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HEDP and New Directions For Fusion Energy

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Abstract:

The Quest for fusion energy has a long history and the demonstration of thermonuclear energy release in 1951 represented a record achievement for high energy density. While this first demonstration was in response to the extreme fears of mankind, it also marked the beginning of a great hope that it would usher in an era of boundless cheap energy. In fact, fusion still promises to be an enabling technology that can be compared to the prehistoric utilization of fire. Why has the quest for fusion energy been so long on promises and so short in fulfillment ?

This paper briefly reviews past approaches to fusion energy and suggests new directions. By putting aside the our old thinking and vigorously applying our experimental, computational and theoretical tools developed over the past decades we should be able to make rapid progress toward satisfying an urgent need. Fusion not only holds the key to abundant green energy, but also promises to enable deep space missions and the creation of rare elements and isotopes for wide-ranging industrial applications and medical diagnostics.

THE EXTREMES: MFE & IFE

Current technology limits the magnetic field strength that can be employed for magnetically-confined fusion energy (MFE), which in turn limits the density of an ionized plasma that can be trapped in a given magnetic configuration (i.e., a "magnetic bottle"). In addition, the absence of magnetic fields in inertially-confined fusion energy (IFE) leads to a requirement for out-running the rapid energy loss from the fusion plasma, hence the need for huge pressures which result in extremely short time scales. Siemon and Lindemuth [1] have argued that the costs of most experimental fusion facilities are dominated by energy requirements (e.g., ITER, originally the International Thermonuclear Experimental Reactor, now the international tokamak engineering/research project) and/or by power requirements (e.g., NIF, the National Ignition Facility). Between IFE & MFE, there appears to be a minimum for the cost of the necessary experimental facilities, hence development cost.

Development at the extremes (MFE & IFE) is paced by the development of the necessary technology which is typically at the cutting edge, and the use of cutting edge technology causes the development time to be limited by the advance of the necessary technology. The expense for that development falls squarely on the shoulders of the fusion approach that demands it. Development at the extremes is both slow and expensive.

REQUIREMENTS FOR FUSION

For thermonuclear (TN) fusion, overcoming the Coulomb barrier between two reactant nuclei translates into a minimum ion temperature, hence a minimum specific energy for the particular TN fusion scheme. Also, some minimum power is needed to raise the TN plasma to the requisite temperature. For MFE a minimum power is needed to maintain the plasma at fusion temperatures, while for IFE, the power must also be concentrated onto the target, leading to a minimum power density or intensity for the driver, and the target must implode fast enough to overcome (through shocks and compressional heating) the losses into the confining shell. The slower the energy input, the slower the implosion, the more the loss, and the more the energy required to achieve significant fusion. Energy that arrives at the IFE target later than the acceptance time is poorly utilized. Analogous comments can be made concerning MFE. For fast ignition [2], it is proposed to instantaneously heat a central volume of pre-compressed fuel to thermonuclear temperatures using a laser as the primary source of energy to create energetic particles that penetrate the outer layers of the fuel to heat that volume to thermonuclear temperatures. This requires the energy deposition rate within the ignition volume to be of the same order as the energy release rate expected from the ignited fuel.

For IFE the objective is to ignite the fusion plasma in the target. Once ignited, the degree of burn depends on the quality of the inertial confinement, which is dependent on the hydrodynamic ρR of the target.

WHY SO LITTLE PROGRESS ?

Since the first demonstration of thermonuclear energy release in 1951 progress toward the peaceful uses of fusion energy has been very slow and methodical. This is in stark contrast to the exceptionally quick success based on very meger studies of fusion at Los Alamos during 1943-1946. By 1950 fission energy had become available for driving a fusion experiment, but the best method of employing that energy was still somewhat controversial. So, the "driver technology" was readily available. To be sure, it was on the cutting edge at that time, but also proven. The nuclear data was reasonably secure by that time, but there remained some atomic physics questions, which over the coarse of 1950 were more confidently analysed. This allowed the design of the first fusion experiment, and in 1951 the fact that thermonuclear fusion had been achieved was comfirmed through the measurement of 14 MeV neutrons [3]. This was on the first try. 1950-1951 was a different era. There was a sense of urgency and cost was not a constraint.

It is important to avoid artificial constraints. Discovery is typically a random process. Each added constraint diminishes the size of the box within which a discovery might occur. As the size of the box is diminished by various constraints, the likelihood of discovering the solution to a particular problem is diminished as well.

