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MHD Simulation of X-pinch plasma dynamics

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Abstract

The development of X–pinch plasma dynamics is investigated by means of numerical modeling. The simulation is based on 2 dimensional MHD for a fully ionized plasma. According to our model, plasma streams along the z–axis are formed which are further amplified by plasma originating from the legs of the X-pinch. The influence of the gas pressure in the chamber in relation to the neck formation is also investigated.

Introduction

Pinch devices consist of an electric pulse forming line and a number of thin wires attached between two electrodes. The simplest possible geometry is that of a single wire, the so called Z–pinch [1]. Initially, the wire is heated up until it becomes a column of plasma, which then continues to drive the current along the axial direction. An azimuthal magnetic field is created along with a $\mathbf{J}\times\mathbf{B}$ force, which not only confines the plasma but is also responsible for the appearance of sausage/kink instabilities. Even this simple configuration exhibits intriguing plasma dynamics, making it an interesting physical experiment in its own right. Moreover, pinch devices are interesting for technology and in particular for controlled fusion, as they currently appear to be the most powerful and cost efficient X ray sources available [3].

There are several configurations which utilise more than one wire and depending on their geometry, they may be divided into two categories. The first includes all cylindrical configurations, e.g. when two or more wires are placed parallel to each other in between the electrodes, or the more sophisticated nested [2] array Z–pinch, where a number of wires are distributed on the surface of two coaxial cylinders. Wire array Z–pinches aim to enhance soft X ray production. Nowadays cylindrical wire arrays are capable of converting electrical energy into X rays with efficiency as high as 18%. The second category consists of all X shaped configurations. The simplest X–pinch [5] is that of two wires crossed in a way such that an X is formed between the electrodes. A two wire X–pinch is a special case of a multi-wire X–pinch, where a number (>2)

of wires are distributed on the surface of a double cone. Compared to Z–pinches, X–shaped configurations exhibit richer dynamics. Moreover, X–ray emission is much more advantageous: in addition to the $m = 0$ instability that act as bright spots along the legs of the X–pinch, an intense pointlike source is formed at the crossing point which dominates the X–ray emission. The resulting X ray pulse is reasonably reproducible regarding its intensity, emission time and physical location. All these properties are indeed necessary for the backlighting needed in hot dense plasmas diagnostics.

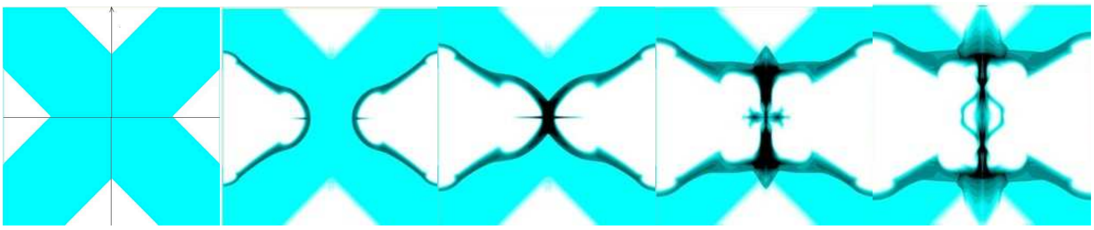
Regarding the dynamics of the pinching process, is not fully understood. Numerical simulations [4] have been proven to be a powerful tool for understanding the dynamics of hot dense plasmas. Wire implosions are physically divided into two successive but distinct phenomena: the phase transition from solid to plasma, followed by the pinching process. However, as we currently lack of a concise theory of phase transitions, simulations of pinching processes usually omit the first stage, starting directly from the fluid state. Ideal or resistive MHD is usually employed as a theoretical framework for simulating wire pinches. As computational complexity increases severely with the number of dimensions, Z–pinches are much easier to simulate due to cylindrical symmetry. However, there exist certain features such as the kink mode instability, which are intrinsically three dimensional. X–pinches are also three dimensional by nature and therefore their simulation requires complex and time consuming methods. Despite the latter, we will argue below that if one focuses on the dynamics of regions close to crossing point, rotational symmetry may be retained.

