# Summary on Inertial Fusion Energy (IFE) Research

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**Abstract**. Reviewed is the present status of the inertial confinement energy (IFE) research.. The highlights of the IFE presentations are as follows. Toward demonstrating ignition and burning of imploded plasmas, ignition facilities of mega jule class blue laser system are under construction at Lawrence Livermore National Laboratory and the CEA laboratory of Bordeaux. The central ignition by both indirect drive and direct drive will be explored by the middle of 2010's.

A new ignition concept so called "fast ingtion" has also investigated intensively in the last two years. Peta watt level (1pw~0.1pw output) CPA lasers have been used for heating solid targets and imploded plasmas. With 50J~500J/psec pulses, solid targets are found to be heated up to 300eV. They were measured by X-ray spectroscopy, neutron energy spectrum, and so on. Summarized are also researches on simulation code developments, target design and fabrication, heavy ion beam fusion, Z-pinch based X-ray source, and laser driver technology.

## 1. Introduction

Since the high density compression has been demonstrated a decade ago, the objective of the IFE research shifted to generating hot spark in ultra-high density plasmas for ignition. In the past two years after the IAEA Yokohama conference, significant progresses in the implosion physics and engineering researches have been achieved toward demonstrating ignition of fusion burn. Namely, the engineering developments and constructions of the ignition facilities; National Ignition Facility (NIF) and Laser Mega Jule (LMJ) progressed [1] [2], and the simulation and experimental understandings on direct and indirect drive implosion physics and the fast ignition physics advanced at University of Rochester (LLE), Lawrence Livermore National Laboratory. CEA-France and Osaka University(ILE) respectively [3] [1] [4] [5] .

The construction schedule of NIF was reconfirmed toward the completion which is expected to be the end of 2008. The ignition will be achieved by the end of 2010. In the indirect drive, the advanced designs of hohlram and capsule and new fabrication techniques have been proposed to increase gain from 10 to 20~60 for the NIF implosion. In the direct drive implosion experiments, the cryogenic target has been successfully imploded at University of Rochester.

The irradiation uniformity is improved by introducing 2D-SSD, polarization distribution and so on, in the OMEGA-up-grade and the GEKKO-XII-HIPER.

The new ignition concept; the fast ignition research has progressed significantly to produce a hot spark in an imploded plasmas at Osaka University (ILE). In order to produce high temperatures(> 1kev) and high density(>solid density) plasmas, peta watt lasers are under construction at Osaka University (ILE), Ecolepolytechnique(LULI), Rutherford Appleton

Laboratory and so on. The imploded plasmas heating experiment with kJ level input energy will start in the middle of 2001, at ILE, Osaka University.

The driver technologies for IFE reactor, the computer simulation technologies for target design, target fabrication and diagnostic technologies for implosion experiments have also advanced in this past 2 years. In particular, progressed is the understanding on the energy conversion mechanism from pulse power energy to X-ray radiation in the fast Z-pinch.

In this report, the present status and new results presented in this conference are summarized on the following subjects. In section 2, the present status of large experimental facilities is summarized. In section 3, the topics and the high lights in the implosion physics are presented. In section 4, the integrated implosion code developments are reviewed. In section 5, the fast ignition and related relativistic laser plasma researches are summarized. The section 6 is devoted to the summary on the heavy ion beam fusion research. In section 7, new understandings of the fast Z-pinch X-ray source is reviewed. Finally, in section 8, future prospects of IFE research are presented.

## 2. Present status of Large Facilities for IFE experiments

Toward the demonstration of ignition and fusion burning, mega joule lasers, peta watt lasers, high repetition-rate energy drivers are operated and/or under construction in all over the world. The present status of those facilities is summarized by the table 1. The implosion experiments were carried out by NOVA [1], PHEBUS [2], OMEGA-upgrade [3] and GEKKO-XII lasers [5] in the past two years. However, NOVA and PHEBUS have been shut down and their components were distributed to LULI(France), Rutherford Appleton Lavotatories ; (RAL,UK), GSI (Germany) and so on for constructing new experimental facilities like peta watt lasers. At present, only two implosion lasers, namely, OMEGA-upgrade and GEKKO-XII are available, which play important rolls as worldwide user's facilities.

As the ignition facilities, National Ignition Facility and Laser Mega Jule(LMJ) are under constructiion. The detail schedules are presented in the conference. Though the construction schedule of NIF has delayed by a few years, the schedule was refined and became optimum. The first light will be in the end of 2004. The 96 beams will complete and be used for the implosion experiment by the end of 2007, and the full NIF will complete at the end of 2008 to demonstrate the ignition by the end of 2010 . [1] ,[6] The LMJ construction schedule is almost parallel to that of NIF. Although the LMJ beams are not used for plasma experiments before completion of full system, the module of LMJ; LIL (60kJ/8 beam) will start to deliver beams for experiments from the beginning of 2002. [2]

For the scientific proof of principle of the fast ignition concept, a few 100TW lasers are operated at Institute of Laser Engineering of Osaka University, RAL and LULI. Those lasers can deliver up to 100J/1ps. In particular, the peta watt module laser beam has been injected into imploded plasmas which are produced by the GEKKOXII laser. The construction of peta watt lasers started at ILE, Osaka University [5], RAL and LULI in 2000. The peta watt laser will be injected into imploded plasmas in the middle of 2001 at ILE. Those peta watt lasers will deliver 500J~1kJ/ps to produce hot ultra-high dense plasmas.

As the X-ray source for radiation driven implosion. The large-scale Z-pinch machine has been operated at Sandia National Laboratory(SNL) to generate 1.5MJ X-ray pulse in 8ns .[7] The radiation driven implosion experiments will be carried out in near future. The fast Z pinch experiments are continuing also at Kruchatov Institute and Imperial College . [8] , [9]

As the high reprate energy driver for IFE reactor, KrF lasers (Electra:NRL [10], Electro Technical Laboratory [11]) DPPSL(diode pumped solid state laser; ILE Osaka Univ [12] , [13] and LLNL), HIB(GSI and LBL [14] ) are under development.

