Some comments on

Physics of Magnetic Flux Compression in Plasmas

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Without going to the extreme conditions required for laser fusion, it should be possible to reduce the size of magnetic confinement systems by increasing the strength of the confining field through flux compression.

A.E. Robson, Report of NRL Progress on LINUS project, June 1973, pp. 7-16.
Predecessors: Frascati (Italy), see J. G. Linhart *et al*., Nucl. Fusion **2S**, 733 (1962),
Kurchatov Institute (USSR), see E. P Velikhov *et al*., Zh. Tekh. Fiz. **43**, 429 (1973)…

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Why ultrahigh magnetic field is “less extreme” than ultrahigh density in spherical hot-spot ignition

About the same ignition mass and energy @ 100 MG, but

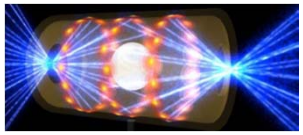
- Lower energy density at ignition $\beta = \dfrac{16\pi nT}{B^2} > 5$ $\begin{cases} n > n_{\text{solid}} \\ T = 10\ \text{keV} \\ B = 100\ \text{MG} \end{cases}$

- More energy is available for cylindrical implosion geometry

Z: ~2 MJ cylindrical

NIF: ~1.6 MJ cylindrical…

…and ~0.16 MJ spherical

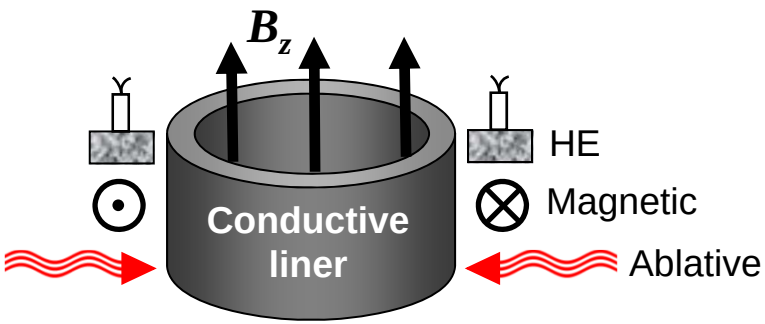


Heavy ion fusion?

To reap the benefits, ICF driver should compress magnetic flux with a plasma liner

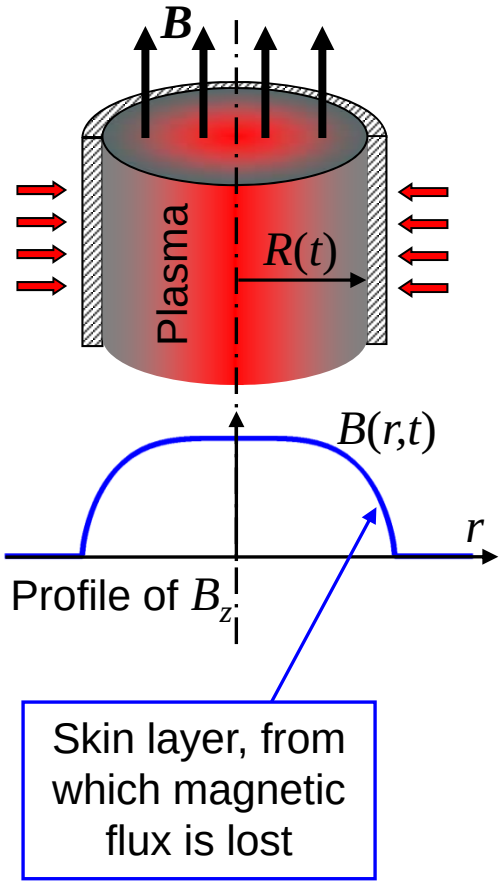
M. A. Liberman and A. L. Velikovich, J. Plasma Phys. **31**, 381 (1984).
F. S. Felber *et al*., Appl. Phys. Letters **46**, 1042 (1985).

