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Investigation of the effect of a power feed vacuum gap in solid liner experiments at 1 MA

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We present an experimental study of plasma initiation of a solid metal liner at the 1 MA level. In contrast to previous work, we introduce a vacuum gap at one of the liner connections to the power feed to investigate how this affects plasma initiation and to infer how this may affect the symmetry of the liner in compression experiments. We observed that the vacuum gap causes non-uniform plasma initiation both azimuthally and axially in liners, diagnosed by gated optical imaging. Using magnetic field probes external to the liner, we also determined that the optical emission is strongly linked to the current distribution in the liner. The apparent persistent of azimuthal non-uniformities may have implications for fusion-scale liner experiments. © *2015 AIP Publishing LLC*.
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We present an initial study examining if a power feed vacuum gap can affect the evolution of a solid liner experiment at the MA level. The primary concern is that an azimuthally non-uniform closure of the coaxial power feed gap may lead to similar asymmetries in the current density profile in the liner, and hence drive an asymmetry in an implosion phase at higher drive currents. This would clearly have a strong impact on fuel compression for liner-on-gas fusion loads, which are presently under examination at Sandia National Laboratories.[1] Since a ~1 MA level current drive cannot compress a fusion-scale liner design, we focus on the plasma initiation phase through both imaging and magnetic field measurements.

High voltage vacuum gaps are present in a variety of devices, including various switch designs and transmission line technologies. A significant volume of research was undertaken over several decades to examine the vacuum gaps breakdown processes (e.g., Refs. 2 and 3). Typically, simplified geometries are examined, for example, point-to-plane or sphere-to-sphere geometries for triggered spark gap applications, or plane-to-plane geometry in high voltage failure modes investigations. Coaxial electrode arrangements have been largely overlooked. However, if the distribution of the current density about the azimuth is important after coaxial gap breakdown, the characteristics of such a gap will directly influence load behavior.

Previous studies have examined liner loads at the ~1 MA- and several- MA level, both at relatively long current rise times[4] and ~100 ns rise times.[5,6] Of particular relevance are two recent studies carried out on ~1 MA devices. Awe *et al.*[7] examined the formation of surface plasma on a clean, smooth metal surface at ZEBRA in the absence of contact problems. They concluded that a 2.2 MG surface magnetic field was required to initiate plasma. At the COBRA facility, Blesener *et al.*[8] examined the axial simultaneity of plasma formation for thin (<collisionless skin depth) liner loads, concluding that a sufficiently high current density rise rate was required to achieve good symmetry, confirming earlier work by Van Devender *et al.*[9] Both these studies used well-controlled, excellent current contacts to the liner. The work presented here is the first to intentionally introduce a vacuum gap in the power feed and examine the effect on plasma formation at the liner surface. Note that the surface B-field and current density rise rates here are well below those identified by Awe and Blesener/Van Devender, and plasma formation is facilitated by gap breakdown processes.

Electrical breakdown of a vacuum gap depends on many factors, including geometry, material, surface finish, the applied electric field value and its temporal profile, the ambient temperature, and the vacuum level. Here, we hold these parameters constant to discern the effects of the vacuum gap in cylindrical geometry.

The load is driven by a voltage pulse applied to the AK gap at room temperature under a vacuum of $\sim 1 \times 10^{-5}$ Torr, and so breakdown is initiated by field emission processes. Liners are made from aluminum 1100 (pure aluminum) turned on a lathe with no further surface preparation. The liners are 3.05 or 6.3 mm in outer diameter, and they have a 150–300 μm wall thickness. We ensure the liner makes good electrical contact with one end of the liner and establish a vacuum gap at the other, which is the subject of our analysis. Experiments were carried out on the COBRA machine at Cornell University,[10] which produces a current pulse of 1.05 MA peaking at 105 ns.

For experiments investigating a power feed gap at the cathode, the liner is mounted in the anode plate and suspended over the cathode, the lower electrode in COBRA. It is then lowered into a collar in the cathode which is machined to give an azimuthally symmetric radial vacuum

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gap of 25–400 μm (Figure 1). The anode placement was optimized by incrementally translating the liner, checking electrical continuity between electrodes to find limits, and then locating the liner in the center of the cathode collar. This provides a reasonable centering of the liner in the power feed gap.

