Technique for Insulated and Non-insulated Metal Liner X-Pinch Radiography on a 1 MA Pulsed Power Machine

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Broadband, high resolution X-pinch radiography has been demonstrated as a method to view the instability induced small scale structure that develops in near solid density regions of both insulated and non-insulated cylindrical metallic liners. In experiments carried out on a 1-1.2 MA 100-200 ns rise time pulsed power generator, μm scale features were imaged in initially 16 μm thick Al foil cylindrical liners. Better resolution and contrast was obtained using X-ray sensitive film than with image plate detectors because of the properties of the X-pinch X-ray source. We also discuss configuration variations that were made to the simple cylindrical liner geometry that appeared to maintain validity of the small-scale structure measurements while improving measurement quality.

I. INTRODUCTION

Radiography is a common diagnostic in a wide array of applications such as medical imaging, product inspection for material integrity, airport security, etc. In the field of plasma physics, it is very useful for probing high density regions of a plasma. For example, it was used in the Magnetized Liner Inertial Fusion (MagLIF) experiments to show the existence of a helical structure in the liner when an axial magnetic field was applied[1]. In those experiments, monochromatic X-rays were produced using a laser source. Another source of X-rays that can be used for dense plasma radiography in the $\lesssim 5$ keV range is the X-pinch[2,3], a very small and broadband source that can lead to high resolution imaging. If the experiment uses a pulsed power machine designed to drive sufficiently high current, then a benefit is the ability to put an X-pinch in series or in parallel with the main experimental load so that a separate X-ray driver is not needed. This is especially useful when a high-power laser is not available to produce X-rays.

In the MagLIF experiments, features of the order of 10-100 μm were observed to develop[4,5] in the liner and were mitigated using thick dielectric coatings[6]. In this paper, we describe a means to use radiography to study the development of such structure. We present the first demonstration of using X-pinch radiography in cylindrical liner experiments with and without dielectric coatings where the high-density regions of both liner and insulator were directly observed. We make use of a method that allows looking though only one layer of liner, as opposed to the default of two layers, by employing a slit that we will show does not significantly affect the radiography results at the time of measurement. We also compare images from two types of detectors, image plate and film, showing the difference in results from similar experiments. Finally, we discuss extra diagnostic protection needed in experiments with solid dielectrics due to the presence of destructive debris.

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II. EXPERIMENTAL ARRANGEMENT AND DIAGNOSTICS

A. Liner and X-pinch Setup

A sample experimental configuration is shown in Fig. 1. There is a 4.2 mm diameter, 11 mm long, and 16 μm thick cylindrical Al foil liner located in the center of Fig. 1 (a), serving as the load of the 1-1.2 MA 100-200 ns rise time Cornell Beam Research Accelerator (COBRA)[7]. It delivers ~ 5 kJ of energy to the liner in a 200 ns pulse. It is made by taking flat Al foil, wrapping it once around a rod, positioning it between anode and cathode holders, letting the foil's elasticity expand it against the inner wall of the holders (e.g., the hole in the brass anode in Fig. 1 (b)), and finally removing the rod. Similar wrapping methods have been used in previous experiments, one group using foils as thin as 400 nm[8]. Such methods allow using sufficiently thin liners to enable radiography through the solid regions of the liner. A schematic diagram of what the X-ray radiography detector sees in such foil setups is shown in Fig. 1 (c). Using the Center for X-ray Optics' (CXRO) free online database, we show in Fig. 2 that there is very little transmission through 50 μm Al, but there is significant transmission for 10 μm Al over a portion of the $\approx$ 1 - 4 keV X-ray emission region of a Mo wire X-pinch[3]. As foils generally enable liner thicknesses and tolerances that are much smaller than is practical to machine, they are an attractive means to make liner loads for 1 MA pulsed power generators.

A clear disadvantage of using foils in the manner described above is the lack of symmetry this will induce near the overlap region in the wrapped foil. Complete azimuthal symmetry must be not of vital importance to the experiment if this configuration is to be valid. Furthermore, if symmetry is not critical, a narrow axial slit can be made, as shown in Fig. 3 (a), for radiography purposes. The approximation then is that the resulting physical and magnetic field perturbations from side B in Fig. 3 (b) do not affect the development of the observed structure on side A at the time of the radiograph. The advantage of this compromise is that one can now use thicker foils for the liner and still obtain high-

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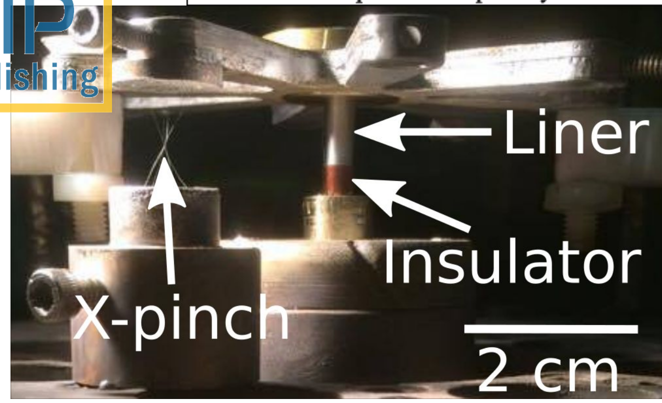
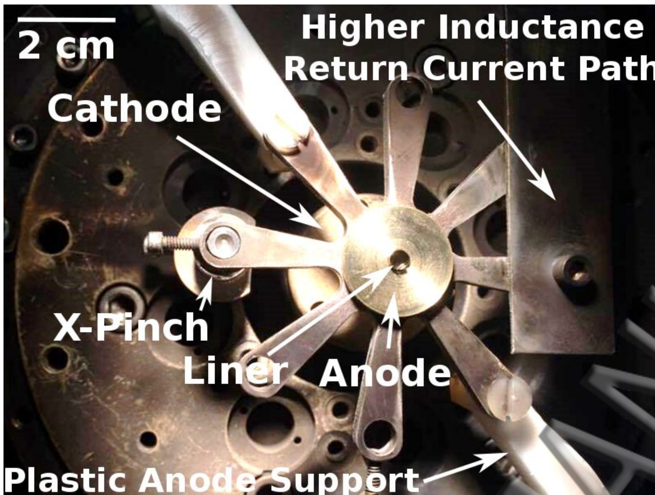
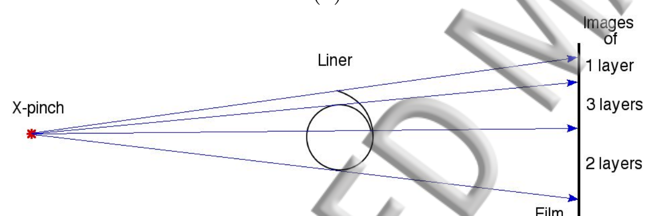


(a)



(b)

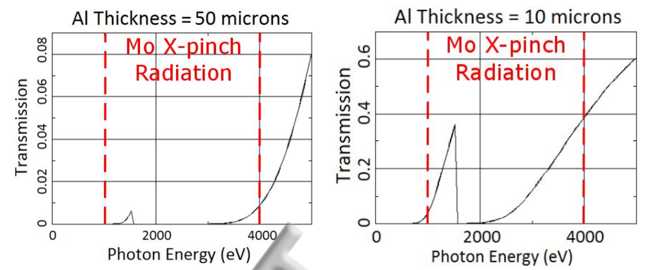


(c)

FIG. 1. (a) Side view and (b) top view of a half-insulated Al liner setup. The 11 mm long, 16 μm thick liner in the center is surrounded by a 4 mm long 50 μm thick solid insulator. There is a 4-wire 25 μm Mo X-pinch positioned in place of one of the return current posts. The second return current post is positioned radially farther out than the X-pinch in order to increase its relative current path inductance. The anode is held in place by the white plastic supports. (c) Top view schematic representation of a liner showing X-ray paths through different layers of foil. The diagram is not to scale.

