Implosion and Heating Experiments of Fast Ignition Targets by GEKKO-XII and LFEX Lasers

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Abstract

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Implosion and heating experiments of Fast Ignition (FI) targets for FIREX-1 project have been performed with Gekko-XII laser for implosion and LFEX laser for heating at the Institute of Laser Engineering, Osaka University. After the first integrated experiments of Fast Ignition with LFEX laser in 2009, in which we concluded that the existence of the prepulse in the heating laser may have affected the heating efficiency by modifying the hot electron spectrum to unexpected higher energy range, we tried to significantly reduce the prepulse level in the LFEX laser system. Also we have much improved the plasma diagnostics to be able to observe the plasma even in the hard x-ray harsh environment. A variety of improved plasma diagnostics was used to observe implosion and heating dynamics, fusion yield, x-rays and gamma rays, electrons, and ions. Particularly, Neutron yield and its spectrum were measured with many types of the neutron detectors including multi-channel single-hit detectors, fast-decay liquid scintillators, bubble detectors, and activation detectors. Ultrafast x-ray imaging with x-ray streak cameras and x-ray framing cameras were used to observe imploded core plasma and its heating dynamics. Relative time of heating beam injection to the core plasma life was experimentally determined accurately by using non-imaged signals of hard x-rays generated from hot electrons due to the heating beam irradiation. A plastic (CD) shell target, 7-microns thick and 500 microns in diameter, with a hollow gold cone for guiding the heating short-pulse laser at the time of the maximum compression was used in this experiment. The shell target was imploded with 9 or 12 beams of Gekko-XII laser (527 nm) with energy of 300 J/beam in a 1.5 ns pulse. Two beams among four of LFEX laser (1053 nm) were injected to the interior tip (bottom) of the cone with energy up to 0.7 kJ/beam in a 1.5 ps pulse at the time around the maximum implosion. We have observed neutron enhancement up to 3.5×10^7 with total heating energy of 301 J on target, which is higher than the yield obtained in 2009 experiment and the previous data in 2002. [R. Kodama, et al. Nature 418, 933 (2002)]. We found the estimated heating efficiency is at a level of 10-20 %. It may still be due to the existence of the preformed plasma, which was observed again in a separate planar target experiment. Further investigations of mechanism how the preformed plasma is generated and methods how we can control it and increase the efficiency are needed, and are underway. 5-keV heating is expected at the full output of LFEX laser by controlling the heating efficiency.

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    Laser output (2 kJ / 2 beams / 1 ps) delivered to experiment
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    Pulse compression and Focusing

3. **Integrated experiment of Fast Ignition**

    Implosion and heating of shell target with Au cone
    Preformed plasma effect
    Plasma diagnostics in hard x-ray harsh environment
    Enhanced neutron yield and heating efficiency

4. **Conclusions and near future plan**

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1. FIREX, Fast Ignition Realization Exp't

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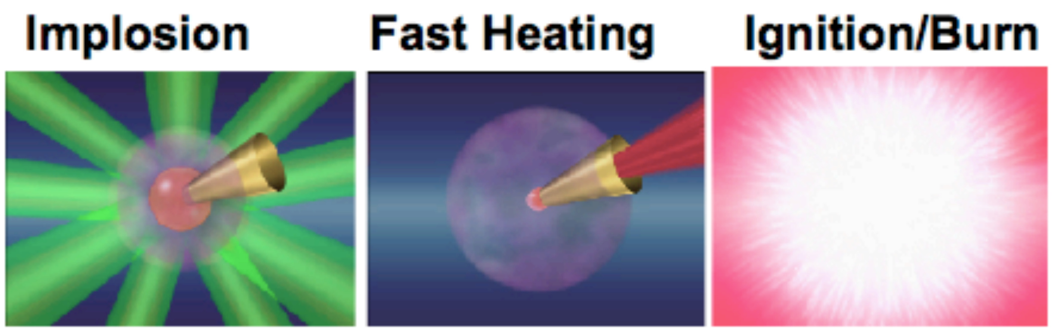

- **preliminary: Demo of 600 times liquid density**
  Demo of 1 keV temp. by 1kJ/1ps.

- **FIREX-I：Demo of 5-10 keV temperature by 10kJ/10ps.**

- **FIREX-II: Demo of ignition and burn by FI**

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P. Norreys *(Rutherford Appleton Lab)*
J. Pasley *(University of York)*

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2. LFEX laser – construction and tuning

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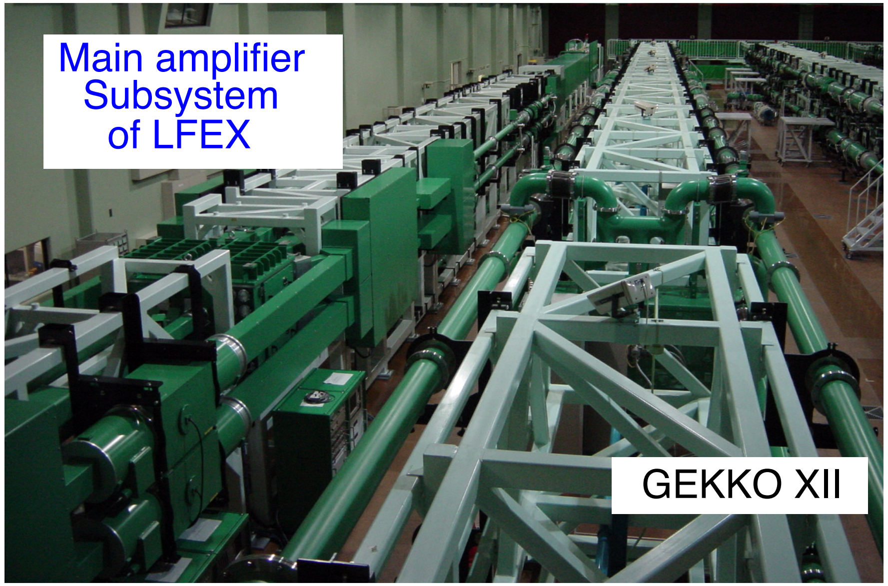
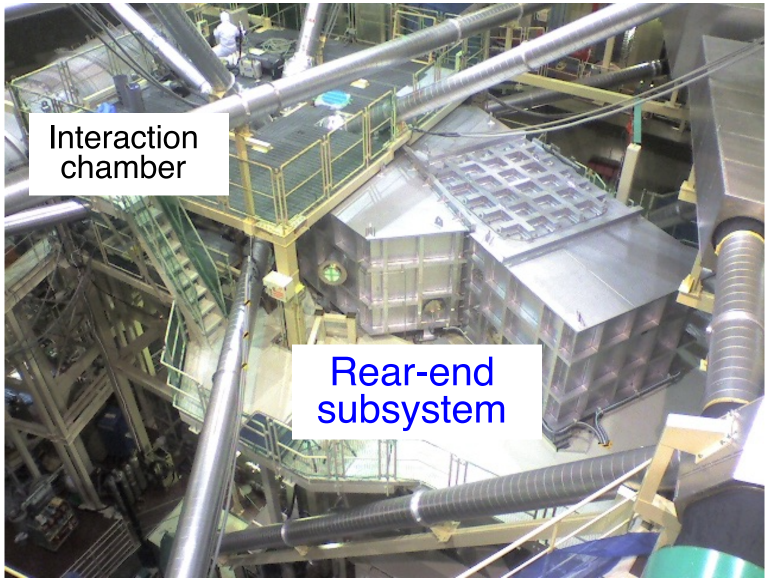
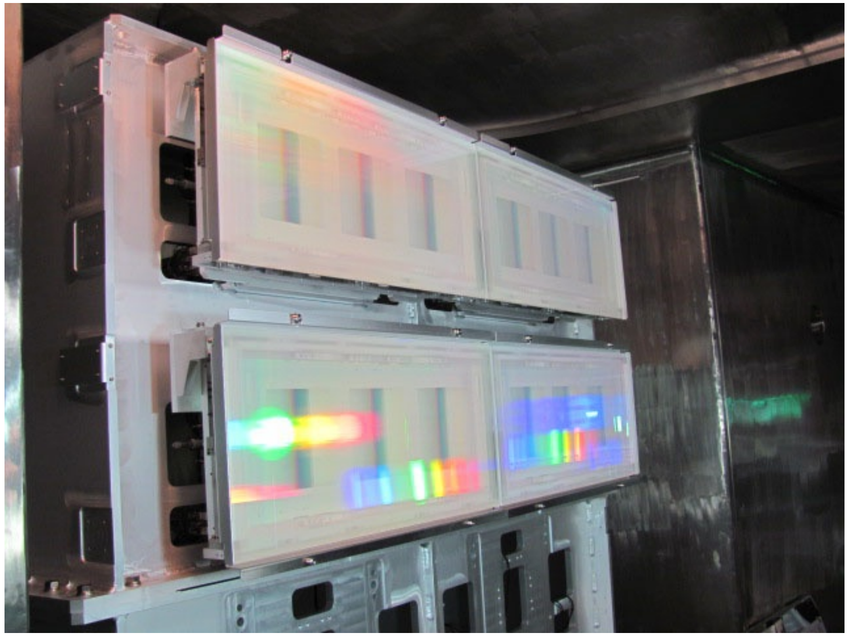




Nov, 2008	**Precision alignment of pulse compressor**
Dec, 2008	***Target irradiation with high-power beam started***
Feb, 2009	***Irradiation of Fast Ignition (FI) target started***
June, 2009	***FI integrated experiment started (5 ps)***
Sept, 2009	***FI integrated experiment (1 ps) / 1 beam***
Aug, 2010	***FI integrated experiment (1 ps) / 2 beams***

