# Observation of an Electron Beam in an Annular Gas-Puff Z-Pinch Plasma Device

D. R. Kania and L. A. Jones
*Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
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We report on the first observation of an electron beam formed in an argon gas-puff Z pinch at the time of pinch. An on-axis Faraday cup in conjunction with thin foil filters was used to measure the beam parameters. The beam has a pulse width of 4 ns, a peak current on the order of 10 kA, and an energy of 20 keV.

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The characteristics of collapsing annular argon gas-puff Z pinches have been studied by a large number of groups.[1-5] We report on the first direct measurements which verify the existence of an energetic electron beam in the plasma at the time of pinch. The presence of an electron beam was first predicted by Hammel and Jones[6,7] on the basis of their observation of a large number of x-ray lines characteristic of inner-shell excitations.[3,8] It was concluded that the x-ray spectrum resulted from a nonthermal electron distribution and therefore the electron temperature derived from the x-ray spectrum would have to be reinterpreted. This conclusion has far-reaching consequences as to how the plasma is modeled and to the interpretation of the so-called "hot spots." A spectroscopic model was used to estimate the required beam energy ($E > 4$ keV) and current ($I_B \cong 10$ kA) necessary to produce the observed spectra. We have observed a short (4 ns full width at half maximum), intense (on the order of 10 kA), 20-keV electron-beam pulse produced at the time of pinch. These measurements are consistent with the spectroscopic model of Hammel and Jones.

A 72-kJ Marx bank and water-line system[9] with a rise time of 200 ns is used to collapse a 1.0-cm-high, 2.5-cm-diam, 0.25-cm-thick shell of argon gas. The peak current of 600 kA is reached at the

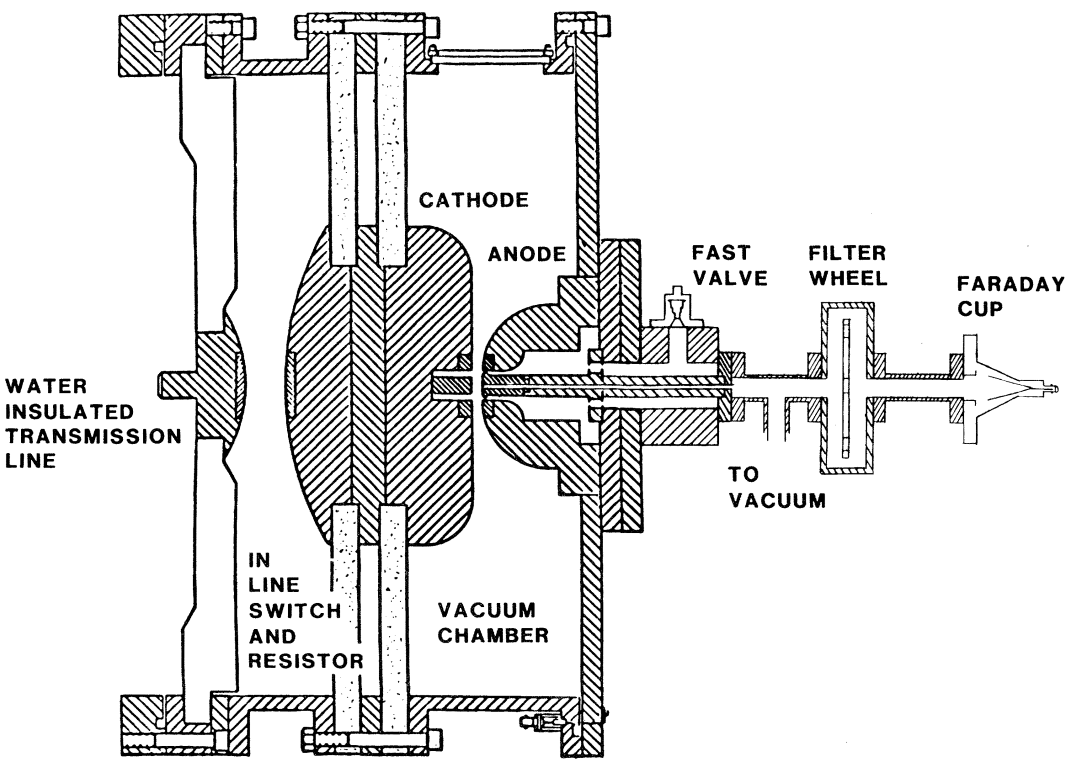


FIG. 1. Schematic diagram of the vacuum discharge chamber including the vacuum drift tube, filter wheel, and Faraday cup.