Magnetic flux compression in the MC-1 geometry (reminder)



† Inferred, not measured

Magnetic Reynolds number – figure of merit for magnetic flux compression



Definition $$\mathrm{Rm} = \frac{t_\Phi}{t_R} = \frac{\left|\Phi / \dot{\Phi}\right|}{\left|R / \dot{R}\right|}$$

Rough estimate $$\mathrm{Rm} \sim \mathrm{Rm}_0 = \frac{\left|R\dot{R}\right|}{\nu_m}$$

where $\nu_m = \dfrac{c^2}{4\pi\sigma}$ (cm²/s) - magnetic diffusivity

$$\frac{\Phi}{\Phi_0} = \left(\frac{R_0}{R}\right)^{1/\mathrm{Rm}} \quad \text{and} \quad \frac{B}{B_0} = \left(\frac{R_0}{R}\right)^{2-1/\mathrm{Rm}}$$

$$\boxed{\mathrm{Rm} = \frac{\ln\left(R_0 / R_f\right)}{2\ln\left(R_0 / R_f\right) - \ln\left(B_f / B_0\right)}}$$

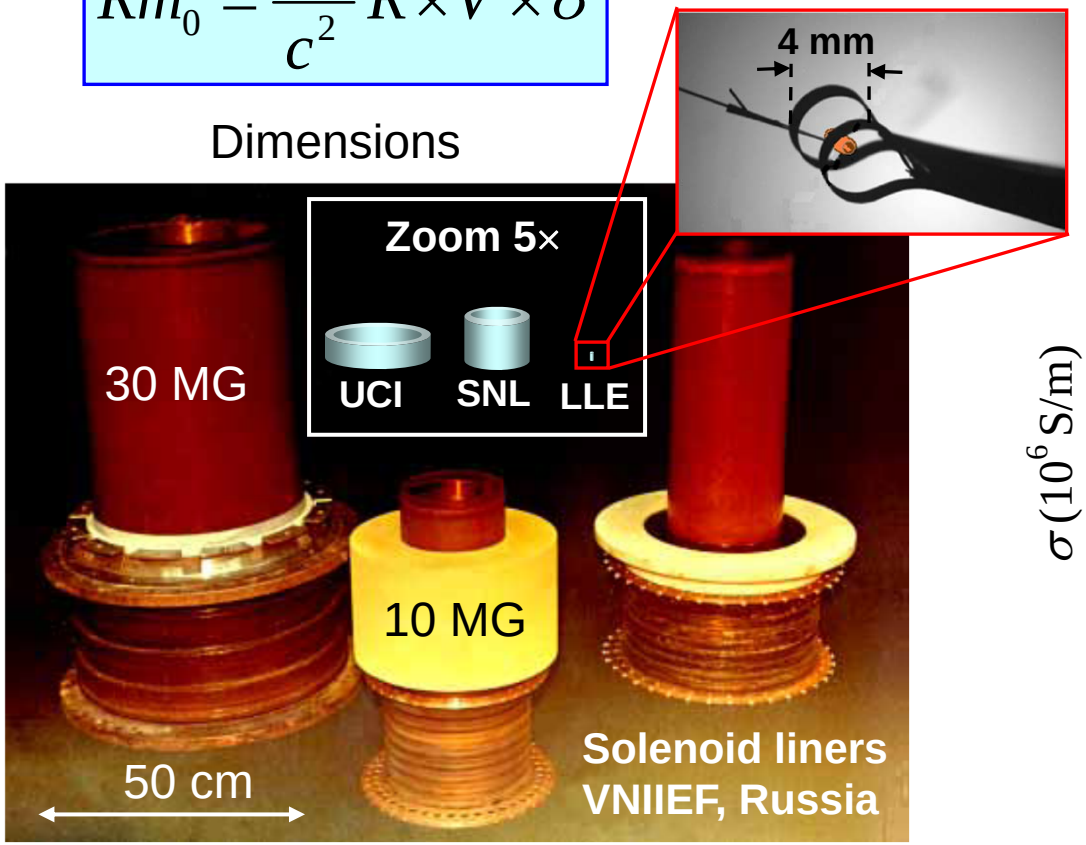
For compression ratio $R_0/R_f = 30$ (stability)

