D-T ignition in a Z-pinch compressed by imploding liner

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Abstract. It has been shown [1] that an $m = 0$ instability of a Z-pinch carrying a current of the order of 10 MA, with a rise time inferior to 10 nsec can generate a spark capable of igniting a fusion detonation in the adjacent D-T plasma channel. A possible method for generating such currents, necessary for the implosion of an initial large radius, low temperature Z-pinch, can be a radial implosion of a cylindrical fast liner. The problem has been addressed in a previous publication, [2][3][4][5], without considering the role played by an initially impressed $m = 0$ perturbation, a mechanism indispensable for the generation of a spark. The liner/Z-pinch dynamics can be solved at several levels of physical model completeness. The first correspond to a zero-dimensional model in which the liner has a given mass per cm length and a zero thickness, the plasma is compressed adiabatically and is isotropic, there are no energy losses and no Joule heating.

The second level is one-dimensional. The Z-pinch plasma is described by the full set of MHD, 2 fluid equations. The liner is treated first as thin and incompressible and subsequently it is assumed that it has a finite thickness and is composed of a heavy ion plasma, having an artificial but realistic EOS. Both plasma and liner are considered uniform in the Z-direction and only D-T reactions are considered. We shall show that, given sufficient energy and speed of the liner, the Z-pinch can reach a volume ignition.

The third level is two-dimensional. Plasma and liner are treated as in the 2nd level but either the Z-pinch or the liner is perturbed by an $m = 0$ non-uniformity. Provided the liner energy is high enough and the initial $m = 0$ perturbation is correctly chosen, the final neck plasma can act as a spark for D-T ignition.

1. Introduction

A significant fusion output from an inertially confined D-T target (ICF) can be obtained after either a volume ignition or a spark ignition of the D-T fuel. Assuming a 20 MeV output per one D-T reaction, the reactor equation for a volume-ignited target can be written as (ignition temperature $T_i = \alpha \cdot 10^8\ ^\circ K$)

$$b > 26\frac{\alpha G}{\varepsilon}(\%) \qquad (1)$$

where b is the degree of burn, ε the efficiency (in %) of generating ignited plasma out of a pool of thermal energy and G is the gain of the reactor ($G = 1$ corresponds to a zero-output reactor). The minimum α may be as low as 0.6 but considerations of inertial confinement duration suggest $\alpha \approx 1$. In most schemes of ICF the efficiency ε will be of the order of a few percent. Consequently for $G \geq 1$ the burn must be larger than $26\varepsilon^{-1}$. Since it is unlikely that b can amount to much more than 30% a reactor based on volume ignition will have $G < 4$, implying an uncomfortably large circulating power.

A much more favourable scenario is offered by spark ignition. Unfortunately, the usual shock and compression of a spherical target does not produce a well-defined spark – the spark ignition (simulation results) is energetically only about twice as good as a volume ignition. The recently proposed fast-ignition scheme [6][7] is beset by enormous ballistic and beam penetration difficulties – it is unlikely to progress beyond a laboratory demonstration. A more promising approach is based on a spark created in a neck of a dense Z-pinch. The neck is formed as a result of an $m = 0$ instability (*Fig. 1*) starting from an initial small $m = 0$ axial perturbation. The advantage of this approach is that the spark can be programmed to occur at the moment of maximum pinch current at the correct place and time by choosing suitable initial configuration. The disadvantage is that one must provide an initial magnetic flux and the associated current I_0 and that the current rise time t_r must be short, in most cases $t_r < 10$ (ns). The current required for spark ignition [1] is

$$I \approx 10^3 \left(\alpha_d \cdot \frac{n_s}{n'} \right)^{1/2} \kappa^{-1} \text{ (MA)} \qquad (2)$$

where n' is the density and $T_d = 10^8 \alpha_d$ the detonation temperature in CH. The magnitude of I in realistic experiment will be of the order of 20(MA) which implies $\dot{I} \geq 10^{15}$(MA/s). Considering the short t_r's required, it seems that the direct use of present day megampere generators [8][9] is inadequate and the only possible means for getting $\dot{I} > 10^{15}$(A/s) is the compression of a B_φ-flux of a Z-pinch by a fast imploding liner (*FIG. 2*). This is a complicated problem and we shall discuss it in the two following sections.

