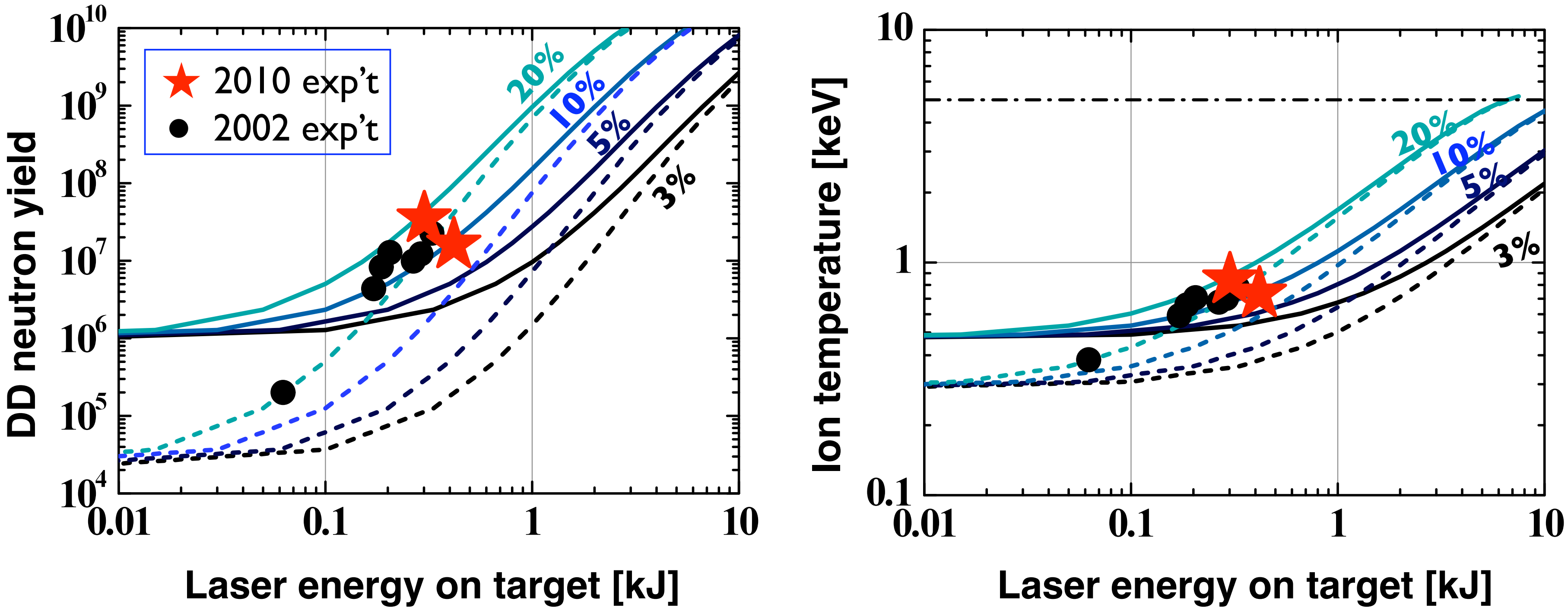
Fast Ignition Integrated Experiments on GEKKO-LFEX Laser Facility



Shinsuke Fujioka*, and FIREX-1 Project Team

***Institute of Laser Engineering, Osaka University**

24th IEEE Symposium on Fusion Engineering

Chicago, Illinois, June 29, 2011

Summary

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Status of kJ-PW LFEX laser:

- 1.4 kJ/1.5 ps/2 beams are in operation.
- will be upgraded 10 kJ/4 beams.

Pedestal of LFEX laser pulse:

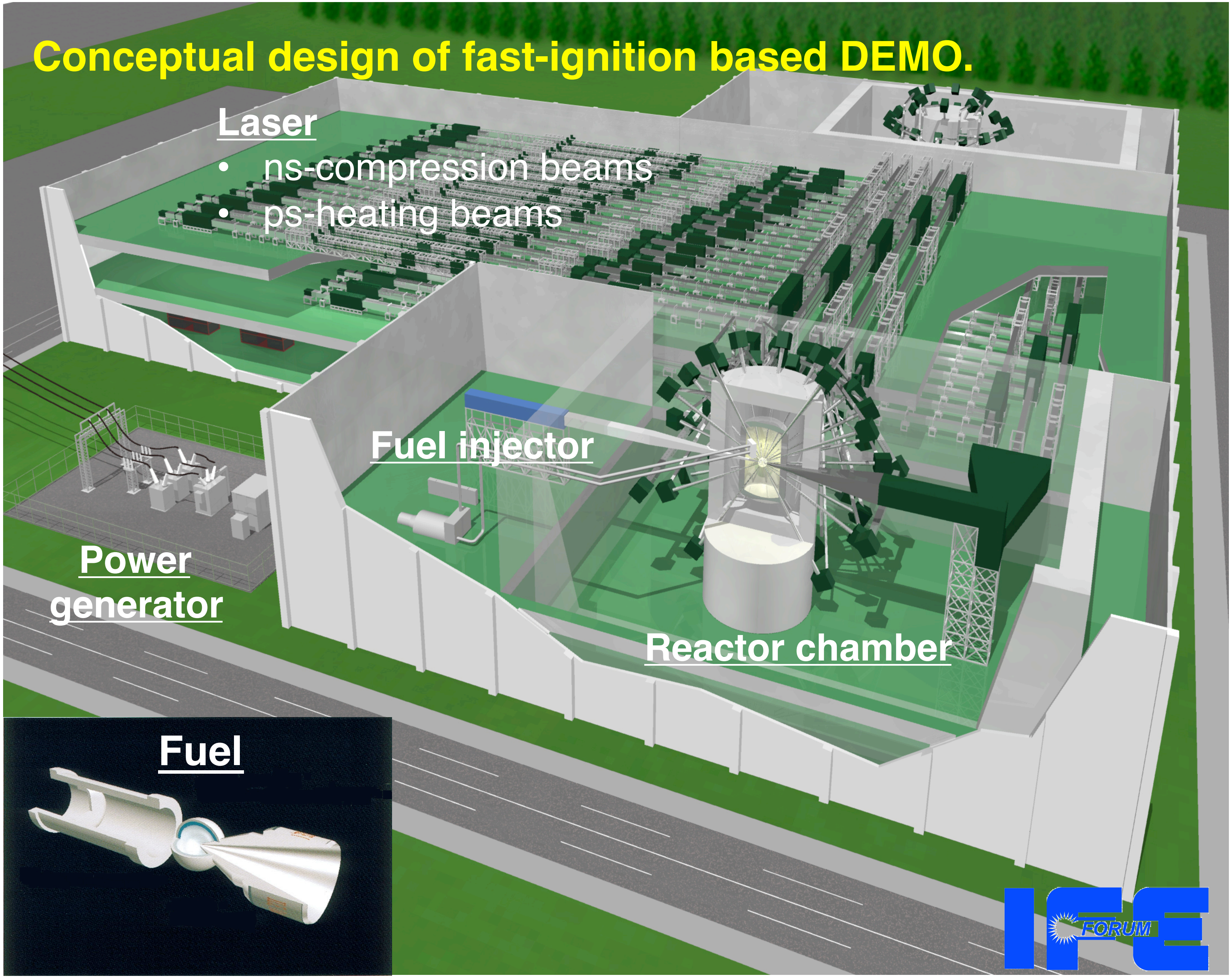
- Reduction of pedestal is a key issue for the FI experiment.
- Reduction of pedestal intensity results in enhancement of heating efficiency.

Diagnostics:

- Neutron yield was evaluated with the consideration of (γ,n) and (γ, γ) background.
- Timing of the heating laser injection was measured with an accuracy of 10 ps with an x-ray streak camera.

Integrated experiment:

- Neutron yield increased up to 3.5 x 10^7.
- Heating efficiency of 20% were achieved.


Conceptual design of fast-ignition based DEMO.
Laser
• ns-compression beams
• ps-heating beams
Fuel injector
Power generator
Reactor chamber
Fuel
IFE FORUM

Efficient heating up to 5 keV should be demonstrated on the GEKKO-LFEX laser facility for fusion power plant.

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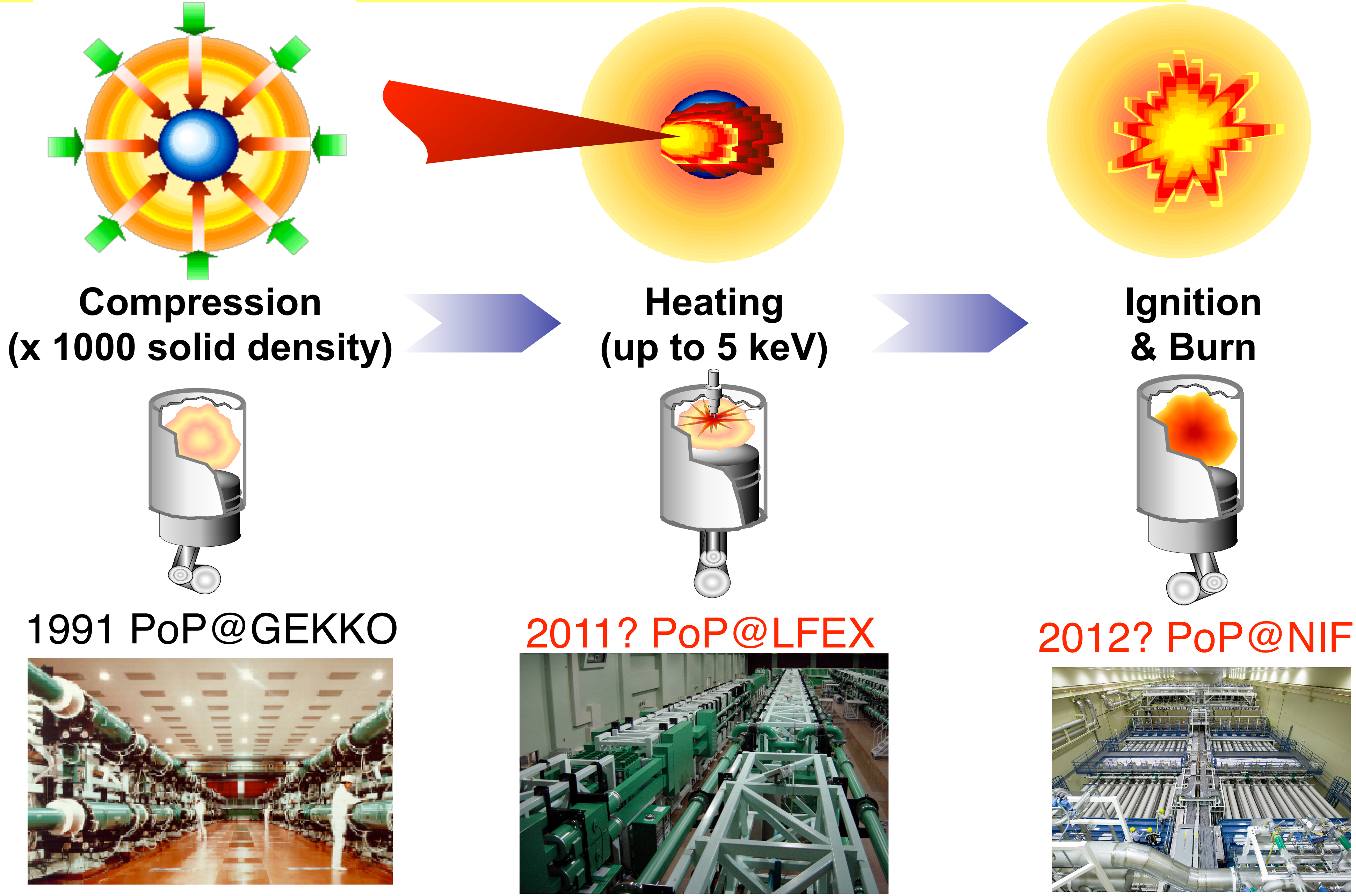

Status of kJ-PW LFEX Laser

Two beams of the LFEX laser are now in operation.
The full four beams will be completed in FY2011.

