Alternatives to CT Merging for Forming/Magnetizing a Plasma Target

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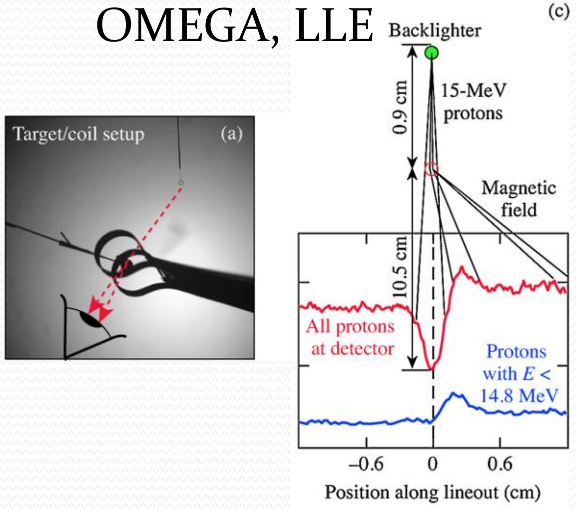
Motivation

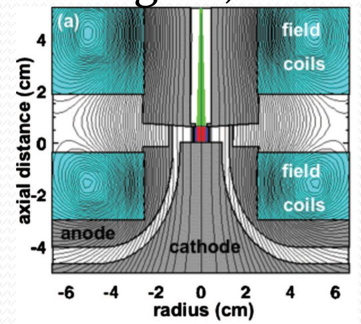
- Embedded magnetic fields modify plasma behavior in the ionosphere and in laboratory experiments. Magnetized plasmas in inertial fusion permit longer duration and smaller density-radius product fuel implosions by **reducing energy transport** significantly.
  - Requires $H \equiv \omega_c / \nu_m > 1$.
  - To maximize DT alpha heating, $r_\alpha = \dfrac{\gamma\beta c m_\alpha}{Z_\alpha e m_e B} < r_{fuel}$,

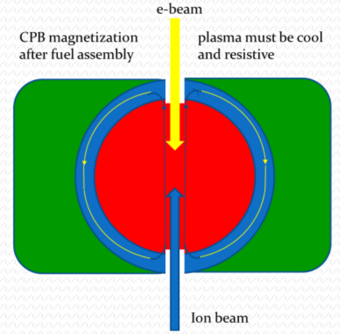
    or $B_\alpha = 4$ kT (100 μm $/r_{fuel}$).
- Advanced coil technologies have been used/proposed.[1,2]
- For fusion energy, fields must be created with significant standoff distance.
  - A promising technique for magnetic field production is the beat-wave interaction.[3]
  - Electron/ion beams have been used/proposed to embed fields. Rotating beams can produce closed magnetic field structures.[4]

Magnetized target on OMEGA, LLE



MagLIF, SNL



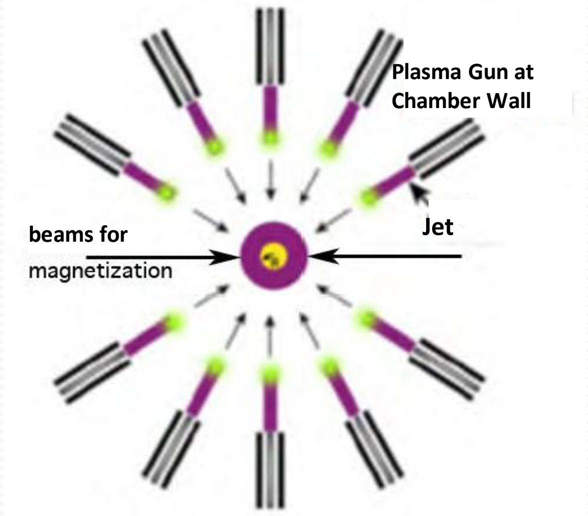


We discuss the utility of lasers and charged particle beams to magnetize target plasmas remotely.

1 O.V. Gotchev, et al., J. Fusion Energy **27**, 25-31 (2008).
2 S. A. Slutz, et al., Phys. Plasmas **17**, 056303 (2010).
3 J. H. Rogers and D. Q. Hwang, Phys. Rev. Lett. 68, 3877 (1992);
4 J. D. Sethian, K. A. Gerber, D. N. Spector, and A. E. Robson, Phys. Rev, Lett. **41**, 798 (1978).

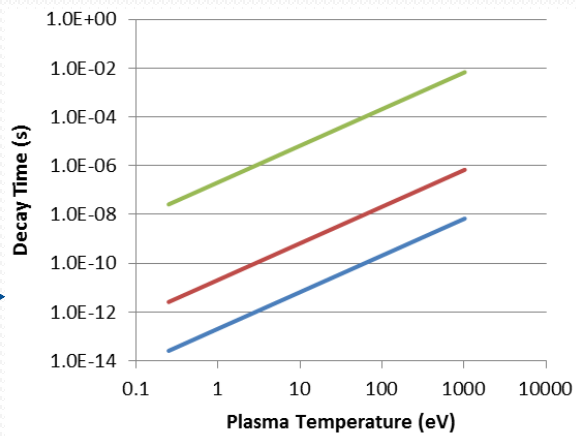
Generally, plasma conductivity must be *low* to embed fields, *high* to sustain them.

- Plasma currents decay on time scale: $\tau_m = \frac{4\pi\sigma r^2}{c^2}$
- Remotely driven current pulse must persist $t_p > \tau_m$
- *Anomalous resistivity* from instabilities (two stream, velocity shear, Weibel) assist field penetration.
- The embedded magnetic field must remain for the hydrodynamic implosion time, i.e. $t_h < \tau_m$.
- Both conditions met if the magnetization increases τ_m.

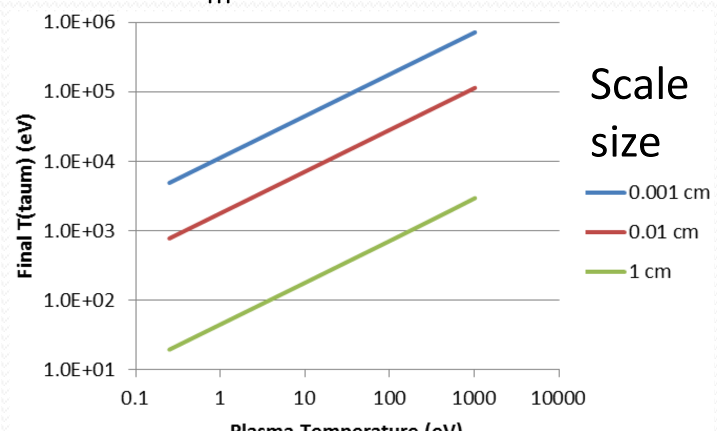


Plasma return currents heating increases with decreasing scale size of current drive. Here, *classical resistivity* assumed.

