INSTABILITY MEASUREMENTS OF AN INTENSE RELATIVISTIC ELECTRON BEAM PROPAGATING IN AN ION FOCUSING REGIME CHANNEL*

R. F. Schneider, K. T. Nguyen, J. R. Smith, and H. S. Uhm

Naval Surface Weapons Center, White Oak
10901 New Hampshire Avenue
Silver Spring, Maryland 20903-5000

Abstract

A several kA, 700 kV, 100 ns electron beam is propagated in ion focusing regime channels. Both pre-formed channels and beam-induced channels have been used. The pre-formed channel is produced with a low energy electron gun in low density (10^{-4} Torr) gases. The beam induced channel is created in 10-160 mTorr gas. Various beam instabilities including ion-hose and two-stream have been investigated.

Introduction

In recent years, space charge neutralized electron beam propagation has been successfully utilized for beam transport in linear induction accelerators.[1] In general a plasma channel is pre-formed by a UV laser discharge through an organic gas such as benzene, or by a low energy electron gun[2] in a variety of gases. The electron beam is injected into the plasma channel and subsequently ejects the low energy plasma electrons from the channel, leaving the positive ions behind so as to neutralize the space charge of the beam electrons allowing the beam to propagate. Because of this dependence on the positive ions, this has been called Ion Focusing Regime (IFR) propagation. One major advantage of this method is obvious in that it eliminates the requirement for strong magnetic fields to transport the beam which may be difficult to align and lead to instability. Unfortunately, an instability has been predicted for IFR propagation. The so-called ion resonance, or "ion-hose" instability[3] is a transverse instability and can be thought of as the electrostatic "hosing" of the electron beam about a stationary ion channel. Another instability which may occur when the pre-ionized plasma channel has a higher electron density than the beam (or fractional charge neutralization, f>1), is the two stream instability. The distinguishing feature of the two is their characteristic frequencies. While the two-stream generally has a frequency near the plasma frequency (GHz range), the ion hose occurs at a much lower frequency (10's MHz range). Both of these instabilitites are investigated in this work. Two methods of producing the IFR channels are employed. In the first, beam electrons are used to ionize the channel in 10-160 mTorr of H_2, He, Ne, N_2, and Ar. In the second, a pre-formed channel is created using a low energy (-400 V bias) electron gun in 10^{-4} Torr of these gases. At these low pressures beam induced ionization is insignificant. Note that much higher pressures are required for beam induced ionization in order to achieve the same channel ion densities during the 100 ns beam pulse.

Setup and Diagnostics

The accelerator used for this work utilizes a high voltage transformer to charge a coaxial 7 ohm water-filled pulse-forming line. When the line is switched to the impedance matched field emission diode, a nominal 700 kV, 100 kA, 100 ns electron beam is generated. The diode consists of a 7.5 cm diameter plane carbon cathode and a carbon anode with a 2 cm diameter hole on axis. During the beam induced channel experiments, the drift chamber is filled with gases above 10 mTorr, hence a titanium anode foil is used to seperate the drift chamber from the diode vacuum. Note that in the pre-formed channel experiments, the channel will extend to the cathode surface. Approximately 2 kA of the beam is injected into the gas-filled drift region in both cases. The radial profile and root-mean-square emittance of this beam have been measured with an emittance meter and it was found to exhibit a radius of 7-12 mm and a transverse temperature of 35 keV.

Passively integrated Rogowski coils are used to measure the net current, and a magnetic probe array is utilized to determine the current centroid position of the beam. See Fig. 1. The probe array consists of four identical magnetic probes of single turn, oriented to detect the B_θ component of magnetic field produced by the electron beam. They are equally spaced along the circumference of the drift tube interior with a mean radius, R. The signals from the probes are transmitted to the screen room with cables of identical length and then integrated with an integrating time constant (τ). The resulting signal from each probe is a result of the net current inside the drift tube and its image,

$$V = \frac{B_0 A}{\tau} \left(\frac{1-\rho^2}{1+\rho^2 - 2\rho\cos\theta} \right) , \qquad (1)$$

where B_0 is the magnetic field at the probe position with current on axis, $\mu_0 I/2\pi R$, A is the probe's cross sectional area, $\rho = r/R$ is the fractional distance off axis, and θ is the angle between a radius to the probe and the line from the system axis to the current centroid position. When two diametrically opposing probe signals are differenced, the resulting signal is given by,

$$V_{diff} = \frac{4B_0 A\rho\cos\theta}{\tau} \left(\frac{1-\rho^2}{(1+\rho^2)^2 - 4\rho^2\cos^2\theta} \right) . \qquad (2)$$

For small displacements, $\rho \ll 1$, the resulting signal is proportional to the displacement,

$$\Delta x = k\, V_{diff} , \qquad (3)$$

where $\Delta x = \rho R\cos\theta$, and the constant of proportionality is given by,

$$k = \frac{R\tau}{4B_0 A} . \qquad (4)$$

The probes are calibrated by comparison with a current viewing resistor of known value. In addition, a check is performed to verify that an on axis current will give no signal when the voltage waveforms of two diametrically opposing probes are passed through a differential oscilliscope plug-in amplifier. Both of these are accomplished with the following method. A 0.005 Ω current viewing resistor is connected to a graphite block with an aluminum rod placed on axis. The graphite block

*Work supported by Independent Research Fund at Naval Surface Weapons Center.

placed just outside the anode aperture collects the current which is injected into the drift region by the accelerator. The signals from the magnetic probes are passively integrated with RC integrators. The current traveling along the aluminum rod on axis is simultaneously recorded by the current viewing resistor and the magnetic probes. The calibration of the Rogowski coil is accomplished similarly. The Rogowski is integrated with a passive RC integrator and compared with the current viewing resistor signal.