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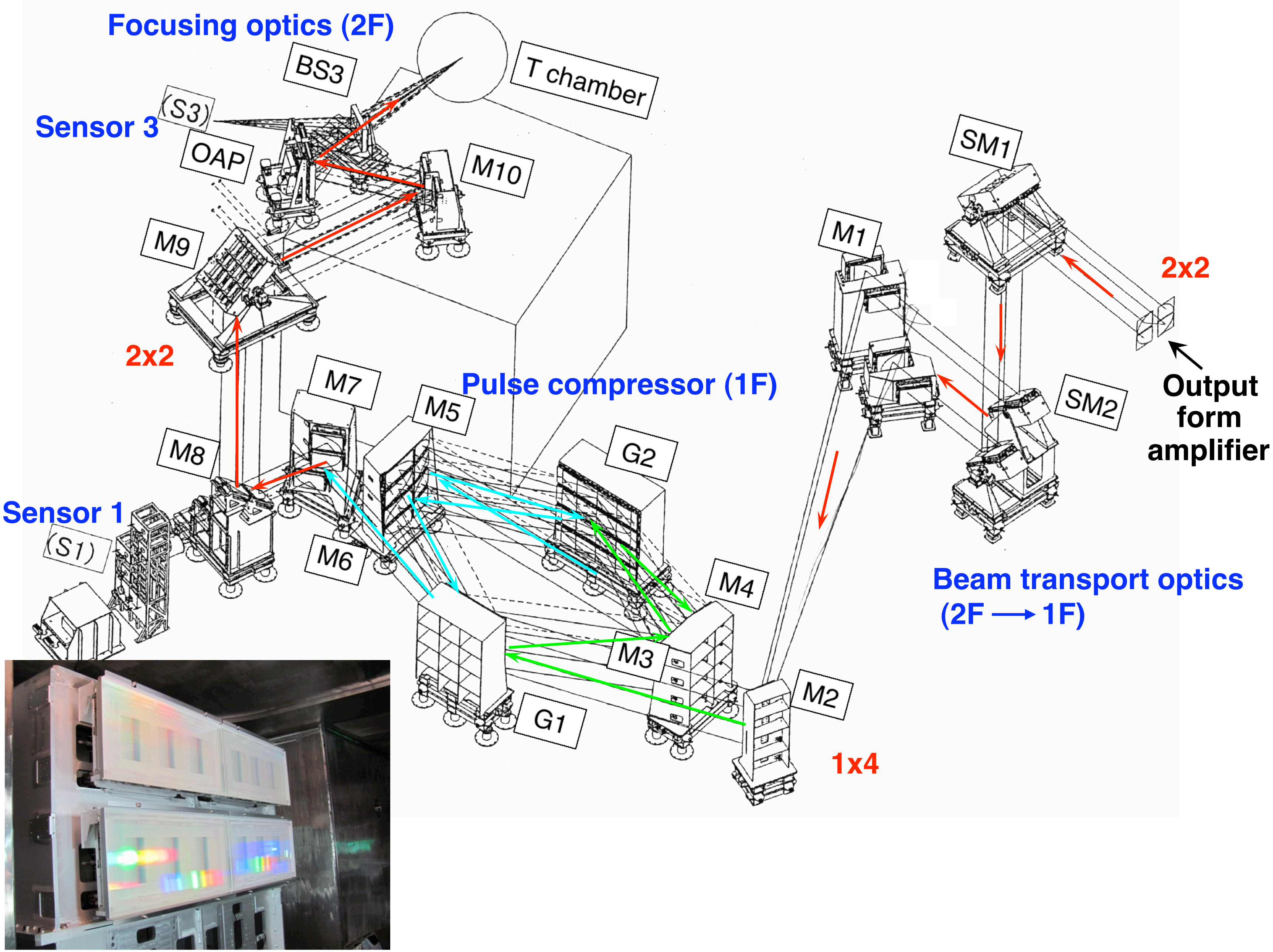

The heating laser beams are compressed down to 1.3 ps.
Two beams are synchronized with an accuracy of 0.2 ps.

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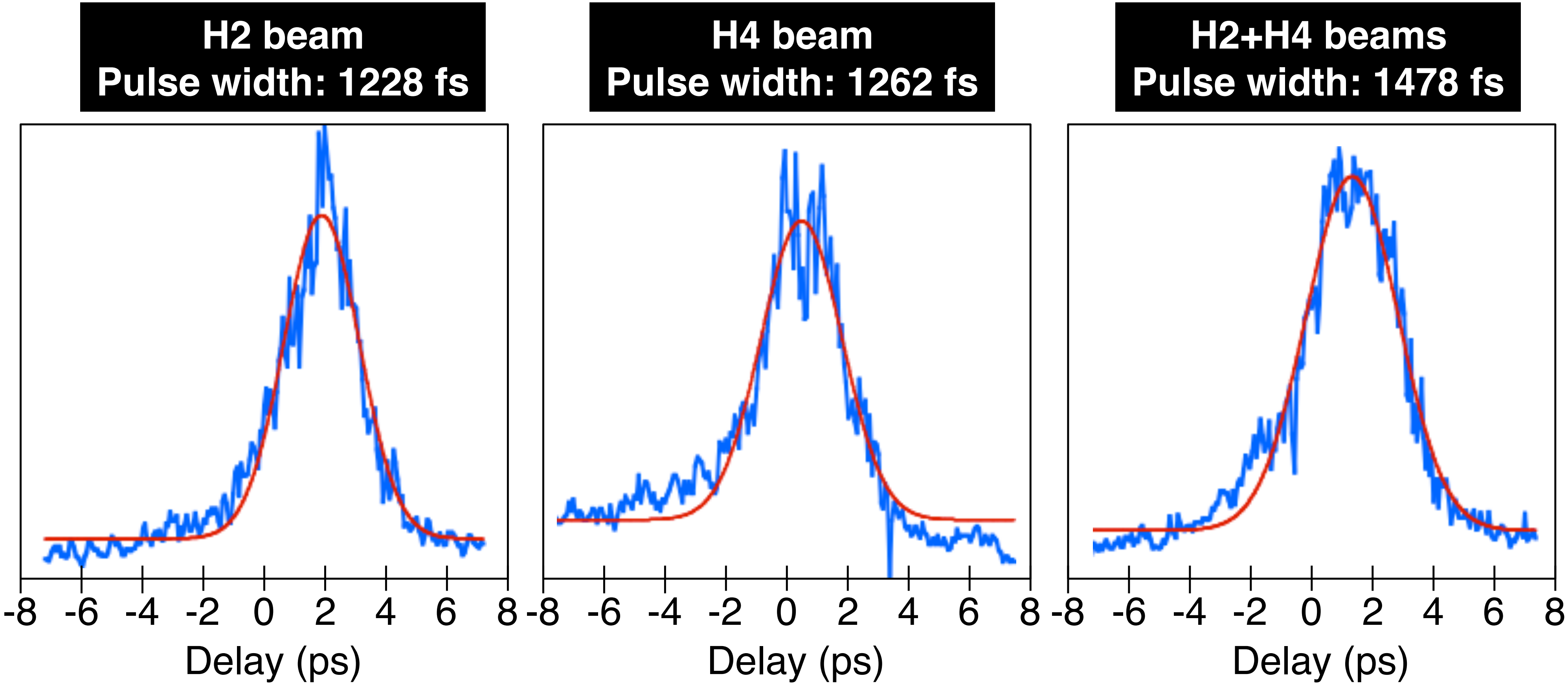

SHG auto-correlation signal
Fitted correlation function

Two heating beams were overlapped correctly and focused within 60 μm in diameter.

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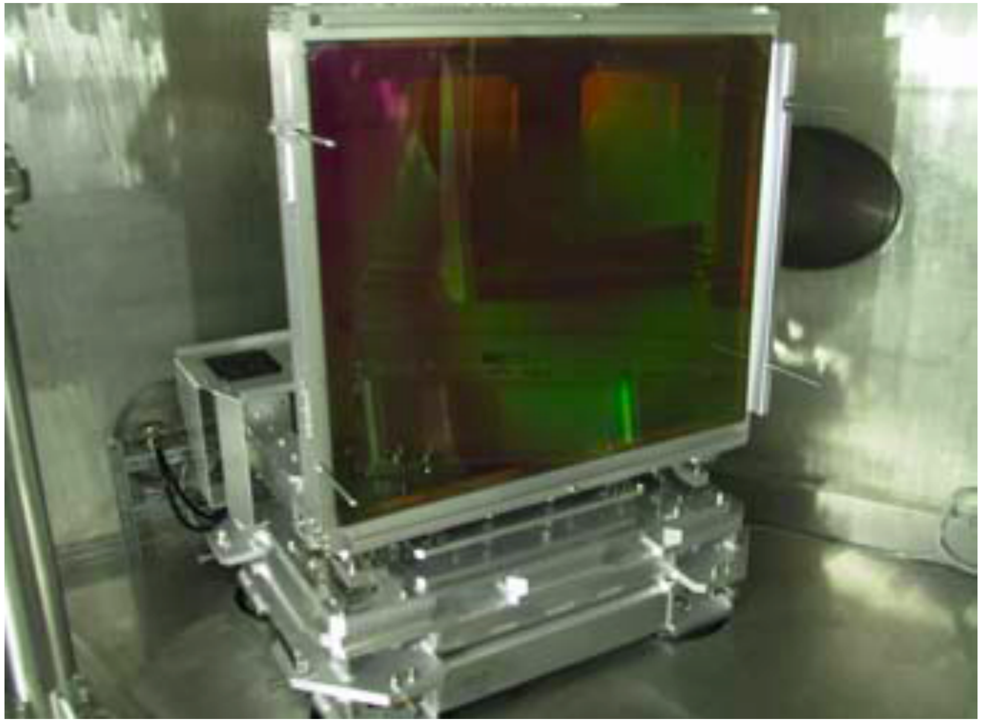
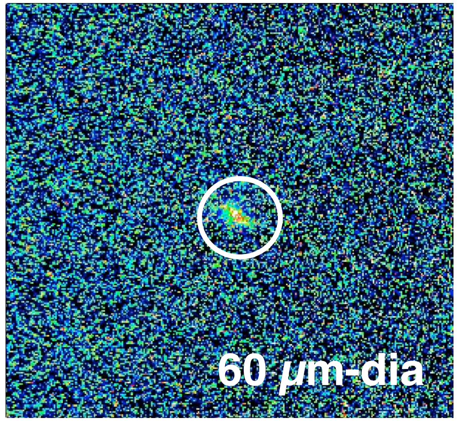
Off-axis parabola mirror



X-ray image

2010 experiment
2 beams



Square shaped beams were focused with an off-axis parabola mirror (f = 4000 mm).

