UNIVERSITY OF PÉCS

Doctoral School of Physics

Laser Physics, Nonlinear Optics and Spectroscopy Program

Investigation of the laser active, waveguiding and electron accelerating plasma medium by a self-developed capillary Z-pinch model

PhD Thesis

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1. Overview and objectives

The Z-pinch, perhaps the oldest subject in plasma physics, nowadays it has become the focus of research groups. The Z-pinch is the name of a unique class of magnetically driven or confined plasma in which a current is passed through a cylinder of plasma parallel to the axial or z-direction. The resulting interaction of the azimuthal self-magnetic field and the axial current produces an inward radial $\boldsymbol{J} \times \boldsymbol{B}$ or magnetomotive force (the pinch effect). The huge advantages of the Z-pinch are that large quantity of plasma can be produced with very high energy density. One of the reasons for the increased interest of the research groups is this and the compactness. Since we have built and continuously developing the soft X-ray laser excited by current pulse with amplitude of ~ 20 kA and half cycle duration of 150 ns [1, 2] it was in our interest to understand on a theoretical level what physical processes take place in the Z-pinch plasma generated in a 3 mm inner diam. Al_2O_3-capillary.

From the practicality of understanding, the following expectations for the model to be developed were important:

- the maximal completion of the given problem with the finite computing capacity of the available tools;
- the unknown plasma parameters should be a function of space and time;
- for direct comparison with experimental results, plasma parameters should be macroscopic.

The MHD model met these requirements the most, which describes plasma as a charged fluid. Although many MHD-based plasma models exist in the literature (see e.g.: [3, 4, 5, 6, 7, 8]), and open-source online code is available, but since most of the latter are designed for fusion, astrophysical and general plasma, none of them can be used for the special cases of capillary Z-pinch plasma. However, the three fundamental transport processes in the plasma is a good basis that can be converted to the desired configuration with appropriate Z-pinch assumptions.

I show that starting from the three fundamental transport processes in the plasma (particle, momentum and heat transport), a capillary Z-pinch 0D and 1D MHD model can be developed. By comparing calculated results and measured pinching times, I check the dynamic authenticity of the two models.

A major breakthrough occurred with the work of Rocca *et al*. [9] who in a 4 mm internal diameter capillary and a 40 kA discharge rising in 60 ns gave a population inversion in the $J = 0 – 1$ energy transition of neon-like

Ar^{+8}-ions. With gain *G* of 0.6 cm^{-1} at a wavelength of 46.9 nm, three lengths of discharge were tried: 3, 6 and 12 cm. The longest gave a gain-length product, *Gl* of 7.2. At this time the pinch radius was 100…150 μm. A buffer gas of hydrogen was added in a 1:2 mixture to reduce radiative trapping on the lower laser level. This level must quickly decay to the ground state. Neon was also explored as a buffer gas, but pure argon also lased well at a full pressure optimized at 0.7 Torr. To obtain successful lasing action required hot, dense and axially uniform plasma (i.e. no instabilities), and sufficiently fast current rise to give collisional excitation.

The G(r) gain distribution of 46.9 nm spectrum line of neon-like Ar^{+8}*-ions depends on the plasma temperature and density, thus, by comparing the time-averaged transmission distribution with the transverse intensity* *distribution of soft X-ray laser radiation I also check the spatial authenticity of the 1D MHD model.*

Another and perhaps even more important application of the capillary Z-pinch is its use in forming a straight channel of axially uniform plasma with a radial minimum density on axis, for guiding an intense short pulse. It has been established by several research groups [10, 11, 12] that laser-driven acceleration of electrons to 200MeV energy can be achieved in a medium of a mm-scale helium gas jet. Pukhov and Meyer ter Vehn [13] had earlier in simulations shown how a monoenergetic beam of electrons could be accelerated in the wakefield scheme proposed by Tajima and Dawson [14]. Here the electric fields, caused by charge separation, can be of order 10…100 GV/m. By using instead a capillary Z-pinch a much longer acceleration length can be achieved in principle. Without the guiding channel the laser-plasma interaction length would be limited to the order of a Rayleigh length which is proportional to the spot size. Leemans *et al*. [15] demonstrated the production of a monoenergetic electron beam of 1 GeV energy in a 3.3 cm long hydrogen gas-filled capillary discharge in which a 40 TW peak-power 1 μm wavelength 38 ps laser pulse was axially propagated.

I show that in a shrinking Z-pinch plasma column a guiding channel always emerges transiently, which is suitable for single-mode transmission, important in terms of laser wakefield electron acceleration. This property is strongly depends on the input beam spot size, so my goal is to determine the optimum spot size at which the single-mode transmission can be maximally utilized. I will also show that at the end of the waveguide channel existence a *repetitive focus-defocus pattern is always observed in the laser beam intensity distribution. This waveguiding regime leads to the intensity modulation of the input* TEM_{00} *mode laser pulse. Finally, I examine the effect of this intensity modulation on plasma oscillations and, consequently, on longitudinal electric field (wakefield) that accelerates electrons.*

2. Methods

My model building concept was to create the simplest possible model in accordance with experimental experience by combining equations, reducing dimension owing to symmetries and neglecting the insignificant terms of fundamental transport processes in the plasma (particle, momentum and heat transport) [3, 4, 5]. This was important because, in terms of finite computational capacity, revealing connection between the plasma parameters with the simplest model is most effective. Following the acquisition of basic correlations next step was to understand spatial distribution of these parameters. To do this, I had to increase the degree of freedom of the model by involving a radial variable.

