On the experiments of Surfatron concept with use of capillary plasma.

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Abstract. In the middle of 1980th, the VpxB concept for accelerating electrons are found by Nishida et al, with the use of plasma wave excited by high power microwave in the interaction with weakly magnetized plasma. This acceleration concept was called "Surfatron effect" in the relativistic regime. However, there is no experimental evidence so far in the relativistic regime, although the acceleration efficiency is highest in all of the concepts based on the plasma wave acceleration scheme, and we are now under experiments. In order to make longer the acceleration distances, there are several ideas including 1)ducting of the electromagnetic waves (EM wave) in the preformed plasma, 2)self-channeling of the EM waves, and others. In this paper, the experimental results are shown on the ducting phenomena by using strong microwave for simulating the laser ducting, and on the capillary plasma scheme.

1. INTRODUCTION

Recently there is a great interest growing in advanced accelerators based on laser and plasma acceleration mechanisms, which have tremendous potentiality for applications to wide range of sciences and technologies. Plasma based high energy particle accelerators were introduced theoretically in 1979 by Tajima & Dawson(1), and in 1985 by Chen et al.(2). The experimental investigations started in1980th. By Tajima et al, we need to use the ultra-short laser pulse that has the pulse width of the order of plasma periods, and there was no such a laser system at that time. Instead they also suggested using the beat wave method by modulating the electromagnetic wave with use of two laser beam with slightly different frequencies, the difference of which matches with the plasma frequency in the back ground plasma and the plasma wave excitation were observed by Amini and Chen (3). Chen et al.(2) suggested using high energy electron bunch as a driver to excite the plasma waves. The successive electron bunch can be accelerated to higher energy than that of driver bunch. The excitation of wakefield by an electron bunch and also ion bunch had been demonstrated to show the possibility of realizing the plasma wakefield accelerator (4,5).

In 1984, Nishida and his colleagues (6-7) found new phenomena for producing high energy electrons, and proposed to use this mechanism for high energy particle accelerators. This mechanism was named "**VpxB** acceleration", where, *Vp* is the phase velocity of the plasma wave and *B* is the static magnetic field applied vertically to the wave propagation direction (see Fig.1). In successive investigations, Nishida's group showed the real accelerator concepts, by injecting electron beam into the plasma waves excited by high power microwave. The injected electrons had been effectively accelerated when the injected beam velocity was close to the wave phase velocity, and the electrons were resonantly trapped to be accelerated (8). This mechanism is also applied to the vacuum accelerator system and more effective acceleration took place (9). In 1983, Katsouleas and Dawson proposed the "Surfatron" concept (10), and this is clarified later that the Surfatron phenomenon is exactly the same phenomenon as the VpxB accelerator scheme. In Nishida's experiments, the mode converted plasma waves from the incident high power electromagnetic wave (EM wave) are used. This mode conversion takes place at the layer where the resonance absorption conditions are satisfied. The question in this scheme is the conversion efficiency from the EM waves into electrostatic plasma waves. This transition is linear process, and most of the EM wave energy might be reflected back to the incident direction of the EM wave.

There are two major problems in the plasma based accelerators, 1) the acceleration length is limited by the Rayleigh length, if there is no additional effects are taken into account, and 2) the particles trapped in the wave trough are not stay at the highest field phase, resulting in no monochromatic energy particles are produced.

In the VpxB acceleration (Surfatron) scheme, the trapped particles for acceleration stay all the time at the maximum field strength and are accelerated stably in the *VpxB* direction, slightly oriented from the wave traveling direction, the angle of which is given by

$$\sin\theta = 1/\gamma_p = \sqrt{1 - V_p^2/c^2}\,, \qquad (1)$$

where c is the speed of light. Therefore, in the relativistic situations the angle θ is quite small. The trapping condition for the particles is given by $E_z > \gamma_p cB$, where E_z is the field strength of the plasma wave.

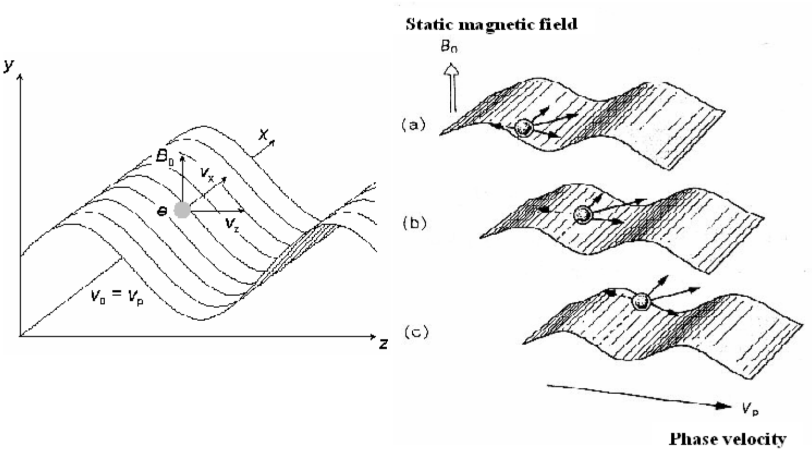

FIGURE 1. Conceptual figures showing the *VpxB* acceleration (Surfatron accelerator) mechanism.

