Stabilized Liquid Liner Implosions for Repetitive Compression of Plasma Targets

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The Linus program at the Naval Research Laboratory (c. 1971-1980) explored many notions of using liner implosions to achieve fusion at much higher fields than conventional magnetic fusion schemes.

Solid-liners

- **Demonstrated large radius-ratio (30:1) implosions of aluminum liners (30 cm diam) driven electromagnetically by theta-pinch style coil.**
- **Achieved 1.3 MG over cm-diam clear bore.**

Liquid liners

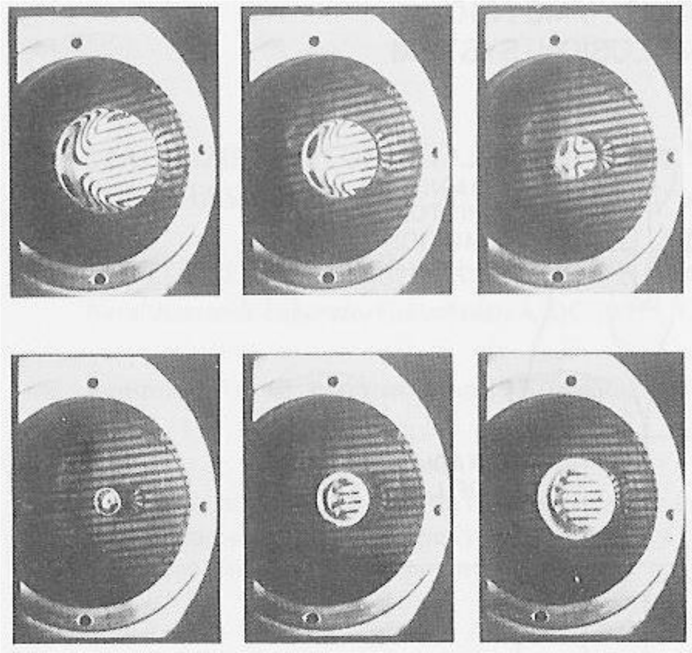
- **Concept of rotational stabilization of inner surface, demonstrated with NaK liners imploded electromagnetically.**

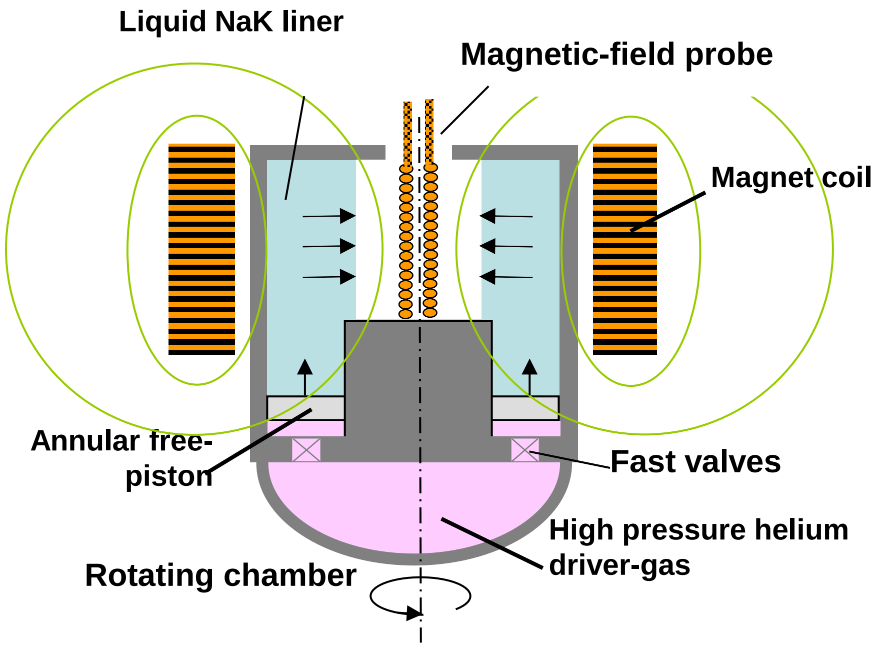
Calculations indicated scientific breakeven experiment would require > 75 MJ.
Need to control explosion of liner material, both for reactor concept and for experimental path forward.

