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Quantification of Electric Fields in Fast Breakdown During Lightning Initiation From VHF-UHF Power Spectra

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Key Points:

- Electric fields that drive fast breakdown (FB) processes are quantified using 1–750 MHz VHF-UHF spectral measurements
- FB spectra exhibit a −10 dB cutoff frequency of 430 MHz that implies an *E*-field of 2.0 E_k driving streamer growth inside the FB process
- This field is >7 times higher than the large-scale field, implying that the FB process involves a narrow electrically conducting structure

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract This work applies a new remote sensing approach to indirectly probe the electric fields in the discharge region of fast breakdown (FB) processes during lightning initiation. A VHF-UHF broadband (1–750 MHz) measurement system is used to record the radiation spectra of FB. The average spectrum over 4 FB events exhibits a −10 dB spectral cutoff at 430 MHz, which yields an electrical field of 1.96–2.02 times the conventional breakdown field at 8–9 km altitudes. This in turn implies a localized field enhancement inside the region dominating the VHF-UHF emissions of >7 times the expected pre-discharge background field for lightning initiation. Such a high field has implications for the dynamics of individual streamers and their impact on the immediate environment, and also constrains the geometry of parts of the FB structure, suggesting that streamers initiate continuously in the enhanced field ahead of a narrow (aspect ratio >4) and conducting region.

Plain Language Summary The electric field inside the region of lightning initiation is one of the most fundamental quantities in a lightning discharge, but it is nearly impossible to make any in situ measurement. Recent studies found that lightning can be initiated by a distinct process named fast breakdown (FB). Here, we apply a new remote sensing approach to indirectly probe the electric fields in the discharge zone of FB. A carefully calibrated broadband measurement system is used to record the radio signatures and power spectra of FB processes. We find that the electric field responsible for the FB streamer propagation is as high as 2.0 times the conventional breakdown field. This high field has implications for the immediate environment and dynamics of individual streamers, and also put constraints on the geometry of the fast breakdown structure.

1. Introduction

How lightning initiates inside storm clouds has long been poorly understood as a result of its random nature in time and space that eludes in situ observations. Recent studies have found that some lightning initiates with narrow bipolar events (Le Vine, 1980; Smith et al., 1999) that are caused by a distinct process named fast breakdown (FB; Lyu et al., 2019; Rison et al., 2016). Originally observed only as positive polarity breakdown, further measurements showed that FB also occurs in a dominantly negative polarity form (Tilles et al., 2019). More recently it has been shown that streamers of both polarities can propagate simultaneously in at least some FB events, and that apparent negative FB events likely first develop as positive streamers (Huang et al., 2021). The state-of-the-art very high frequency (VHF) lightning imaging applied in these studies showed the propagation speed ($3 \sim 5 \times 10^7$ m/s), spatial extent (~500 m, vertically) and charge moment change (~100 C · m) of FB (Rison et al., 2016; Tilles et al., 2019), but the physics underlying FB is still unclear. It is thus of great interest and importance to measure or infer electric fields in the ambient environment or even inside the discharge regions of FB processes to gain insights into the internal physics.

One such effort was made by Cummer (2020) in which the background electric fields prior to FB discharge of about $E_k/6$ was inferred from the charge moment change and altitude extent derived from observations (Rison et al., 2016), where E_k is the conventional breakdown field of 3,000 kV/m at sea-level pressure. Recent theoretical work (Liu et al., 2019) suggests a link between the streamer-produced VHF radiation spectrum and the electric field in the streamer growth region, thus suggesting a new type of measurement that probes electric fields inside the streamer zone by measuring the lightning radio spectrum. This approach has been demonstrated by Pu et al. (2021) to infer electric fields in the positive streamer region at the tip of a cloud-to-ground positive leader using 10–250 MHz VHF spectra. But since the FB spectra seem to have a broader bandwidth extending to ultra-high frequency (UHF, 300–3,000 MHz), a broader bandwidth measurement system is needed to obtain a sufficiently complete broadband radio spectrum of FB.

