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DEVELOPMENT OF PLASMA WAVEGUIDE USING FAST Z-PINCH CAPILLARY DISCHARGE

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Abstract

A Laser wake field acceleration (LWFA) experiment with 100 TW laser is planed at JAERI-KANSAI. Development of the plasma waveguide using a fast Z pinch capillary discharge is one of the issues of this plan. A 10 cm long plasma wave guide is developed. Preliminary results of PIC simulations show the acceleration gradient of the order of 1 GeV/cm is achieved.

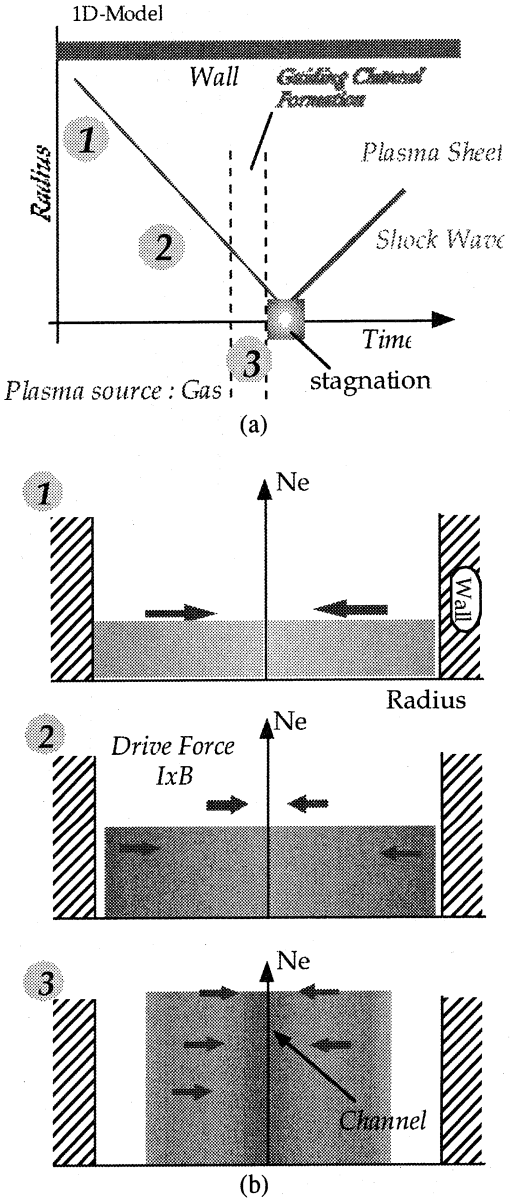
1 INTRODUCTION

A short laser pulse propagating in a plasma excites the electron plasma wave (laser wakefield) which can accelerate an electron beam [1]. The laser wakefield accelerator (LWFA) has high acceleration gradient, 100 to 1000 times larger than that of the traditional rf accelerators. Recent experiments [2-5] have demonstrated the acceleration gradient of 10 GeV/m and the energy gain of 300 MeV.

Acceleration length of LWFA is limited to the diffraction length of the laser. One of the issues for GeV LWFA experiment is developing a plasma waveguide to extend acceleration length of LWFA. Several techniques have been proposed to make the acceleration length exceed the vacuum diffraction length [6-8]. A new plasma waveguide using a fast Z-pinch discharge in a capillary is proposed [9]. We succeeded in guiding a 2 TW laser over 2 cm, 12.5 times larger than the diffraction length, in the Z-pinch plasmas. Development of the new plasma waveguide with acceleration length up to 10 cm has been started at JAERI-KANSAI as shown in Section 2. Section 3 shows preliminary results of simulation study of the plasma waveguide. Section 4 summarizes this report.

2 DESIGN OF PLASMA WAVEGUIDE

In the previous experiment [9], we have used a capillary with an inner diameter of 1 mm and a length of up to 2 cm. The capillary was filled with helium. With this configuration we obtained a discharge current of 4.8 kA with a rise time of 15 ns and a duration of 70 ns (FWHM). A DC discharge circuit was used to pre-ionize helium gas. A Ti:Sapphire laser pulse $\lambda_L = 790$ nm, 90 fs, was focused to > 1×10^{17}W/cm^2 on the front edge of the capillary with a spot size of 40 μm in diameter. The transmitted laser beam profile at the exit of the capillary was measured through a band pass filter ($\Delta\lambda = 1$ nm) with a CCD camera.

