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The energy distribution of the electron beams in z-pinches with different load geometries

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A wide variety of z-pinches are host to energetic electron beams whose energies and origins have yet to be sufficiently characterized. Knowing the electron energies and currents of these electron beams can give insight into the mechanism responsible for the acceleration of the electrons to such high energies. Measurements with a magnetic analyzer have been carried out to determine the energy distribution of electron beams on a variety of aluminum wire array z-pinch geometries at the Nevada Terawatt Facility at the University of Nevada, Reno. These measurements show that as the geometry of the wire array is changed so that the initial angle of inclination, or necking shape, is enhanced, there is an increase in electron beam activity and electron energies. Measurements such as these can be useful to benchmark spectroscopic techniques used to characterize these energetic beams and give insight into the mechanisms responsible for the generation of such energetic beams in z-pinch plasmas. *Published by AIP Publishing.* https://doi.org/10.1063/1.5045343

I. INTRODUCTION

The presence of energetic electron beams has been noted in a variety of z-pinch configurations including but not limited to gas-puff z-pinches,[1] vacuum spark discharges,[2] fiber pinches,[3–5] dense plasma focus,[6–9] and wire array z-pinches[10–22] most notably in x-pinches. The peak electron energies in these energetic beams can be much higher than the applied anode-cathode voltage.[3]

Commonly, energetic beams of electrons are inferred as a result of their interaction with the surrounding environments. When interacting with the hardware or the background plasma in surrounding regions, beams can generate hard x-ray radiation.[3,5,11,12,15–18] In fact, the existence of such energetic electrons was initially inferred from the presence of very high energy x-rays. Additionally, energetic electron beams create damage to load hardware. This damage has been used to infer the total energy in these beams.[11,14,17]

Based on the presence of high energy x-rays, it was known early on in z-pinch research that z-pinches were powerful x-ray sources in which an important part of the radiation resulted from energetic electron beams that could not be explained by standard magneto-hydrodynamic equations.[23–25] Often, the generation of intense electrons beams is correlated with bright, or "hot," x-ray spots during the pinch stagnation phase. These "hot" spots are suspected to be related to the generation of electron beams and are usually correlated with $m = 0$, or necking, instability.[4,5,16] Although this is not always believed to be the case,[8] the generation of microinstabilities[24] is thought to lead to the extremely high energy particles. The presence of energetic electron beams has been correlated with the presence of intense beams of ions.[5,7,26] The presence of electron and ion beams suggests that a high strength electric field is responsible for high energy particles.

How the beam creating electric fields are generated is another question. In many experiments, beam generation is correlated with a dip in the current. In some instances, this dip is thought to result from the necking, or constriction, of the plasma column leading to a rapid cutoff of the pinch current. In other instances, plasma turbulence[27] is thought to increase plasma resistivity creating the current disruption. Some have concluded that only a small fraction of the electrons can be accelerated to such high energies,[28] while others have concluded that the instabilities from the turbulence[24] can produce the large amounts of fast electrons seen in experiments. Turbulent instabilities have been theoretically investigated to understand how resistivity arises.[29] When the plasma has fuel components that are conducive to fusion reactions, the production of neutrons is also correlated with beam formation,[30,31] suggesting neutron production of beam-target origin. Although more recently,[32] experiments have isotropic neutron yields suggesting thermonuclear neutron production.

There are many spectroscopic signatures of energetic electron beams. One is the presence of "cold" characteristic spectral lines which cannot be generated by thermal electrons.[11,12,15–22,33] Electron beams also influence thermal transitions and the emitted spectrum. Spectroscopic modeling has been used to understand these effects and interpret recorded spectra from z-pinch plasmas.[10,33,34] The forms of the electron energy distribution function (EDF)[35] for these beams and the effect on the recorded spectra have also been examined. See Lamoureux[36] or Rosmej[37] for reviews of the modification of spectra due to hot electrons. Electron beams, or anisotropic electron distributions, in plasmas also leave there mark spectroscopically with a partial polarization of emitted x-rays.[38] Polarization spectroscopy, spectropolarimetry, has been used to diagnose the presence of electron beams in z-pinches.[39–42]

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Energetic beams of electrons have been directly measured with Cerenkov detectors[6,8] and collected with Faraday cups.[1,15,17,18,22] The energy distribution of these beams has been measured using a magnetic analyzer.[2,9,43] In some cases, magnetic analyzers have been coupled with scintillation detectors[44] or Faraday cups[7] for time and energy resolution.

