Effect of Neutral Atoms on a Capillary-Discharge *Z* Pinch

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We study the effect of neutral atoms on the dynamics of a capillary discharge *Z* pinch, in a regime for which a large soft-x-ray amplification has been demonstrated. We extended the commonly used one-fluid magnetohydrodynamics model by separating out the neutral atoms as a second fluid. Numerical calculations using this extended model yield new predictions for the dynamics of the pinch collapse, and better agreement with known measured data. [S0031-9007(99)09000-6]

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Z-pinch collapse has been extensively studied since the late 1950s, being a simple and effective way of producing hot and dense plasma. In this process, an electric current flowing through a plasma column interacts with its self-magnetic field, and the resulting force contracts the plasma column in the radial direction. Today *Z*-pinch plasma is widely used for various applications such as high power radiation sources and neutron sources [1,2]. An exciting new application of *Z*-pinch plasma was recently demonstrated by Rocca *et al.* [3–5]. In this work, large amplification of soft-x-ray light was obtained in Ne-like Ar and S plasma, created by a fast ($\sim$40 ns) *Z*-pinch discharge inside a capillary. Compared with the alternative approach of laser driven excitation [6,7], the capillary discharge has the advantage of allowing for compact (*tabletop*), efficient, and simpler soft-x-ray lasers.

In this paper we study the role of neutral atoms in the dynamics of a capillary discharge *Z* pinch, in the regime for which soft-x-ray amplification was demonstrated. The commonly used one-fluid *magnetohydrodynamics* (MHD) model assumes that all the particles in the plasma are charged, and drift together. We, however, show that for the case discussed here, large portions of the plasma contain an appreciable amount of neutral atoms. Since these are not affected by the electromagnetic forces, but only by the much weaker mechanical forces, they flow with much smaller velocities than the ions and the electrons. To account for this effect, we extend the one-fluid MHD model by introducing a separate fluid for the neutral atoms (in addition to the standard electrons-ions fluid). Results of calculations using this extended model give new predictions for the dynamics of the pinch collapse, with some features in better resemblance with the measured data. This confirms our previously reported estimates [8].

We start with the standard one-fluid two-temperature MHD model, commonly used for numerical calculations of *Z*-pinch processes [9–13]. It considers hydrodynamic flow including shock waves, heat conduction, heat exchange (between ions and electrons), magnetic field dynamics, magnetic forces, Ohmic heating, radiative cooling, and ionization. We use a simple ionization model, and assume a quasi steady state, taking into account collisional ionization, and two-body and three-body recombination. Since the plasma is assumed to be optically thin, ionization and excitation by radiation are neglected. The latter assumption should hold at least to the end of the collapse. This model is incorporated into our numerical code, SIMBA, where the equations of motion of the system (see [9–14]) are solved in a Lagrangian mesh [15], assuming one-dimensional axial symmetry.

Shown to be remarkably stable [16], and having a high length-to-diameter ratio (of 50-500), the capillary discharge *Z*-pinch experiment is naturally described in the framework of this 1D MHD model. Previously reported works [10] have indicated that taking into account ablation of the plastic capillary wall is necessary for the correct description of the pinch dynamics. According to this, the calculation should thus be extended to include a narrow region of the plastic capillary wall. However, it was also shown in [10] that even with this effect taken into account, good agreement with the measured data still requires some major *artificial adjustments* of the plasma transport coefficients. We have repeated these calculations using the same one-fluid MHD model, and found them to agree with the reported results. In particular, we also find that the measured data is reproduced by one-fluid MHD calculations only when artificial adjustments are introduced, as demonstrated in Fig. 1. The figure displays the calculated radius of the collapsing Ar plasma as a function of time in a capillary discharge *Z* pinch. The parameters of the calculations are those used for soft-x-ray amplification experiments [3,4,10]: initial Ar density of $\rho_0 = 1.7 \times 10^{-6}$ g/cm^3 or $n_0 \approx 2.5 \times 10^{16}$ atoms/cm^3, initial temperature of $T_0 \approx 0.5$ eV, and a maximum current of 39 kA, with its peak at $t = 32$ ns [17]. The figure also presents some measured data, of the radius of soft-x-ray source, as a function of time, taken from [10]. Since the radii of the soft-x-ray source and that of the collapsing Ar plasma are related, it is clear that there are disagreements between the calculated and measured data: For example, the calculated pinch peak is about 10 ns earlier than the measured one. It is shown in Fig. 1 that multiplying the classical electrical conductivity [18] by a factor of 15 results in a good agreement with the measured instant of the pinch peak; however, at the same

