

**Observation of Radially Emitted Proton Beams from Low-Mass  $X$ -Pinch Plasmas**

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Ion acceleration in  $Z$ -pinch plasmas is traditionally linked to the axial direction of current. Here, we report the radial emission of MeV protons from a low-mass, hydrogen-containing  $X$  pinch. Proton energies up to 3 MeV are observed in a hybrid  $X$  pinch with a 30  $\mu\text{m}$  polyethylene fiber at a 400 kA peak current. The low-mass load, correlation of protons with hard x-rays, and timing of hard x-ray emission point to proton acceleration driven by current disruption following fiber disintegration. A new insight into the acceleration mechanism arises from the use of an interelectrode gap that is too short for magnetic fields to bend axially accelerated protons by  $\pi/2$  radians; thus, the observed radial emission implies a substantial radial acceleration component. The radial emission also enables  $X$ -pinch-driven proton radiography, the exceptional potential of which is demonstrated with exploding wires.

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The acceleration of charged particles in astrophysical and laboratory plasmas is a fascinating area of research aimed at improving our understanding of energetic processes in the Universe [1–3] and exploring the development of compact particle accelerators for various applications in high-energy-density physics, materials science, radiobiology, radiotherapy, etc. [4–6]. Since the 1950s, ion acceleration has been observed in pulsed-power-driven plasmas [7], namely in a  $Z$  pinch—a cylindrical current-carrying plasma column, which is compressed by its own magnetic field through the  $\mathbf{j} \times \mathbf{B}$  force density. At present,  $Z$  pinches are primarily used in research on controlled thermonuclear fusion [8–10] and laboratory astrophysics [11–13].

Research on ion acceleration in  $Z$  pinches remains of considerable interest as the mechanism has yet to be clearly identified [14–16]. The exceptional performance of this mechanism was highlighted by the observation of hydrogen ions with energies up to 60 MeV in a 3 MA deuterium gas-puff  $Z$  pinch [17]. For a deeper understanding of the acceleration process and for greater application potential, a localized and compact source would be useful. One possible candidate for concentrating electric current in time

and space is an  $X$  pinch, including both standard (two or more micron-scale wires crossed at a single point [18]) and hybrid (solid conical electrodes connected by a single wire [19]) configurations.  $X$  pinches are studied and employed primarily as pointlike sources of soft x-rays [20–22], and less frequently hard x-rays [23], electron beams [24,25], and neutrons [26]. Their potential for ion production remains largely unexplored.

Recently, we investigated the DD-fusion proton production from a hybrid  $X$  pinch with 80–160  $\mu\text{m}$  thick deuterated polyethylene fibers on the MAIZE generator at 500 kA currents. During this research, we unexpectedly observed deuterons accelerated up to 3 MeV [27]. However, this occurred in a single shot only as no MeV deuterons were detected in the subsequent dozens of shots, preventing reliable characterization of the ion acceleration.

This Letter presents results from a hybrid  $X$  pinch using a natural polyethylene ( $\text{CH}_2$ ) fiber with a small diameter ( $\leq 40 \mu\text{m}$ ), which allows reproducible proton beam emission and detailed study of the acceleration process and its properties. Using 30  $\mu\text{m}$   $\text{CH}_2$  fibers on two generators with a 400 kA peak current, we independently observe protons up to 3.3 MeV, the highest energy reported to date in  $X$  pinches. At this energy, the size of the (virtual) proton source is of about 200  $\mu\text{m}$ . MeV protons are produced after fiber disintegration and detected in the radial direction, i.e., perpendicular to the fiber axis. The measured current and the anode-cathode (A-K) gap distance are insufficient to bend axially accelerated protons toward radial detectors, indicating a radial acceleration component. Acceleration

