Summary talk to 21st IAEA FEC, Chendu, 2006

Inertial fusion advance towards ignition and gain

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Summary of IFE topics at 21st IAEA FEC

The summary is mainly based on the synopses of 24 papers submitted to the conference

Among them,

three overview presentations [OV/5-1, 5-2, 6-1],

five presentations [IF/1-1, IF/1-2R(a~c), IF/1-3],

fourteen posters [IF/P5-1~IF/P5-14],

two fusion technology posters [FT/P5-39,FT/P5-40].

outline

I. Introduction

II. Status of central ignition scheme

III. Progress of fast ignition scheme

IV. Z-pinch fusion scheme

V. heavy ion fusion scheme

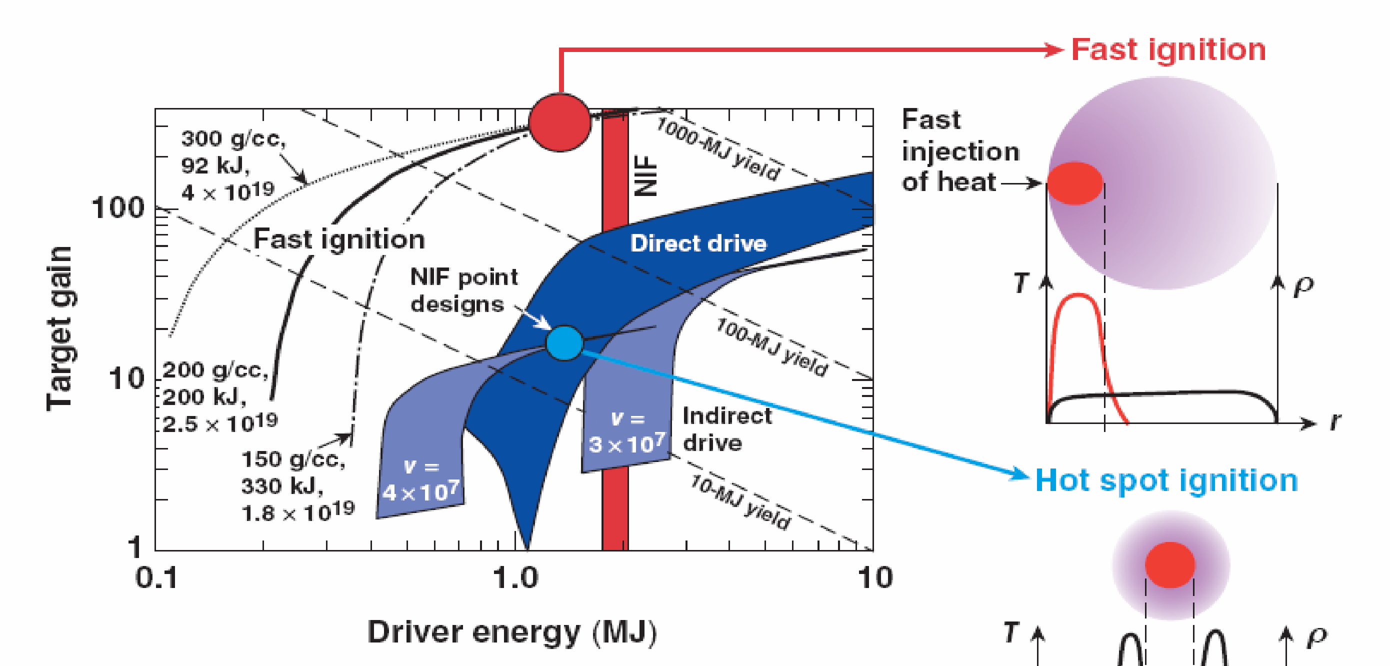
VI. Other miscellanies

VII. Brief remarks

I. Introduction

♦ IFE based on ICF

Inertial confinement fusion (ICF) parallel to magnetic confinement fusion (MCF) is an alternative approach to gain inertial fusion energy (IFE).



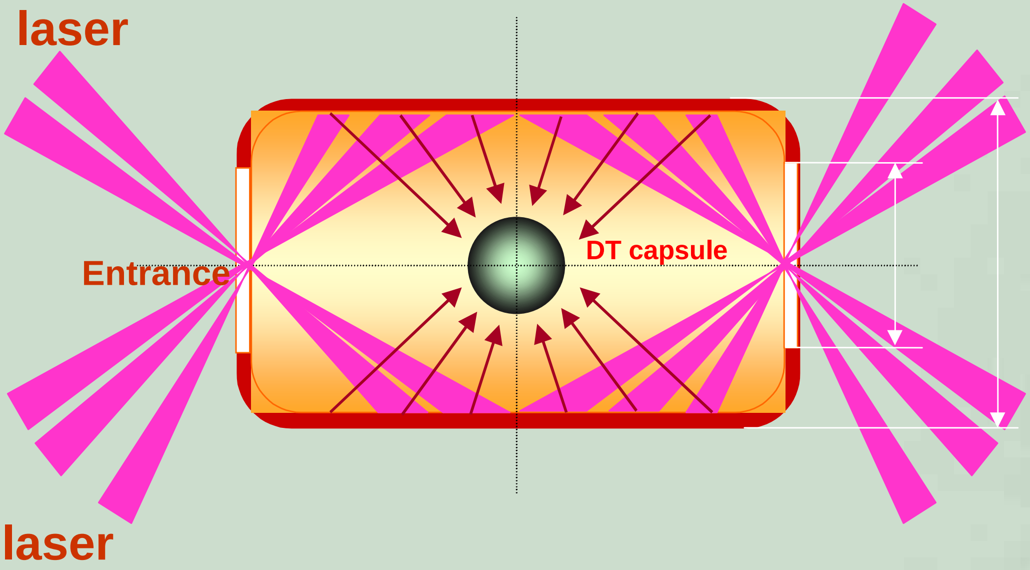
For same drive energy, the gain for fast ignition is about 30 times of that for central ignition.

I. Introduction

♦ Central ignition scheme

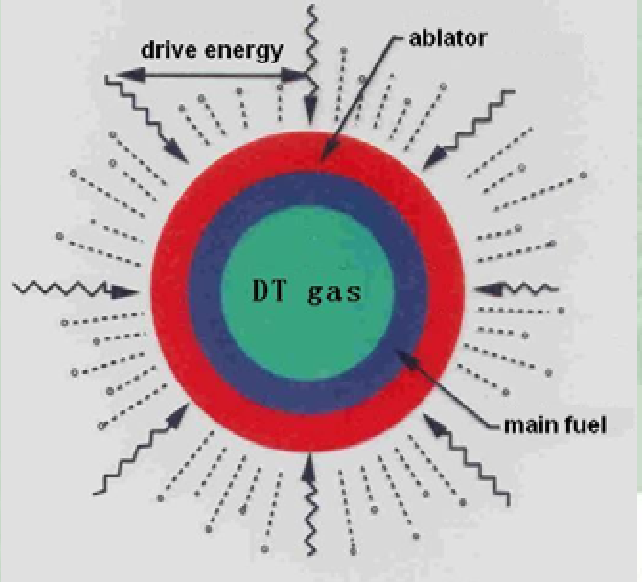
Indirect drive

Capsule inside the hohlraum, the surface is ablated by radiation.



direct drive

Capsule surface ablated directly by laser



I. Introduction

♦ Status of central ignition scheme

Ignition of single capsule (filled DT) will be demonstrated by using National Ignition Facility (NIF) in USA and Mega Joule Laser (LMJ) in France in future 4-6 years and by using SG-IV laser facility (China) in 2020.

- **First ignition experiment is expected in the indirect-driver implosion on the NIF with the conventional scheme based on a central hot spot scheme in 2010.**
- **Next, LMJ laser will achieve Ignition and burning.**
- **China is performing a similar program that will be to reach the ignition goal on SG-IV in 2020.**