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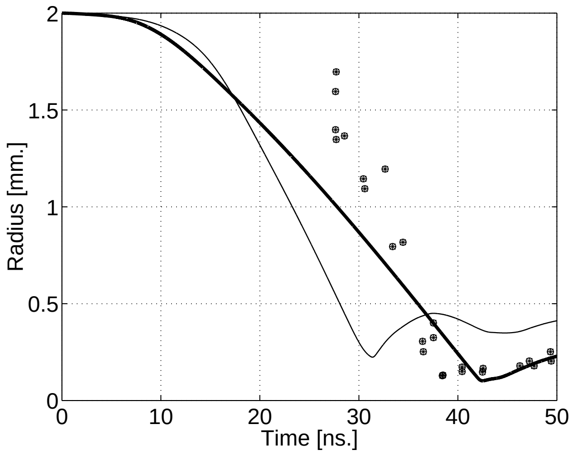

FIG. 1. Z pinch of Ar plasma inside a plastic capillary. Thin line: Calculated outer boundary of Ar plasma, assuming classical electrical conductivity. Thick line: Calculated outer boundary of Ar plasma, with a factor of 15 on the classical electrical conductivity. Dots: Measured radius of soft-x-ray source [10].

time it also spoils the agreement with measured collapse velocity. We notice that both calculations do not properly reproduce the initial stages of the collapse, which is delayed by about 10–15 ns. According to [10], reproducing the whole stages of the measured collapse requires more artificial adjustments in the plasma transport parameters, up to 20–40 times their classical values. This need for artificial adjustments of plasma parameters in one-dimensional one-fluid MHD calculations cannot be explained by two- or three-dimensional effects in the modeled experiment: The work of Bender *et al.* [16] has proven a perfect azimuthal (ϕ direction) symmetry in this *same* capillary discharge Z pinch, and the demonstrated amplification gain [3–5] indicates a very good Z direction symmetry.

In order to better understand the dynamics of the pinch collapse, we have focused our study on the importance and the role of neutral atoms in this process. The one-fluid MHD model assumes that the plasma consists of two components: electrons and *effective* single-type ions, with their charge being the average charge of all the differently charged ions in the plasma, including the neutral atoms. In addition, these two components are assumed to flow together, as a single fluid. These assumptions are reasonable for regimes for which at least one of the two following conditions is fulfilled: (i) All the atoms in the plasma are ionized, or (ii) the neutral atoms are strongly coupled to the charged particles, and hence follow them in the same single fluid.

Figure 2 presents the percentage of neutral atoms as a function of electron temperature in argon plasma, based on our ionization model. According to this figure, a plasma of electron temperature lower than 2–3 eV contains an appreciable amount of neutrals. In carbon plasma, which is a typical representative of the ablated capillary wall, the picture is similar. Our MHD calculations show that the Ar plasma starts to heat up above 2–3 eV only 5 ns after the beginning of the pinch, and its central region stays below this temperature for the next 25 ns [8]. Major portions of the plastic wall plasma remain below 2–3 eV even after the pinch collapses at the axis. The percentage of neutral atoms in the plasma is hence far from being negligible. We thus conclude that condition (i) does not hold. The plasma contains three different components: electrons, ions, and neutral atoms. We now turn to check whether or not condition (ii) is satisfied, by examining the couplings between these different ingredients of the plasma. The electrons and ions, being charged particles, are coupled through Coulomb forces. A measure of the strength of this coupling is given by the plasma frequency, ω_P. For the case discussed here, $1/\omega_P \approx 10^{-5}$–$10^{-3}$ ns, which is negligible compared to the typical pinch collapse times of $\tau_{\text{pinch}} \approx 40$ ns. This means that the coupling between the electrons and ions is very strong, and that they practically drift together, as a single fluid. The neutral atoms, however, are coupled to the charged particles only by collisions, and may thus flow separately, as a second fluid. We therefore assume two fluids, one of *charged species* (electrons and ions) and the other of *neutral species* (atoms), with flow velocities u_i and u_a, respectively. The collisional momentum transfer between these two fluids is evaluated assuming a hard spheres approximation: We regard the two fluids as two clouds of hard spheres, drifting through one another. In that case, the collision frequency per unit volume equals

$$\nu_{ai}^{\text{coll}} = \alpha r_a^2 n_a n_i |u_a - u_i|, \qquad (1)$$

and the collisional momentum transfer rate, per unit volume, is thus

$$F_{ai}^{\text{coll}} = \alpha r_a^2 m_a n_a n_i |u_a - u_i| (u_a - u_i), \qquad (2)$$

where α is a coefficient of about 2π. Here r stands for the particle radius, m for its mass, and n for the number density. The indices a, i denote atoms and ions, respectively. Later on we will use the index e for electrons.

