Inertial Confinement Fusion: steady progress towards ignition and high gain (summary talk)

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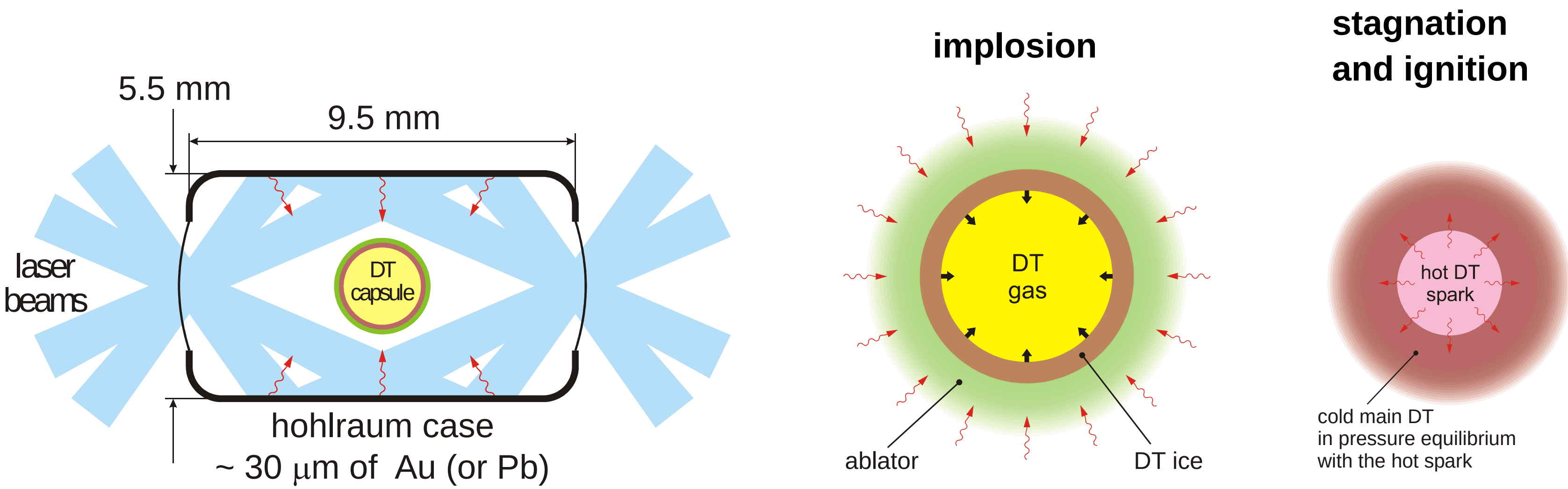
20th IAEA Conference on Fusion Energy,
November 1–6, 2004, Vilamoura, Portugal.

Main route to ignition: indirect laser drive with central hot-spot ignition

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 $\geq (2\text{–}3)\times 10^7$ cm/s.

What have been the latest new developments?

NIF and LMJ construction is underway

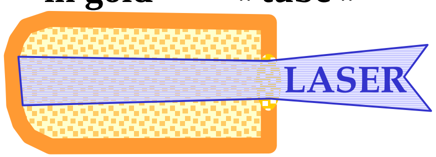
Construction of the ignition facilities – NIF in the US and LMJ in France – is fully underway !

The NIF Early Light (NEL) has been commissioned with 4 NIF beams (J.Lindl, OV-3/1)**:**

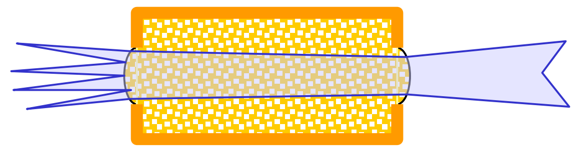
- 21 kJ in 1ω (full NIF = 4.0 MJ), 11 kJ in 2ω (full NIF = 2.2 MJ), 10.4 kJ in 3ω (full NIF = 2.0 MJ) – which means about 10% more energy than originally planned;
- 25 ns shaped pulse has been demonstrated;
- first 4 beams installed on the target chamber; experiments with 4 beams (16 kJ in 3ω) on laser-plasma interaction in ignition-size hohlraums have begun.

First experiments are planned with LIL (LMJ prototype, ~ 30 kJ) for 2005 (P.A.Holstein, IF/1-3)**:**

outer beams: Brillouin (SBS) dominant in gold => « tube »



inner beams: Raman (SRS) dominant in gas => « open cylinder »

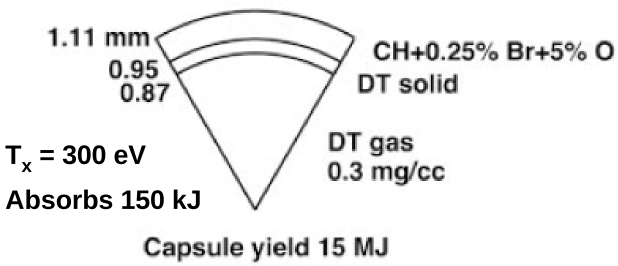


Important new experimental data are being constantly accumulated on currently operating non-ignition-scale lasers at Rochester, LANL, ILE, UK and France.