For FI integrated experiment in 2010



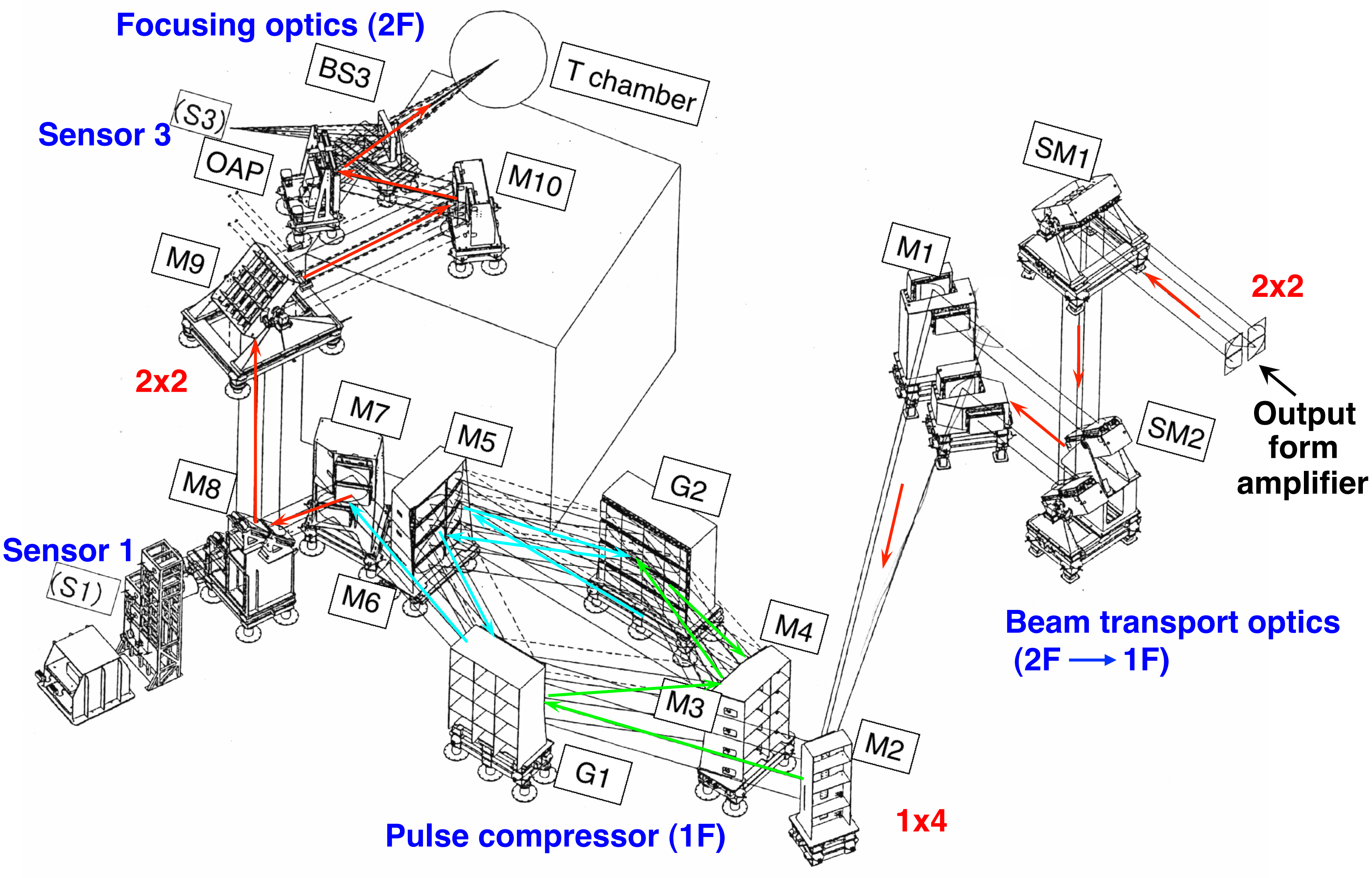
The 2nd beam has been activated.

- 1 kJ in 1 beam (2009)
  → *2 kJ in 2 beams (2010)*
- Beam profile improved

Contrast in LFEX pulse was substantially improved by introducing

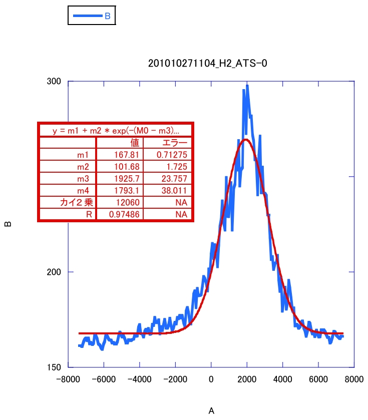
- saturable absorber, and
- AOPF (amplified optical parametric fluorescence) quencher
  for a few ns range, and
- reduced spectral ripples
  for ps range.

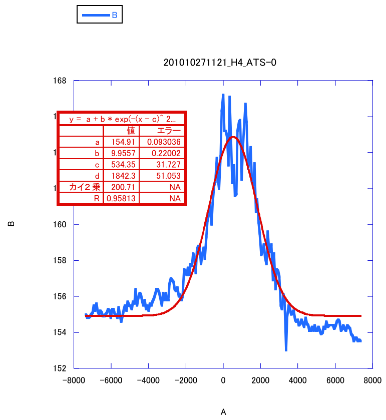
Pulse compression and focusing system of LFEX

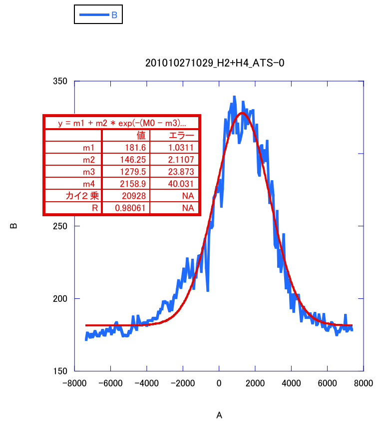


Pulse width of two beams of LFEX

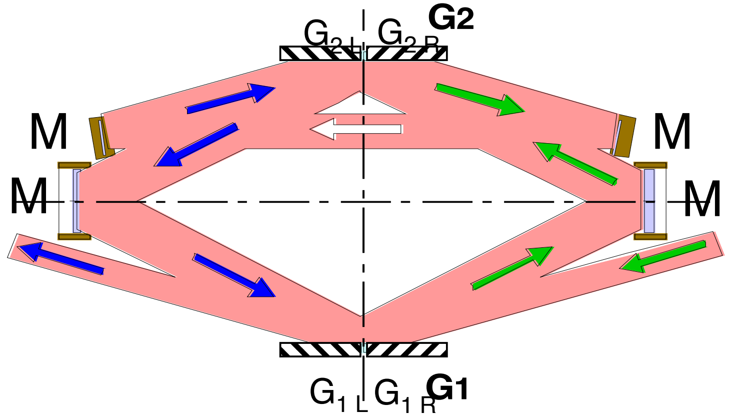
SHG auto-correlation







H2	H4	H2+H4
Pulsewidth = 1228fs	**Pulsewidth = 1262fs**	**Pulsewidth = 1478fs**



Two LFEX laser beams were overlapped and focused within 60 μm

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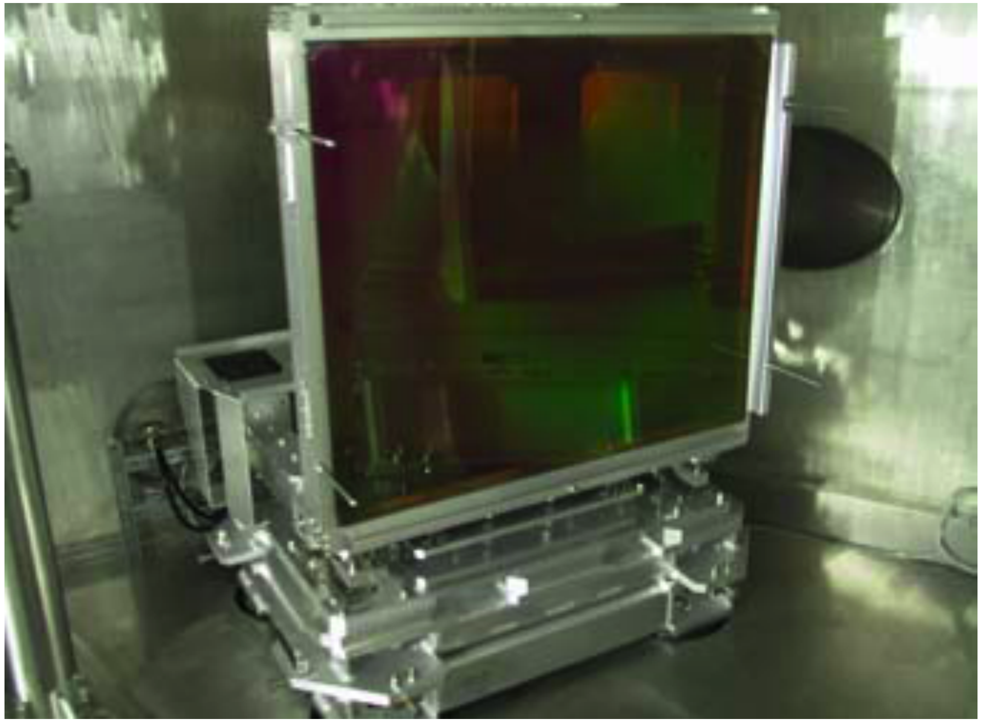
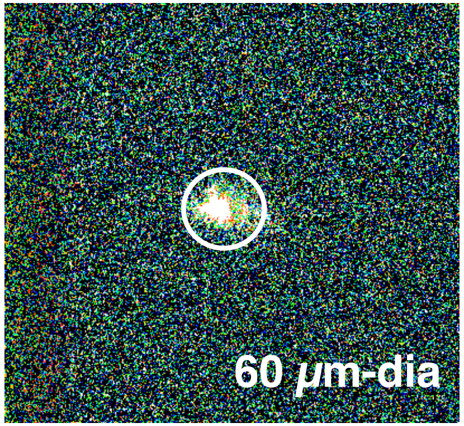
X-ray images



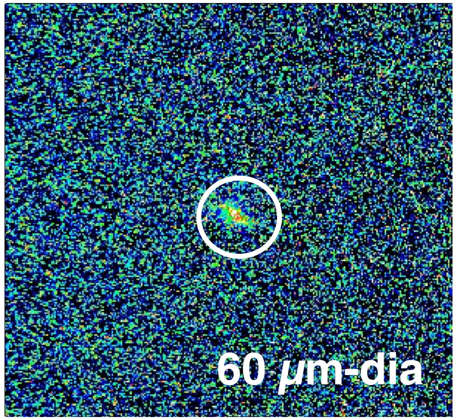
Off-axis parabola mirror installed into chamber

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

2009 experiment
1 beam



2010 experiment
2 beams



Present status of LFEX laser system

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- **2 beams operational among 4 in 2010**
- **Pulse-compressed and focused on the target**
- **Output energy level limited by damage handling of optical components, particularly the gratings**

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

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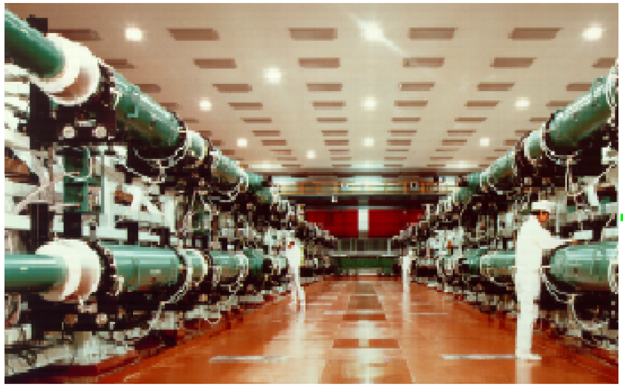
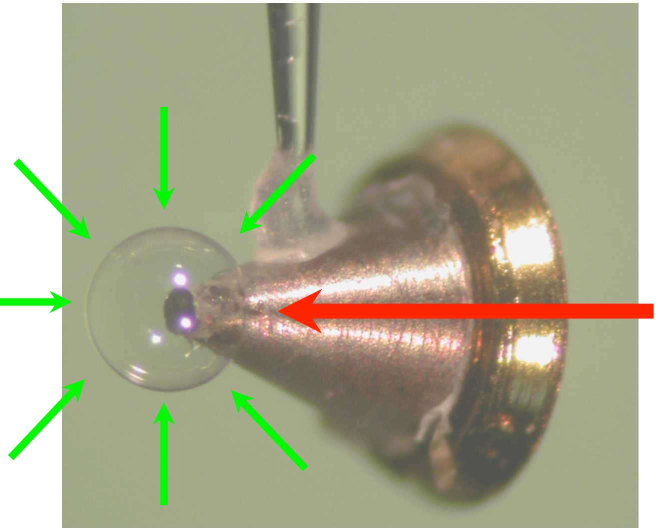
Compression Laser: GEKKO-XII



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

Fusion Fuel Target



<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 ~ 2000 J

Duration 1.5 - 2 ps
Wavelength 1053 nm

Experiment Φ1 : Aug. 16 – Dec. 24, 2010 (GXII + LFEX)
Φ2 : Jan. 5 – Jan. 25, 2011 (LFEX only)

Issues in Fast Ignition experiment found in 2009

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Prepulse

→ preformed plasma
→ long-scalelength
→ too-hot electrons
→ less efficient heating of the fuel plasma

Prepulse must be suppressed.