$B_0 = 150$ kG, $B_f = 100$ MG => Rm = 11

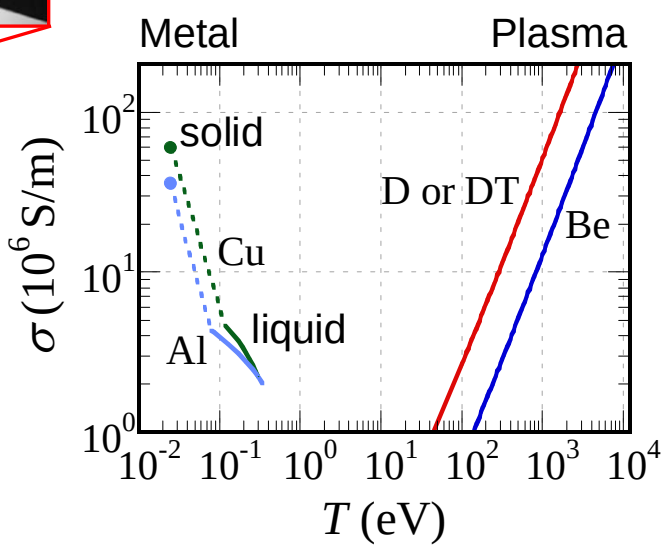
Magnetic flux compression favors large size, high velocity and good conductivity

$$Rm_0 = \frac{4\pi}{c^2} R \times V \times \sigma$$

Dimensions



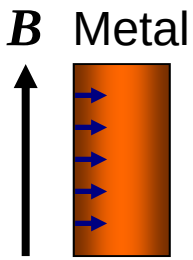
Conductivity



B. A. Boyko *et al*., in Digest of Technical Papers, 12th IEEE International Pulsed Power Conference, Monterey, CA, June 27-30 1999, ed. By C. Stallings and H. Kirbie.

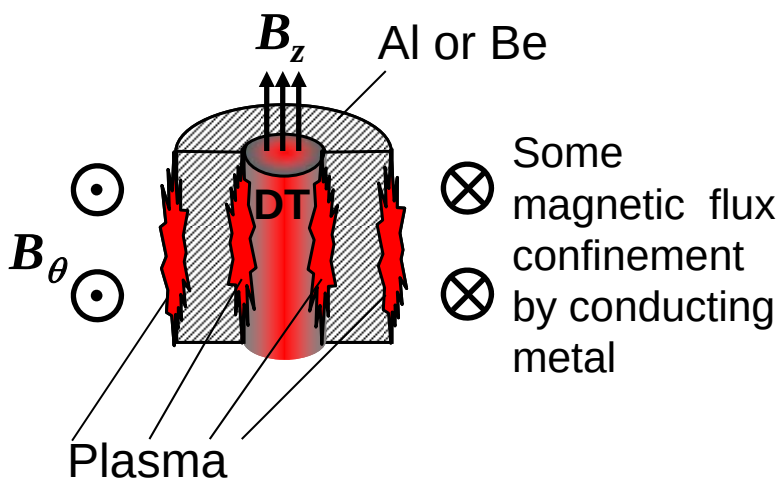
O. V. Gotchev *et al*., Phys. Rev. Lett. **103**, 215004 (2009); J. P. Knauer *et al*., Phys. Plasmas **17**, 056318 (2010).

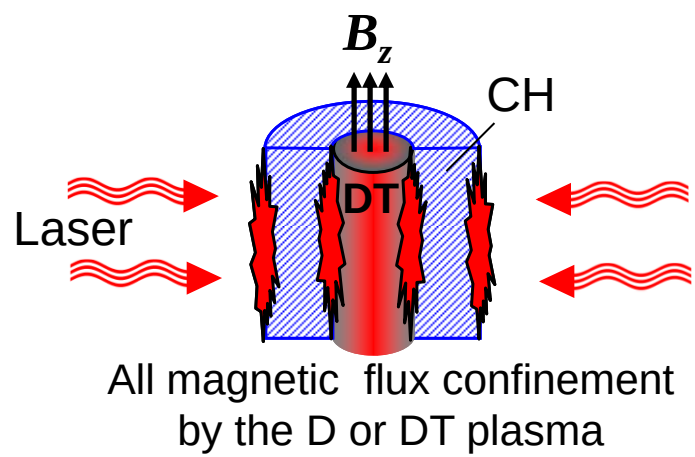
Why we have to work with plasma liners



$$\frac{B^2}{8\pi} = 4\ \text{Mbar} \ @\ B = 10\ \text{MG}$$

Any metal turns into a plasma under a multi-Mbar shock pressure.
The multi-MA current or laser beams burh the liner from the outside.



