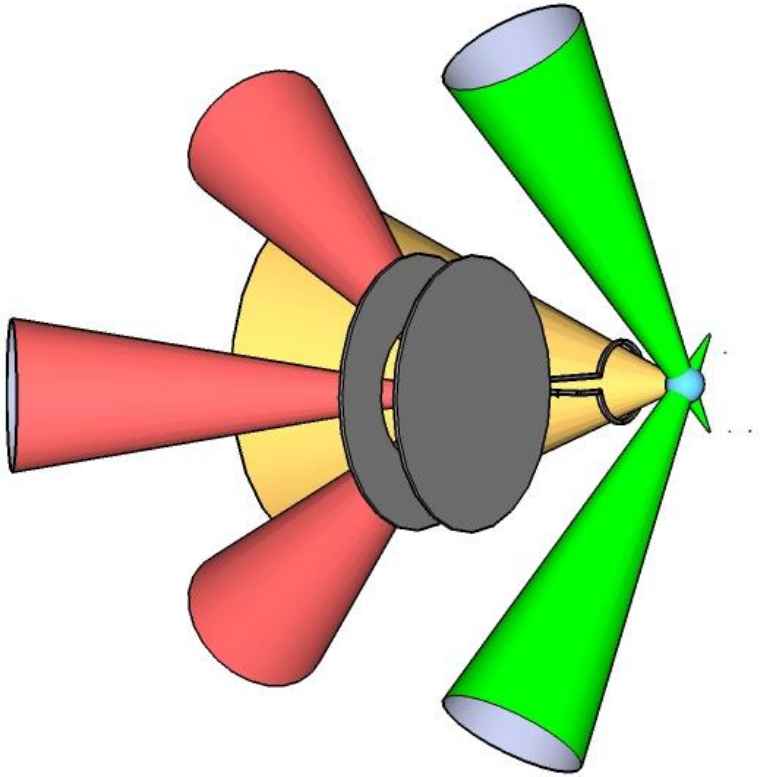
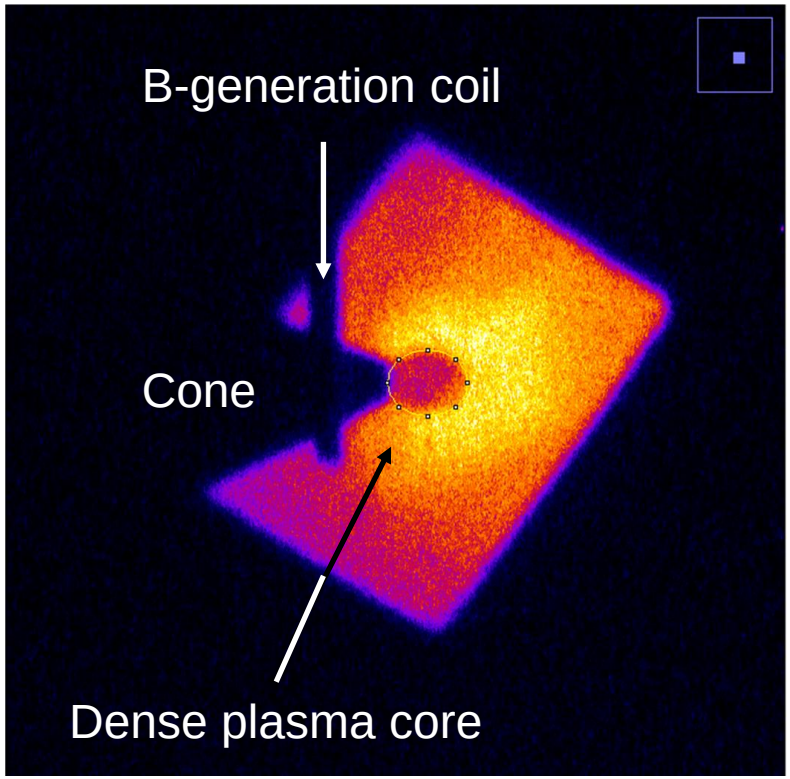
Fast Ignition Inertial Confinement Fusion with Kilo-Tesla Magnetic Field





FUJIOKA Shinsuke
Institute of Laser Engineering, Osaka University
IAEA-FEC2016, 20th October 2016

Summary

Fast ignition with external B-field

- ✓ A critical problem of the fast ignition scheme is a large divergence of laser-accelerated relativistic electron beam (REB).
- ✓ The diverging REB can be guided to a fuel core by application of external B-field.
- ✓ Magnetized Fast Ignition (MFI) has been proposed to increase heating efficiency owing to the guidance of the REB with the B-field.

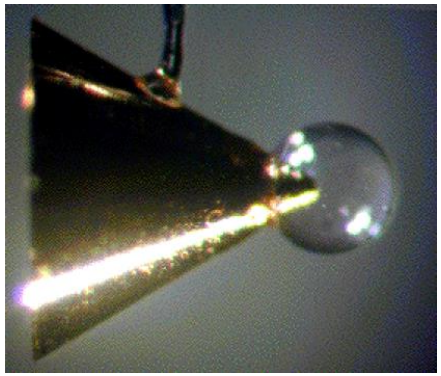
Heating of a dense plasma with the assistance of external B-field

- ✓ Laser-driven capacitor coil scheme generates kilo-tesla B-field.
- ✓ Magneto-Hydrodynamics (MHD) of a laser-produced plasma must be considered for fuel compression of MFI.
- ✓ Li-like and He-like Cu ions were generated in a heated Cu-doped plasma only in the case that external B-field was applied.
- ✓ 3 keV of a heated plasma temperature was inferred from spectral shape of x-rays emitted from Cu dopants.

Nano-second TW laser beams compress a fuel, and pico-second PW laser beams heat a dense fuel core.

