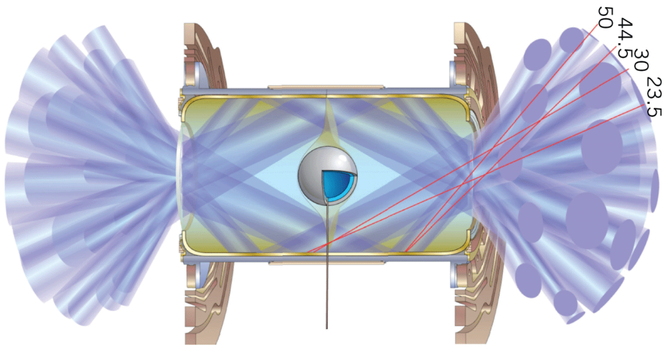
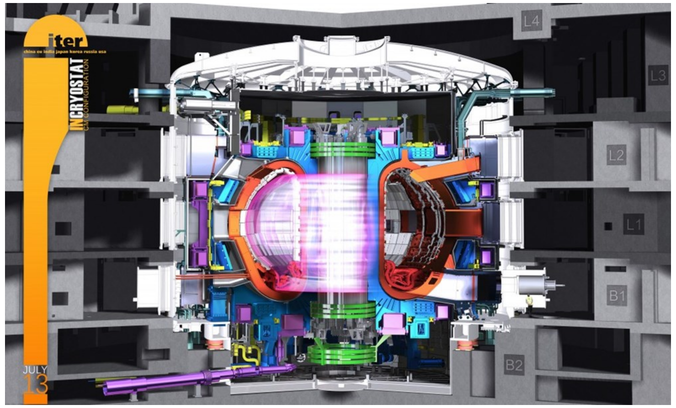
First experimental demonstration of magnetized fast isochoric heating = MFI =

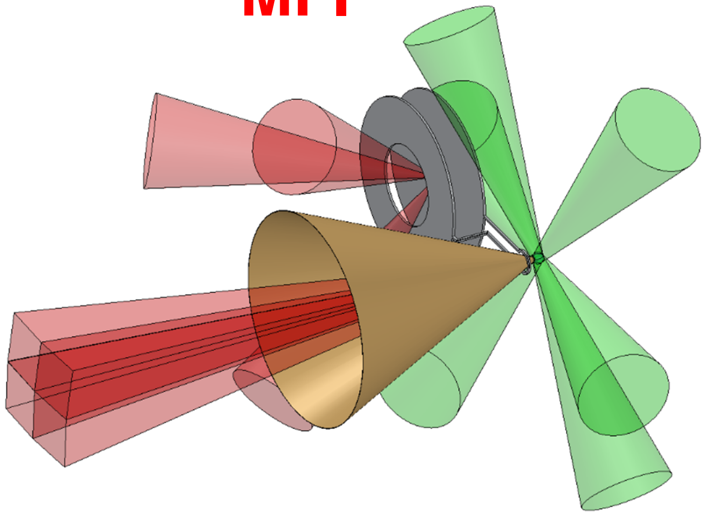
ICF



MCF



MFI



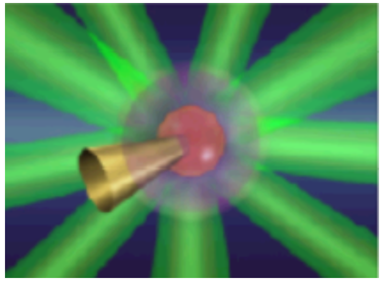
Shinsuke FUJIOKA (Institute of Laser Engineering, Osaka Univ.)

There are three critical problems in the fast-isochoric heating.

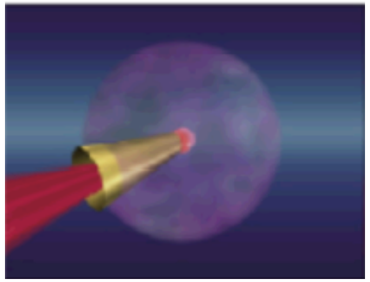
Too energetic and diverging electron are accelerated to heat a fuel.

ILE, Osaka

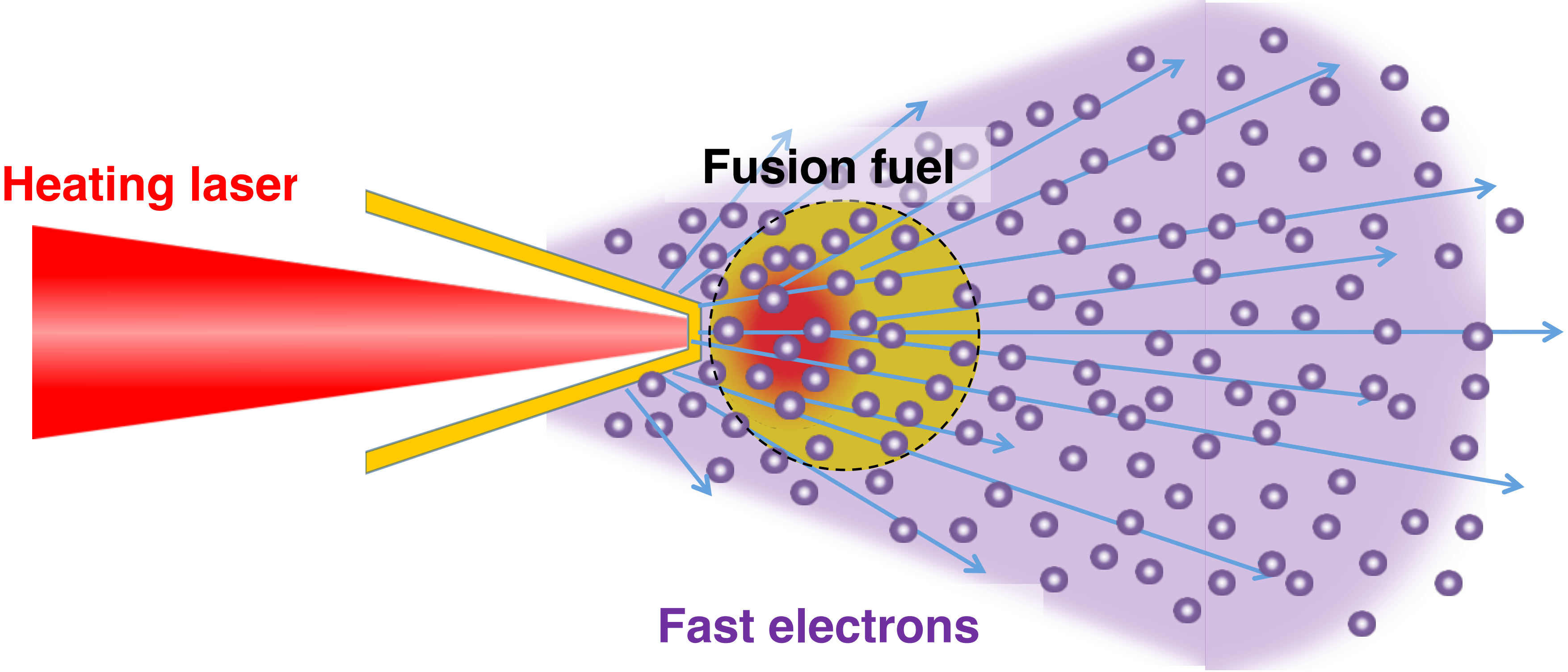
Fuel compression by multiple ns beams



Heating by ps beams



Ignition & burn



Scattering --- Electron beam is scattered in ionized high-Z cone tip.

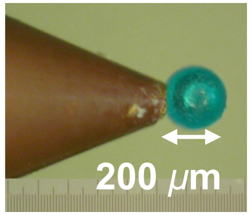
Diverging --- Electron beam have a large divergence angle (> 100 deg.).

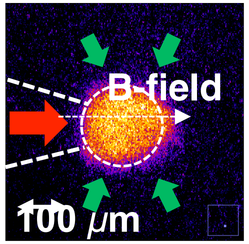
Energy flux of the REB decreases significantly during transport.

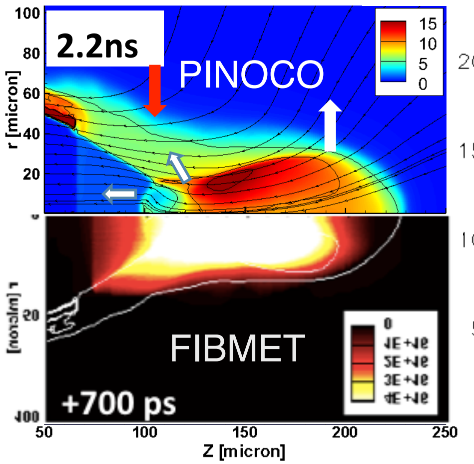
Unstoppable --- Too energetic electrons are generated by laser-plasma interactions in a long-scale under-dense plasma.

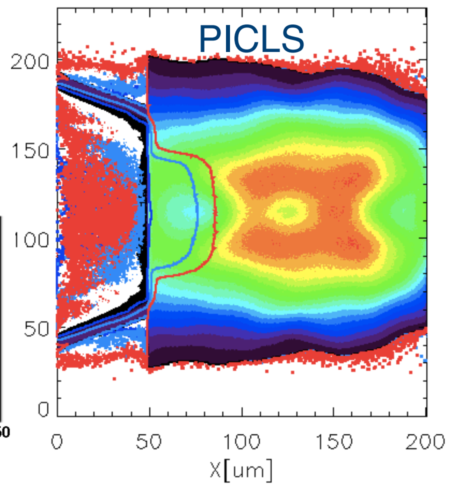
Summary

- "Fusion" between magnetic confinement of an energetic electron beam and inertial confinement of a fuel leads to efficient laser-to-core energy coupling.
- 8% of the laser-to-core coupling was achieved by using the MFI scheme even with a small pre-compressed core ($\rho R \sim 0.1$ g/cm^2).
- Energy density increment was 1 Gbar (= 50 J in 100-μm-spherical volume).
- 15% is achievable with a 0.3 g/cm^2 core based on a simplified estimation.
- We hope to conduct a scale-up experiment in the US facilities (OMEGA & NIF).









