MASTER

High-energy phenomena in long streamers (in STP air)

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High-Energy Phenomena in Long Streamers (in STP Air)

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Abstract

Lightning initiation and propagation have been studied intensively both experimentally and theoretically in the past. The lightning natural occurrence is quite random in time and position, making it a difficult object for detailed study at high altitudes. The scientific study of spark discharges began with the invention of the electrophore, which opened the door to laboratory research on spark discharges. Even after decades of (laboratory) research, still not everything is known about the processes involved in a spark discharge. This master's thesis concerns the aspect of high energy radiated from the spark discharge. Or more precisely the production of X- or even Gamma (γ)-ray during the streamer development prior to a complete electric breakdown.

The experiments were performed in the High-Voltage laboratory in the Corona building at Eindhoven University of Technology (TU/e). A Marx generator was used to produce a lightning voltage waveform. A spark discharge was created over two aluminum point electrodes. Several types of scintillation detectors were used for registering the energies coming from the discharge. Various electrode setups were investigated, different electrode materials were used. The data collected were analyzed in *Matlab*. The energies detected have been calibrated by the 662 keV line of a ^{137}Cs source. An energy spectrum of the scintillation detectors used during the experiments was also fitted to investigate (and compare) their accuracy.

Results show that indeed a huge a mount (up to several MeV) of hard radiation is coming from the spark discharge with as well positive as negative voltages applied to the floating electrode. Experiments using electrode materials with different atomic number confirmed the suspicion that the detected radiation is indeed a result from Bremsstrahlung. Timing of radiation detected, links the γ-production to the leader formation. From measurements with an absorber in front of the detector we concluded that these high energy pulses are pile-up of multiple smaller γ-bursts of > 62 keV. The pile-up should then occur within the rise time of the detector's response, about 10 ns. The consistent timing with the high voltage (HV) surge excluded background radiation as a source for these high intensity pulses. When changing the tips from aluminum to lead, the gamma energy increased and γ's occurred more frequently. Localization measurements indicate for positive discharges that γ-production occurs near both electrodes. In the case of negative discharges γ-production occurs near both electrodes and in the air between the electrodes as well. The energies detected with laboratory spark discharges are in accordance with energies detected from atmospheric discharges. This implies that experimental research on long sparks performed in the Eindhoven High-Voltage laboratory can contribute to further studies of atmospheric phenomena.

Contents

1 Introduction

The spark discharge is one of nature's most fascinating and at the same time illusive phenomena. Lightning, which in itself is nothing more than a tremendous discharge, is even until now a big topic of interest. More strongly, the mechanism of the lightning flash and among others the characteristics of electromagnetic fields generated by the lightning still has a big impact on technology and infrastructures. Therefore it is important to have a thorough understanding of this ubiquitous process in nature and technology. Spark breakdown and spark discharge soon became a subject of interest for fundamental physicist and engineers. Interest in the (atmospheric) discharge phenomenon has risen again with the first observations of Terrestrial Gamma-ray Flashes (TGF's) in the early 1990s and recent discovery of atmospheric phenomena such as sprite, blue jets, etc., which occur in association with thunderstorms [9].

When starting with this master project on lightning, it soon became clear that the research on lightning is an interdisciplinary subject where the needs of various branches of engineering and physics converge. In the last decades fundamental studies in long air gap discharges in laboratory environments have mainly been focused on the external spark characteristics [11]. An overview of theoretical and experimental studies is given in [1, 2]. Although the knowledge of the physical mechanisms leading to the formation of electrical discharges has improved substantially, the facts necessary to come up with a complete model of the phenomenon are surprisingly elusive.

As early as 1924 Wilson envisaged that charged particles could be accelerated to high energies in a dense gas under the action of a strong electric field. The last few years, the energetic radiation generation near long discharges is intensively discussed. High-energy phenomena have indeed been related to lightning, either as a cause or a result of the discharge. A possible explanation is Bremsstrahlung due to run-away electrons with energies above 100 keV [10]. Gurevich et al. indeed observed runaway breakdown phenomenon in low pressure laboratory experiments [8]. Dwyer detected energetic radiation, synchronous with the leader steps in growing lightning channel [4]. He also observed such radiation in the laboratory, at the breakdown of a 1.5-2.0m long spark gap fed by a Marx generator [5].

1.1 Objectives

The main objective of this master project is to studied long sparks of about 1 m length in the laboratory, with about 10 nanosecond resolution in gamma detection. The goal is to study the gamma production, where and when it occurs in order to find the underlying mechanisms to accelerate electrons to these high energies. A current measurement may tell something about the streamer development en its relation to the γ-production. Measurements with an absorber will give an indication of energies involved in this process. This work adds to [5] a large number of measurements, also with different electrode-material and varying gap distances, a good control of the experimental circumstances, and finally a faster scintillator.

1.2 Outline

In the next chapter a description of the experimental setup and the equipments used is presented. The actual measurements and its results are described in chapters 3, where data obtained with different scintillation detectors are shown. Some specific experiments will be elaborated in more detail in this chapter. In chapter 4 some concluding remarks will be given and recommendations for future work will be made. Also an outlook is included.

2 Experimental Setup

The High-Voltage Laboratory at Eindhoven University of Technology is equipped with a Marx generator, intended to produce a lightning voltage waveform up to 2 MV. Twelve stages of two 0.25µF/100kV capacitors in series are charged in parallel and then connected in series by spark gap switches, producing a total voltage of twelve times the voltage over one stage. The waveform is standardized, with 1.2 µs rise and 50 µs decay time to half of the maximum voltage. A 1:2000 divider is also a part of the wave shaping circuit; its output is further reduced by a factor of 40 to allow for recording by an oscilloscope. In most of the measurements we adjusted the Marx generator to a maximum of 1 MV, negative or positive. The distance between generator and divider is 7.8 m, see Fig. 2.1. This large distance reduced the chance that the detector located in the EMC-cabinet also detects the gammas produced at the spark switches in the generator. To give an impression about the laboratory environment, several pictures of the experimental setup are shown in figure 2.1.

Figure 2.1: Pictures from experimental setup.

2.1 Equipment positioning

Two types of electrode positioning have been investigated in order to find the optimal gamma detection setup. One electrode positioning was in line with the detector and produced a spark discharge in line with it (positioning 1), see Figure 2.2a. The other electrode positioning was placed perpendicular to the detectors free view (positioning 2), see Figure 2.2b.

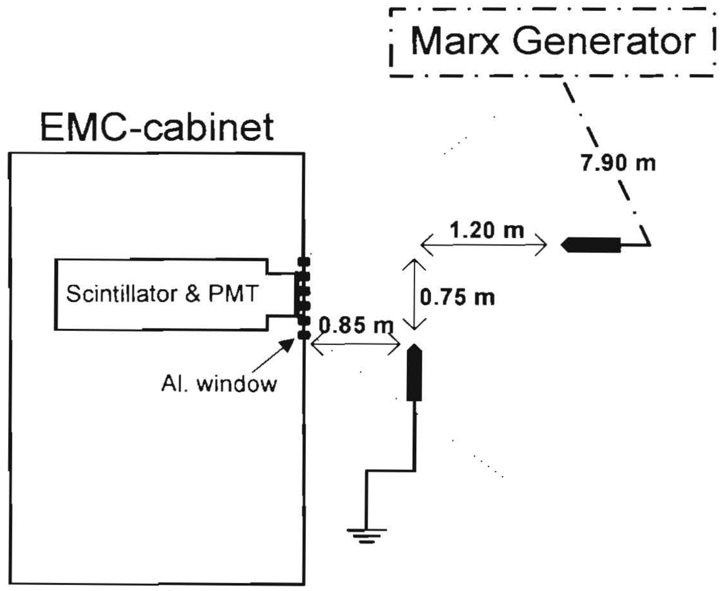


Figure 2.2a: Example setup of electrode discharge experiment (side view).

In positioning 1 the spark gap consists of two sharply pointed electrodes, placed nearly horizontal. The distance between the tips varied between 0.25 and 1.33 m during various experiments. A gamma detector stands in the EMC-cabinet at 0.85 m from the grounded tip, looking along the spark.

