An Exploration of Pulsed Magnetic Field Driven Fusion in Z-pinch Configuration

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Abstract: Scheme to exploit the magnetic field driven near-isentropic compression of matter and explosion of metallic conductors is explored to attain density and temperatures suitable to generate fusion reactions. A cylindrical metallic shell, containing a capsule of deuterated matter, is radially compressed by (JxB) force and then made to explode "just at the end" of current peak by optimum thickness. An attempt is also made to enhance the final pressure at center by allowing the return conductor also to burst. Resultant shock may be directed inwards through the effect of impedance mismatch at different interfaces. A 1-D radiation hydrodynamic code, modified to include ohmic heating and self-generated magnetic field pressures by pulsed currents, is validated against results for some of the reported experiments. The model is then used to simulate a target structure for relatively slow sub-MJ capacitor banks such as the recently commissioned 280 kJ/ 40 kV capacitor bank at Trombay.

1. Introduction

Alternate approach to achieve ICF conditions based on capacitor bank driven imploding liners and pinches have been proposed and discussed extensively with many possible configurations for optimum energy transfer to the target [1]. These appeared to have reached a limiting stage until the recent experiments on imploding wire array demonstrated conversion of a large fraction of driver (capacitor bank) energy into soft x-rays [2]. This radiation pulse is strong enough [3] to create radiation *hohlraum* cavity. A variant of scheme also led to compress of hydrogen to Mbar pressures using shaped quasi-spherical implosion. Such experiments clearly suggest a need to attempt further variation and optimizations in the imploding assembly to realize full capabilities of such devices.

A constraint on implosion experiments with capacitor-banks is the sharp dependence of driving electromagnetic pressure on current ($P \sim I^2$). Thus in a moderate energy (sub-MJ, several μs time-period) capacitor-banks only a small part of full current (around first peak) is directly responsible for driving and delivering energy to the target. But with efforts to shape the current profile or the target assembly, such banks can help to study the physics and dynamics of various targets besides generating important experimental data. It is generally realized that imploding liners need to be thin cylindrical (essentially plasma) shells [5]. This is to maximize the implosion velocity and the fact that for thickness beyond a limit, ohmic heating would contribute more towards raising internal energy rather kinetic energy, which is finally delivered to the target. The time taken by energy coupled in a particular region, generally boundary to get *communicated* to center is also an important consideration.

In the present work an attempt is made to explore the possibility of utilizing relatively thick metallic liner which collapses and explodes just after the peak of current to form a plasma. As the electromagnetic and electrical circuit equations have not been included fully into numerical simulation, we analyze the problem in parts using analytical and numerical models consistent with the overall physical processes. Basis of selecting layers and their parameters including choice of material is discussed in next section. This is followed by a brief description of the numerical model, its adaptation for present studies and validation against results for reported experiments. A typical case of imploding liner for *slow* capacitor bank and effect of outer layers on the velocity of inner boundary are discussed in the last section. Parameters that need to be further investigated and optimized are also identified.

2. Target Assembly and Assessment of Parameters

Schematic of the target assembly under consideration is shown in FIG.1. Full assembly consists of a number of coaxial cylindrical shells. The current enters the inner metallic shell and returns through a thin outer co-axial shell, with a plastic liner between the two. For both the inner (imploding) and outer (exploding) liners, only aluminum is considered as foil material due to its well known physical properties and use in many of the reported experiments. Fusile material (not shown) is as usual placed in the central region. Dimensions of various stages may be derived by considering the dynamics as briefly discussed below.

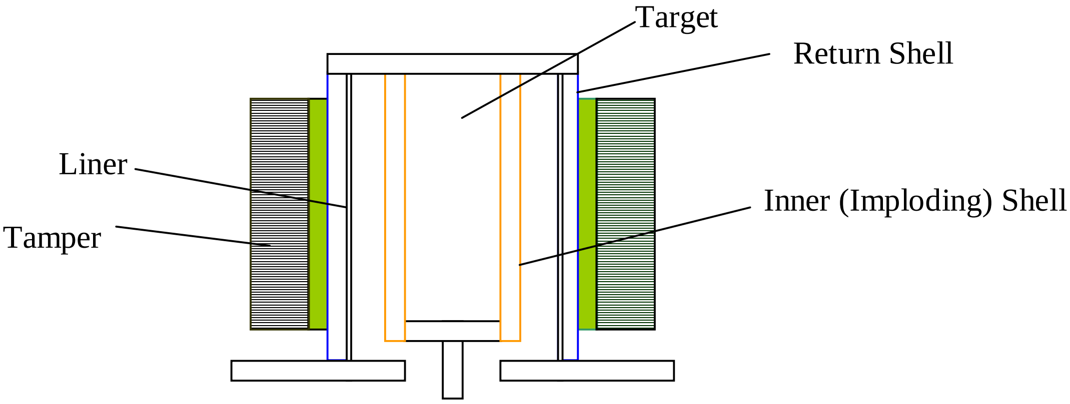

FIG.1. Schematic of the Assembly

2.1 Dynamics Considerations

In pinches or imploding liner assemblies, it is the balance of material (shell or the plasma) pressure against the driving magnetic pressure, generated by the discharge current, that governs its motion. For a cylindrical shell of radius r, carrying a current I the driving pressure (P_d) is

