# Laser-Driven Magnetic Field Compression

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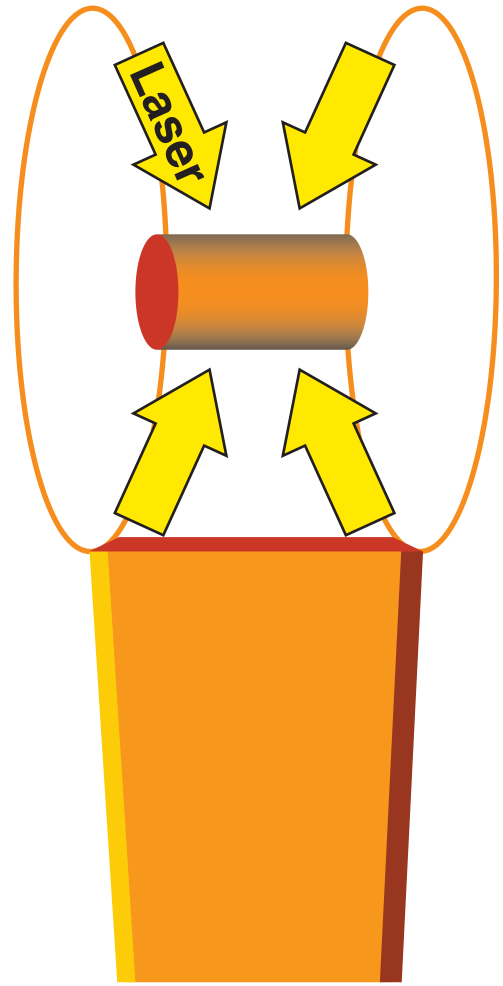
# Abstract

An experiment was designed to compress magnetic fields to ultrahigh intensities through laser-driven implosions. A seed axial magnetic field is produced by Helmholtz coils and capacitor discharge. The seed-field generation circuit is designed to produce an initial field of several Tesla (5 to 10 T) inside a cylindrical CH shell. The plastic shell is then imploded by direct laser irradiation with a 20 kJ laser pulse. Two implosion pulse shapes have been considered: a square pulse and a shaped, low-adiabat pulse. One-dimensional simulations of the magnetic field compression resulting from the shell convergence show magnetic field amplifications of 400 for the square pulse and 1200 for the shaped pulse, thus leading to peak magnetic fields of $4 \times 10^3$ T and $1.2 \times 10^4$ T, respectively for a 10 T seed. Details of the experimental design and simulations are presented, and the experimental plans for implementation are outlined.

# Motivation

- Ultrahigh intense magnetic fields ($10^3$ to $10^4$ T) are achievable through laser-driven compression
- A high-intensity magnetic field has a variety of physical implications including
  - improvement of the hot-spot energy confinement through magnetic insulation,
  - improvement of collimation of fast electrons for fast ignition, and
  - the study of magnetic collimation of plasma jets.

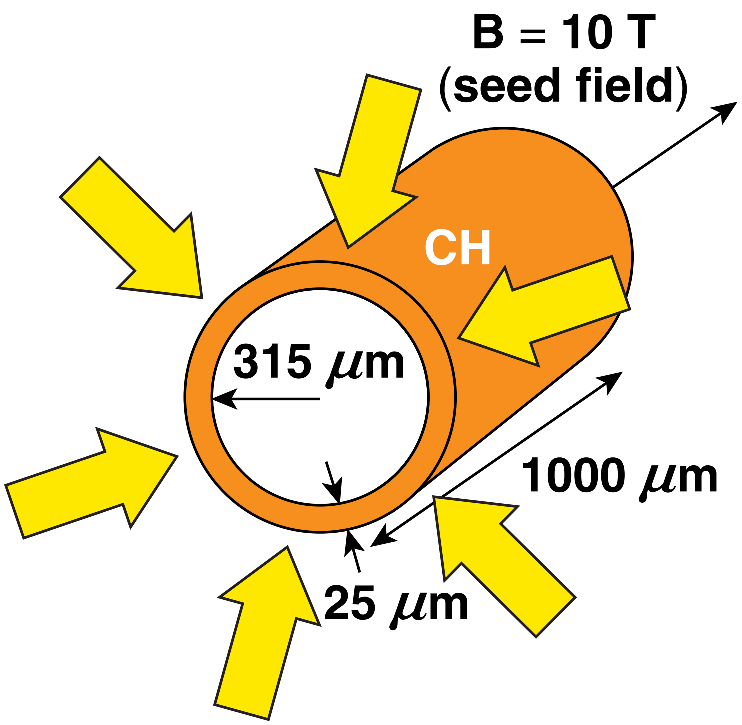



Helmholtz coils and implosion target.