| Name of Facility | Main Objective | Nation | Scheme | Beam Parameters | Present Status |
|---|---|---|---|---|---|
| NOVA | Indirect D. | USA | Glass L. | 40kJ/10b | Shut Down |
| OMEGA-U.G. | Direct D. | USA | Glass L. | 30kJ/60b | Operated |
| NIF | Indirect D. | USA | Glass L. | 1.8MJ/192b | Const.(2008) |
| GEKKO XII | Direct D. | JAPAN | Glass L. | 20kJ/12b | OP. |
| GEKKO-PWM | Fast Ignition | JAPAN | Glass L. | 100TW/1ps | OP. |
| GEKKO-PW | Fast Ignition | JAPAN | Glass L. | 1PW/0.8ps | Const.(2001) |
| VULCAN | Fast Ignition | UK | Glass L. | 0.1PW/0.5ps | OP. |
| RAL-PW | Fast Ignition | UK | Glass L. | 1PW/0.5ps | Const.(2002) |
| PHEBUS | Indirect D. | France | Glass L. | 6kJ/2b | Shut Down |
| LIL | Indirect D. | France | Glass L. | 60kJ/86 | 30kJ/4b(end of 2001, full scale, 2004) |
| LMJ | Indirect D. | France | Glass L. | 1.8JM/240b | Const.(2008) |
| SG-II | Indirect D. | China | Glass L. | 8kJ/8b | Op. |
| SG-III | Indirect D. | China | Glass L. | 30kJ/32b | Constructing |
| Z |  | USA | Z-pinch | 1.8MJ/X-ray | OP. |
| Mag pie |  | UK | Z-pinch | 90kJ/X-ray | OP. |
| S-300 |  | Russia | Z-pinch | 20kJ/X-ray | OP. |
| NIKE | Direct D. | USA | KrF laser | 5kJ/0.25_ m | OP. |
| Electra | Direct D. | USA | KrF laser | 700J/5Hz | Constructing |

*Table 1. Large Facilities for IFE research*

## 3.Implosion Physics

The two types of implosion schemes; direct drive and indirect drive implosion are explored in the past two years since the last IAEA conference.

In the indirect (X Ray) drive implosion physics, radiation intensity uniformity and coupling efficiency of laser energy to capsule have been critical issues to increase target gain. Those issues have been investigated by the experiments of NOVA , OMEGA , PHEBUS, and so on , together with computer simulation and theory.

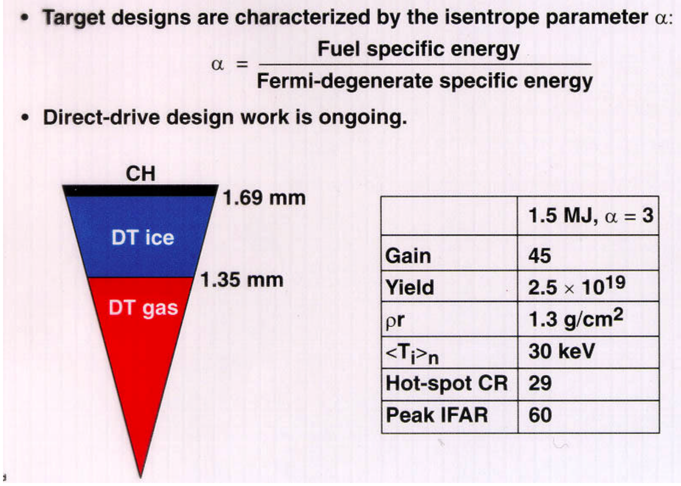
In the direct drive implosion physics , the laser irradiation uniformity and hydrodynamic instabilities have been critical issues. They are investigated by using the lasers of GEKKO Xll ,NIKE ,VALCAN , and so on.

In this chapter , the present understandings on the above issues and new findings in the conference are presented.

## Section 3.1 Direct Drive Implosion Physics

In the direct drive approach, the laser irradiation uniformity and the hydro instabilities associated with ablative acceleration are in particular important. In US, the direct drive implosion physics has been investigated for direct drive ignition of IFE targets on the NIF. In the direct drive implosion, gain (30-50) [3] [10] is higher than that of standard indirect drive implosion (~15). The mission of University of Rochester's Laboratory for Laser Energetics (LLE) is to study the physics of direct-drive IFE target physics through both experiments on the 60-beam, 30kJ OMEGA-upgrade laser system and simulations with the direct drive implosion codes .

The baseline LLE/NIF direct drive ignition design is a cryogenic DT target which is irradiated with 1.5MJ/0.35μm laser pulse [3]. The laser pulse consists of two parts which are the fast pulse (4.25ns long at a power of 10TW) for launching a first shock of 10Mbar pressure through the DT ice. At the time of shock breakout at the rear surface of the DT ice, the pulse ramps up to 450TW which lasts 2.5ns. The pellet structure and the laser pulse shape with 1D simulation results are shown in the Fig.1. The 1-D simulation of the above fast-line target is expected to have a gain of 45.



- **Target designs are characterized by the isentrope parameter $\alpha$:**

$$\alpha = \frac{\text{Fuel specific energy}}{\text{Fermi-degenerate specific energy}}$$

- **Direct-drive design work is ongoing.**

| | **1.5 MJ, $\alpha = 3$** |
|---|---|
| **Gain** | **45** |
| **Yield** | **$2.5 \times 10^{19}$** |
| **$\rho r$** | **1.3 g/cm$^2$** |
| **$\langle T_i \rangle_n$** | **30 keV** |
| **Hot-spot CR** | **29** |
| **Peak IFAR** | **60** |

*Fig.1 Direct Drive target design for NIF*
*(a) pellet structure and 1D simulation results*

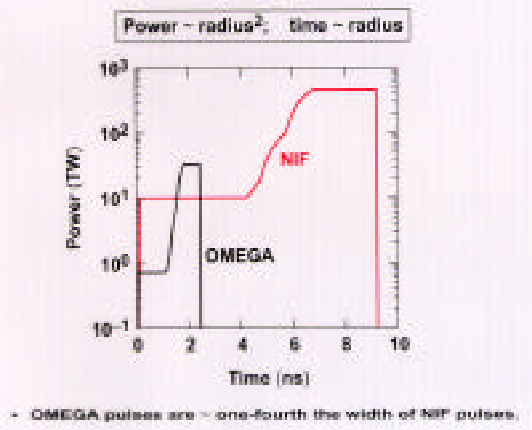


*Fig.1(b) a pulse shape for NIF target and that for a down scaled OMEGA target*

The direct drive target has to tolerate four sources of nonuniformity which are inner-DT-ice roughness, (2) outside CH Capsule nonuniformities (3) initial laser imprinting and (4) main driver pulse asymmetry.

The OMEGA direct-drive experiments [3] are designed to address issues of direct driver laser fusion and to provide the necessary data to validate the predictive capability of the LLE implosion code ORCHID.