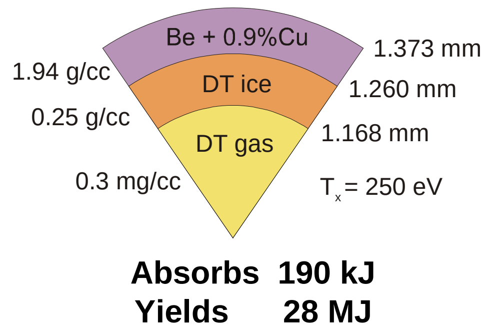
Conceptual advances: alternative capsule designs

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

NIF baseline capsule



Be-ablator capsule



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

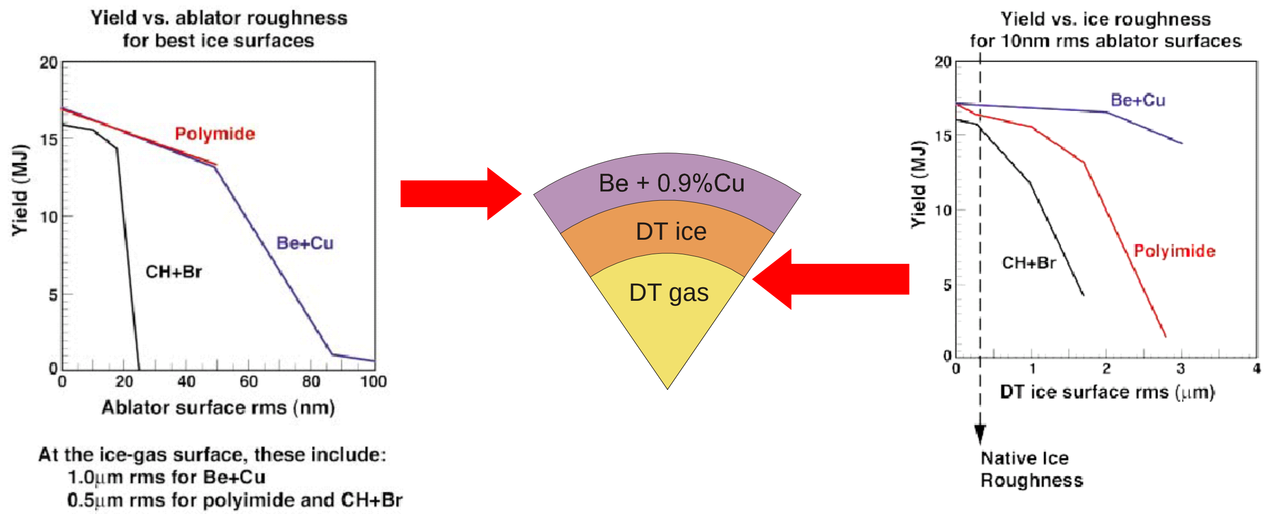
- A 250-eV Be capsule is more susceptible to the Rayleigh-Taylor instability than a 300-eV one, but a remedy for that has been found recently (see next slide).
- Be capsules are more difficult to fabricate, but significant technological progress has been reported recently (J.Lindl, OV-3/1).

Better control of hydrodynamic instabilities

All radiatively driven implosions are hydrodynamically unstable !

No more than $e^{6-7}\approx 1000$–fold increase of initial perturbations can be tolerated $\Rightarrow$ severe technological demands.

For the same X-ray drive temperature T_x, Be-ablator capsules prove to be superior to the NIF baseline CH capsule:



3-D simulations for T_x = 300 eV

(J.Lindl *et al.*, PhP **11**, 339,2004)

Latest discovery: **with graded Cu doping of the Be ablator, the ablator surface roughness $\Rightarrow$ 60 x NIF standard (~ 500 μm); ice roughness 1 μm $\Rightarrow$ 5 μm !** (J.Lindl, OV-3/1)

Graded ablator doping provides an additional degree of freedom in controlling the entropy (density) gradient across the ablator during the acceleration phase of implosion.

- Recent technological advances in reducing the D_2–ice roughness: **below 1 μm !** (S.P.Regan, OV-3/3).
- Constraints on roughness are significantly relaxed when E_{caps} goes beyond 200 kJ (see next slide).

Increased margin with respect to the ignition energy

Very encouraging is the fact that the energy margin with respect to the ignition threshold is increasing as the NIF ignition scheme is being refined !