Cone-attached surrogate fuel capsules were compressed by GEKKO-XII laser and heated by LFEX laser

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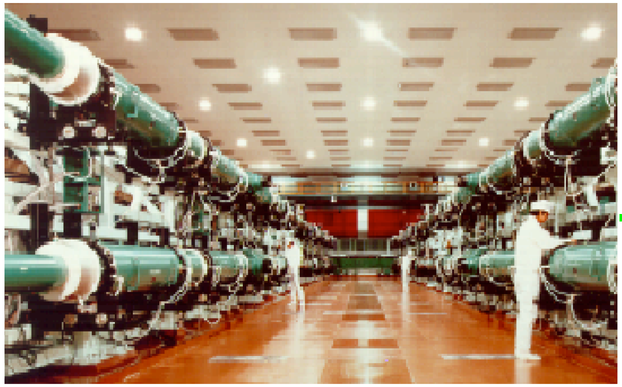
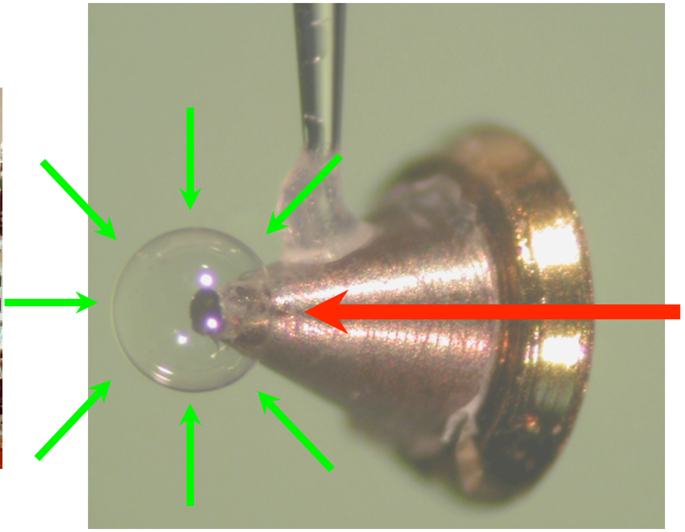
Compression Laser: GEKKO-XII



Beam#	9/12 beams
Energy	280 J/beams (2.5 kJ total)
Duration	1.5 ns (Flat top)
Wavelength	527 nm

Fusion Fuel



Shell

Diameter	500 μm
Thickness	7 μm
Material	CD plastic

Cone

Angle	45 deg.
Material	Gold

Heating Laser: LFEX

Beam#	2 beam
Energy	400 ~ 1400 J
Duration	1.5 ps
Wavelength	1053 nm

GEKKO-XII and LFEX lasers are synchronized precisely by using the same oscillator.

A pedestal of the heating laser generates a preformed plasma in the cone.

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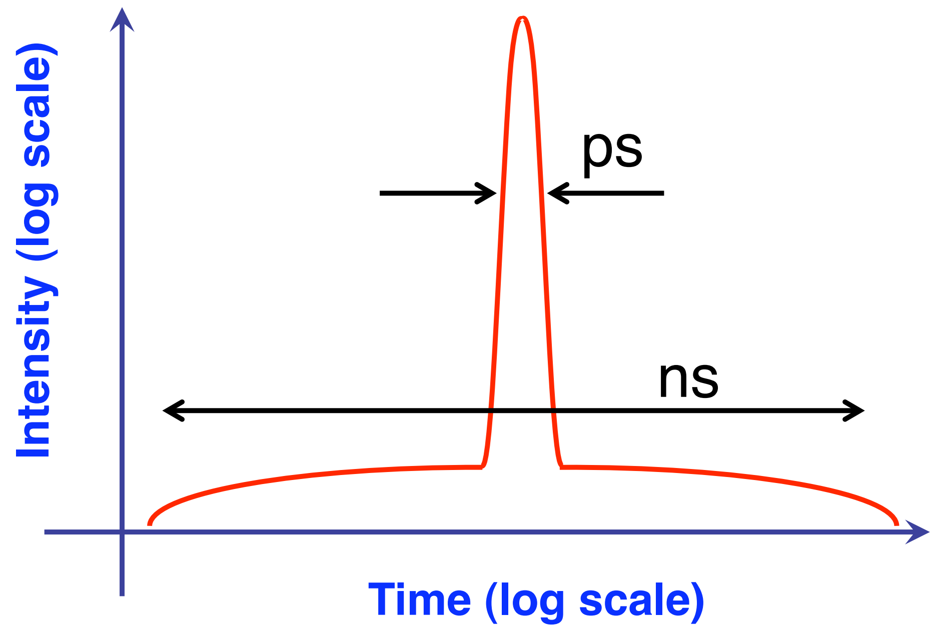
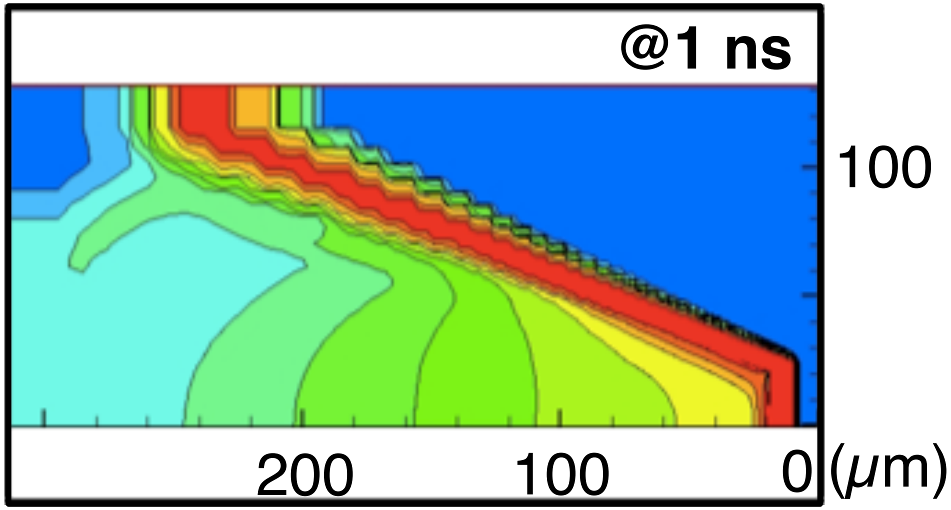
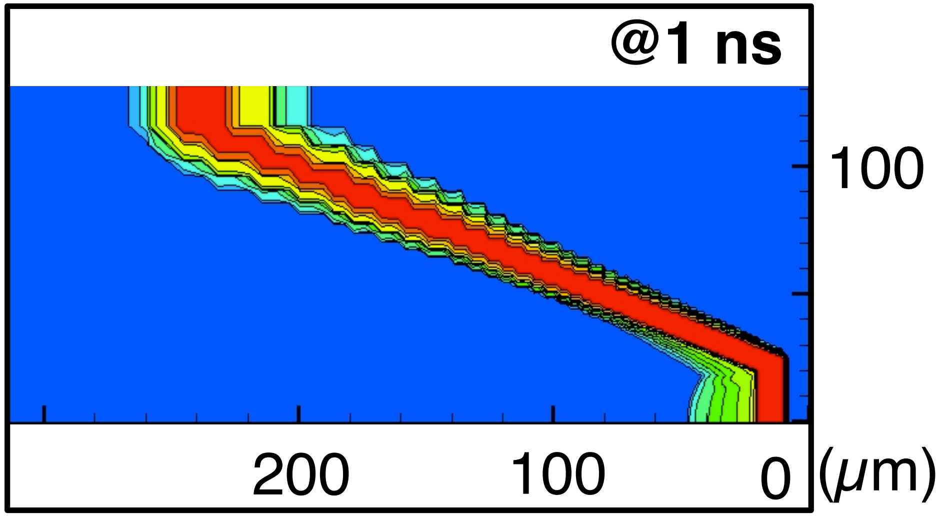
Pulse shape of LFEX



Pedestal intensity 1×10^{13} W/cm^2



Pedestal intensity 1×10^{10} W/cm^2



Pedestal intensity should be < 1×10^{10} W/cm^2 to make the scale-length of the pre-plasma to be < 1 μm.

Laser-plasma interactions in the long-scale preformed plasma generates too energetic electrons to heat the fuel core.

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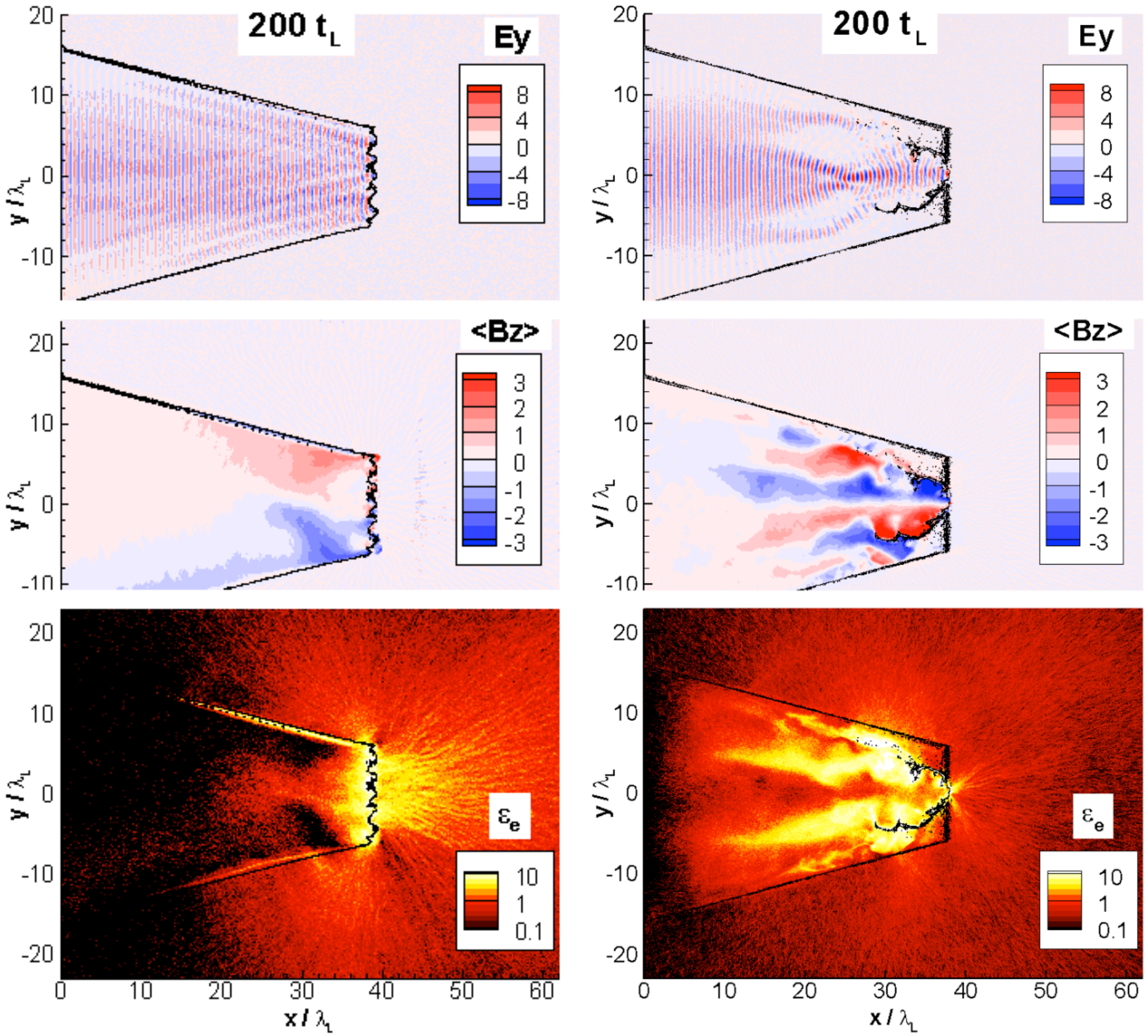
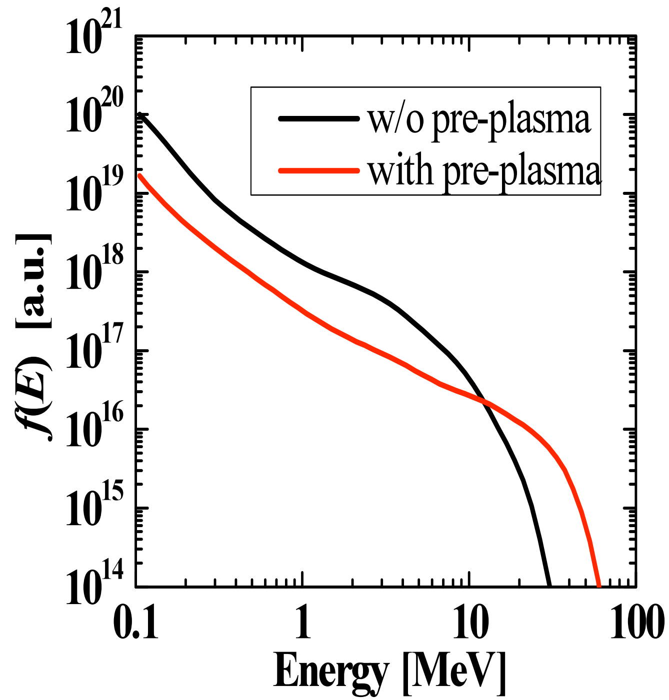
w/o pre-plasma

