X-ray Emission from Thunderstorms and Lightning

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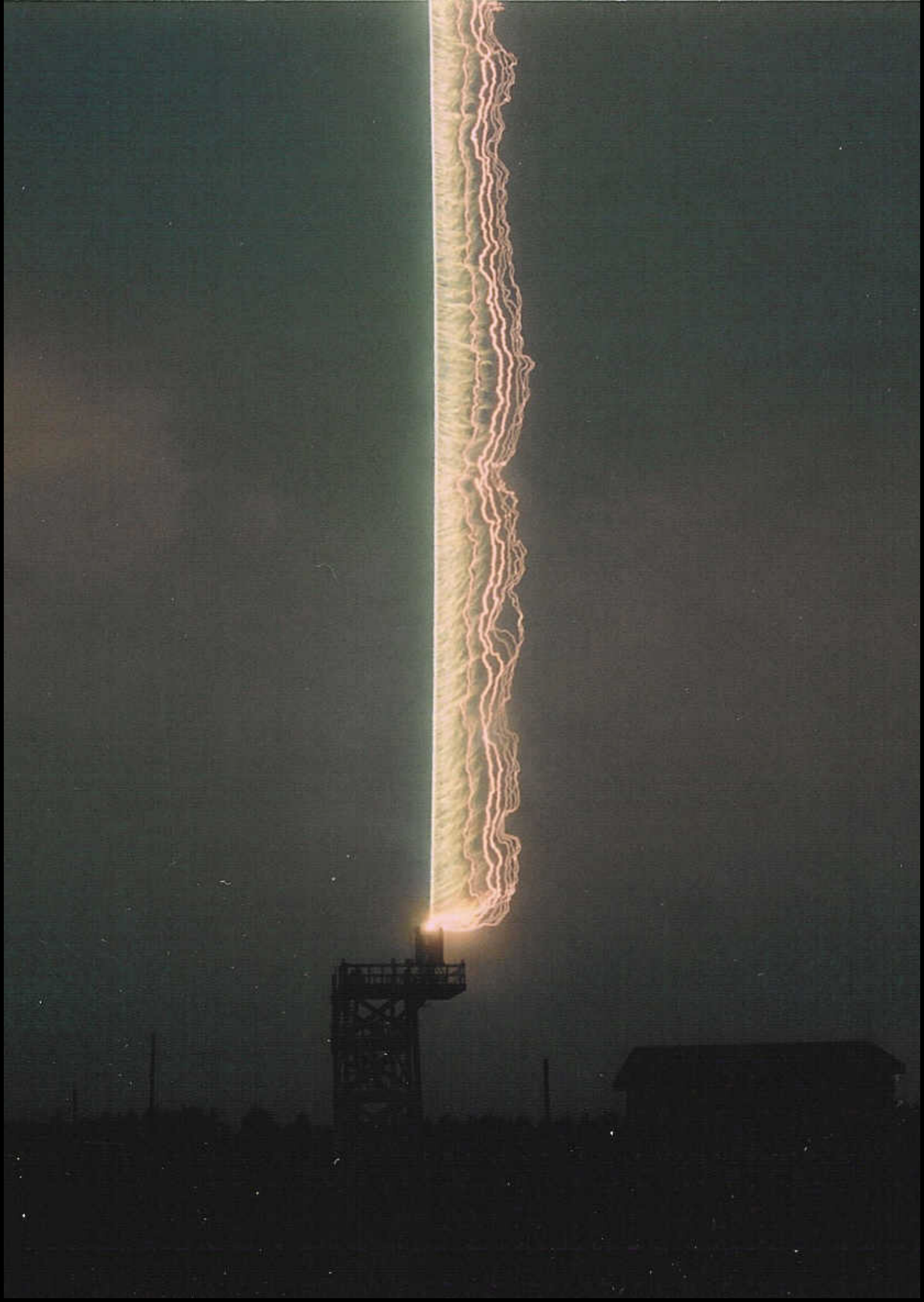


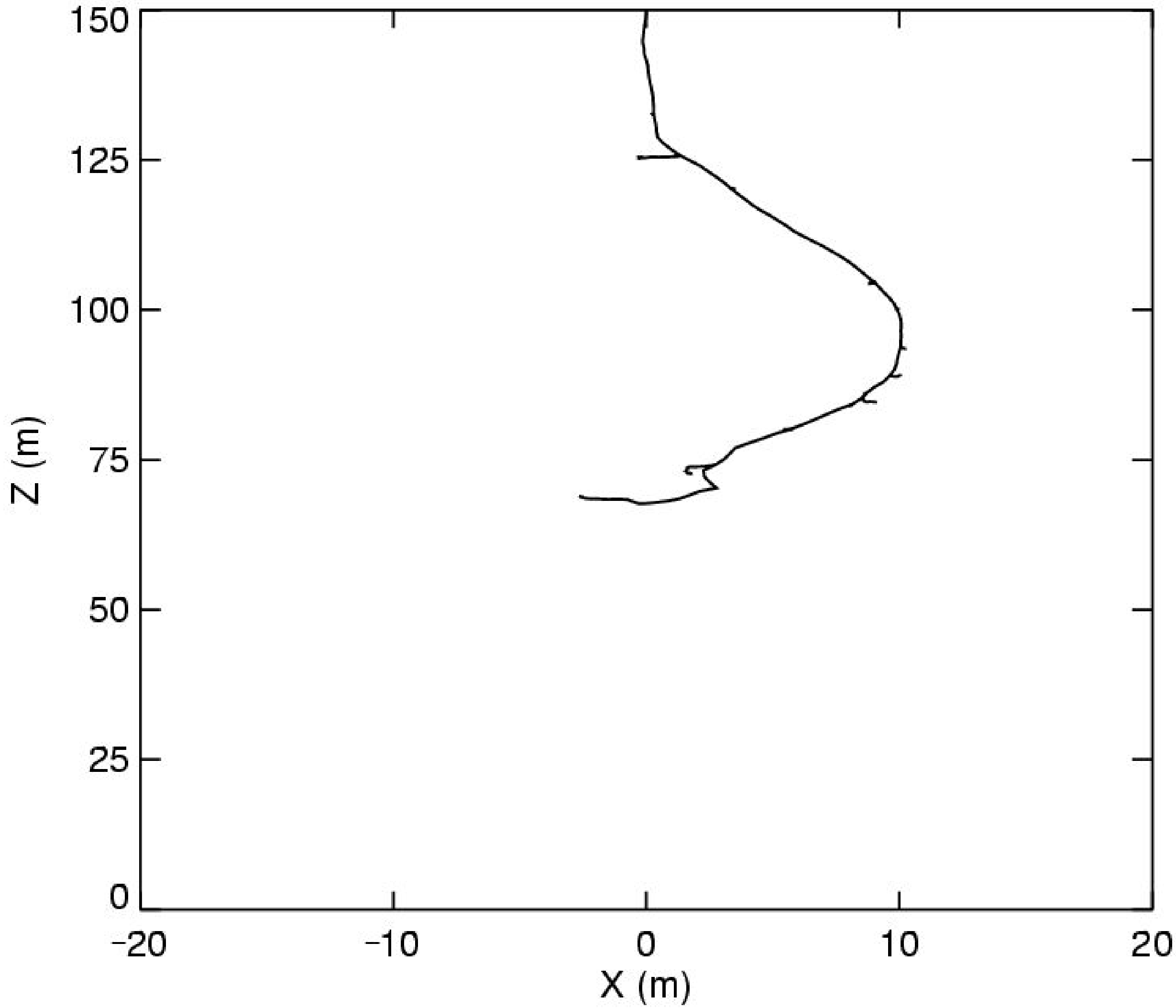
Despite its familiarity, lightning remains a mystery

- Big question #1: What microphysical processes are responsible for thunderstorm electrification?
- Big question #2: How does lightning get started with the relatively low electric field strengths inside thunderstorms?
- Big question #3: How does lightning travel through tens of kilometers of air?

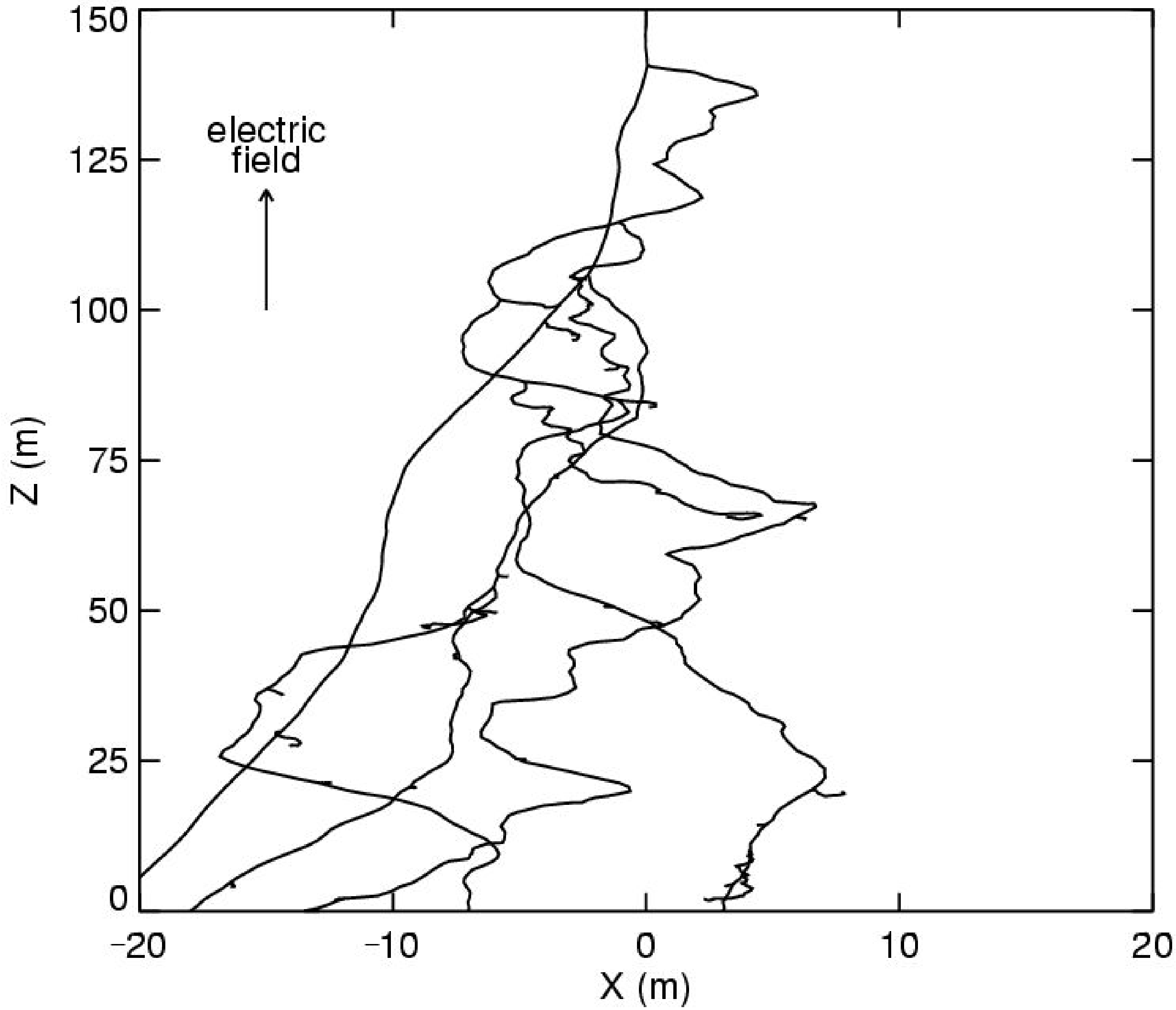
Since we are still struggling to understand how lightning works 250 years after Franklin's kite experiment, perhaps we are missing something important….

Runaway Electrons

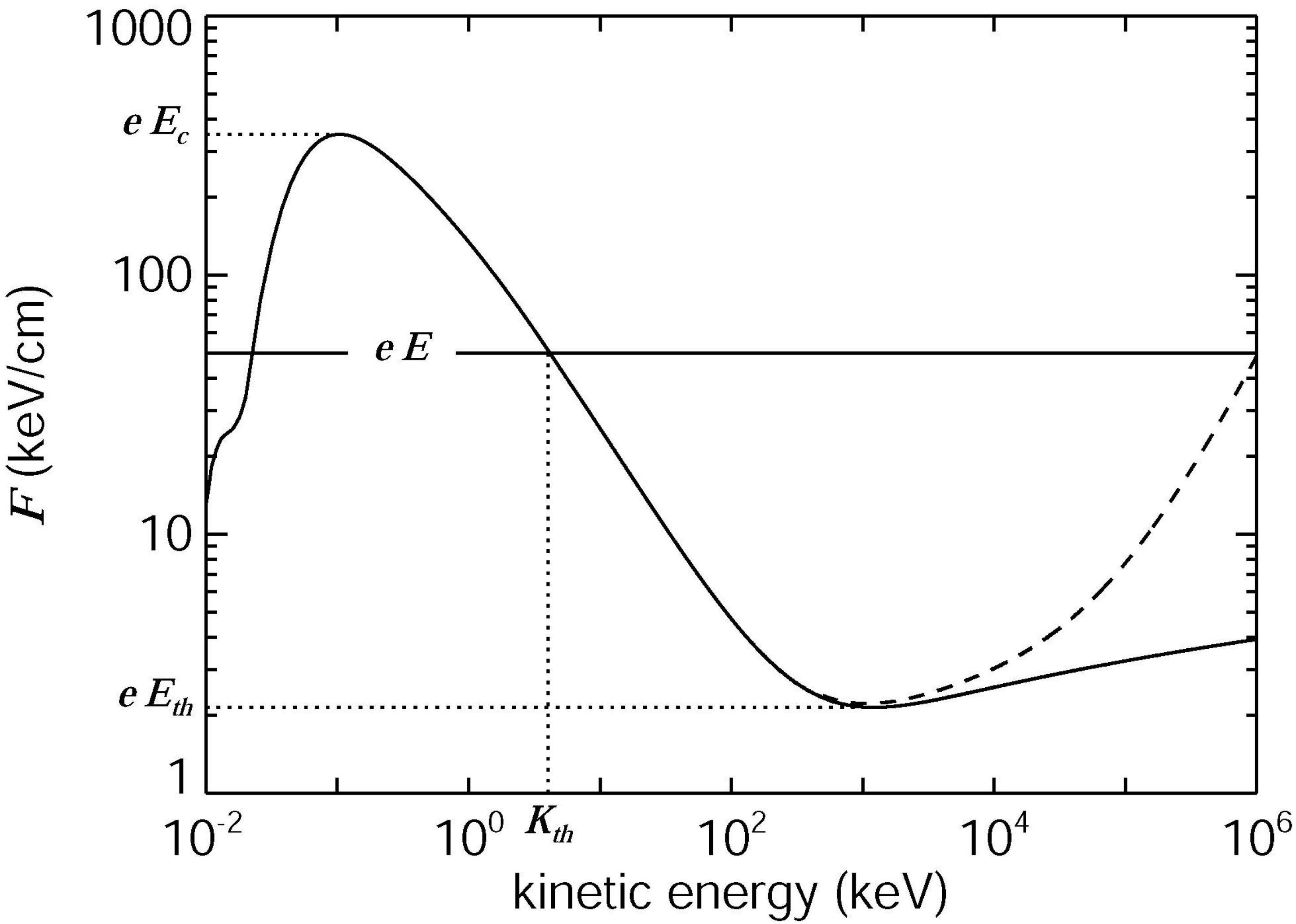
25 MeV electron moving through air at 1 atm



25 MeV electron moving through air at 1 atm in a 3 kV/cm electric field



Energy loss and gain experienced by an electron in air



Extensive air showers trigger lightning?

