First experimental demonstration of magnetized fast isochorhic heating = MFI =

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Critical problems in FI

There are three critical problems in the fast-isochoric heating.
Too energetic and diverging electron are accelerated to heat a fuel.

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).
Achievement of FIREX project

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

Simple model of laser-to-core coupling

\[
\text{Laser-to-core coupling} = \frac{\text{Laser-Electron Conversion Efficiency}}{\text{Fuel cross section @fuel}} \times \frac{\text{E-beam cross section @fuel}}{\text{Electron Energy Deposition Fraction}} \times 2 \times \text{fuel areal density}
\]

\[
\begin{align*}
0.4\% @2013 &= 40\% \times 40\% \times 2.5\% \\
\approx 8\% @2016 &= 40\% \times 80\% \times 25\%
\end{align*}
\]
Laser-produced magnetic field was used to guide the diverging electron beam to a fuel core.

**B-field 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 REB by the external B-field

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

"Diverged" electron beam

Heating laser

"Collimated" electron beam

Heating laser

Experimental results

M. Bailly-Grandvaux et al., Nat. Comm. (accepted).
Integrated experiments of MFI scheme

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

Experimental set-up

- Cu-Kα spectroscopy
- Cu-Kα imaging
- Spherical crystal
- Flat crystal
- GEKKO-XII (2ω) for implosion
- GEKKO-XII (1ω) for B-field generation
- (a) B-field generation laser pulse
- (b) Compression laser pulse

Cu-doped CH solid ball (250 μmφ)

Current

Gold cone (45 deg. full angle)

S. Sakata et al., submitted.

Fusion Power Association 2017
Integrated experiments of MFI scheme

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

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Cu-$K_\alpha$ spectra

Dependence of laser-to-core coupling

![Cu-$K_\alpha$ spectra](image)

![Dependence of laser-to-core coupling](image)
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.

(a) $K_\alpha$ emission @0.38 ns
(b) $K_\alpha$ emission @0.62 ns
(b) Mass density @0.35 ns
(d) Mass density @0.72 ns

S. Sakata et al., submitted.

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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.

X-ray spectrum from heated core plasma
(heating pulse was shot @ ~350 ps before maximum compression)

S. Lee et al., in preparation.

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Fast Ignition Realization EXperiment (FIREX) project in JAPAN

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

✓ Integrated experiments in 2016 followed by the fundamental experiments demonstrated $\sim 8\%$ 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.

(1) B-field generation and diffusion

(2) Fuel compression under strong B-field

(3) Laser plasma interactions and REB transport in B-field

(4) Thermal electron and $\alpha$-particle confinement by B-field

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Integrated experiments of MFI scheme
REB-induced Cu-$K\alpha$ emission profiles are recorded with sufficient signal-to-background ratio.

S. Sakata et al., in preparation.

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

- w/o heating (Only implosion)
- w/ heating
- w/ heating + w/ B-field
Integrated experiments of MFI scheme

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

S. Sakata et al., in preparation.

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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.

Backlight experiment layout

- Capacitor coil
- Spherically Bent crystal
- Copper plate
- Image plate
- Gold hollow-cone

(1) GEKKO-XII for B-field generation
(2) GEKKO-XII for implosion
(3) LFEX for X-ray generation

Cu-Kα backlight image on imaging plate

Plasma core

2D density profile

Radial distance (µm)

Distance (µm)

$t = 0.38$ ns
$t = 0.72$ ns
$t = 0.92$ ns
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 $dB/dt$.


Calculated 2D magnetic field profile (430 kA)

- **B-field strength (T)**
- **Z-distance (µm)**
- **r-distance (µm)**
- **σ = 10^7 S/m**
- **σ = 10^6 S/m**

$\tau_{\text{diff}} = \mu_0 \sigma L^2$

- **Diffusion time scale** ~ 120 ps
- **Electrical conductivity** 2 x 10^6 S/m (0.1 eV-gold)*
- **Diffusion spatial scale** 7 µm cone wall

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