Irradiation uniformity of the OMEGA-Up-grade has been improved on single-beam uniformity and power pulse. The requirement for single beam nonuniformity is 5% rms when averaged over 500ps. To achieve such uniformity levels, random phase plate/distributed phase plates (DPP), distributed plorazation rotators and smoothing by spectral dispersion (SSD) has been introduced. Recently 2D-SSD with a band width of 1THz was installed on the OMEGA laser system. The power balance was also improved to the level of 5% rms power imbalance. By these improvements, the achieved ρR of Ds gas filled in a plastic capsule increases by a factor 1.5. This is measured by the enhancement of the secondary proton yield as shown in Fig.2.

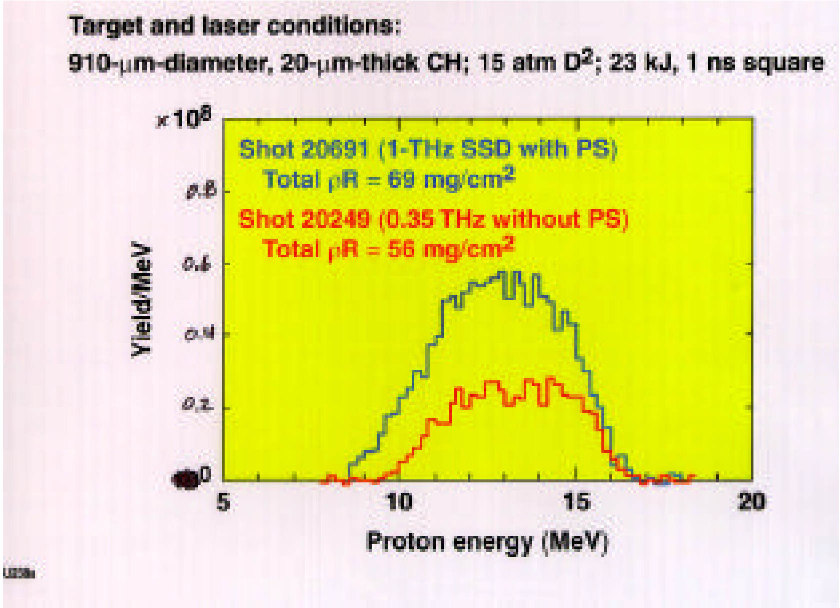


*Fig.2 Increase of secondary proton yield by introducing 1THz SSD with PS*

## Section 3.2 Indirect Drive Implosion Physics

The recent objective of the research is to predict the ignition and burning performance in coming ignition experiments of NIF and LMJ. Namely, the physics related to the design of ignition target has been explored by using OMEGA , NOVA , PHEBUS and so on ,and implosion simulation codes like LASNEX , HYDRA-3D , ORCHID-2D and so on. The margin to the ignition has increased by the recent new findings in hohlraum and capsule physics [1] [15].

Coupling efficiency of input laser energy injected into hohlraum to X Ray energy absorbed by fuel capsule are in particular concerned in enhancing target gain. The coupling efficiency is found to increase by taking into account (1) cocktail wall effects in hohlraum (2) laser entrance hole reduction (3) laser scattering loss by parametric instabilities and (4) reducing case to capsule ratio. As it is shown in Fig. 1 , the expected fusion yield is increased by the improvements in target physics and potential enhancement to NIF performance. So, the target performance of NIF will be far above the ignition threshold. Since the coupling efficiency will increase from 8.5 % to 20 % by the above improvements , the absorbed X ray energy will be 360 kJ for the laser(0.35 micron wave length). Furthermore, by the NIF performance improvement , namely by improving the conversion efficiency to 3 omega , the X ray energy absorbed by a capsule will be 400kJ. The gain estimated by the simulation is higher than 30. If such high performance implosion is realized , the alpha particle heating physics of extremely high density plasmas and the burning plasma physics will be disclosed. This will be enable us to design high gain targets.

The improvement of implosion uniformity was demonstrated by OMEGA experiment. The laser irradiation geometry on the inner surface of a hohlraum was one cone configuration in the NOVA experiment. On the other hand, that in the OMEGA experiments is multi-cone configuration which is similar to the irradiation configuration in the NIF ignition experiments. The normalized neutron yield of the OMEGA experiments is higher than the required level for igniting DT fuel in NIF even in the high convergence implosion which corresponds to high gain target as shown in Fig 3, although it was about 0.1 in the yield of NOVA experiments. Here, the neutron yield is normalized by that of the 1D simulation including the mixing model which describes hot spark-main fuel mixing associating to short scale pellet surface irregularities. The above results indicate that large scale non-uniformities is significantly reduced in the NIF irradiation symmetry to make the prediction by 1D simulation with the mixing model reliable.

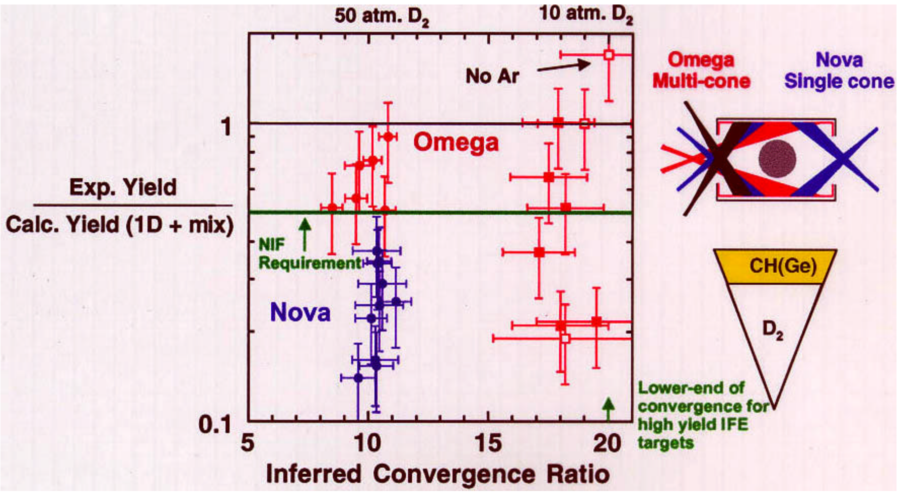


*Fig.3 Increase of normalized neutron yield for multi-cone irradiation on OMEGA*

In the hohlraum physics, the finding on the effectiveness of the cocktail wall is in particular important for improving the coupling efficiency. It was discovered by the work [16] on the radiation transport in the mixed materials. In a material which consists of single atomic species, the frequency dependence of the opacity has many transmission band associating absorption edges though which radiation escapes. When the wall material consists of multi atomic species which are combined appropriately, the absorption edges are arranged to reduce the transmission windows in the soft X-ray spectrum. For an example , the mixture of gold and gadrinum are used for the hohlraum wall in which the coupling efficiency is enhanced by 3% in the NIF target design.