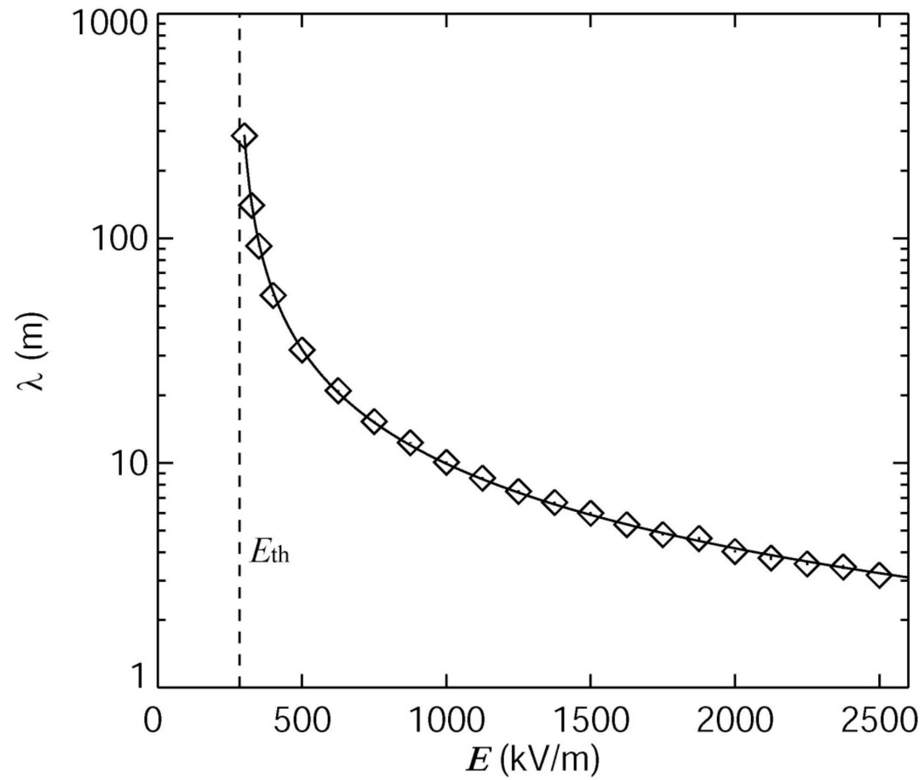
For a typical thunderstorm electric field $\lambda \sim 100$ m.

If the high field region has a depth of 2000 m then $\exp(20) \sim 10^8$ runaway electrons are produced for each energetic seed particle

An extensive air shower with 10^7 particles passing through such a thunderstorm would produce 10^{15} relativistic electrons and many more low energy electrons

Maybe extensive air showers and runaway breakdown initiate lightning

λ = Runaway electron avalanche (e-folding) length

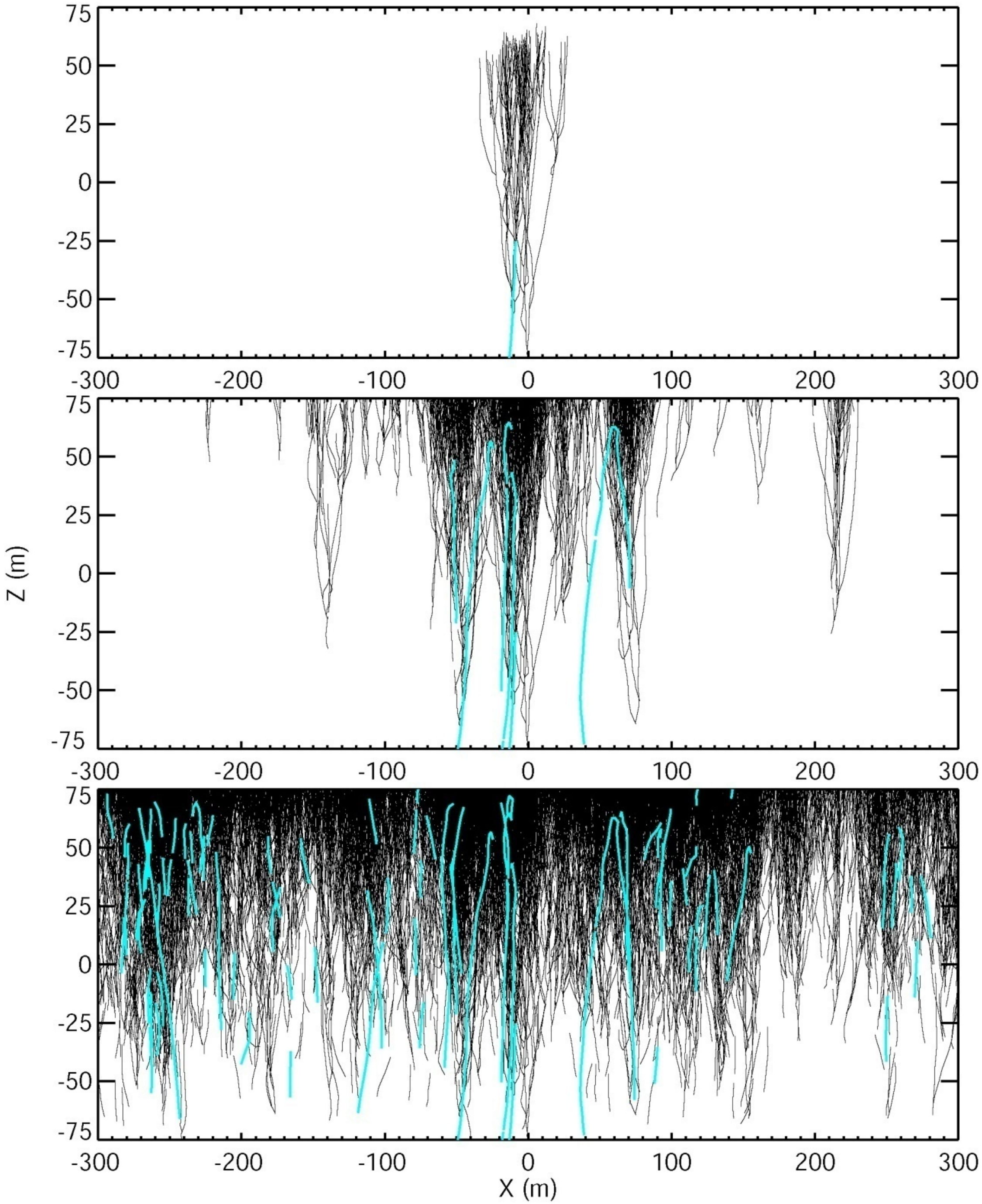


The average energy of runaway electrons is 7 MeV

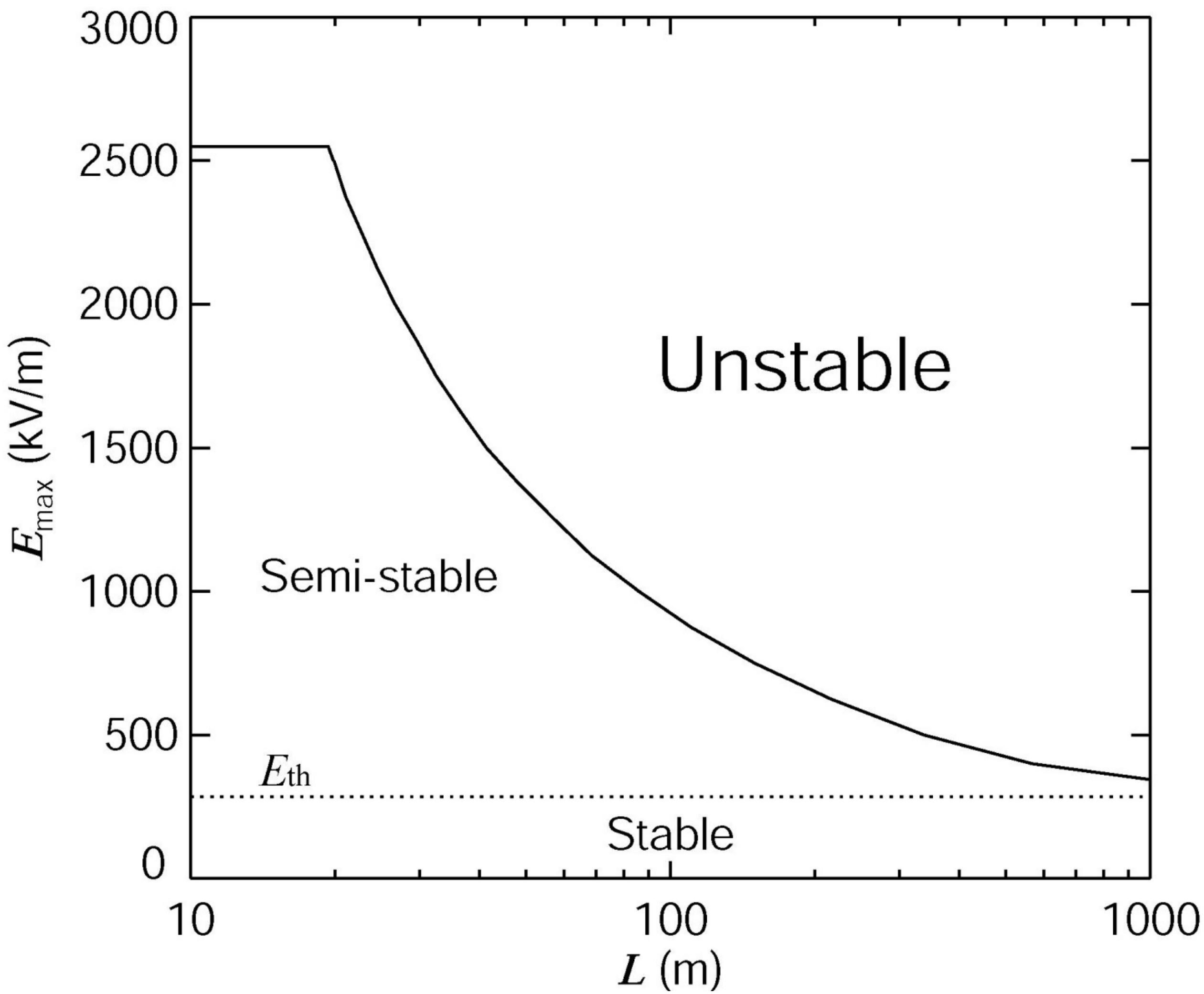
The runaway breakdown threshold electric field E_{th} = 284 kV/m at STP

Relativistic Breakdown due to x-ray and positron feedback.

The central avalanche is due to the injection of a single, 1 MeV seed electron. All the other avalanches are produced by x-ray and positron feedback. The top panel is for times, t < 0.5 μs. The middle panel is for t < 2 μs, and the bottom panel is for t < 10 μs.



Relativistic Breakdown limits the electric field that can be achieved in air and prevent large avalanche multiplication



Does runaway breakdown actually occur?

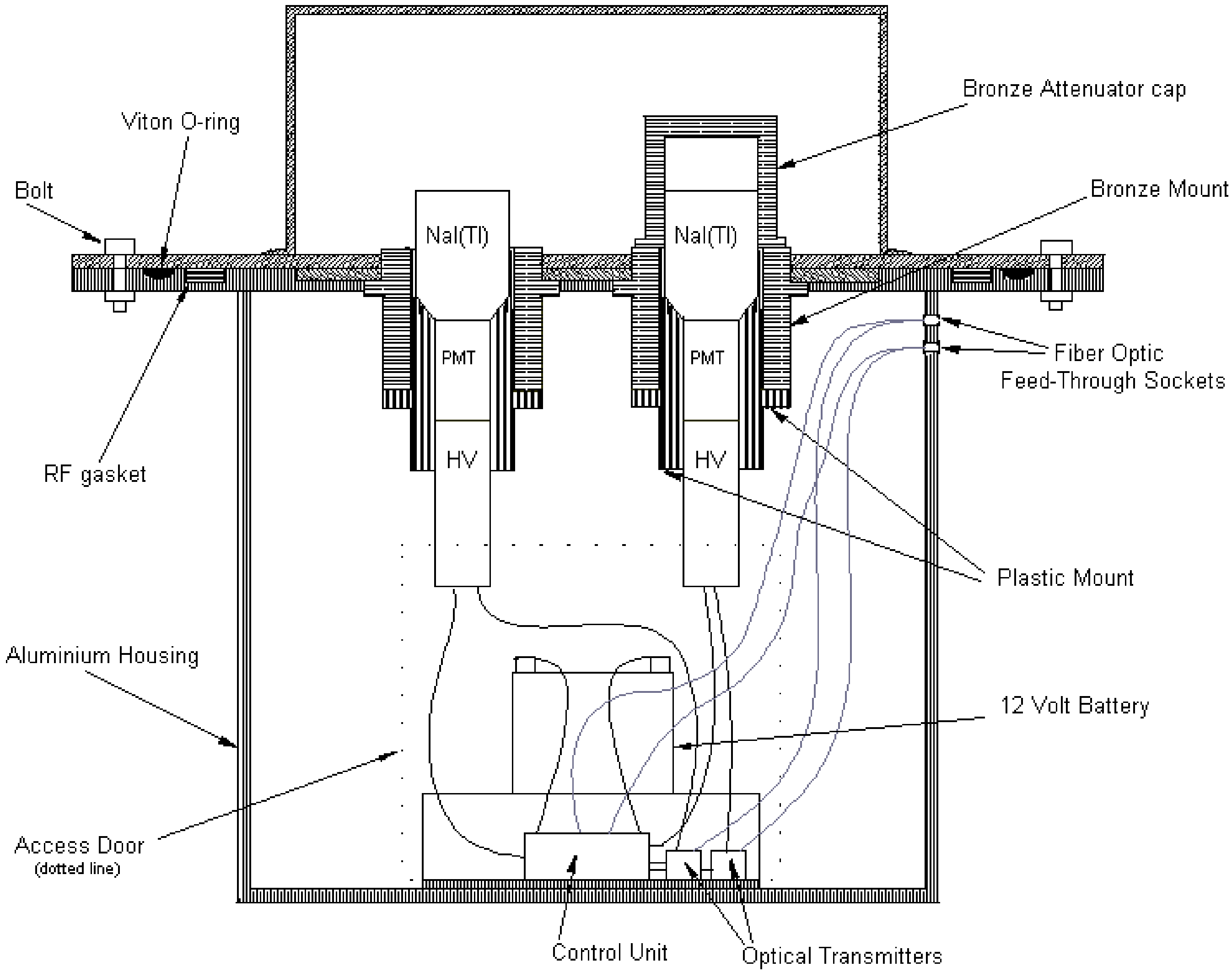
One signature of runaway breakdown is x-ray emission.