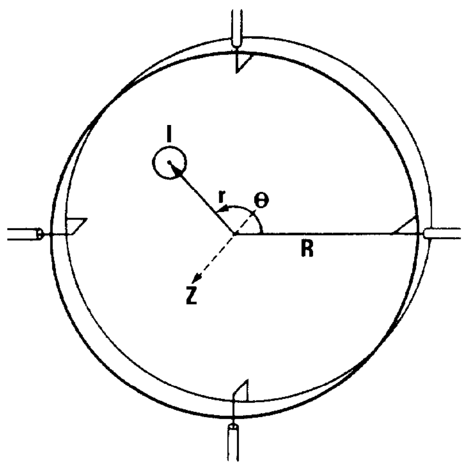

Figure 1. Current centroid displacement probe geometry.

Beam-Induced Channel[4]

In this experiment, the relativistic electron beam is utilized to ionize the channel. The beam space-charge subsequently ejects the plasma electrons leaving the ions to charge neutralize the beam allowing it to propagate. The experiment is performed with 10, 20, 30, 40, 80, or 160 millitorr of H_2, He, N_2, Ne, or Ar as filling gas. Transverse displacements are detected from the probe array in all gases especially at the lower pressures. See Fig. 2 which shows the experimental setup with a current and displacement trace. In some cases the instability is so violent that the current abruptly drops as if some portion of the beam had been lost to the drift tube walls.

The lower pressure limit of the occurance of this instability seems to be determined by the fractional charge neutralization (f) which allows the beam to propagate. At the higher pressure limit the displacement is not of an oscillatory nature, but rather an offset to one side. Also at higher pressures a noisy, high frequency displacement signal is present, evidence of a two-stream instability. This signal may be caused by some combination of actual transverse two stream displacements and/or microwave generation by the two stream instability which is picked up by the probe's B-dot loops.

Interpretation of the results of this experiment depend on the correct understanding of the role of noise in "tickling" the instability.[e] Inside of this conducting drift tube only certain modes of noise will survive corresponding to integral half wavelengths fitting into the 1 meter drift tube length. The beam produces an increasing fractional charge neutralization during the pulse until a certain f is reached at which time the ion resonance wavelength corresponding to this f is in resonance with the noise surviving in the drift tube and the instability occurs. Hence, inside this conducting drift tube the ion resonance wavelengths observed are those in which the half wavelength will fit into the drift tube an integral number of times. Complete details of this theory which predicts frequency of oscillation as well as the time from the beginning of the electron beam to the onset of the instability may be found in another paper at this conference.[5]

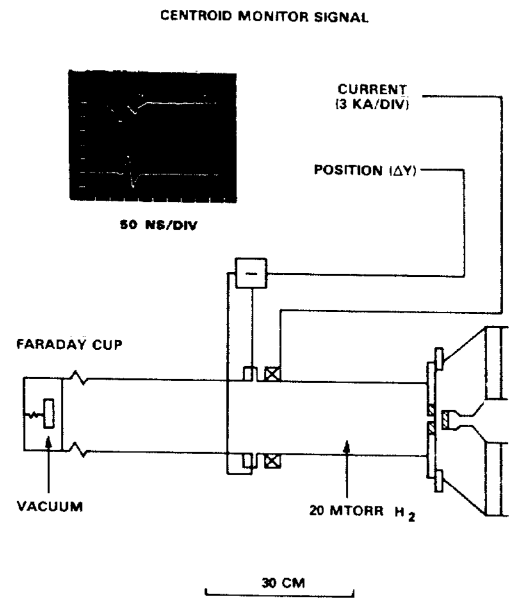

Fig. 2. Beam induced channel experiment showing the location of diagnostics and a 20 mTorr H_2 result.

Pre-Formed Channel

In this experiment, the electron beam is injected into a pre-formed plasma channel.[6] The channel is created in flowed gases at approximately 10^{-4} to 10^{-5} Torr by low energy electron impact ionization. The electrons are boiled off a hot filament which is biased to -400 Volts with respect to the grounded drift tube which is 2.25 meters long and 15 cm in diameter. The filament is located 2 meters downstream of the diode. In the propagation region the channel is contained by a solenoidal magnetic field of approximately 100-140 Gauss which extends from the filament to the cathode. The graphite anode has a of a 2 cm aperture on axis.