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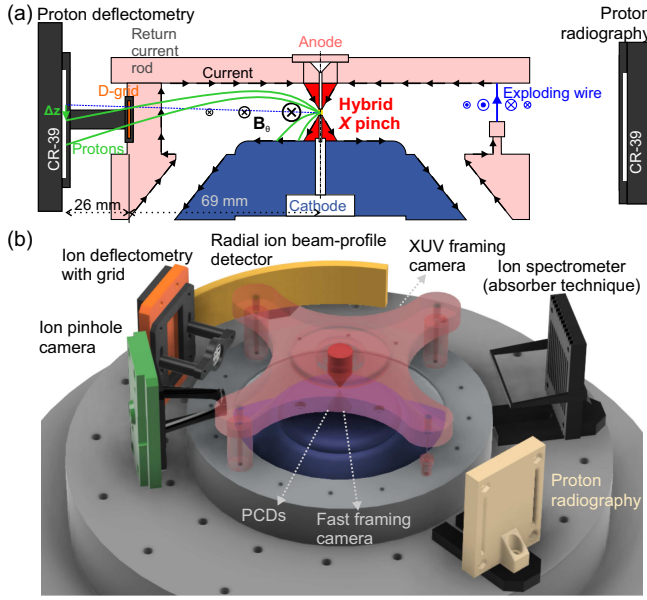


FIG. 1. Schematics of (a) the hybrid X pinch and (b) the in-chamber diagnostics on MAIZE. The same set of ion detectors is used on XP.

mechanisms in Z-pinch plasmas have so far been associated with the axial direction toward the cathode [15]. This Letter therefore reveals new aspects of the ion acceleration and demonstrates the potential of an X-pinch-driven proton source as a novel platform for the study of pulsed-power plasmas.

**Experimental setup**—The ion emission from the  $\text{CH}_2$  fiber X pinches is studied on the XP (390–500 kA, 70 ns rise time, Cornell University [28]) and MAIZE (350–490 kA, 200 ns rise time, University of Michigan [29,30]) generators. Since the fibers are nonconductive, most of the experiments are performed in a hybrid X-pinch configuration with a short A-K gap. The hybrid X pinch consists of solid conical electrodes with a cone angle of  $60^\circ$  and a 1-mm hole on the axis. The A-K gap between the cones varies from 1.5 to 3.3 mm. The  $\text{CH}_2$  fibers, 30 to 90  $\mu\text{m}$  in diameter, are loaded through the holes in the cones. Figure 1 shows the experimental setup and layout of the diagnostics used on MAIZE.

Properties of the ion emission are measured by a suite of ion detectors, some of which were described in [27]: an

ion spectrometer based on an absorber method, an ion pinhole camera, an ion slit step-wedge camera, a radial ion-beam profile detector, and an ion deflectometry detector with a grid. In several shots, the protons from the X pinch are used to probe an exploding wire placed in the return-current post [see Fig. 1(a)]. The ion diagnostics use CR-39 detectors and GafChromic HD-V2 films. The time evolution of soft x-rays is monitored by filtered photoconducting detectors (PCDs). On MAIZE, a scintillator-photomultiplier tube detector (PMT), shielded by 5 cm of lead, measures high-energy bremsstrahlung radiation ( $> 0.5$  MeV) and, if produced, neutrons [31]. Neutron yields are detected by a Be-activation probe and bubble detector-personal neutron dosimeters [32]. To observe X-pinch dynamics, a 12-frame visible self-emission imaging diagnostic and a 4-frame extreme ultraviolet (XUV) camera with 200  $\mu\text{m}$  diameter pinholes, both with 5 ns exposure, are fielded.

**Experimental results**—The hybrid X-pinch experiments on MAIZE and XP utilize  $\text{CH}_2$  fibers of different diameters. Figure 2 shows the dynamics of the 30  $\mu\text{m}$  fiber on MAIZE. Such a thin fiber disintegrates rapidly with a gap observed at the cathode shortly after 47 ns. Necking at both electrodes leads to a characteristic spherical-like expansion in the center of the A-K gap. Multiple implosions of the plasma generated from the fiber and the electrodes may occur. At about 67 ns, the implosion at the anode results in plasma ejection and another gap that occupies a large part of the interelectrode space. This event is typically accompanied by a nanosecond pulse of  $> 0.5$  MeV photons, as shown in Fig. 3, which displays the waveforms of the current, soft x-ray, and hard x-ray emissions. During the hard x-ray emission, the current reaches 250 kA, i.e., more than half the 380 kA peak at 200 ns. The intensity of the hard x-rays on MAIZE and XP correlates closely with the proton energy observed at the radial ion detectors [33].