Many researchers have searched for such x-rays associated with thunderstorms and lightning.

Experiment	Location	X-rays in thunderstorms?	X-rays in lightning?
Appleton & Bowen (1933)	ground	No	No
Macky (1934)	balloon	No	No
Clay et al. (1952)	ground	Yes	No
Hill (1963)	300 m tower	No	No
McCarthy & Parks (1985)	aircraft	Yes	No
Fishman *et al.* (1994)	space	Yes (sprites?)	No
Moore *et al.* (2001)	mountain (3288 m)	No	Yes

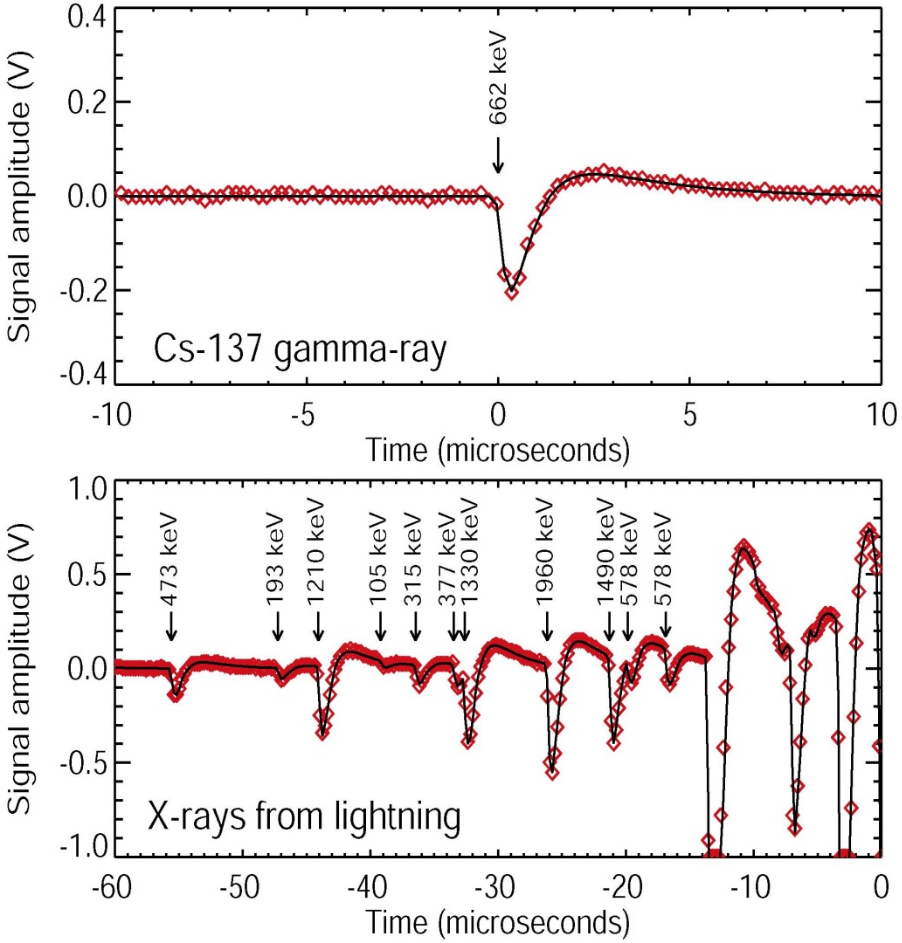
Rocket-triggered lightning

Instrument used to measure x-rays from lightning at the UF/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL

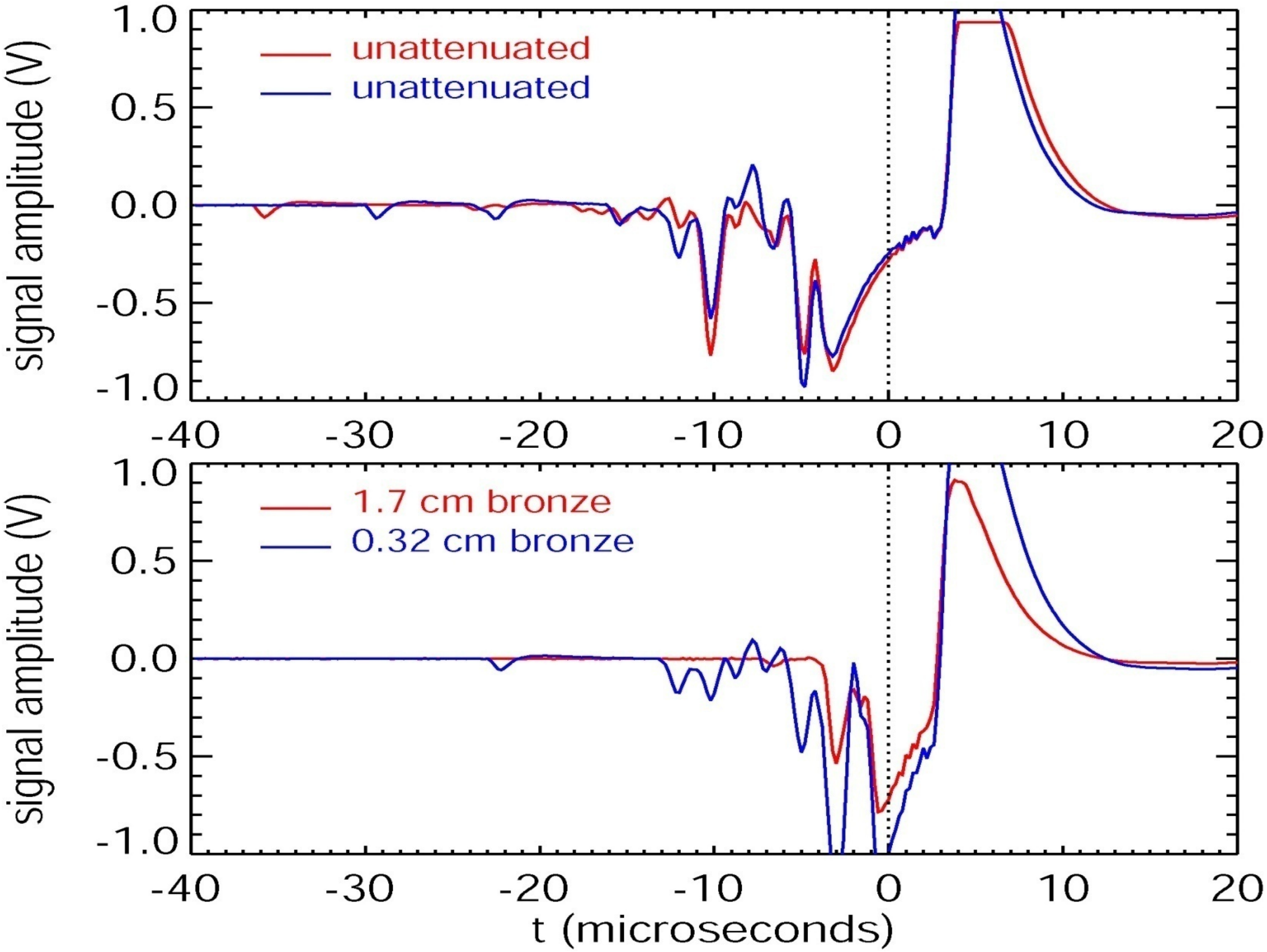


X-ray instruments in front of rocket launch tower used to trigger lightning

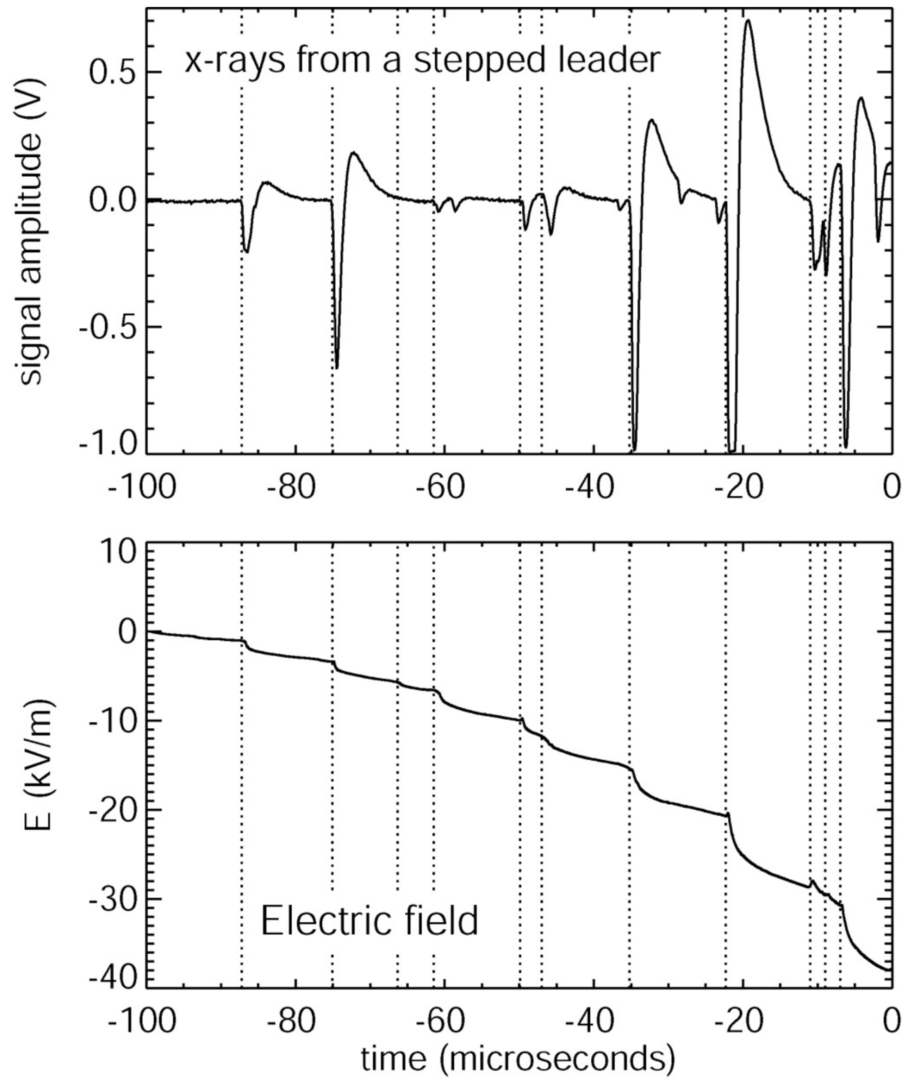
X-rays from rocket-triggered lightning dart leaders