Background noise

intensity > 10^{19} W/cm^2
energy > 1000 J
→ large amount of hot electron generation
→ intense hard x rays (γ rays) and EMP
→ too large background noise and other nuclear reactions

Diagnostics must be compatible to such harsh environment.

Experimental steps to approach 5 keV

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1. Improve pulse contrast to reduce preformed plasma
2. Develop robust diagnostics compatible to hard x-ray/EMP harsh environment, and confirm genuine signals
3. Integrated experiment to confirm 2002 experiment
4. Confirm fundamental processes, and verify scalings for fast heating
5. Examine advanced target concepts
6. Demonstrate 5 keV heating

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Pre-formed plasma with L > 50 μm observed in 2009 exp't, enough to cause higher hot electron temperature

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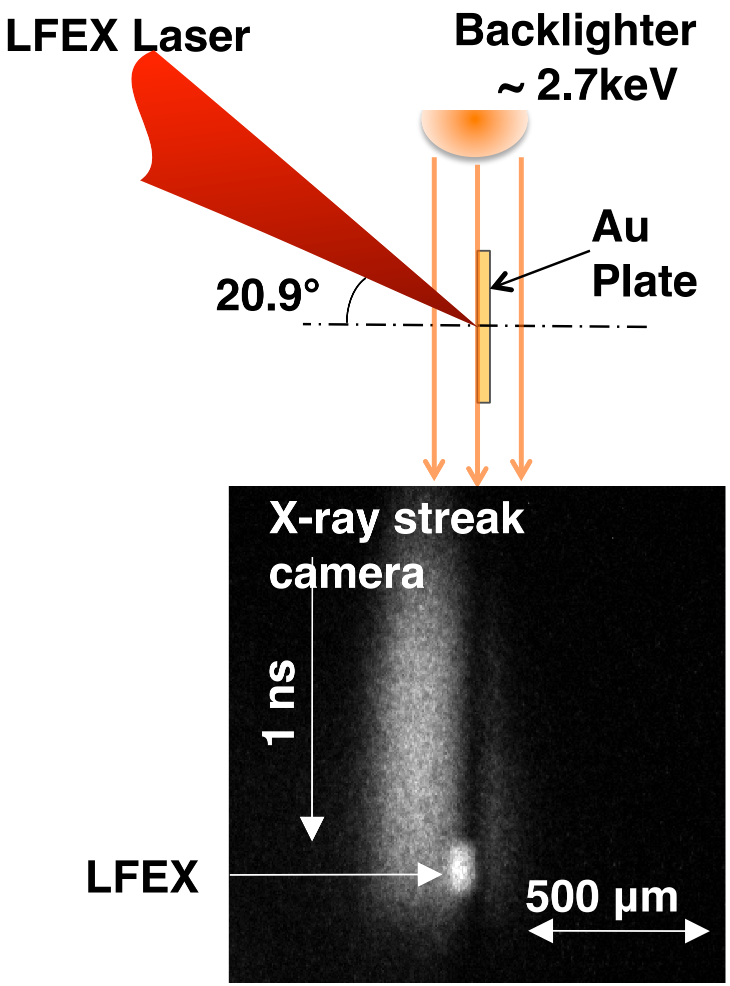

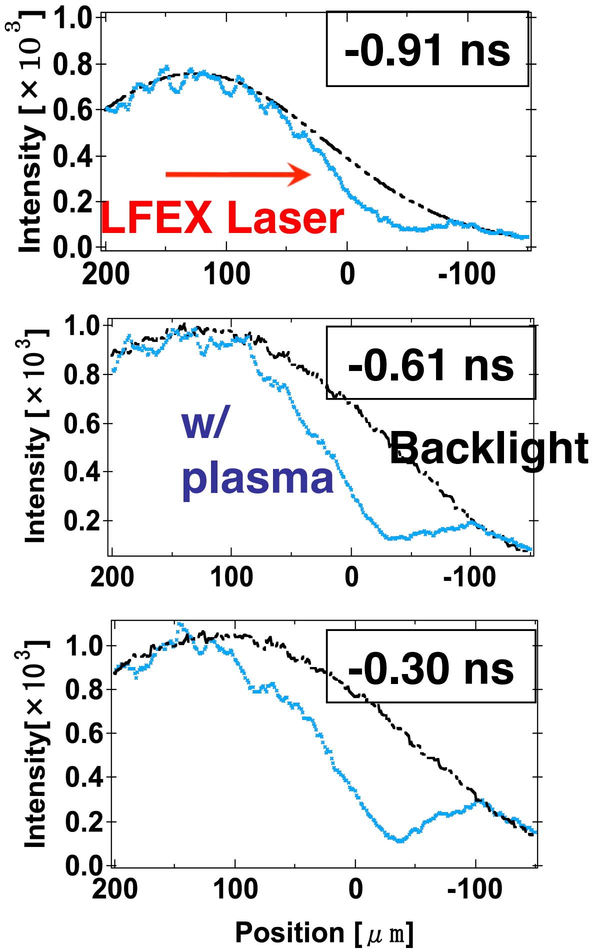

We have to reduce the pre-formed plasma to increase the coupling efficiency of heating.

Electron acceleration in a preformed plasma may enhance too-hot electron generation

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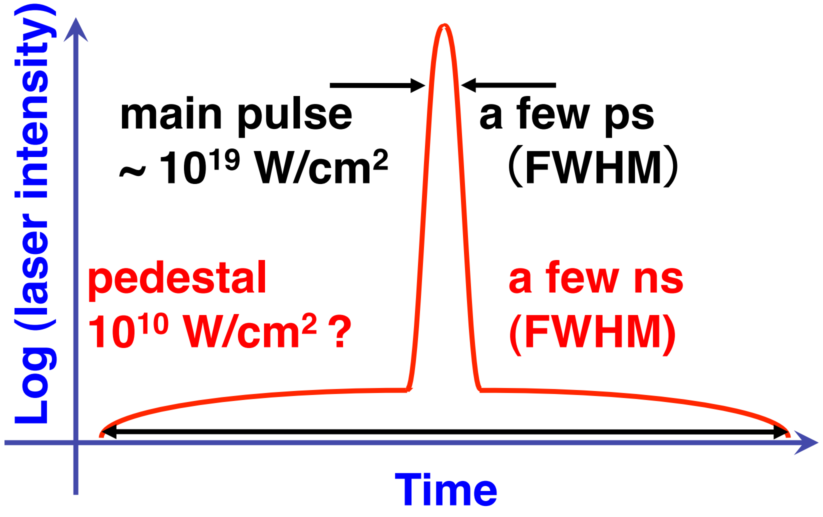
Laser pulse shape