Therefore, in this work, we use a carefully calibrated broadband VHF-UHF (1–750 MHz) measurement system to obtain the source radio spectrum of FB processes, aiming to quantify the electric fields that drive the streamer propagation during FB following previous theoretical and numerical studies (Kosar et al., 2012; Liu et al., 2019; Liu & Pasko, 2004; Shi et al., 2016). In summary, our measurements have implications for: (a) the immediate environment and dynamics of individual streamers and the overall streamer system in FB, (b) and the pre-discharge background electric field and the morphology of FB.

2. Instrumentation

The data analyzed in this work are from a broadband VHF-UHF measurement system that we refer to as the ultra-broadband (UBB) system. The system consists of a 6-inch-long monopole antenna over a metal mesh ground plane. This antenna is electrically short compared to a wavelength below 500 MHz and was chosen to have a simple and predictable radiation pattern and impedance across our very wide bandwidth of interest. The antenna impedance is almost entirely capacitive below the antenna resonance, which results in a relatively modest $1/f$ voltage decay with frequency at lower frequencies. It is poorly matched to 50 Ω, but for strong VHF-UHF sources like FB, above-noise signal is measured from a few MHz up to hundreds of MHz. A GaGe TB3-ENE123G20 digitizer is used to sample the signal channel at 1,500 MS per second with 12-bit resolution, enabling a signal bandwidth extending to 750 MHz. This system has been fully calibrated from end to end with network analyzer two-port S-parameter measurements of the antenna, filters, the preamplifier, and the cable. Such calibration has been done several times on different days in the summer of 2020 and 2021 to ensure consistent results. The system transfer function obtained from the calibration is then used to compute the source radio spectrum incident on the antenna.

Simultaneously, a short-baseline VHF interferometer (1–250 MHz) ran in parallel with the UBB system to locate the 2-D positions of lightning sources. Detailed descriptions about this interferometer can be found in Lyu et al. (2019) and Pu and Cummer (2019). We employ the lightning source maps from this interferometer to determine what lightning subprocesses are measured on the UBB system. In present study, we analyze the FB signals recorded on the UBB system with their occurrence context and source altitude provided by the VHF interferometer. Note that we also refer to the National Lightning Detection Network (NLDN) for lightning location information.

3. Results and Analysis

3.1. Measured VHF-UHF Spectra of FB

FB was originally identified as fast positive breakdown with the apparent fast movement of positive polarity sources in one direction (Rison et al., 2016) but later it was also found to occasionally have negative polarity sources moving in the opposite direction (Tilles et al., 2019) or even a mixture of both (Huang et al., 2021). Here, we focus on positive polarity FB but call it FB for simplicity. Our UBB system has been collecting lightning data since year 2020. The FB signal waveforms in the VHF-UHF frequency band look apparently the same as they normally appear at lower VHF frequencies (<100 MHz), namely a strong continuous burst of VHF-UHF energy with a time duration of ∼10 μs. We have observed 11 FB events over the summer of 2020 and 4 more on 7 August 2021. Here, we only show the latest 4 FB events since they were acquired after we improved the antenna ground plane in 2021 and thus have slightly better data quality. But the additional results of 11 FB from 2020 are consistent with these 4 cases and can be found in the Supporting Information S1.

The occurrence details about 4 FB cases analyzed here are listed in Table 1. These 4 cases were observed both on the UBB system and the VHF interferometer system. The first 3 FB events occurred especially closely in time and space within just 5 min from similar distances of about 30 km to the antenna. With elevation angles determined by the VHF interferometer and plan distances known from NLDN locations, we can estimate the source altitudes of these FB processes, which ranges from 7.9 to 8.8 km. The altitude information is necessary since the electric fields later estimated from measurements are dependent on the air density and thus altitude (Liu & Pasko, 2004).

