PLASMA LINEAR ACCELERATOR

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(presented by T. Ohkawa)

1. INTRODUCTION

It has been proposed by V. I. Veksler [1] in the preceding symposium in 1956 that the coherent interaction between plasmas, and between plasmas and electromagnetic fields, may be used to accelerate charged particles. Two applications of the principle have been studied. One [2] is to use a plasma as a medium for guiding a microfrequency wave and to amplify or to slow down the propagation of the wave. Another [3] is to accelerate a bunch of plasma by the radiation pressure of the electromagnetic wave. We shall consider an experimental method to study the latter type of acceleration in this report.

A plasma may be produced by a gaseous discharge or by injection from a plasma gun into a waveguide. Then microwave power may be introduced into the guide, so that the plasma will reflect the wave and be accelerated by its radiation pressure. The waveguide not only guides the wave efficiently, but also helps to achieve the complete reflection of the wave by the plasma. The acceleration and the stability of the plasma will be discussed only qualitatively, since the linear theory on the interaction between plasmas and waves fails at the high power level required due to the large disturbances in the plasma. A brief description of the experimental model will be given.

2. CALCULATION OF FORCES ON PLASMAS

We shall first consider a diffuse plasma so that the reaction on the electromagnetic field is assumed to be small. The dimensions of the plasma bunch are much less than the wavelength of the wave; the force F exerted by the wave on the plasma is given by

$$F = M\frac{8\pi}{3}N^2 r_0^2 \pi_0 E^2 \,, \quad \text{if} \quad \frac{2\pi N r_0}{\lambda} \ll 1 \qquad (1)$$

where r_0, λ, N and E are the classical radius of electron, the wavelength of the wave, the total number of electrons in the plasma and the electric field of the wave, respectively. M is the radiation magnification factor defined by

$$M = \frac{\text{Power radiated from a unit dipole in the waveguide}}{\text{Power radiated from a unit dipole in free space}}$$

and depends on the parameters of the waveguide. The force increases with N and begins to saturate as the reaction on the wave becomes important at the larger values of N.

Since it is obvious that the maximum transfer of the momentum from the incident wave to the plasma is attained at the saturation of the force or at the complete reflection of the wave, we shall consider the plasma as a medium and derive the condition for complete reflection. The equivalent permitivity ε_p of plasma for a wave having a frequency ω is given by

$$\varepsilon_p = \pi\varepsilon_0(1-\omega_p^2/\omega^2) \qquad (2)$$

where ω_p and ω are the plasma frequency and the wave frequency, respectively.

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In the configuration shown in Fig. 1, a rectangular waveguide contains a bunch of plasma, the cut-off frequency of the guide with plasma for the H_{10} mode is given by

$$\tan \frac{\omega}{c} \frac{a-d}{2} = \frac{1}{\sqrt{\varepsilon_p/\varepsilon_0}} \cot \frac{\omega}{c} \sqrt{\varepsilon_p/\varepsilon_0}\, \alpha/2 \tag{3}$$

where a and d are the width of the guide and the plasma. The waves having a frequency lower than the cut-off frequency will be reflected by the presence of the plasma, provided that the length of the plasma is larger than the penetration depth of the wave.

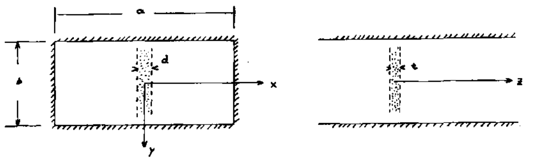

Fig. 1 Waveguide and the plasma configuration considered.

The accelerating force for complete reflection is simply given by

$$F = 2v_g \bar{W}/c^2 \quad \text{if} \quad v_g \gg v \tag{4}$$

where $\bar{W}$ is the power of the wave, v_g and v are the group velocity of the wave and the velocity of the plasma. If the velocity of the plasma is small compared to that of the wave, the reflected wave suffers little shift in its frequency and still is at a high power level. To use this power again, a microwave filter may be inserted between the wave generator and the accelerating waveguide. The filter should have narrow band-pass characteristics centred at the frequency of the incident wave, so that the reflected wave, having a frequency lower than that of the incident wave, will be sent back towards the plasma by the filter. The wave will travel back and forth until the frequency reaches the cut-off frequency of the guide itself, thus the power density of the wave will be increased.

When the velocity of the plasma approaches the group velocity of the wave, this method of acceleration becomes rather inefficient, since the wave has to fill the whole space behind the plasma moving almost as fast as the wave.