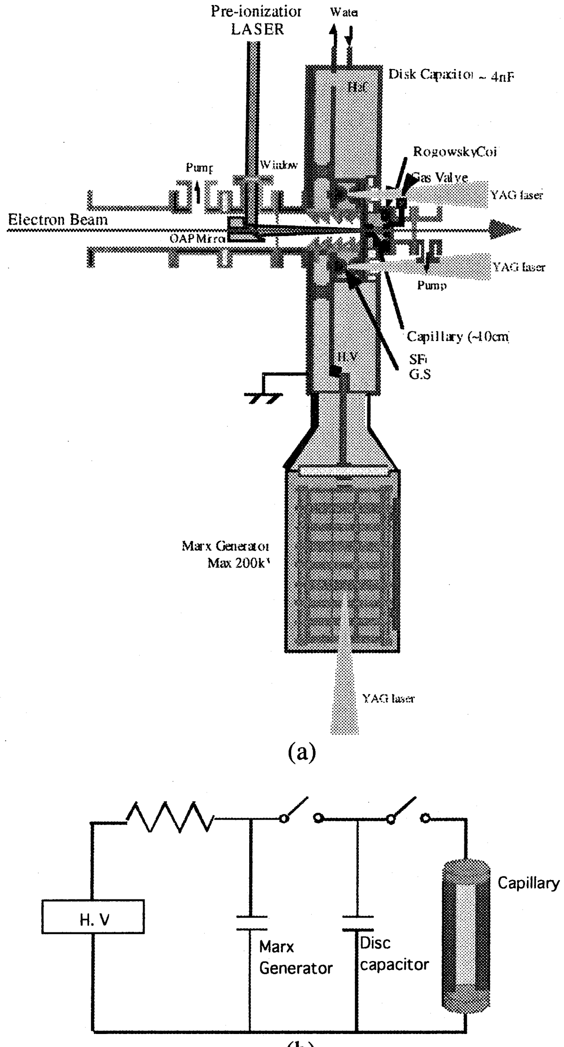


(a)

(b)

Figure 1: Temporal evolution of (a) fast Z-pinch capillary discharge and (b) electron density profile.

A high current fast Z-pinch discharge generates strong azimuthal magnetic field, which contracts the plasma radialy inward down to 100 μm in diameter. The imploding current sheet drives the converging shock wave ahead of it, producing a concave electron density profile in the radial direction just before the stagnation phase as shown in Figure 1 (a) and (b). The concave electron density profile is approximately parabolic to out of radius of 50 μm, after which the density falls off (Fig.1(b)).



(a)

(b)

Figure 2: (a) Schematic drawing of the plasma waveguide. (b) Equivalent circuit of the fast Z-pinch discharge.

We have started to develop a 10 cm long plasma wave guide. A fast rising high current generator is needed to produce the fast Z-pinch discharge. Figure 2 shows a design of the plasma waveguide using fast Z-pinch discharge. A Marx generator stores the energy up to 68 J. The maximum output is 200 kV. A laser triggered spark gap switch (LTSG) is used to minimize jitter of the Marx generator. A 10 cm long ceramic capillary is connected to the center of a water filled disk capacitor (4 nF). Four LTSGs are symmetrically located on the disk capacitor to generate axially symmetric current in the capillary. A solenoid valve is used to supply gas into the capillary. Pre-ionization by YAG laser is adopted to produce the stable plasma waveguide.

3 SIMULATION OF PLASMA WAVEGUIDE

We are developing particle-in-cell (PIC) [10] codes to simulate the channel formation of the plasma waveguide, the laser propagation, the wake field excitation and the electron acceleration. Newton-Lorentz equations,

$$m\frac{\partial \mathbf{u}}{\partial t} = q\left(\mathbf{E} + \frac{\mathbf{u}}{\gamma c} \times \mathbf{B}\right)$$

$$\frac{\partial \mathbf{r}}{\partial t} = \frac{\mathbf{u}}{\gamma}, \qquad (\mathbf{u} = \gamma \mathbf{v}), \qquad (1)$$

describe the relativistic motion of the plasma particles and the electron beam in the laser wake field. The laser and the wakefield propagations are described by Maxwell equations

$$\begin{aligned} \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} &= 0 \\ \nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} &= \frac{4\pi}{c}\mathbf{j} \end{aligned} \qquad (2)$$