I. Introduction

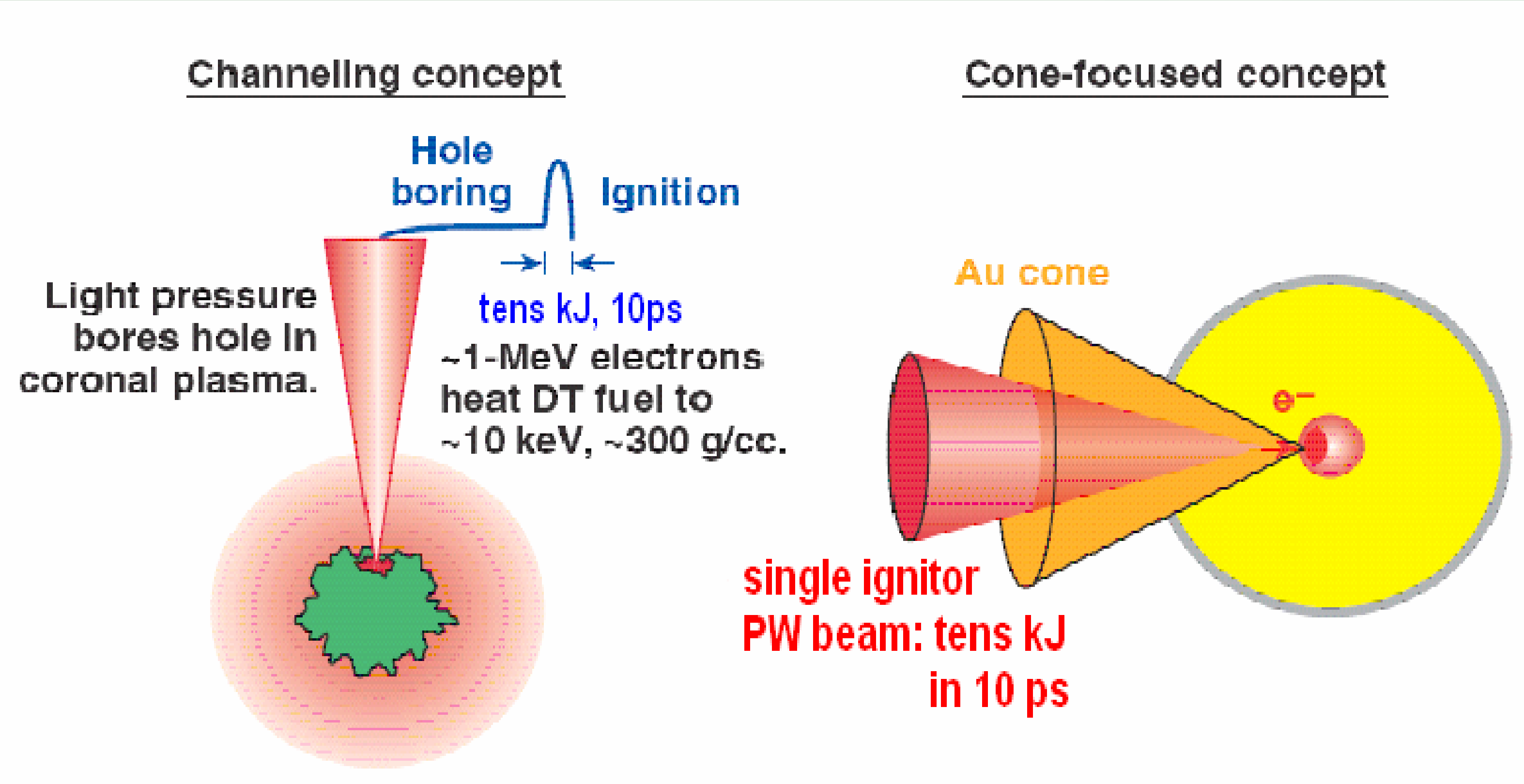
♦ From single capital ignition to IFE

After achieved single capital ignition, the energy gain implosion with several Hz toward IFE has to be performed, and also drivers with repetition rates and high efficiency have to be constructed. Among them, the diode pumping laser being developed is of possibility to reach this goal.

I. Introduction

♦ Fast ignition scheme

Different from the central ignition scheme, alternative ignition concept-fast ignition, in which the ignition is separated from imploding fusion fuel compression, is also being actively explored.



I. Introduction

♦ Advanced studies of fast ignition toward ignition

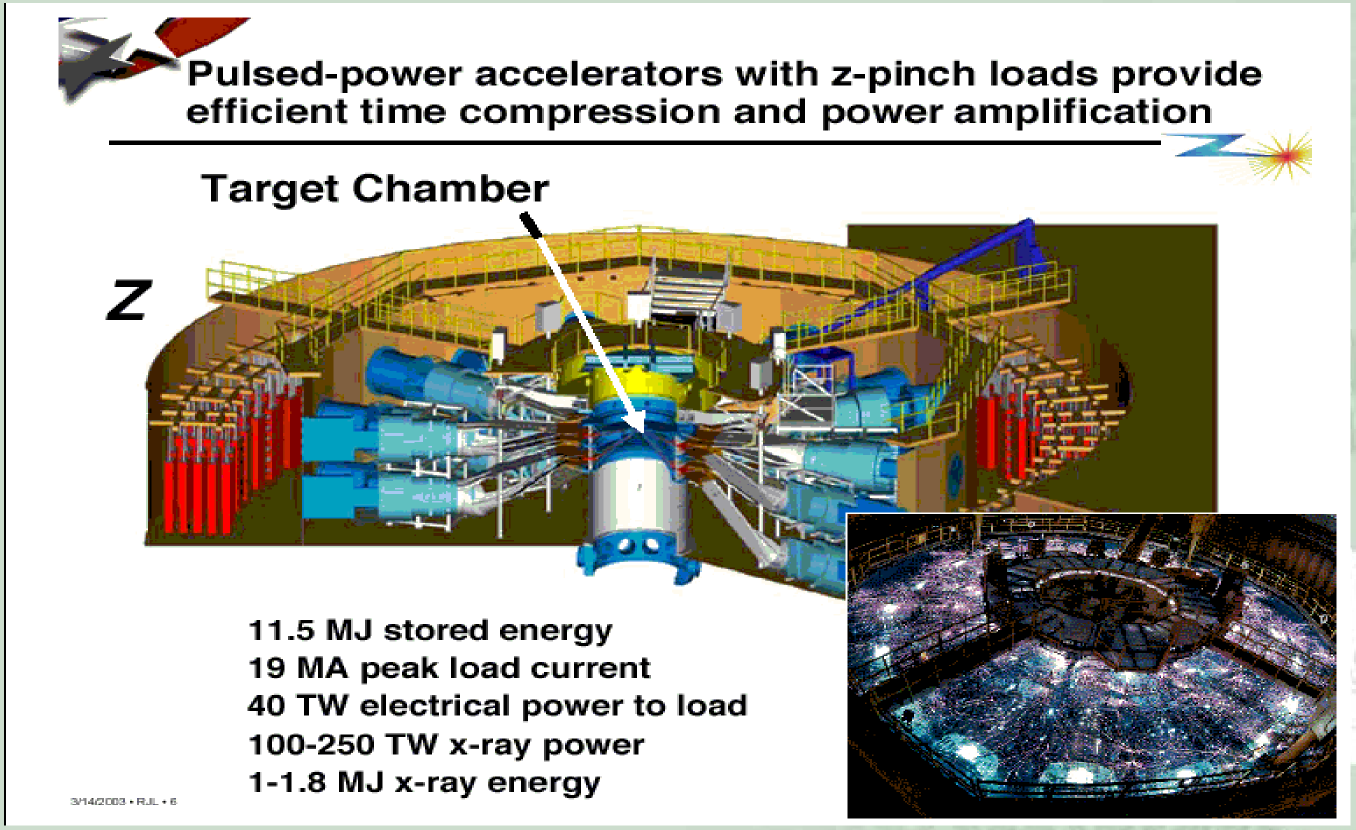
Plans for fast ignition toward ignition are being developed. The PW lasers with over several kJ's are under the way of construction. And the advanced studies of hot spot before ignition will be performed in future 1-3 years.

I. Introduction

♦ Other drivers for inertial fusion

Except for laser drivers such as NIF and LMJ etc., the Z- pinch drivers and the heavy ion drivers are also widely investigated.

For example, 20MA z-pinch facility is running in USA.



outline

I. Introduction

II. Status of central ignition scheme

III. Progress of fast ignition scheme

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VII. Brief remarks

II. Status of central ignition scheme

Central ignition scheme has been studied for over 30 years, and has made great achievements. Now, for this scheme it is going on the eve of the ignition

One still makes efforts to concern:

how to control the symmetry of capsule,

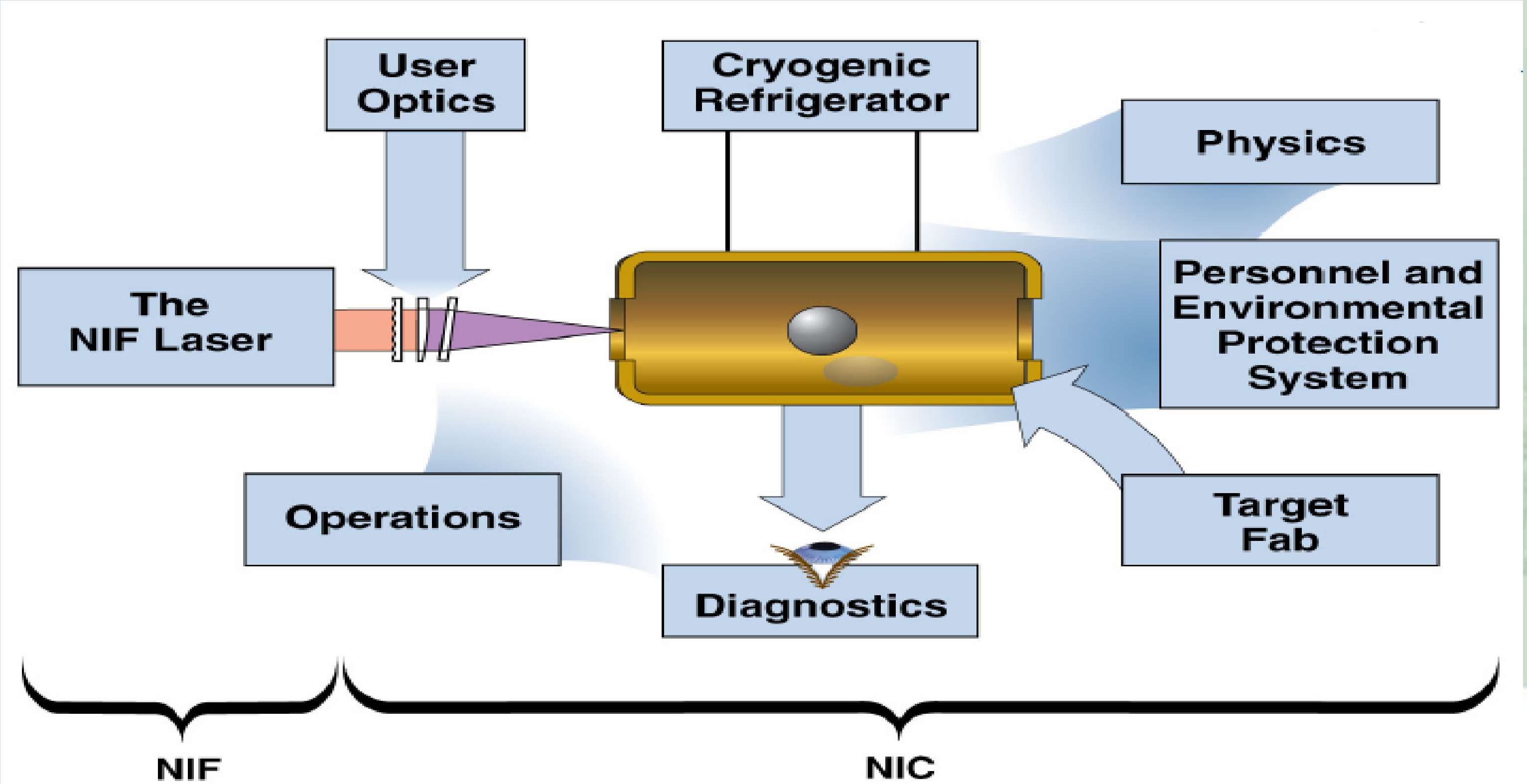
how to design it to be robust,

how to ensure the precision in technologies.