with pre-plasma



Energy spectrum



Preferable electrons decrease

Energetic electrons increase

Preformed plasma was observed by using side-on x-ray backlight technique in the previous experiment.

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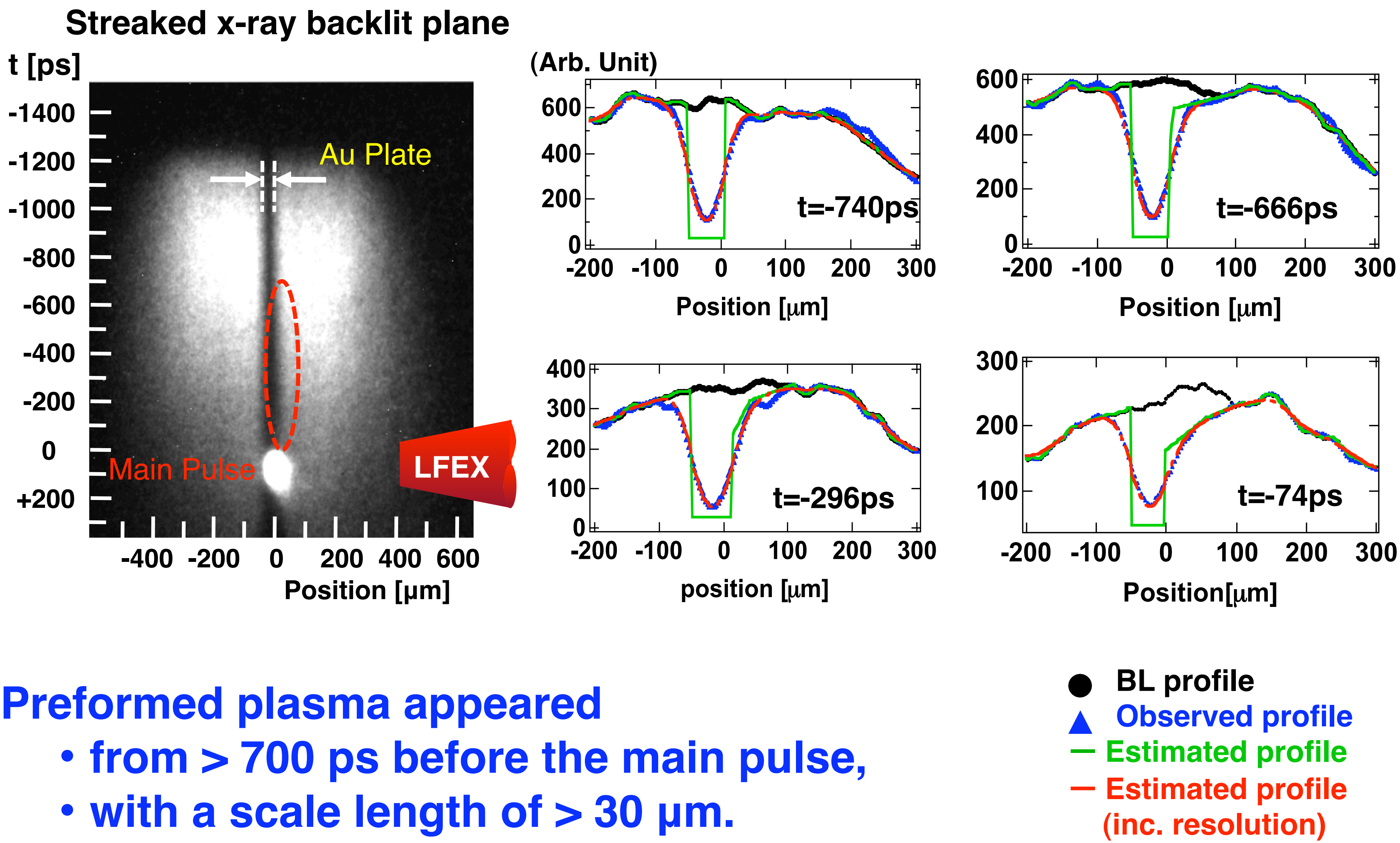

Preformed plasma appeared

- **from > 700 ps before the main pulse,**
- **with a scale length of > 30 μm.**

Additional pedestal reduction technique will be introduced.

Coupling efficiency reduction was caused by the preformed plasma generated by a pedestal.

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	w/o pre-plasma	with pre-plasma	ratio
E-beam energy*	**2.05J/um (48%[#])**	**1.57J/um (36%[#])**	**24%**
Fraction			
E < 2 MeV	0.56 (13%[#])	0.12 (3%[#])	**78% ↓**
E = 2~10MeV	1.16 (26%[#])	0.34 (8%[#])	**71% ↓**
E > 10 MeV	0.34 (8%[#])	1.10 (25%[#])	**230% ↑**

* Observed at end of tip ($x = 42\lambda_L$) in the region of ($-7.5\lambda_L < y < 7.5\lambda_L$)

[#] Energy coupling of laser to E-beam up to 1.6ps.

Pre-plasma	**$\eta_{L\rightarrow fe}$ [%]**	**$\eta_{fe\rightarrow core}$ [%]**	**$\eta_{L\rightarrow core}$ [%]**	**$\langle Ti \rangle_{DD}$[keV]**	**Yn_{DD}**
w/o	**48**	**16**	**7.5**	**0.75**	**1.2e+6**
with	**36 (24%↓)**	**4.7(71%↓)**	**1.7(78%↓)**	**0.35**	**8.7e+4**

The Values in () are the ratio to the case w/o pre-plasma (first line).

AOPF quencher* and saturable absorber are introduced to reduce the pedestal intensity.

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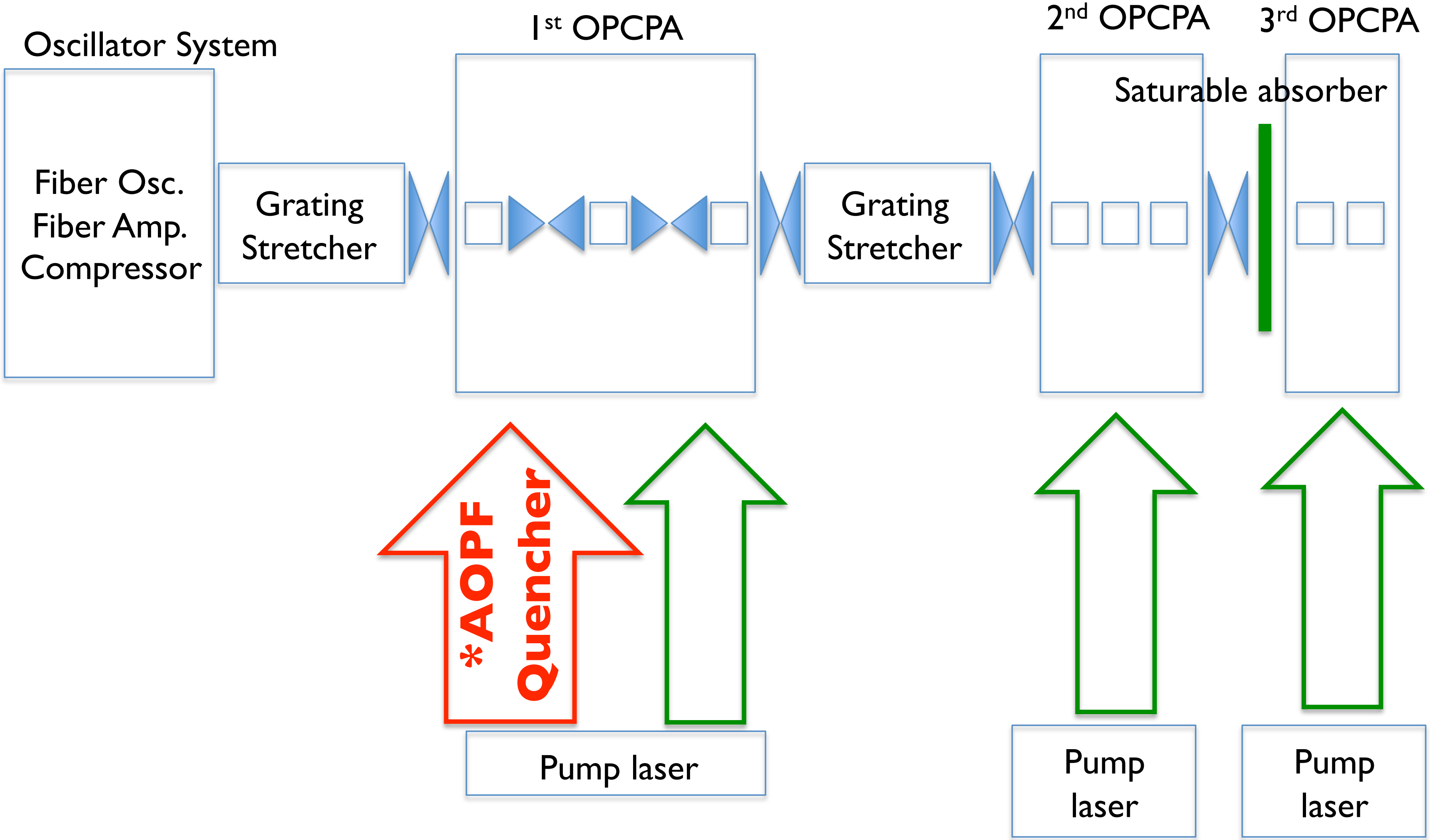

*K. Kondo *et al.*, J. Opt. Soc. Am. B, Vol. 23 (2006).

Energy spectrum of the vacuum electrons is sufficiently cooled down by the pedestal reduction.

