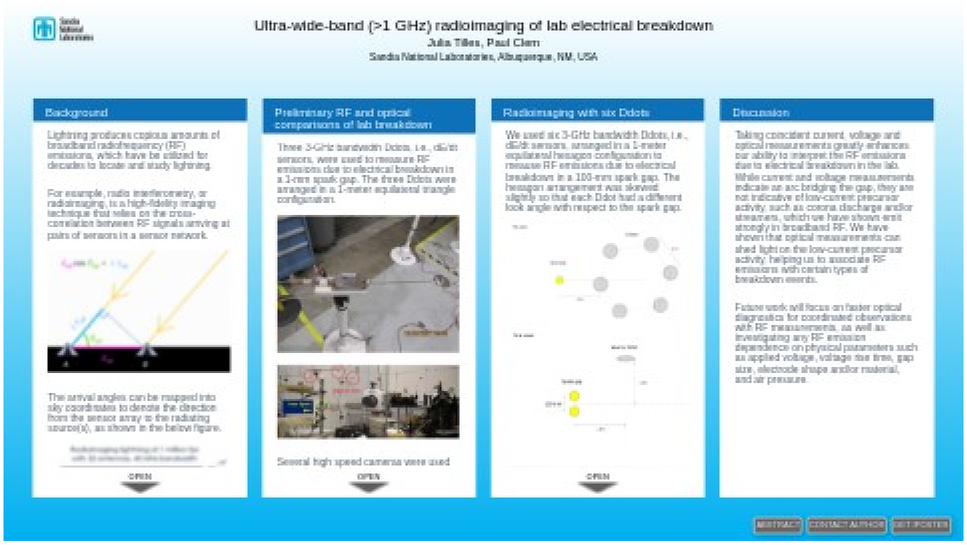
SAND2021-15718C

Ultra-wide-band (>1 GHz) radioimaging of lab electrical breakdown



Julia Tilles, Paul Clem

Sandia National Laboratories, Albuquerque, NM, USA

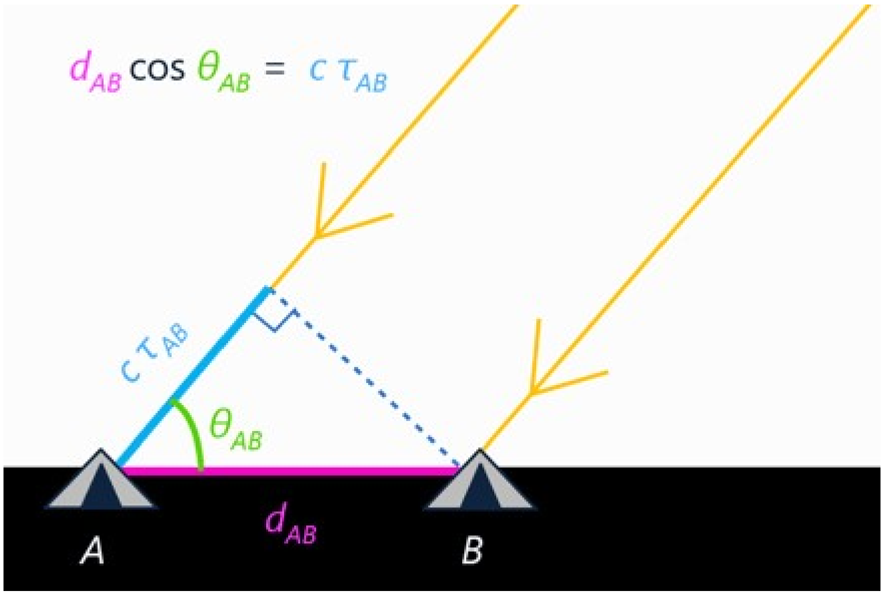
PRESENTED AT:

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

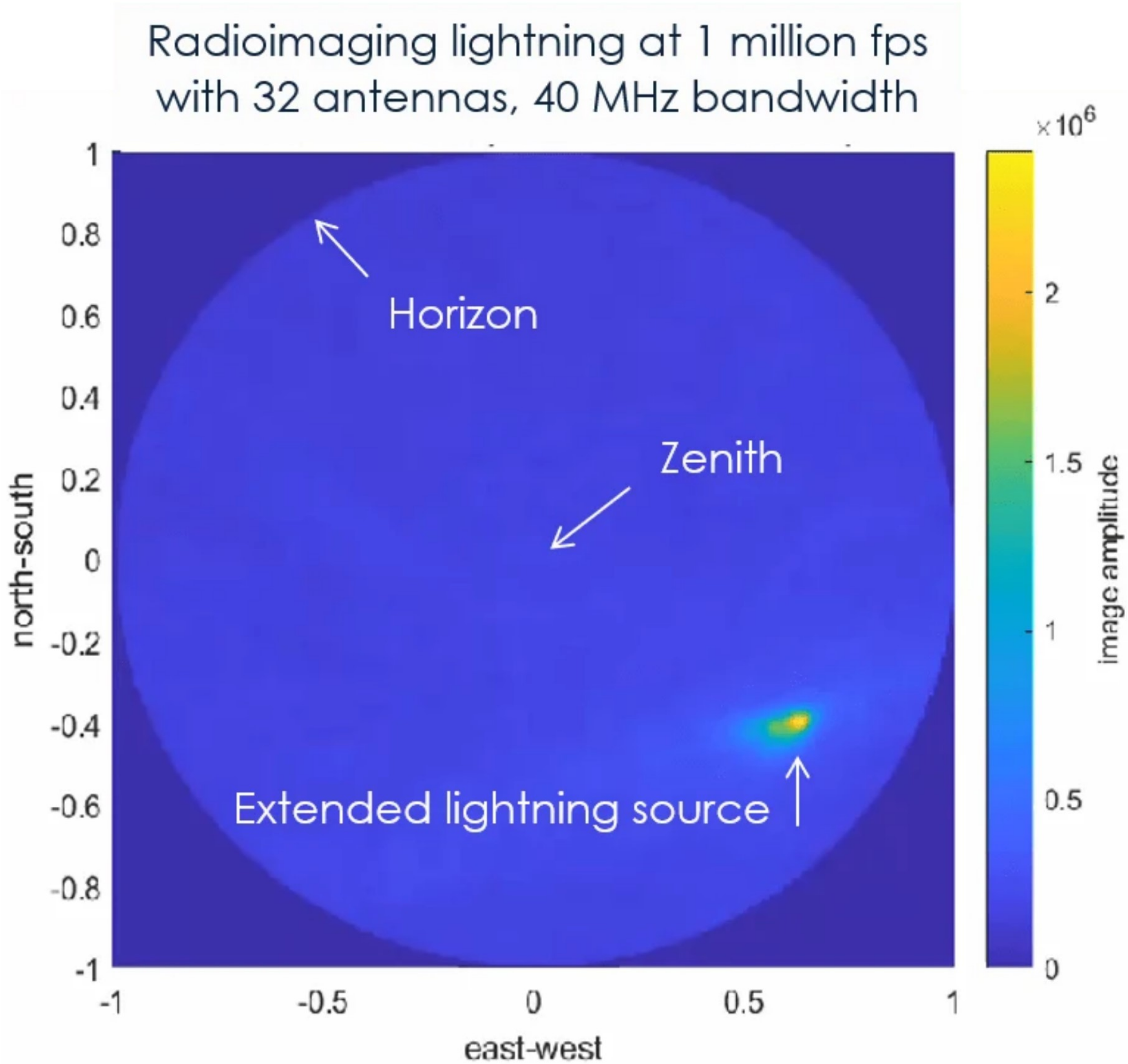
BACKGROUND

Lightning produces copious amounts of broadband radiofrequency (RF) emissions, which have be utilized for decades to locate and study lightning.

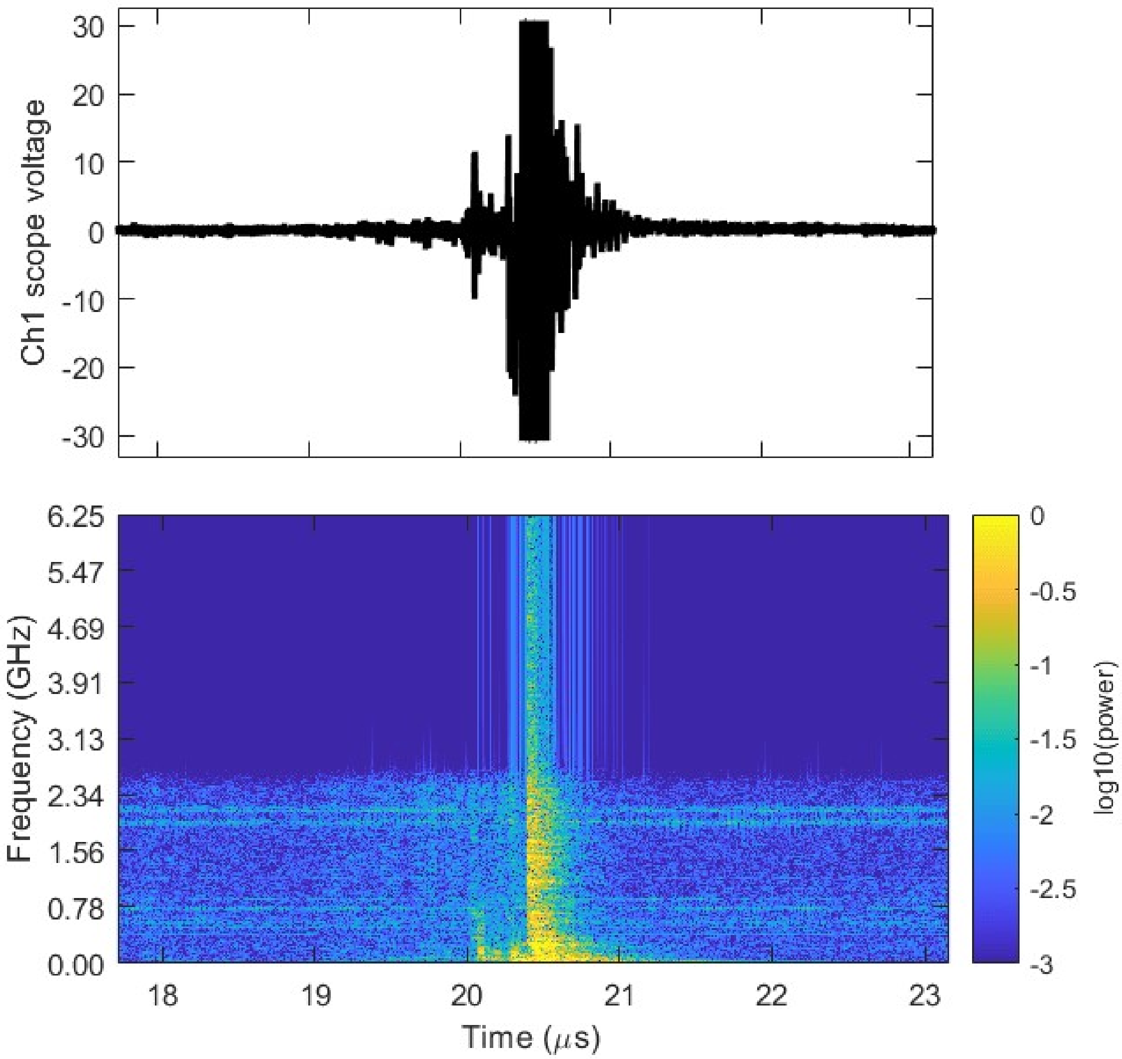
For example, radio interferometry, or radioimaging, is a high-fidelity imaging technique that relies on the cross-correlation between RF signals arriving at pairs of sensors in a sensor network.