II. Status of central ignition scheme

♦National ignition Campaign (NIC) in USA [OV/5-2]

- **The NIC is a comprehensive effort to deliver ignition and gain on NIF. The major elements are as follows:**

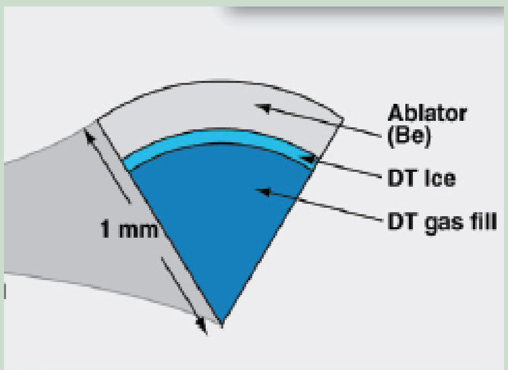


- **Four integrated experiment teams are developing the requirements for the campaigns leading up to ignition**

II. Status of central ignition scheme

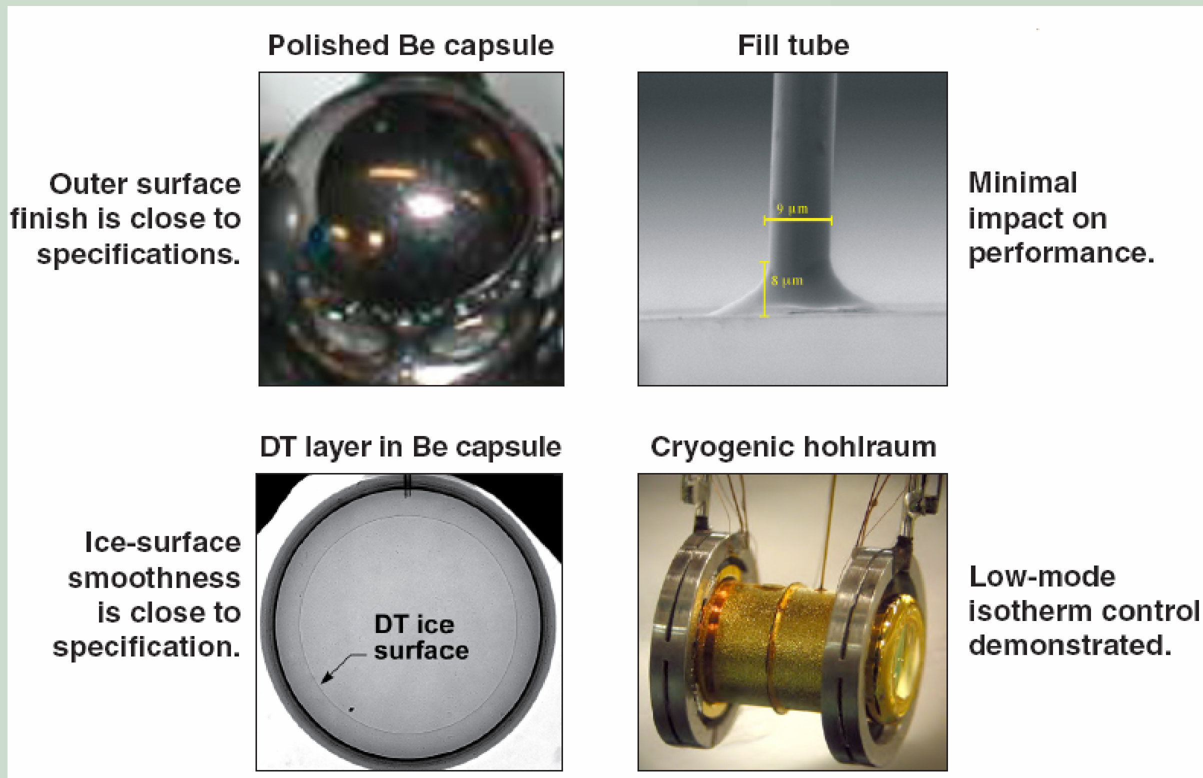
♦ First ignition on NIF in USA [OV/5-2]

- **Indirect drive ignition point design**
- **The challenge now is to fabricate the indirect-drive point-design target to specification.**



The point design fully specifies the laser-target system

- Pulse shape, energy
- Spot size, uniformity
- DT ice layer roughness
- Capsule dimensions and surface roughness
- Hohlraum dimensions, materials, and efficiency
- Target thermal and position stability
- Diagnostics



II. Status of central ignition scheme

♦ Quality target with high precision for ignition on NIF [OV/5-2]

- **The inner-ice-smoothness requirements are similar for direct- and x-ray-drive ignition (0.91μm for X-ray drive).**
- **A spherically symmetric temperature gradient across the DT (or D2) ice is required to form a uniform layer (mK precision) .**
- **For transparent ablators, the smoothness of the inner ice surface is measured using optical shadowgraphy (rms=1.3μm).**
- **More than half of the DT capsules created to date have produced layers with sub-1-μm-rms roughness.**
- **DT layers in Be shells at 0.3 mg/cc meet the NIF smoothness standard for modes $\geq$10 (Request DT ice to be 18.3K).**
- **For target physics, the peak areal density ρR_{peak} may be inferred by using core self emission to backlight the fuel shell (as high as 180 to 190 mg/cm^2 for 1D simulation).**

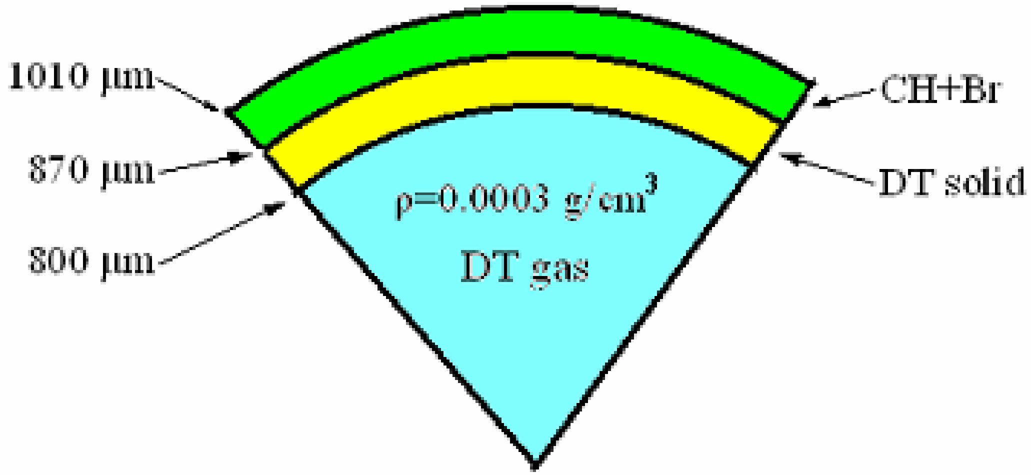
II. Status of central ignition scheme

♦ Preliminary design for indirect drive in China [OV/6-1]

Preliminary capsule design for indirect-drive.

Radiation temperature T_r=300eV(main pulse 4 ns)

.Yield E_Y=12.7MJ (particle transport) , laser E_L=1.0 MJ.



Implosion velocity	3.26×10^7 cm/s
Fuel mass	0.15mg
Ablator mass	1.87mg

outline

I. Introduction

II. Status of central ignition scheme

III. Progress of fast ignition scheme

1. Implosion compression
2. Hot electron generation and transport; ignition hot spot formation
3. Proton beam fast ignition

IV. Z-pinch fusion scheme

V. heavy ion fusion scheme

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III. Progress of Fast ignition scheme