20X improvement of the laser-to-core coupling was achieved by reducing pre-plasma filling in the cone and guiding diverged electrons.

ILE, Osaka

Simple model of laser-to-core coupling

S. Fujioka, T. Johzaki *et al.*, Phys. Rev. E (2015).

Laser-to-core coupling = Laser- Electron Conversion Efficiency X $\frac{\text{Fuel cross section}}{\text{E-beam cross section @fuel}}$ X Electron Energy Deposition Fraction

Electron Energy Deposition Fraction ≈ $\frac{2 \times \text{fuel areal density}}{\text{Range of e-beam}}$

0.4% @2013 = 40% X 40 % X 2.5%

Guiding of REB by B-field (Today's topic)

Reduction of pre-plasma filling

~8 % @2016 = 40 % 80 % 25%

B-field generation for MFI scheme

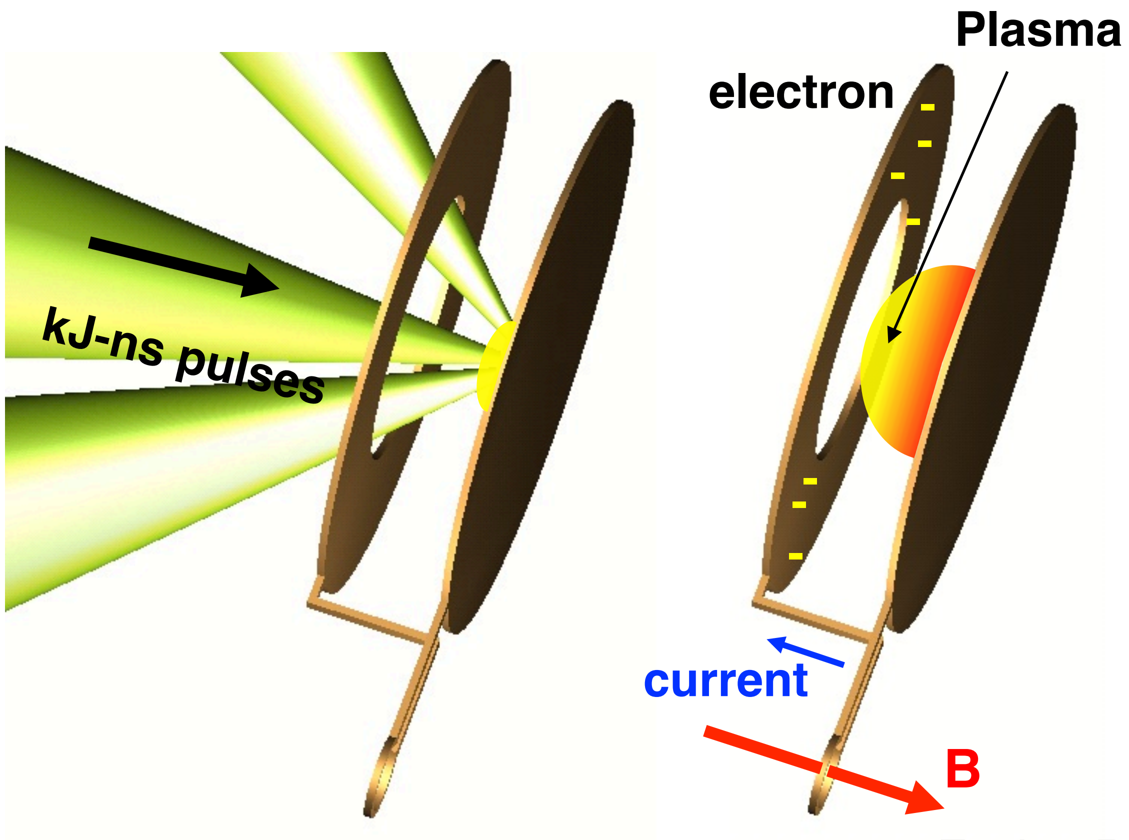
Laser-produced magnetic field was used to guide the diverging electron beam to a fuel core.

ILE, Osaka

#H. Daido *et al.*, PRL (1985), C. Courtois *et al.*, JAP (2005).
*S. Fujioka *et al.*, Sci. Rep. (2013), K. Law *et al.*, APL (2016).

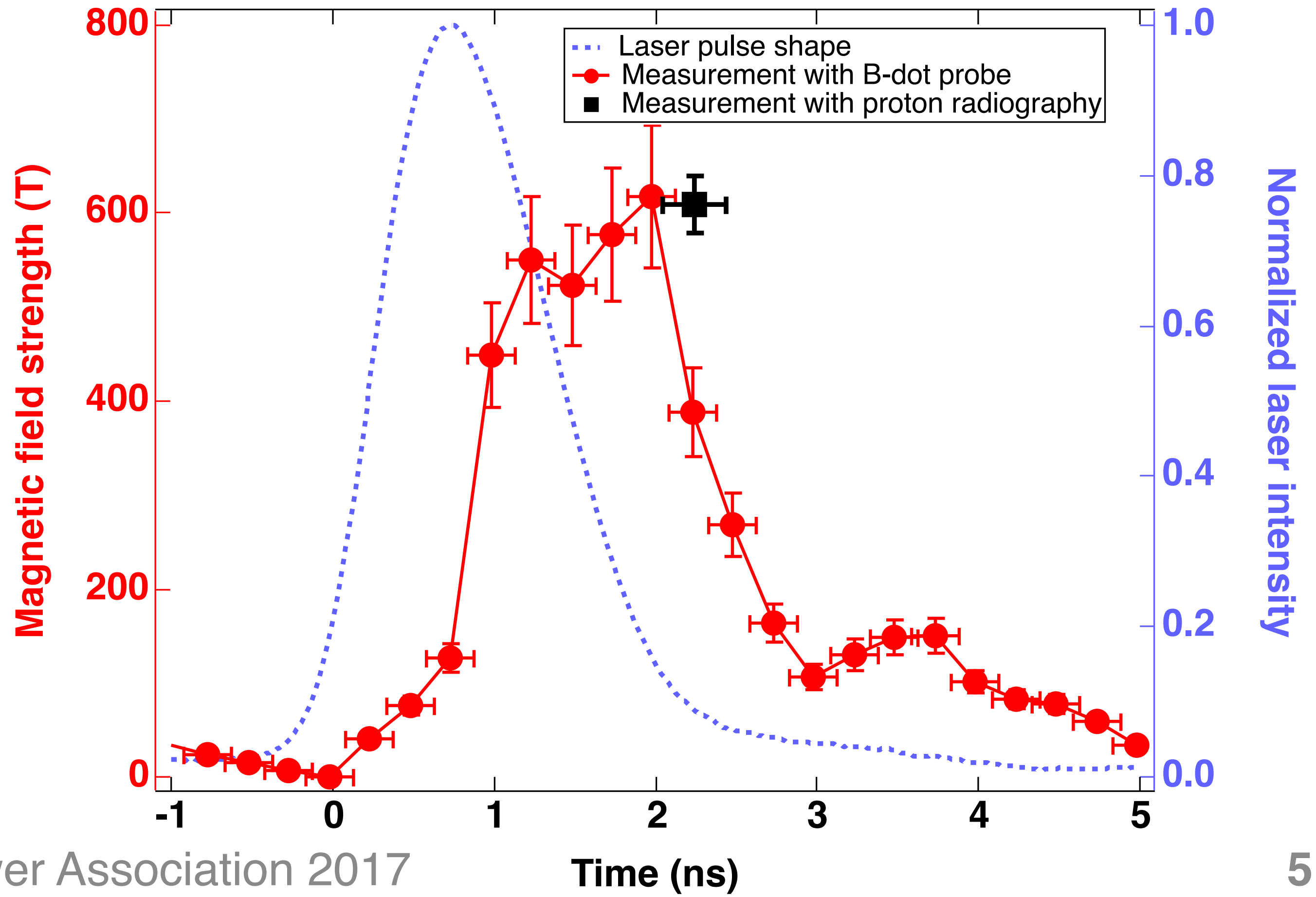
B-feild generation with capacitor-coil target