The arrival angles can be mapped into sky coordinates to denote the direction from the sensor array to the radiating source(s), as shown in the below figure.



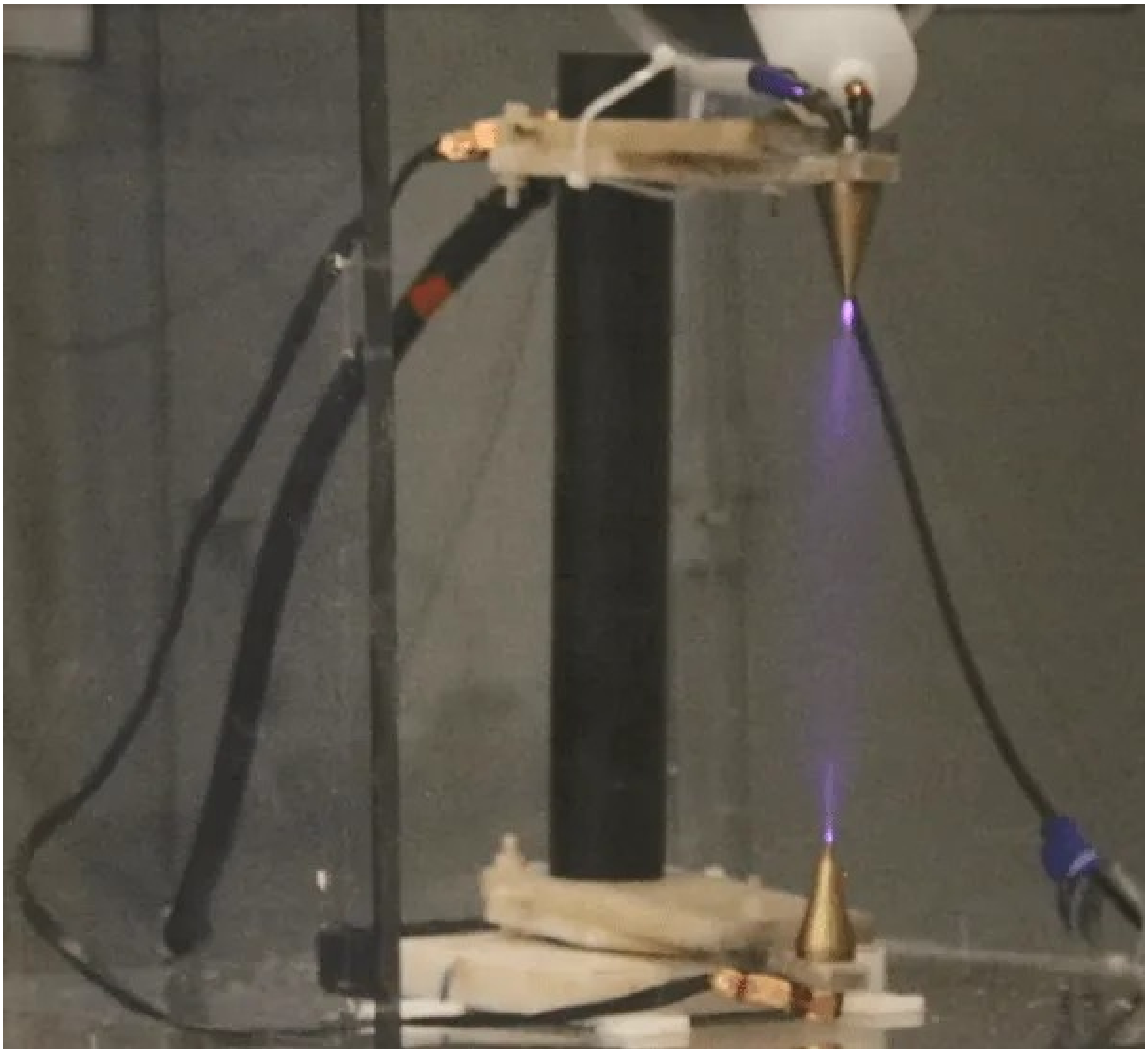
Radioimaging is a relatively new technique for studying lightning, and is an emerging diagnostic for high voltage systems at Sandia National Labs. We have previously shown that electrical breakdown at lab scales emits copious amounts of broadband RF emissions from DC up to at least 3 GHz. In the below figure, the top plot shows the time-domain RF signal associated with an arc bridging a 142-mm spark gap, and the bottom plot shows the spectrogram on the same timescale.



Despite the strong RF emissions due to electrical breakdown, it is unclear what physical processes generate the RF. In this poster, we begin to answer this question by utilizing coordinated RF, current, voltage, and optical measurements to demostrate that radioimaging can detect and locate non-catastophic precursors to the arc discharge. The ability to detect and locate precursors or electrical weakness in components is a boon for designing, testing, and deploying electric components for critical systems and infrastructure.

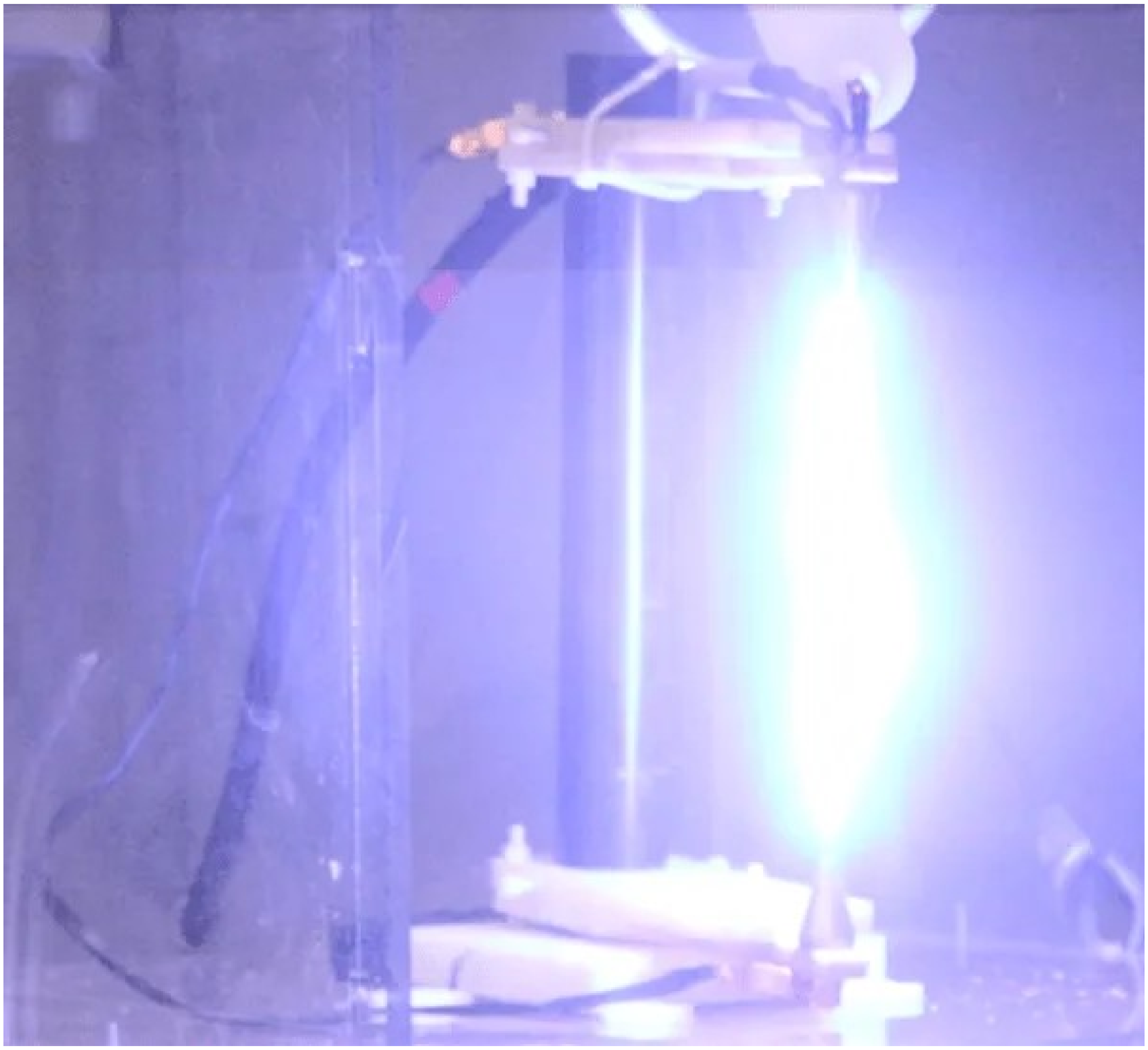
Example of a non-catastrophic precursor to the arc discharge:

