Plasma Physics Study and Laser Development for the Fast Ignition Realization Experiment (FIREX) Project

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Since the approval of the first phase of Fast Ignition Realization Experiment (FIREX-I), we have devoted our efforts on designing advanced targets and constructing the world highest-energy Peta Watt laser. The new target design has the following features. The coupling efficiency from the heating laser to the thermal energy of the compressed core plasma can be increased by the two ways:1) Low-Z foam layer on the inner surface of the cone for optimum absorption. 2) Double cone. Electrons generated in the inner surface of the double cone will return by sheathe potential generated between two cones. The implosion performance can be improved by three ways: 3) Low-Z plastic layer on the outer surface of the cone may suppress the expansion of the Au cone that flows into the interior of the compressed core. 4) Br doped plastic ablator may significantly moderate the Rayleigh-Taylor instability, making implosion more stable. 5) Evacuation of the target center to prevent gas jets from destroying the cone tip. For project robustness, we also explore 6) impact ignition scheme that eliminates complexity of laser-plasma interaction while keeping the compactness advantage of fast ignition. The fully integrated fast ignition experiment is scheduled on 2009. If subsequent FIREX-II will start as proposed, the ignition and burn will be demonstrated shortly after the ignition at NIF and LMJ, providing a scientific database of both central and fast ignition.

1. Introduction

Thermonuclear ignition and subsequent burn are key physics for achieving laser fusion. Laboratory ignition with very large laser systems is now anticipated with the National Ignition Facility (NIF) in the US and Laser Mega Joule (LMJ) in France. Fast ignition has a potential to achieve ignition and burn with about one tenth of laser energy required for these programs. With the fast ignition, the fuel compression and heating are separated, with ignition initiated by a short very high power laser pulse incident on the already compressed fuel. The fast heating of a compressed core [1], together with the scalability to high-density compression [2], has provided the scientific basis for the start of the Fast Ignition Realization EXperiment (FIREX) project. The goal of the first phase (FIREX-I) is to demonstrate ignition temperature of 5-10 keV, followed by the second phase to demonstrate ignition and burn. Coupled with the achievement of central ignition on NIF and LMJ, the research focus would then move to the demonstrations of high gain and of the inertial fusion energy technology. These programs would converge onto a laser fusion test reactor that can deliver net electric power.

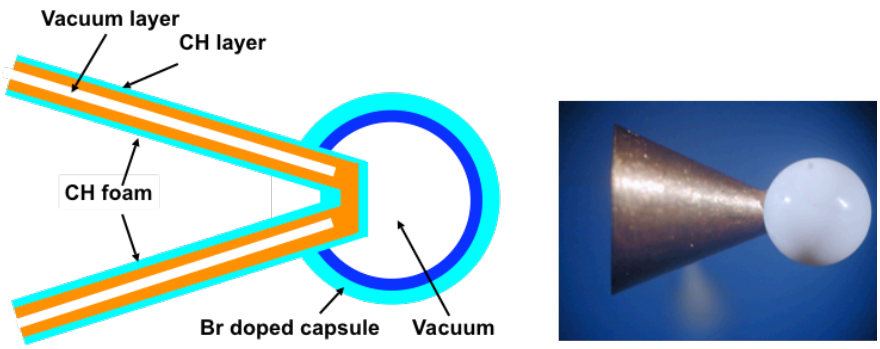

Fig. 1. Advanced target for FIREX-I and PIC simulation result of double cone.

2. Plasma Physics Study

Since the start of the FIREX-I project, plasma physics study in the Institute of Laser Engineering, Osaka University has been devoted to increase the coupling efficiency and to improve the compression performance. We have designed an advanced target for FIREX-I as schematically illustrated in Fig. 1.

The coupling efficiency can be increased by the following two ways:
1) Low-Z foam layer on the inner surface of the cone [3]. The coupling efficiency strongly depends on the plasma density at which the laser interacts with the plasma. If the density is too low, the hot electron temperature becomes too high (due to forward stimulated Raman scattering) for the electrons to be efficiently absorbed by the core plasma. If the density is too high, the laser absorption rate becomes too low due to the small interaction volume. Thus the optimum density apparently exists. Moreover, the plasma is snowplowed by the strong radiation pressure of the incident laser to such density that the fast electron intensity is substantially reduced; therefore the plasma has to be thick enough so that the plasma is not completely snowplowed during the laser pulse.

