Anode Plasma Density Measurements in a Magnetically Insulated Diode

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The surface-flashover anode plasma in a magnetically insulated ion diode was investigated spectroscopically. From the Stark broadening of the neutral hydrogen H_β line an average electron density of about $2\times10^{15}/cm^3$ was observed in the $\lesssim 1$-mm anode plasma, 30 nsec into the 400–475-kV diode voltage pulse. Thereafter, the plasma front advanced into the diode gap at an average rate of 2 cm/μsec. This may be explained by the ionization of neutral atoms injected into the gap during flashover.

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Recent progress in the production of intense light-ion beams[1] has led to considerable interest in their application in several fields of research including magnetic and inertial confinement fusion,[1] pumping of high-power lasers,[2] and materials science.[3] Magnetically insulated diodes are one widely used technique of generating such beams.[1] In these diodes, ions are extracted from an anode plasma which is usually produced by the surface-flashover mechanism[1,4] : the anode surface consists of a dielectric material with small holes or grooves which may or may not be filled with metal pins or strips; when a high-voltage pulse arrives at the anode-cathode gap, the strong fringing electric fields at the holes or grooves cause surface breakdown on the insulator, perhaps aided by energetic electron bombardment and induced electric fields.[5] The development of an understanding of the operation of magnetically insulated diodes and, therefore, their predictability and reproducibility, has suffered from a shortage of measurements within the diode. For example, it is not known why an epoxy-filled groove anode produces a mostly proton beam in some experiments[1] and a mostly C^+, C^{+2}, etc., beam in others.[6] In this Letter, we report results of a spectroscopic investigation of the surface-flashover–generated anode plasma which has yielded information on its properties as a function of time during the high-voltage pulse. These measurements have made an important contribution to our understanding of magnetically insulated diode operation because in addition to revealing the plasma density and temperature, they have also suggested a key role for the neutral-atom component of the partially ionized anode plasma.

The difficulty in making measurements in a magnetically insulated diode arises because the anode-cathode gap is typically quite small (~ 5 mm), the anode plasma layer is thin (~ 1 mm), and the applied voltage is large. Therefore, insertion of a material probe is impossible. Some work has been done in measuring free-electron line densities and propagation behavior of anode and cathode plasmas by a holographic interferogram technique.[6,7] An estimation of the electron temperature was also obtained by using ultraviolet spectroscopy.[6] In this Letter we report measurements of anode plasma characteristics by the method of emission spectroscopy in the visible region. Light in the H_β line (4861.3 Å) of neutral hydrogen, spontaneously emitted within the anode plasma, was analyzed for Stark broadening by plasma electrons[8] to obtain electron density information. An average electron density of the order of 10^{15} cm^{-3} was observed during the diode voltage pulse, and an electron temperature of about 1 eV was estimated. In this parameter regime other broadening mechanisms (e.g., Doppler) are negligible. Our observations show that neutrals, having a density $\gtrsim 10^{16}/cm^3$, were also injected into the diode gap when surface flashover occurred. The motion of the neutrals and their ionization by beam protons appeared to contribute to the rate at which the anode plasma expanded into the gap. The importance of these neutrals may be that they determine the rate of collapse of diode impedance in a magnetically insulated diode, similar to observations by Prono *et al.*[9] in a different kind of ion diode.

A magnetically insulated ion diode of the type described by Maenchen *et al.*,[10] illustrated in Fig. 1, was used for the present spectroscopic investigation. An insulating magnetic field, B (<11 kG), to inhibit electron motion across the gap was produced by an external current through a single-turn coil, which also acted as the cathode. The dielectric-anode surface region was made up of sixteen epoxy-filled 14-cm-long grooves oriented parallel to the magnetic field. They were 3 mm wide with 0.8 mm of aluminum between grooves. A 14-cm-long thin stainless-steel vane connected

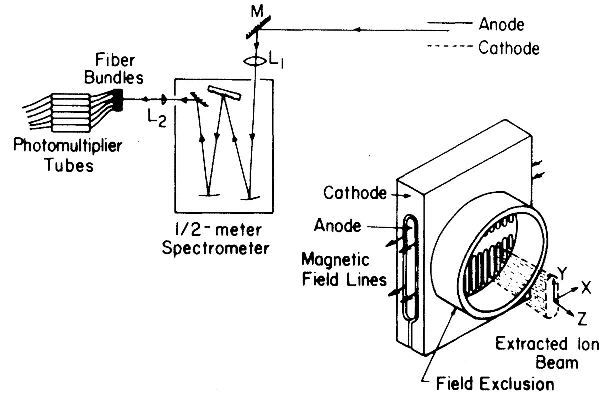

FIG. 1. Schematic diagrams of the optical setup and the "racetrack"-diode assembly.

