IFE/1-3

Fast Ignition Integrated Experiments with Gekko-XII and LFEX Lasers

H. Shiraga, S. Fujioka[1], M. Nakai[1], T. Watari[1], H. Nakamura[1], Y. Arikawa[1], H. Hosoda[1], T. Nagai[1], M. Koga[1], K. Shigemori[1], H. Nishimura[1], Z. Zhang[1], M. Tanabe[1], Y. Sakawa[1], T. Ozaki[2], K. A. Tanaka[3], H. Habara[3], H. Nagatomo[1], T. Johzaki[4], A. Sunahara[4], M. Murakami[1], H. Sakagami[2], T. Taguchi[5], T. Norimatsu[1], H. Homma[1], Y. Fujimoto[1], A. Iwamoto[2], N. Miyanaga[1], J. Kawanaka[1], T. Jitsuno[1], Y. Nakata[1], K. Tsubakimoto[1], K. Sueda[3], N. Sarukura[1], T. Shimizu[1], K. Mima[1] and H. Azechi[1]

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1) Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871 Japan
2) National Institute for Fusion Science, Toki, Gifu 509-5292 Japan
3) Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871 Japan
4) Institute for Laser Technology, Suita, Osaka 565-0871 Japan
5) Faculty of Science and Engineering, Setsunan University, Neyagawa, 572-8508 Japan

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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 and LFEX lasers at the Institute of Laser Engineering, Osaka University. The goal of the project is to achieve fast heating of the imploded fuel plasma up to 5 keV by injection of the heating laser beam. 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 improve the pulse contrast of the LFEX laser beam. Also we have much improved the plasma diagnostics to be able to observe the plasma even in the hard x-ray harsh environment. In 2010-2011 experiment after the previous IAEA/FEC-23, a plastic (CD) shell target with a hollow gold cone was imploded with Gekko-XII laser. LFEX laser beams were injected into the cone at the time around the maximum implosion. We have successfully observed neutron enhancement up to 3.5×10^7 with total heating energy of 300 J, which is higher than the yield obtained in the experiment with previous heating laser, PW, in 2002 [1]. We found the estimated heating efficiency assuming a uniform temperature rise is at a level of 10-20 %. Fuel heating up to 5 keV is expected with full-spec output of LFEX.

Outline of the talk

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1. FIREX-1 project

2. Progress in 2010-2011 experiment
   - LFEX laser
   - Integrated experiment

3. New approaches underway for improved heating efficiency
   - Reduction of the preformed plasma
   - Low-Z material for the cone
   - Hot electron guiding with external B field

4. Summary and conclusions

Related papers in IAEA/FEC-2012

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OV/4-2
H. Azechi
Present status of Fast Ignition Realization Experiments and Inertial Fusion Enwergy Development

IFE/P6-05
H. Nagatomo
Computational Study of the Strong Magnetic Field Generation in Non-Spherical Cone-Guided Implosion

IFE/P6-11
Y. Arikawa
Study on the Energy Transfer Efficiency in the Fast Ignition Experiment

IFE/P6-18
A. Iwamoto
FIREX Foam Cryogenic Target Development: Attempt of Residual Voids Reduction with Solid Hydrogen Refractive Index Measurement

1. FIREX, Fast Ignition Realization Exp't

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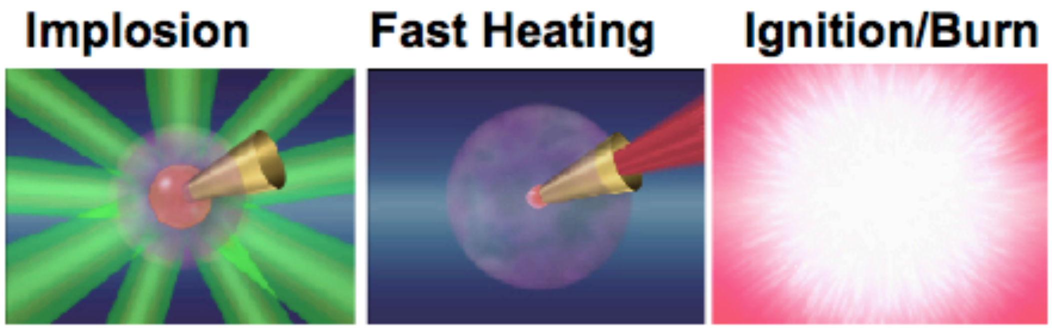

- **preliminary: Demo of 600 times liquid density**
  Demo of 1 keV temp. by 1kJ/1ps.

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

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

OV/4-2
H. Azechi

2. Progress in 2010-2011 experiment

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In IAEA/FEC-2010, we have reported

- ・LFEX laser activated
- ・Integrated experiment started

Progress in 2010-2011

１. LFEX laser – construction and tuning

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

２. Integrated experiment of Fast Ignition

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

LFEX laser – construction and tuning

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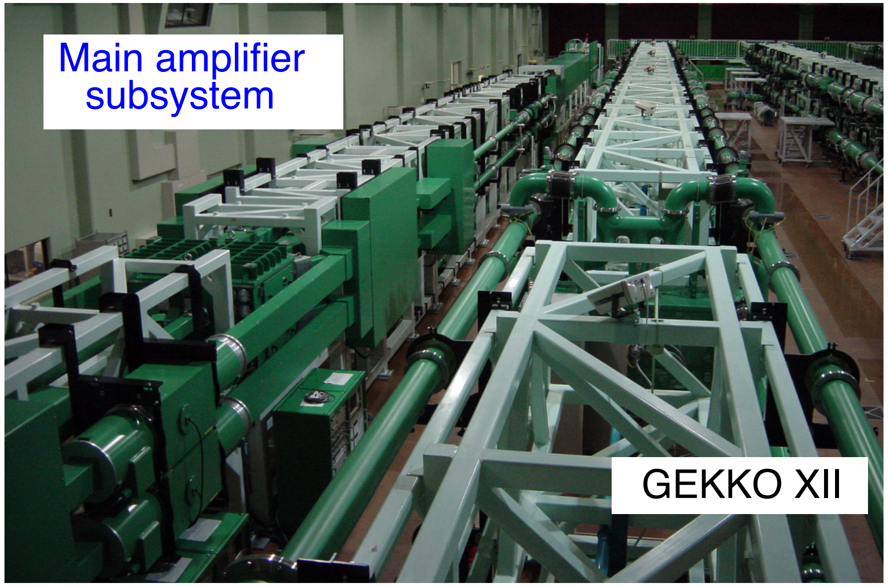

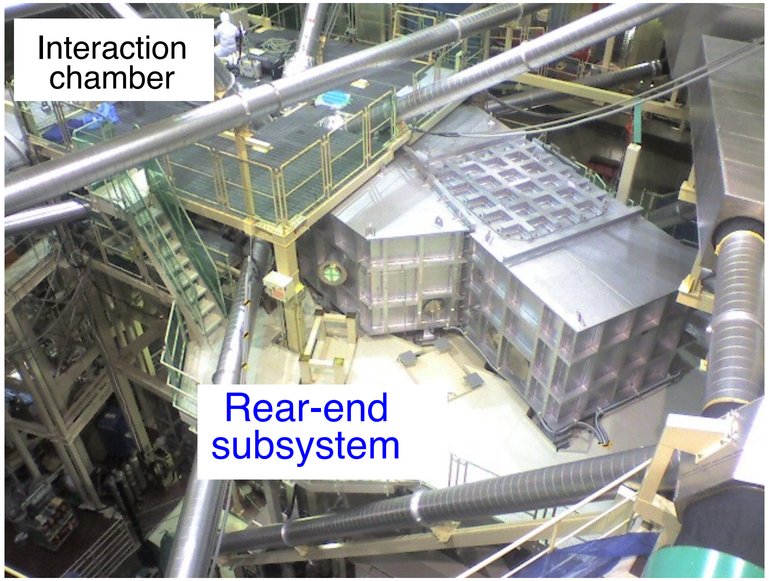

Nov, 2008	**Precision alignment of pulse compressor**
Dec, 2008	***Target irradiation with high-power beam started***
Feb, 2009	***Irradiation of Fast Ignition (FI) target started***
June, 2009	***FI integrated experiment started (5 ps)***
Sept, 2009	***FI integrated experiment (1 ps) / 1 beam***
Aug, 2010	***FI integrated experiment (1 ps) / 2 beams***
Mar, 2012 ～	***FI fundamental and integrated experiment***

For FI integrated experiment

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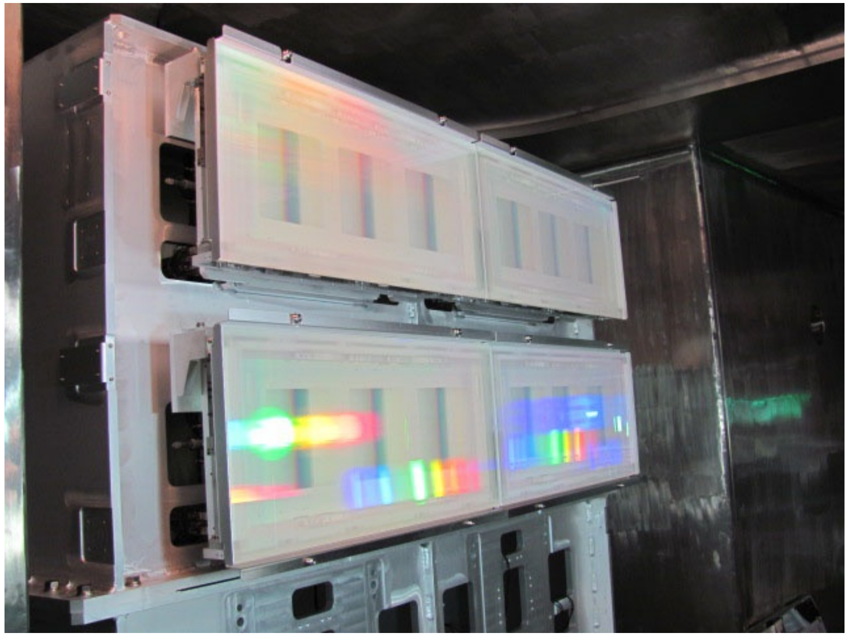

The 2nd beam has been activated.