**Proton emission**—Reproducible proton acceleration to energies  $> 1$  MeV is achieved using  $\text{CH}_2$  fibers with diameters  $\leq 40$   $\mu\text{m}$  and specific A-K gaps: 2.1–2.8 mm on MAIZE and 2.0–2.5 mm on XP [33]. The peak proton energy of 3.3 MeV occurs with the thinnest fiber (30  $\mu\text{m}$ ) and is observed on both the MAIZE and XP generators. The most energetic protons are recorded by CR-39 solid-state nuclear track detectors, which have the great

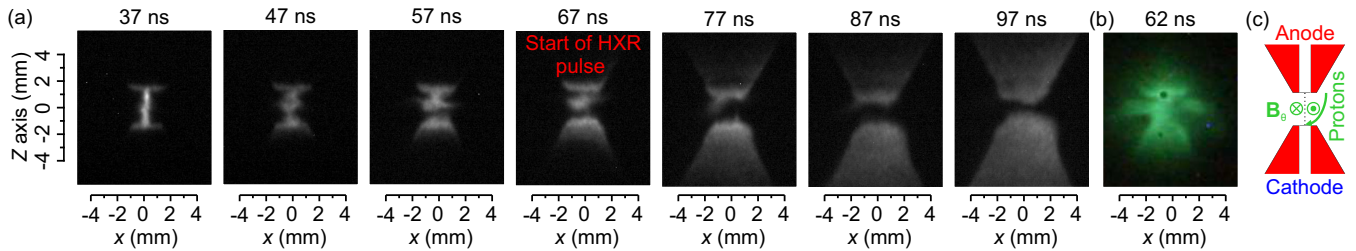


FIG. 2. Data from MAIZE shot no. 3369 with a 30  $\mu\text{m}$   $\text{CH}_2$  fiber. (a) Visible and (b) XUV images of low-mass hybrid X-pinch dynamics. (c) Schematic of the conical electrodes.

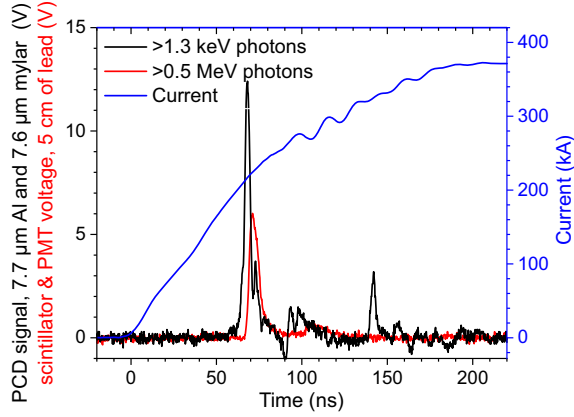


FIG. 3. Waveforms of current, PCD signal ( $> 1.3$  keV), and bremsstrahlung radiation ( $> 0.5$  MeV) from MAIZE shot no. 3369 with a  $30\ \mu\text{m}$   $\text{CH}_2$  fiber. All signals are adjusted to account for variations in transit times from each detector to oscilloscopes. The time-of-flight of photons and the transit time of electrons in PMT are also taken into account.

advantage of being able to unambiguously assign etched tracks to ions. The use of  $\text{CH}_2$  fibers (rather than  $\text{CD}_2$  fibers [27,31]) further simplifies the analysis, as the contribution of DD-fusion protons to the observed signals can be neglected. This is supported by measured DD-fusion yields, which, for natural polyethylene fibers, are below the detection limit of our neutron detectors ( $< 10^6$ ). Additionally, the energy spectrum of the detected protons decreases monotonically, with cutoff energies typically reaching 2.3 MeV—a characteristic that is inconsistent with the DD-fusion reaction.

Near the cut-off energy, the proton emission shows angular anisotropy and is not detected by all radial detectors. The specific radial direction of the proton beam varies from shot to shot (see Supplemental Material [33]). In the shot presented in Fig. 4, the proton beam hit the deflectometry detector. The fastest protons penetrated  $10\ \mu\text{m}$  of Al and a single layer of  $109\ \mu\text{m}$  thick HD-V2 film, indicating a proton end-point energy of at least 3.15 MeV. As shown in Fig. 4(d), the proton fluence in the selected area is above  $10^7$  protons/ $\text{cm}^2$ . Calculating with the detector distance of 95 mm, the peak fluence of 3.15 MeV protons exceeds  $10^9$  protons/sr.