In conclusion the recent OMEGA experiment and the improvement of the target design suggest that the NIF and LMJ will probably not only achieve ignition and burn by indirect drive implosion but also demonstrate high gain implosion.

### Section 3.3 Implosion Hydrodynamics and plasma diagnostics

A new laser irradiation system have been constructed to test implosion hydrodynamics related to direct drive high gain implosion [17]. The twelve beams of 2ωand 3 ω GEKKO XII are bundled to irradiate planer target in order to investigate implosion hydrodynamics of large scale and high ablation pressure acceleration (see Fig.4). A combination of a green PCL foot pulse and a blue 2D-SSD main drive pulse is proposed for the high gain pellet implosion. Namely, a partially coherent laser light (PCL) of the wavelength of 0.527 μm is the most uniform beam which have ever been obtained. Since the conversion efficiency of PCL beam to third harmonics is not high in comparison with coherent laser beam , the smoothing technique ; 2D-SSD is applied for a 0.351 μm main pulse.

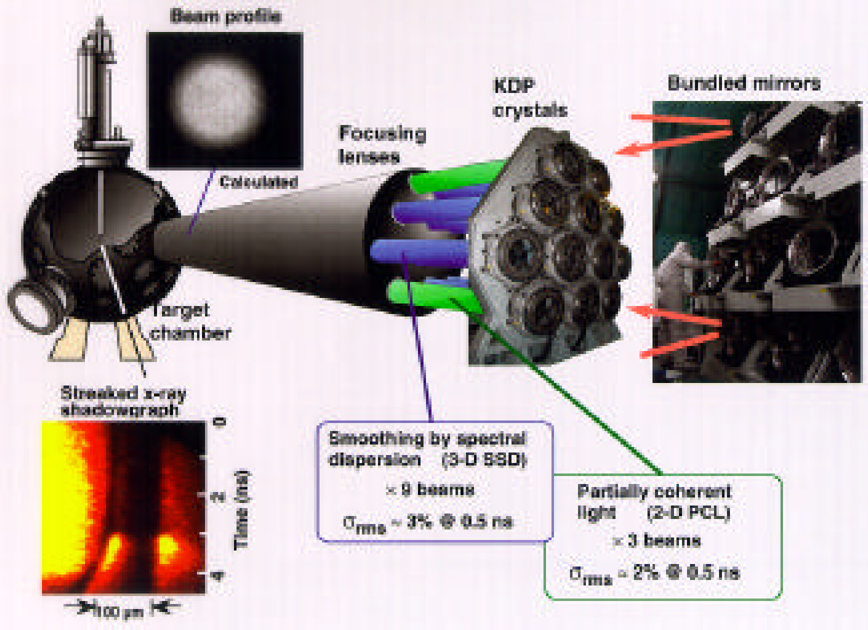


*Fig.4 HIPER irradiation system of GEKKOXII laser and a beam profile with planer target acceleration X-ray shadow graph*

At ILE Osaka University , a series of experiments on the ablation driven planer target hydrodynamics have been conducted by the GEKKO XII laser [18] [19]. Investigated are initial laser imprint , imprint mitigation in foam buffered target and X ray pre-irradiation and Rayleigh- Taylor instability growth. The dynamical property of initial imprint is investigated by using time dependent interference pattern generated by the Young's interferometer with two different frequency laser beams. Plastic foils were irradiated with this dynamically modulated foot beam of 0.527 μm wavelengh laser , which were then irradiated with a uniform main pulse to be accelerated. The resultant ρr perturbations were measured by the face on back lighting. When the modulation frequency is higher than 2.5 GHz , the 40 μm wavelength imprint is significantly mitigated and the Rayleigh-Taylor mode amplitude is lower than the detection limit(see [18] [19]). The R-T instability growth rates of short wavelength modes are measured with a moire' interferometry . The growth rate of wavelength shorter than 10 μm was successfully measured for the first time. Although the growth is found to decrease as the wavelength decreases below 10 μm , the growth rate is not zero and the cut-off wavelength is found to be shorter than this wavelength as shown in Fig.6 of [18].

By the EU group, it is proposed that the driving pressure is enhanced by introducing adding a foam layer in front of the radiation driven plastic layer doped with Br. The total pressure at the foam/foil interface is ablation pressure + material pressure of heated foam. The total pressure is measured for various density of the foam layer. It turns out that there is an optimum density for maximizing the pressure. In the paper (IAEA-CN-77/OV3/4) , the velocity of the accelerated foil is maximum when the foam density is 50mg/cc for the thickness of 50 μm.

As for the diagnostics of laser produced plasmas, several new findings are presented in the conference. The X-ray spectroscopy is a current method for plasma density and temperature measurement. The paper ; [20] presented spectrally and time resolved measurements of the K-shell emission of various low Z-targets which are heated by a shot pulse(200fs)laser. From this ,a plasma with an electron density of $10^{24}$/cc and a temperature of 380 eV was inferred. The line shape of Lyman-α is not understood. The line shapes of Lyman-α and satellites are compared with those of Stark-broadening line profile simulation in Fig.5. The experimental result shows much broader profile than the simulation results.

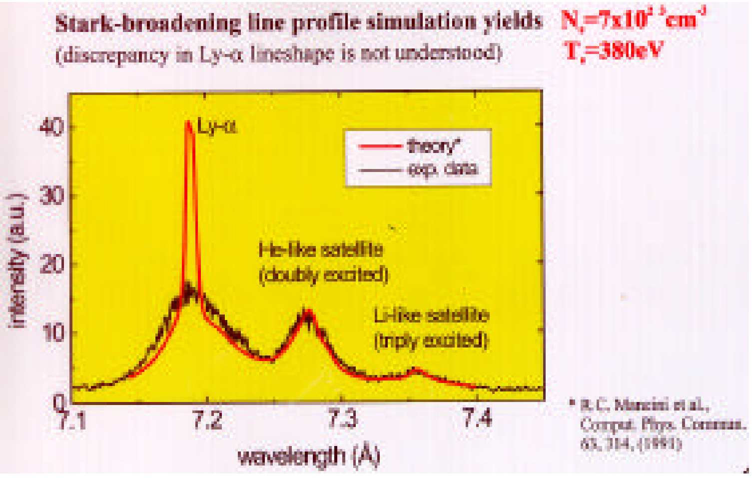


*Fig.5 Comparison of stark-broadening line profile of simulation with that of experiment*

As a new diagnostic tool, 15MeV proton beam produced by an intense short pulse laser has been used as a proton radiography [4]. The proton beam generated in intense short pulse laser plasmas is emitted from a small laser spot and well collimated. Therefore, the space and time resolution of images taken by proton radiography can be very high. It may be applicable to diagnose magnetic fluctuations in dense plasmas. It is very crucial for the electron heat transport in non-uniformly heated laser plasmas. The plasma density structure on an Al foil is measured by the proton back-lighter. Further investigations are necessary to clarify actual applications to the plasma diagnostic .