τ_m vs. plasma T



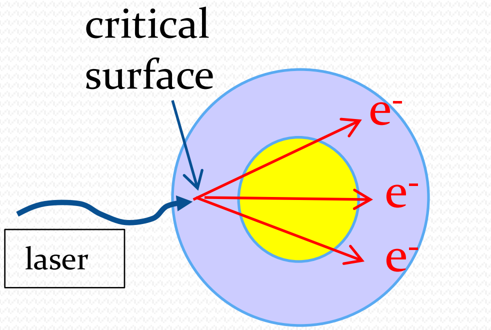
T(τ_m) for 1 MA drive

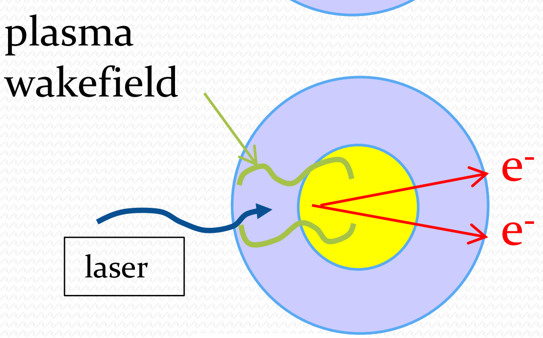


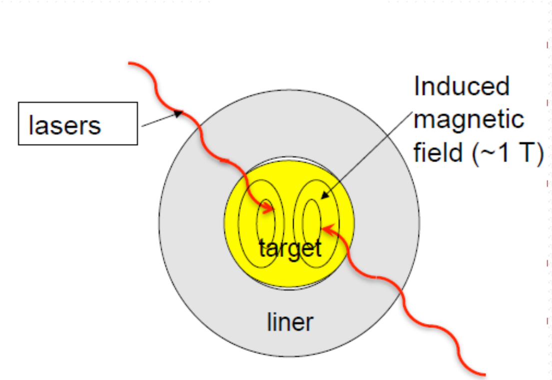
10^{17} cm^{-3} D plasma

Lasers can produce charged particle beams for current drive

- PetaWatt scale beams can drive enormous currents but efficiency is low for producing magnetic fields in over dense plasmas $\omega_{laser} < \omega_p$.
- Short pulse lasers can also drive currents/fields via wakefield acceleration in underdense plasma.[&]
- The laser beatwave technique* can drive currents at the Alfven limit with precision and reasonable efficiency for $\omega_{laser} > \omega_p$.



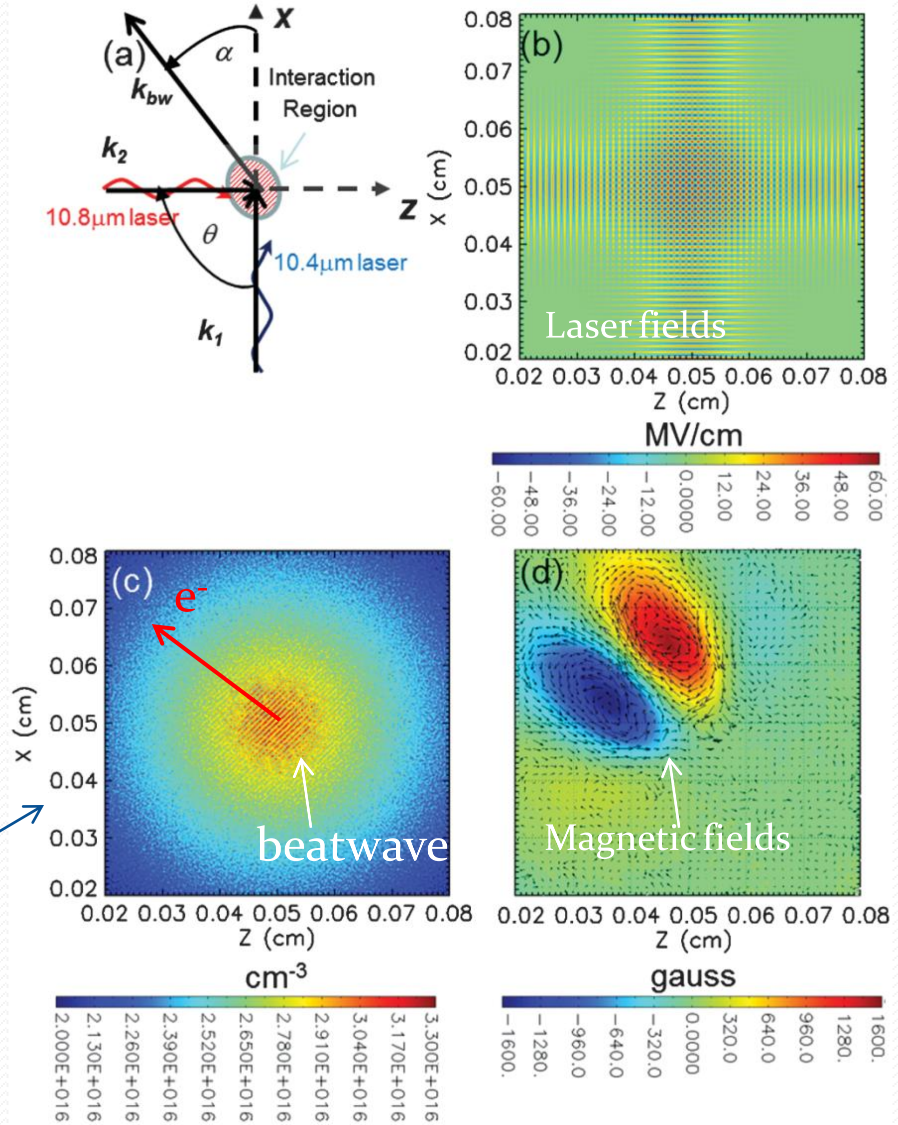




*M. N. Rosenbluth and C. S. Liu, Phys. Rev. Lett. 29, 701 (1972) ;
B. I. Cohen, Comments Plasma Phys. Controlled Fusion **8** 197 (1984).
[&] L.M. Gorbunov, P. Mora, T. M. Antonsen, Phys. Plasmas **4**, 4358 (1997).

Laser Beatwave Current Drive from overlapping electromagnetic waves

- Beatwaves are created by tuning 2 EM waves such that $\omega_1 - \omega_2 \sim \omega_{pe}$ where $\omega_{pe} \sim n_e^{1/2}$ is the electron plasma frequency.
- Beatwave imparts momentum onto the plasma electron population if $v_e \sim v_{ph}$ from Landau damping.
- Unidirectional electrons produce magnetic fields within the plasma.



Through beatwave generation, EM waves couple to a wide range of plasma densities.

Contours of the logarithm of **electron density (cm^{-3})** as a function of the center and difference wavelengths of the injected electromagnetic waves.

