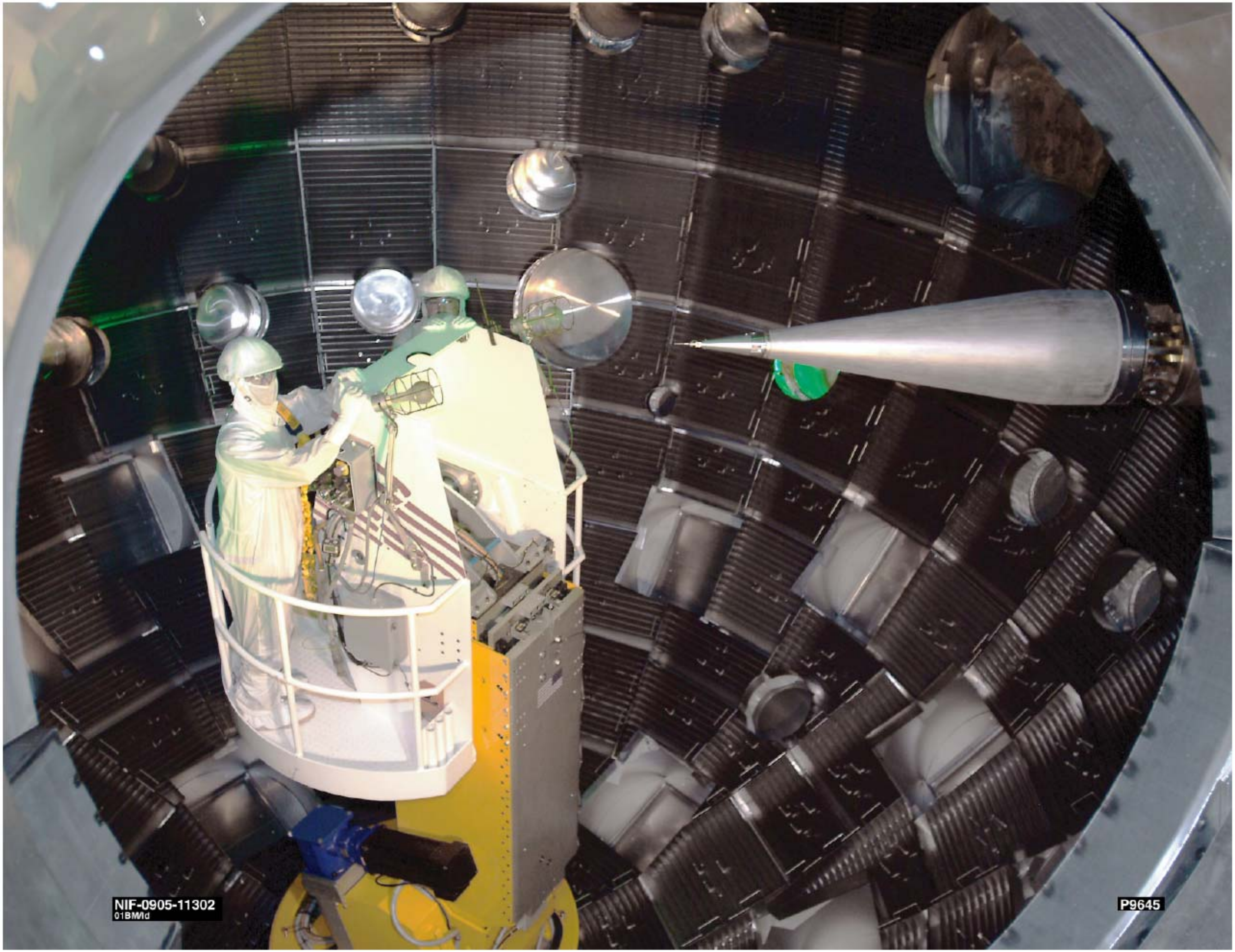


November, 2008


NIF-0905-11302
01BM/ld
P9645

NIF target

hohlraum by 1-micrometer-thick polyimide foil windows that cover each hole. Before a shot, the hohlraum will

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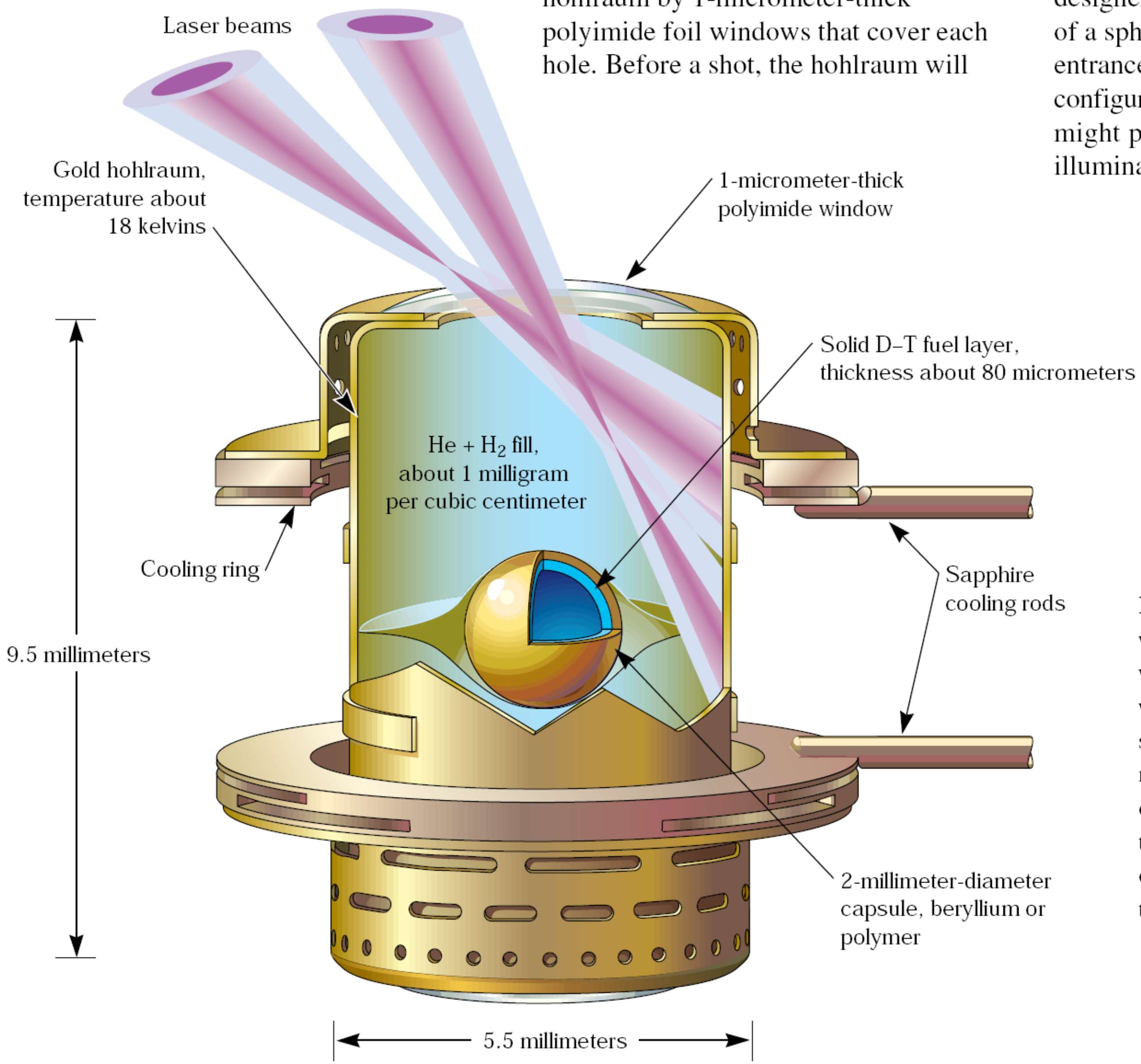
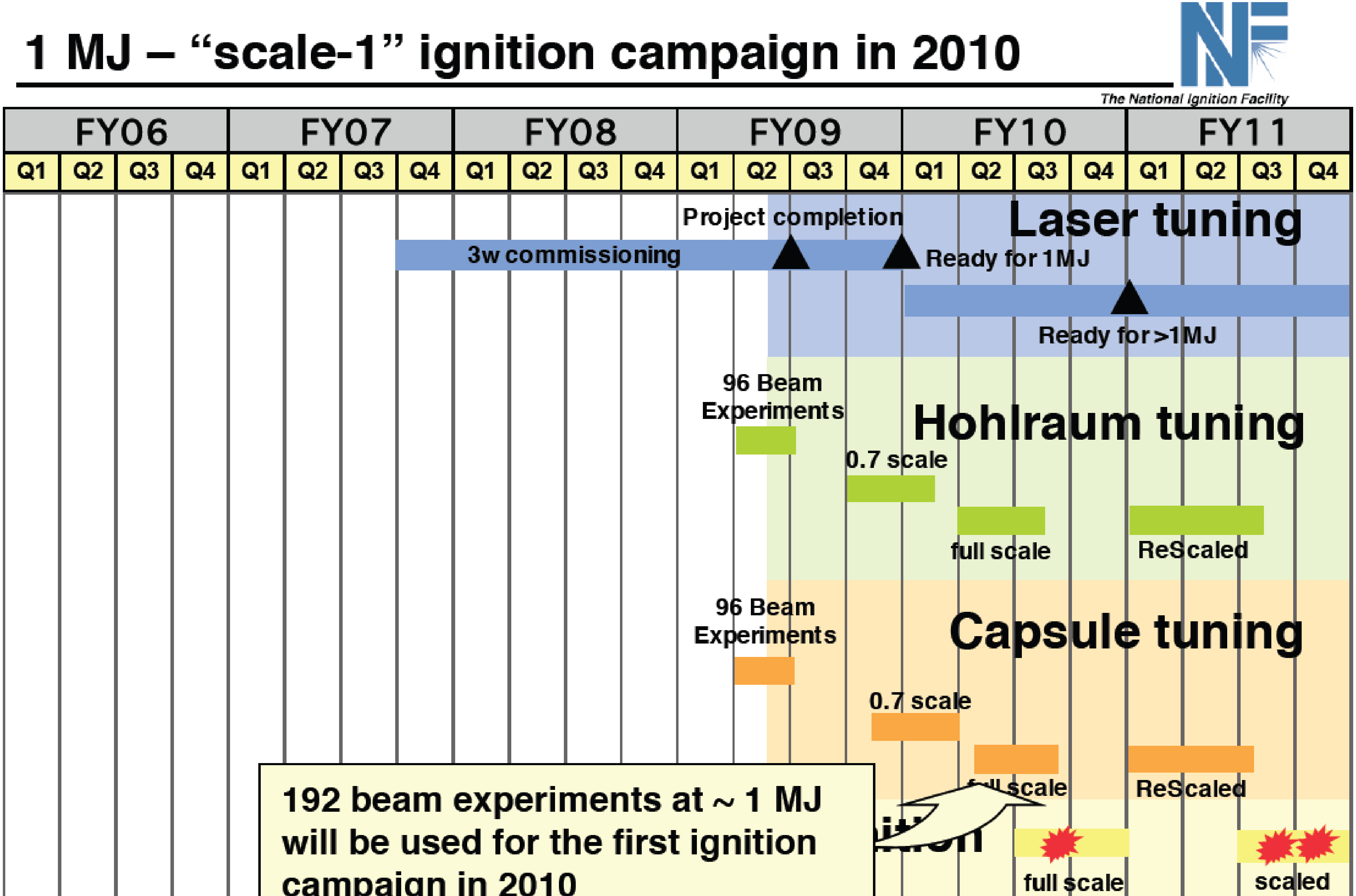


