Liner compression of a MAGO / inverse-pinch configuration

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Abstract. In the "metal liner" approach to Magnetized Target Fusion (MTF), a preheated magnetized plasma target is compressed to thermonuclear temperature and high density by externally driving the implosion of a flux conserving metal enclosure, or liner, which contains the plasma target. As in inertial confinement fusion, the principle fusion fuel heating mechanism is pdV work by the imploding enclosure, called a pusher in ICF. One possible MTF target, the hard-core diffuse z pinch, is being studied in MAGO experiments at VNIIEF, and is scheduled for study in a new inverse-pinch experiment at the University of Nevada, Reno. Numerical MHD simulations show two intriguing and helpful features of the diffuse z pinch with respect to compressional heating. First, in two-dimensional simulations the m=0 interchange modes, arising from an unstable pressure profile, result in turbulent motions and self-organization into a stable pressure profile. The turbulence also gives rise to convective thermal transport, but the level of turbulence saturates at a finite level, and simulations show substantial heating during liner compression despite the turbulence. The second helpful feature is that pressure profile evolution during compression tends towards improved stability rather than instability when analyzed according to the Kadomtsev criteria. A liner experiment is planned for the pulsed-power Atlas facility which will study compression of magnetic flux without plasma as a first step. The Atlas geometry is compatible with a diffuse z pinch, and simulations of possible future experiments show that keV temperatures and useful neutron production for diagnostic purposes should be possible if a suitable plasma injector is added to the Atlas facility.

1. Magnetized Target Fusion with a hard-core diffuse z pinch

A plasma target under consideration for application to Magnetized Target Fusion (MTF) (see *e.g.*, [1,2] and references therein) is the hard-core diffuse z pinch. The magnetic topology of the configuration is shown in Fig. 1. This configuration occurs in various types of coaxial accelerators such as the MAGO experiments [3,4], or planned inverse pinch experiments at the University of Nevada, Reno [5,6]. In recent simulations [1], the intriguing feature by which a diffuse z pinch self-organizes into a stable pressure profile appears to be a robust process, which is consistent with MAGO experimental results [3]. This paper discusses how the hard core z pinch responds to ideal adiabatic compression, and through numerical modeling what might be expected under more realistic circumstances with heat losses. The results show that thermonuclear temperatures should be achievable by means of plasma compression using liner technology

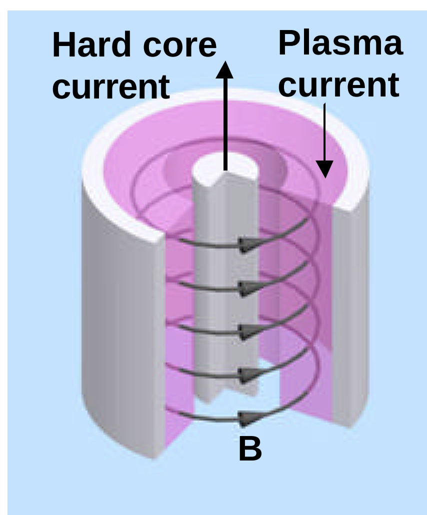

FIG. 1. Magnetic field in the hard-core stabilized diffuse z pinch.

such as that being developed for Explosive Magnetic Generators [7] and the new Atlas pulsed power facility [8]. As an example, parameters are selected for modeling that correspond to a low-cost experiment that might be done on the Atlas facility.

