**Controlling the Expansion of Laser-
Fusion Plasma to Minimize Impact
Damage**

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Controlling the expansion of laser-fusion plasma to minimize impact damage

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I propose to analytically model the rapid, nonequilibrium expansion of laser-fusion plasma from an initial diameter of 1 mm to a final diameter of 10 m. The aim is to devise a counterforce that minimizes the impact damage on optics by laser-plasma debris. This flow model is the basis of an idea for a dynamic target that efficiently converts laser energy to x-rays while minimizing the total mass propelled as debris. Also, the flow model is the basis of an idea to magnetically deflect material away from the optic ports in the vacuum chamber wall.

The model combines results for supersonic one-dimensional gas flow of cylindrical-hemispherical symmetry, with a transition from thermal to nonequilibrium ("frozen") plasma flow, which is set differently along each characteristic line (the "Bray criterion" as a Riemann invariant). The model shows how density, pressure, velocity, ionization fraction, electron temperature, and electrical conductivity vary over space and time, given an impulsively-heated source mass. The model is analytical, and examples are calculated on a desktop computer. This ease-of-use makes it possible to iterate quickly when refining ideas, such as a dynamic metal-vapor target that propels minimal debris, and a magnetohydrodynamic generator as a brake on the flow speed directed at the optic ports. The work involved here is that of an individual refining his analysis.

The productivity of laser-fusion facilities being planned and built (NIF in the USA, LMJ in France) will be limited by the frequency of cleaning and repair as a result of debris impact (aside from component reliability). Grams of material dispersed throughout a 10 m diameter and moving at tens of km/s are involved. No active countermeasures for protecting optics are now planned. This analytical flow model can provide quantitative information on which to engineer active and passive debris mitigation schemes. For example, the mechanical impulse of the target flow hitting a support 3 cm away can be 30 kbar (3×10^4 ATM), and at 10 cm it can be

3 kbar. Does this cause shattering and generate shrapnel? Would a different support geometry or material reduce debris? The analytical model can span twelve orders of magnitude in density, and describe the flow history from tens of ns to hundreds of μ s. Advanced flow simulators such as CALE and LASNEX have greater detail and precision, but for a density span of four or five orders, for an extent of centimeters, and for intervals $<1 \mu$ s.

All laser-fusion theory and experimentation focuses on an interval of about 4 ns during which UV irradiation, compression, x-ray emission and fusion occur. It is the subsequent interval of 400 μ s that this proposal addresses, a time during which up to 30% of the total energy is dissipated kinetically.

Motivation

Laser-fusion experiments are planned that will deposit a megajoule [1] of energy on a gram [2], [3] of material. Within several nanoseconds, about 70% of this energy has radiated away, and the many intricate processes involved in inertial confinement fusion have occurred. X-rays emitted during this time ablate material from all exposed surfaces within the vacuum chamber [4], [5]. The target mass has cooled to, say, 200 eV, and it begins expanding to dissipate its remnant energy, up to 500 kJ. The expanding laser-plasma will ram into intervening structures, shattering some to generate shrapnel, before finally striking the inner wall of the vacuum chamber, which is at 5 m radius at NIF. Laser-plasma can expand as fast as 20 km/s. Both the x-ray ablated matter as well as the expanding laser-plasma are called "debris," and the flow of debris can occur for hundreds of microseconds. This flow will hit the optic ports to pit their surfaces and deposit as splats and films [4], [5]. If these windows have to be cleaned and repaired often, it will reduce the productivity of the facility.

I propose to analytically model the outflow of material to have a consistent, quantitative description of ionized flow properties over space and time, [6], [7]. The intent of the work is to spur engineering innovations to limit the production of shrapnel, and to actively deflect debris-flow away from optic ports. I present two ideas of this type: first, a low-mass, under-dense, metal-vapor target created by electron-beam pulse-heating of a metal fleck [8], and second, magnetohydrodynamic (MHD) braking of plasma-flow directed at the optics. The basic tenet of this proposal is that 500 kJ is just too much

energy to be discarded as "debris." Rather, how can we tap this source and modify its outflow to our convenience?

