Measurements of the Electric Field Distribution in High-Power Diodes

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We have measured the electric field in the high-voltage gap of a magnetically insulated intense–ion-beam diode by observation of the Stark shift of line emission from ions accelerating in the gap. The electric field distribution as a function of distance from the anode plasma has been compared with a theoretical model and is not consistent with a well confined electron sheath near the cathode. Furthermore, a very rapid gap closure at early time in the pulse was clearly observed.

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Intense electron- and ion-beam diodes operating in the 10^8–10^{13}-W range have the common feature that electrons and ions (drawn from the cathode and the anode plasmas, respectively) are accelerated by 0.1–10-MV/cm electric fields in gaps of a few millimeters to a few centimeters in width.[1,2] In magnetically insulated ion diodes (MID's), a magnetic field is applied parallel to the electrodes in order to inhibit the electron flow to the anode, thereby enhancing the efficiency of ion-beam generation. Equilibrium solutions[3,4] for the charge and potential distributions and the beam current densities in MID's have been obtained for one-dimensional (i.e., infinite planar) accelerating gaps. However, the charge flow in a real MID does not obey these solutions, and substantial electron leakage currents can flow, presumably due to the finite size of the diodes,[5] nonuniformities of the applied magnetic field,[2,6] and nonuniformities of the plasmas in the diodes.[7,8]

Measurements of conditions inside high-power diodes are difficult because of the small gap spacings and high-voltage stresses. Prior to the present work, only the plasmas in the diodes have been studied by spectroscopic and interferometric techniques.[9-11] The present work was motivated by a suggestion[12] that the electric field in the acceleration gap of a high-power ion diode can be determined by measurement of the Stark shift of line emission from ions drawn from the anode plasma and accelerated in the gap, as shown schematically in Fig. 1(a).

In this Letter we report measurements of 0.4–1.5-MV/cm electric fields in the 0.5–1-cm gap of a MID by use of ion spontaneous emission. At each position x [see Fig. 1(a)], the measurement integrates over the entire plane of points at a given distance from the anode in the planar MID[13] illustrated in Fig. 1(b). The insulating magnetic field ($B_z = 5$–8 kG) was produced by an external current through the single-turn cathode coil. The dielectric anode surface was made up of a $140\times 50\times 1.6\text{-mm}^3$ polyethylene sheet (with the long dimension parallel to B_z). The results are not consistent with a well-defined electron sheath near the cathode.[3,4] Furthermore, we see a rapid gap closure at early time in the voltage pulse which slows down considerably later on.

Measurements of the electric field E by emission spectroscopy require that ions being accelerated out of the anode plasma be in the upper level of a transition which has a lifetime of about the ion transit time in the gap (a few nanoseconds), and that the Stark shift of the resulting emission (due to the second-order Stark effect) exceed the Doppler broadening from the ion transverse velocities, but be smaller than the spectral distance to nearby lines. For a large Stark shift in light ions in the $\lesssim 1.5$-MV/cm electric field range of interest here, emission from a high-lying level should be sought. We have used the Al^{++} ions produced in the anode plasma from a light aluminum coating on the polyethylene anode which resulted from aluminum blown off the diode electrodes. The estimated density of this species in the accelerating gap is $\lesssim 10^{11}/\text{cm}^3$.

The Stark shift of the Al^{++} $4d$ level (20.6 eV), mainly due to the interaction with the $4f$ level, is observed in the transition to the almost unshifted $4p$ level. Most of our measurements were made on the $4d_{5/2} \rightarrow 4p_{3/2}$ (4529.2 Å) line which splits into three

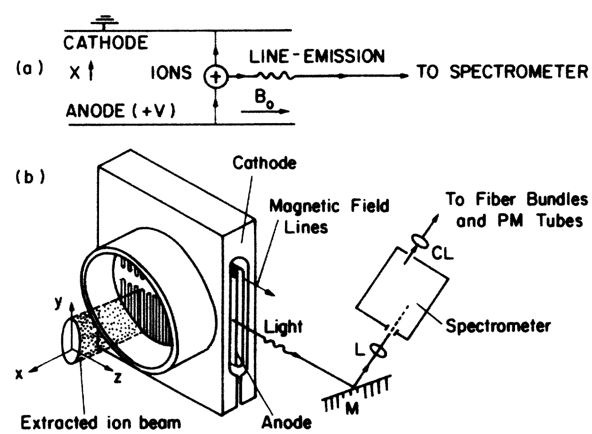

FIG. 1. (a) Method for measurement of the electric field in the acceleration gap of a magnetically insulated diode. (b) Schematic illustration of the planar MID and the optical arrangement. The distance of the observation region from the anode is varied by movement of the mirror M in the x direction.

