MHD SIMULATIONS OF MTF IMPLOSIONS WITH TABULAR EOS AND CONDUCTIVITIES

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ABSTRACT

Magnetized Target Fusion (MTF) is a pulsed approach that compresses magnetized fuel to achieving burning hydrogen plasma conditions. The compression in one MTF-scenario comes from uses a conducting liner that is imploded due to the action of high electrical currents that flow on the outer surface of the liner. This implosion compresses and heats a dense, warm magnetized deuterium or deuterium-tritium plasma. In the present work, MHD numerical simulations of a representative MTF configuration are used to study the effect of radiative losses on the compressional heating rate and the stability of the liner/plasma system late in time. SESAME equations of state and conductivity tables are used for all materials.

I. INTRODUCTION

A fusion scheme has been proposed[1] in which a dense ($10^{17\text{-}18}$ cm^{-3}), warm (50-300 eV) magnetized deuterium or deuterium-tritium plasma would be adiabatically heated to burning conditions by a fast compression. The scheme has become known as Magnetized Target Fusion (MTF) and has been studied by many groups[2-4]. One realization of MTF uses the current from a pulsed-power machine to implode a conducting liner. The liner, in turn, compresses and heats the magnetized plasma. The plasma is magnetized in the sense that thermal diffusion is inhibited, by a simple Braginskii mechanism when $\Omega\tau >> 1$ where Ω is the electron cyclotron frequency. It is is important to note that this magnetic field is not relied upon for confinement or stabilization. In fact, with an expected implosion timescale of only a few microseconds, a certain range of nominal MHD instability may be tolerated. Previous zero-dimensional studies[1] showed significant ranges of initial plasma conditions and liner implosion velocities under which positive fusion gain could be obtained. In the present work, we have employed numerical MHD simulations to relax the assumptions of the zero-dimensional idealization. One- and two-dimensional studies of a Z-pinch MTF configuration, have been conducted using SESAME equations-of-state[5] and conductivity tables are used for all materials, and radiation transport is included.

Adiabatic heating in the thermodynamic sense is the starting point for all MTF studies. This means that no heat is exchanged between the plasma and the walls. The temperature in the plasma is then simply related to its volume $T(t) = (V_o/V(t))^{\gamma-1}\ T_o$, where the subscripted variables refer to the temperature and volume of the initial plasma. Of course energy is certainly exchanged between the plasma and the walls, through thermal diffusion, radiation losses, and possibly injection of impurity materials from the walls. The evaluation of the competition of such effects with the heating dynamics is treated through the MHD simulations.

Temperatures ~1-2 keV are needed for fusion gain, but unmagnetized thermal diffusion scales ~ $(T(t)/T_o)^{5/2}$. This diffusion loss overwhelms the work that any real liner can pump into the plasma. Such conditions therefore can not be attained. With Braginskii reductions ($\Omega\tau > 1$) in thermal transport, adiabatic variation of plasma conditions then leads to temperatures high enough that fusion rates can reach breakeven.

High currents (~20-30 MA) are needed to accelerate a solid liner to velocities ~ 10 km/s. This high current will heat the aluminum liner, partially or completely melt it, and make it more susceptible to unstable plastic deformation. The inner liner surface and the plasma chamber walls must furthermore carry significant currents to sustain the magnetic field in the plasma. The Ohmic heating of such surfaces (~ ηJ^2) may lead to impurity desorption, wall vaporization, and loss of strength. This last factor is especially significant for the inner liner surface, which can exhibit Rayleigh-Taylor instability at the critical point of the implosion in which plasma pressure becomes high enough to decelerate the liner. We have observed such phenomena in idealized

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Magnetized Target Fusion (MTF) is a pulsed approach that compresses magnetized fuel to achieving burning hydrogen plasma conditions. The compression in one MTF-scenario comes from uses a conducting liner that is imploded due to the action of high electrical currents that flow on the outer surface of the liner. This implosion compresses and heats a dense, warm magnetized deuterium or deuterium-tritium plasma. In the present work, MHD numerical simulations of a representative MTF configuration are used to study the effect of radiative losses on the compressional heating rate and the stability of the liner/plasma system late in time. SESAME equations of state and conductivity tables are used for all materials.