The fast Z-pinch discharge simulations carried out by the 1D MHD model showed that a plasma channel, suitable for waveguiding, is always created transiently. I have done examination of the properties of Ar-plasma channel produced inside a 3-mm inner diameter and 50-mm long capillary on the central wavelength (10.6 μm) of the CO_2-laser pulse with input peak intensity of 1.3×10^{15} W/cm^2. During the discharge the guiding channel occurs far from capillary wall which makes possible pure plasma waveguiding free from any wall influences. At the end of the channel existence a repetitive focusing and defocusing pattern (intensity modulation) can be observed with significant intensity increase at the focal points.

Density perturbation modeling of the hydrogen plasma showed that intensity modulation of high intensity (10^{17} W/cm^2) laser pulse, capable to generate a wakefield, in the form of beat appears in plasma waves too. Via charge separation, amplitude of the plasma waves is in connection with the longitudinal acceleration field, so that the beat effect appears in the energy of the accelerated particles too. In order to demonstrate this, I have carried out a PIC simulation of the self-injected bubble regime on 10^5 pcs of electrons by using CO_2-laser pulse with pulse duration of 0.5 ps and input peak intensity of 10^{18} W/cm^2.

3. New scientific results

1. Starting from the three fundamental transport processes in a plasma (particle, momentum and heat transport) I have developed an "one-fluid" two-temperature 0D and 1D MHD model of the capillary Z-pinch in accordance with the literature and our experimental experiences. I have carried out the dynamic validation of both models by comparing computed and measured pinching time of different initial setups [S1].
2. I have showed that the time-averaged transmittance distribution of the plasma column computed for 46.9 nm spectrum line of the neon like Ar^{+8}-ions is in line with observed transversal distribution of the X-ray laser radiation at different pressures [2]. Thus, I

could check the 1D MHD model spatial authenticity too [P4, P7].

3. The fast Z-pinch discharge simulations carried out by the 1D MHD model showed that a plasma channel suitable for waveguiding is always created transiently (5...10 ns), irrespectively of the used gases [P2]. I have demonstrated that by introducing a correlation coefficient an optimal beam spot size can be determined for maximizing the single-mode transmission ability of the channel, important in terms of LWFA [S2, E1].

4. Via a series of study, I came to the conclusion that at the end of the waveguiding existence when the optimal spot size exceeds the theoretical matched spot size, irrespectively of the used lasers and gases, a waveguiding regime with repetitive focusing and

defocusing pattern (intensity modulation) is always created with significant intensity increase at the focal points [S2, E1, P2, P5].

5. With a spectrum of the plasma oscillations I have confirmed that intensity modulation caused by the guiding channel in the form of beat appears in amplitude of the plasma waves. Via charge separation, this amplitude is in connection with the longitudinal acceleration field, so that the beat effect appears in the energy of the accelerated particles too [S3, E1].

6. With a PIC simulation of the self-injected bubble regime I have demonstrated that during the acceleration electrons gain their energy in a cascaded way, and this process is in quasi-sync with intensity modulation of the laser pulse [S3, E1].

4. List of publications related to the thesis

[S1] **A.A. Shapolov**, M. Kiss and S.V. Kukhlevsky, *A Simplified MHD Model of Capillary Z-Pinch Compared with Experiments*, Contrib. Plasma Phys. **56**, 10, 959-967 (2016).

[S2] **A.A. Shapolov**, M. Kiss and S.V. Kukhlevsky, *Theoretical Investigation of Z-Pinch Ar-Plasma Waveguide in a Millimeter-Scale Cross Section Capillary*, IEEE Transactions on Plasma Science 46, 11, 3886-3890 (2018).

[S3] **A.A. Shapolov**, B. Fekete, M. Kiss, S. Szatmari and S.V. Kukhlevsky, *Theoretical Study of Wakefield Acceleration of Electrons in Capillary Z-Pinch Plasma Waveguide*, Proceedings of 3rd International Conference on Engineering Physics and Optoelectronic Engineering (2019), pp. 1-10. (publikálásra befogadva 2018. december 7.)

[E1] **A.A. Shapolov**, B. Fekete, M. Kiss, S. Szatmári and S.V. Kukhlevsky, *Waveguiding of the high intensity laser pulse in a hydrogen Z-pinch plasma and its influence on the LWFA in the bubble regime*, 4th Global Summit & Expo on Laser Optics & Photonics, 15-16 April 2019, Dubai, UAE.

[P2] **A.A. Shapolov**, B. Fekete, M. Kiss, S. Szatmari and S.V. Kukhlevsky, *Optimization of the Excitation Current Pulse of Capillary Z-pinch*

Plasma Waveguide by Using Different Gases, 28th Symposium on Plasma Physics and Technology (SPPT 2018), 18-21 June 2018, Prague, Czech Republic.

[P4] **A.A. Shapolov**, B. Fekete, M. Kiss, S. Szatmari and S.V. Kukhlevsky, *Two MHD models of capillary Z-pinch argon plasma versus experiments regarding the lasing in 46,9 nm line of* Ar^{+8} *ions*, 19th International Congress on Plasma Physics (ICPP 2018), 4-8 June 2018, Vancouver, Canada.

[P5] **A. Shapolov**, B. Fekete, M. Kiss, S. Szatmari and S.V. Kukhlevsky, *Waveguide properties of the capillary Z-pinch plasma*, 45th IOP Plasma Physics Conference, 9-12 April 2018, Belfast, UK.

[P7] **Anatoliy A. Shapolov**, M. Kiss and Sergei V. Kukhlevsky, *Study of the X-ray radiation gain in context of MHD modeling of capillary discharge plasma*, 3rd International Workshop on Frontiers of X&XUV Optics and its Applications, 4-6 October 2017, Prague, Czech Republic.

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