At early time, very little plasma is observed at any point on the load. As the current increases, plumes of plasma are observed to originate from the cathode region. Figure 1 shows a high magnification gated optical image of the cathode gap taken 146 ns into the current drive for a shot using a 25 μm cathode vacuum gap. The plasma plume is noticeably brighter than the emission at the liner edge. Figure 1 also shows a laser shadowgram at late time, where a plasma plume from the cathode gap has continued to expand. Similar plasma evolution is observed for all shots carried out.

The presence of localized plasma formation was also observed in streak images (Figure 2). Here, we show images from two nominally identical liner shots with a 100 μm cathode gap. The left hand streak is produced from a slit placed close to the cathode, whilst the right hand image is from an axial slit placed centrally on the liner image. Streak data are taken over 500 ns, but note that the current drive peaks at 100 ns. In the upper images (shot 2416), the radial cathode slit shows multiple bright spots beginning at $\sim$50 ns and evolving over the streak timescale. This resembles the formation of individual plasma plumes observed in the images. On the axial slit on the same shot, emission is observed at the cathode first and then at the anode. The liner does not light up uniformly along its height even at late time. In the second pulse (shot 2417), the radial slit shows a cluster of emission towards the center of the liner, at smaller radius than the liner radius. These remain relatively fixed in position until very late time. The axial slit shows strong emission only at the cathode until $\sim$200 ns, with some emission visible throughout the liner height after $\sim$400 ns. It is clear that plasma formation and visible light emission from the liner are non-uniform at the cathode power feed gap and show strong shot-to-shot variation.

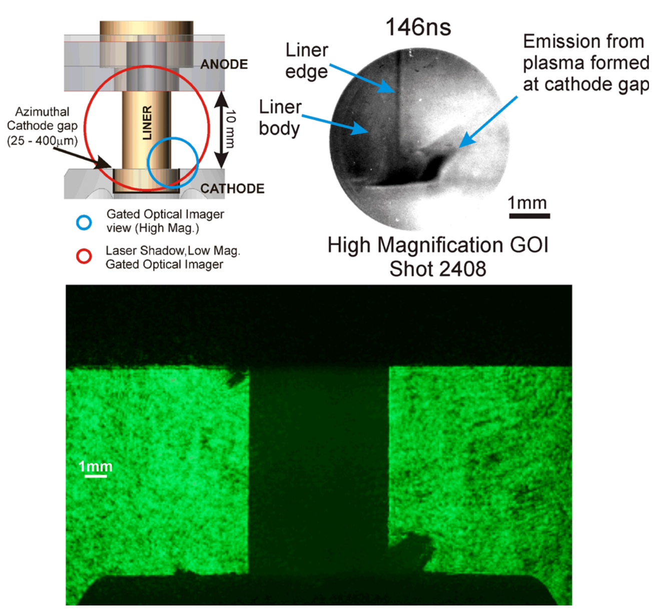

FIG. 1. (Top left) Schematic of diagnostic view, (top right) high magnification 5 ns gated optical image, and (lower) laser shadowgram of plasma formation at a cathode power feed gap on COBRA.