Better use of the same laser:

- going back from 3ω to 2ω $\Rightarrow$ about 10% more energy for the same 1ω output;
- using longer pulses with lower T_x and larger capsules $\Rightarrow$ more laser output at 1ω.

The net result should be $\geq$ 2.5 MJ of laser energy (instead of 1.8 MJ) to drive the target.

Improved hohlraum efficiency:

- advanced wall composition (high-Z cocktail instead of Au);
- reduced hohlraum/capsule radial ratio (more accurate simulations);
- lower T_x with larger Be-ablator capsules.

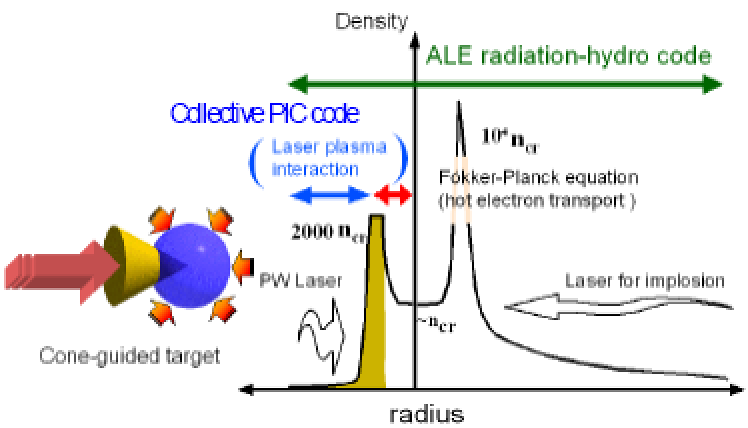
The net result: up to 400-600 kJ (instead of 150 kJ) may be absorbed by the capsule.

$\boldsymbol{G \approx 10}$ (baseline NIF)	$\Rightarrow$	$\boldsymbol{G \approx 30–60}$ (enhanced NIF)

Moderate individual advances along different directions tend to add up in a cumulative manner !

Code development: a steady increase of the predictive power

- 3-D simulations of the target performance (so far, separately for the hohlraum and the DT capsule) have become almost routine at LLNL (J.Lindl, OV-3/1).
- A 3-D hydro code for implosion studies is about to be "commissioned" in France (P.A.Holstein, IF/1-3).
- Development of a 3-D LPI/hydro code for modeling the propagation of laser beams through hohlraum plasmas.
- Development of a "Fast Ignition Integrated Interconnecting" code at ILE (Osaka) (Y.Izawa, OV-3/2, H.Nagatomo, IF-P-7/29) for integrated fast ignition simulations.
- Verification of simulation models with ongoing experiments.

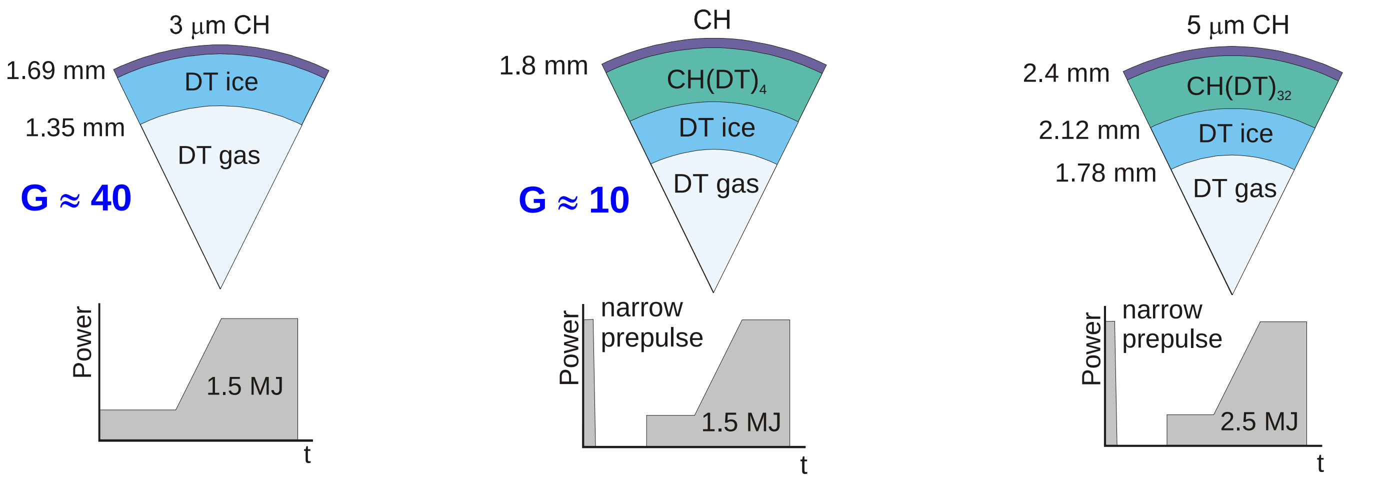


Laser direct drive

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

Advances in target design:

