Measurements of the Ion Transverse Velocity Distribution in the Gap of an Ion Beam Diode*

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ABSTRACT

We have measured the distribution of ion transverse velocities in the acceleration gap of a magnetically insulated ion diode. The measurement is based on observing the spectral profile of the Doppler broadened spontaneous line-emission from accelerating ions. The velocity distributions of C^{++} and Al^{++} ions were peaked at zero transverse velocity and symmetric with respect to the directions parallel and antiparallel to the magnetic field lines. The mean transverse velocities for the two ion species corresponded to energies of about 200eV in experiments with a gap potential difference of 260-330kV. The divergence angles observed for both ion species are significantly smaller than previously observed for protons outside ~~the~~ the diode.

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I. Introduction

Intense ion beams in excess of 1 TW have been produced using magnetically-insulated-diodes[1] and pinch reflex diodes[1,2]. The use of these beams for inertial confinement fusion[3] and for plasma confinement and heating[4] requires, to varying degrees, that the ion beams have low angular divergence, i.e., small transverse velocities relative to the intended propagation direction. The divergence of intense ion beams should, therefore, be reliably measured and controlled. One likely source of ion transverse velocities is electric field fluctuations within intense ion beam diodes. An understanding of the nature of spatial and/or temporal electric field fluctuations within such a diode may be assisted by studying ion transverse velocities as a function of position and time within the diode. Such measurements are the subject of this letter.

Until recently, transverse ion velocities have been measured only after the ions had passed through the cathode structure and were drifting outside of the diode. The methods used have been shadowbox photography[2], Faraday cup measurements as a function of propagation distance[5], and streak photography of a scintillator sheet hit by an ion beamlet after it passed through a pinhole[6]. Obviously, using such measurements, it is quite difficult to identify the source(s) of the ion beam divergence. Possible sources include the dynamics of the anode plasma in the diode, disturbances in the charge flow in the diode gap, irregularities in the extraction cathode region, and self fields in the drift region. Furthermore, these methods do not readily discriminate between ions of different masses and charges.

Recently Maron and Litwin[7] suggested that the transverse ion velocities (perpendicular to the acceleration direction) in an intense ion diode acceleration gap could be measured by observing the Doppler broadening of line-emission from ions traversing the gap, as depicted in Fig. 1a. Spontaneous line-emission from accelerating ions (produced and excited in the anode plasma) is collected parallel to the electrodes of a planar magnetically insulated diode[5]. The spectral line profile, being dominated by Doppler broadening, gives the transverse velocity distribution averaged over the field of view. By varying the distance x between the anode and the region viewed by the optical system on successive sets of diode pulses, the variation of the transverse velocities across the gap can, in principle, be measured. Here we report measurements of the transverse velocity distributions of C^{++} and Al^{++} ions made parallel to the applied magnetic field of the diode. The results show that the transverse velocity distribution in the gap is peaked at zero and is symmetric with respect to the directions parallel and antiparallel to the magnetic field lines. C^{++} and Al^{++} ions had similar divergence angles. Furthermore, our measurements indicate that the transverse velocities in the gap are considerably smaller than those previously observed for protons drifting outside the diode using a similar diode configuration[5].

II. The Experimental Arrangement

Ions suitable for the measurement described here must be reproducibly and abundantly produced in the anode plasma. The upper level of the emission line must be sufficiently populated to ensure measureable emission from the (low particle density) diode gap. For ~1MV/cm ion diodes the total ion density in the gap is about 10^{12} cm^{-3}. However, in a proton magnetically insulated diode such as that used here, the densities of the C^{++} and Al^{++} (present as "impurities" in the anode plasma) are estimated to be $\lesssim 10^{11}$ cm^{-3}. In addition, the emission must be in the visible or in the near U.V. region. Hence, for relatively light ions, transitions from high-lying levels should be selected, resulting in weak emission. Furthermore, the lifetime of the upper level should be comparable to the ion transit time across the gap (a few nanoseconds) in order to allow the measurement across the entire diode gap to be made. Finally, the line emission must not be Stark shifted (or split) in the diode gap, so that the spectral line width will be determined mainly by its Doppler broadening. This requirement is usually fulfilled for light-ion lines under the MV/cm electric fields in intense ion beam diodes.