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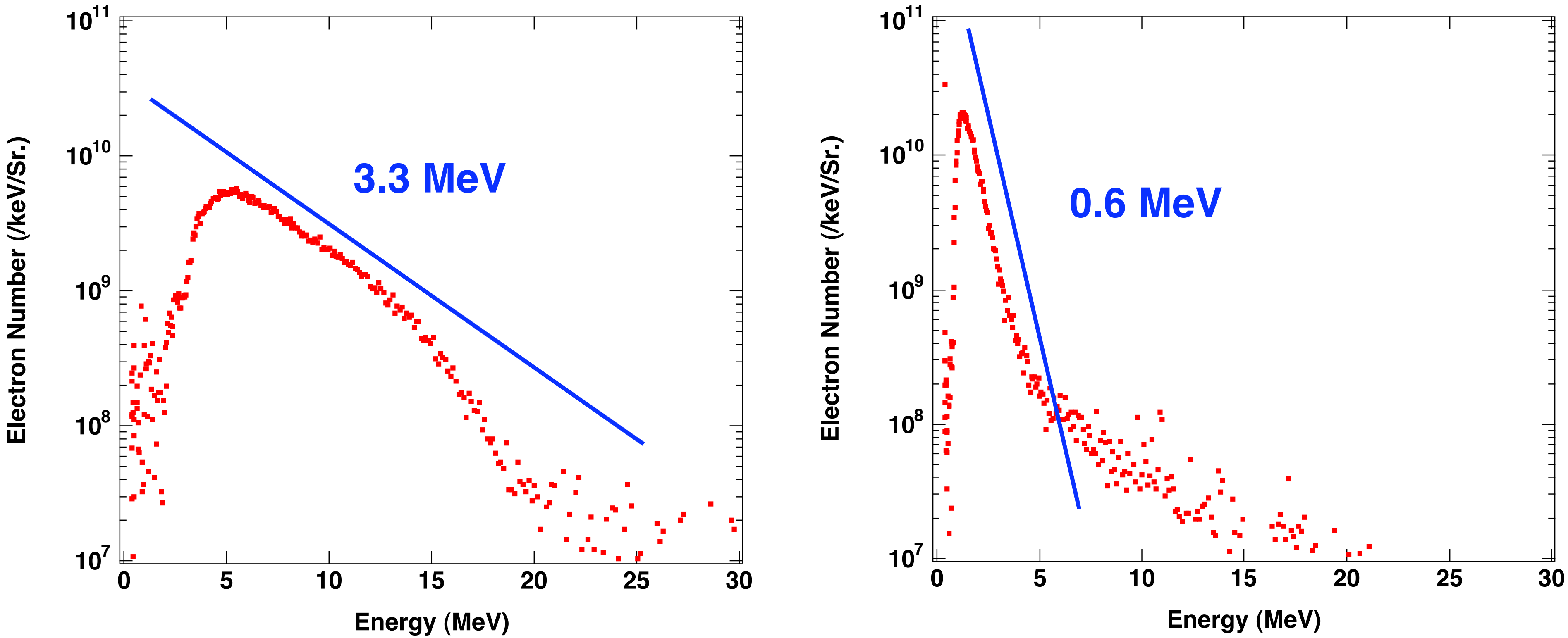
2009 experiment
212 J/1.2 ps/50 μm-dia (full width)
~ 6 x 10^{18} W/cm^2

2010 experiment
210 J/1.8 ps/60 μm-dia (full width)
~ 3 x 10^{18} W/cm^2



0.6 MeV of the slope temperature is close to the value calculated with no pre-plasma conditions.

Development of Plasma Diagnostics

Diagnostics should be operated in the presence of intense (γ, γ') and (γ, n) produced by laser-matter interactions.

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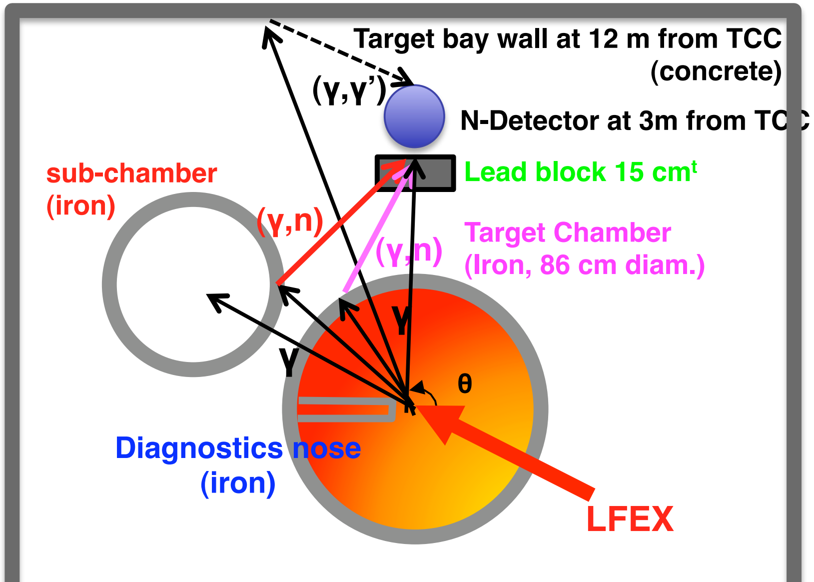
(γ, n) : photodisintegration, (γ, γ') :scatter

Geometry for calculation (Top view)



Assumed input gamma source

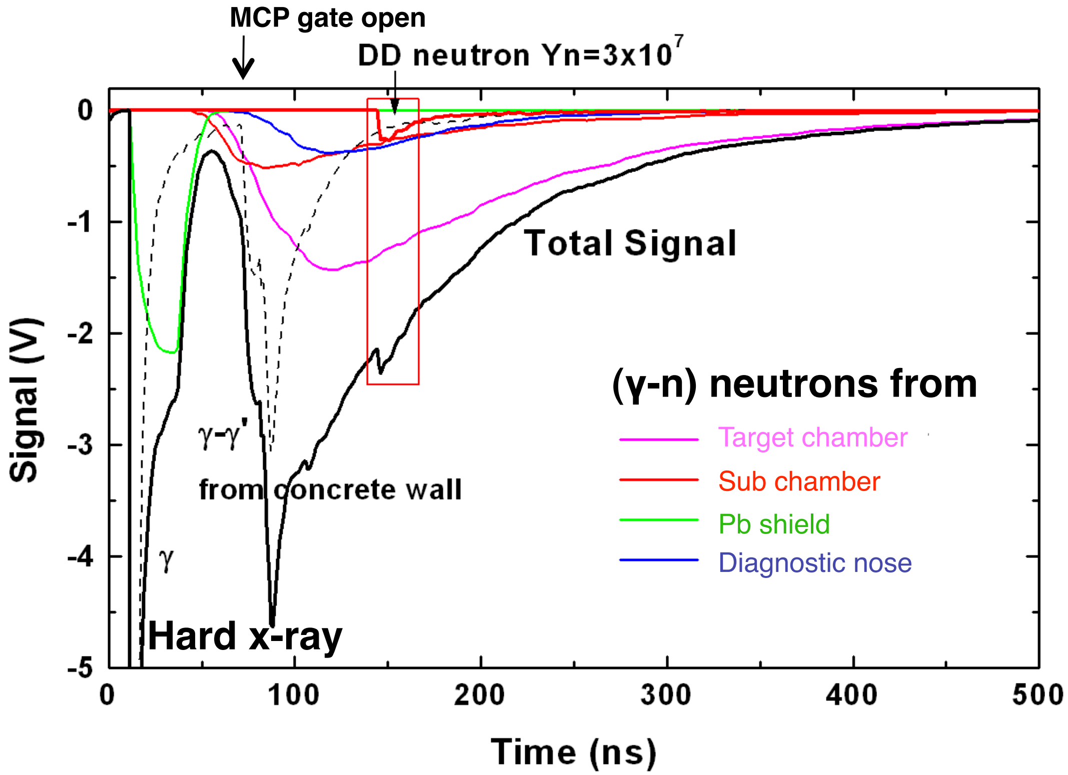
T_γ = 5 MeV

Y_γ = 8 x 10^{11}

$\theta \sim \sin(0.5\theta)^{1.7}$

Synthesized n-TOF signal calculated with the MCNP5 code

*MCNP5 (A general Monte-Carlo N-Particle transport code)



Target chamber is the dominant source of the background neutron.

Neutron collimator in the front of the detector excludes (γ-n) neutrons generated in the target chamber wall.

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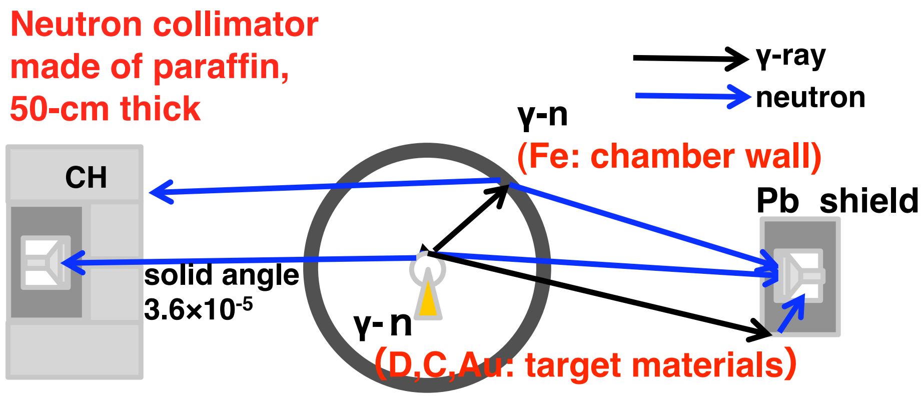
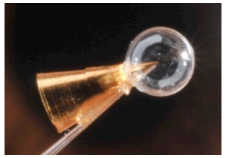
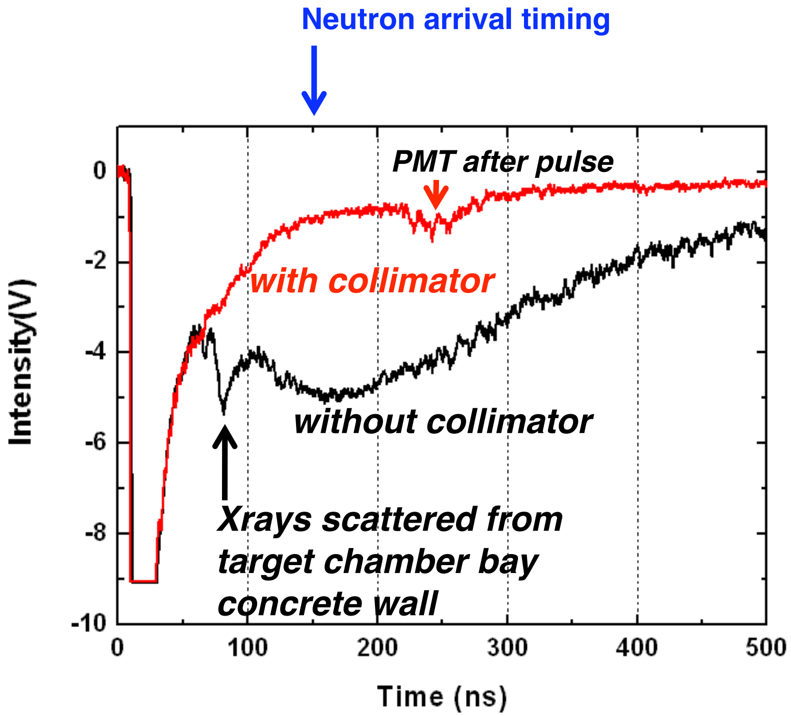
Geometry for experiment (Top view)



Shot # L1635 (25 Jan, 2011)
Fast ignition target
LFEX 427.7 J ,
without Implosion



TOF signal



Collimators will be fully installed in 2011 exp't.
Not installed in the 2010 exp't (this talk).