ILE, Osaka

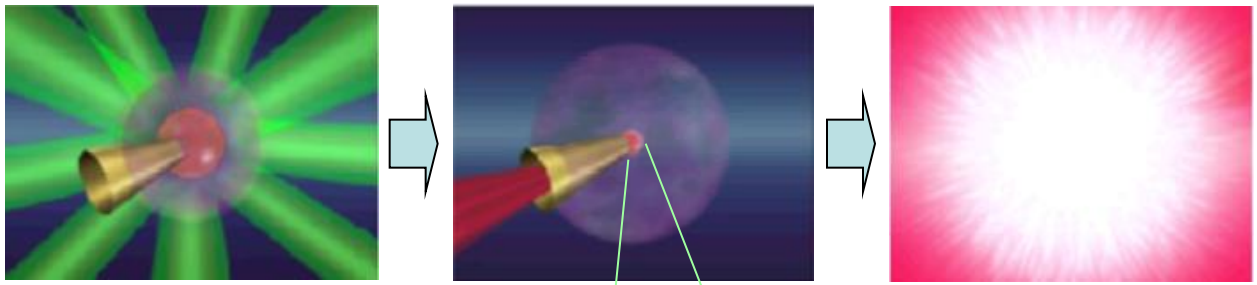
Fusion fuel with a cone



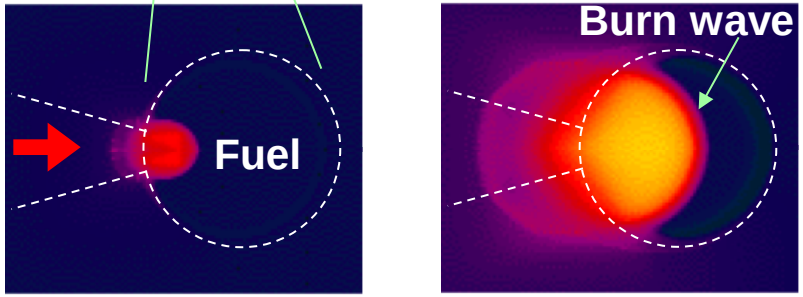
Fuel compression by Multiple ns beams

Heating by ps beams

Ignition & burn



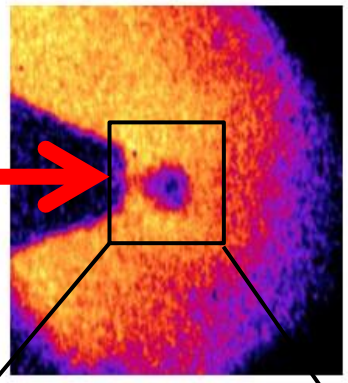
Heating laser



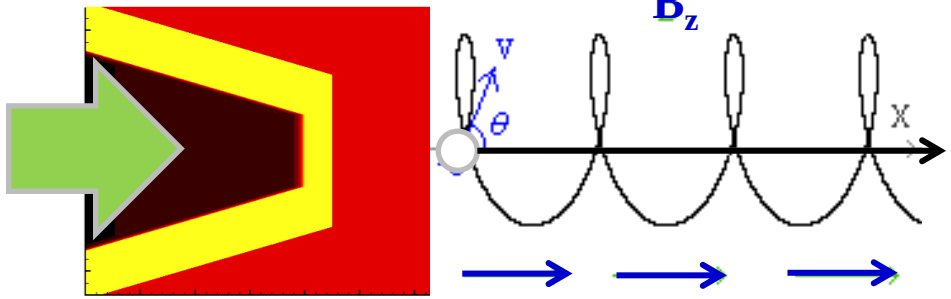
Diverging REB can be guided to a fuel core by application of kT external B-field.

ILE, Osaka

Heating laser

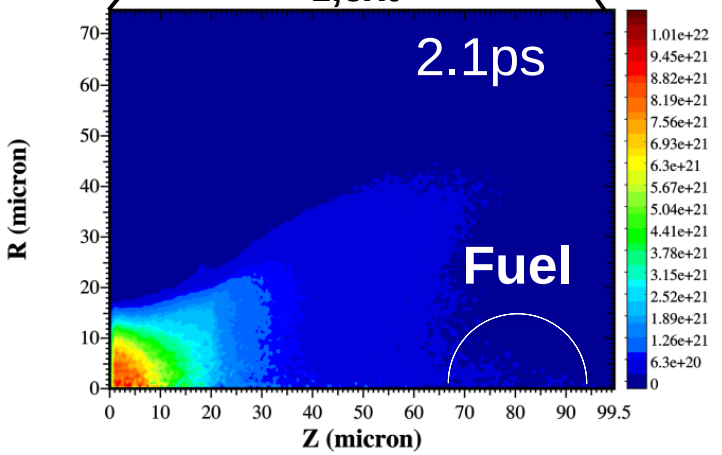


Gyromotion by compressed B-field

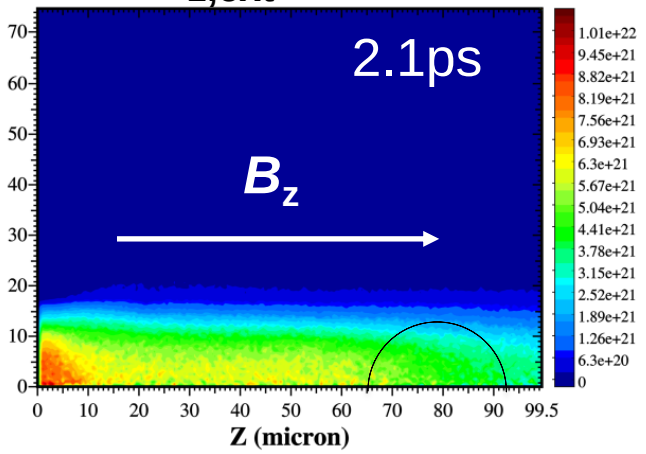


n_b (cm^{-3})