Complete stabilization of repetitive implosion/expansion using pneumatically-driven, free-pistons applied to outer surface of rotating liquid (water; NaK for repetitive flux compression).

For efficient transfer of energy from an imploding liner to the lower mass-density target, the liner must rotate to avoid Rayleigh-Taylor instability. A free-piston stabilizes the outer surface during drive and recovery.

Stabilized, Cyclic Liner Implosions, Naval Research Laboratory, c. 1979

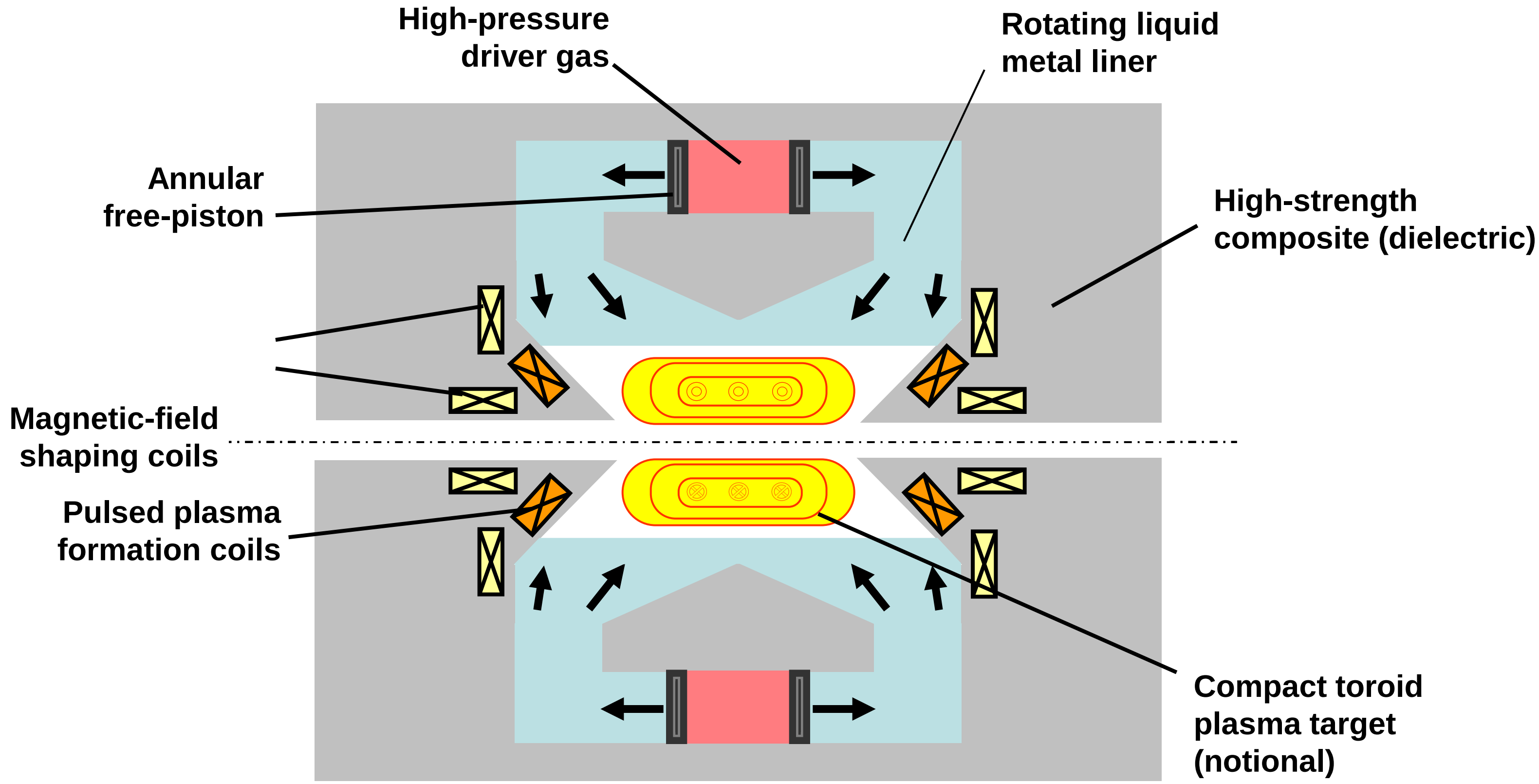




P.J. Turchi , et al, "Review of the NRL Liner Implosion Program," in Megagauss Physics and Technology, ed. P.J. Turchi (Plenum, 1980). P. 375.

The ability to drive and recover liquid liner material efficiently enables repetitive exchange of energy with a fusion plasma.