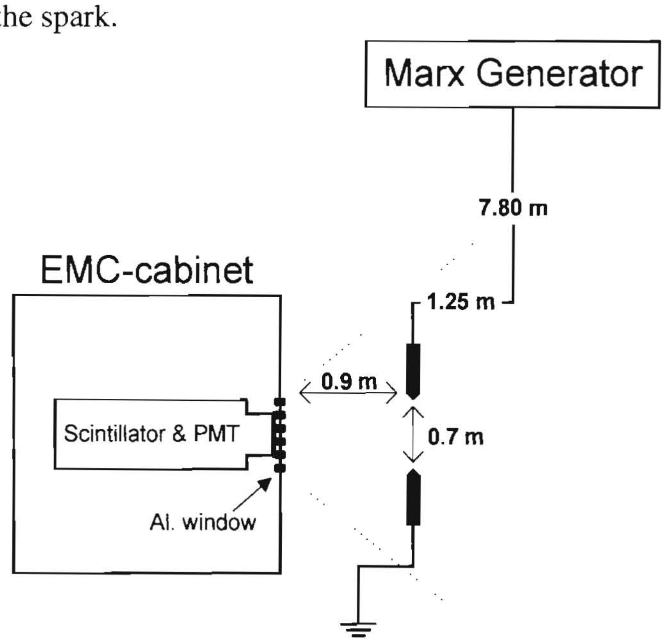


Figure 2.2b: Example setup of electrode discharge experiment (top view).

In positioning 2 the spark gap was placed near the 1:2000 divider. It consisted of two aluminum point electrodes, both placed at the height of 2 m on insulating stands. One electrode was connected to the divider high voltage end, the other was grounded. The distance between the tips varied between 0.7 and 1.2 m during various experiments.

For both electrode positionings, the electrode tip radius was 1 mm. A lead cover could be placed over the tips, increasing the tip radius up to 3 mm.

A shielded cabinet was placed, facing the spark at around 0.9 m distance. The scintillator detector (with a 0.5 mm casing) inside the cabinet looked at the spark through a 0.05 mm thin aluminum window. The cabinet and window ensured proper protection against the electromagnetic interference produced by the Marx generator and the spark. This was demonstrated in the few discharges where no gammas were detected, and only the noise floor of the oscilloscope was recorded. Due to the shielded construction for measurement, the combination of window thickness and casing of the scintillation crystal will have an 1/e cut-off photon energy of 17 keV. Energies above this level reach the scintillation crystal with a chance of 36%, rapidly increasing to near 100% with increasing energy. Figure 2.3 shows the mass attenuation coefficient and the mass energy-absorption coefficient as a function of photon energy (X-ray, gamma ray, Bremsstrahlung) from 1 keV to 20 MeV for aluminum. Atomic absorption edges are indicated by the shell designation. The μ/ρ values are taken from the current photon interaction database at the National Institute of Standards and Technology (NIST), and the μ_{en}/ρ values are based on the new calculations by Seltzer described in Radiation Research **136,** 147 (1993).

In several later experiments we also measured the current through the lead towards the grounded electrode with a Pearson 110 current probe. The probe has a rise time of 20 ns. A Tektronix TDS 3054 four-channel oscilloscope, bandwidth limited to 200 MHz, recorded all signals. After each discharge, data were automatically transferred to a computer inside the shielded cabinet. Hundreds of discharges have been produced. In order to limit the thermal loading of the generator we worked with small series of five discharges at intervals of about 30 seconds.

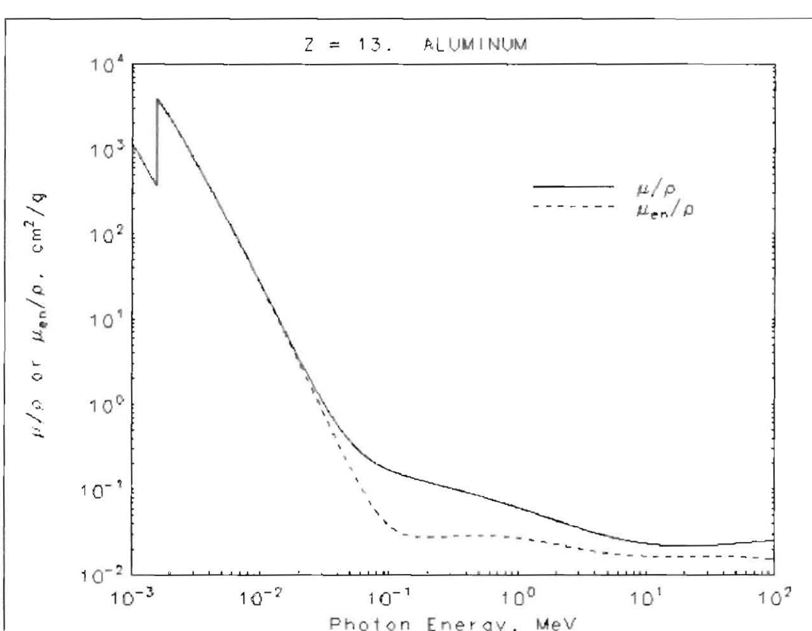


Figure 2.3: Graph of the photon mass attenuation coefficient μ/ρ and the mass energy-absorption coefficient μ_{en}/ρ for Al. (From http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html)

2.2 Scintillation detectors

Scintillation detectors make use of the property of chemical compounds containing heavy elements to emit short light pulses after excitation by the passage of charged particles or by photons (X-rays and gamma-rays). The scintillation is characterized basically by the light yield, the absorption and emission spectrum. Such detectors are often used in nuclear material detection and emission spectrum. There detectors suit our research perfectly.

We started the investigation with an old Philips PW4119 detector consisting of a well-known NaI(Tl) scintillator crystal with an 11 stage photomultiplier. If the quantum is fully absorbed, the scintillator produces about $38{\cdot}10^3$ photons per MeV quantum energy. The rise and decay time of the scintillation light are 0.04 and 0.23 μs. Later this detector has been replaced by a modern St. Gobain Brilliance 380 detector with $LaBr_3$(Ce) as scintillator [12]. The crystals dimensions are 38.1 mm in diameter and 38.1 mm thick. This material has an even better conversion rate of $63{\cdot}10^3$ photons per MeV, a twice better energy resolution and a measured rise and decay time of 11 and 23 ns, respectively. Both materials are known to be relatively insensitive to temperature and radiation damage. A few measurements have also been taken with a BaF_2 scintillator. The latter material has a low conversion rate of $1.8{\cdot}10^3$ photons per MeV, with a much lower detection efficiency and energy resolution than NaI(Tl) or $LaBr_3$(Ce). The real advantage above the other two detectors is a faster response (4 ns pulse duration). A plastic scintillator has also been tried out, but it was not a success and we did not use it in our experiments. All scintillators were attached to photomultipliers selected for adequate speed.

2.2.1 Detectors response on ^{137}Cs source

The response of the NaI(Tl) and $LaBr_3$(Ce) detectors on the 662 keV gamma's from a ^{137}Cs source is given below. Since our interest was more directed to fast time resolution than amplitude resolution, the photomultiplier output has been measured by a 10 Gsample/s scope with 8 bit resolution (Lecroy wavepro 7300). The input impedance of the scope was 50 Ohm, its bandwidth was limited to 200 Mhz. No further waveshaping has been applied. The data of 5000 recordings have been analyzed by curve fitting each recorded signal to obtain the amplitudes with its rise and decay times. Figure 2.4a and b show the histogram of amplitudes for NaI(Tl) and $LaBr_3$(Ce), respectively. The well-known features are the photopeak corresponding to the full conversion of the gamma quantum into light, and the Compton ridge where only a part of the energy is converted. The energy spectrum for 662 keV photons from ^{137}Cs has a FWHM (full width at half maximum) of 7.8 and 3.3 percent for NaI(Tl) and $LaBr_3$(Ce) respectively for the full energy peak. With less than 1% difference, this is in good agreement with published data for both materials. The chances of a gamma quantum to be detected in the Compton edge or in the photopeak are 7:1 and 4:1 for both materials. As a result, a single gamma quantum is recorded with only 12 (NaI) and 20 (LaBr3) percent chance at its proper equivalent energy. For the rest the signal will correspond to lesser energy. Similar data for BaF_2 cannot be given, since a clear photopeak could not be defined in the recorded data.