pedestal >10^{10} W/cm^2

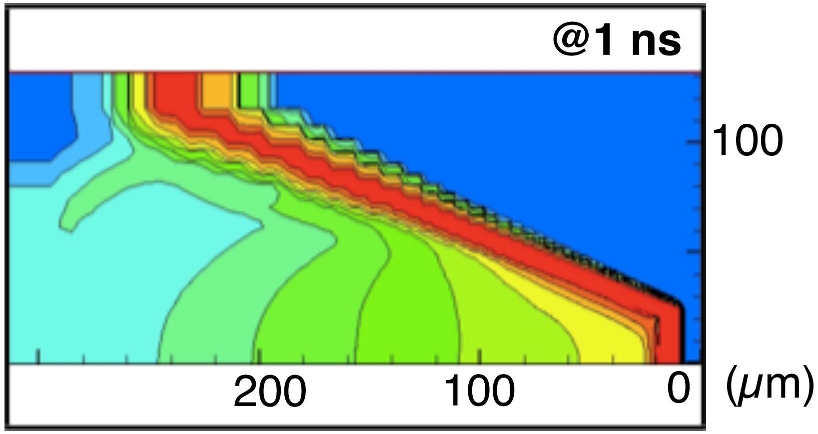
→ pre-plasma formed in cone

→ electrons accelerated in long-scalelength plasma

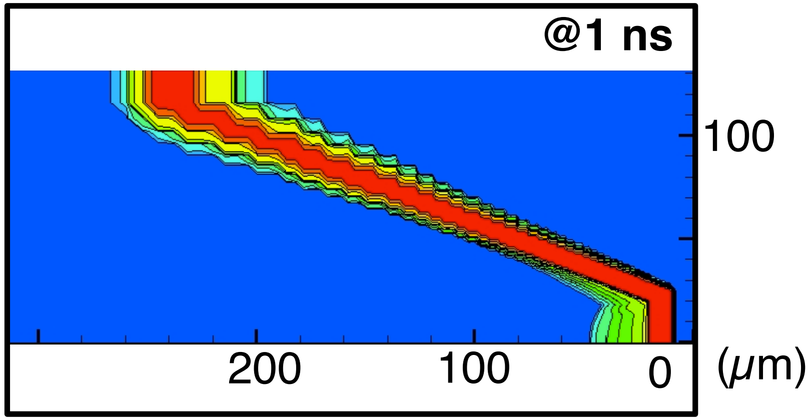
→ too-hot electrons generated

→ coupling efficiency reduced

Pedestal intensity
1 x 10^{13} W/cm^2



Pedestal intensity
1 x 10^{10} W/cm^2



Hot electron temperature was reduced with ***AOPF-reduced*** *operation*

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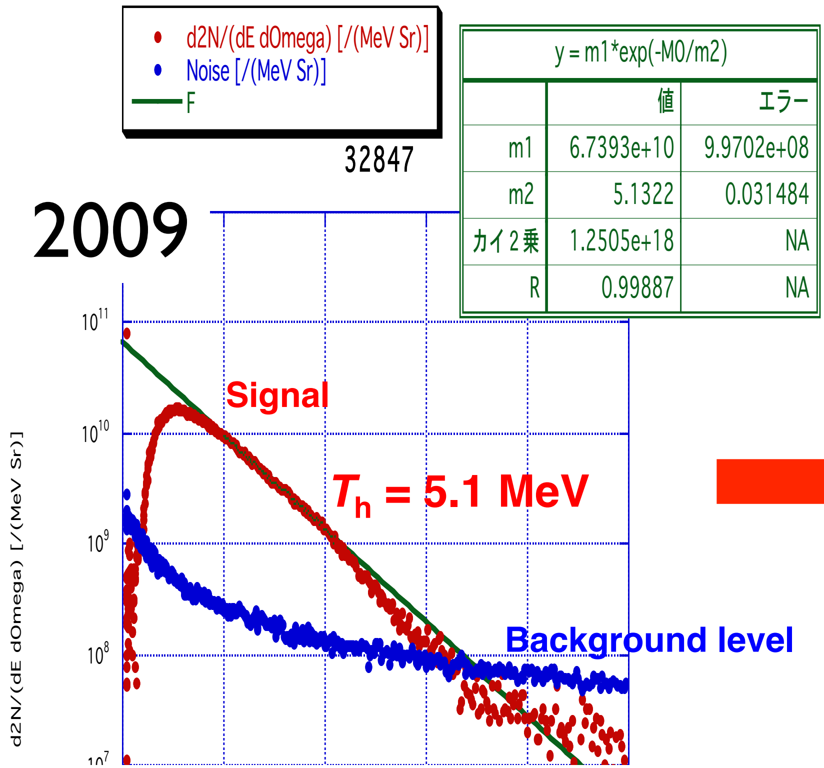
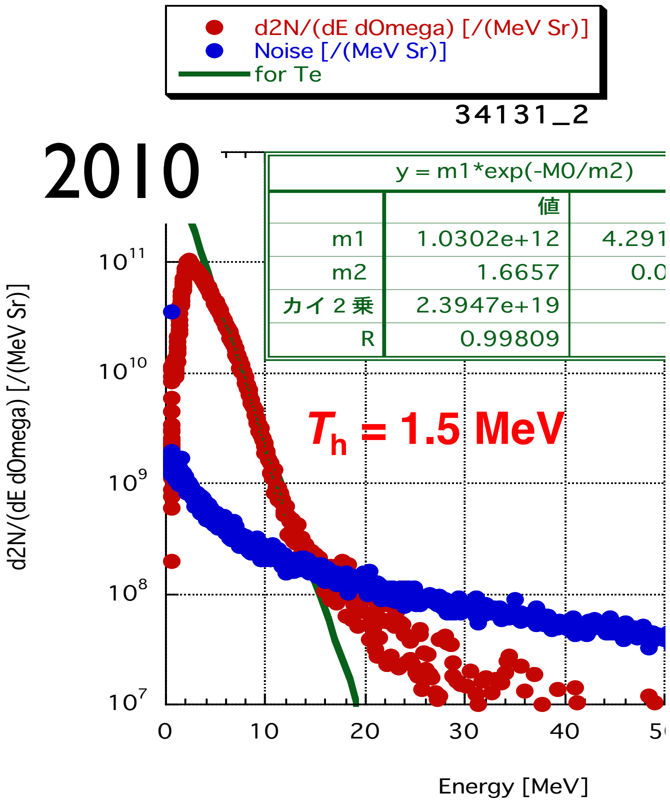
We installed SA (saturable absorber) and AOPF (amplified optical parametric fluorescence) quencher in OPCPA system

2009/9/25
SN32846 (L1404)
Au plate 10 μm thick
212 J@IMAP

$I_L = 10^{19}$ W/cm^2

2010/11/15
SN34131 (L1541)
Au plate 10 μm thick
253 J@IMAP





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Plasma diagnostics compatible to hard x-ray and EMP harsh environment were required

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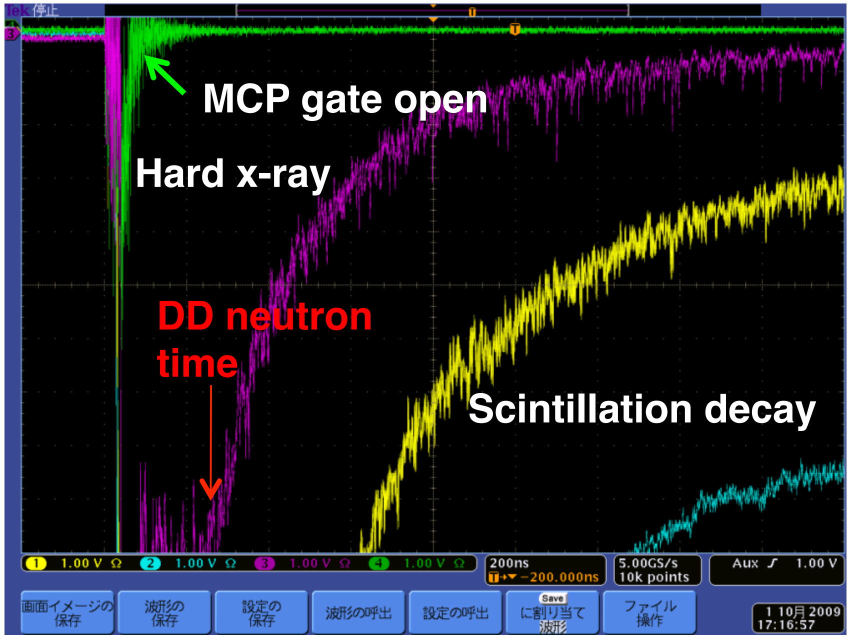
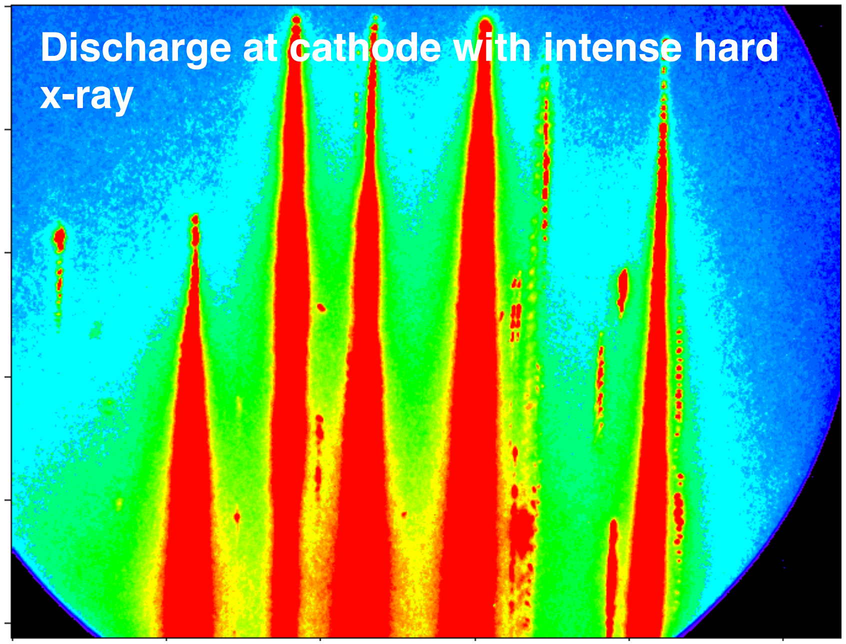
Diagnostics troubles in 2009 experiment with large energy LFEX shot

- Freezed PC's, violent noises in oscilloscopes
- Too big scintillation decay signal overwhelming the DD neutron signal
- Intense background noise and cathode discharge in x-ray imaging devices

Neutron TOF scintillation detector



Multi Imaging Xray streak camera



EMP shield box for electro circuits worked well

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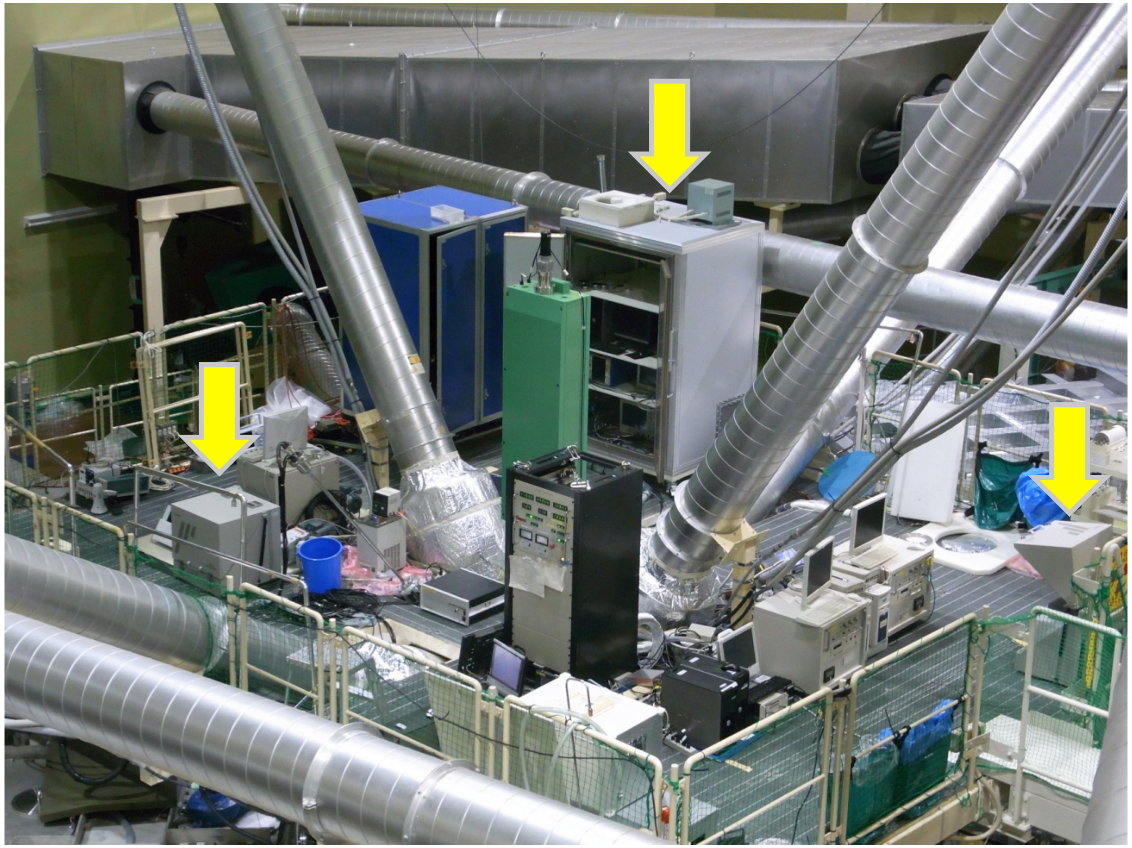

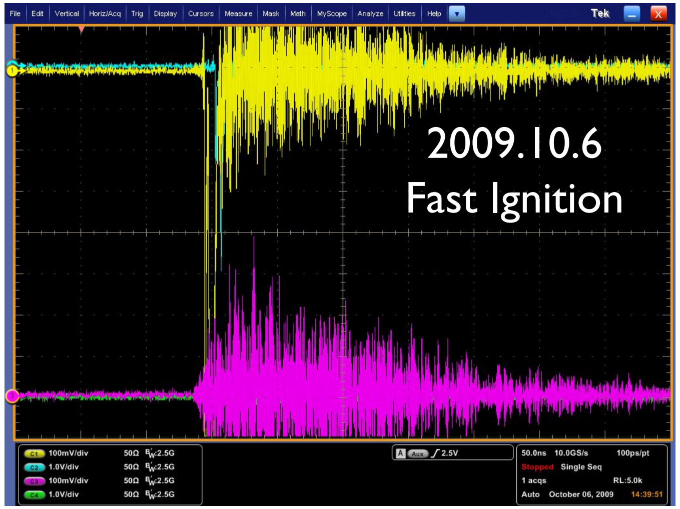

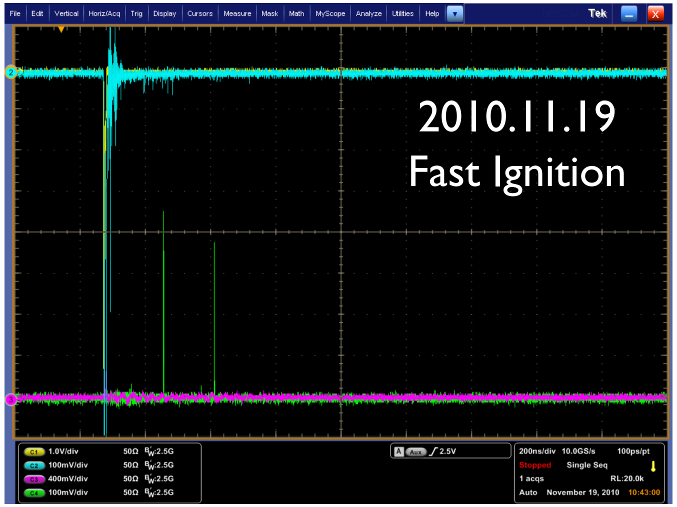

EMP noise effects on photodiodes, PC's, and oscilloscopes were significantly reduced.