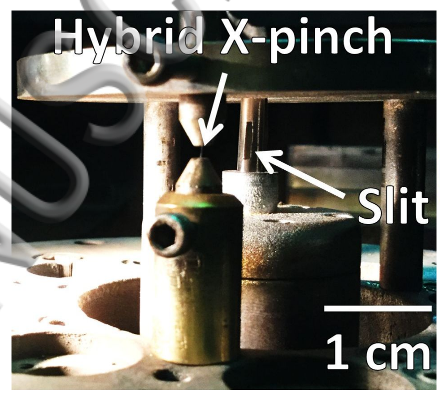
resolution radiography of side A as the X-rays are transmitted through only one layer. Comparing data with and without slits, we find similar small scale structure sizes for both, between 17 and 25 μm, meaning that the approximation concerning the impact of the slit evidently holds for our radiography measurements.

A comprehensive review of X-pinches as X-ray sources for radiography has been given by Pikuz *et al.*[2,3] and Shelkovenko *et al.*[9]. The hybrid X-pinches that were used, shown in Fig. 3 (a), consisted of two conical stain-

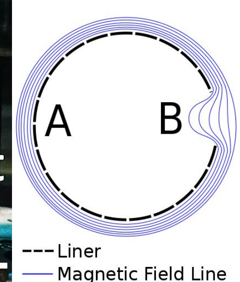


(a) (b)

FIG. 2. X-ray transmission percentage through solid Al as a function of photon energy, data obtained from CXRO's online X-ray database. The increased transmission with decreased Al thickness from (a) 50 μm to (b) 10 μm is evident. The X-ray emission range of Mo-wire X-pinches is highlighted.



(a) Photo



(b) Cross-section

FIG. 3. (a) Photograph showing the liner with a slit cut in it and a hybrid X-pinch on the return current post. (b) Cross-sectional view of the liner illustrating the magnetic field line bending.

less steel electrodes with a 2 mm long wire connecting them. Both these hybrid X-pinches and the 4-wire X-pinches, shown in Fig. 1, are discussed in detail in the review articles above. They were both used successfully in experiments described here when positioned in return current posts on COBRA. For Al liners, the filter we used in front of the detector was 12.5 μm thick Ti foil as the latter has a transmission-vs-wavelength curve that matches well with our Al foil absorption characteristics in the $\approx$ 2.8-4.8 keV range and the radiation spectrum produced by a 1 μm source size Mo wire X-pinches. If a different liner material is used, such as Cu, different filters must be used to better match the transmission wavelength range of the foil. Also note that one can change the source spectrum if needed by changing the X-pinch wire material[2,3].

An important aspect of the radiography method described here is the combination of the Mo X-pinch with the specific filters. The X-pinch produces a small, 1-2 μm, source size for a limited energy range only. Anything below or above that range has a larger source size, reaching 10 - 100 μm. If we look at a 12.5 μm Ti filter for example, the transmission below 6 keV is substantial in the ≈ 2.8 - 4.8 keV window. This also happens to be the spectral region where the Mo X-pinch source size is near 1 μm.

In our experiments, we have used 1, 2 and 3 X-pinches in parallel in the COBRA return current circuit using Mo wires that were 17-40 μm in diameter, depending on the experiment. The magnification factor, determined by the relative distances between detector, liner, and X-ray source for point-projection radiography, was 12-13 and was limited by the size of the experimental vacuum chamber rather than by X-pinch intensity or detector sensitivity.

B. Insulator Considerations

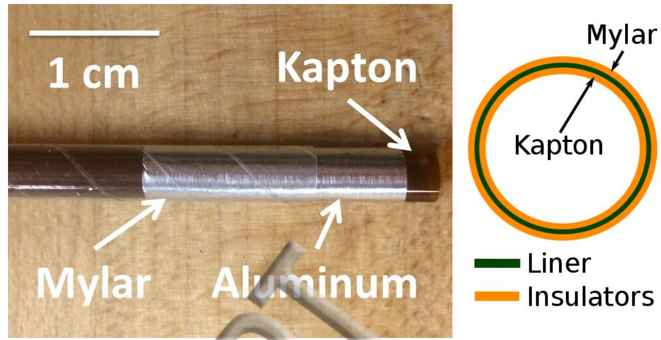
One possibility for an insulating coating on a metal liner is a liquid dielectric which will flow over the whole liner, effectively covering the entire surface. This can be useful when used in conjunction with solid dielectrics placed outside the liquid as a solid insulator may provide better expansion inhibition compared to a liquid one, with the combination also providing good contact between liner and solid insulator. Solid dielectrics alone should not be expected to fully contact the liner if one relies only on the liner's elasticity to expand against the insulator using the method described in Section II A. We have experimented with both liquid+solid and solid only insulators. However the focus of this paper, when discussing insulated liners, will be on solid only insulators. We used 50 and 75 μm thick Kapton tubes, obtained from Precision Products Group, and 100 μm thick Mylar tubes, obtained from Euclid Spiral Paper Tube Corp.

Another method to reduce the problem of gaps between liner and insulator is by "sandwiching" the liner between two layers of solid insulators, as shown in Figure 4. To do this, we can take two flexible insulators whose gap between outer surface of the inner insulator and inner surface of the outer insulator is less than the thickness of the liner. As the insulators are plastic, they have some flexibility to stretch/compress to allow room for the foil. This sandwiching technique along with using thin liners is a simple, inexpensive method that enables radiography through the liner in experiments in which we inhibit expansion of the metal. Note that this method is effective to reduce gaps down to the μm scale. Foils may have inherent structure below that scale that create gaps, such as ripples, that sandwiching would not eliminate.

Furthermore, we radiographed insulated liners using an insulator that only partially covered the liner axially. We could then simultaneously radiograph insulated and non-insulated portions of the Al liner to make a direct comparison on the same shot, while also observing the processes taking place at the boundary between the two regions.

III. RESULTS AND ANALYSIS

Choosing the right detector was critical to being able to observe the small scale features of interest here. We



(a) Photo (b) Cross-section

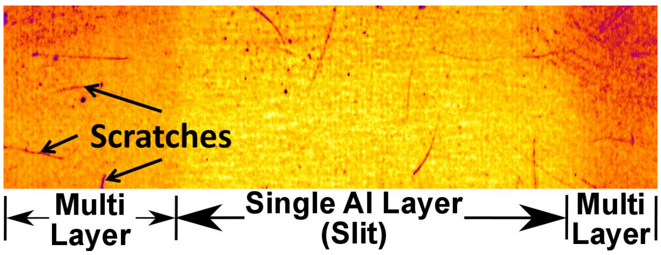
FIG. 4. (a) A photo of a liner "sandwiched" between two insulators. Here, the Kapton acts as the inner insulator and the Mylar as the outer insulator. In the picture, the Al foil has been axially extended from underneath the Mylar, and the Kapton from underneath the Al, to clearly show all three layers. (b) An axial cross-sectional schematic of the setup.

tried using both Carestream's DR50 film, which is advertised by the company as "an ultra-fine grain, very high contrast film", and Fujifilm's BAS-SR 2040 image plates, which are detectors commonly used in the medical field. The scanner used for the image plates was the Typhoon FLA 7000, scanning at 25 μm pixel size, a 650 nm wavelength and a photomultiplier tube (PMT) voltage setting of 500. The time between an experiment and scanning the image plate was no more than 10 minutes and exposure of the image plate to light in that period was practically nil. A result is shown in Fig. 5 for a 16 μm Al liner with a slit cut into it, as shown in Fig. 3 (a). The experiment had an image plate positioned immediately behind the film. We can see a region where the X-rays are absorbed by a single layer (lighter) and regions where they are absorbed by two layers (darker) in both detectors. The image plate shows the small-scale structure through a single layer but, in spite of substantial software contrast enhancement to show the structure, not through two. On the other hand, the DR50 film clearly shows features in both regions. Similar behavior was observed with the image plate in numerous experiments, both behind film or without any film in front of it. Placing no film in front is important as the film otherwise absorbs a significant amount of the 3 - 4 keV X-ray radiation that is responsible for the high resolution achieved with the X-pinch. For Cu, Ni, and Ti liners, out of 16 experiments, none showed any visible features using image plates with no film in front of them. Out of a similar number of experiments using film, roughly half the experiments displayed features. Cu, Ni, and Ti tended to have smaller feature sizes and/or smaller contrast compared to Al, which we believe accounts for the reduced fraction of experiments with visible features.