Description of the model

Our model [6] is based on ideal one fluid 2D MHD equations in Euler coordinates under the equal temperature assumption, i.e. $T_i = T_e = T$. Once the number density and the temperature are retrieved, the Bremsstrahlung radiation power loss may be calculated from $P_B \sim \int T^{1/2} d^3\mathbf{r}$, where the proportionality factor depends on whether Coulomb collisions are treated classically or quantum mechanically. In any case it scales like the square of the charge number of the ions (Z). Our code originally aimed at simulating systems with perfect cylindrical symmetry. However, the topic of this work is the X–pinch, which, at first sight, is far from being axially symmetric. On the other hand it is known that the dynamics at least in the neighborhood of the crossing point does not depend on the number of wires used: the same dynamical structures (e.g. neck, axial jets) appear, no matter if the wires are only two or more, densely distributed on the surface of a double cone. The latter geometry exhibits, to a certain extent, cylindrical symmetry which becomes more exact as one approaches the crossing point. This is an indication that, at least qualitatively, the dynamics of the crossing point does not depend on the azimuthal coordinate, thus resulting in cylindrical symmetry for this particular region. That was the first motivation to use our 2D code for a two wire X–pinch, simply by changing the initial conditions. Although the results are reasonably consistent with experimental data, there are certain drawbacks in our approach. First, the model does not take into account the phase transition from solid to liquid, but it rather starts with a perfect one–fluid distribution. Second, radiation losses are not incorporated in the model as a cooling mechanism. However, as our X–pinch device operates at low currents ($\sim 40-60$ kA), the absence of radiation cooling is not expected to have significant influence on the physical picture.

Results

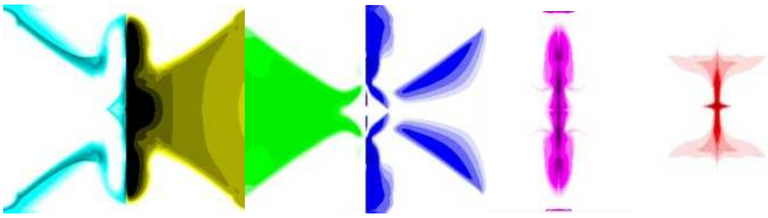
For reasons explained above, we focused on the dynamics of the crossing point and in particular, on a region within a radius of 2mm around it. This is sufficient to study the formation of the so called neck of the the X–pinch, a structure which looks like a miniature Z–pinch. In figure 1, frames of the plasma density are shown in sequential order, starting



(a) $t = 0$ns (b) $t = 60$ns (c) $t = 65$ns (d) $t = 70$ns (e) $t = 80$ns

Figure 1: Frames of plasma density evolution. Darker areas represent denser plasma

from the initial plasma distribution. The first observation is that compression starts long enough after the beginning of the discharge. Both ∇P and $\mathbf{j}\times\mathbf{B}$ forces are large at the ends of the developing neck and negligible at the center and therefore, mass located in the middle of the neck stops collapsing. The axial length of the neck becomes much larger than its radius and ultimately, two smaller collapsing necks begin to form at the ends of the primary neck. As for the axial plasma jets, the most commonly accepted mechanism for their generation is due to the formation of the neck. However, from our simulation there is evidence that two more factors may be important. First, plasma originating from the lower parts of the legs, which finally converges to the z–axis and second, poor vacuum in the chamber. Residual low pressure gas may drive part of the current and become plasma, which also converges to the axial direction. A secondary effect of gas presence in the chamber is that the current that goes through the wires becomes smaller, an effect that is more prominent at low current devices. However, all these issues are currently speculations and as such, they must be further investigated. An interesting feature is the formation of a rhombus–like structure at the center of the neck, that emerges



(a) B (b) $v_r - v_z$ (c) T (d) P_B

Figure 2: Profiles of various quantities of interest 80 ns after the discharge: (a) plasma density – magnetic field, (b) Current, (c) radial/axial velocity, (d) plasma temperature and (d) Bremsstrahlung power.

relatively late after the beginning of the discharge. This structure becomes evident not only from the plasma density profile, but also in the current profile (Figure 2b), where we observe that current flows around the border of the rhombus, as well as in the velocities profile (Figure 2c) where it appears that plasma inside this area is stationary.

Conclusions

A two dimensional MHD simulation of the area close to the crossing point of a two wire X–pinch has been carried out. Although the latter is seemingly a three dimensional system, our modeling is consistent with experimental experience. It is proposed that the neck of the X–pinch is amplified from plasma originating from the parts of the legs close to the cross point and that poor vacuum may further amplify the neck as well as reduce the current that goes through the wires. An interesting rhombus–like area of stationary plasma has been observed in the middle of the neck.

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