In 1988, the CPA(-Chirped Pulse Amplification) method were invented by Maine and Mourou (11), and ultra-high intensity laser pulse system were realized to be popularly used for exciting the plasma wave in high density plasma, with enough field strength and short pulse width for exciting strong plasma wave. The wave breaking field strength of the plasma waves reached up to 1GeV/m (12), more than three orders of magnitude higher than the conventional accelerator field strength which is limited by the breakdown voltage of the material surface of the RF cavity.

2. SIMURATION EXPERIMETS ON DUCTING OF HIGH POWER ELECTROMAGENETIC WAVE

When the ultra-short, high power laser pulse is employed for realizing the plasma based accelerators, there is a serious problem, namely the short acceleration length which is limited by the Rayleigh length. Therefore, several ideas for overcoming the short acceleration length were proposed. Ducting of the laser beam, that is, the EM wave, is major solution for overcoming the short acceleration length. The experiments by using the ultra-short laser is not easy to understand the physics involved, which is quite important for improving the system further. Here, we used the high power microwave instead of laser and experimental simulations have been done, showing clear mode pattern in the duct and the propagation characteristics are clarified (13-15). These results are quite useful for making ducting system in the accelerator using ultra-high power laser scheme.

2-1 Experimental Set-up and Results

Propagation characteristics of high power microwaves are investigated in preformed plasma density channel. Plasma density channel is formed by inserting a thin glass strip along the axis of the chamber (see Fig.2). The width and depth of the

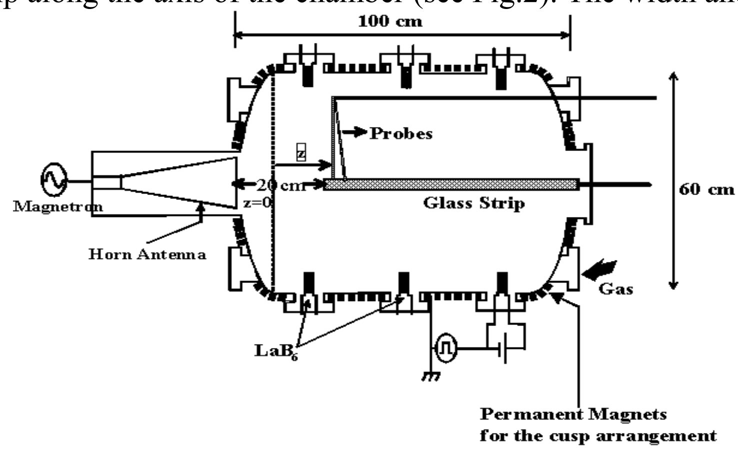

FIGURE 2. Experimental set up. Typical parameters are; Argon gas pressure: 3.5×10^{-3} Torr , resonance plasma density: $1\times10^{12}\,\mathrm{cm}^{-3}$, electron temperature: $2.3\,\mathrm{eV}$, microwave frequency:9 GHz, Max power:250 kW, and pulse width:1 μs .

density channel can be adjusted by changing the background plasma density. When the width (FWHM) of the density channel is kept less than the half wavelength of the incident microwaves ($\lambda_o = 3.3$ cm, $f_o = 9$ GHz, $P_{\max} = 250$ kW), one expects microwaves not to penetrate into the density channel. However, it is observed when the incident microwaves with power more than 50 kW are launched, the density channel is expanded and EM wave penetrates into the channel for almost five Rayleigh lengths (~50 cm). The preformed density channel acts as a waveguide to guide the high power microwaves. The width of the density channel increases, while the width of the electric field spatial pattern decreases with the increase of the incident EM power such as shown in Fig.3. These results show that microwaves modifies the refractive index of the density channel to increase it at the center and remains trapped in the region of higher refractive index. Expansion of the preformed channel is due to the ponderomotive force of the trapped microwaves within the channel. Preformed channel is created in such a way that its width, in absence of microwaves, is a function of axial distance. Hence, it is observed that expansion of the density channel is more at the locations where its original width is relatively small.

Mode structure analysis is carried out by Fourier transforming the spatial distribution of electric field within the channel. It is observed that mode of propagation remains very similar to the fundamental mode in a dielectric waveguide having step-index profile for widths as large as 2 times the vacuum wavelength of the incident microwaves as an example is shown in Fig.4.