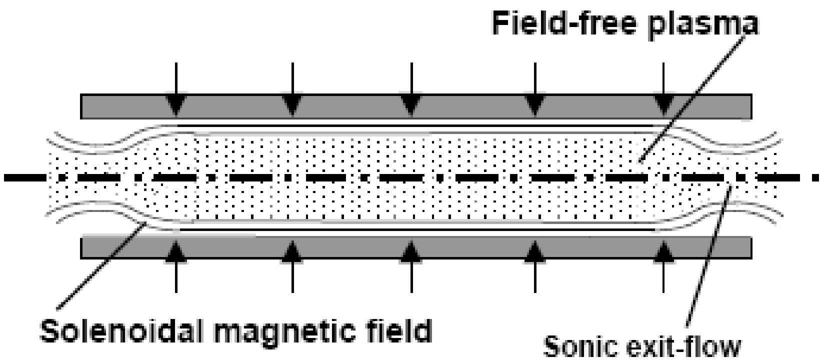
Basic conceptual design of Linus reactor closely resembles the prototype stabilized liner implosion system demonstrated at NRL.



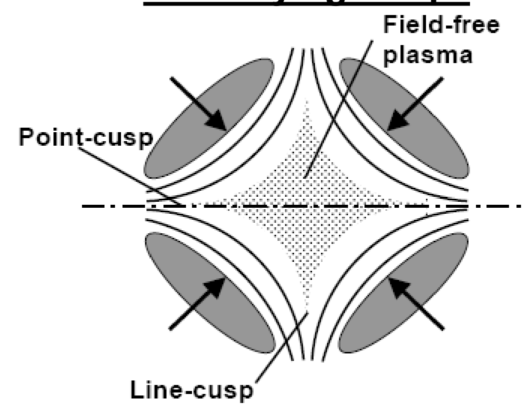
The same arrangement would be used for laboratory experiments, including scientific breakeven, adjusting the size, liner material and plasma conditions. Note that the pneumatic energy storage/pulsed power subsystem is contained within the device, but could be replaced by a high-field, theta-pinch coil (as in early NRL experiments).

In the Linus program, we explored several types of possible plasma target, starting with sharp-boundary, high-beta notions, but eventually accepting need for plasma/field mixture.