The force in Eq. (2), F_{ai}^{coll}, depends quadratically on the velocity difference between the charged-species and

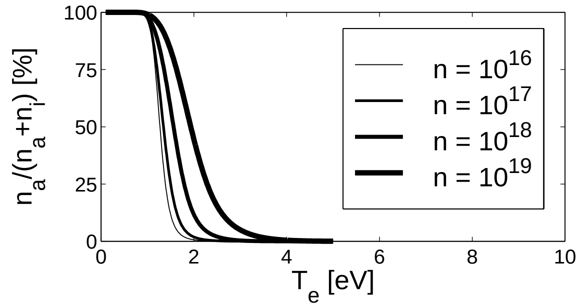

FIG. 2. Percentage of neutral atoms in Ar plasma, as a function of electron temperature. Each line corresponds to a different plasma density.

the neutral-species fluids. This coupling thus restrains the separation between the two fluids. Taking reasonable densities of $n_a \approx 10^{16}$, $n_i \approx 10^{15}$ (10% ionization), and an appreciable velocity difference of $|u_a - u_i| \approx 10^6$ cm/s, we get for Ar plasma a collisional coupling term of the order of 10^6 dyn/cm^3. This is 2–3 orders of magnitude less than the estimated magnetic ($\vec{j} \times \vec{B}/c$) and hydrodynamic (∇P) forces.

We conclude that in the regime discussed here, both of the above conditions for the validity of the one-fluid MHD fail to be satisfied. The two fluids are indeed expected to flow separately. However, they exchange mass, momentum, and energy due to exchange of particles (by ionization and recombination) and due to atoms-ions collisions. By $S_a(r,t)$ we denote the mass sink (per unit volume, per unit time) in the neutral-species fluid due to *ionization* of neutral atoms ($S_a \geq 0$). S_a plays a role of a source in the charged-species fluid. Similarly, $S_i(r,t)$ denotes the mass sink in the charged-species fluid, due to *recombination* of ions^{+1} ($S_i \geq 0$). The total mass transfer *from* the neutral-species fluid *into* the charged-species fluid due to ionization and recombination is thus $S_a - S_i$.

To account for the exchange of mass, momentum, and energy between the two fluids the standard one-fluid MHD for the charged-species fluid (see [14], for example) are amended, and new, separate equations for the neutral-species fluid are added. The revised mass equation for the charged-species fluid is then (we use cylindrical coordinates and assume $\frac{\partial}{\partial\phi} = 0$, $\frac{\partial}{\partial z} = 0$)

$$\frac{d}{dt}(\rho_i + \rho_e) + \frac{(\rho_i + \rho_e)}{r}\frac{\partial}{\partial r}(ru_a) = (S_a - S_i), \tag{3}$$

where ρ stands for mass density, and $\frac{d}{dt} \equiv \frac{\partial}{\partial t} + u \cdot \nabla$ is the comoving derivative. The separate mass equation for the neutral-species fluid is then

$$\frac{d}{dt}(\rho_a) + \frac{\rho_a}{r}\frac{\partial}{\partial r}(ru_i) = -(S_a - S_i). \tag{4}$$

The revised momentum equation for the charged species fluid is

$$(\rho_i + \rho_e)\frac{d}{dt}u_i = -\frac{\partial}{\partial r}(P_e + P_i) + \frac{\vec{j} \times \vec{B}}{c} + F_{ai}^{\rm coll} + S_a(u_a - u_i), \tag{5}$$

where P stands for pressure, $\vec{j}$ for current density, and $\vec{B}$ for magnetic field. $F_{ai}^{\rm coll}$ is the collisional momentum exchange between the neutral-species fluid and the charged-species fluid, given in Eq. (2). The momentum equation of the neutral-species fluid should then be

$$\rho_a\frac{d}{dt}u_a = -\frac{\partial}{\partial r}(P_a) - F_{ai}^{\rm coll} + S_i(u_i - u_a). \tag{6}$$

Similarly, the one-fluid MHD ion-energy equation [9–13] is also properly amended, and a separate atom-energy equation for the neutral-species fluid is introduced. Collisions between the two fluids, as well as particles' exchange due to ionization and recombination, are considered in these equations in the same manner as in the mass and momentum equations. The MHD electron-energy equation is left unchanged.

