Electron Beam Instability and Stabilization by Dilute Plasma in the Dielectric-Loaded Slab-Symmetric Waveguide

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Abstract

The $V_P \times B$ acceleration scheme with use of a transverse electromagnetic wave (TE-wave) is demonstrated experimentally. However, in order to couple particles with the transverse wave, at present have to use a slow-wave structure because of low electron beam velocity($\sim c/2$). When the electron beam propagated through the slow-wave structure composed of dielectric-loaded slab-symmetric waveguide in this present paper, an orbit of the beam became unstable. We have obeserved the electron beam the instability to investigate its mechanism. As a result, an electron beam in the dielectric-loaded waveguide is deflected to the opposite direction from the material on the waveguide wall. By adding the beam-generated plasma with the slow-wave structure are have observed the electron beam to become stable.

1 Introduction

An electron linear accelerator was proposed, in which a TE-mode wave is used to drive charged particles using $V_P \times B$ acceleration acceleration [1-4], and the experimental demonstration of this acceleration phenomena has been reported elsewhere[5,6]. However, in order to couple particles with the transverse wave, at present have to use a slow-wave structure composed of dielectric-loaded slab-symmetric waveguide, because the electron beam velocity is low ($\sim c/2$). When the electron beam propagats through the slow-wave structure, an orbit of the beam become unstable. In the present experiment, we used the beam-generated plasma in the accelerator for stabilizing the beam orbit. The experimental demonstaration of $V_P \times B$ acceleration scheme with TE-wave assisted by dilute plasma for beam stabilization has been reported[7].

In this paper, we have observed the electron beam orbit precisely in the slow-wave staructure in vacuum and gases respectively, and investigated the mechanism of beam instability and its stabilization by assiting the dilute-plasma.

2 Experimental setup

A schematic view of the experimental setup is shown in Fig.1, and the cross section of the dielectric-loaded waveguide employed here is shown in the inset of Fig.1. The used dielectric materials are Macorl and Folsteright. The dielectric constants of these materials are 5.68 (f = 8.6 GHz) and 7.0 (f = 1 MHz), respectively. The dimensions of the dielectric-loaded waveguide are listed in Table I.

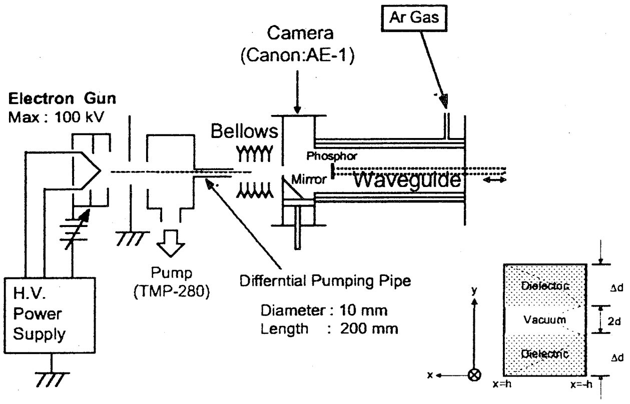

Fig. 1 Experimental apparatus. The inset shows the cross sectional view of the dielectric loaded waveguide.

Table 1
Dimensions of the dielectric-loaded waveguide

Waveguide length	48 cm
Thickness Δd	50 mm
Width $2h$	50 mm
Separation $2d$	13-33 mm
Height $l\ (= 2d + 2\Delta d)$	113-133 mm

The injected electron beam is initially accelerated by a high-voltage DC power supply with a maximum energy of up to 100 keV and current of 1 mA. Here we used a Pierce-type gun with a hair-pin-type cathode.

The vacuum system employes the differential pumping system with one turbomolecular pump. The base pressure in the area of the electron gun, and the dielectric-loaded waveguide is below 1.5×10^{-6}, and 1.5×10^{-4} Torr, respectively. These area is separated each other by a steel pipe with a diameter of 10 mm and a length of 200 mm. There is an oriffice with a diameter of 2 mm at the inlet of the waveguide, because of limitting the electron beam size.