- Corona discharge
- "Cold" plasma
- Carries low current
- Generally non-destructive



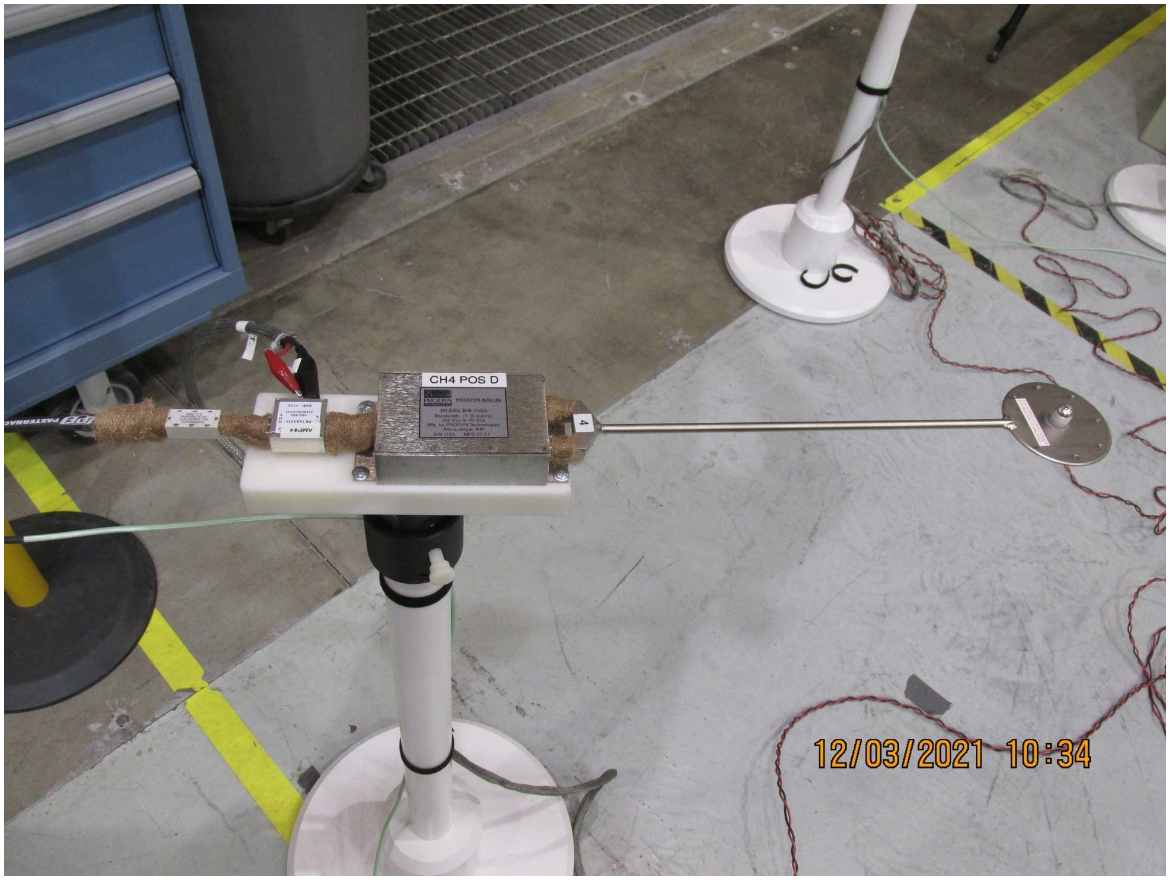
Arc discharge

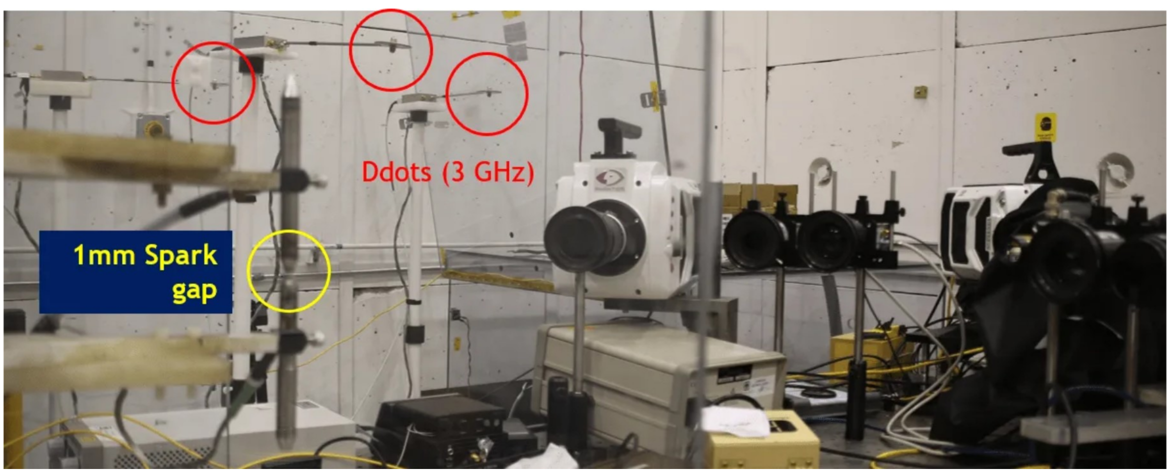
- "Thermal" plasma
- Carries high current
- Generally highly destructive



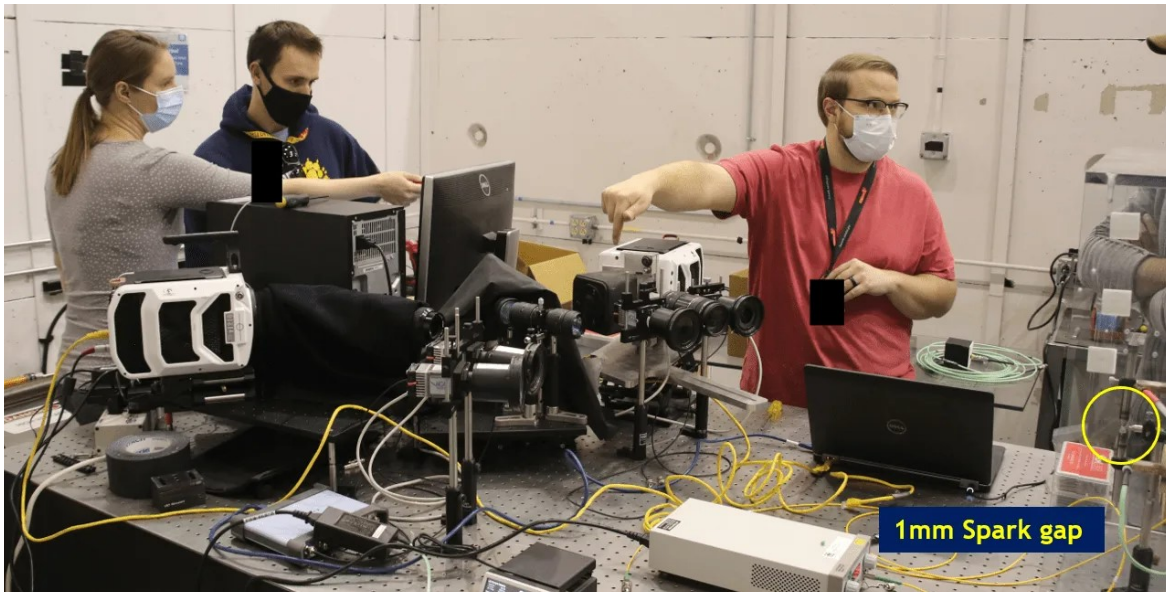
PRELIMINARY RF AND OPTICAL COMPARISONS OF LAB BREAKDOWN

Three 3-GHz bandwidth Ddots, i.e., dE/dt sensors, were used to measure RF emissions due to electrical breakdown in a 1-mm spark gap. The three Ddots were arranged in a 1-meter equilateral triangle configuration.