Laser driven current produce kT-level B-field



Temporal history of B-field measured with B-dot probe

600 T of the peak magnitude and 2 ns of the duration

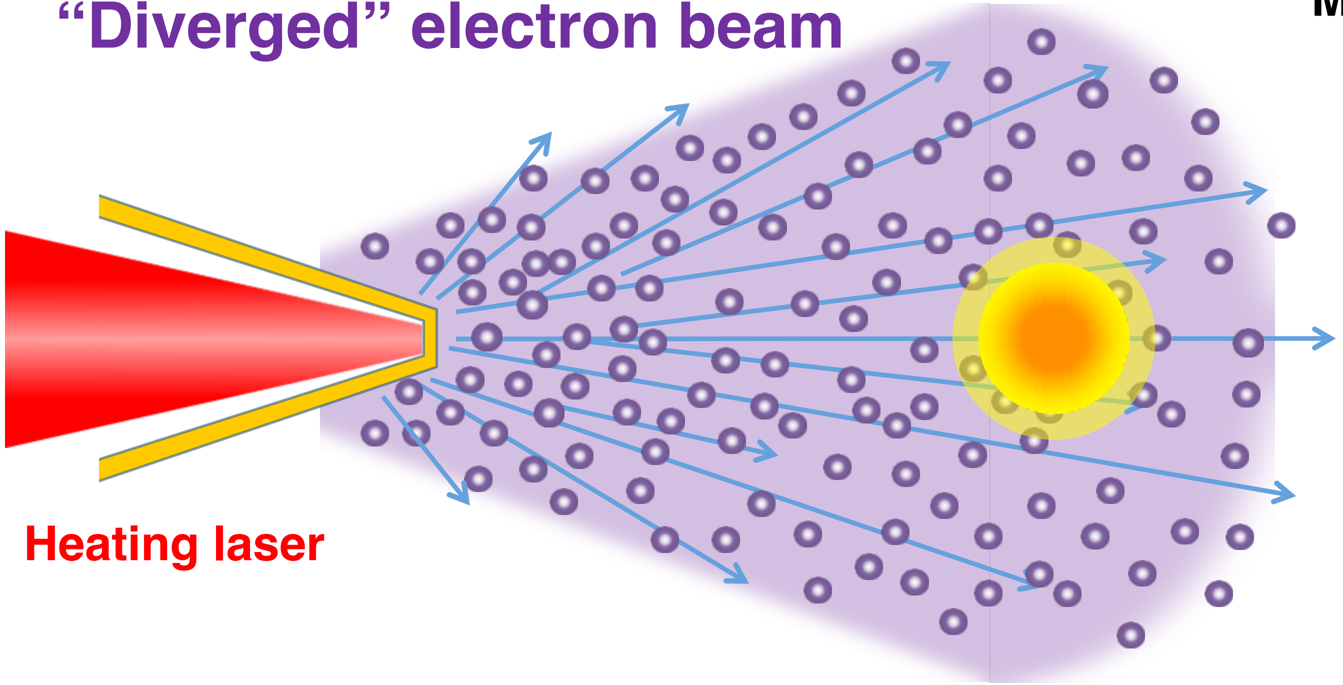


Guiding of the diverged REB by laser-driven magnetic field was demonstrated in a planar geometry.

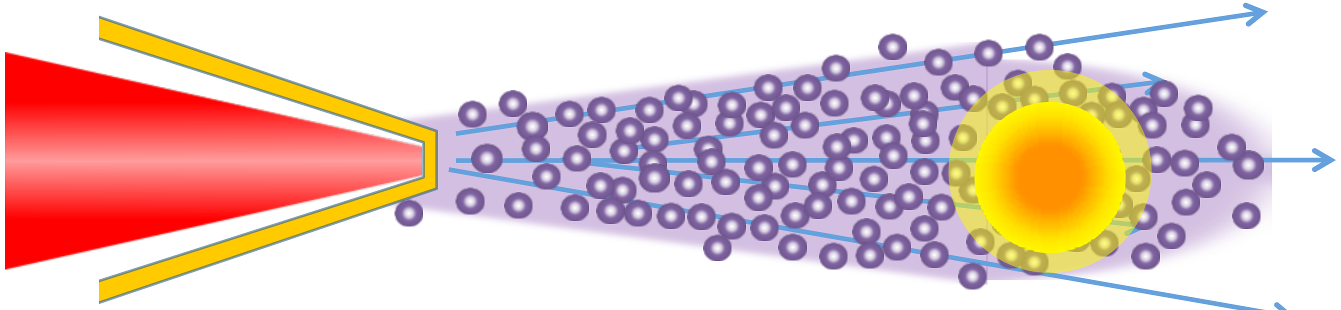
ILE, Osaka

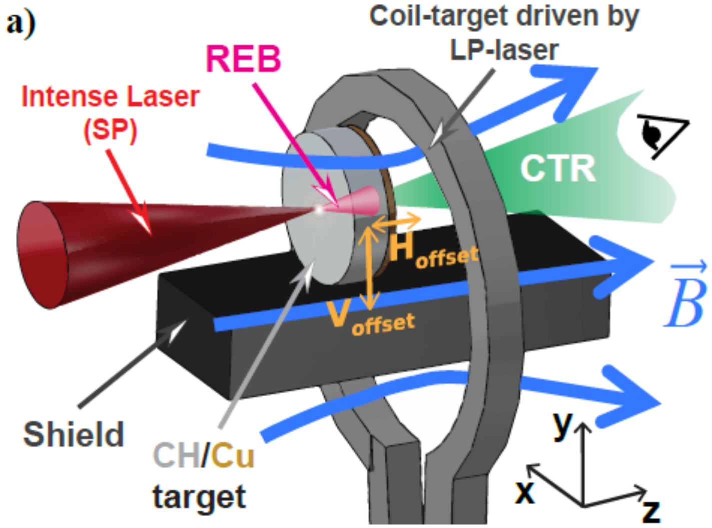
M. Bailly-Grandvaux *et al.*, Nat. Comm. (accepted).