Energy of x-rays from triggered lightning

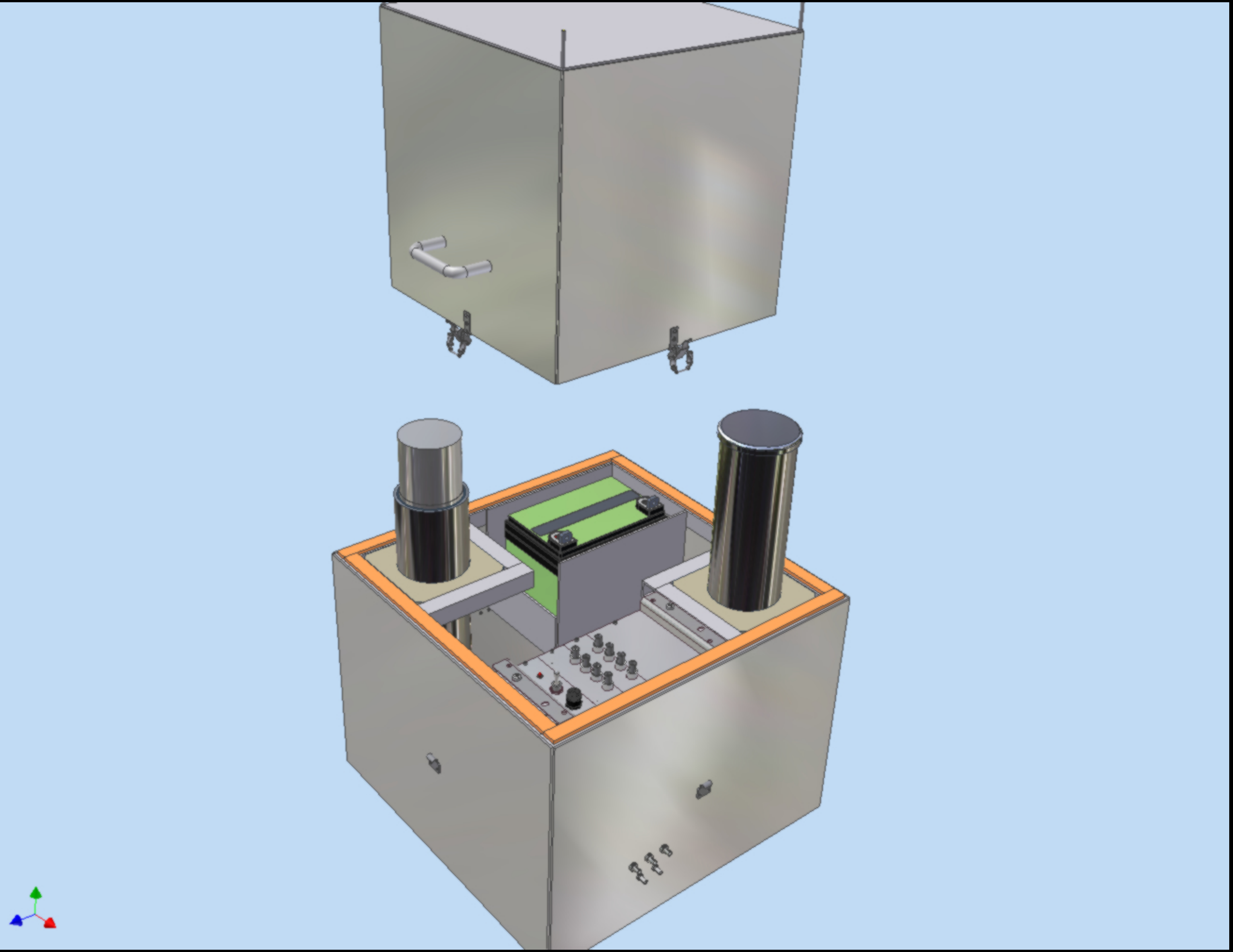


X-rays from natural cloud-to-ground lightning

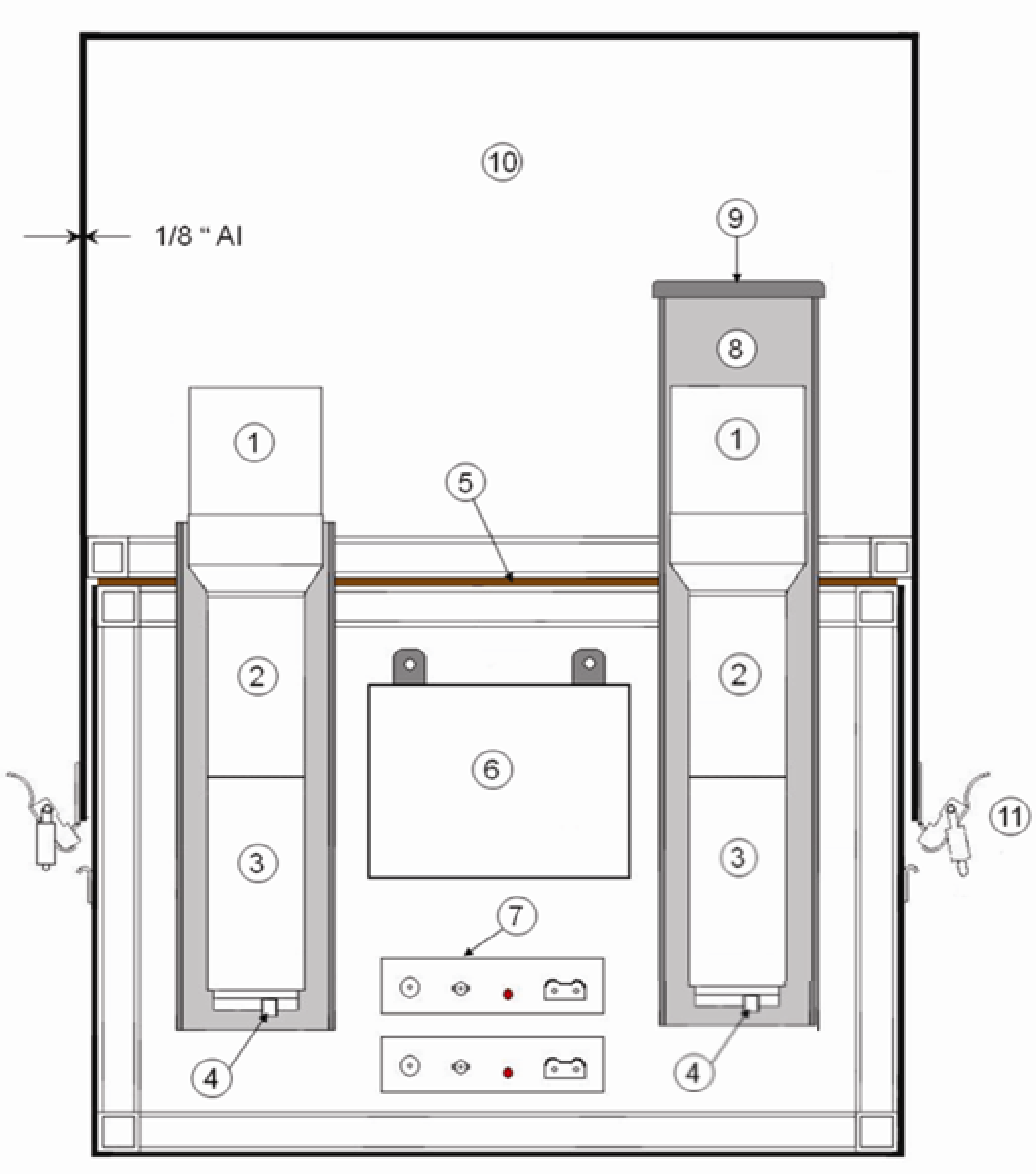


TERA at the UF/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL

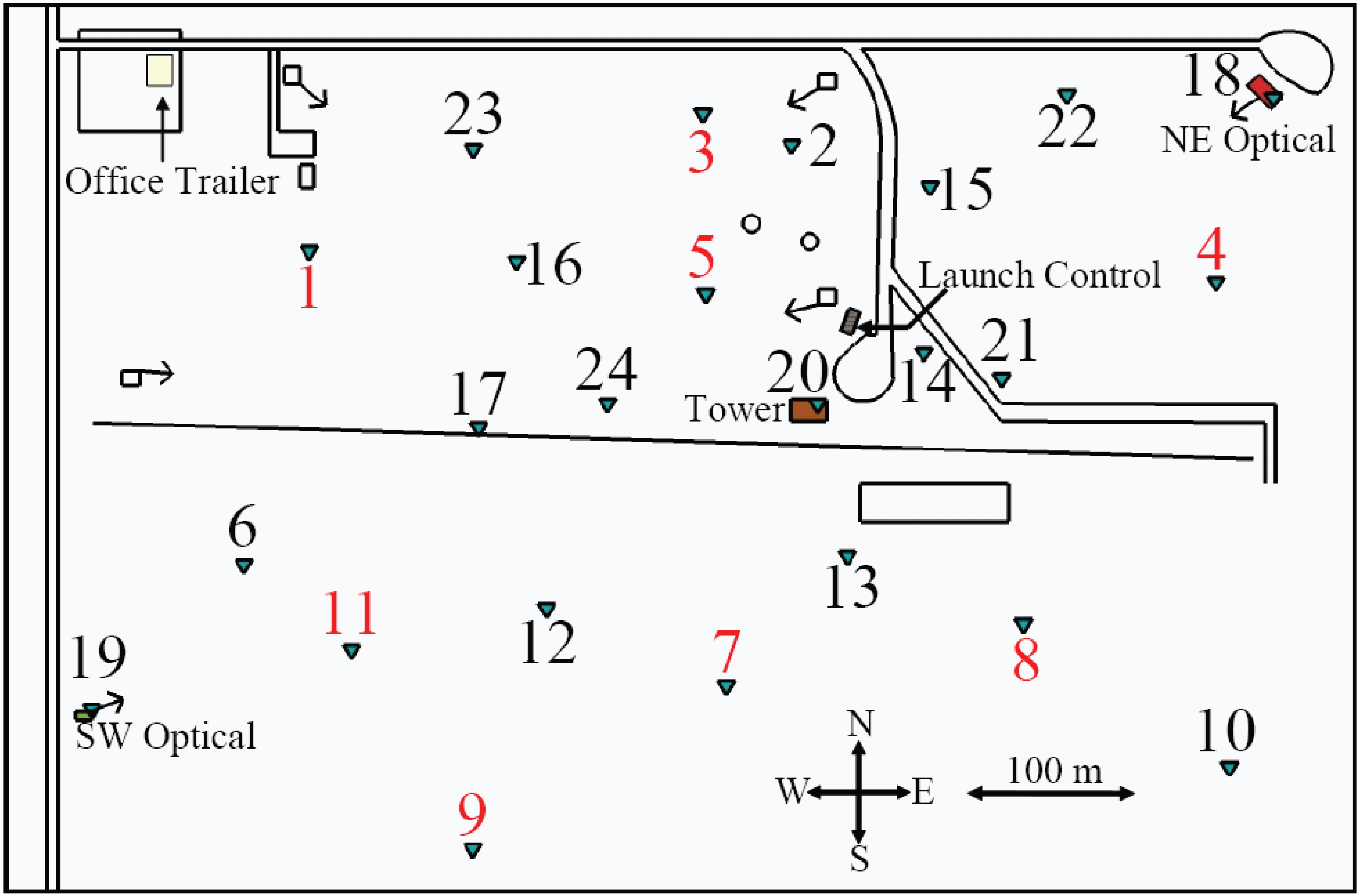
TERA Instrument Design



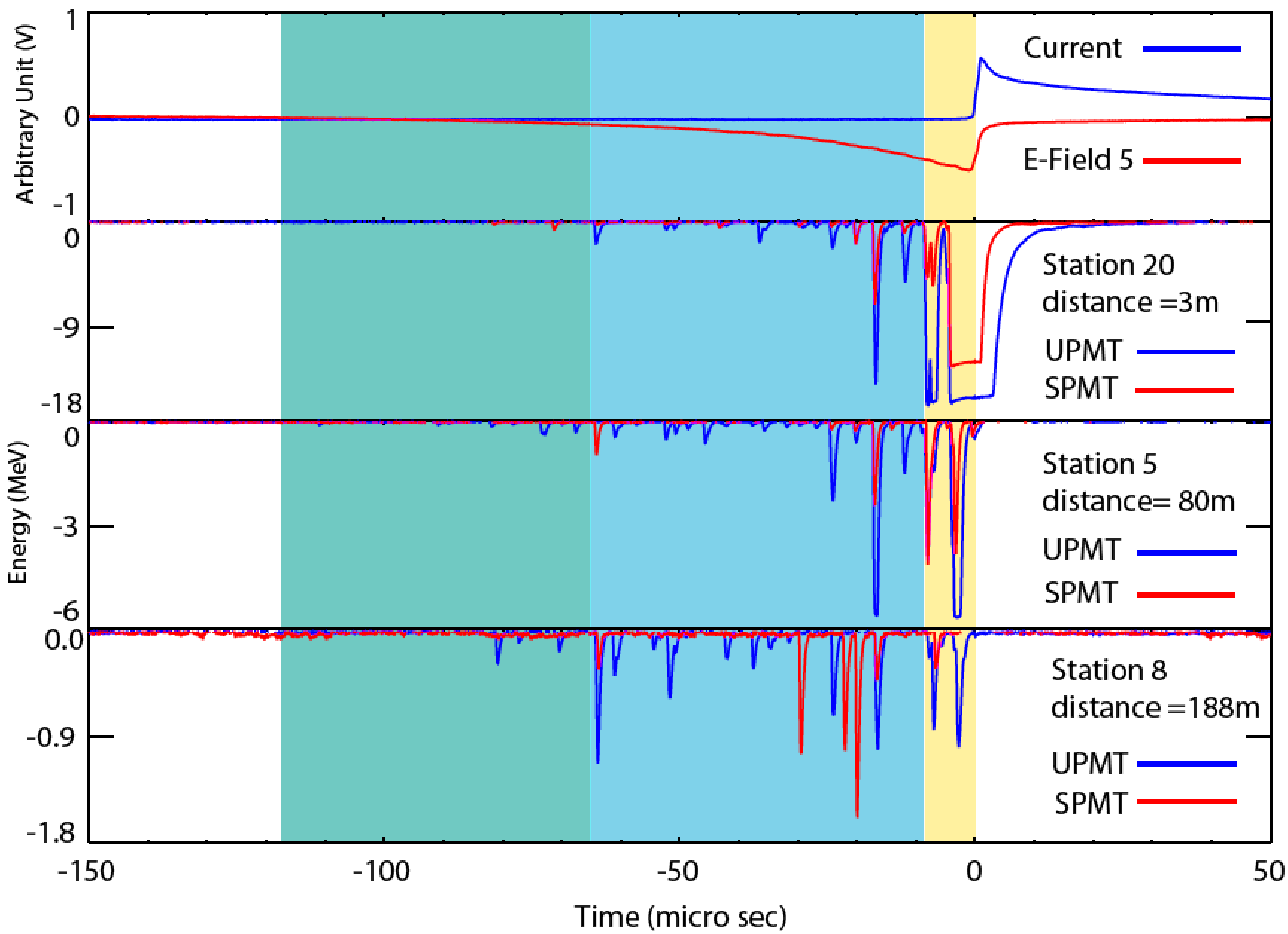
