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Temperature and Velocity Estimation of the Implosion in Wire Array Z-Pinch

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Abstract

Z-pinch nuclear fusion system is the mechanism of creating nuclear fusion by magnetic confinement method. In this paper, temperature and velocity of implosion is estimated. By introducing a proper model, the parameters of Z-pinch are estimated and calculated and then the introduced model is confirmed by using experimental data of Sandia lab. At the end, by comparing these two models and the experimental results, the validity of the model is investigated. In practice, all estimates based on assumptions are often correct only within the order of parameters magnitude.

Keywords: Confinement magnetic; Wire array; Dynamic Z-pinch; Implosion velocity

Introduction

A Z-pinch is a column of plasma in which current is driven in the axial (z) direction producing an azimuthal magnetic field that confines the plasma. In experiments using Z-pinch, when the wire arrays imploded and turned into gas, immediately pinch occurred. Pinch plasma response to the applied current at first seems simple, but in spite of the simplicity, complexity is. Pinch understanding is difficult to understand qualitatively let alone quantitatively [1].

Bright spots may appear in dynamic Z-pinches in the low implosion velocity. Soft x rays are emitted mainly from these spots. The amount and spectra of this radiation is very sensitive to the dynamics of the implosion. Many physical models are described Z-Pinch that each of them may be appropriate to describe a specific Z-pinch. Choice of a proper model is sometimes very difficult. In this paper, by using simple physical concepts and matching with the selected model, we tried to introduce an appropriate model for Z-pinch. Our aim in this paper is to verify the model that was presented previously in 1980 by Hussey et al. In the following, calculations of the temperature and implosion velocity of Z-pinch are presented.

First model: A simple theoretical model

Consider a wire-array liner which made of wires. Electric current that passes through the wire, a magnetic field is created around it that can be calculated. An electromagnetic force ($\vec{J}\times\vec{B}$) is applied to each wire. In this way, we can compute the external magnetic field around the liner, with assumption: the field was created by wires with infinite length that is not the reality. So, this calculation only gives some order of magnitude.

Some evidence of a helical m=1 unstable kink mode at late times in the discharge, but it does not appear at stagnation. The time of stagnation, mainly long wavelength m=0 modes can be. Calculations and estimation at the confining time is difficult because of the pressure and field gradient [1,2]. But, these gradients are not at stagnation and equations become easier. So, all calculations were performed for stagnation moment. Figure 1 shows the configuration of Z-Pinch at the stagnation.
So for Magnetic field can be written [3]:

$$B = \frac{\mu_0 I}{2\pi r} \quad (1)$$

Where B is magnetic field, r is pinch radius and I is current passing through.

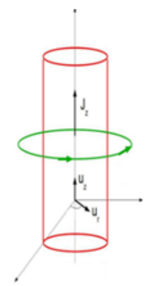

Figure 1: Z-pinch configuration.

If n is the number of wires, electric current that passes through each wire is equal to I / n. using the Lorentz force are:

$$\frac{I}{\pi n} B = \frac{\mu_0 I^2}{2\pi n r} \quad (2)$$

If M, is the mass per unit length of the wire, we have:

$$a_{rB} = -\frac{\mu_0 I^2}{2\pi r M} \quad (3)$$

Where a_{rB} is radial acceleration due to the Lorentz force, replaced wires by plasma cylindrical that an electric current passes through it. Plasma pressure is sufficient to balance magnetic pressure at stagnation.
Ion pressure is equal to:

$$P_i = n_i k T_i \quad (4)$$

Where k is Boltzmann constant, Ti is the ion temperature and n_i is the number of ions per unit volume.
The pressure force acting on each plasma cylindrical per unit length is:
The equation of motion is as follows:

$$\frac{M}{n} a_r = -\frac{\mu_0 I^2}{2\pi n r} + n_i k T_i \frac{2\pi r}{n} \quad (5)$$

Where a_r is radial acceleration and $n_i = N_i / \pi r^2$, yields:

$$a_r = -\frac{\mu_0 I^2}{2Mr} + \frac{2N_i k T_i}{Mr} \quad (6)$$

Where N_i is the number of ions per meter.
Since the temperature varies over time, we cannot get it at all times. But the acceleration is zero at stagnation. So, the temperature can be estimated at stagnation:

$$T_i = \frac{\mu_0 I^2}{4\pi N_i k} \quad (7)$$

If V is the radial velocity of ions at stagnation condition, we have:

$$\frac{1}{2} m_i V^2 = \frac{3}{2} k T_i \quad (8)$$

K is Boltzmann constant, Yields:

$$V = \sqrt{\frac{3kT_i}{m_i}} \quad (9)$$

Note: 30% of the mass lost during the implosion that should be considered in the calculations [4].