"Diverged" electron beam

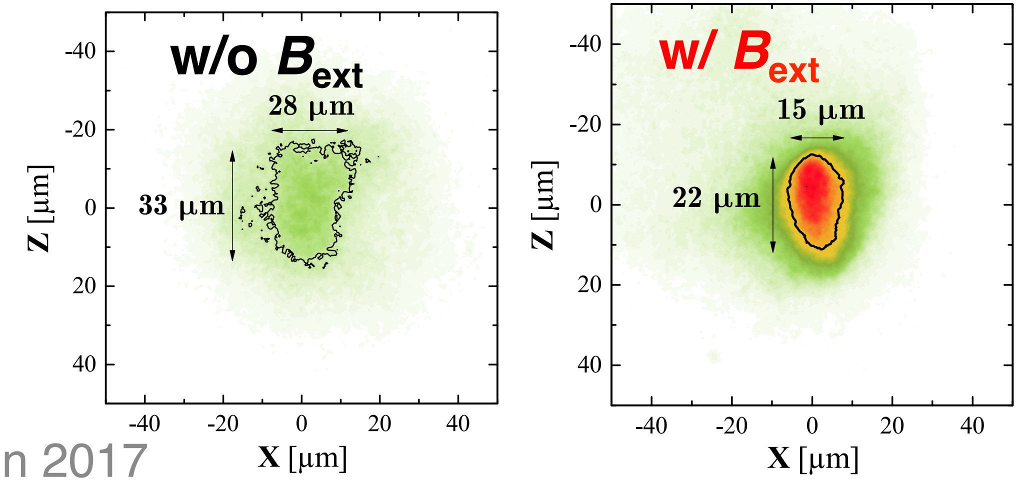


"Collimated" electron beam





Experimental results



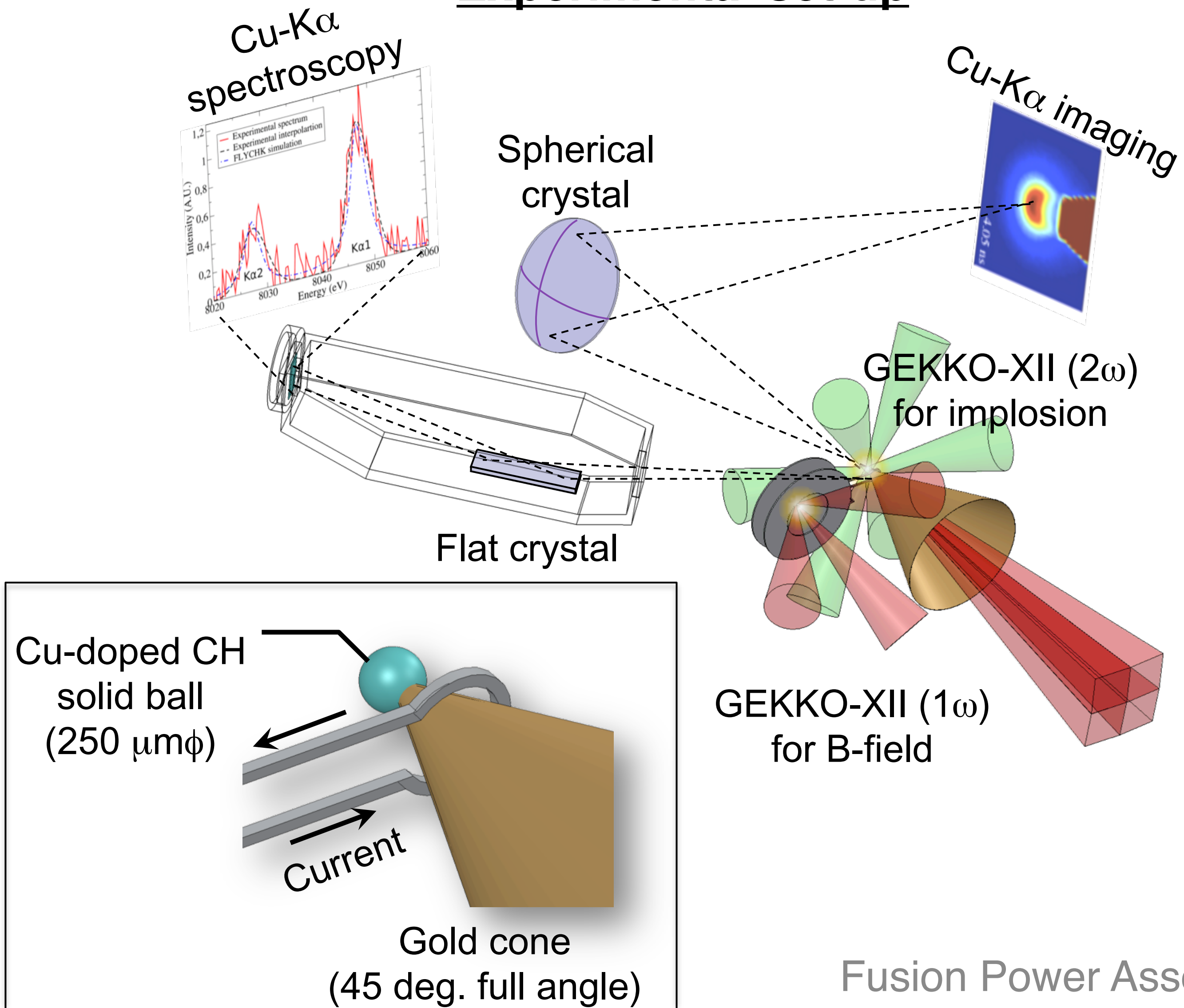
Integrated experiments of MFI scheme

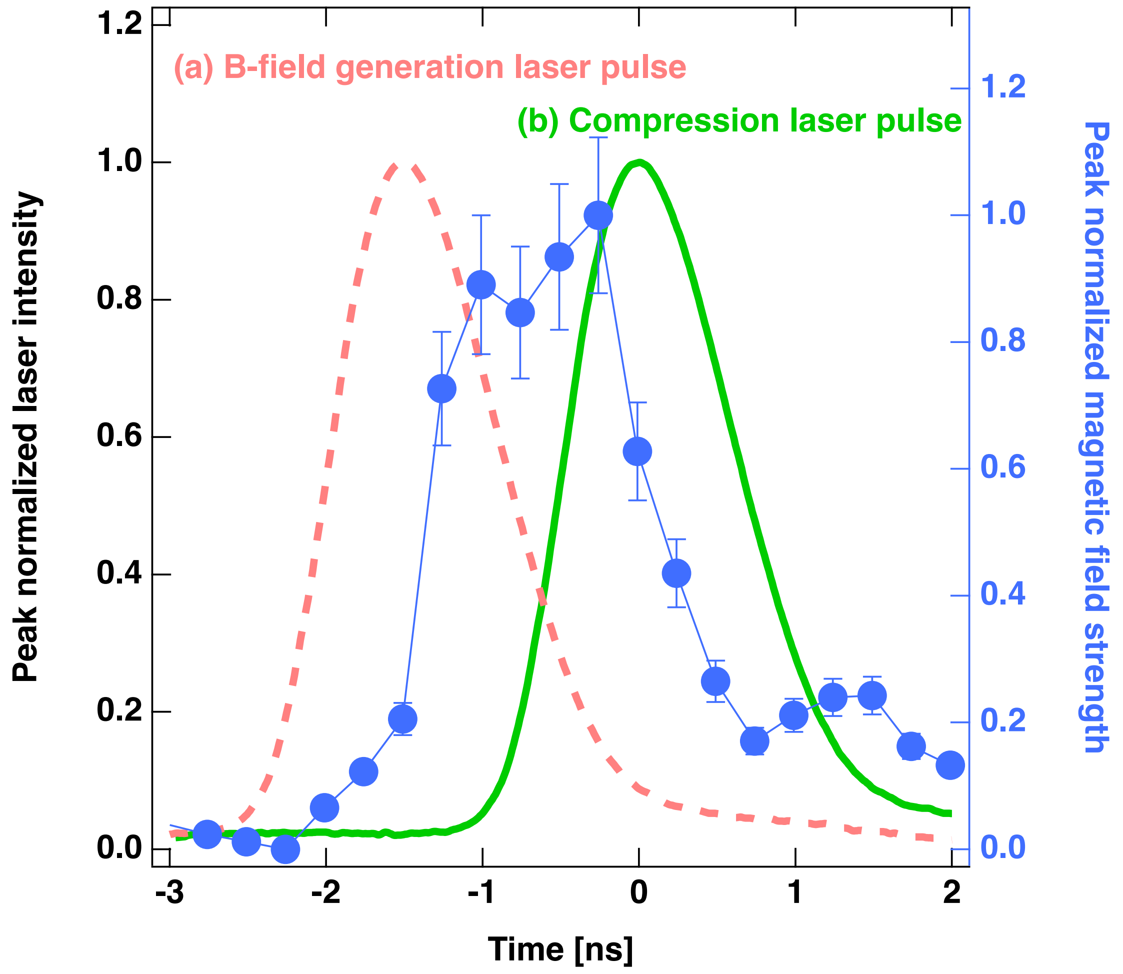
Cu-doped solid ball were used in integrated experiment for visualization of energy-deposition and measurement of temperature.