The experimental system and the diagnostic set up are shown in Fig. 1b. The planar magnetically insulated diode[5] was powered by $\leq$ 400 kV, 100 ns pulses delivered by a 10 Ω water dielectric pulse-forming line. The externally applied magnetic field was produced by the single turn cathode-coil. The anode plasma was produced by a surface flashover of a 1.6 mm thick, 14cm x 6cm polyethylene sheet which covered the planar aluminum anode. The long dimension was parallel to the applied magnetic field. A 14 cm-long vane attached to the cathode projected 3.5 mm into the gap just across from the top of the anode. Electrons emitted from the tip of the vane E x B drifted downward to form a "virtual cathode" in front of the anode. The distance between the vane tip and the dielectric anode was 6.5 mm in the experimental run for which results are presented in this paper. Line emission was collected from a planar region (of area equal to that of the anode but not including the vane tip) parallel to the anode and was focussed by the lens L (Fig. 1) onto the input slit of a 0.5 m spectrometer. The width of the observed diode region (i.e. the spatial resolution in the x direction) was mainly determined by the width of the spectrometer slit multiplied by the demagnification factor of the focusing lens. The spatial resolution was varied in the experiments between 0.6 and 1.2 mm. In order to measure the line profile in one discharge, the spectrometer output was magnified by the cylindrical lens CL (Fig. 1) and then observed by a rectangular fiber bundle array. Each one of the seven bundles in the array transmitted the light to a PM tube, giving seven points of the spectral line profile as a function of time for each discharge. The spectral windows observed by the fiber bundles were each 0.67 Å wide and were separated by 0.67 Å from each other. The spectral response of the system was approximately Gaussian with a FWHM which varied in the experiments between 0.7 and 0.85 Å. The fiber bundle-photomultiplier channels were calibrated relative to each other.

We performed our measurements using both C^{++} and Al^{++} ions. The C^{++} ions probably came from the carbon in the polyethylene. The origin of the Al^{++} ions in the anode plasma was a thin layer of aluminum on the polyethylene anode surface. The coating on each new anode was made by an aluminum "blow-off" plasma produced by electrons which hit the aluminum anode stalk in a few discharges in which low magnetic field was applied.

III. Measurements and Results

Line-emission was first observed from the anode plasma which extended over a 3mm wide region near the anode[8]. A spectral profile of the 4647.4 Å C^{++} ($2s3p \rightarrow 2s3s$) line, obtained at a distance $x = 1mm$ from the solid anode surface, is shown by the circles in Fig. 2a. The spatial resolution in this measurement was 0.6 mm. The Zeeman splitting for this line amounts to 0.2 Å, assuming the applied magnetic field totally penetrated the plasma. The density broadening for this line is calculated[9] to be small for our anode plasma density, which was previously measured[10] to be about 10^{15} cm^{-3}. Thus, the measured line profile in the anode plasma is mainly determined by the system spectral resolution as shown by the spectral response curve, determined using a low-pressure lamp, in Fig. 2a.

The profile of the C^{++} 4647.4 Å line emission from the diode gap, obtained with a spatial resolution of 1.2 mm, is shown in Fig. 2b. The data points were obtained in different discharges in which the line center was moved by increments of 0.1 Å over the fiber-bundle array. For each position of the line center two identical discharges were performed. Thus, each set of data points separated by 0.67 Å was obtained by summing two discharges.

The emission signal from the gap was (as expected) a few hundred times lower than from the anode plasma. Indeed the error bars indicated in Fig. 2b result mainly from the small number of photons detected during the resolution time. An additional difficulty, due to the weak emission from the gap (with respect to that from the anode plasma), was caused by plasma light which was scattered from the vacuum window into the detection system when the system looked into the diode gap. By varying the position of the window and placing collimation slits between the diode and the window we verified that the emission from scattered plasma light contributed less than 10% of the signal observed from the diode gap. These tests were further supported by an independent measurement[8] using Stark shifted lines. In those measurements, we observed the Al^{++} 4529 Å line-emission both from the anode plasma and from the diode gap. The emission from ions in the gap was shifted by a few Å under the gap electric field. Thus, the portion of the signal from the gap which was centered at the zero-field wavelength was solely due to scattered (unshifted) plasma light. Its magnitude was less than one tenth of the shifted emission, confirming the previous conclusion. Subtraction of the contribution of the scattered light from the emission observed from the gap would make the gap-emission wider but to a small extent. Thus we ignored this effect in our data analysis.