Characterizing the energies of the electrons in these beams is important for determining if a theory for one acceleration mechanism is preferable to another mechanism. Knowing the energy distribution for these intense beams can also help to benchmark efforts to develop non-invasive spectroscopic techniques. In this paper, we will present results from measurements to characterize the energies of electrons and the relative current carried in energetic electron beams in a variety of aluminum wire array z-pinches with different geometries. Aluminum is chosen for the ongoing work in the development of a single-crystal x-ray spectropolarimeter.[45] Measurements were carried out on the 1-MA Zebra pulsed power generator at the Nevada Terawatt Facility at the University of Nevada, Reno. The results show that as the necking of the wire configuration is increased, there is increased electron beam activity.

II. EXPERIMENTAL SET-UP

An array of Faraday cups coupled with a magnetic analyzer, similar to that used in the past,[7] was fielded on cylindrical, conical, and x-pinch wire array z-pinches. The cylinders and cones consisted of eight, 15 μm, aluminum wires. The x-pinches consisted of four, 25 μm, aluminum wires. The cylindrical and x-pinch configurations had a diameter of 12 mm. The conical geometry had an anode diameter and a cathode diameter of 18 mm and 6 mm for the regular cone and 6 mm and 18 mm for the inverted cone, respectively. The distance between the cathode and the anode, d_{ca}, is 20 mm. Figure 1 depicts these wire array configurations.

Figure 2 shows the set-up for the Faraday cup array when fielded above the anode of the z-pinches. Electron beams that are generated in the pinch region are collected axially from above the pinch through an opening in the anode. Beams are cut further with a collimating aperture of diameter 5 mm. The distance between the anode and the aperture, d_{aa}, is equal to roughly 100 mm. Electrons which enter the magnetic spectrometer travel another 20 mm to the region of the magnetic field, 12 mm height × 25 mm width, and are deflected depending on their energy. Once leaving the backside of the magnet, electrons travel an additional distance, d_{mfc}, of 100 mm to be collected by Faraday cups. The Faraday cups were fielded so that the centers of the Faraday cup openings were at angles of 20°, 40°, 60°, and 80°. The Faraday cups have an opening of 5 mm. The cups were terminated with 50 Ω and previously found to have a capacitance of 10.4 pF,[46] giving them a response of $\sim$0.5 ns. In this way, a signal of 100 V corresponds to a current of 2 A collected by the cup, which is a small fraction of the current expected in the pinch. Aluminum foils with a thickness of 16 μm were used at the openings of each of the Faraday cups. These filters were intended to serve a few purposes, including rejection of plasma jets, x-rays from creating secondary electrons, and stopping less energetic electrons.

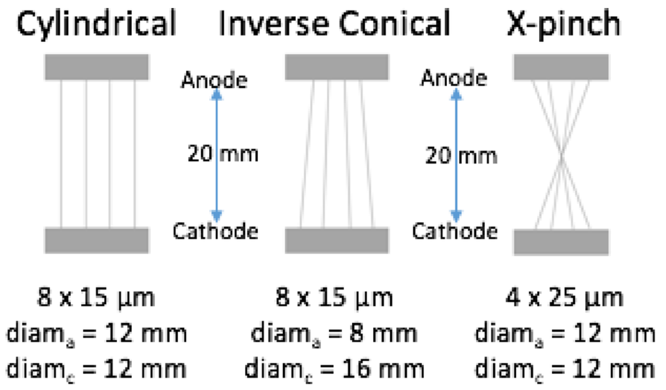

FIG. 1. Styles of wire array geometries in this paper.