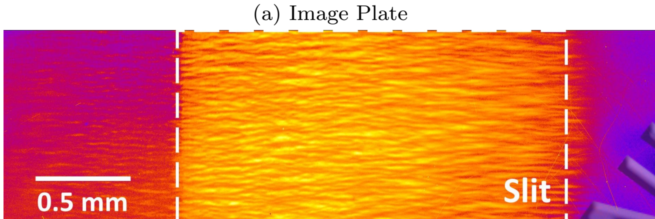
Comparing detectors, these results show that using film produces results with better resolution and contrast than using SR image plates. A summary of this comparison is shown in Table I. The smallest features observed on film were roughly 5 μm at the object. Hence, we estimate the resolution from using film with the magnifi-

TABLE I. Detector Comparison - Feature Detection

Material	Film - Visible Features	Image Plate - Visible Features
Al (1 layer)	Yes	Yes
Al (2 layers)	Yes	No
Cu, Ni, Ti	Yes at 50% Occurrence	No



(a) Image Plate



(b) Film

FIG. 5. X-pinch radiographs of an Al liner with a slit cut into it, as described in Section II A, on (a) an image plate and (b) a DR50 film. The radiographs were taken at 105 ns in a 140 ns rise time 1.1 MA peak current pulse. At that time the current was 0.85 MA. The white dashed lines in (b) are delimiting the area of the slit.

(a)

(b) (c)

FIG. 6. (a) A post-experiment picture of a protective window placed roughly 45 cm away from an insulated liner. (b) A piece of foam that was used to capture the debris to prevent the latter's vaporization upon impact. (c) A zoomed in picture of the debris extracted from a few locations in the foam catcher shown in (b) - curled solid black thin filaments enveloped by the red foam.

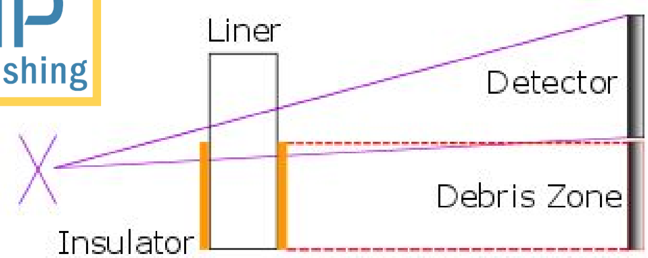
cation of 12-13 to be around 5 μm. We believe that the better results with film in our experiments is due to the image plates' being more sensitive to harder X-rays than the film. That matters because the source size of the X-pinch, as previously mentioned, increases for X-rays > 5 keV to 10-100 μm. As the features of interest are 10-25 μm in size, the larger source size will cause a blurring of the structure on the image plates.

There is an important benefit of using the image plate positioned behind the film. In combination with signals from photoconducting diodes monitoring the soft X-ray intensity, the image plate exposure gives a good indication of the intensity of the X-pinch(es) on a particular shot, thereby providing guidance on how long to develop the film in order not to cause overexposure or underexposure. In our experiments, we have changed development time by up to 50% based upon this cueing.

For experiments with insulators, we found it necessary to protect the detectors and other diagnostics in the experiment from debris. Figure 6 (a) shows the typical damage from debris incurred by a protective window placed approximately 45 cm away from the load region. In one experiment out of about ten, the window shattered. To learn the state of matter of the debris, we used foam to catch it. Note that foam is critical here as a harder surface, e.g. glass, can cause a high-velocity solid to vaporize upon impact, not to mention shattering the glass. We caught solid black thin filaments, as shown in Figs. 6 (b) and (c). Hence, at least a portion of the debris appears to be bits of solid insulator. Evidently not all of the insulator vaporized. Instead, it was turned into a solid projectile by the foil explosion pressures propelling the insulator radially outward. Note that we estimate delivering about three orders of magnitude more energy to the load than would be needed to vaporize the insulator. While only a small fraction of the energy at the load will go into heating the insulator, the presence of solid insulator might not be expected from this energy estimate comparison.

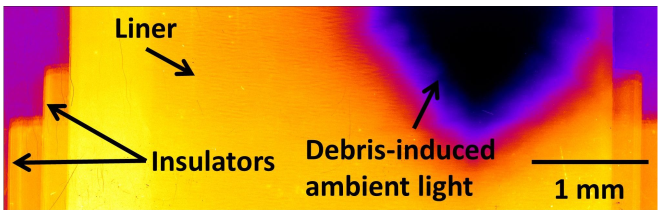
To protect the X-ray sensitive detectors from the debris, we found that using a 250 μm thick mylar protector was not sufficient. The debris pierced straight through the protector and the Ti filter and lodged itself in the DR50 film. Finding that the debris moves nearly perpendicular to the axis, detector integrity in future experiments can be assured with reasonable confidence by angling the line-of-sight, as shown in Fig. 7.

Figure 8 shows results from an experiment with two outer solid insulator layers only partially covering the liner axially. We can clearly see the two layers of insulator and their edges. There are vacuum gaps visible between insulators and between insulator and liner. This shows

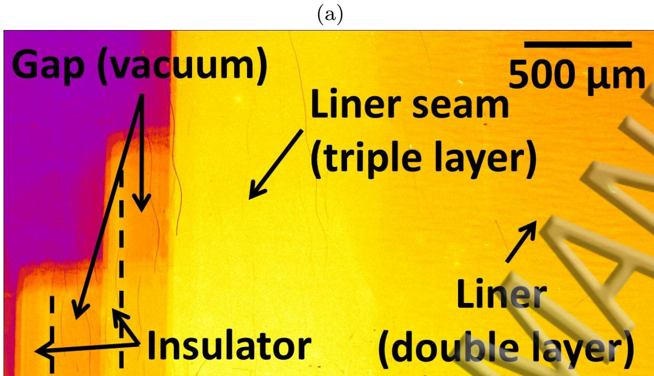


(a)

FIG. 7. Sketch depicting a method that prevents damage caused to the radiography detector from the liner debris.



(a)



(b)

FIG. 8. (a) Radiograph of an Al liner with 2 layers of solid insulator surrounding it. The insulators are only partly covering the liner axially. (b) A zoomed-in view of the insulators. In the case shown, the vacuum gaps between solid insulators and between the inner insulator and the liner, which can easily be filled with a liquid dielectric, if desired, is pointed out. The blurry edges are due to two X-pinch soft X-ray bursts, one at 70 ns the other at 80 ns in a 110 ns rise time pulse, that create multiple images overlaying one another.

that the liner's expansion is not inhibited by the insulator until ≈ 200 - 300 μm expansion occurs in this setup. However, the gap(s) can be filled by a liquid dielectric to inhibit expansion. Note that the blurry features at the edges of the insulator are a result of multiple bursts of the X-pinch in this experiment. The dark spot covering a large portion of the image is a consequence of the debris tearing through the mylar and Ti filter, as explained above, and exposing a portion of the film to the ambient light.

We have presented a method to effectively radiograph thin metallic liners with and without expansion inhibition using the X-pinch as the X-ray source. X-pinch radiation enables radiography through both insulated and non-insulated liners, and may be very useful for better understanding the physics involved in the early stages of liner experiments. Experiments are continuing using this diagnostic to investigate the development of small scale features in metal liners thought to be caused by the electrothermal[4,5] and electrochoric[10] instabilities.