As shown in Fig. 2, the C^{++} 4647Å line-emission from the acceleration gap is wider than from the anode plasma. This can be attributed only to Doppler broadening due to the ion velocities parallel to the electrodes (the Stark shift of this line under the 1 MV/cm gap electric field is less than 0.1 Å). The spectral centering of the emission from the gap with respect to that from the anode plasma was accurate to within 0.3 Å. Thus, the data show that the distribution is symmetric with respect to zero Doppler shift and is peaked at zero transverse velocity to within at most ±2.0 cm/μsec (about 20 eV). Our measurement accuracy does not allow us to deduce the actual line shape, and so we have analyzed our data assuming both Gaussian and Lorentzian shapes. The best fit of a Gaussian curve to the data points is shown in Fig. 2b. It has a FWHM of 1.9 Å which corresponds to 50% of the ions having transverse velocities <3.8 cm/μs (after deconvolving the curve using the known spectral response of the system). From a Lorentzian best fit, we obtain 5cm/μs. Including the uncertainity which results from the range of curves which can fit the data, we conclude that 50% of the C^{++} ions have a transverse velocity less than a number in the range (4.5 ± 1.5) cm/μs, corresponding to transverse energies in the range 54-216eV, parallel to the magnetic field.

In order to determine the mean divergence angle of the ions, the axial velocity must be known. This velocity can be calculated at each position in the gap from the variation of the electrostatic potential across the gap, since $v_i(x) = [(2q/m)\ (V_0-\phi(x)]^{1/2}$, where $v_i(x)$, $\phi(x)$, V_0, m and q are the ion velocity at the position x, the electrostatic potential, the voltage at the anode, the ion mass, and the ion charge, respectively. The potential $\phi(x)$ was obtained from integration of the previously measured[8,11] electric field distribution across the gap. For the present diode configuration the potential varied between +200 and +110 kV (the anode potential was +265 kV) over the 1.2 mm wide gap region centered at x=5.5 mm from the solid anode surface. The axial velocity averaged over this region is thus 185 cm/μs. Therefore, the divergence angle of 50% of the ions is less than 1.4°±0.5° averaged over the 1.2 mm wide field of view. If the ions gain no additional transverse energy in traversing the remainder of the accelerating gap, the 1D divergence angle of 50% of the C^{++} ions parallel to the magnetic field upon their extraction from the diode is 1.2°± 0.4.

The transverse velocities of the Al^{++} ions were measured using the 3602 Å line (4p→3d). Figure 3 shows emission profiles from the anode plasma and from the gap. (For this line the density broadening in the plasma is known[12] to be small, 0.02 Å for our anode plasma density. The Stark shift in the gap is about 0.05 Å.) The emission from the gap is peaked at zero transverse velocity ±2.3 cm/μs. The best Gaussian fit to it (see curve A in Fig. 3b) implies that the transverse velocities of 50% of the ions are <3.3 cm/μs. Analyzing the aluminum line spectrum data similarly to the analysis for the C^{++} line gives the range (3.4 ± 1.1) cm/μsec (70-270eV) as the 50th percentile velocity for the Al^{++} ions. This corresponds to a divergence angle for 50% of the ions of less than 1.6°±0.5° averaged over the 1.2 mm wide field view. Projecting this result to the extracted ions, again assuming they gain no additional transerve velocities, would yield about 1.1°± 0.3°.