$B_{z,ext}$ = 0



$B_{z,ext}$ = 2 kT

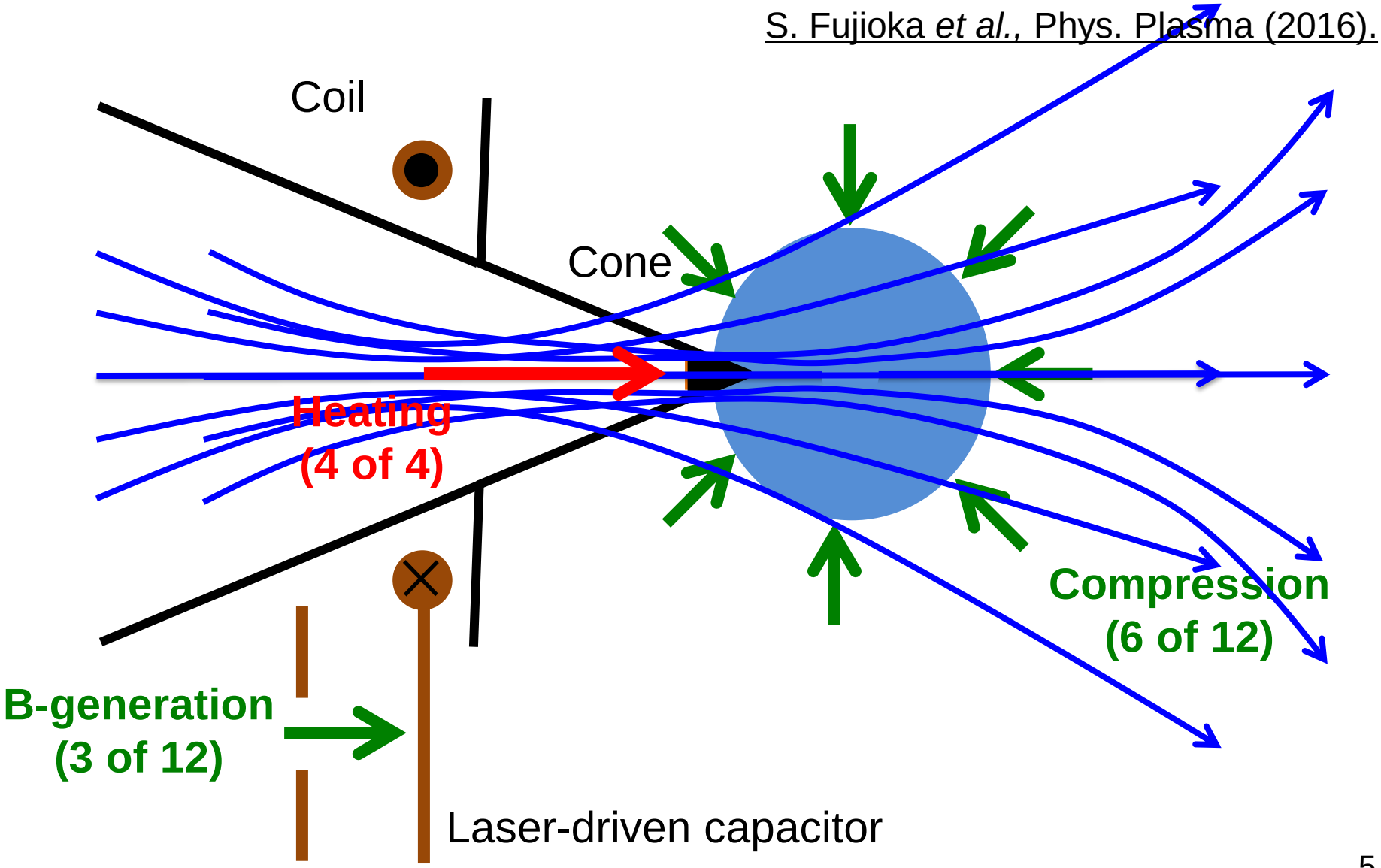


#Simulation by Prof. Honrubia.

Kilo-tesla B-field generated by a capacitor-coil target is applied externally before the fuel compression.

ILE, Osaka

S. Fujioka *et al.*, Phys. Plasma (2016).



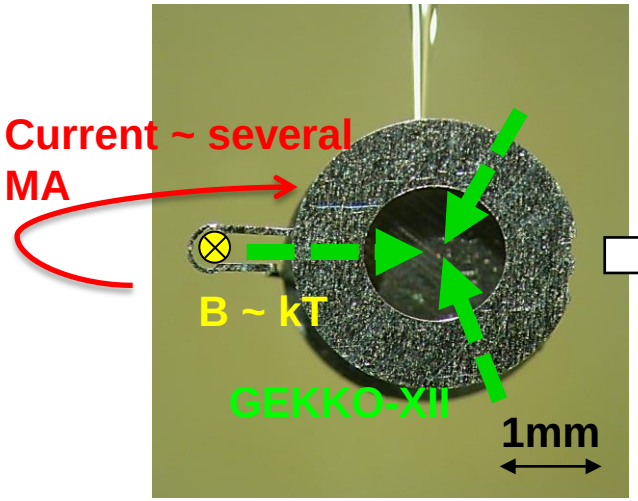
GEKKO-XII (kJ/ns) is used for fuel compression and B-field generation. LFEX (kJ/ps) is used for fuel heating.

ILE, Osaka

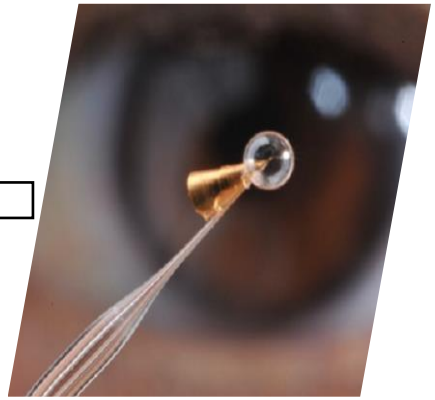
Kilo-joule nano-second laser
GEKKO-XII

High-contrast 2PW laser
LFEX

Kilo-tesla *B*-field generation



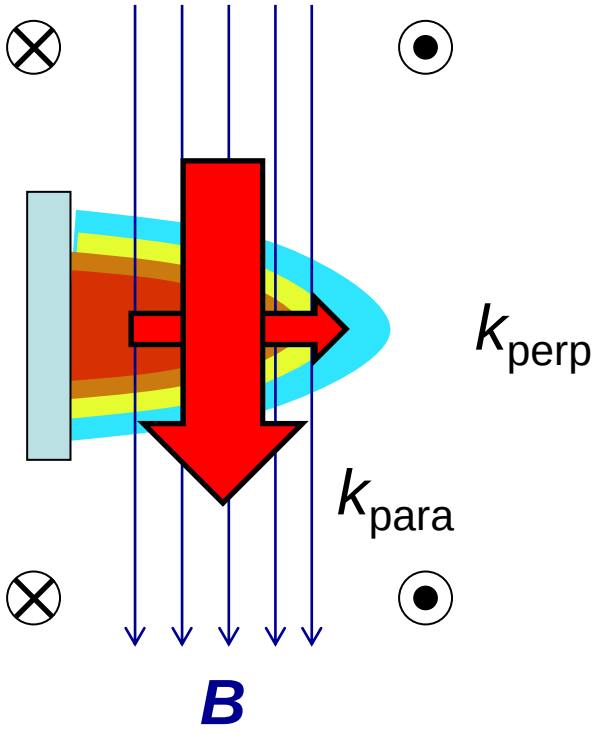
Compression + Heating



Thermal conductivity becomes anisotropic in strong B-field.
Thermal electron motion across B-field lines is reduced.