- **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**
- **Reduced spectral ripples**

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

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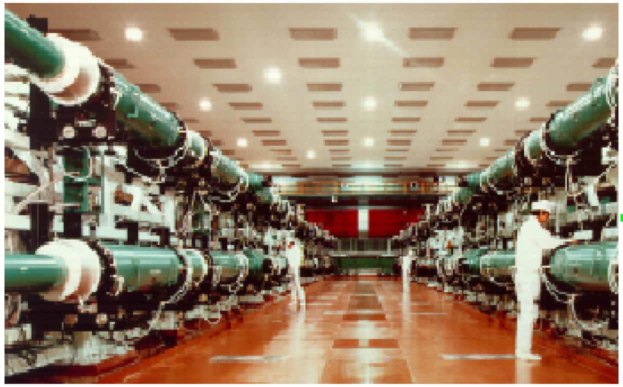
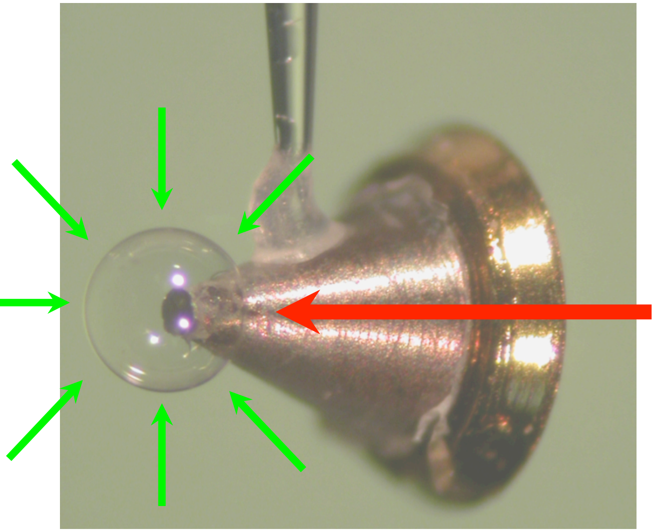
Compression Laser: GEKKO-XII



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

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

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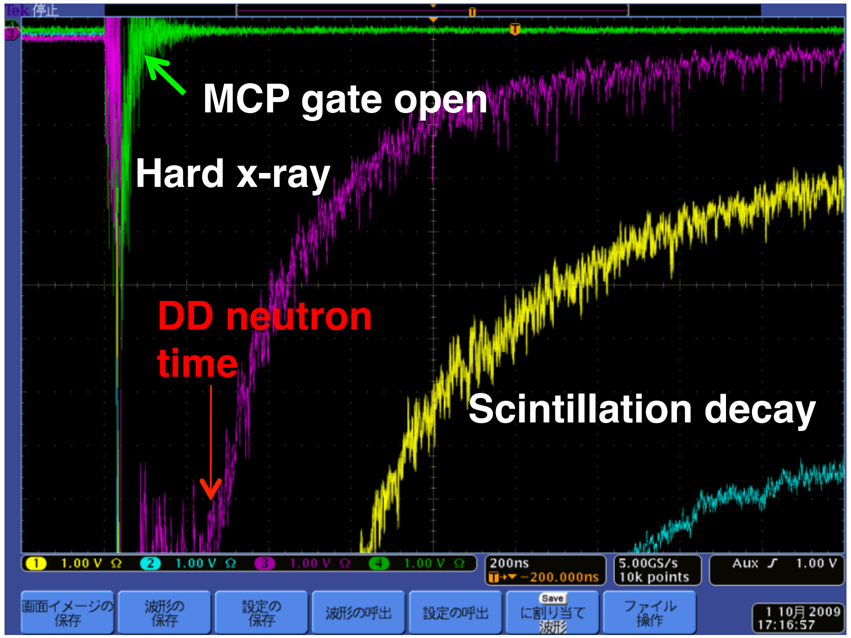
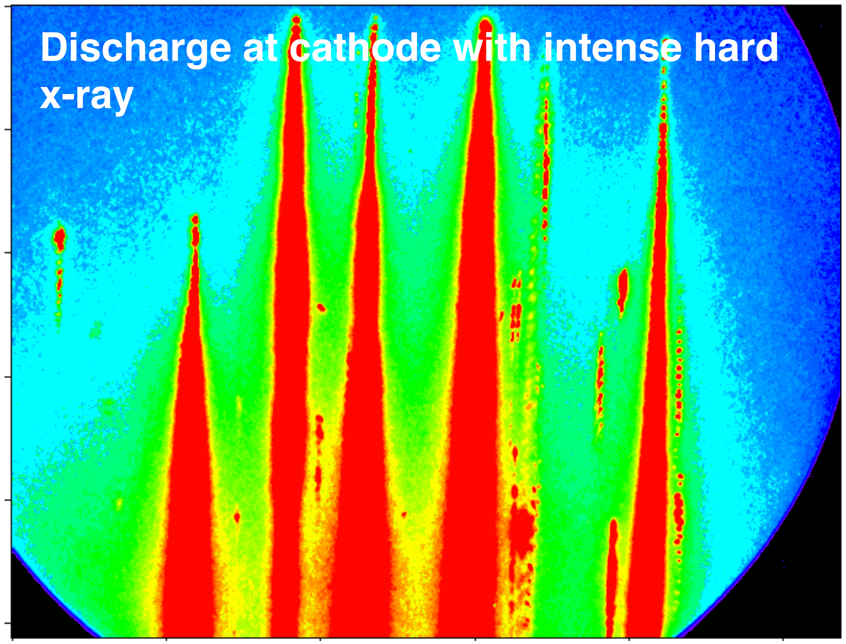
Diagnostics troubles in 2009 experiment with large energy LFEX shot

- 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



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

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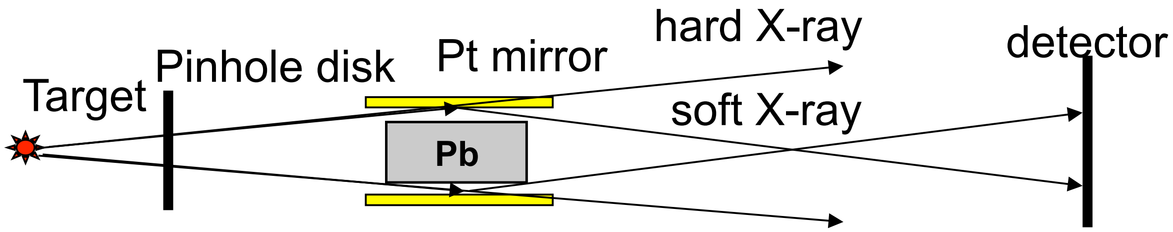
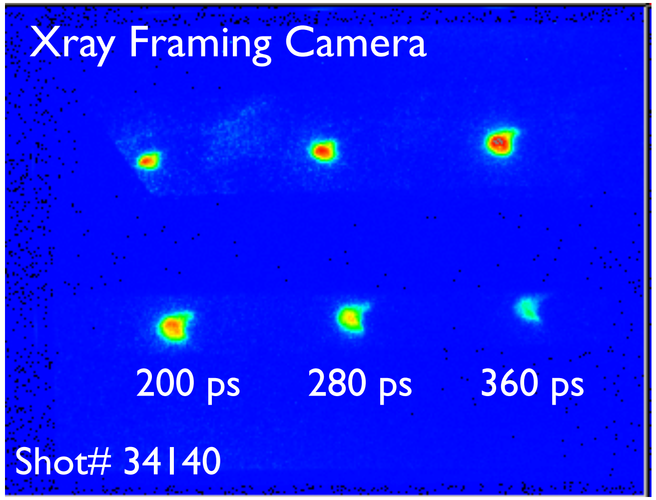
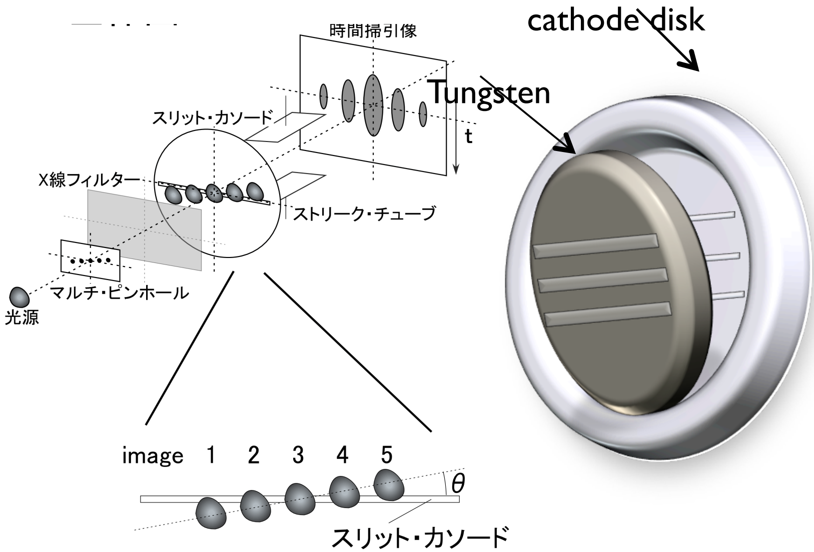
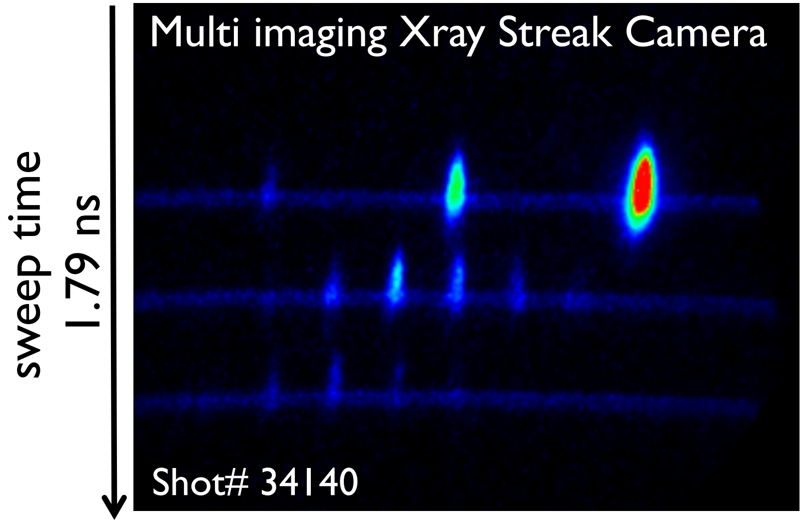
X-ray framing camera with total reflection mirrors to eliminate hard x-rays