## 4. Target Fabrication ,Target Design , and Integrated Implosion Code Simulations

### 4.1 Target Fabrication

In the target fabrication technology, we have to develop technologies on uniform capsule fabrication ,cryogenic layering ,hohlraum fabrication ,characterization of pellet ,pellet injection ,mass production ,and so on . The fabrication technology of plastic capsule for ignition experiment have developed significantly in the past two years . As shown in Fig.5 , the surface finish of the capsule meets the conditions set by the present ignition target design (see [21] and [22]). As stable NIF targets , new kinds of pellet like polyimido capsule ,Be capsule , and so on are considered. However, the fabrication technology of those capsules is still premature. The hohlraum manufacture technology has been also been developed in US substantially. On the other hand , the uniform layering of DT fuel is under development. The decay heating method and RF heating method are under investigation .

We need more efforts for developing the mass production of target , in particular , indirect drive target production with reasonable cost. The pellet injection into a reactor chamber is also a critical issue because of the distortion of the pellet and heating by hot residual gas in the chamber. The target design efforts to relax the uniformity requirements are also expected. For an example , the fast ignition scheme may relax the condition significantly.

### 4.2 Target Design and Integrated Implosion Code Simulation

**[Indirect Drive Target Design]**

The ignition and medium gain target designs have been proposed for indirect drive and direct drive laser fusion, in particular for the NIF and LMJ target(see [15] and [2] ). The degradation of the gain due to the target surface roughness has been checked with 3D code HYDRA. It is found that the tolerance is higher for the polyimido capsule and Be capsule in the indirect target. As for the coupling efficiency enhancement , the reducing the inlet hole diameter and the ratio of hohlraum radius to capsule radius are connected with the radiation intensity uniformity on the pellet surface. In order to determining the reduction factor , the 2D and 3D integrated code simulations are necessary. They has been done with LASNEX and HYDRA-3D. As the results of the simulation, the coupling efficiency could be enhanced by several % by tuning the above ratios.

The original ignition point designs for NIF were made conservative to provide margin for uncertainties in laser absorption , X ray conversion efficiency , radiation uniformity , and hohlraum-capsule coupling efficiency . Recently , experimental efforts on NOVA and OMEGA lasers have reduced uncertainties in coupling efficiency and irradiation uniformity of multi-cone irradiation geometry. Now, it is possible to explore confidently target enhancements which couple more NIF energy to a capsule. These include using optimum mixture of materials to reduce X ray wall losses , smaller entrance hales to reduce hole X ray losses ,reduced case to capsule ratio. It is found that by the above simultaneous improvements, the overall efficiency increases by 1.5-2.0 times at radiation temperature 300 eV and 2-2.5 times at 250 eV.

In addition to the increase of the hohlraum coupling efficiency , it is found that it is possible to increase the conversion efficiency of 1 μm light to 0.35 μm light to about 70% by using a technique known as “ultra fast pickets”. Consequently , the full NIF might be able to derive a target with up to 2.5 MJ of blue light . The improvements of both hphlraum coupling and laser extraction indicate that capsules absorb 300kJ of X ray energy at 300keV and 600kJ at 250 kJ. This would lead to yield of 50MJ to 150MJ which corresponds to energy gain of 25 to 50.

By the integrated code simulation (see [23]), implosion dynamics including multi-Rayleigh-Taylor modes is simulated to investigate the stability of the capsule with beryllium ablator. . Those capsules are found to be ignited with the surface finishes of an order of magnitude worse than the NIF specification. When the low quality capsule ignites on the NIF , the surface finish condition of the reactor-scale capsule will be reluxed. However, it is still not known how to mass-produce and fill DT in capsules with beryllium ablators

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## [Direct Drive Target Design]

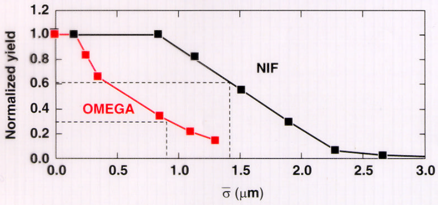
The LLE of University of Rochester has proposed a base-line NIF direct drive ignition design which is based on a cryogenic DT target. In the design , input energy of 1.5 MJ and alpha(the specific energy of the fuel divided by the Fermi specific energy ) = 3 are required. Recently, the sensitivity of the designs to laser pulse characteristics has been investigated extensively [3].

The base-line capsules are 3.5 mm in diameter and consist of a 340 μm layer of DT ice enclosed by a 1 to 2 μm thick plastic shell. The laser pulse creates two main shocks in the DT ice layer. At a foot pulse intensity of ~10 TW, a 10 Mbar shock is launched. At the time of shock breakout at the rear surface of the DT ice , the pulse ramps up to drive region, which lasts for 2.5 ns at a power of 450 TW. At this stage , an approximately 80 Mbar shock is generated to accerelate the DT ice inward.

The above base-line point design is predicted , by 1 D simulation , to attain a gain of 45, a neutron averaged ion temperature of 30 keV, and a peak ρR of 1.3 g/cm~2. The in-flight aspect ratio (IFAR) is 60, and the convergence ratio is 28(initial target radius divided by the hot spot radius.

The instability postprocessor cannot self-consistently determine the degradation of target yield for a given initial level of non-uniformity. ORCHID 2-D hydro-code simulations were used to determine the effect of non-uniformity of inner ice surface distortion. The calculation indicate the that the NIF targets with 1-THz ,2D SSD and 1.5 μm of inner-ice-surface roughness will give a gain of 28, a reduction of 60 % of the 1D yield. The NIF target design is scaled down to the OMEGA direct dive target in which input energy is 30kJ and the radius of the capsule is 30% of the NIF design. The reductions of the yield due to ice surface roughness are shown in Fig. 5 for both NIF and OMEGA designs.

- 2-D *ORCHID* calculations have shown that the NIF gain and OMEGA yield can be related to $\bar{\sigma}^2 = 0.06\,\sigma^2_{\ell=1-9} + \sigma^2_{\ell\geq 10}$



- The smaller hot-spot radius in OMEGA designs leads to a greater reduction in yield for a given level of nonuniformity at the onset of deceleration.