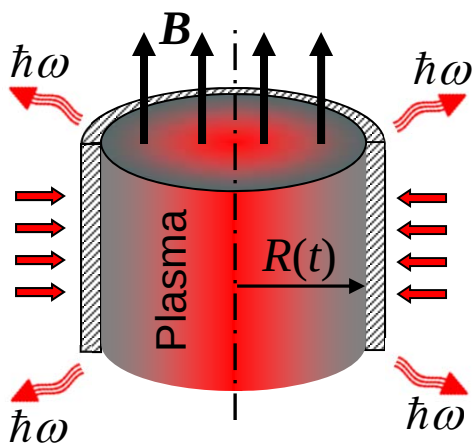


T. J. Awe *et al*., Phys. Rev. Lett. **104**, 035001 (2010); Phys. Plasmas **17**, 102507 (2010).
S. A. Slutz *et al*., Phys. Plasmas 17, 056303 (2010).
O. V. Gotchev *et al*., Phys. Rev. Lett. **103**, 215004 (2009); J. P. Knauer *et al*., Phys. Plasmas **17**, 056318 (2010).

Plasmas are notorious for letting the magnetic field leak

There are all kinds of anomalous resistivity and many mechanisms of fast penetration

Even if presumed dense and collisional, the plasma shapes its thickness and profiles self-consistently, not necessarily in favor of good magnetic field compression



Radiation-controlled plasma temperature:

$$T = T_0 = \text{const}$$

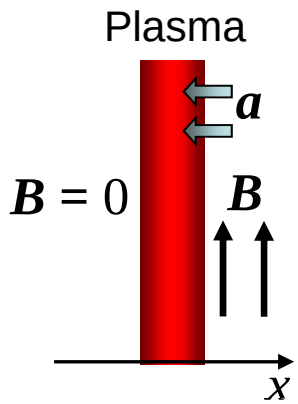
$$2nT \sim \frac{B^2}{8\pi}$$, but $$\frac{n}{n_0} = \left(\frac{R_0}{R}\right)^2$$ and $T = T_0$, hence

$$\boxed{\frac{B}{B_0} = \left(\frac{n}{n_0}\right)^{1/2} = \frac{R_0}{R} = \left(\frac{R_0}{R}\right)^{2-1/\mathrm{Rm}}}$$ => $\boxed{\mathrm{Rm} = 1}$

To obtain 100 MG @ Rm=1 one needs to start from 3 MG – not possible.

EMHD and Hall fast penetration of magnetic field into a nearly collisionless plasma/POS and astrophysics
A. Fruchtman and K, Gomberoff, Phys. Fluids B **5**, 2371 (1993); A. V. Gordeev *et al*., Phys. Rept. *243*, 215 (1994).
L. I. Rudakov *et al*., Phys. Plasmas **10**, 4435 (2003).