Figure 1a shows the mean raw uncalibrated power spectral density of the 4 FB events measured on the UBB system. The FB spectra are calculated using a 10 μs time window of UBB FB pulse burst. The individual spectra for each FB are essentially the same with comparable amplitude and we compute the ensemble mean of 4 FB spectra to reduce the fluctuation and uncertainty in one single spectrum. We also compute the corresponding

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Table 1
Occurrence Details of Four Fast Breakdown on 7 August 2021

No.	UTC time	Latitude (N)	Longitude (W)	Distance from UBB (km)	Centroid elevation (degree)	Altitude (km)
FB1	09:47:03.261	35.9501	79.4203	29.6	16.5	8.8
FB2	09:49:42.554	35.9630	79.4285	30.2	16.3	8.8
FB3	09:52:32.485	35.9613	79.4128	28.8	16.5	8.5
FB4	10:06:38.987	35.9942	79.3651	24.6	17.8	7.9

noise spectra using waveforms shifted 40 μs earlier in time when lightning has not yet initiated. Some significant noise bands due to the FM and TV transmitters are marked. We remove those frequencies at which the noise strength is stronger than the FB signal strength in the further analysis. Note that the FB signal strength is not significantly higher than the noise level at frequencies below 6 MHz. The raw measurement power spectrum spans approximately 40 dB above the noise floor, which is a modest dynamic range but adequate for our purposes. In addition, the end-to-end system transfer function measured through a full two-port S-parameter calibration on 11 August 2021 is also shown in the figure. It can be seen that the overall shape of the FB spectrum is consistent with the transfer function, including key features such as resonance peaks associated with multiple reflections in the 50 m cable between the antenna preamp and the digitizer.

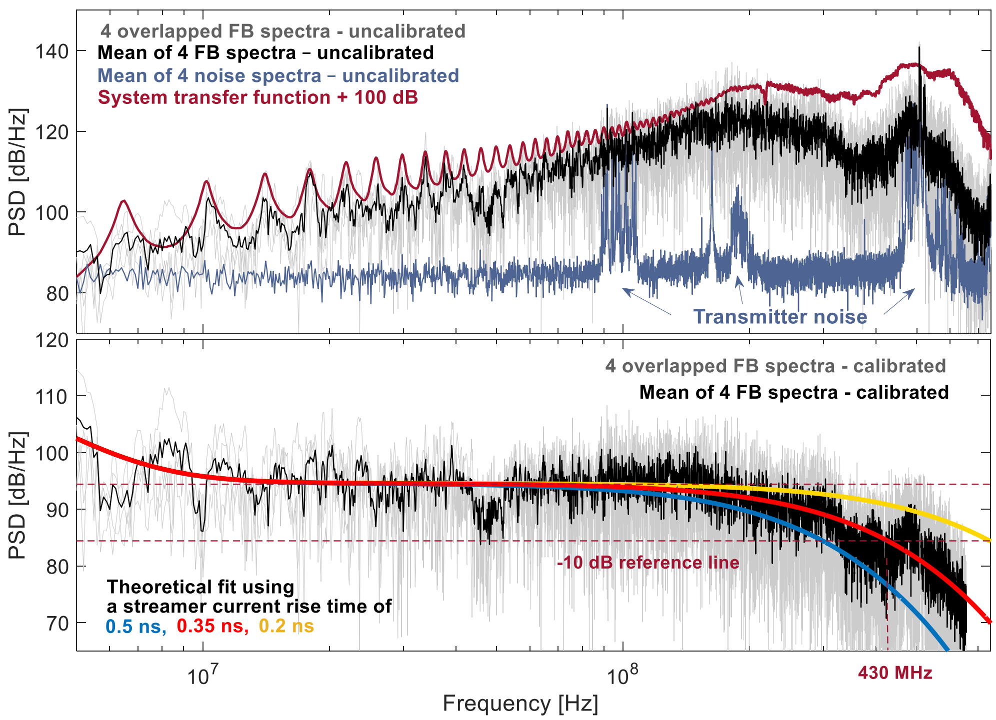

Figure 1. Uncalibrated and calibrated radio spectra of fast breakdown (FB) processes at VHF-UHF (5 ~ 750 MHz). (a) Uncalibrated radio spectra of 4 FB events and background noise observed on 7 August 2021, and the corresponding system transfer function measured on 11 August 2021. We compute the average spectra for both FB events and background noise to reduce spectral fluctuations and uncertainties in a single spectrum. Some strong background noise spikes from transmitters (e.g., FM and TV) can be seen in the noise spectrum as marked. (b) Calibrated source spectra of the 4 FB events, computed by dividing the system transfer function into the measured uncalibrated spectra. Transmitter noise spikes of energy higher than FB are removed. The calibrated FB spectra roll-off at higher frequencies and have a −10 dB cutoff frequency of 430 MHz. Theoretical fit to FB spectra with variant streamer current rise times is also shown. The best fit indicates a streamer current rise time of 0.35 ns. PSD: power spectral density.