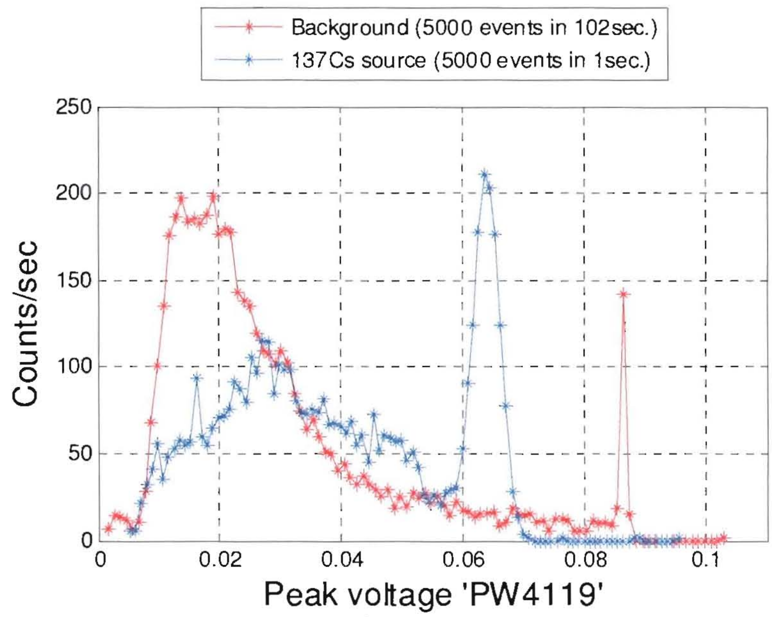


Figure 2.4a: NaI(Tl) response on ^{137}Cs source (5000 counts); photo / Compton = 1:2.55, low background.

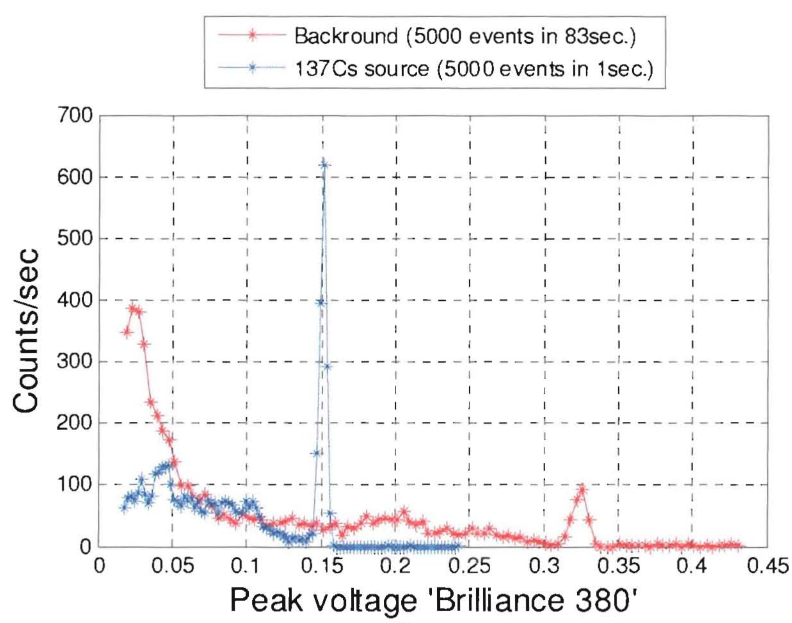


Figure 2.4b: $LaBr_3(Ce)$ response on ^{137}Cs source (5000 counts); photo / Compton = 1:2.5, low background.

The striking peak at the end of the background recordings is consistently present in every set of 5000 events taken. This is probably due to the presence of some radiation source in the vicinity of the place these samples were taken. Since the experiment on spark discharges were performed in another room, this background source has no consequences.

3 Results and Discussion

Data's registered with the scintillation detectors (NaI(Tl), $LaBr_3$(Ce) and BaF_2) are presented in this chapter. Fist typical γ-pulses for each type of detectors are shown, after that recordings of some experiments performed are described.

3.1 NaI(Tl) detector

Figure 3.1 shows some striking records taken with the NaI(Tl) detector, together with the voltage measured at the divider. With the detector aimed at the discharge arc over the aluminum electrodes we tried to detect X-ray. This measurement was done for different gap distances varying from 0.25 to 1.35 m (see figure 1a), the surge voltages varied from 850 kV to 1 MV. We expected to see X-ray pulses in the order of a few hundred keV's. To our amazements we detected in some cases even gamma signals equivalent to more than 1 MeV.

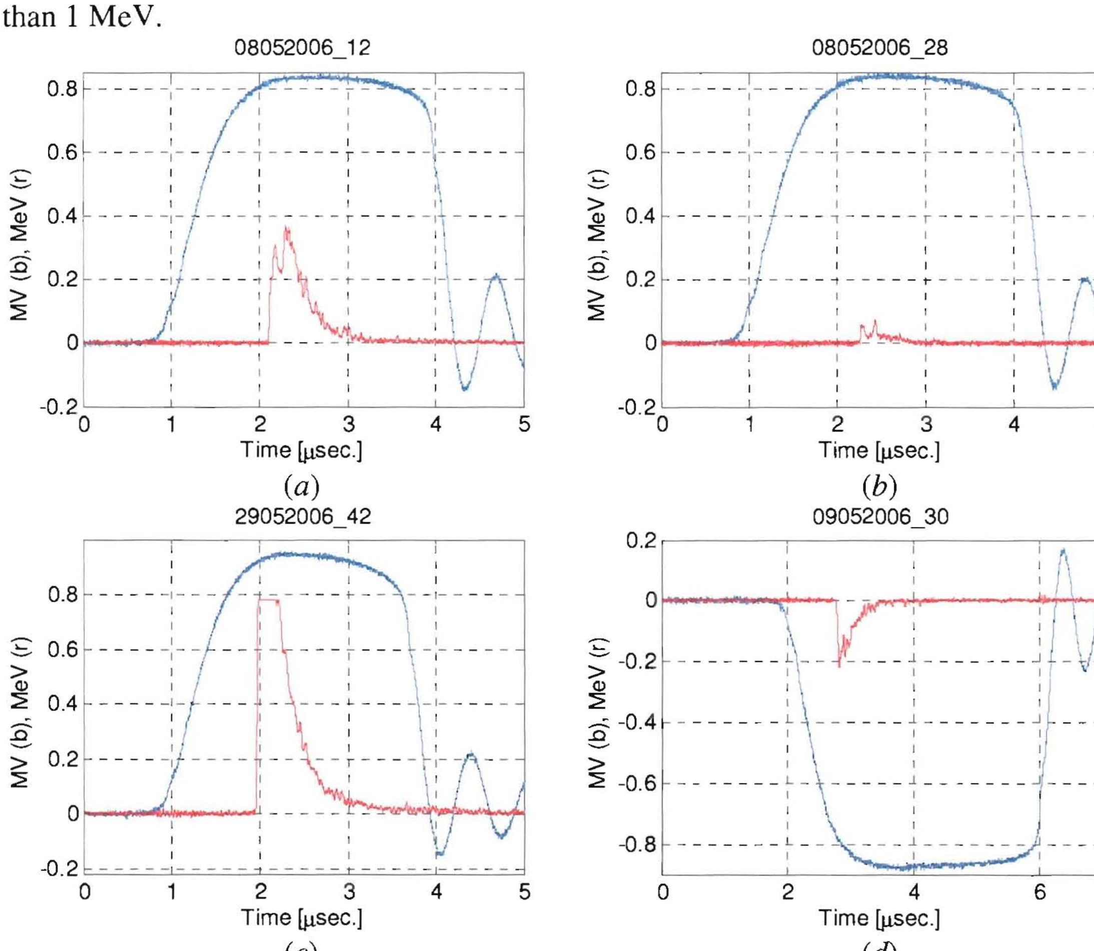


Figure 3.1: Examples surges, with gamma's detected by the NaI(Tl) detector. The vertical scale is in MV for the voltage and in MeV for the scintillator response, based on calibration with the ^{137}Cs photopeak.

For the samples shown above, the electrode distance used was 1.2 m. The record is similar to those published in by Dwyer [5]. The voltage surge starts at 0.9 μs, reaches the maximum at 2.5 μs and falls due to the spark gap breakdown at 3.7 μs, after that time a damped oscillation occurs in the circuit formed by the divider, leads and spark. In figure 3.1a the response of the scintillator shows two barely resolved peaks at 2.18 and 2.3 μs. The equivalent energies have been obtained by fitting the signal to the response on individual ^{137}Cs 662 keV gamma quanta in the photopeak. The amplitudes correspond to 310 and 370 keV respectively. Two possibilities exist: Either the amplitudes are due to a single gamma quantum; in this case the energies mentioned are a lower bound since there is a 7:1 chance that the detected quantum is not fully absorbed in the scintillator crystal. Or, the signals are due to simultaneous registration of several gamma quanta of unknown energy, likely but not necessary smaller than what would be derived from the ^{137}Cs calibration. We tried to resolve this ambiguity by absorption measurements, to be discussed in Sect. 3.6. Figure 3.1b shows the same percept. In Figure 3.1c a large gamma pulse has been recorded. It is likely to be a recording of one individual photon very high energetic photon and like Dwyer we tend to believe that this is a burst of multiple photons with a total energy exceeding eV_{max}, with V_{max} the maximum of the voltage. Figure 3.1d shows an example of gamma detection with a negative discharge. The timing of γ-detection is the same as for positive discharges, to be between 75% of V_{max} up to the maximum breakdown voltage. In 50% of the positive discharges gammas were detected. With negative discharge hard radiation is still detected, but less often. No difference in amplitude and occurrence between Pb- and Al-electrodes were observed during the experiments with NaI(Tl). In addition, to give an impression of the energies detected with NaI(Tl), figure 3.2 presents results of a series of test.