Figure 4(b) displays the shadow of the deflectometry grid produced by the proton beam (on CR-39) and the soft x-rays (on HD-V2 placed in front of CR-39). The azimuthal magnetic field, acting on moving protons through the Lorentz force  $e\mathbf{v} \times \mathbf{B}$  [see Fig. 1(a)], causes the virtual proton source to appear above the anode. Consequently, the 3 MeV proton grid shadow is below the shadow formed by the soft x-rays. According to the method described in [27], the proton shadow shift of  $4.5 \pm 0.5$  mm corresponds to a current of  $240 \pm 30$  kA, which matches the current of  $260 \pm 10$  kA measured by the Rogowski coil during the  $> 0.5$  MeV bremsstrahlung emission. From an analysis of

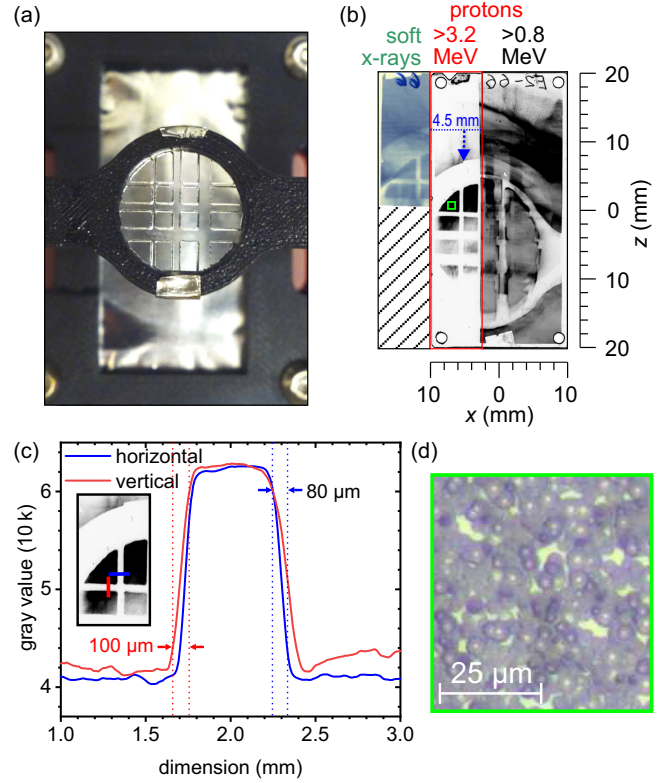


FIG. 4. Data from MAIZE shot no. 3366 with a  $30\ \mu\text{m}$   $\text{CH}_2$  fiber. (a) Photo of the deflectometry grid. (b) Grid shadow formed by soft x-rays ( $> 1$  keV) on the HD-V2 film and by protons on CR-39. The values of  $> 0.8$  MeV and  $> 3.2$  MeV represent the proton energies needed to penetrate (i)  $10\ \mu\text{m}$  Al foil, and (ii)  $10\ \mu\text{m}$  Al foil together with one HD-V2 layer, respectively. The darkness of CR-39 is proportional to the number and visibility of proton tracks. (c) Horizontal and vertical profiles of the bar shadow produced by  $> 3.2$  MeV protons. (d) Optical microscope image recording proton tracks at the location marked by the green rectangle in part (b).

the penumbra of the 0.4-mm-wide grid bar in Fig. 4(c), the effective size of the proton source can be determined. Considering the 26:69 magnification [see Fig. 1(a)], the  $> 3$  MeV proton source is calculated to be  $210\ \mu\text{m}$  in diameter and  $270\ \mu\text{m}$  in height. Vertical blurring of the grid shadow can result not only from the source size but also from a time-variable azimuthal magnetic field. This provides a method for estimating the upper limit of the proton pulse duration. The vertical penumbra of  $100\ \mu\text{m}$  in Fig. 4(c) corresponds to a rapid current variation of 5 kA [27]. At the time of hard x-ray (and presumably proton) emission, this rapid current variation occurs within 1 ns. Consequently, the 3 MeV proton source is estimated to last less than 1 ns. At lower proton energies, both the pulse duration and proton source sizes are larger. For proton energies  $> 0.8$  MeV [see Fig. 4(b)], the deflectogram often comprises several exposures mutually shifted, likely by different magnetic field values. Multiple sources of MeV protons are also observed in the images obtained by the ion

pinhole camera and the ion slit-step wedge spectrometer [33]. These observations provide the key insights into the parameters of the ion source, which are essential for understanding the ion acceleration mechanism.