ILE, Osaka

Experimental set-up

S. Sakata *et al.*, submitted.



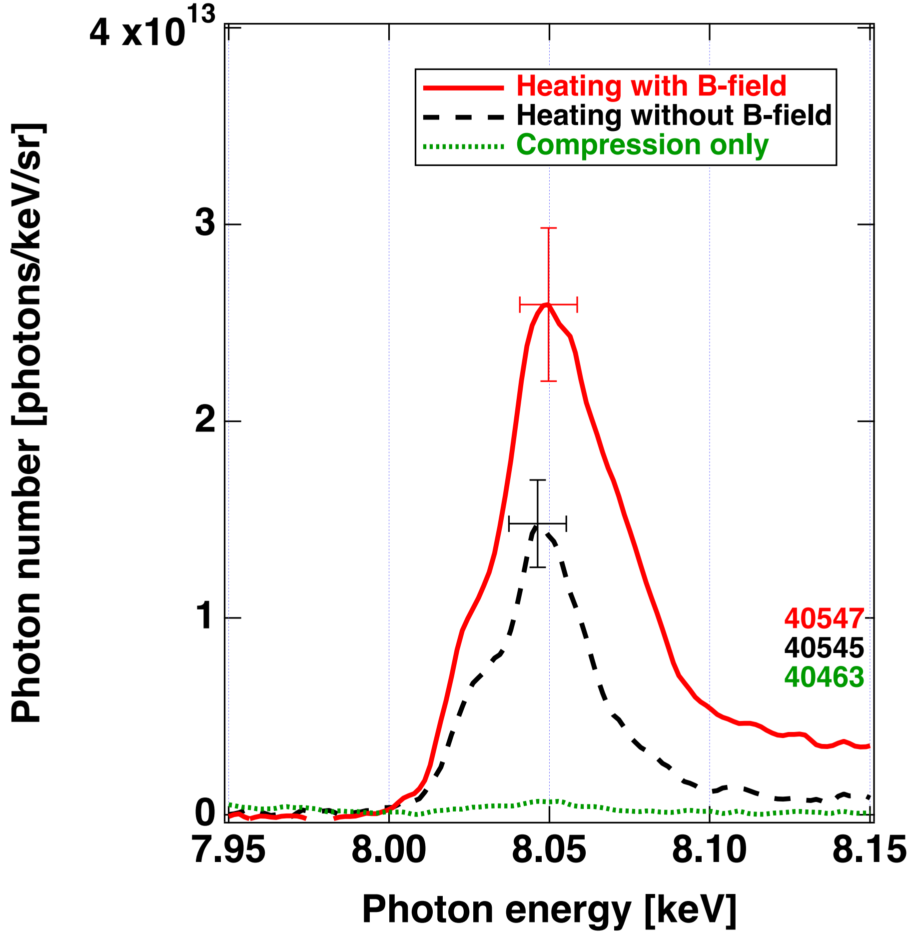


Integrated experiments of MFI scheme

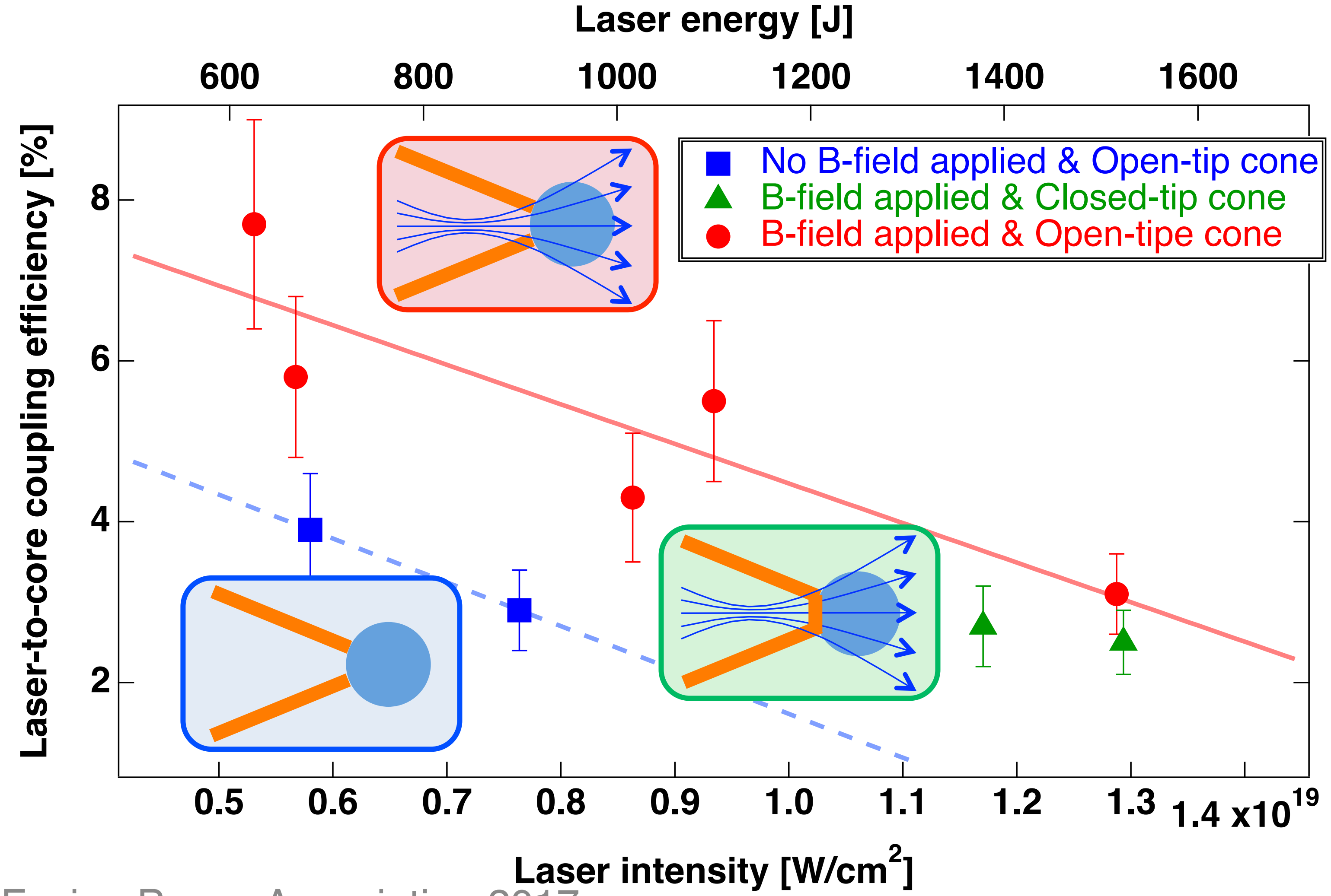
Efficient laser-to-core coupling (~8%) was achieved even with a relatively small ρR core (~ 0.1 g/cm^2) by application of external *B*-field.

ILE, Osaka

Cu-$K\alpha$ spectra



Dependence of laser-to-core coupling

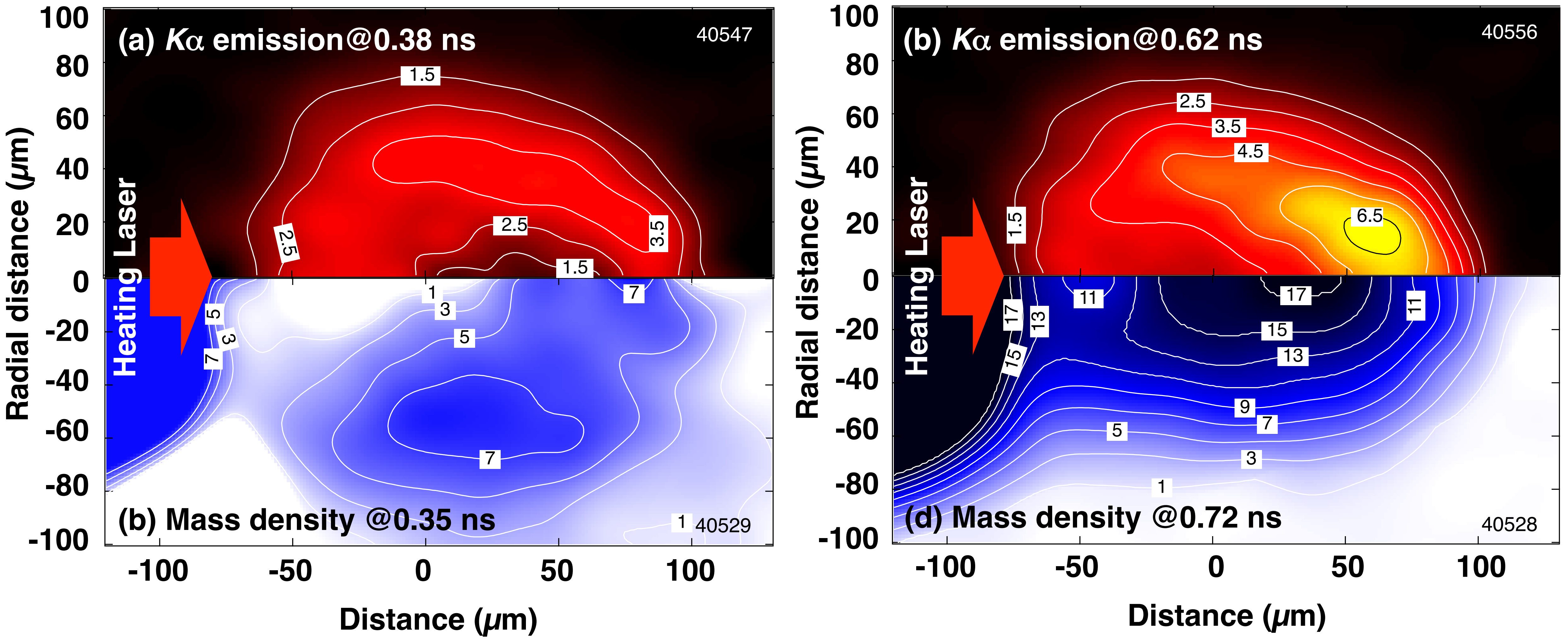


Integrated experiments of MFI scheme

REB energy deposition in the shocked region and the far edge of the core was clearly enhanced in the magnetized core.

ILE, Osaka

S. Sakata *et al.*, submitted.



S. Sakata, S. H. Lee, K. Matsuo, K. F. F. Law, Y. Iwasa, Y. Arikawa, A. Yogo, A. Morace, Y. Abe, S. Kojima, T. Gawa, S. Tosaki, Y. Fujimoto, T. Jitsuno, J. Kawanaka, M. Hata, Y. Hironaka, K. Mima, M. Murakami, N. Miyanaga, H. Nagatomo, M. Nakai, Y. Nakata, K. Nishihara, H. Nishimura, T. Norimatsu, T. Sano, Y. Sakawa, Y. Sentoku, K. Shigemori, K. Tsubakimoto, H. Shiraga, S. Tokita, K. Yamanoi, H. Azechi

ILE, Osaka

Institute of Laser Engineering, Osaka University, Japan

A. Sunahara

Institute for Laser Technology, Japan

T. Johzaki

Hiroshima University, Japan

K. Kondo

Tokyo Inst. Tech., Japan

A. Iwamoto, T. Ozaki, H. Sakagami

National Institute for Fusion Science, Japan

T. Shirato, N. Ohnishi

Tohoku Univ., Japan

H. Sawada

University of Nevada, Reno, USA

Z. Zhang

Institute of Physics, China

J. Santos, M. Bailly-Grandvaux, D. Batani, R. Bouillaud, P. Forestier-Colleoni, S. Hulin, Ph. Nicolaï, V. Tikhonchuk

CELIA, Univ. Bordeaux, France

L. Giuffrida

ELI-Beamline Project, Institute of Physics, Czech Republic

J.L. Dubois, J. Gazave, D. Raffestin and J. Ribolzi.

CEA, France

M. Chevrot, S. Dorard, E. Loyez, J.R. Marques, F. Serres

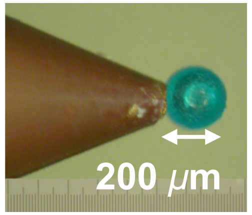
LULI, Ecole Polytechnique, France

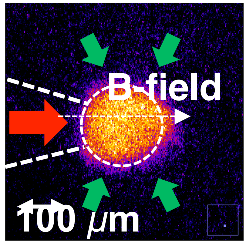
J. Honrubia

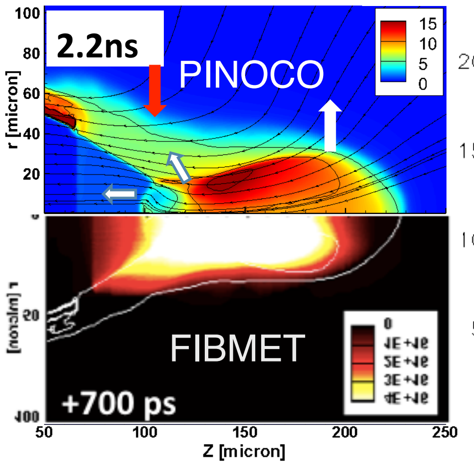
Universidad Politécnica de Madrid, Spain

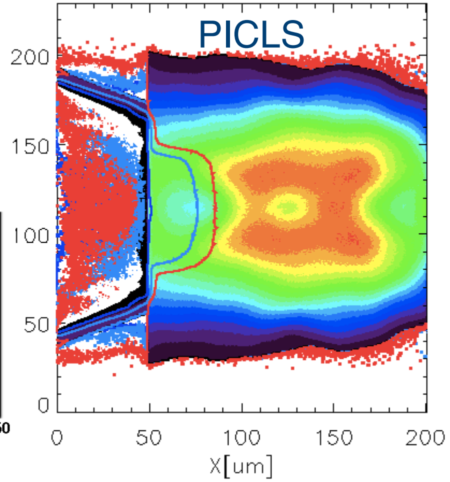
Summary

- "Fusion" between magnetic confinement of an energetic electron beam and inertial confinement of a fuel leads to efficient laser-to-core energy coupling.
- 8% of the laser-to-core coupling was achieved by using the MFI scheme even with a small pre-compressed core ($\rho R \sim 0.1$ g/cm^2).
- Energy density increment was 1 Gbar (= 50 J in 100-μm-spherical volume).
- 15% is achievable with a 0.3 g/cm^2 core based on a simplified estimation.
- We hope to conduct a scale-up experiment in the US facilities (OMEGA & NIF).