*Fig6 Degradation of neutron yield by implosion nonuniformity*

NRL designs have been compared with the above LLE's design [10], where the NRL targets have CH foam layer and/or a thin Au layer. The NRL targets are for both NIF and 1.6 MJ of 0.25μm light.. The CH foam layer mitigates perturbations generated by irradiation non-uniformity and the thin Au layer emits soft X rays which heat the ablation surface to reduce the front density and Rayleigh-Taylor instability growth rate . In those designs , introduced is the laser zooming which adjusts focused beam diameter to imploding shell size. The gains of NIF parameter and KrF laser with 1.6 MJ are about 60 and 100 respectively.

**[Integrated Simulation Code ]**

The simulation codes for describing laser and X ray irradiation and implosion radiation hydrodynamics have been developed in EU , USA , Japan ,and so on. 1-D implosion codes like ILESTA-1D(ILE) , LILAC(LLE) ,LASNEX-1D(LLNL), FCI1(CEA/France),and so on have been used for parameter survey of capsule to design targets. In order to investigate implosion non-uniformity, 2D and 3D implosion codes have been developed ,which are ILESTA-2D(ILE), ORCHID(LLE), LASNEX-2D (LLNL), HYDRA-3D(LLNL), FASTA-2D , 2D-FCI2(CEA/France), and so on. In those codes , recently included are new physics models such as non-local heat transport [24] and [2], DT dissociation EOS model ,electron deflection by self generated magnetic fields [2] , α−particle heating and momentum deposition effects on 2D hydrodynamics [25],and so on and new numerical schemes such as Adaptive Mesh Refinement (AMR) [26], Cubic-Interpolated Pseudo Particle(CIP) method [24] , and so on .

Physics of the inertial fusion is based on a variety of elements such as compressible hydrodynamics , radiation transport , non-ideal equation of state , non-LTE atomic process ,and so on. In order to study such complex phenomena , the above integrated codes includes all important physics in the implosion process. Together with numerical physics models , it is necessary to develop hydrodynamic equation solver which is robust to the shear flows associating non-uniform implosion. The ILESTA-2D (ILE/Osaka) has been modified to be an implicit arbitrary Eulerian Lagrangian code (ALE) for the robustness and saving the computational time. Nevertheless , the difficulty of the rezoning/remapping was still remained when Rayleigh-Taylor instability becomes nonlinear. In order to overcome this difficulty , the CIP method has introduced , which has high-order accuracy in space and time [24].

## 5. Fast Ignition

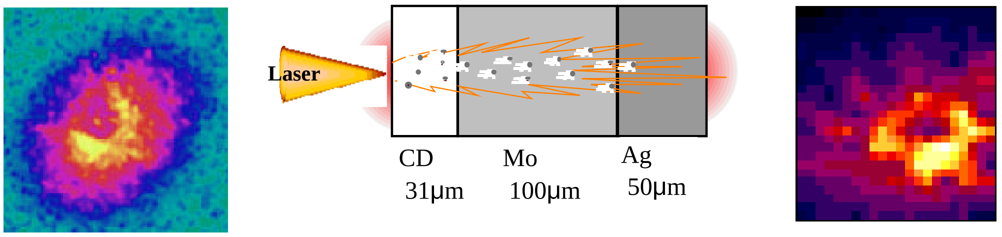
The concept of fast ignition(FI) is to inject an ultra-intense laser pulse into a highly compressed, high density fuel core within the core assembling time , making use of relativistic laser focusing or guided channel formation. The ignition may be achieved by heating with relativistic electrons and/or high energy ions , whose temperatures are of the order of MeV. The attractive points of the concept are possibly to obtain much higher fusion gain and requiring laser irradiation uniformity less than those in the central ignition scheme.

In the last IAEA conference, the self focusing and the guiding channel formation have been demonstrated in experiments and computational simulations. Since then ,the MeV electron generation ,transport and plasma heating have been investigated in Japan (ILE/Osaka; [27] and [28]),USA(LLNL,GA; [23] and [29] ) and EU(LULI/France , RAL/UK; [4] and [20] ).

Since the Fusion Energy Conference of 1998, the main progresses are on energy transport of relativistic electrons and heating of imploded dense plasmas. As for the relativistic electron transport, LULI , LLNL and ILE/Osaka have found in ultra intense short pulse experiments that relativistic electron current forms filaments and/or annular ring. They were measured by shadow graph , UV radiation and X ray images ,and so on. By PIC simulations at MPQ/Garching [30] and ILE/Osaka [27], it is shown that although high energy electron current is neutralised by cold electron return current , the Weibel instability and current tearing occur to generate magnetic fields and small scale filaments. In several μm penetration , the filaments merge and self-organise larger scale filaments(for instance, see Fig.7). Although the PIC simulations describe well high energy electron generation processes and generation of current filaments near the critical surface , it is not possible at present to describe relativistic electron propagation and stopping in large scale high density plasmas because of lack of computer capability. To overcome this difficulties, developed are hybrid codes where high energy electrons are described by the PIC method and high density cold electron dynamics is described by magneto-hydro-dynamic(MHD) equations. The hybrid codes ; PARIS(LULI/France) and DAVIS(RAL/UK) have been developed and used to investigate macroscopic behaviour of relativistic electron in dense plasmas. The results show that the relativistic electron stream is well confined in a relatively narrow channel by self-generated magnetic fields , when heat flux is higher than the threshold value which is typically $10^{19}$ W/cm$^2$.

*Fig.7 3D PIC simulation results for merging of magnetic field electron channels*

In Figure 8 , the front side X ray image and rear side UV image show that the heating pattern on target rear surface corresponds to the front side X ray image which may indicate a relativistic electron flow pattern in over dense plasma. These data indicate that the relativistic electron divergence angle could be 20-30 degree(FWHM) [28]. CD plastic plane targets are irradiated by intense short pulse laser to measure heated plasma temperature with neutron energy spectrum . The ILE experiments show that significant thermal DD reactions are observed. This indicates that solid density plasmas are heated by a relativistic electron beam to 300eV[28]. Similar experiments have been done in many laboratories. They observe DD neutrons by both thermal fusion and beam fusion. The beam fusion is related to ion acceleration by the radiation pressure near the cut-off. Multi-mega eV ions have been observed on both front side and rear side in computer simulations and experiments [4] [29] . Although further investigations are required , the ion beams generated by the intense laser could be used as an energy carrier for fast ignition.