shifted components which are, in turn, slightly split by the Zeeman effect. The oscillator strengths for the Al^{++} ion were calculated[14] with a 20% uncertainty. [The uncertainty affects the magnitude of E, but not the shape of the distribution $E(x)$.] Line radiation emitted in the z direction from a plane parallel to the $14\times 5\text{-cm}^2$ anode was directed by the mirror M and the lens L onto the input slit of a 0.5-m spectrometer [see Fig. 1(b)]. The spatial resolution perpendicular to the electrodes, and the spectral resolution, were 0.6 mm and 0.7 Å, respectively. By use of the cylindrical lens CL, the spectrometer output was magnified by a factor of 10 perpendicular to the output slit and focused on an array of seven fiber bundles. Light transmitted by each bundle was recorded by a photomultiplier-multiplier oscilloscope system with a temporal resolution of 8 ns. Thus, seven points of the spectral line profile were usually obtained, allowing the electric field to be inferred as a function of time for each position x with a single pulse of the ion diode. When E was $\geqslant 1.2$ MV/cm, the shifted line profile was sufficiently broad that the complete profile had to be obtained on 2 successive shots.

The Al^{++} line profile from the anode plasma is shown in Fig. 2(a). Each point represents the signal recorded by one channel. The profile is unshifted, consistent with previous measurements[15] and the known[10] anode-plasma density of less than $6\times 10^{15}/\text{cm}^3$. The observed anode-plasma linewidths were determined by the system spectral resolution.

Emission from the ions in the diode acceleration gap was a few hundred times smaller than that from the plasma on the electrodes, as expected. The red-shifted gap emission of the 4529-Å line is shown by the typical profile given in Fig. 2(b). Measures were taken to discriminate against scattered anode-plasma light which ultimately reduced the signal at the zero-field wavelength (4529.2 Å) to the level shown. Most of the remaining signal at that wavelength was determined to be due to scattered anode-plasma light and so it was ignored when the data were analyzed. Emission from the gap began coincident with the start of the anode-plasma signal, consistent with the short ion transit time into the gap. Later on in the pulse, at each position in the gap, when the anode plasma had expanded enough to reach that point, the line emission became unshifted and much more intense, as expected.

The theoretical emission along the magnetic field was calculated with account taken of contributions of the electric field, E, the magnetic insulation field, B_z, and the Doppler broadening of the line.[16] For B_z, we used the value of the externally applied magnetic field, since diamagnetic effects in our diode are too small[3,4] to affect the shifted pattern. The electric field was inferred from a "least squares" fit of the calculated shifted emission pattern to the measured points. Since this procedure assumes a single value for the electric field, which could vary over the observed region, the $E(x)$ should be considered a mean value.

The electric field at each position was repeatable to within 20% over the useful life of the anode (about 100 discharges). Thus we were able to obtain the electric field distribution across the entire diode gap with one diode setup. Figure 3 shows an $E(x)$ profile obtained using an anode-cathode gap $d_0=7.5$ mm and $B_z=8.0$ kG. The solid anode surface is at $x=0.0\pm 0.5$ mm. The points at $E=0.2$ MV/cm are shown with a 100% error as 0.4 MV/cm is the lower limit of the electric field we could measure with the

