Laser-driven magnetic field in quasi-hohlraum geometries: from JLF to NIF

NIF and JLF User Group Meeting 2016


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Laser-driven magnetic field generation schemes can provide \~100 T on ns-timescales

Laser driven plasma sheath creates voltage source for current

**Solenoid loop current**

**Blow-off plasma**

**Hot electron current**

Faraday rotation is used to measure the field inside and outside the loop.

Experimental setup

- **Internal glass**
  - 0.5 mm diameter,
  - 1.1 mm long fused Si

- **External glass**

- **4ω probe**

- **X-ray shield**

- **Laser drive**

Wollaston separates polarizations

Crystal birefringence employed to separate orthogonal polarizations into 2 beams with equal intensity for no polarization rotation.
Quantitative measurements of the field inside the loop is limited to low drive energy.

Faraday rotation angle: $\theta \propto B lv$

(analysis from D. Turnbull)

At Omega EP, with 250 J of drive we measured 5.3 T field. Increasing the drive energy causes blanking of the interior glass.
At 1kJ of drive energy the fringing field is sufficiently large to measure rotation in the exterior glass.

External field measurement

Axial field estimates

Axial field inferred from Biot-Savart model that predicts $1/r^2$ falloff outside target

Axial $B \approx 40T \pm 20T$ for 500J of drive
(analysys from D. Turnbull)

Faraday rotation measurements outside the loop allows us to increase the drive energy though the error bar is fairly large.
Titan provides a way to further diagnose the generated B-field

- proton deflectometry
- Electron spectrometer
- Target geometry and composition

**Titan**

![Diagram showing B-field target, W proton source foil, electron spectrometer, and 1 ps backlighter beam with 300J in 1ns.]

- $\lambda = 1.053$ $\mu$m
- 8 $\mu$m focus
- 16.5° from normal

- $\lambda = 1.053$ $\mu$m
- 100 $\mu$m focus
- 22.5° from normal
Proton measurement show evidence of parasitic current through the x-ray shield

<table>
<thead>
<tr>
<th>Proton deflectometry data</th>
<th>Simulated data</th>
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<tr>
<td>Spectrometer</td>
<td></td>
</tr>
<tr>
<td>Fused Si</td>
<td></td>
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<tr>
<td>X-ray shield</td>
<td></td>
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</table>

The presence of the shield is affecting the current distribution inside our target. If the shield and loop conductivity are equal, it reduces the magnitude of the field inside the loop by a factor of 3.
CH coating on the rear plate improves the hot electrons generation by 3x.

(analysis from A. Hazi)

CH coating on the rear plate increases the total number of fast electrons by a factor of three. Increase of the magnetic field due to the CH coating has been observed on Omega (x2 at low drive energy).
Janus experiments was focused on understanding the behavior between the plates

- Thomson Scattering between the plates
- Shadowgraphy between the plates
- Voltage measurement
Double foil shows higher density and temperature relative to single foil (Thomson Scattering)

Measurement of thermal EPW with Thomson scattering to characterize plasma conditions in between the plates. Plotted 3.5 ns after the beginning of the drive.
Plasma blow-off is observed on both plates with time resolved shadowgraphy.

The plasma quickly fills the gap between the plates. The estimated expansion speed of the rear plate is $\sim 10^7$ cm.s$^{-1}$. 
The plasma between the plates is expected to limit the magnetic field amplitude.

X-ray emission from the back plate causes the front-plate blow-off. If $T_r \sim 150$ eV then

$$I_{x-ray} = \sigma T^4 \Phi_{las}^2 / 4 \sim 2 \times 10^{12} \text{ W/cm}^2$$

- The Cu plasma is at $\sim 0.7$ keV
- Ion sound speed is

$$C_s = \sqrt{\frac{ZT_e}{M_i}} \approx 1.4 \times 10^{7} \text{ cm.s}^{-1}$$

- The time to cross the 0.05 cm plate separation is: **3.5 ns**

The plasma should fill the gap between the plates after a few ns of drive and may short-circuit the system. Can we measure the duration of the magnetic field and its time behavior?
New target design to measure the voltage between the plates used on JLF

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inductance</td>
<td>0.1 – 0.4 nH</td>
</tr>
<tr>
<td>Capacitance</td>
<td>35 – 60 fF</td>
</tr>
<tr>
<td>Skin-depth resistance</td>
<td>0.008 Ohm</td>
</tr>
</tbody>
</table>

Loop target

1053 nm drive laser

Micro-strip transmission line

SMA connector
The voltage between the target can be maintained for several ns with longer pulse duration.