IV. ACKNOWLEDGMENTS

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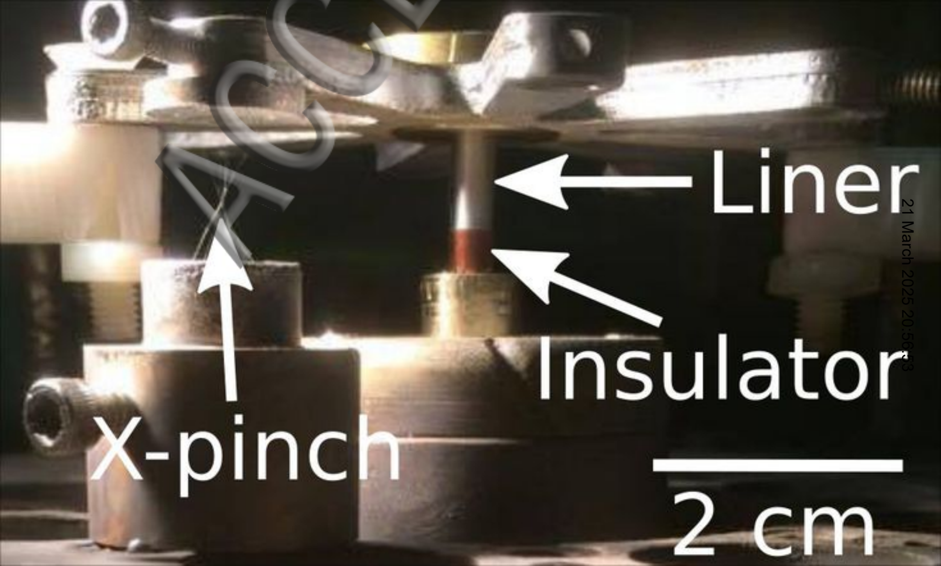
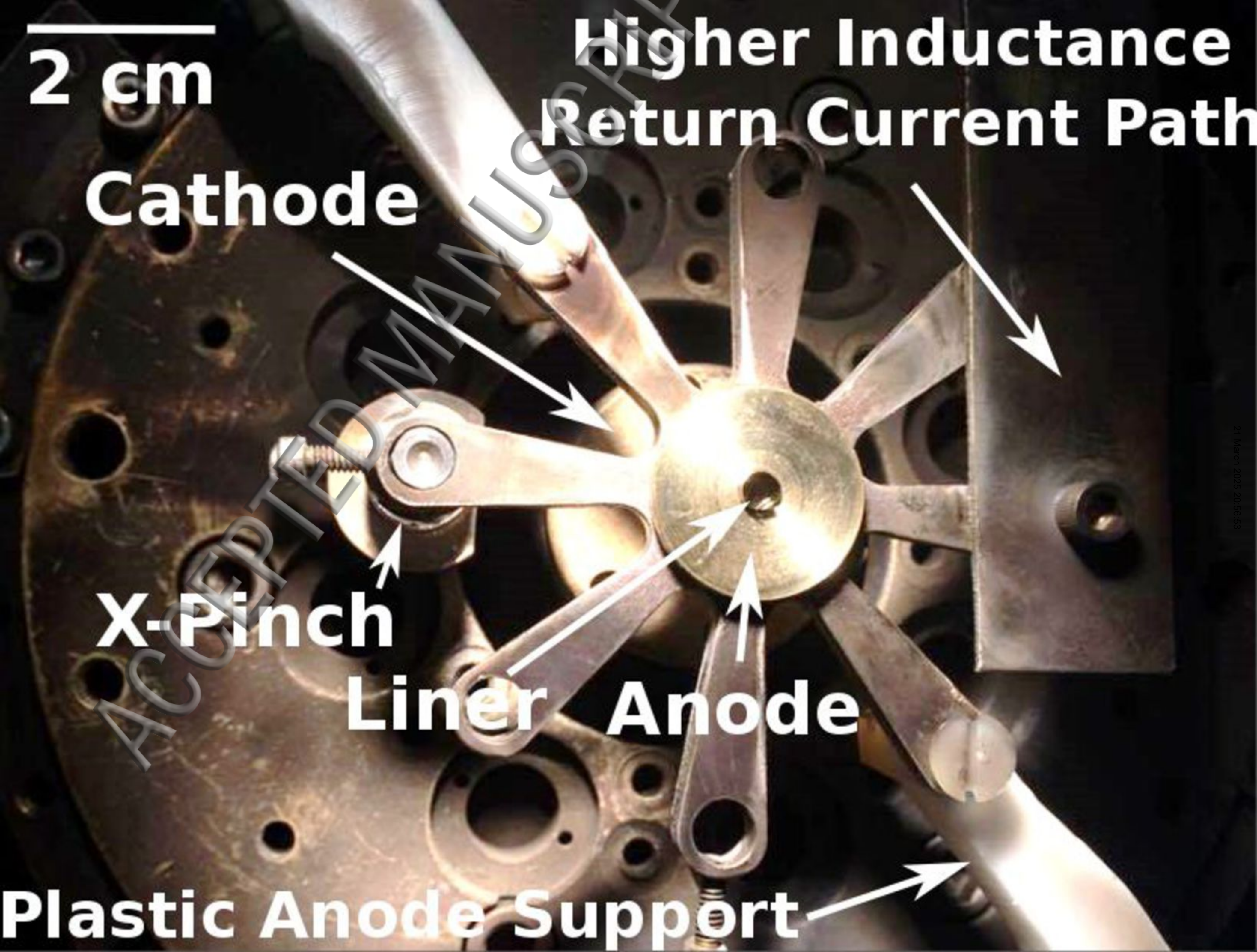