$$P_d = \frac{\mu_0 \breve{I}^2}{8\pi r^2}$$

μ_0 being magnetic permeability in vacuum. To make it implode, this pressure needs to be higher than material pressure. As implied by the above relation, the condition is obtained by reducing the radial dimension or increasing the driving current. However, maximum current is limited for a given device unless transformed into a shorter pulse by a secondary stage like crowbarring the magnetic field and subsequent compression. In general the energy in return conductor can not play much role, as the net force would always drive it away from the axis. However, if the current pulse and typical dimensions of the assembly are such that magnetic pressure at surface is less than material pressure, outer shell may be placed practically adjacent to the imploding shell. If properly optimized in dimension, the outer shell explodes at a desired time to generate an inward motion of the plastic liner, in turn delivering energy to target through collision with the inner shell. Confinement by magnetic field and tamper helps in enhancement of internal energy at burst.

To a good approximation, the time of burst of a conductor is obtained from action integral [6]. For a typical capacitor bank discharging with time period T, instantaneous current I(t) in first quarter cycle may be taken as I_0 Sin ωt where ω (=2π/T) is the frequency and $I_0=V_0$ $(Ck/L)^{1/2}$, for a charging voltage V_0, capacitance C, inductance L and reversal factor k. Thus using the definition of action integral A, cross-sectional area a, which changes at much smaller rate than current and hence taken as constant, of an element to burst at time (t_b) such that $t_b = fT_p$; (T_p=T/4 and f is a factor) may be obtained as

$$A = \frac{T_p I_0^2}{2\pi a^2}[\pi f - Sin\pi f)]$$

Another factor that needs to be considered is that usually current will not flow into a layer much deeper than skin depth (δ) which depends mainly on the material resistivity (η) and the discharge frequency (ω). While the latter does not change much, resistivity of the material goes up by an order of magnitude up to the time of explosion. Thus a foil or shell thickness 2-3 times the skin depth at normal temperature may be considered as maximum that can fully explode. These factors serve as a guide to decide the initial parameters specially the cross sectional area of the element and in turn estimate the radius and thickness of a cylindrical foil which may be refined through detailed computations.

2.2 Computational Method

The discharge current profile is also governed by the dynamics of circuit elements specially the motion of foil and change in its resistivity. To account for this, we use a zero dimensional model [7] of exploding foil coupled to a capacitor bank circuit for generating the current profile. The model, which includes empirical resistivity [8] and specific heats for the foil, has been found to be in reasonable agreement with experimental observations on electrically exploded foils [7].

Simulation of cylindrical implosion is carried out using a 1-dimensional 2-temperature hydrodynamic code with multi-group radiation transport [9]. The code has been modified to include ohmic energy deposition and self-generated magnetic fields. Instantaneous current density j(r), is distributed throughout the conductor thickness, in a exponentially decreasing manner from the boundary (r_0) i.e. $j(r) = j_o \exp[-(r_0-r)/\delta]$ with j_o, normalized with respect to total current I(t) such that

$$I(t) = 2\pi \int_0^{r_0} r j(r) dr$$

The current profile is given as tabular data input while resistivity model is same as used in zero-dimensional exploding foil simulation. The magnetic field is applied as inward driving pressure either as a boundary condition or at mesh boundaries. Equation of State is found to play a crucial role in hydrodynamic predictions [10-12], we therefore use EOS data generated using a model [13] that takes into account the condensed matter effects, and found to be in good agreement with experiments. Opacity data, also provided as tabular input, are generated separately from a model that has been well tested against available literature. In the center of imploding assembly, a low-density (1 kg/m^3) material represents a typical gas density at atmospheric pressure. To minimize run times and avoid handling EOS and opacity data for several materials, aluminum is chosen as standard material to study most of the effects.

3. Results And Discussion

The criteria of burst time with respect to foil dimensions and capacitor bank parameters has been confirmed by *experiments*. A 0.35 mm thick x 5 mm wide aluminum foil was designed and observed to burst at the peak of a 42 nH, 38μF capacitor bank operated at 17 kV.

To test the validity of modified hydrodynamic model, results for two different types of implosion experiments have been simulated. In an array of 90 aluminum wires [14], the wires are assumed to expand and form a cylindrical shell of uniform density i.e. the total array mass is distributed to fill the inter wire gap. The calculations are initiated with a starting temperature of 1eV, a value which is commonly observed in experiments and also considered in simulations [14]. The model shows maximum implosion velocity of 38.5 and 48.5 cm/μs at 76 and 80 ns as compared to 50 cm/μs peak reported implosion velocity. The peak values are delayed by about 5 ns so that mass averaged electron and ion temperatures reach a value of 1.6 keV and 22 keV respectively at 85 ns.