TERA instrument



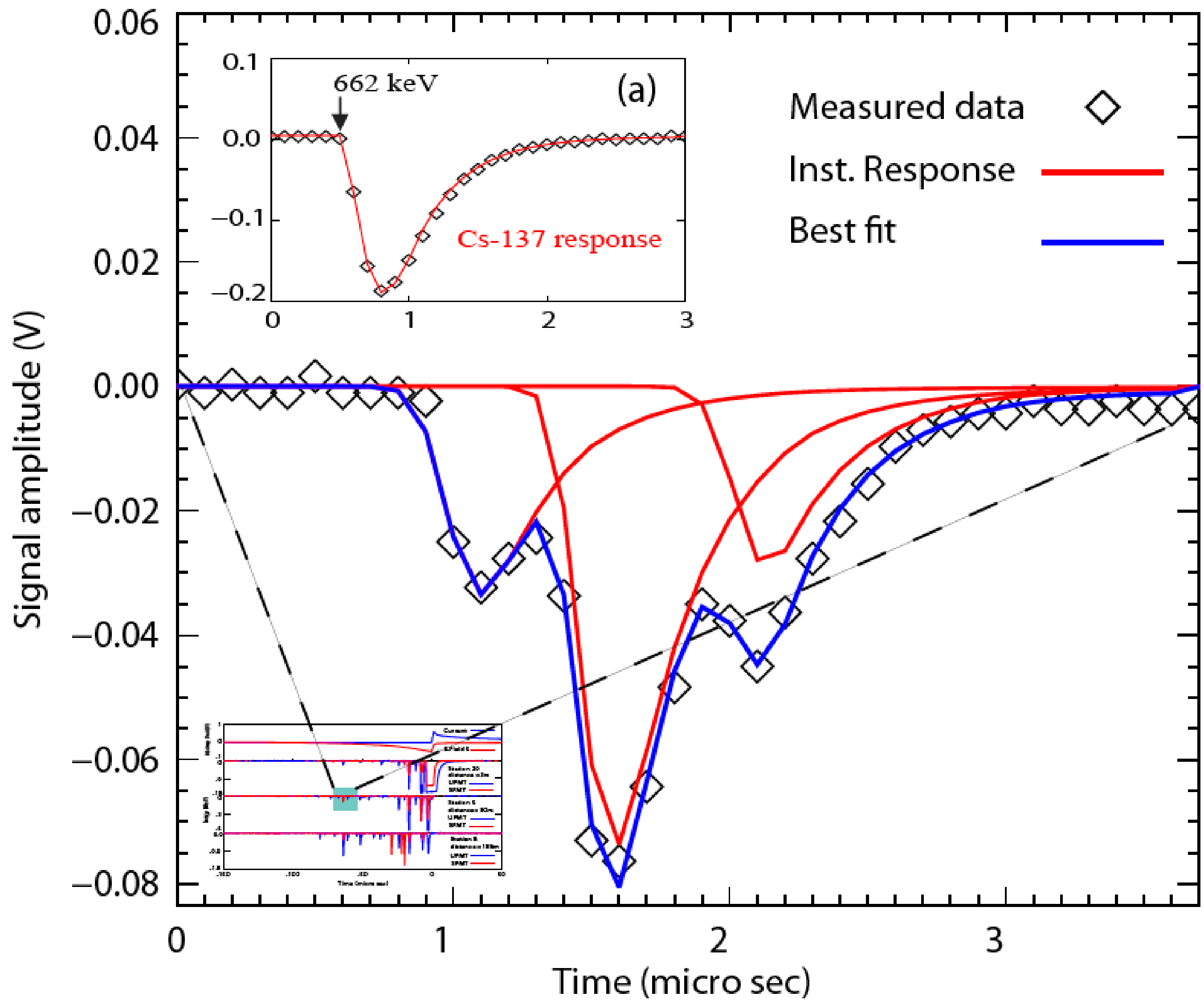
TERA locations



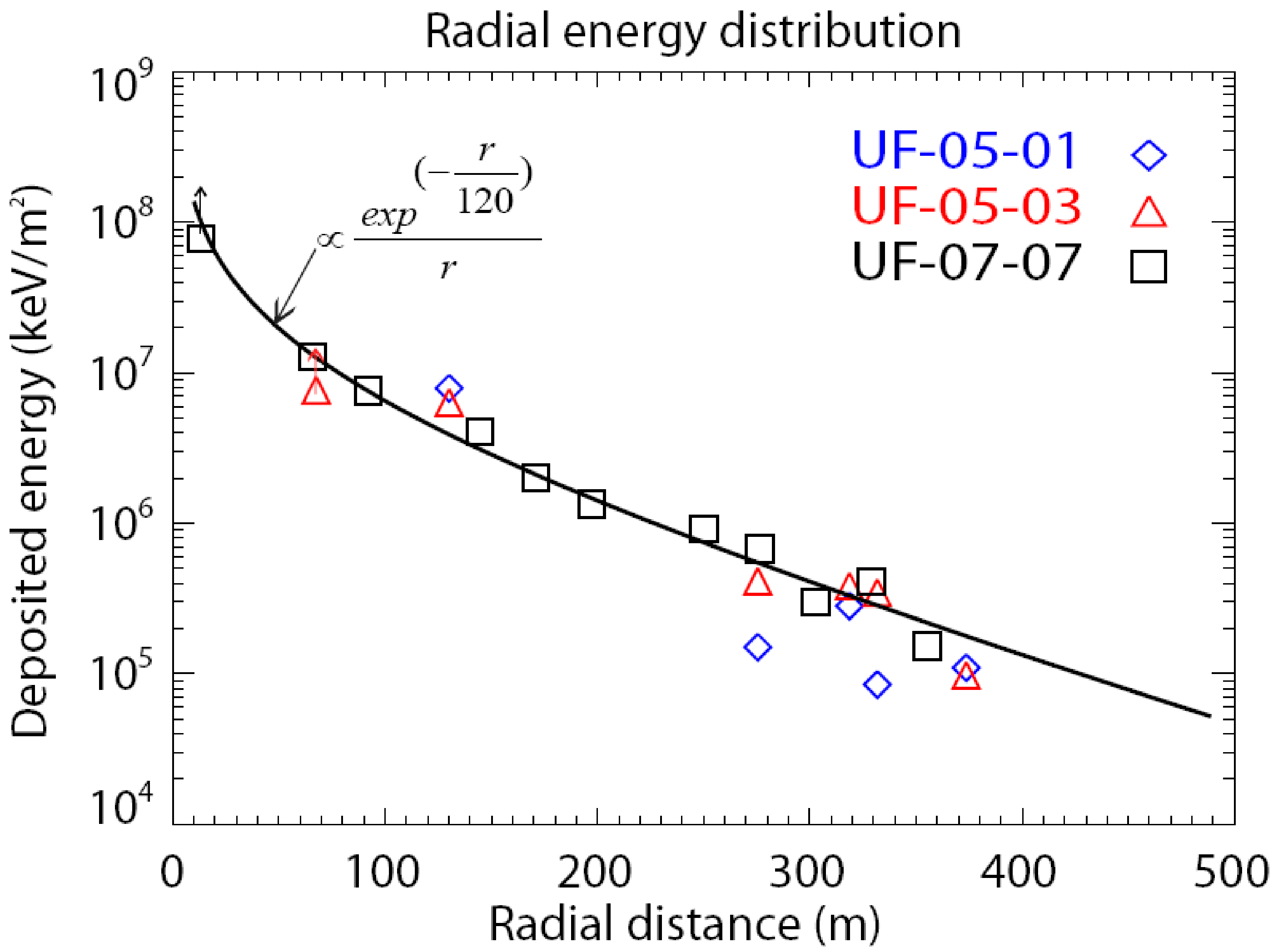
X-rays from triggered lightning using TERA



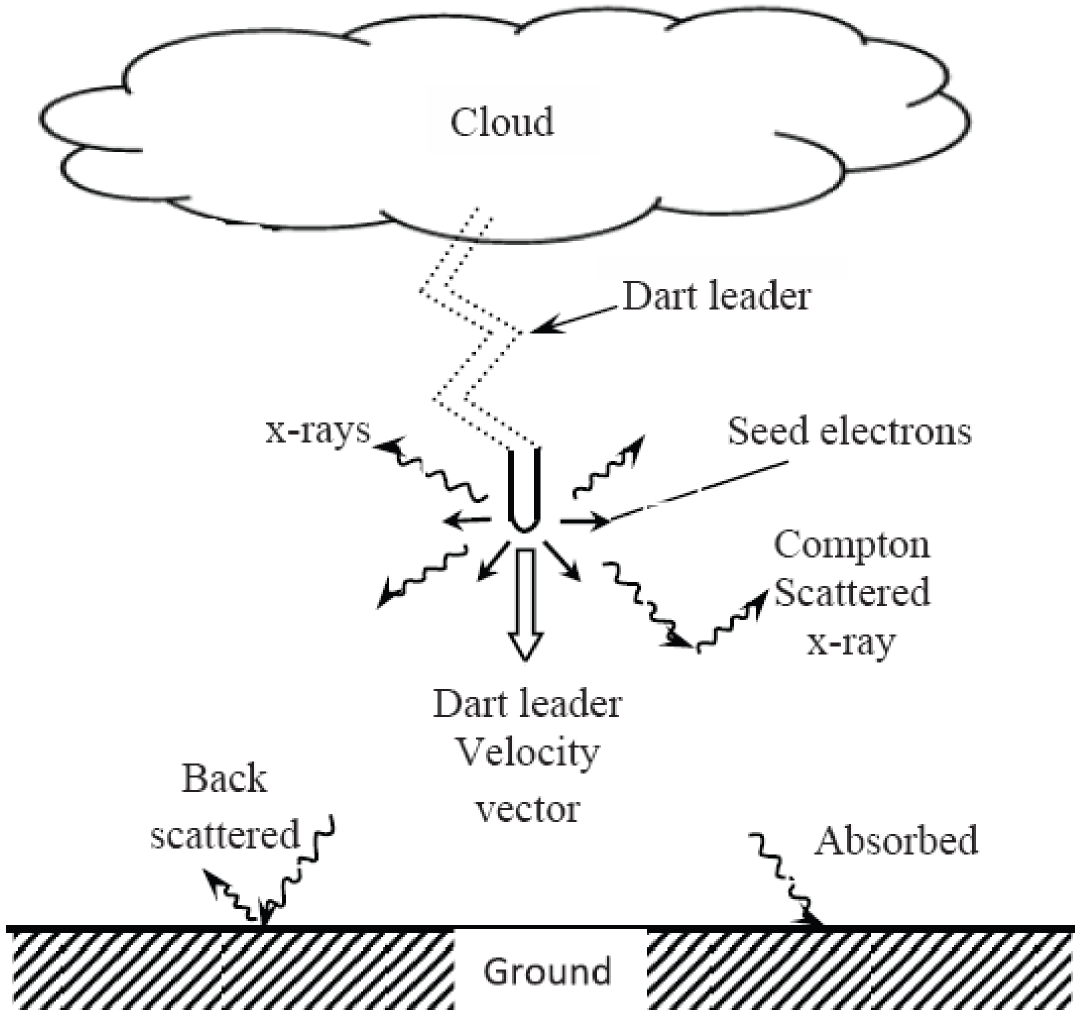
Detector response fits to x-ray pulse from lightning



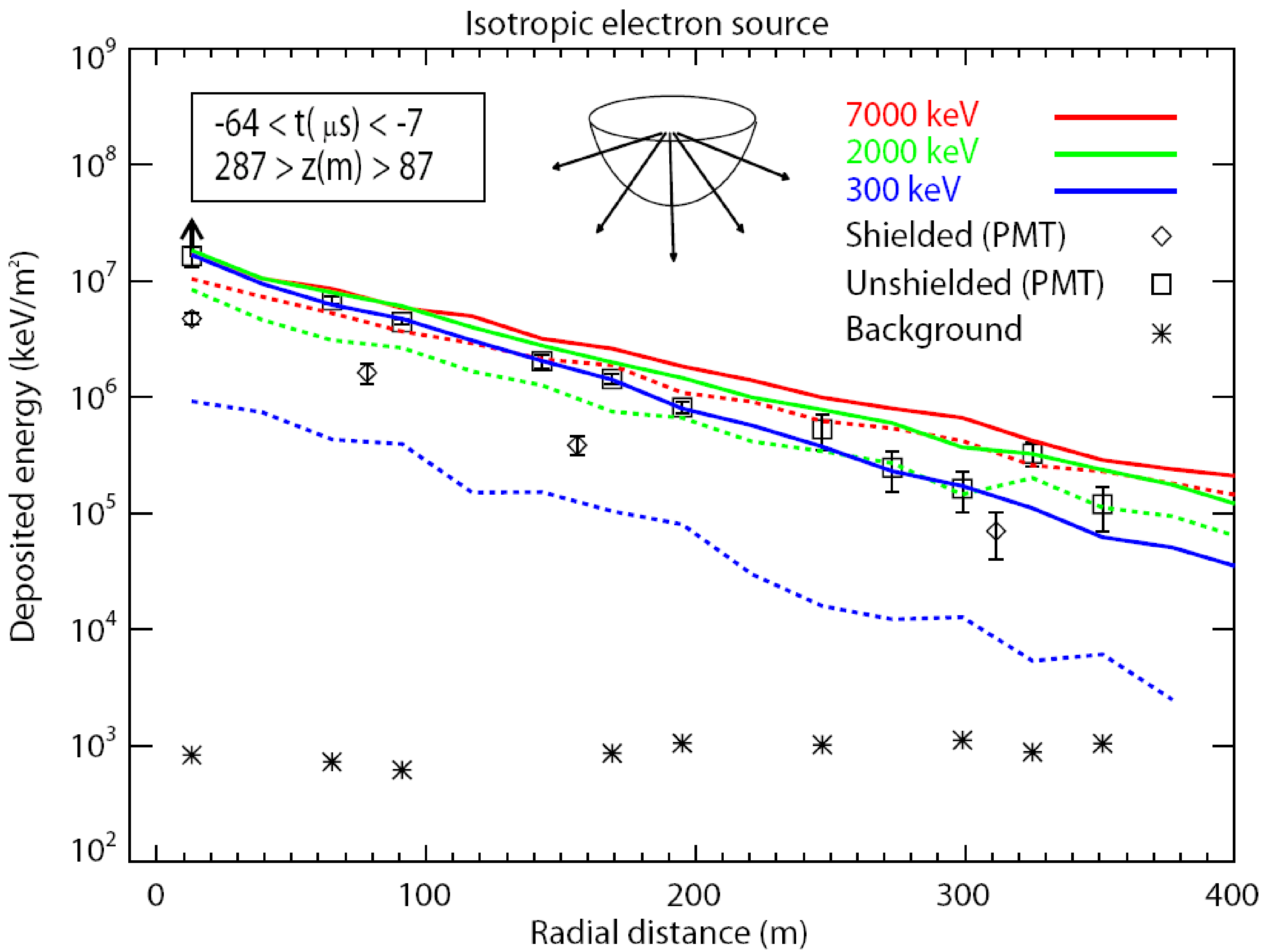
Radial fall-off of the x-rays from the triggered lightning channel