We have attempted to use the results just discussed to determine the mass dependence of the transverse velocities. Assuming the C^{++} line has a Gaussian profile, curves B1 and B2 in Fig. 3b were obtained by scaling the C^{++} spectral width by $1/m^{1/2}$ and $1/m$, respectively. In both cases, the amplitudes were adjusted to give the best fit to the Al^{++} data. Curve B1 is much closer to curve A, the best Gaussian fit to the Al^{++} data, than is curve B2, suggesting that $1/m^{1/2}$ is the proper scaling. Repeating this procedure using

Lorentzian curves leads to the same conclusion. However, the range of curves which fit the data does not preclude the possibility that the transverse velocities scale as 1/m or are independent of mass.

We note that the velocity distribution for the Al^{++} ions was determined from pulses with different peak diode voltages and magnetic fields (indicated in Fig. 3b) showing similar results within the experimental accuracy. In an earlier[13] presentation of preliminary divergence measurements, we quoted a smaller angle for Al^{++}. This was due to a larger error in those measurements, and to the assumption of a higher ion energy in the observation region of the diode than we now know to be the case, based upon electric field profile measurements[8,11].

IV. Summary and Conclusions

We have measured the transverse velocity distribution of the C^{++} and the Al^{++} ions in the gap of a magnetically insulated diode by observing the Doppler broadening of the ion line emission. Although our results do not preclude the possibility that the ion transverse velocities scale as 1/m or are independent of mass, $1/m^{1/2}$ scaling gives the best fit to the data. Note that the latter scaling implies that the divergence angle is independent of mass for C^{++} and Al^{++}.

Our measured divergence angles for C^{++} and Al^{++} can be compared with those deduced from Faraday cup measurements of a proton beam made outside the diode. Those measurements[5] gave a half-angle divergence of 4 to 5° in the direction parallel to the magnetic field, higher than the values obtained here. If the divergence angle of C^{++} ions outside the diode were the same as that of the protons, the implied C^{++} transverse velocity would be about 27cm/μs, at least 4.5 times the value we have measured in the diode gap.

Because our measurements of the ion emission were made from a region about 1 mm wide in the axial direction (in order to detect enough photons to obtain reasonable accuracy), and in mid-gap to avoid signal contamination by substantial amounts of scattered electrode plasma light, we were unable to obtain the dependence of the velocity distribution on the axial position. More intense line-emission from the diode gap could be achieved with higher voltage diodes due to the larger ion current densities, by the use of stronger lines of different ions, or by repeating this measurement using a diode in which the ion to be observed is the majority species instead of an impurity. Improved spatial resolution, and temporal resolution of the transverse velocities would be obtained. Using the spatial dependence, and by measuring transverse velocities of ions of different masses (or charges), it may be possible to determine the origin(s) of the ion transverse velocities.

Our system can be arranged to operate with a spectral resolution of 0.2 Å, thus allowing transverse velocities as low as 1 cm/μs (i.e., divergence angles of ~0.2°) to be measured. Such small divergence angles would be even easier to measure for a higher voltage diode since the same ion beam divergence results in larger transverse velocities. Determining ion beam divergence angles in the gaps of high power diodes with this level of resolution is needed since divergence angles of about 1° have been observed[1] outside of such diodes. It should be mentioned that our measurements can also be employed for ions that have been extracted from the diode gap. For instance, C^{++} ions traverse a 1 cm wide A-K gap of a 2 MV diode in 2 ns, while the lifetime of the upper level of the 4647 Å line is 12 ns. Thus, the emission signal from ions beyond the cathode will not be significantly smaller than from the diode gap. Finally, as a non-perturbing method, this method can be employed in parallel with other diagnostics used for the investigation of high power devices.