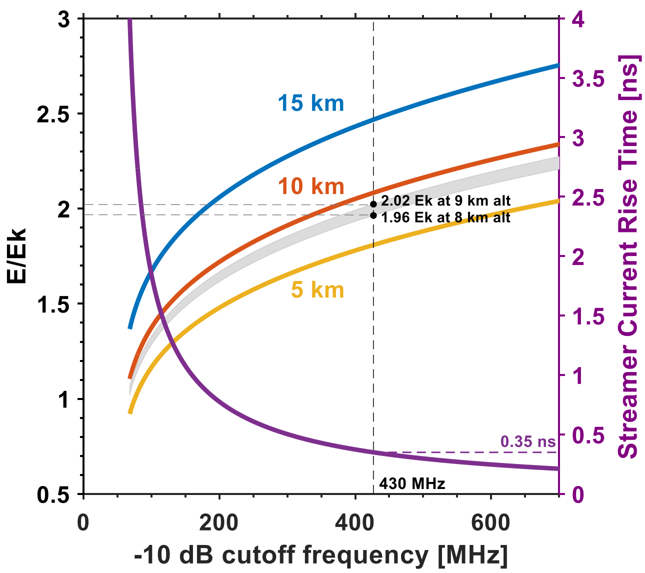

Figure 2. Relationship of electric field, streamer current rise time and −10 dB cutoff frequency summarized from previous simulation and theoretical work by Kosar et al. (2012), Liu et al. (2019), Liu and Pasko (2004), and Shi et al. (2016). Results at different altitudes are scaled using similarity laws (Pasko et al., 1998). E_k represents the conventional breakdown field, and at sea surface pressure E_k has a value of 3,000 kV/m. The measured 430 MHz cutoff implies a streamer current rise time of 0.35 ns, which in turn implies a streamer growth region electric field very close to 2.0 E_k for the observed 8∼9 km fast breakdown altitudes.

3.2. Calibrated FB Spectra and Cutoff Frequency

Dividing the measured average FB spectrum by the system transfer function (namely, average FB spectrum/system transfer function) yields the source FB spectrum as shown in Figure 1b. There are some small features near 50 and 350 MHz which were not present in the 2020 data (see in the Supporting Information S1) that we attribute to environmental factors. However, the overall shape of the FB source spectrum is relatively smooth. The most important feature here is that the average FB spectrum has a relatively flat portion from 10 to 200 MHz but rolls off smoothly above 200 MHz, with a −10 dB cutoff frequency of 430 MHz. This spectral shape is in close agreement with theoretical predictions in which the streamer growth rate drives the shape of the spectrum (Liu et al., 2019). We thus conclude that streamers are involved in the FB process and are the main source of VHF-UHF radiation. Note that we also measured a negative FB (not shown) from the same storm in 2021 that has a similar spectrum and a cutoff frequency up to a few hundred MHz. A further study on the similarity/difference between the positive FB and the negative FB is needed.

More specifically, that theory predicts a VHF-UHF spectrum in which the roll-off frequency is controlled by the streamer growth rate, which in turn is controlled by the electric field in the streamer growth environment. The theoretical FB spectrum is proportional to $\omega^2|\tilde{f}_s(\omega)|^2(|\tilde{f}_{\mathrm{NBE}}(\omega))|^2 + \frac{1}{N_p}$, with the overall FB current waveform $f_{\mathrm{NBE}}(t)$ and the individual streamer current pulse $f_s(t)$ being approximated by an asymmetric two-sided exponential function and a double exponential function, respectively (Liu et al., 2019). Although there are several parameters in the expression, it is only the individual streamer current $f_s(t)$ rise time that determines the VHF-UHF roll-off frequency. We thus fit the measured calibrated FB spectrum with different streamer current rise times (see Figure 1b), and 0.35 ns yields the best agreement. Note that we also observed spectral roll-off and obtained the same best fit of 0.35 ns using 11 FB events in 2020.