Figure 3. The hohlraum will be filled with hydrogen–helium gas (which will be contained inside polyimide windows) to minimize laser light scattering. The hohlraum will be maintained at 18 kelvins (see cooling ring) to keep the deuterium–tritium (D–T) fuel frozen and the central D–T gas core at the correct temperature and density.

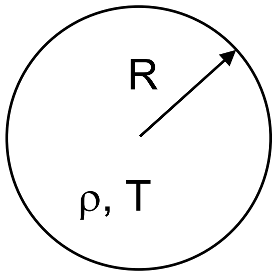
1 MJ – "scale-1" ignition campaign in 2010



192 beam experiments at ~ 1 MJ will be used for the first ignition campaign in 2010

Key physics issues

ICF: criterion of inertial confinement



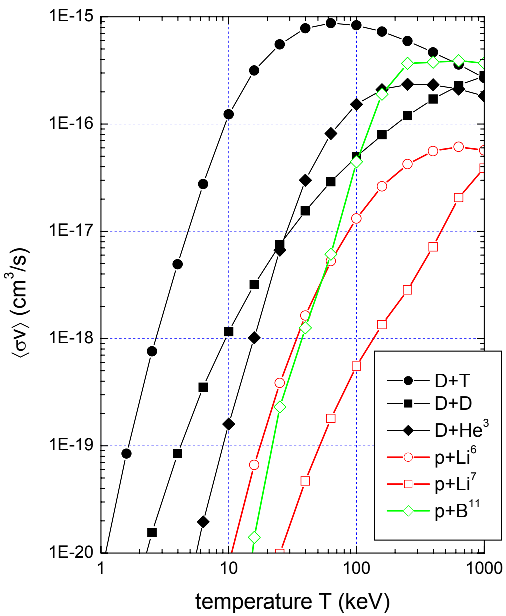
D + T → ^{4}He (3.52 MeV) + n (14.06 MeV)

Time of inertial confinement: $t_{con} \approx \frac{R}{c_s} \propto \frac{R}{\sqrt{T}}$

Number of fusion events per unit volume: $\frac{dn_{fus}}{dt} = n_D n_T \langle \sigma v \rangle$

Fuel burn fraction:

$$f_b = \frac{n_{fus}}{n_T} \approx n_D \langle \sigma v \rangle t_{con} \propto \frac{\rho R}{T^{1/2} \langle \sigma v \rangle^{-1}} = \frac{\rho R}{H_b}; \qquad H_b \approx 7\, g/cm^2;$$



If we want $f_b > 0.1 - 0.3$, we need $\rho R > 1 - 3\ \mathrm{g/cm^2}$

For comparison: in the Pu fission bomb $\rho R \geq 100\ \mathrm{g/cm^2}$

ICF: fuel compression

To achieve a critical ρR in a small fuel mass, we need strong compression.

Fuel mass:

sphere: $M = \frac{4\pi}{3}\rho R^3 = \frac{4\pi}{3}\frac{(\rho R)^3}{\rho^2}$ cylinder: $M = \pi\rho R^2 L = \pi L \frac{(\rho R)^2}{\rho}$

To achieve $\rho R = 3\ \mathrm{g/cm^2}$ in a spherical mass of $M = 1\mathrm{mg}$, we need

$\rho > 330\ \mathrm{g/cm^3}$ = 1500 × solid-DT density.

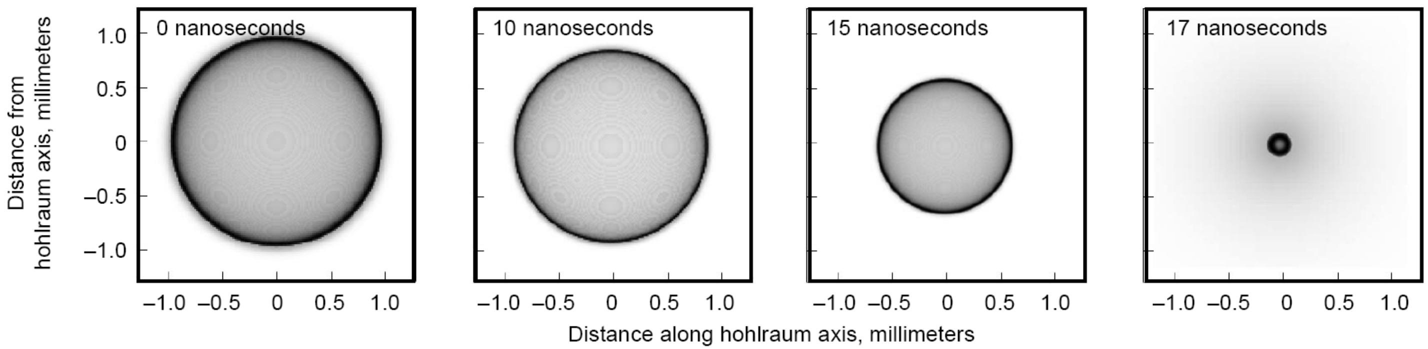
Conclusion: a small DT mass (a few milligrams or less) can be efficiently burnt out only after it is strongly compressed – by a factor 1000-3000 in density!

Such a compression is a principal challenge for ICF.

Strategy of compression to super-high densities

To compress matter, we have to apply external pressure P. Practically achievable are: static pressures about $P \sim 2$ Mbar, and dynamic pressures about $P \sim 100$ Mbar.

- If we apply our external pressure abruptly, we generate a strong shock and compress by no more than a factor 4 in density;
- If we apply our external pressure "gently", we compress quasi-adiabatically; $P_{DT} = 2.2\ \text{Mbar}\ \rho^{5/3}$ (zero specific entropy, pressure of degenerate electrons);
- The only way to achieve unlimited (in principle) compression by applying a limited external pressure is to implode a thin spherical (or cylindrical) shell !

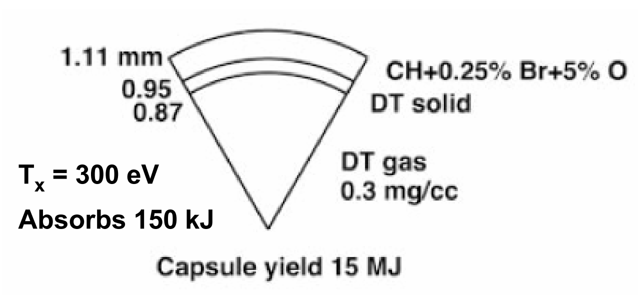


External pressure is created by radiative ablation!

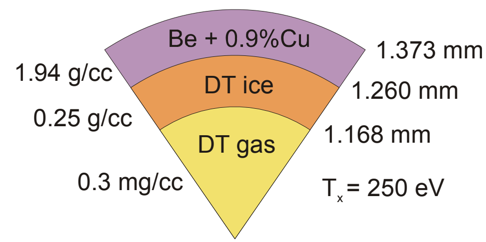
NIF fuel capsules

Target performance: an impressive progress in the confidence level and safety margin !

NIF baseline capsule



Be-ablator capsule



Absorbs 190 kJ
Yields 28 MJ

(G.L.Strobel et al., PhP **11**, 4261, 2004)

- A 250-eV Be capsule is more susceptible to the Rayleigh-Taylor instability than a 300-eV one, but a remedy for that has been found recently.
- Be capsules are more difficult to fabricate, but significant technological progress has been reported recently.

The issue of the implosion symmetry

The required high degree of fuel compression can be ensured only if the fuel implosion is almost ideally spherically symmetric

Main causes of departure from ideal symmetry:

- large-scale non-uniformities of capsule irradiation;
- the Rayleigh-Taylor instability – when a fluid layer is accelerated in the direction of the density growth.