Fast-response, low-aftergrow BBQ liquid scintillator# has been developed for neutron detector in the presence of strong x-ray radiation.

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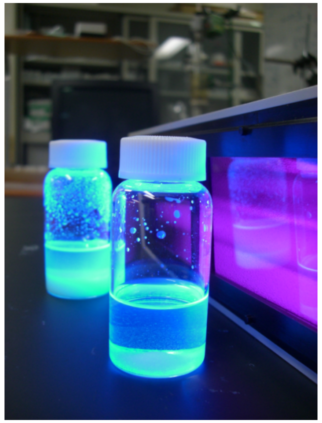
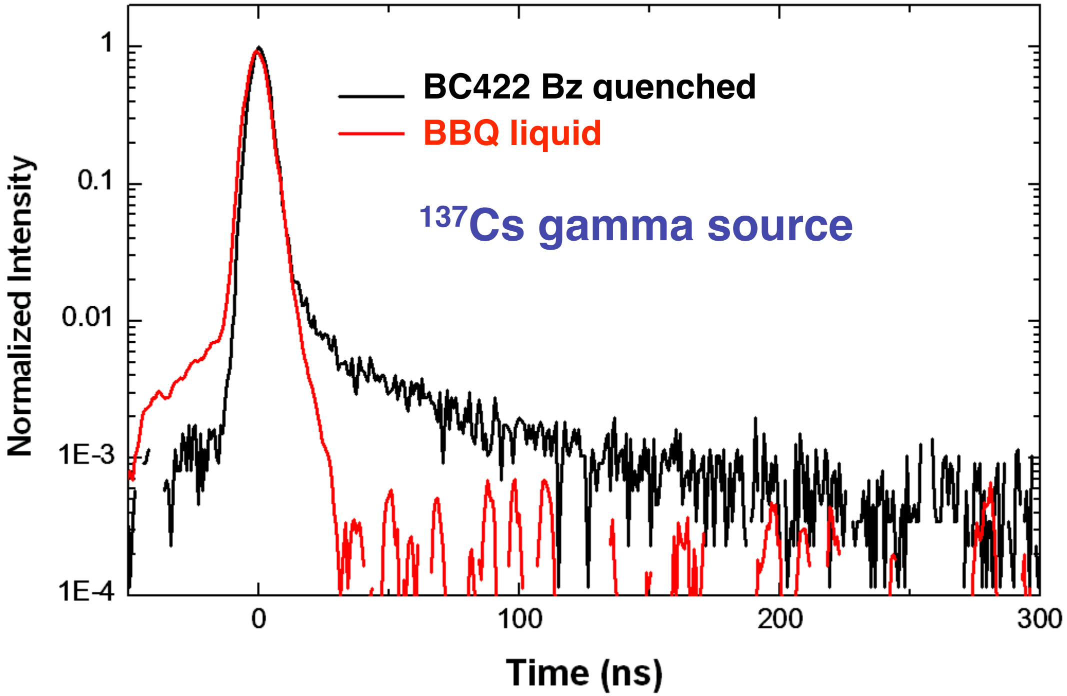
#T. Nagai et al., JJAP (accepted)

BBQ
4,4'''-Bis-(2-butyloctyloxy)-p-quatarphenyl dye



Host: Xylene
Quencher: Oxygen

Time history of scintillation



The BBQ scintillator dramatically improve neutron diagnostics in the fast-ignition experiments where neutron have to be detected in the presence of an intense x-ray burst.

Hard x-rays induce discharges at the photocathode of an x-ray streak camera.

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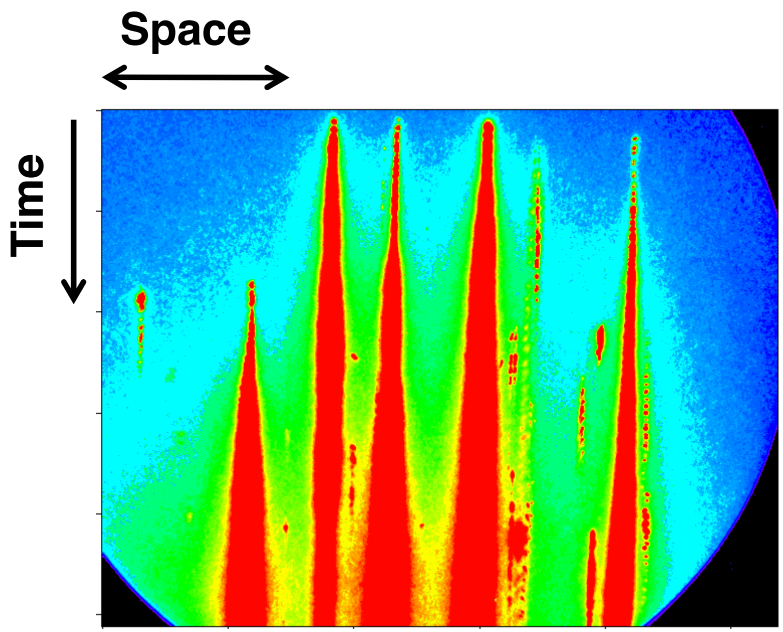
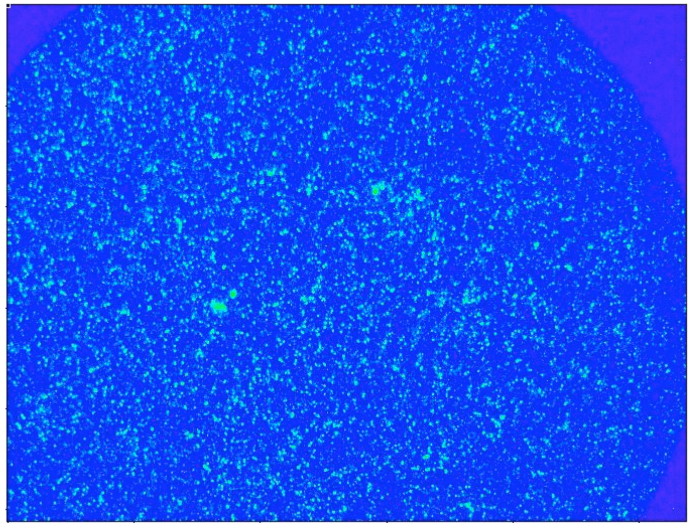
Streak image w/o shield



Au plate/212 J/1 ps

Streak image w/o 2 mm Pb shield



Au plate/ 249 J/ 1 ps

Discharges are suppress by introducing Tungsten slit disk.
Injection timing can be evaluated from the non-imaged hard x-ray signal.

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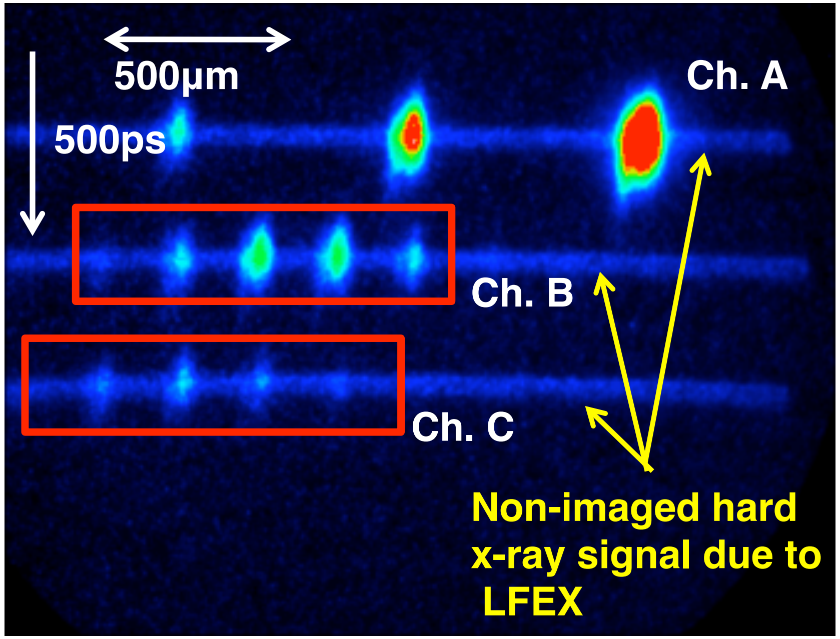
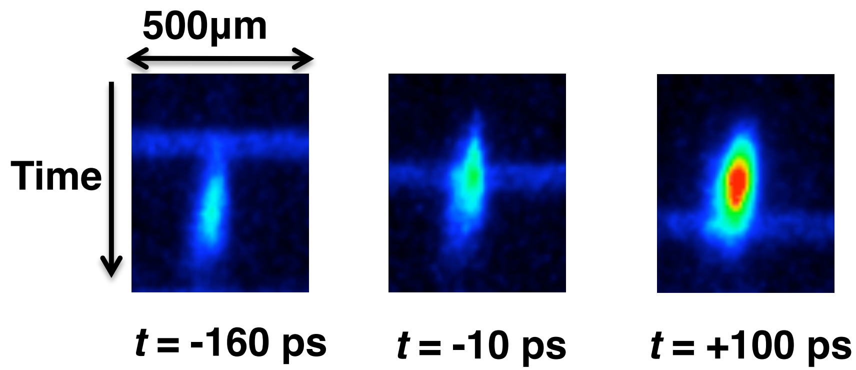
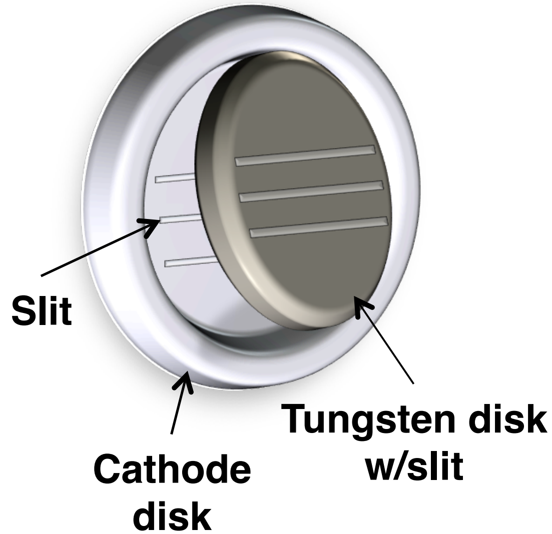
Streak image w/o shield



Balk shielding resulted in :
- Stopping cathode discharge
- Reducing background noise



Relation between hard x-ray signal and the imploded core plasma



Integrated Experiment

Cone-attached surrogate fuel capsules were compressed by GEKKO-XII laser and heated by LFEX laser