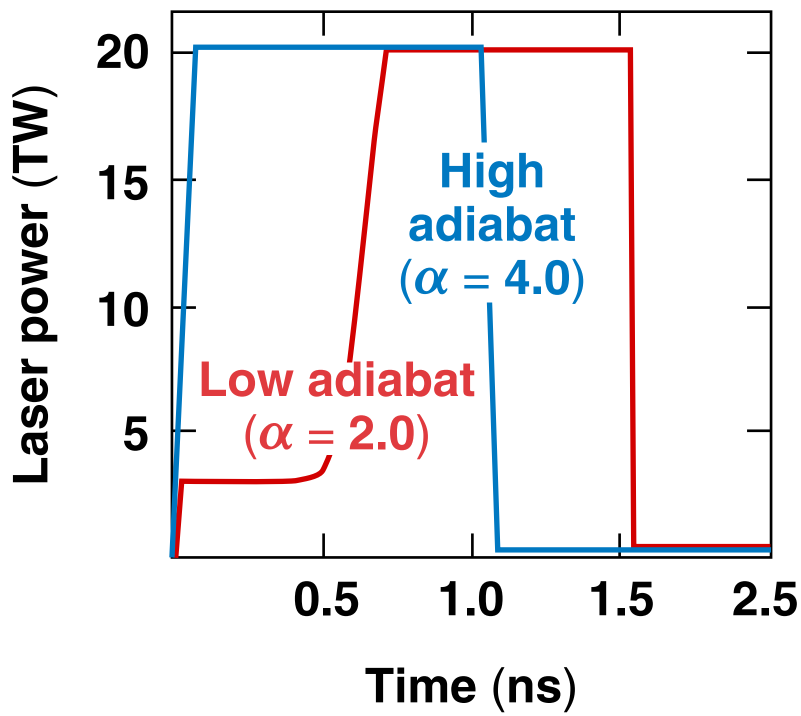
# Resistive MHD equations were added to the 1-D hydrocode *LILAC*

- Use the existing program *LILAC* to simulate the target implosion.
  - *LILAC* is based purely on radiative hydrodynamics.
  - Modifications are required to build in the effects of the magnetic field. (The code will be referred to as *LILAC*-MHD.)
- Resistive MHD equations added to *LILAC* are
  - Magnetic field diffusion: $\partial_t \vec{B} + \vec{V} \cdot \nabla \vec{B} = - \vec{B} \nabla \cdot \vec{V} + \vec{B} \cdot \nabla \vec{V} + \nabla \cdot \eta \nabla \vec{B}$
  - The magnetic pressure $B^2/2\mu$ is added to the hydrodynamic pressure.
  - The ohmic heating $\eta J^2$ is added as a source of heat.
  - Electron and ion thermal conductivity are reduced by the reduction factor determined by gyrofrequencies and collision rates.