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





These schemes worked well and contributed to efficient experiment.

Various neutron diagnostics were developed

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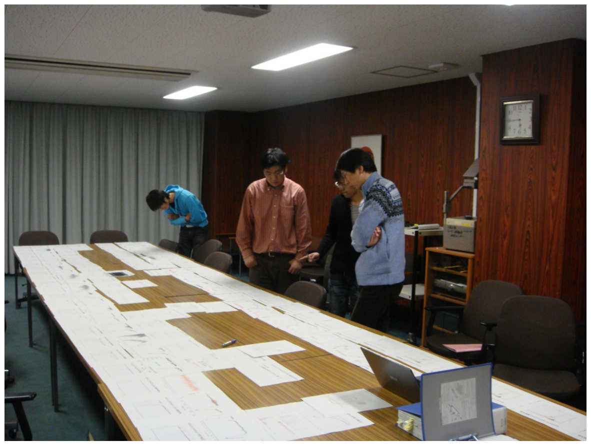
Time-resolving detectors

1. MANDALA: 4p shielding
2. TOFscintillator: 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

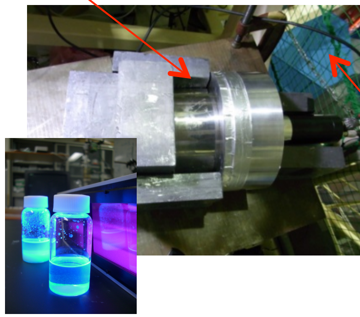
g-ray insensitive detectors

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



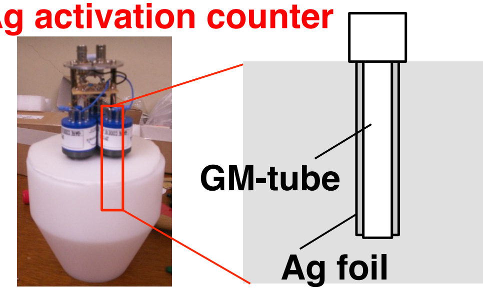
MANDALA

0-saturated quenching Liq. scintillator



PMT with gated-dinode

Ag activation counter

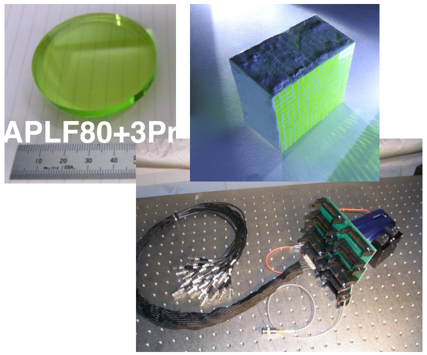


n-moderator (polyethlene)

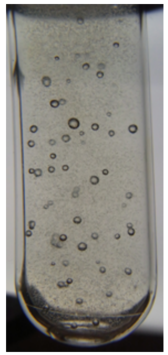
$$^{109}Ag + n \rightarrow ^{110}Ag + \gamma$$

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

^{6}Li scintillator



Bubble detector



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New liquid scintillator was developed

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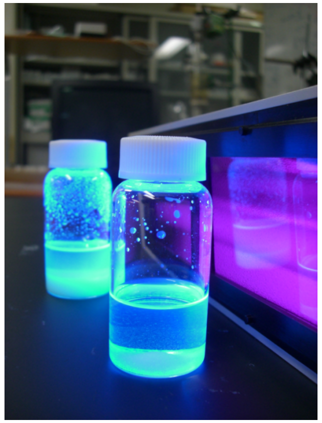

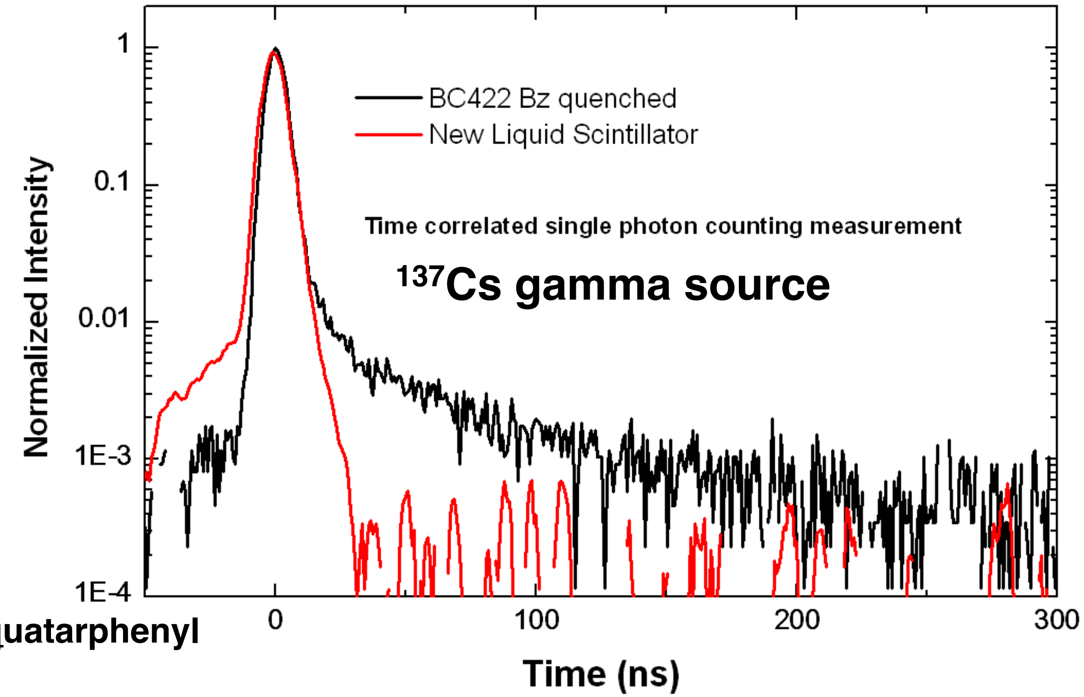

scintillation：
BBQ (used for dye lasers)
4,4’’’-Bis-(2-butyloctyloxy)-p-quatarphenyl