2. Formation, equilibrium, and self-organized stability

As reported at the last IAEA meeting [2], simulations of target plasma formation in an inverse pinch show $m = 0$ instabilities. During the dynamics of formation, plasma acceleration in the radial direction causes Rayleigh-Taylor and Richtmeyer-Meshkov instabilities [6]. As plasma approaches pressure balance between jxB and ∇p, there are also curvature-driven $m = 0$ instabilities as described by Kadomtsev [9]. An intriguing feature is that initially unstable pressure profiles self-organize by means of $m = 0$ interchange motions into stable pressure profiles in the following sense. When fluctuating plasma quantities are averaged along the z direction, the radial profiles of average current and average pressure settle into a one-dimensional equilibrium with finite fluctuations in time and space about equilibrium [1]. The averaged pressure profile becomes stable when examined with respect to the Kadomtsev $m = 0$ criterion for pressure gradient. The $m = 0$ stability criterion can be stated as $Q_0 < 1$, where Q_0 is defined (gas parameter $\gamma = 5/3$):

$$Q_0 = \frac{-(6+5b)}{20}\frac{r}{p}\frac{dp}{dr} \qquad (1)$$

In simulations, the kinetic energy associated with instability and turbulent $m = 0$ motion grows exponentially at first, but then saturates as Kadomtsev stable profiles are obtained. The maximum level of turbulent kinetic energy is typically a few percent of the thermal energy. For example, Fig. 2 shows simulation results for pressure profiles at two times after plasma formation in an inverse pinch. By t = 8 μs, the plasma has settled into a stable profile that closely matches the Kadomtsev $Q_0 = 1$ marginal state at large radius (indicated with heavy line). At smaller radius the value of Q_0 is less than 1.

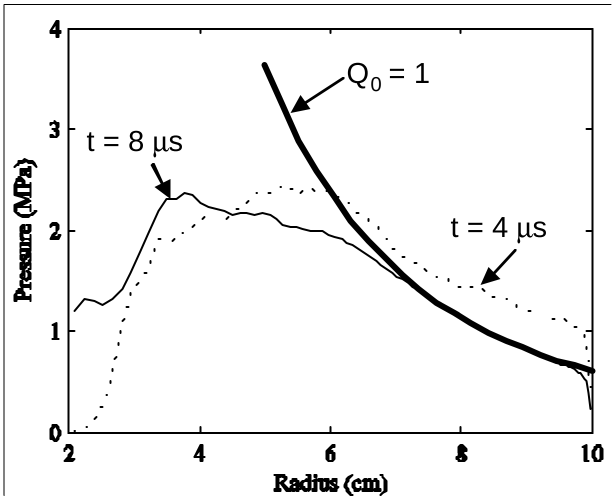

FIG. 2. Simulated profiles of z-averaged pressure vs. radius at different times during formation in an inverse pinch. The heavy line is a Kadomtsev marginal profile with $Q_0 = 1$.

Also according to Kadomtsev, the stability of $m = 1$ requires separately that $Q_1 < 1$, where:

$$Q_1 = -b\,\frac{r}{p}\frac{dp}{dr} \qquad (2)$$

Comparison of Eqs. 1 and 2 shows that the $m = 1$ criterion is the one more stringent when b exceeds 2/5. Simulations suggest that b can be controlled during formation in an inverse pinch, and kept below 2/5 at all radial locations, by introducing a sufficient amount of initial bias magnetic field before plasma is formed. Typically the required bias current is about ¼ of the final level of applied current.

3. Compressional heating

The hard-core z pinch configuration suggests a liner compression approach in which the hard core remains stationary and the outer boundary implodes radially inward A possible geometry is shown conceptually in Fig. 3. As the liner begins to implode, the region labeled "switch" in Fig. 3 causes the plasma injection gap to close. After that, plasma with flux is trapped in a toroidal chamber surrounding the hard core, and compressional heating occurs as the liner implodes. The liner shaping required for the switching action has not been examined in detail, but experience with shaped liners suggests that workable designs are possible [10].