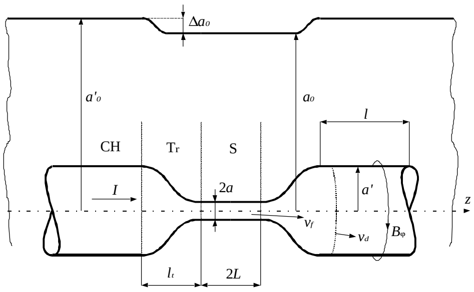

FIG. 1. Sketch of a D-T spark..

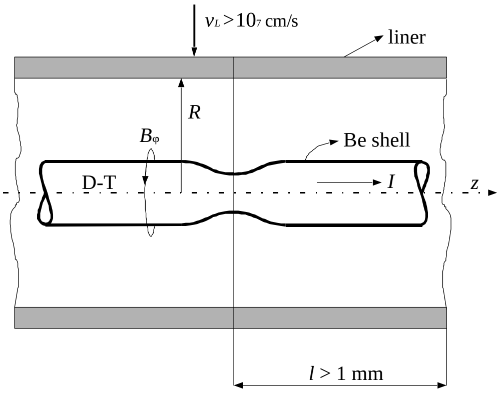

FIG. 2. Implosion of cylindrical liner on a Z-pinch.

2. Liner implosion on an axially uniform pinch

This is essentially a 1-D problem and can be treated on two levels. The first one corresponds to a 0-D formulation in which the liner has a given mass per cm length and an initial speed v, zero thickness and is superconducting, the pinch is compressed adiabatically, is isotropic with no energy loss and no Joule eating. This has been treated in several publications [2][3][4][5], the results are useful only as examples for comparison with the more realistic 1-D and 2-D results of numerical simulation. There will be several classes of phenomena not taken into account in the 0-dimensional treatment. An analytical extension of 0-D, taking into account these effects is impossible – one has to resort to 1-D numerical simulation. The numerical simulation uses the usual MHD 2-fluid equations with diffusion coefficients applicable to hot, dense plasmas. Initially the liner is assumed to be thin and a perfect conductor, later, we use the same set of equations also for a plasma liner having a simple, artificial but not unrealistic EOS. Let us now examine pinch compression effected by a liner of finite thickness. We have modelled the liner as an Ag plasma whose degree of ionisation α_i follows from

$$\alpha_i \cong 10^{-2} \sqrt{T_L} \qquad (6)$$

Where T_L is the local liner temperature (here $T_i \approx T_e$) and the ionisation energy $W_i = qkT_L = 3kT_L$. In most cases we have assumed that initially the Ag plasma resembles an exploded Ag foil whose thickness $d_{L0} = 100\ \mu\text{m}$ and $T_{L0} = 5 \div 15$ eV. However, we have verified, *a posteriori*, that at maximum compression the state of the Ag liner (i.e. $T_L(r)$ and $\rho_L(r)$) is almost independent of the initial liner conditions. For computational commodity and to provide some energy transfer between the liner and the pinch we have assumed the space between to be occupied by a thin plasma whose total mass per cm length is negligible as compared with that of the pinch.

Ex. a: The radius of the pinch $a(t)$, the inner edge $R_1(t)$ of the liner and the current $I(t)$ are shown in *FIG. 3a*, the T_e, T_i and ρ on the axis in *FIG. 3b*. Only the time interval of 9.2 to 10.2 ns is displayed. At t = 10.2 (ns) the T_e, T_i and ρ are almost uniform except in the δ_J skin (*FIG. 4a*). The ρ, T and B distributions in the liner at 10.2 (ns) are seen in *FIG. 4b*. The maximum current reaches 8 (MA), the efficiency $\varepsilon_p = \left(\frac{W_p}{W_{k0}}\right)_{max}$ at t = 10.2 (ns) is 22.7%.

Only about 35% of the total M_L is effectively involved in the compression. The rest of M_L, i.e. 0.65 M_L arrives later and slows down the expansion of the pinch. The compression and expansion have, therefore, different effective times, the expansion being substantially longer. The W_α is almost 10^{11} (ergs/cm) which is a sizeable fraction of W_p (= $4.2 \cdot 10^{11}$ ergs/cm) and represents an output of $1.78 \cdot 10^{16}$ (neutrons/cm). It is clear that we have not reached a volume ignition, but are not too far from it. In order to reach a volume ignition with an extended (thick) liner we have tried to start with T_0 = 200 eV and/or to increase M_L and/or start with higher $a_0/R_0 = x_0^{-1}$. All these changes have resulted in ignition with various degrees of burn. The most effective and natural among these alternatives was the increase in a_0/R_0. Let us now compare a case in which a_0 = 738 μm, M_L = 20 mg/cm, with Ex. a, all other parameters being equal.