The plasma with suitable density and thickness can be preformed, in principle, by a pedestal or pre-pulse of the heating laser. However creating plasmas by such a way requires troublesome works including very careful control of the pedestal/pre-pulse level. To control the preformed plasma density and thickness, we propose to set up a low-density foam layer on the inner surface of the cone target. The foam layer will be fully ionized by a low intensity pedestal/pre-pulse.

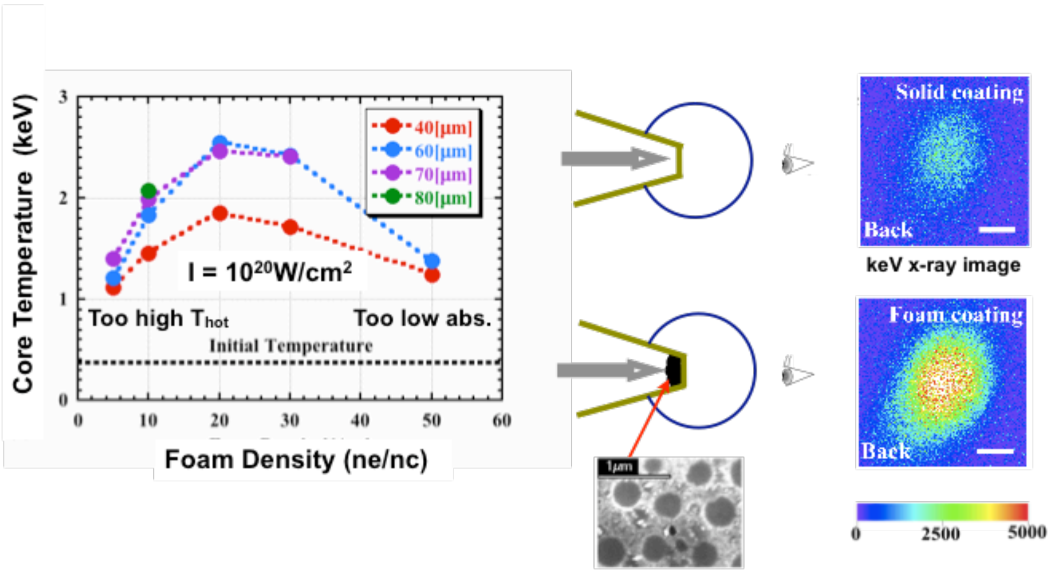

Fig. 2. (Left) Averaged core electron temperature for different foam thickness as a function of the foam density. (Right) Foam effect for increasing coupling efficiency.

The electron temperatures averaged over the dense region (ρ >10 g/cm^3) as a function of the foam density for different thicknesses are shown in Fig. 2. The averaged core electron temperature becomes the maximum at the form density of 20 times critical density of the heating laser and the thickness of 60 μm. It appears that we can appropriately control the fast electron generation for core heating with the low-density foam coated on cone targets.

Our previous experiment has demonstrated the increased coupling with a low-density foam[4]. Despite of the gold foam used in this experiment, low-Z plastic foam is desired for efficient electron transport since the collisional defects (collisional and resitive drags and scattering) can be reduced. For the same reason, the low-Z material is preferable for the cone tip material [5]. In this case, a thicker cone tip is required to hold against the jet-like plasma flow from the imploded fuel shell.

2) Double cone. Electrons generated in the inner surface of the double cone will be returned by sheathe potential generated between the two cones (Fig. 3). This potential disappears immediately after the plasma from the inner cone fills the gap. But subsequently generated magnetic fields are strong enough for most of the electrons to return. The separation distance should be larger than the Debye length, that is estimated to be 0.2 μm for 1-MeV electron temperature and the critical density of the heating laser. Thus a few μm separation distance is large enough for the electrons to be returned. Our two dimensional PIC simulation indeed indicates the improvement of the electron confinement by a factor of 1.7 [6]. Recent model experiments have favorably demonstrated this effect.