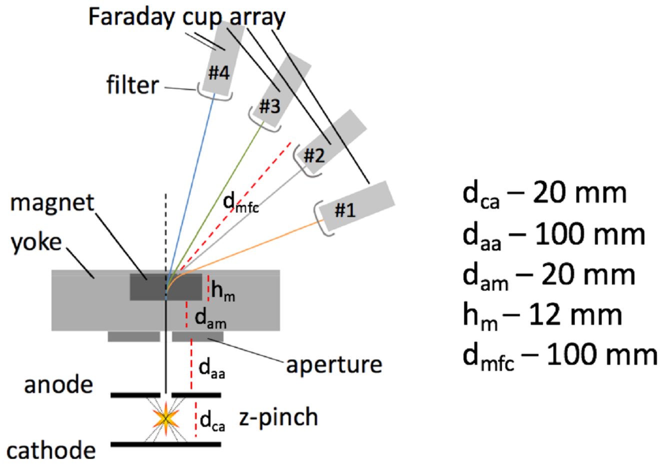

FIG. 2. Set-up of the Faraday cup array when fielded on wire-array z-pinches. Collecting anode directed electron beams.

The magnetic field has been mapped, with a resolution of 2 mm. The energy ranges for the Faraday cups were determined by particle tracing through a smoothed magnetic field profile.[47] In these calculations, electrons were generated with random initial energy and a random initial direction constrained by the two collimating apertures. The energy ranges for each cup based on these calculations are shown in Table I. The central energies will be used when referring to these cups.

III. RESULTS ON ALUMINUM WIRE Z-PINCHES

Figures 3–8 show the results from the three styles of arrays. Each geometry wire array leads to a different temporal signature of electron beam activity, and this has been seen in the past.[17] In addition, each array leads to differing

TABLE I. Approximate energy ranges for the Faraday cup array. E_{label} will be used when referring to the Faraday cup data.

Cup	Angle	E_{min}-E_{max} (keV)	E_{label} (keV)
1	20	30–60	50
2	40	50–150	100
3	60	150–450	300
4	80	500–3000	1000

electron energies and beams currents. Each figure shows the normalized current registered with a B-dot probe located on the anode plate about 150 mm from the pinch region. Current maximum corresponds to $t = 0$. In addition to the current and the signals recorded from the Faraday cups, signals from a filtered photo-conducting detector (PCD) give information about the x-ray output. The PCD is filtered with 25 μm of Kapton giving a response to Al K-shell radiation. For Al He-α, at 1.58 keV, and Al Ly-α, at 1.72 keV, the transmission through the filter is ~6% and ~12%, respectively. The x-ray energy for 1% transmission through the filter is ~1.32 keV. For each figure, the y-axis scale for the PCD signals are the same. Whereas for the Faraday cup signals the y-axis scale is five times larger for the conical and x-pinch than for the cylinders.

Figures 3 and 4 show results from aluminum cylindrical wire-array z-pinches. For the cylindrical wire arrays, the electron beams produced had lower energy electrons and the lowest beam currents when compared to other array geometries. The cylindrical arrays typically had a single main electron beam event. However, the case seen in Fig. 3, cylinder 1, shows that there could be additional smaller events of electron beam activity registered on the lowest electron energy Faraday cup.

The conical style wire arrays produced more energetic electrons and larger beam currents when compared to the cylindrical arrays. Figures 5 and 6 show results from aluminum inverse conical wire-array z-pinches. The increased necking shape in the inverse conical style arrays leads to the production of higher energy electrons as seen in the higher energy Faraday cups. The inverse conical arrays typically had somewhere from three to four events of electron beam activity registered on the lowest electron energy Faraday cup, with fewer events registered on the higher energy cups.