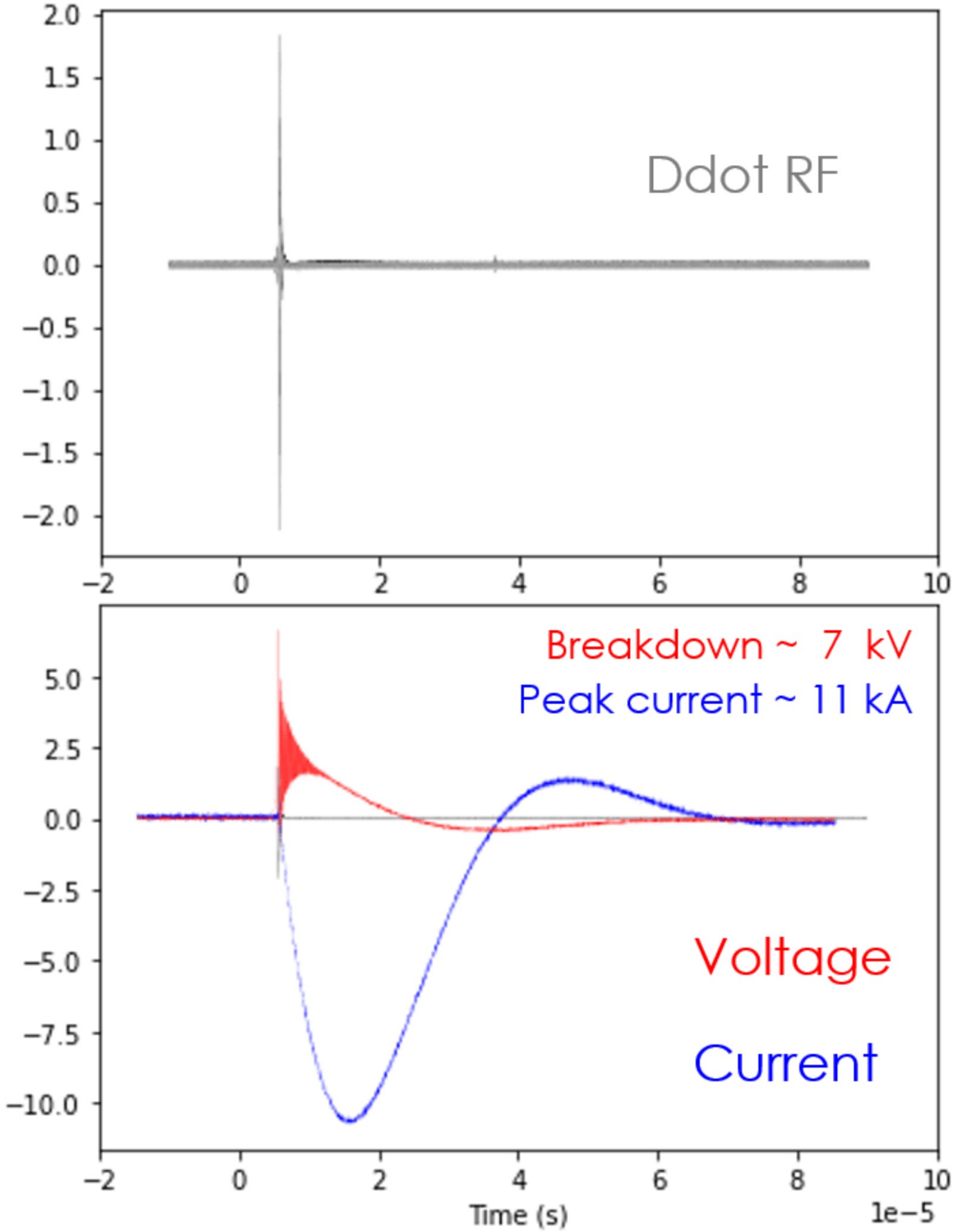




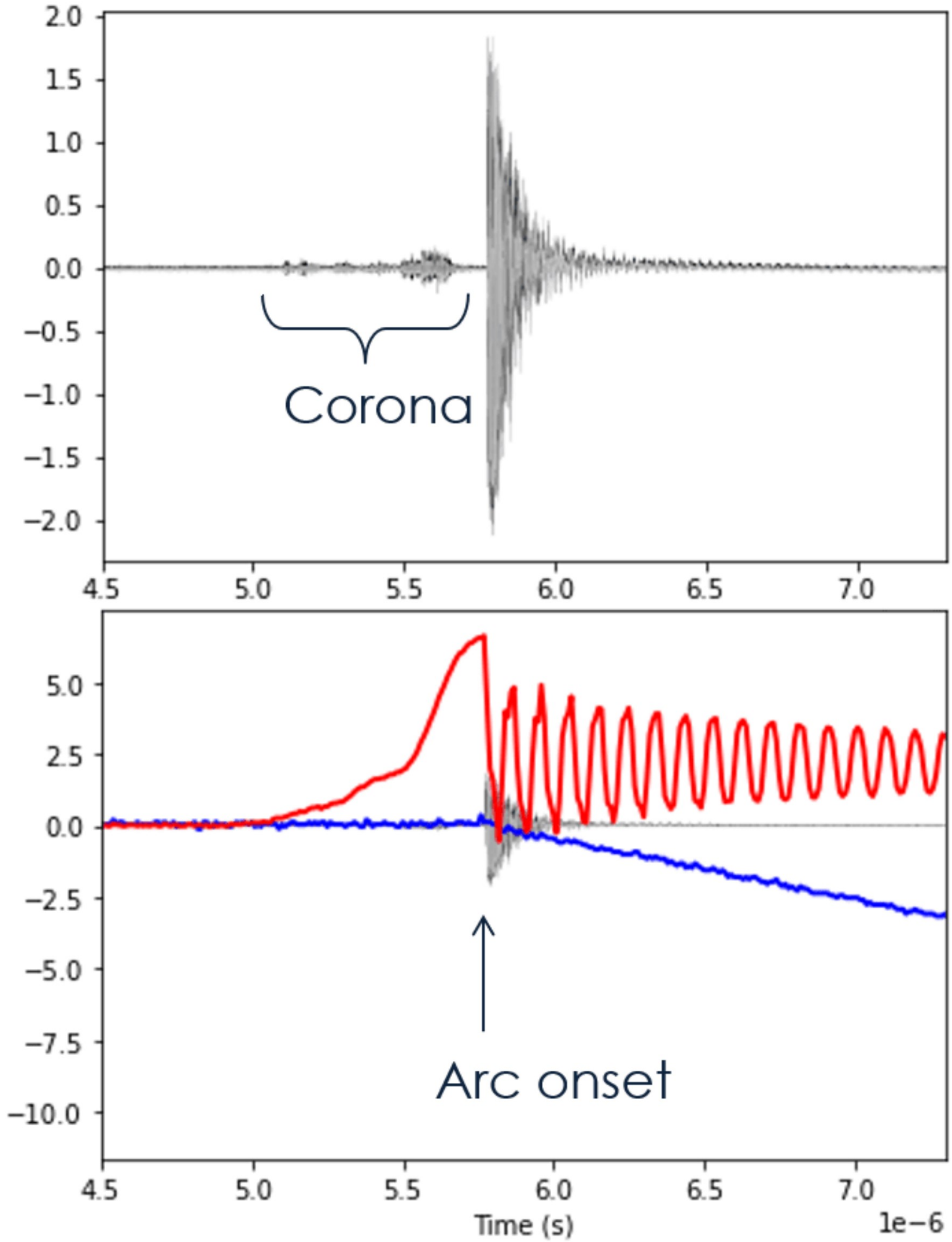
Several high speed cameras were used for both optical imaging and spectroscopy.



Time-aligned RF, voltage, and current measurements of breakdown in the 1-mm spark gap are shown below. Note that the red and blue curves in the below figure denote voltage and current, respectively.



The current through the hot arc lasted nearly 100 us, while the RF was incredibly prompt in comparison.The same data is shown below on a shorter time scale, showing a burst of RF activity nearly coincident with the arc current onset (also note the voltage collapse). There were also RF emissions prior to arc onset, presumably due to corona discharge.



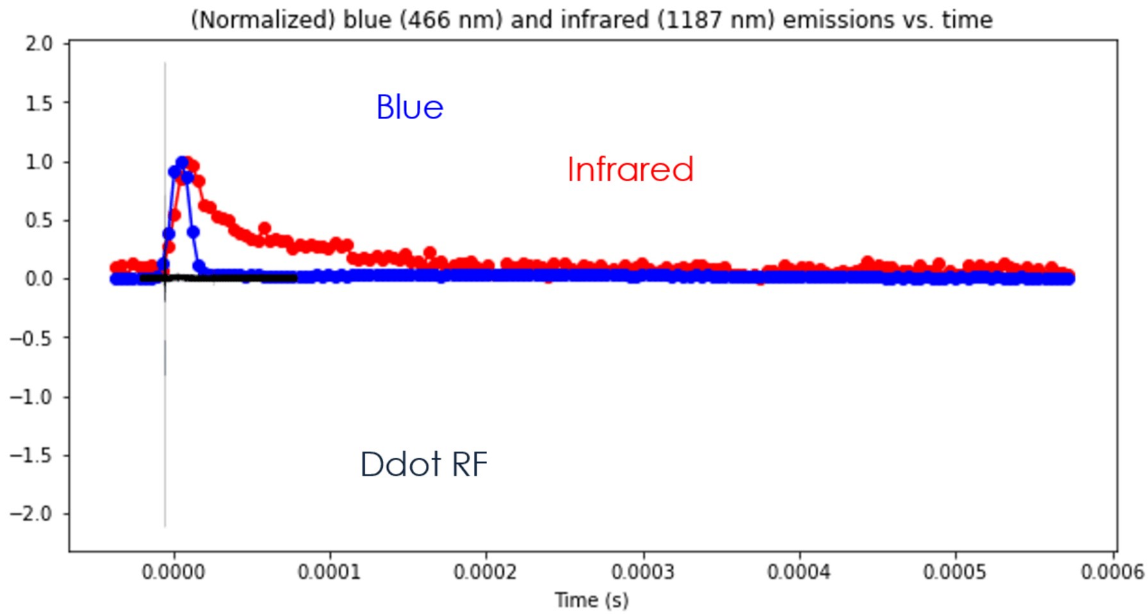
The below color video was captured at 120 kfps (8.3 us / frame) with a Phantom Miro M310. An arc bridged the 1-mm gap, but no precursor activity was visible on this timescale.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639103375/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/20210318_Test09_playbackFps5_svef2p.mp4

