Fast Ignition

In conventional ICF, the hot spot is a low-density, high-temperature thermonuclear plasma heated to ignition temperatures by compressional work of the surrounding cold, overdense shell driven by the laser energy. The hot spot mass is typically much smaller than the shell mass and the energy required to heat the hot spot to 10 keV is comparable to the energy required to compress the cold shell to several hundred g/cc (~ 500 g/cc for a NIF-like target). In conventional ICF, the driver must provide the compressional work to simultaneously heat the hot spot and compress the DT shell. The assembly of both the hot spot and the surrounding shell is difficult. The hot spot can only be heated to thermonuclear temperatures if the surrounding shell remains reasonably uniform during the hot-spot assembly. However, since the hot spot-shell interface is hydrodynamically unstable during the assembly phase, small nonuniformities of the shell inner surface will grow exponentially, causing "fingers" of the cold shell plasma to penetrate and cool the hot spot. Two and three-dimensional simulations indicate that this "deceleration phase instability" often prevents the achievement of ignition conditions inside the hot spot. All ICF implosions must be designed to minimize the impact of such hydrodynamic instabilities. The overdense cold fuel assembly can also be problematic in conventional ICF. The imploding cold shell is unstable to the "acceleration phase" Rayleigh-Taylor instability when a fraction of the absorbed laser energy is converted into the shell kinetic energy. This instability causes the nonuniformities on the shell outer surface to grow exponentially resulting in a large scale distortion of the accelerating shell. A distorted shell supplies large initial seeds for the deceleration phase instability and does not provide efficient compressional heating of the hot spot. Both the acceleration and deceleration instabilities impose severe constraints on the target design and driver requirements for conventional ICF.

The fast ignition scheme has the great advantage, with respect to conventional ICF, of removing the constraints associated with the hot-spot formation while at the same time alleviating some of the requirements imposed by the cold fuel assembly. In fast ignition, the target is first compressed to the required density (~300 g/cc) by either direct drive from nanosecond lasers, or indirect drive from x-rays using a hohlraum driven by nanosecond lasers, ion beams or a z-pinch. The ignition is initiated by a fast laser pulse (the so-called "ignitor pulse"), which "bores" through the outer, lower density edges of the target, then deposits its energy into fast electrons (~MeV energy per particle) near the relativistic critical-density surface. Since the igniting spark is externally supplied, the hydrodynamic constraints associated with the hot spot assembly are relaxed. The cold fuel still needs to be assembled fairly carefully in order to achieve the required high densities, which are typically less than the densities required in conventional ICF. The optimum compressed-fuel configuration for FI is an approximately uniform density spherical assembly of high density DT fuel without a central hot spot. Gain in FI can be considerably larger than in conventional ICF because lower fuel densities can be used with an acceptable ignition threshold. Furthermore, the central hot spot is not needed and the driver energy can be entirely used to compress the cold fuel.

Key questions in the fast ignition research include: (1) how to assemble an optimum fast

ignition fuel pellet with well-connected uniform fuel mass density (no hot spot)? (2) what are the characteristics of the energetic electrons produced through laser-plasma interactions? and (3) how do the huge currents of the energetic electrons transport through the dense plasma and how do the energetic electrons deposit their energy to create a hot spot? All research in these areas relies heavily on computer simulations. The fuel assembly simulations use hydrodynamic codes. The laser-plasma interactions are simulated by Particle-in-Cell (PIC) codes. For the electron transport and energy deposition in the dense fuel region, even though the physics there is most likely highly kinetic, due to computational limitations a hybrid approach with a fluid description of the background plasma and a particle description of the energetic electrons is envisioned.

The computational challenges faced in the fast ignition research can be illustrated by considering a full-scale PIC simulation of the laser-plasma interaction region. The relevant volume is at least $200\text{x}(100)^2$ $(\mu\text{m})^3$ with an average plasma density of 10 times the critical density. A fully explicit PIC simulation would need >250 billion cells and > 10^{12} particles. About 1.5 million time steps are needed for simulating a 10-ps long ignition pulse. Therefore, we are restricted to scaled-down simulations at present. Here, a plot is shown from a recent 2D PIC simulation, which employs 280 million particles on a 12000x12000 grid (corresponding to a region of 100 μm x 100 μm) for 60,000 steps (corresponding to 1 ps).

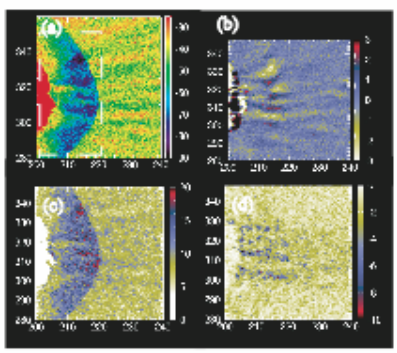

Figure 1 (color). For a circular target with p-polarization at t=964 fs, (a) electron density (in units of n_c), (b) magnetic field b_3 (in units of $mc\omega/e$), (c) return current (in units of $n_c ec$), and (d) fast electron current. Distance in units of $\lambda_0/2\pi$. [Ren et al, Physical Review Letters, **93**, 185004 (2004)]