**X-ray front Image**

**UV target rear Image**

*Fig. 8 Front view and rear view of hot spot heated by relativistic electron transport*

The imploded plasmas are heated in the PWM + GEKKO XII laser system [27]. Significant enhancement of neutron yield has been demonstrated at ILE. In the recent experiments, a 50J/1ps pulse is injected into a imploded plasma produced with 500 μm-diameter CD shell and 1.5 kJ GEKKO XII green laser. The neutron yield reaches $10^6$ which is about 10 times higher than that without short pulse laser. However , the neutron energy spectrum was broad to indicate that the average energy spread is the order of 100keV. Namely , the neutrons may be generated mainly by over dense plasma interaction with high energy ions accelerated by the radiation pressure of short pulse laser . In the present implosion plasma heating experiments, it is not sure that the direct injection of ultra intense laser is feasible to heat the compressed plasma effectively because beam fusion may overcome the thermal fusion. According to the following cone target experiments , level of thermal neutron is the order of $10^5$ , which is one order of magnitude lower than that of beam fusion.

Recently, a new target design for fast ignition scheme has been proposed. That is “a capsule with guiding cone “. This concepts has been proposed by Osaka, LLNL, and Rutherford groups . The shape of the target is shown in Fig. 9. In this target, the fuel shell is imploded to produce a compressed core plasma near the top of the cone. When the cone density is high enough like a gold , the cone walls remain as it is initially. The 2 -D simulation is shown in the Fig. 10 where an imploded plasma density is as high as 80% of the spherically symmetric case. For a reactor size cone target , 2D simulations are carried out at LLNL to indicate that the density reaches 1000 times solid density and $\rho r$ is higher than $2 g/cm^2$ . The heating pulse will be injected through the cone at the maximum compression. Inside of the cone will be kept vacuum to keep the coupling of the incident laser energy to the core plasma high.

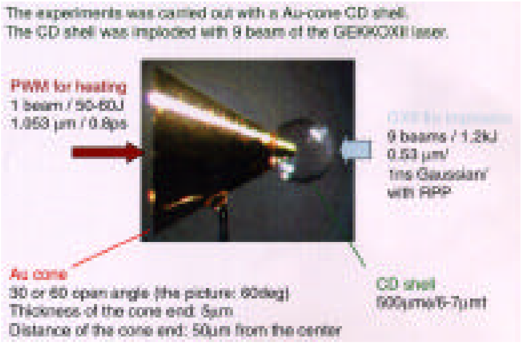
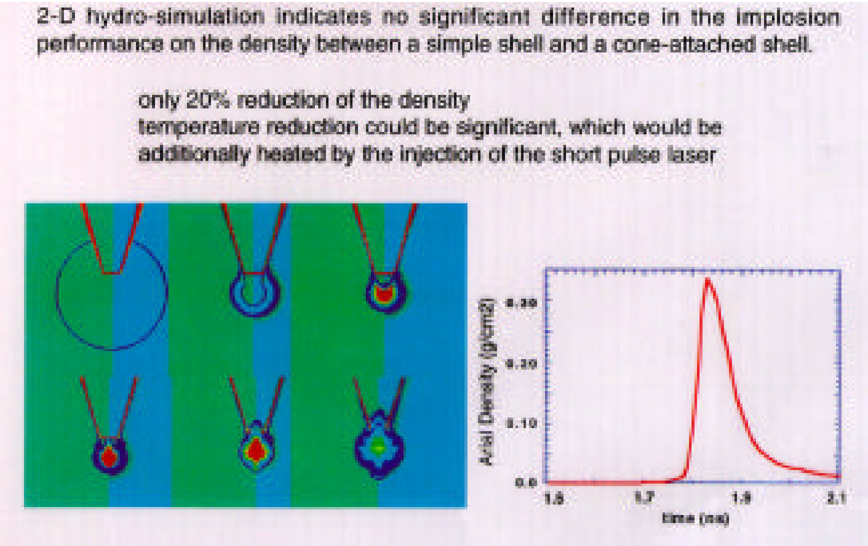


*Fig.9 Cone-target photograph made by ILE and RAL target fabrication team*

The experiments on cone target implosion and injection of short pulse laser have been done at ILE Osaka University in collaboration with RAL(UK). The experimental results show that the imploded plasma density is as high as expected by simulation and the neutron yield increased by a factor 10 in comparison with no heating. Furthermore , the neutron spectral width is narrow to indicate that the thermo-nuclear reactions occur. Although the further investigations are required to make sure that this concept will really work, the above simulation and experiment researches are very exciting.



2-D hydro-simulation indicates no significant difference in the implosion performance on the density between a simple shell and a cone-attached shell.

only 20% reduction of the density
temperature reduction could be significant, which would be additionally heated by the injection of the short pulse laser

*Fig.10 2D hydro-simulation of a cone-target implosion*

## 6.Heavy Ion beam Fusion

Three IFE drivers have advanced from the concepts exploration level to the proof of principle (PoP)level which are diode pumped solid state laser [31] , KrF laser [16], and heavy ion beam [14]. The current(PoP) phase of the program in USA has several tasks for heavy ion beam fusion. They are target design [23], target fabrication and injection , chamber dynamics , and accelerator research .To manage the increased institutional participation efficiently, a Virtual National Laboratory(VNL) for heavy ion fusion has been created in USA. The individual people working in the VNL remain employees of the laboratories that created the VLN. It combines three largest accelerator research programs(LBNL,LLNL,and PPPL) under a single management . The virtual laboratory for technology manages the research in the chamber and target fabrication.

### [Target Design]

Several years ago the best U.S. target design required 6MJ of beam energy for getting a target gain of 70. More recent designs , according to 2D numerical simulations , require 1 to 3 MJ of beam energy to obtain a gain of 90 to 130 . The improvements in energy and gain are obtained by improving the target coupling by reducing the size of the hohlraum relative to the size of the capsule. This design requires small focal spot sizes of beams leading to increased demands on beam brightness and focusing systems.

### [Accelerators and Beam Physics]

Accelerator research at the PoP level has been underway for about two years. The PoP phase of the program is the Single Beam Transport Experiment(SBTE) and the Multiple Beam Experiment with 4 Beams(MBE-4) at LBNL. These experiment show that it is possible to produce , transport , and accelerate heavy ion beams with more than adequate brightness for fusion application. The present experiments typically transported and accelerated approximately 10mA of current per beam. The corresponding current in afull scale driver is expected to be of the order of 1A per beam at low energy end of the accelerator, increasing to the order of a 1kA per beam at final focus. There are still unresolved issues associated with the absolute scale of the current. The experiments at LBNL , 2 MeV injector, deliver approximately 1A of beam current, to allow us to address the critical issues related to the high current.