# A cylindrical target is driven by a 20 kJ, direct-drive OMEGA laser pulse



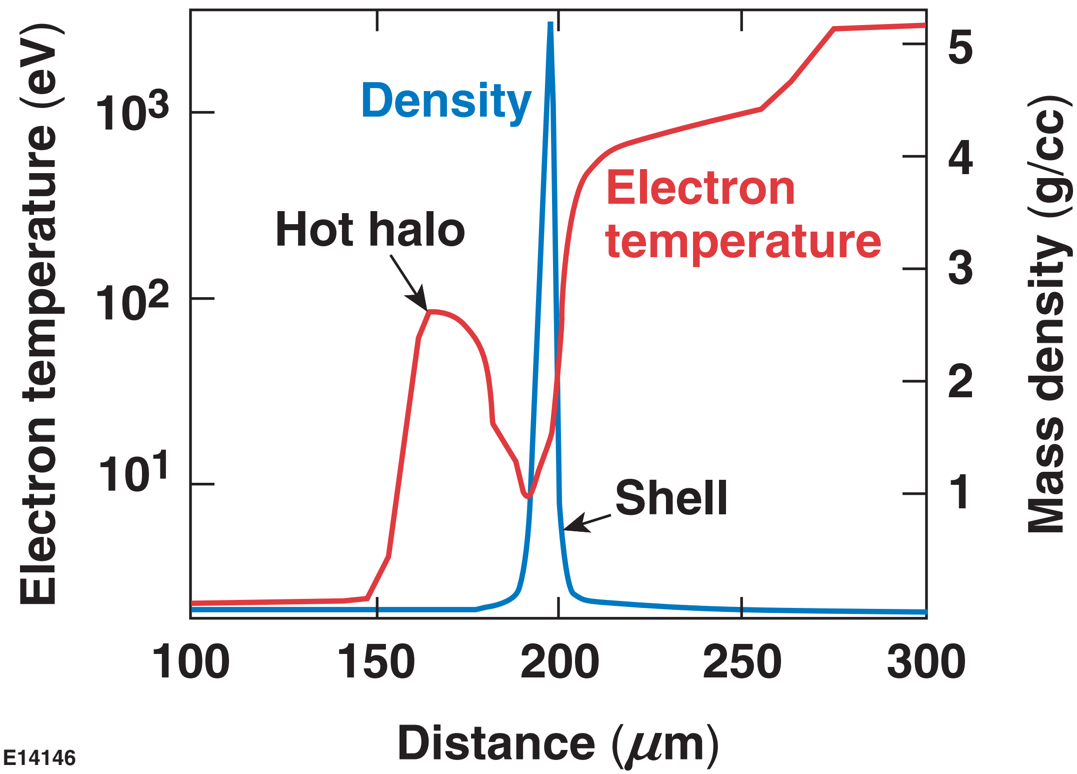

Cylindrical plastic shell
simulated with *LILAC*-MHD

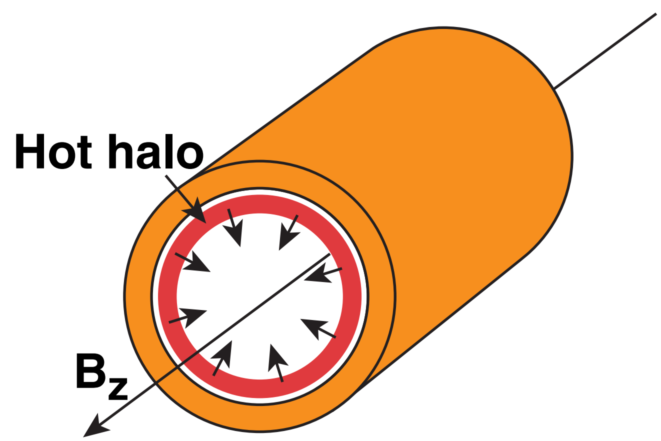



20 kJ laser pulses used
in *LILAC*-MHD simulations

# The seed field is trapped by the inner layer of plasma with a high temperature ahead of the shell

- Magnetic diffusivity is inversely proportional to the temperature ($\eta \sim T^{-3/2}$). In the high temperature