V. Acknowledgements

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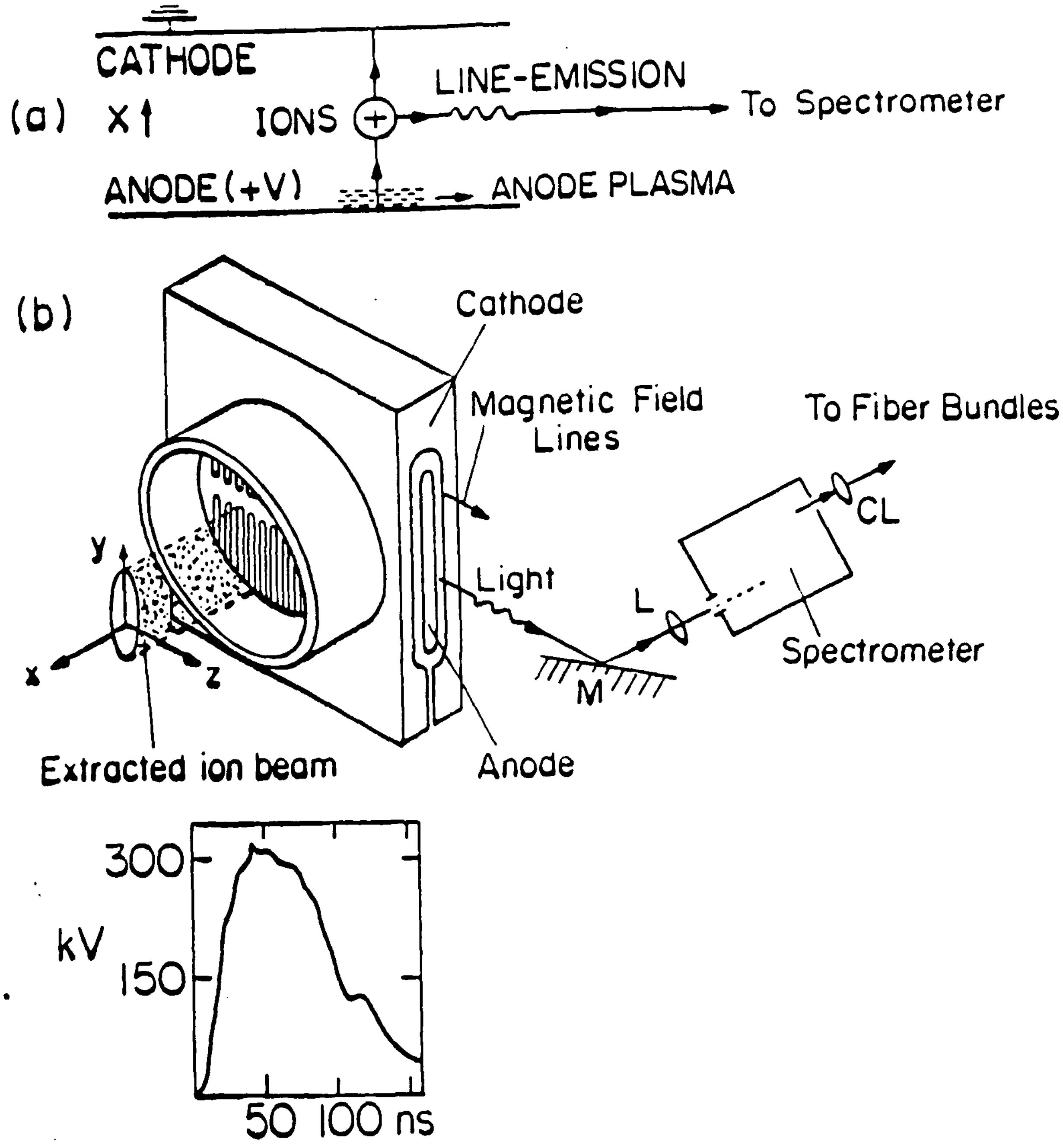
Figure Captions:

Fig. 1 (a) Schematic diagram illustrating the method for measuring the ion transverse velocity distribution in the acceleration gap. (b) Illustration of the magnetically-insulated-diode and the diagnostic arrangement used for these experiments. The distance x of the viewed region from the solid anode surface is determined by the position of the mirror M. Also shown is the diode-voltage waveform.

Fig. 2 Spectral profiles of the C^{++} 4647.4 Å line-emission: (a) The circles give the emission from the anode plasma at x = 1 mm from the solid anode 50 ns after the start of the diode voltage pulse. The solid points and the curve which indicates the trend give the system spectral response. Spatial and spectral resolutions are 0.6 mm and 0.75 Å, respectively. (b) Emission from the acceleration gap, x=5.5 mm. The emission intensity is averaged over t=30 to t=70 ns. Spatial and spectral resolutions are 1.2 mm and 0.85 Å, respectively. The wavelength is given with respect to the line center in the anode plasma. The curve is a Gaussian fit to the data.