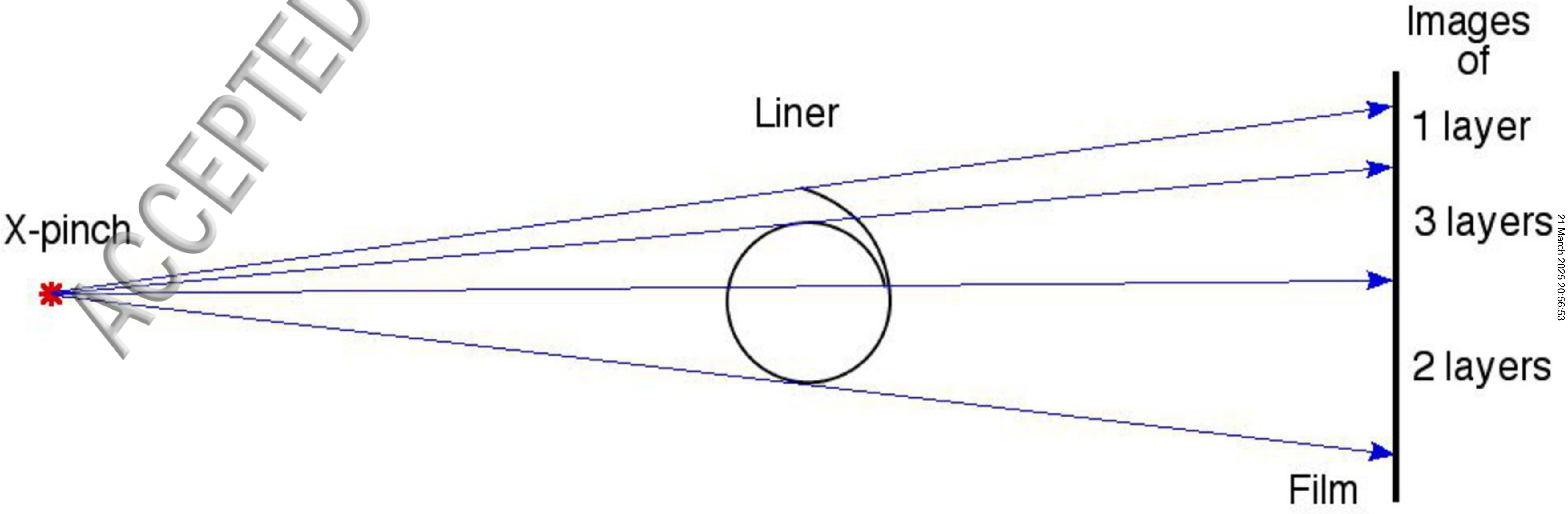
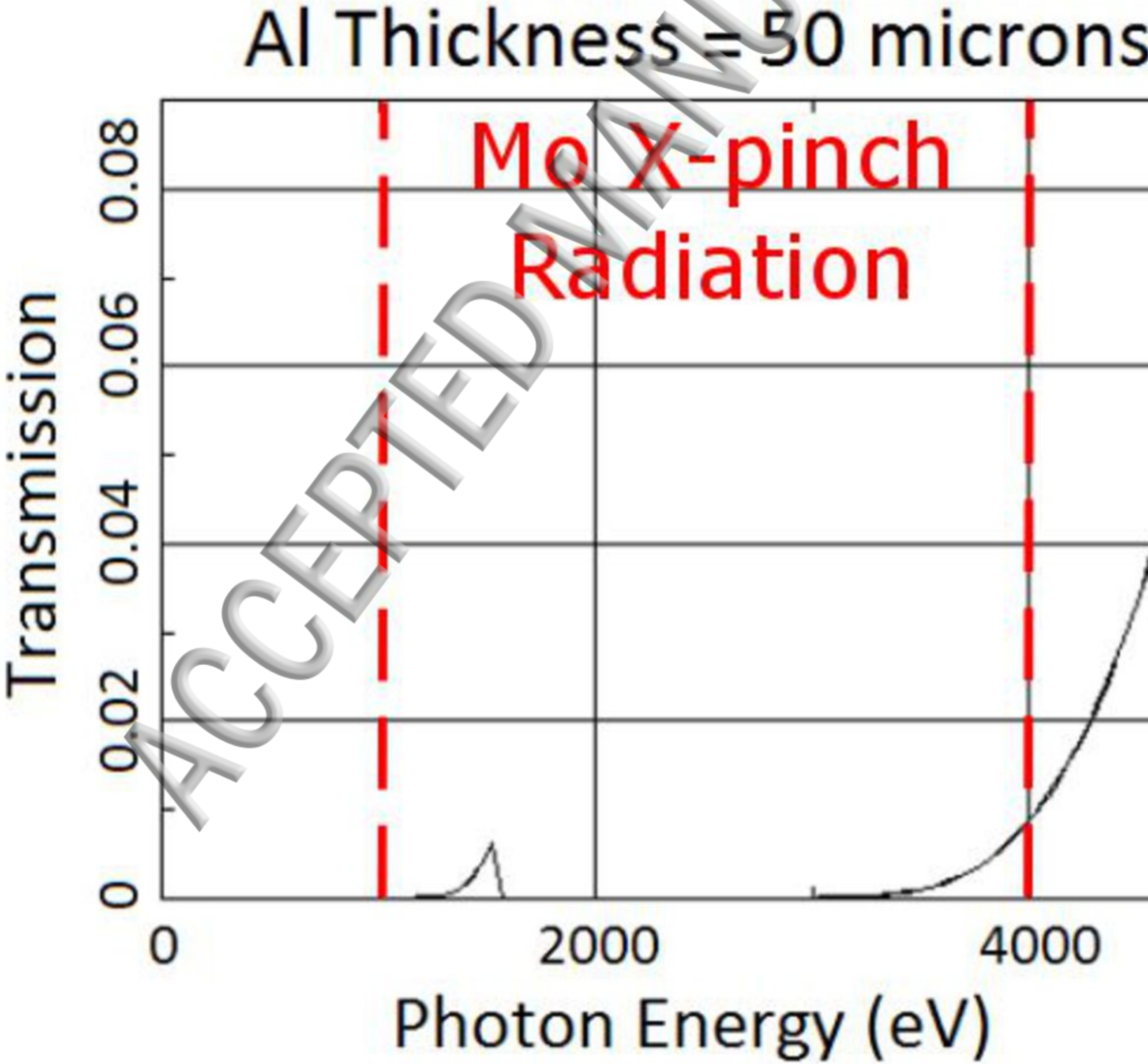
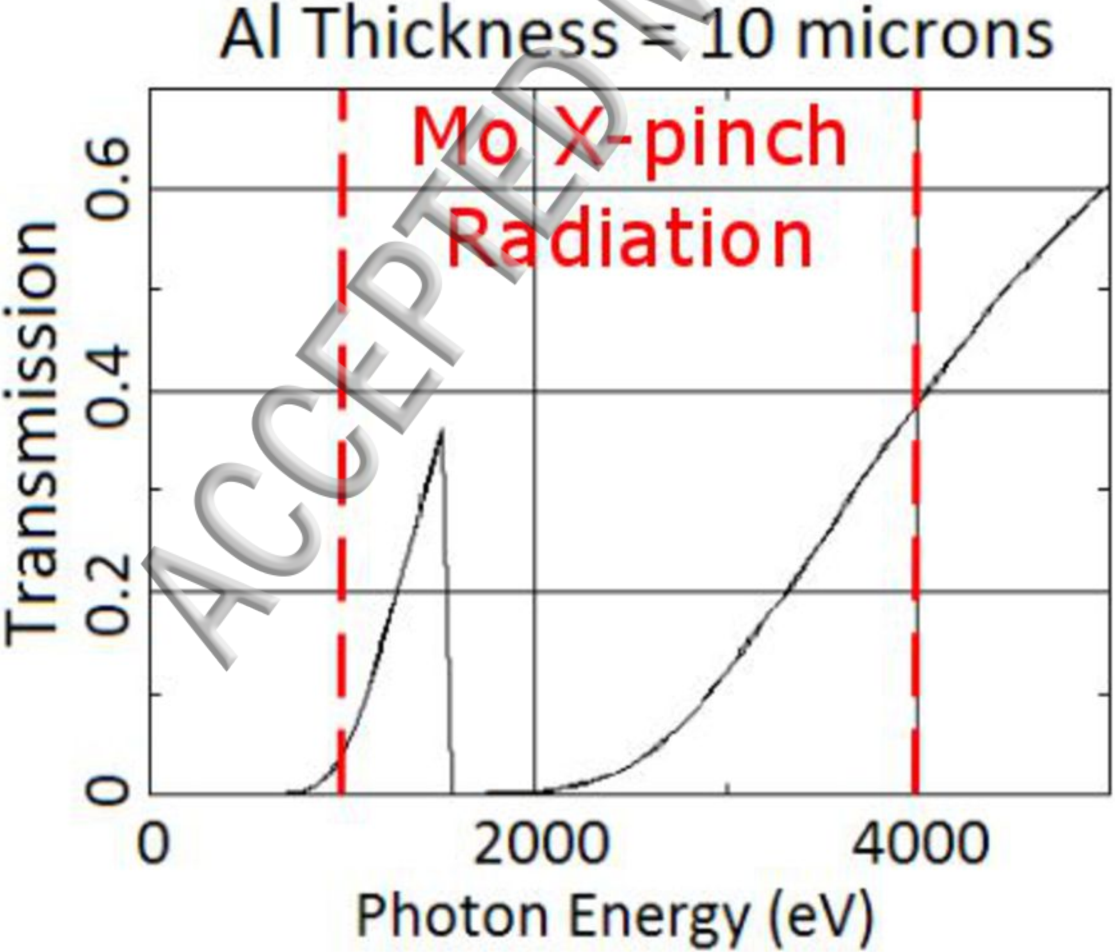
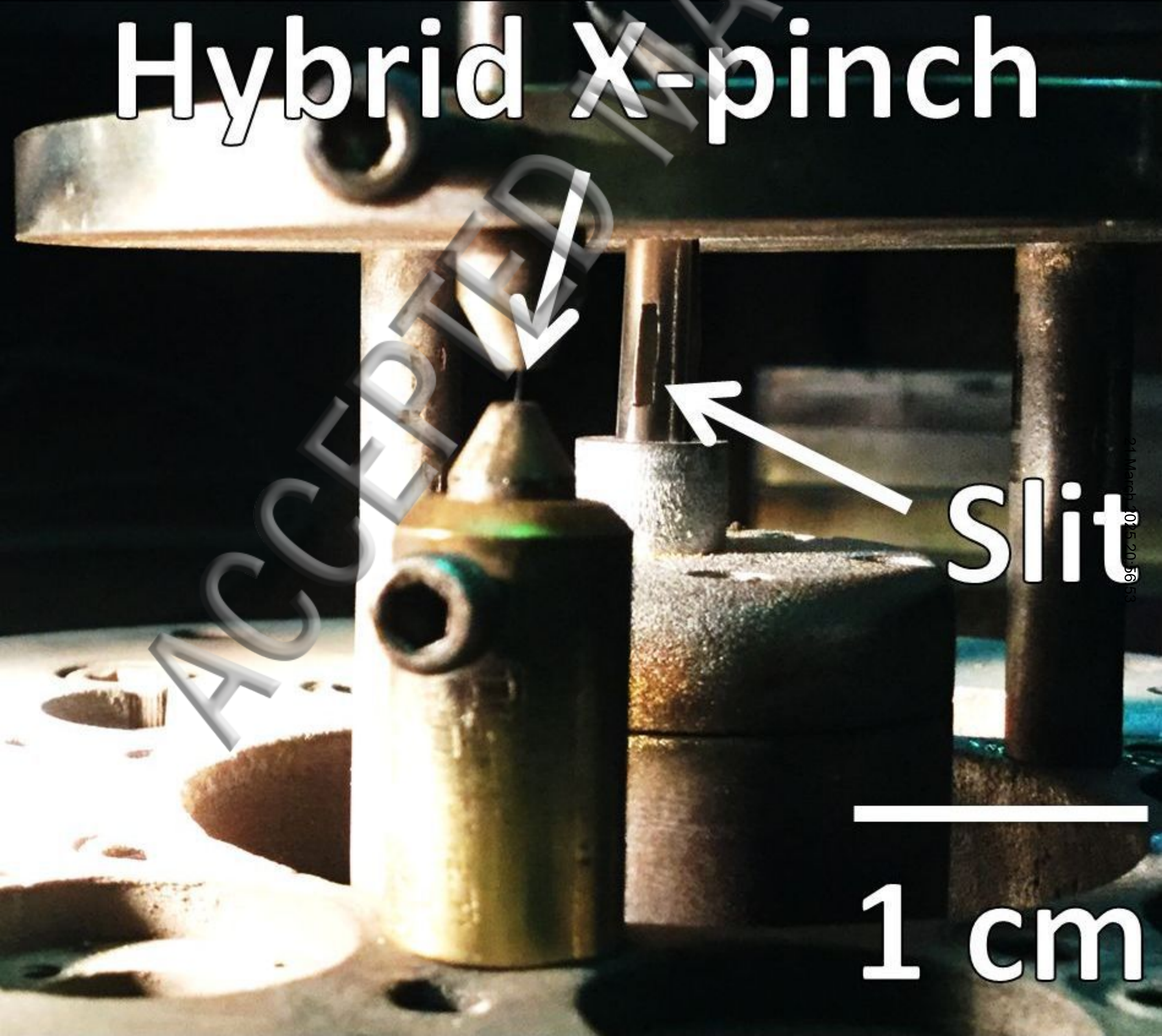