1D simulations confirm these simple arguments

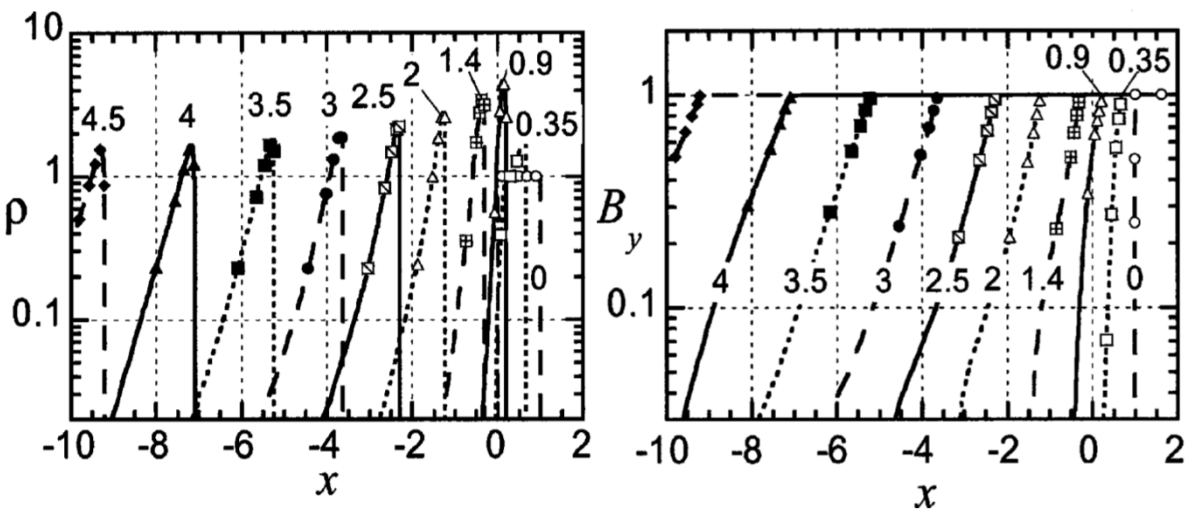


Self-similar profiles

$$n \sim \exp\left(-\frac{|x - x_p|}{L(t)}\right)$$

$$\Rightarrow B \sim \sqrt{n} \sim \exp\left(-\frac{|x - x_p|}{2L(t)}\right)$$

Self-consistent skin depth = twice the density gradient length



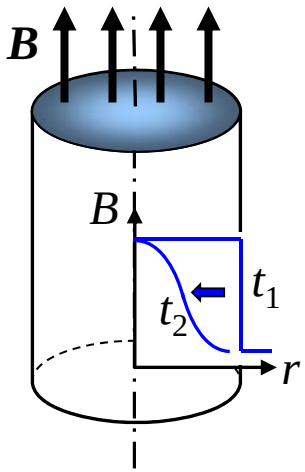
Simulations for radiation-controlled plasma temperature (A. Chuvatin)

L. I. Rudakov *et al*., Phys. Plasmas **10**, 4435 (2003).

N. Qi *et al*., IEEE Trans. Plasma Sci. **38,** 545 (2010).

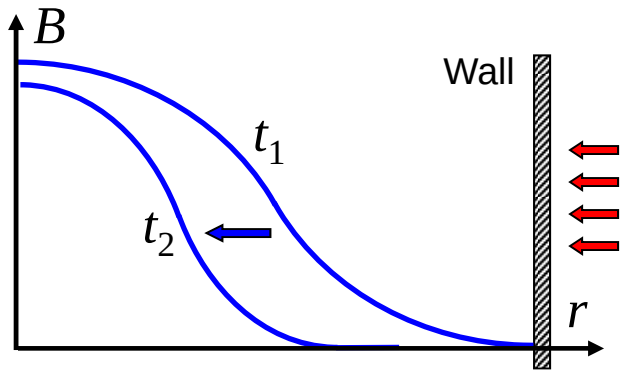
…And even if the plasma temperature is not radiation-controlled, as in D or DT…

Metal liner



Only diffusive losses of magnetic flux. Material strength ensures pressure balance

Plasma liner



Diffusive losses of magnetic flux…

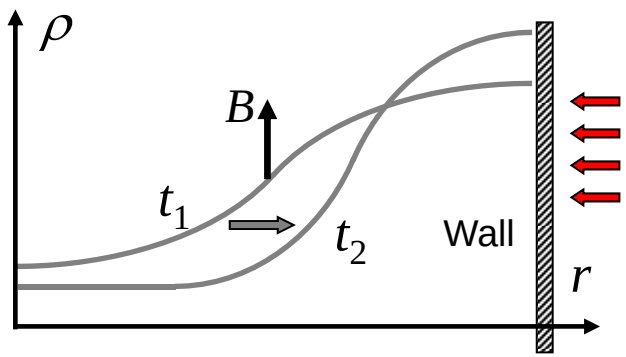
$$\nu_m \sim \nu_{m,\mathrm{Spitzer}} \times \omega_e \tau_e$$

$$\mathrm{Rm} \approx 3$$

$$@\, u = 300\ \mathrm{km/s}$$

Pressure balance requires

$$\frac{\partial}{\partial r}\left(2nT + \frac{B^2}{8\pi}\right) = 0$$



Through pressure balance, give rise to convective losses of magnetic flux

G. E. Vekshtein, Sov. Tech. Phys. Lett. **10**, 319 (1984); "On the possibility of ultrahigh magnetic flux production in imploding liners: Magnetic flux retention," Preprint 86-33, Nucl. Phys. Institute, Novosibirsk, Russia, 1986.