For x-pinch wire arrays, the electron beams produced contained the most individual electron beam spurts or events. The results for the Faraday cups from four wire x-pinches are shown in Figs. 7 and 8. For these x-pinches, there were

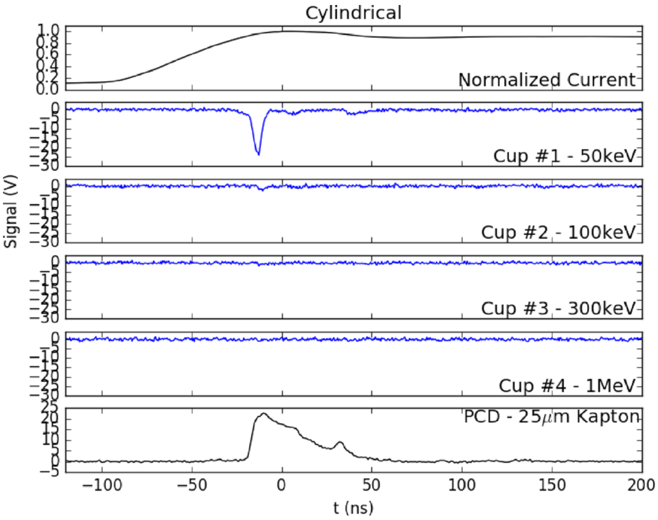

FIG. 3. Cylinder 1: normalized current, Faraday cup results, and the filtered PCD signal from an Al cylindrical wire-array (shot 3024).

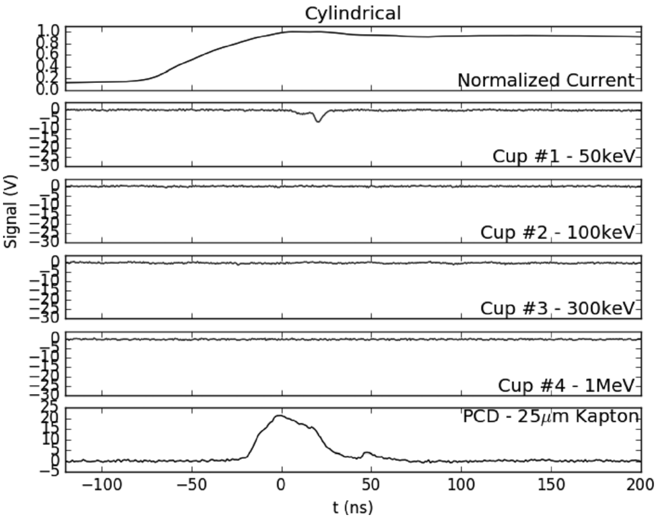

FIG. 4. Cylinder 2: normalized current, Faraday cup results, and the filtered PCD signal from an Al cylindrical wire-array (shot 3026).

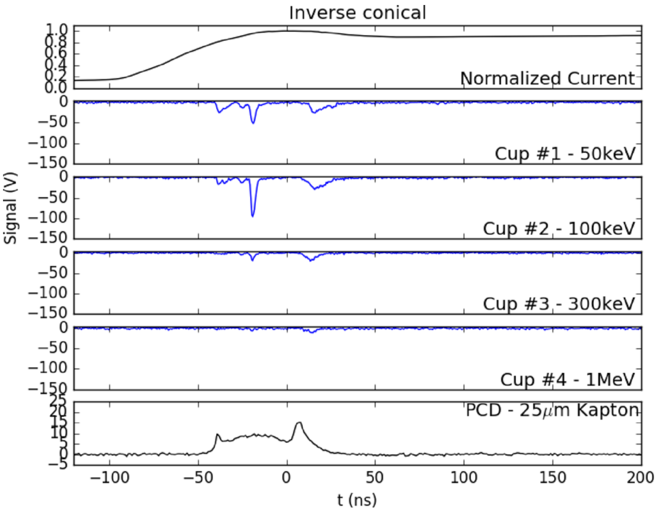

FIG. 5. Conical 1: normalized current, Faraday cup results, and the filtered PCD signal from an Al inverse conical wire-array (shot 3020).