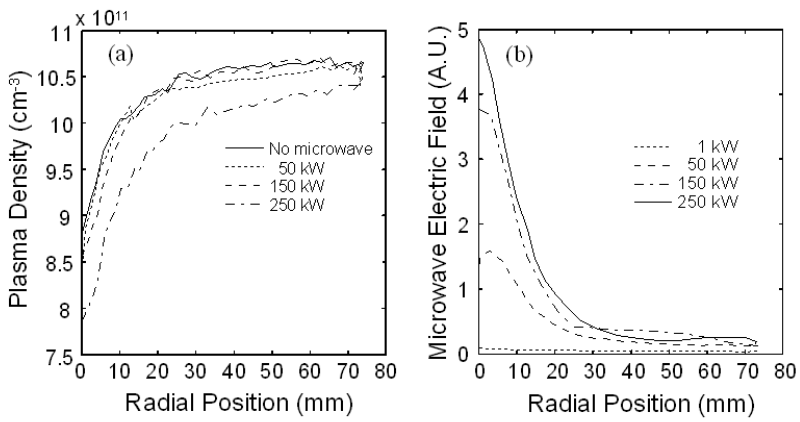

FIGURE 3. Examples of experimental results, showing the change of the density profile (a) and the field pattern (b) in the radial direction. .

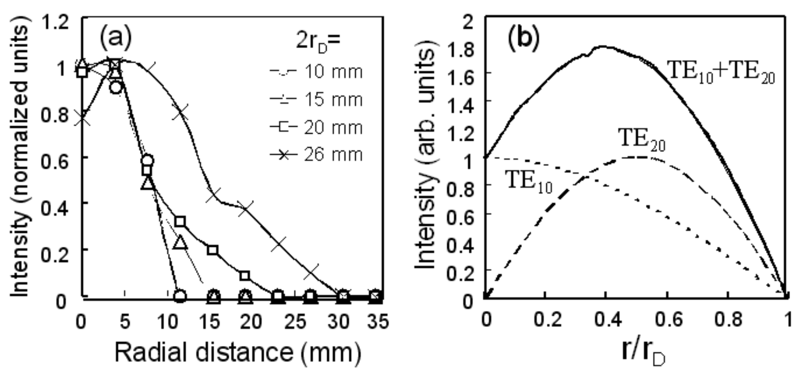

FIGURE 4. Example of propagation mode pattern. Observed mode is the mixture of $TE_{01} + TE_{02}$ mode in the rectangular wave guide..

Analytical treatment to the problem of propagation of electromagnetic waves in a dielectric waveguide having step-index profiles shows good agreement with the experimentally measured electric field profiles. It also confirms the fact that the width of the electric field is inversely proportional to the refractive index.

3. CAPILLARY PLASMA PRODUCTION FOR GEV ACCELERATORS

In order to make longer acceleration length, one possible, and most confident way of making the ducting system is to use the capillary plasma. In this section, we wish to give brief description on the capillary plasma production and the VpxB accelerator plan for the future Gev accelerators.

3-1 Capillary Discharge Waveguide

There are several methods to use the capillary discharge wave guide. 1) "Dielectric-ablated capillary" waveguide uses the dielectric material for capillary and the life time of it is expected to be several hundred shots. 2) "Gas-filled capillary" waveguide, in this typically two methods are employed. (2-1) "Z-pinch discharge capillary" waveguide, which has the life time typically more than10^4 shots and the life time of plasma channel in it less than a few ns. (2-2) "Fully-ionized plasma" waveguide, which has the life time of capillary more than 10^6 shots and the plasma life time in the channel about 100 ns. Here, we employed (2-2) system, and the capillary system used is shown in Fig.5.

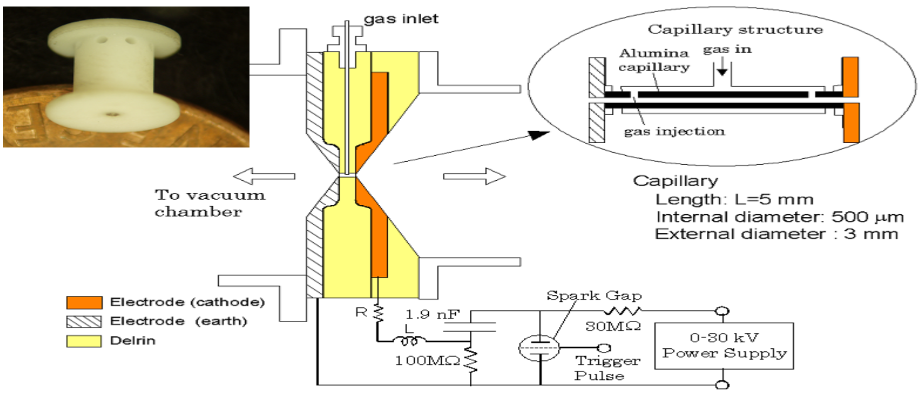

FIGURE 5. Capillary plasma source with dielectric capillary and the discharge system.