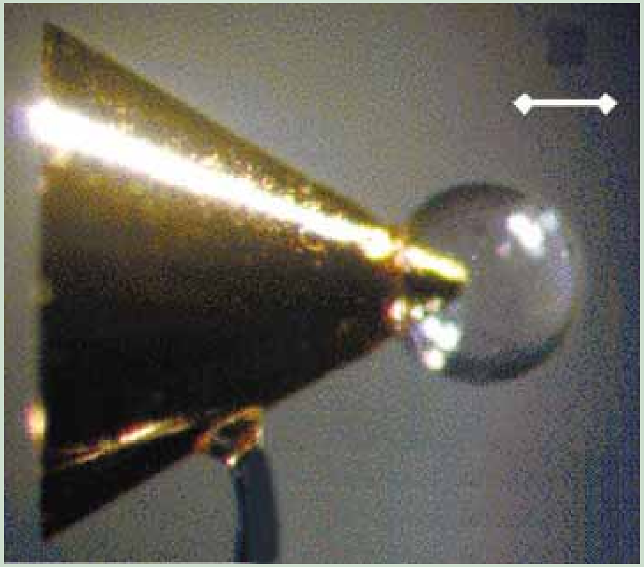
♦ Worldwide projects in future 5 years

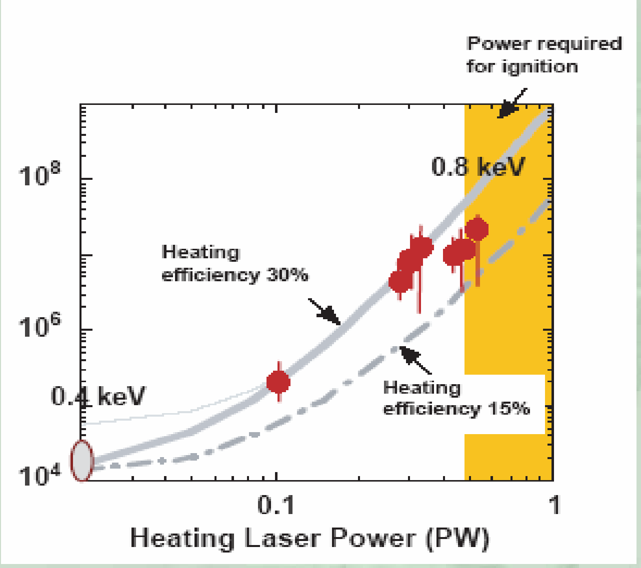
- **FIREX-I (Japan):** missions to construct LFEX with 10-kJ PW laser energy achieving a heating temperature of 5-10keV and to further develop laser technology for FIREX-II [IF/1-1].
- **OMEGA EP (US):** multi-PW, multi-kJ laser beam to couple OMEGA will provide an integrated platform for the validation of fast ignition relevant physics [OV/5-2].
- **HiPER (Europe):** long pulse laser (200kJ) combined with PW laser (70kJ) will provide a flagship civilian laser facility for fast ignition research [www.hiper-laser.org]. Basic researches on relevant physics are conducting in France and UK.
- **SG-IIU+PW (China):** 20kJ laser coupled with PW laser (1.5kJ) will provide a platform for relevant physics of fast ignition. SG-III + PW serves for fast ignition demonstration [OV/6-1].
- **And so on**

III. Progress of Fast ignition scheme

♦ Integrated experiments of cone-shell targets

Kodama *et al.* [Nature, 01; 02] demonstrated that fast ignition is viable. It shows that the insertion of the cone marginally reduces the compressed density (by about 20-30%) compared to full spherical implosion, and neutron yield increases by about three orders-of-magnitudes.





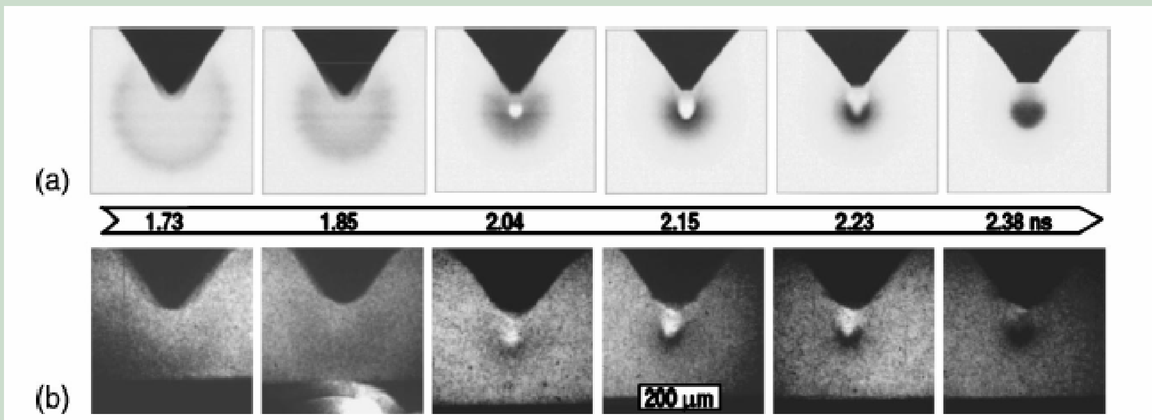
Lasers: 0.5 PW; 2.5kJ (1.2ns)

- **Heating efficiency (laser to hot spot): 15%~30%,**
- **REB divergence angle: ≤20 ° (cone) ; ≤ 40 ° (plane)**

III. Progress of fast ignition scheme

♦ Imploding compression of cone-shell target experiments on OMEGA

LASNEX simulations (a) and OMEGA experiments (b) by Stephens et al., [PoP, 05] agreed well.



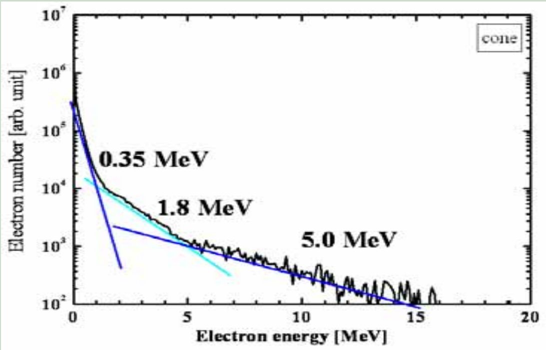
$(\rho R)_{max} > 1/2\ (\rho R)^{1D}_{max}$ (1D simulation) is achieved from OMEGA experiments.

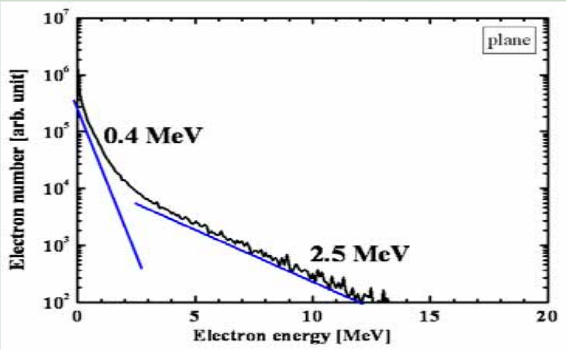
	Experiment	Simulation	
	Cone shell	Cone shell	Sphere
$\rho R(\mathrm{mg/cm^2})$	100/60–80 (±20%) (x-ray/laser drive)	130/200	130/150

III. Progress of fast ignition scheme

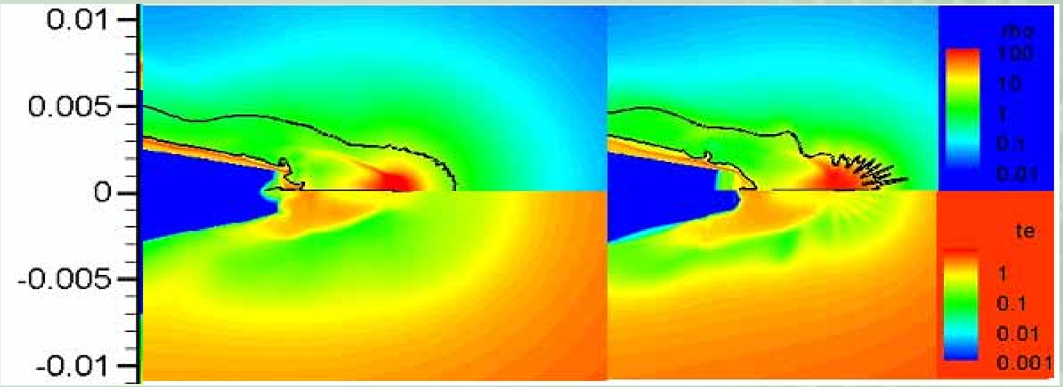
♦ 2D simulations with FI^3 code investigations by Miyanaga et al. [IF/P5-2]

- Electron energy spectrum on cone target consists of three parts(electron acceleration and transport at the side wall via surface magnetic field; ponderomotive acceleration at the cone tip; electro-static field deceleration to heat up bulk electrons to be the temperature of sub-MeV). Energy deposition sensitively depends on electron spectrum (see Fig. 1).





- Maximum imploding compression to a high density core with perturbed shell of mode l=24 (RT instability) is same as non-perturbed shell, shown in Fig. 2.



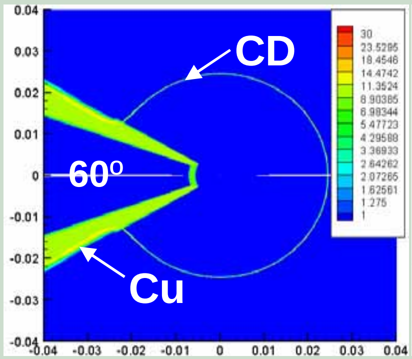
III. Progress of fast ignition scheme

♦ Implosion simulation under SG-IIU conditions (18kJ, 3ns) [OV/6-1]

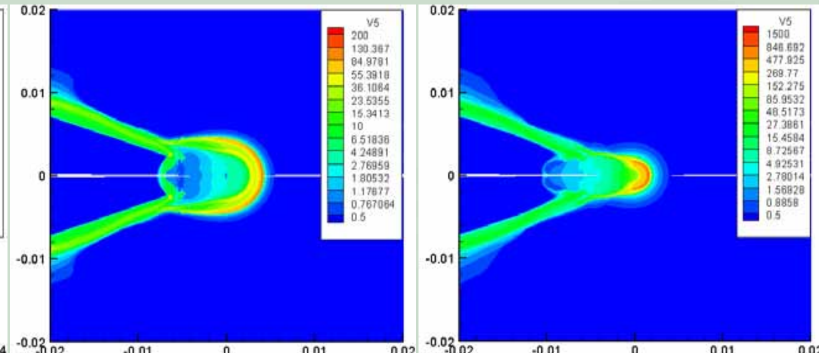
LARED simulations of implosion dynamics under SG-IIU conditions (18kJ, 3ns) show:

Profiles of density and temperature with RTI (P_4) are clearly deformed compared to those without RTI