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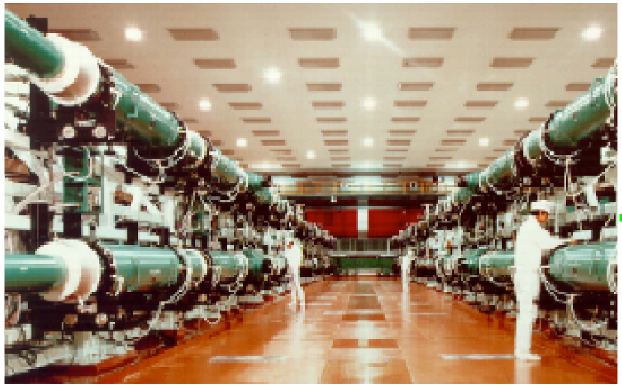
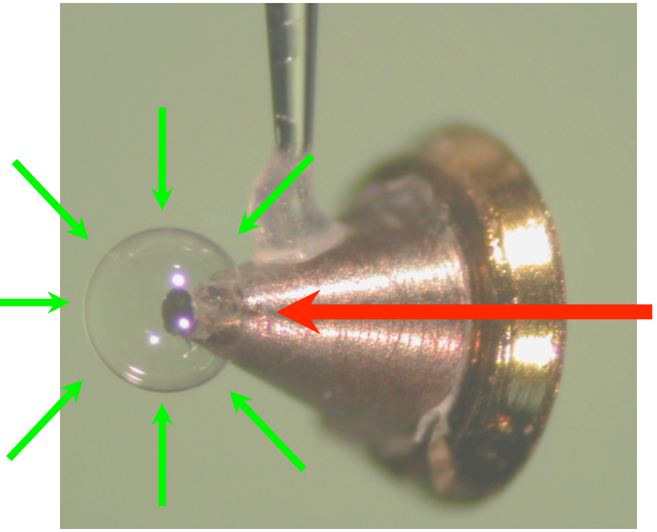
Compression Laser: GEKKO-XII



Beam# 9/12 beams
Energy 280 J/beams (2.5 kJ total)
Duration 1.5 ns (Flat top)
Wavelength 527 nm

Fusion Fuel



<u>Shell</u>
Diameter 500 μm
Thickness 7 μm
Material CD plastic
<u>Cone</u>
Angle 45 deg.
Material Gold

Heating Laser: LFEX

Beam# 2 beam
Energy 400 ~ 1400 J
Duration 1.5 ps
Wavelength 1053 nm

GEKKO-XII and LFEX lasers are synchronized precisely by using the same oscillator.

Enhancement of neutron yield was observed when the heating pulse was injected within 25 ps around the core x-ray emission peak.

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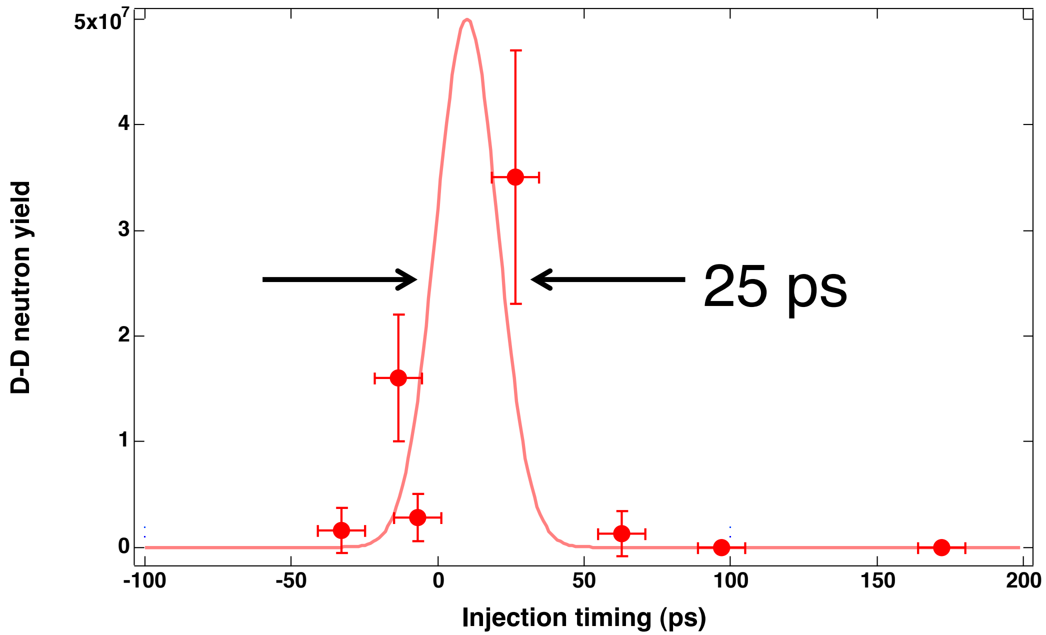
Shot#	DD-n ± γ-n err	**DD-Yn**	LFEX injection timing (ps)	LFEX energy @Target (J)
34177	$(1.25\pm0.5)\times10^6$ $\pm2\times10^6$	$\mathbf{(1.25\pm2.1)\times10^6}$	+63 +/- 8	279
34183	$(3.5\pm1.2)\times10^7$ $\pm2\times10^6$	$\mathbf{(3.5\pm1.2)\times10^7}$	+27 +/- 8	301
34186	$(2.8\pm1.0)\times10^6$ $\pm2\times10^6$	$\mathbf{(2.8\pm2.2)\times10^6}$	- 7 +/- 8	486
34187	$(1.6\pm0.6)\times10^7$ $\pm2\times10^6$	$\mathbf{(1.6\pm0.6)\times10^7}$	-14 +/- 8	419
34189	$(1.6\pm0.5)\times10^6$ $\pm2\times10^6$	$\mathbf{(1.6\pm2.1)\times10^6}$	-33 +/- 8	223
34193	$(1.44\pm0.5)\times10^6$	$\mathbf{(1.44\pm0.5)\times10^6}$	**w/o heating laser**	

Neutron yield vs injection timing



DD-neutrons was baried in γ-n neutrons for > 500 J of heating laser.

2D burn code calculates dependence of neutron yield with heating laser energy and coupling efficiency for simplified conditions.

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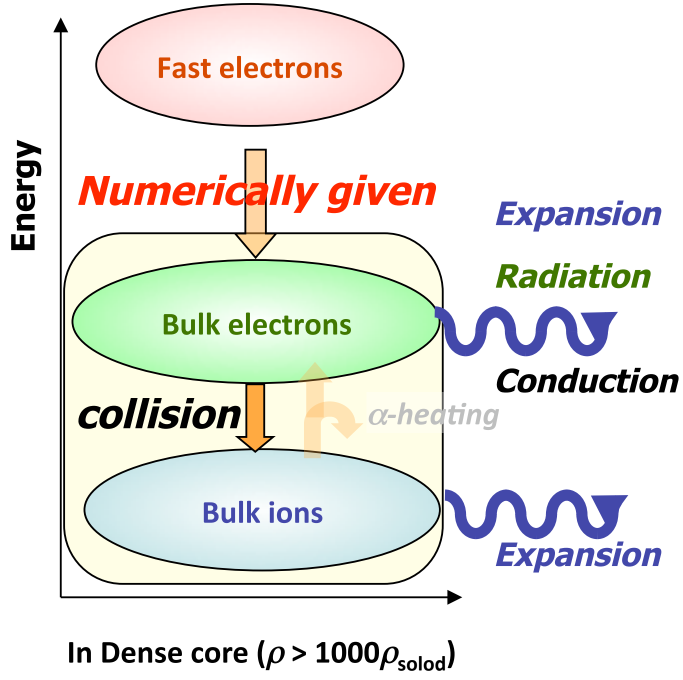
2D Burn simulation code "FIBMET"

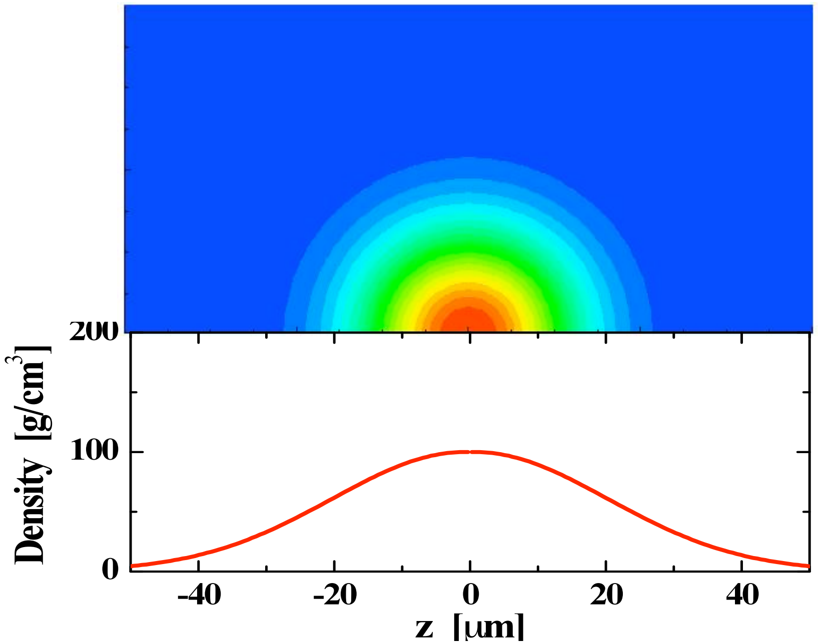
base : 1 fluid 2 temperature Euler-type Hydro code

+ radiation transport (multi-group flux-limited diffusion),
+ α-particle transport (multi-group flux-limited diffusion)
+ ~~fast electron transport(Fokker-Planck transport)~~
+ fusion reactions（DT,DD,D^3He)



Bulk Plasma: CD plasma

Ti & Te: uniform、ρ:Gaussian profile



Core heating:

Uniform heating for bulk electron

- Duration τ_h = 1～20 [ps] (Gaussian or square pulse)
- Heating energy E_h = 0 ～ 5 [kJ]
- Region ρ > 1 [g/cc]
- Heating rate Uniform / electron

The comparison between the experimental results and the calculations indicates that **the max coupling efficiency is 20%** in the 2010 exp't.