As a test for a *thick* liner, another experiment [12] where 1mm thick, 50 mm dia. aluminum liner was imploded using a *slow* current with a peak value of 12MA, was also simulated. In this case the results are in good agreement. Time history of shell boundaries shown in FIG. 2 closely follow that reported from experimental observation or simulations up to the final collapse. Implosion velocity of the inner surface (7.5 km/s as compared to 5 km/s, though the latter is derived from measurements much earlier than turn around [12]) at turn around appear to be more. While maximum collapse is affected by the nature of gas and its filling pressure, diffusion of magnetic field is likely to become more crucial at this stage.

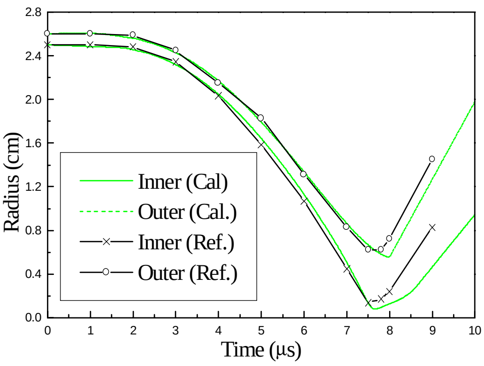

FIG. 2. Validation Result for Implosion of Thick Liner [Ref. 12].

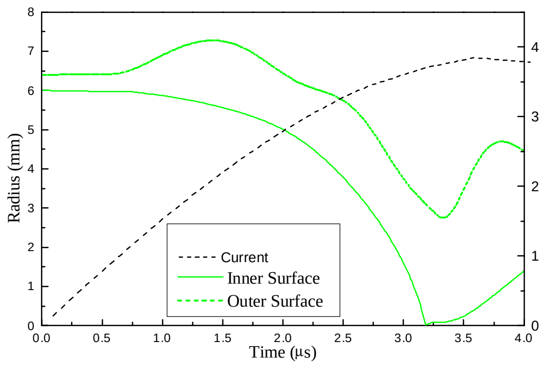

FIG. 3. Features of Liner Implosion on the 280 kJ Bank.

We have simulated the collapse of an imploding cylindrical liner suitable for the recently commissioned 280 kJ/ 40 kV capacitor bank (at Trombay) which has a "system" inductance of 15 nH and a peak current of 4.3 MA at 40 kV. The liner cross section optimized for given voltage is used to generate the current profile to be given as input in hydrodynamics. Typical time variations of total current, velocity of inner and outer surface for a single shell are shown in FIG.3. Radial implosion velocities of 11 km/s are obtained for a shell of 6 mm radius and 0.5 mm thickness. Peak temperature of up to 100 eV and duration of 20-100 ns are attained in the central gaseous region, with a radial compressions of 15 for radius of 4-8 mm.

The effect of outer shell exploding just before final collapse of the inner shell is assessed in an independent manner. As seen from FIG.3, with typical dimensions of shell, material pressure is higher than the driving pressure until about 1.5 μs. For outer shell in the configuration considered here, this duration would be still longer due to lower driving pressure and higher material pressure. If energy from the outer shell is to reach center just before maximum of implosion, it should explode 0.5-1μs (at a velocity of 6-12 km/s) before the current peak. The adjacent liner is then imparted inward acceleration until encountered by the imploding shell or two pressures are equalized. At solid density and temperature of 1 and 2 eV (typical state of exploding foils), we get velocity of 5 and 9.7 km/s respectively for a 0.4 mm thick, 6 mm radius unconfined shell. These velocities, acquired in less than 100 ns, are enhanced by about 30% if surrounded by a tamper (4 mm thick cylindrical shell). There is a marginal increase of 1% if tamper is replaced by a material such as gold. In less than 0.5μs, the exploded shell collapses to a radius of 3.8 mm which is the position of outer surface of imploding shell at 2.5 μs. Inner surface of a 1mm thick *expanded* shell placed at this position, is found to be accelerated to a velocity of 3-5 km/s. This can be considered as contribution from the exploding shell to the velocity of inner magnetic field driven surface. Expected gain in the temperature of central region of target material by a factor of 1.7 is thus significant.

To conclude, present analysis does indicate an advantage in using exploding return conductor to accelerate a plastic liner inwards, and collide with the electro-magnetically imploding shell. A purpose of this liner is also to provide electrical insulation, which is not certain after acceleration but by that time the process is expected to be over. Another effect not considered here is the quasi spherical geometry that has experimentally been demonstrated [4] to compress appreciable volume of hydrogen plasmas. Although, the effects of tamper and shock reflection at interfaces [14-15] are well known processes, dynamics of a multilayered target being a complex process, more computations are required. Further work including coupled MHD equations is in progress to bring out the effects.

Acknowledgements

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