Ex. b: The initial total flux ϕ_t is 1.9 times smaller than in a) and the vacuum flux ϕ_v disappears earlier, i.e. the liner and pinch touch each other earlier in b) than in a). The most important feature is that at 9.5 ns the $T_i \cong 8.6$ keV, well above the ignition temperature (*FIG. 5a,b*). In ex. a) at the same time $T_i \cong 5.2$ keV. Consequently the pinch ignites well before the maximum compression (a_m = 36 μm at t_m = 9.8 ns) and reaches $T_{I\,max} \cong 21$ keV, 200ns after t_m. This results in a considerable fusion output, in fact $W_\alpha = 2 \cdot 10^{12}$ erg/cm, and the burn b ≅ 5% and G = W_f/W_k = 2.5.

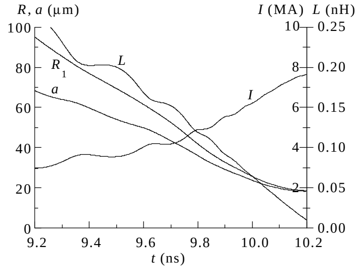

FIG. 3a. R_1, a and I for a thick liner implosion.

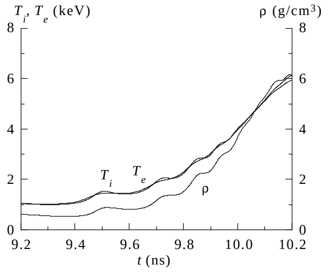

FIG. 3b. r, T_i, T_e on axis corresponding to case of Fig. 3a.

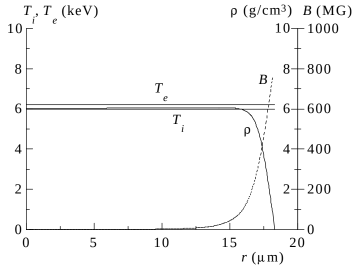

FIG. 4a. r, T_i, T_e and B at t = 10.2 ns corresponding to case of Fig. 3a.

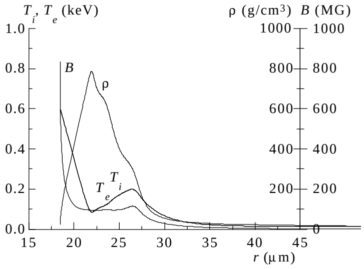

FIG. 4b. r, T_i » T_e and B in the liner at t = 10.2 ns.

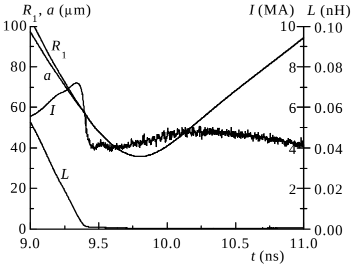

FIG. 5a. R_1, a and I for a_0 = 738 mm.

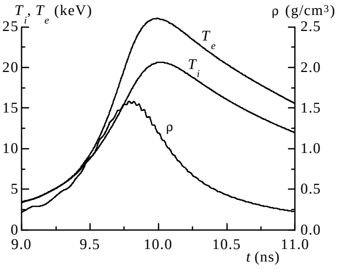

FIG. 5b. r, T_i, T_e on axis corresponding to case of FIG. 5a.

This would indicate that the larger a_0/R_0 the better the compression efficiency. We have performed simulations with $a_0/R_0 > 0.37$ and found ignition scenarios even better than the case b), however, beyond $a_0/R_0 = 0.8$ the situation deteriorates as ϕ_t becomes small and the B_φ ceases to isolate thermally the pinch from the heavy liner. It is clear that analysis and simulation based on the ideal, thin, superconducting liner is misleading. Considering a realistic, extended plasma liner one must start with $T_0 > 100$ eV and optimise the a_0/R_0 ratio in order to obtain ignition.

