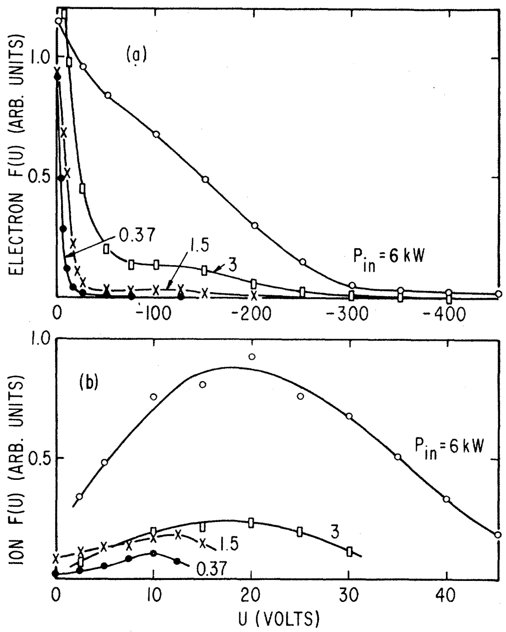

FIG. 3. (a) Electron distribution function versus energy (U). (b) Ion distribution function versus energy. $f_0/f_{ce} = 0.5$, $n_0 \simeq 5\times10^{12}$ cm^{-3}. The input rf power, P_{in}, is the parameter.

was varied showed that at early times an energetic tail was produced, and that at later times the population of the tail was built up.

We also made a study of the heating and the decay spectrum as a function of the uniform magnetic field. We found that although the lowest thresholds occurred near $\omega_0/\omega_{ce} \simeq 0.70$, the heating and the saturated spectrum level increased with increasing magnetic field. Thus, a lower threshold did not necessarily lead to increased heating. In particular, Figs. 2 and 3 show that although the low-frequency, long-wavelength decay occurs at very low power levels (presumably due to the $\vec{J}\times\vec{B}_w$ type of decay), no substantial heating occurs until the higher-frequency, shorter-wavelength fluctuations are excited.

In conclusion, we have presented experimental results which demonstrate the fundamental aspects of the parametric and the $\vec{J}\times\vec{B}_w$ mode-mode coupling type of decay instability of large-amplitude whistler waves. The strong heating of both the electrons and the ions occurred on time scales of a few microseconds. The fast plasma heating was believed to be caused by anomalous absorption due to the short-wavelength fluctuations associated with the parametric instability.

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Neutron Production and Collective Ion Acceleration in a High-Current Diode*

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New measurements demonstrate that neutrons produced in a high-current pulsed diode with deuterium-bearing electrodes are of beam-target origin. During a brief portion of a 70-nsec, 2-MV, 50-kA pulse, positive ions from the anode and cathode plasmas were observed to be accelerated toward the anode rather than the cathode as dictated by the externally applied field. Energetic deuterons were observed, behind a small aperture in the anode, which were the source of neutrons produced with Li or C anodes.

The development of surface-breakdown prepulse switches has made possible the effective use of small-diameter cathodes with small anode-cathode gap spacings on high-voltage pulsed electron accelerators. The resulting high-current densities have inspired new attempts to heat targets to thermonuclear temperatures. Uglum, McNeill, and Graybill[1] first used small-diameter long metal cathodes at close gap spacing, and Morrow *et al.*[2] later studied a similar configuration which employed glass cathodes. Condit and Pellinen[3] subsequently reported using a glass cathode to obtain a current density of 160 kA/cm^2. Kerns, Rogers, and Clark[4] first reported the production of neutrons using glass-rod cathodes close to deuterated targets. Relying primarily on measurements of neutron isotropy, they concluded that the neutrons were of thermonuclear origin.[5] However, their isotropy measurements may be questioned since the silver activation counters used in their experiment were not ideally placed.[6] New experimental results presented in this Letter suggest a new interpretation of the previous neutron observations.

In studies of vacuum and plasma discharges at relatively modest power levels (100 kV, 5 kA), Korop and Plyutto[7] showed that positive ions could be accelerated in the direction of electron flow. They found that when a pointed cathode was used with a planar anode, energetic positive ions emerged from an aperture in the anode simultaneously with the appearance of a current burst and strong electron beam pinching. Accelerating fields for these ions were estimated to be at least 1 MV/cm for gap lengths of several millimeters, and ion energies greatly in excess of the applied potential were measured. Later measurements,[8] which confirmed and extended some of these results, prompted the present experiments on a large pulse-forming line.