3.3. Implications for Electric Fields in FB

This streamer current rise time is controlled by the electric field in the streamer growth zone according to previous simulation-based and theoretical studies (Kosar et al., 2012; Liu et al., 2019; Liu & Pasko, 2004; Shi et al., 2016). Since FB events occur at altitudes ranging from 5 to 16 km (Bandara et al., 2020), and the relationship between the streamer growth rate and electric field is altitude dependent, we show the scaled fields at three explicit altitudes of 5, 10, and 15, and also at 8 and 9 km for the present 4 FB events, using the known streamer similarity laws (Pasko et al., 1998). Figure 2 links the observable quantity, namely the −10 dB cutoff frequency in the lightning source radio spectrum, to the streamer current rise time, and to the electric field in the streamer growth zone. It also indicates that when a certain cutoff frequency is observed, we can constrain a plausible range of electric fields considering FB occurring at all reasonable altitudes from 5 to 15 km if the actual altitude is unknown.

For the present study, the −10 dB cutoff frequency of 430 MHz corresponds to a 0.35 ns streamer current rise time (right axis), and then a streamer growth region electric field of about 2.0 E_k (left axis), or 2,200 kV/m for FB near 8–9 km altitude. Although this cutoff frequency may vary from event to event, Figure 2 shows that any −10 dB cutoff frequency higher than 150 MHz in the 8∼9 km altitude range would indicate an electric field value higher than 1.5 E_k. In addition, a detailed analysis of 1-μs-long sub-sections of FB pulses in Figure S2 in in Supporting Information S1 illustrates the dynamical properties of FB. It indicates that the cutoff frequencies of individual FB streamers first increase and then decrease over the course of the entire process between 230 and430 MHz. This suggests that the FB process is not due to discrete bursts of streamers but instead is a continuously propagating system of streamers in high electric fields that grows and decays over the ∼10 μs duration of the FB.