NIF baseline **NIF PDD** **IFE-scale target**



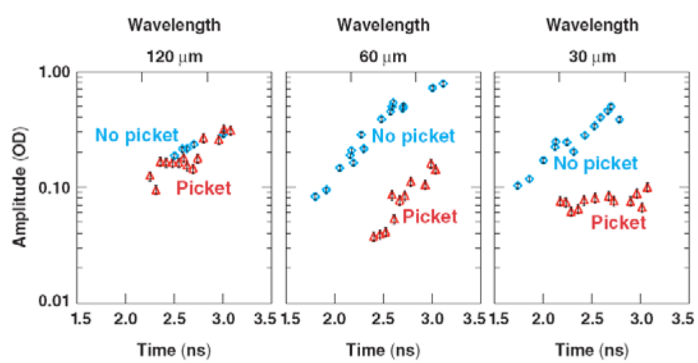
2-D energy gain

G = 160

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

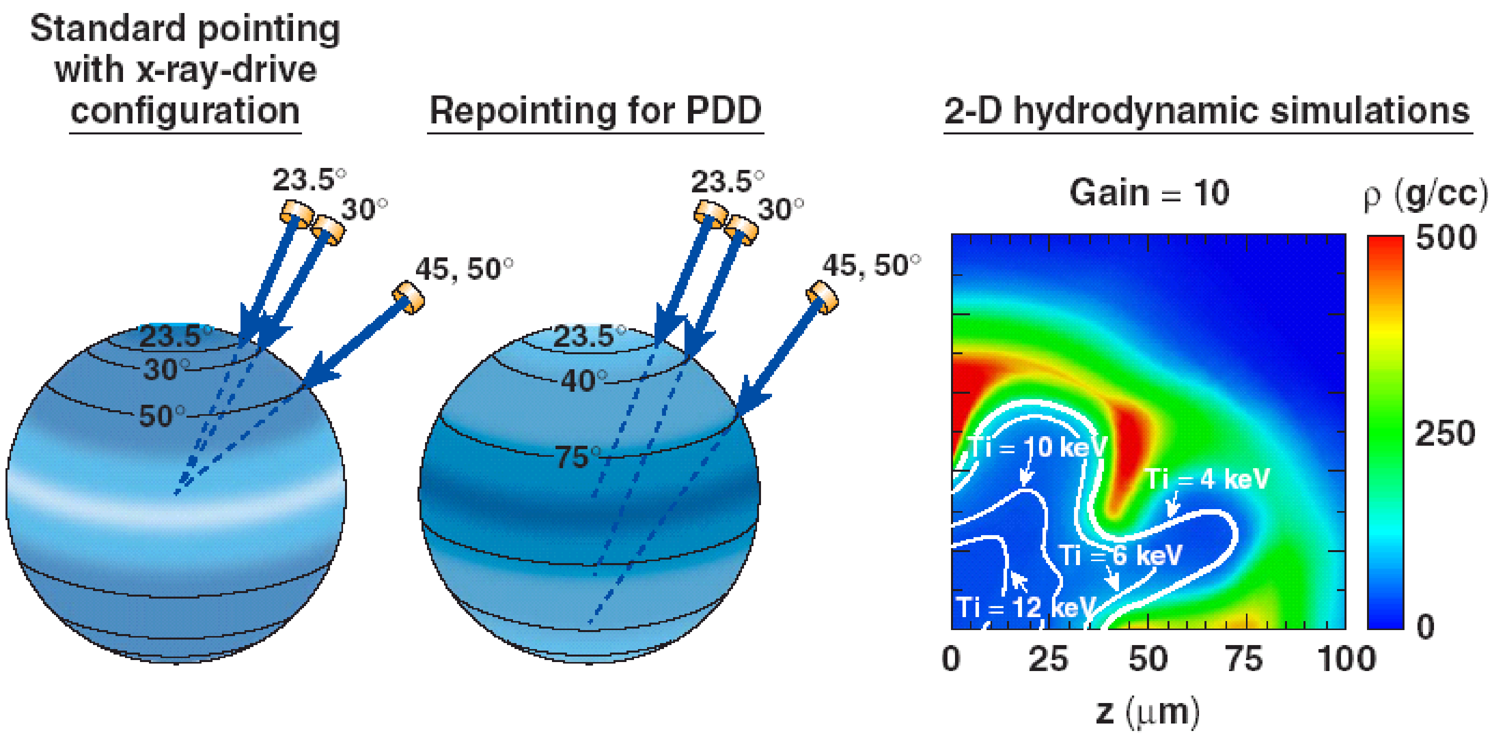
Suppression of the RT instability:

- Adiabat shaping by a "picket stake" pulse: investigated theoretically and experimentally on OMEGA (S.P.Regan, OV-3/3).
- Double ablation layer in a high-Z doped CH ablator (H.Azechi, IF/1-1Ra).