Reba,[9] a 17-Ω, 70-nsec-long Blumlein line, provided a nominal 1–3-MV pulse at up to 100 kA for this experiment. A dielectric section, acting as a surface-breakdown switch at least 15 cm long and the same diameter as the cathode shank (2–10 mm), was used to prevent the 30-kV prepulse associated with the charging of the pulse-forming line from affecting the gap dynamics. The cathode tip was either conical (30° half angle) or flat; conical geometry helped maintain an axial discharge and apparently aided the reproducibility by more directly hitting targets which were usually 13-mm-diam inserts in the anode. No neutron yield increase has been attributed to conical cathode geometry. Anodes of CD_2, TiD_2, C, Li, Ti, and Ta, and cathodes of CD_2, Ti, TiD_2, C, SiO_2, Pyrex, and brass were used in various combinations to study the effect of cathode and anode materials on the production of ions and neutrons.

Polyethylene-moderated silver activation counters were placed at angles of 26° and 90° from the forward direction, and a lead activation counter (threshold sensitivity, 1.6 MeV) was placed at 26°. The counters were calibrated *in situ* using a laboratory neutron tube. Time-of-flight neutron detectors (scintillator photomultipliers shielded from x rays by 10 cm of lead) were placed 30° off axis in the forward direction at 0.4, 5, and 10 m from the target. Hard x rays were monitored by *p-i-n* diodes. Ions were observed directly by a Thomson-parabola mass spectrometer placed 1.5 m from the anode. Luminosity in the anode-cathode gap was recorded with streak and time-integrated photography.

Figure 1 shows a typical streak photograph of the discharge together with current and voltage traces. Great light-intensity variations across the field of view prevented the acquisition of a single photograph containing clear details of the entire discharge. The features outlined in the next paragraph were determined by examination of several streak pictures. Since the voltage monitor is separated from the actual discharge region by approximately 800 nH of inductance associated with the cathode shank and insulating structures of Reba, a correction to the voltage arising from an LdI/dt term is ordinarily made. In the present case such corrections are omitted because there is an undetermined contribution arising from an IdL/dt term as the discharge

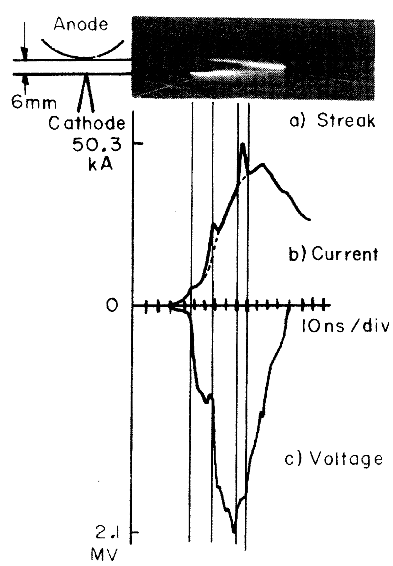

FIG. 1. Gap characteristics: (a) Streak photograph with slit parallel to and centered on axis. (b) Current, with normal current shown as dashed line. (c) Voltage, not corrected for $L\,dI/dt$.

pinches, and the accuracy of the current monitor has not been established for the high-frequency transients encountered.

It may be observed on streak photographs similar to that in Fig. 1 that early in the voltage pulse a faint cathode plasma luminosity starts to cross the gap at 2 cm/μsec. The onset of cathode luminosity is presumed to occur within several nanoseconds of the closure of the glass prepulse switch, in agreement with the exploding-whisker model of Messyats.[10] According to this model, microprotrusions on the cathode surface, under the influence of geometrically enhanced electric fields, emit electrons resulting in rapid and intense Ohmic heating. The vaporized material from many such whiskers on the surface expands and forms a continuous plasma sheath across the cathode surface. The anode luminosity may be seen to originate several nanoseconds after that of the cathode, and moves toward the cathode at 6 cm/μsec. After approximately 20 nsec, one can observe the presence of a luminous front in the cathode plasma moving toward the anode at 12 cm/μsec. When this front reaches the anode plasma at 45 nsec, the luminosity is observed to vanish in the region of the interaction and a new front appears in the central area of the gap. The resulting dark region near the anode is observed to last about 10 nsec.