*Discussion*—Ion acceleration in current-carrying plasma configurations has been studied since the 1950s [7,34], but the underlying mechanism remains unexplained [15]. Our hybrid *X*-pinch experiments reproduce several earlier observations while also providing new insight into the acceleration process.

A key result from both MAIZE and XP is the proton acceleration to 3 MeV. This energy corresponds to an acceleration voltage  $\sim 20$  times higher than the MAIZE output voltage. The voltage multiplication may arise from rapid disruption of the conduction current, likely on a subnanosecond timescale [16]. Supporting this, a fast *B*-dot probe on MAIZE detects a sharp  $dI/dt$  dip during the hard x-ray pulse, with the fast Fourier transform showing a frequency spectrum extending to 1.5 GHz. Importantly, the current dip is only a response to rapid changes within the *X* pinch itself. This raises a critical question: what generates the impedance  $Z$  causing the current drop and driving the voltage according to  $V = ZI \approx -LdI/dt \approx 3$  MV (see discussion in [16]). From this perspective, it is worth noting that the emission of energetic particles correlates with the gap formation seen in Fig. 2. This observation suggests that the current disruption could be caused by the transition from a collisional current in unstable plasmas to a beam current in a collisionless gap [16]. Additionally, the formation of this gap highlights the importance of using low-mass fibers, as confirmed also in neutron-producing experiments with deuterated fiber *Z* pinches [35] and *X* pinches [26]. On MAIZE and XP, the highest proton energy occurs with 30  $\mu\text{m}$   $\text{CH}_2$  fibers. This diameter corresponds to a linear mass of 7  $\mu\text{g}/\text{cm}$ , which is at least one order of magnitude lower than the optimal mass for x-ray-producing *X* pinches on MAIZE and XP [36]. The dynamics of *X* pinches aimed at ion acceleration and x-ray emission are therefore fundamentally different, with the low mass leading to early implosions. Multiple implosions and explosions during the current rise allow gaps to be formed at later times, enabling proton acceleration at sufficiently high currents even on MAIZE with a 200 ns rise time. Multiple proton pulses may occur but do not hinder applications, as the most energetic beam can be isolated using thicker absorbers.

So far, most hypotheses explaining ion emission in *Z* pinches have focused on axial acceleration toward the cathode [14,15]. A new phenomenon observed in the hybrid *X* pinches on MAIZE and XP is the emission of MeV protons in the radial direction. One might argue that the radial emission comes from axially accelerated protons that are bent in the azimuthal magnetic field. This hypothesis is precisely what the well-defined *A-K* gap of the hybrid *X* pinch helps us to rule out: we must explain a significant

radial velocity component of 3 MeV protons. Suppose that a 300 kA current flows uniformly within a 30  $\mu\text{m}$  radius, and the entire *A-K* gap is used to deflect protons—i.e., they are accelerated axially to 3 MeV over a short distance and deflected across 2.5 mm [see Fig. 2(c)]. Even under these extreme conditions, the protons cannot be bent by  $\pi/2$  radians. Moreover, we must consider the bending back toward the axis due to the azimuthal magnetic field on the opposite side of the *X* pinch [see Fig. 1(a)]. Based on this, we believe that the hybrid *X*-pinch experiments provide the first evidence of ion acceleration in the radial direction, or even toward the anode. This conclusion also accounts for the unexpected anisotropy of neutron emission observed in deuterated *X* pinches [31]. The radial acceleration can still be explained by current disruption, provided a disrupted current has a significant radial component  $j_r$ , generating a radial electric field  $E_r$  via  $(\partial/\partial t)E_r \sim -(1/\epsilon)j_r$  [cf. radial flares before the disruption in Fig. 2(b)]. Alternatively, the observed radial emission could point to collective ion acceleration by an electron beam [37], Coulomb explosion [38], or an as-yet-unknown mechanism. To unambiguously identify the underlying mechanism, diagnostics capable of detecting transient electric and magnetic fields during ion acceleration are needed. Proton radiography offers a suitable approach and is planned for future experiments. Given the radial proton emission observed here, the *X* pinch itself could serve as a natural source for this technique.