ILE, Osaka

Thermal conductivity In parallel B-field



Braginskii's coefficient

$$k_{para} = k_{w/o\ B}$$

$$k_{perp} = k_{w/o\ B}/(1+(\omega_{ce}\tau_e)^2)$$

$k_{w/o\ B}$: conductivity (w/o B)
ω_{ce} : elec. gyrofrequency
τ_e : elec. collisional time

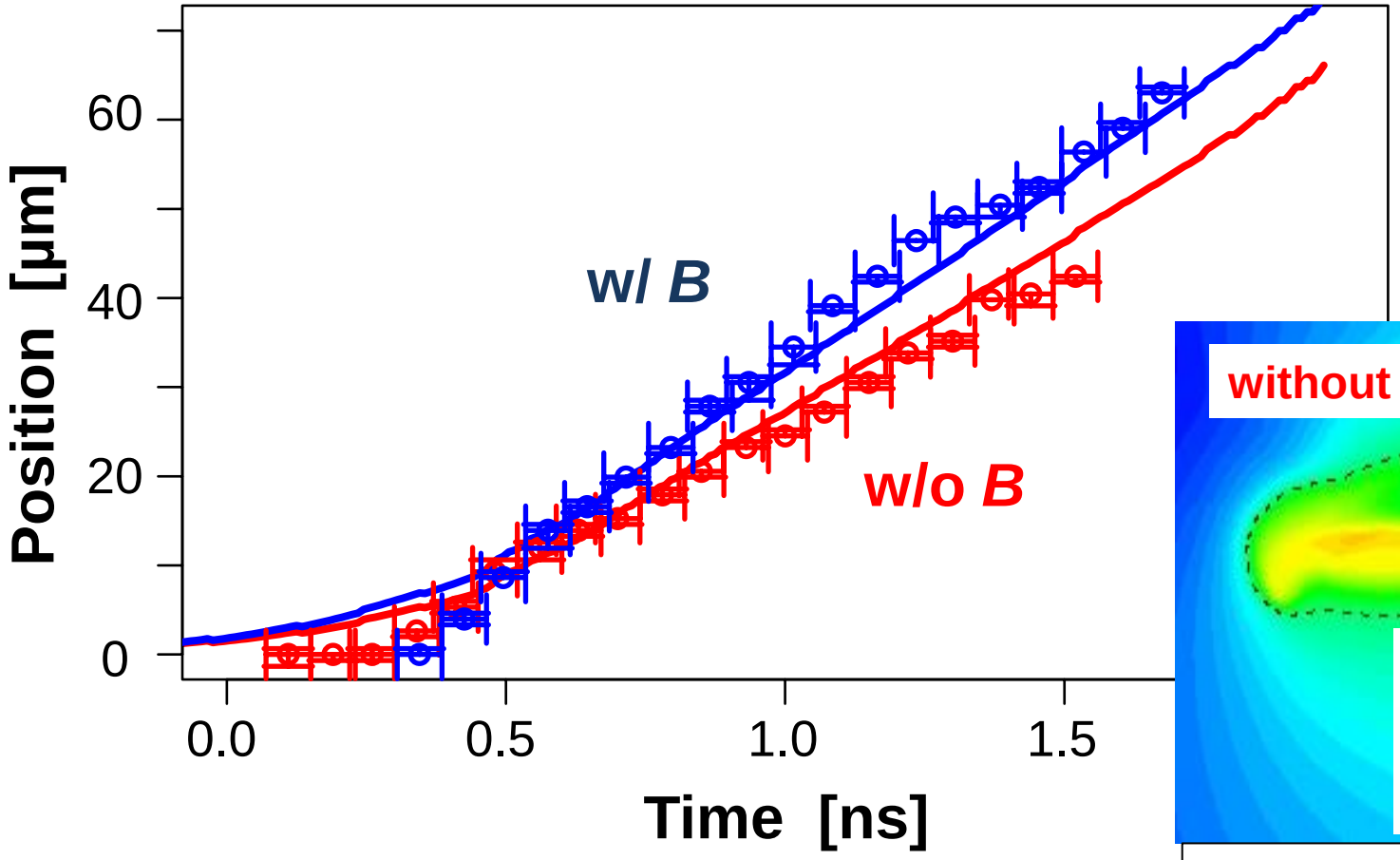
T_e = 100 eV, n_e = 9 x 10^{21} cm^{-3}
$\omega_{ce}\tau_e$ ~ 1 for 1 kT

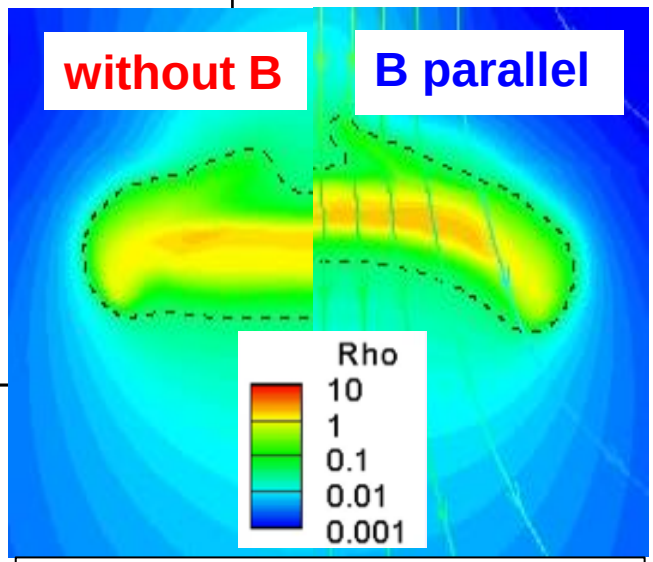
External B-field changes flying velocity of a laser-driven foil due to anisotropic heat conduction.