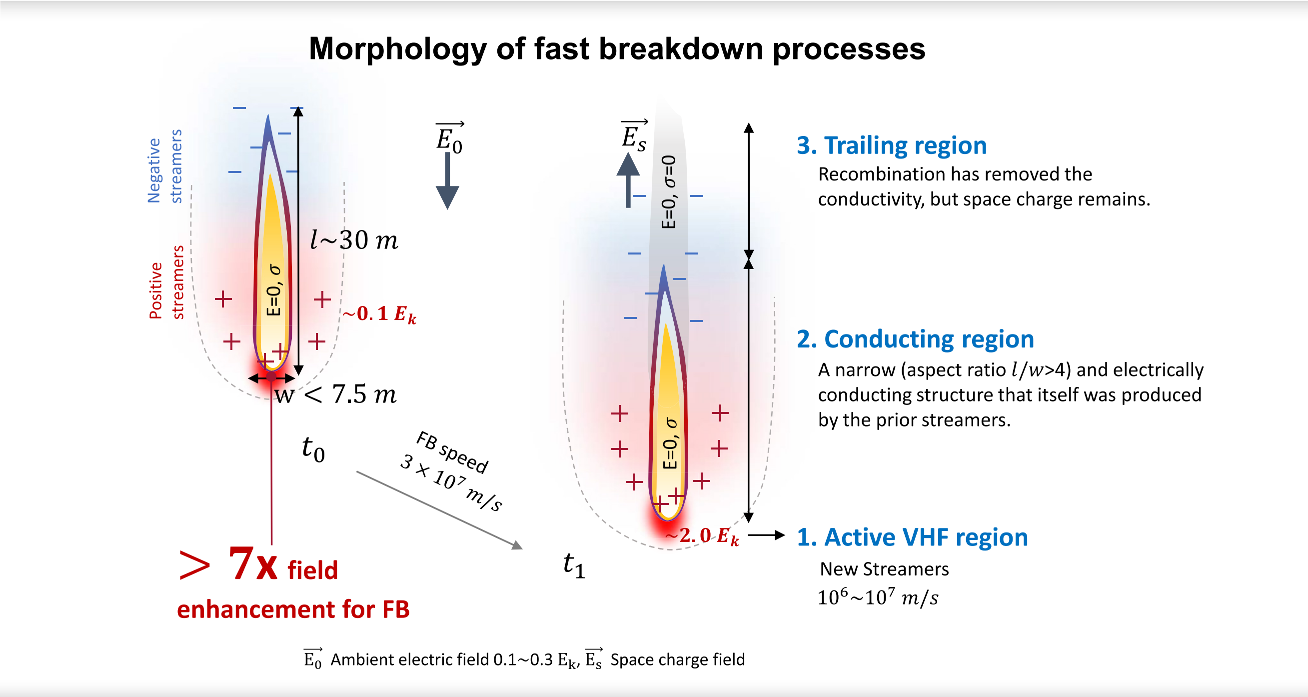

Figure 3. Illustration of the large-scale background field and morphology of fast breakdown (FB) processes. Unlike a fan-out/tree-like streamer system at the tip of a leader, the overall structure of the FB is more like a short active streamer system ahead of a narrow and conducting region of aspect ratio >4, so as to provide a >7x field enhancement at the front region of the entire structure to be consistent with the present measurement.

It is important to emphasize that this electric field of 2.0 E_k is inside the portion of the region of active streamer growth that dominates VHF-UHF emissions, which is moving in time. Streamers undoubtedly extend beyond this region into lower electric fields, but they apparently produce significantly less VHF-UHF radiation. This 2.0 E_k is also distinct from the large-scale, pre-discharge background electric field. Direct balloon-borne measurements of this pre-discharge electric field have been as high as at 0.2–0.3 E_k (Stolzenburg et al., 2007), and indirect measurements tied directly to the lightning initiation region have found comparable values (0.1–0.15 E_k; Cummer, 2020). The higher electric field in the streamer growth region is the sum of this ambient background field and the electric field produced by the new local electric charge created by the growing streamers and the overall geometry of the FB discharged volume.

Ultimately, however, the streamer growth region electric field is driven by the large-scale background electric field. This raises the question of what geometry of the FB process is required to produce the >7x enhancement of the background field (and maybe as much as 20x for a 0.1 E_k background field) indicated by the 2.0 E_k measurement. An expanding wide and quasi-planar streamer system, for example, can only enhance the background field by at most a factor of 2 in the region just ahead of the active streamer zone (which also results in zero electric field behind the active streamer zone). This is easily shown by Gauss's law and is confirmed by more detailed simulations of branching streamer systems (Luque & Ebert, 2014).

Bazelyan and Raizer (1998, p. 78) provide an empirical formula for how much the background electric field is enhanced by an electrically conducting cylinder (length l and radius r) as a function of l/r (alternately, the aspect ratio $l/2r$). A 7x field enhancement requires $l/r = 8$ (aspect ratio = 4), while a field enhancement of 20 requires $l/r = 40$ (aspect ratio = 20). This indicates that, throughout the entire FB event, there must be a relatively long and narrow electrically conducting region of near-zero electric field that enhances the background field and drives new streamer growth in a much shorter active streamer region ahead of the long conducting region. This low-field region is not pre-existing but is instead created by the streamer growth itself.

Figure 3 schematically illustrates a physically plausible scenario consistent with the constraints described above. Conceptually, we divide the FB process into three regions: the short and narrow VHF active region in the high electric field of 2.0 E_k where new streamers grow most strongly, the long conducting region with an aspect ratio

>4, and a trailing region where recombination has removed the conductivity but space charge remains. The length of the conducting region depends on the lifetime of ionization. Assuming that the region is not heated, with a time scale of the three-body attachment process of 1 μs and an FB propagation speed of 3×10^7 m/s, the length of the conducting region is limited to 30 m. This further constrains the width of the conducting region to be about 1.5 ~ 7.5 m to meet the aspect ratio requirement of 4~20. However, if significant heating occurs, the ionization lifetime and therefore the conducting channel can be longer.