Implosion symmetry is an important issue for high convergence ratio targets

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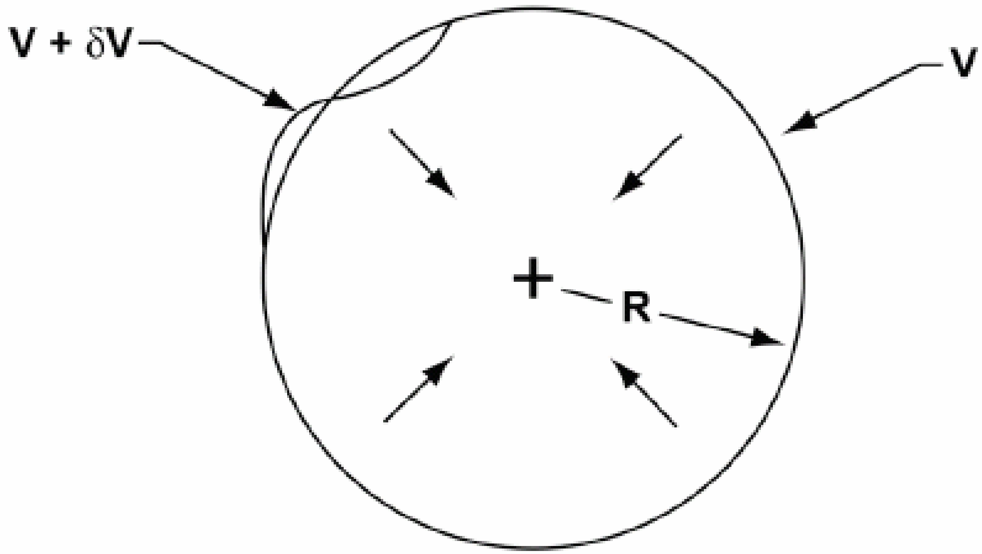
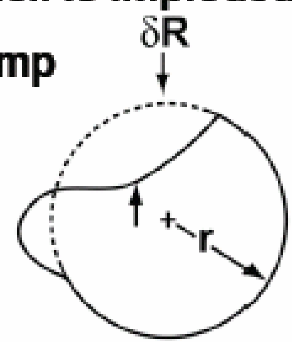
Small nonuniformity when outershell is at large radius



Becomes magnified when shell is imploded to a very small radius

Lower peak compression, temp
Lower r R

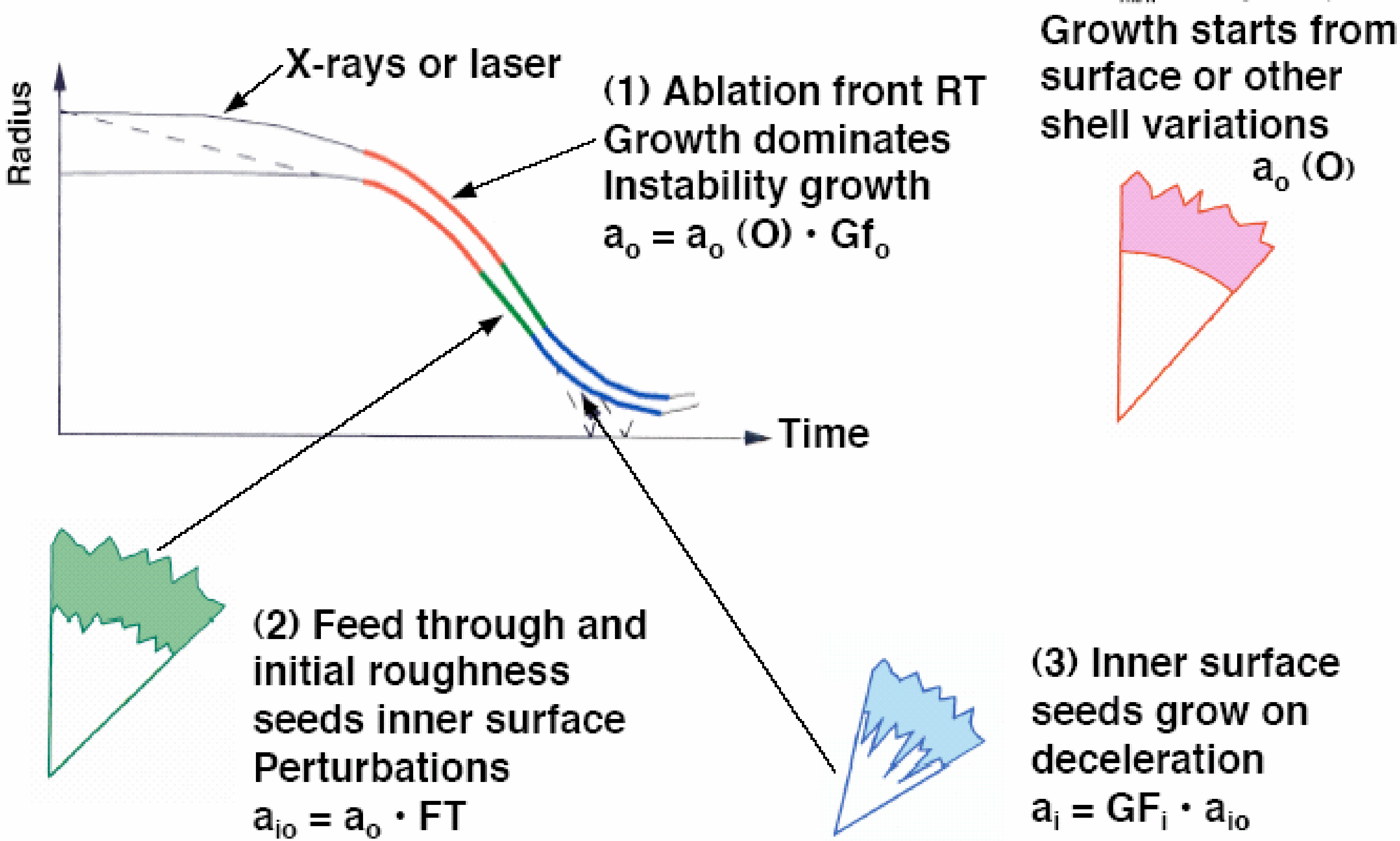


$$dR = (dV)t \sim dV\frac{R}{V} < 1/2\ r$$

$$\backslash\ \frac{dR}{r} = \left(\frac{dR}{r}\right)\frac{R}{r} < 1/2$$

$$\backslash\ \frac{dV}{V} < 1/2\ \ \frac{r}{R} < 1/2\ (\text{conv. ratio})^{-1}$$

The ablation front hydrodynamic instability can destroy an imploding shell



Cocktail ignition target burns with near 1D yield in 3D calculations with both asymmetry and surface roughness

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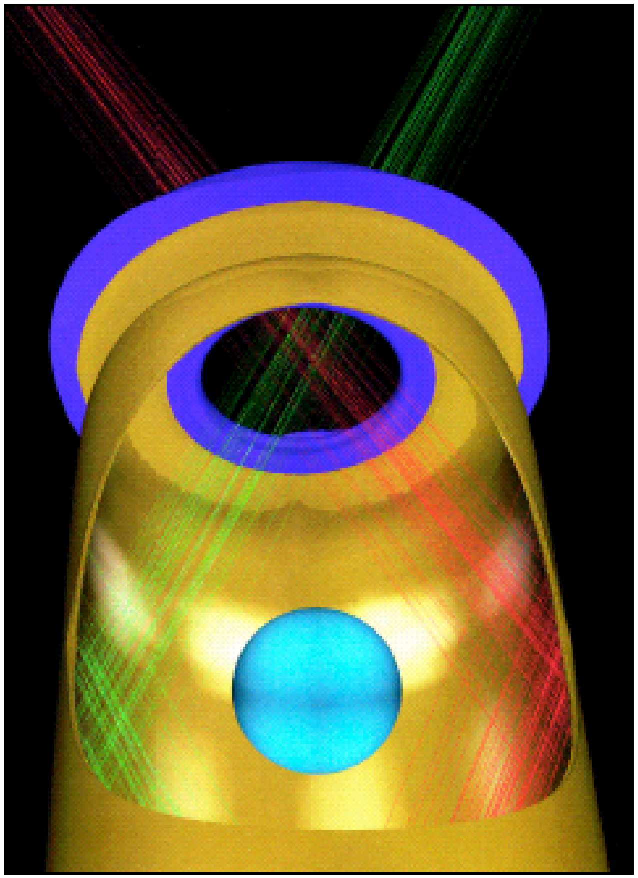
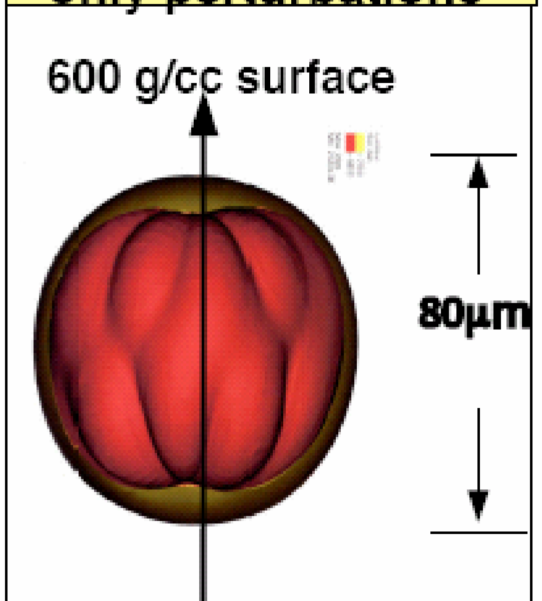
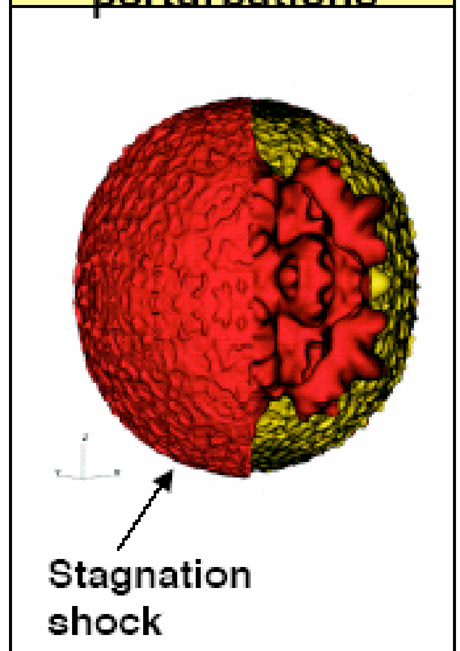


Ignition - hohlraum only perturbations



Hohlraum Axis (z)

Ignition - capsule and hohlraum perturbations



400 g/cc density isosurface

The Hydra code is used for 3D calculations on the ASCI computers

Be Capsule designs using graded dopants for pre-heat shielding have the best calculated performance

