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Measurement of Ion Transverse Energy and the Electric Field in the Acceleration Gap of a Magnetically Insulated Diode

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Abstract

The electric field and the ion transverse velocities in the gap of a Magnetically Insulated Diode were measured for the first time using visible emission spectroscopy. The technique used utilizes line emission from Ba^+ ions accelerated in the gap. The observed Doppler line broadening and the Stark shift yielded the distribution of the ion velocities parallel to the electrodes and the electric field magnitude, respectively. Transverse ion energy of a few hundred electronvolts and an electric field about 1.6 times larger than the vacuum field were measured. The inconsistency of the results with a one-dimensional equilibrium is discussed.

As the range of applications of intense pulsed ion beams has expanded to include such diverse fields of research as inertial[1] and magnetic confinement[2] fusion, gas laser excitation,[3] and material science[4] it has become more important to understand the physics of the operation of the ion diodes. Theoretical models have been developed which predict the electric field and potential distribution within the accelerating gaps of such diodes.[5-7] However, the difficulties of making measurements within the centimeter size gaps have prevented a comparison of theoretical predictions with experimental results. In this letter, we report results of a pilot experiment which shows that measurements of the electric field as a function of position in an ion diode can be made by monitoring the Stark shift of an emission line of an accelerating ion. Furthermore, the Doppler broadened width of the line can be used to infer transverse velocities of the ions as a function of position in the diode gap. Previous measurements of ion transverse velocities using other methods have been made only outside the ion acceleration region.[8] In the present experiment, the Stark shift and Doppler broadening measurements were made in a magnetically insulated ion diode. However, the visible spectroscopic techniques used here, based upon the work of Maron and Litwin,[9] should be applicable to ion diodes of any kind.

Local measurements of the ion transverse velocities and the electric field within the acceleration gap of an ion diode are of great value since the source of ion beam divergence and operating characteristics of the gap may be inferred from them. For example, it should be possible to distinguish between source limited and space charge limited

conditions[10] at the anode, whether nonuniformities in the anode plasma[11] are responsible for most of the ion beam divergence, and the extent to which existing theoretical models[5-7] of ion diode operation describe the behavior of practical diodes.

The principles of the measurements in the present experiment are as follows. The accelerating ions, drawn from a surface-flashover plasma[12] in a magnetically insulated ion diode, spontaneously emit light while traversing the diode gap. The emission lines of the ions will be shifted from their natural wavelength because of the Stark effect due to the diode electric field. If the light is viewed transverse to the acceleration direction, the width of the line will mostly be determined by Doppler broadening due to ion transverse velocities, since the particle densities (10^{12}-10^{13}/cm^3) do not contribute significantly to the line width.[13] Thus, by localizing the region in the ion diode from which the emitted light is collected, the electric field can be determined from the Stark shift, and the ion beam transverse velocities can be inferred from the Doppler broadening, as a function of position. Since the ion temperature in the anode plasma is relatively low[14] ($\lesssim$1 eV) only electronic states within a few eV of the ground state are significantly excited. As a consequence, since the ion density in the gap is low ($\lesssim 10^{13}$/cm^3), the detection of spontaneous emission requires the use of ions having transitions from levels which are close to ground state. Therefore, we have chosen the 7s $\rightarrow$ 6p transition of the Ba^+ ion (4525 Å wavelength), which has a Stark shift of about 1.3 Å in an electric field of 1 MV/cm. The lower lying 6p $\rightarrow$ 6s transitions have a Stark shift of only about 0.1 Å under the same condition. The Barium ions

were produced by the use of BaF_2 crystals as the surface-flashover material[15] in the magnetically insulated diode. To summarize the results, an electric field of about 1.5 MV/cm was inferred from the Stark shift of the 4525 Å line measured over the range 0.25 mm to 1.25 mm from the anode in a 400 kV ion diode. The width of the lines implied transverse velocities corresponding to a temperature of about 350 eV 1.25 mm from the anode when the anode was damaged by 200-300 previous pulses; the line width measurement was limited by the spectrometer resolution when the anode was undamaged (implying <100 eV of transverse temperature).