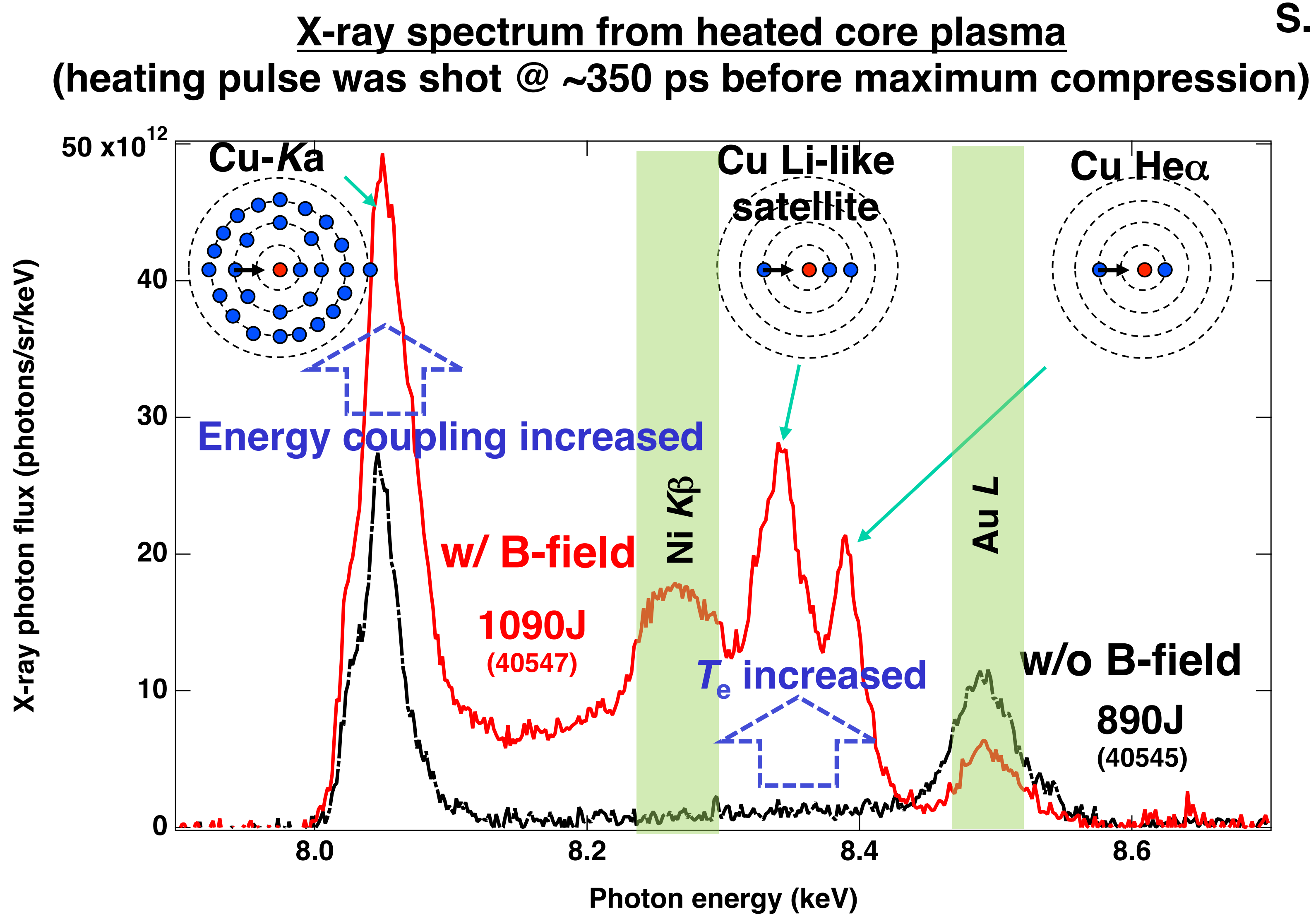


Integrated experiments of MFI scheme

X-ray spectrum indicates that a part of the core is heated up to 1.7 keV by relativistic electron beam.

ILE, Osaka

S. Lee *et al.*, in preparation.



Fast Ignition Realization EXperiment (FIREX) project in JAPAN

ILE, Osaka

We have conducted series of fundamental experiment to solve the critical problems as obstacles to efficient laser-to-core coupling of the electron-driven fast heating, *i.e.* "generation of too energetic electrons" and "large beam divergence", and so on.

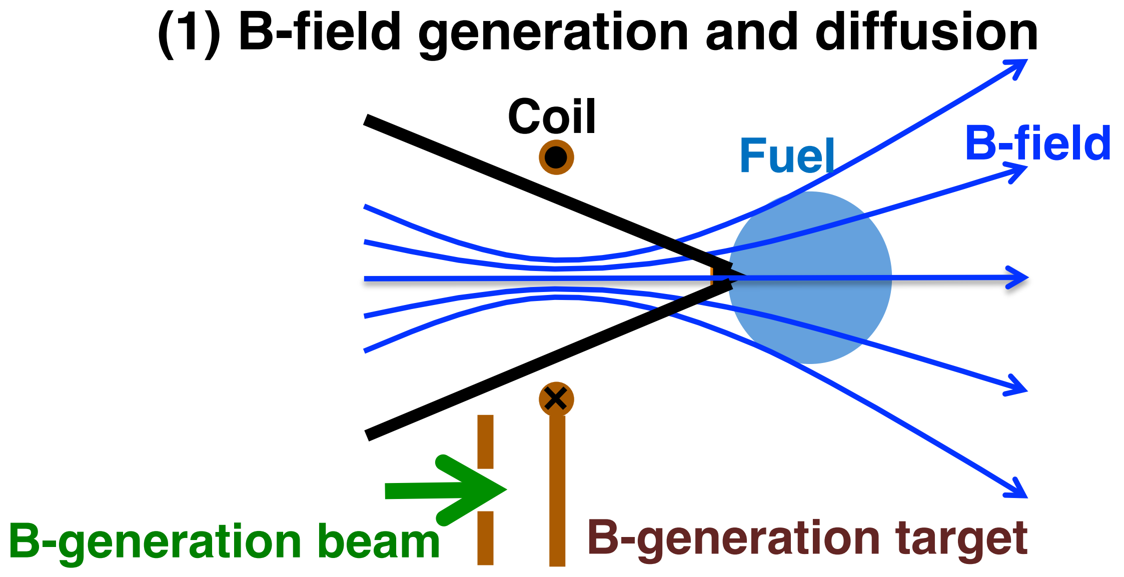
- Lowering the electron energy → reducing generation of pre-plasma by improving the contrast ratio of the heating laser 10^7 → > 10^9
- Reducing the beam divergence → beam guiding by externally applied magnetic fields.
- Reducing the loss during propagation of electron beam → introduction of open-tip cone.
- Stable core formation → introduction of solid ball targets instead of spherical shell targets.

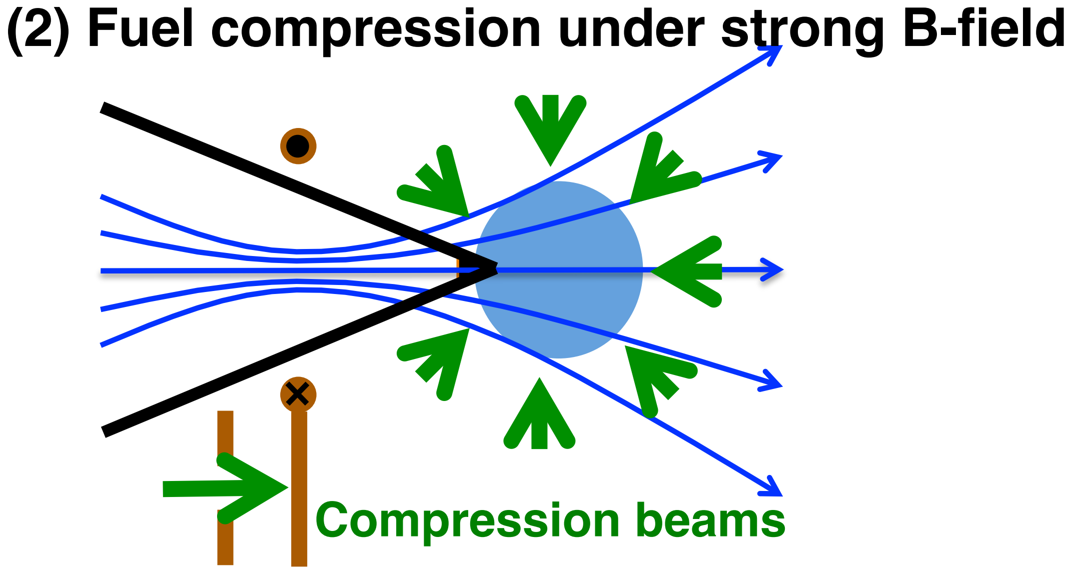
✓ **Integrated experiments in 2016 followed by the fundamental experiments demonstrated ~8 % of the laser-to-core coupling (0.3 - 0.4 % in 2013), 1 Gbar of the energy density increment, and 1.7 keV of the heated core temperature (not detected in 2013).**