The current trace [Fig. 1(b)] shows bursts at the onset of the fast cathode plasma front and when the cathode and anode fronts collide. At the time of the second current burst, the voltage [Fig. 1(c)] decreases rapidly. The $L\,di/dt$ correction is in such a direction that on the leading edge of each current burst the voltage is reduced in amplitude, and on the falling edge of the current burst the voltage is increased in amplitude. A Faraday-cup array at the anode plane showed that the beam was initially diffuse (< 50 kA/cm^2) and that at the time of the second current burst, there was an increase in the current density; the resolution of the array did not permit detailed analysis of the local pinch dynamics. The application of pinhole x radiography indicated that the current density on axis was greater than 1 MA/cm^2. A 20-nsec-wide hard–x-ray pulse was observed during the interval between the two current bursts, and sometimes exhibited a spike corresponding to the structure of a particular current burst. Time-of-flight neutron data showed that all or most of the 2.5-MeV neutrons originated during the second current burst maximum (within ± 20 nsec). Other neutron energies were present, but not in sufficient quantity to permit time-of-flight analysis.

Protons, D^+, and $C^{+1,2,3}$ passing axially through a 1–3-mm-diam aperture in the anode were identified with the Thomson-parabola mass spectrometer. Protons and carbon ions were present on all shots from pump-oil contamination. Negative ions were not observed, although the spectrometer was sensitive to all species. Maximum ion energies were 2–2.5 MeV and the bulk of the ions had lower energies. This direct observation clearly established that energetic positive ions were accelerated with the electrons toward the anode. Accelerating fields were estimated to be at least 4 MV/cm, using the observed 2.5-MeV ions and a 0.6-cm gap.

Observations of neutron yields obtained using different anode and cathode materials were used to determine the relative importance of an ion-beam–target interaction, a heated plasma in a tight pinch (boiler), a thermonuclear burn in the anode, and photoneutron production. Selected data are summarized in Table I to demonstrate these differences, and the following observations relate to these data.

Neutrons were produced by using a deuterated cathode and C or Li anodes. Knowing from the spectrometer that deuterons were accelerated toward the anode, the appropriate reactions are $C^{12}(d,n)N^{13}$, and $Li^{6,7}(d,n)Be^{7,8}$. The simultaneous observation of neutrons and 2-MeV anode-directed ions under these conditions is strong indication of an ion-beam–target interaction. Neutron production was increased by a factor of 2–50 by the use of a deuterated anode with a deuterated cathode. This increase is reasonable, since a deuterium-bearing target is a more efficient producer of neutrons at the low average energy of the collectively accelerated deuterons. In addition, deuterium in the anode may be accelerated in the conventional manner to the cathode where various neutron-producing reactions can occur. However, since the neutron yields with all types of cathodes used were nominally the same when used with a CD_2 anode, the effect of anode ions impacting the cathode and producing neutrons is considered to be of secondary importance. The presence or absence of apertures up to 3 mm diam in the anode had no significant effect on the neutron yield, but the presence of a 1.2-cm hole in a carbon anode coated with TiD_2 suppressed neutron production. This observation is taken as further indication that anode material hitting the cathode is not very important. The dielectric

TABLE I. Neutron yields determined by a silver activation counter at 90° and assuming 2.5-MeV neutrons. The yields can be in error by a maximum factor of 2 over an energy range of 0.5–14 MeV.

Cathode \ Anode	CD_2	TiD_2	C	Li	CD_2 covered by 0.48 mm Ta	Pure Ti
Bare SiO_2 of Pyrex	2.5×10^8	...	...	...	...	$<5\times10^5$
Conical glass covered with TiD powder	5×10^8 typical 2×10^9 max	2×10^8	2×10^7	1.5×10^8	$<5\times10^5$	$<5\times10^5$
Solid conical CD_2	5×10^8	...	...	...	...	...

properties of the anode material are not important because either deuterated polyethylene or deuterated titanium gave large yields.

A pinch (boiler) producing neutrons from cathode atoms is improbable since a low yield was obtained with a deuterated cathode and pure Ti anode. A boiler using anode ions seems equally unlikely because the presence of C or Ti in the anode (using CD_2 or TiD_2) would be expected to produce greatly different neutron yields; this difference was not observed. In addition, the neutron yields obtained with pure Li and C anodes could not be explained by a pinch of reasonable temperature.

Neutron isotropy measurements using the silver-activation method showed a forward-to-lateral enhancement of >1.4. This supports the ion-target model in preference to a thermonuclear-burn model. (Calibrations demonstrated that our detectors would record a forward-to-lateral enhancement of only ~ 1 if placed in intimate contact, as in Ref. 3, which appears to invalidate their conclusions regarding the existence of a thermonuclear plasma.) However, since the mass spectrometer was adjusted to record ion energies from 0.2 to 6 MeV, we have insufficient data to predict the degree of neutron anisotropy based on the ion-target model. It is also possible that accelerated ion trajectories may not be limited to axial flow; incidence on the target at angles away from the axis would make the yield more isotropic.