host：p-Xylene

Quenching by oxigen

T. Nagai et al., JJAP (2011).

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

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

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

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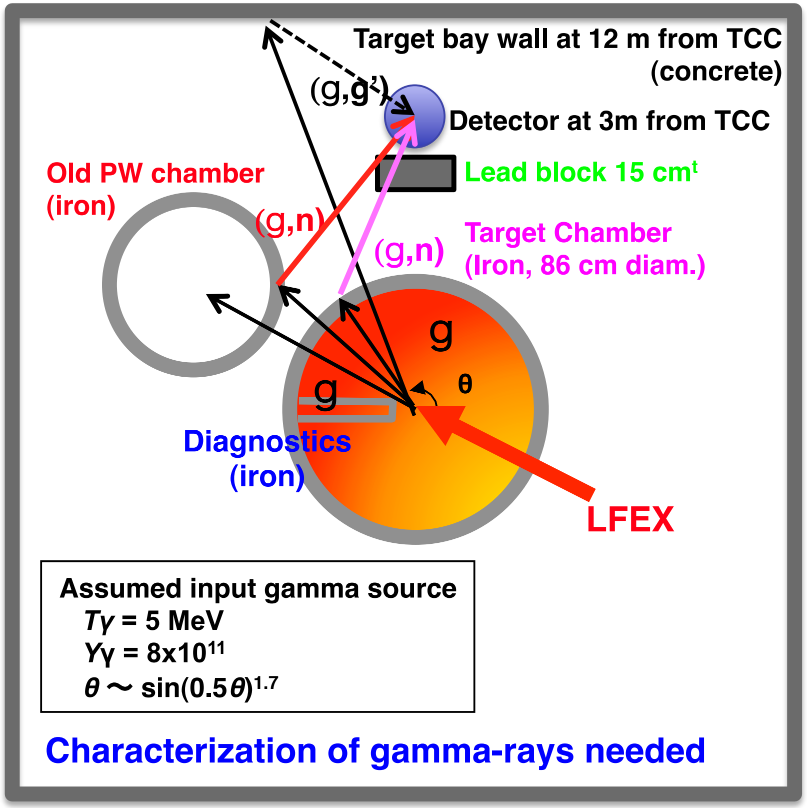
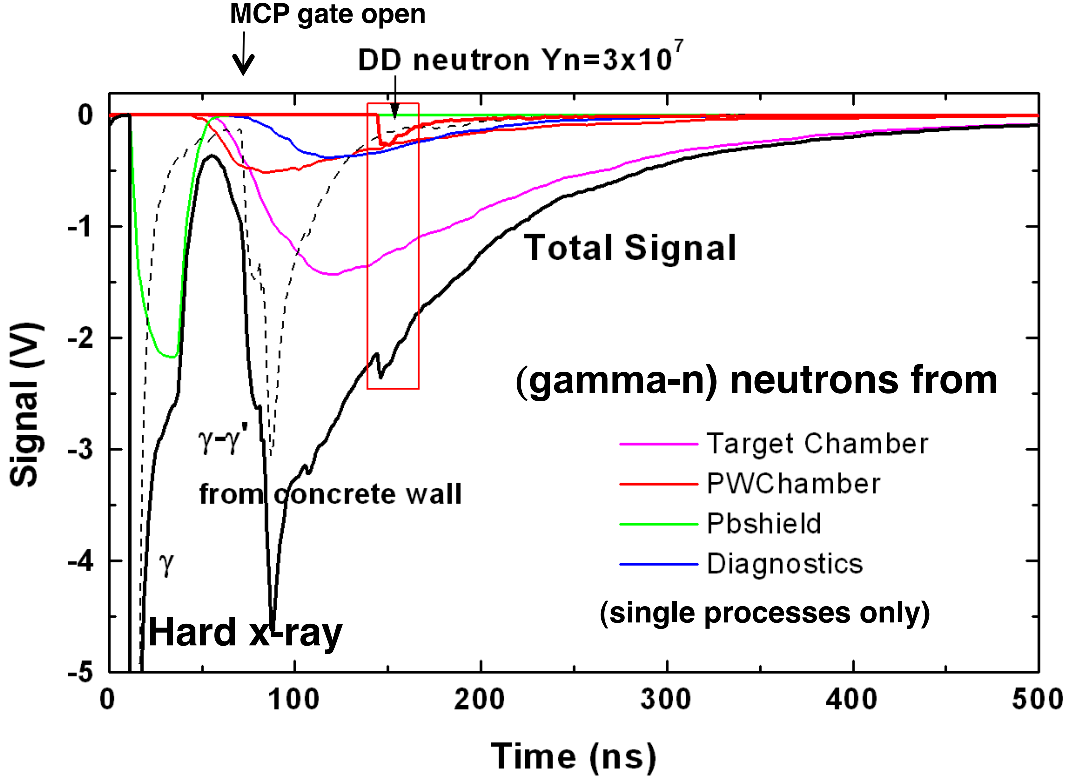
(gamma,n) and (gamma,gamma') in materials elsewhere in and around the target chamber and at the concrete walls



(gamma,n) and (gamma,gamma') 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.

Neutron yield was 30-times enhanced with LFEX injection

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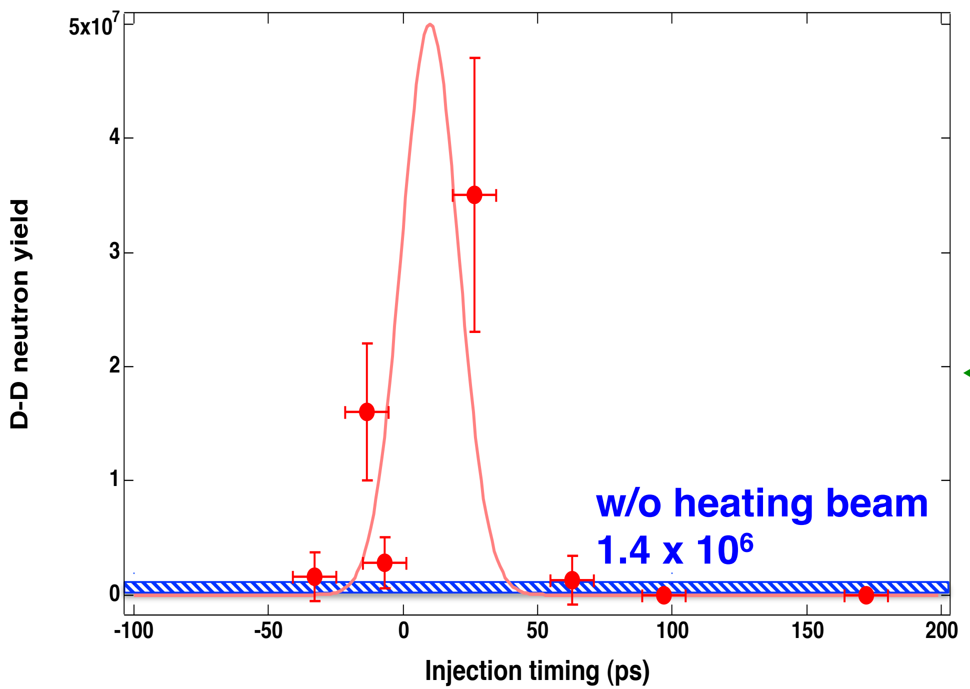
Shot#	DD-n ± γ-n err	**DD-Yn**	LFEX injection timing (ps)	LFEX energy@IMAP(J)
34177	$(1.25\pm0.5)\times10^6$ $\pm2\times10^6$	**$(1.25\pm2.1)\times10^6$**	+63 +/- 8	397.91
34183	$(3.5\pm1.2)\times10^7\pm2\times10^6$	**$(3.5\pm1.2)\times10^7$**	+27 +/- 8	430.5
34186	$(2.8\pm1.0)\times10^6\pm2\times10^6$	**$(2.8\pm2.2)\times10^6$**	- 7 +/- 8	694.1
34187	$(1.6\pm0.6)\times10^7\pm2\times10^6$	**$(1.6\pm0.6)\times10^7$**	-14 +/- 8	598.3
34189	$(1.6\pm0.5)\times10^6\pm2\times10^6$	**$(1.6\pm2.1)\times10^6$**	-33 +/- 8	318.8
34193 w/o LFEX	$(1.44\pm0.5)\times10^6$	**$(1.44\pm0.5)\times10^6$**		