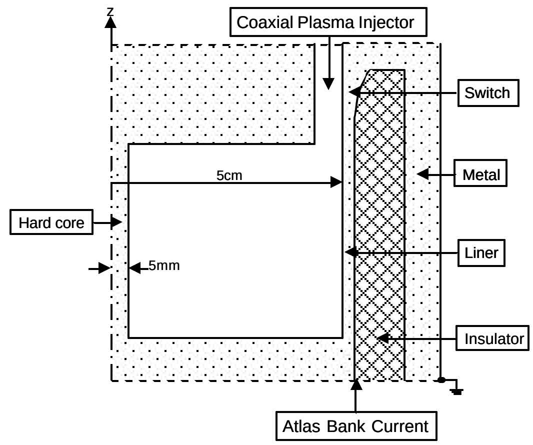

FIG. 3. Liner and diffuse z pinch geometry for implosion heating. Apparatus for injection of plasma connects electrically at the top. A liner implosion circuit such as Atlas connects at the bottom.

Compressional heating of a sub-kilovolt target plasma appears to be an effective way to achieve thermonuclear temperatures. For a preheated target the required implosion velocity can be less than the sound speed of the plasma, in contrast to ICF where carefully timed shocks are required to reach thermonuclear temperatures. If plasma compression is sufficiently fast compared to the energy loss rate, the plasma response is adiabatic. To illustrate the potential, the adiabatic heating response is shown in Fig. 4, assuming the pressure profile starts initially as a uniform-temperature Kadomtsev-marginal profile (Q_0 = 1 curve in Fig. 2) that extends from the hard core to the liner. Average temperature <T> is defined as total thermal energy U divided by 3N, where N is the (constant) number of ions in the chamber. The aspect ratio is $A=b/a$, where liner inner radius is b and core radius is a. The value of A decreases with time as the liner moves inward Average beta <*b*> is defined as 2U/3Emag, where Emag is the total magnetic field energy in the chamber. Fig. 4 shows that starting with A = 10 (like that shown in Fig. 3), <T> in the adiabatic approximation can be increased by 10x (or 100x) as the aspect ratio is reduced to 1.4 (or 1.02). Average beta increases from 0.10 at first, reaches a maximum of 0.16 at A = 1.6, and then decreases.

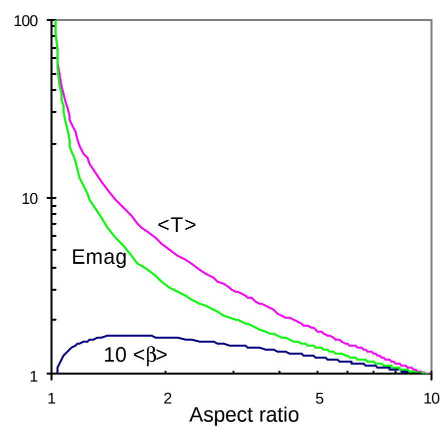

FIG. 4. Adiabatic compression increases temperature and magnetic field energy as aspect ratio decreases.

An important issue for compressional heating is what happens to stability during the process. To analyze $m = 0$ stability it is helpful to introduce a Kadomtsev parameter, $K = p^{3/5} r / B$, where the exponent of p is the reciprocal of the gas parameter. Given equilibrium as a constraint, the condition $\frac{\partial K}{\partial r} > 0$ is then equivalent to $Q_0 < 1$. For the case of adiabatic compression, the pressure profile evolves in a way that conserves mass, flux and entropy. Therefore, an ideal plasma with no resistivity or heat losses conserves $r\,r\,/\,B$ and $p/r^{5/3}$ in each fluid element, and also the value of K. This means that if plasma elements do not change their relative radial positions, then for ideal isentropic motions they will stay in the same condition relative to $m = 0$ stability (stable, unstable, or marginal). In particular, if a plasma begins in the marginally stable state with $Q_0 = 1$ or equivalently K independent of r, then the value of Q_0 stays constant during compression.