The low yield obtained with the Ta-covered sample of CD_2 shows that photoneutron production in the anode is of little importance, in agreement with Kerns, Rogers, and Clark.[4] The Ta in this case provided a greater fluence of x rays than was present in the bare CD_2.

Space-charge–limited flow of an initially diffuse electron beam, and cathode plasma motion consistent with the observations of Messyats, dominate the early gap behavior. Later the ion density increases sufficiently to allow neutralization between electrostatic and magnetic forces and a pinch occurs. At this time our direct observation of ions, neutron anisotropy, and application of several nuclear reactions, establish that collectively accelerated ions are present in the diode and play an important role in the production of neutrons. We have not determined as yet the relative yields of neutrons caused by acceleration of ions toward the anode and in the opposite direction. The intent of this Letter is not to rule out the possibility of a thermonuclear mechanism in similar configurations, but to establish that collectively accelerated ions are present and can contribute importantly to observed neutron production.

A small number of high-energy protons or deuterons produced by a process similar to that observed in this work may be responsible for recent observations of neutron production using hydrocarbon filaments (wires) in similar diodes.[11] Current bursts and pinching which might be indicative of collective ion acceleration have been observed by others in our laboratory and elsewhere.[12]

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Two-Photon Absorption and Stimulated Raman Scattering on Excited Helium Atoms in a Plasma*

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By focusing simultaneously microwave radiation and the beam from a tunable dye laser into a helium plasma, we observe two-photon absorption and stimulated Raman scattering on excited helium atoms. Both effects can be used to measure high-frequency electric fields in plasmas, and we discuss the advantages of this method as compared with the standard technique where such fields are investigated in emission spectra.

High-frequency electric fields can stimulate optical transitions between quantum states of atoms and ions involving more than one quantum. The new spectra are characterized by satellite lines around allowed and forbidden spectral lines. In 1961 Baranger and Mozer[1] pointed out the relevance of this phenomenon to plasma physics and proposed these effects as a diagnostic tool to study oscillating electric fields in plasmas. The first experiments were done by Kunze and Griem[2] observing plasma electric fields and by Cooper and Ringler,[3] who in a model-type experiment generated the high-frequency electric field in a microwave cavity and applied it to a separately generated plasma. In the meantime, this very powerful diagnostic technique has been studied further not only theoretically,[4,5] but also in many experiments (for a brief review, see Bekefi[6]).

Like all spectroscopic measurements, this diagnostic technique has the inherent disadvantage that light is collected along the line of sight through the entire length of the plasma, i.e., only correspondingly averaged quantities are obtained directly. It suggests itself, therefore, to apply light-scattering techniques to this problem, which offer the great advantage of local measurements. Tunable dye lasers make this now possible, and the feasibility of such techniques has been demonstrated only recently by the authors[7] who observed the resonance scattering on excited helium atoms. The new technique is complementary to the technique of collective laser scattering[8] from a plasma because it measures the spectrum of local electric field fluctuations, whereas the latter gives the spectrum of the local electron density fluctuations. Because the upper levels of both the allowed and satellite transitions are very strongly collisionally coupled, the intensity of satellite lines are enhanced by the same factor as the intensity of the allowed line when the allowed transition is optically pumped. As will be discussed later in greater detail, further advantages are obtained by using pump light at wavelengths corresponding to the satellites: The resulting processes correspond to a two- or more-quanta absorption process and to stimulated Raman scattering. The calculation for both processes has been done by Reinheimer[9] using sec-

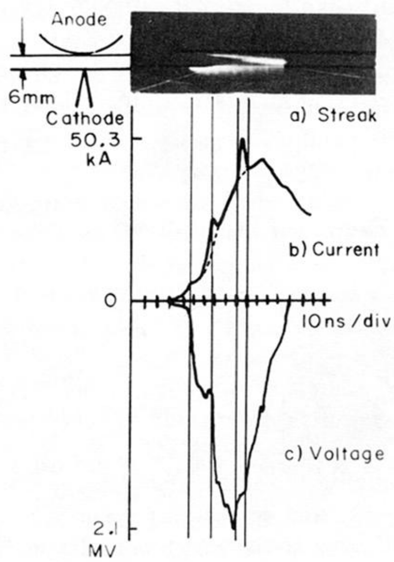

FIG. 1. Gap characteristics: (a) Streak photograph with slit parallel to and centered on axis. (b) Current, with normal current shown as dashed line. (c) Voltage, not corrected for $L\, dI/dt$.