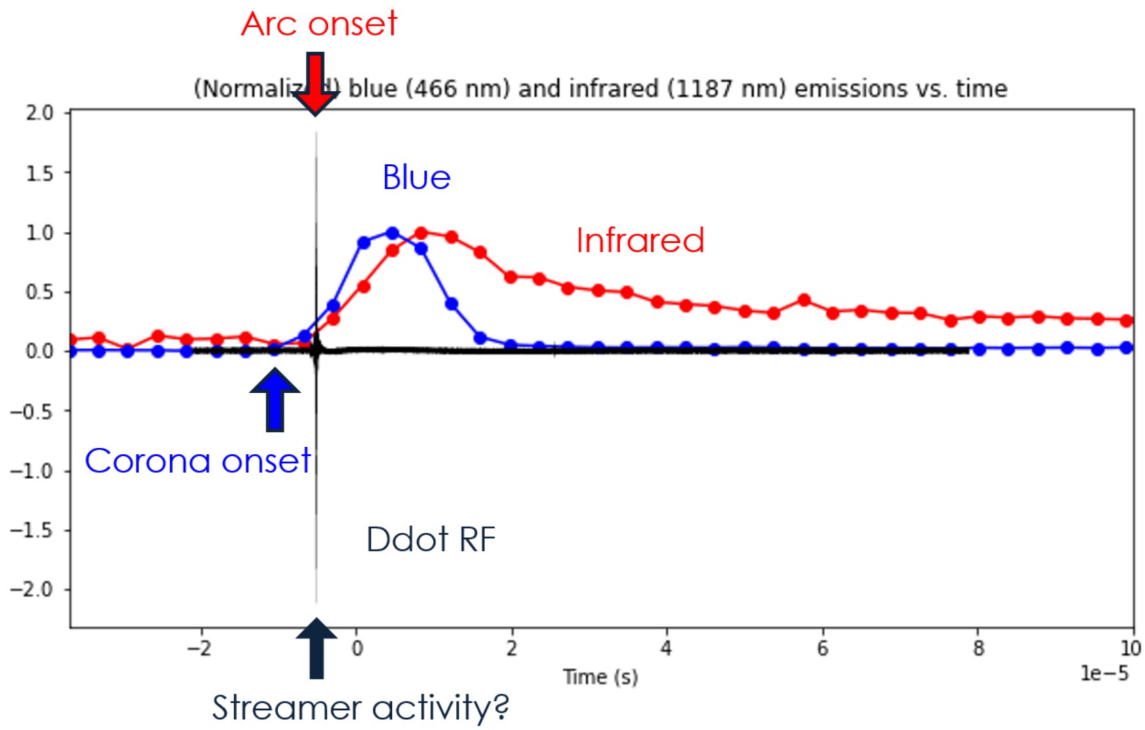
The below video is of the same event, but the incoming light was passed through a slit before being recorded by a Phantom V1210 at 266 kfps (3.76 us / frame). Several distinct lines appear from infrared to ultraviolet (left to right).

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639103512/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/20210318_Test09_cp140_playbackFps5_fnwg9t.mp4

RF emissions were also incredibly prompt compared with optical emissions from the discharge. Note that the red and blue curves in the below figure denote red and blue optical emissions. Actual measurement points are denoted by dots, and were taken from specific lines in the above video:



Note that the blue emissions, presumably due to corona discharge (cold plasma) turn on and off quickly compared to the IR emissions, presumably due to the (thermal) arc discharge.



To put this in the context of lightning, there may be a hot leader and extensive current flow present even when observed RF emissions have ceased.

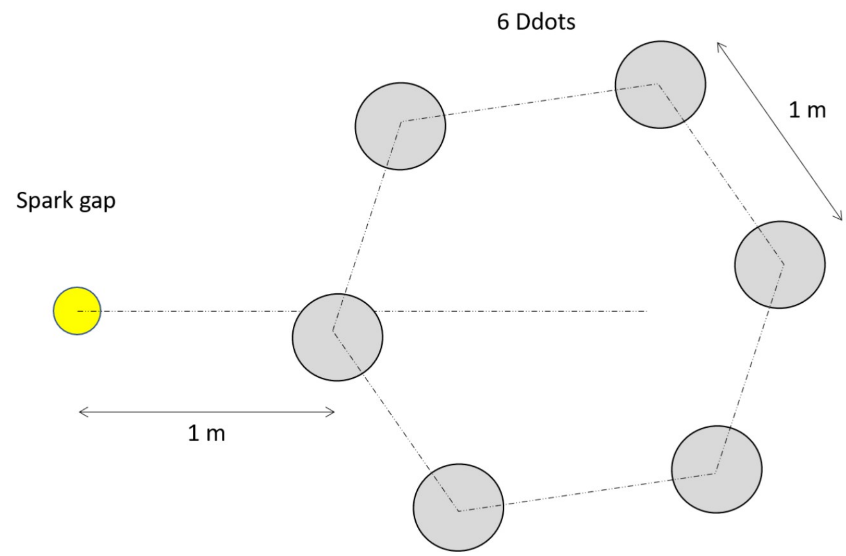
The temporal resolution in our preliminary observations doesn't allow a definitive correlation between corona onset or arc onset and RF onset.

Future experiments will utilize photodiodes to probe the finer timescales differentiating corona onset and arc onset.

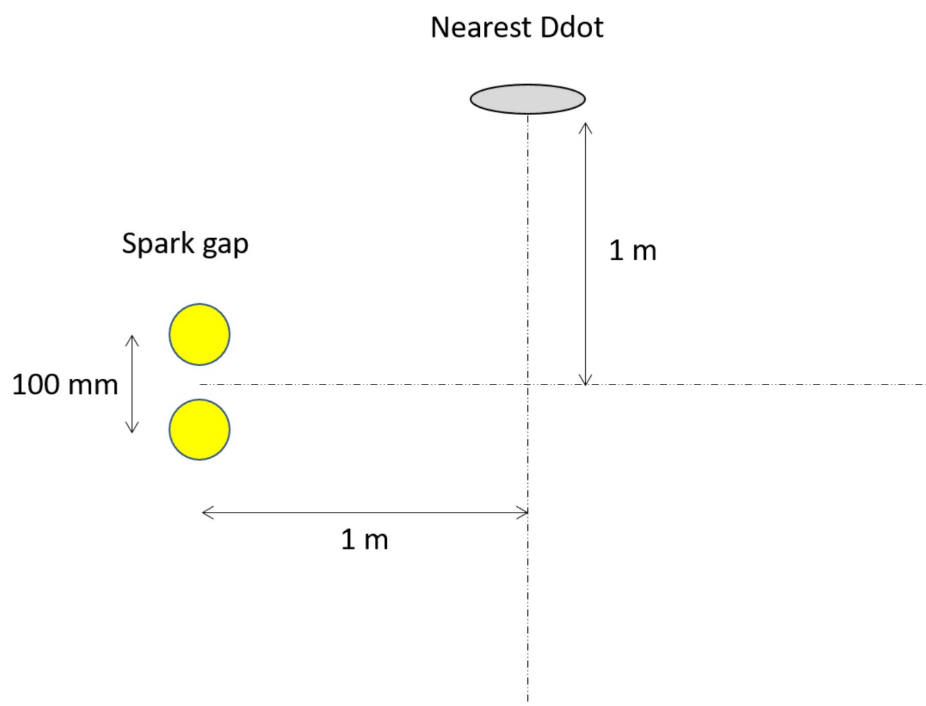
RADIOIMAGING WITH SIX DDOTS

We used six 3-GHz bandwidth Ddots, i.e., dE/dt sensors, arranged in a 1-meter equilateral hexagon configuration to meause RF emissions due to electrical breakdown in a 100-mm spark gap. The hexagon arrangement was skewed slightly so that each Ddot had a different look angle with respect to the spark gap.

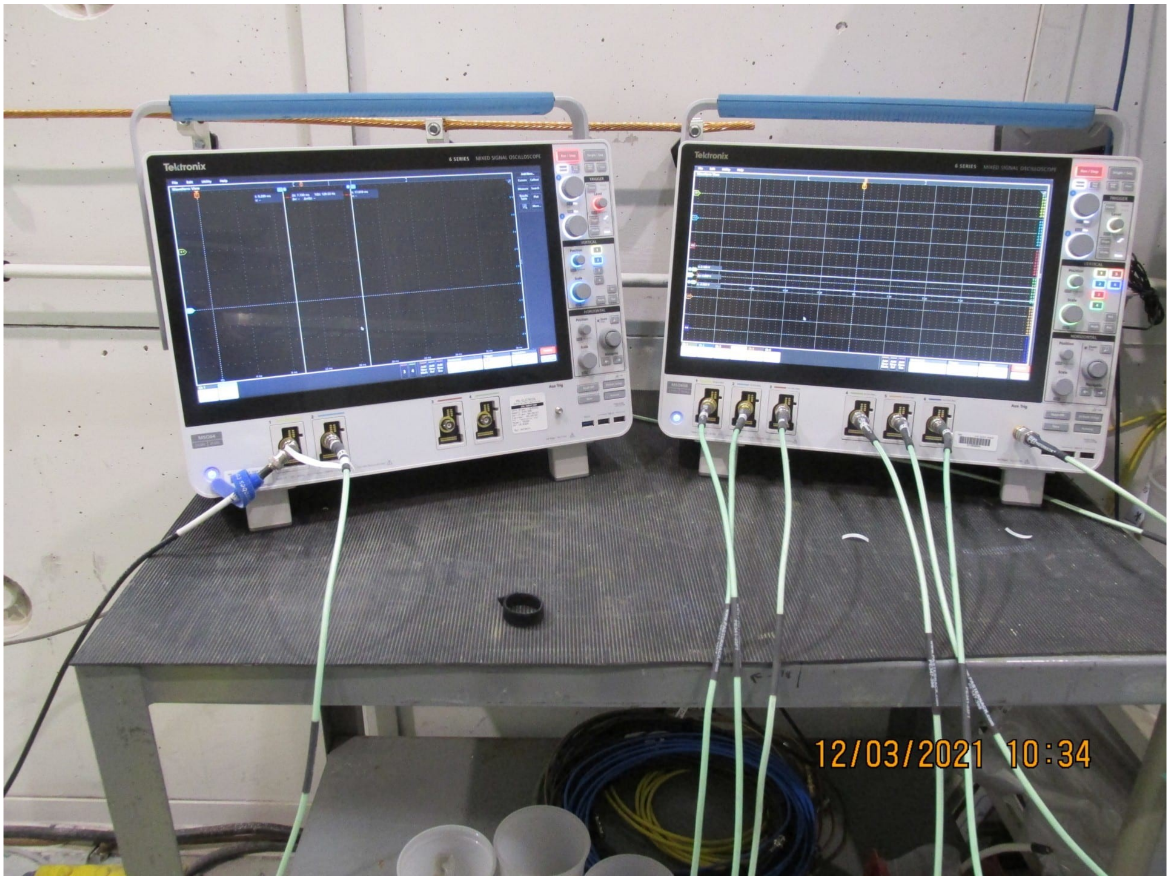
Top view:



Side view:



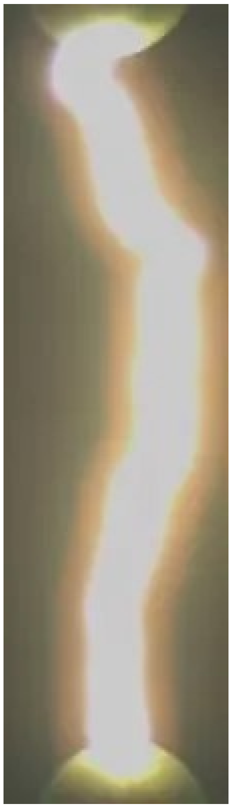
The Ddot signals were recorded on a six-channel Tektronix oscilloscope (MSO66B) at 1 TSps with 3 GHz bandwidth for a 10 us window, and the window was roughly centered in time on the arc (current) onset. A second oscillscope (MS064) recorded current through the gap and voltage at the top electrode, also at 1 TSps with 3 GHz bandwidth. The first (Ddot) scope was triggered off the current on the second scope, and the scopes were time synchronized.