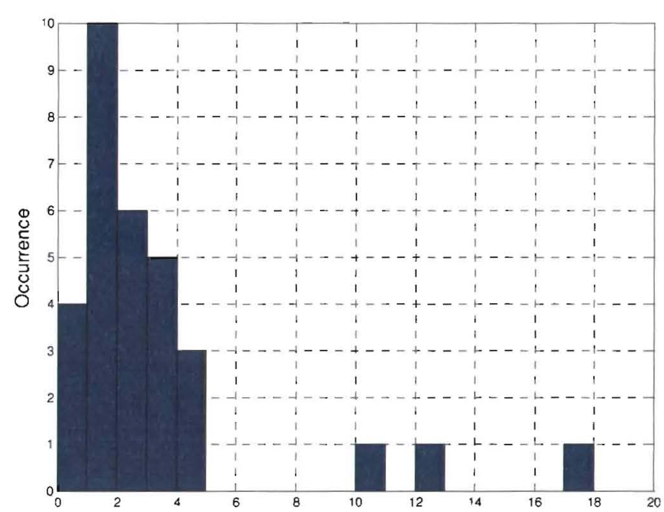


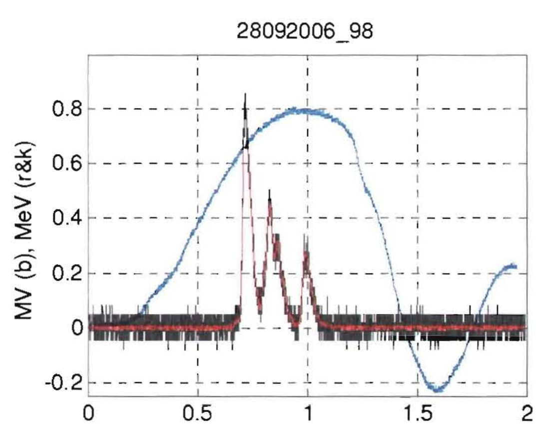
Figure 3.2: Results of a series tests with NaI(Tl).

Looking at the waveforms in figure3.1a and 3.1b it is obvious that a faster gamma detection system with high energy resolution was needed. We decided to switch over to a $LaBr_3(Ce)$ scintillation detection system. With an 1/e decay time of 31 ns it is not the fastest detector, but the energy resolution is superior. (The 1/e decay time for NaI(Tl) was 340 ns).

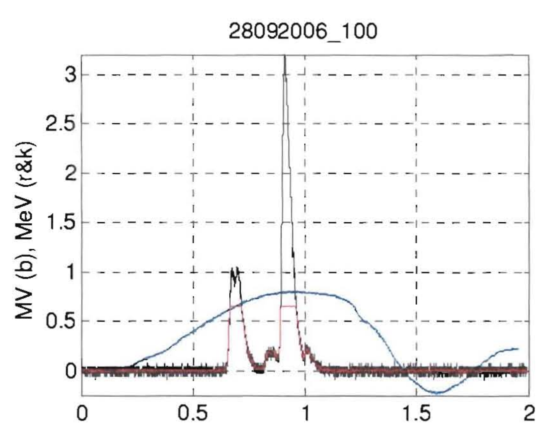
3.2 $LaBr_3(Ce)$ detector (Brilliance 380)

In two series of 25 lightning surges with 0.8 - 1.0 MV positive applied to the floating electrode hard radiation has been detected during all 50 surges. The gap distance used was 0.7 m (see figure 1a). Not only did we have a 100% detection, the $LaBr_3(Ce)$ detector was also able to separate individual γ-pulses during one lightning surge. The measurements of γ-pulses were done using the 200 MHz bandwidth setting of the oscilloscope (Tektronix TDS 3054).

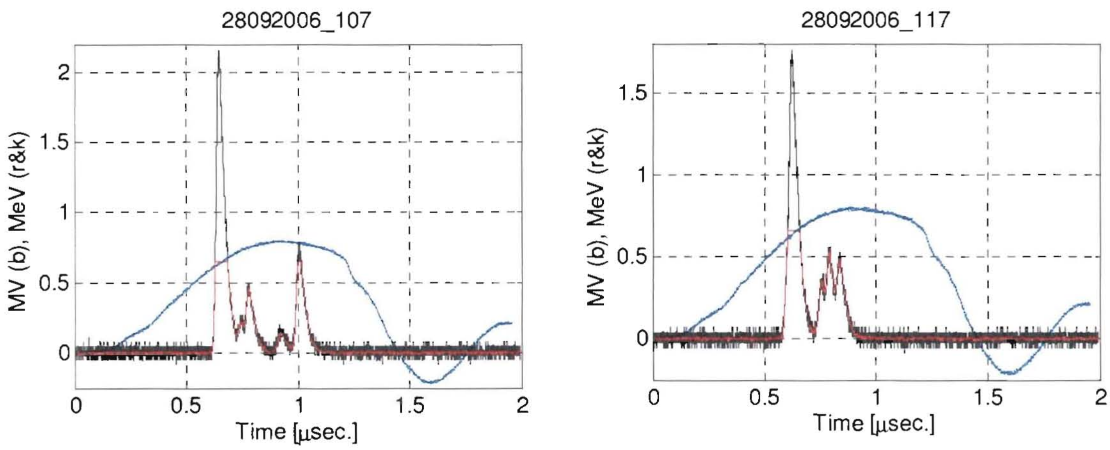
The detector registered gamma quanta at 0.3 μs before until 0.2 μs after the maximum voltage, the average energies per pulse (not per discharge) lays between 400 to 550 keV. Experiments covering the aluminum electrode material with lead influenced both energy and occurrence of gammas produced, Pb being more productive than Al. The results confirm our assumption that with a heavier material (higher Z-value), the Bremsstrahlung process would produce γ-bursts with higher energy and also more frequently. In the limited amount of data, no characteristic spectral energies became clear. However, a detector with a view restricted to the spark channel registered amazingly large energies. Interestingly, a few gamma-signals were equivalent to 1.5 - 3 MeV for positive discharges and up to 7 MeV for negative, far above what was obtainable from the maximum voltage. Pile-up of lesser energy gammas was possible, but should then have occurred within the 10 ns rise time of the detector. Pile-up implied a large intensity if isotropic distribution was assumed, or a narrow angle beam of radiation in the 10^{-4} sterad solid angle of the detector. In either case, electrons must have been accelerated to high energy, well above 17 keV, the low-energy limit of additionally placed absorbers. Some striking signals registered with the $LaBr_3(Ce)$ detector are given in figure 3.3 and 3.4. The sharp spikes are inverted γ-bursts from the PMT. The larger positive pulse is the voltage over the electrode gap.