region, referred to as the hot halo, the diffusion of the magnetic field trapped inside is prevented. Thus the imploding cold shell acts like a piston compressing the magnetic field.




The hot halo layer prevents the diffusion of the magnetic field in the radial direction.

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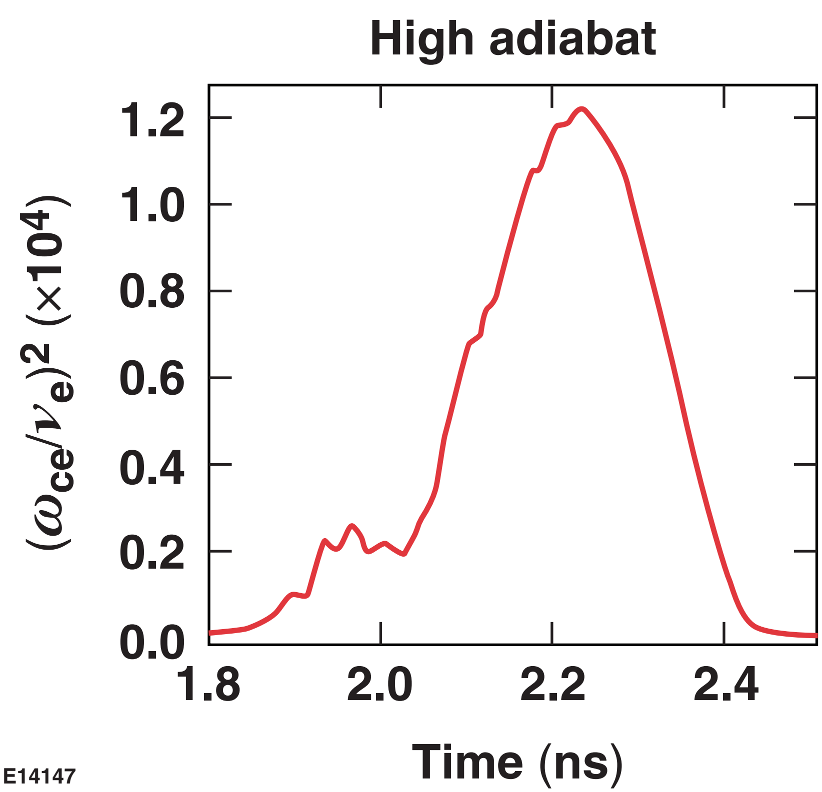
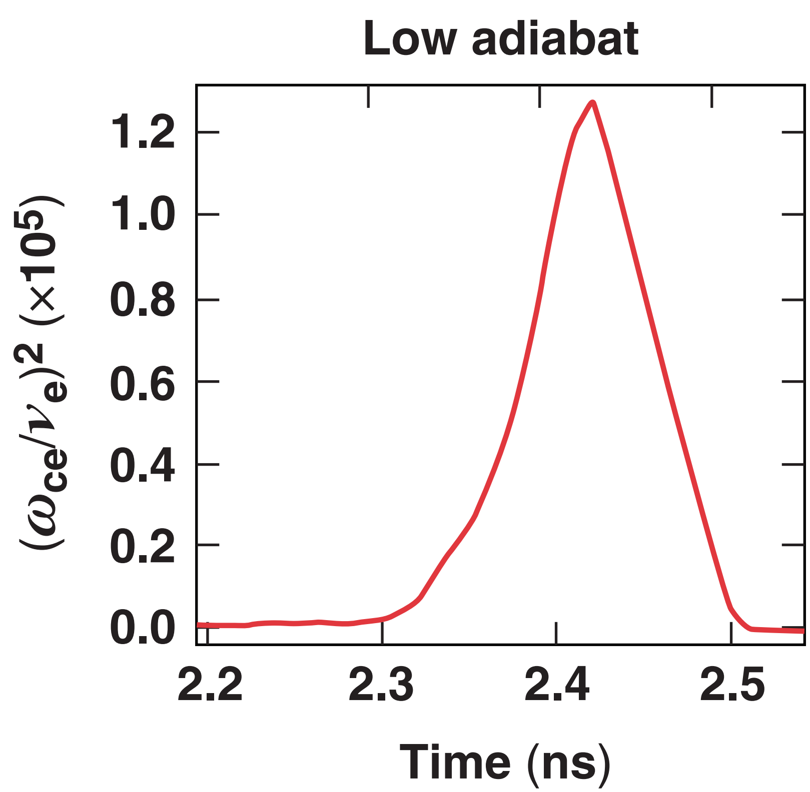
# Classical thermal conductivity is reduced by 4 to 5 orders of magnitude in the hot spot