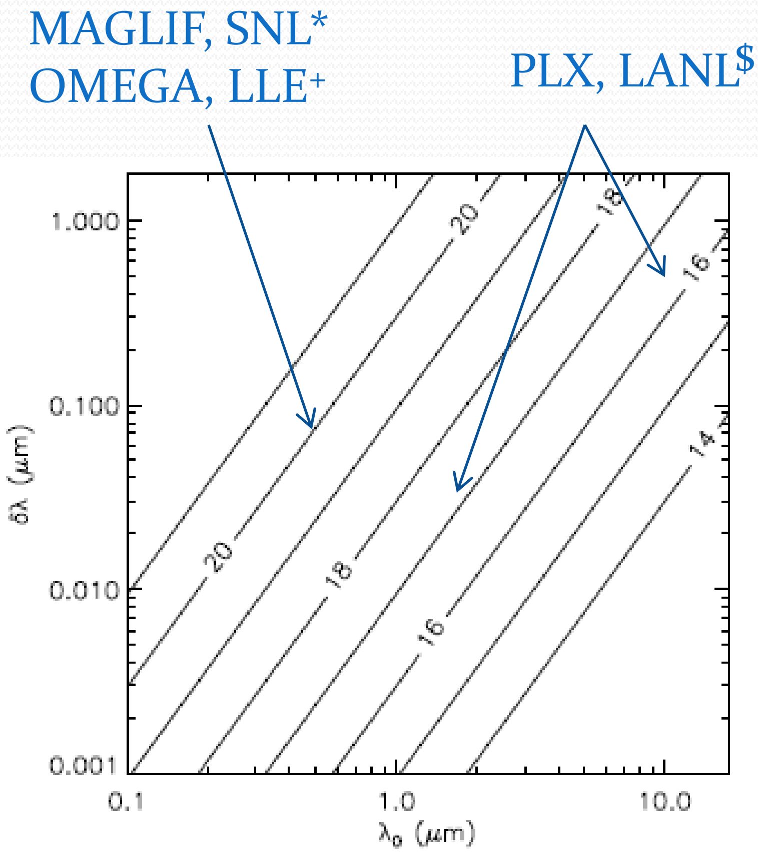
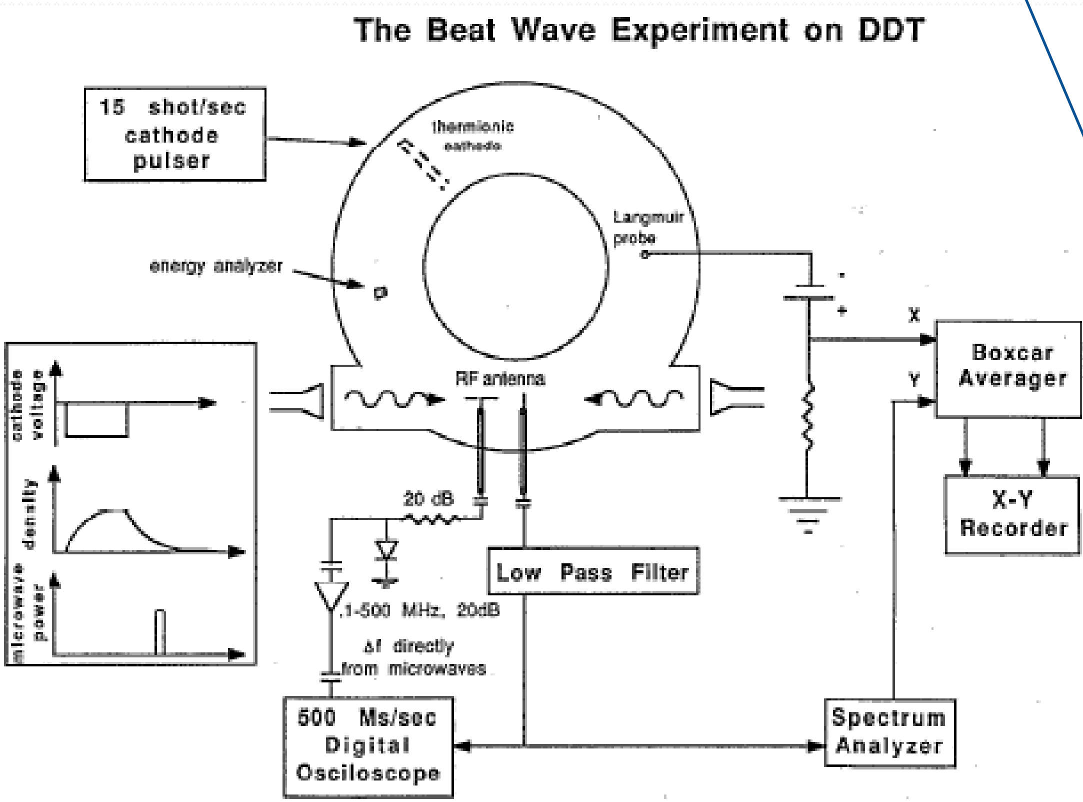


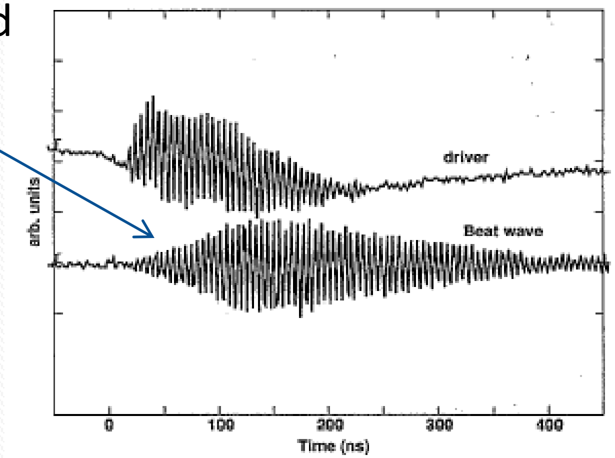
Figure 8 *Contour lines of the logarithm of the plasma density (per cc) satisfying the condition* $|\omega_1 - \omega_2| \approx \omega_{pe}$ *for* $\delta\lambda = |\lambda_1 - \lambda_2|$ *versus* $\lambda_0 = (\lambda_1 + \lambda_2)/2$.

*S. A. Slutz, et al., Phys. Plasmas **17**, 056303 (2010).
+Gotchev, et al., Phys. Rev. Lett., **103** 21 (2009).
$S. Hsu, et al., IEEE Trans. on Plasma Sci., (2012).

(UC) Davis Diverted Torus experiment measured beatwave amplitudes and electron current.*

beatwave and current drive observed





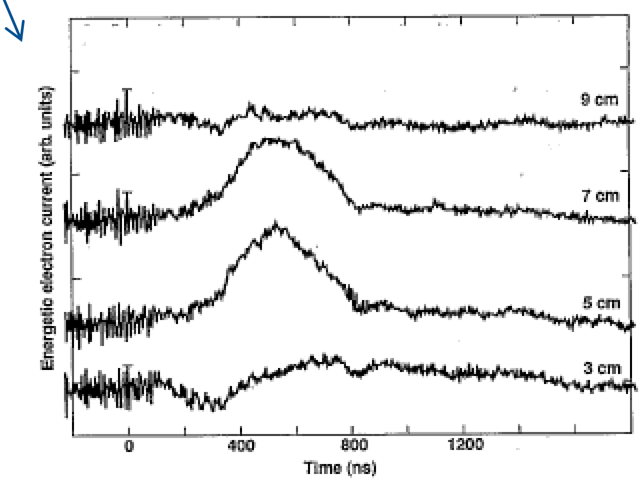


FIG. 9. Energetic electron current (≥13 eV) at different radial positions versus time illustrates the radial localization of the current.