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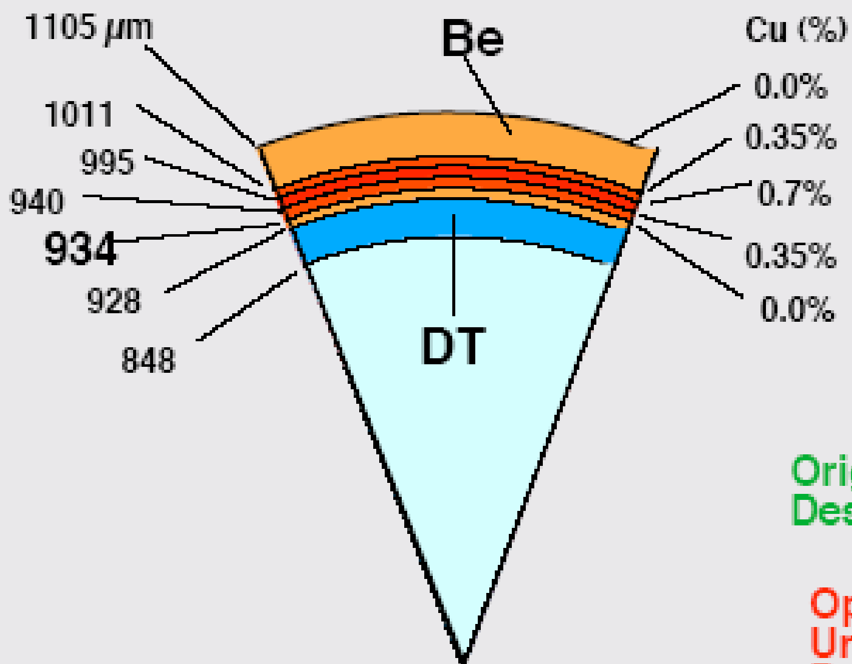
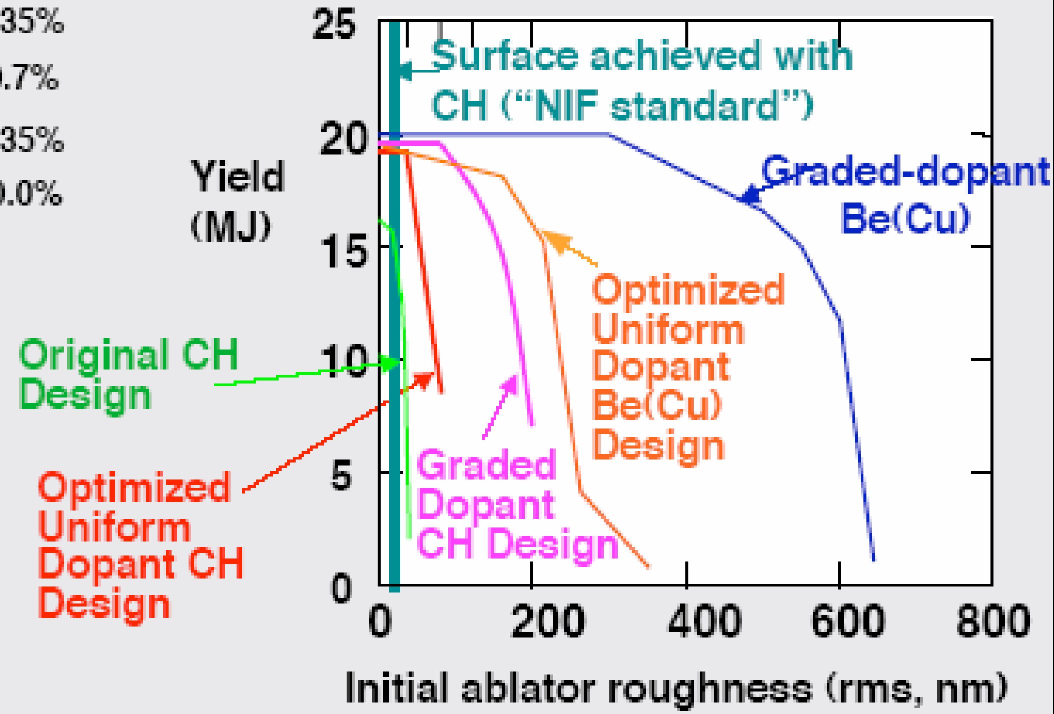
300 eV design:



The graded doped Be capsule can tolerate 60x the NIF standard

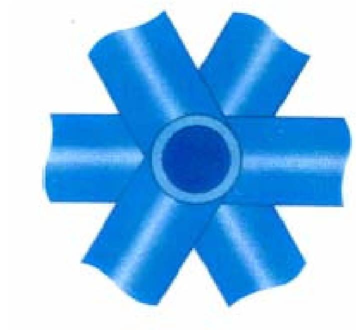


Tolerance to ice roughness is also better (5 μm compared to 1 μm)

Direct versus indirect drive

Direct drive with laser or ion beams

Here the driver beams (either laser or ion) directly irradiate the spherical fusion capsule.



Critical issues:

- spherical uniformity of irradiation
- the RT instability at the acceleration stage

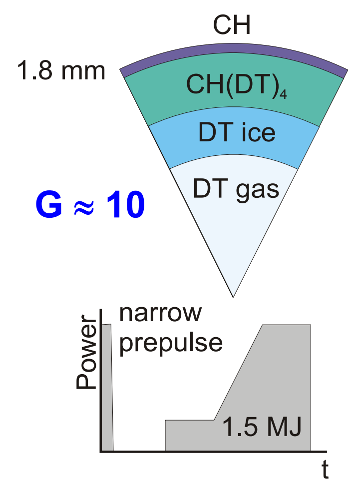
Direct drive is difficult with lasers, and appears to be hopeless (in spherical geometry!) with the ion beams.

A target for the polar-direct-drive experiments on NIF:

Suppression of the RT instability:

Adiabat shaping by a “picket stake” pulse: investigated theoretically and experimentally on OMEGA (S.P.Regan).

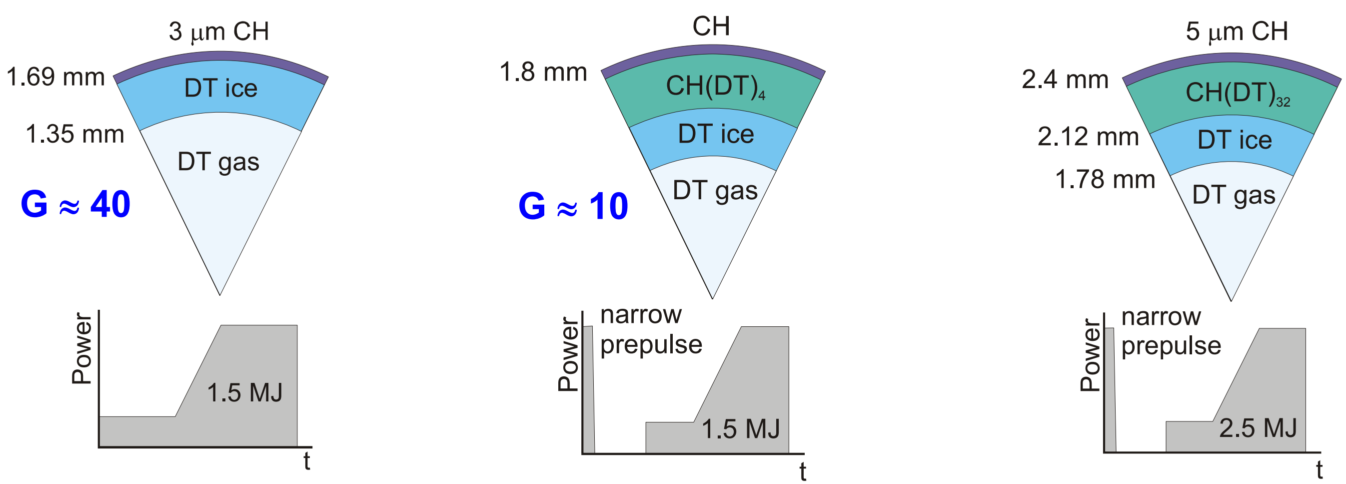
NIF PDD



Laser direct drive

Good prospects for IFE, but more problems with hydrodynamic instabilities.

Advances in target design:



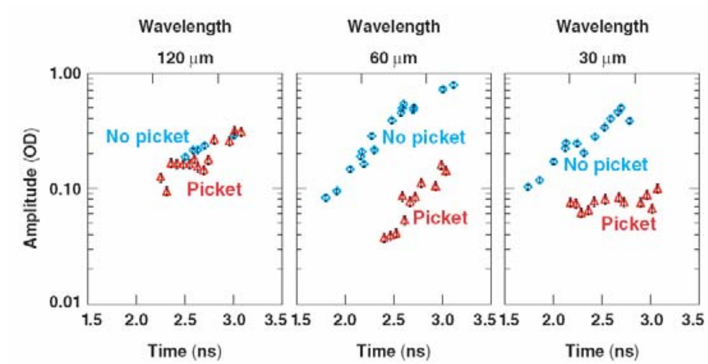
2-D energy gain

G = 160

(A.J.Schmitt *et al.*, PhP **11**, 2716, 2004)