We shall now consider the stability of the plasma under the force by the electromagnetic wave. In the configuration of Fig. 1, all quantities are independent of the y-direction and there are no forces in the y-direction. Since the intensity of the electric field in the guide has dependances on x as $\cos(2\pi\ x/a)$, it will cause the plasma either to expend or to compress depending on the density of the plasma. By assuming sharp boundary and uniform density of the plasma, it can be shown that positive ε_p gives the force which tends to expand the plasma and negative ε_p to compress it. In the z-direction, the plasma will be compressed continuously. For the case where the plasma density increases linearly with z, the force in the z-direction has been calculated and is shown in Fig. 2. A small part of the plasma will be separated and left behind due to the reversed direction of the force.

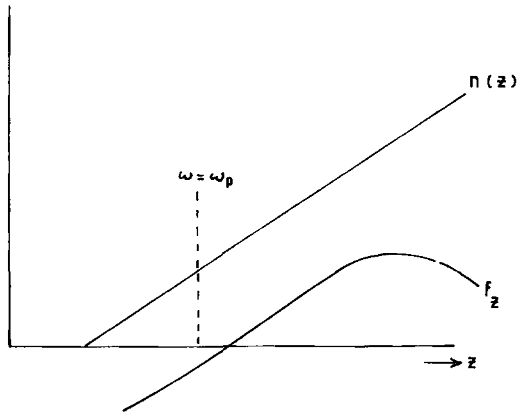

Fig. 2 Effect of particle density gradient upon stability (qualitative). $n(z)$: electron density. f_z: force in z-direction.

3. EXPERIMENTAL MACHINE

An experimental machine has been constructed and is now undergoing preliminary tests. Fig. 3 shows the schematic diagram of the machine. All relevant parameters of the machine are listed below.

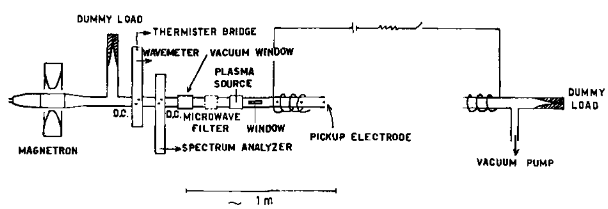

Fig. 3 Block scheme of the model machine.

List of parameters

Accelerating wave

Oscillator : Magnetron V 4061

Frequency : 2 998 Mc

Peak power : 2 MW

Duration : 2 μs

Waveguide (accelerating part)

Shape : Rectangular

Size : Inner dimension 72 mm × 34 mm, 2 m long

Radiation magnification: $\frac{3}{2\pi}\frac{\lambda^2}{ab}\frac{1}{\sqrt{1-(\lambda/2a)^2}} = 2.7$

Plasma

Kind : H^+ and e^-

Typical size : $d = 2$ mm, $t = 2$ mm

Electron density : $\sim 10^{13}$

Number of electrons : $\sim 10^{12}$

Acknowledgment

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LIST OF REFERENCES

1. Veksler, V. I. Coherent principle of acceleration of charged particles. CERN Symp. 1956, *1*, p. 80-3.
2. Fainberg, Ia. B. The use of plasma waveguides as accelerating structures in linear accelerators. CERN Symp. 1956. *1*, p. 84-90.
3. Ohkawa, T. Preliminary considerations on the acceleration of particles by reflection of electromagnetic waves. MURA (*) 214, February 6, 1957.

DISCUSSION

CHRISTOFILOS : What energy have you achieved thus far with your experiments?

OHKAWA : The energy designed is about 1 MeV for protons. It depends on the density of the plasma. If there are too many particles one cannot get a high energy because there is too much current.

VEKSLER : In what way are you going to get the isolated plasma bunches?

OHKAWA : The plasma " bunch " is not really a bunch but a section of the guide. We plan to use a vertical discharge at one end and it is for this geometry that the calculations have been performed.

HARRISON : In the first proposal the torus is in the shape of a figure 8. This is to produce a rotational transform in the field. Could this not be done by windings outside the torus as is done in the later models of the Stellarator?

OHKAWA : You mean by helical winding? Well, if one uses the helical winding the usable cross-sections of the tube is reduced because of the shape of the lines of force. In the figure 8 donut we can use the whole cross-section. Since we are not interested in interchange instabilities, we might use a figure 8 as well.

(*) See note on reports, p. 696.