$$k_{\perp} = \frac{k_{||}}{1 + \left(\omega_{ce,ci}/\nu_{e,i}\right)^2}$$

$\omega_{ce,ci}$: electron and ion gyrofrequencies
$\nu_{e,i}$: electron- and ion-collision rates

- Average values of reduction factor in the DT gas are plotted below for high- and low-adiabat pulses.

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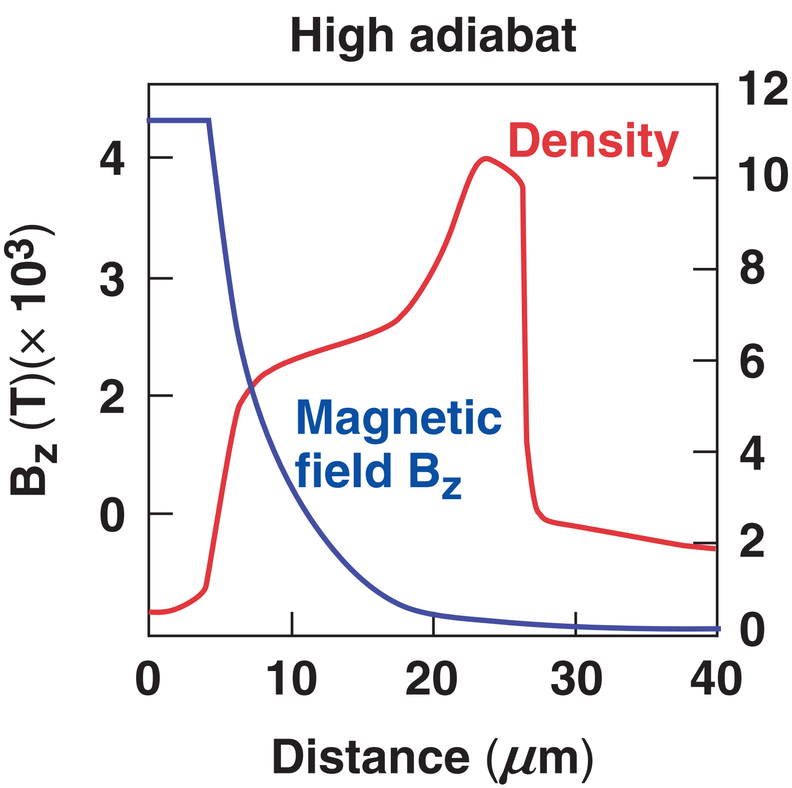
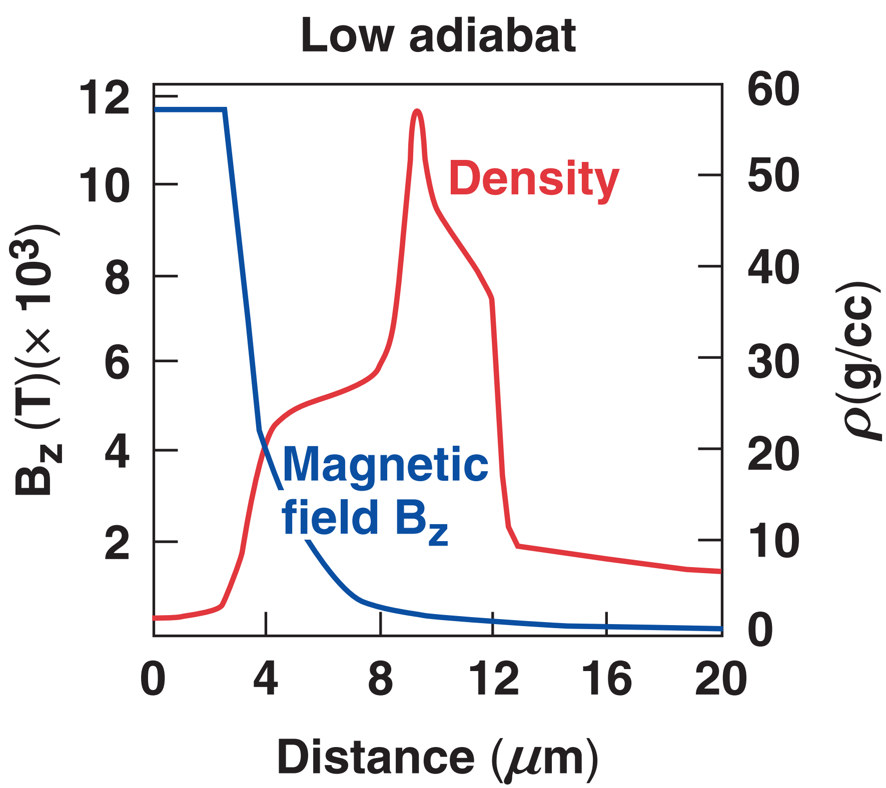
# The magnetic field at peak compression is 3 orders of magnitude higher than the seed field

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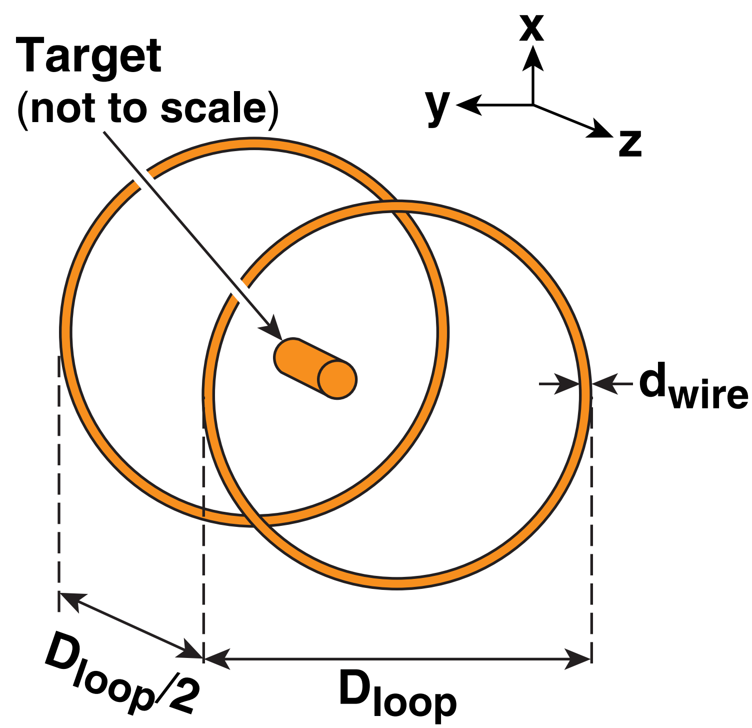
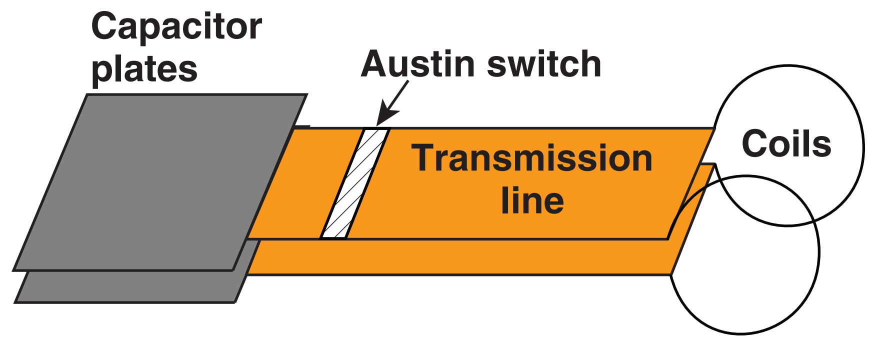
# Helmholtz coils are designed to generate the seed magnetic field