Reduction of hard x-rays in x-ray imaging diagnostics

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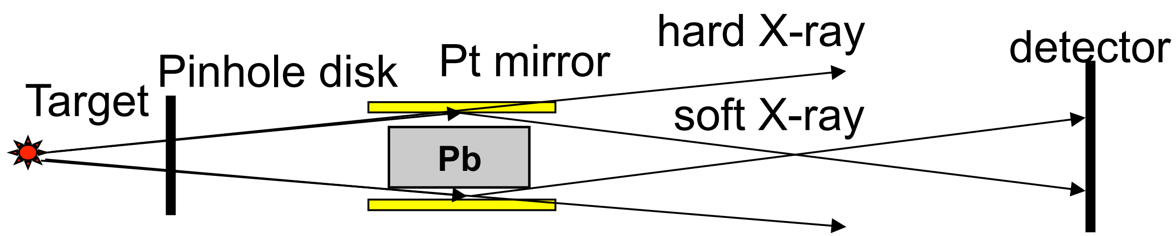
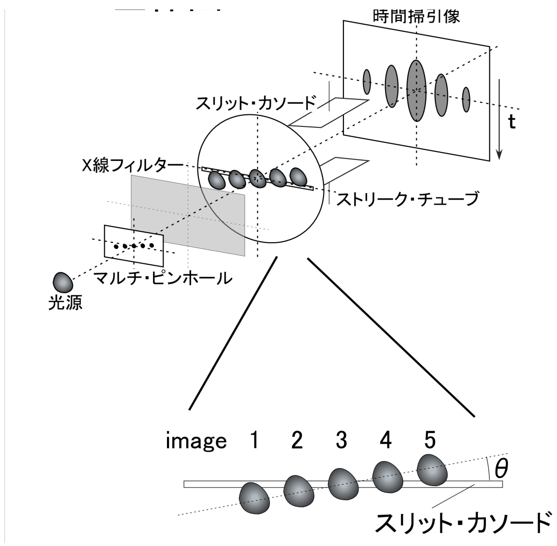
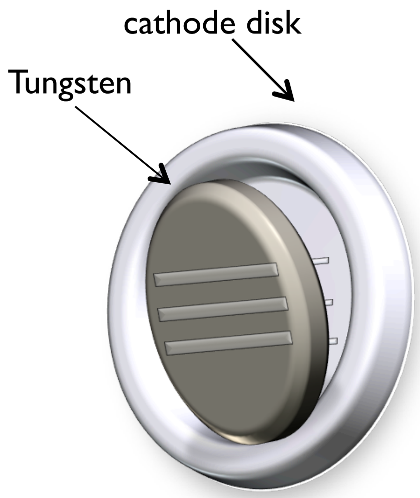
X-ray framing camera with total reflection mirrors to eliminate hard x-rays



Hard x-ray shielded cathde for x-ray streak tube





These schemes worked well and contributed to efficient experiment.

Hard x-rays are eliminated with Pt total reflection mirors, and only thermal x-ray images are recorded

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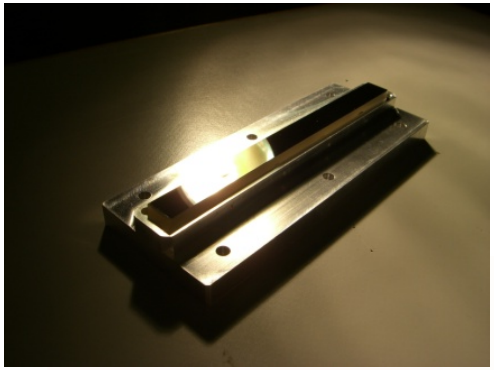
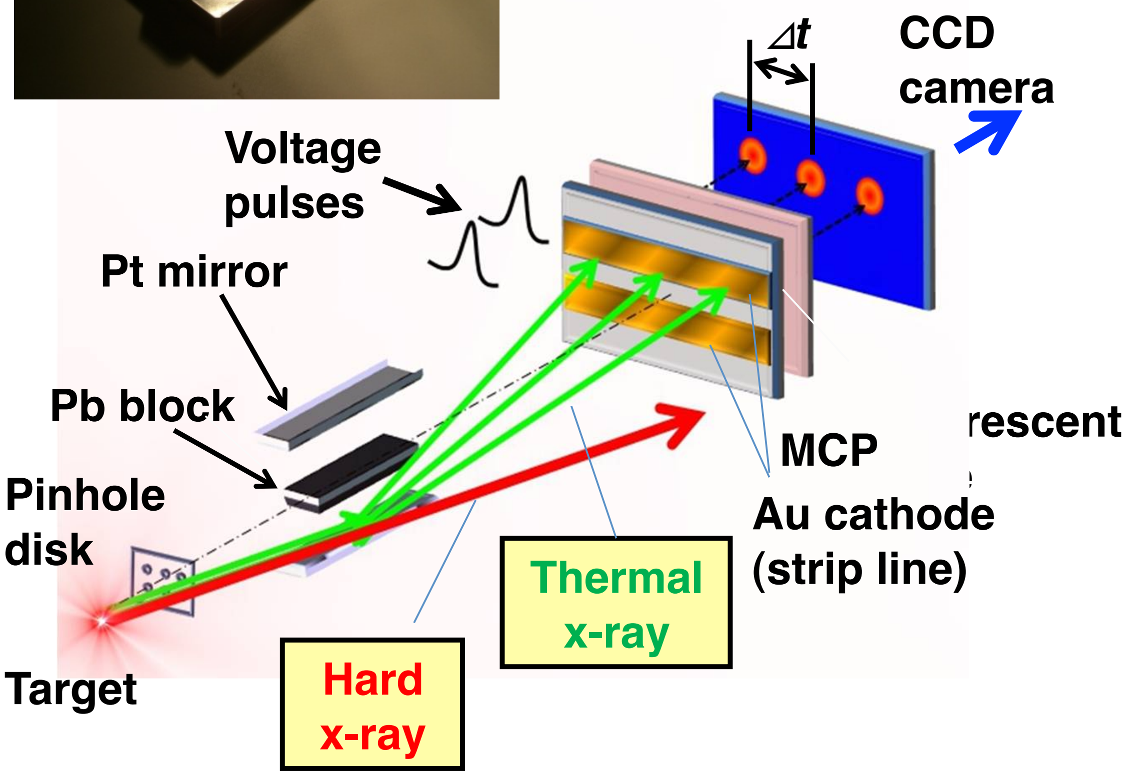
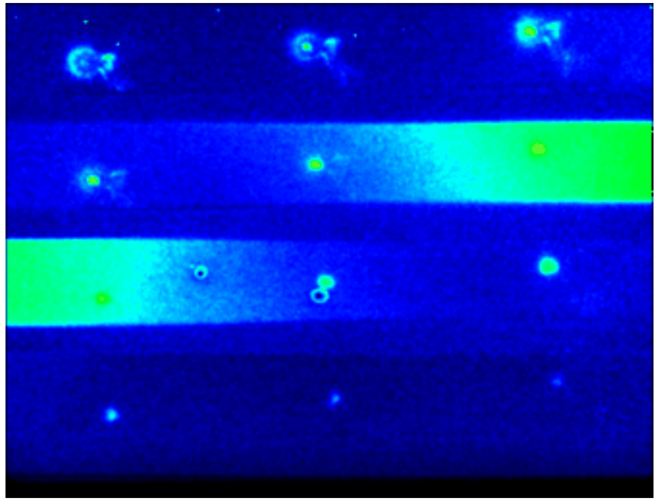
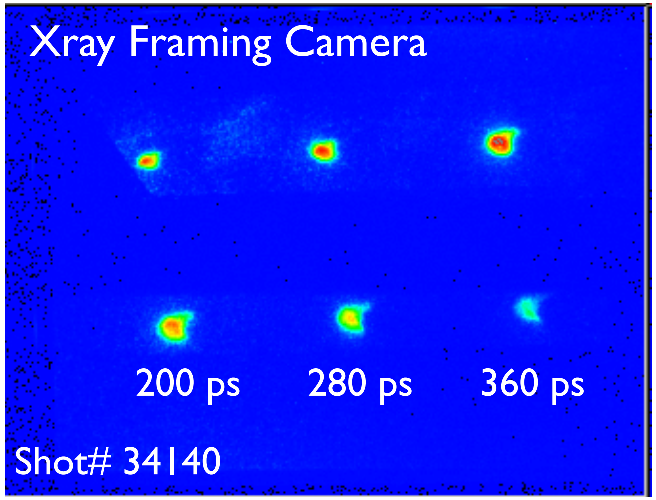






w/o mirrors



w/ mirrors

Shielding worked, and LFEX injection time was accurately monitored using non-imaged hard x-ray signal in x-ray streak cameras