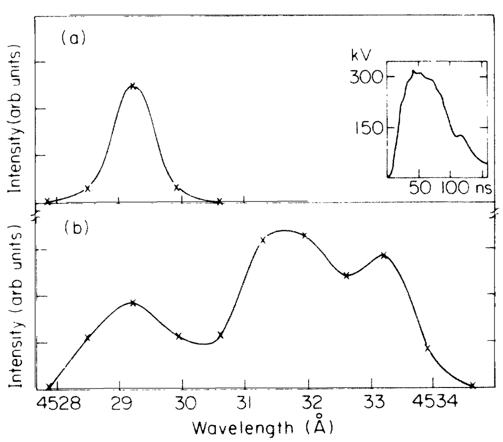

FIG. 2. Measured profiles of the $4d_{5/2}\rightarrow 4p_{3/2}$ Al^{++} emission (zero-field wavelength is 4529.2 Å). The initial anode-cathode gap is 6.5 mm, peak diode voltage 300 kV, and $B_z=8.4$ kG. The spectral window of each fiber channel is 0.67 Å. (a) Emission from the anode plasma: $x=1.5$ mm, $t=70$ ns after the start of the diode voltage pulse, the trace of which is shown in the inset. (b) Emission from the acceleration gap: $x=3.75$ mm, $t=65$ ns. The lines indicate the trend.

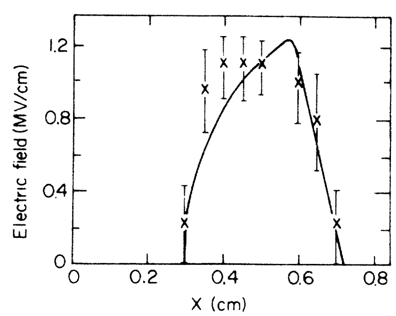

FIG. 3. Measured electric field distribution $E(x)$ at $t=35$ ns. The initial anode-cathode gap is 7.5 mm (solid anode and cathode surfaces are at $x=0$ and $x=7.5$ mm, respectively). Each point is an average of two discharges. The curve shown is the theoretical (Ref. 4) $E(x)$ obtained with use of the measured B_z (8.0 kG), V_d (360 kV), and the actual diode gap $d=4.25$ mm.

setup used. The diode regions between these points and the closest electrode are occupied by the diode plasmas; these regions gave intense and unshifted line emission.

An upper limit for the actual diode gap d (i.e., the distance between the diode plasmas) is obtained from the distance between the positions at which intense, unshifted anode- and cathode-plasma light is observed. A lower limit is the distance between the positions on the anode and the cathode sides of the gap in which an electric field certainly larger than zero (i.e., >0.4 MV/cm) is observed. These limits determined an uncertainty $< \pm 0.75$ mm in inferring (for each time instant) the actual diode gap d from the measured $E(x)$ profiles. The diode voltage $V=\int_0^{d_0} E(x)\,dx$, obtained from an integration of $E(x)$ across the gap, is 365 kV for the profile shown in Fig. 3. The diode voltage V_d measured by the capacitive monitor at the output of the pulsed power generator at the same time instant was 355 kV. The difference is well within the experimental errors of V and V_d.

The main source of measurement error in the present experiments is the photon noise due to the weak light signal. An uncertainty in the inferred electric field also results from the finite spectral width of each of the fiber channels and from the range of electric fields that gave a calculated emission pattern that fits the experimental profile with reasonable accuracy.

We confirmed results by also observing other Al^{++} emission lines from the gap. The $4d_{3/2} \rightarrow 4p_{1/2}$ transition (4512 Å) was also shifted as expected, yielding the same electric field inferred from the 4529-Å line. In addition we observed two Al^{++} transitions which should not have been shifted by the electric field, and they were not. The latter also yielded the Doppler line broadening due to the ion transverse velocities in the gap.[16] This broadening was taken into account in the calculation of the shifted pattern for the Stark-shifted lines. However, it had little effect on the inferred values of E since the broadening was smaller than the line Stark shift.