Liner
Insulator
X-pinch
2 cm

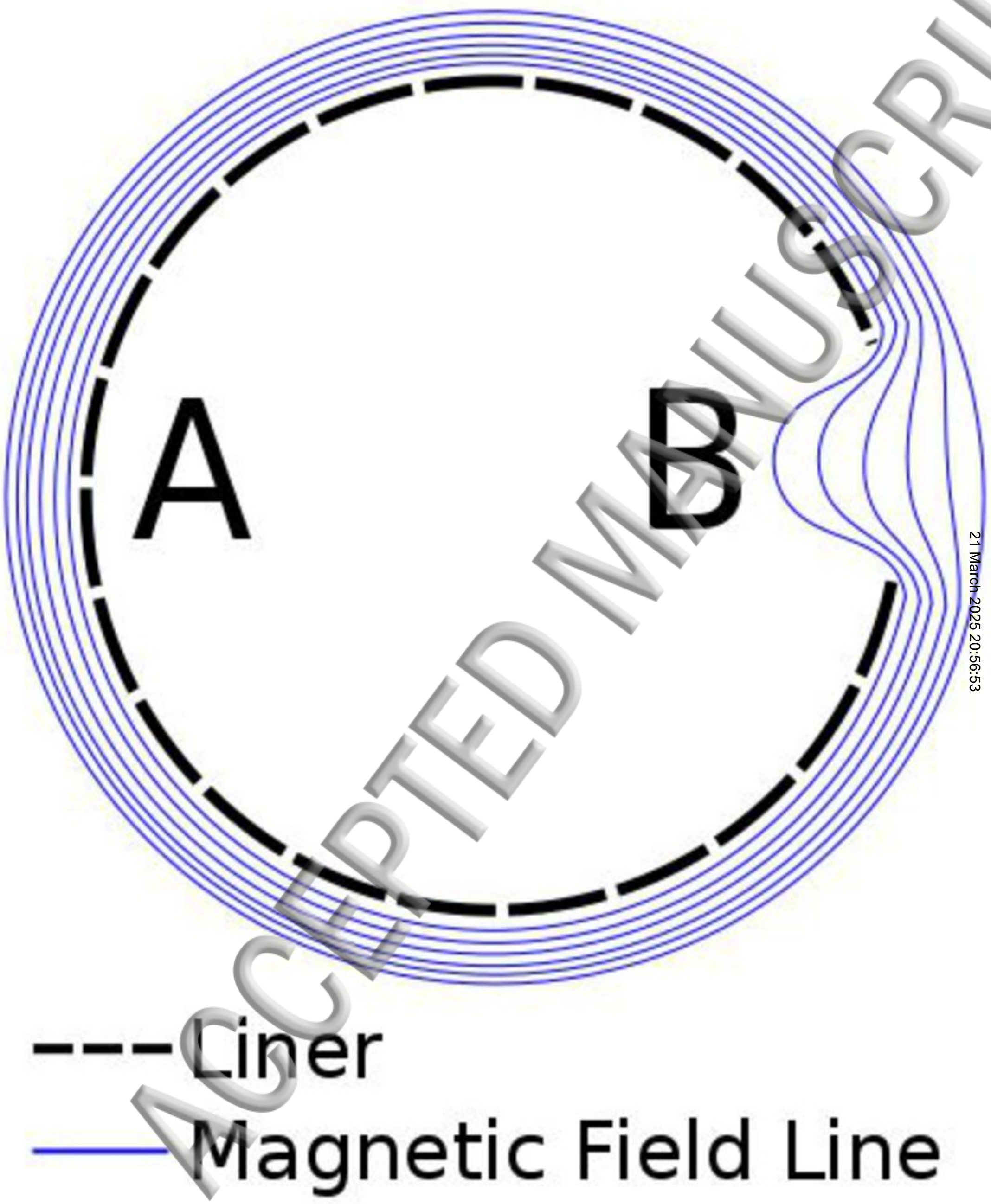

2 cm
Higher Inductance Return Current Path
Cathode
X-Pinch
Liner
Anode
Plastic Anode Support