(a)



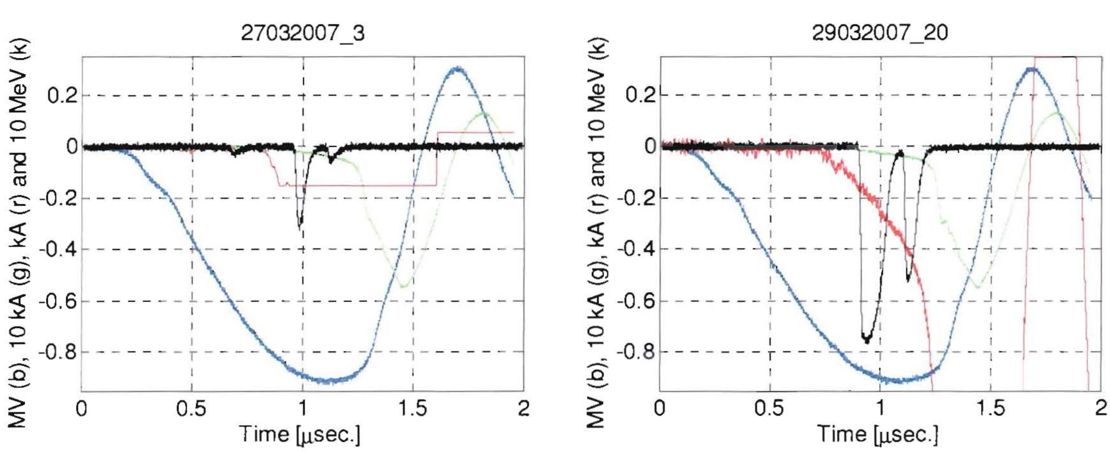
(b)



(c) *(d)*

Figure3.3: Typical waveforms of the γ-bursts detected with the $LaBr_3(Ce)$ detector, with Pb coated electrode tips. Blue: the voltage measured by the Marx generator divider scale in MV; breakdown occurs at 1.25 μs. Red: the gamma detector response, scale in MeV (signal data shown inverted) clamped by the oscilloscope. Black: the detectors' response divided by 10. Multiple γ-bursts are apparent, some of them barely resolved in time. Some bursts have a total energy exceeding eV_{max}, with V_{max} the maximum of the voltage.

As mentioned briefly above, the energies for negative discharges are quite amazing. Some recordings of very energetic response of the scintillator response are given below, together with current measurements by a Pearson 110 probe with 20 ns rise time. The data show that the gammas appear during the formation of a conductive channel (green line) at t = 0.7 μs, before the complete breakdown with 5.4 kA peak current. The details of the current before t = 0.7 μs are not accurately measured yet.



(a) *(b)*

Figure 3.4: Recordings for negative polarity over a 0.7 m gap. Blue: Marx generator voltage, scale in units of in MV. Red: current through low-voltage electrode, scale in units in kA. Green: same current divided by 10. Black: the gamma detector response, scale in units of 10MeV

The slightly rounded scintillator wave shape in figure 3.4b may indicate pile up, or less likely, multiplier saturation. The measurements demonstrate that the electrons are accelerated to the high energies needed for the gammas during the formation of the conductive channel. One is tempted to conclude that the discontinuities in the current coincide with the gamma production (in one burst), analogous to the stepped leader formation in natural lightning [4], but here on a shorter scale in distance and time.

With a 1/e decay time of 31 ns for $LaBr_3(Ce)$ it is one of the fastest scintillation detector available, but it is still not fast enough. According to Stankevich and Kalinin [13] we need a decay time less than 1 ns in order to be able to capture a single energetic photon. Barium fluoride (BaF_2) scintillator with a 1/e decay time of 0.6 - 0.8 ns (in theory) is presently the fastest known scintillator available. Major drawback is it's photoelectron yield of only 3% with respect to NaI(Tl) scintillators.

3.3 BaF_2 detector

Measurements with a faster BaF2 scintillator showed that the burst duration is less than 10 ns. Because of the pour energy resolution of BaF2, it was not possible to determine the energies of the pulses detected. Below are some examples of gammas recorded.

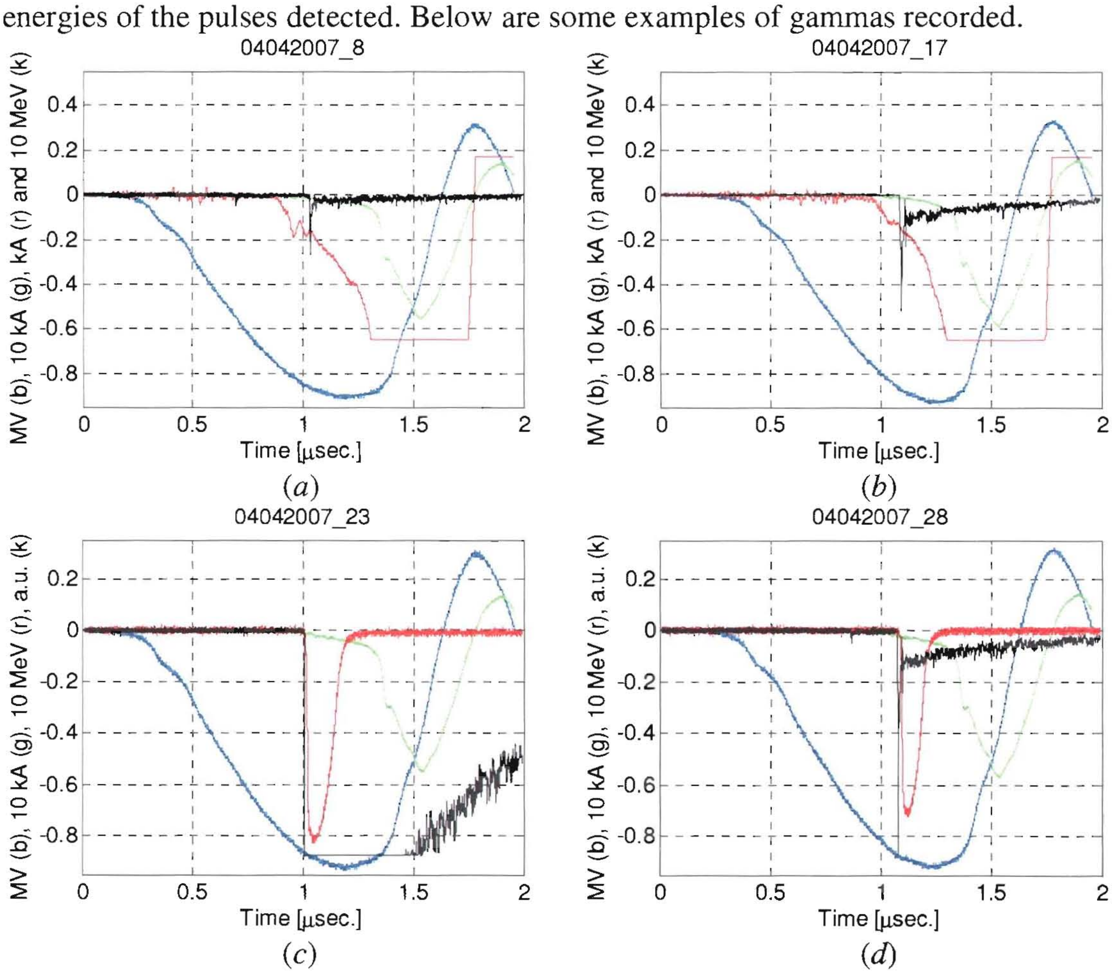


Figure 3.5: Recordings for negative polarity over a 0.7 m gap, with Al electrode material. Blue: Marx generator voltage, scale in units of in MV. Red: current through low-voltage electrode, scale in units in kA. Green: same current divided by 10. Black: the gamma detector response, a.u.

There are two kinds of detector responses, a slow one (figure 3.5b, c and d) and a fast one (figure 3.5a). This is due to the BaF_2 properties.

3.4 Localization γ-production

In order to measure and find the origin of the high energy electrons in the developing spark discharge, measurements involving a layered lead cylinder of 1.2cm thick and 33cm long have been performed. In addition we want to determine their consequences for growth of discharges in STP air. These measurements indicate that the γ-production occur in the vicinity or on the electrodes itself. The cylinder was used to restrict the view of the scintillator. Since positive and negative discharges have different characteristics, they will be treated separately. This experiment was performed with the $LaBr_3(Ce)$ detector only.

3.4.1 Positive discharge

When aiming at the HV electrode (anode), X-ray was registered. When aiming in the air (area between electrodes only) nothing has been detected in 65 surges measured over 5 days, the same observation was made when aiming at the cathode. This measurement was repeated several times leading to the same observation. This implies that electrons are accelerated towards the anode where the production of X-ray occurred due to Bremsstrahlung. Figure 3.6 gives an example of such a recording.