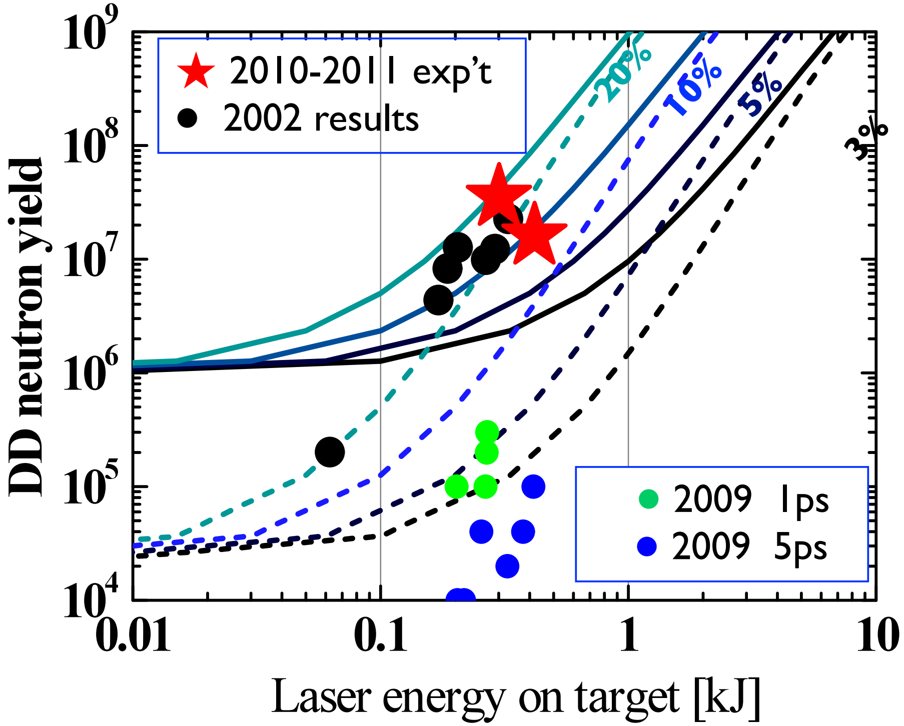


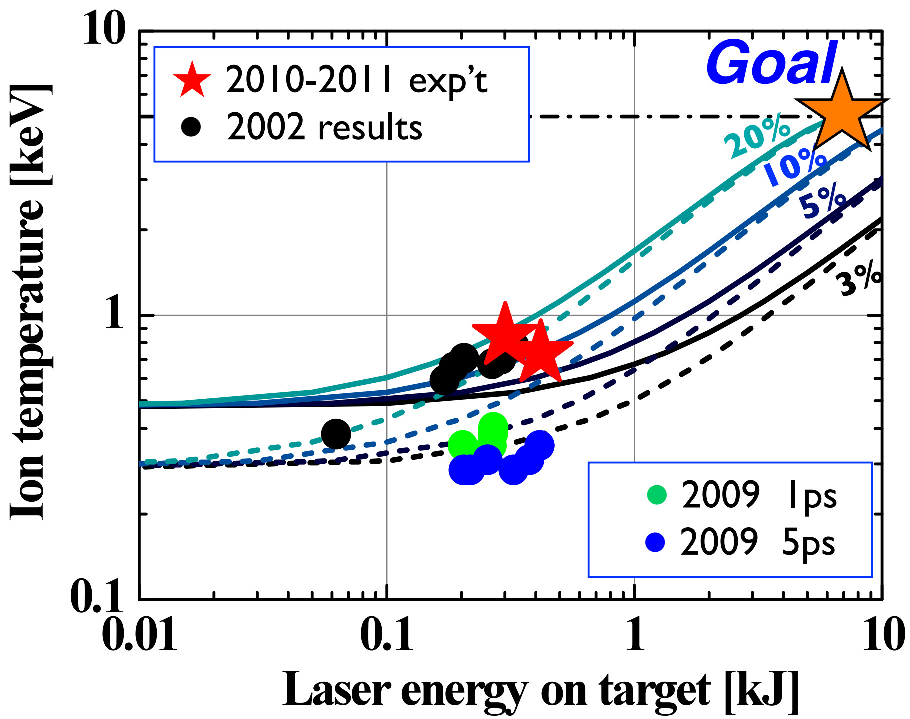
5 guaranteed shots among 38 (Others were too much noisy.)

← 2002 exp't

Y_n exceeded result in 2002.

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





Marks→ experiments
Lines → simulations
dashed lines : for 2002, 2009 exp't
solid lines : for 2010-2011 exp't

Initial density profile of the core plasma assumed:
Gaussian profile
r_{max} = 100 g/cm³, R = 20µm

Not yet optimized:

- *Input energy and heating efficiency to be increased*
- *Heating physics to be clarified and controlled*

3. New approaches underway in 2012 to improve the heating efficiency

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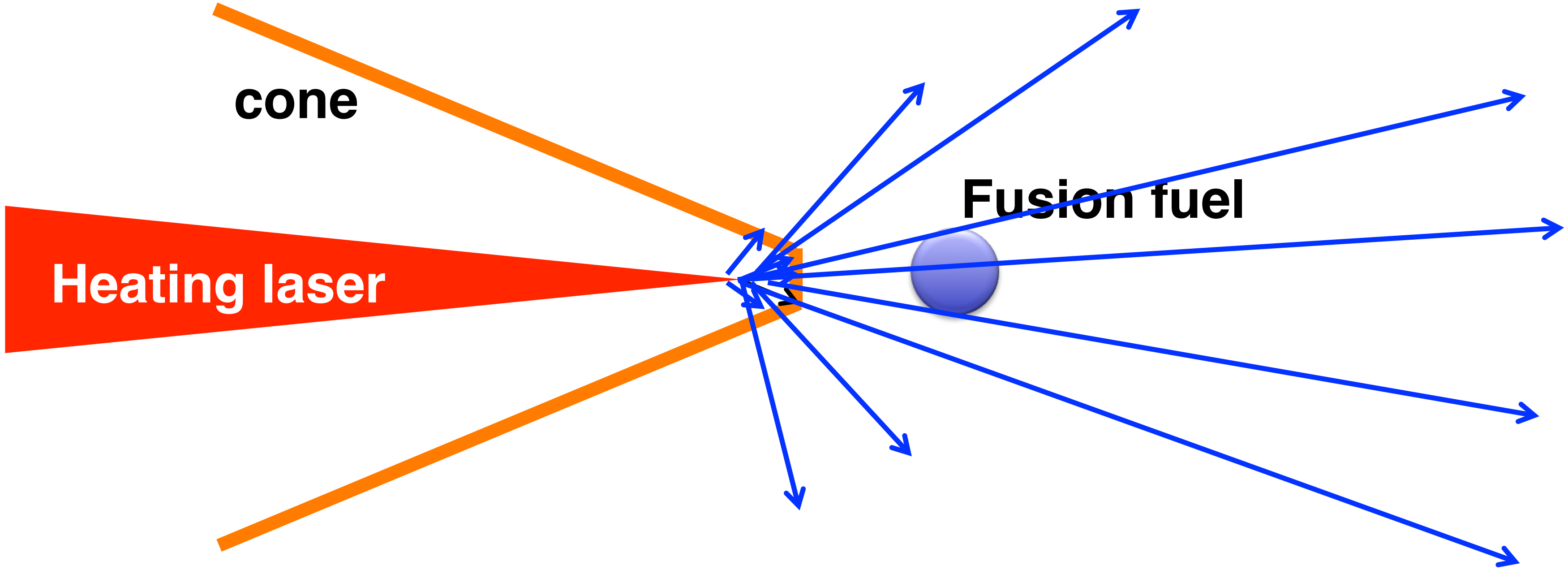

a. Reduce pre-plasma → *Reduce hot electron temperature*

b. Low-Z cone → *Better hot electron transport*

c. External B field → *Reduce hot electron divergence*

a. Preformed Plasma Reduction

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

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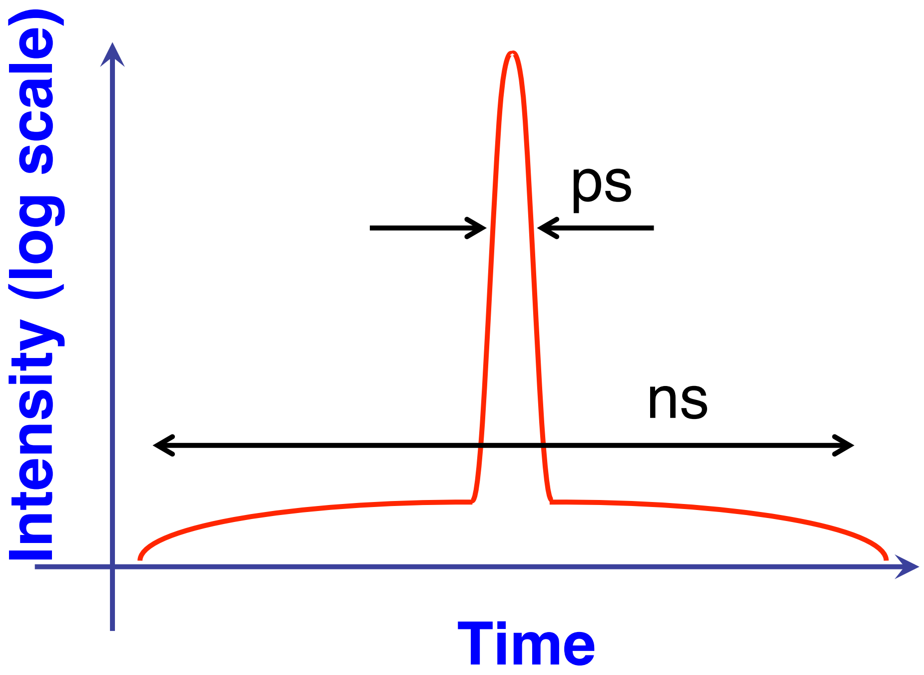
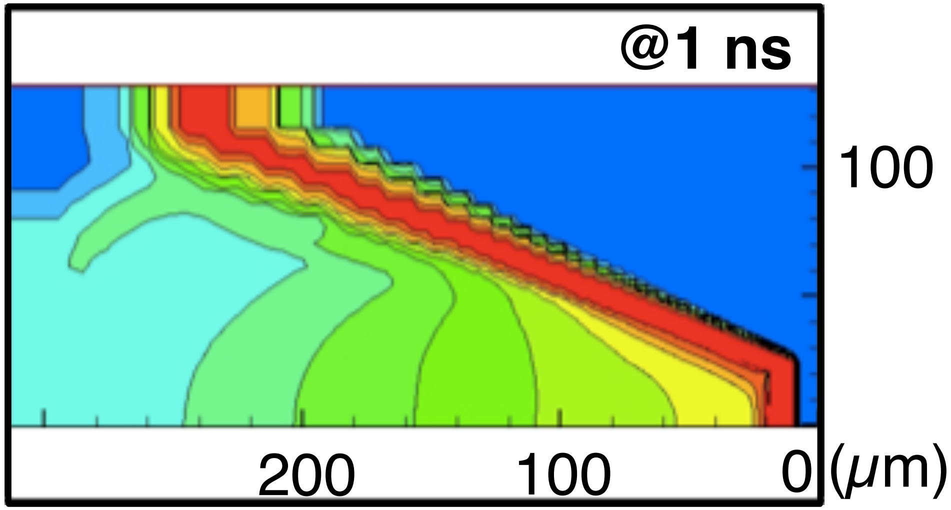
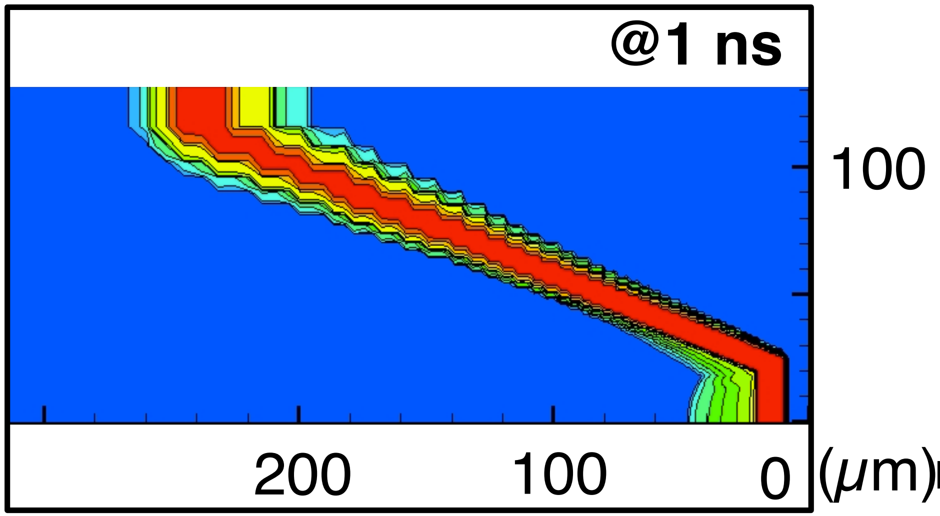
Pulse shape of LFEX