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.



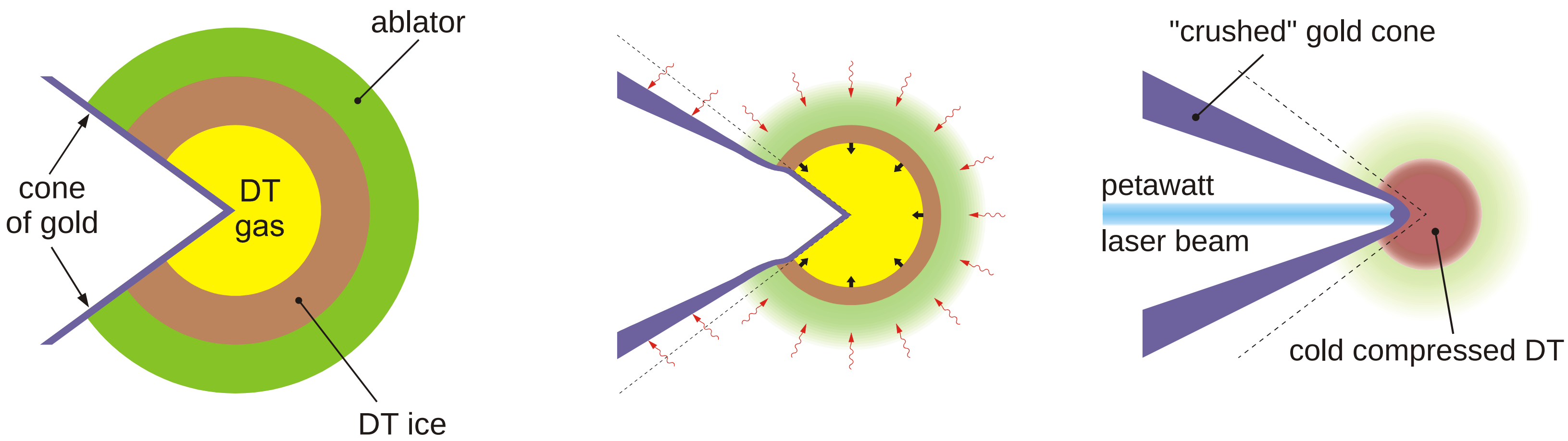
Polar direct drive is based on the optimization of phase-plate design, beam pointing, and pulse shaping (S.P.Regan, OV-3/3).

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

Fast ignition approach to ICF

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.

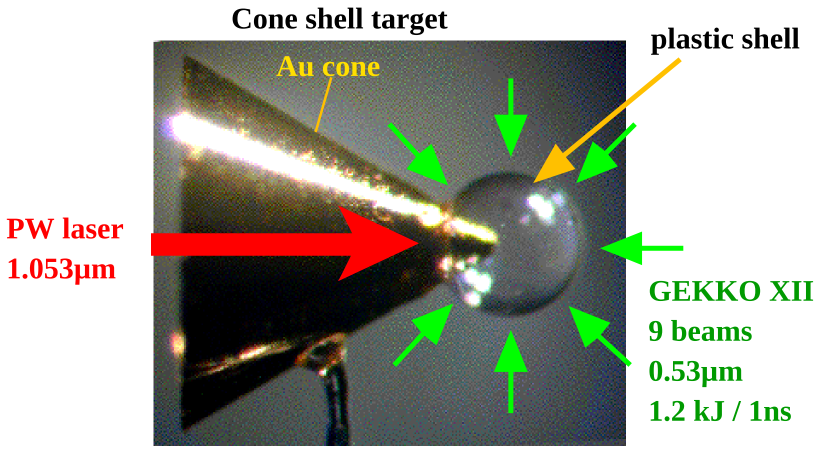
The FI approach to ICF does not have the highest priority, but is also making a steady progress.



- A dedicated program for FI at ILE in Osaka (next slide) (Y.Izawa, OV-3/2).
- 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, OV-3/3).
- Experiments at ILE on PW laser beam penetration into overdense plasmas (K.A.Tanaka, IF-1/4Ra).
- Experiments on a comparative study of plasma heating by electron and proton beams from PW lasers (M.H.Key, IF/1-4Rb).

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, OV-3/2).