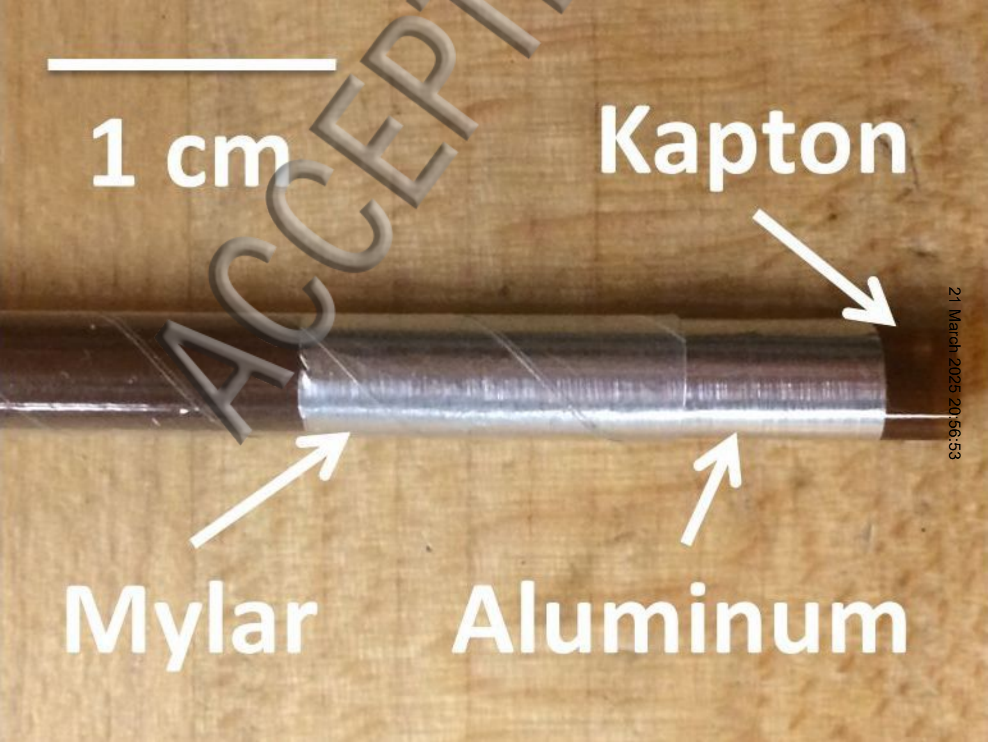

Images
of
Liner
1 layer
X-pinch
3 layers
2 layers
Film


Al Thickness = 50 microns
Mo X-pinch
Radiation
Transmission
0.08
0.06
0.04
0.02
0
0
2000
4000
Photon Energy (eV)

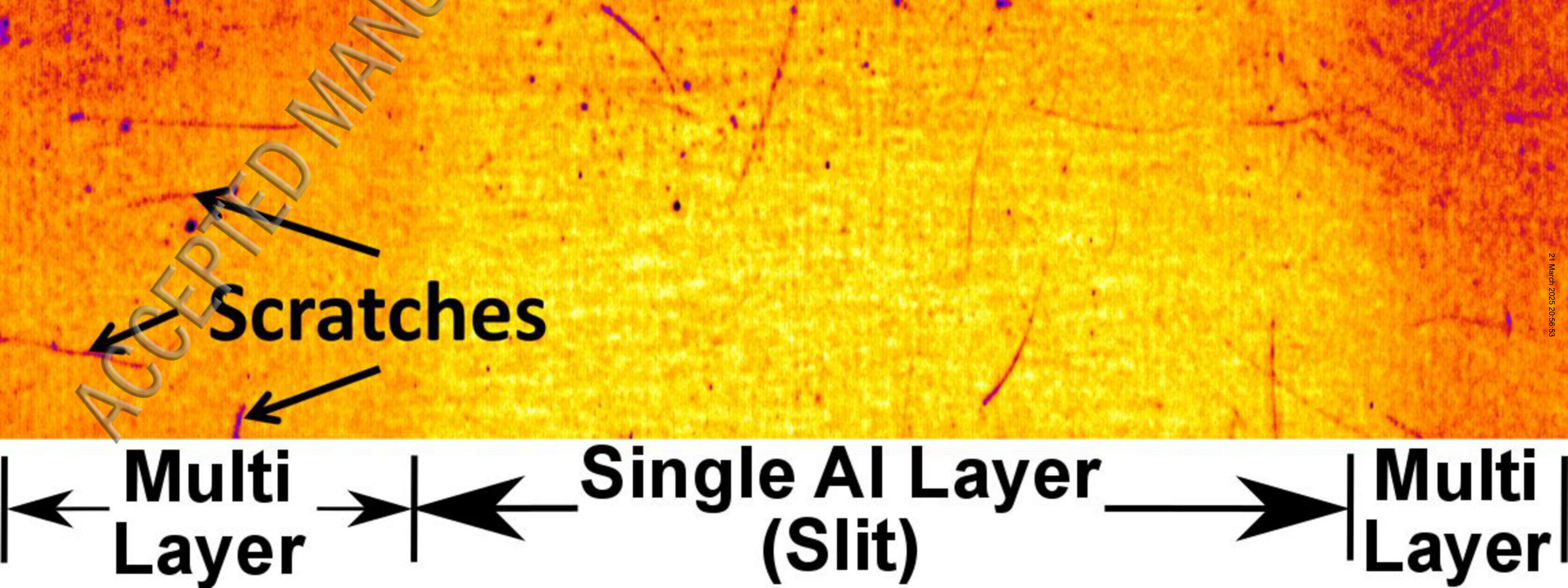

Al Thickness = 10 microns
Mo X-pinch
Radiation
Transmission
0
0.2
0.4
0.6
0
2000
4000
Photon Energy (eV)