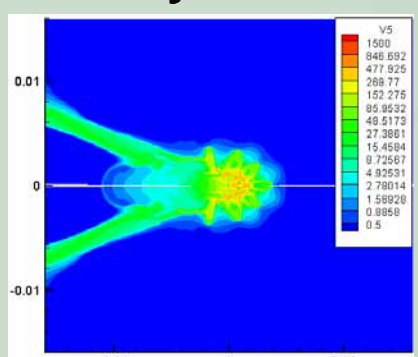
Initial



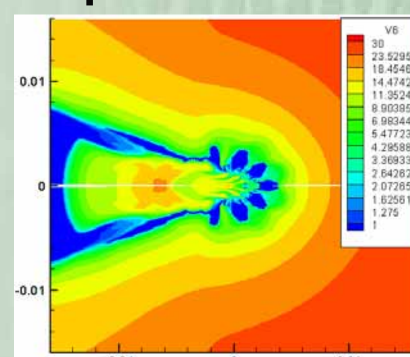
Density without RTI



Density with RTI



Temperature with RTI

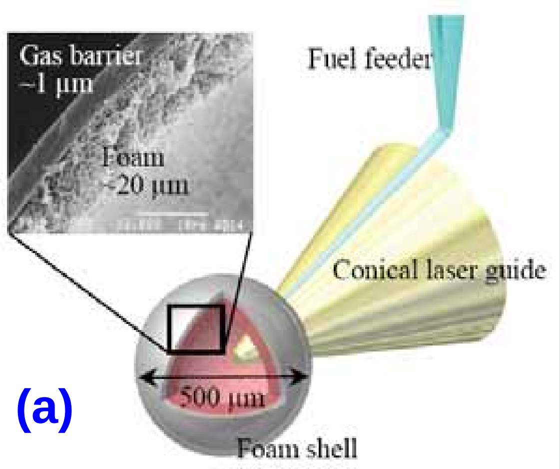


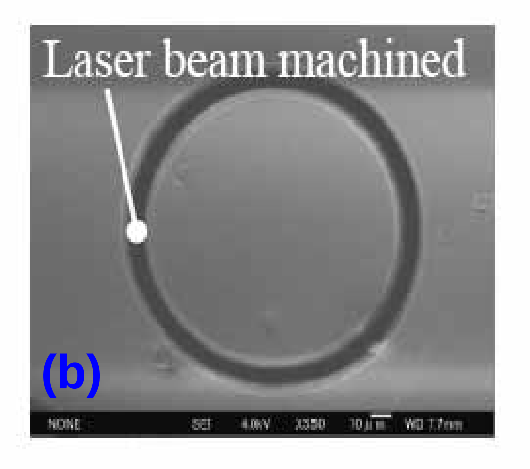
Laser energy :10kJ
CD density: 1g/cm3
R_{out}=325μm; ΔR= 25μm
Cone tip to center 56μm

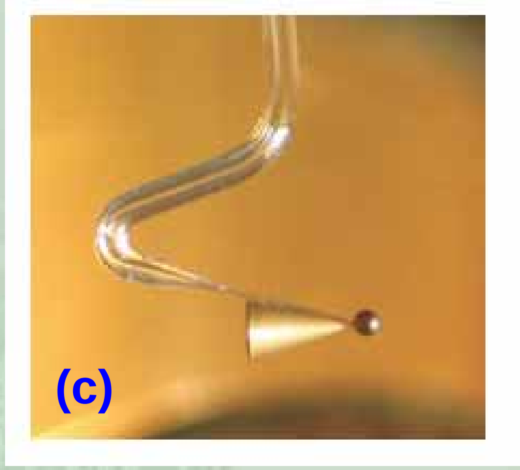
III. Progress of fast ignition scheme

♦ Development of the foam cryogenic target for the FIREX project was presented by Iwamoto et al. [OV/5-1, IF/P5-1].

- Construction of the cryogenic target is in progress: (a) foam target for FIREX-I, (b) RF-PF foam shell (diameter: 504μm; layer thickness: 19μm), (c) foam target.





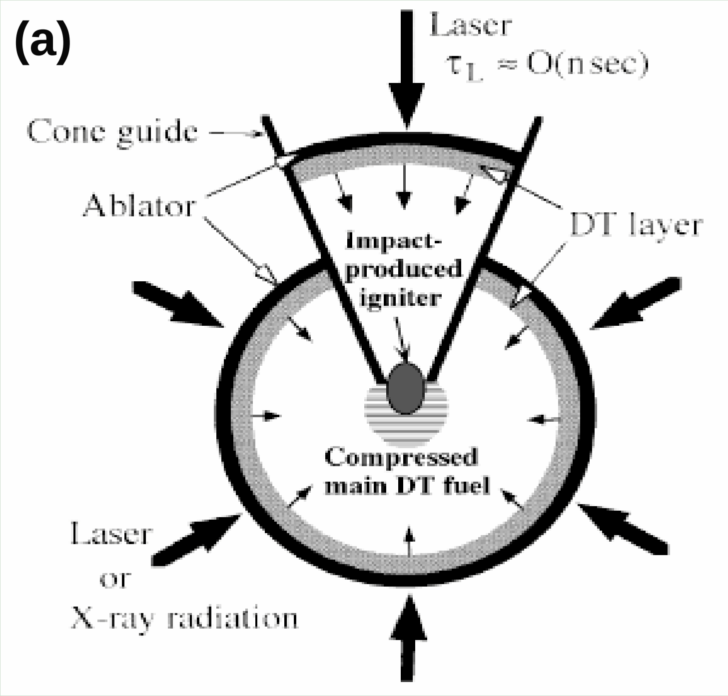


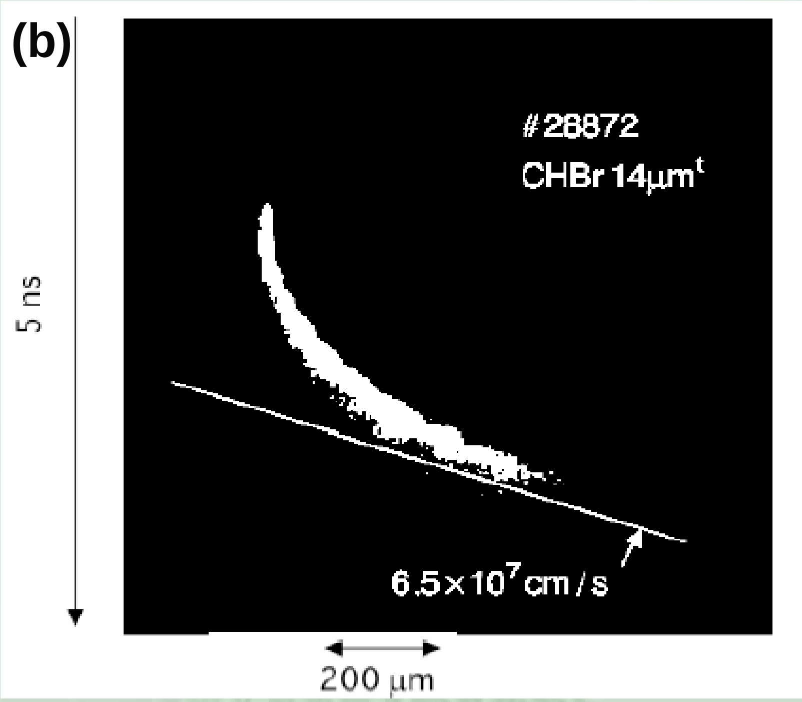
- The foam fabrication method has to be modified to realize ultra low density of 10mg/cm3; fuel layering in the practical foam target is going on; uniform fuel layer formation and fine fuel-quantity control will be challenging.

III. Progress of fast ignition scheme

♦ **New ignition scheme - impact fast ignition (IFI) is proposed by Murakami et al. [IF/P5-3].**

A hollow conical target impacts onto the spherical shell to produce an ignition spot [Fig. (a)]. The shock velocity is requested to reach at least (1.1~1.5)x10^{8}cm/s to provide ignition condition. Preliminary experiment on plane target has shown in Fig. (b).



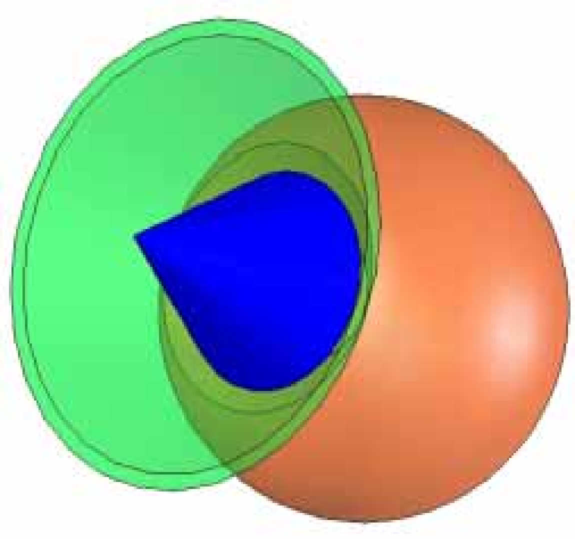


▪ III. Progress of fast ignition scheme

♦ **Recent developments in the design of the fast ignition jet impact concept are presented by Velarde et al. [IF/P5-5]**

Experimental results using low-Z material have demonstrated the production of adiabatic jets by collapsing a Al cone target (figure below) irradiated by a laser. The jet velocities of 1.5×10^{7}m/s with laser intensities 3.5×10^{14}W/cm^{2} was measured, which are still well below the minimum to be practical for fast ignition scenario, but shaping the cone profile and material may increase the jet velocity and density.

Schematic view of the jet impact fast ignition target with the conical liner (blue) and guiding Au cone (green)



III. Progress of fast ignition scheme

2. Hot electron generation and transport; ignition hot spot formation

Key issues:

- Hot electron generation and collimation in PW laser plasma interaction.

- Hot electron beam penetration and collimation in overdense plasma.

- PW laser heating efficiency and hot electron beam energy deposition to form ignition spot in fuel core.