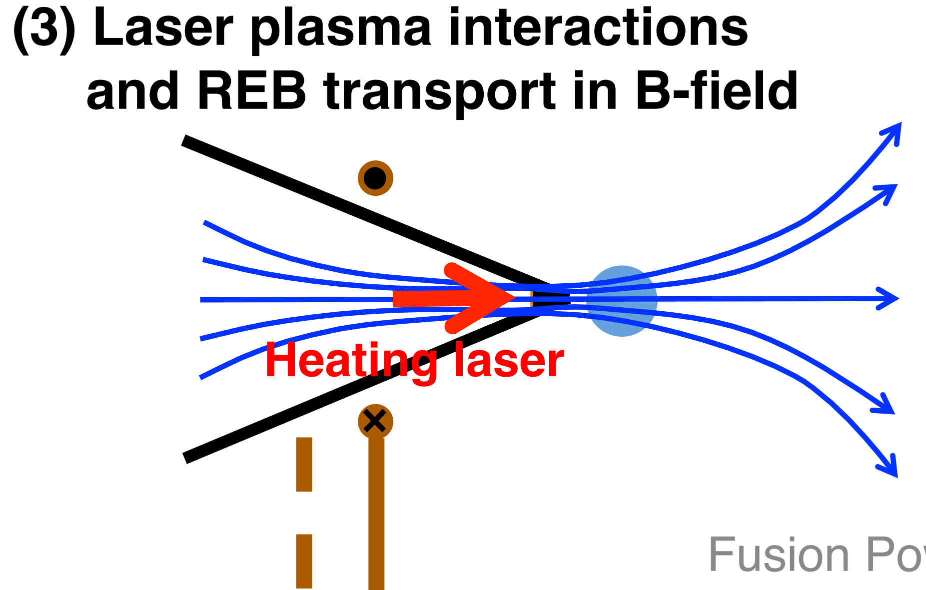
MFI process

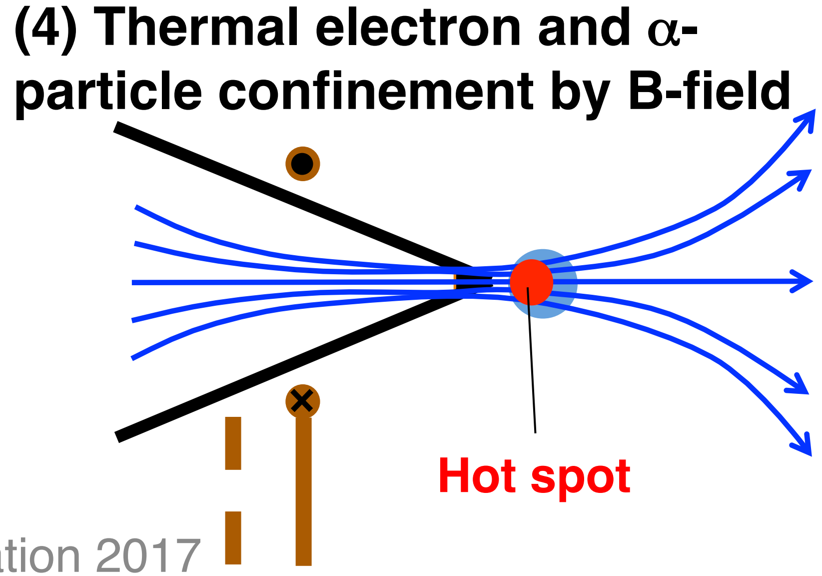
The external magnetic field is applied to the "insulator" fuel before the compression beam irradiation.

ILE, Osaka









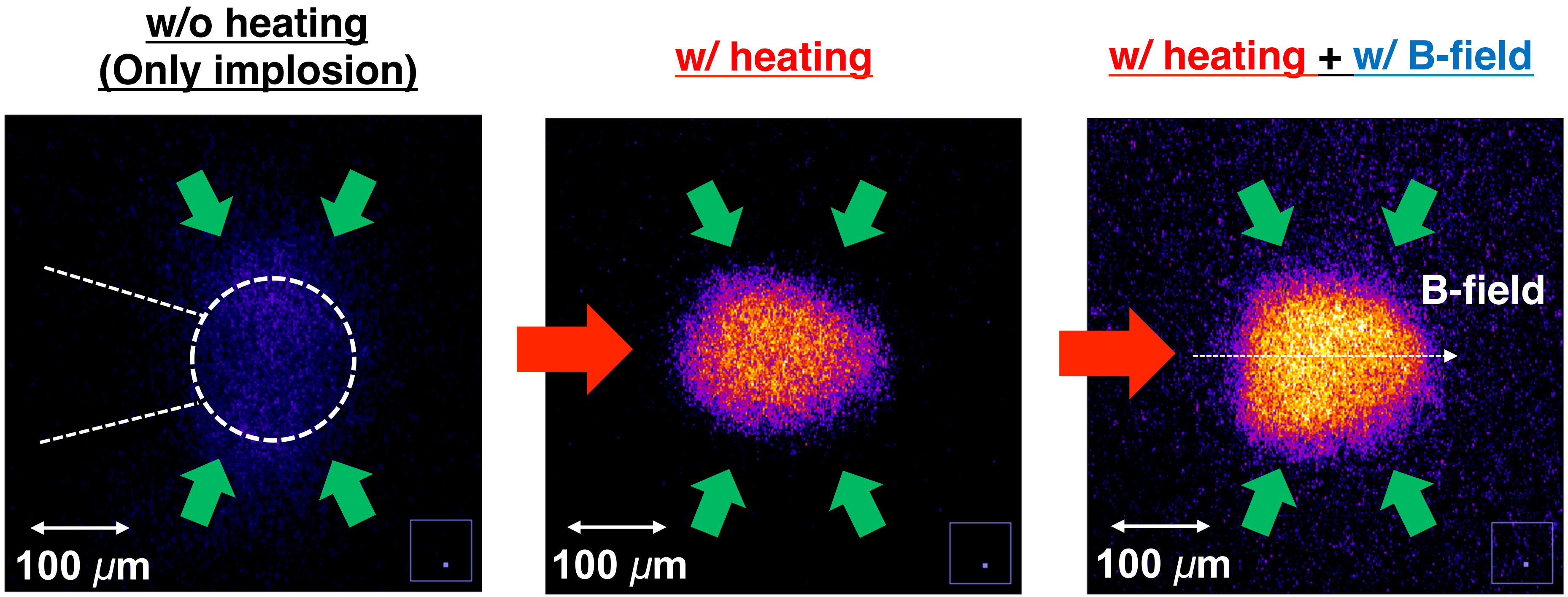
Integrated experiments of MFI scheme

REB-induced Cu-$K\alpha$ emission profiles are recorded with sufficient signal-to-background ratio.

ILE, Osaka

S. Sakata *et al.*, in preparation.

Raw monochromatic Cu-$K\alpha$ (8.05 keV) image from the core



Integrated experiments of MFI scheme

Core-to-fuel coupling degrades gradually by increasing laser energy (= laser intensity with unchanged pulse duration and spot size).

ILE, Osaka

S. Sakata *et al.*, in preparation.

Shot ID	*A*	T_{REB1} [MeV]	T_{REB2} [MeV]	Cu-$K\alpha$ yield [J/phton/sr] x10^{11}	Deposited energy [J]	Heating Laser Energy [J]	Tip	B-field application	Laser-to-core coupling [%]
40545	0.881	1.0	4.7	5.6	28	899	Open	**No**	3.1 +/- 0.5
45041	0.951	0.7	4.4	5.5	28	683	Open	**No**	4.2 +/- 0.7
40558	0.956	**4.6**	**23.6**	12	49	**1516**	Open	Yes	3.2 +/- 0.6
40556	0.933	**2.2**	5.4	10	50	**1016**	Open	Yes	4.9 +/- 0.8
40547	0.907	**1.6**	2.8	13	71	**1100**	Open	Yes	6.5 +/- 1.1
40549	0.999	**0.8**	10	7.3	48	**668**	Open	Yes	7.2 +/- 1.2
40543	0.971	**0.5**	4.1	9.3	50	**625**	Open	Yes	8.0 +/- 1.4
40560	0.991	0.9	21.7	8.2	34	1523	**Closed**	Yes	2.3 +/- 0.4
40562	0.890	1.5	5.6	8.0	38	1378	**Closed**	Yes	2.7 +/- 0.4