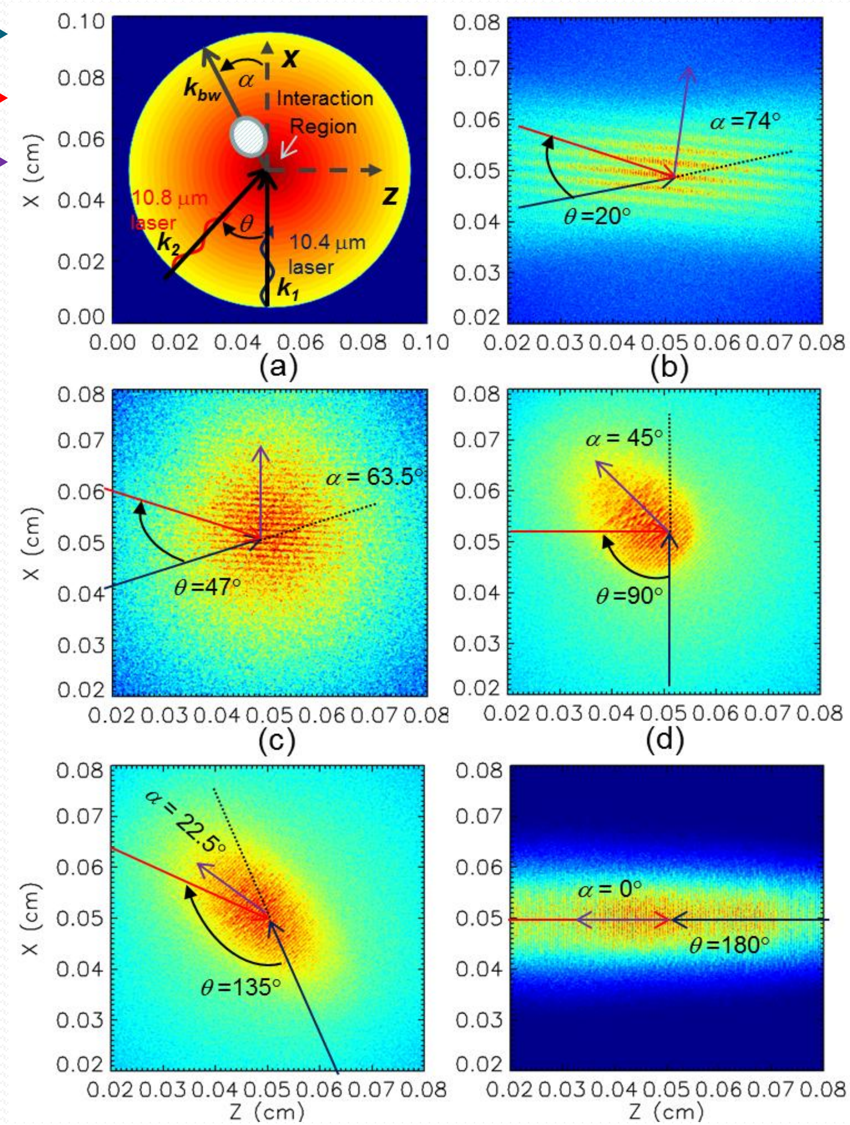
~ 9 GHz, ~10^5 W/cm^2 microwave in 10^{8-9} cm^{-3} plasma

*J. H. Rogers and D. Q. Hwang, Phys. Rev. Lett. 68, 3877 (1992).

Freq. and angle of waves allow for precise placement/direction of current

Two dimensional LSP simulations*

Laser 1 →
Laser 2 →
Beatwave →



10.4 and 10.8 µm lasers, $3x10^{12}$ W/cm^2 laser intensity.

10 eV, $2x10^{16}$ cm^{-3} density D plasma.

Weak resonance near 1.07 THz, >5 µm beatwave decreasing with angle.

Beatwave phase velocity decreases with angle.

*D. R. Welch, PRL, **109**, 225002 (2012).

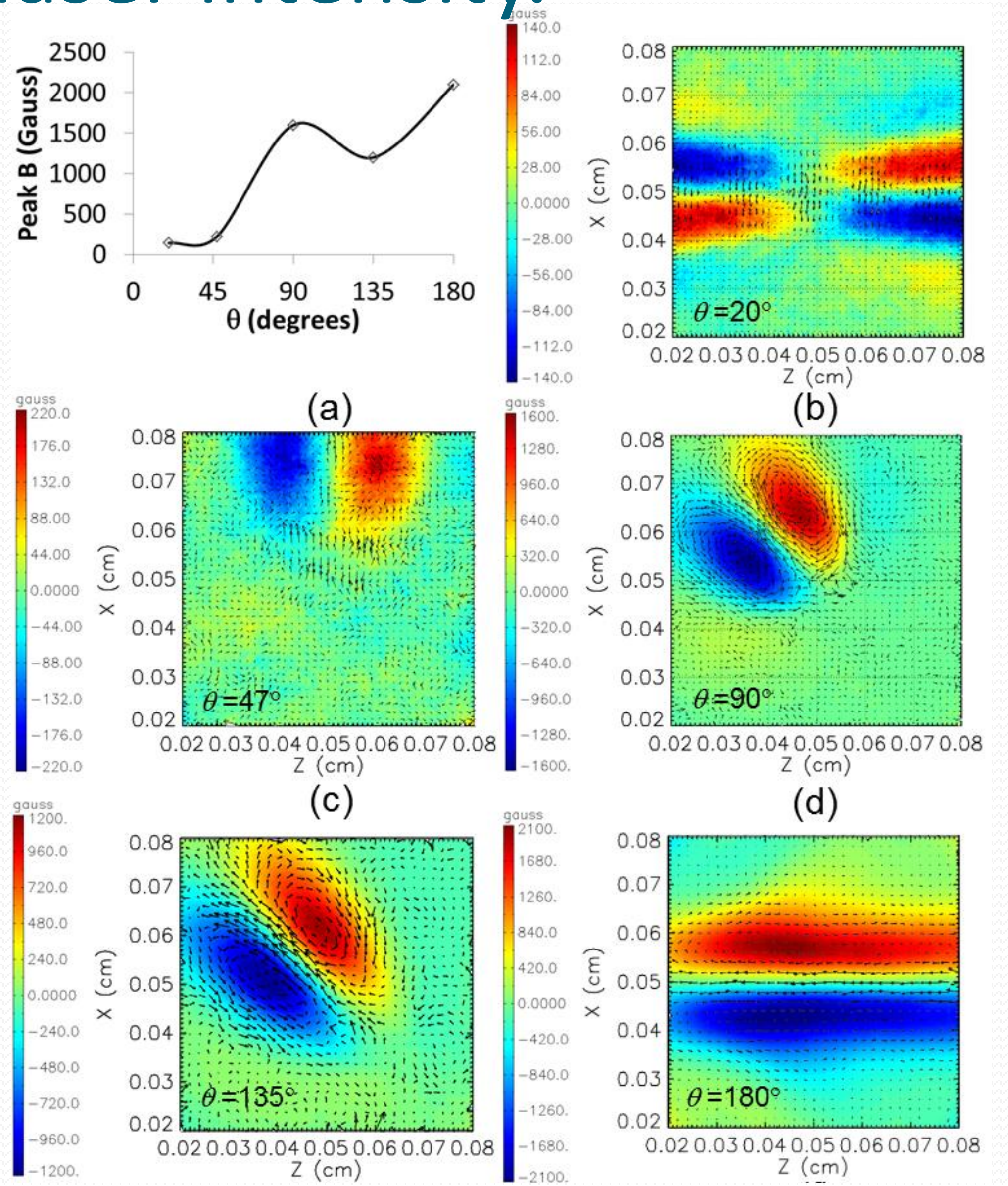
Current drive, plasma magnetization increase with angle, laser intensity.