A Phantom V711 captured high-speed optical video of the entire 100-mm arc discharge at 34 kfps (29.4 us / frame).

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639105278/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/cine4a_resolution13us_playback15fps_cpoe14.mp4

Below is a still (29.4 us) color image taken from the above high speed video of an arc bridging the gap between top and bottom electrode in a 100-mm spark gap:

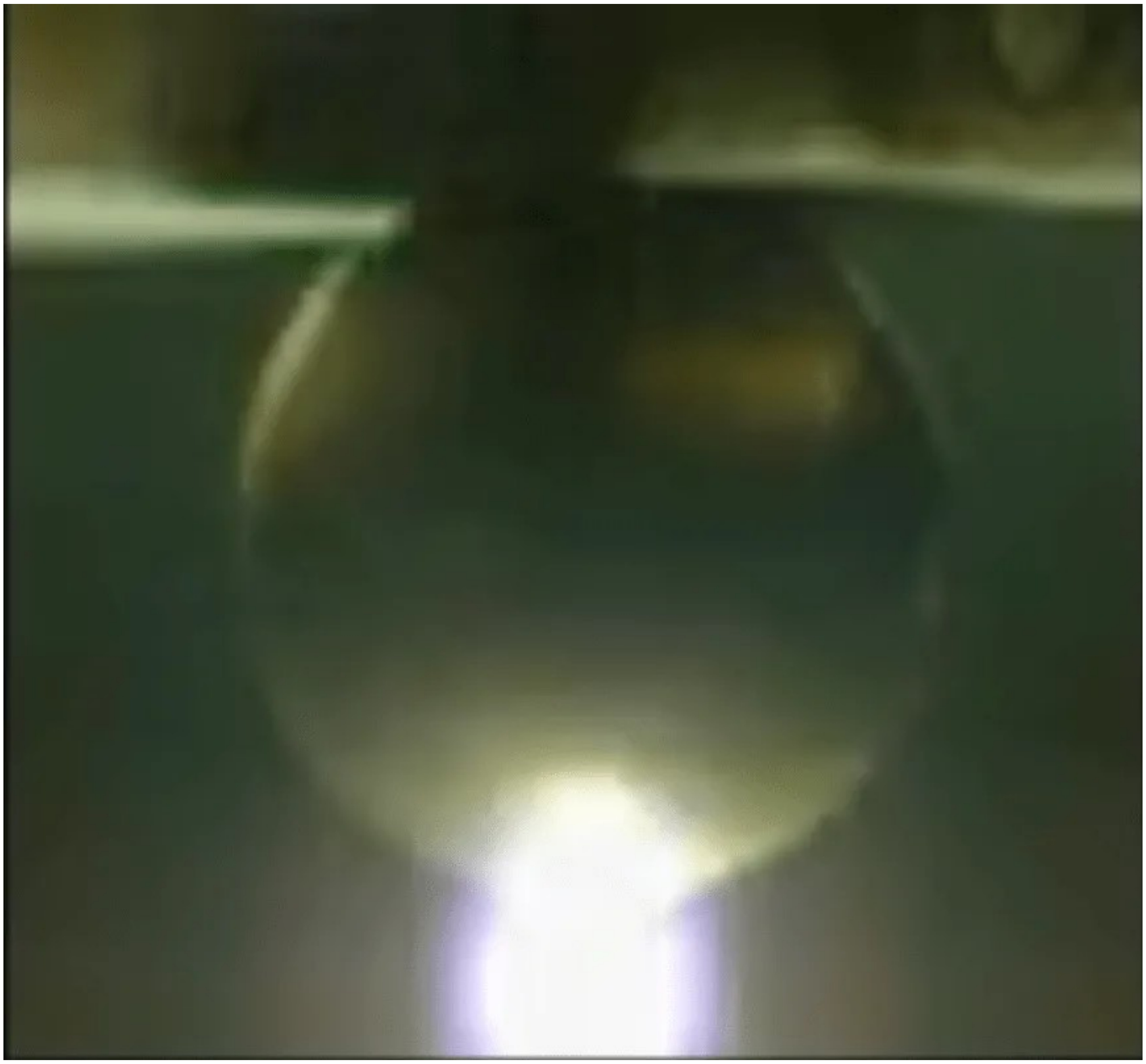


Any precursor activity (e.g., corona discharge) prior to arc onset was not visible at this timescale.

Zooming in on the top electrode only (where positive voltage was applied), the V711 captured the arc discharge at 260 kfps (3.8 us / frame). Again, any precursor activity prior to arc onset was not visible at this timescale.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639106045/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/cine2_playback5fps_k4trsi.mp4

Below is a still (3.8 us) color image taken from the above high speed video of the arc at the top electrode.



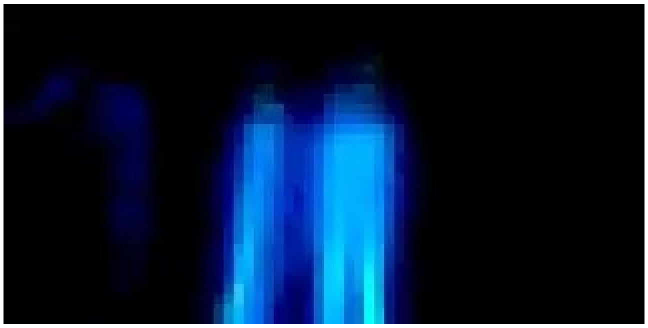
However, at 440 kfps (2.26 us / frame), one frame of streamer activity preceded the arc onset. Note that the 711 was zoomed in on the very bottom of the top (positive voltage) electrode. The streamers are visible as blue filaments in the frame prior to saturation.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639107624/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/cine11_playback_1fps_streamers_vsop65.mp4

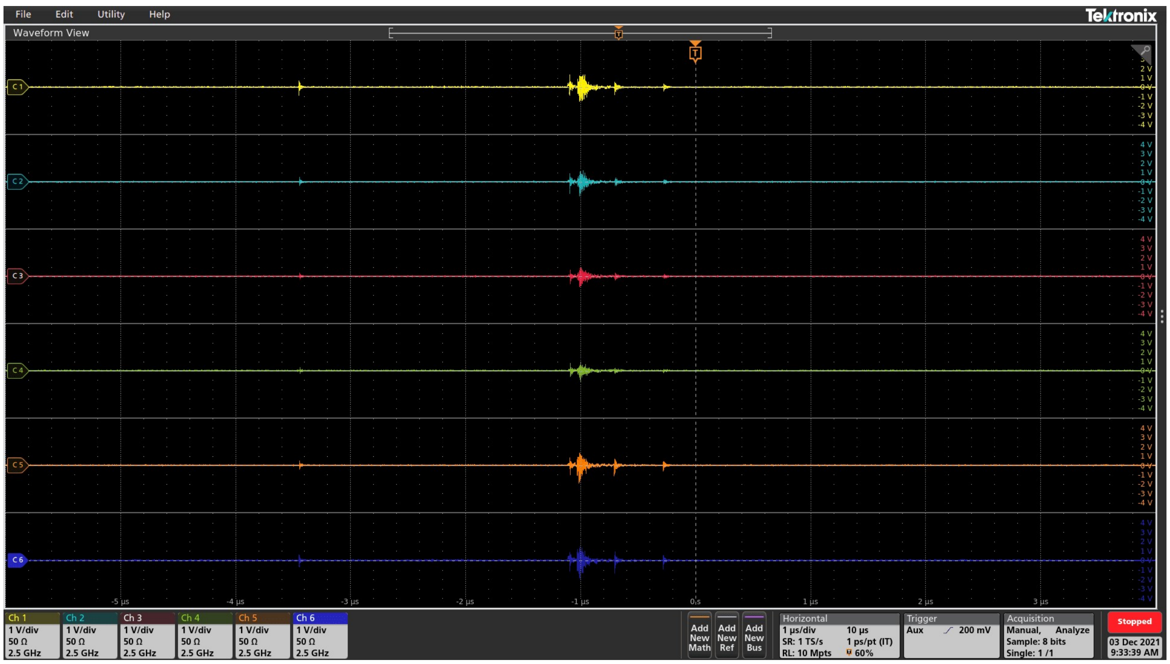
At 680 kfps (1.47 us / frame), we got somewhat lucky and recorded streamers two frames before arc onset:

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639107667/agu-fm2021/DA-D1-16-B8-65-E3-99-10-71-58-7F-06-68-17-16-D9/Video/cine12_playback1fps_streamers_f7l1fq.mp4