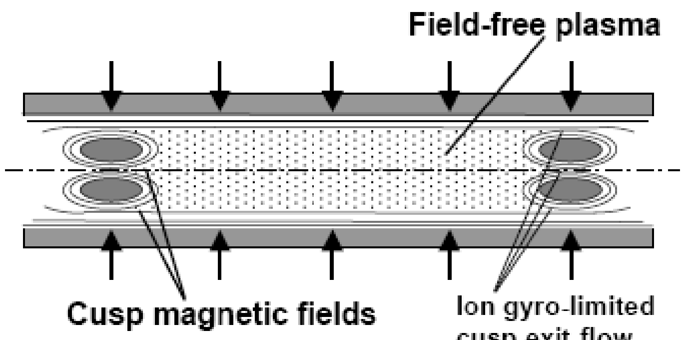
"Theta-pinch with liner"



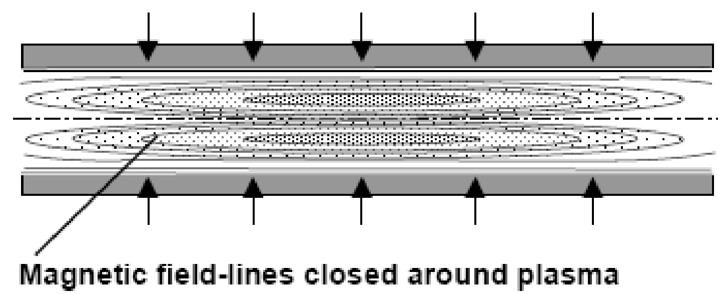
"The Flying Cusp"



Cusp-ended Theta-pinch (CEΘP)



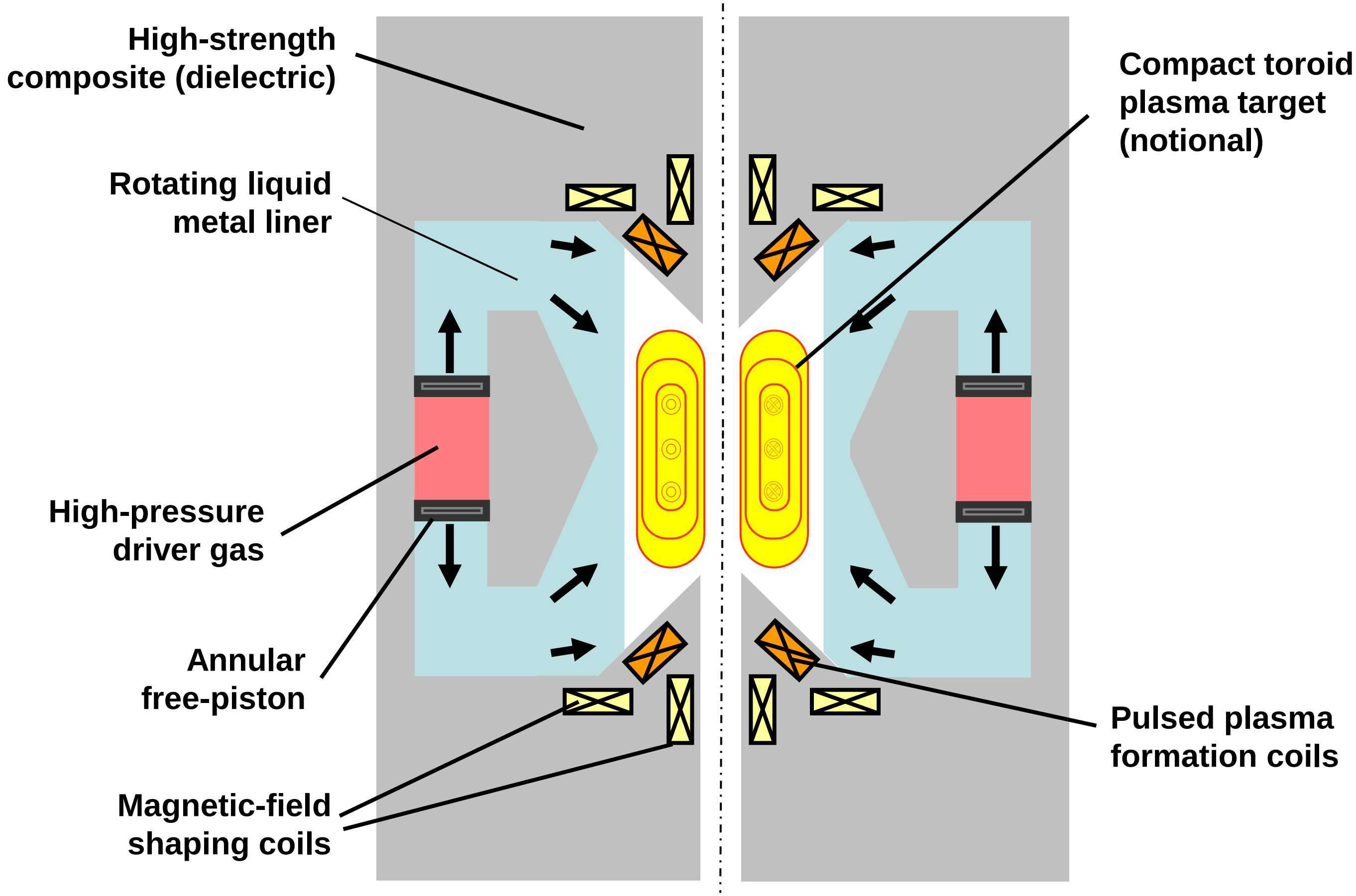
Field-Reversed Configuration (FRC)



