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Sixteen samples of standard insulating materials with electrodes were exposed to the full variety of the Earth's space radiation belts for 14 months. Spontaneous discharges were recorded for each sample and are compared to the radiation levels which were simultaneously monitored. Samples with the most exposed insulator surface pulsed most frequently. Pulsing correlated with electron flux, but not at all with proton flux. The pulse rate per unit electron flux was initially small, rose continuously for 7 months, and then fell slightly during the last seven months. A computer model predicts the charging of the insulators by the high energy electron flux; It took 1 to 6 months for the electric fields to approach steady state levels. Most of the pulses were less than 50 volts on 50 ohms. The pulsing rate decays when the satellite leaves the electron belts; the decay became more rapid after 7 months. Pulsing during the first six months had different characteristics than later pulsing.

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CHARACTERISTICS OF SPONTANEOUS ELECTRICAL DISCHARGING OF VARIOUS INSULATORS IN SPACE RADIATIONS

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Abstract

Sixteen samples of standard insulating materials with electrodes were exposed to the full variety of the Earth's space radiation belts for 14 months. Spontaneous discharges were recorded for each sample and are compared to the radiation levels which were simultaneously monitored. Samples with the most exposed insulator surface pulsed most frequently. Pulsing correlated with electron flux, but not at all with proton flux. The pulse rate per unit electron flux was initially small, rose continuously for 7 months, and then fell slightly during the last seven months. A computer model predicts the charging of the insulators by the high energy electron flux; It took 1 to 6 months for the electric fields to approach steady state levels. Most of the pulses were less than 50 volts on 50 ohms. The pulsing rate decays when the satellite leaves the electron belts; the decay became more rapid after 7 months. Pulsing during the first six months had different characteristics than later pulsing.

Introduction

The Internal Discharge Monitor, IDM, has previously been described at length [1-3]. The IDM has been flying on the CRRES spacecraft and sampling insulator discharge pulses from 16 samples for 14 months. The instrument has worked nearly flawlessly and has recorded a total of approximately 4300 electric pulses from the 16 samples. The time of occurrence of each pulse is known within 32 seconds and can be compared to the space radiation spectra which is being simultaneously recorded by several radiation spectrometers on the same satellite. We find patterns of pulsing which are characteristic of the kinds of insulator materials and the electrode geometries. Even at the low radiation fluxes experienced by CRRES we see occasional pulses.

The experiment exists to see if radiation-induced pulsing does occur in space at the low fluxes there, and if so, how often. It seems possible that dark conductivity would prevent pulsing at low flux levels.

Since the previous report [1], which was written once the insulators had produced 660 pulses, the radiation belts have been active and another 3640 pulses have occured. We have collected enough pulses that now the patterns of pulsing amongst the samples can be differentiated. We see several phenomena that have been seen in the laboratory on a much shorter time scale, and some that are new to us.

The Samples and The Apparatus

Figure 1 describes the sample-electrode geometries. The planar samples are approximately 5 cm by 5 cm in size. The wires are about 20 cm long. Table 1 is a brief presentation of the sample materials and their pulsing histories. The samples were chosen to represent typical spacecraft electronic materials. Ground testing "proved" that pulsing does not occur in the instrument under radiation when the samples are removed.

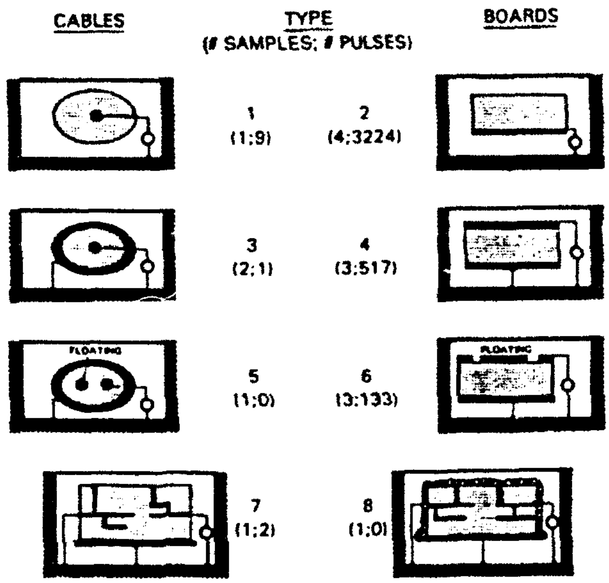

Fig. 1. Sample-Electrode Geometries. The small circles indicate the 50 ohm pulse detectors, heavy lines indicate metal electrodes. Each sample is contained in it's own "grounded" aluminum box. See Refs. 1-3 for details.

The apparatus, complete with samples attached, was tested for noise and crosstalk. One week of round the clock on-the-ground monitoring during the most noisy operations by all instruments on the satellite found not one detected pulse on IDM. Satellite operations did not produce a false count. Crosstalk between samples was measured by impressing a known 5 nsec. pulse on one sample at a time while looking for responses by the other samples. Previous testing [2] indicated that nearly all pulses are 1 to 10 ns wide and up to 100 volts high.