Beatwave phase velocity decreases with θ, better couples to 10 eV plasma for $\theta > 90°$.

Coupling best for $F \equiv v_{ph}/v_e = 1.9\text{-}2.7$.

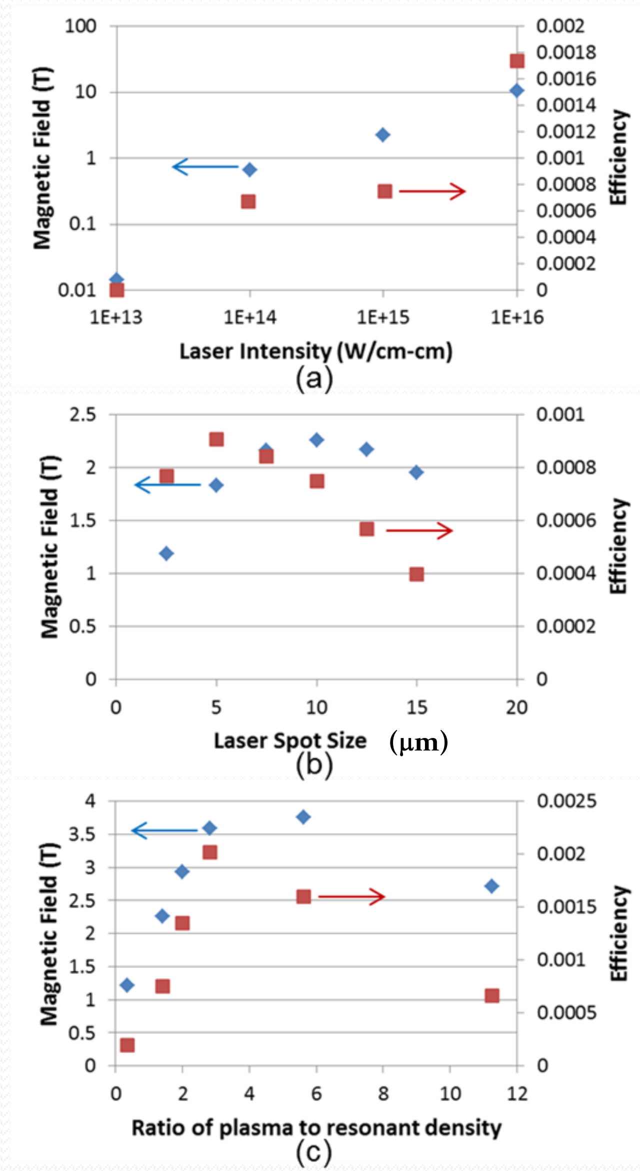
Beam divergence is roughly 1/F, can extend field region if small.

Complex current paths could be constructed (FRCs).

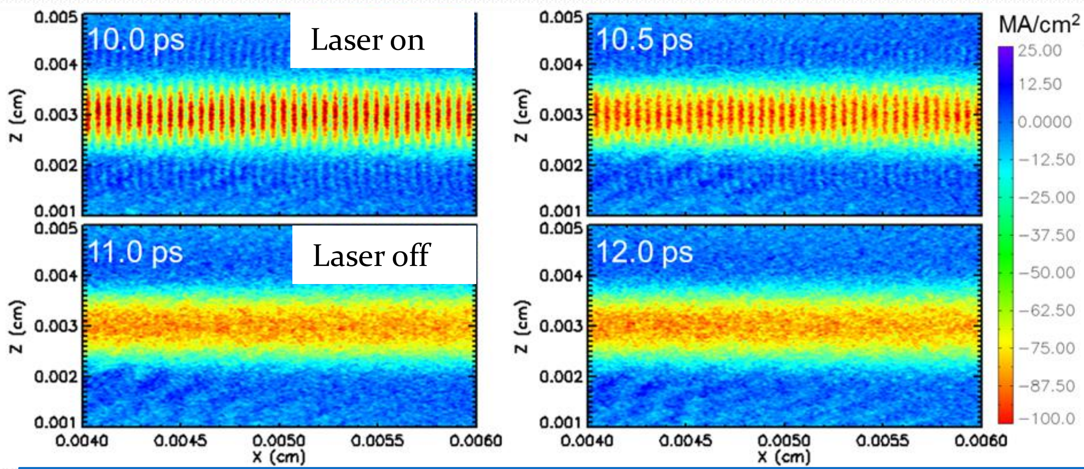


1-μm lasers with 4% Δλ can truly embed 10 T in up to 10^{19} cm^{-3} plasma

2 counter propagating **highly elliptical lasers**
2—15 micron spot
10-ps pulse
10^{13-16} W/cm^2 intensity
1.4×10^{18} cm^{-3} resonant density
3.7 μm skin depth



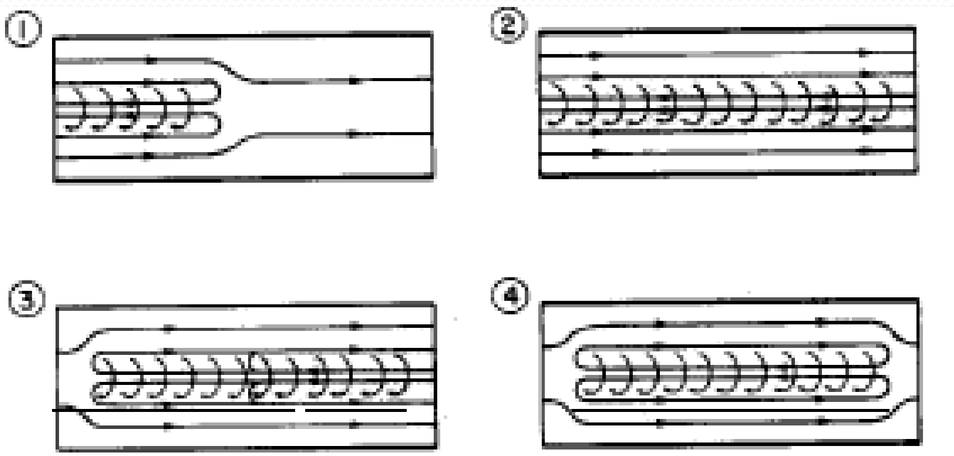
Embedded beatwave-driven current density



Proof-of-Concept experiments at 1-μm laser wavelength have been proposed on the Trident Laser Facility at LANL.(Hsu-Welch)

Charged Particle Beam (CPB) current drive in neutral or initially-low conductivity gas.