Figure 1 shows a schematic diagram of the diode and the optical arrangement. The barium beam was produced using a small magnetically insulated ion diode powered directly from a Marx bank as described by Neri et al.[15] Six 5-mm-wide, 1.8-mm-thick BaF_2 crystals filled 5-cm-long grooves in an aluminum anode. The grooves were separated by 0.6 mm of aluminum, and were oriented parallel to the 12.6 kG applied magnetic field which inhibited electrons from crossing the 4.5 mm diode gap. The critical magnetic field[6] for magnetic insulation at the applied voltge of 400 kV is 5.7 kG. When the high voltage pulse was applied, a surface-flashover plasma formed on the BaF_2 surface from which the beam ions were extracted. Magnetically insulated biased (-300 V) Faraday cups were used to monitor the ion current density. The ion emission started during the 50 nsec rise of the voltage pulse, and current densities up to 50 A/cm^2 were seen during the pulse. Detailed analysis of the ion beam in previous experiments[15] with the same machine using a BaF_2 anode showed that Ba^+ ions were the majority species, although there we F^+ and Ba^{++} ions as well.

Spontaneously emitted light from the entire 3.5 cm x 5 cm area in front of the anode was viewed anti-parallel to the insulating magnetic field direction (Fig. 1). It was dispersed by a 0.5-meter, f/10 Jarrell-Ash spectrometer. The lens L in Fig. 1 (focal length ~5 cm, f/3.5), was located 130 cm away from the center of the dielectric-anode region. The self-absorption of the 7s → 6p transition was calculated to be negligible for the Ba^+ ion number density in the diode gap ($\leq 10^{13}/cm^3$). The mirror, M, could be moved so that the focal point of lens L was at different distances from the anode. One photomultiplier tube (RCA C31034) was used to measure light at the exit slit of the spectrometer. With a 20 μm-slit the spectral resolution was 0.35 Å, and the spatial resolution in the diode gap was less than 0.7 mm, both determined experimentally. The 4525 Å line profile at different positions was obtained by scanning the line on a shot-to-shot basis. This introduced an uncertainty in determining a line profile due to shot-to-shot fluctuations. The errors were ±0.2 Å and ±0.1 Å in obtaining the line-width and the line-center, respectively. The error bars could have been reduced by taking a large number of shots at each wavelength position. However, the approximately 400 shot life of a BaF_2-anode prevented the use of this method. Instead, profiles were repeatedly obtained with different BaF_2 anode surfaces to reduce the uncertainty of the results.

Figure 2 shows typical line profiles of the 4525 Å line viewed at four different positions from the anode at 160 nsec after the start of the voltage pulse; all were obtained with the same BaF_2 anode. The uncertainty in determining the position of the anode was ±0.5 mm. The

time delay between the beginning of the voltage pulse and the first observation of light even 1.25 mm away from the anode was less than 20 nsec. This indicated the presence of multikilovolt Ba^+ ions even ignoring the normal 10-15 ns turn-on time of the surface flashover anode plasma.[14]

In Fig. 3, the total intensity of the line is plotted as a function of distance from the anode surface at three different times. As the line intensity fell off rapidly with distance into the gap it was not possible to obtain line profiles throughout the anode-cathode gap. This figure also shows that the light emitting region was significantly wider than the spatial resolution.

Figure 2 shows that the 4525 Å line was shifted to longer wavelength by 3 Å ± 0.5 Å. The ±0.5 Å uncertainty is from the determination of the location of the unshifted line center by a calibration of the spectrometer using various nearby spectral lines. Since the electric field can be

$$E\left(\frac{MV}{cm}\right) = \left(\frac{\Delta\lambda(Å)}{1.3}\right)^{1/2}$$

for this barium line,[9] the implied electric field is (1.5 ± 0.15) MV/cm. (In addition to line shift measurement error, there is a 20% error in the calculated Stark shift of 1.3 Å at 1 MV due to the 20% uncertainty in the oscillator strength of the transition.[9]) The profiles in Fig. 2 also show that the line center 1.25 mm from the anode surface was shifted by 0.2 Å ± 0.1 Å more than at 0.25 mm, and that the line width was greater than the 0.35 Å instrument resolution, with the width tending to increase as the observation point was moved further