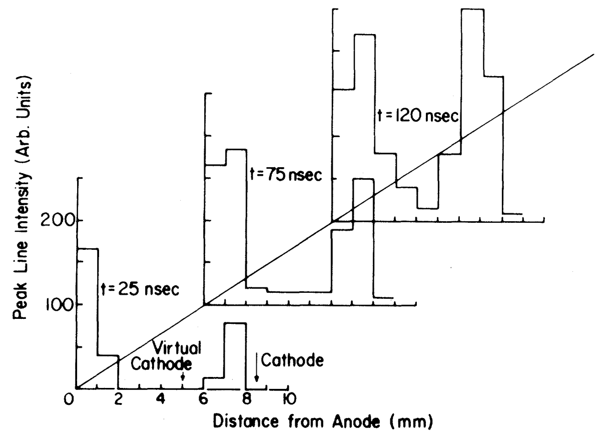

FIG. 2. Peak line intensity (PMT signal of channel 1 with $\lambda = 4861.5$ Å) as a function of distance from anode at different times. Spatial resolution ≈ 1 mm.

to the cathode projected about 3.5 mm into the gap; it was positioned 3 mm off the anode in the direction such that a "virtual cathode" was formed by electrons undergoing $\vec{E}\times\vec{B}$ drift over the anode surface after originating from the tip of the vane. The distance from anode to virtual cathode was about 5 mm. Powered by a 10-Ω pulse-forming line, the diode delivered 110–140 A/cm^2 of proton current density at up to 475 keV energy.[11] Diode current and inductively corrected voltage were monitored with standard magnetic and capacitive probes, respectively. Ion current was measured by negatively biased (-500 V) charge collectors[12] both with and without a thin (2 μm) polycarbonate foil, Kimfol, covering its aperture. Further details of the apparatus and the diode operating characteristics are available elsewhere.[11]

A schematic diagram of the optical setup is also shown in Fig. 1. Spontaneously emitted diode light was viewed parallel to the anode surface along the magnetic field direction. An $f/3.5$ lens (L_1) collected the light reflected from a plane mirror (M) into a λ-Minuteman 0.5-m spectrometer with $f/6$ grating. The lens (focal length 5 cm) was focused 80 cm away at the anode center. The mirror could be moved so as to view the light emitted at different distances from the anode. The output optics from the spectrometer consisted of a cylindrical lens (L_2), fiber-optic bundles, light pipes, and photomultiplier tubes (RCA C31034). The cylindrical lens magnified the slit image about 40 times which made it possible to employ three photomultiplier tubes to provide three channels at about 1-Å intervals. X-ray disturbance to the tubes was avoided by use of lead shielding. Using a 40-μm slit, spectral resolution was about 0.4 Å in each channel and spatial resolution in the diode gap was about 0.5 mm. Many shots were taken at each position in the diode gap to reduce error bars due to shot-to-shot fluctuations. The uncertainty in determining a linewidth was less than ± 0.5 Å which amounted to an error in electron density of less than $\pm 0.5 \times 10^{15}$ cm^{-3}.

Observation of light intensity when the spectrometer was set at the H_β line center showed two distinct regions of intense light on the two sides of the diode gap, corresponding to anode and cathode plasmas, as illustrated in Fig. 2. Alignment of the optical system to view the light parallel to the anode surface was evidently better than 0.5 mm in the gap even in this case of an 80-μm slit (corresponding to spatial resolution of 1 mm in the gap). Plasma light close to the anode was first observed 10–15 nsec after the voltage pulse started rising ($t=0$) coincident with the appearance of ion current. Light was first observed later in time further away from the anode. However, cathode plasma light was observed 20–30 nsec after the anode plasma light, suggesting that the former was created by ion bombardment of the aluminum cathode. We note that the variation of the peak intensity is not indicative of the plasma density variation since the intensity also varies strongly with plasma temperature and neutral density.

The electron density inferred from the Stark-broadened line profiles is plotted in Fig. 3 as a function of distance from the anode at different times during the diode voltage pulse. The uncertainty in determining time in the data analysis was ± 5 nsec. Conditions were as follows: peak diode voltage, current, and ion current density were 400 kV, 19 kA, and 120 A/cm^2, respectively, and B/B^* was 1.5. B^* is the critical insulating magnetic field for electrons,[13] given by

$$B^* = (2mV/e)^{1/2}(1+eV/2mc^2)^{1/2}/d,$$

where V is the diode voltage, m and e are the electron mass and charge, respectively, and c is the speed of light, and all quantities are in mks units. From the intensity of the H_β line the electron temperature and the neutral density in the anode plasma were estimated to be near 1 eV and $>10^{16}$/cm^3, respectively. The Saha equilibrium equation was used in the estimations. However, it should be noted here that the neutral-density estimation is strongly dependent on temperature: Only a 10% lower temperature would imply an order-of-magnitude higher density.