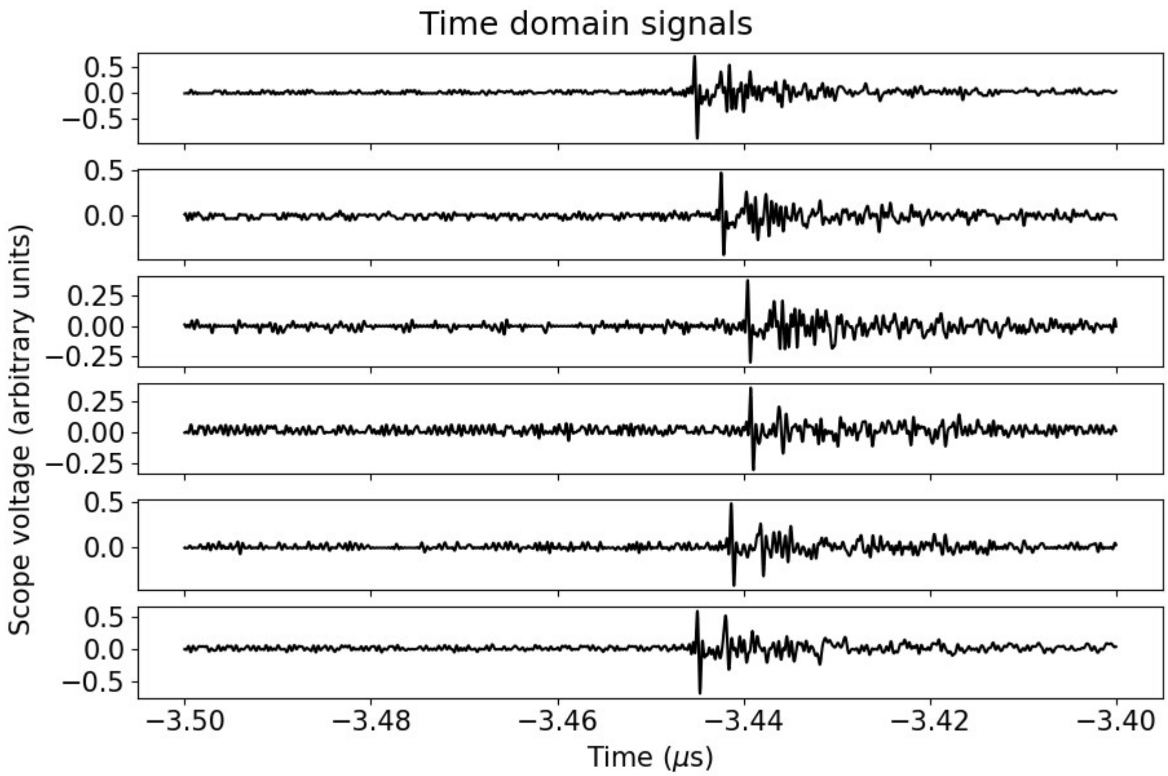
Below is a still (1.47 us) color image taken from the above high speed video of streamers prior to arc onset:



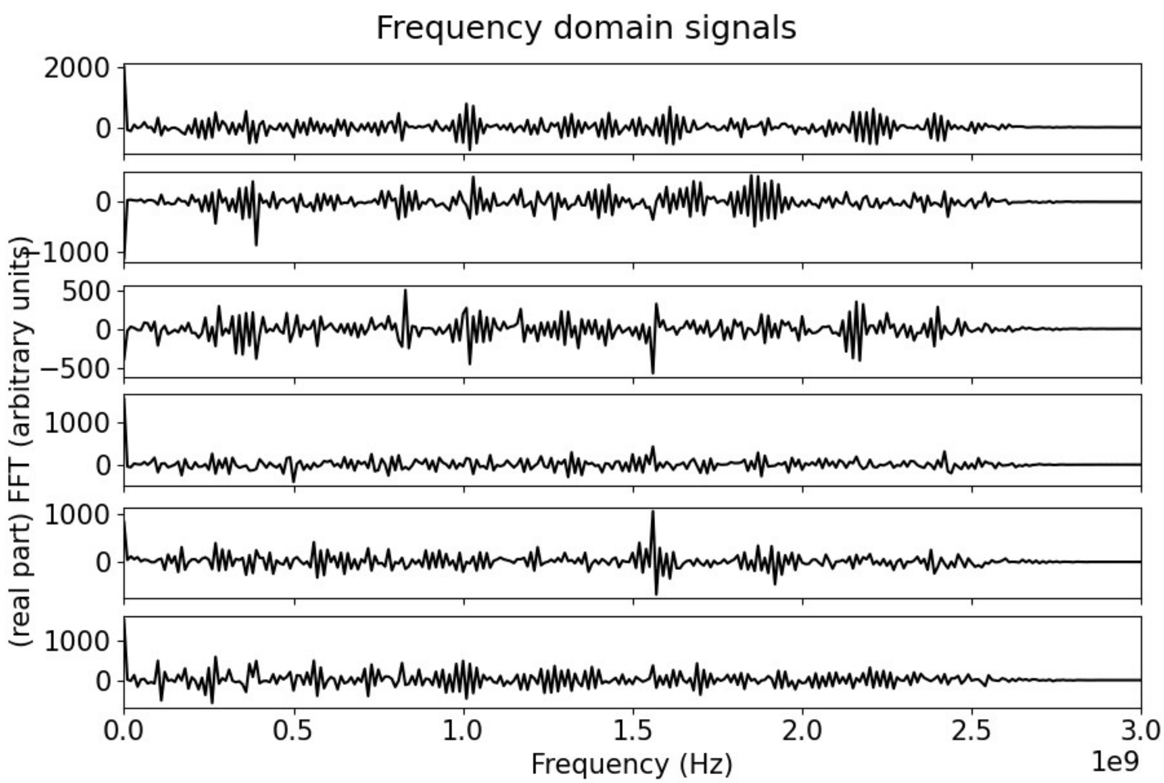
Interestingly, there was a consistent burst of RF emissions about 2-3 us prior to arc onset. The pre-arc RF burst is visible between -4 and -3 us in the below plot of the six Ddot signals. Note that the arc onset occured near -1 us (larger RF burst).



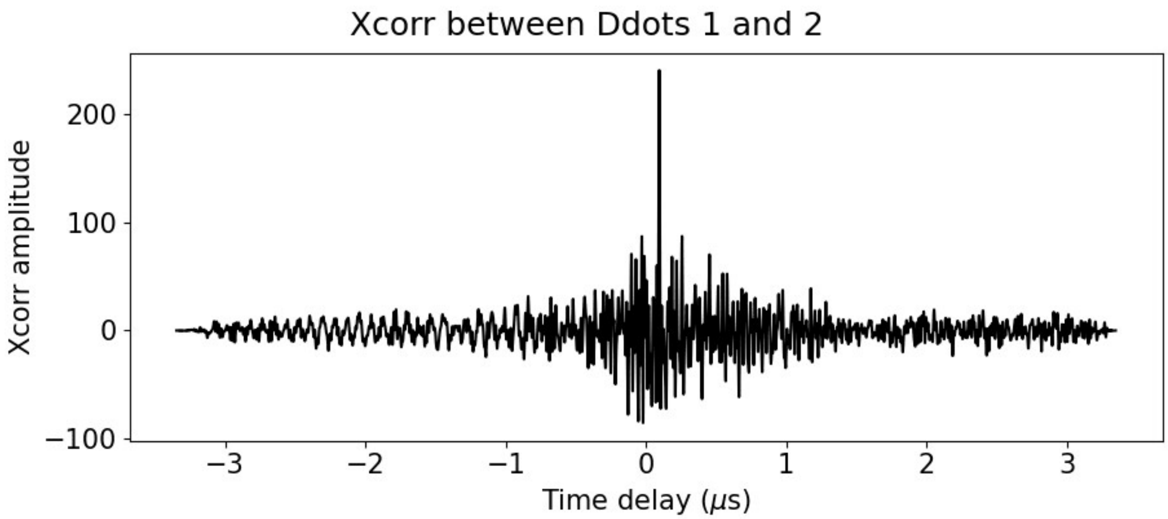
The precursor RF activity is shown on a shorter timescale (100 ns across) below, clearly showing different arrival times at the six Ddots. The top trace comes from the closest Ddot to the spark gap (placed 1 m away from the spark gap), and the following traces come from Ddots placed counter-clockwise with respect to the first Ddot.



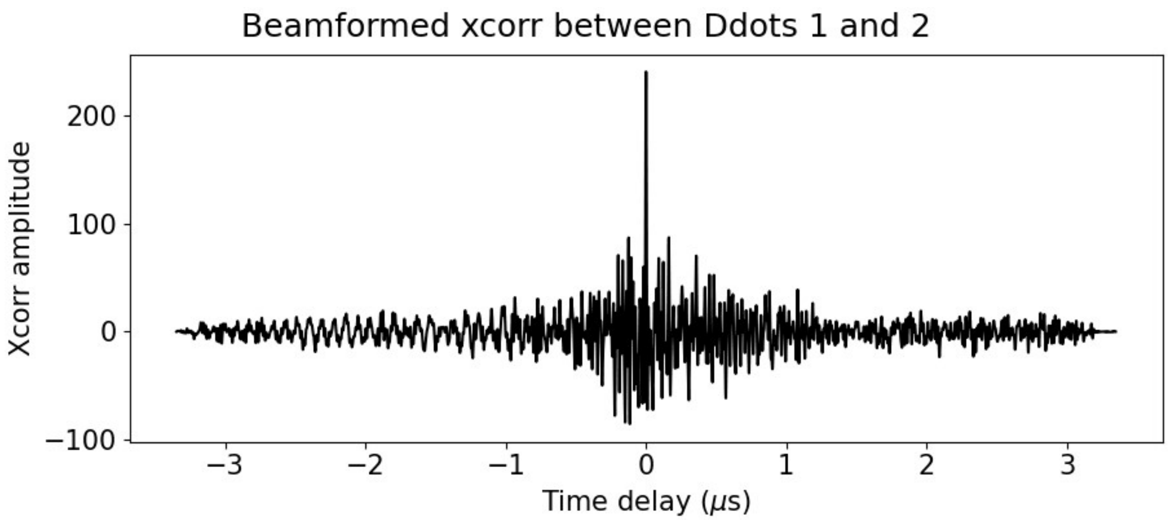
The above signals are Fourier transformed and shown in the next plot. Note the broadband emissions from DC to about 3 GHz.