"Imploding Liner Compression of Plasma: Concepts and Issues," IEEE Transactions on Plasma Science, Vol 36, No. 1, Feb 2008

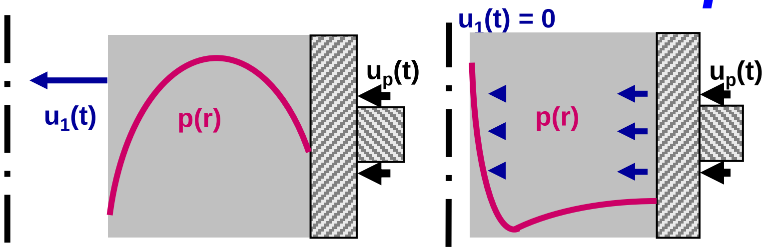
Diversion of funding to study FRCs led to demise of Linus program as interest shifted from MTF/MIF goals to possibility that compact toroids could compete with tokamaks.

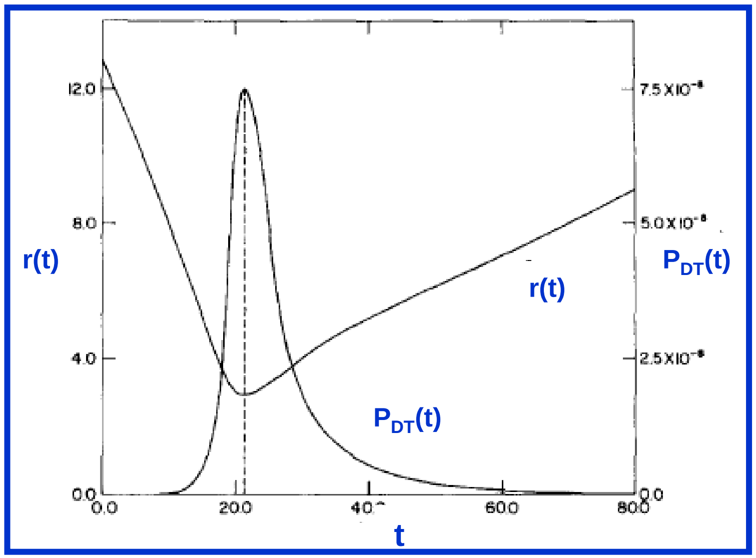
The Linus program began when theta-pinch notions were still mainline within the US fusion effort, but after these were cancelled, we should have depicted our device with a vertical axis.