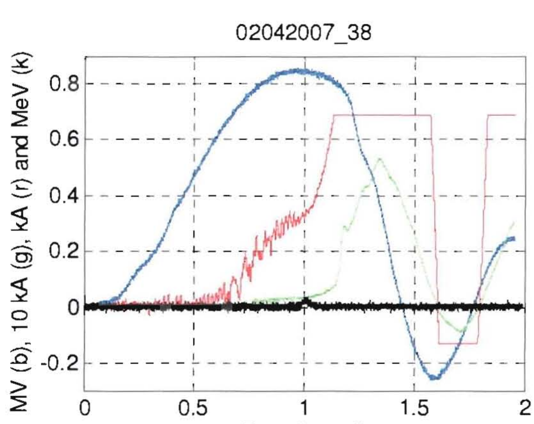
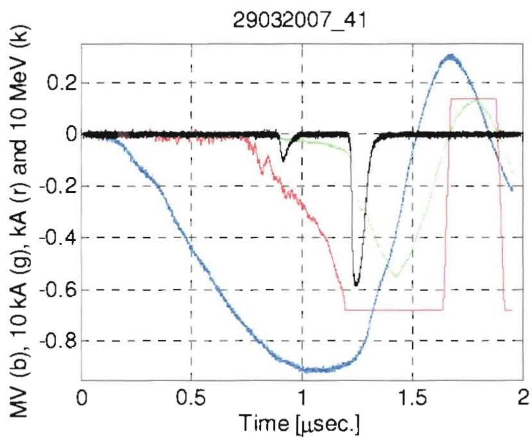


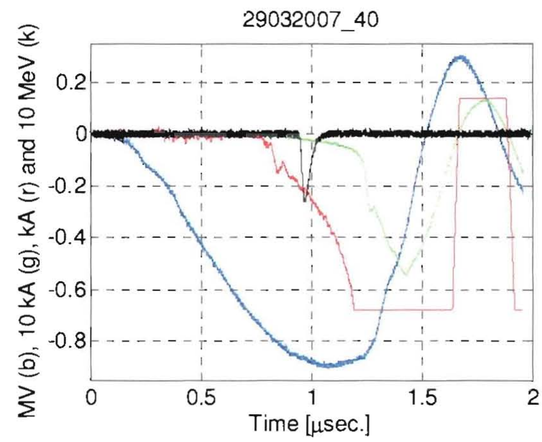
Figure 3.6: Aiming the detector in at the anode only. Blue: Marx generator voltage, scale in units of in MV. Red: current through low-voltage electrode, scale in units in kA. Green: same current divided by 10. Black: the inverted gamma detector response, scale in units of MeV.

3.4.2 Negative discharge

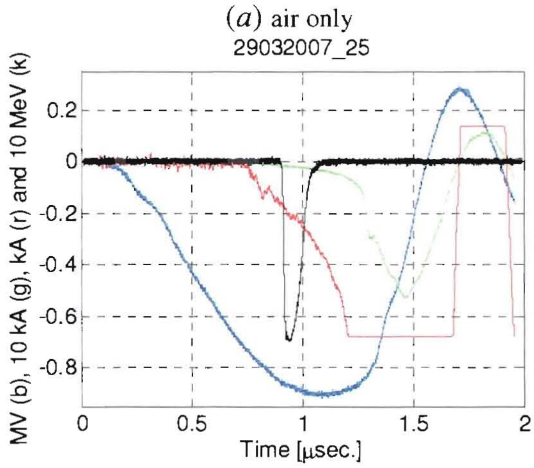
In the case of negative discharges the results are more interesting. As can be seen from the recorded data below, X-ray (or gammas) were detected everywhere, near both electrodes as well as in the air in between. Especially the detection of gammas in the air between the electrodes during the streamer development is interesting. This led to the conclusion that gamma production is somehow related to the streamer propagation. What is also interesting is the possible relation between gamma production and the stepping of the streamer. Alas, due of the lack of a suitable (fast and robust) current probes, this experiment ended here (for the moment).



(*a*) air only



(*b*) anode (grounded electrode)



(*c*) cathode (negative electrode)

Figure 3.7: Localization measurements with $LaBr_3$(Ce) detector. Blue: Marx generator voltage, scale in units of in MV. Red: current through low-voltage electrode, scale in units in kA. Green: same current divided by 10. Black: the gamma detector response, scale in units of 10 MeV.

3.5 Measurement with two $LaBr_3$(Ce) detectors simultaneously

Thanks to St. Gobain's generosity to lend us their $LaBr_3$(Ce) detector for a while (after we ordered one), we were able to perform a multi-angle measurement. The floor plan is shown in figure 3.8. It is the same setup as figure 1b, but with a second EMC-cabinet a little bit lower on the other side. The main difference is the lack of a thin window to decrease the cut-off energy, which has an 1/e of 78 keV (versus 17 keV from EMC-cabinet 1). Some striking data's recorded are presented down below in figure 3.9.

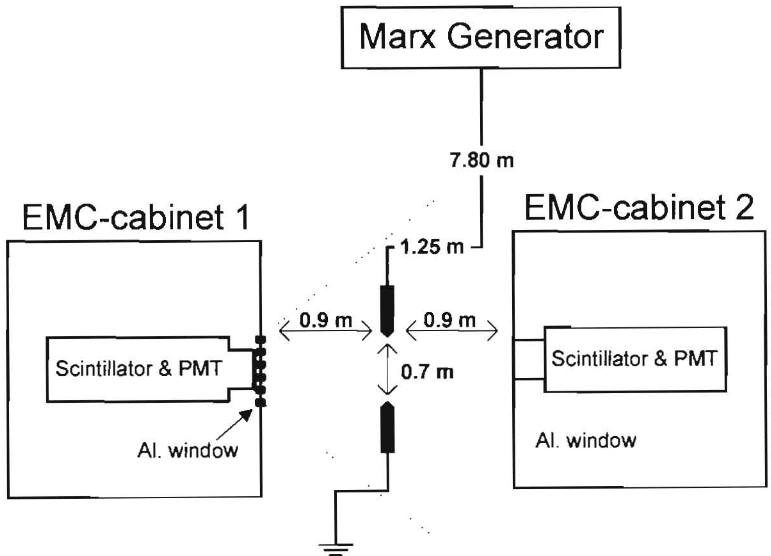
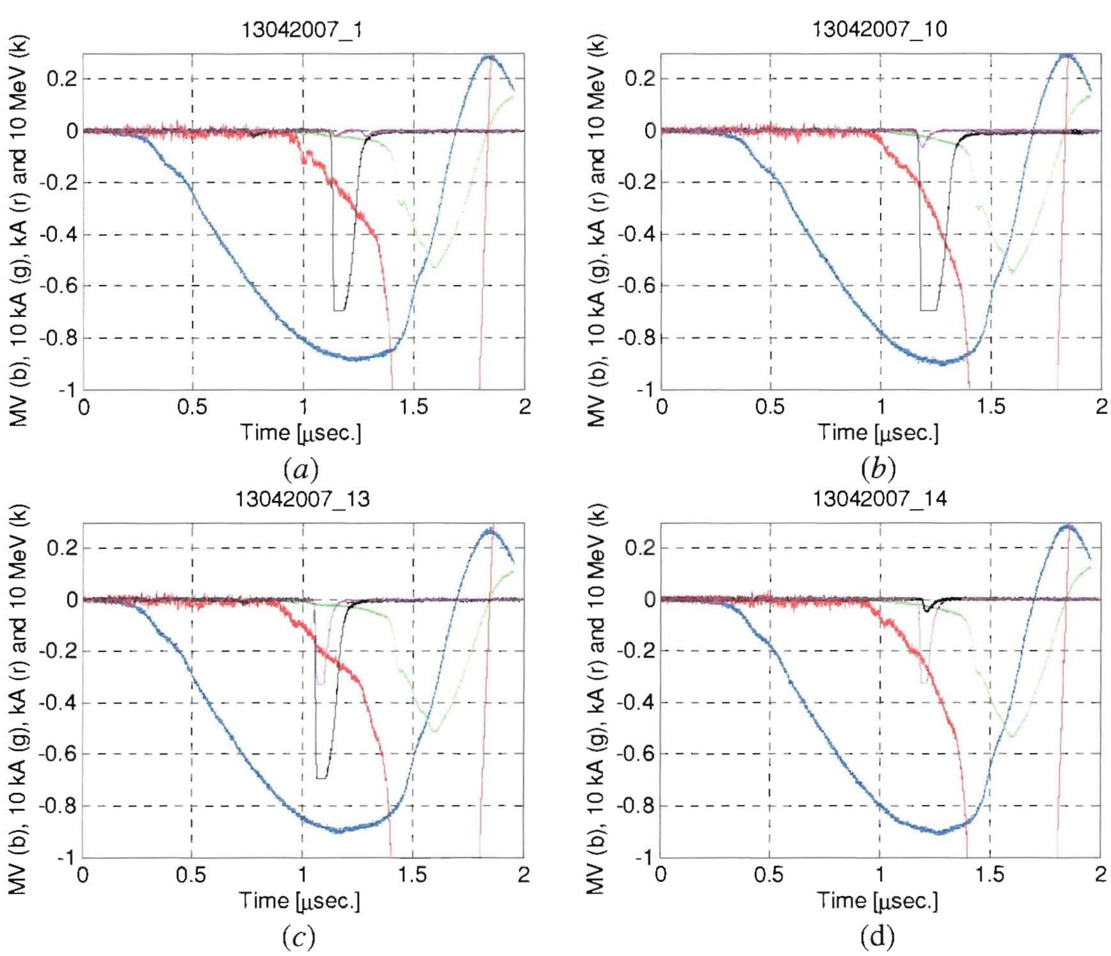


Figure 3.8: Floor plan of multi-angle measurement (top view).