*Proton radiography*—Recently, proton radiography has proven to be a powerful diagnostic tool of high-energy-density laboratory plasmas [39], but its wider use in pulsed-power plasma research is limited by the scarcity of high-intensity lasers in conventional laboratories [40]. The MAIZE and XP experiments show that hybrid *X* pinches can provide pointlike, nanosecond proton sources for radial radiography, even at modest currents. To test this capability, one return-current rod was replaced with an exploding wire test object to be imaged (see Fig. 1) [41]. We note that the radial proton emission from the *X* pinch is not fully isotropic. Nevertheless, with optimal fiber diameters (30–40  $\mu\text{m}$ ), radiographs are obtained in roughly half of the shots [33]. As an example of this capability, Fig. 5 shows a radiograph of a 25  $\mu\text{m}$  Al wire on MAIZE. This point-projection radiograph, taken with  $> 1.3$  MeV protons at 73 ns, captures not only a wire core and an expanding corona, but also previously unobserved regions characterized by turbulent structures. These structures have not been resolved in exploding-wire experiments before and become accessible through this radiography platform. The radiograph demonstrates 100- $\mu\text{m}$  spatial and nanosecond temporal resolution. Despite some nonuniformity in proton fluence, the characteristic features of the exploding wire are easily identifiable, as they appear on both sides of the wire. Typical radiograph features include flared shadow images of the core, corona, and bolt head, where the flaring makes these objects appear wider at the

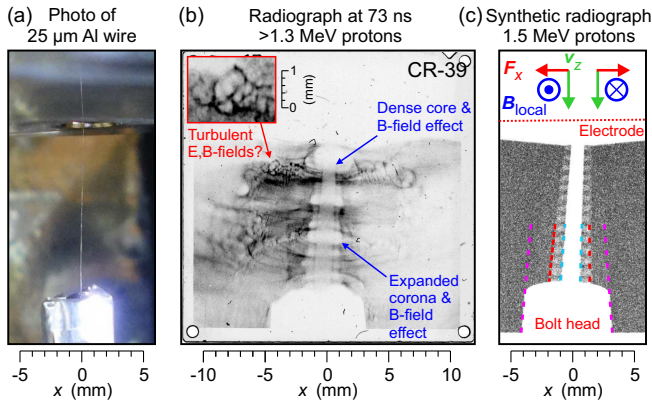


FIG. 5. (a) Preshot photograph, (b) experimental, and (c) synthetic X-pinch-driven proton radiographs of the 25  $\mu\text{m}$  Al wire in MAIZE shot no. 3369. A 20  $\mu\text{m}$  Al foil is used to absorb protons with energies below 1.3 MeV. Spatial scales correspond to the plane of the wire.

bottom than at the top. As the protons traverse the local azimuthal magnetic field of the exploding wire  $\mathbf{B}_{\text{local}}$ , they are deflected by  $\mathbf{v} \times \mathbf{B}_{\text{local}}$  with the  $x$  component  $v_z B_{\text{local},y}$ . The flaring effect is due to the trajectories of the probing protons being more steeply vertical near the lower parts of the objects being imaged (cf. Fig. 1). From the flare angles [see the nearly vertical dashed lines in Fig. 5(c)], particle-tracking simulations of the radiograph reveal enclosed currents of 3 kA at the dense core, 28 kA at the edge of the expanding corona, and 51 kA through the bolt head [33]. A more detailed analysis of this radiograph will be the subject of further publications. This example nonetheless demonstrates the applicability of the diagnostic platform. An even more versatile configuration would place the X pinch in the return-current post and the object of study in the center of the machine. However, this arrangement requires higher-energy protons to traverse the main load on axis and reach the detector on the opposite side [42].

**Conclusions**—An X pinch has been researched as a point x-ray source for over 40 years. The experiments on MAIZE and XP significantly advance our understanding by demonstrating that the hybrid X pinch with  $\text{CH}_2$  fibers can also serve as a nanosecond, sub-mm source emitting proton beams in the radial direction. A critical requirement for reproducible MeV proton beam production is the use of low linear-mass fibers. Protons with energies up to 3 MeV are produced using 30  $\mu\text{m}$   $\text{CH}_2$  fibers at peak currents of 400 kA with rise times of 70 ns (XP) and 200 ns (MAIZE). The MAIZE results confirm that proton acceleration is not constrained to sub-100-nanosecond generators. These findings highlight the low-mass hybrid X pinch as a promising platform for investigating ion acceleration mechanisms and enabling proton radiography, which opens new diagnostic opportunities for studying pulsed-power-driven plasma physics, in particular the measurement of magnetic fields at a plasma periphery [43,44].

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**Data availability**—The data that support the findings of this article are openly available at [45].

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