ILE, Osaka

K. Matsuo *et al.*, submitted to Phys. Rev. Lett..

Trajectory of laser-driven plastic foil



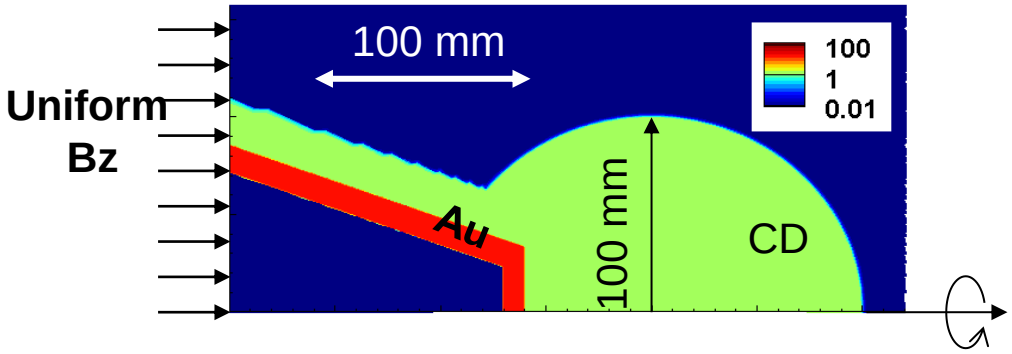


Density@ 1.5 ns

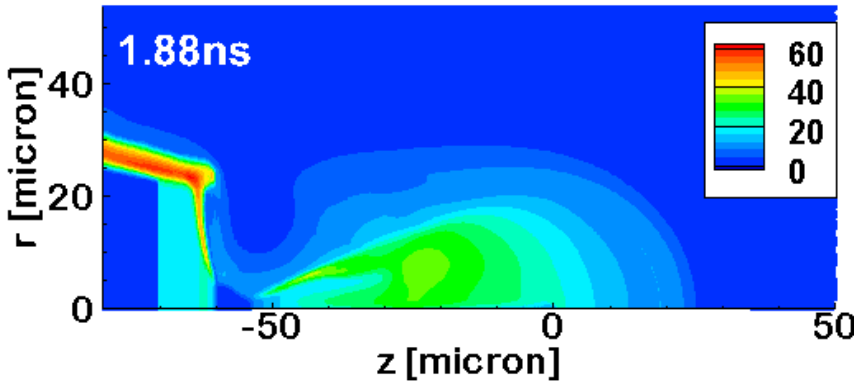
Compression is significantly affected by external B-field due to anisotropic thermal conduction.

ILE, Osaka

Initial plasma profile

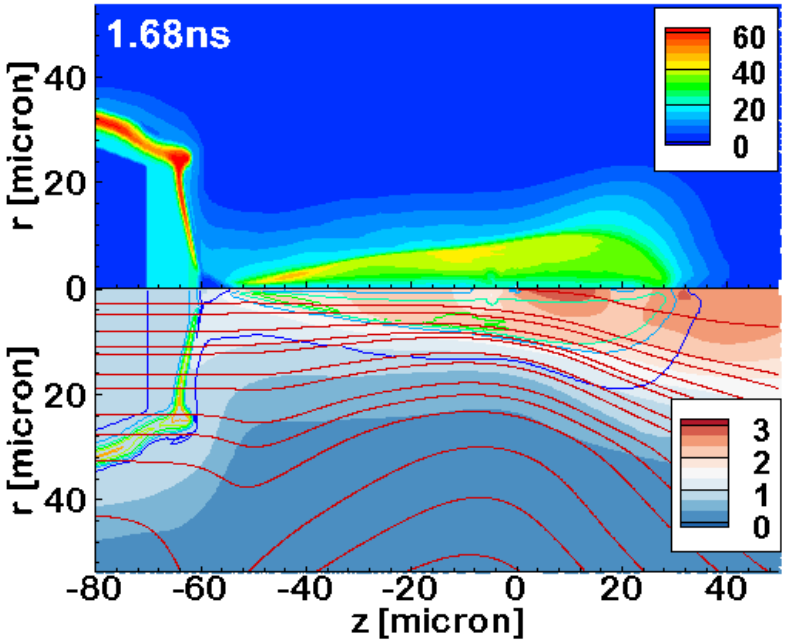


Density w/o B_{ext}



Density & Field line with B_{ext} = 1 kT

Mirror ratio is ~3 due to fast diffusion of *B*-field in a shock compressed region.



Kilo-tesla *B*-field deforms significantly a core shape.

Heated with guided REB

Cu-doped solid beads were used for visualization of heated region and temperature.

University of Nevada, Reno

ILE, Osaka

Target layout

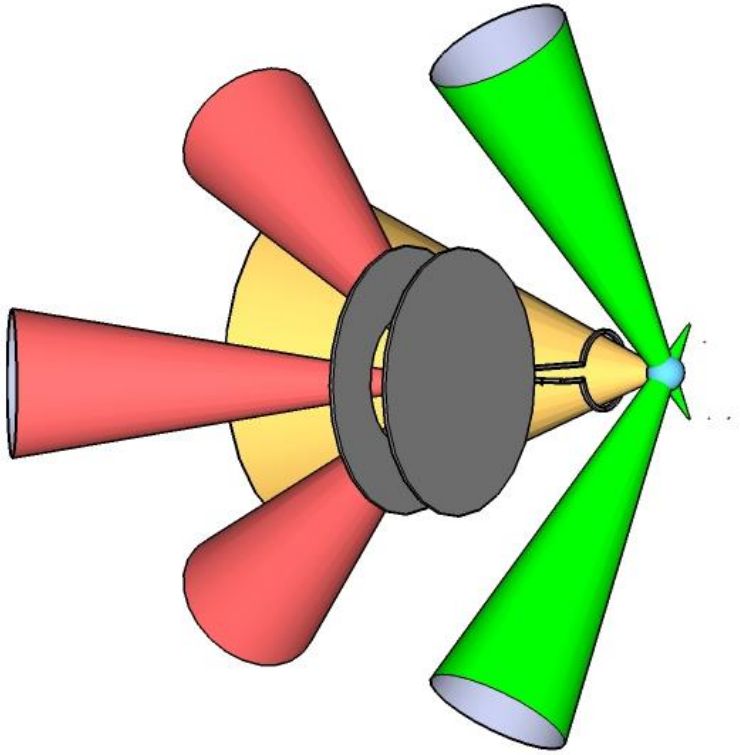
The capacitor-coil target was driven by 3 beams, and a bead was compressed by 6 beams.