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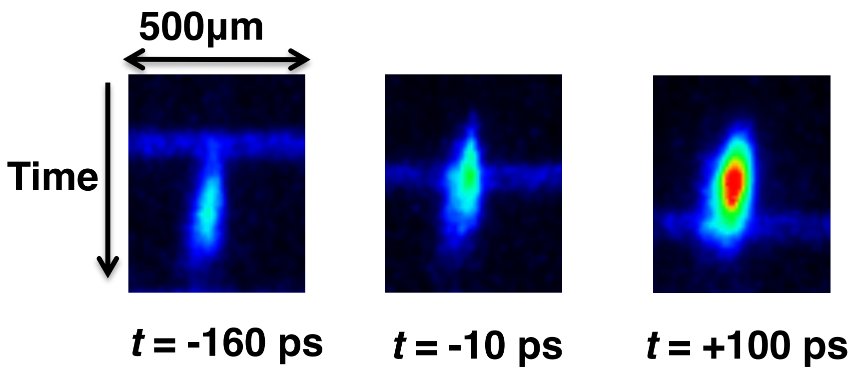
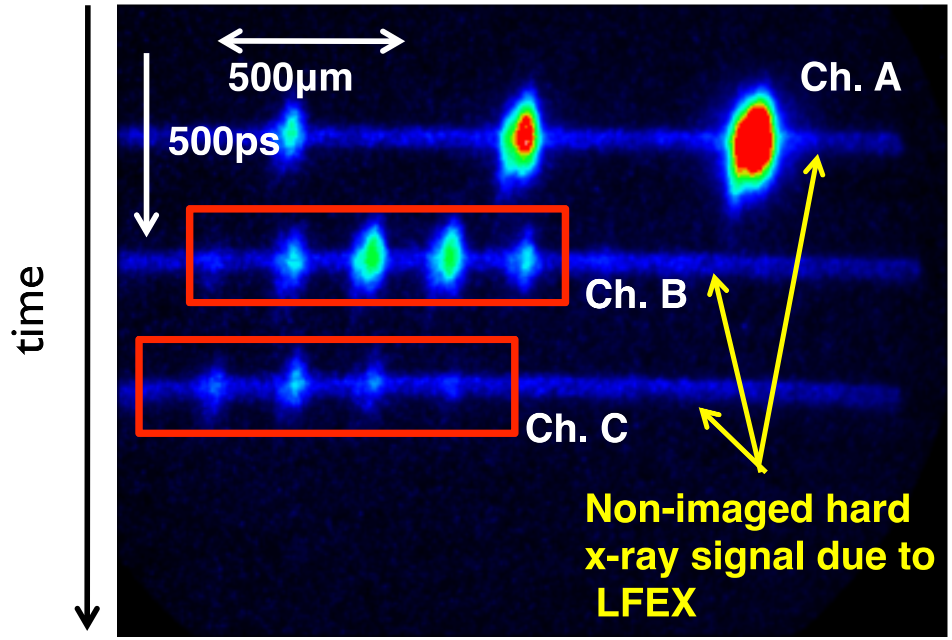
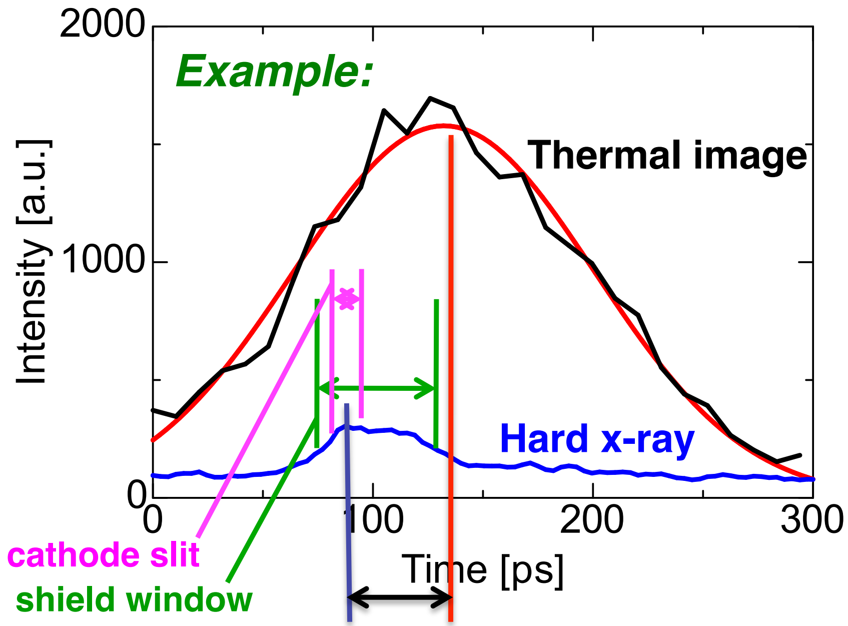
Bulk shielding resulted in :
- Stopping cathode discharge
- Reducing background noise





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



Injection time was measured within an accuracy better than +/-10 ps.

Various neutron diagnostics were developed

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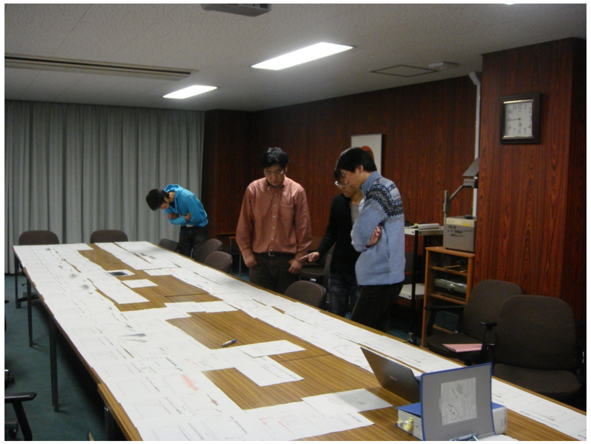
Time-resolving detectors

1. MANDALA: 4π shielding
2. TOF scintillator: shielding hardened
3. Fast fiber scintillator: shielding hardened
4. BC422: position changed
5. Gated TOF scintillator: New
6. Gated Liq. scintillator # 1: New
7. Gated Liq. scintillator #2: New
8. Gated ^{6}Li scintillator #2: New
9. Multi-ch. ^{6}Li counting mode: New

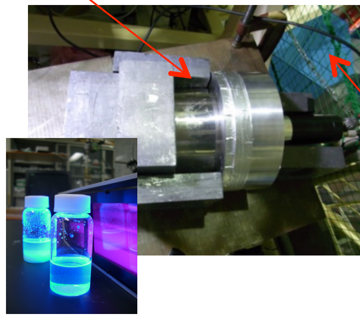
γ-ray insensitive detectors

10. Bubble detector: Revival
11. CR39 auto-reading: New
12. Radiochromic film: New
13. Ag counter: Revival



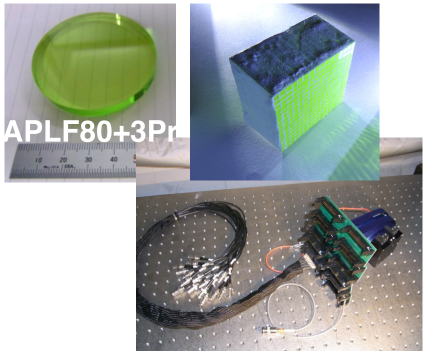
MANDALA

0-saturated quenching Liq. scintillator

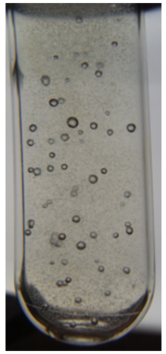


PMT with gated-dinode

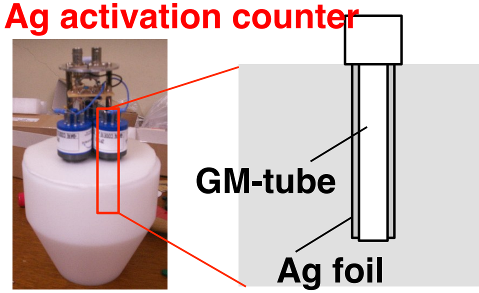
^{6}Li scintillator



Bubble detector



Ag activation counter



n-moderator (polyethlene)

$$^{109}Ag + n \rightarrow {}^{110}Ag + \gamma$$

$$\Rightarrow {}^{110}Ag \rightarrow {}^{110}Cd + \beta^-$$

New liquid scintillator was developed

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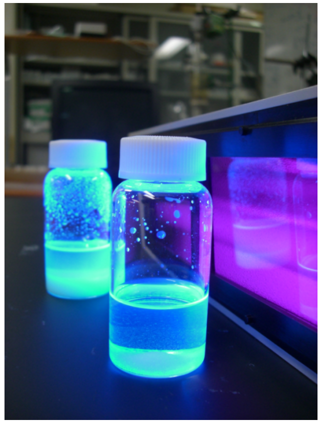
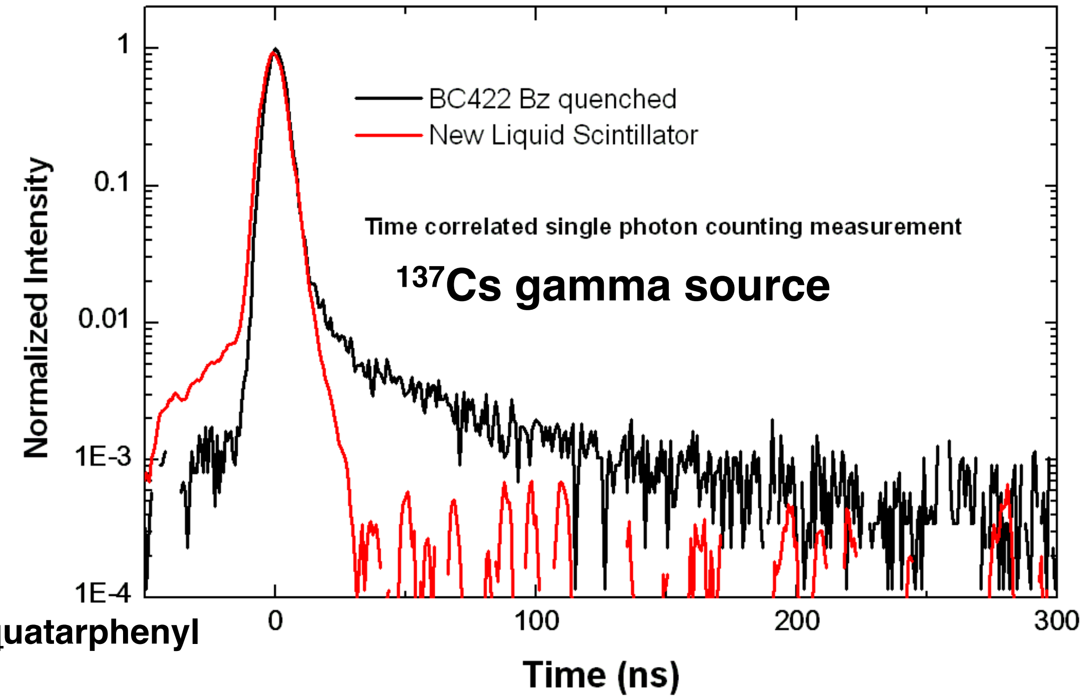




scintillation：
BBQ (used for dye lasers)
4,4’’’-Bis-(2-butyloctyloxy)-p-quatarphenyl

host：p-Xylene

Quenching by oxigen

T. Nagai et al., to be published

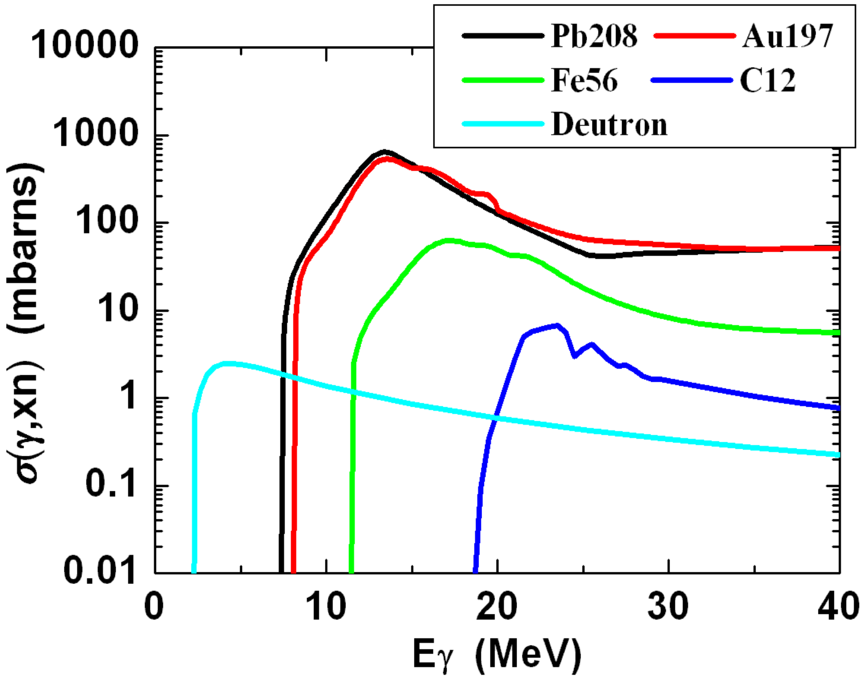
- ***Slow decay component was significantly reduced.***
- ***Coupled with gated PMT, and used in FI integrated experiment.***

(γ,n) reactions take place in γ-ray rich environment in high-intensity experiments

We observed:

- **Neutron signals in *gamma-insensitive* detectors (bubble, Ag activation)**
- **Broadband neutron signals observed in shots *without* implosion**
- **Correlation with gamma-ray signals**

→ ***There are neutron signals coming from (γ, n) reactions.***



$$^{M}A + \gamma(h\nu) \rightarrow {}^{M-1}A + n(h\nu\text{-B.E.})$$

Neutrons in the MeV range can be created due to (γ,n) reactions (*photo disintegration reactions*) in materials in and around the target.