Diagnostics are placed from the diode to the filament at the following locations: Rogowski coils at 34 and 160 cm, displacement monitor at 97 cm. At the end of the drift tube, either a glass window or a metal endplate is used. The glass window is used when observing strong X-band microwave signals with a microwave horn and crystal detector. These microwaves may be produced by the two stream instability since their frequency is approximately the beam plasma frequency. This diagnostic gives an indication of whether f is greater than or less than unity.

Typical results of the displacement and current signals are shown in Fig. 3. These Ar and H_2 results correspond to f values of approximately 0.6 as measured 20 cm downstream of the diode. The traces shown in Fig. 3 were obtained with a metal endplate. As mentioned previously, this endplate maintains a shielded enclosure in which to perform the experiment and has an effect in obtaining clear results. Both Ar and H_2 discharges show oscillations in the ion resonance frequency regime. The Ar, and to a lesser degree the H_2 signals show evidence of two stream as well, indicating that the channel f is both greater than and less than 1 due to the nonuniformity of the channel.

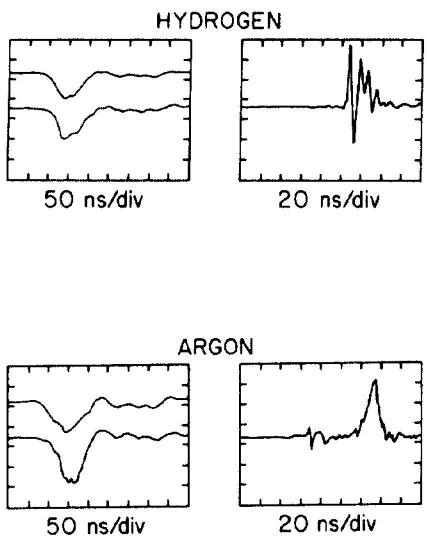

Fig. 3. Pre-formed channel experimental results. The current traces on the left are 1.35 (upstream) and 1.60 (downstream) kAmps/div. The displacement trace is on the right. The calibration for small displacements is 15/I(kA) cm/div.

Discussion

The presence of both two stream and ion resonance with the pre-formed channel may be a result of an longitudinal nonuniformity of the channel. At larger distances from the filament, i.e., near the diode, the f may decrease depending on diffusion and atomic processes. It was noted that higher pressures, typically around 1 mTorr led to more uniform channels along the z axis. This was also confirmed by Langmuir probe measurements.

The channel needs to be diagnosed carefully in order to see the effects of longitudinal uniformity. Understanding of atomic processes important in the channel formation such as recombination rates are not yet complete enough to predict under what conditions a channel would be uniform. A non-uniform channel in our 2.25 meter tube may provide for natural detuning of the long wavelength ion resonance oscillations. In addition the presence of two-stream in one portion of the channel (near the filament) and ion resonance in the other portion (near the diode) with the displacement probe near the center made interpretation of the data difficult.

In conclusion, we have observed transverse oscillations near the ion resonance frequency (10's of MHz) of an electron beam propagating in the ion focusing regime. In a beam induced channel experiment, these oscillations occur generally at pressures which would yield a fractional charge neutralization of less than 1 with our electron beam. At higher pressures, the current is often displaced to one side and shows no oscillatory behavior. High frequency signals, evidence of two-stream instability, are observed at pressures which would give f greater than 1. A pre-formed channel has been prepared into which our electron beam is injected. The pressure at which the channel is formed is such that beam induced ionization may be neglected. The nature of the channel uniformity may be important since both two stream and ion resonance oscillations occur during the same electron beam discharge.

REFERENCES

1. D. S. Prono, et. al.,"Recent Progress of the Advanced Test Accelerator," IEEE Trans. Nucl.Sci. NS-32, 3144, 1985.
2. S. L. Shope, C. A. Frost, C. A. Ekdahl, J. R. Freeman, D. E. Hasti, G. T. Leifeste, M. G. Mazarakis, R. B. Miller, J. W. Poukey, and W. K. Tucker, "Ion Focused Transport of Relativistic Electron Beams," IEEE Confernce Record - Abstracts, 1986 IEEE International Conference on Plasma Science (IEEE, New York, 1986) p. 46.
3. H. S. Uhm and R. C. Davidson, "Kinetic Description of Coupled Transverse Oscillations in an Intense Relativistic Electron Beam - Plasma System," Phys. Fluids 23, 813, 1980.
4. R. F. Schneider and J. R. Smith, "Transverse Oscillations of an Electron Beam Propagating in the Ion Focused Regime," Phys. Fluids 29, 3917, 1986.
5. K. T. Nguyen, H. S. Uhm, R. F. Schneider, and J. R. Smith, "Relativistic Electron Beam Ion Hose Instability in a Beam Induced Ion Channel," Proceedings of this conference, 1987.
6. J. R. Smith, R. F. Schneider, K. T. Nguyen, and H. S. Uhm, "Plasma Channels used for Relativistic Electron Beam Transport," Proceedings of this conference, 1987.