- Magnetization with CPB requires careful staging:
  1. Beam injection - rotating or not.
  2. Beam B fields setup in low conductivity plasma/gas.
  3. Ionization/heating of now magnetized plasma produces high σ.
  4. Beam shuts off leaving fields intact.



Sethian, et al. experiment used 900 kV, 110 kA, rotating electron beam to inject an FRC into gas.

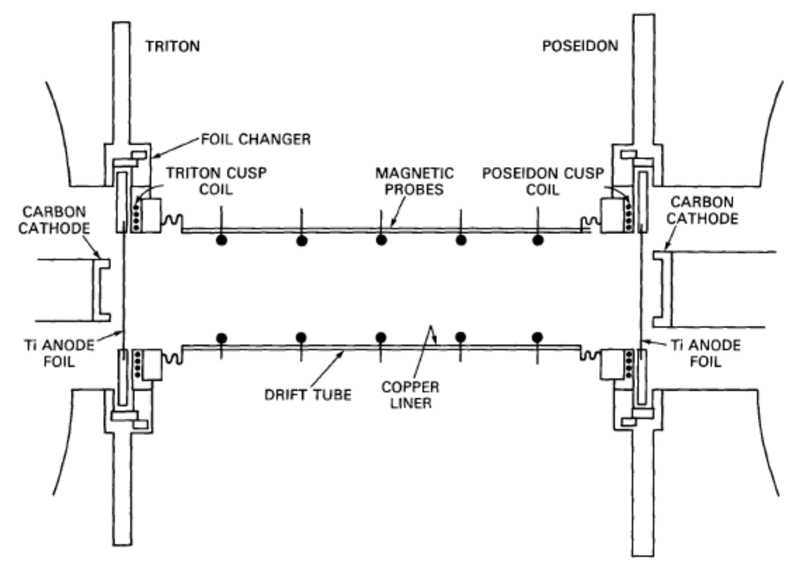
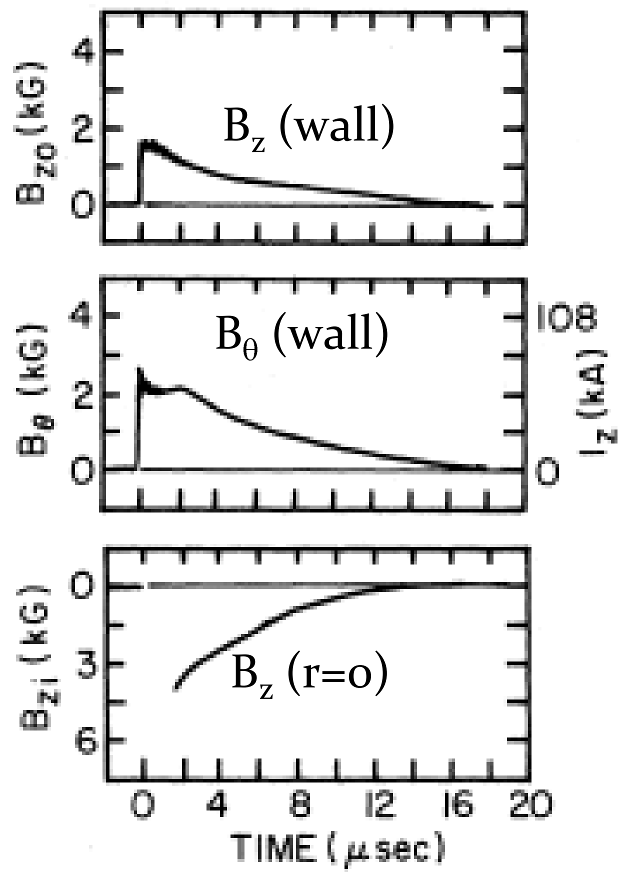


Fig. 2 – The Experimental Facility

J. Sethian, et al., NRL Report 4932, 1982.

Rotating Electron Beam creates FRC in experiment*

- Magnetically immersed cathode produces rotating beam
  - 10-cm length, 40--300mTorr D_2 neutral gas
  - 900 kV, 110 kA, 100 ns
- Rotating beam is not limited by Alfven current (here $I_A = 40$ kA)[&]



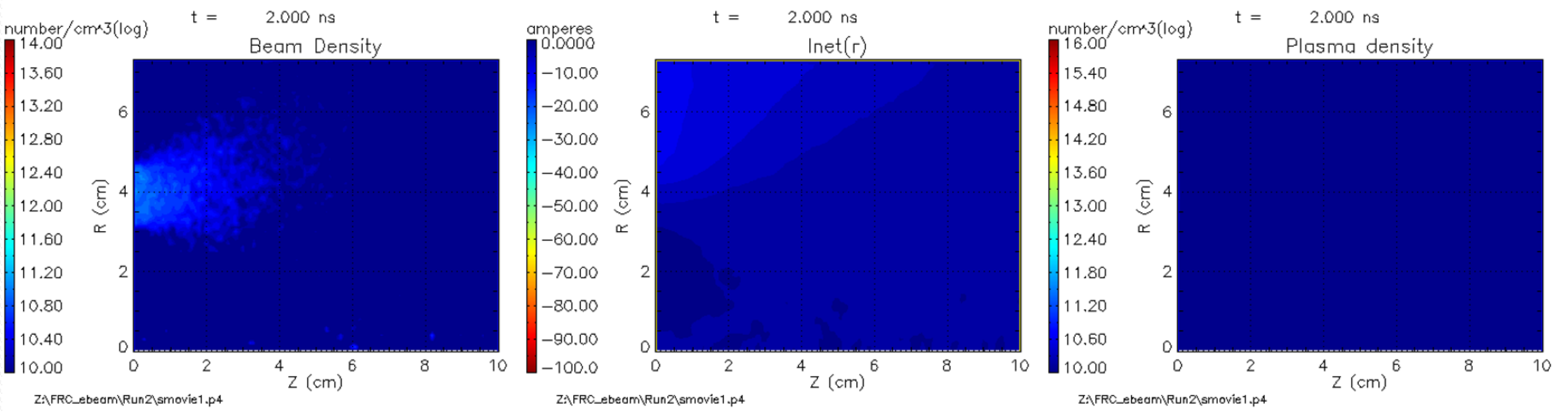
Measured on-axis field reversal

* J. D. Sethian, K. A. Gerber, D. N. Spector, and A. E. Robson, Phys. Rev, Lett. **41**, 798 (1978).