Second model: Thin shell model, an appropriate model for predicting the kinetic energy, speed and time of explosion
Dynamical properties of the pinch implosion can be computed reasonably in the thin shell model. In this model, the imploding plasma is assumed in the form of a very thin layer with cylindrical symmetry and the radial position of the plasma shell is defined as a function of time, linear density of mass and acceleration which is determined by the Lorentz force.
The equation of motion the shell of radius R(t) is [1]:

$$\mu \frac{d^2R}{dt^2} = \frac{I^2(t)}{Rc^2} \qquad (10)$$

Where μ is the mass per unit length of the shell.

With the integration of the above equation for $I = I_{\max}$ and with initial conditions $R(0) = R_0$, $\dot{R}(0) = 0$ we obtain:

$$\frac{dR}{dt} = \frac{R_0}{\tau_A}\sqrt{2\ln\left(\frac{R_0}{R(t)}\right)} \qquad (11)$$

$\tau_A = c\mu^{1/2}R_0 / I_{\max}$ is the Alfvèn transit time.

The next equation is circuit equation. Z-pinch equivalent circuit is as follows (Figure 2):

$$(R_0 + R_P)i + \frac{d}{dt}(L_0 + L_P)I - \frac{1}{C}\int Idt = 0 \qquad (12)$$

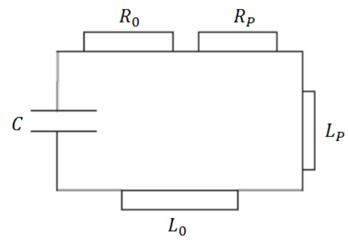

Figure 2: Z-pinch equivalent circuit.

Where R_0, L_0 are respectively the resistivity and inductance of the circuit. R_P and L_P are respectively the resistivity and inductance of the plasma and C is capacitance.

$$L_P = \frac{\mu_0 z_0}{2\pi}\ln(\frac{r_0}{r_P}) \qquad (13)$$

Where r_0 is the initial radius of plasma and z_0 is the length of Z-pinch

Evalution of the two models and comparison with the experimental data

Except Sandia, some other countries such as Germany, Spain [5], and France and more recently in Egypt [6-8] on devices with different energy, 10 kJ and 5 kJ, activities have taken place. But the laboratory Z Pinch apparatuses are much smaller than the Z machine in Sandia.

Substituting into above relation the parameters of Z Pinch experiments with the 30TW Saturn accelerator, one of drivers at Sandia National Laboratories (1989) $I_{\max} = 10MA$, $\mu = 5\times10^{-4} g/cm$ we obtain (Table 1):

	First model	Second model
Velocity (km/s)	1170	900
Temperature (keV)	279	163

Table 1: Parameters of Z Pinch experiments (1989).

Substituting into above relation the parameters of Z machine, one of the most powerful drivers at Sandia National Laboratories (2006) $I_{\max} = 18MA$, $\mu = 4.5\times10^{-5} kg/m$ we obtain (Table 2):

	First model	Second model
Velocity (km/s)	1715	1600
Temperature (keV)	593	516

Table 2: Parameters of Z machine experiments (2006).

The velocity are in both models very close together, Shows, These formulas are suitable for devices with wire arrays. The formulas and estimates, is only an estimate and it is possible, in practice, the measured parameters are less than the estimated values or vice versa. This calculation applies only for Z Pinch devices with wire arrays [9,10]. Figures 3 and 4 show the results of the two models using parameters Sandia Laboratories in 1989 and 2006. The results are in reasonable agreement with the experimental data.