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MHD calculations and are presently studying the process in more realistic simulations.

II. COMPRESSION DYNAMICS IN 1-D

Many aspects of cylindrical liner compressions of a MTF plasma, do not require treatment of side-walls or instability. Such aspects can profitably be studied with one-dimensional calculations. We have used a Lagrangian MHD code (RAVEN) that includes radiation transport for such studies. All materials, including the deuterium plasma, the aluminum liner and a central return conductor are treated with tabular EOS tables[5] and advanced tabular conductivity tables. An external circuit that models the operations of the ATLAS pulsed-power system[6] is used to calculate self-consistent currents for driving the liner. Most calculations were done for a bank-charging voltage of 162 kV. This yields 21.1 MA peak current across the outer surface of the liner.

With an aluminum liner of initial inner radius, 50.0 mm and 1.3 mm thick, the liner reaches a velocity ~6.5 km/s when driven by 21 MA peak current. For a return conductor at radius 15.0 mm, the total implosion time is ~ 12 μs. (The "implosion time" is not exact since the pressures on the inner conductor become so great that *it* begins to compress.) The radial dynamics of the liner, the inner current conductor and the outer return current conductor are shown in Fig. 1.

Plasma heating was first modeled under conditions that approximate adiabatic compression. Energy transport was "turned-off" so that no direct energy exchange was permitted between the plasma and the liner or the inner conductor. Magnetic diffusion was still permitted between plasma and the other materials, so an indirect path of energy transfer was possible. The calculations were performed with initial plasma temperatures of 10-40 eV. Such temperatures are significantly lower than that needed to reach breakeven conditions ($T_o \cong$ 50-200 eV). For an initial deuterium density of 2.0×10^{-5} g/cm^3 (ie. N_o~6.3×10^{18} cm^{-3}) this is near the lower bound for justifying an LTE approximation, and so making our "Gray-body" computational algorithm reasonable. A current of 250. kA was initialized in the walls of the MTF chamber; no current was initially flowing in the plasma. The calculation showed that, with tabular EOS for the deuterium, heating very closely followed an adiabatic scaling with $\gamma \cong$ 1.665 (Ideal gas law scaling gives $\gamma = 1.667$.)

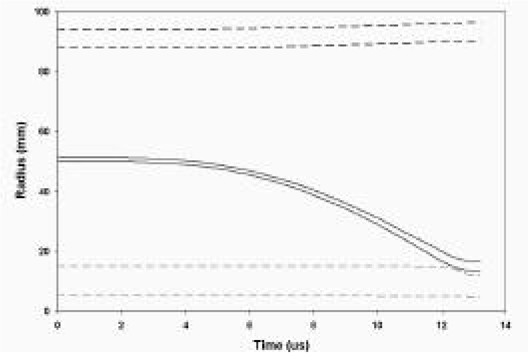

Figure 1. Time-dependence of the liner surfaces (solid), the inner conductor surfaces (dash-dot), and the outer return-current conductor surfaces (dash) for a typical set of parameters for a 1-D MHD calculation; I_{max} = 21.1 MA, $\rho_o = 2.0 \times 10^{-5}$ g/cm^3, T_o = 10. eV)

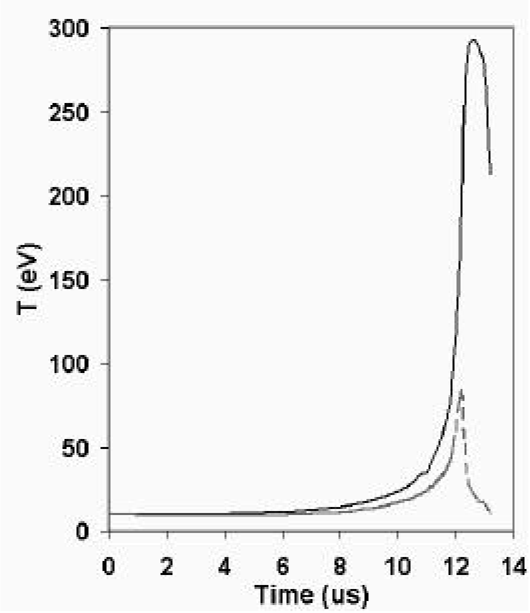

Figure 2. Comparison of the time-dependence of heating in a representative Lagrangian cell from a similar set of calculations as shown in Fig.1; Complete thermal insulation, radiation transport not included (solid), radiation transport included (dash).