In this geometry, magnetic field line tension causes a complicated change of fluid element positions during compression. Fluid elements originally located at r_0, move to a new radius r as the outer boundary (liner) located at radius b moves inward. Eq. 3 determines $r(r_0,b)$ given the initial profiles of pressure $p(r_0)$ and $B_o(r_0)$. Analytic solutions for either large or small b can be used to understand the qualitative behavior, and numerical solutions can be obtained for any b.

$$\frac{d}{dr_0}\left[p_0(r_0)\left(\frac{r}{r_0}\frac{dr}{dr_0}\right)^{-5/3}\right]+\frac{1}{2m_0 r^2}\frac{d}{dr_0}\left[(rB_0)^2\left(\frac{dr}{dr_0}\right)^{-2}\right]=0 \qquad (3)$$

An example of profile evolution obtained numerically is shown in Fig. 5 for the same Kadomtsev-stable profile of $Q_0 = 1$ used for Fig. 4. The change of plasma b, which affects stability, has an interesting behavior that can be described qualitatively as follows. The value of b always decreases near the hard core during compression (r/a~1), but it increases in regions of large r/a. There is a region where b remains nearly constant during large aspect ratio compression. Then as A approaches unity, b decreases at all radial locations.

The initial maximum b at the inner wall is assumed to be 2/5, so at that location Q_1 is unity. At larger radii, b is smaller, so the value of Q_1 is smaller. Fig. 5 shows the values of Q_0 and Q_1 after compression as determined numerically by taking the derivatives defined by Eqs. 1 and 2 The numerical value of Q_0 is nearly constant, which is the expected result, for initial stages of compression with large A, but Fig. 5 shows that numerical errors result in a slight decrease of Q_0 that becomes noticeable as A approaches unity. The numerical values of Q_1 become approximately uniform in radius and well below unity (away from the edge regions where numerical errors introduce inaccuracy), which shows that the margin for stability to $m = 1$ is increased. To summarize, the previously described self-organization tends to generate $Q_0 < 1$, adiabatic compression does not change Q_0, and reduces Q_1, and so compression of a diffuse z pinch appears to be a promising approach for heating.

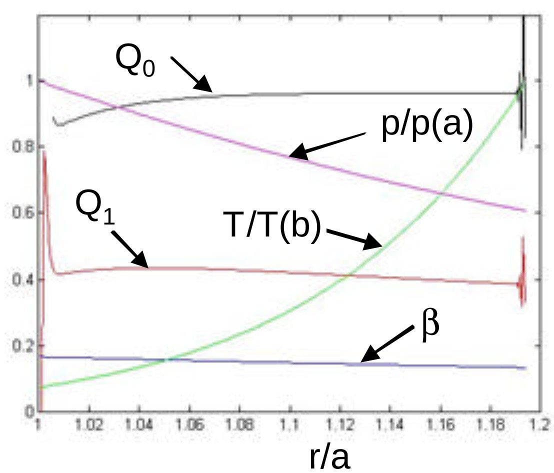

FIG. 5. Plasma pressure, temperature, beta, and Q profiles after adiabatic compression from A = 10 to A = 1.2.

4. Liner behavior during implosion.

TABLE 1. ATLAS PARAMETERS

Voltage	240 kV
Stored energy	24 MJ
Source inductance	~ 25 nH
Peak current	30 MA

MTF relevant parameters for liner implosions are typically MA of current and MJ of energy. The Atlas facility, which is located at the DOE Nevada Test Site, is a good example of such a facility. Typical Atlas parameters are listed in Table 1. It was designed primarily for the purpose of imploding cylindrical liners to generate high pressures for studies of dynamic material properties, but the facility offers interesting potential as an MTF driver. The typical liner dimensions used in Atlas are similar to the sketch shown in Fig. 3.