These equations were incorporated into our SIMBA code. For simplicity, and in order to emphasize the effect introduced by separating the neutral atoms from the charged-species fluid, we assume, in the following calculations, that the capillary wall is also made of argon. The other pinch parameters are left unchanged; however, we now use the classical transport coefficients [18], without any artificial adjustments. Figure 3 shows the effect of the neutral-species fluid on the calculated outer boundary of the collapsing Ar plasma. It is clearly indicated that the effect of the neutral component in the capillary discharge Z pinch is not negligible. When the neutral-species fluid is included, the collapse seems to be delayed; however, after it starts it is more rapid. This trend seems to better resemble the data presented in Fig. 1, where it was shown that compared to one-fluid MHD calculations the measured collapse is delayed, and after it starts the collapse rate is much higher.

We have also examined the effect of neutral atoms on the electron density distribution during the pinch. In Fig. 4, the calculated spatial distribution of electron density at time = 25 ns is plotted, with and without the neutral-species fluid. Both models predict a collapsing plasma sheath, and show some ablated material from the capillary wall. However, when the neutral-species fluid is taken into account, the collapsing plasma sheath is wider and less dense, compared to the predictions of the standard one-fluid MHD model.

We like to offer a qualitative explanation for the results presented in Figs. 3 and 4. In the one-fluid MHD model, the atoms and ions are assumed to flow together with the

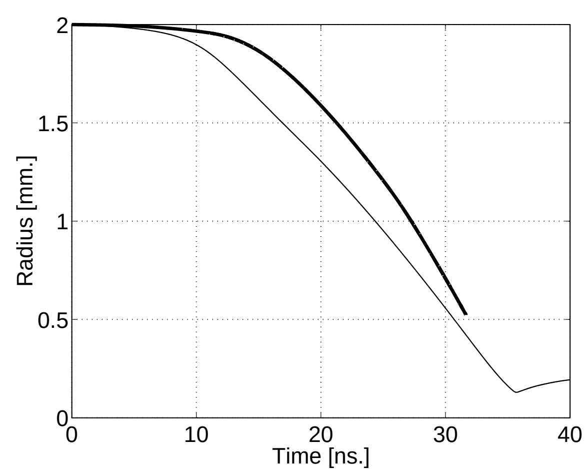

FIG. 3. Calculated outer boundary of Ar plasma during a capillary discharge Z pinch. Thin line: Neutral atoms neglected (standard one-fluid MHD). Thick line: Neutral atoms included (extended model).

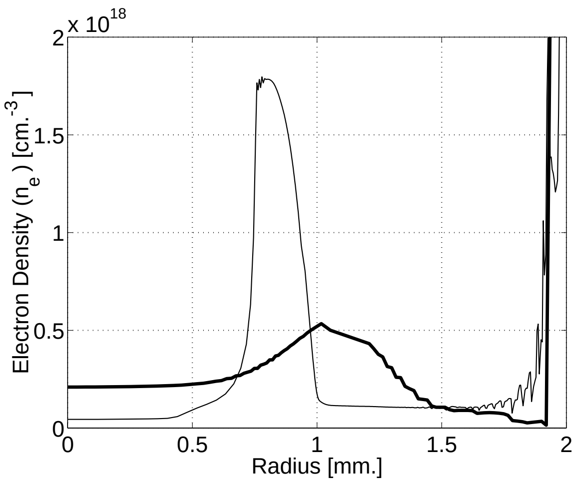

FIG. 4. Calculated electron density profiles at time = 25 ns of an Ar Z-pinch capillary discharge. Thin line: Neutral atoms neglected (standard one-fluid MHD). Thick line: Neutral atoms included (extended model).

electrons. The magnetic forces, which are dominant in this case, thus accelerate the whole plasma body. In reality, however, only the ions flow together with the electrons, while the neutral atoms flow separately. Since the plasma is initially mostly neutral, the magnetic forces act only on a small fraction of the total mass, which is then rapidly accelerated inwards. Most of the Ar stays outside, almost at rest. While the process evolves, more atoms get ionized, and join the charged-species fluid. This effect is seen in Fig. 3 as a delay in the collapse. At any given spatial and temporal point, the magnetic forces act on a "freshly" ionized matter, almost at rest. The resulting acceleration is thus more gradual, leading to a wider and less dense plasma sheath, as seen from Fig. 4.

In conclusion, we have shown that the effect of neutral atoms on the dynamics of the capillary discharge Z pinch is not negligible. We have demonstrated that separating out the neutral atoms as a second fluid produces a different pinch collapse dynamics, with some features similar to the measured data. It is expected that the improved modeling of the pinch collapse dynamics will yield a better understanding of capillary discharge x-ray lasers, since the amplification gain, as well as the propagation and refraction of radiation in the lasing media are both dominated by the details of the plasma state.

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