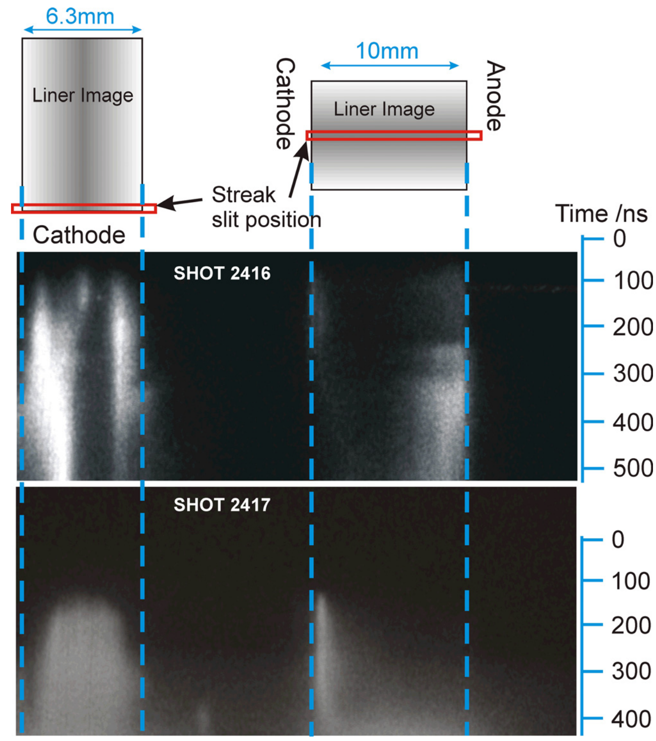

FIG. 2. Streak photographs of two nominally identical liner shots with a 100 μm cathode power feed gap. Cartoons show slit alignments for the images, recovered simultaneously.

Gated optical images taken at peak current suggest that the effect of plasma formation at the cathode can directly affect the evolution of the axial development of plasma on the liner. Figure 3 shows images from two shots, one with a cathode gap of 25 μm, and one in which the cathode gap is filled with electrically conductive adhesive. With a vacuum gap, the plasma flares evolving from the cathode gap appear to provide a current path which bypasses the lower part of the liner. Emission is seen at the cathode only outside the liner diameter, before being observed across the liner at the anode end. With no cathode feed gap, the emission profile is very different. The lower part of the liner emits more strongly throughout the current drive, with very little emission at the anode. Clearly, if the plasma formation at the cathode can affect the both the azimuthal and axial current density profiles, this has significant implications for liner compression experiments. It would be useful, however, to more directly examine the formation of plasma at the power-feed gap.

For experiments investigating a power feed gap at the anode, the liner was fixed directly to the cathode using silver epoxy to ensure a good electrical contact. The anode plate was then placed over the liner, and an alignment cap was used to center the liner. The alignment cap is essentially a thin-walled tube, where the outer diameter is equal to the anode aperture, and the inner diameter is equal to the outer diameter of the liner. The cap therefore directly defines the vacuum gap. Both electrodes are fixed in place using the alignment cap, and finally the cap is removed (Figure 4).

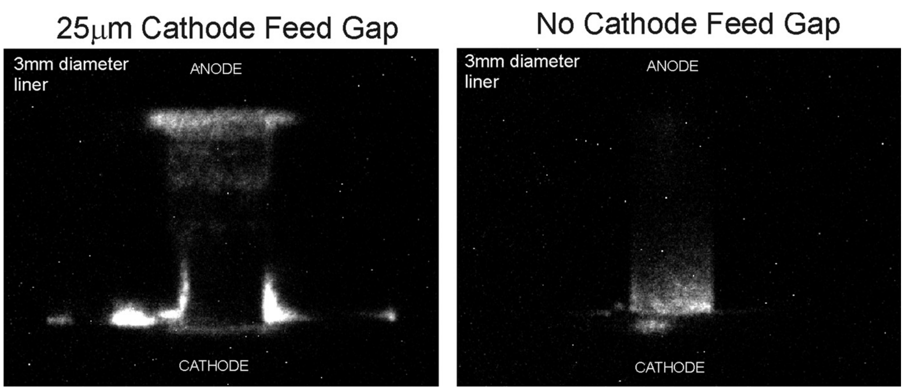

FIG. 3. Self emission images (30 ns gate) of liner experiments both (left) with and (right) without a power feed gap at the cathode at peak current.