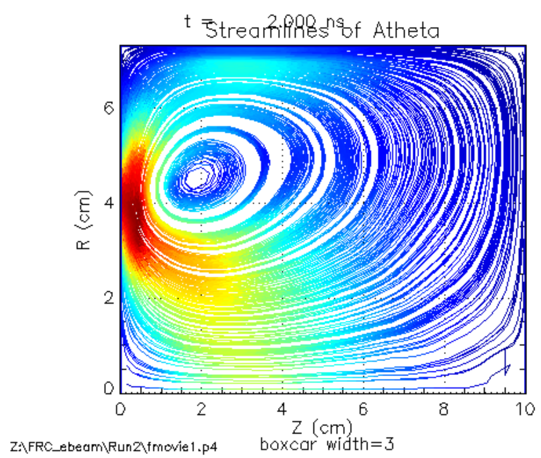
[&] S. Yoshikawa, Phys. Rev. Lett. **26**, 295 (1971).

Advanced LSP kinetic simulations show rotating electron beam creates FRC.

- Simulation of abbreviated NRL experimental setup
  - 10-cm length, 100mTorr D_2 neutral gas
  - 900 kV, 110 kA, 60 ns FWHM, 4.8 radian/ns rotation
  - At t=160 ns, $B_z(0)$ = 5 kG, $B_z(6.3)$ = 1.8 kG, B_θ = 1.8 kG

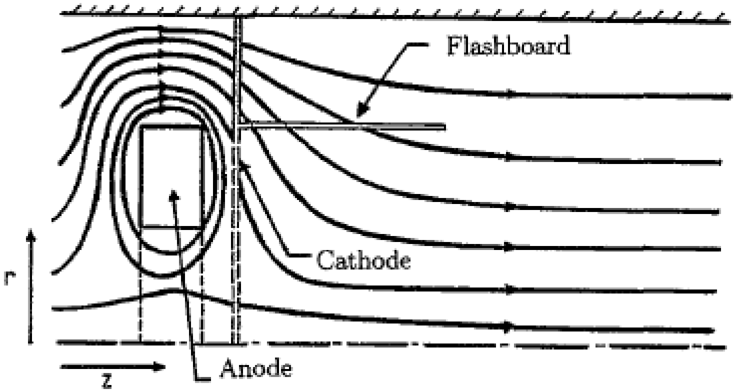


Beam betatron oscillation lead to an imprint of strong B_θ fields. These fields can be avoided by injecting a beam from the opposite end reinforcing B_z but canceling B_θ .
(J. Sethian, et al., NRL Report 4932, 1982) .



Similarly ion beam/rings have been studied for FRCs and magnetized fusion.

- FRC can be induced with trapped ion rings.



Magnetically insulated ion diode

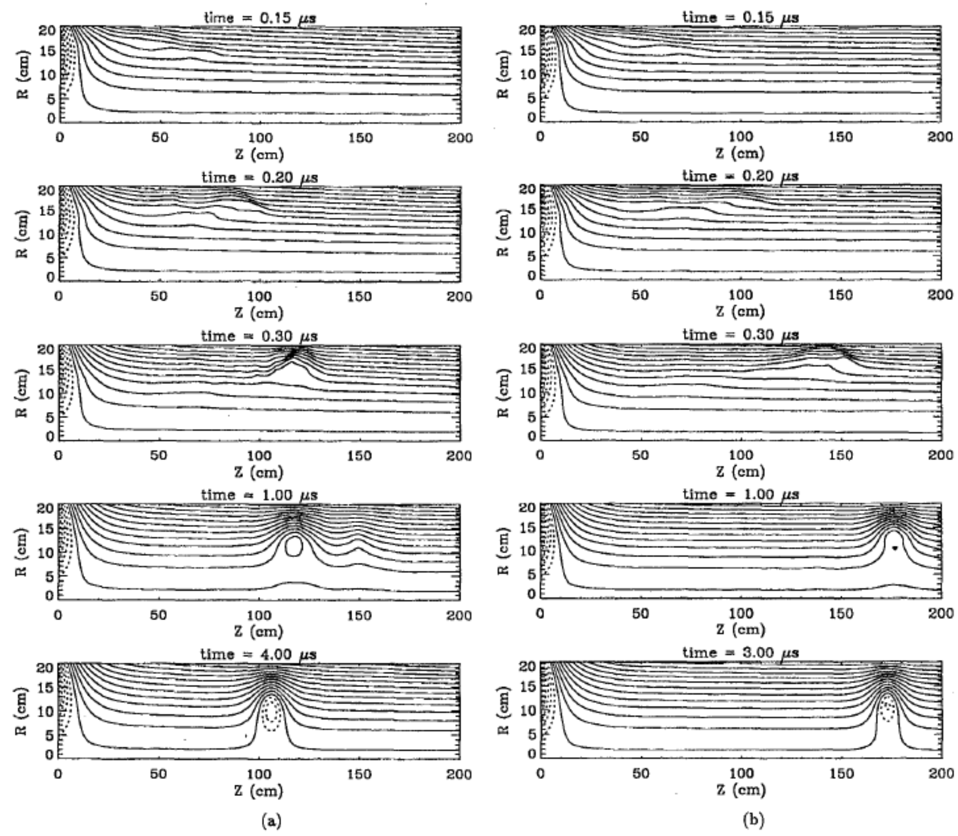


FIG. 10. Temporal evolution of magnetic field flux ψ ($N_b = 4\times10^{17}$): (a) $\beta = 0.2$/m; (b) 0.05/m. The self-field develops through Alfvén perturbations; field reversal on axis occurs on the diffusive time scale ~2 μs.

Yu. A. Omelchenko and R. N. Sudan, Phys. Plasmas 2, 2733 (1995).

Application of Laser/CPB current drive to PJMIF, MagLIF, Railgun concepts

For Plasma Jet Magneto Inertial Fusion,* plasma can be magnetized at lower density.

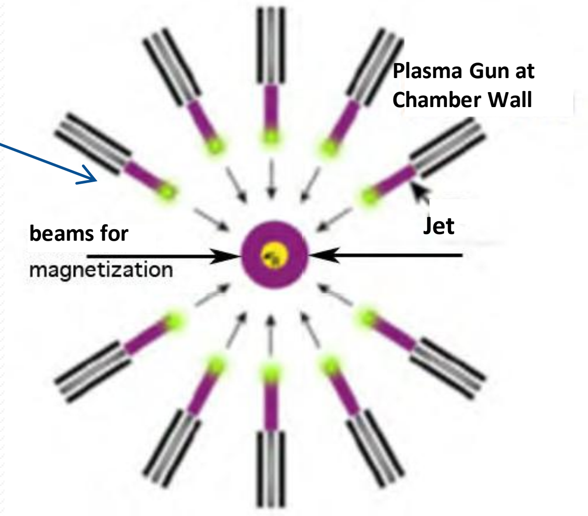
DT jets (green) followed by high-Z jet (purple)

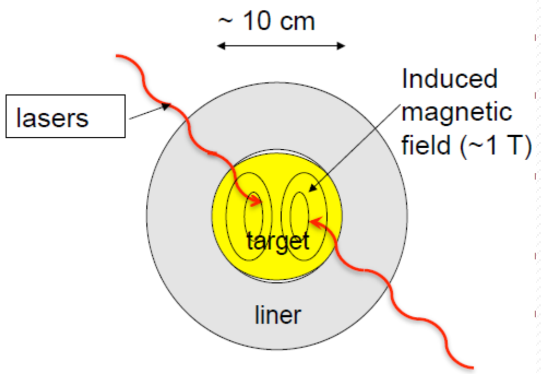
~100 km/s implosion velocity.