Fig. 3 Spectral profiles of the Al^{++} 3602 Å line-emission: (a) and b) are emission from the anode plasma and in the acceleration gap, respectively. Spectral resolution in a) and b) are 0.70 and 0.80 Å, respectively. Other details are as in Fig. 2. Curve A in (b) is a best Gaussian fit to the data. Curves B1 and B2 are obtained from that in Fig. 2b by scaling according to $1/m^{1/2}$ and $1/m$, respectively.



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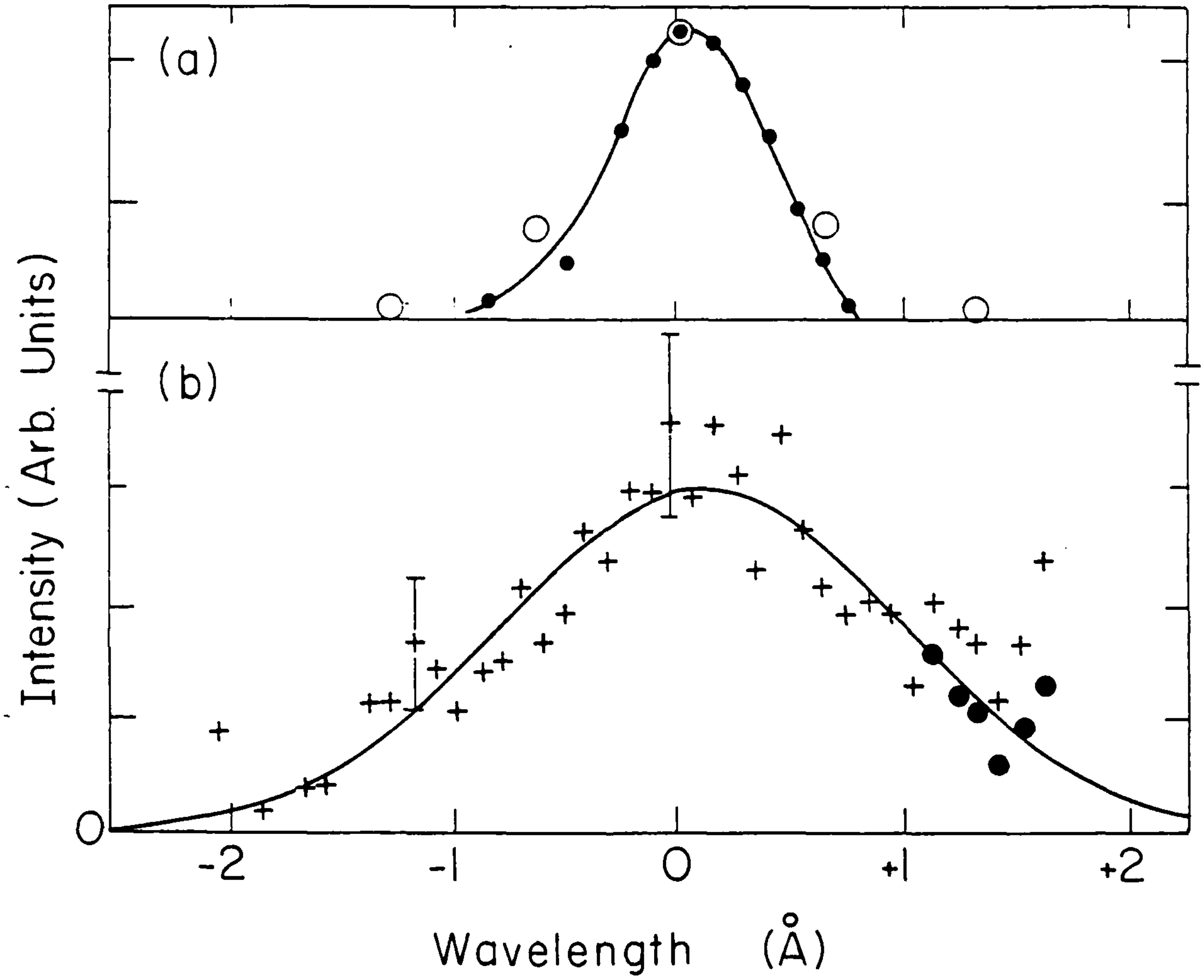