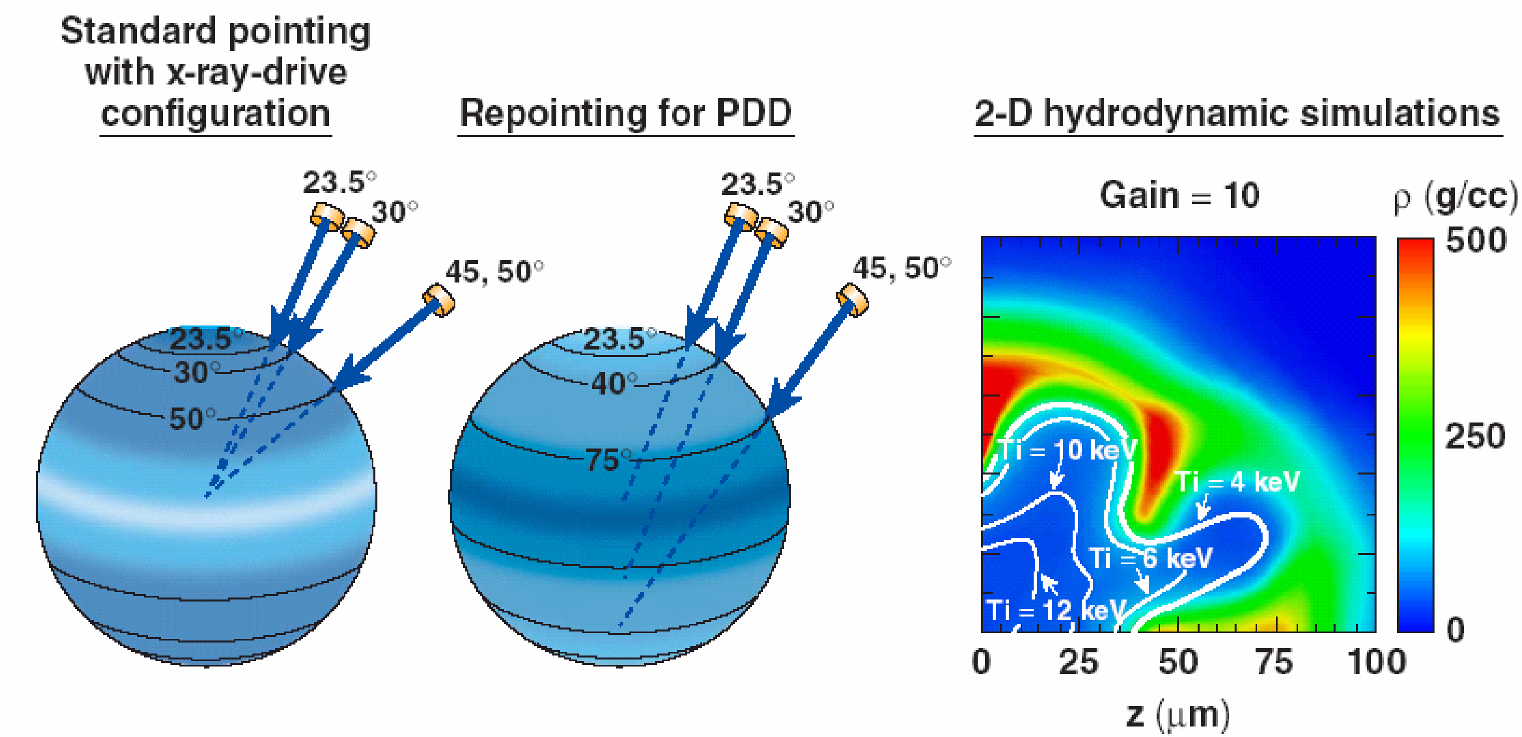
Suppression of the RT instability:

Adiabat shaping by a “picket stake” pulse: investigated theoretically and experimentally on OMEGA (S.P.Regan, OV-3/3).



Laser direct drive: prospects for ignition

PDD (polar direct drive) – ignition at NIF without laser beam rearrangement from their indirect-drive configuration; 2-D gain predictions G≈10.

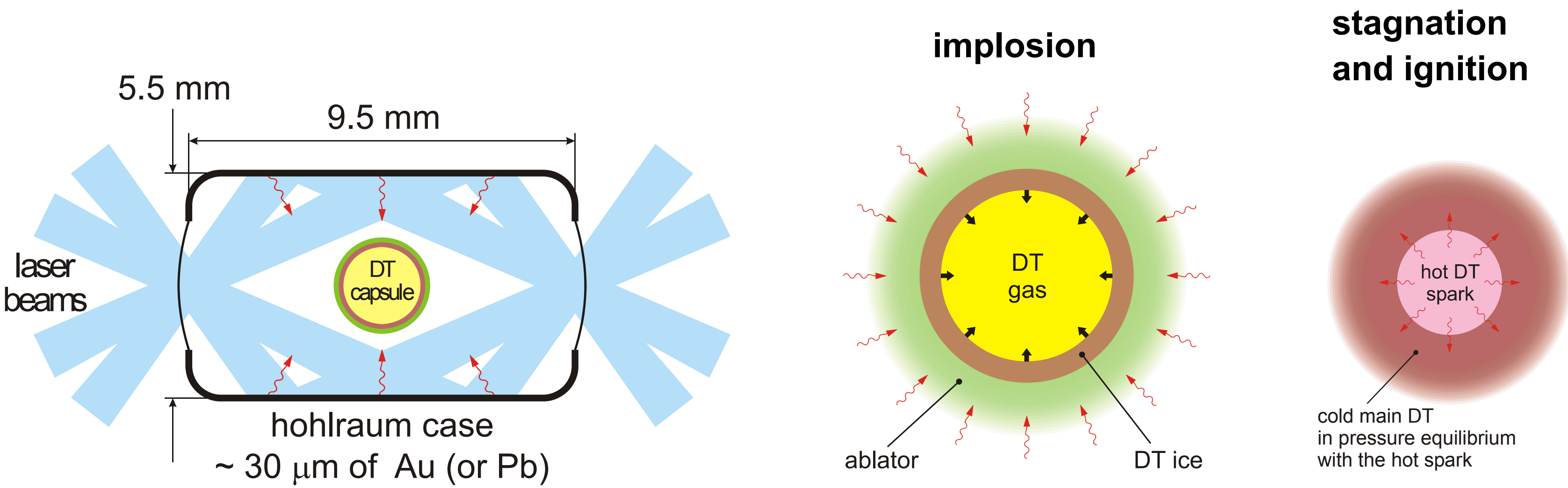


Polar direct drive is based on the optimization of phase-plate design, beam pointing, and pulse shaping (S.P.Regan).

Early ignition in the PDD mode would be an important step towards IFE !

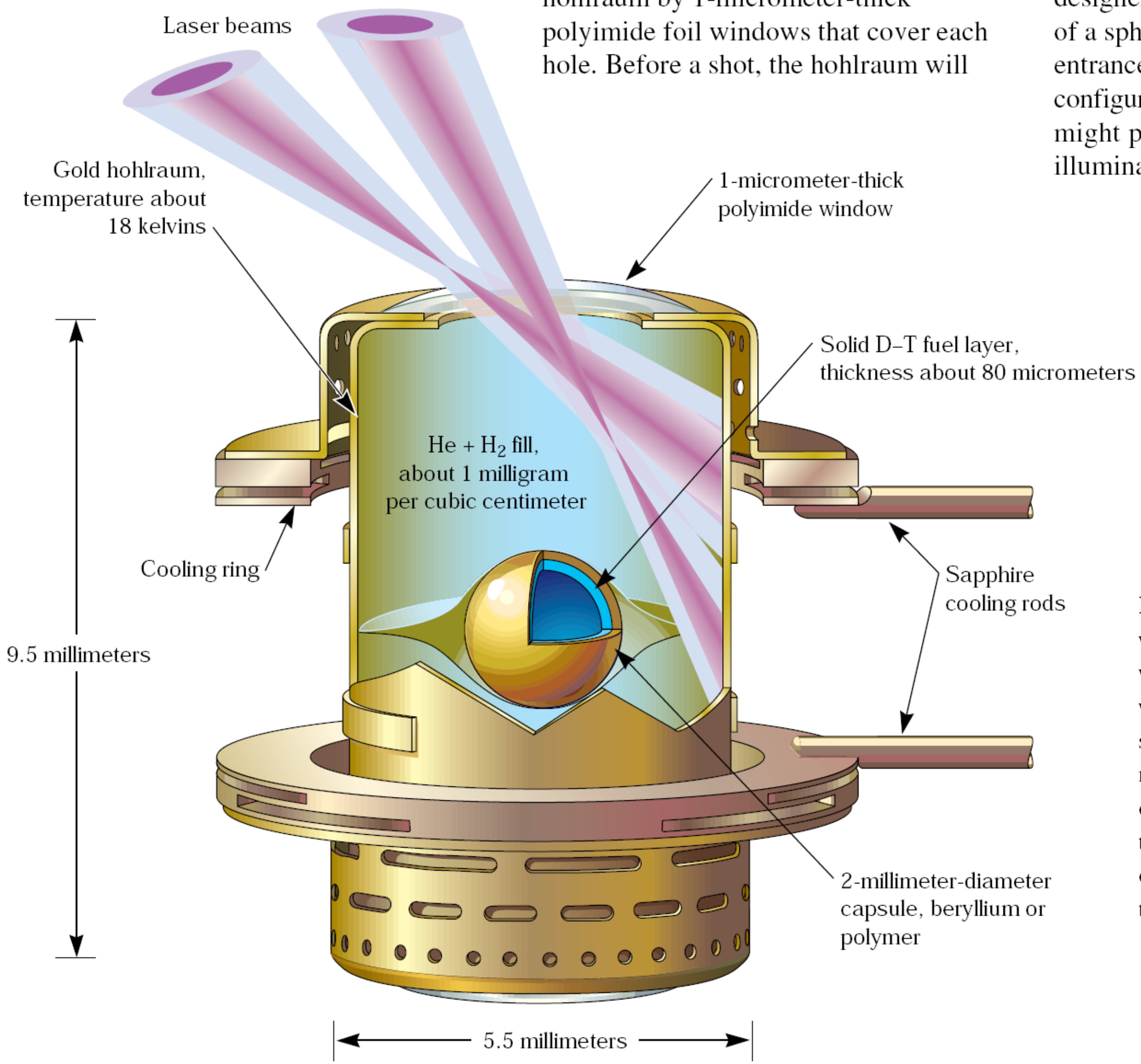
Indirect laser drive with a central hot spot

Baseline target and driver designs for NIF have been worked out more than 10 years ago.



- Laser light creates a "bath" of thermal X-rays in a cylindrical hohlraum, which then drive spherical implosion of a DT capsule.
- The compressed DT is ignited from a central hot spot, which is naturally formed in the process of implosion provided that the implosion velocity $\geq (2\text{–}3)\times10^{7}$ cm/s.