Thermal conduction into the metallic walls was completely inhibited. The effect of radiation losses on plasma temperature is shown in Figure 2. Whereas in the "adiabiatic" calculation the plasma continued to heat until the total plasma pressure was sufficient to stagnate the liner motion, inclusion of radiation coupling (a) provided a loss term that lead to consistently lower temperatures, even when the plasma/radiation coupling was weak and (b) yielded plasma/radiation equilibration once the compressed plasma density becomes sufficiently high.

The simulation conditions result in rapid evolution of the radiation temperature to about 6 eV (within 100's ns) when the initial plasma temperature was 10. eV. There was little significant increase in this temperature until the compressed plasma density reached ~ 1.0 x 10^{-3} g/cm^3. Thereafter the radiation field coupled strongly to the plasma and increased rapidly to ~30 eV. For the remainder of the calculation the electron, ion, and radiation temperatures were equilibrated. The enhanced losses from the warm radiation field (proportional to T^4) completely overwhelmed the power input from the liner compression into the plasma. Instead of peaking at 291 eV as in the "adiabatic" calculation, the plasma reached only 80 eV when the radiation was included. Increasing the initial plasma temperature resulted in higher absolute temperatures but with reduced amplification factors.

III. COMPRESSION DYNAMICS IN 2-D

Two-dimensional MHD calculations were also performed, to study the possibility of instability during the plasma compression. An Eulerian RMHD code[7] was employed in the same configuration as the above Raven calculations, except a finite width was permitted in the longitudinal, z-direction. These calculations did not include the transverse walls or the perturbations that such introduce into the dynamics.

A variety of different zoning and interface treatments were used to facilitate comparisons between the Eulerian and Lagrangian simulation methods. Figure 3 shows a comparison of results for temperature scaling with volume change. It is surprising that inclusion of radiation losses does not alter the power-law dependence of temperature on inverse volume ratio ($V_o/V(t)$). The effective coefficient $\gamma \cong 1.665$ was reduced to $\gamma \approx 1.5 \pm 0.03$.

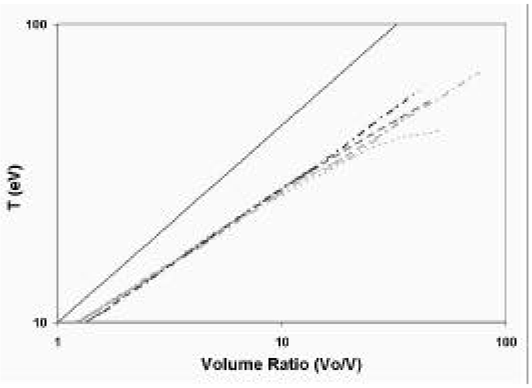

Fig. 3 Plasma temperature scaling versus volume. Curves: 1-D "adiabatic" calculation(solid); 1-D with radiation included(dot-dash); 2-D calculations with various zoning and interfaces. The dashed curve is a particularly interesting 2-D calculation.

The exception that suggests a systematic late-time departure from power-law scaling is the dashed curve. This curve followed the power-law scaling up to $V_o/V \approx 30$ but at higher compressions, the temperature fell significantly below the scaling curve. Analysis of this calculation indicated that the inner liner surface had become highly unstable late in the compression. The density distribution, shown in Fig. 4, shows clear evidence of the highly nonlinear phase of Magnetic Rayleigh-Taylor (MRT) instability. This calculation was unstable, while others reached much higher compression ratios, because an anomalous amount of magnetic flux had been transported from the high-flux region (driving the liner) into the plasma. This calculation was coarsely zoned, with the smaller-scale features resolved through Automatic Mesh Refinement. This particular treatment did not compute the flux diffusion