"*The potential is there, but it's so much harder when no one has done it before*"

- Producing ~100 MG in magnetic flux compression appears to be well within the capabilities of both refurbished Z and NIF
- The results from flux compression experiments on Omega are very encouraging
  - Peak magnetic field of >36 MG measured by proton radiography agrees with 1D simulations and indicates Rm>>10
- The considerable potential for magnetic flux compression to ~100 MG with pulsed power needs to be demonstrated
  - Peak compressed magnetic fields have never been measured above the level where magnetic probes measurements are possible
  - Data from explosively driven magnetic flux compression does not extend beyond 28 MG
  - RMHD codes used to design experiments and predict their results need both verification and validation

J. Lindl, NIF's chief scientist, quoted in Science **334**, 449 (2011).

O. V. Gotchev *et al*., Phys. Rev. Lett. **103**, 215004 (2009); J. P. Knauer *et al*., Phys. Plasmas **17**, 056318 (2010).

Experimental data on magnetic flux compression in plasmas, 1986-2010

Ref.	Institution	Plasma material	R_0 (mm)	h (mm)	I_m (MA)	B_0 (kG)	B_m (MG)	B_m/B_0
[1]	UC Irvine	H_2, He, CH_4, N_2, CO_2, Ar, Kr, Xe	20	10	0.47	9-18	>1.6	>180
[2]	HCEI	Al	20	10-15	0.13	1-2	>0.065	>55-65
[3]		Ne	7.5	15	1.4	18	2.5	140
[4]		Ar	13.5	24	1.0	18	0.6	33
[5]	Sandia	Ne	12.5	20	7.5	100	42	420
[6]	Imperial College	H_2, He, D_2, Ne, Ar, Kr	15-18	12-15	0.5	3	0.38	126
[7]	TRINITI	W	10	10	3	5	0.3	60
[8]	LLE	D_2	0.225	1.5	N/A	62	36	580

inferred

[1] F. S. Felber *et al.*, J. Appl. Phys. **64**, 3831 (1987).
[2] R. B. Baksht *et al.*, Sov. Phys. - Tech. Phys. **32**, 145 (1987).
[3] S. A. Sorokin and S. A. Chaikovsky, in *Dense Z-pinches*, AIP Conf. Proc. **195**, 438 (1989).
[4] S. A. Sorokin, IEEE Trans. Plasma Sci. **38**, 1723 (2010).
[5] F. S. Felber *et al.*, Phys. Fluids **31**, 2053 (1988).
[6] R. K. Appartaim and A. E. Dangor, J. Appl. Phys. **84**, 4170 (1998).
[7] G. G. Zukakishvili *et al.*, Plasma Phys. Reports **31**, 652 (2005).
[8] O. V. Gotchev *et al.*, Phys. Rev. Lett. **103**, 215004 (2009).

Wish list

- Experimental data for demonstrating the viability of the concept and for code validation
  - Measure the peak magnetic field ~100 MG in plasma (Faraday/Zeeman/other spectroscopic methods?)
  - Measure the peak plasma temperature ~10 keV (dopant line spectroscopy, bremsstrahlung continuum)
  - Measure the degree of mixing between the wall material and compressed D/DT plasma
- Experimental, numerical and theoretical studies for code verification and validation
  - None of the RMHD codes used by the pulsed power community has been validated/verified in the relevant conditions; no experiments have been modeled
  - Effects of major importance in this context, such as Nernst and Ettingshausen effects in plasma, not even included in most codes; verification issues
  - Atomic physics issues for spectroscopic diagnostics (parameter range, dopant materials, spectral lines chosen for diagnostics)
  - Kinetic theory issues: diffusion approach to the transport of fast alpha particles in fusion plasma across the magnetic field still requires clarification