NIF target



hohlraum by 1-micrometer-thick polyimide foil windows that cover each hole. Before a shot, the hohlraum will

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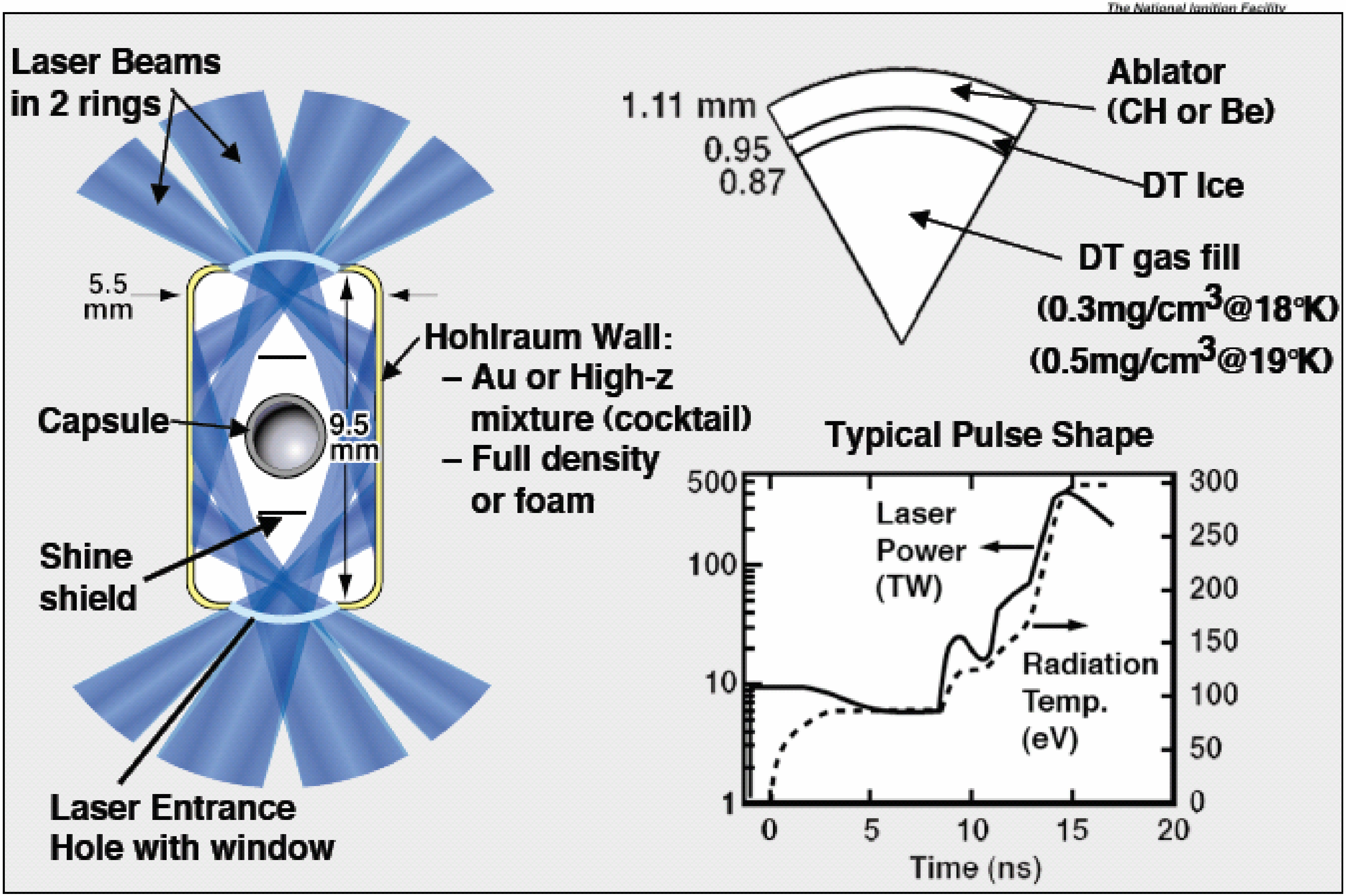
Figure 3. The hohlraum will be filled with hydrogen–helium gas (which will be contained inside polyimide windows) to minimize laser light scattering. The hohlraum will be maintained at 18 kelvins (see cooling ring) to keep the deuterium–tritium (D–T) fuel frozen and the central D–T gas core at the correct temperature and density.

NIF Indirect Drive target schematic



The Indirect drive ignition point design continues to evolve to optimize coupling efficiency

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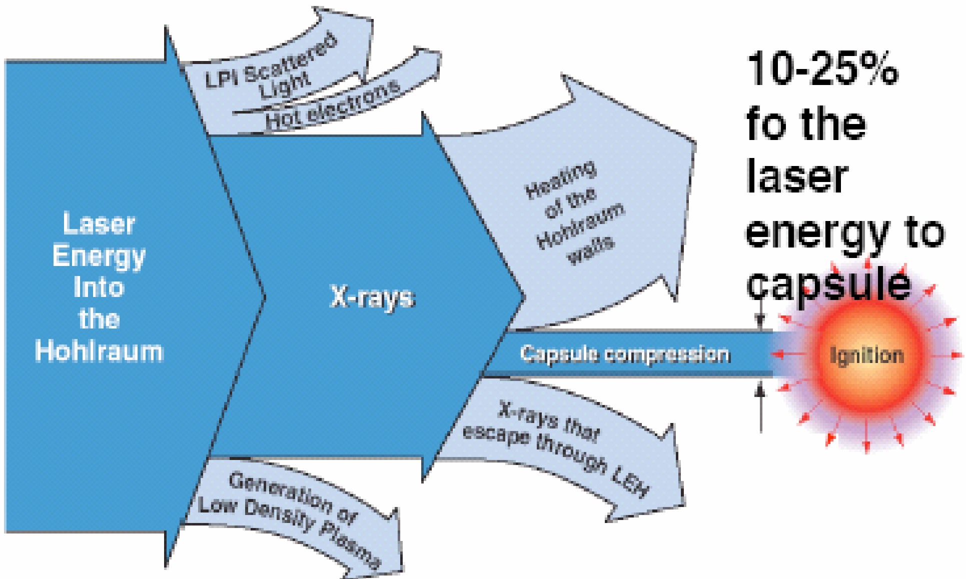


10-25% fo the laser energy to capsule

	Au with CH Capsule	Au with Be Capsule	Cocktails with Be Capsule
Laser light	1.45	1.45	1.45
(MJ) Absorbed	1.30	1.30	1.30
xrays	1.10	1.10	1.10
wall loss	0.65	0.62	0.53
hole loss	0.30	0.28	0.33
capsule	0.15	0.20	0.24
efficiency (%)	10.5%	13.5%	16.5%

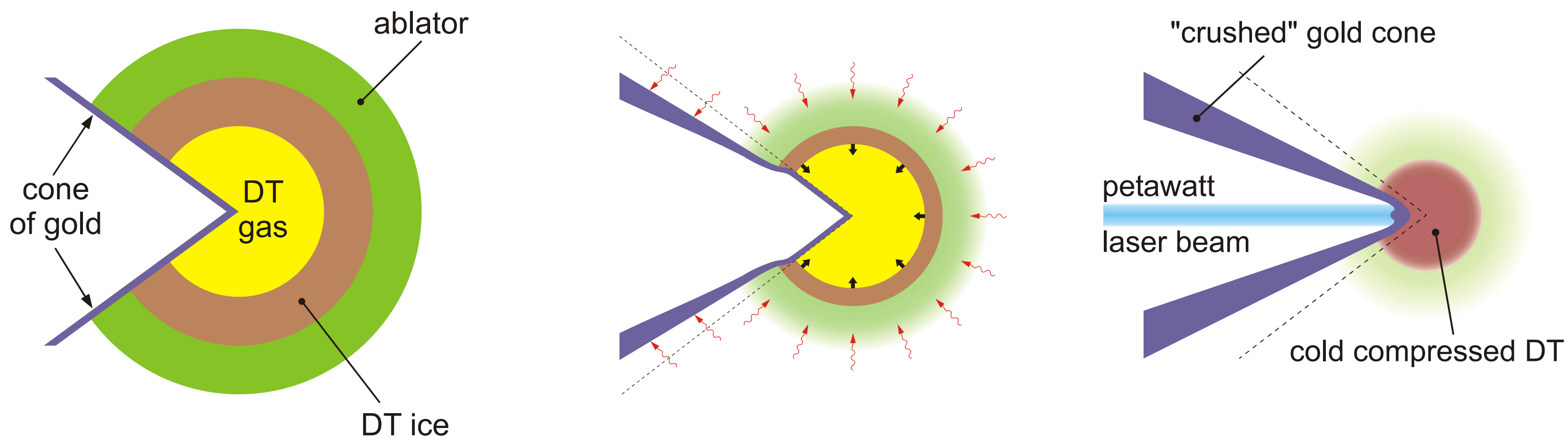
Fast ignition mode

Fast ignition with a PW laser

Fast ignition offers an alternate, potentially more efficient, route to ICF.

Principal option: a cone-guide implosion of the cold fuel is followed by a fast ignition pulse.

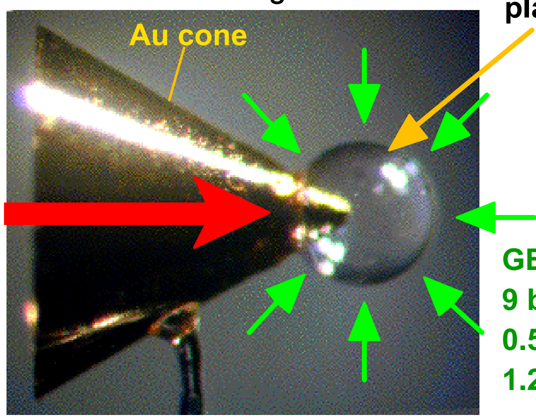
The FI approach to ICF does not have the highest priority, but is also making a steady progress.