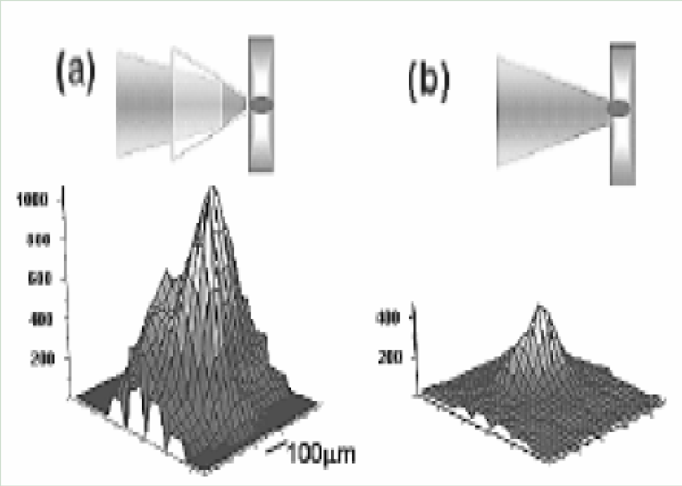
III. Progress of fast ignition scheme

♦ Cone target enhanced laser brightness and electron beam flux, experiments by Kodama et al. [IF/1-2Rb] .

- The laser peak brightness for the cone-target is 2~3 times higher than for the plane target because the wall of the cone would reflect and refocus the lost laser light into the cone tip .
- The electron peak flux was enhanced by a factor of 2 in cylinder and by a factor of 4.5 in cone compared to in block target

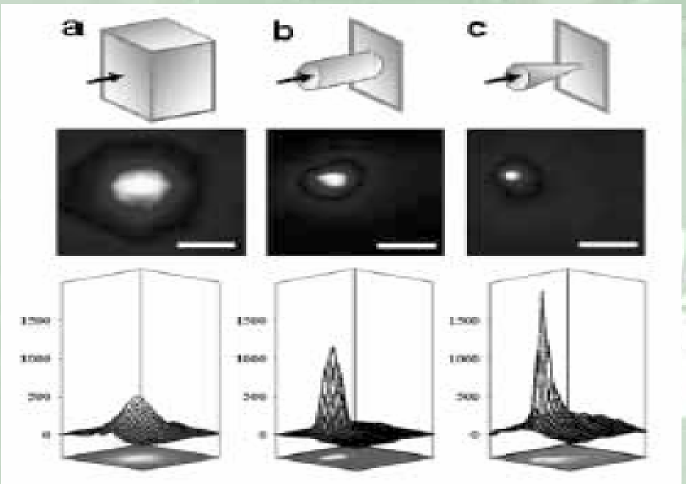
Al plane target

(a) Au cone (60º) (b) without cone



Al targets

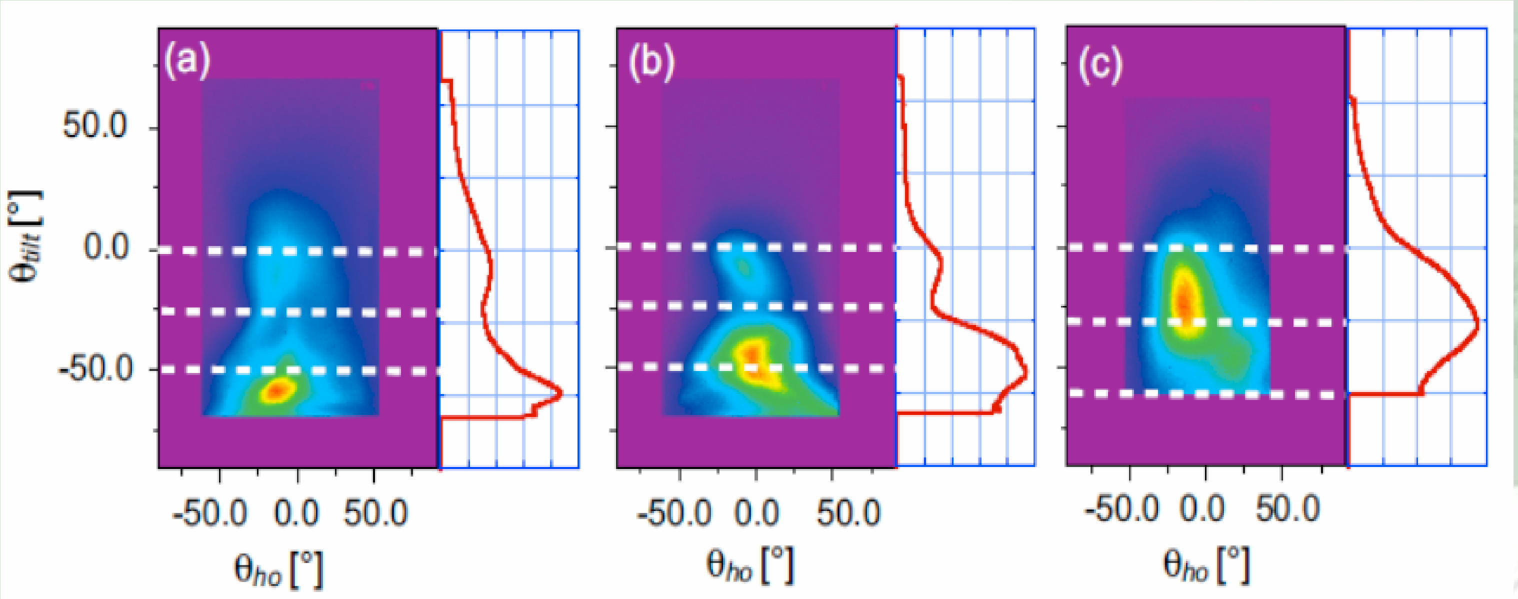
(a) block (b) cylinder (c) cone



III. Progress of fast ignition scheme

♦ **Generation and transport of hot electrons along cone surface, investigated experimentally by Tanaka et al. [IF/1-2Rc]**

Hot electron beam created on cone surface can be attracted toward cone tip pinched by magnetic field (>30MG, resulted in hot and cold returning electrons) , when the laser intensity is up to 3x 10^{18}W/cm^2. See Fig. (c).



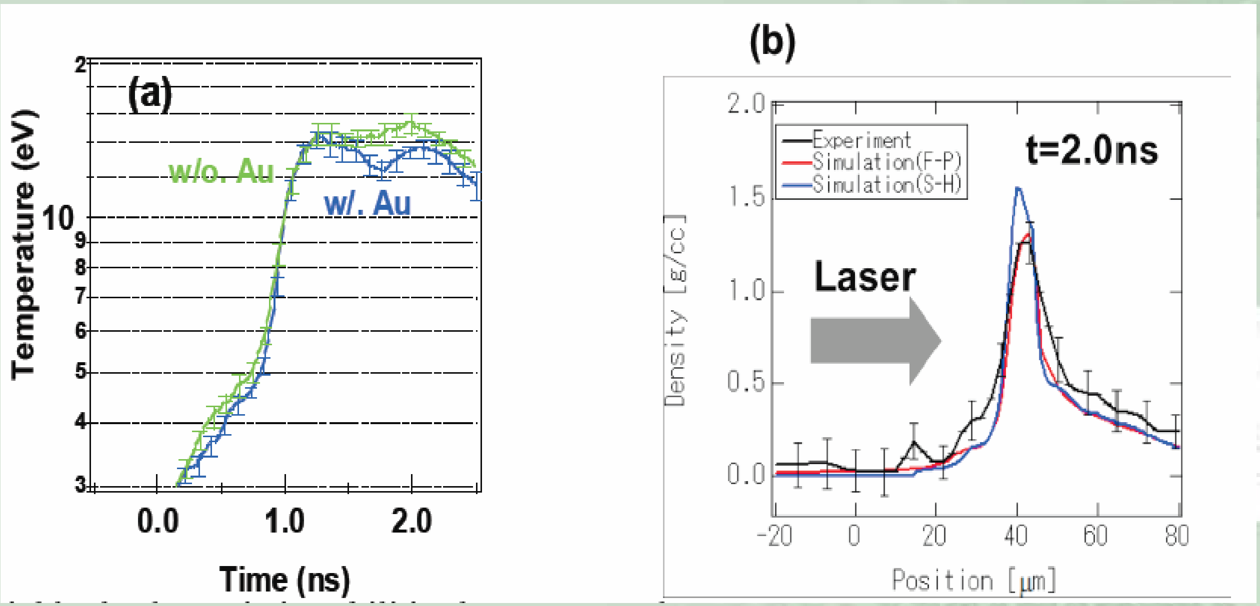
(a)1×10^{17}W/cm^2 (b) 1×10^{18}W/cm^2 (c) 3×10^{18}W/cm^2

III. Progress of fast ignition scheme

♦ Preheating during implosion and heating efficiency from laser into hot spot are investigated in Azechi et al.'s experiment [IF/1-1].

Cryogenically liquid D_2 targets instead of previous CD target are used to experimentally explore two essential issues, achieved:

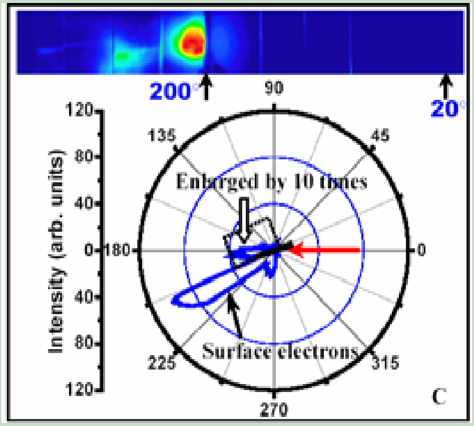
- Fuel preheating temperature : 5eV (Fermi temperature) in Fig. (a),
- Heating efficiency : DD neutrons were observed [It indicates hot electrons transported through the shell and deposited energy in the compressed core, see Fig. (b).]

