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Some physics issues relevant during stagnation phase of the Z pinch

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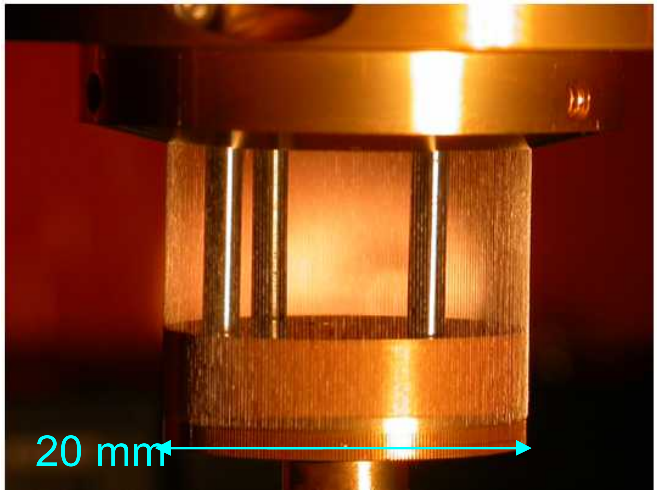
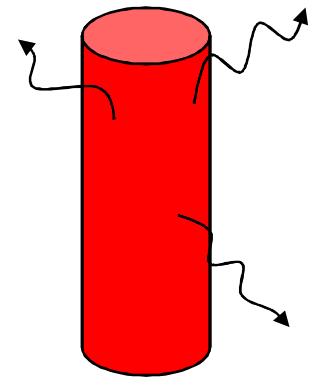
Z pinches exhibit enhanced radiation

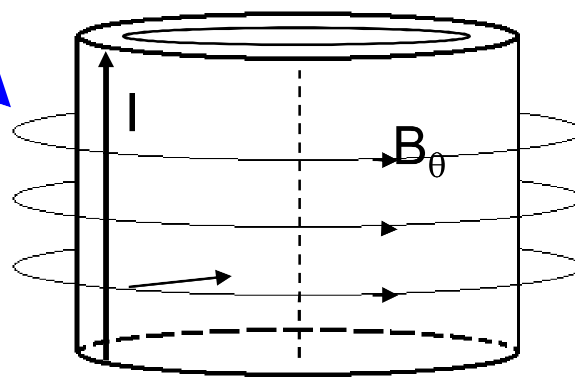
A wire-array Z pinch is a cylindrical array of fine metal wires



$$E_{kin} = \int \frac{B^2}{2\mu_0} 2\pi R l \left(-\frac{dR}{dt} \right) dt$$
$$\simeq \frac{\mu_0 I_{max}^2 \ln(R_0/R_{min})}{4\pi}$$



In simplest picture, wires convert to plasma shell. Magnetic pressure implodes shell, which acquires kinetic energy



Radial J x B Force

But
$$E_{rad} \sim (2-3) \times E_{kin}!$$

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Typical power pulse

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Courtesy
D. Sinars

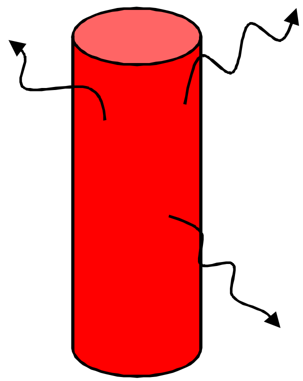
Energy up to here
$\simeq E_{kin}$

Energy source for this portion of radiation pulse is not clear

So 2 issues:

1. Most 1D and 2D simulations predict very large convergence ratios, over predict radiation power
2. Experimentally $E_{rad} \sim (2-3) \times E_{kin}$

Where's additional radiated energy come from?



There is plenty of magnetic energy stored in the vacuum surrounding the pinch

$$W_{mag} = \int \frac{B^2}{2\mu_0} dV$$

But how can it convert to radiated energy?