We could then have represented Linus as a very high-field, wall-stabilized version of the Adiabatic Toroidal Compressor experiment at Princeton and TUMAN II in Leningrad. ("Liner Imploded Toroid Experimental Reactor")

Liner compressibility results in conceptual reactor design (c. 1979) at near half-megagauss peak magnetic fields, suggesting flux-compression to very high fields <u>not</u> most important feature.





<u>Important features of liner implosion</u>:

- **High compression ratio to increase plasma temperature adiabatically and increase plasma density**
- **High magnetic field by flux-compression**
- **Extraction of work by expanding plasma allows direct conversion of nuclear energy without thermal cycle**
- **Liner serves as reactor blanket for neutron deposition, tritium breeding, thermal processing, and self-replenishing first-wall**

This early design (507 MWe at 1Hz and C = 15%), while conceptually valid, did not include several features of liner implosion, e.g., axial convergence, and had only primitive understanding of plasma target.

Concluding Remarks

- **Megagauss magnetic field technology enables operation of plasma at much higher densities than conventional magnetic-fusion schemes, but much lower power densities than ICF, so fusion systems of lower cost and energy should be possible. This is now referred to as MTF or MIF.**

- **Stabilized liquid liner implosion based on rotation and free-piston drive provides repetitive operation, and avoids the "kopek" problem of explosion and re-furbishment of the inner portion of the apparatus. This applies to both the reactor and the necessary laboratory experiments for the path forward.**

- **Stabilized liquid liner implosions offer opportunities for direct conversion of nuclear energy to useful work, reducing the necessary Q-values. The distance between a breakeven experiment and a power reactor (core) is thus reduced compared to schemes that do not capture energy without passing through a thermodynamic cycle.**

- **The stabilized liquid liner approach provides answers to many problems with other fusion schemes using D-T, by employing the liner as the blanket for neutron deposition, tritium-breeding, thermal processing, and a self-replenishing first-wall.**

Elements of a Path Forward

Energy Storage and Pulsed Power

The conceptual arrangement depicted includes the energy storage needed to drive the liquid liner implosion and receive the subsequent re-expansion.

- **Pneumatic-drive offers a lower-cost approach for the main driver-energy than electromagnetic-drive using capacitor banks. This is a significant mechanical engineering challenge at pressures equivalent to Suzy II experiments at NRL (> 20 kpsi).**
- **Pulsed coils for plasma target formation still need pulsed electrical power.**

Liner Dynamics

Prototype systems at NRL (Helius and Linus-0) were successful in demonstrating the basic stabilized implosion technique, but further work is needed. Much of this can be performed with easier liquids, e.g., water.

- **Operation of liners with tangential injection and shaped ducts, (both explored in a few experiments at NRL).**
- **Operation of liners with convergence to follow plasma target more efficiently.**