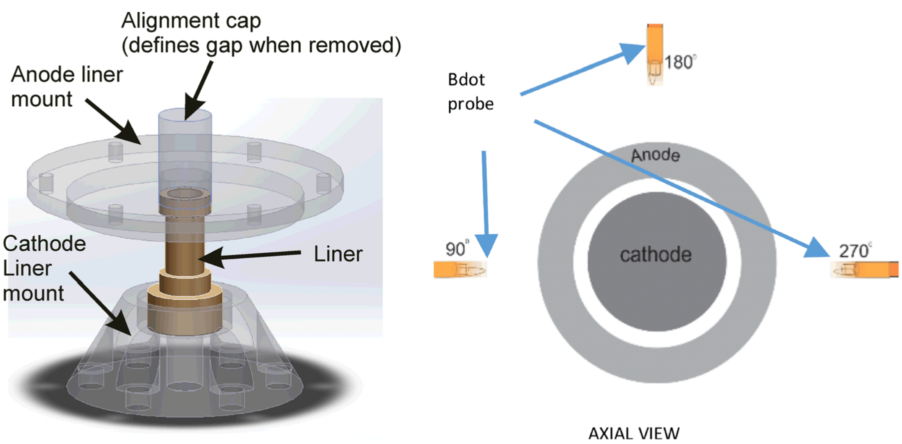

FIG. 4. Experimental setup on COBRA for Anode power feed gap experiments, showing the axial view of the gap and generic magnetic field probe arrangement.

This method allows excellent centering of the liner in the coaxial anode aperture.

A multi-frame gated optical camera (Invisible Vision UHSi 12/24) imaged the load in the axial direction, obtaining a direct view of the vacuum power feed gap (Axial View in Fig. 4). An example of the data obtained is shown in Figure 5, which presents images from two nominally identical shots using a 400 μm anode gap. The evolution of the emission profile proceeds similarly for both cases. Initial emission is seen in the first 5–10 ns as localized hotspots randomly about the azimuth. As the current drive continues, more hotspots are observed and occupy an increasingly large portion of the gap circumference. Note that the full circumference is not lit up at any time for these two shots, or in any shot performed.

The evolution of plasma in the gap proceeds similarly for each gap size from 50 μm to 600 μm. An example is given in Fig. 6 for the last of these, in which simultaneous axial and radial views were recorded. In shots with such large vacuum gaps, a single flashover point tends to form and dominate the emission profile, although the formation of other localized plasma regions occurs and evolves as for smaller gaps. In Fig. 6, the first plasma region at 37 ns is imaged in both the radial and axial views. As the current drive continues, it can be seen that despite the formation of additional plasma regions around the azimuth, the radial view shows only plasma formation on one side of the liner located at the position of the initial plasma flashover (see image at 107 ns). Again, some portions of the azimuth that do not show emission even close to peak current.

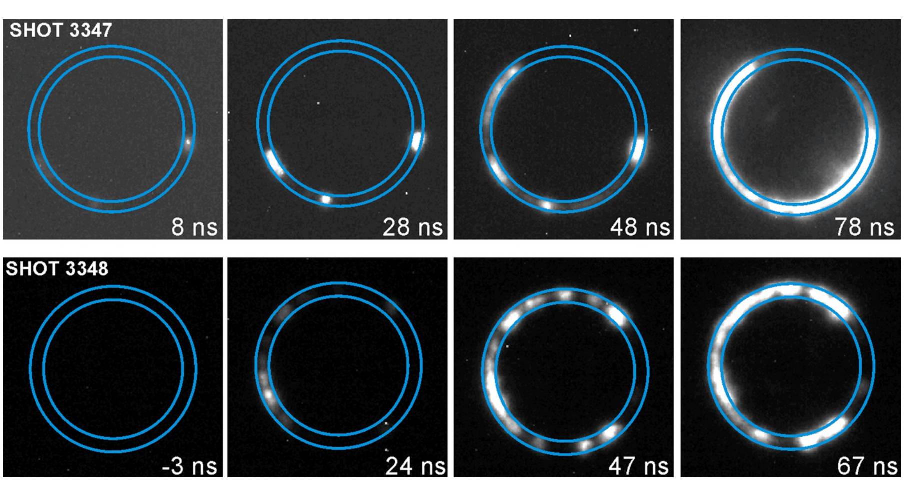

FIG. 5. Gated optical frames (10 ns exposure) showing plasma evolution in a 400 μm anode vacuum power feed gap in two experiments (frame times are relative to start of current drive).