 

time of pinch. A cutaway view of the experiments is shown in Fig. 1. This device produces a plasma with an electron density $n_e \sim 10^{20}/\mathrm{cm}^3$ and an electron temperature $T_e \sim 300$ eV.[10]

The machine was modified to allow an axial view of the pinched plasma through the anode. A fast Faraday cup[11] was used to detect axial electrons at the end of an evacuated 80-cm-long drift space. The Faraday cup and recording system had a 400-MHz bandwidth. Thin foil filters and a transverse magnetic field could be interposed between the Faraday cup and the plasma. By applying a magnetic field and a voltage to the Faraday cup we were able to identify the observed pulses unambiguously as due to electrons. Signals resulting from photoemission could be easily distinguished from the electron beam pulses.

Detailed investigation of the energy and the time of production of the electron pulses required the use of thin foil filters. Unfiltered Faraday-cup data showed two distinct bunches of electrons arriving at the Faraday cup. The amplitude of the earlier pulse was much less than that of the later pulse while the early pulse was much narrower (4 ns) than the later pulse ($\sim 15$ ns) [see Fig. 2(a)]. When a thin aluminum filter (0.75 $\mu$m thick) was inserted in the beam path both pulses were attenuated, the earlier pulse less. With the addition of a thicker aluminum filter (8.0 $\mu$m) the later pulse was completely attenuated while the earlier pulse suffered only modest attenuation. An example of the early pulse is shown in Fig. 2(b). In addition to the attenuation of the signals with increasing thickness, the time of flight of the early pulse as measured from pinch time is increased with increasing filter thickness. These data for the early and late pulses are summarized in Fig. 3. The error bars indicate one standard deviation of the shot-to-shot variations in the experiment.

These data permit three methods of estimating the beam energy: (1) time of flight, (2) filter attenuation, and (3) energy loss in the filter. The use

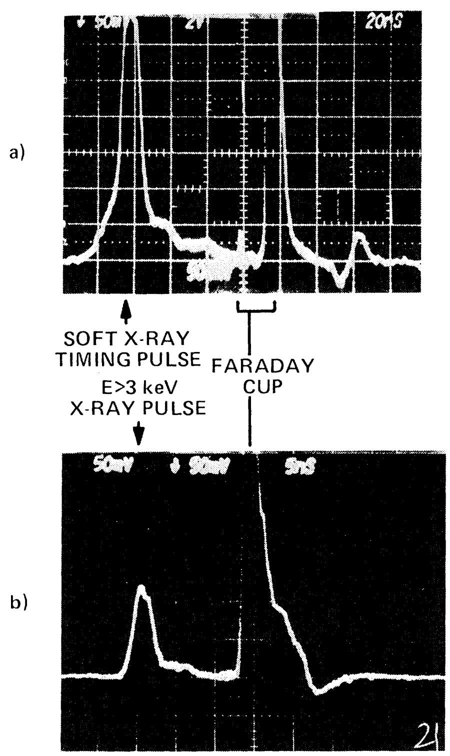


FIG. 2. Oscillographs of x-ray and Faraday-cup signals: (a) The Faraday-cup signal (unfiltered) showing the fast and slow pulses. The low-energy x-ray pulse $E \leqslant 1$ keV is used as a timing marker, 100 ns/div. (b) A filtered (8 $\mu$m aluminum) Faraday-cup signal and the $E > 3$-keV x-ray pulse displayed on the same trace at 20 ns/div.