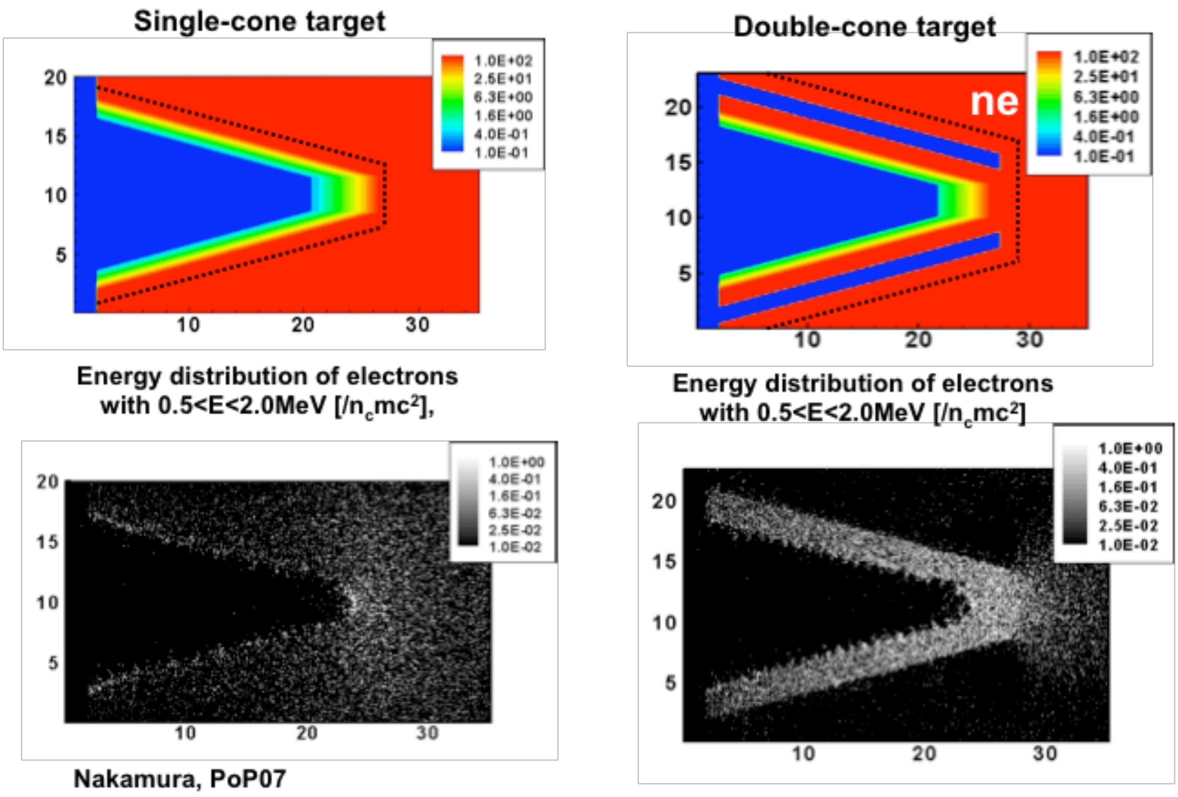

Fig. 3. Double cone design for higher coupling efficiency.

The implosion performance can be improved by three ways:

3) Low-Z plastic layer on the outer surface of the cone The imploding shell emits considerable amount of x rays, that irradiate the tip of the cone; then the heated cone tip expands into the interior of the core (Fig. 4). This degrades the core density as well as density-radius product. A low-Z plastic layer on the outer surface of the cone absorbs these x rays and tamps the expansion of the cone tip. The 2D hydro-simulation PINOCO predicts that

a 2-μm thick plastic target well suppresses the expansion of the cone. As a result the density and areal density are expected to increase by a factor of 1.5 and two, respectively.