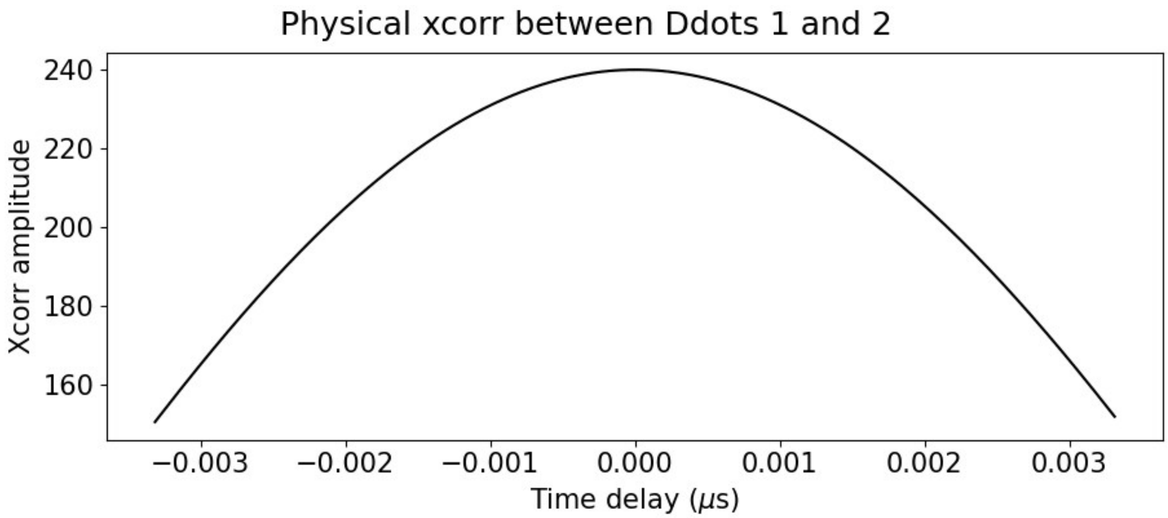
Below is an example cross correlation between Ddots 1 and 2 for the above 100 ns window.



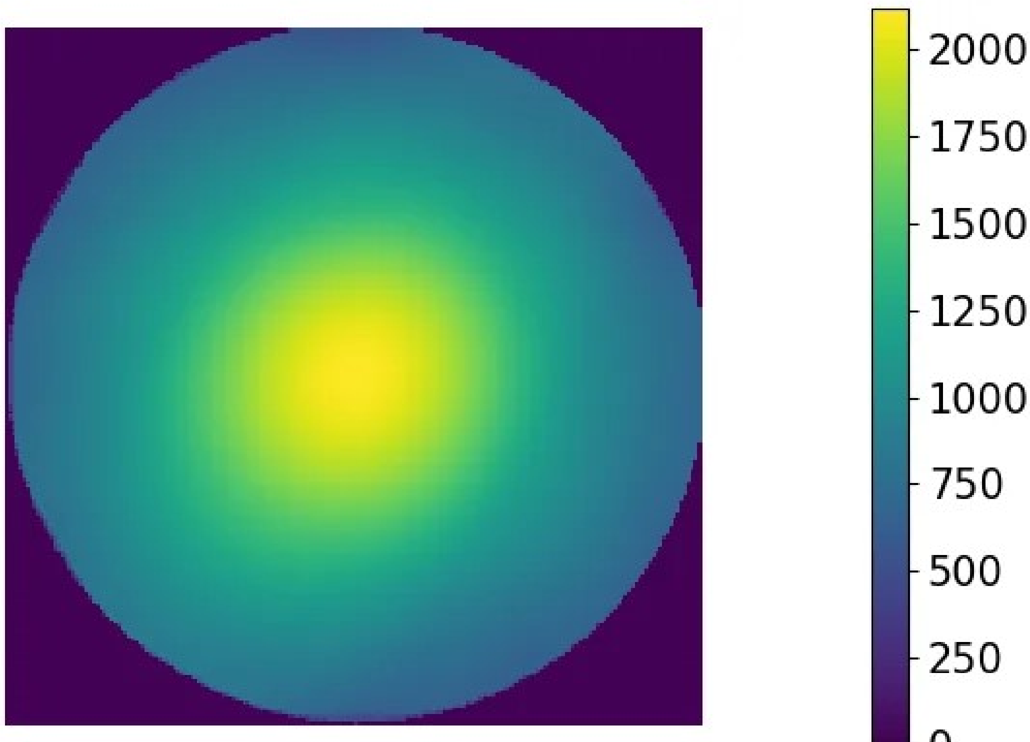
Because the spark gap is low on the "horizon" of the Ddot array, we used beamforming to center the source in the image plane. In the following plot, the peak of the cross correlation between Ddots 1 and 2 was centered at zero time delay. The other Ddot signals were similarly shifted in time with respect to Ddot 1 to perform beamformed radioimaging.



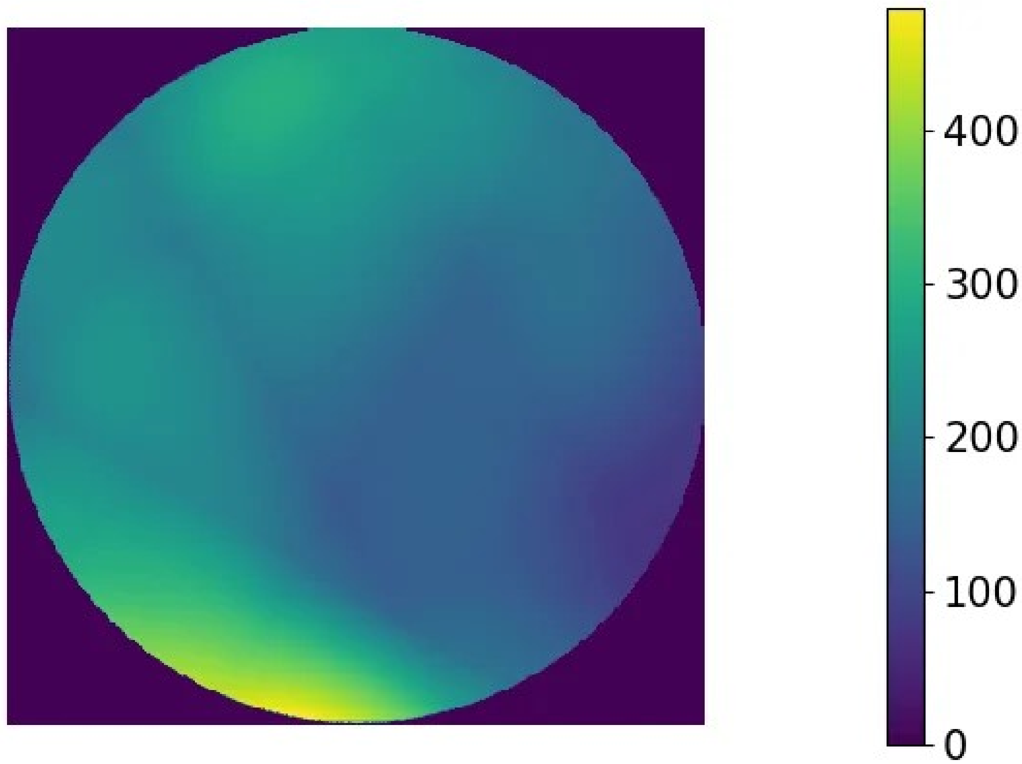
Not all the time delays shown on the above x-axes are "physical." That is, the distance between Ddots 1 and 2 is about 1 m, so that the longest light time of flight between the sensors in about 300 ns. In the below plot, the time delays (x-axis) are limited to values between -d/c to +d/c, where d is the baseline length and c is the speed of light.



The "physical" cross correlation above is what is used to make the resulting radioimage. Note that for a point source, we would ideally like a sharp peak in the cross correlation. However, our source region was likely on the order of the spark gap size, so 100 mm, which was comparable to the size of the array with its 1-meter baselines. Hence our source appears to be very broad and fuzzy in the below 6-sensor radioimage.



The below plot shows the same radioimage but without beamforming, clearly showing that the physical direction to the source was low on the horizon.



In future work we will experiment with longer baselines, additional RF sensors/Ddots, and also investigate CLEAN algorithms for removing the array response or point spread function from the images.

DISCUSSION

Taking coincident current, voltage and optical measurements greatly enhances our ability to interpret the RF emissions due to electrical breakdown in the lab. While current and voltage measurements indicate an arc bridging the gap, they are not indicative of low-current precursor activity, such as corona discharge and/or streamers, which we have shown emit strongly in broadband RF. We have shown that optical measurements can shed light on the low-current precursor activity, helping us to associate RF emissions with certain types of breakdown events.

Future work will focus on faster optical diagnostics for coordinated observations with RF measurements, as well as investigating any RF emission dependence on physical parameters such as applied voltage, voltage rise time, gap size, electrode shape and/or material, and air pressure.

ABSTRACT

Broadband (~100 MHz) radiofrequency (RF) interferometry has enabled recent advances in our understanding of lightning initiation and lightning propagation [Rison et al., Nat. Commun., 7, 10721, 2016; Stock et al, J. Geophys. Res. Atmos., 122, 8135-8152, 2017; Tilles et al., Nat. Commun. 10, 1648, 2019; Hare et al., Nature, 568, 2019], leading naturally to new questions concerning lightning physics, particularly with regards to the production of broadband RF emissions.

Here we adapt the lightning interferometry technique to lab scale high-voltage breakdown (HVB) using a large network of ultra-wide-band (>1 GHz) RF sensors to perform radioimaging at nanosecond time scales. Lightning is a natural large-scale atmospheric HVB, so by conducting our study in a controlled lab environment where electric potential, current, optical spectra and morphology are all readily observable, we attempt to answer the questions: How broadband is lightning RF? Can we differentiate HVB types (e.g., corona, streamer, arc, leader) based on the RF emissions and/or radioimages? How is RF amplitude related to electric potential, current, pressure? Our lab capabilities include pulsed and DC power sources in excess of 100 kV and 200 kA, capable of current rise times from tens of nanoseconds upward, and producing air HVB tens of centimeters in extent.

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-mission laboratory managed and operated by NTESS LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's NNSA under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.