Intense (γ,γ') and (γ,n) signals were found to be the main components of the background signal

(γ,n) : photodisintegration reaction, (γ, γ') :scattering

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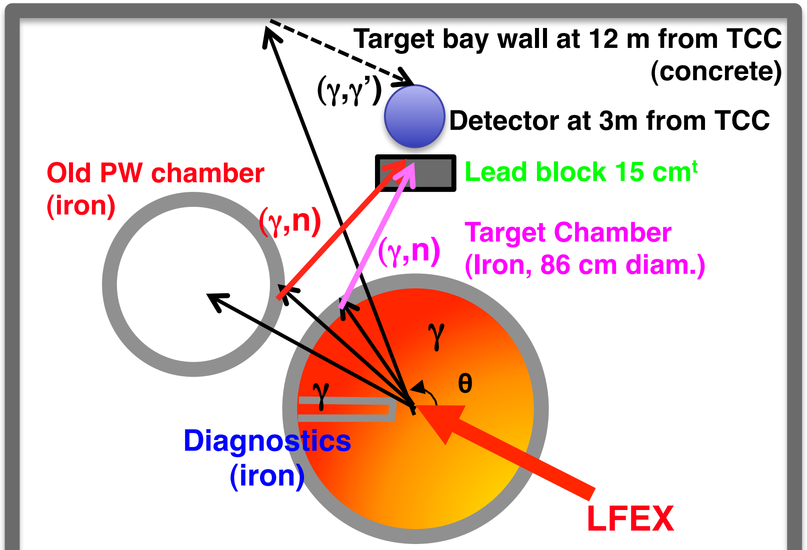
(γ,n) and (γ,γ') in materials elsewhere in and around the target chamber and at the concrete walls

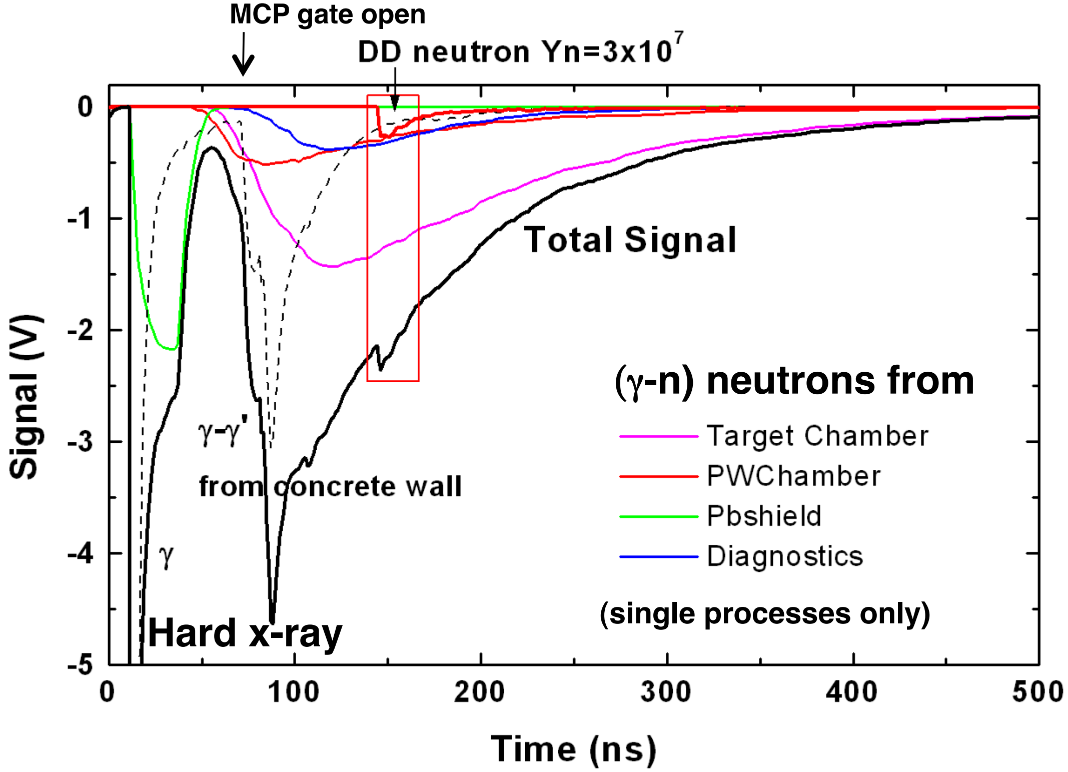


Assumed input gamma source
$T\gamma$ = 5 MeV
$Y\gamma$ = 8×10^{11}
$\theta \sim \sin(0.5\theta)^{1.7}$

Characterization of gamma-rays needed

(γ,n) and (γ,γ') signal components calculated with Monte-Carlo code* assuming materials configuration

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



Now we know nature of the background signals, and can accurately identify the DD neutron signal even with the heavy backgrounds.

(γ, n) and (γ,γ') signals from surroundings can be eliminated by using appropriate collimators

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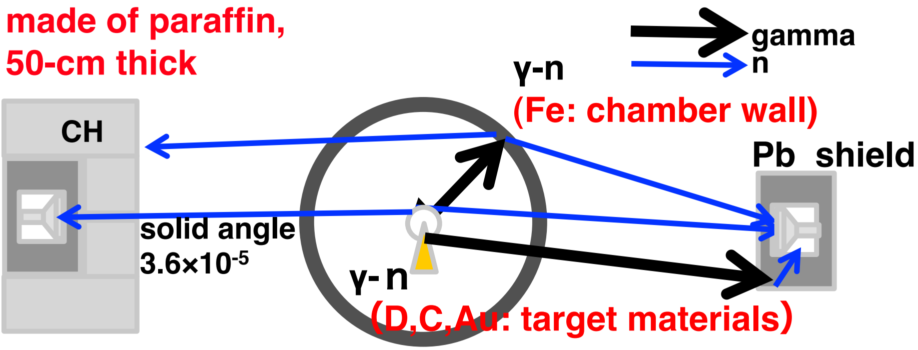
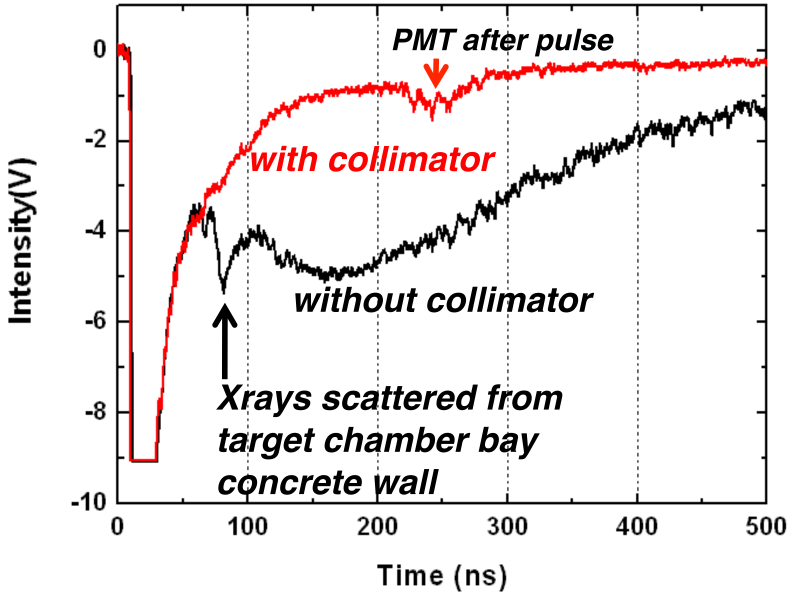
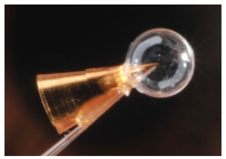
gamma-n observation shot





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



Collimators will be fully installed in 2011 exp't.

Contents of the talk

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1. FIREX project

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2. LFEX laser – construction and tuning

   Laser output (2 kJ / 2 beams / 1 ps) delivered to experiment
   Improved pulse contrast
   Pulse compression and Focusing

3. Integrated experiment of Fast Ignition

   Implosion and heating of shell target with Au cone
   Preformed plasma effect
   Plasma diagnostics in hard x-ray harsh environment
   Enhanced neutron yield and heating efficiency