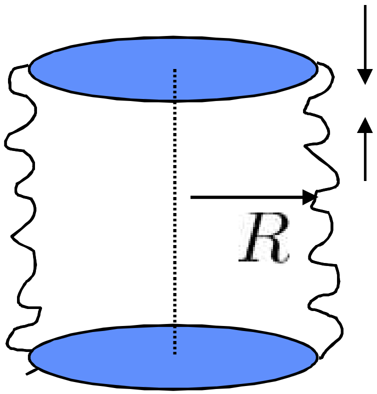
pdV? No, once assembled on axis, stagnated pinch not observed to compress further significantly

Joule heating? No, with classical Spitzer resistivity, too small to account for difference in E_{rad} and E_{kin}

Many models have been developed to explain the dissipation of magnetic energy. Among them:

Ion viscous heating

Proposed by M.G. Haines (Phys. Rev. Lett 96, 075003 (2006))



$$\lambda \sim \frac{2\pi}{k}$$

Involves viscous damping of short wavelength m=0 interchange/sausage modes, to which Z pinch is very unstable

$$E_{mag} \rightarrow E_{kin} \rightarrow E_{int,ion} \rightarrow E_{int,e} \rightarrow E_{rad}$$

via m=0 modes $\gamma_k \sim v_A \sqrt{\frac{k}{R}}$

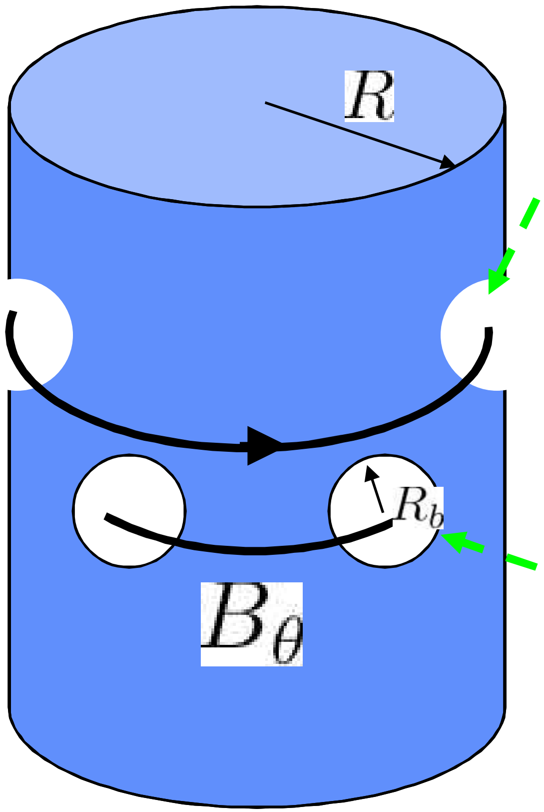
viscous heating $\sim \mu(k\tilde{v})^2$

For λ~10-100 μm, this process is sufficiently fast, converting E_{mag} to $E_{int,ion}$ in 1-2 ns

Due to small λ, Oliver,Genomi, and Sotnikov have reconsidered m=0 instability in the presence of Hall currents and anisotropic viscosity.

Magnetic flux tubes

Rudakov and Sudan (Phys. Reports 283, 253 (1997))
Velikovich (Phys. Plasmas 7, 3265 (2000))



m=0 interchange instability (or RT) seeds a toroidal magnetic bubble. R_b/R is a parameter of the model ~ 1/4

As the bubble travels toward axis (due to field curvature), it does pdV work on the plasma, thus dissipating its magnetic energy

Hence, although the pinch radius is unchanged, bubbles allow field to continue to do pdV work on plasma.

MHD turbulence

In regular fluid turbulence $v = V + \tilde{v}$

mean flow

rapidly fluctuating "eddy" velocity

Can define turbulent kinetic energy $K_{turb} = \dfrac{\langle \tilde{v} \cdot \tilde{v} \rangle}{2}$

As well as a turbulent pressure $P_{turb} \propto \rho K_{turb}$

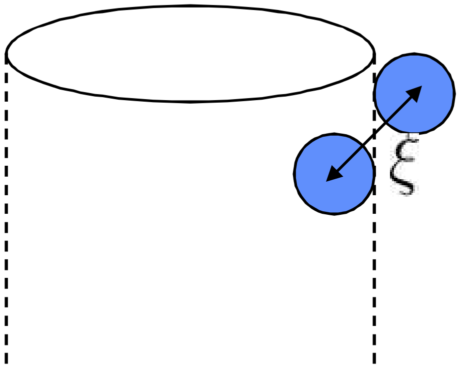
$$K_{mean} \longrightarrow K_{turb} \longrightarrow E_{int}$$

Energy in large eddies transfers to small eddies, then dissipated by viscosity

In MHD turbulence, in addition to above, also have $E_{mag} \to K_{turb}$, $E_{mag} \to E_{mag,turb}$