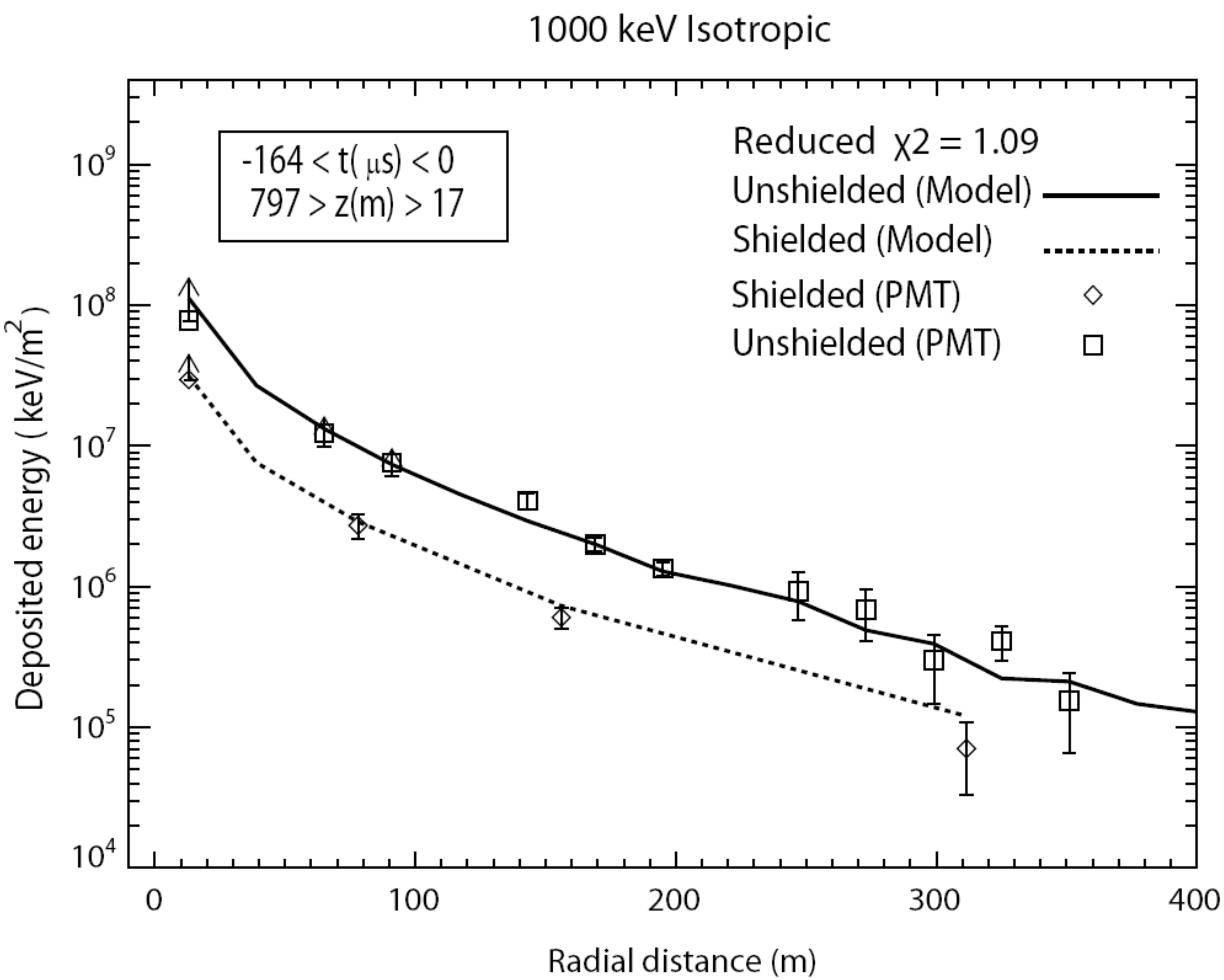
Schematic of Monte Carlo simulation



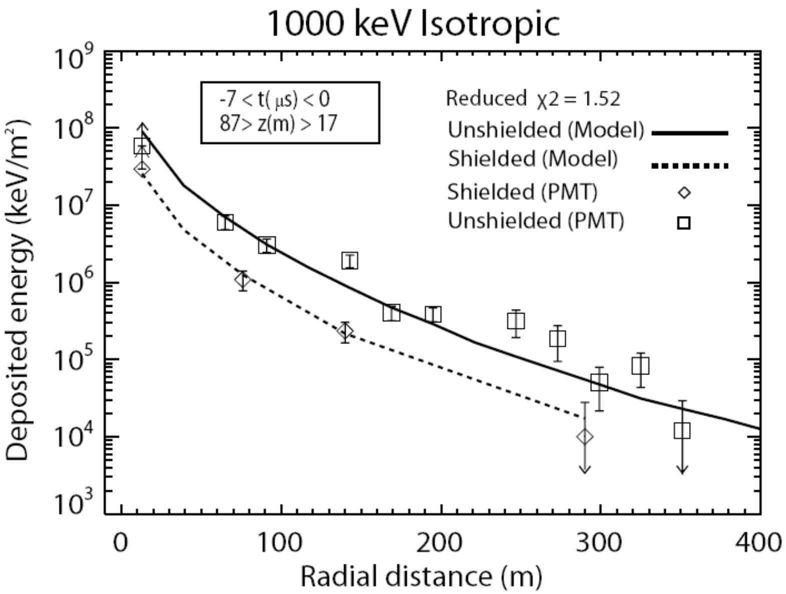
Model fits to x-ray data for different runaway electron energies

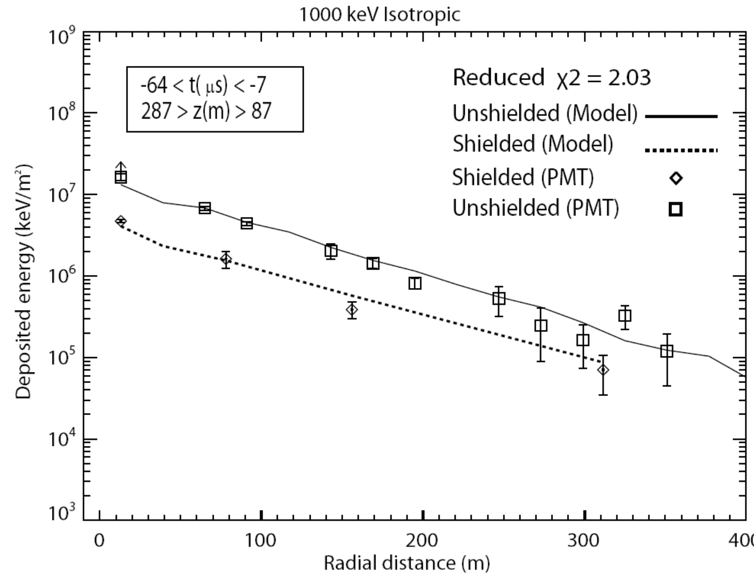


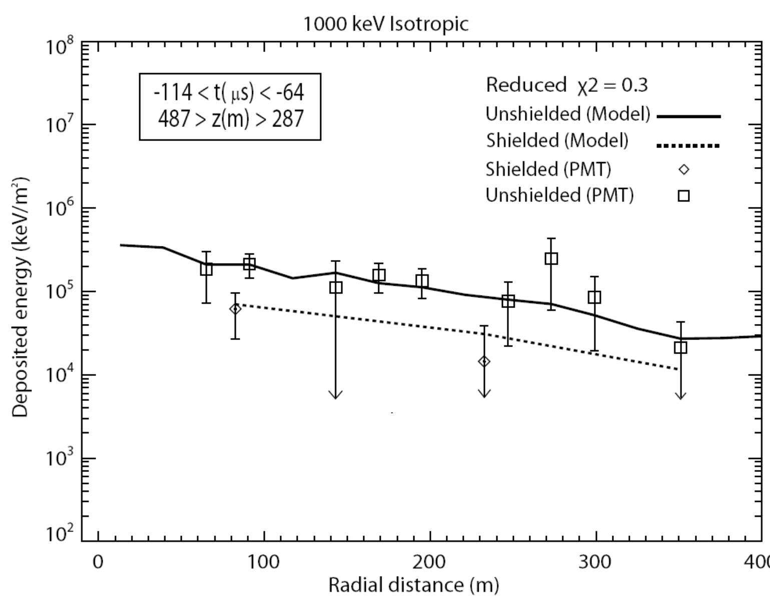
Best model fit to x-ray data



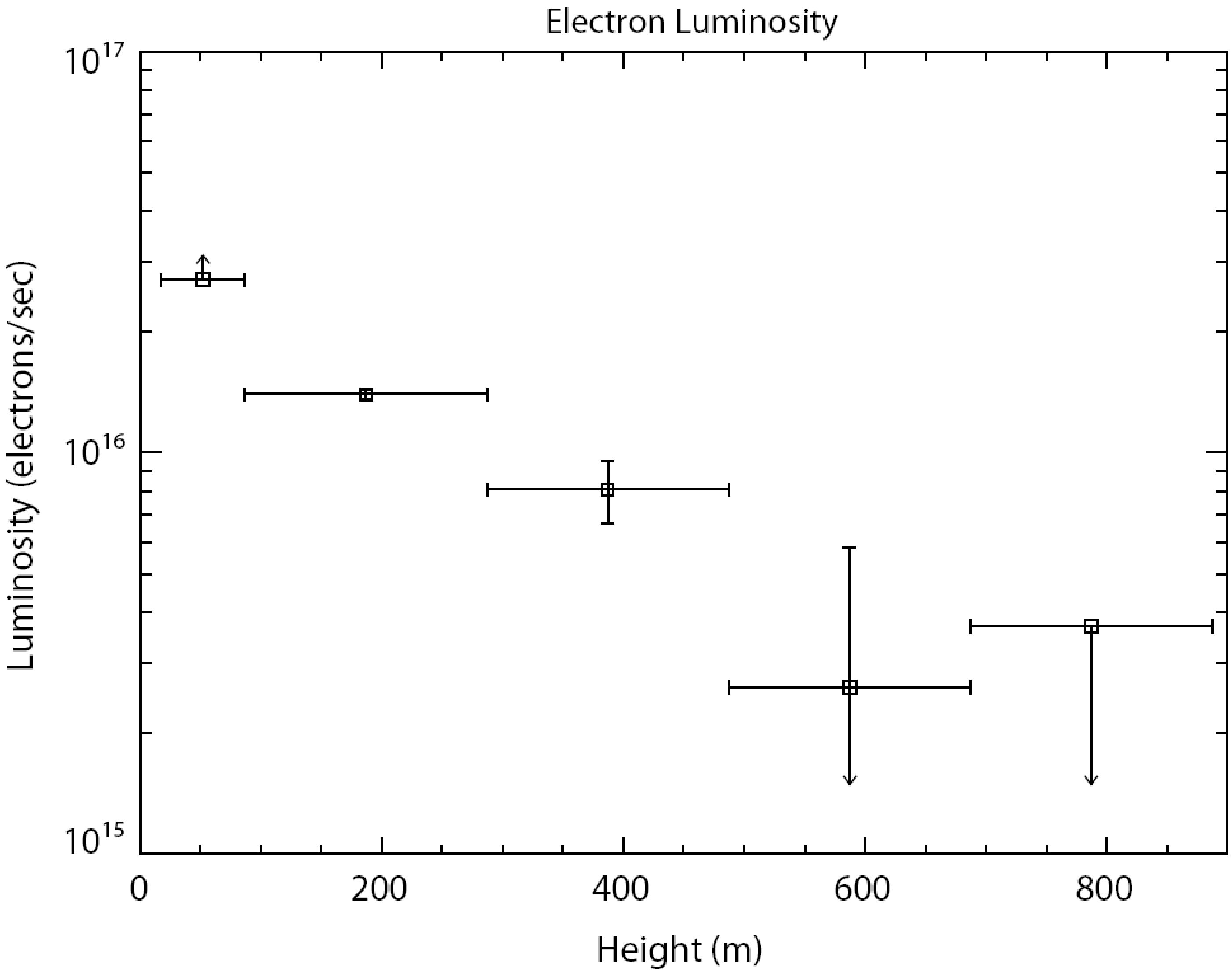
Model fits to x-ray data for different lightning leader altitudes



