Alternatives to CT Merging for Forming/Magnetizing a Plasma Target

D. R. Welch, D. V. Rose, C. Thoma, and T. Genoni
Voss Scientific, Albuquerque, NM

Presented at the Drivers for Low-Cost Development Towards Economical Fusion Power ARPA-E Workshop
October 29, 2013
Work Supported by LANL/DOE
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, \( r_\alpha = \frac{\gamma \beta cm}{Z_a e m_\text{e} B} < r_{\text{fuel}} \),
    or \( B_\alpha = 4 \text{ kT} \) (100 \( \mu \text{m} \)/\( r_{\text{fuel}} \)).

- Advanced coil technologies have been used/proposed.\(^1\text{-}^2\)

- 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.\(^4\)

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

---

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 \( \tau_m \).

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

**\( \tau_m \) vs. plasma T**

**\( T(\tau_m) \) for 1 MA drive**

10^{17} \text{ cm}^{-3} \text{ 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 $\omega_{\text{laser}} < \omega_p$.
- Short pulse lasers can also drive currents/fields via wakefield acceleration in underdense plasma.
- The laser beatwave technique* can drive currents at the Alfvén limit with precision and reasonable efficiency for $\omega_{\text{laser}} > \omega_p$.

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.

*MAGLIF, SNL*  
*OMEGA, LLE*  
*PLX, LANL*

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

*S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010).*  
(UC) Davis Diverted Torus experiment measured beatwave amplitudes and electron current.*

beatwave and current drive observed

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

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

Two dimensional LSP simulations

10.4 and 10.8 µm lasers, $3\times10^{12}$ W/cm$^2$ laser intensity.

10 eV, $2\times10^{16}$ 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).*
Beatwave phase velocity decreases with $\theta$, better couples to 10 eV plasma for $\theta > 90^\circ$.

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

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

Complex current paths could be constructed (FRCs).
1-μm lasers with 4% $\Delta \lambda$ 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
1.4x$10^{18}$ 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 $\sigma$.
  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.

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) &

Advanced LSP kinetic simulations show rotating electron beam creates FRC.

- Simulation of abbreviated NRL experimental setup
  - 10-cm length, 100mTorr D₂ 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, $B_\theta = 1.8$ kG

Beam betatron oscillation lead to an imprint of strong $B_\theta$ fields. These fields can be avoided by injecting a beam from the opposite end reinforcing $B_z$ but canceling $B_\theta$.

(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.

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)

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.
Standoff of a B-theta toroidal target with railguns using lasers or CPBs*

Plasma must be resistive for magnetization after fuel assembly.

Anomalous resistivity will be driven by instabilities associated with opposing beams and possibly Weibel. Beam betatron wavelength must be order size of fuel assembly.

Opposing rotating electron beams are another option (similar to proposed by Sethian). Would not require hole in capsule.

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/$B_\theta$ 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 $B_\theta$ fields. These fields can be avoided by injecting a beam from the opposite end reinforcing $B_z$ but canceling $B_\theta$.

- Issues with beam control and propagation:
  - How much standoff can be achieved?
  - 2$^{nd}$ Electron beam equilibrium complex.
  - Must remotely produce conductive “can” to constrain fields

Optimization will require detailed modeling.

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.