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Magnetic and kinetic effects in the hot-spot of inertial confinement fusion implosions

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Laser compression of inertial confinement fusion (ICF) plasma leads to conditions that are dense and hot enough to initiate nuclear reactions. The standard scheme aims to produce a 30 micron sized hot-spot plasma region that produces enough fusion reactions to ignite the surrounding dense fuel. The hot-spot plasma has density 100gcm^{-3} and temperature 5keV.
Experiments at the national ignition facility concluded that contaminant jets enter the hot-spot and cause radiative cooling, depleting the fusion yield [1]. One major source of higher-Z contaminants is the fuel fill tube perturbation and the surrounding carbon ablator.
We go on to analyse the effect of this colder jet region on the alpha and fuel ion populations. Modelling of the stagnated hot-spot has predominantly used a radiation-hydrodynamics approach [2]. However, there are several effects that reach beyond this model. Near the cold plasma boundary and the mix jets, the tail of the fuel ion distribution is depleted. Since reacting ions are mostly from the tail, this can significantly reduce the fusion rate below the hydrodynamic prediction [3].
Secondly, the mix region acts as a heat sink and transport barrier to the fast fusion alphas. Finally, the charged alpha ions stream in and draw a resistive return current. This changes the electric field properties around the jet, changing the diffusion rate of the carbon when compared to standard plasma diffusion models. Diffusion of mix across the hot-spot may increase its overall radiative losses compared to a purely hydrodynamic model. We investigate this effect with theoretical models and a Vlasov-Fokker-Planck simulation.
A further effect of the mix jet is the self-generation of magnetic fields during the implosion [4]. This is due to the Biermann battery mechanism acting on density and temperature gradients around implosion asymmetries. We used an extended-magnetohydrodynamics approach to post-process a 2D xRAGE radiation hydrodynamic implosion simulation. The simulated field is compressed to magnitudes of 5000T. The self-magnetization is especially prominent around the encroaching higher-Z jet from the fill tube perturbation. We discuss the various roles played by Nernst advection, resistive dissipation and magnetic compression. Magnetization effects are inherently tied to the plasma asymmetries that have always limited the performance of ICF implosions.
In fact, multi-species plasma also has a contribution from a new magnetic source term [5], of similar magnitude to the standard Biermann term [Fig. 1]. This arises due to the Z dependence of the Coulomb collision rate. We derive this new source term and discuss its relevance in the hot-spot. Furthermore, we show that this Z-gradient source term can become unstable, leading to exponential growth of magnetic fields, with a growth rate typically on hydrodynamic time-scales. This thermomagnetic instability occurs due to the coupling of the new source term with the magnetized deflection of the heat flux. We derive its growth rate, including various dissipative effects, to be within the 100ps fuel stagnation time-scale.
Magnetic fields are important due to the deflection and reduction of electron heat conduction. This changes the heat flux into the cold mix region, which is a primary loss source from the plasma. Furthermore, this will change the hydrodynamics of the mix jet as it enters the fuel. As such, full self-consistent MHD implosion simulations will be required, rather than just the post-processing presented here.
Magnetization effects are expected only to increase as the ignition boundary is reached. Field strengths may exceed 10kT, strong enough to confine fusion alpha particles, meaning that accurate yield prediction for igniting capsules will also require full MHD simulations. Much of the existing burn wave theory may require magnetic modifications of this sort.

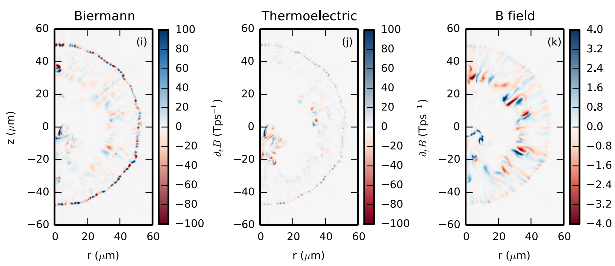

Fig 1: MHD post-processing of a 2D cylindrical coordinates ICF implosion simulation, shown at bang time. Panels show the Biermann magnetic source rate, the new collisional thermoelectric source term resulting from Z-gradients, and the total integrated magnetic field. Peak B field is 5kT, strong enough to change hydrodynamic energy transport.

References

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