The Characteristics of Precursor Plasma and its Effects on the Implosion Performance of Wire-Array in Z-Pinch

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The numerical results on the precursor plasma show that there generally exist higher magnetic field and current density in the precursor column, which are enhanced with the increase of electrical conductivity and plasma flow velocity, while weakened with the increase of the diameter of corona and the width of thermalization layer of ablated plasma stream, as well as with the decrease of coronal plasma temperature. The current in the precursor column is about a few tens kA, and about 5~10% of the total current takes the path in the precursor and ablated plasmas at the end of the ablation for the studied current of 3-MA level. They would decrease with the increasing diameter of the corona and the decreasing coronal plasma temperature. In the corona region the magnetic diffusion is dominant, while in the precursor region, especially in the column, the magnetic convection is dominant. The simulated results on the implosion performance reveal that the existence of the pre-filled precursor plasma and the ablated plasma make for the plasma shell pinched and the following implosion after the wire-array ablation, respectively. The implosion started from the ablation seems to develop more rapidly than that from the shells under the same conditions. The more mass of wire-array material has been ablated before its implosion, the better quality of the Z-pinch performance would be.

I. Introduction

It is well known that the instabilities of Z-pinch are suppressed, and in turn the x-ray power output is dramatically increased if a cylindrical foil liner is replaced by a cylindrical wire-array load consisted of many fine metallic wires.[1-3] The main difference between wire-array and foil liner implosions is the appearance of a prolonged wire-array ablation process and the precursor plasma formation in the wire-array Z-pinch. This indirectly demonstrates that the precursor plasma impacts the implosion performance of the wire-array Z-pinch. The most powerful laboratory x-ray source (up to 280TW and 2MJ) on the earth has been come into being on Z machine by imploding a cylindrical wire-array load.[4] That shows the possible application of wire-array Z-pinch in inertial confinement nuclear fusion. So it is theoretically required to understand the characteristics of the precursor plasma and its effects on the following implosion in wire-array Z-pinch.

II. The Characteristics of the Precursor Plasma

During the wire-array ablation, the flowing motion of the ablated plasma is relatively simple. And the magnetic field evolution during the ablation phase of the wire-array Z-pinch is highly concerned and is needed to be understood. Here it is numerically investigated through solving rocket model of wire ablation and one-dimensional magnetic field equation, based on some roughly reasonable assumptions, such as the velocity and temperature of the ablated plasma and the diameter of the wire corona. A wire-array load, with radius 6mm, 60 tungsten wires of diameter 6-micron, mass per unit length 327 $\mu g/cm$, height 1.5cm, was used in the z-pinch experiments on Angara-5-1 facility. The outer diameter of the corona plasma surrounding the cool wire-core is supposed as 120 micron. The velocity is assumed that the ablated plasma from the wires is accelerated in radial direction by $\vec{j}\times\vec{B}$ force from zero to $1.5\times10^7 cm/s$, and then that the plasma flows inwards with the constant velocity $1.5\times10^7 cm/s$, and finally that in the region of radius less than 1mm the plasma velocity linearly decelerate to zero at axis.

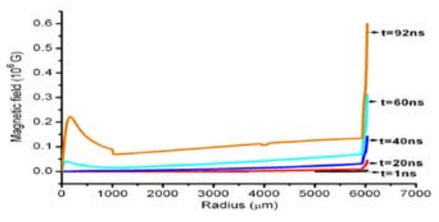

Fig. 1 The magnetic field profiles in the precursor, pre-filled and coronal plasmas at different time.

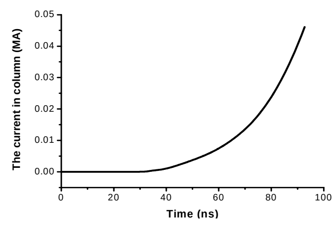

Fig. 2 The variation of the current flowing through the precursor column plasma with time.