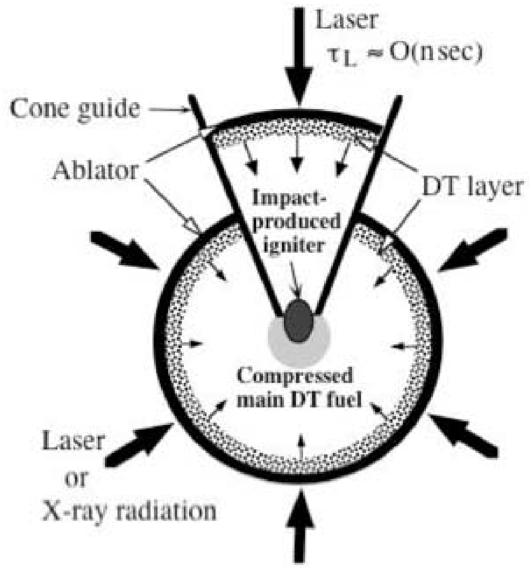
Future developments:

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)

Impact ignition – another variant of fast ignition?

Fast ignition of a precompressed cold DT could also be initiated by a high-velocity impact of a separate DT shell (H.Azechi, IF/1-1Ra; M.Murakami, IF-P-7/31)**.**



Preliminary experiments for impact ignition at ILE:

a 4×10^{7} cm/s velocity has been demonstrated for a 10μm CH foil with a moderate irradiance of 10^{14} W/cm^2 (H.Azechi, IF/1-1Ra).

Simulations for a similar approach, with ignition by a high-velocity jet, have also been done at DENIM (G.Velarde, IF-P-7/34).

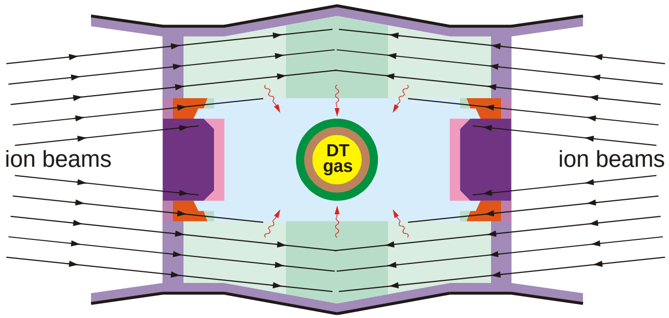
To become realistic, this concept needs to be studied in more detail.

Heavy ion fusion

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.



Dstributed-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.

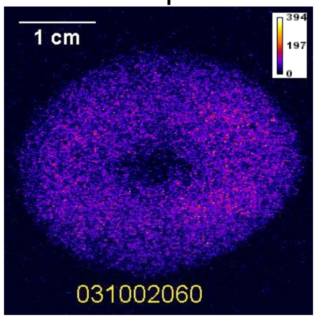
Ongoing experiments:

- Currently experiments are being conducted to explore various physics and engineering aspects of generation, transport, and final focus of high-current heavy ion beams (B.Yu.Sharkov, OV-3/4; B.G.Logan, IF-1/2).

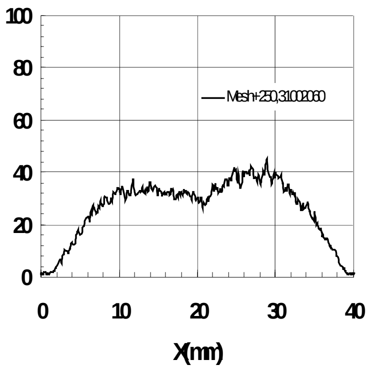
Experiments on neutralized beam transport (LBNL)

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, IF-1/2).

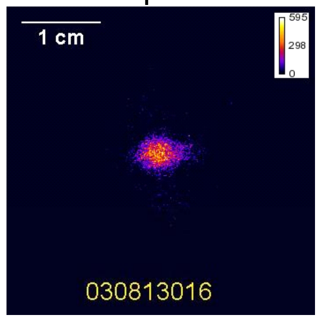
Non-neutralized transport



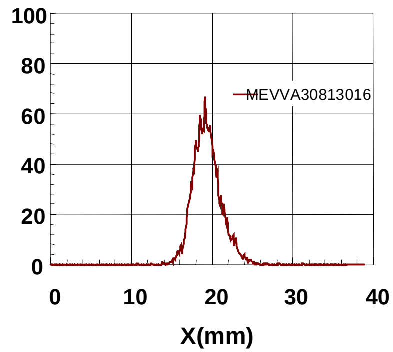
FWHM: 2.7 cm



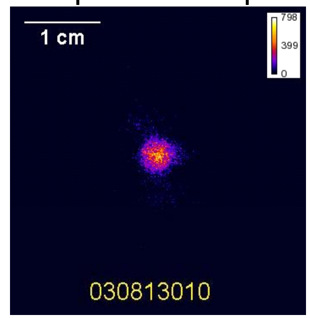
Effect of plasma plug on spot size



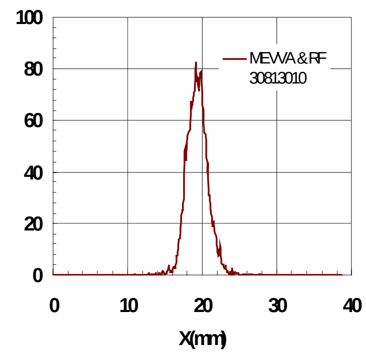
FWHM: 2.83 mm



Effect of plasma plug and volume plasma on spot size



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, IF-1/2).