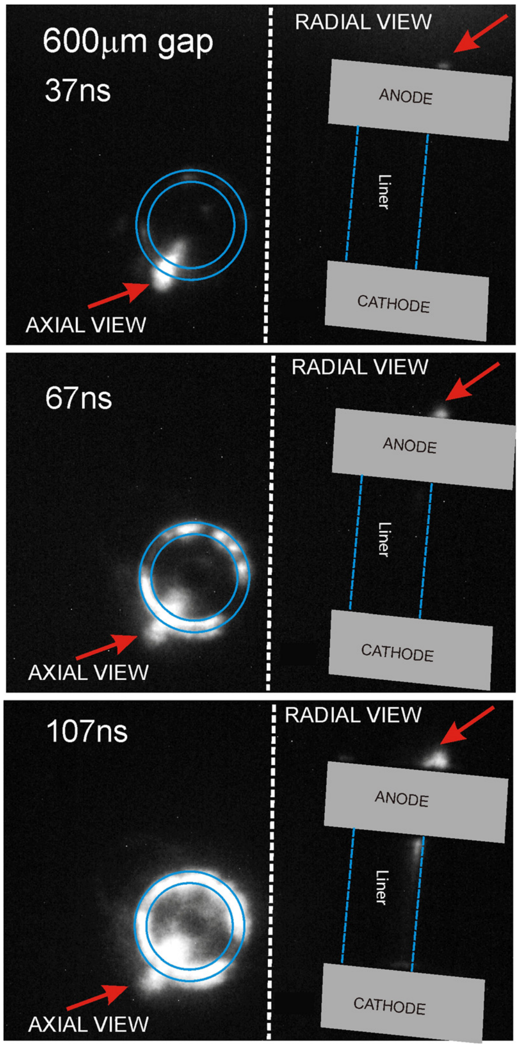

FIG. 6. Simultaneous axial and radial gated optical emission views (10 ns exposure) showing the evolution of plasma at a 600 μm gap.

Data from the magnetic field probes can be used to triangulate the region in which current is flowing at a particular time in the experiment. This methodology was recently published by Cordaro *et al.*[11] An example is shown in Fig. 7 for an experiment with a 100 μm anode gap. The value of the magnetic field recorded by each of the three probes, along with the value of the current drive, can be used to determine the effective distance, $r_{effective}$ at which current is flowing from the probe through $B_{probe} = \mu_0 I / 2\pi r_{effective}$. By plotting a circle of this effective radius centered on each of the probes, the centroid of the current flow can be determined by the overlap region of the circles from all three probes: i.e., the region in which one radius value satisfies the signals strengths from all probes at a given time. Superimposed on the photograph is a gated self-emission image, taken at the time indicated by the vertical dashed line on the bdot probe data in Fig. 7. The region of emission at the liner gap is well correlated with the triangulation region independently determined by the bdot probes. This strongly suggests that regions of strong optical emission are correlated with regions of high current density. This example is interesting since even after 70 ns, the emission and inferred current density profile is azimuthally non-uniform as a result of the initial vacuum gap.

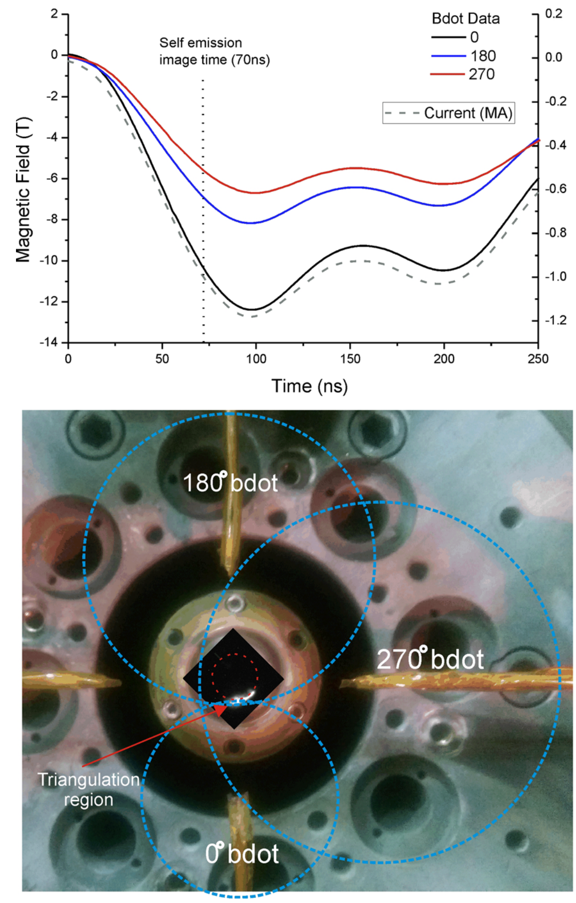

FIG. 7. Plot of bdot probe signals from the 3 probes indicated in lower photograph. Also shown is the calculated triangulation region from these signals, overlaid with the time gated emission images at 70 ns.