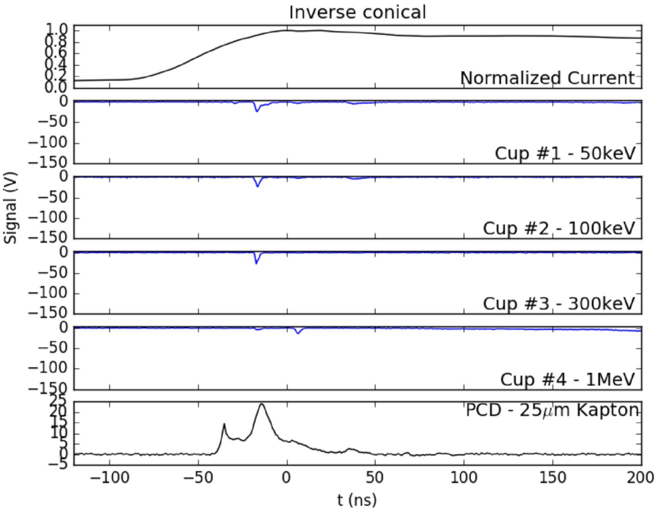

FIG. 6. Conical 2: normalized current, Faraday cup results, and the filtered PCD signal from an Al inverse conical wire-array (shot 3025).

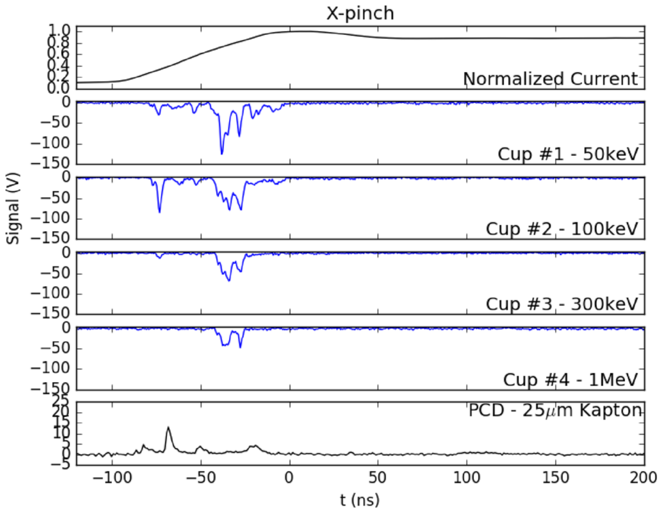

FIG. 7. X-pinch 1: normalized current, Faraday cup results, and the filtered PCD signal from an Al wire-array x-pinch (shot 3019).

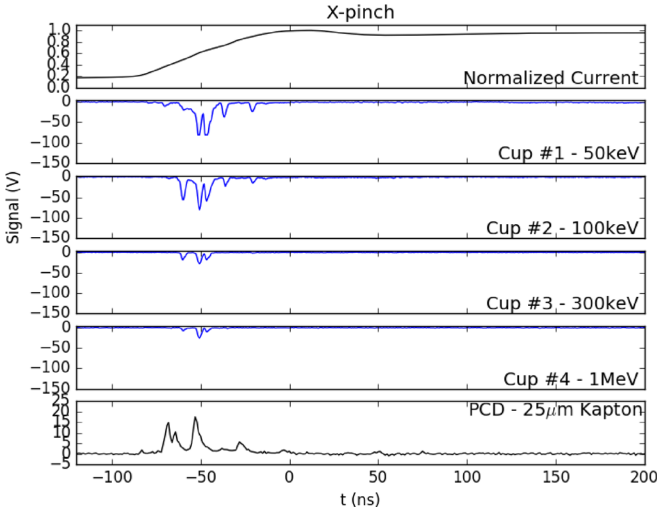

FIG. 8. X-pinch 2: Normalized current, Faraday cup results, and the filtered PCD signal from an Al wire-array x-pinch (shot 3023).

typically somewhere around six or more events of the electron beam activity registered on the lowest electron energy Faraday cup. This style array also produced the highest beam currents for the highest electron energy Faraday cups when compared to the cylindrical and conical style wire-arrays.

Time-integrated electron beam energy spectra can be generated for these shots. Figure 9 shows the time-integrated energy distribution. With the x-pinches generating the most electron beam activity (higher energies and currents) and cylinders the least, these results suggest loads with increased necking generated more intense electron beams. In addition, the signals recorded with the PCD sometimes show peaks in the x-ray power output that correlate with electron beam emission. However, other peaks show no correlation. Figure 10 shows the relative x-ray yield recorded by the integrated PCD signal as a function of the total charge collected in all of the Faraday cups together. The figure shows a trend of decreased x-ray emission as more electron beams are generated, and this could be a result of a decrease in the size of the x-ray emitting region.