Magnetization can occur before 1 μs before compression and while DT jet plasma is cool.

Magnetic fields order >1 T can be compressed with liner to > 100 T.

Jet densities at roughly 10 cm radius 10^{17} cm^{-3} 1—10 micron laser technology, 20-200 micron spots. Decay times for heated plasma >> 1 μs.



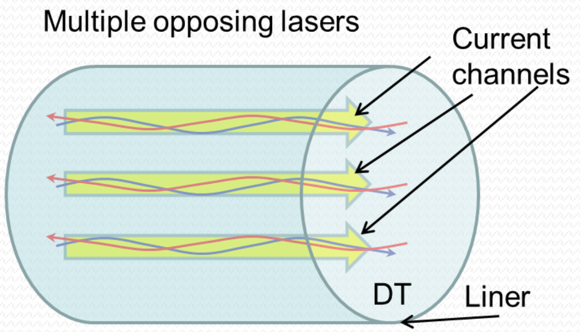


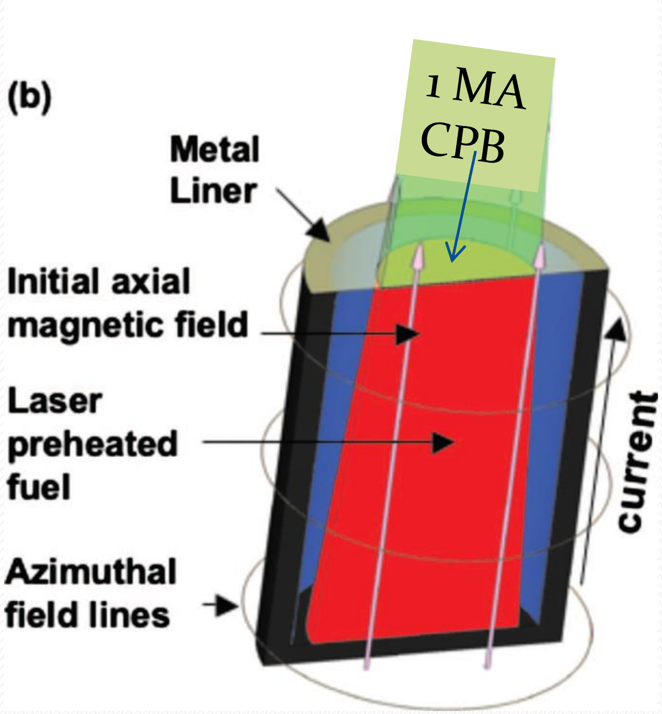
Proof-of-Concept experiments at 1-μm laser wavelength have been proposed on the Trident Laser Facility at LANL.(Hsu-Welch)

*Y. C. F. Thio, E. Panarella, R. C. Kirkpatrick, C. E. Knapp, F. Wysocki, P. Parks, and G. Schmidt, "Magnetized target fusion in a spheroidal geometry with standoff drivers," in Proc. 2nd Int. Symp.— Current Trends International Fusion Research, E. Panarella, Ed., 1999, p. 113.

For MagLIF and OMEGA experiments, initially neutral D_2 gas can be magnetized with either lasers or CPBs

- 0.5-mm radius fuel at 10^{20} cm^{-3} density would require many laser channels with 0.5 μm laser technology.
  - Merging of channels is an issue.
- A 1 MA electron/ion beam can possibly magnetize, ionize and heat the plasma to interesting conditions.
  - The high density gas requires **direct ionization and heating** which is more efficient with an ion beam.





Remote seeding of simple and complex fields is possible for a low cost fusion scenario.

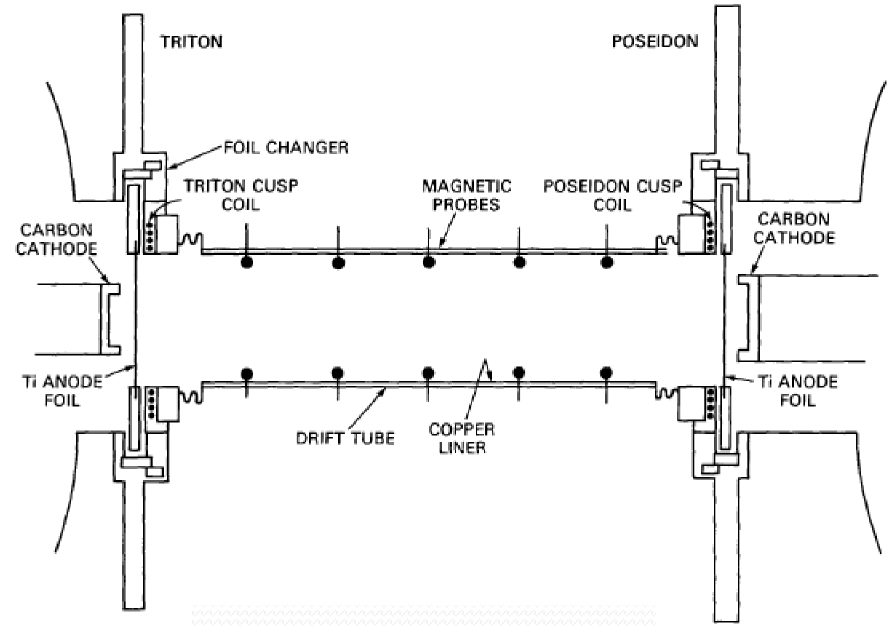
- Laser beatwave current drive is applicable to converging plasma jets (PJMIF) and possibly MagLIF/OMEGA.
  - Laser technology exists for up to 10^{17} cm^{-3} density plasmas, a proof-of-principle experiment using 1-μm lasers has been proposed for up to 10^{19} cm^{-3} density on Trident.
  - Large volumes at high density required many channels and merging must be examined.

- FRC/B_θ fields can be initialized using rotating/paraxial beams in initially low conductivity gas.
  - Accelerator technology has improved since initial experiments.
  - Achieving closed field lines, significant standoff not yet demonstrated, but feasible with 2 beams.
  - Magnetizing ionized plasma is more difficult, but anomalous resistivity is likely high for opposing beams.

Backup slides

With staged counter propagating beams, closed field lines are possible.

- Beam betatron oscillation lead to an imprint of strong B_θ fields. These fields can be avoided by injecting a beam from the opposite end reinforcing B_z but canceling B_θ.
- Issues with beam control and propagation:
  - How much standoff can be achieved?
  - 2nd Electron beam equilibrium complex.
  - Must remotely produce conductive "can" to constrain fields



2 beam experiment

Optimization will require detailed modeling.

J. Sethian, et al., NRL Report 4932, 1982.

CPB current drive challenging in low temperature plasma.

- Magnetization is more difficult with ionized gas.
- Rotating *ion beams* better suited to higher density gas where ohmic heating is small.
- Energy requirement increases with initial plasma T, n.

Scale size of channel