from the anode. Although the errors associated with each line center and line width determination were relatively large, the quoted results were confirmed by repeating the scans. The line center and line width at each position did not change significantly during the 100 nsec of the voltage pulse during which measurements could be made. After 160 nsec into the pulse, the rapidly rising continuum background due to plasma light in the gap made the measurement impossible. As seen in the inset in Fig. 1, the voltage pulse was very constant during the first about 200 ns of the pulse. The line broadening was small, less than the 0.35 a instrument resolution, with a new anode, and it gradually increased as the anode was used, reaching the level shown in Fig. 2 after 200-300 pulses.

There is also some asymmetry in the line profiles shown in Fig. 2. This may be due to the increased Stark shift on the cathode side of the 0.7 mm wide observation region due to increased electric fields towards the cathode. The varying light intensities in the diode gap as shown in Fig. 3 must also be folded in. The contribution to the line broadening by this variation of the electric field in the region observed in each measurement should be small since the relative Stark shift observed over the entire 1.25 mm light emitting region was only 0.2 Å. Therefore, the Doppler broadening at 1.25 mm distance (Fig. 2) is about 0.55 Å ± 0.2 Å (assuming the instrument profile and the Doppler broadening are both Gaussian), which corresponds to a transverse energy of 350 eV ± 200 eV. This indicates that the fully accelerated Ba^+ beam had gained a divergence of 1.7° ± 0.6° within 1.25 mm of the anode surface. However, whether there was any more divergence gained beyond his point

by the Ba^+ ions could not be determined because of the lack of light intensity further away from the anode. The instrument-resolution-limited profiles obtained with new anodes corresponded to <100 eV of transverse temperature. Line profiles obtained in a later series of pulses using another well used anode showed even more broadening (~0.7 Å) at about the same distance (≈1.25 mm) from anode. This corresponded to 500 eV of transverse energy. The broadening increased from 0.5 Å to 0.7 Å from 0.25 mm to 1.25 mm. These observations suggest that the beam quality degrades as the anode surface is damaged over a large number of shots.

It was expected that the measured width of the observed line would be affected by Zeeman splitting because of the 12 kG diode magnetic field. Given the observation direction along the magnetic field lines, the two side components of the normal Zeeman pattern, separated by about 0.35 Å, should be seen. Since the system spectral resolution is 0.35 Å the observed line should have a width of ~0.7 Å minimum due to the Zeeman splitting. However, in our case the Stark shift is an order of magnitude larger than the Zeeman splitting. Therefore, it may be that the normal Zeeman pattern is not obtained.[16] We are continuing to look into this point.

In addition to demonstrating the feasibility of making local measurements in the diode gap with visible spectroscopy, the results of the present experiment imply two things about the ion diode used here. Firstly, a high level of shot-to-shot reproducibility (a few percent in the electric field) is indicated for the diode pulse since the line profiles were obtained by scanning the line over many pulses. Secondly,

there is a small (only about 3%) increase in the electric field between the two positions 0.25 mm and 1.25 mm. This is not consistent with the predictions of the one-dimensional equilibrium derived by Antonsen and Ott,[5] in which space charge limited ion emission from the anode and a well defined cathode sheath are assumed. Also, we observed an enhancement of a factor of 1.6 ± 0.2 in the electric field in about a 1 mm region near the anode relative to the vacuum field for our gap, whereas the solution of Antonsen and Ott predicts an electric within a few percent of the vacuum field in that region. This together with the fact that the anode suffers damage over the course of many pulses, which is probably due to electron bombardment,[11] suggest that both assumptions underlying the equilibrium solution are not valid in our experiment.

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Figure Captions

Fig. 1 Schematic diagram of the diode assembly and the optical setup are shown together with typical diode voltage trace (inset).

Fig. 2 Typical line profiles of the 4525 Å line of Ba^+ obtained at 160 nsec into the diode voltage pulse.

Fig. 3 Total line intensity of the 4525 Å line as a function of distance from the anode at various times into the diode voltage pulse.