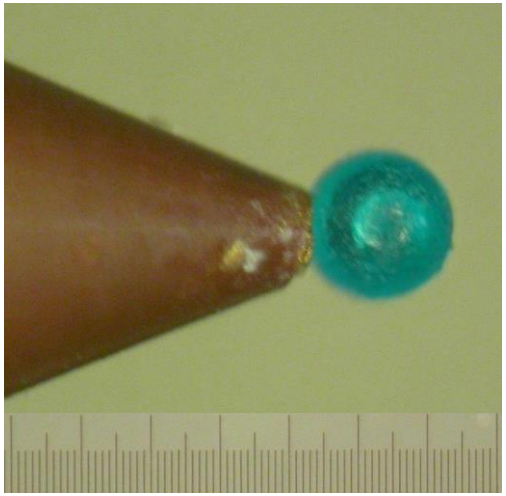
Cu-doped small beads

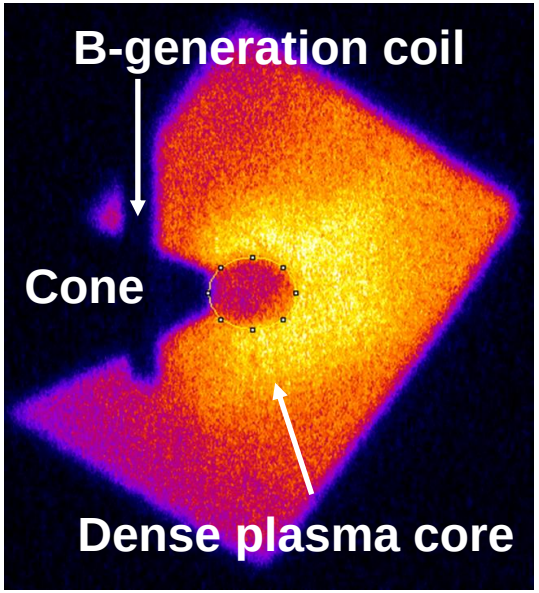
Cu-doped oleic-acid was used to produce Cu-doped small beads.

X-ray radiograph

Density of a compressed beads was measured with x-ray radiography.







Heated with guided REB

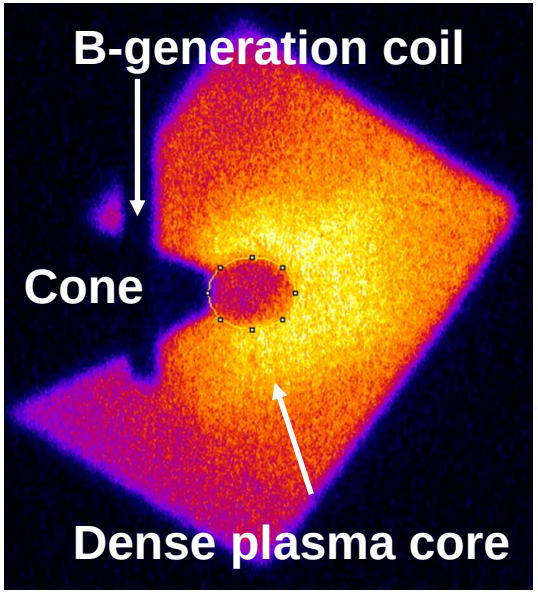
~8 g/cm^3 of plasma density was obtained at the heating laser pulse injection timing.

University of Nevada, Reno

ILE, Osaka

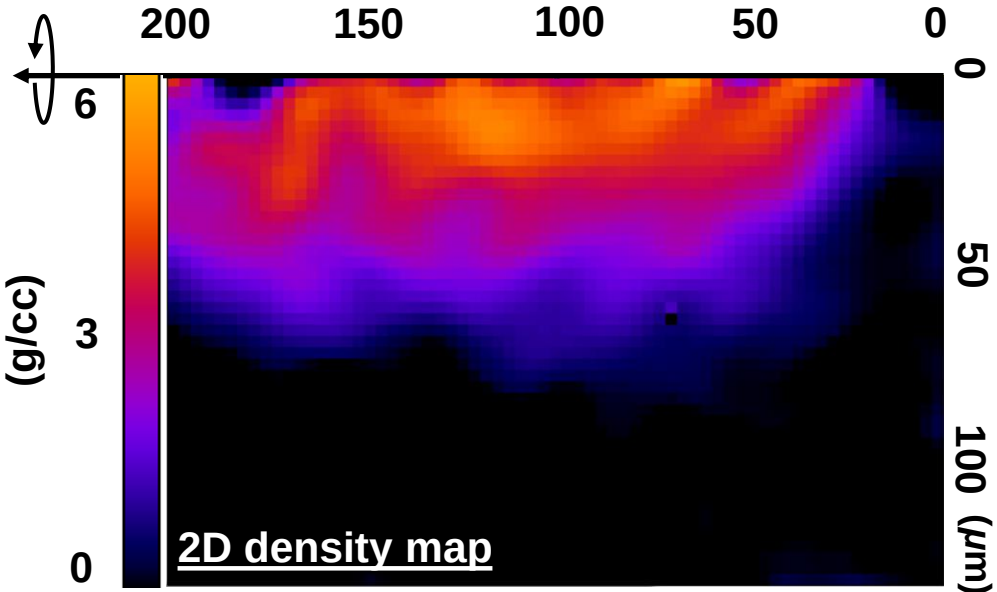
X-ray radiograph

Density of a compressed beads was measured with x-ray radiography.