- Two copper wires are in a Helmholtz coil formation. The separation distance between the coils is equal to their radius.
- Physical dimensions
  - Coil diameter: 6 mm or 4 mm
  - Coil wire diameter: 25 $\mu$m
- Based on the information above
  - inductance $L_{coil}$ = 21 nH or 13 nH
  - resistance $R_{coil}$ = 0.64 $\Omega$ or 0.43 $\Omega$
- Then the required current per coil for generating seed field of 10 T
  - 33.3 kA for 6-mm-diam coil
  - 22.2 kA for 4-mm-diam coil

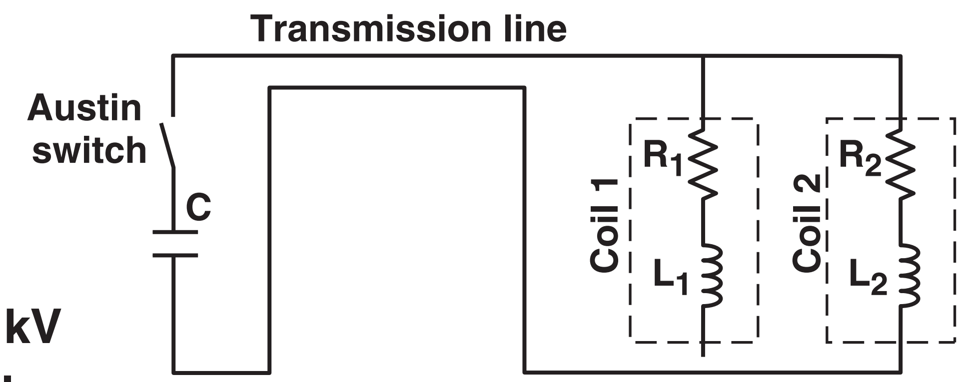


# The coils are powered by capacitor discharge

- High-voltage capacitor provides the needed power.
- Fast, high-voltage Austin switch is implemented.
- Important parameters to consider are
  - capacitance value: 10 to 100 nF
  - impedance of the transmission line: as low as 0.4 to 0.6 Ω to match with the resistance of the coils
  - working voltage: 20 to 80 kV
  - coupling to Helmholtz coils: efficiency of power delivery