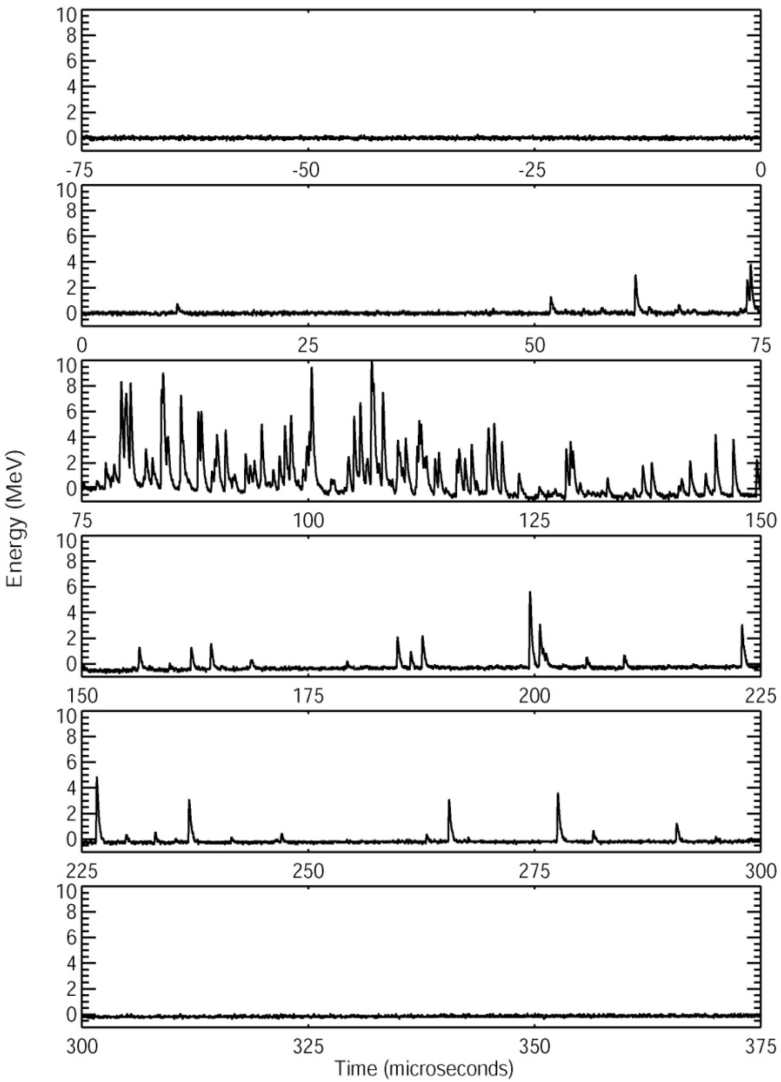




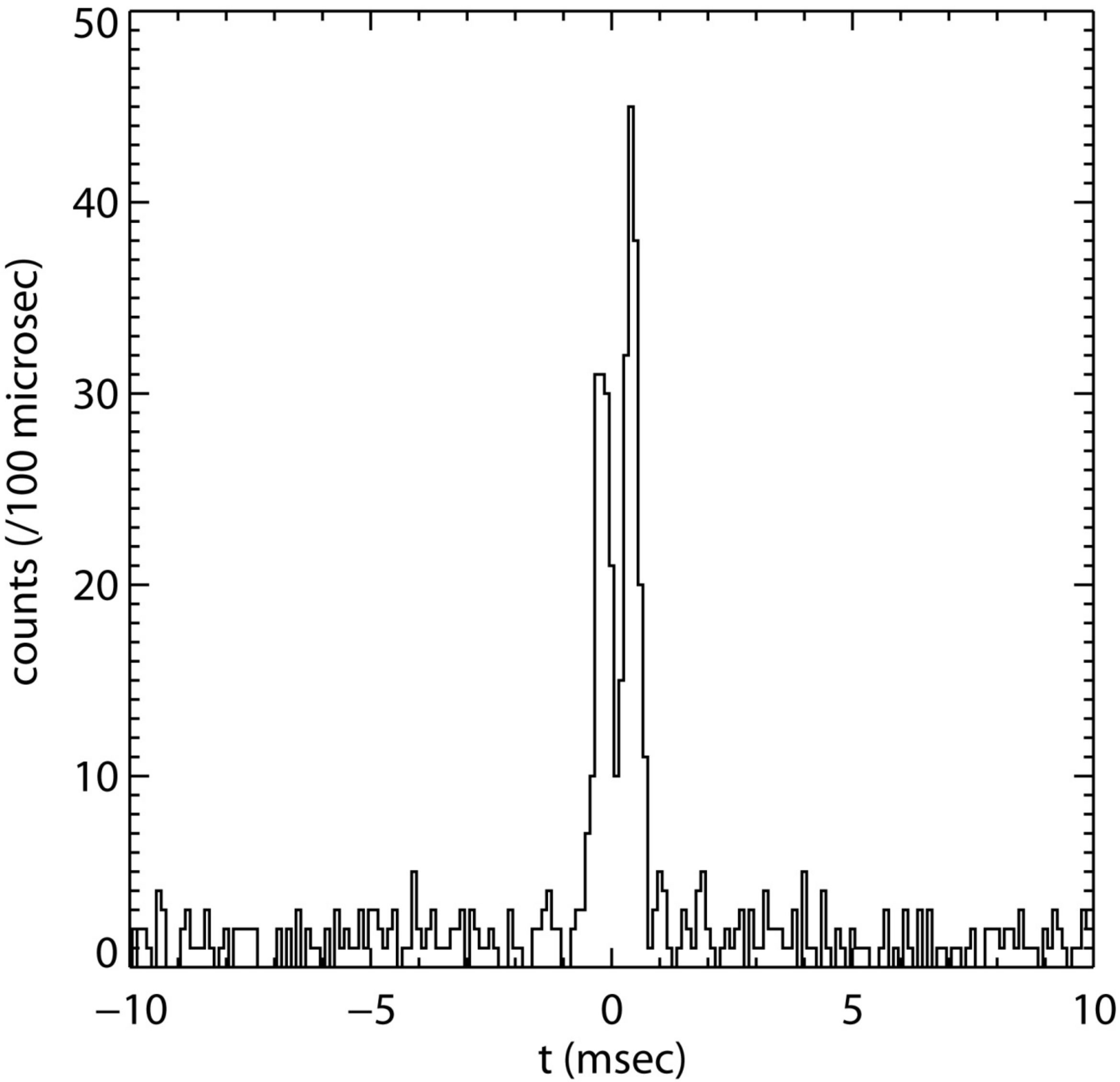
Energetic electron luminosity from lightning (electrons/sec)



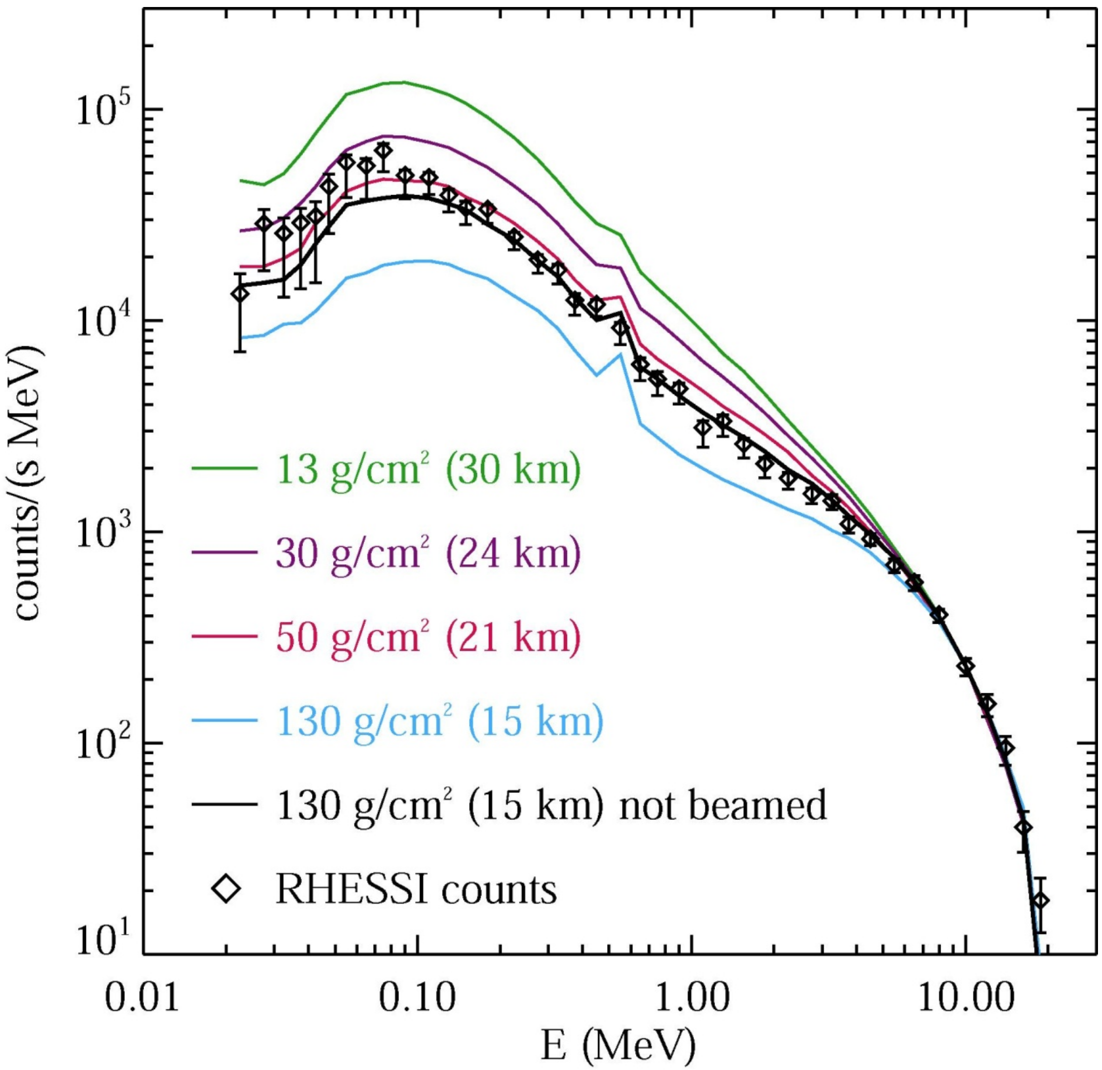
A ground level gamma-ray flash observed during the initial stage of rocket-triggered lightning



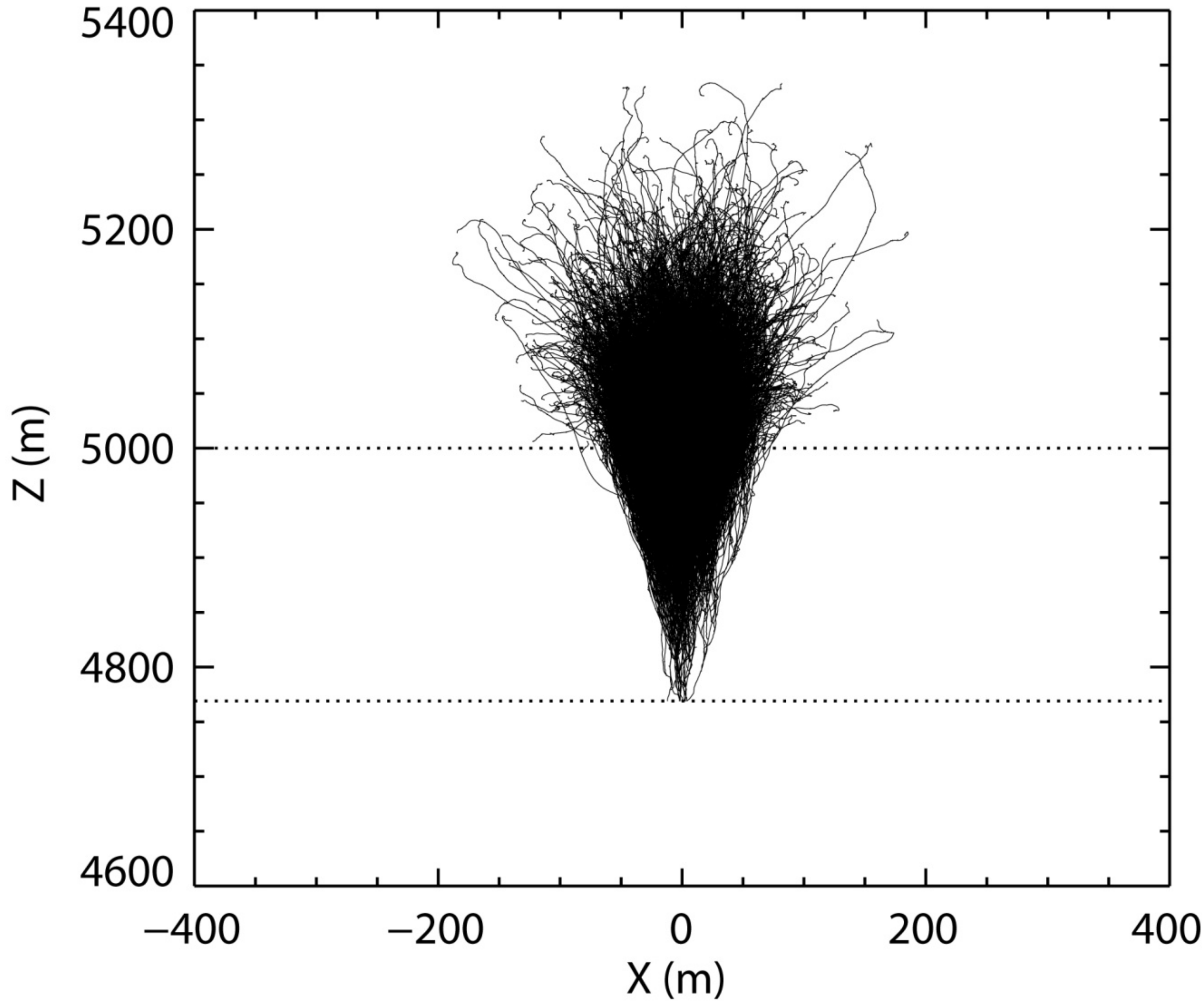
CGRO/BATSE Terrestrial Gamma-ray Flash (TGF)



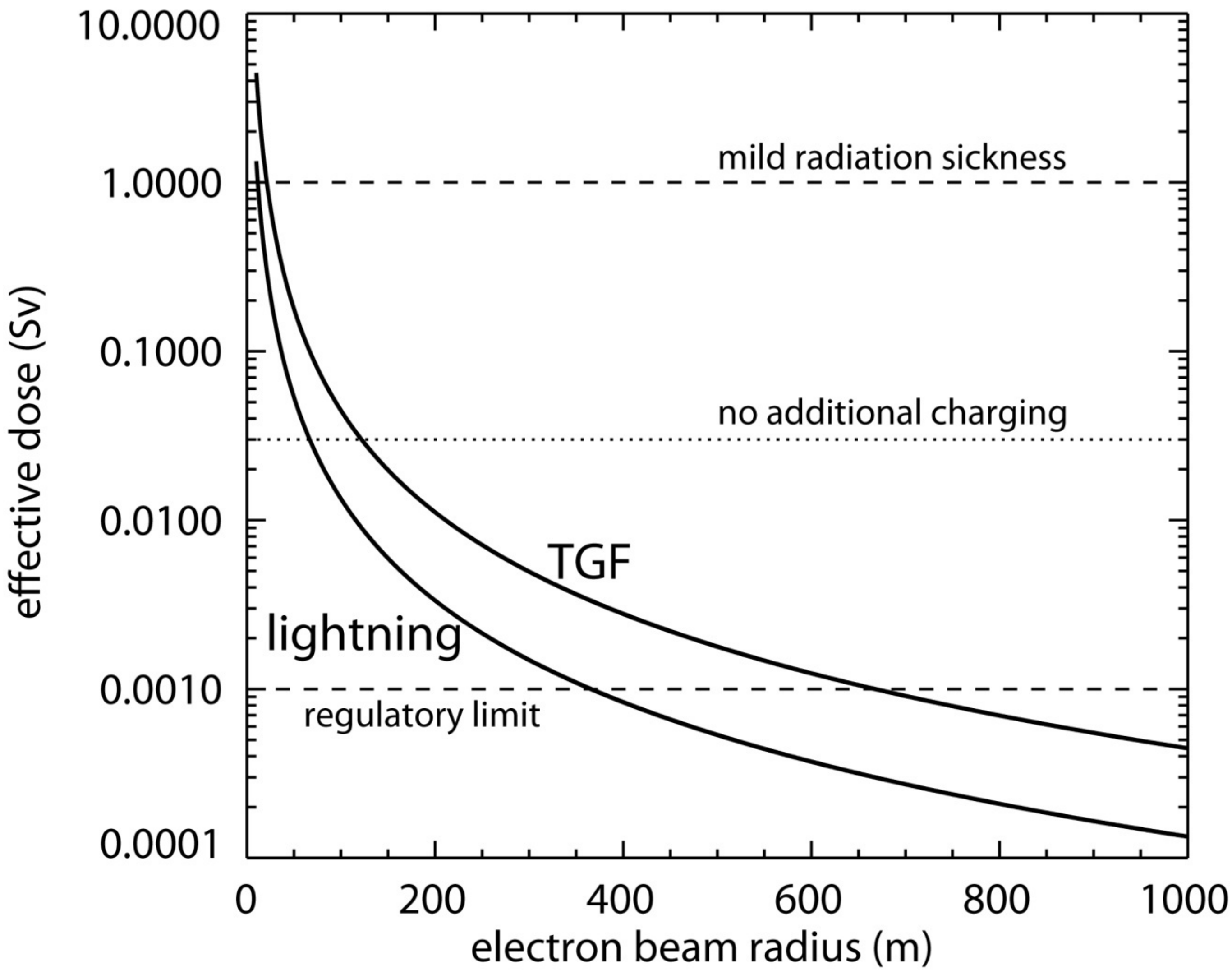
Terrestrial Gamma-Ray Flash (TGF) spectrum and results of Monte Carlo simulation for different source altitudes



Monte Carlo simulation showing runaway electron trajectories, injected by lightning, inside a thundercloud at 5 km altitude.