A reasonable approximation for liner behavior during the early stages of implosion is to assume the liner material is an incompressible fluid. The motion can then be calculated using a zero-dimensional approximation [11]. At peak compression, Mbar pressures are generated. Then the liner and hard-core compressibility becomes important, and one source of inefficiency is the energy that goes into material compression. Another important effect is the eddy current heating of the liner and hard core surfaces. These effects can be quantified using a Los Alamos one-dimensional MHD code called RAVEN. The Lagrangian code uses material properties such as equation of state and resistivity obtained from the Los Alamos tabulated Sesame tables. Fig. 6 shows the expected behavior of a 10-cm long, 2-mm-thick aluminum liner driven by Atlas using the geometry of Fig. 3 The initial hard-core current is assumed to be 1.5 MA, and the space between the liner and the hard core is assumed to be a vacuum. The inner surface reaches a velocity of 3.3 km/s, and the liner KE reaches 650 KJ before deceleration begins. The implosion time is about 23 μs. The finite compressibility of aluminum can be seen by the displacement of the hard core surface at the time near peak compression. The magnetic field in the gap reaches a value of about 500 Tesla. The energy lost to compression effects is about 380 KJ or 42% of the kinetic energy.

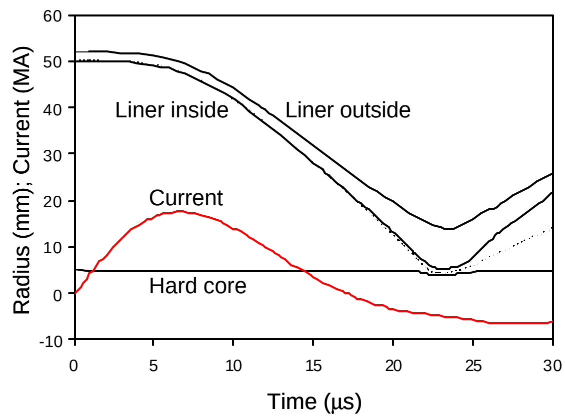

FIG. 6. Liner inner and outer radius, hard-core radius, and Atlas current vs. time assuming zero liner resistivity. Dotted line is inner liner radius with Sesame resistivity.

Eddy current heating during implosion causes the aluminum hard-core surface to boil just before the time of peak compression for the case presented in Fig. 6. Fig. 7 shows the temperature in eV near the hard-core surface for times near peak compression in the implosion. The liner inner surface boils slightly later in time

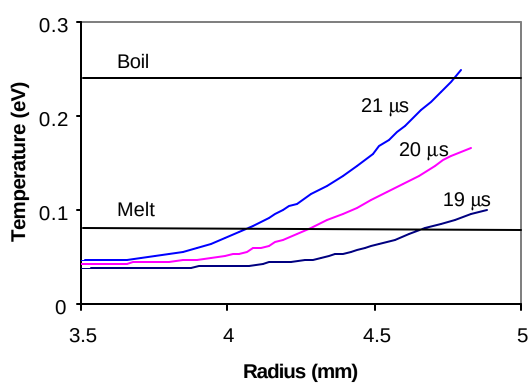

FIG. 7. Temperature (eV) vs. radius near surface of hard core at times near peak compression.

because the larger radius has lower current density.

Because the space between the liner and the hard core is modeled as vacuum, flux diffuses at a rate determined by aluminum surface temperature and resistivity. The situation with a conducting plasma in the gap is different because the amount of flux that diffuses becomes limited by the plasma conductivity. The modeling reported here does not quantify this effect, but for reference, liner motion is computed either with perfect conductivity or realistic conductivity shown as a solid line or a dotted line respectively in Fig. 6. For the case with aluminum resistivity and vacuum conditions, the liner inner surface impacts directly upon the hard-core surface as seen by the dotted line.

5. Simulations of liner compression including plasma energy losses

It would be difficult in practice to implode as fast as required for strict application of the adiabatic approximation. Stable equilibrium of a hard-core diffuse z pinch requires plasma contact with metallic boundaries in both radial and axial directions. Thus heat losses and some degree of non-adiabatic behavior are expected. Taking into account thermal conduction and the Hall effect can destroy the Kadomtsev stable profiles and result in high convection fluxes. The convective effect near external metallic boundaries was analyzed and reported elsewhere [12]. Radiation losses are also expected to be important for plasma near the boundaries as wall impurities are swept into the chamber by plasma convection [13]. Efforts continue to be directed towards estimating and understanding these effects with increasingly realistic numerical simulations.