These differential-equations are translated to space- and time-centered finite-difference equations. **B** and **u** are updated by leap-frog method over **E** and **r**. Field quantities, **E** and **B**, are staggered in space grid. This guarantees second order accuracy and space-time reversibility. The PIC algorithm consists of two phases: In the particle push phase, the new particle position and velocities are determined according to Eq. (1). In the following field solve phase, the fields are updated, according to the particle motion. In order to push the particles, the field quantities at the particle positions are determined by linear interpolation. Current density, **j**, on each grid point is calculated from the particle position and velocity with the volume weighting scheme.

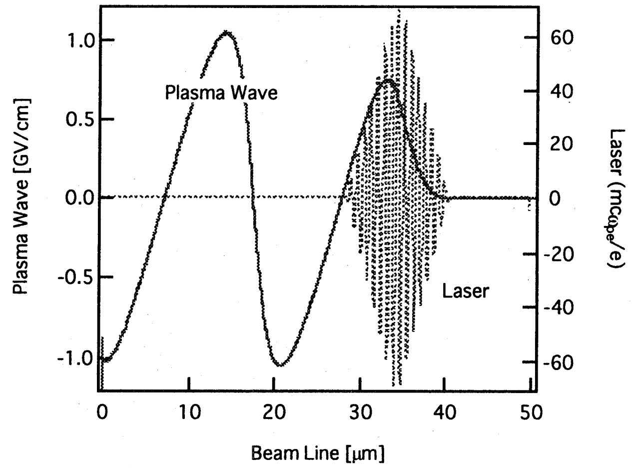


Figure 3: Wakefield excited by the short laser pulse, P=100 TW, 20 fs. $n_e = 3\times10^{18}\mathrm{cm}^{-3}$.

Preliminary results of 1D PIC simulations have been obtained. Figure 3 shows a typical wakefield profile excited by the short laser pulse. The laser power is 100 TW and pulse width is 20 fs. Spot size is 30 μm in the plama. The acceleration gradient reaches 1 GeV/cm at the plasma density $n_e = 3\times10^{18}\text{cm}^{-3}$. In the range of the plasma density from 10^{17} to 10^{19}cm^{-3}, the acceleration length from 1 to 10 cm is required for the 1 GeV LWFA experiment (Fig.4).

Multi dimensional simulations are needed for more realistic simulation such as the laser propagation in the plasma waveguide. Next issue is development of 3D PIC code.

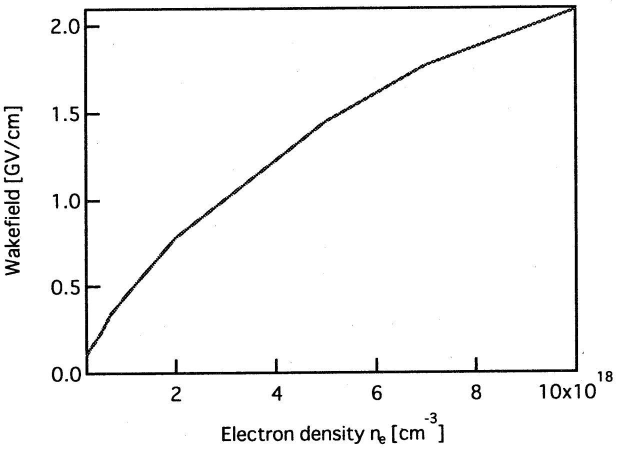


Figure 4: Wakefield strength as a function of the plasma density.

4 SUMMARY

The optical guiding development has resulted in a cm-scale plasma waveguide using the fast Z-pinch capillary discharge. We have succeeded in demonstrating propagation of 2 TW, 90 fs laser pulses over 2 cm in the Z-pinch plasma waveguide.

Development of the 10 cm plasma waveguide at JAERI KANSAI is reported. 1D PIC simulations show the plasma parameter required for 1 GeV LWFA experiment. The study of dynamics of the fast Z-pinch discharge and a laser guiding experiment are planed in this year. The plasma waveguide will be installed into the beam line and LWFA experiment will be conducted next year.

5 REFERENCES

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