MHD turbulence II

J. Hammer (APS meeting abstracts, 2005) has considered this process through the usual m=0 interchange analysis



$$\frac{\delta W}{V} = \frac{\delta W_{int}}{V} + \frac{\delta W_{mag}}{V} + \frac{\delta W_{grav}}{V}$$
$$= \xi \cdot \overline{\overline{W}} \cdot \xi$$

If we associate ξ with turbulent motion

$$\langle \frac{\delta \dot{W}}{V} \rangle \approx D_T Tr\overline{\overline{W}}$$

turbulent diffusion coefficient

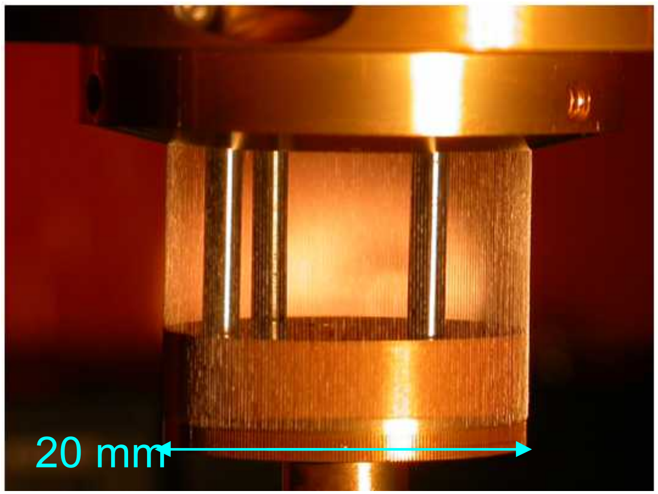
$$\rho \frac{dK_{turb}}{dt} = -\langle \frac{\delta \dot{W}}{V} \rangle$$

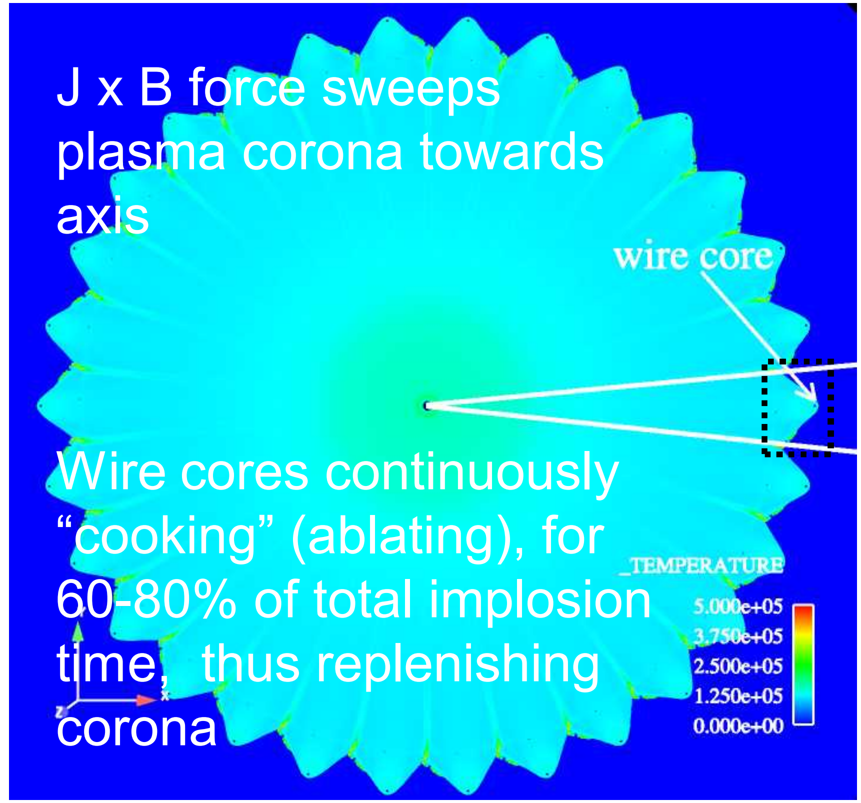
$$E_{mag} \rightarrow \begin{array}{l} K_{turb} \\ E_{mag,turb} \end{array} \rightarrow E_{int} \rightarrow E_{rad}$$

Also P_{turb}, $P_{mag,\ turb}$ will resist high compression at stagnation (see Kyle Peterson talk)

mass ablation

In fact, the simple model of the wire array converting to a plasma shell is incorrect.

