PRELIMINARY STUDY OF FILAMENTATION OF INTENSE PULSED ION BEAMS*

X.L. Jiang, S.C. Jiang, Y.B. Piao

Lanzhou University
P.O. Box 44 Lanzhou, China

Abstract

Filamentation instability of the heavy-ion beam has been experimentally investigated by using multiplate chamber which can produce the intense nanosecond-ion beams with energies below 80 keV. The beam pulses propagating in the environment of gas density about 10^{15} /cm^3 without external magnetic field are shredded into many thin magnetic pinches due to transverse velocity spread of the ion beams. The estimation of high power density of beam filaments can be evidentially made by the craters produced by the bombardment of ion clusters on the surface of metallic target. A central filament with some tens of micrometers in diameter is found owing to the attraction of the filaments which proceed to coalesce into a continually decreasing number of larger filaments. The metallic plate electrodes with coaxial holes are proved to be a good guiding channel for the transportation of intense ion beams under certain geometry.

Introduction

As a driver for inertial confinement fusion, a pulsed beam of heavy ion is required to propagate, with almost no disruption, inside the reactor vessel. Possible unstable modes during the propagation of ion beam in the environment of low pressure gas are the resistive hose, the sausage, and the filamentation. The filamentation instability is regarded as the main danger, it has been theoretically studied by many authors[1,2].

The applications of pulsed ion beams with low energies, for instance, below 100 keV, in the areas of the ion implantation, surface amorphization of metallic alloy, direct pumping of gas and chemical lasers show great promise to investigate the behavious of the transportation for such beams[3,4].

The processes of propagation of an ion beam are determined by a large number of parameters: beam radius, beam current, shape and duration of beam pulse, energy of ions, pressure and kind ofgas in the drift tube, its geometry and lateral spread of the beam ions, therefore, it is a complex issure for the quantitative understanding of the processes. The authors of the paper have observed the filamentation of intense pulsed ion beam with duration less than 100 ns, propagating in the 10^{15} /cm^3 dense gas with no external magnetic field. An attempt of making qualitative analysis is aimed in this paper.

---

* Subjects supported by National Science Foundation of China.

Experimental observation and theoretical consideration

The high power density of pulsed ion beams produced by the multiplate chamber(MPC) is evidentially proved by the crater on the surface of the metallic target bombarded by the series of beam pulses. The current density is estimated to be an order of 10^4 A/cm^2 by the effect of metal sublimation(Fig. 1).

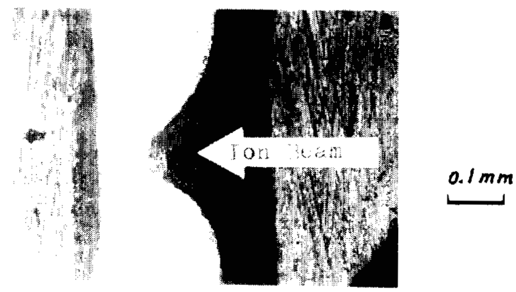


Fig. 1. Micrograph of the cross section of the copper target bombarded by a series of beam pulses with ion energy about 50 keV.

For efficient transportation of a pulsed ion beam with short duration less than 100ns, rapid space charge neutralization is required. A variety of methods have been developed to add negative charge to ion beam to reduce space charge effects[5]

The plasma formed by the collisions of beam ions with background gas, provide the electrons to neutralize the space charge of beam ions in a time scale $1/\omega_p$, where ω_p is the plasma frequence, $\omega_p=(4\pi e^2 n_p/m_e)^{1/2}$, n_p is the plasma density. For a typical plasma density of about 10^{14} /cm^3, the time scale is less than 1 ns.

The intense pulsed ion beam is initially created from the anode plasma, which is formed from the anode material vaporized and ionized by intense electron beam. At this point, it is similar to the processes of the "vacuum diode" so called. The ion charge state distribution varies with anode material and with the gas density. When an ion beam passes through the central holes of the electrode plates, the charge neutralization of the beam ions occurs rapidly with electrons which have been field emitted from nearby surface. Such processes are illustrated in Fig. 2. The energy of the comoving electrons for neutralizing beam ions is estimated about $m_e v_i^2/2$, here v_i is the velocity of beam ions.

The beam filaments extracted from the anode plasma will proceed to coalesce into a continually decreasing number of larger filaments. Such processes could be deduced from the micrograph shown in Fig. 3. The central

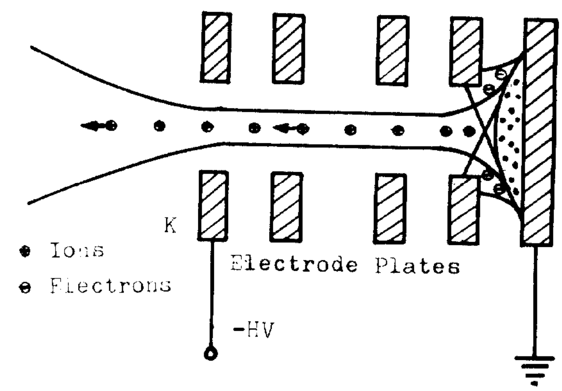
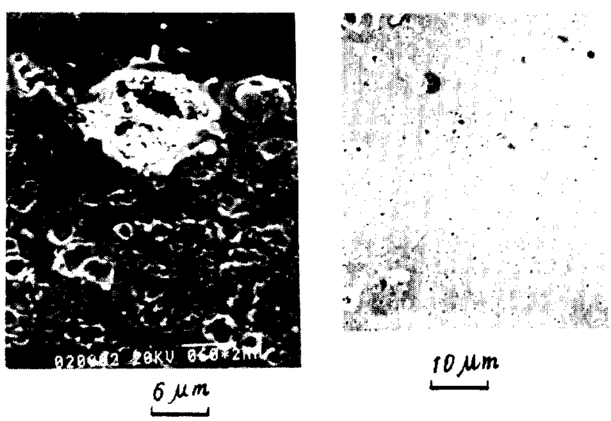