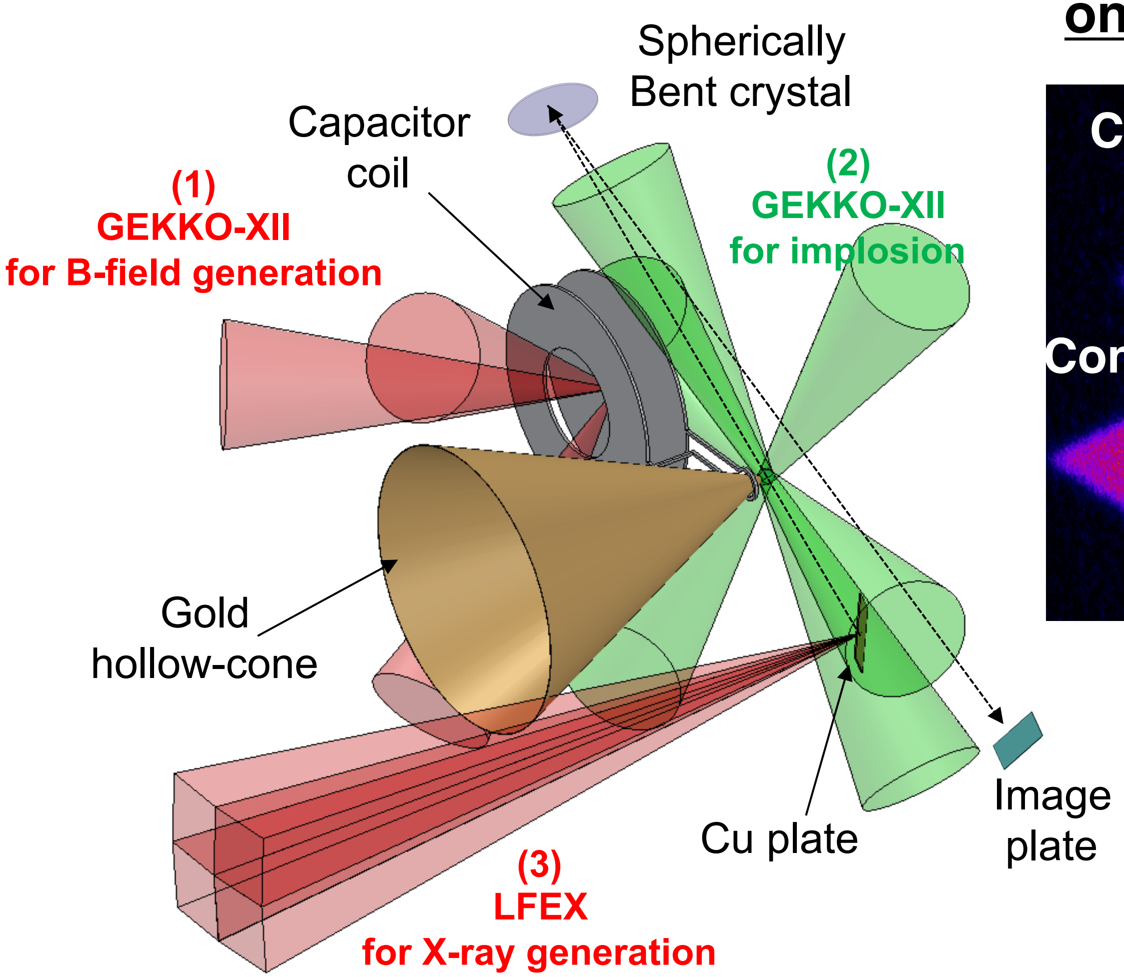
Dependence on REB temperatures is considered.

Integrated experiments of MFI scheme

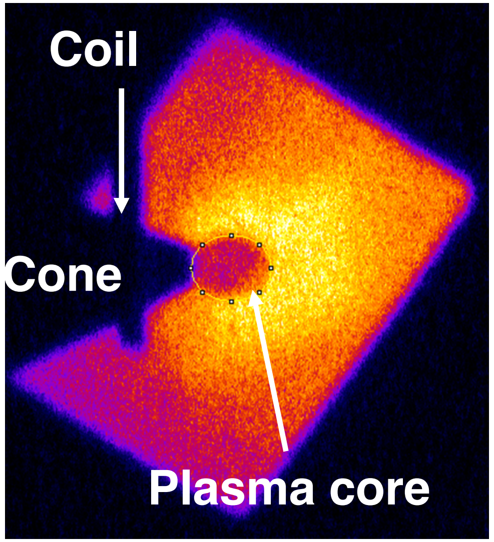
Temporal change of core compressed under external magnetic field was measured with a flash x-ray backlighting technique.

ILE, Osaka

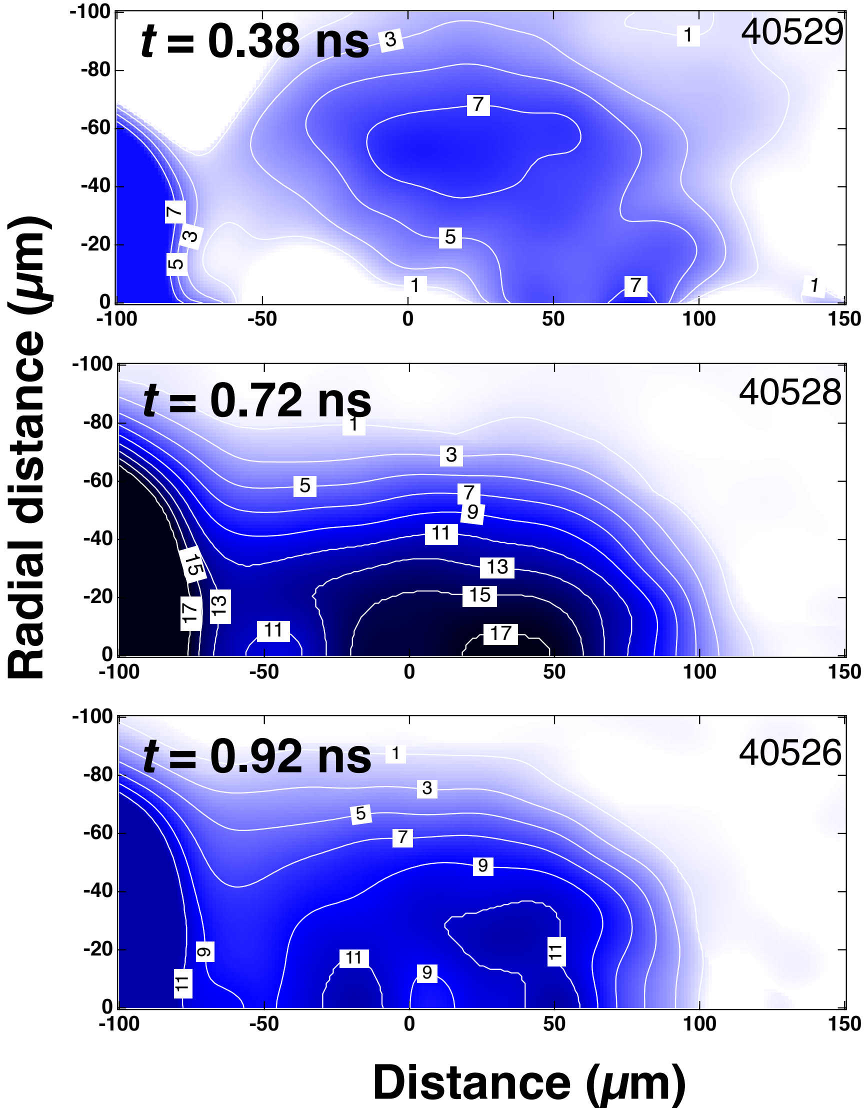
Backlight experiment layout



Cu-$K\alpha$ backlight image on imaging plate



2D density profile



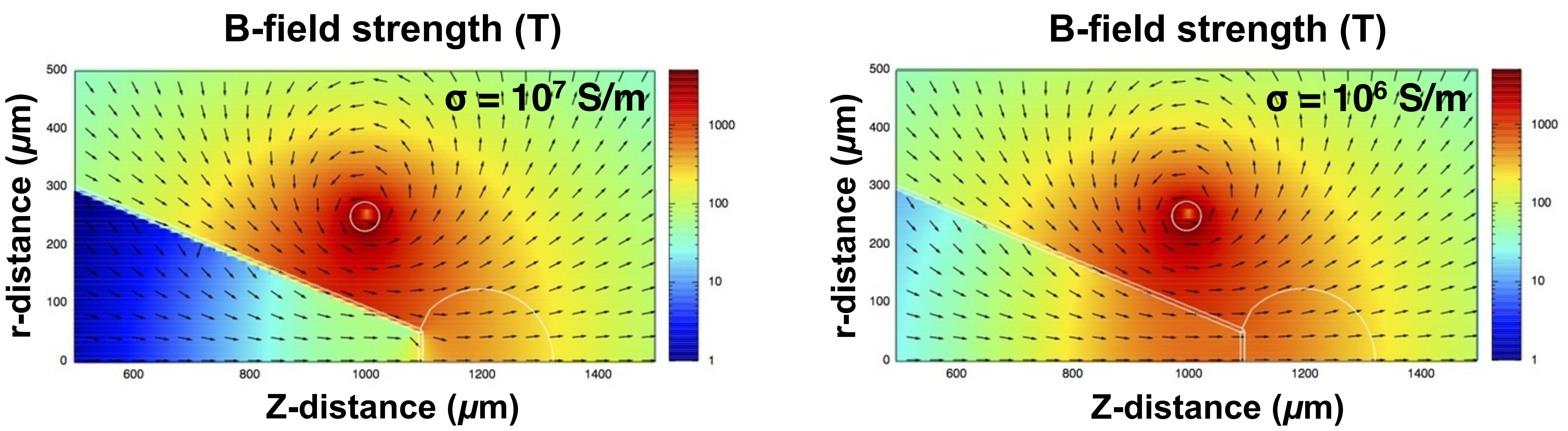
Integrated experiments of MFI scheme

Magnetic field can penetrate into the 7 μm-thick Au cone, if the Au cone is heated to 0.1 eV by Eddy current induced by dB/dt.

ILE, Osaka

* M. Dharma-wardana *et al.*, Phys. Rev. E (2006).

Calculated 2D magnetic field profile (430 kA)



$$t_{\mathrm{diff}} = \mu_0 \, \sigma \, L^2$$

Diffusion time scale
~ 120 ps

Electrical conductivity
2 x 10^6 S/m (**0.1 eV-gold**)*

Diffusion spatial scale
7 μm cone wall