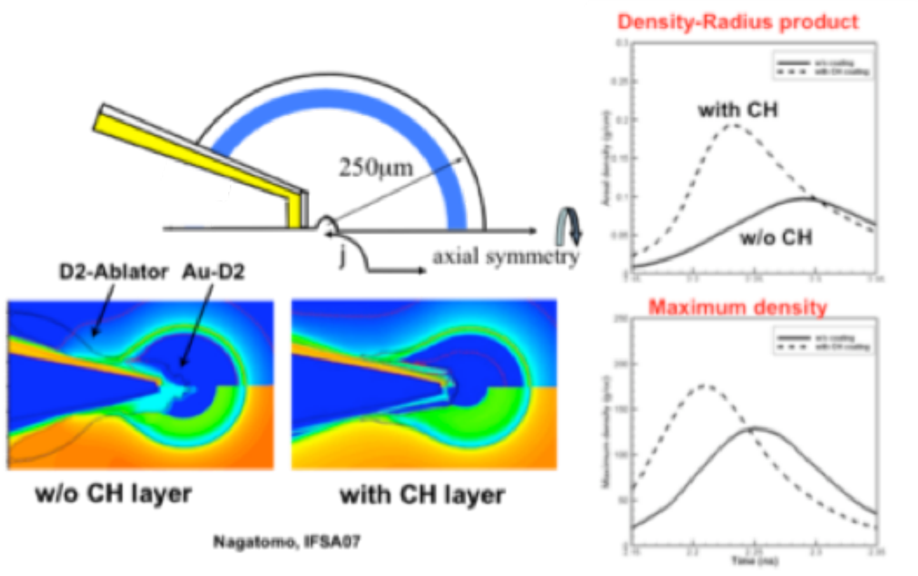

Fig. 4. A plastic layer tamps cone expansion.

4) Br doped plastic ablator emits suitable amount of x rays and creates a second ablation surface in addition to the electron driven ablation surface (Fig. 5). The x-ray driven ablation surface is relatively stable to the Rayleigh-Taylor (RT) instability, because the x-ray ablation effectively removes the perturbation away from the unstable surface. The RT instability in the electron driven ablation is almost completely stabilized because of the extremely large ablation velocity there. Thus the Br doped plastic ablator may significantly moderate the RT instability [7], making implosion more stable.

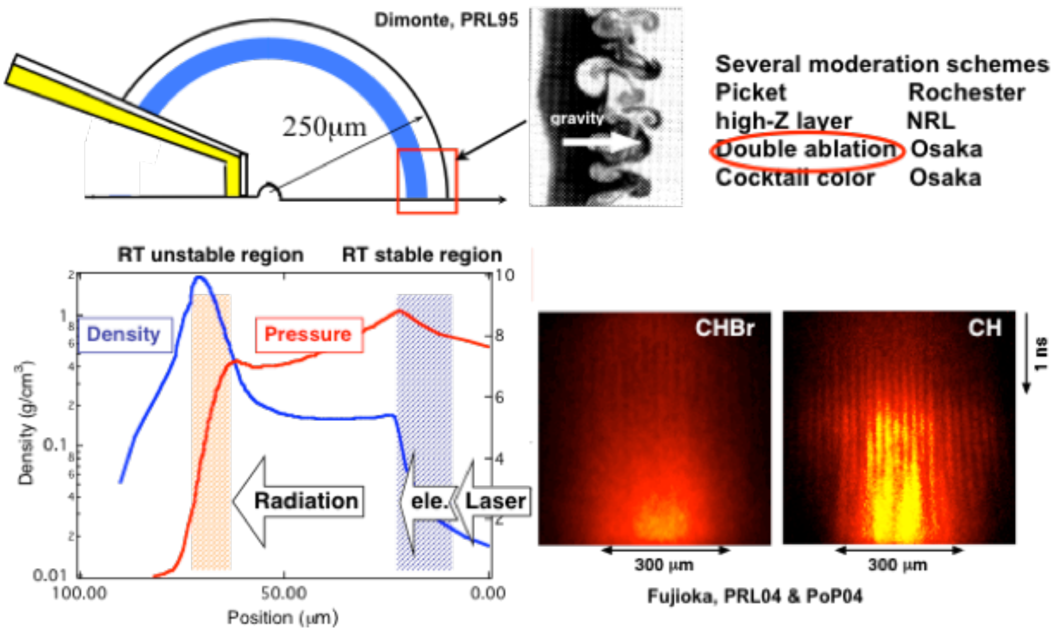

Fig. 5. Moderation of the Rayleigh-Taylor instability by double ablation technique

5) Evacuation of the target center. If there is the vapor gas in the target, it generates a gas jet that may potentially destroy the cone tip and thus hinder the efficient coupling of the heating laser with the plasma (Fig. 6). This unwanted effect was suggested in the previous Japan-US collaboration experiments [8]. The corresponding 2D simulation (bottom) clearly indicate this early penetration.