The most important step in developing a fusion energy scheme is to prove physics viability. In doing this it is unwise to set artificial constraints. These are often tied to the projected desirable characteristics of the envisioned fusion reactor, but unreasonable desires should not be allowed to obviate the physics viability. Once the physics viability is demonstrated, the range over which it is applicable needs to be established so that a reactor study can be initiated. A sufficiently large number of constraints can make any envisioned fusion reactor fail a physics &/or economic viability test.

THE PARAMETER SPACE BETWEEN MFE & IFE

In the late 1970s Sandia National Laboratory conducted a series of small scale experiments referred to as the Phi-target experiments. These were very low level experiments and involved the creation of an initially warm magnetized plasma inside small microballoons that were subsequently compressed to reach temperatures on the order of 400 eV. In the early 1980s, spurred by an analysis of the Sandia Phi-target experiments [4], Lindemuth and Kirkpartick [5] explored the vast paramerter space between MFE and IFE. Even without allowing the possibility of fusion ignition, there appeared to be an island of significant gain at moderate densities and significant magnetic field strength, and only a modest compression rate was required to overcome losses into the imploding spherical shell that contained the magnetized fusion plasma.

There are several possible embodiments for what has come to be called magneto-inertial fusion (MIF). In 2008 Woodruff [6] provided a survey of various spheromak configurations, some of which would in principle make excellent target plasmas. MIF uses a liner to compress a warm, magnetized plasma to fusion temperatures. Despite a wide range of initial conditions, which sets a wide range of driver requirements for energy, power and power density, these requirements are well within the realm of current technology.

The parameter space for magnetized target fusion (MTF, one version of MIF) is shown in Figure 1. The ICF ignition region shown in occurs for the case of no magnetic field. However, a modest initial magnetic field can dramatically extend this region. In part, this is based on an empirical fit to numerical results for tracking DT alpha particles through a dense magnetized plasma. Notice the huge potential reduction in the areal mass density ρR required for fusion ignition. This translates into a greatly reduced implosion velocity, which makes many existing pulsed power facilities interesting for break-even fusion experiments. Such relatively low-tech facilities should be fairly inexpensive, which suggests the possibility of a great reduction in capital expense for a fusion power plant.

Our survey of parameter space and other preliminary studies are encouraging, but a solid demonstration of physics viability (i.e., a proof of principle) is still needed. Issues that threaten success include the creation of an adequate warm, magnetized plasma, hydrodynamic instabilities, impurities that may ensue, and some aspects of fusion self-heating.

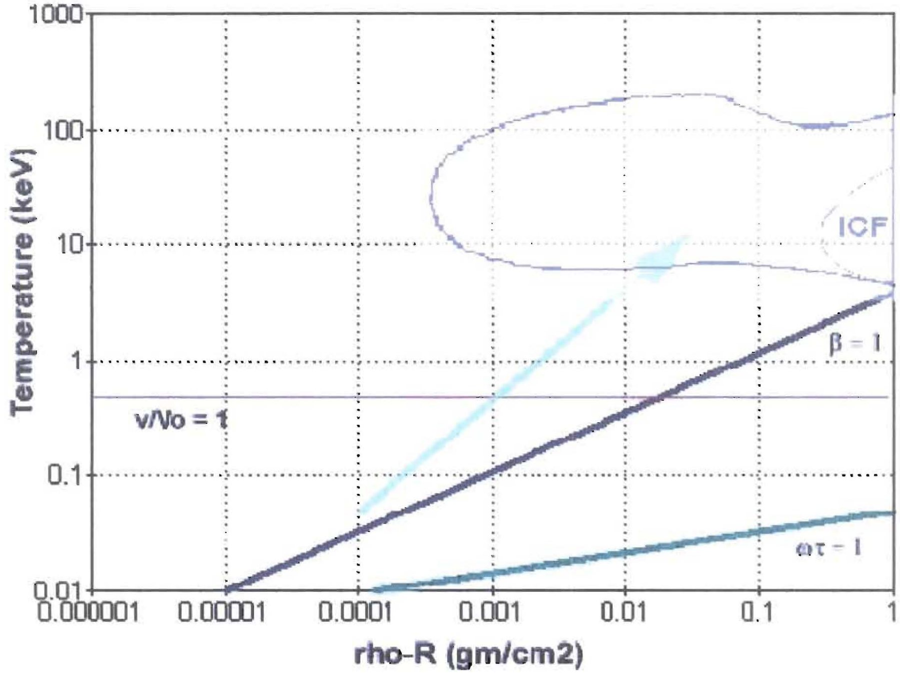

Figure 1. Lindl-Widner diagram for MTF parameter space. The green arrow represents adiabatic compression. The ICF regime in upper right, and extends to higher ρR. This diagram was drawn for $\rho_o = 10^{-4}$ gm/cc, $T_o = 50$eV, $B_o = 30$ tesla, and complete loss of radiated energy.