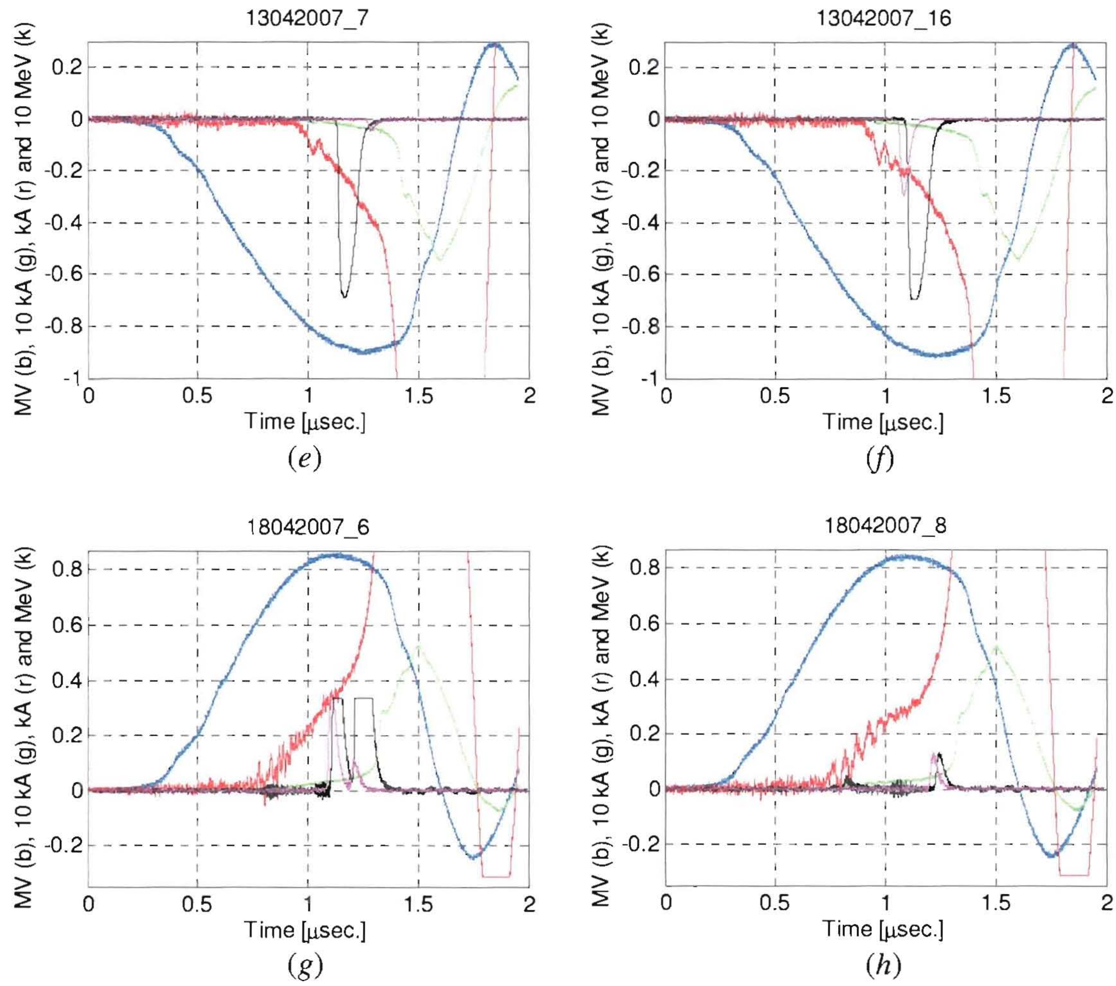


Figure 3.9: Multi-angle measurements with two $LaBr_3(Ce)$ detectors. **(a)**-**(f)** were measured with a negative discharge, **(g)** and **(h)** were measured with a positive discharge. Blue: Marx generator voltage, scale in units of in MV. Red: current through low-voltage electrode, scale in units in kA. Green: same current divided by 10. Black: the gamma detector response from cabinet 1, scale in units of 10 MeV for **(a)**-**(f)** and MeV for **(g)** and **(h)**. Purple: the gamma detector response from cabinet 2, scale in units of 10 MeV for **(a)**-**(f)** and MeV for **(g)** and **(h)**.

Figure 3.9a shows the most interesting recordings. It shows two gamma pulses in the same interval, except the purple line (cabinet 2) is a lot smaller. The energies corresponding to the black line (cabinet 1) are 180 keV and 6.9 MeV (overloaded), and those from the purple line are 220 keV and 240 keV. Since the two smaller pulses from the purple line fall in the same interval with the 6.9 MeV pulse, this indicate that the larger pulse of 6.9 MeV must be a pile up of multiple smaller bursts of X-rays. A rough calculation of 6.9 MeV divided by 17 keV results in around 400 energetic photons entering the detector. It should be noted that this is only a rough estimation with the assumption of an angular homogeneous distributed photon flux! This contrast in pulse amplitude due to the difference in cut-off energy of the cabinets is also noticeable in other figures. Figure 3.9e, f and h show two γ-pulses close to each other, partially overlapping. This can be interpreted as a difference in timing of detection or, simply because there are multiple overlapping γ-bursts possible. More experiments with multiple detectors with varying cut-off energies must be performed to arrive at a more definite conclusion on pile up.

3.6 Absorption measurement

It is hard to believe that those energy levels detected earlier (several MeV) are actually from one individual high-energy photon, especially since these values exceeded the eV_{max} applied by the Marx generator. The experiments described in the previous section already indicate pile up to occur, but that was mere an incidental observation. We decided to perform an absorption test to be able to tell more about the composition of such MeV pulses. Measurements with aluminum (Al) plates (0.3 by 0.5m) as an absorber in front of the detector could shine some lights into this matter, see figure 3.10.

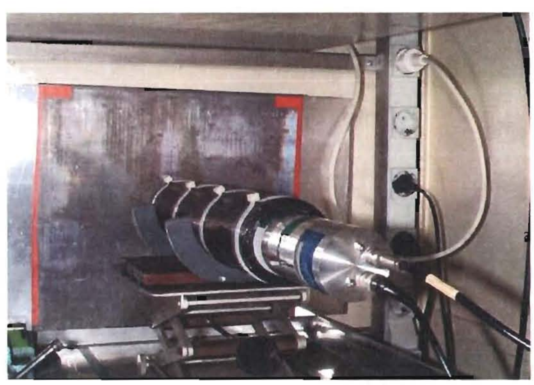


Figure 3.10: Absorption measurement with $LaBr_3(Ce)$ detector.

Aluminum plates with thicknesses of 14 mm (1/e cut-off energy = 62 keV) and 28 mm (1/e cut-off energy = 190 keV) were used. The mass absorption coefficient for aluminum was taken from the NIST database [14]. An absorption histogram is given in figure 3.11.

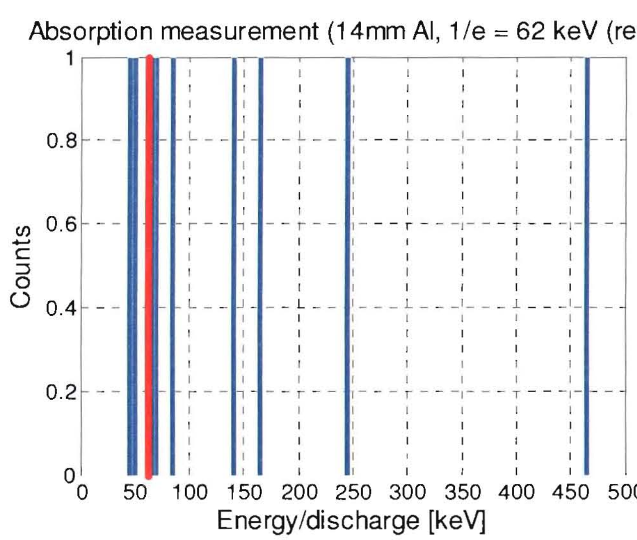


Figure 3.11: Absorption histogram with 14 mm Al plates.