Figure 3 shows that at $t=35$ ns, the actual diode gap d (4.25 ± 0.75 mm) was already considerably smaller than the initial gap. Since the 4529-Å emission from the anode plasma started at $t \approx 15$ ns we infer an expansion velocity of 10 ± 5 cm/μs for the electric-field–excluding anode plasma. This early-time expansion velocity is significantly larger than the few centimeters per microsecond value obtained by observation of the profile of the H_β line.[10] Thus, our results show that the electric-field–excluding anode plasma propagates faster than the 10^{15}-cm^{-3} electron-density plasma front which was observed in Ref. 10. The present measurements show, however, that at later times ($t>35$ ns) the anode-plasma velocity decreases by an order of magnitude. The cathode plasma expands at about 2 cm/μs throughout the entire pulse. Hence during most of the pulse (35 ns $< t <$ 90 ns) the actual diode gap changes by only a small amount. Therefore, for the pulse shown, the diode is operating at about $B/B_* = 1.4$ (B_* being the critical field[3,4] for magnetic insulation for $d=4.25$ mm) for most of the pulse. The ion current density, based upon biased Faraday-cup results, was $\lesssim 30$ A/cm^2. This is about half the value predicted by the one-dimensional solution[4] if we use the measured $B_z=8.0$ kG, $V_d=360$ kV, and $d=4.25$ mm, and take into account that the nonprotonic component of the ion beam was about 35% (obtained from Faraday-cup measurements and time-of-flight considerations). This may have been because, at this early time in the power pulse, the entire anode was not yet fully "turned on." (Diode current was twice as large 20 ns later, but the measured gap was similar.) If we used $d_0=7.5$ mm, an ion current-density enhancement of about 2 would have been inferred (again taking into account the nonprotonic beam component).

For the actual gap d, the measured $E(x)$ can be compared at each instant of time with a theoretical $E(x)$ profile determined from Ref. 4, as shown in Fig. 3. The measured electric field seems to be larger close to the anode and smaller close to the cathode than the calculated one. This tendency was observed to greater or lesser extents for several diode configurations using planar aluminum cathodes with different values of B_z, V_d, and d_0. It implies electron presence outside the theoretical[4] electron-sheath region. A quantitative analysis of $E(x)$ profiles for several specific configurations (B_z, V_d, and d_0), together with the measured ion current densities, have been used to obtain the electron and ion number-density distributions in the accelerating gap. These results, to be discussed in a more complete paper on the present experiments,[17] show that the expansion of the electron sheath toward the anode was, in certain cases, associated with the generation of ion current densities up to a few tens of percent higher than the predicted value even with the actual measured gap spacings taken into account. This is consistent with expectations if the ion current density is space-charge limited ($E=0$ at the anode-plasma surface).

The electric field profile was also measured in a diode which used a "virtual cathode" vane array which projected about 3.5 mm into a 10-mm gap diode. The presence of electrons near the anode was even more clear in these experiments than in the ones with the planar anode. Using the actual diode gap and the theory of Antonsen and Ott,[4] we find that the electron population in the gap was 2–3 times larger than the calculated electron sheath. As a result, the ion current density was 3–5 times larger than the theoretical value with use of the actual gap d (and again with the 35%

nonprotonic beam component taken into account). If this comparison had been made with use of the vane tip-to-solid anode spacing, 6.5 mm, an ion current-density enhancement of 5–12 would have been inferred. This illustrates the need to know the actual diode gap in order to understand the charge flow in a high-power diode.

Although the effect of electrode plasma expansion on ion current-density enhancement over the initial gap space-charge–limited flow value, J_0, has been discussed previously,[18,19] such discussion could be only qualitative since the boundaries of the electric-field–excluding plasmas have not been previously known. (Previous measurements[9,10] of electrode plasmas were sensitive to densities higher than the density necessary to exclude the electric field.) Likewise, diffusion of electrons toward the anode from the cathode sheath is an often-cited reason for current-density enhancement, with recent theoretical and computational results of several authors providing quantitative predictions.[8,18–20] In Slutz, Seidel, and Coats,[20] a virtual-cathode diode configuration operating at 1.5–3 MeV was studied by computer simulation, but no anode-plasma expansion was included. (The actual configuration was substantially different from ours, but the B/B_* in the simulations was similar to ours including anode-plasma expansion.) Because of the highly diamagnetic nature of the high–current-density relativistic electron flow in the simulations, the virtual cathode moved toward the anode substantially more than in the absence of that diamagnetism, resulting in a factor of 15–20 ion current-density enhancement relative to J_0. The authors[20] suggest that a factor of about 4 of that enhancement is attributable to diamagnetism and therefore would not be present in our experiments. If anode-plasma expansion were included in those simulations as per our experimental results, the factors of 40 or more ion current-density enhancement seen in short-pulse high-power experiments[21] could be obtained.

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