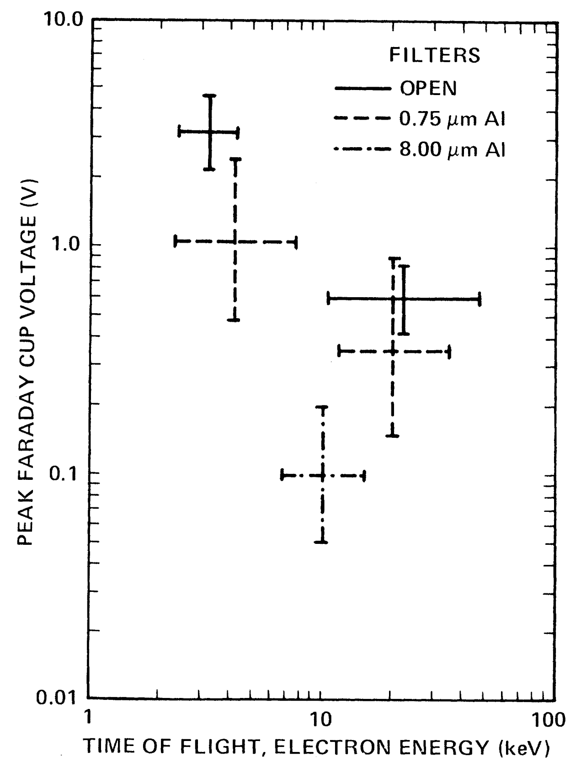


FIG. 3. The peak Faraday-cup voltage vs the time-of-flight electron energy for the unfiltered and filtered signals. The two low-energy points are for the slow pulse of electrons. The 8-$\mu$m-aluminum filtered signal was too small to be recorded for the late pulse. The three high-energy pulses are for the fast electrons. These data are uncorrected for filter attenuation and energy loss.

of time of flight to measure the beam energy relies upon the assumption that the electron beam is produced at the time of pinch. With the time of peak production of 3–4-keV x rays as observed on a filtered, CsI-photocathode x-ray diode as the operational definition of pinch time, the time of flight was directly measured. The electron energy could be calculated from the time of flight and path length of the electrons. This model is consistent with the spectroscopic model which proposes that these fast electrons directly produce the bulk of the 3–4-keV x rays via direct collisional excitation and ionization. By use of the measured electron beam attentuation and energy loss in the filters to determine the energy of the beam, the time-of-flight analysis may be used to demonstrate that the beam was formed at the time of pinch. The time-of-flight analysis indicates that the unfiltered early electron beam pulse has an energy of 22 keV which decreases as a result of energy loss in the filter with increasing filter thickness. Using the tabulations of electron stopping power of aluminum one can correct for the integrated energy loss due[12,13] to the presence of the filter to determine the incident electron energy. There is excellent agreement for the high-energy (earlier) electron pulse yielding corrected incident energies of 22 (unfiltered), 20 (0.75 $\mu$m aluminum), and 23 (8 $\mu$m aluminum) keV. The amplitude correction to the filtered signals can be made with tabulations of the electron attenuation factors.[12,13] Application of this correction for 20-keV incident electrons yields corrected amplitudes of 0.63 V for the 8-$\mu$m filter and 0.42 V for the 0.75-$\mu$m filter. These agree within experimental error with the unfiltered amplitude of 0.60 V. Using time-of-flight analysis, electron energy loss in the filters, and beam attenuation in the filters, we have determined that the incident electron energy is $\approx 20$ keV and the beam is produced at the time of pinch. The corrected data are displayed in Fig. 4.