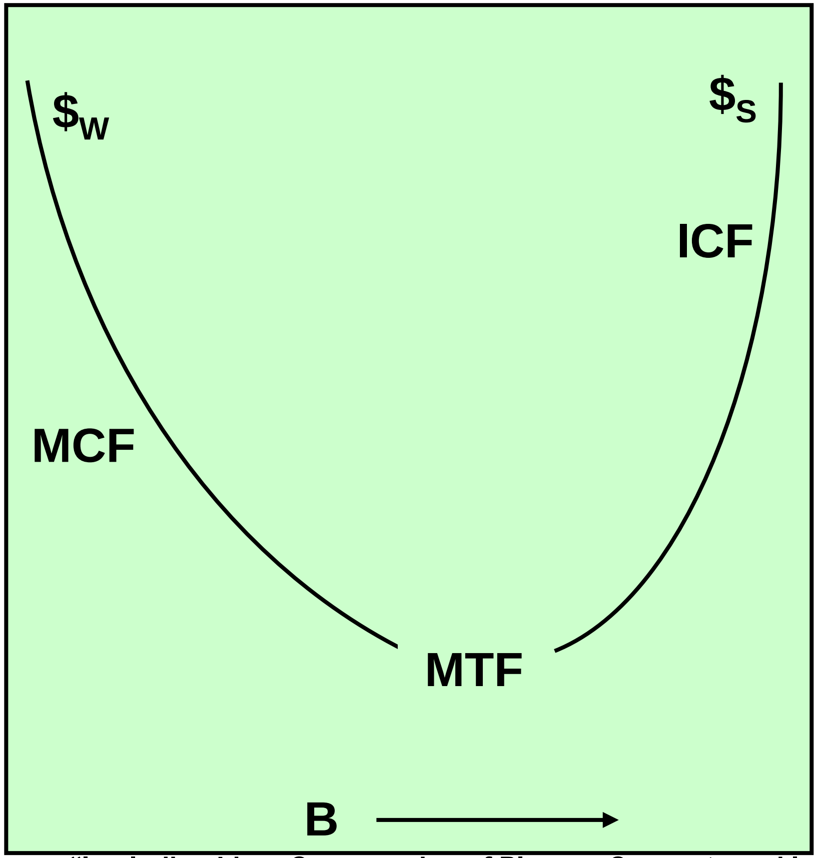
Plasma Target

Much work is still needed to understand best techniques for target formation and subsequent behavior to match MTF/MIF goals of economical fusion power.

How do we avoid past problem of driver development lost to study of plasma?

Back-up Slides

Magnetized Target Fusion (MTF) offers possible optimum between conventional magnetic- and inertial-confinement fusion regimes.



Fusion energy gain: $Q \sim n\tau$

At a given plasma temperature $n \sim B^2$, $\tau \sim x^2/D$ and $D \sim 1/B^{1 \div 2}$, so needed energy for <u>magnetic-confinement fusion</u> (MCF), based on diffusion is

$$W_p \sim B^2 x^3$$
$$\sim Q^{3/2} / B^{2.5 \div 4}$$

For <u>inertial-confinement fusion</u> (ICF),

$$W_p \sim Q^3 / B\rho^{3/2}$$

But power density is critical

$$S \sim W_p / x^2 \tau_p \sim Q^9 / W_p^{\ 3} \rho^5$$
$$\sim B^3 / \rho^{1/2}$$

System cost: $\$ = K_W W_p + K_S / W_p^{\ 3}$

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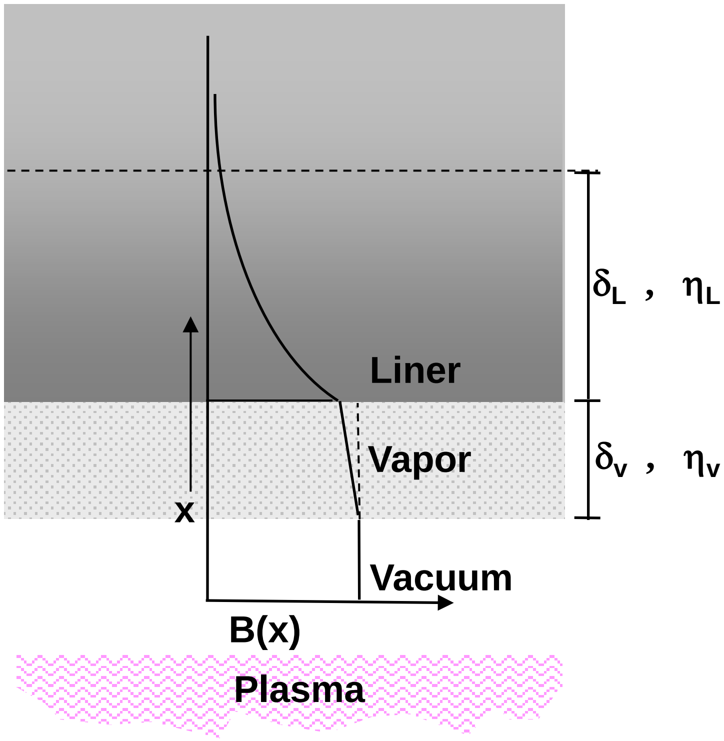
To achieve very high magnetic fields (~ megagauss-levels) requires dynamic conductors, known as imploding liners.