1 ns laser pulse

10 ns laser pulse

Peak current \(\sim 2 \text{ kA}\)

At lower drive energy \(\leq 10\text{J}\) we can sustain a voltage between the two plates for several nanoseconds.
Experiments on JLF and Omega have allowed us to pursue high B-field and understanding

- **Omega EP**
  - Push the field as high as we can
  - Omega is an important step to prepare for NIF

- **JLF**
  - Development of new diagnostics.
  - Focus on the mechanism generating the current.
  - Obtain data to allow the modeling of our target.

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Omega and JLF provide an important combination of resources for advancing the laser-driven B-field project.
Using our improved target/diagnostic we demonstrated 170 T field on Omega EP and are on track to try it on NIF.

We have demonstrated up to ~170 T in ~mm³ with 800 J of drive energy.
JLF allowed for new insight on laser generated B-field.

**JLF capability**

- Versatility/flexibility of the facility
  => can field a variety of diagnostics
- Staff is really helpful
  => building and fielding of the voltage target
- Valuable opportunity to develop experimental expertise and sharpen data analysis abilities

**Possible improvements**

- Additional probe beam availability (~J, 100s of ps) in both Janus and Titan
- Better pulse shaping capability on the drive beam.
- Improved relative timing between various laser beams
- Clone Scott and Steven? (have someone asking for shots after the cooling time has expired in Titan and Janus)
Obtained multi-Tesla fields in Holhraum geometry
Omega EP faraday rotation data limited to low drive energy

JLF experiments allowed us to increase the magnetic field
— development additional diagnostics to measure the B-field
— insight on the time evolution of that field

Scaling of the field magnitude with laser drive
— latest field achievement
— scaling to NIF
Nominal NIF size hohlraum would require higher currents to generate 10 T fields

<table>
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<tr>
<th>Omega EP</th>
<th>NIF estimates</th>
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| 170 T in ~ 1ns, r = 0.25 mm  
For a constant voltage  
=> \( V = \frac{\Delta B}{\Delta t} \pi r^2 \sim 30 \text{ kV} \) | For a nominal hohlraum size  
r = 5 mm  
=> \( B \sim 0.5 \text{ T for 1 ns drive} \)  
“Sub-scale” hohlraum r~3 mm would be better suited to have a measurable magnetic fields. |
Equivalent circuit

- Electrons
- 1053 nm laser
- Current loop inductor
- Skin-depth resistance
- 50 Ohm strip-line to scope input
Estimating the circuit parameters

**Capacitance:**
Two flat plates

\[ C = \varepsilon_0 \frac{A}{d} \]
\[ A = \text{area} = 2\text{mm} \times 1\text{mm} \]
\[ d = \text{separation} = 0.5\text{mm} \]

**Inductance:**
Half-loop:

\[ L = 2l \left[ \ln \left( \frac{2l}{w + t} \right) + 0.5 \right] + 0.2235 \left( \frac{w + t}{l} \right) \text{nH} \]
\[ l = \text{length(cm)} = 0.05 \]
\[ w = \text{width(cm)} = 0.08 \]
\[ t = \text{thickness(cm)} \leq 0.005 \]

**Resistance:**
Skin-depth

\[ \delta = \sqrt{\frac{2\rho}{\omega\mu_0}}; \text{skin-depth} \]
\[ R \approx \frac{\rho L}{2w\delta} \]
\[ \delta = 0.8 \text{ µm for Au;} \]
\[ = 0.65 \text{ for Cu} \]

Using frequency \( = 1\text{GHz} \)

**Results:**

\[ C \approx 0.035 - 0.06 \text{ pF} \]

\[ \sqrt{LC} \approx 3.5 \text{ ps} \]

\[ L \approx 0.1 - 0.4 \text{ nH} \]

\[ f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} = 32 \text{ to } 85 \text{ GHz} \]

\[ \frac{L}{R} \approx 30 \text{ ns} \]

\[ R = 0.0077 \text{ Ohms} \]
Biermann battery field is not strong enough to perturb measurements in the loop region

100J
1ns pulse

x-ray transient darkening of SiO₂

4.6±0.3T

L. Biermann
Biermann battery field is not strong enough to perturb measurements in the loop region.

29.5 MeV

300 J of drive delivered to the target.
1200J shot data protons arrive 650 ps after the beginning of the laser driving the B field
B field for different target geometry

early time
4 T field
Bx > 0