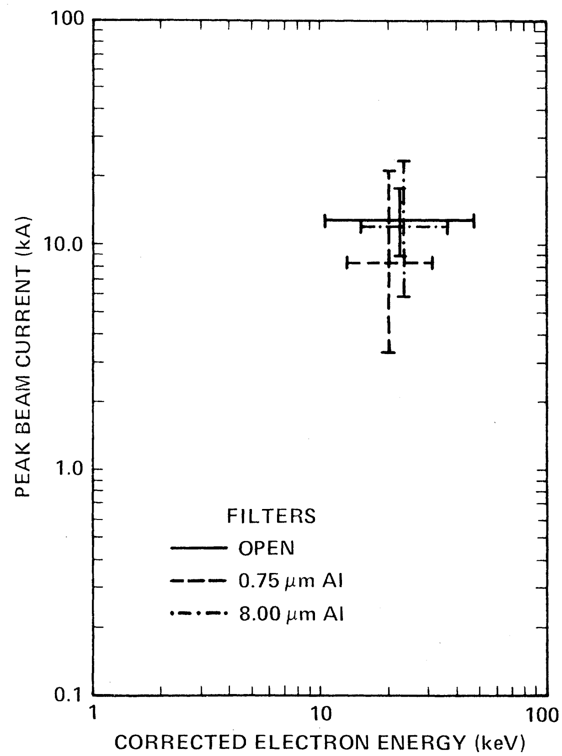


FIG. 4. The corrected fast-signal data from Fig. 3. The Faraday-cup voltage has been converted to beam current and corrected for filter attenuation. The electron energy has been corrected for the integrated energy loss through the filters.

Time-of-flight analysis of the later pulse yields an energy of $\approx 3$ keV, too low to produce the observed x-ray excitations. Corrections to the low-energy pulse are based upon extrapolation of tabulated cross sections, which may not be reliable below 10 keV. All corrections, especially the total attenuation of the late pulse by the 8-$\mu$m-aluminum filtering, are consistent with $\sim 3$-keV electrons.

The magnitude of the beam current can be estimated from measured Faraday-cup voltage and a free-expansion model for the vacuum electron transport. The envelope equation[14] including the self magnetic field and excluding the effects of the drift-tube wall was used to estimate the attenuation of the electron beam between the plasma and the Faraday cup. An attenuation factor of $\sim 10^{-6}$ was calculated for the fast electrons. This rough estimate yields peak currents of order 10 kA and has been applied to the vertical axis of Fig. 4. The resultant beam current agrees with the spectroscopic estimates. This is only a small fraction of the 600 kA flowing through the plasma at pinch time. The measured electron-beam pulse width is similar to the 3–4-keV x-ray pulse width; an example of both pulses is shown in Fig. 2(b). This is also consistent with the spectroscopic model. The attenuation estimation does not apply to the slower electrons which are probably a result of the interaction of the high-energy electron beam with the drift-tube walls. We note that the bulk of the lower-energy electrons, $E \sim 3$ keV, do not have sufficient energy to excite the observed x-ray transitions.

The production of fast electrons may be a direct result of the large inductive or resistive voltages present at pinch time. The large azimuthal magnetic fields ($\sim 1$ MG) may preclude a simple explanation of the presence of the electron beam as a result of a classical runaway process.[15] Detailed investigation of other processes such as the dissipation of magnetic energy in pinched regions,[16] singular orbits,[17] and turbulent or nonlinear acceleration[18] may lead to a more accurate description of this phenomena.

In summary, the first direct measurement of an electron beam produced at the time of pinch in a $Z$-pinch plasma has been made. The energy, $\sim 20$ keV, has been directly measured and the peak beam current was estimated to be on the order of 10 kA. These results are consistent with beam-parameter estimates based upon x-ray spectroscopy.

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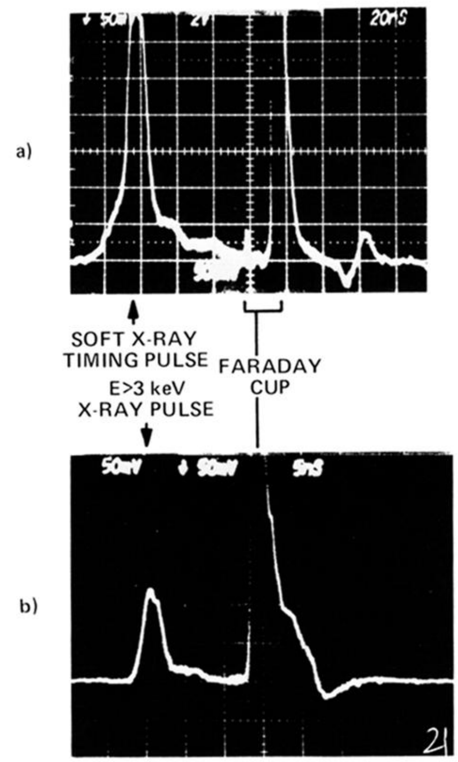


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