MATCHING THE DRIVER TO THE FUSION PLASMA

The design of the plasma confinement scheme sets specific minimum requirements for the driver, be it beam characteristics, temperature for indirect drive, or external heating for MFE. It is necessary to satisfy these requirements in order to achieve "ignition". However, it is possible to get ignition without achieving break-even, or even break-even without ignition. For some MFE approaches actual ignition is avoided by keeping self-heating by the DT alphas to only a fraction of the that necessary to maintain the plasma at fusion temperature. Such operation sets a definite limit on the gain that can be achieved by that kind of approach.

TODAY'S FUSION POWER ENDEAVORS

The most obvious successful steady state fusion energy system is that of stars. Stars are so massive that they are confined by gravity. As a first wall element, the earth is comfortably remote and its composition adequate to endure the radiation and even convert a substantial fraction of the solar energy into other forms of energy, much of which in the past has been stored as the fossil fuels that we use today. In some ways the sun is the perfect fusion reactor and is responsible for almost all our energy-intensive endeavors to date. For the most part, solar and wind energy, and yes: oil, coal, etc., all owe their existence to the sun. However, even though we may finds ways to better utilize its output, we can't use the sun for all our perceived needs. Are we just too demanding ?

Why do we need fusion ? While fission power is a proven technology, the supply of suitable stock for producing fuel seems to be limited and the build-up of long-lived radioactive waste is a big concern. Neither seems to be the case for fusion. In addition, fusion can potentially supply energetic neutrons for transmuting fission waste into a more manageable, short lived form. While fission-based rockets were built and tested in the 1960s, and have been proposed for space exploration, they appear to be too heavy for missions beyond Mars. Some studies indicate that fusion propulsion systems should meet the power-to-weight requirements for deep space missions.

COMMENTS

1) Regarding Fast Ignition (FI), transition to self-supported fusion burn requires the rate at which driver energy is deposited in the ignition volume to approximately equal that of the fusion burn at the ignition temperature. Also, laser light is absorbed at the critical surface, not deep inside the pre-compressed target where it is needed, so hot electrons must deposit a (only) fraction of the laser energy deeper into the target. But, then the problem of

stopping power comes into play. All these considerations enter into the volumetric deposition of driver energy needed to provide ignition in the hot spot. Isochoric ignition differs from hot-spot ignition. It also differs from an ignition critical profile based on pressure equilibrium at turn-around. What is the minimum energy for FI ignition ? How does that compare with hot-spot ignition, or with MTF ?

2) One consideration that has driven IFE to use frequency conversion for the laser light (thereby taking a 50% hit in energy delivered) is the hot electron problem. A further hit is taken when it is used for indirect drive. Hot electrons impact the implosion dynamics, causing the pusher to self-heat as it converges on the fusion plasma inside. The MTF approach to MIF does not need the degree of convergence that IFE does because the plasma is initially warm. This reduces the concern over pusher self-heating and also mitigates hydro instability problems, so that a longer wave length laser may be perfectly acceptable. In fact, the requirement to provide an initially warm, magnetized target plasma may be eased and even enabled by the presence of hot electrons.

3) The problem of IFE target fabrication on a scale needed for a reactor may be avoided by the stand-off driver concept [7], which dynamically creates a target. First the magnetized target plasma is produced in a central volume, and then multiple plasma jets are used to heat and compress it to fusion conditions. This concept is worth much more investment in resources than it is presently receiving.

4) The insistence on a monolithic reactor design dooms various fusion approaches. In years past, some car engines had up to 16 cylinder. If the cost of the technology is reasonable, then the use of multiple chambers, is a reasonable, prudent, and preferred option.

5) Fusion will eventually be developed to its fullest potential. We just can't fully define that potential at present. Current efforts to develop fusion energy have been divided into two diametrically opposed camps, MFE and IFE. A certain degree of antagonism between these two camps has created a virtual no-man's-land. If the desire to create a successful fusion reactor eventually out-weighs the desire to prove two extreme points of view, then we may have common ground for making rapid progress. MIF promises to provide that common ground. The parameter space [8] (the box) appears to be vast, and the potential for discovery great.

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