The presence of a power feed gap can affect both the azimuthal and axial uniformity of plasma formation in liners. The agreement of the optical imaging data with the magnetic field external to the liner demonstrates that current distribution correlates well with the optical emission. In a compression experiment, the liner would show strong asymmetries resulting from the non-symmetric azimuthal and/or axial features reported here. It is interesting that, in general, the total fraction of the circumference of the gap showing high emission (current density) does not change rapidly. This suggests that even if gap closure occurs well before a time of interest, the initial effect of non-uniform breakdown may persist.

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[1]S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson, and M. E. Cuneo, Phys. Plasmas **17**, 056303 (2010).
[2]G. A. Mesyats and D. I. Proskurovsky, *Pulsed Electrical Discharge in Vacuum* (Springer-Verlag Press, 1989).
[3]A. S. Denholm, Can. J. Phys. **36**, 476 (1958).

[4]R. E. Reinovsky, W. E. Anderson, W. L. Atchison, R. J. Faehl, R. K. Keinigs, I. R. Lindemuth, M. C. Thompson, and A. Taylor, AIP Conf. Proc. **706**, 1191 (2004).
[5]D. B. Sinars, S. A. Slutz, M. C. Herrmann, R. D. McBride, M. E. Cuneo, C. A. Jennings, J. P. Chittenden, A. L. Velikovich, K. J. Peterson, R. A. Vesey, C. Nakhleh, E. M. Waisman, B. E. Blue, K. Killebrew, D. Schroen, K. Tomlinson, A. D. Edens, M. R. Lopez, I. C. Smith, J. Shores, V. Bigman, G. R. Bennett, B. W. Atherton, M. Savage, W. A. Stygar, G. T. Leifeste, and J. L. Porter, Phys. Plasmas **18**, 056301 (2011).
[6]S. B. Hansen, M. R. Gomez, A. B. Sefkow, S. A. Slutz, D. B. Sinars, K. D. Hahn, E. C. Harding, P. F. Knapp, P. F. Schmit, T. J. Awe, R. D. McBride, C. A. Jennings, M. Geissel, A. J. Harvey-Thompson, K. J. Peterson, D. C. Rovang, G. A. Chandler, G. W. Cooper, M. E. Cuneo, M. C. Herrmann, M. H. Hess, O. Johns, D. C. Lamppa, M. R. Martin, J. L. Porter, G. K. Robertson, G. A. Rochau, C. L. Ruiz, M. E. Savage, I. C. Smith, W. A. Stygar, R. A. Vesey, B. E. Blue, D. Ryutov, D. G. Schroen, and K. Tomlinson, Phys. Plasmas **22**, 056313 (2015).
[7]T. J. Awe, B. S. Bauer, S. Fuelling, and R. E. Siemon, Phys. Rev. Lett. **104**, 035001 (2010).
[8]I. C. Blesener, K. S. Blesener, J. B. Greenly, D. A. Hammer, B. R. Kusse, C. E. Seyler, and B. Blue, "Ablation dynamics, precursor formation, and instability studies on thin foil copper liners," in *Proceedings of the IEEE International Conference Plasma Sciences, Chicago, IL, 26–30* June 2011, p. 1.
[9]P. Van Devender *et al.*, private communication (2015).
[10]J. B. Greenly, J. D. Douglas, D. A. Hammer, B. R. Kusse, S. C. Glidden, and H. D. Sanders, Rev. Sci. Instrum. **79**, 073501 (2008).
[11]S. Cordaro, S. Bott-Suzuki, L. S. Caballero Bendixsen, L. Atoyan, T. Byvank, W. Potter, B. Kusse, and J. Greenly, Rev. Sci. Instrum. **86**, 073503 (2015).