3. The *m* = 0 spark and the 2-D model

In the case of a spherical pellet compressed by an ablation driven pusher we have mentioned that the gain corresponding to a central spark ignition is not much greater to that of volume ignition. This is the main reason why recently a lot of interest is directed towards the so-called "*Fast Ignitor*". The version of this concept based on an $m = 0$ necking of a Z-pinch has been described in previous publications [10][11]. Here we shall address ourselves to a Z-pinch spark generated by a liner implosion. There are at least two possibilities of achieving it. The first method is depicted in *FIG. 6*. It is hoped that an initially correctly perturbed Z-pinch will develop an $m = 0$ instability producing a minimum radius neck at the moment of maximum compression by the liner. Ideally the initial magnetic flux ϕ will be then concentrated around the neck, resulting in a current amplification

$$\frac{I_m}{I_0} = \frac{L}{l}\frac{\ln\left(R_0/a_0\right)}{\ln\left(R_m/\langle a\rangle\right)} \tag{7}$$

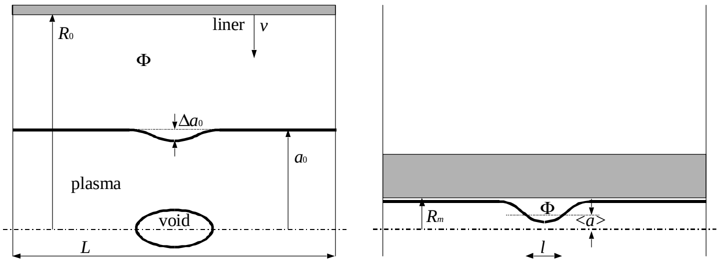

FIG. 6. Formation of a pinch neck from an initial small m = 0 perturbation.

It can be shown that in this case a sufficiently strong spark can launch a detonation wave in the plasma cylinder ($a \approx R_m$) adjacent to the neck. The liner-energy required for such a spark-ignition is considerably less than that necessary for a volume ignition. Of course, the plasma compression by the liner will not be as simple as anticipated in *FIG. 6* and one needs, therefore, an investigation based on a 2-dimensional simulation. The second method of creating a Z-pinch neck is to implode on a uniform Z-pinch a cylindrical liner with a larger central mass per unit length M (*FIG. 7*). If the initial implosion speed v is the same for all z, such non-uniformity in M implies a larger η in the centre and consequently, smaller a_m and higher T_m (eq.5). Preliminary 2D calculations using the above configurations show that if the liner energy is high enough and the initial $m = 0$ perturbation is correctly chosen, the final neck plasma can act as a spark for D-T ignition. The main difficulty is to match the plasma and liner parameters in order to get maximum magnetic flux around the $m = 0$ instability at the time the spark conditions are met.

4. Conclusions

A liner whose $M_L = 10$ mg/cm, speed $v = 2 \cdot 10^7$ cm/s and length 4 mm appears to be capable to produce a Z-pinch spark and detonation in an adjacent high density, low temperature DT channel. The burn may be as high as 10%, the fusion gain $G = W_f/W_k \approx 1000$. The total W_k required is only 80kJ. Of course, in order that such a Z-pinch be of interest for fusion reactors the efficiency with which the liner energy W_k is furnished is of great importance. This is the main problem of energy transfer and staging and cannot be affronted here [12][13].

Let us mention, however, that the obvious extrapolation of the ideas presented here must go towards a possibility of using the fusion detonation in DT to trigger a much more substantial ignition of a volume of advanced fuel (D, D-Li, D-He^3). This has been attempted in [14].

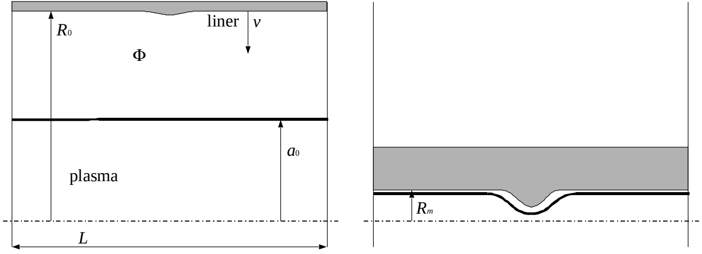

FIG. 7. Formation of a pinch neck by a non-uniform liner impact.

Finally, let us not forget that fusion ignition (volume or spark) has not only the fusion reactor as an application. At much smaller outputs it can be an efficient neutron source, of interest e.g. for sub-critical fission reactors. At large outputs it could be a source of energy for space ship propulsion.

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