Typical results

Typical results are shown for an expansion of 0.5 g of gold from a cylinder 5 mm in diameter and 5 mm long, heated to 200 eV by 460 kJ. These results are for the flow at 3.3 μ s. Figure 1 shows the number density in cm^{-3} as a function of distance in cm. In a similar fashion, Figure 2 shows both the fluid temperature and the electron temperature in eV, Figure 3 shows the electron density in cm^{-3} , and Figure 4 shows the velocity in m/s. In this model, flow emerges from the disc areas of the solid and evolves towards hemispherical flow fronts with increasing distance, [8]. Prior to 3.3 μ s this flow is sufficiently dense and hot that ionization is in thermal equilibrium. Beyond 3.3 μ s the fluid is cool and rarefied, and the electron temperature and ionization fraction "freeze" to set values (as Riemann invariants unique to each characteristic line, see [7]). Figure 5 shows the ram pressure ($\rho v^2/2$) in standard atmospheres (1 ATM = 14.696 psi = 1.01143×10^5 Pascals, Pa = Newtons/m²) at a 10 cm distance and over a period of 35 μ s.

MHD braking

The electrical conductivity of the flow just described is about 200 mho/m (= $\text{ohm}^{-1}\text{m}^{-1}$) for distances beyond 2 cm and times beyond 3.3 μ s. This plasma flow of 20 km/s polarizes to 10 kV/m in an MHD channel with a magnetic induction of 0.5 T (5000 gauss), $E = -\mathbf{v} \times \mathbf{B}$. Imagine a cylindrical radial outflow, and the electrodes as "washers" with inner and outer radii of 0.2 m and 1.2 m, respectively, and separated axially by 1 m. The imposed magnetic field circles the azimuth within this gap. Plasma-flow within the gap creates a voltage of 10 kV. The net impedance across the gap is about 1 m Ω , while the impedance between the electrodes through the exterior plasma is about 3 m Ω . A current of 2.5 MA flows through this circuit, dissipating the kinetic energy of the flow within the gap at a rate of 25 GW. After 50 μ s, the time to flow 1 m, 125 kJ would be expended. The plasma is like a brake pad, absorbing the energy of a decelerated mass by heating up.

On NIF, a pair of "washer electrodes" (probably nets) could define a tapered gap extending from the azimuthal band containing

the optic ports in the northern hemisphere to a region less than 1 m from the target. Current loops in a toroidal solenoid would supply the azimuthal magnetic field. Laser beams would shoot between loops. The southern hemisphere would have a similar MHD brake. If the electrode gaps are 30° sectors in latitude, then one-third of the flow is to be decelerated, and this energy is 153 kJ for the example described earlier. Figure 6 may help visualize MHD braking.

Uniqueness

This work is unique in that it seeks to use the dynamics of expanding plasma to create better laser-fusion targets, and to "short-circuit" laser-plasma debris-flow away from optic ports. More generally, the work seeks to find a unity of description of expanding ionized flow over a very wide range of parameters.

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Figure captions

- 1 Number density at distance from target. External density profile at 3.3 μ s of flow from a source mass of 0.5 g of Au initially at 200 eV in a cylinder of 5 mm diameter and 5 mm length. Distance is along the perpendicular of a disc area. Flow fronts are essentially hemispherical beyond 1 cm.
- 2 Electron and fluid temperature profiles. This is nonequilibrium flow, the electron temperature diverges from the fluid temperature. The electron temperature "freezes" to 0.4 eV.
- 3 Electron number density profile. The extremely fast expansion creates a much higher degree of ionization in the distant flow than would be expected on the basis of thermal equilibrium.
- 4 Velocity profile. Flow extracts heat and mass from the source mass, and the external flow is an acceleration expending thermal energy. Over time the source mass cools and rarefies, and subsequent emission of material accelerates to lower speed. At distant time, the flow is an expanding spherical shell and the original source volume is a cold void.
- 5 Ram pressure history at 10 cm. The impact pressure is $\rho v^2/2$. This is the shock experienced by any surface perpendicular to the flow.
- 6 MHD braking in a laser-fusion target chamber. Conical MHD generators are shown that would act as brakes on flow directed at the optics. An optic port, laser beam, and target are also shown. Plasma in the unmagnetized volume "shorts out" the voltage generated within the MHD channels. The kinetic energy

within the channels is dissipated as heat to the unmagnetized plasma. Current loops in toroidal solenoids create the magnetic induction, two loops are shown.

Epilog

This report was submitted as a proposal to the Laboratory Directed Research and Development competition for FY2000. It did not win funding. Perhaps a wider readership will find some value in it.

Figure 1. Number density at distance from target

Figure 2. Electron and fluid temperature profiles

Figure 3. Electron number density profile

Figure 4. Velocity profile

Figure 5. Ram pressure history at 10 cm
(1 ATM = 14.696 psi = 1.01143×10^5 Pascals,
Pascals = Newtons/m²)

Figure 6. MHD braking in a laser-fusion target chamber