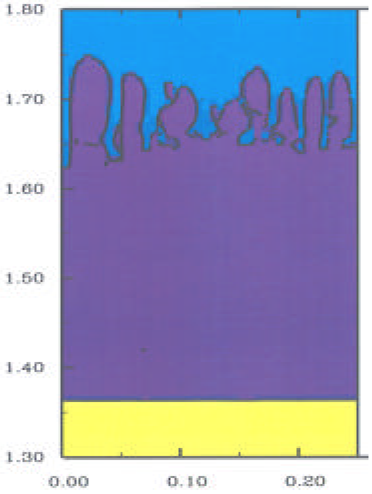

Figure 4. Mass distribution (R-Z) showing instability of the liner material (gray) into the plasma region and the inner center-conductor(white). Note that the initial inner conductor radius was 1.50 cm.

accurately. The result was that magnetic pressure in the plasma region was high enough to slow the liner motion. Since the liner inner surface had already melted, this magnetically-induced deceleration caused MRT instability. This effect had a physical basis, though it should not have occurred for these initial conditions. Had a much larger magnetic flux been initiated in the plasma, MRT distributions of cold, dense high-Z material would have occurred as in Fig. 4. This would undoubtedly have "poisoned" the hydrogenic warm plasma. It is possible that an initial plasma pressure that is too high would also have lead to Rayleigh-Taylor disruption of the liner. These issues are currently being studied more carefully.

A final interesting observation can be made about some 2-D calculations that did not show MRT and reached compression ratios ~ 100. At the very highest compressions, strong radial gradients were established in the plasma density, pressure and temperature. At least in some cases, these strong gradients resulted in instability of the axially homogeneous plasma/magnetic field configuration. Fig. 5 shows the two-dimensional distribution of the radial velocity field (ie. V_r). The axial velocity field showed analogous structures, consistent with convective cells with mean dimensions ~ 1.0-1.5 mm. It is very suggestive to identify these convective cells with the Benard instability in fluids in which temperature gradients have been induced. Further analysis is currently underway to establish the nature of the basic instability. Such an instability could be very destructive to an MTF system, since convective cells could transport cold, entrained impurity material near the liner surface into the heart of the MTF plasma. Such mixing could prevent the plasma from remaining in the hot compressed state long enough to attain positive fusion gain.

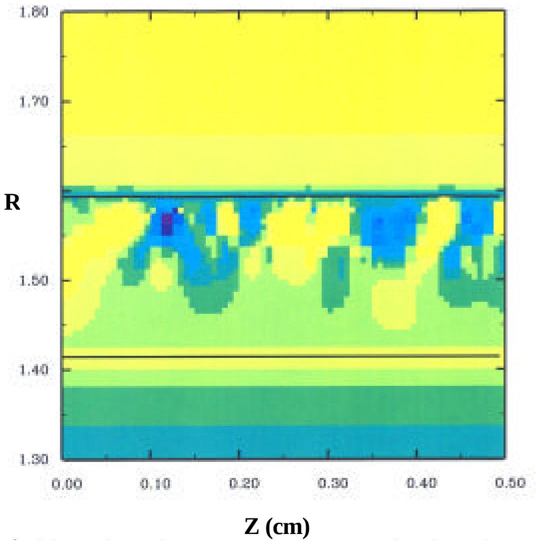

Fig. 5 R-Z distribution of the V_r-velocity field in the plasma (1.41<R<1.59) late in the compression. Note plasma/magnetic pressure has already moved the solid inner conductor.

IV. CONCLUSIONS

This study concentrated on 1- and 2-D MHD simulation of time-dependent MTF plasma compressions. Previous zero-dimensional studies found "islands" in MTF-parameter space where fusion gain appears feasible. Our studies confirmed that radiation is important in MTF compressions, especially for higher density scenarios. MRT was seen when the liner stagnated on the compressed plasma. Another instability was tentatively seen in MRT stable states. It may be related to the Benard instability but further analysis is required to confirm that. Further analysis is being taken on both MRT and "Benard" instability to establish their relevance to MTF compressions.

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