## 7. Fast Z-pinch X-ray Source

Recent Z pinch experiments utilising cylindrical arrangements of fine metallic wires as loads have produced record X ray powers and efficiencies. Theory and experimental researches have been carried out at Sandia National Laboratory(SNL) , Kruchatov Institute , and Imperial college [7] [8] [9]. On the Sandia Z accelerator , X ray energy is approaching 2MJ and X ray power is exceeding 200TW. In utilising these X rays to drive IFE capsules, several different hohlraum and target configurations have been proposed.

The figure 11 shows that the SNL pulse power accelerator with Z-pinch load provides efficient time compression and power amplification. The top view (Z) shows pulse shapes of power in Marx (11.4MJ),water pulse forming line ,vacuum transmission line and X rays. The X ray pulse is 1.8 MJ for 6 ns. The conversion efficiency from electric power to X ray was approximately 15%. The experimental works have advanced at SNL. The new findings on the wire array implosion increased conversion efficiency to X ray. Optimized are choice of wire array materials, wire arrangement , pulse shape , and so on.

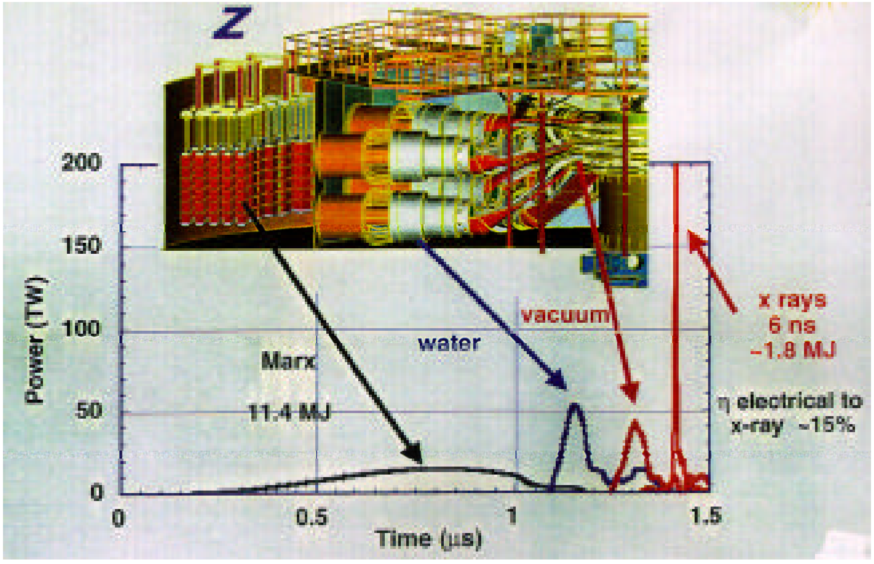
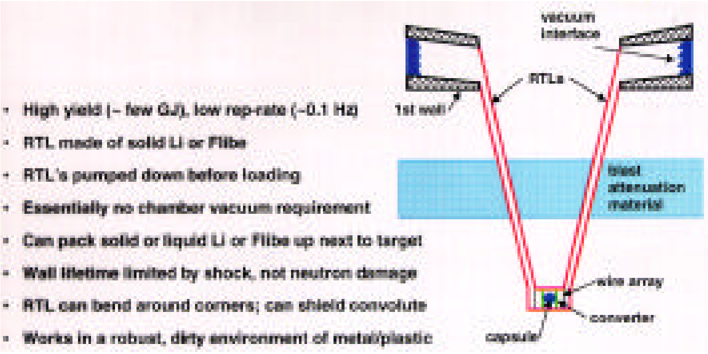


*Fig.11 Pulsed-power accelerators with z-pinch loads provide efficient time compression and power amplification*

In the experiments on S-300 (4MA , 100ns) ( , 1.5 TW of soft X ray radiation(hν > 100 eV) was achieved as a result of a multi-wire tungsten liner. The total energy of the X ray pulse was approximately 20 kJ . The spectrum of the X rays was in the range of 50-500eV. In the experiment , an array of 80 tungsten wires with 6 μm-diameter was used.

At imperial college [8], plasma formation and implosion dynamics of array z-pinches have been studied experimentally using the MAGPIE generator (1.4 MA,240ns). Theory and simulations verify much of the data. Both laser probing and X ray radiography show after an initial volumetric heating of the wires the presence of dense wire cores surrounded by low density coronal plasma. Radiography shows development of perturbation on the dense core of each wire , while laser probing shows inward jetting of the coronal plasma caused by the global JxB force, and these plasma streams are axially non-uniform on the same spatial scale as later seen in the wire cores . Images obtained by the optical streak camera shows that the implosion trajectory deviate significantly from that expected from 0-D analysis. An increase of the number of wires (decrease of inter-wire gap) resulted in a transition to 0-D trajectory for aluminium wire arrays , but not for tungsten .

A rep-rated Z-pinch fusion power plant concept is proposed in which a recyclable transmission line (RTL) is used. In this concept , the rep-rate (~ 0.1 Hz) is low and high gain (~ a few GJ ) is required. The RTL is made of solid Li or Flibe and pumped down before loading as show in Fig. 12 [7]. Essentially , no chamber vacuum is required. Together with demonstration of a fuel capsule implosion by X ray produced by Z pinch , many technology issues have to be investigated for clarifying possibility of applying RTL concept to IFE driver.



- High yield (~ few GJ), low rep-rate (~0.1 Hz)
- RTL made of solid Li or Flibe
- RTL's pumped down before loading
- Essentially no chamber vacuum requirement
- Can pack solid or liquid Li or Flibe up next to target
- Wall lifetime limited by shock, not neutron damage
- RTL can bend around corners; can shield convolute
- Works in a robust, dirty environment of metal/plastic

*Fig.12 A Reported Z-pinch fusion power plant concept*

## 8. Concluding Remarks

In the inertial fusion energy research of the last two years , the researches toward demonstrating ignition burning have progressed significantly. In particular, research and development of ignition target design and fabrication technology have advanced. The building and laser construction in USA and France continued to complete mega jule lasers until 2008. In the relation with ignition facility projects ,both indirect and direct drive target designs are further progressing .

As a new concept, the fast ignition scheme has been explored intensively in many countries . 100TW level experiments have been curried out in Japan , UK , and France to show deep penetration of relativistic laser pulse into over-dense plasmas and generation of intense relativistic electron beam . Furthermore electro-magnetic fields effects on the transport are widely investigated by theory and experiments. It is found that relativistic electron streams are well guided by strong self-generated magnetic field channel.

HIF project in USA have expanded toward the development of technology for IFE reactor size accelerator . Laser driver technology ( high average power laser technology) have also developed significantly. As the third candidate for IFE driver , X ray source generated by Z pinch wire array is becoming feasible.

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