Furthermore, although the VHF-UHF emission is dominated by the small, high electric field region ahead of the conducting region, there should also exist streamers expanding laterally to the boundary defined by the critical field of streamer propagation of 0.1 E_k. All these streamer discharges together make up the entire FB process and contribute to the charge moment change in the whole air volume. For the future, an independent measurement of the width of the FB structure would provide valuable insight into the process such as verifying whether it is plausible that FB creates a hot conducting channel, and would help bound the pre-discharge background electric field in the FB lightning initiation region (Cummer, 2020).

These findings suggest several more questions that may merit investigation. This electric field of 2.0 E_k inside the region of active streamer growth is capable of driving significant high energy electron acceleration. The *e*-folding runaway electron avalanche length for a field of 2.0 E_k is only about 3 m at 8 ~ 9 km altitude (Dwyer, 2012), although it remains uncertain how long the active streamer region is or, equivalently, how long this high field persists at a fixed location. For a typical observed FB velocity of 3×10^7 m/s, the field would persist for only 0.1 μs if the high field region is 3 m long. Additionally, having confirmed that growing streamers are almost certainly the source of VHF radiation in FB, it is reasonable to ask how the overall FB velocity (~3×10^7 m/s) can exceed the typical velocity of the component streamers (10^6–10^7 m/s, Liu et al., 2004). This strongly indicates that photoionization helps initiate new streamers significantly ahead of the currently propagating streamers, enabling the velocity of the propagating streamer zone to exceed the velocity of individual streamers.

4. Summary

The electric field inside the VHF-UHF producing FB regions during lightning initiation is an important quantity for understanding the internal physics of this process. Here we indirectly measure that electric field by measuring the VHF-UHF radio spectrum produced by the FB process. The underlying physics of this remote sensing approach is that this electric field controls the growth rate of streamers, and a system of streamers with certain growth rate generates a radio spectrum with a measurable cutoff frequency that depends on the streamer growth rate (Kosar et al., 2012; Liu et al., 2019; Liu & Pasko, 2004; Shi et al., 2016). A single sensor broadband (1−750 MHz) measurement system that has been carefully calibrated is thus used to record the signals and spectra of FB processes. We analyzed 4 FB cases and found that they all exhibit spectral shapes entirely consistent with the streamer theory, confirming that the FB consists of a system of streamers. The −10 dB cutoff frequency for the mean spectrum of these FB events is found to be 430 MHz, which corresponds to a streamer growth region electric field of 2.0 E_k. This field is at least 7 times larger than typical large-scale pre-discharge background fields expected from previous work. This level of field enhancement requires that the streamers are being produced at the tip of a narrow (aspect ratio >4 and perhaps as large as 20) and electrically conducting region that itself was produced by the prior streamers. Looking forward, these measurements provide new insight on the immediate environment and dynamics of streamers and overall morphology of the FB process, and are an example of how detailed information about the structure of streamers and lightning can be inferred from a relatively simple radio spectrum measurement.

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Data Availability Statement

The data are available on the data repository website (https://doi.org/10.5281/zenodo.5762780).

References

Bandara, S., Marshall, T., Karunarathne, S., & Stolzenburg, M. (2020). Electric field change and VHF waveforms of positive narrow bipolar events in Mississippi thunderstorms. *Atmospheric Research*, *243*, 105000. https://doi.org/10.1016/j.atmosres.2020.105000

Bazelyan, E. M., & Raizer, Y. P. (1998). *Spark discharge*. CRC press.