Fig. 2. Schematic diagram of the processes of the production, the focusing, and the filamentation of intense pulsed ion beam in a MPC.



a) b)

Fig. 3. Micrograph of metallic target showing the filamentation of pulsed ion beam, a) average ion energy 60 keV, b) ion energy 40 keV.

filament with larger radius measured about 15 μm, contains most of beam ions(Fig. 3, a)). The ion density in the filament increases until space charge neutralization fails. The small filaments sized up the order of micrometer distribute beside the central filament. From the shapes of the craters formed by the bombardment of filament pulses with high power density, one can deduce that the ion density of the filaments increases roughly as 1/r, here r is the radius in a filament. Furthermore, one might expect more difficulty in obtaining neutrality near the axis[6]. At this point, the beam space charge deters further collapse of the filament.

After passing through the cathode hole of the MPC, the ion filaments blow up rapidly due to lack of field emitted electrons from the electrode surface. The larger filaments are shredded into many thin magnetic pinches. At some centimeters away from the cathode, a few of ion filaments remain. The total beam envelop expands as the current density decreases. The beam spot is shown in Fig. 4. The diameter of the spot contour is about 2.5 mm which is larger than the diameter of cathode hole.

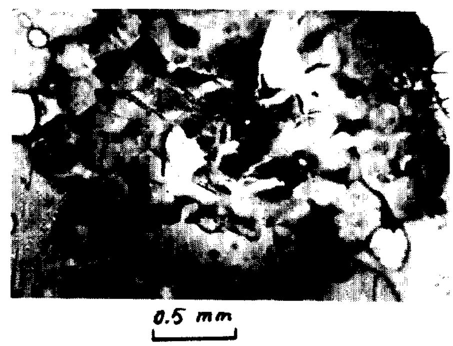


Fig. 4. Micrograph of the witness film surface, which is located 1 cm away of the cathode of the MPC. The witness film consists of Mylar foil covered by thin layer of pentamethoxyl red.

For observing the influence of the beam energy on the filamentation, the pulsed ion beams with a lower energy about 40 keV are used to bombard a metallic target. No crater with the diameter larger than 10 μm has been found in the micrograph shown in Fig. 3. b). There are some other effects, such as the bunching of time of flight, the stripping of beam ions, and the electro-magnetic interaction of beam with the metal electrodes etc., which should be taken into consideration.

According to the effect of the field escalation[7], a ramp of the voltage waveform appearing on the gap near anode, makes that the ions emitted later in the pulse would have a high velocity gradually overtaking those created earlier in the pulse. This would reduce the pulse length and increase the current density[6]. Such process is called the bunching of time of flight.

Since the heavy ion beam transverses the gas medium, it goes through a continous process of stripping, which results in an increase in the beam current.

As the current increases due to the effect of time of flight and the effect of the stripping of the ions, the equilibrium radius of the filament falls off rapidly due to the decrease of the electric stiff of beam ions.

The effect of the wake field on the filamentation of the pulsed ion beam is a complex issue, we can not discuss it in detail in the paper.

Conclusions

As a highly versatile source of the electron beam and the ion beam, the multiplate chamber could be used for the investigation of the filamentation instability of the pulsed heavy ion beam. Theoretical analysis of the filamentation physics is a complex subject because it contains too many parameters. The results of the experimental observation and the qualitative analysis presented in the paper show that

- The fractional charge neutralization for a pulsed ion beam propagating in a channel filled with gas medium, should be equal to unit, i.e., $f_i \doteq 1/\gamma^2 \doteq 1$.
- For efficient transportation of a pulsed ion beam with a time duration less than 100 ns, a reasonable geometry of the transporting channel is required.
- It is expected to have many potential applications in the areas of the solid state Physics, nuclaer fusion etc. for the high power density of the beam filaments.
- A good understanding of the filamentation physics could open a new field to study the micropinching on a supercontracted hot plasma.

It is hopeful for that a systematic investigation of the filamentation will certainly lead to better understanding of the propagation of the intense pulsed ion beams.

References

1. E.P. Lee, S. Yu, H.L. Buchanan, and F.W. Chambers, Phys. Fluids, vol. 23, pp.2095-2110(1980).
2. D. Tidman, in Proceedings of the Heavy Ion Fusion Workshop, edited by L.W.Smith (Brookhaven National Laboratory, Upton, N.Y., 1977), p. 52.
3. X.L. Jiang, S.C. Jiang, K.F. Chen, and T.M. Wang, IEEE Vol.NS-32, pp.3341-3343, Oct. 1985.
4. H. Dwivedi, L. Frey, and H. Lanhoff, Appl. Phys. A39, pp. 155-158(1986).
5. S. Humphries, Jr. and T.R. Lockner, Applied Charged Particle Optics, edited by A. Septier, Academic Press 1983 p.397.
6. G.W. Kuswa, J.P. Quintenz, J.R. Freeman, and J. Chang, ibid, pp.295-394.
7. X.L. Jiang, K.F. Chen, S.C. Jiang, and Y.B. Piao, IEEE Vol. NS-32, pp.1814-1816, Oct. 1985.