Typical results are shown in Fig.6. Here, in order to measure the plasma structure in the capillary, He-Ne laser interferometer system is used. In Fig.6(A), the mask to prevent the laser light through the capillary into the detector is shown. The "outer mask" prevents the laser light going through the periphery area of the plasma in the capillary, while the "inner mask" prevents the light going through the center area. In Fig.6(B), the typical results are shown. The top trace, I_o, shows the light intensity through the center area of the plasma with outer mask, and the third trace from the top, I_i, shows the light through the periphery area with inner mask. The bottom trace shows the laser light through whole of plasma in the capillary. The second trace from top corresponds to the light intensity without laser light (only the plasma light). In the center area, laser light intensity increases, so that the plasma density decreases, while in the periphery area, the light intensity decreases, i.e. the plasma density increases to make a duct structure within the capillary. The increments of the transmitted light through the plasma is estimated as follows,

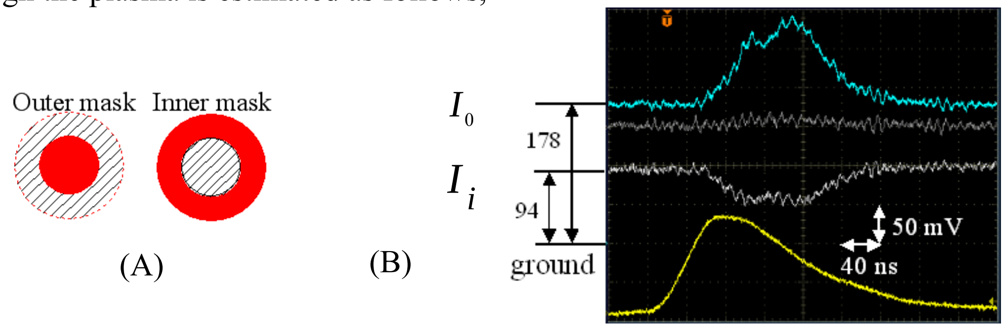

FIGURE 6. Capillary plasma structure observed by the He-Ne laser. (A) is the mask for preventing the transmission light. (B) is the transmitted laser light through the plasma observed by the detector. I_o is observed in the center area with "outer mask", and I_i shows the light observed in the periphery area with "inner mask".

In the center area, the increment of the laser light is given as $\Delta I_0 = \left({(280 - 178)}/{178} \right) \times 100 = +57\%$, that is, the light intensity is increased, showing the plasma density is decreased, while in the periphery area, the laser light intensity is decreased such as $\Delta I_i = \left({(52 - 94)}/{94} \right) \times 100 = -45\%$, showing the plasma density is increased. Therefore, plasma density in the center area is lower than in the periphery area, and existence of duct structure in the capillary is clearly seen as is expected. Still there are several unknown phenomena. First, when the high-power ultra-short laser pulse is introduced into the capillary, the extra plasma appear by further ionization?,

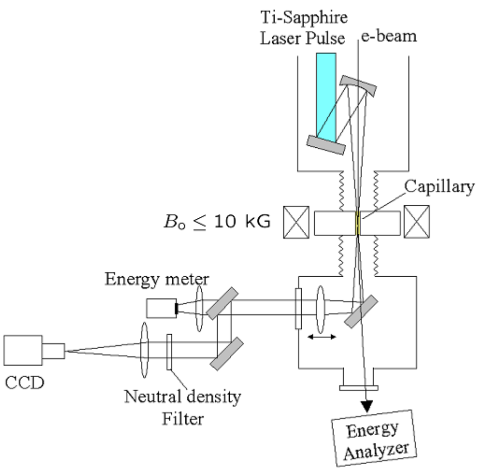

FIGURE 7. Experimental set-up for observing the VpxB accelerator phenomenon, in which Ti-Sapphire laser system is employed for high enough wakefield excitation.

Second, in that occasion, can the strong enough wakefield be excited? , 3rd, how many shots are expected without serious damages on the capillary? and so on. The observed life time of the plasma guide is about 100 ns in the present experiments, and this is long enough for the present purpose.

By using capillary plasma, the experiments on the VpxB phenomena are underway. The experimental set-up is shown in Fig.7. Here, the static magnetic field applied vertically to the wakefield excited within the capillary plasma is up to 10 kG. Accelerated electrons should have the dependence on the magnetic field strength and their spectrum is expected to be monochromatic energy.

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