Experimental setup of Helmholtz coils and capacitor




Circuit diagram of the experimental setup

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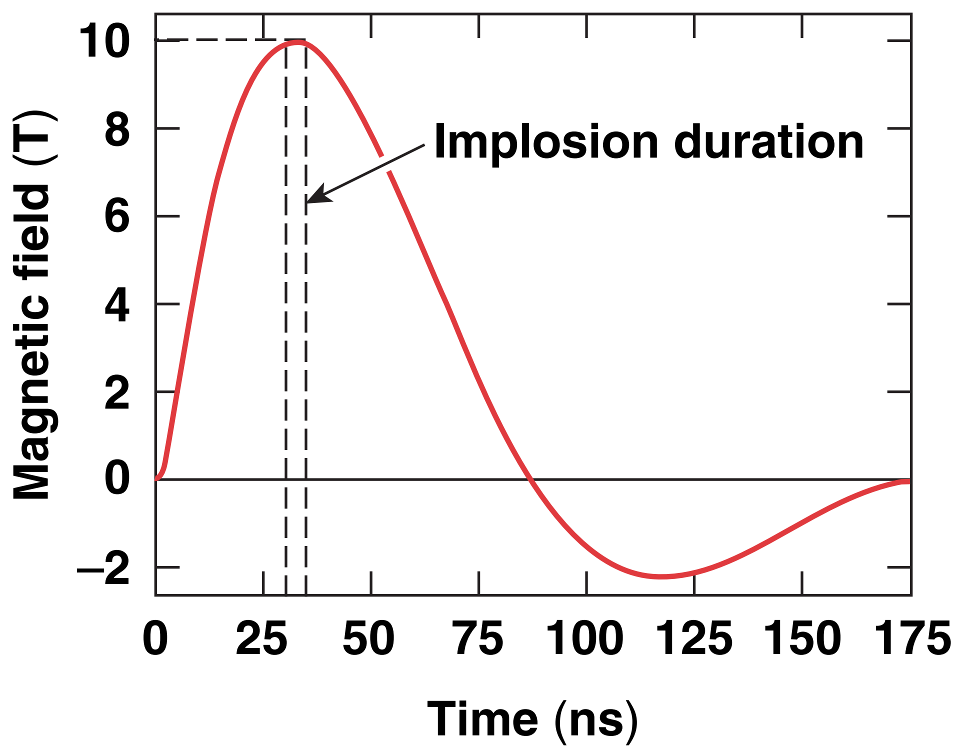
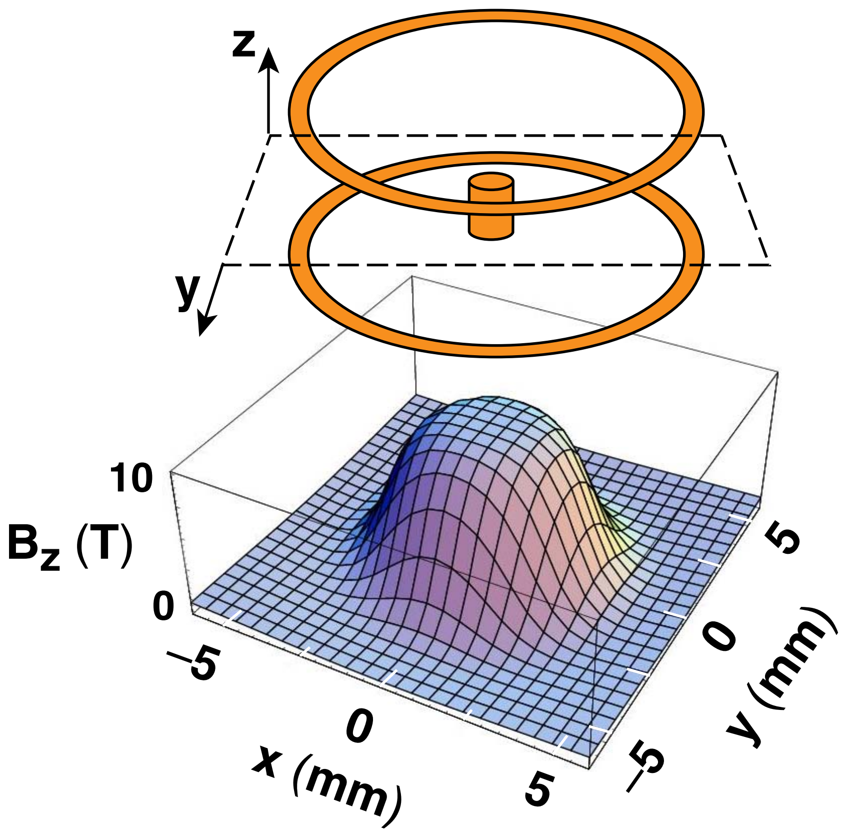
# During the implosion, the seed field is at quasi-steady state

- The target implosion happens over ~3 ns, which is much shorter than the oscillation period.
- Generally, the oscillation period is between 50 to 230 ns for the setup used with a 10- to 100- nF capacitor and 4- or 6- mm coils.