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



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



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

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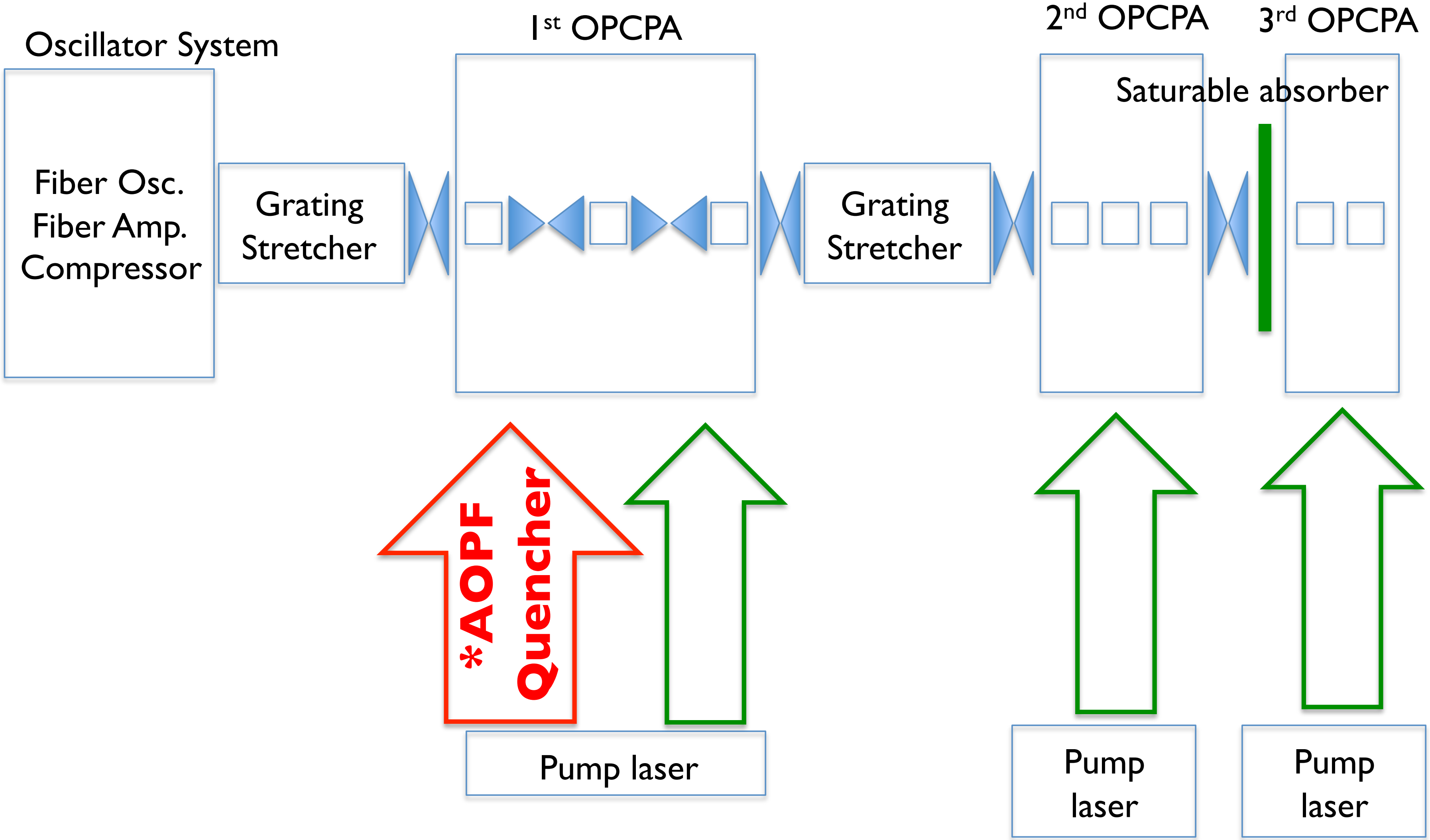

***K. Kondo *et al.*, J. Opt. Soc. Am. B, Vol. 23 (2006).**

Preformed plasma was clearly reduced in 2012 experiment

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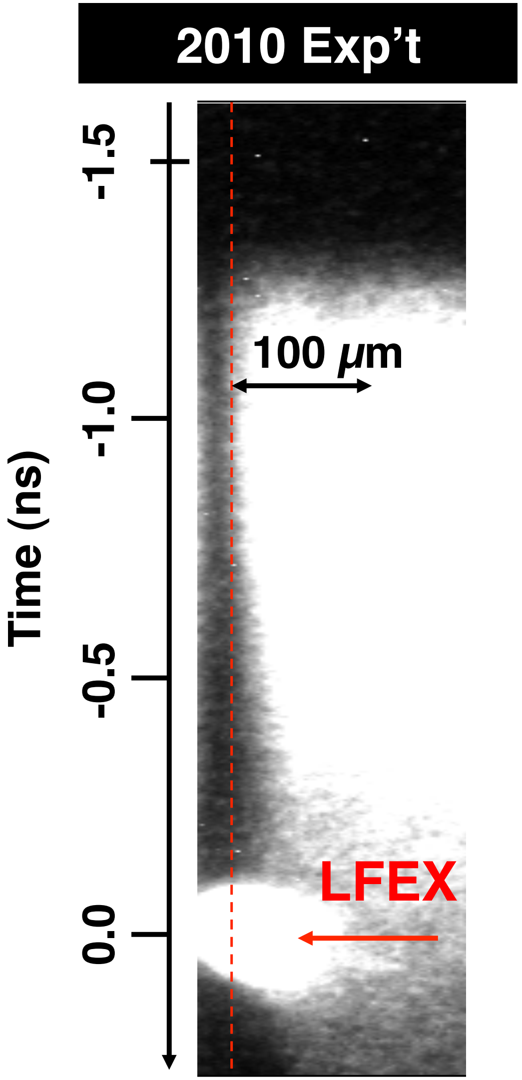

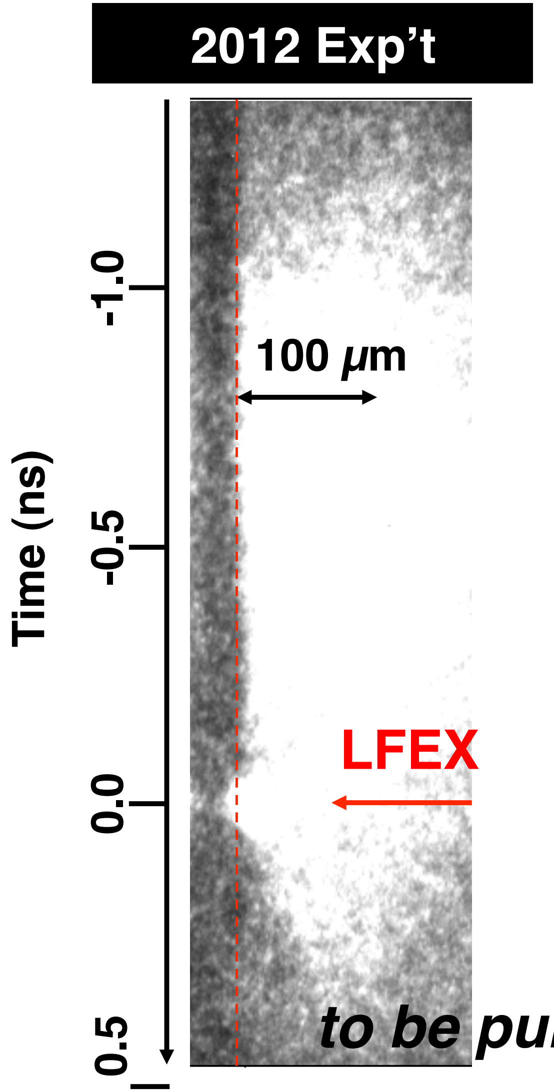

to be published in RSI

High energy-coupling is expected.