Density profile

Density profile was derived from x-ray shadow image with inversie Abel inversion.



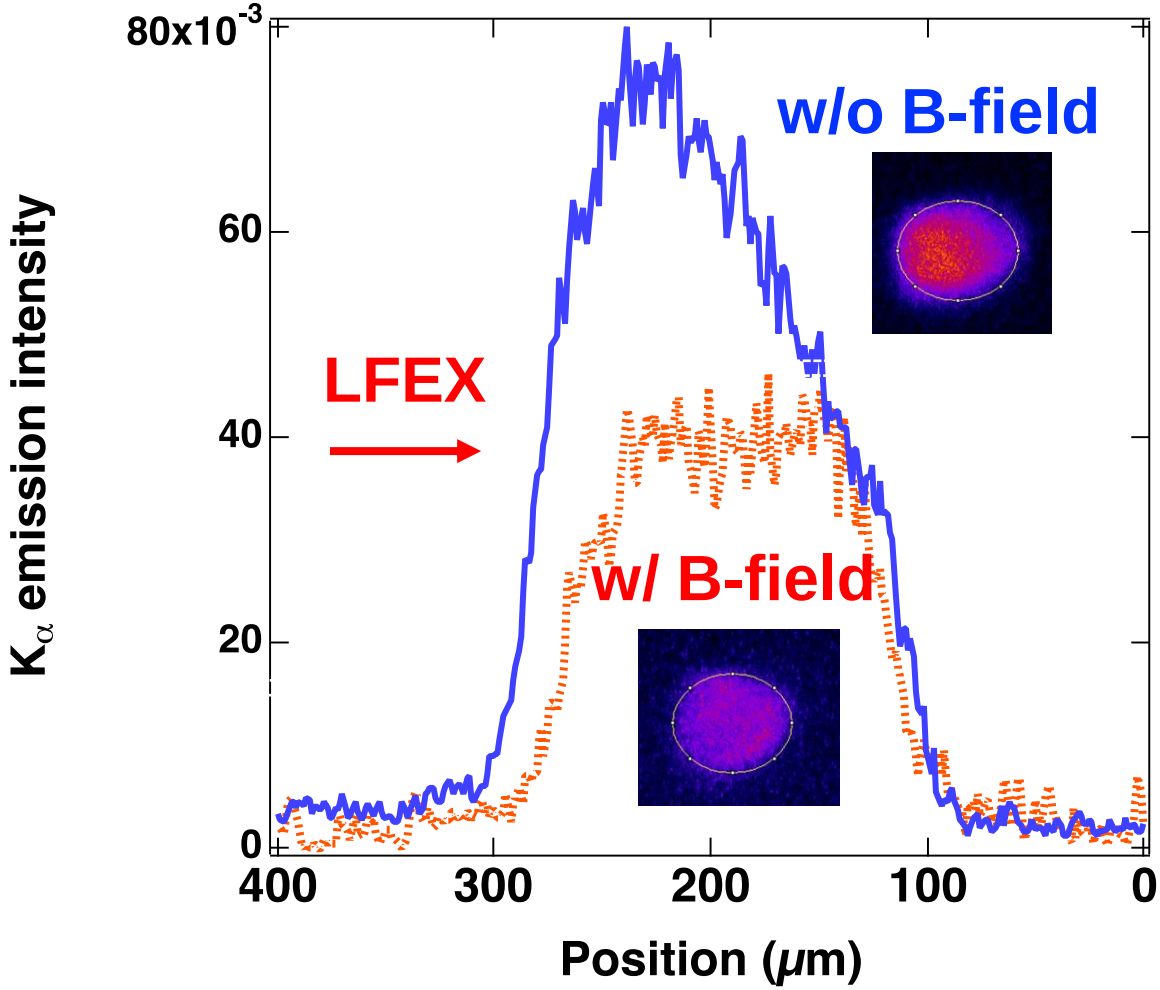
Heated with guided REB

*K*α energy of Cu dopants shifts to out-of-band of the crystal imager due to ionization of Cu atoms.