Magnetic flux diffuses into the conductor surface, raising the material temperature by resistive heating.



Current density in liner surface:

$$j_L \approx B/\mu\delta_L$$

with flux skin-depth $\delta_L = (\eta_L\tau/\mu)^{1/2}$

Resistive heating increases temperature:

$$c\partial T/\partial t = \kappa\partial^2 T/\partial x^2 + \eta_L j_L^2$$

Surface temperature:

$$T = sB^2/2\mu c$$

Equilibrium vapor pressure:

$$p_v = p_c \exp(-T_c/T)$$

Force balance across the vapor layer gives thickness of vapor:

$p_v = j_v B\delta_v$, with $\eta_L j_L = \eta_v j_v$, so $\delta_v = \delta_L(\eta_v/2\eta_L)[p_v/(B^2/2\mu)]$

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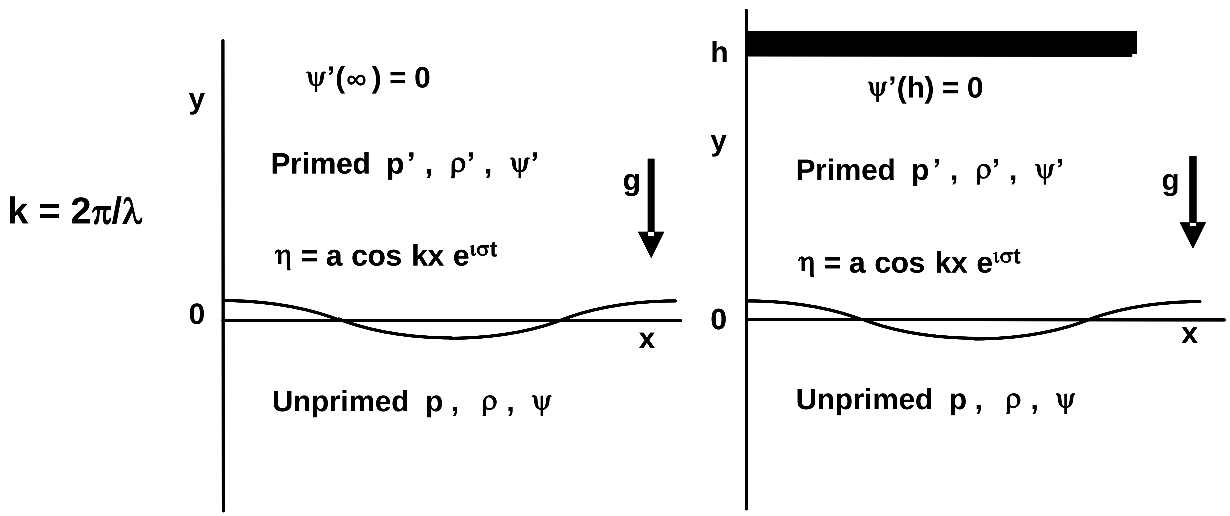
Electrical conductivity of vapor is enhanced when plasma-target is present to provide heating and UV-radiation.

Dwell time at high pressure depends on inertia of liner material, so we may have high-density fluid slowing down on low-density target (magnetic flux and plasma). This is generally unstable for efficient energy transfer.



(a) (b)

Growth rates for $\rho' \gg \rho$: (a) Classical $\sigma_c = (gk)^{1/2}$ (b) Finite-layer $\sigma_h = \sigma_c\,[\tanh(kh)]^{1/2}$

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Growth rate is reduced for wavelengths large compared to thickness of layer near rigid surface. This helps to keep vapor-layer thin, but liner surface may still be unstable.