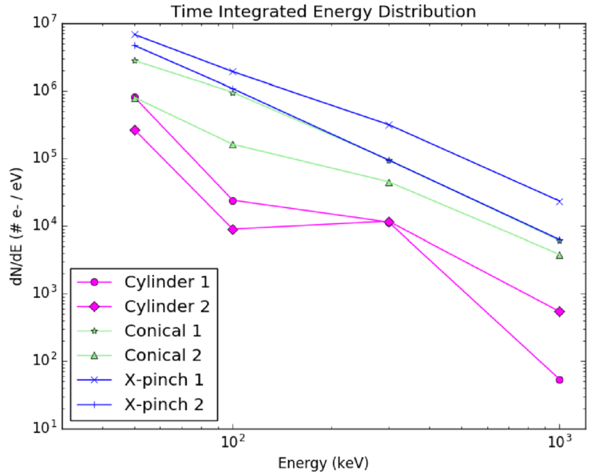

FIG. 9. Time-integrated electron beam energy spectra for these 6 shots, 3 load styles.

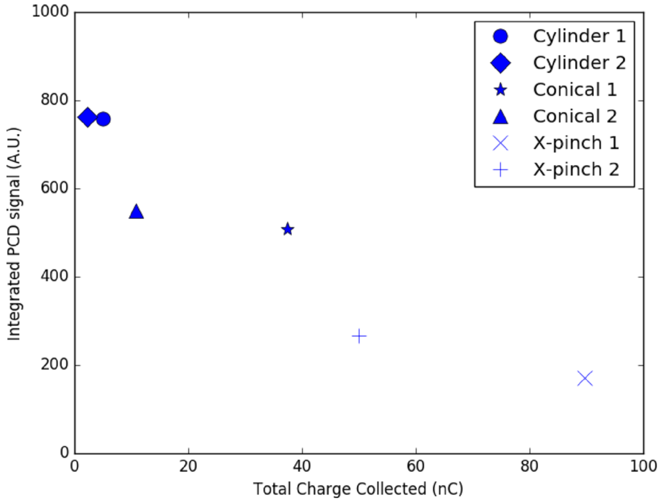

FIG. 10. Integrated x-ray output versus the total charge collected with the Faraday cups.

IV. CONCLUSIONS

The results from a magnetic spectrometer to determine the electron energy distribution in intense electron beams in wire-array z-pinches were shown. The measurements of the energy of electrons presented here show that the energies of the electrons in the beams are affected by the style of the array. The cylinders produce the least beam activity, then the conical with more, and x-pinches with most. An interesting result is that almost every electron beam event has a different energy distribution. This could be a real phenomenon, and not all electron beam events are created equally. Different types of electron beams at various stages in x-pinches have been noted in the past.[14,15] In addition to beam episode variability within a single shot, shots of the same array geometry had differences in the electron beam activity, demonstrating the irreproducible nature of z-pinches.

Measurements such as these are useful to gauge what is responsible for producing energetic electron beams in z-pinch plasmas. However, when characterizing the beams outside of the plasma region, realistic considerations need to be made regarding what is registered at the detectors.[15] For instance, attenuation of the beams as they propagate through the plasma and the working of the detectors themselves greatly affect the results and influence interpretation of the currents and energies of the electrons beams. Beam attenuation through the plasma column may be what leads to some of the recorded signals here. In addition, the direction of electron beam propagation may prohibit them from making it through the collimating apertures to the detectors. Spectroscopic signatures left by the beams in the regions they are generated are most desirable as they offer a non-invasive way to characterize the energetic electron beams. Future experiments to characterize the electron beam energy distribution and currents are useful for benchmarking the non-invasive spectroscopic techniques, such a spectropolarimetry, and for understanding where and how energetic beams of electrons are produced in z-pinch plasmas.

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