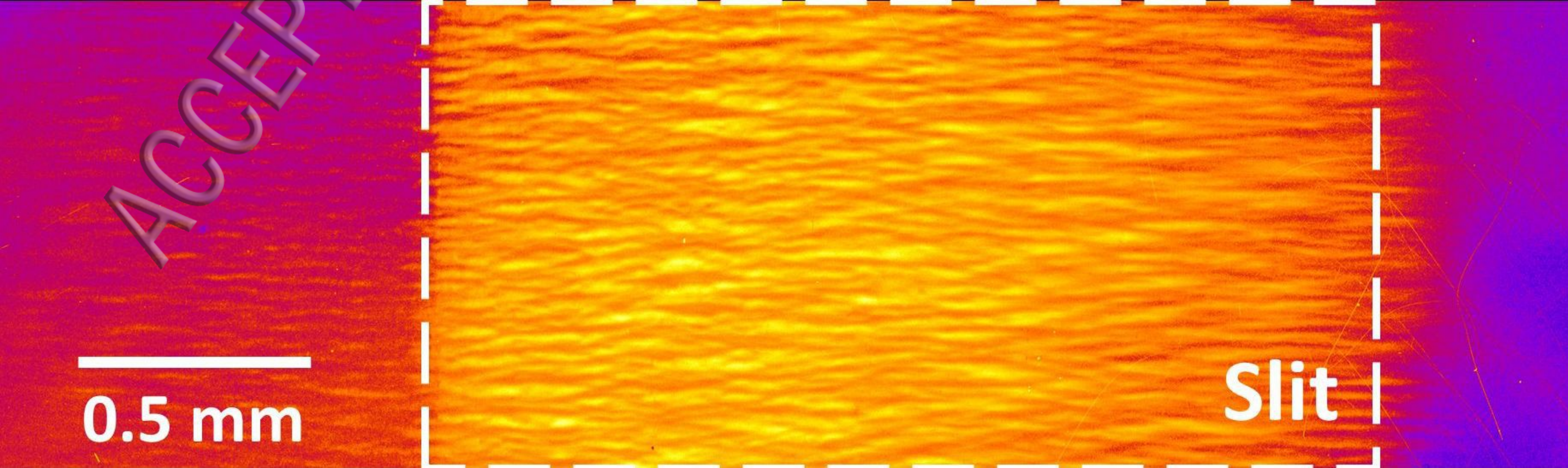

Hybrid X-pinch
Slit
1 cm


A
B
Liner
Magnetic Field Line


1 cm
Kapton
Mylar
Aluminum


Mylar
Kapton
Liner
Insulators

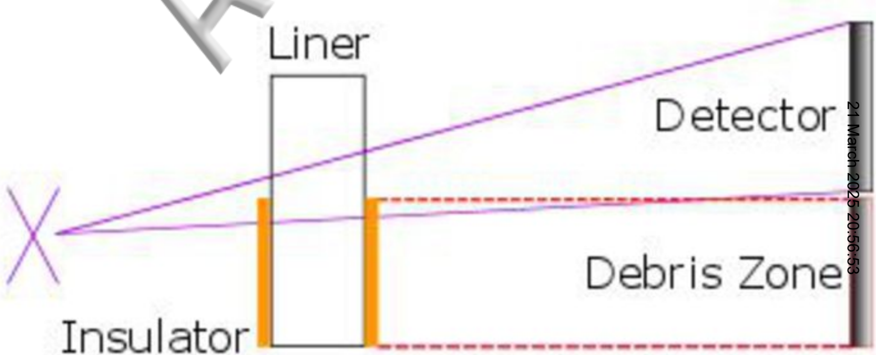

Scratches
Multi Layer
Single Al Layer (Slit)
Multi Layer

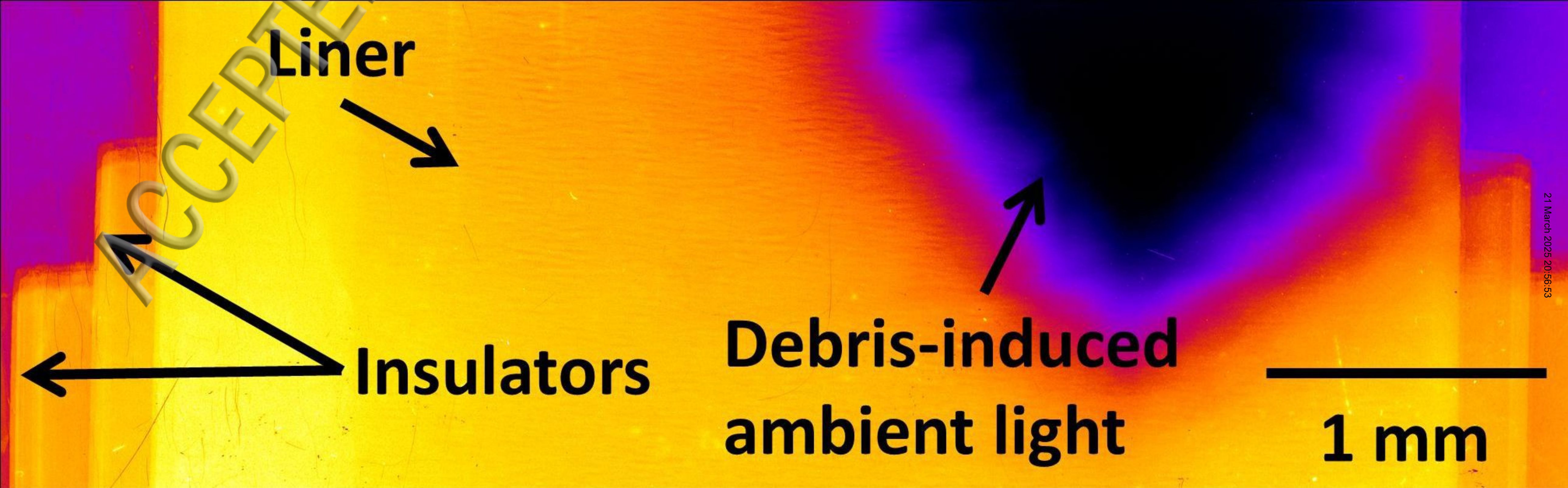

0.5 mm
Slit

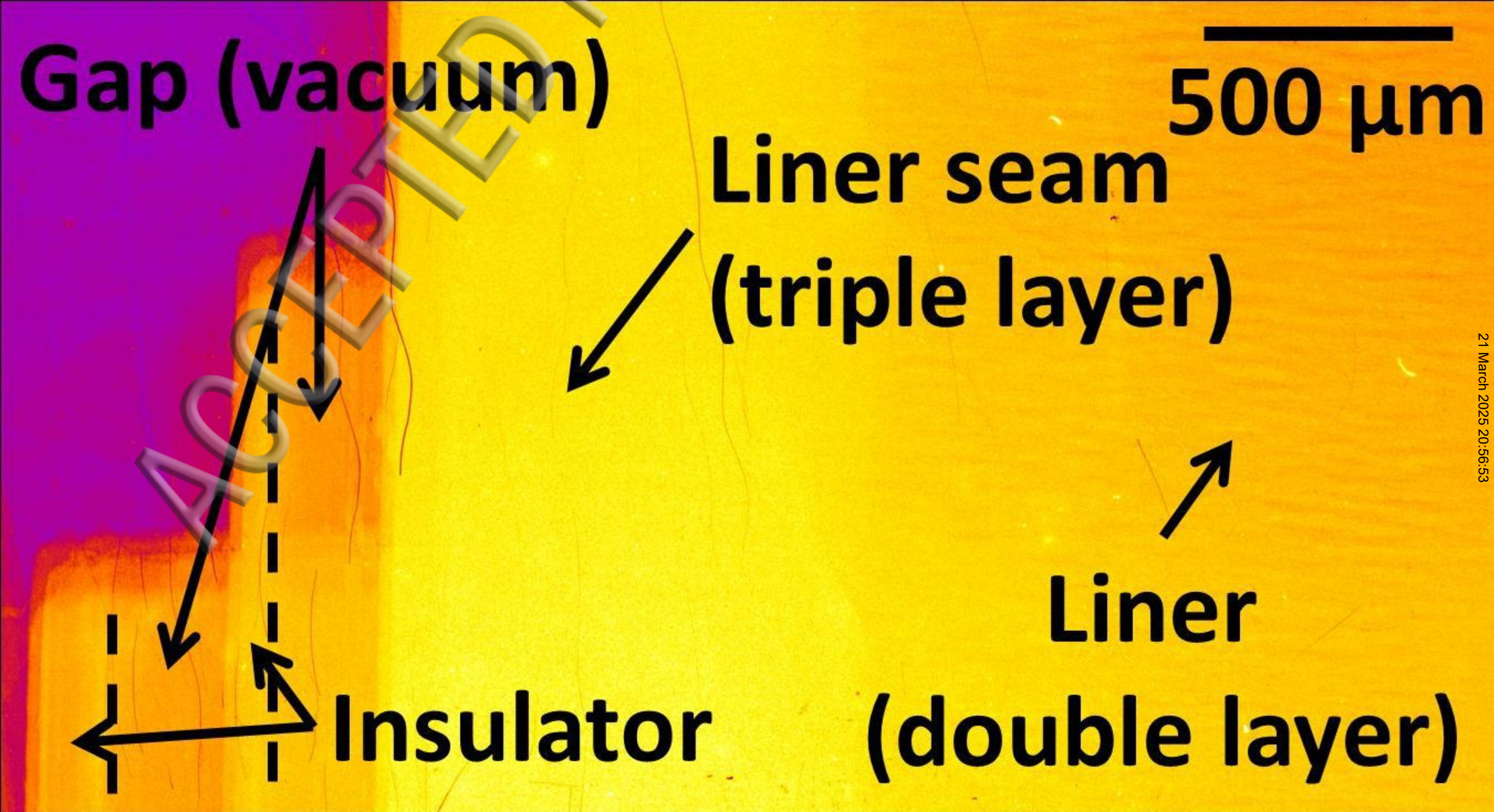

4 cm


2 cm


2 mm


Liner
Detector
Debris Zone
Insulator


Liner
Insulators
Debris-induced
ambient light
1 mm


Gap (vacuum)
500 µm
Liner seam
(triple layer)
Liner
(double layer)
Insulator