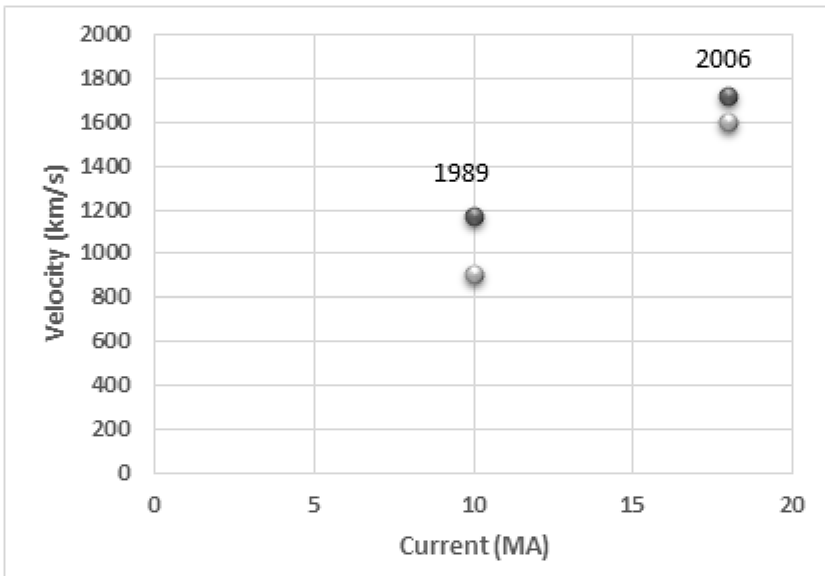

Figure 3: The changes of implosion velocity with respect to current; dark points: first model, light points: second model.

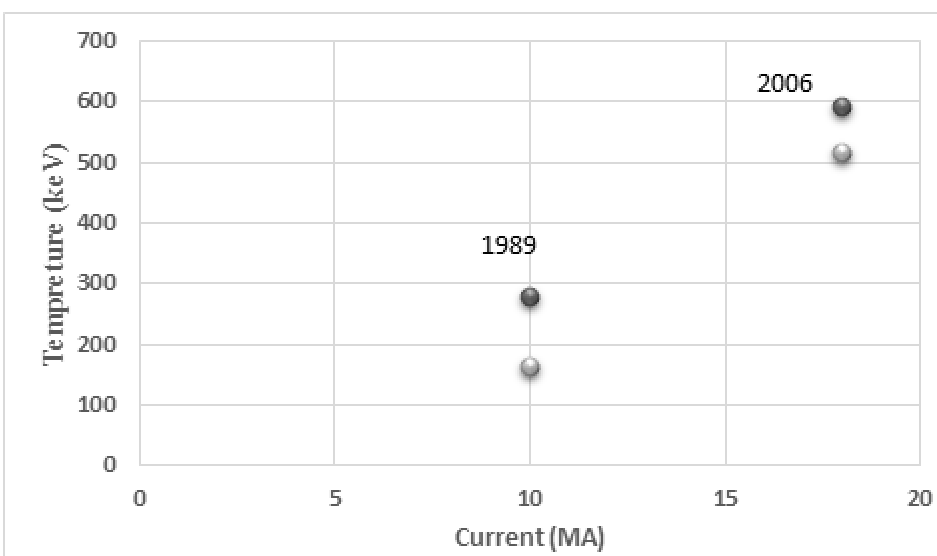

Figure 4: The changes of implosion temperature with respect to current; dark points: first model, light points: second model.

Conclusion

For the design of systems and devices, physics of them must be recognized. Obviously, without sufficient knowledge of the physics of the system or Trial and error method to achieve an optimum design, just waste time and money. Disregarding the physical issues in the design of systems, especially in the fusion systems, it may endanger the safety of people and expensive equipment. Attention to this equation and using them to predict and estimate the parameters of the device play a fundamental role in the optimization, will increase the efficiency and safety systems. In this paper, by using simple physical concepts and matching with the selected model, we tried to introduce an appropriate model for Z-pinch. In Z-pinch devices, it is difficult to calculate and obtain the equations. In practice, all estimates based on assumptions are often correct only within the order of parameters magnitude. Therefore, they are convenient and, therefore, conventionally used. Since, thin shell model is a proper model, in the future, can numerically solve equation (11) and (12) and obtain the pinch radius at every time of confinement. Of course, we must thank Mr. Jean-Pierre Petit (French scientist, senior researcher at National Center for Scientific Research as an astrophysicist in Marseille Observatory, now retired) that we used some of his analysis in this paper.

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