- A dedicated program for FI at ILE in Osaka (next slide) (Y.Izawa).
- OMEGA EP (extended performance) is under construction at LLE in Rochester, which should add two 2.6-kJ petawatt beams for FI experiments (S.P.Regan).

Fast ignition research at ILE (Osaka)

ILE has a dedicated experimental program for investigation and realization of fast ignition.



- **High density compression was realized with the cone-shell target.**
- **Experiments with the PW laser demonstrated the heating efficiency of 20%** (Y.Izawa).

Future developments:

2003 - 2008 : FIREX-I (Phase 1)

New heating laser (10kJ, 10ps, 1PW) + GEKKO XII

Heating of cryogenic target to 5 ~ 10keV

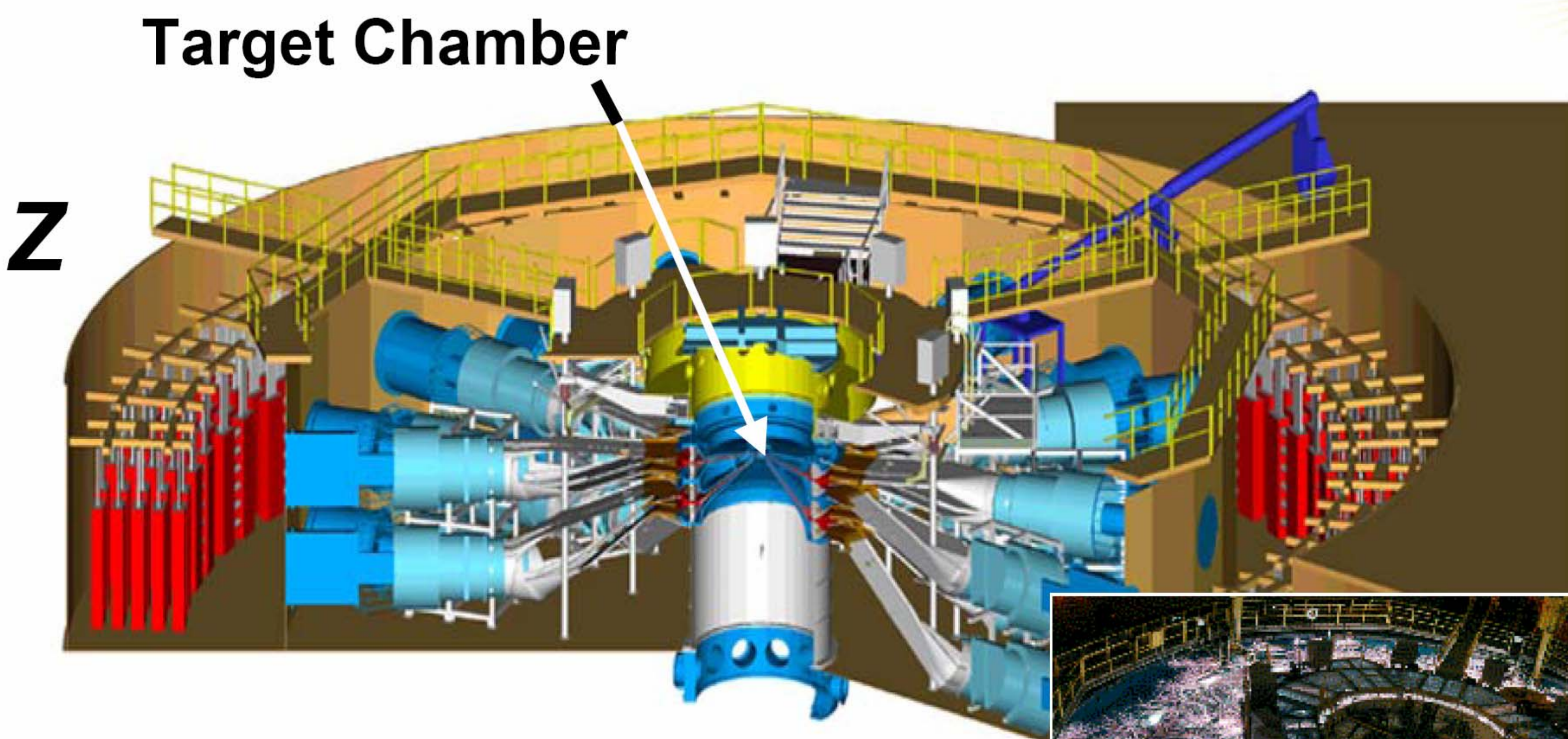
2009 - 2014 : FIREX-II (Phase 2)

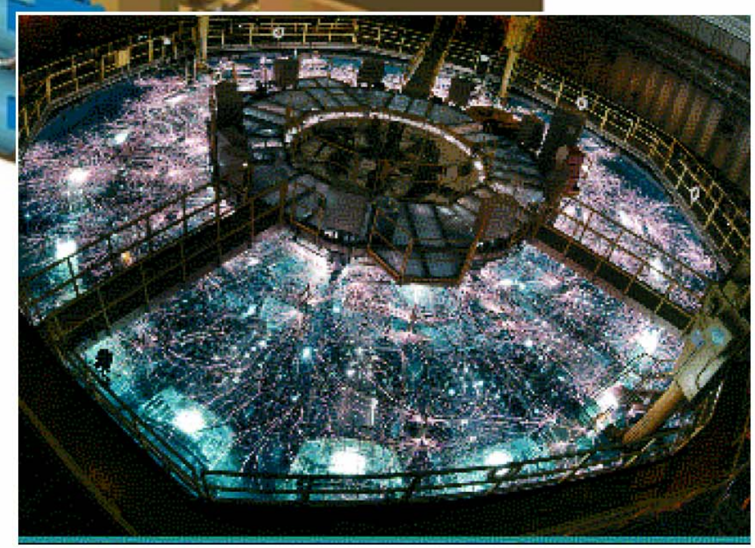
New compression laser (50kJ, 350nm) + Heating laser (50kJ, 10ps)

Ignition and burn, gain ~ 10 (Y.Izawa, OV-3/2)

ICF with wire-array Z-pinch

Pulsed-power accelerators with z-pinch loads provide efficient time compression and power amplification





- 11.5 MJ stored energy
- 19 MA peak load current
- 40 TW electrical power to load
- 100-250 TW x-ray power
- 1-1.8 MJ x-ray energy

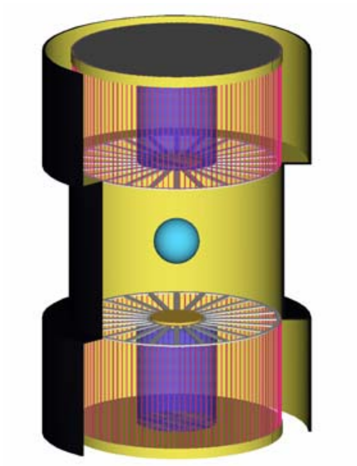
ICF with wire-array Z-pinch

Spectacular progress has been made in recent years by multi-wire Z-pinches:

up to 2.0 MJ, 290 TW in thermal X-rays (Sandia, US)

Attractiveness for IFE: (i) high efficiency (15% → 25%) of energy conversion into thermal X-rays;
(ii) the lowest cost per output MJ of energy for all IFE drivers.

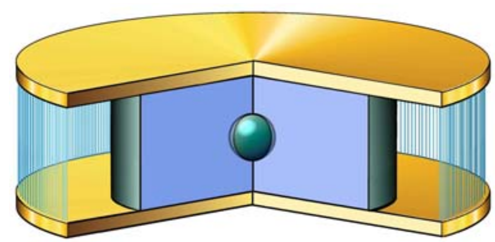
Double-pinch hohlraum target



Conventional ignition scheme with a central hot spot.

Ignition on the next-generation facility with **I ~ 60 MA** (20 MA on Z)

Dynamic hohlraum target



Demonstrated on Z (Sandia):

$T_x \approx 70$ eV, $C_r = 14 – 20$

(C.L.Olson)

Demonstrated on Z (Sandia):

$T_x \approx 220$ eV, $C_r \approx 10$,
~ 24 kJ into capsule,
8×10^{10} DD neutrons

ICF with a heavy-ion driver

Rationale behind HIF

Heavy ions become an attractive driver option when one aims at commercial energy production.

For efficient energy generation we need

$$\eta G > 10$$

where η is the driver efficiency, and G = (fusion energy)/(driver energy) is the target energy gain.

The NIF and LMJ lasers have $\eta < 1\%$. Target energy gains $G > 1000$ are not realistic.

Advantages of a heavy ion accelerator:

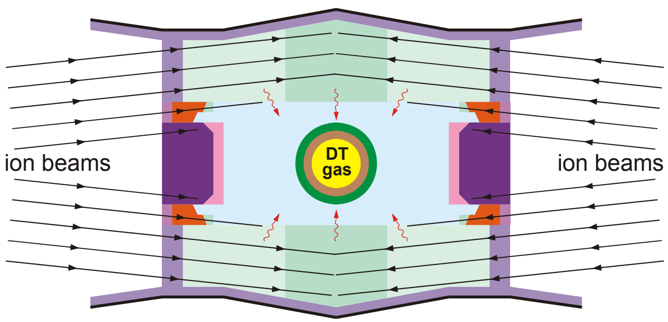
- efficiency $\eta = 25 – 35\%$ is guaranteed by the existing technology,
- high repetition rate (tens of shots per second) comes for free.

Heavy ion fusion: the Livermore approach

Attractiveness for IFE: **high efficiency (≥ 25%) and high repetition rate of the ion accelerators.**

Only small-scale activities have been funded so far; no implosion experiments in view.

Conventional approach: indirect drive, DT capsule "borrowed" from the laser indirect-drive targets, conventional ignition mode from the central hot spot.