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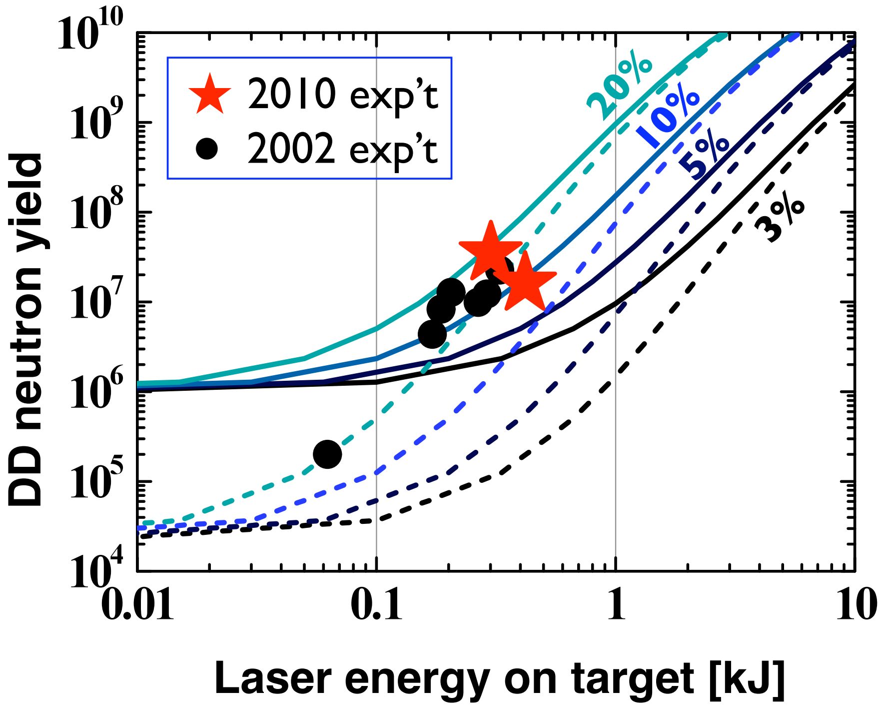
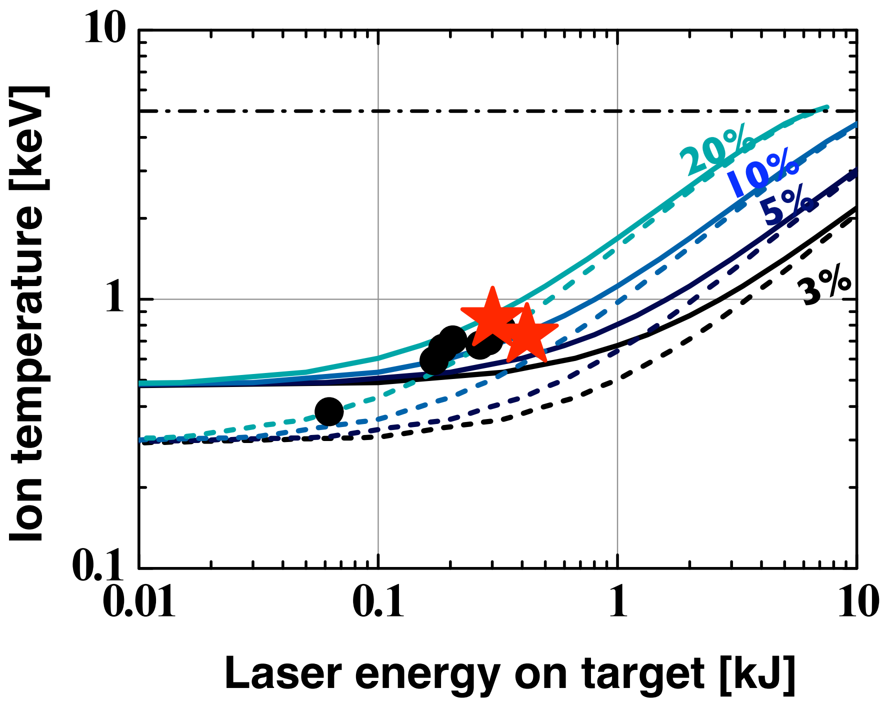
Neutron yield vs heating laser energy



Ion temperature vs heating laser energy



DD-neutrons was baried in (γ, n) neutrons for > 500 J of heating laser.

Neutron yield obtained in the 2010 exp't is the largest value in the fast ignition integrated experiment in GEKKO facility.

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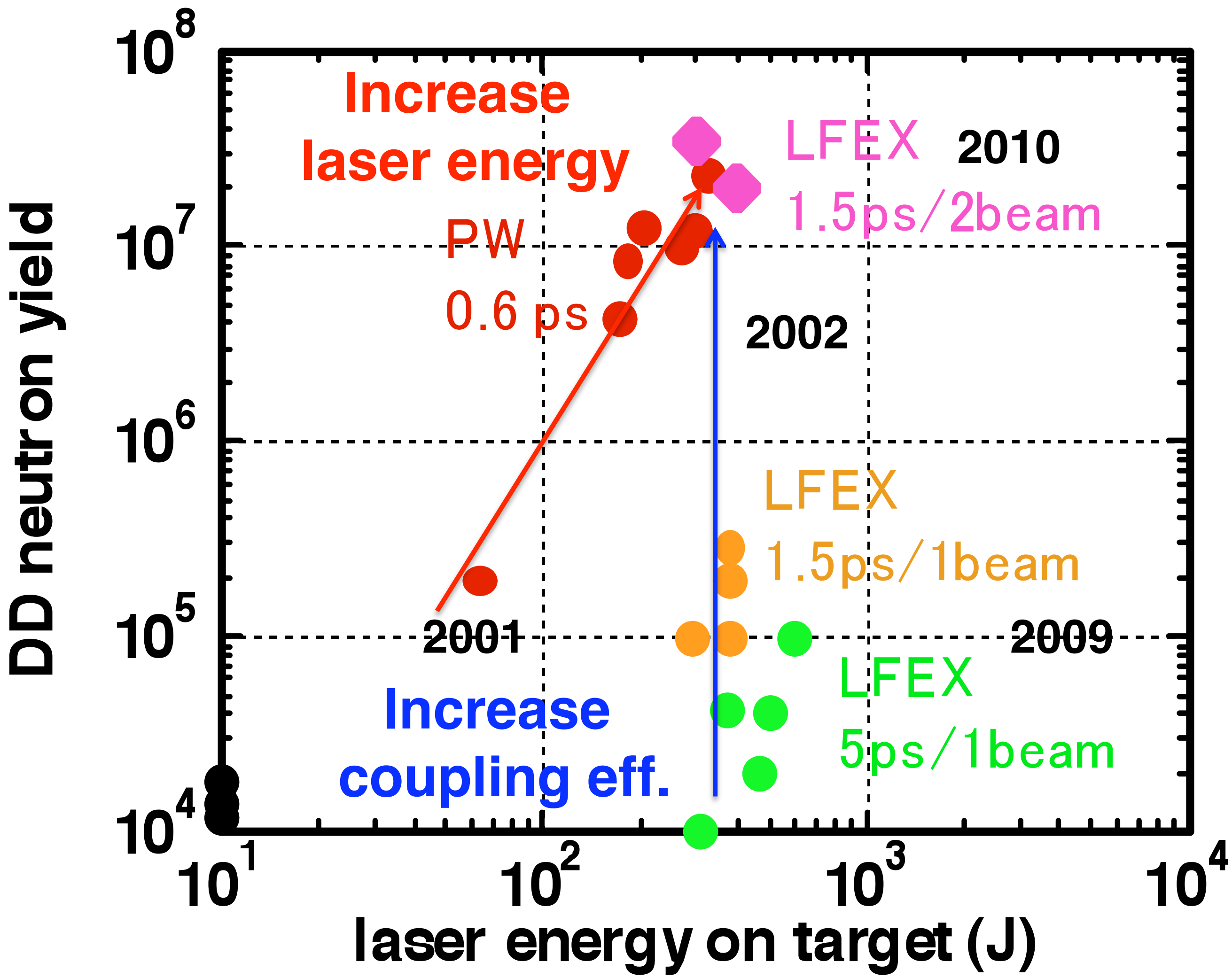

2001 : PW-M
2002 : PW
2009 - : LFEX

Increment of x-ray signal was observed in some shots. Reproducibility are under investigation.

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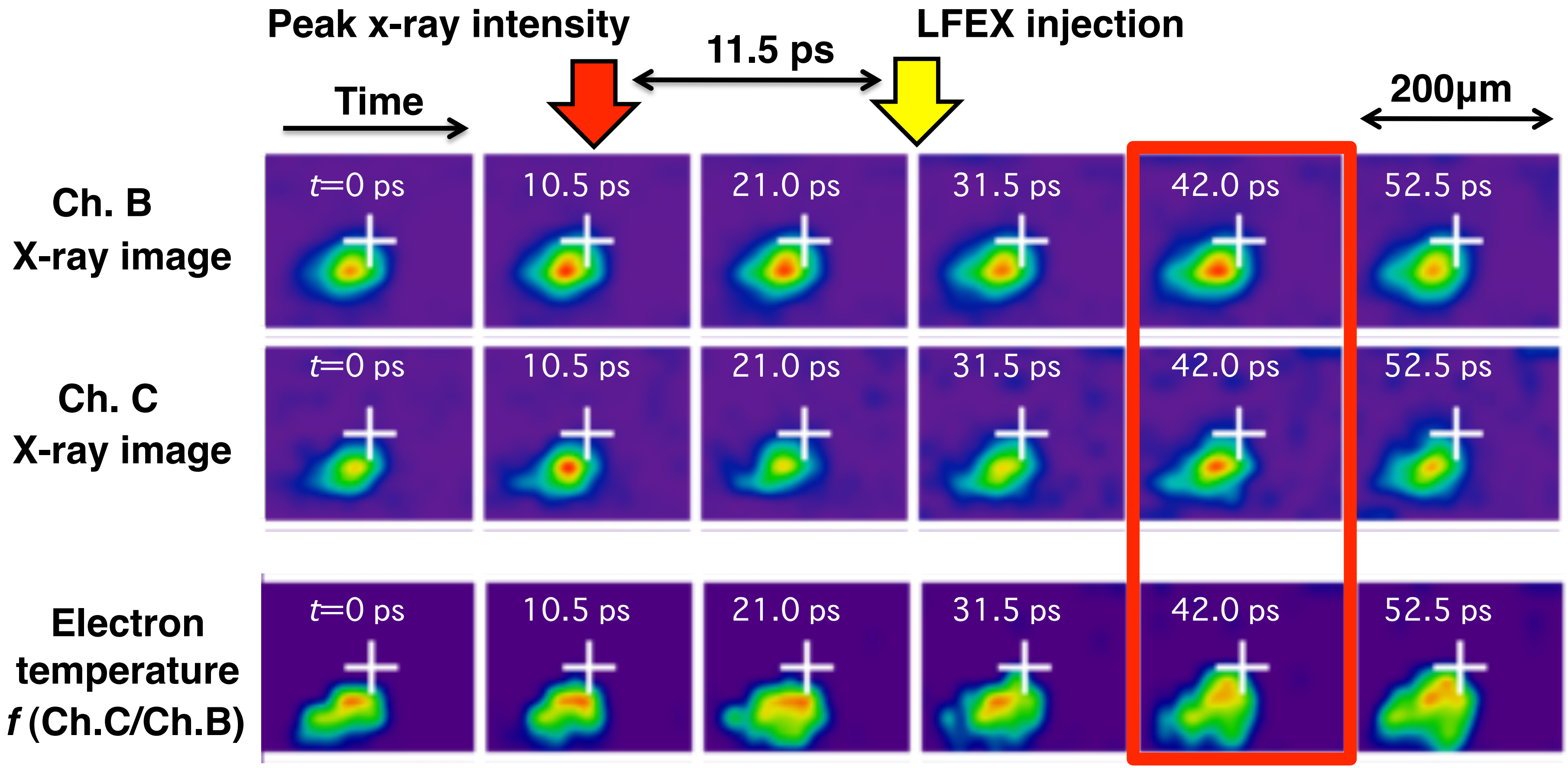

"Go" for experiment in 2011:

- To complete LFEX laser system (10 kJ/4 beams/2 – 10 ps) with even higher pulse contrast.
- To do further improvements (shielding and collimation) of diagnostics for full LFEX laser energy.
- To verify heating mechanism and FI scenario in basic experiments.
- To improve heating efficiency and to demonstrate Ny and temperature scaling on laser energy.

Project members:

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H. Habara, T. Iwawaki, T. Morioka, K. Morita, K. A. Tanaka *(Faculty of Engineering, Osaka University)*

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K. Kondo *(Japan Atomic Energy Agency-KPSI)*

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T. Taguchi *(Setsunan University)*

Y. Nakao *(Kyushu University)*

M. Key *(Lawrence Livermore National Laboratory)*

P. Norreys *(Rutherford Appleton Lab)*

J. Pasley *(University of York)*

F. Beg, H. Sawada, T. Yabuuchi *(University of California, San Diego)*

Summary

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- 1.4 kJ/1.5 ps/2 beams are in operation.
- will be upgraded 10 kJ/4 beams.

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Diagnostics:

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