Fast ignition with heavy ions: ignition pulse

Heavy ions would be a far better than laser candidate for a fast ignitor beam provided that the required intensity of irradiation could be ensured.

Recent proposal by D.G. Koshkarev from ITEP:

- increase the ion energy from the conventional E_i = 3–5 GeV to E_i = 100 GeV per ion;
- employ the method of non-Liouvillian compression of beams of simultaneously accelerated ions with 4 different masses and opposite electric charges (neutralized beams);
- use beam charge neutralization by combining pairs of beams with opposite charges at the last stage of the beam compression. (B.Sharkov, OV-3/4)

As a result, one can obtain a heavy ion beam with the following parameters:

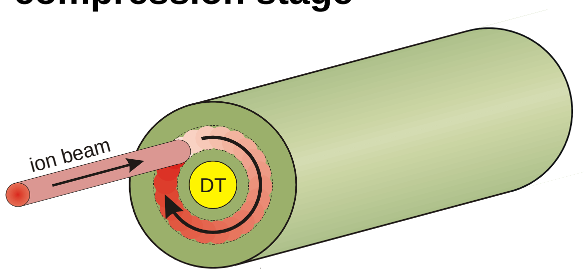
beam energy:	E_{igb} = 400 kJ
pulse duration:	t_{igp} = 200 ps
beam power:	W_{igb} = 2 PW

focal radius:	r_{foc} = 50 μm
irradiation intensity:	$I_{igb} = 2.5\times10^{19}$ W/cm^2

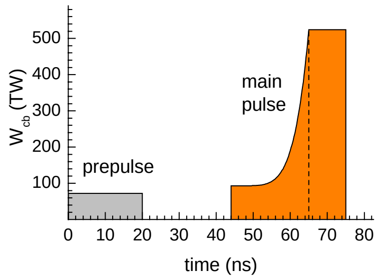
In this proposal, heavy ions with energy E_i = 100 GeV have a rather long stopping range – $\langle\rho l\rangle \approx 0.6$ g/cm^2 in DT !

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

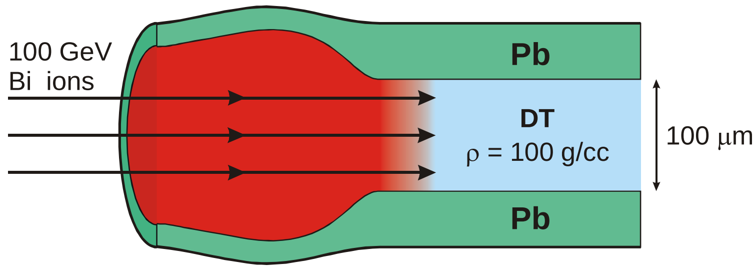


Compression pulse:



- 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:	$r_{foc} = 50\ \mu$m
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.**

An energy gain of **$G \approx 100$** can be expected.

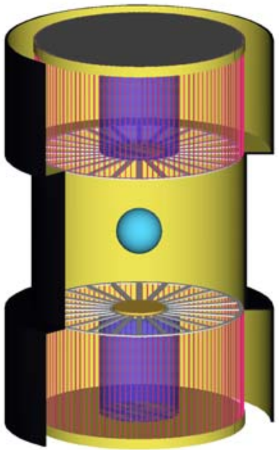
ICF with wire-array Z-pinch

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

up to 1.8 MJ, 230 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.

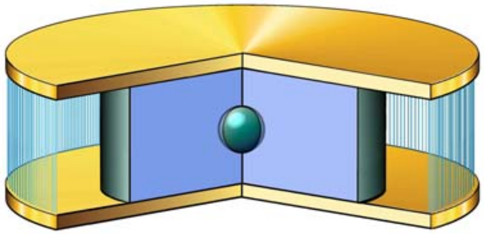
Ignition on the next-generation facility with **I ~ 60 MA** (20 MA on Z)

Demonstrated on Z (Sandia)**:**

$$T_x \approx 70 \text{ eV}, \; C_r = 14 - 20$$

(C.L.Olson, OV/3-5Ra)

Dynamic hohlraum target



Demonstrated on Z (Sandia)**:**

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

Inertial Fusion Energy with wire-array Z-pinch ?