Cummer, S. A. (2020). Indirectly measured ambient electric fields for lightning initiation in fast breakdown regions. *Geophysical Research Letters*, *47*(4), e2019GL086089. https://doi.org/10.1029/2019gl086089

Dwyer, J. R. (2012), The relativistic feedback discharge model of terrestrial gamma ray flashes, *Journal of Geophysical Research-Space Physics*, *117*, 25, https://doi.org/10.1029/2011ja017160

Huang, A., Cummer, S. A., & Pu, Y. J. (2021). Lightning initiation from fast negative breakdown is led by positive polarity dominated streamers. *Geophysical Research Letters*, *48*(8). https://doi.org/10.1029/2020gl091553

Kosar, B. C., Liu, N., & Rassoul, H. K. (2012). Luminosity and propagation characteristics of sprite streamers initiated from small ionospheric disturbances at subbreakdown conditions. *Journal of Geophysical Research: Space Physics*, *117*(A8). https://doi.org/10.1029/2012JA017632

Le Vine, D. M. (1980). Sources of the strongest RF radiation from lightning. *Journal of Geophysical Research: Oceans*, *85*(C7), 4091–4095.

Liu, N., Dwyer, J. R., Tilles, J. N., Stanley, M. A., Krehbiel, P. R., Rison, W., et al. (2019). Understanding the radio spectrum of thunderstorm narrow bipolar events. *Journal of Geophysical Research: Atmospheres*, *124* (17–18), 10134–10153. https://doi.org/10.1029/2019jd030439

Liu, N., & Pasko, V. P. (2004). Effects of photoionization on propagation and branching of positive and negative streamers in sprites. *Journal of Geophysical Research: Space Physics*, *109*(A4), 17. https://doi.org/10.1029/2003ja010064

Luque, A., & Ebert, U. (2014). Growing discharge trees with self-consistent charge transport: The collective dynamics of streamers. *New Journal of Physics*, *16*(1), 013039.

Lyu, F. C., Cummer, S. A., Qin, Z. L., & Chen, M. L. (2019). Lightning initiation processes imaged with very high frequency broadband interferometry. *Journal of Geophysical Research: Atmospheres*, *124*(6), 2994–3004. https://doi.org/10.1029/2018jd029817

Pasko, V. P., U. S. Inan, and T. F. Bell, (1998), Spatial structure of sprites, *Geophysical Research Letters*, *25*(12), 2123-2126, https://doi.org/10.1029/98gl01242

Pu, Y. J., & Cummer, S. A. (2019). Needles and lightning leader dynamics imaged with 100–200 MHz broadband VHF interferometry. *Geophysical Research Letters*, *46*(22), 13556–13563. https://doi.org/10.1029/2019gl085635

Pu, Y. J., Cummer, S. A., & Liu, N. Y. (2021). VHF radio spectrum of a positive leader and implications for electric fields. *Geophysical Research Letters*, *48*(11). https://doi.org/10.1029/2021gl093145

Rison, W., Krehbiel, P. R., Stock, M. G., Edens, H. E., Shao, X. M., Thomas, R. J., et al. (2016). Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms. *Nature Communications*, *7*, 12. https://doi.org/10.1038/ncomms10721

Shi, F., Liu, N. Y., & Rassoul, H. K. (2016). Properties of relatively long streamers initiated from an isolated hydrometeor. *Journal of Geophysical Research: Atmospheres*, *121*(12), 7284–7295. https://doi.org/10.1002/2015jd024580

Smith, D., Shao, X., Holden, D., Rhodes, C., Brook, M., Krehbiel, P., et al. (1999). A distinct class of isolated intracloud lightning discharges and their associated radio emissions. *Journal of Geophysical Research: Atmospheres*, *104*(D4), 4189–4212.

Stolzenburg, M., Marshall, T. C., Rust, W. D., Bruning, E., MacGorman, D. R., & Hamlin, T. (2007). Electric field values observed near lightning flash initiations. *Geophysical Research Letters*, *34*(4), 7. https://doi.org/10.1029/2006gl028777

Tilles, J. N., Liu, N. Y., Stanley, M. A., Krehbiel, P. R., Rison, W., Stock, M. G., et al. (2019). Fast negative breakdown in thunderstorms. *Nature Communications*, *10*, 1648. https://doi.org/10.1038/s41467-019-09621-z