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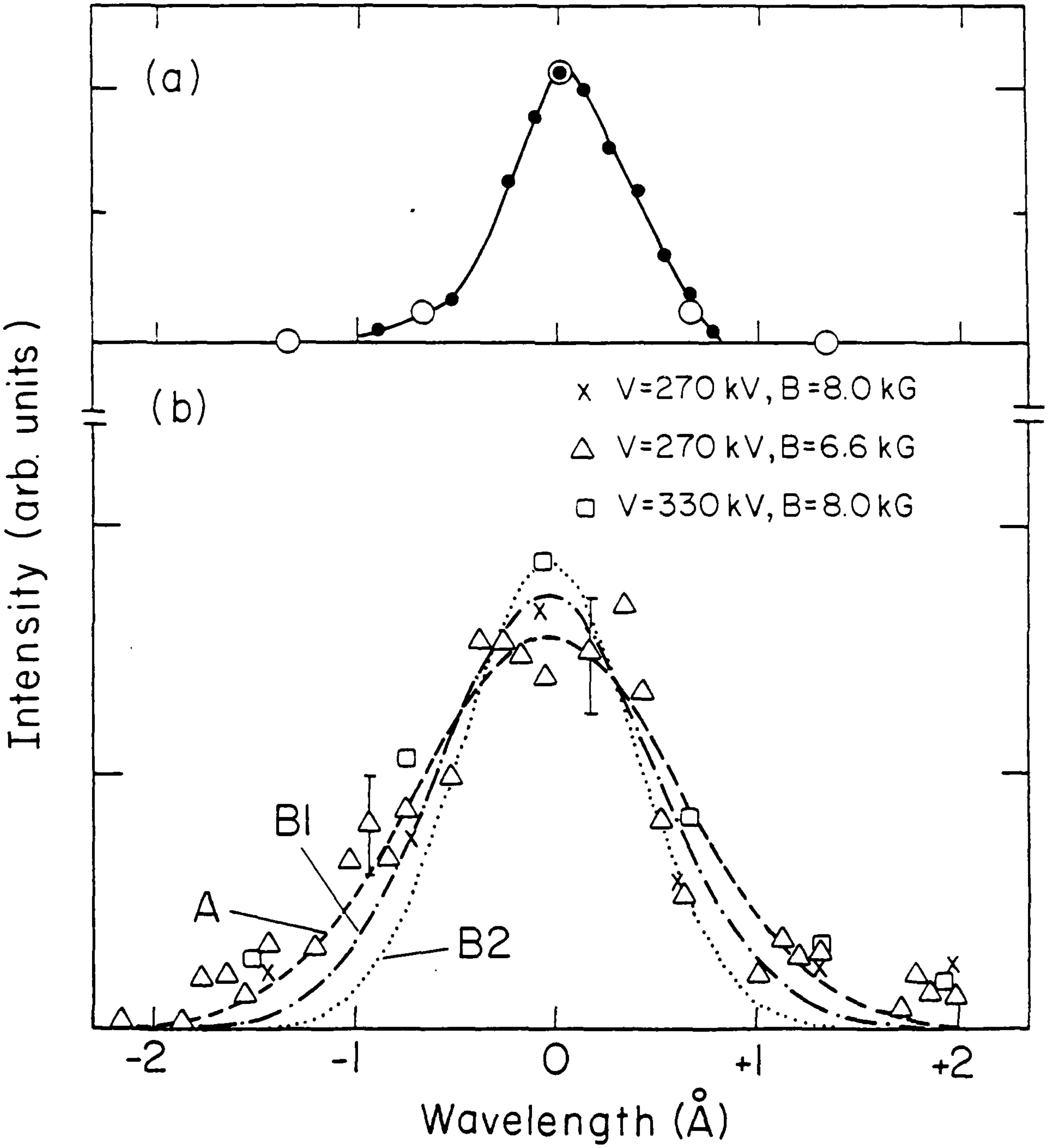

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