b. Low-Z Cone

Scattering loss is less in low-Z cone than in high-Z cone

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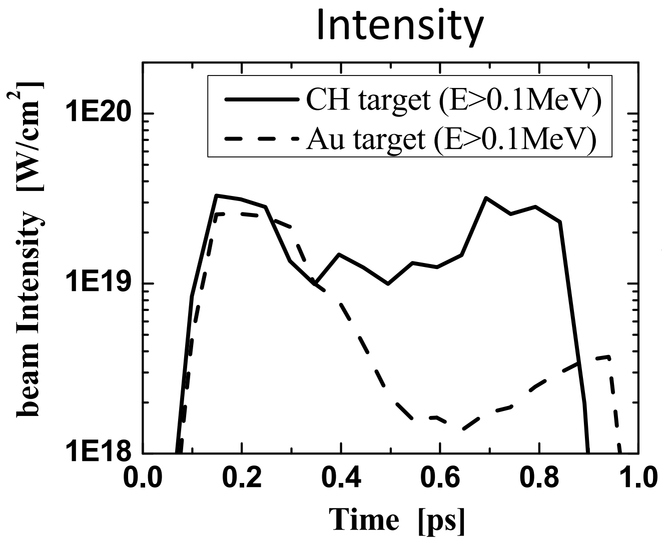

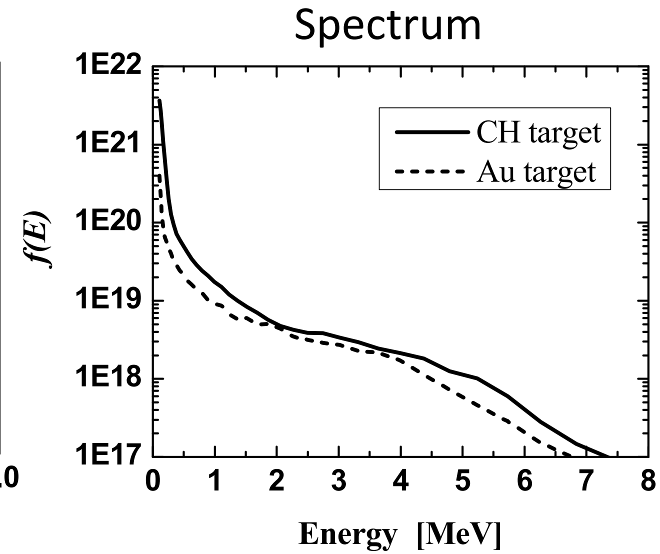

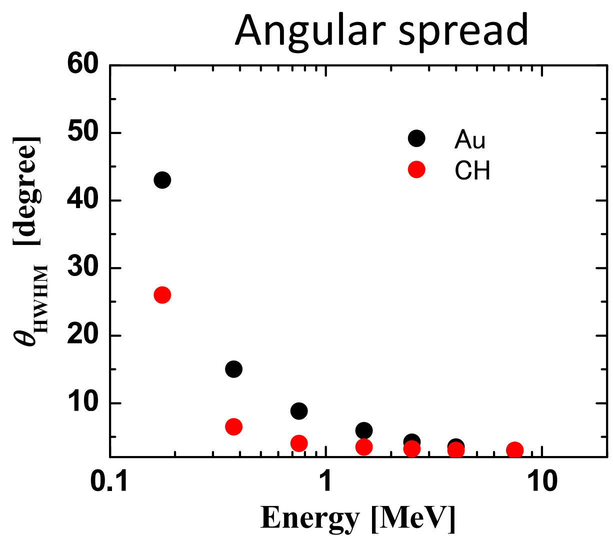

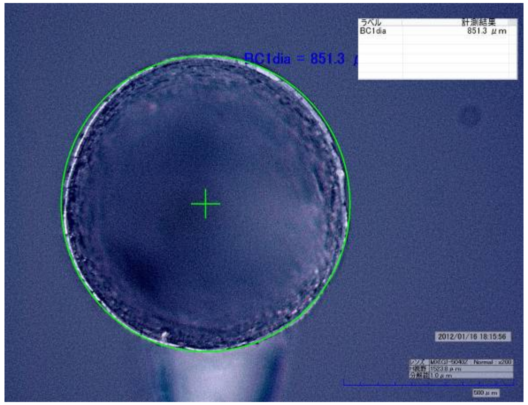

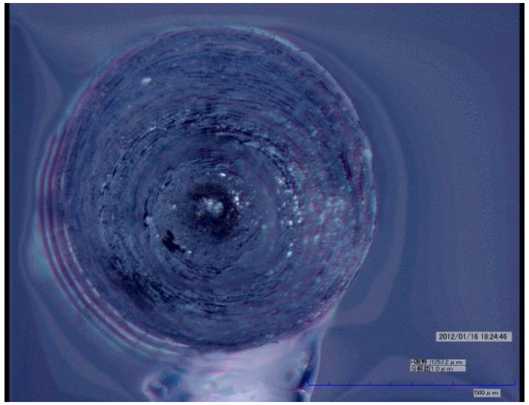

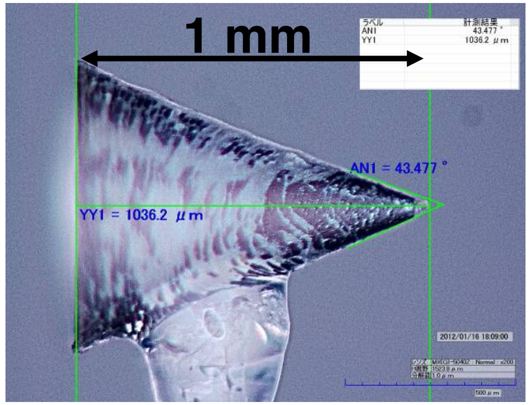

Diamond-like-carbon (DLC) cone is a suitable candidate from the stand point of low-Z and mechanical strength.

Diamond-like-carbon (DLC) cone attached to CD shell was successfully introduced to the FI integrated experiment

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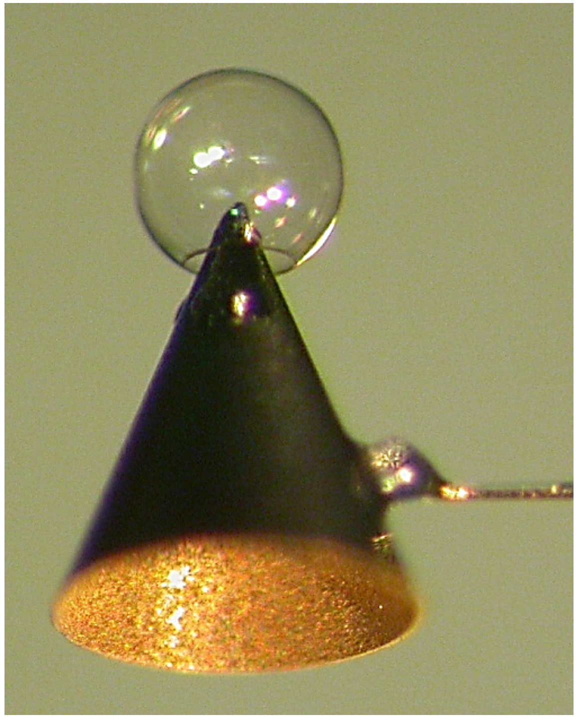
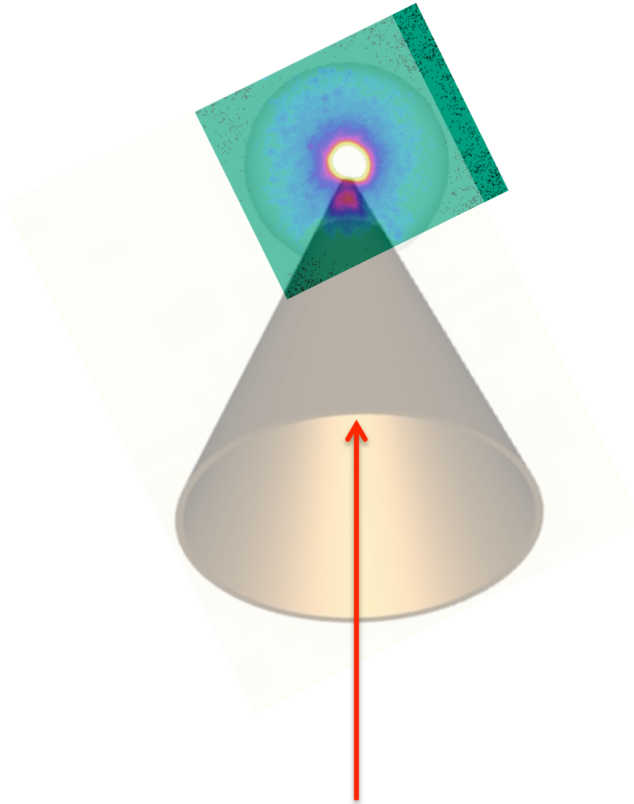
Photo of DLC cone



20-μm-thick DLC cone. Inner surface is coated with 100-nm-thick Au.