4. Conclusions and near future plan

Neutron yield was 30-times enhanced with LFEX injection

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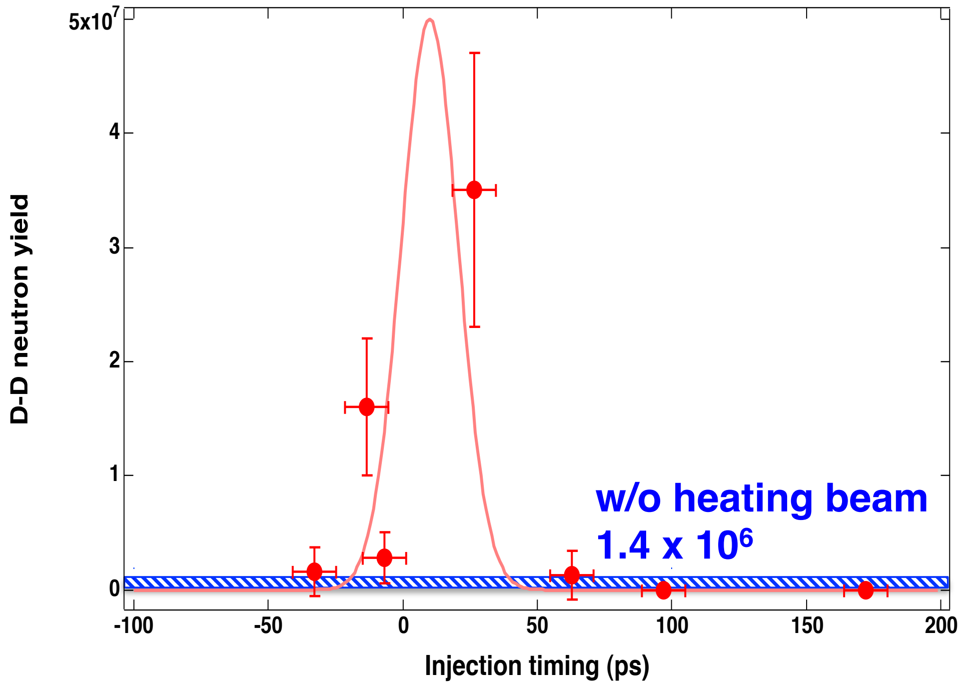
Shot#	DD-n ± γ-n err	**DD-Yn**	LFEX injection timing (ps)	LFEX energy@IMAP(J)
34177	(1.25±0.5)×10^6 ±2×10^6	**(1.25±2.1)×10^6**	+63 +/- 8	397.91
34183	(3.5±1.2)×10^7±2×10^6	**(3.5±1.2)×10^7**	+27 +/- 8	430.5
34186	(2.8±1.0)×10^6±2×10^6	**(2.8±2.2)×10^6**	- 7 +/- 8	694.1
34187	(1.6±0.6)×10^7±2×10^6	**(1.6±0.6)×10^7**	-14 +/- 8	598.3
34189	(1.6±0.5)×10^6±2×10^6	**(1.6±2.1)×10^6**	-33 +/- 8	318.8
34193 w/o LFEX	(1.44±0.5)×10^6	**(1.44±0.5)×10^6**		



5 guaranteed shots among 38
(Others were too much noisy.)

← 2002 exp't

Y_n exceeded result in 2002.

Dependence of neutron yield on coupling efficiency and heating energy was calculated with 2D code

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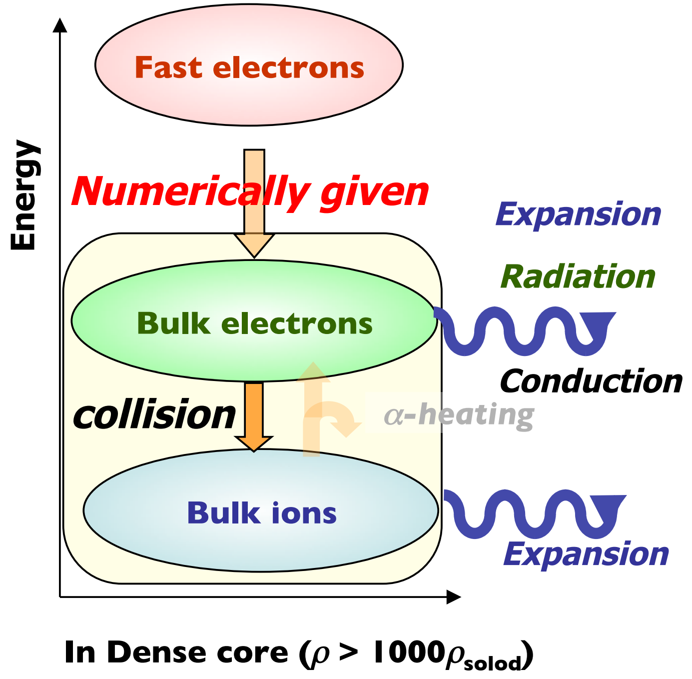
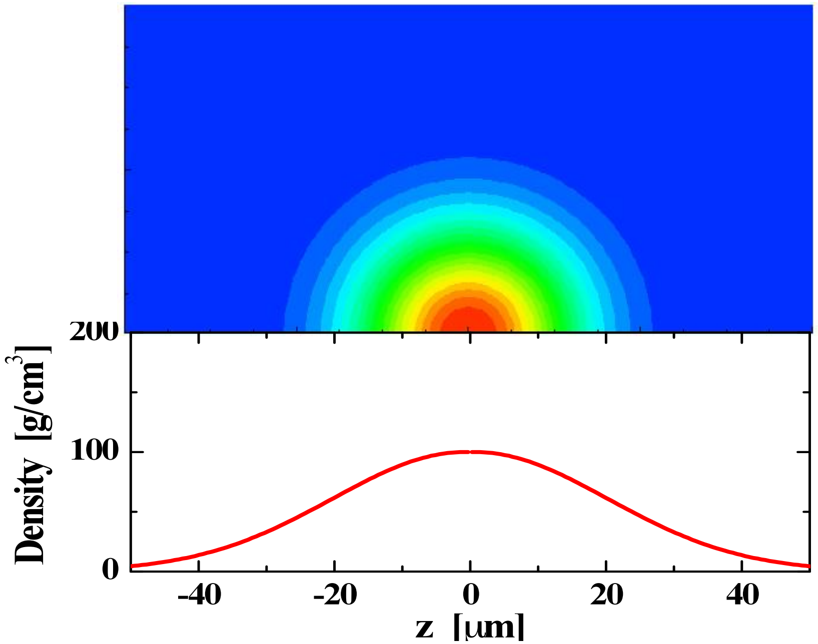
2D Burn simulation code "FIBMET"

base : 1 fluid 2 temperature Euler-type Hydro code
+ radiation transport (multi-group flux-limited diffusion),
+ α-particle transport (multi-group flux-limited diffusion)
+ fusion reactions (DT,DD,D^3He)



Assumed Bulk Plasma: CD

Ti & Te: uniform、ρ:Gaussian profile



Core heating:

Uniform heating for bulk electron

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

2010 results reconfirmed 2002 exp't, heating efficiency of 10-20% achieved

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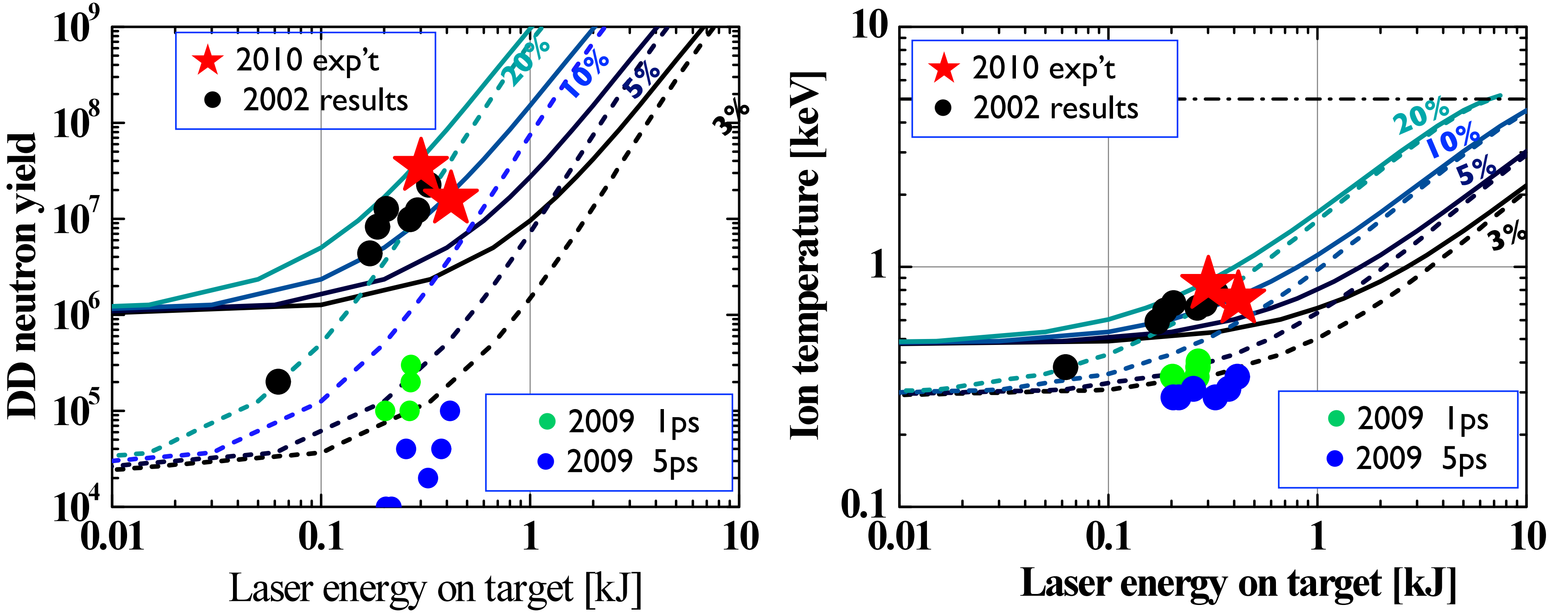

Marks→ experiments
Lines → simulations
dashed lines : for 2002, 2009 exp't
solid lines : for 2010 exp't

Initial density profile of the core plasma assumed:
Gaussian profile
ρ_{max} = 100 g/cm^3, R = 20μm

Not yet optimized:
input energy and heating efficiency to be increased

Summary of the 2010 experiment

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Interaction and fundamental process:

- Reduced hot electron temperature by reducing AOPF in CPA system
- Pre-formed plasma still observed
- Many fundamental processes not yet experimentally clarified

  → Further investigations required

Diagnostics: background problem has been cleared up.

- (γ,n) and (γ, γ') signals evaluated, and precise neutron yield measurement
- Heating beam injection time with 10 ps accuracy by x-ray streaked imaging

Integrated experiment: neutron enhancement in 2002 was reconfirmed.

- Neutron enhancement up to 3.5E7 achieved

  Higher than 2002 and 2009 experiments
- Heating efficiency up to 10-20 % and temperature increase by 300 eV achieved

  → Further improved efficiency needed

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4. Conclusions

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LFEX laser has been activated and used with Gekko laser.

- 2 kJ / 2 beams /1.5 ps operation was performed.
- AOPF was significantly reduced.
- Will be upgraded to 10 kJ / 4 beams.

FI integrated experiments has been successfully performed, and Neutron enhancement in 2002 experiments were reconfirmed.

- Accurate plasma diagnostics compatible to hard x-ray harsh environment were developed.
- (γ,γ') and (γ,n) reactions were identified in the neutron measurement.
- Neutron yield up to 3.5E7 and heating efficiency of 10-20% have been achieved.
- Heating efficiency will be improved with advanced targets.

We are "Go" for FIREX-1 experiment in 2011-2012:

- Increase LFEX energy in 4-beam operation with even higher pulse contrast
- Further improve diagnostic instruments : shielding and collimation
  →more significant heating, more accurate signals in heating diagnostics
- Verify heating mechanism and FI scenario
- Demonstrate improved heating efficiency and temperature scaling

Near future plan

Year	Laser construction	Milestones
2008	Compressor activation	
	1-beam operation	Gamma-ray test
2009		*FI integrated experiment*
		Advanced target
2010	2-beam operation	FI integrated experiment
2011	*4-beam activation*	*CD heating* (5 keV) ← Goal of FIREX-1
- 2012		Advanced target
2013		D2 heating (cryo)
201x		DT heating (cryo)

We thank:
Gekko-XII and LFEX laser operation crew,
target fabrication group,
plasma diagnostics group, and
computer operation stuffs
at ILE for their great contributions to this work.

Thank you for your attention!