3 Beam envelope

Before observing the electron beam instability, we measured the electron beam current, beam radius, normalized emittance and beam envelope in the waveguide without dielectrics. In order to observe the beam current I_b, we used a Faraday cap with an apartures of 10 mm indiameter and a length of 20 mm. observing the beam radius r_b and normalized emittance ε_n, we used a movable phosphor plate of 14 mm by 14 mm, which moves along the axial direction (z direction). A beam shape on the phosphor plate is recorded photographically after it reflecting the shape by the mirror. The experimental results with the injected electron beam energy of 60 keV, beam current of 0.1 mA and 0.5 mA are listed in Table II.

Table 2
Experimental results of beam parameter

Injected current [mA]	0.1	0.5
I_b [μA]	0.002	0.3
ε_n [mmrad]	1.67	5.30
r_b [mm]	2.6	3.4

Next, we observed an electron beam envelope for the investigation of beam characteristics. In order to observe the beam envelope, we used the same method mentioned above. Typical experimental results for the beam envelope are shown in Fig.2. Here an example of the electron beam figure on the phosphor is shown in the inset.

In this figure, the solid circle is the experimental result with the beam energy of 60 keV and current of 0.1 mA. The solid line denoted "Cal." is obtained from the enevelope equation,

$$r'' - \frac{2}{(\beta\gamma)^3}\left(\frac{I_0}{I_b}\right)\frac{r}{r_0^2} = 0, \qquad (1)$$

where $\beta = v/c$, $\gamma = \{1-(v_b/c)^2\}^{-1/2}$ is Lorentz factor of the beam energy, I_0 is space charge limited current, 17 kA, and r_0 is beam radius at the entrance of the waveguide. I_b is substituted by above experimental result "0.002 μA ". This implies that the expantion of electron beam in the radial direction is caused by the normalized emitance, not by the space charge in electron beam.

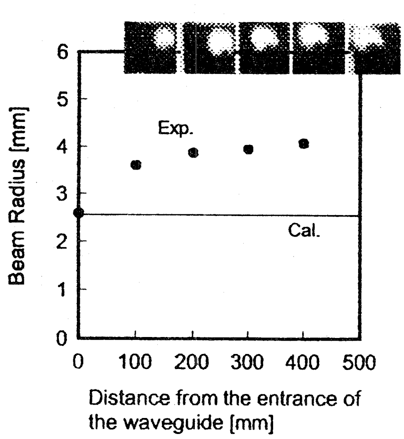

Fig. 2 Electron beam envelope with the incident beam energy 60 keV and current 0.1 mA. Inset shows the beam shape observed at each location.

4 Observation of electron beam instability in the dielectric-loaded waveguide

When the electron beam propagates through the dielectric-loaded slab-symmetric waveguide, an orbit of the beam become unstable[7]. In order to investigate the beam instability, we observed the beam orbit in the waveguide under the several conditions shown below :

- without dielectrics (only metal waveguide)
- loaded only upper-side
- loaded only lower-side
- slab-symmetrically loaded.

An electron beam orbit in the waveguide without dielectrics is also shown in the inset of Fig.2. The center of the beam propagates through the waveguide in stable, without the deflection to the transverse direction.

Next, we observed an orbit the case of loading the dielectrics in either one side of the waveguide with an incident beam energy of 60 keV, and current of 0.1 mA. The distance between the beam center at the center to the waveguide and the surfase of the dielectric materials is 16.6 mm (beam radius : 2.6 mm).

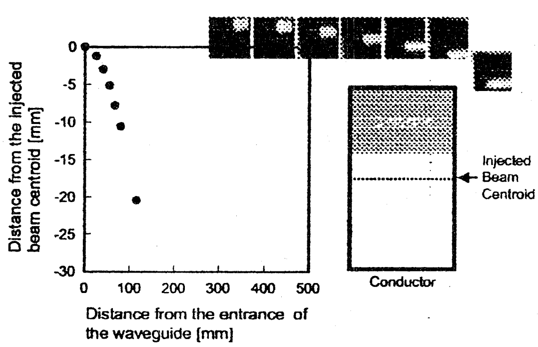

Fig. 3 Observation result of electron beam orbit in the upper-loaded material

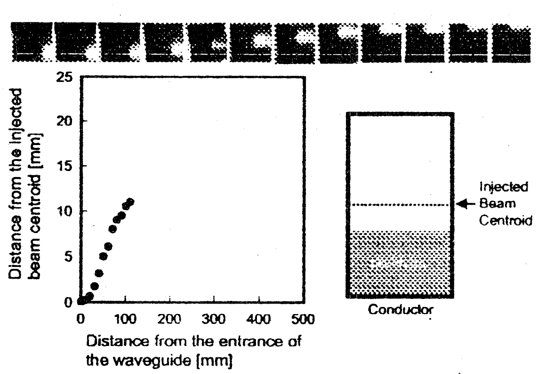

Fig. 4 Observation result of electron beam orbit in the lower-loaded material

A typical experimental result of the beam orbit in the case of upper-loaded and lower-loaded is shown in