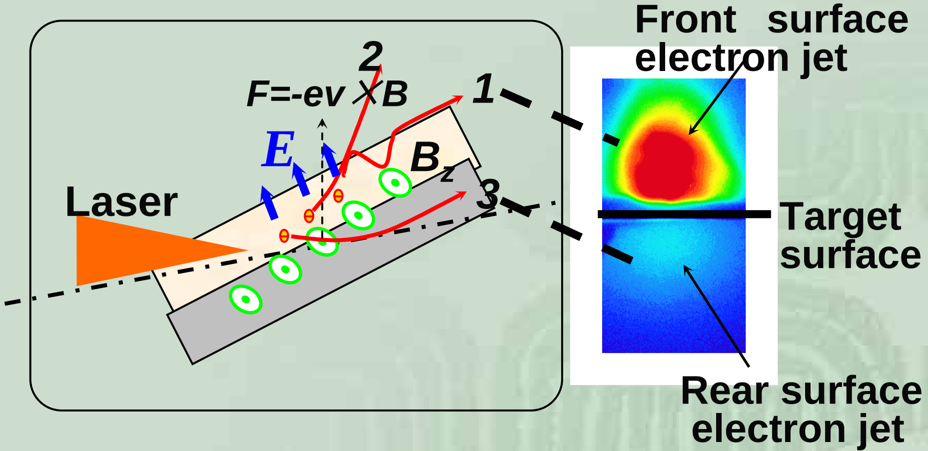


III. Progress of fast ignition scheme

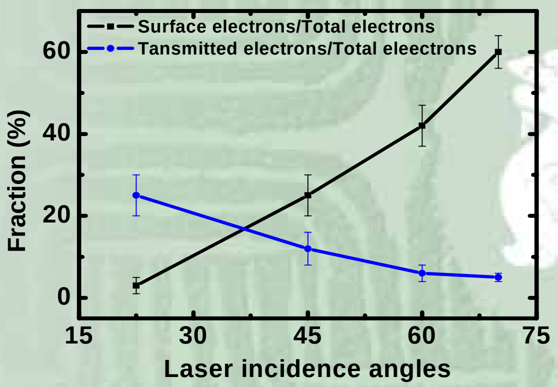
♦ Electron transport along target surface by experiments. [PRL, 06],[OV/6-1]

- A fast electron jet along the front target surface was observed experimentally when an intense laser pulse (~10^{19}W/cm^2, 30 fs) irradiates target with an incident angle$\geq$70^o. – direct confirmation of focusing effects of fast electrons by cone targets





- 2D PIC simulations: jets formed due to confinement of the surface quasistatic electromagnetic fields.

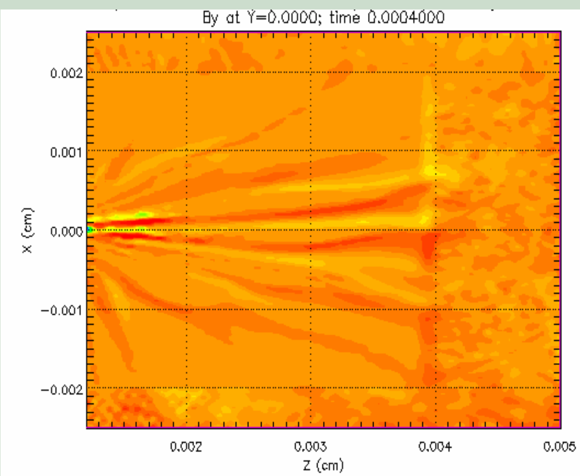


III. Progress of fast ignition scheme

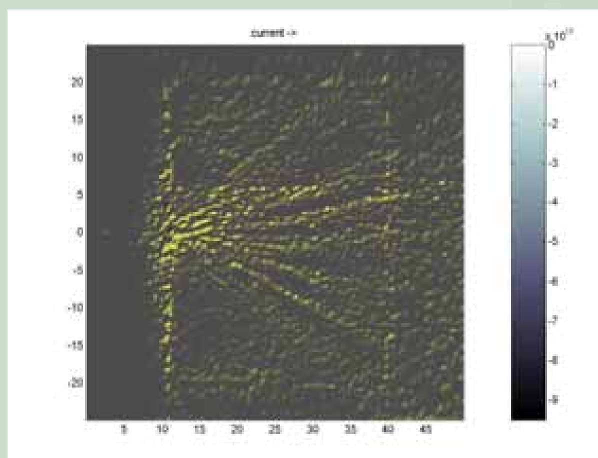
♦ **Electron penetrating in overdense plasma (Al target) by 3D HF-PIC simulation (2D) [OV/6-1]**

Hot relativistic beam with divergence 30º~60º (FWHM) is generated in Al target interacting with laser ($I=3\times10^{20}W/cm^2$, $r_0=3\mu m$) by integrated simulation.

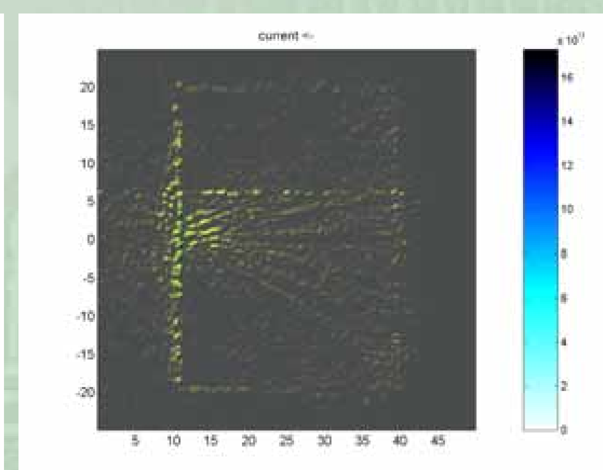
magnetic field
$B_{max} \approx 200MG$



Forward current
$J_{forward} \approx 10^{13}A/cm^2$



return current



III. Progress of fast ignition scheme

♦ Electron isochoric heating was measured in two limiting case , small planar foils and hollow cones, by Mackinnon et al. [IF/1-2Ra] .

In order to investigate electron isochoric heating effects, experiments have shown :

- Thin foils : eliminating Ohmic heating effects by the return current of cold electrons (Figs. a, b)
- Hollow cone: maximizing Ohmic heating by the return current. (Figs. c, d)

These help to establish models that enable extrapolation from small scale experiments to full scale fast ignition.

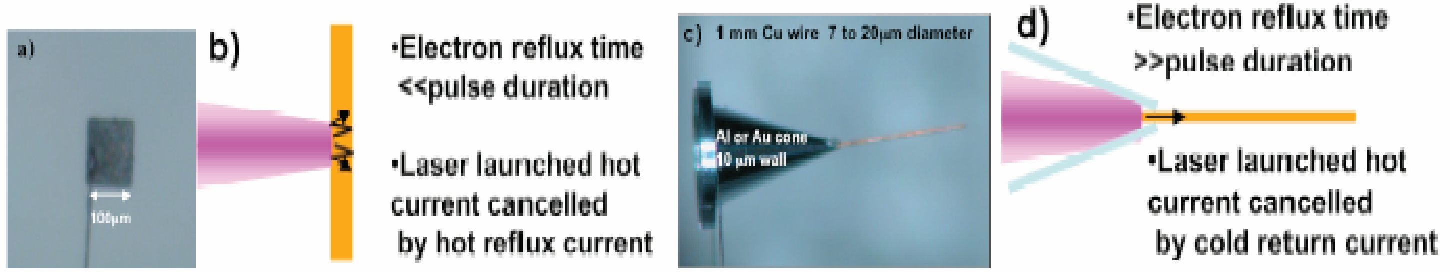
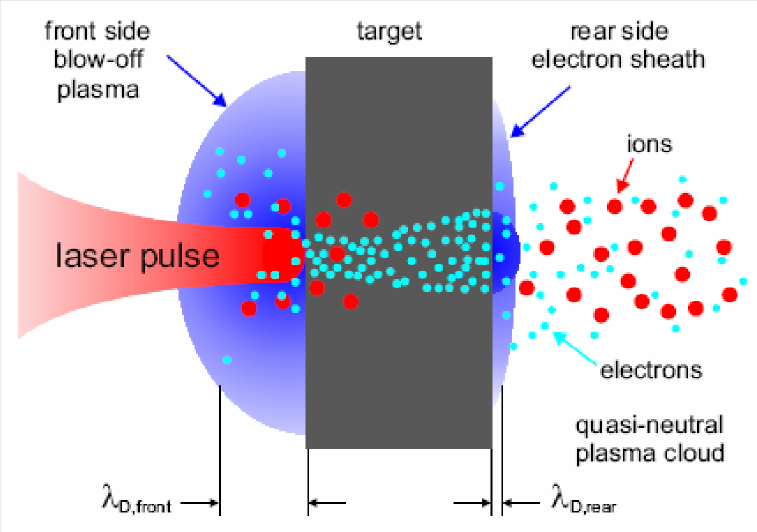


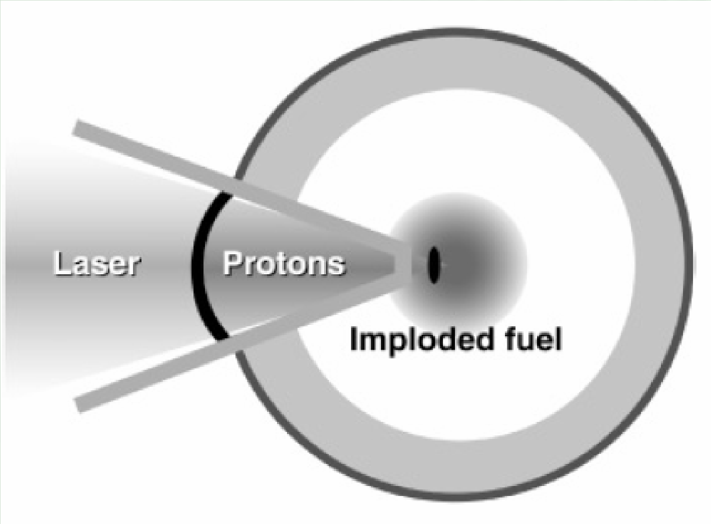
Figure 1: Targets for electron transport studies. a,b) low mass foil which maximizes hot electron refluxing. c,d) wire that has no refluxing.