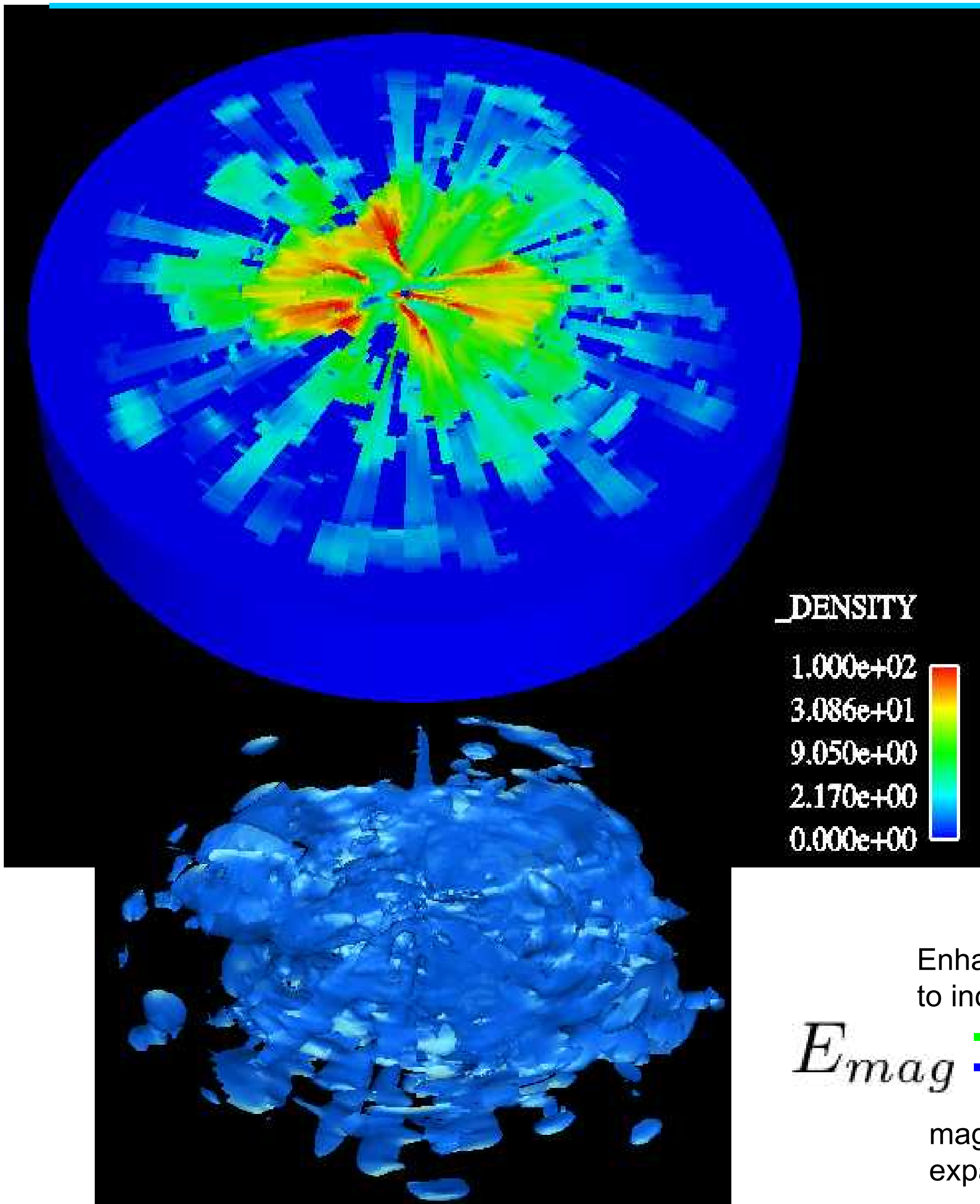




QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

So mass ablation / resulting implosion is inherently 3D!

3D nature of implosion



J. Chittenden (Plasma Phys. Control. Fusion 46, B457 (2004)) randomly perturbed the mass ablation rate of each wire in his simulations, leading to a highly non-uniform implosion.

Consequently, he found a broad power pulse, reasonable convergence ratio

Also, the non-uniform implosion seeds an m=1 instability, which dissipates magnetic energy

Enhanced joule heating due to increased length of pinch

$$E_{mag} \rightrightarrows E_{int} \longrightarrow E_{rad}$$

magnetic field does work expanding the helix

So what?

3D simulations explain broad power pulse and enhanced radiation without invoking any physics other than MHD.
But how sensitive are results to resolution, initial perturbation, etc?

It may be that all the models discussed play some role in the enhanced radiation output. I will examine the pre-existing wealth of data and try to find clues as to which models might be most important.