Fig.3 and Fig.4, respectively. In these figures, the cross sectional view of the waveguide employed here is shown in the inset, and the beam figures are taken by camera, is showing in the inset. The closed circle in each figure shows a beam centroid on the photograph. From these experiments, we can see that the electron beam is shifted to the opposite direction against the dielectric material, and the beam shape changes to be "flat" along with the propagation from the inlet of the waveguide.

Finally, we observed an orbit in the dielectric-loaded slab-symmetric waveguide with the incident beam energy of 60 keV, and current of 0.1 mA. The distance between the beam center at the inlet of the waveguide and the surfase of the dielectric materials is the same condition with the above experiment.

A typical experimental result of the beam orbit in the case of the slab-symmetric waveguide is shown in Fig.5.

The beam centroid is static near the inlet, but it becomes unstable to be defrected up and down. This feature looks like "rebound" as it approaches to the dielectric material in this waveguide.

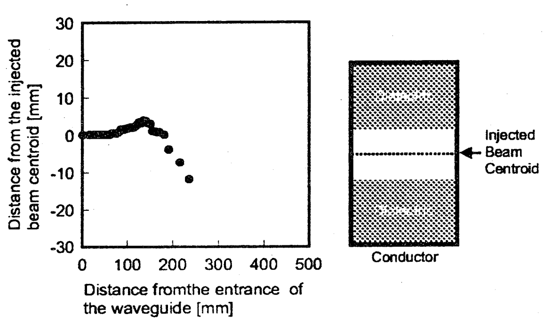

Fig. 5 Observed result of electron beam orbit in the slab-symmetric dielectric-loaded waveguide.

5 Stabilization of the electron beam assisted by dilute plasma

In order to stabilize an electron beam in the slab-symmetric dielectric-loaded waveguide, a dilute plasma is introduced in the waveguide. The used neutral gas is Ar.

It is reported in Ref.[7] that the beam-generated plasma makes the electron beam stable in the slab-symmetric dielectric-loaded waveguide. Here, we observed that the change of location of the beam centroid at certain z posision as a function of gas pressure. A typical example of the experimantal results is shown in Fig.6.

From this result, it is seen that the centroid of the beam returned back to the initial beam position which is observed at the inlet of the wavuguide as a gas pressure increases gradually.

This result implies also that the beam-generated plasma made the electron beam stable.

6 Discussion

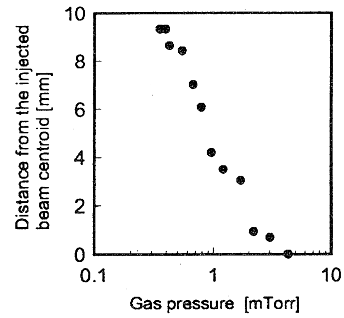

Fig. 6 Change of beam centroid on certain position as a function of the gas prresure

We have descrived that the electron beam instability in the slab-symmetric dielectric-loaded waveguide is caused by the induced space charges by beam current on the mateial surfase in ref.[7].

However, we found that the factor which caused the beam instability was not a space charge inducing by the beam curret. Because the beam current is too small to excite the beam instability, and further-more the beam orbit deflected to the opposite direction from the dielectric material, on which the opposite polarity space charge should be induced. The main factors for deflecting the beam are electric and magnetic field. We discuss that these fields will be electromagnetic field radiated by an electron beam in the waveguide.

Tremaine *et al.* reported that the beam instability occurs by the "wake field" excited by the pulsed electron beam in the slab-symmetric dielectric-loaded waveguige[8]. But, since we use the "coasting DC beam", we don't find whether the wakefield is generated in our experimental setup or not.

In the future, we will perform the observation of the "wave field" in the waveguide.

Acknowledgement

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