III. Progress of fast ignition scheme

3. Proton beam fast ignition

Protons offer an alternative means of fast ignition isochoric heating with very different physical constraints. The possibility of using a concave spherical target surface to focus the proton jet then serving as the ignitor in fast ignition is illustrated in figures below.



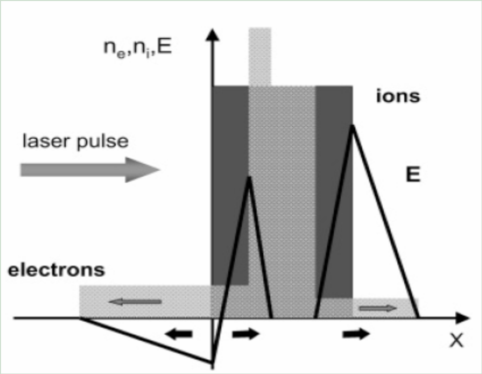


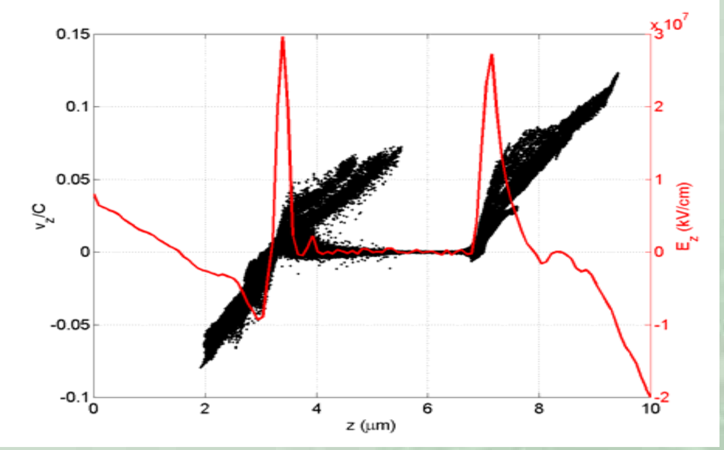
III. Progress of fast ignition scheme

♦ **Proton beam acceleration in laser plasma interaction is observed in the 3D HF-PIC simulation (2D) [OV/6-1]**

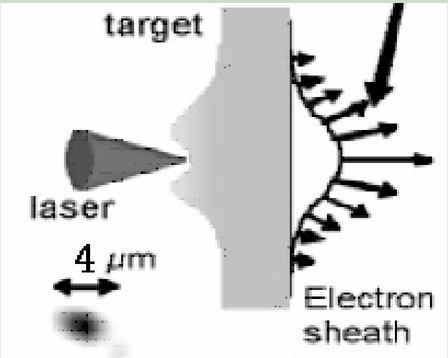
Laser intensity: $I=3\times10^{20}$W/cm^2, CH thickness: $d=4\mu$m

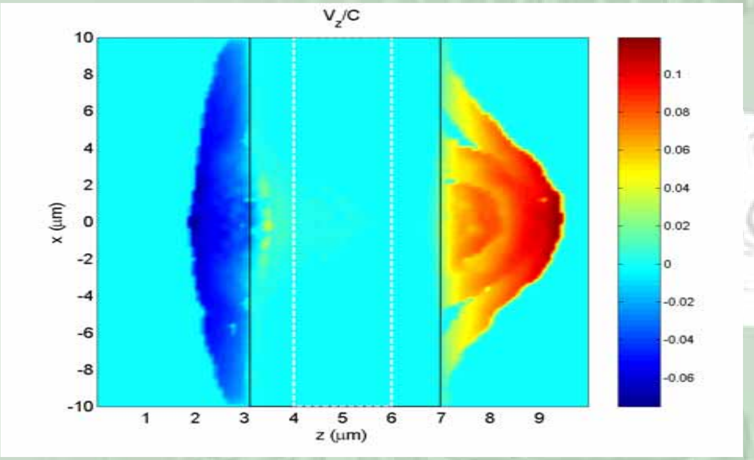
Electric fields (E_{max}=30GV/cm)





Velocity distribution (v_{max}=0.15c)





III. Progress of fast ignition scheme

♦ **Proton isochoric heating for fast ignition are presented by Mackinnon [IF/1-2Ra].**

- **Experiments measured heating by focus proton beam in cone targets. (see Fig. c, d).**
- **Modeling suggested conversion efficiency > 50% (from electron energy to proton energy > 3MeV)**

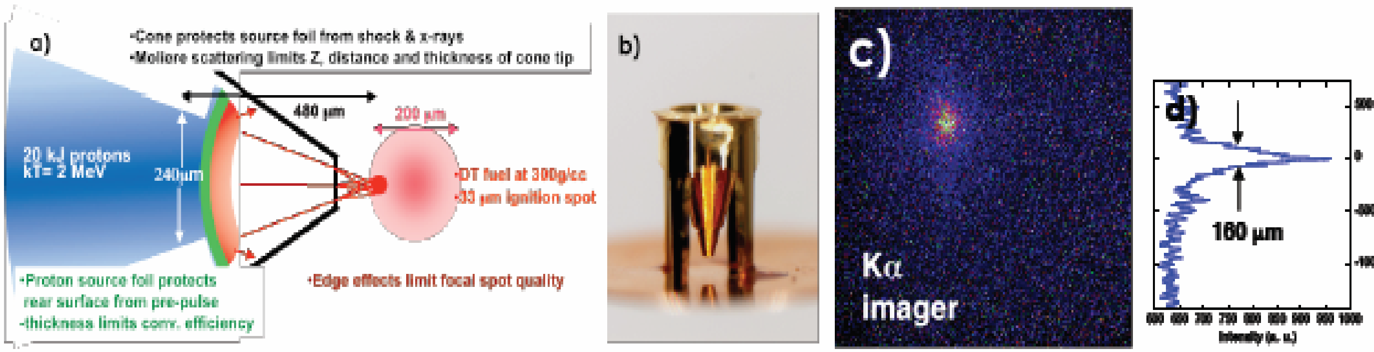


Figure 6: a) Requirements for proton ignition structure. b) Test structure Cu K_α c) image and d) line-out of spot heated by focused protons

In general, requirements for proton fast ignition: deliver about 15kJ to spot <40μm with a proton axial temperature of about 3MeV, conversion efficiency to protons exceed 15%

III. Progress of fast ignition scheme

♦ **Plasma block concept to improve the proton beam for fast ignition are presented by Hora et al. [IF/P5-14]**

The use of the plasma blocks (produced by PW laser interacting with plane target) with ballistic focusing geometry where still very high ion current densities is possible while a minor thermal expansion increases the thickness of the accelerated layer before interacting with the pre-compressed thousand times solid dense DT plasma. This increase of the layer thickness offers the realization of the proton fast igniter.

IV. Z-pinch fusion studies

♦ Radiating Z-Pinch Investigation

- The “MoI” facility, a prototype of the “Baikal” (50MA,10MJ radiation pulse) facility, is under construction in Russia. The wire array compression is under thorough investigation ([IF/1-3]).

- Fast Z-pinch implosion experiments on the S-300 pulsed power machine (3MA,100ns, 0.15Ohm) aimed at IFE are studied by Bakshaev et al.

- Analysis of sheared flow profiles and compressibility effects on Z-pinch MRT instability is simulated by Y. Zhang et al. [IF/P5-13].

V. Heavy ion fusion studies

♦ US progress of heavy ion fusion (HIF) science was summarized by Yu et al. [IF/P5-11].

New recent results:

- NDCX (Neutralized Drift Compression Experiment) achieved longitudinal compression by a factor of 50, total beam density increase achieved is about 2000.
- Studies of beam target interaction have made significant progress in heating material to warm density matter (WDM) and resulting in temperature uniformity.
- Experiments have shown the accumulation of electrons in an ion beam leads to brightness degradation and ultimately beam disruption.

  Simulations have reproduced the key features.
- Experiments demonstrated the feasibility of a compact high-current injector for HIF drivers.
- Experiment verified the predicted PLIA (Pulse Line Ion Acceleration, a new concept for acceleration) beam dynamics. Measured energy gain, longitudinal phase space and beam bunching agreed with 3D simulation.

VI. Other miscellanies

- Nonlinear saturation of the parametric instabilities generated by laser plasma interaction was modeled by Pesme et al. [IF/P5-8].
- Advances in target design and materials physics for IFE at DENIM in Spain was presented by Perlado et al. [IF/P5-7].
- Characteristics of laser source of ions from the targets of different densities were investigated by Khaydarov [IF/P5-10].
- Reactor-scaled cryogenic target formation was mathematically and experimentally studied by Koresheva et al. [IF/P5-6].
- Effects of laser radiation, nanostructured porous lining and electric field on the control of RTI is studied by N. Rudraiah et al. [IF/P5-9].
- Concept design of laser fusion reactor KOYO-F for fast ignition and new laser material development are presented by Norimatsu et al. [FT/P5-39] and Kawanaka [FT/P5-40].

VII. Brief remarks

Today ICF is going on the eve of the ignition. The first experimental demonstration of a single capsule performed ignition, obviously, is the most important milestone on the way to inertial fusion energy (IFE) by means of ICF.

Central ignition by indirect drive, as the first priority, is planned to be performed on NIF in 2010.

The highlight at this session is the advanced results for fast ignition, which aim at the demonstration toward ignition in future years.

New ignition concepts and drivers different from laser beam driver, are also actively explored.

Drivers with repetition rate and higher efficiency for IFE are underway. But, there is still a long way to demo power plant!

Thanks!