X-ray image



Introduced to the FI integrated experiment

c. Strong-B field Generation

Initially 300 T → compressed to 10 kT by implosion, guide electron flow to the fuel

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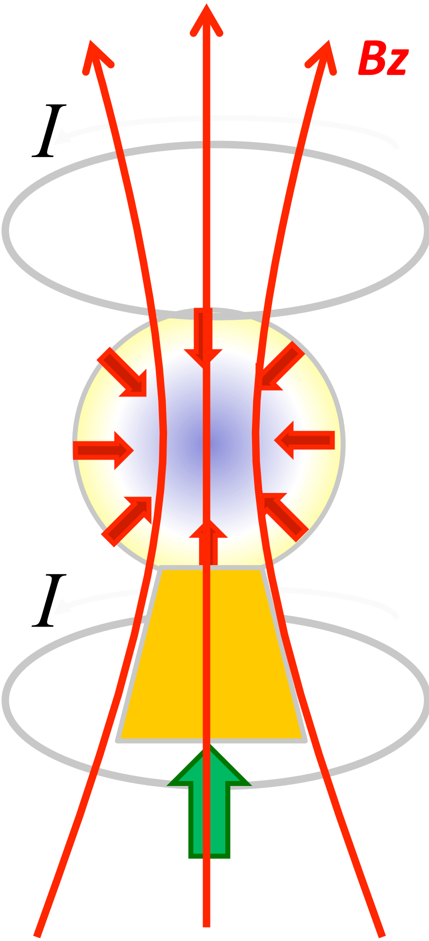
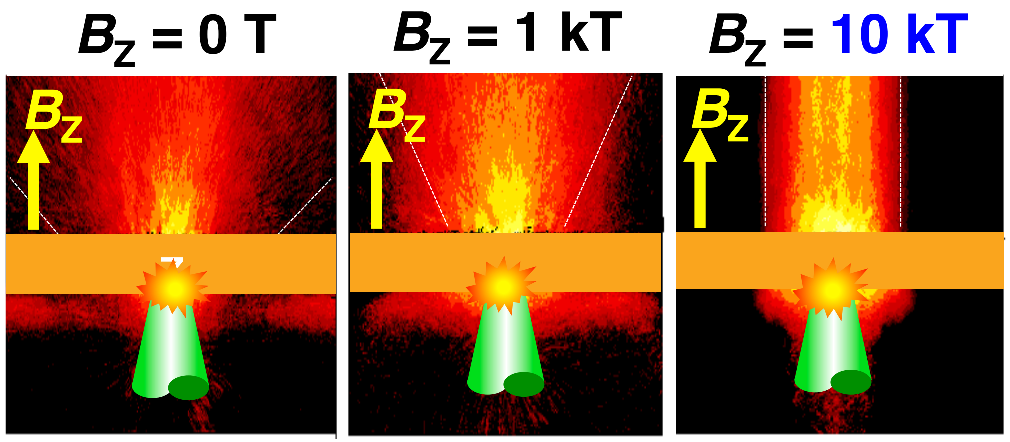
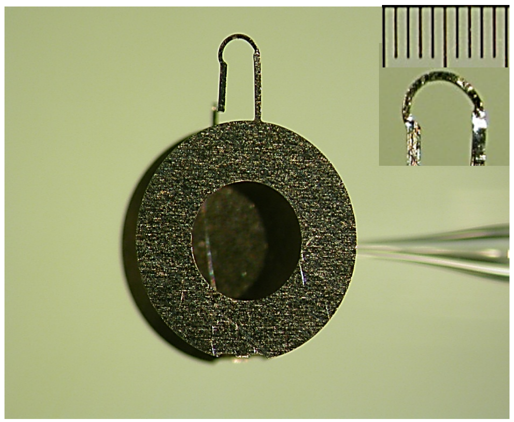
Schematic



PIC simulations



Coil target for *B* field generation



kT-class *B* field generated, and electron flow collimated

(Fujioka, *et al*., to appear in PPCF)

Experimental demonstration has been started.

Strong B field was generated with laser-irradiated coil target

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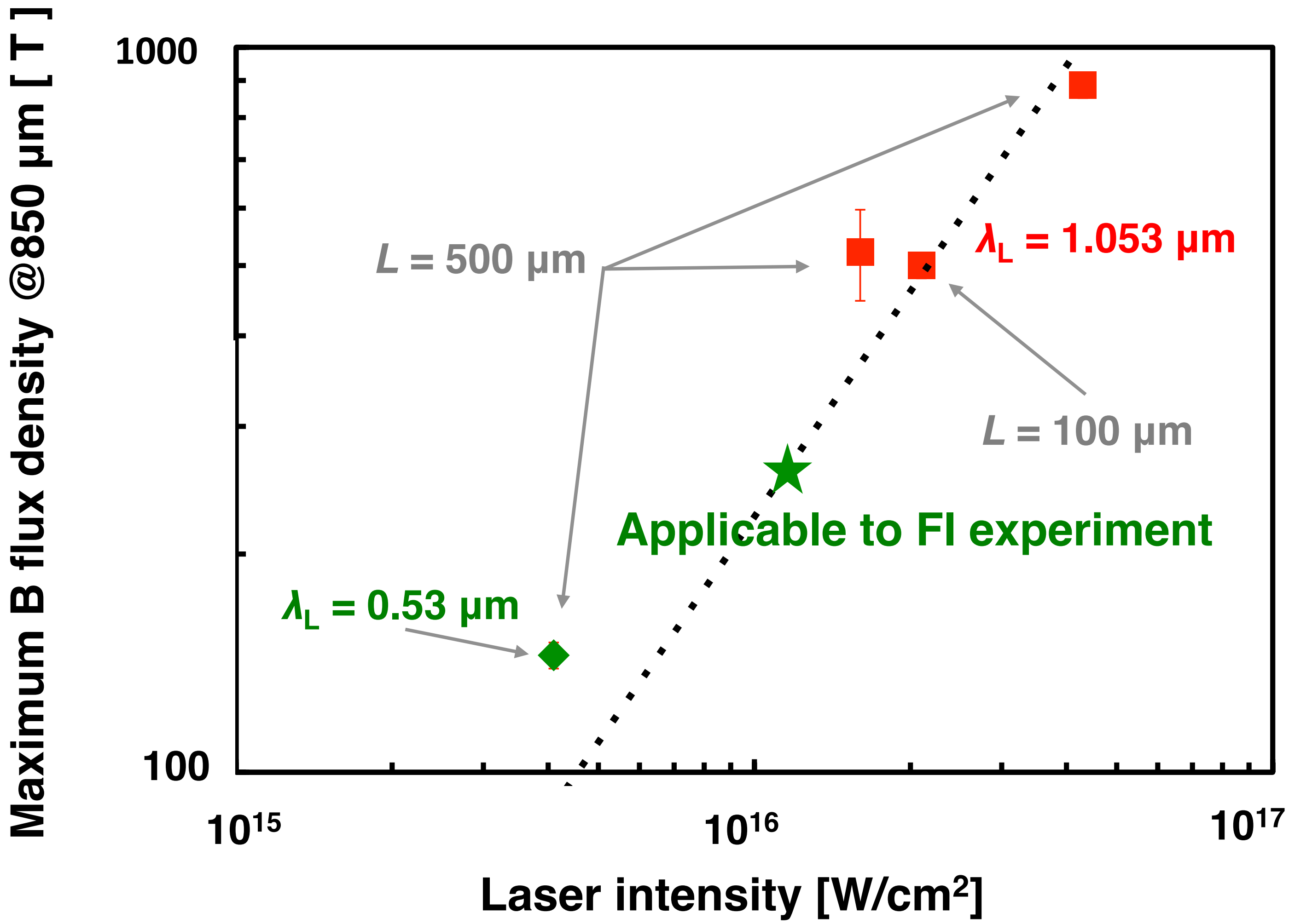

Implosion of the shell is expected to compress the B field to 10 kT.

Summary and conclusions

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1. LFEX laser has been activated and used with Gekko laser.

- **2 kJ / 2 beams /1.5 ps operation performed**
- **Pre-pulse level and pointing stability significantly improved**

2. FI integrated experiments has been successfully performed, neutron enhancement in 2002 experiments was reconfirmed.

- **Plasma diagnostics compatible to hard x-ray harsh environment**
- **Gamma-ray reactions identified in neutron measurement**
- **Neutron yield enhancement up to 3.5E7 achieved**
- **Heating efficiency estimated to be 10-20%**

3. New approaches are underway for improved heating efficiency.

- **Preformed plasma reduction**
- **Low-Z DLC cone**
- **B-field to guide electron flow**

→ We are "Go" for FIREX-1 full-spec experiment in 2012-2013.

- **Increase LFEX energy in 4-beam operation**
- **Further improve shielding and collimation of diagnostics**
- **Goal of FIREX-1: heating up to 5 keV**

Thank you for your attention!