Results are presented here for Atlas-like parameters using the same two-dimensional MHD code previously used to explore self-organization. The compressible two-fluid model uses Braginskii coefficients of thermal conduction and electrical resistivity [6]. The assumed Ohm's law is $\boldsymbol{E}+\mathbf{v}\times\boldsymbol{B} = \eta\boldsymbol{j}$, which relates electric field **E**, fluid velocity **v**, magnetic field **B**, current **j**, and resistivity η. Thus the effects of compressional heating and cross-field thermal losses at cold boundaries enhanced by convective motion are included. Hall terms and thermoelectric terms such as the Nernst current are not included.

Simulation results are shown in Fig. 8. The numerical model uses as input a prescribed motion for the outer plasma boundary and assumes the inner boundary does not move. The outer boundary position is taken from the RAVEN calculations by assuming the gap between the inner liner surface and the hard core is the same as determined by RAVEN assuming zero resistivity (solid line in Fig. 6).

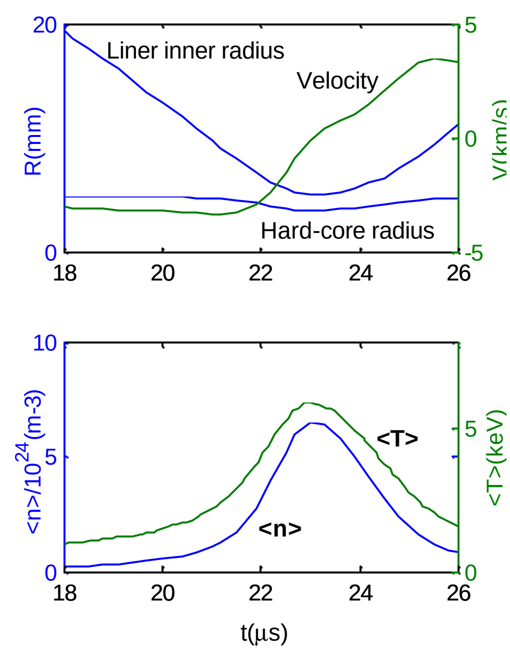

FIG. 8. Numerical simulation of plasma parameters during liner compression assuming prescribed boundary motion based on Atlas parameters.

The injection process is not modeled in the simulation reported here. The target plasma is assumed to have 30 KJ of energy generated with a 1.5 MA pulse of current before the liner implosion begins, which are reasonable parameters expected from coaxial accelerators. The temperature is assumed to be uniform at 500 eV, and the initial pressure profile is assumed to be a Kadomtsev-stable profile with Q_0=1 and <*b*> = 0.1 extending from the hard core to the liner as discussed above. The corresponding average ion density is 4 $x10^{22}$ m^{-3}.

Fig. 8 shows the time dependent average temperature reaching 6 keV and average density of about $6x10^{24}$ m^{-3} at the time of peak compression. According to these results, a deuterium plasma would generate $4x10^{12}$ neutrons. Time-resolved neutrons should be detectable starting at about 20 μs based on previous experience with scintillator detectors. For comparison, a strictly adiabatic calculation would give maximum average temperature of about 7 keV and $3x10^{13}$ neutrons. Note that the graph for liner velocity indicates that liner deceleration and Rayleigh-Taylor instabilities would not be expected until about 22 μs, well after neutron emission should begin. Thus, the time variation of neutron emission would give valuable information about the final stages of plasma compression.

6. Conclusions

The prospects for an interesting MTF liner implosion experiment have been examined based on the existing Atlas facility. Experience with MAGO and other types of coaxial accelerators give hope that a moderate-cost plasma injector with the needed properties could be developed. The stabilized hard-core z pinch appears to have interesting properties for MTF, and the geometry is well suited to the Atlas hardware.

7. Acknowledgements.

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