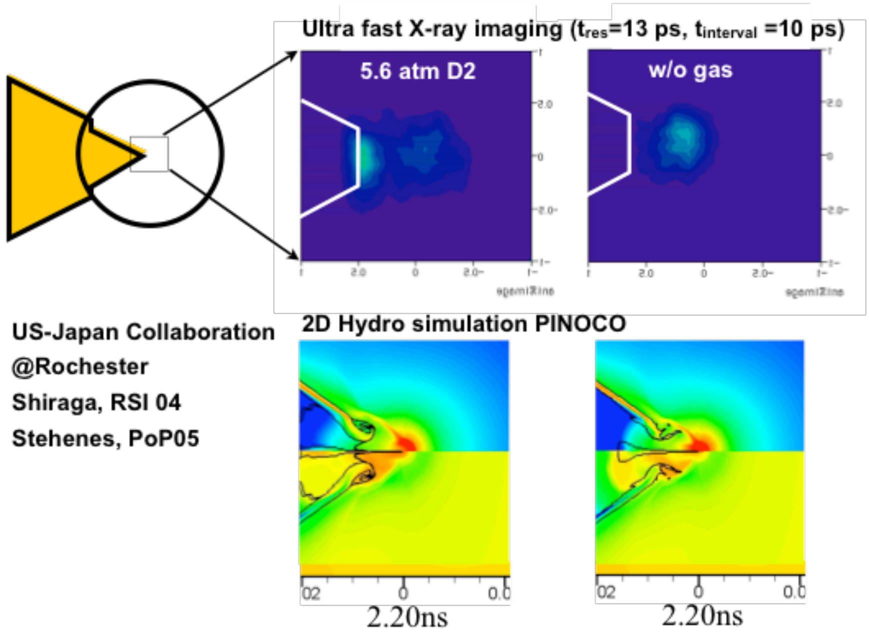

Fig. 6 A gas jet destroys the cone tip before the maximum compression.

6) Impact ignition. Fast ignition still has many intractable physics problems to solve relevant to complex laser-matter interactions, such as the transport of the absorbed energy via hot electrons or energetic ions to the dense compressed fuel. Recently "impact ignition" [9, 10] has been proposed, to eliminate this complexity while keeping compactness advantage of fast ignition. In this ignition concept, a fraction of a fuel (impactor) is accelerated to a super-high velocity, compressed by convergence, and collided with a pre-compressed main fuel. The impactor then becomes an igniter via shock compression and heating. We report the first experimental results on this impact ignition, demonstrating two orders-of-magnitude increase of neutron yield at a right timing of the impact collision.

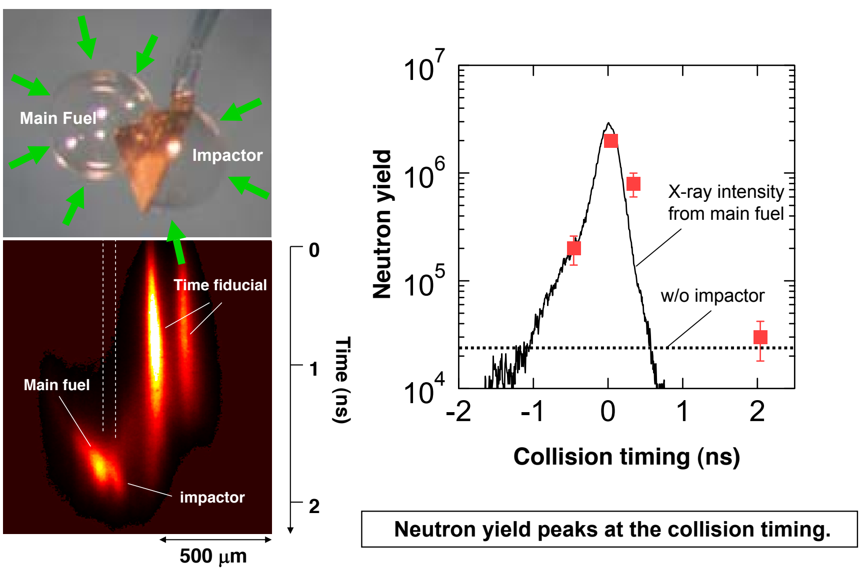

Fig. 7. Impactor collision increases neutron yield by two orders of magnitude.

3. Target and Laser Development

The ultimate FIREX target is a plastic foam shell filled with a liquid or solid DT fuel. At an early phase of the FIREX-I program, non-radioactive fuel will be used. To develop the cryogenic target, fuel layering process has been studied [11, 12].

