Relativistic High Energy Density Physics and High Intensity Laser Physics

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1. There is vast capital, both physical and intellectual, that exists in this field that is ready to be exploited. Computer programs can with adequate accuracy model the high intensity laser-plasma interaction, the transport of the resultant electrons through complex structures, generation of electric fields in the range of teravolts/cm, magnetic fields up to gigagauss, acceleration of beams of ions produced by these immense electric fields, the generation and transport of electro-magnetic radiation at all frequencies, and the generation and transport of macroscopic numbers of antiparticles. These "extreme" phenomena have been coupled to normal matter modeled in radiation-hydrodynamic codes. We are prepared to model very complex phenomena over an extremely broad range of conditions.

   We have invested hundreds of millions of dollars building a large array of short pulse laser facilities that range from those producing femtosecond pulses with a few joules of energy to those working in the picosecond regime producing kilojoules.

   Thermonuclear fusion that can become commercially attractive remains an elusive goal. The costs for ITER, the flagship magnetic fusion facility, are so high that one wonders if reactors based on that machine can ever be affordable for civilian power. This assumes that ITER meets its scientific goals despite being an extrapolation from sub-ignition machines with no existing example at any scale where magnetic confinement led to thermonuclear fusion. Reiterating the obvious, inertial fusion has been demonstrated, but at inappropriate scale. And still at NIF, progress, although continuing, has been slower than hoped. The difficulty arises because, at the NIF energy scale, a pressure of about 350 Gbar must be achieved so that the thermonuclear output exceeds the losses from the fuel and only 100-150 Mbar pressures are available from the laser ablating plasma. The difference must come from accumulating kinetic energy during and implosion that at stagnation provides this pressure. Energy flux at stagnation time is of order 10^{19} W/cm^2 . The implosion requires excellent control of hydrodynamic stability, symmetry and entropy control. Short pulse lasers routinely produce energy fluxes much larger than that required for ignition. New concepts for auxiliary heating of the compressed fuel and hot spot are being explored in universities.

2. The difficulty that Fast Ignition schemes face is not that there is insufficient energy flux, but rather that it doesn't couple efficiently to the fuel. The electrons produced when the laser interacts with the plasma have too large an angular spread and are too energetic. Recent theoretical and experimental results may help to solve this problem. Electrons can be guided by magnetic fields produced via Faraday's law in structures composed of materials with varying resistivity. Not only can these structures bring the electrons closer to the fuel, but they may also be used to rearrange the particle phase space. Although the electrons are born with a large momentum part of phase space, the spatial phase is quite small. In particular, the electrons are born in about 1 micron length near the critical surface. For Fast Ignition, they need to be

delivered to fuel in about 10-20 ps, so the electron column would be 3-6 mm long. We can afford to stretch the longitudinal phase with according to Liouville's theorem concomitant reduction in the transverse phase space. Indeed, we can start with a much larger spot and hence much lower particle energy and bring these particles to a smaller spot with smaller angular divergence. An alternative is the use of multiple laser pulses to generate the required magnetic fields for fast electron guiding in dense plasma. Continued investigation of hole-boring and channel formation are needed.

Ions produced in short-pulse lasers offer an alternate route to ignition. The ionsproduced are non-relativistic and stop in shorter distances than electrons of less energy. In addition, their mass makes them stiff. Ions accelerated via ambipolar potentials(the TNSA process) have recently been produced with 15% efficiency. The potentials that produce these ions are produced by the average motion of electrons over large distances, so the potential surfaces are quite smooth and the ions are produced normal to the emitting surface. Recent calculations(Fernadez, in the special issue) indicate that 10 kJ of ions with the proper spectrum and properly focused can ignite fuel. The ions just mentioned were not produced with the optimum spectrum and were not focused to a required spot. However, ideas developed and tested in the heavy ion and light ion programs, such as space charge neutralized transport may be applied here. At 15% coupling efficiency , a 60 kJ short pulse laser would be required for ignition.

3. Currently, short pulse Joules are much more expensive than long pulse Joules so 10's to 100's of kJ of short pulse energy would be unaffordable. Perhaps, in the long run improved engineering and manufacturing techniques will bring the costs down. But we can investigate, with existing facilities, techniques to produce short pulses so that short pulses of 1 micron light cost as much per joule as long pulses of 1/3 micron light. This requires plasma-based schemes utilizing Raman or Brillioun pulse compression. Currently, the best results produce pulses of less than 1 TW, far from the 10's of PW required. However, recent theoretical results indicate that the results can be improved substantially. The costs of this theoretical and experimental effort are modest, while the importance of the results could be tremendous.

4. The recent results in electron -guiding and phase space control may enable novel radiation sources at existing facilities. By expanding a hot electron beam transversely and longitudinally, its transverse temperature can reduced enormously. This beam could then enter a high density, high Z material and efficiently produce, via bremsstrahlung forward directed gamma rays and via the trident process, electron-positron pairs. Because electron guiding depends on large magnetic fields at interfaces electrons crossing these interfaces are turned rather sharply. The Larmor radius for a 1 MeV electron I a 100 MG field is about 0.3 microns. The critical frequency for synchrotron radiation is c γ^3 /r. So this would radiate at 24 eV. A 10 MeV electron with the same Larmor radius would radiate 24 keV. The field would be required to be 1 Ggauss. We think that the resistive growth of magnetic fields stops as the material heats and and resistivity vanishes. However, recent calculations show that high-Z wires can be radiatively cooled, so that their resistance is maintained and magnetic field growth can continue.