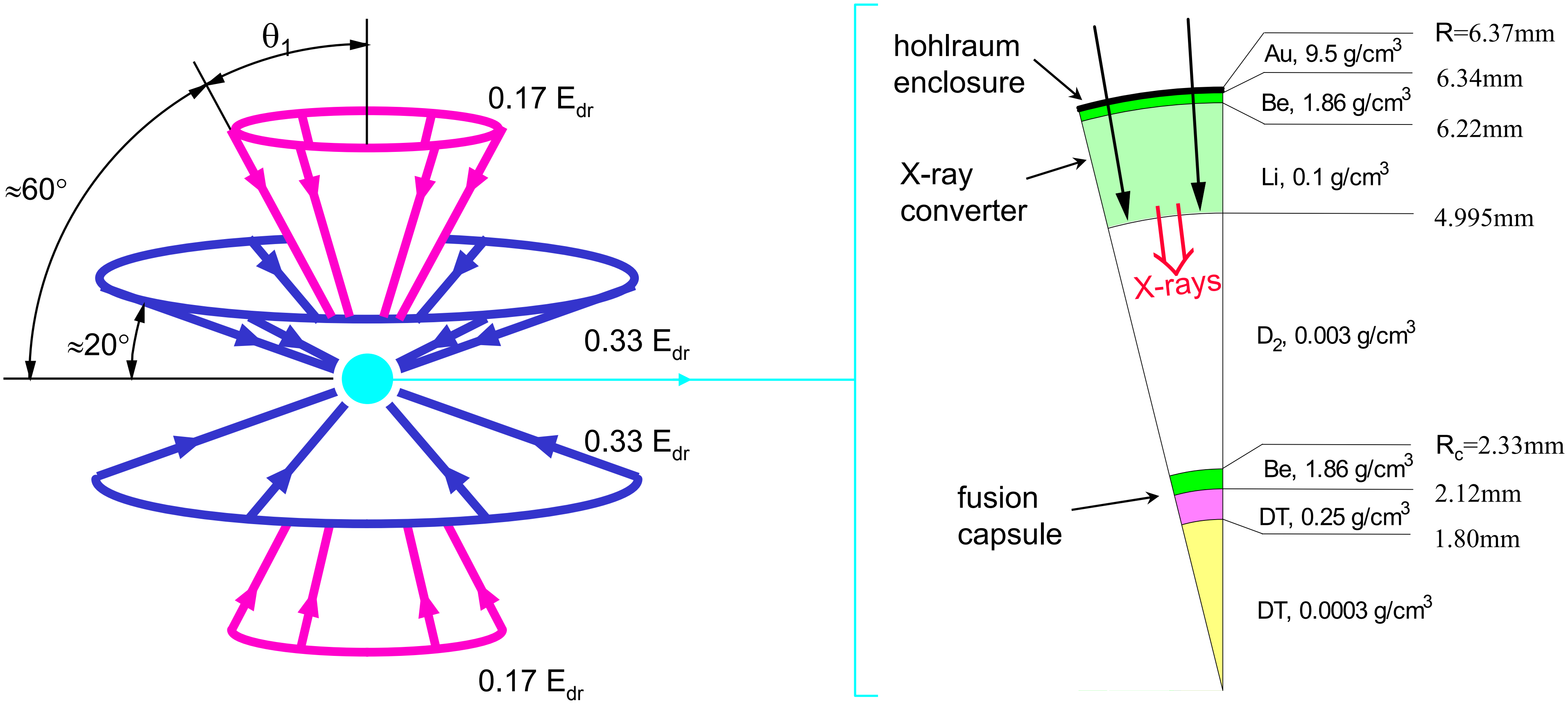
Distributed-radiator target
(D.Callahan *et al.*, LLNL)

Ion energy (Pb):	3 GeV → 4 GeV
Beam energy:	6.2 MJ
Energy gain:	55

Unlike laser beams, heavy ion beams are difficult to compress in space and time to provide the required intensity of irradiation with not too large ion penetration depth.

Problems: an accelerator to generate intense ion beams, the beam transport and focusing systems.

A P4 indirect-drive heavy ion target



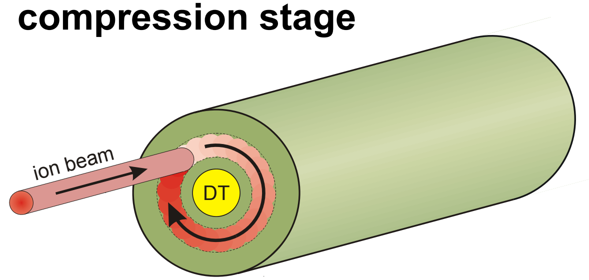
1-D 3-T simulations:

E_{dr} = 6.06 MJ, Y = 471 MJ, **G = 78**

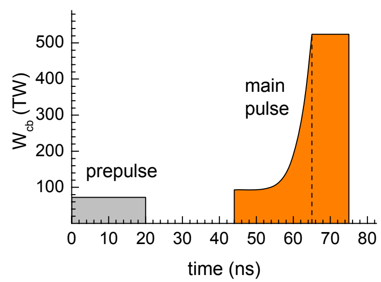
Fast ignition with heavy ions (ITEP proposal)

(i) Increase the ion energy from the conventional $E_i = 3–5$ GeV to $E_i = 100$ GeV per ion, (ii) employ the non-Liouvillian beam compression for 4 different ion masses and opposite electric charges, and (iii) use the beam charge neutralization at the last stage of the beam compression.

Direct drive cylindrical target: compression stage

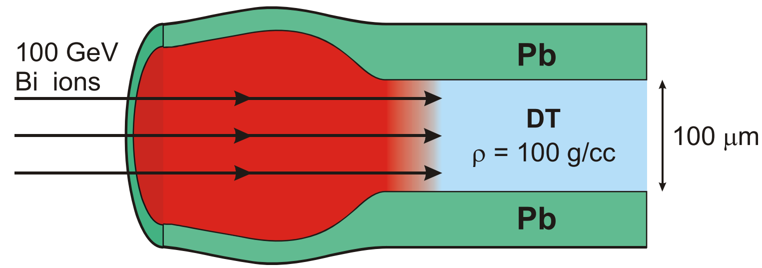


Compression pulse:



- Target compression is accomplished by a separate beam of ions with the same energy of $E_i = 0.5$ GeV/u.
- Azimuthal symmetry is ensured by fast beam rotation around the target axis (~10 revolutions per main pulse).
- Relative inefficiency of cylindrical implosion is partly compensated for by direct drive.

Ignition and burn propagation



Ignition pulse:

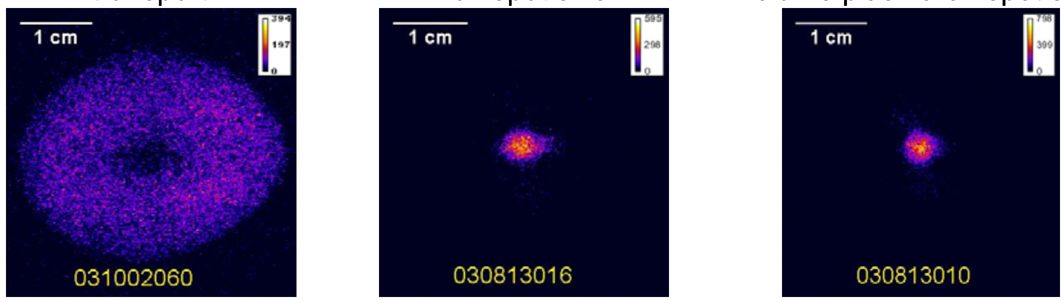
beam energy:	$E_{igb} = 400$ kJ
pulse duration:	$t_{igp} = 200$ ps
beam power:	$W_{igb} = 2$ PW
focal radius:	$r_{foc} = 50$ μm
irradiation intensity:	$I_{igb} = 2.5\times10^{19}$ W/cm^2

2-D hydro simulations (ITEP + VNIIEF) **have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder.**

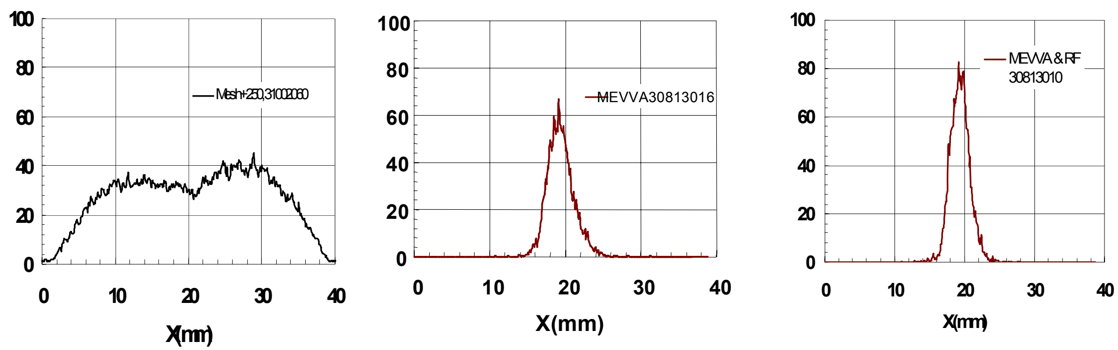
Current experiments relevant to HIF

Transverse beam compression: plasma neutralization of space charge for a 25 mA, 300 keV K^+ beam reduces beam focal spot size by a factor of ~ 10 (B.G.Logan, 2004).

Non-neutralized transport | Effect of plasma plug on spot size | Effect of plasma plug and volume plasma on spot size



FWHM: 2.7 cm | FWHM: 2.83 mm | FWHM: 2.14 mm



Longitudional beam compression:

- **a new experiment is planned to study velocity-chirped longitudinal compression of a space-charge dominated ion beam in a plasma column;**
- **numerical simulations indicate that compression factors >100 might be possible** (B.G.Logan).

Итоговые замечания

- **Лазерная программа ИТС**, основанная на традиционной схеме зажигания, успешно продвигается к демонстрации зажигания на установках NIF и LMJ. С каждым годом возрастает уверенность в работоспособности схемы.

- Идет проработка концепции **fast ignition** как экспериментально, так и теоретически.

- Многопроволочный **Z-пинч** превратился в новое конкурентноспособное направление достижения зажигания в ИТС.

- **Тяжелоионное направление ИТС** пока не получило ощутимой поддержки и развития, в значительной мере из-за его низкой конкурентноспособности на уровне экспериментов по демонстрации зажигания.