From the figure, the plasma front appears to advance into the gap in diffusionlike profiles at an average rate of ≈ 1.5 mm in 75 nsec ($=2$ cm/μsec). Considering that the 11-kG applied magnetic field corresponds to a pressure of 10^7 dyn/cm^2, the motion is not due to high plasma kinetic pressure since the latter was only about 10^4 dyn/cm^2. To estimate a diffusion-driven velocity, we first note that the resistivity of the anode plasma, given the measured conditions, is sufficently high that the magnetic field penetration time scale is small compared with the beam pulse time. Both the classical cross-field diffusion coefficient and Bohm diffusion yield plasma expansion rates one to two orders of magnitude less than the observed plasma expansion velocity, if one assumes a density gradient scale of 0.5 mm (see Fig. 3). Therefore, while at very early

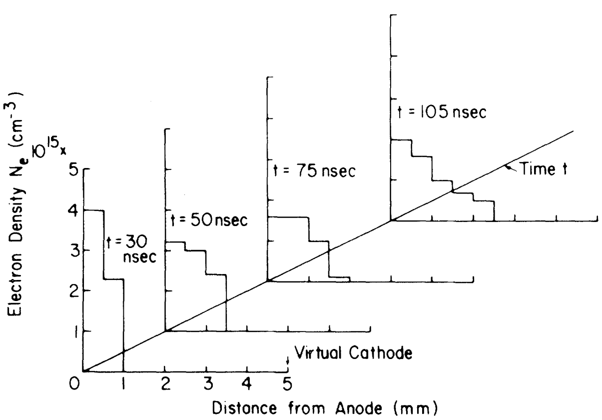

FIG. 3. Electron density as a function of distance from anode at different times. $V_D = 400$ kV, $J_i = 120$ A/cm^2, $B/B^* = 1.5$.

time, when the density gradient scale may be $\ll 0.5$ mm, the plasma propagation can be explained by diffusion, it cannot be explained the same way at later times. Since light emission from the H_β line indicates the presence of neutral hydrogen atoms, it can be assumed that there is an injected flow of neutral gas from the anode into the diode gap. By taking the instant of first observation of light at one particular distance as the time of first arrival of neutral atoms, their average velocity was 2.5 cm/μsec, corresponding to an energy of about 3 eV. The observed neutral velocity is comparable to the observed plasma advancement rate. Therefore, it is possible that plasma further away from the anode is created by ionization of local neutral atoms. One method of ionization is by accelerated protons. The cross section for ionization[14] of hydrogen atoms by 20–100-keV protons is $(1-2)\times 10^{-16}$ cm^2. A cross section of 10^{-16} cm^2, a proton current density of 140 A/cm^2, and a time 25 nsec during which a plasma density of 5×10^{14}/cm^3 must be produced require a neutral density $\gtrsim 2\times 10^{17}$/cm^3. On the basis of measurements discussed above, this is high, but not impossible, and is also consistent with measurements of energetic neutrals made by Nakagawa and Greenly.[15] The source of the neutrals in the accelerating gap in the present experiment is believed to be streaming from a dense, partially ionized plasma close to the anode surface since, in externally driven surface-flashover experiments, large quantities of neutrals are observed.[16] While the time scale for recombination of a 10^{15}/cm^3, 1-eV plasma is 10 μsec, the charge-exchange mean free path and time scale are 0.05 mm and 2 nsec, respectively, for 1-eV protons in a 10^{17}/cm^3 cold neutral layer near the anode. Therefore, the neutral front could represent the faster component of charge-exchange neutrals energized as ions in the surface-flashover process.

In Fig. 3 we see that at early time ($t = 30$ nsec) of observation, the anode plasma was $\lesssim 1$ mm thick with an average electron density of 3×10^{15} cm^{-3}. As time progresses, the peak density decreases, but the thickness increases. The total number of electrons present in the plasma per unit area, obtained by integrating the electron density profiles at various times, was $(2.3-3)\times 10^{14}$ cm^{-2}. Within experimental error it did not change much for the initial 100 nsec, i.e., within the main voltage pulse. By considering the fact that extracting 120 A/cm^2 of ion current density for 100 nsec from the anode plasma requires about 10^{14} ions/cm^2, it may be assumed that there is a continuous production of ions, and this is also supported by the explanation for the plasma front motion as discussed above. We also note that an extracted proton current density of 120 A/cm^2 requires a flux of $\lesssim 10^{21}$ protons/cm^2 sec. Given the assumption that $n_i \approx n_e \approx 2\times10^{15}$ cm^{-3} and $T_i \approx T_e \approx 1$ eV, the average thermal flux in the plasma was 2×10^{21}/cm^2 sec. So the measured plasma just barely meets the condition of being capable of providing enough ion flux to produce the peak observed current density considering only thermal flux.

The presence of neutral gas moving into the diode gap at the observed rate of 2.5 cm/μsec is probably specific to the present experimental conditions. However, it is probable that such neutrals are present in all ion diodes with flashover-type anodes. Indeed, the observations of Nakagawa and Greenly[15] tend to bear this out. Moreover, their estimate of the neutral expansion velocity of about 1 cm/μsec suggests that this velocity is a function of diode power density and that it would be higher in higher-power-density diodes such as that of Johnson *et al.*[6] One would conjecture, therefore, that the rapid collapse of diode impedance from anode plasma expansion in such high-power diodes could be eliminated while maintaining high power density by the use of a dense injected anode plasma in place of the surface flashover source.

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