Figure 1 shows the magnetic field profiles at a few times during the ablation. Due to the convection of magnetic field, there always exist higher magnetic field and current density in the column, and the plasma around there tends to exhibit the dynamic behavior (it might be called as “previous z-pinch”). Further researches reveal the extremum of magnetic field in the column increases with the plasma temperature and flow velocity, while it decreases with the increasing of the corona diameter and width of the thermalization layer of flowing ablated plasma, as well as with the decline of coronal plasma temperature. Figure 2 presents the variation of the current in the precursor column with time. The current is about 50kA at the end of ablation when the corona and the precursor plasma temperature are 100eV and 60eV, respectively. The further studies suggest that it would increase with the velocity of the precursor plasma flowing inwards, and with the decline of corona diameter (see Fig. 4). And it decreases to about 15kA, when the corona and the precursor plasma temperature are going down to 20eV and 60eV, respectively.

Figure 3 is the temporal and spatial variations of the magnetic Reynolds number. In the corona region the magnetic field diffusion is dominant, while in the middle region, especially in the column, the magnetic field convection is dominant. So even though the plasma is at rest, the magnetic field can almost linearly transport in the coronal plasma through the diffusion, while no magnetic field can diffuse into the column. Other results show that the corona temperature obviously affects the profile of current density (magnetic field) in the corona region, while the precursor temperature does not do.

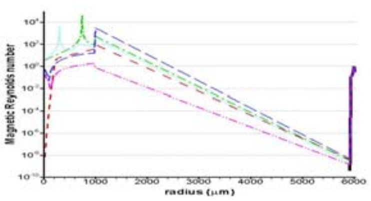

Fig. 3 The magnetic Reynolds number in the precursor, ablated and coronal plasmas under the assumed velocity profile, at 2ns (just solid-line), 29ns (dashed-line), 35ns (dashed-doted-line), 41ns (dotted-line), 60ns (long-dashed-line), and 84ns (dashed-dotted-dotted-line) after the current starts.

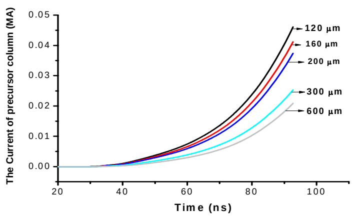

Fig. 4 The temporal variations of the current, flowing through the precursor column plasma, with different diameter of the coronal plasma.

III. The Effects of Precursor Plasma on the Final Implosion

The final implosion of the wire-array Z-pinch is simulated by one dimensional radiation magneto-hydrodynamics (RMHD) code.[5] In this simulation, the obtained profiles of mass density and magnetic field, as well as the assumed velocity and temperature above, are used as the initial conditions of the calculation. The mass ablation rate in the rocket model is reduced by a factor of 0.9, 0.7, 0.5, and 0.3, respectively, in order to change the mass of the precursor plasma. The ablation time and V_{abl} are 80% of the implosion time 116 ns and $1.5\times10^5 m/s$, respectively. The results are summarized in TABLE I. With the increase of the mass ablation rate, the ablated mass, the calculated convergence ratio, maximum implosion velocity, peak power and yield of x-ray increase, while the FWHM reduces. The results suggest that the larger mass ablation rates give better Z-pinch implosion performance.

TABLE I. The effects of artificially modified mass ablation rate on the Z-pinch performance

$\frac{dm}{dt}$ (×)	$m_{ablated}$ (μg/cm)	$r_0/r_{\min}$	$\upsilon_{\max}$ (10^6 cm/s)	t_{imp} (ns)	P_{peak} (TW)	FWHM (ns)	E_x (kJ)
0.3	75.3	2.0	-21.3	135.4	0.68	18.4	14.06
0.5	124.7	2.44	-27.73	131.2	0.99	13.6	17.4
0.7	174.1	3.16	-35.97	127.2	1.73	10.0	23.8
0.9	223.6	4.33	-40.25	122.2	3.7	7.2	34.8

To well understand the role of the precursor plasma, the implosions of plasma shells with and without the prefill are simulated and compared. The results show that the prefill helps to enhance the implosion process. Compared these results with that of the wire-array implosion started from the ablation, it is revealed that the acceleration of the shell is low at the beginning of the pinch process, and it takes a longer time to accelerate it up to the ablated plasma velocity. On the contrary, the ablated plasma speeds up quickly, and gains its velocity (~$1.5\times10^7 cm/s$) as soon as it is swept away from the corona. This might be a main reason why wire-array load is so successful in Z-pinch compared to the gas-puff loads and foil loads.

References

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