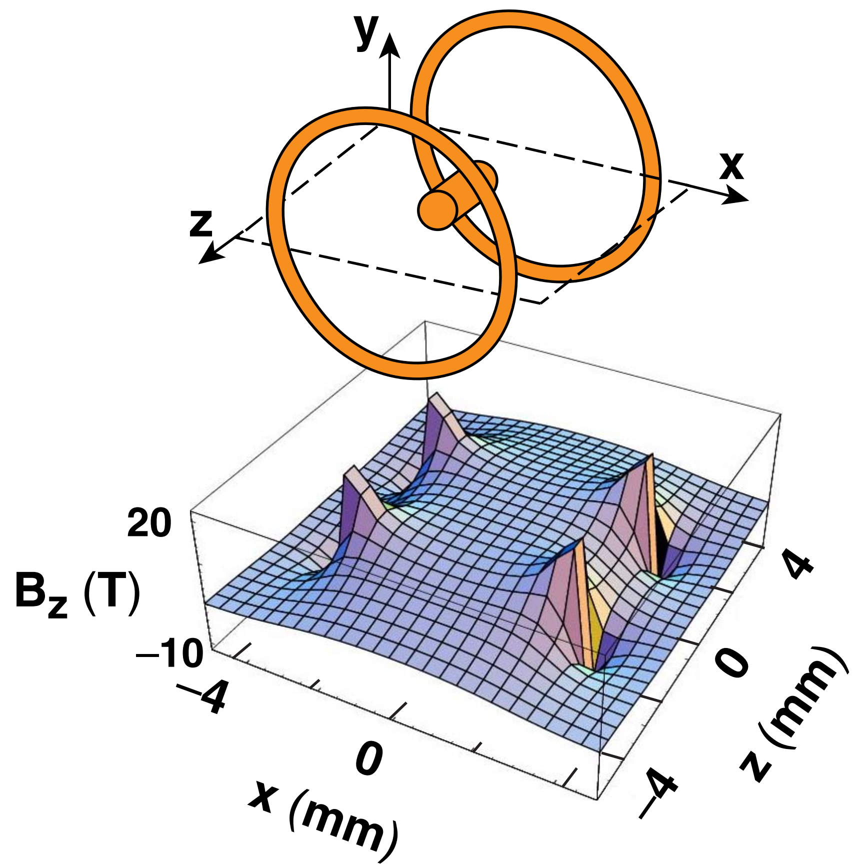



Magnetic field at the center of the coils calculated for a 100-nF capacitor and 4-mm-diam Helmholtz coils

# The magnetic field is spatially uniform at the location of the implosion target




2-D plot of magnetic field in z = 0 plane




2-D plot of magnetic field in y = 0 plane

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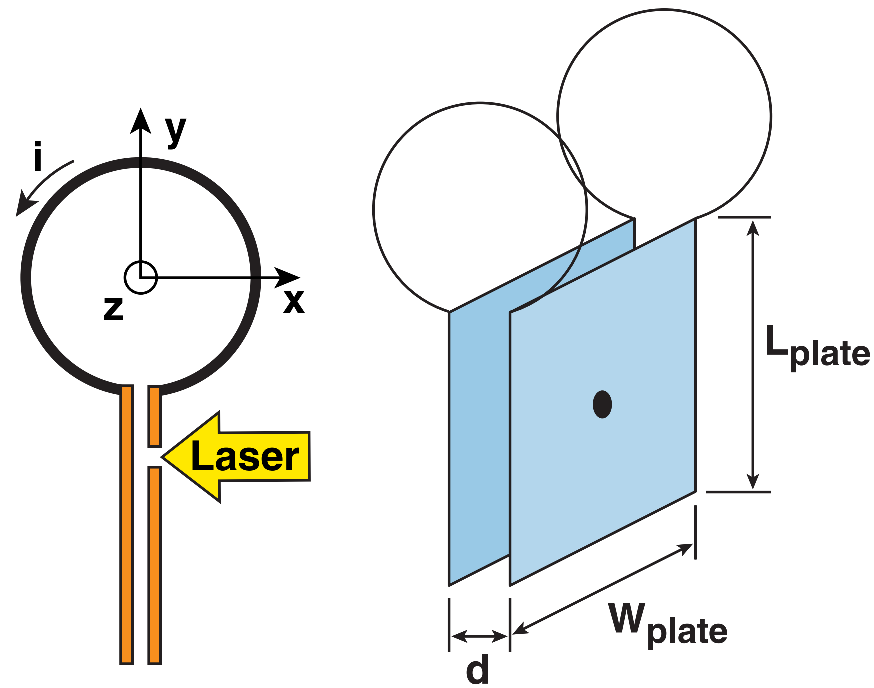
# Alternatively, the seed B-field can also be generated by the laser-driven setup[1,2]

- The laser pulse is focused on the back plate through a hole in the front plate.
- Plasma is created and laser energy is resonantly absorbed by the electrons.
- Hot electrons stream down the electron density gradient and impact the front plate.
- Electrical charges accumulate on the front plate, creating a large electrical potential $V_0$.
- A potential difference drives a reverse current i through the wire loops.
- Current through the coil loops generates the magnetic field in the z-direction.




Helmholtz coils connecting the two capacitor plates in laser-driven setup

[1]H. Daido *et al*., Phys. Rev. Lett. 56 846 (1986).
[2]C. Courtois *et al*., J. Appl. Phys. 98 054913 (2005).

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# Future plans

- Generate the magnetic field by capacitor discharge (December 2005)
- Measure current coupled to the Helmholtz coils
- Determine time dependence of both current and magnetic field
- Optimize the transmission line and transformer assembly
- Measure the magnetic field generated by utilizing the Faraday rotation principle
- Develop the diagnostics for high magnetic field
- Generate the magnetic field by laser pulse
- Capsule implosion and field compression (Summer 2006)

# Conclusion

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- A magnetic field inside an imploding ICF target can be compressed to ultrahigh intensities ($10^3$ to $10^4$ T).
- A seed magnetic field can be generated by capacitor-driven setup.
- An apparatus for generating a 10 T seed field has been designed and is currently under construction at LLE.
- Capsule implosion and magnetic field compression experiments are scheduled for the Summer of 2006.