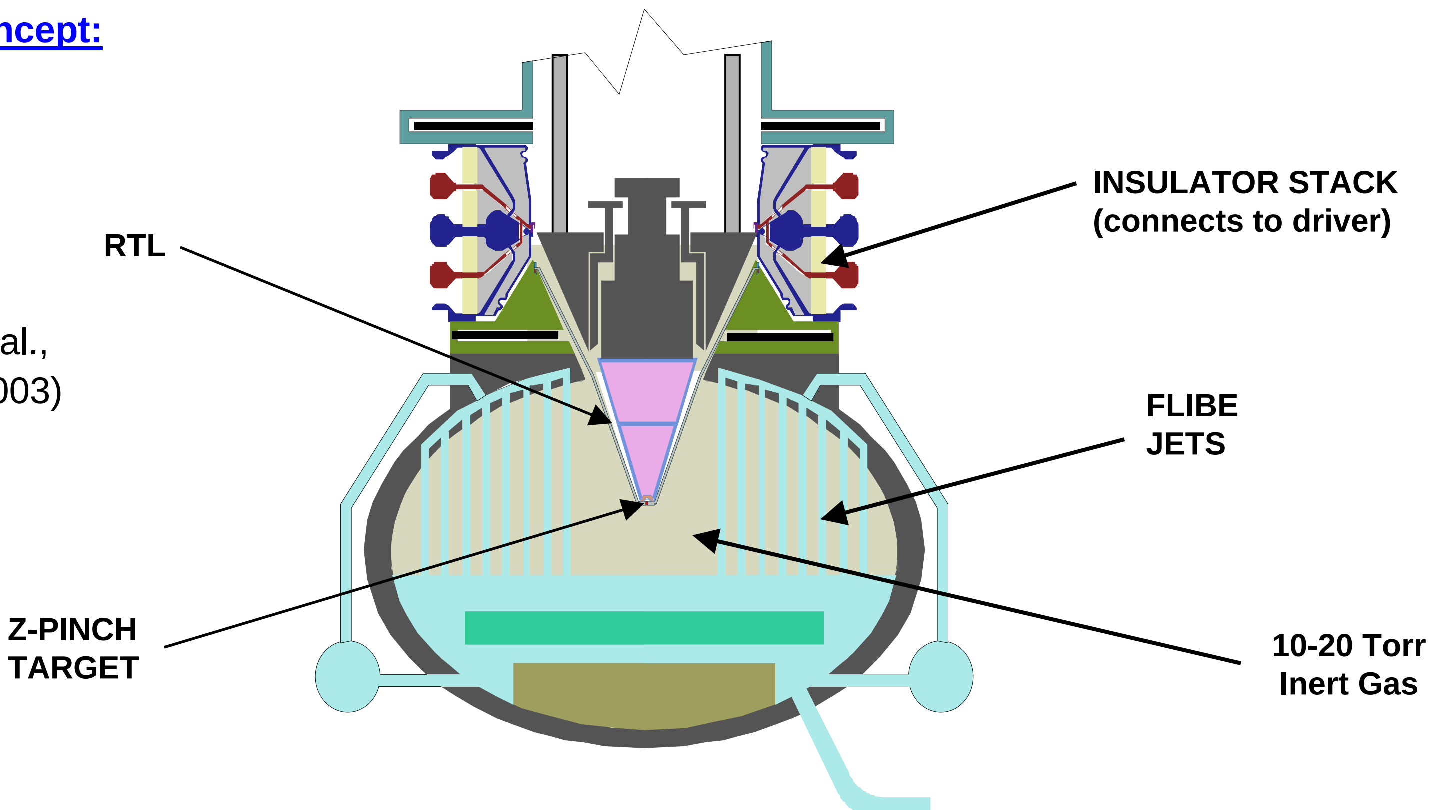
Problems: (i) repetition rate, (ii) separation of driver from target, (iii) X-ray pulse shaping.

Proposed solutions:

- a relatively low repetition rate of 1 shot of ~ 3 GJ yield per 10 seconds;
- a target unit called Recyclable Transmission Line (RTL);
- double-shell DT capsules (for pulse shaping).

Power plant concept:

(G.E.Rochau et al., FST, **43**, 447, 2003)



Final remarks

- The **laser fusion program**, based on the conventional ignition mode, advances steadily towards demonstration of ignition and high gain experiments (NIF and LMJ facilities). A spectacular progress in the confidence level and performance margin has been achieved recently.
- The concept of **fast ignition** is being explored both theoretically and experimentally.
- Wire-array **Z-pinch** becomes a competitive option for achieving ignition in ICF and as a driver option for IFE.