As noted in the previous chapter, the fuel vapor must be evacuated. A possible solution for evacuation of cryogenic fuel is solidification of the fuel. Solidification, however, causes non-uniformity of a solid fuel layer due to the contraction. To make a uniform fuel layer, various processes of the fuel redistribution are considered for the FIREX target. The beta layering is not applicable for non-tritium fuel experiments. The infrared (IR) heating [13] requires target rotation *in situ*, and is technically complicated. The heat generation from the ortho-para conversion can be heat sources of the fuel redistribution. The redistribution of hydrogen (H_2) frozen ice has been demonstrated in the time scale (50h) consistent with that of the ortho-para conversion. Since the ortho-para conversion heat of deuterium (D_2) is quite small, A H_2-D_2 mixture fuel would be a practical solution for the FIREX-I cryogenic target.

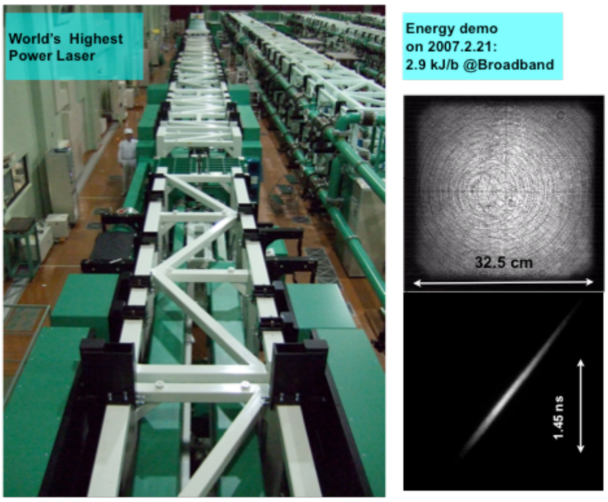

Fig. 7. LFEX laser for FIREX-I

The heating laser called Laser for Fast-ignition Experiments (LFEX) is designed to deliver a laser energy of 10 kJ in 10 ps. The amplifier system of the LFEX laser is completed as shown in Fig. 7. The amplification test has demonstrated a laser energy of 3 kJ/beam at 3nm bandwidth. The equivalent 12 kJ in 4 beams meets the specification of the LFEX laser. The large format gratings for pulse compressor are nearly completed. The fully integrated fast ignition experiment is scheduled in 2009. If subsequent FIREX-II will start as proposed, the ignition and burn will be demonstrated in parallel to that at NIF and LMJ, providing a scientific database of both central and fast ignition. Coupled with the achievement of central ignition on NIF and LMJ, the research focus would then move to the demonstrations of high gain and of the inertial fusion energy technology. These programs would converge onto a laser fusion test reactor that can deliver net electric power (Fig. 8)

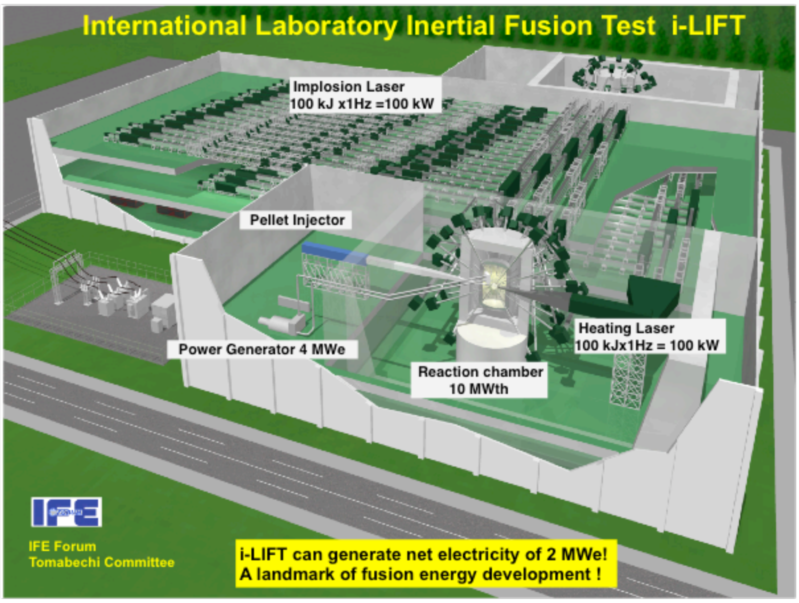

Fig. 8. A proposal of International Laboratory Inertial Fusion Test.

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