Only in 9 out of 30 surges gammas were detected. The red line in figure 3.10 indicates the 1/e cut-off energy of 14 mm Al. The total energy of two recordings was below this cut-off energy, which is an indication for the presence of Compton scattering. For now we can conclude that the high energy pulses detected were actually pile ups of multiple smaller γ-bursts of at least 62 keV. The pile up should then occur within the rise time of the detector response, around 11ns. The same experiment with 28 mm thick Al plates in front of the detector still allows energies up to 214 keV to be detected.

During the absorption measurements we encountered heavy Compton scattering. Even with 8 layers Al plates with a total thickness of 42 mm we still detect pulses with lower energy than the 1/e cut-off energy belonging to this thickness. In order to reduce the Compton scattering effect we decided to cover the absorption plates with lead except for a small circle for the photons to pass. The detector was also shoved into a lead cylinder and put against the Al plate. With this setup a shielded tube was created for the photons to reach the scintillator detector directly. Compton scattering still took place at the wall of the cylinder, but much less. When energies detected are above 1/e cut-off photon energy (obtained with the mass absorption coefficients from the NIST), it was considered as a direct pass. According to data from the NIST absorption in air is negligible for the distance used in our experiments.

3.7 Measurement on a wire-plate corona reactor

Next, a measurement on a wire-plate corona reactor was performed to settle the question whether γ-production occurs without a total breakdown. With the Marx generator it seemed impossible to create only streamers at the tip of the HV-electrodes without a total gap breakdown following. We had a wire-plate corona reactor available [15].

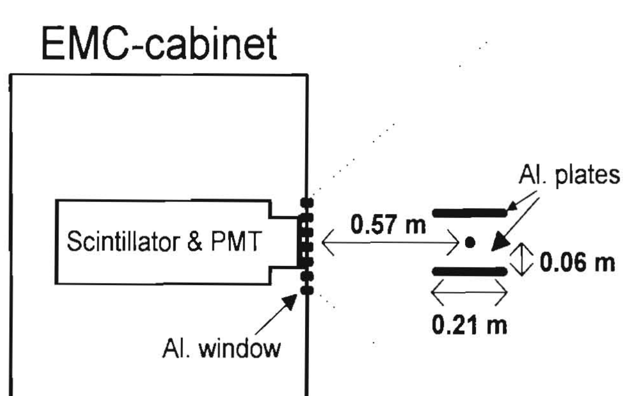


Figure 3.12: Floor plan wire-plate corona measurement.

Figure 3.12 shows the floor plan of this measurement setup. The plate height and width are 1.1 m and 0.25 m, respectively. The plates are positioned 0.118 m from each other. A single wire with a diameter of 0.4 mm and a maximum length of 0.9 m is positioned in the centre between the grounded plates. All sides of the reactor are closed with Lexan-plates to enable controlled air-flow (60 m^3/h, 20 °C, RH 42%) conditions in the reactor.

The corona reactor can be operated at a repetition rate of 10, 20 and 30 Hz. No total breakdown between the wire and the plates occurred during our measurements. Additional information about the wire-plate corona reactor can be found in [7].

A 15/25 ns high voltage pulse with a 100 ns period was applied to the wire. The voltage pulse amplitude was 65 kV with an additional DC offset of +20 kV. With the corona reactor it was possible create streamers at a high repetition rate. The data's were stored on a fast oscilloscope with a large hard disk (Lecroy wavepro 7300). In this way it was possible to perform series of thousands of measurements. After analyzing the data's it turns out that on average at 1 on 450 discharges X-ray was detected for the 10 Hz operation of the corona reactor. When using the corona reactor at 30 Hz it turns out that 1 on 30 discharges resulted in detection of X-ray. Figure 3.13 gives an example of a waveform of the X-ray signal delivered by the PMT.

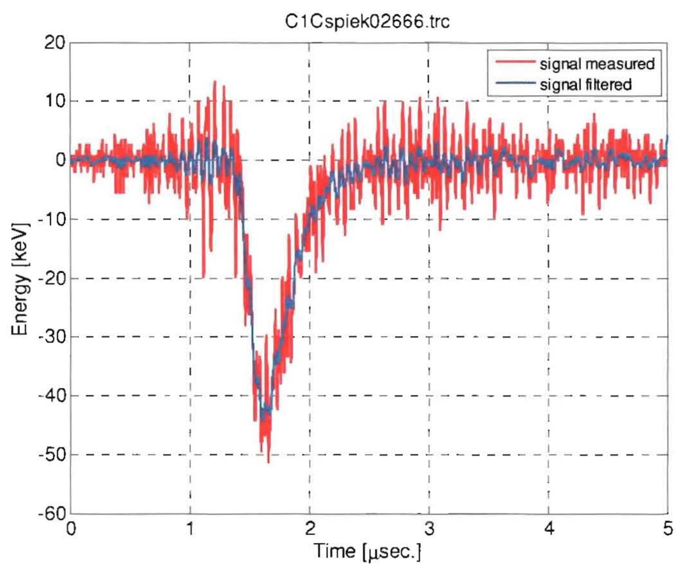


Figure 3.13: Example of X-ray signal detected by $LaBr_3(Ce)$ detector at the corona reactor; 65 kV positive voltage pulse with 20 kV DC_{offset}, 15/25 ns rise/fall time.

4 Conclusion and Recommendations

This master project can be categorized as fundamental research, but it is still too early to come up with hard conclusions. Only observations were made and data's were obtained from experiments, but to be able to come up with a plausible explanation for the results measured is still to premature. More accurate measurements have to be done. Especially with the illusive nature of spark discharges, it requires fast (and often expensive) equipments to record everything properly. Nevertheless some statement can be made based on experiments so far.

Hard radiation (quanta > 50 keV) has been observed during spark discharges with 750-1000 kV positive applied to the floating electrode. The radiation occurred most often in the leading edge at about 75% up to the full maximum voltage, which is 140 ns time span. This timing links the γ-production to the streamer/leader development. About 0.3 μs after the maximum, complete breakdown occurred.

In a few measurements, γ-pulses equivalent to 2-3 MeV were detected for positive discharges, for negative discharges up to 7 MeV had been detected. From absorption measurements we concluded that these high energy pulses must be pile up's of multiple smaller γ-bursts > 62 keV. The pile up should then occur within the rise time of the detector response, around 11 ns. According to Stankevich and Kalinin [13] we need a decay time less than 1 ns in order capture a single energetic photon. The consistent timing with the HV surge excluded background radiation as a source for these high intensity pulses.

According to the localization measurement it seemed that for positive discharges only gammas were produced at the anode. In the case of a negative discharge, it seems that gammas were produced as well near both electrodes as well as in the air through witch the streamer propagates. This is interesting, since this could possibly link the gamma production to the stepping process of the streamer. But first an accurate current measurement needed to be performed to prove the existence of the stepping process.

Experiments with multi-angle measurements showed some interesting recordings due to the differences in 1/e cut-off energies. This experiment should be worked out more thoroughly with more different level of cut-off energies.

From measurements with the three types of scintillation detectors we can conclude that the $LaBr_3(Ce)$ scintillation detector has the best overall performance and is so far the most suitable for our experiments.

The data showed clearly that x-ray emissions can be produced in laboratory sparks. This indicates that research on runaway electron can be performed in the Eindhoven high-voltage laboratory.

Acknowledgement

I would like to thank some people for making the presented work possible. Let me start to thank Dr. Lex van Deursen who came up with the proposition to switch my master project over to this topic (at first I was working on current injection into a power line tower to investigate the reliability of the grounding system of the MV-grid in tower's vicinity). The transition from several mA with kV's into long discharges with several kA and MV was easily made, especially since the new assignment allows room for further explorations to be made. The few presentations given during this research period showed that there is a lot of interest in this newly discovered phenomenon. I'm also grateful for his contribution to the fitting of the data and the discussions we had based on the results measured. I wish to thank Prof. Dr. ir. Jan Blom and Prof. Dr. Ute Ebert for their interest in this work, and their support in Lunteren. I would like to thank Dr. ing. Guus Pemen, Dr. ir. Bert van Heesch and Dr. ir. Eddie van Veldhuizen for their interest and the discussions we had. I would also like to thank ing. Hennie van der Zanden, ir. Hans Winands and ir. Laurens van Raay for their help during the experiments.

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