The effective dose produced by one lightning leader inside a thundercloud and a TGF versus the radius of the energetic electron beam.



Future Work:

Schematic of XL-cam

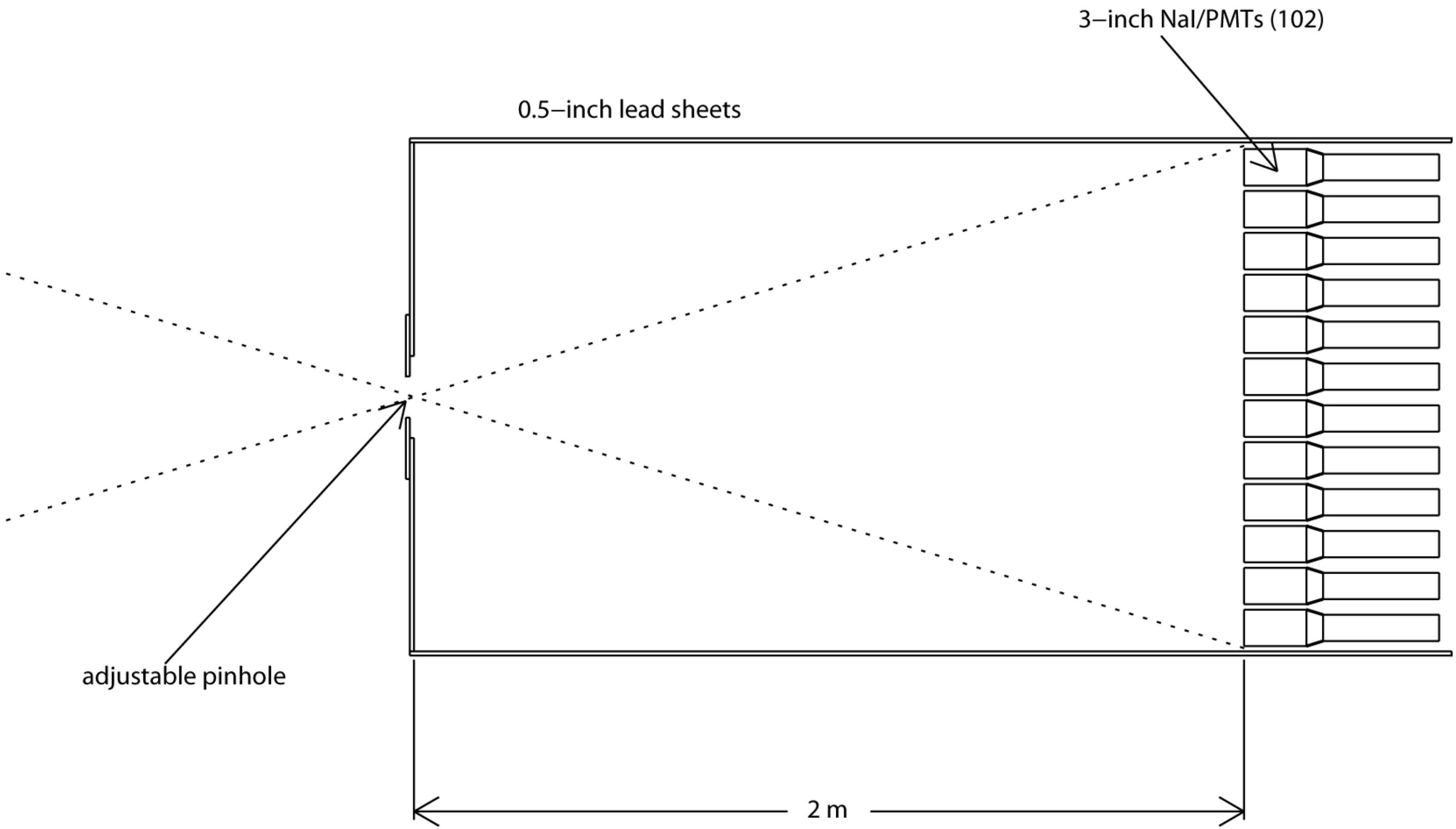
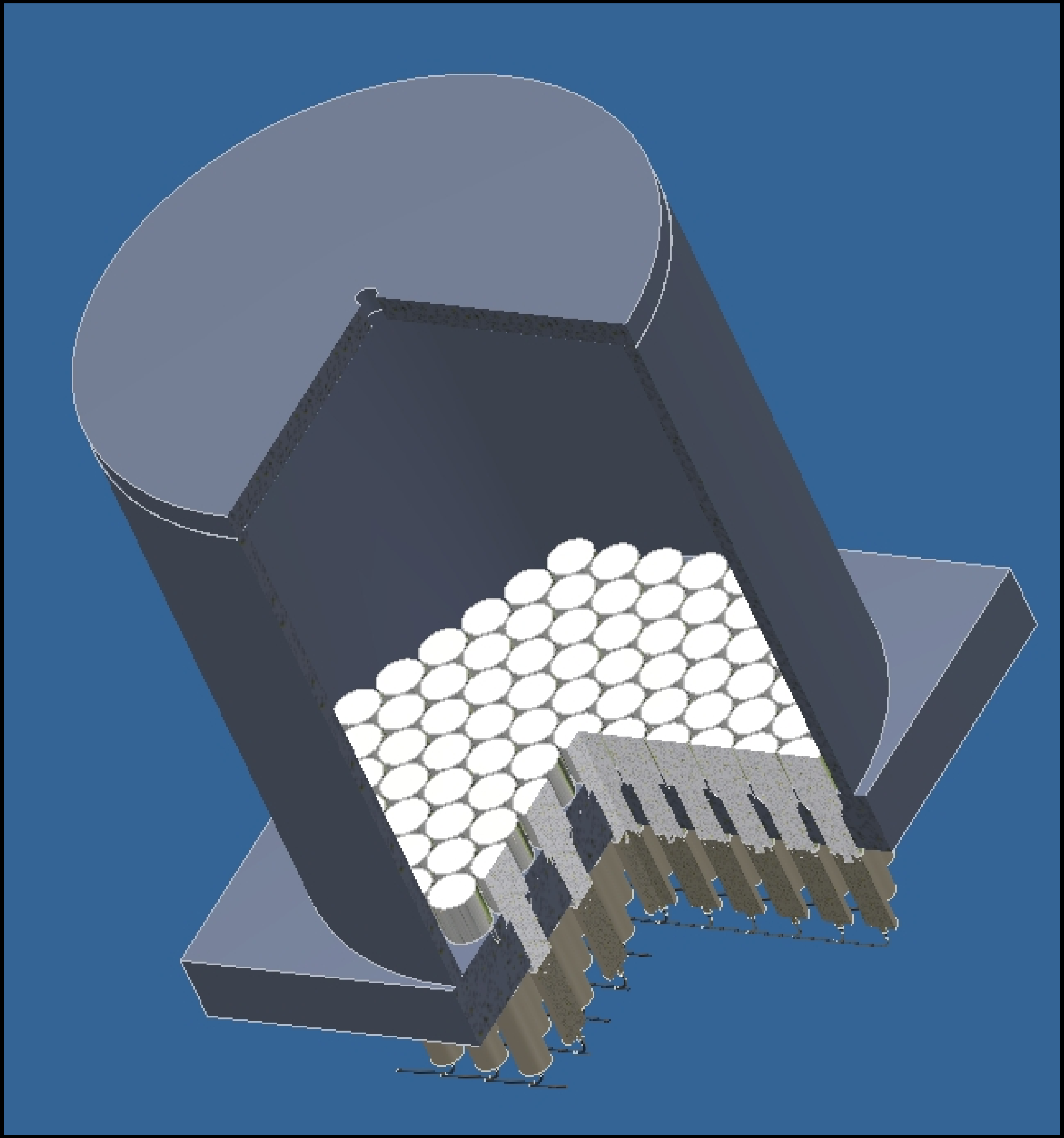
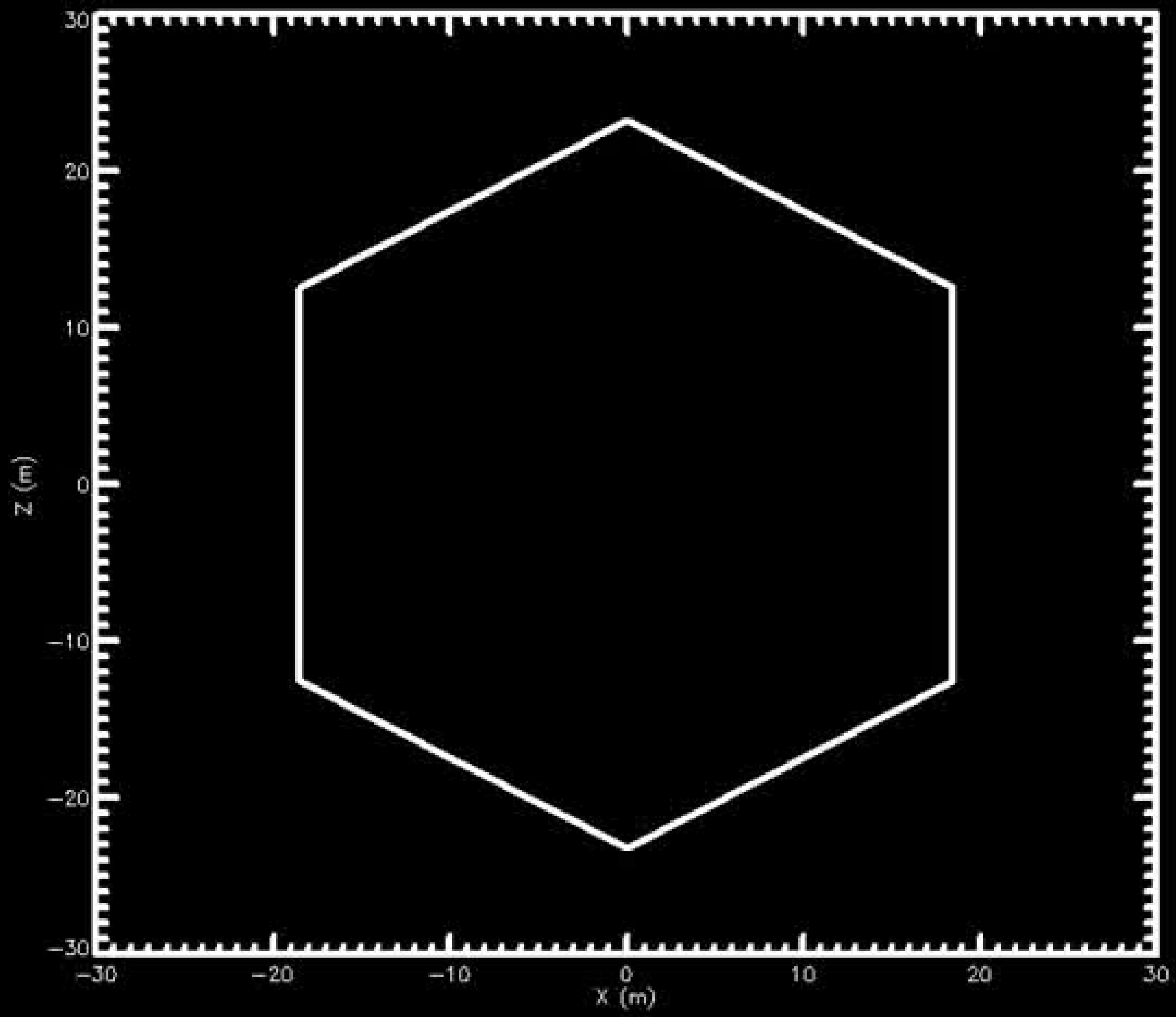


Illustration of XL-Cam



Simulated movie of lightning made with x-rays.

25 microsecond of data shown. The lightning leader channel from a high speed optical camera is superimposed. For this simulation the emission is assumed to come from the bottom of the newly formed leader segment.



Conclusions

- Lightning is not simply a conventional discharge.
- It involves an exotic kind of discharge called runaway breakdown, during which electrons are accelerated to nearly the speed of light and large numbers of x-rays are created.
- Since the standard models of lightning do not include runaway breakdown nor do they predict x-ray emission, clearly we need to revisit these models.
- How lightning works has remained a great mystery. Perhaps runaway breakdown is the missing pieces that we need to solve the puzzle.
- Finally, x-rays give us a new way to look at lightning.