University of Nevada, Reno

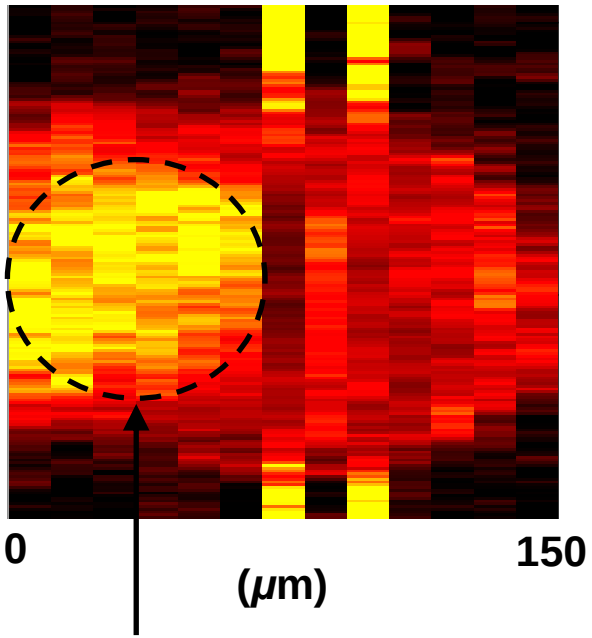
ILE, Osaka

Line profiles of Cu-*K*α



Intensity ratio betwee w/B and w/o B

$I_{w/B}/I_{w/oB} = f(\Delta T)$



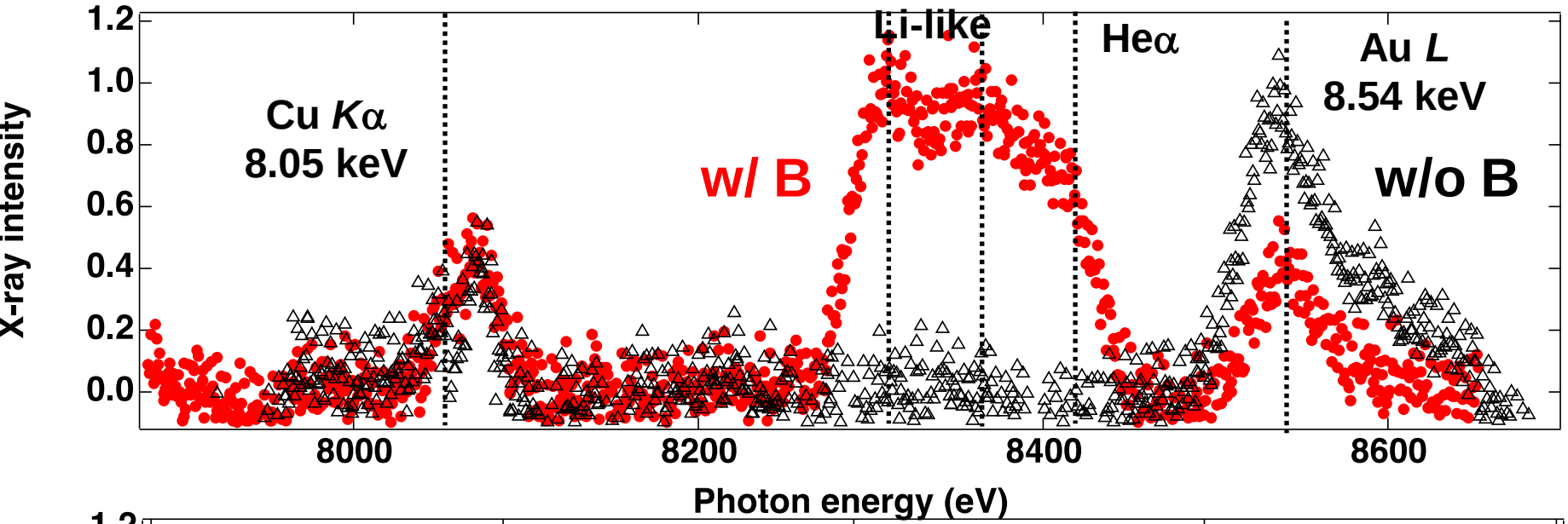
Heated region

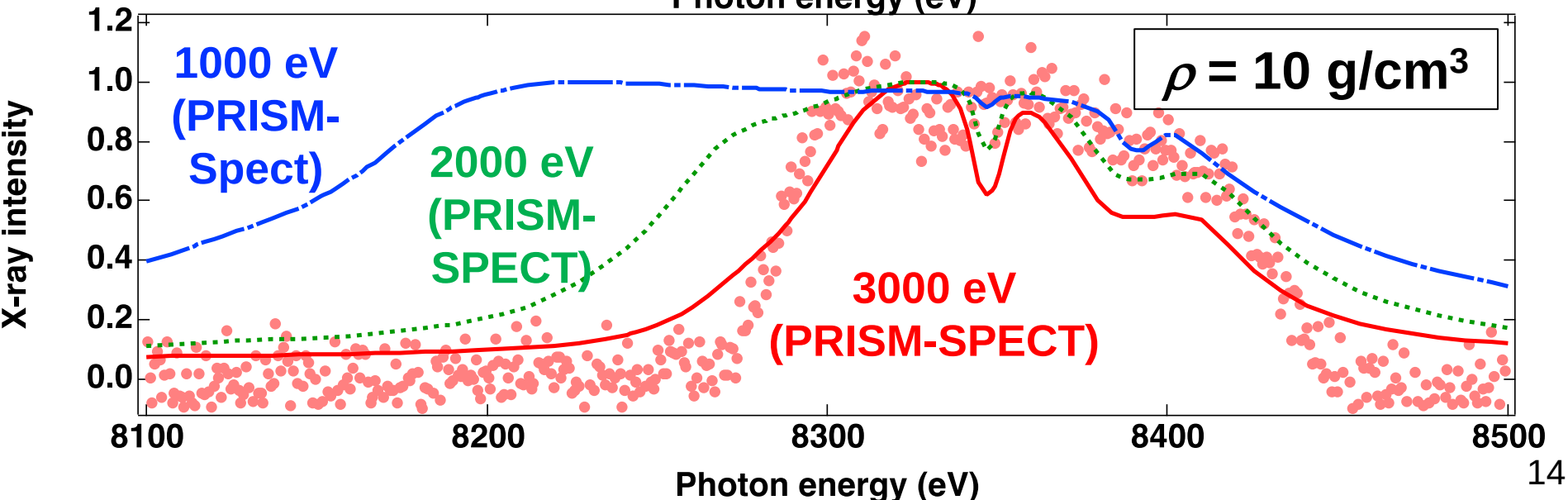
Heated with guided REB

Spectrum emitted from Li- and He-like Cu ions Indicates 3 keV of temperature of the heated region.

University of Nevada, Reno

ILE, Osaka





Summary

Fast ignition with external B-field

- ✓ A critical problem of the fast ignition scheme is a large divergence of laser-accelerated relativistic electron beam (REB).
- ✓ The diverging REB can be guided to a fuel core by application of external B-field.
- ✓ Magnetized Fast Ignition (MFI) has been proposed to increase heating efficiency owing to the guidance of the REB with the B-field.

Heating of a dense plasma with the assistance of external B-field

- ✓ Laser-driven capacitor coil scheme generates kilo-tesla B-field.
- ✓ Magneto-Hydrodynamics (MHD) of a laser-produced plasma must be considered for fuel compression of MFI.
- ✓ Li-like and He-like Cu ions were generated in a heated Cu-doped plasma only in the case that external B-field was applied.
- ✓ 3 keV of a heated plasma temperature was inferred from spectral shape of x-rays emitted from Cu dopants.

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

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

Acknowledgement

This research was supported with Collaboration Research program by National Institute of Fusion Science and by the Institute of Laser Engineering at Osaka University, and with the Japanese Ministry of Education, Science, Sports, and Culture (MEXT), by a Grant-in-Aid, and with Japan Society for the Promotion of Science (JSPS) by ‘Bilateral Program for Supporting International Joint Research’.