Crosstalk produced simultaneous pulse detection in two or more channels when only one channel experienced a real pulse. Crosstalk was seen to occur only between certain channels at pulsed voltages above 25 volts. The pattern of crosstalk in space mimicked that which was measured on the ground, and is used to discern the number of pulses exceeding the voltage threshold for producing crosstalk. Additionally, the instrument reported all of its data every 32 seconds and thereby continuously demonstrated that it worked correctly. Every day it automatically applied four pulses to each channel, one at a time, in order to test its operations. It failed to cleanly record only about 0.2% of these test pulses, a negligible number, and the failures were randomly distributed.

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TABLE 1. Description of IDM Samples with verified pulse count. The indicated dimension is the thickness of the insulating material. V is the maximum pulse voltage during pre-flight ground tests [2]. GEO is the number in figure 1 corresponding to the geometry of electrodes and sample. PULSE is the number of pulses accumulated within the designated voltage range in the 13 months of IDM operations in space, 25 Jul. 90 to 25 Sep. 91. IDM was turned off from 20 Dec. 90 to 20 Jan. 91 in eclipse during a period of weak electron fluxes.

CHA	SAMPLE DESCRIPTION	V	GEO	PULSES
1	SC18 WIRE TYPE ET, 7 mil PTFE	1	1	9, V<16
2	TS TRIAX CABLE, RAYCHEM 44/2421	5	5	0
3	MEP G10 SOLITHANE COATED ONLY	50	7	2, V<70
4	FR4 EPOXY FIBERGLASS, 0.317 cm	5	2	1433, V<25 16, 25<V<60 252, V>60
5	RG 316 CABLE, BELDEN 83284	0.5	3	0
6	SOLID AL JACKET RG402 CABLE	1	3	1, V<30
7	ALUMINA, 0.102 cm, Cu electrodes	40	6	0
8	FR4 EPOXY FIBERGLASS, 0.317 cm	1	4	516, V<45 1, V>60
9	FEP TEFLON, 0.229 cm, Al electr.	100	6	23, V<70 1, V>70
10	FEP TEFLON, 0.229 cm, Al electr.	0.2	4	0
11	PTFE FIBERGLASS, .229 cm, 3M "250"	1	4	0
12	FR4 EPOXY FIBERGLASS, 0.317 cm	5	2	903, V<40 2, 40<V<60 4, V>60
13	FR4 EPOXY FIBERGLASS, 0.317 cm	100	6	101, V<60 8, V>60
14	MEP G10 SOLITHANE, LEAKY PAINT	<1	8	0
15	FR4 EPOXY FIBERGLASS, 0.119 cm	0.25	2	294, V<40 19, V>60
16	PTFE FIBERGLASS, .229 cm, 3M "250"	0.2	2	280, V<30 2, 30<V<60 19, V>60

Pulsing Results

Amplitudes

We report the number and amplitudes of pulses in the "PULSES" column of Table 1. Pulses in the lowest voltage group were cleanly detected in the correct channel and are highly reliable pulse data. Pulses which were detected in two or more channels were identified with the aid of the laboratory-determined channel crosstalk data. These multichannel data are less reliable. But the multichannel data are a source of information on the larger pulse voltage amplitudes.

The occurrence of crosstalk has been a benefit because it has provided an indication of the distribution of pulse voltage magnitudes on 50 ohms. It also has allowed us to detect spacecraft anomalies when all 16 channels respond simultaneously. But the crosstalk problem prevents us from being able to say with certainty that some of the samples (channels 2, 5, 7, 10, 11 and 14) did not pulse. We only know that these samples have been seen to pulse in the laboratory where few irradiation hours have been logged. In space these samples have pulsed rarely, if at all, during 9300 hours.

The pulse count in Table 1 totals 3886 pulses. 186 additional pulses were counted but their channel is unknown because the telemetry in the satellite discarded the IDM data during periods when other experiments had priority. 206 additional pulses were detected in all 16 channels simultaneously and are tentatively identified as satellite anomalies. Finally, additional pulsing was seen in multiple channels which has not yet been related to any particular source: 7 pulses in 5 chs, 1 pulse in 6 chs, 6 pulses in 7 chs, 4 pulses in 8 chs, 4 pulses in 9 chs, 1 pulse in 10 chs, 0 pulse in 11 chs, 2 pulses in 12 chs, 3 pulses in 13 chs, 5 pulses in 14 chs, and 9 pulses in 15 chs.

Sample Pulse Histories

Fig. 2 displays all of the pulses which are associated with each of the 16 samples. Fig. 2 is in bar graph format with the height of each bar representing the number of pulses during one ten hour orbit. Remember, every sample is impacted by the same radiation flux.

Fig. 2 indicates that the pulsing results may be outlined as:
a) Geometries 1 and 2 pulsed early with a low rate.
b) Later, geometry 2 dominated the pulsing.
c) The TFE Teflon rarely pulsed after extended dosage.
d) Fiber-filled samples pulsed most frequently.
e) Geometries 3-6 rarely pulsed at early times, but pulsed moderately after sufficient accumulation of electrons deep in the insulator.
f) Accumulation of electrons deep in the insulator seems to be the major cause of pulsing. It took 600 orbits to accumulate the necessary charge density (see Electric Fields, below).

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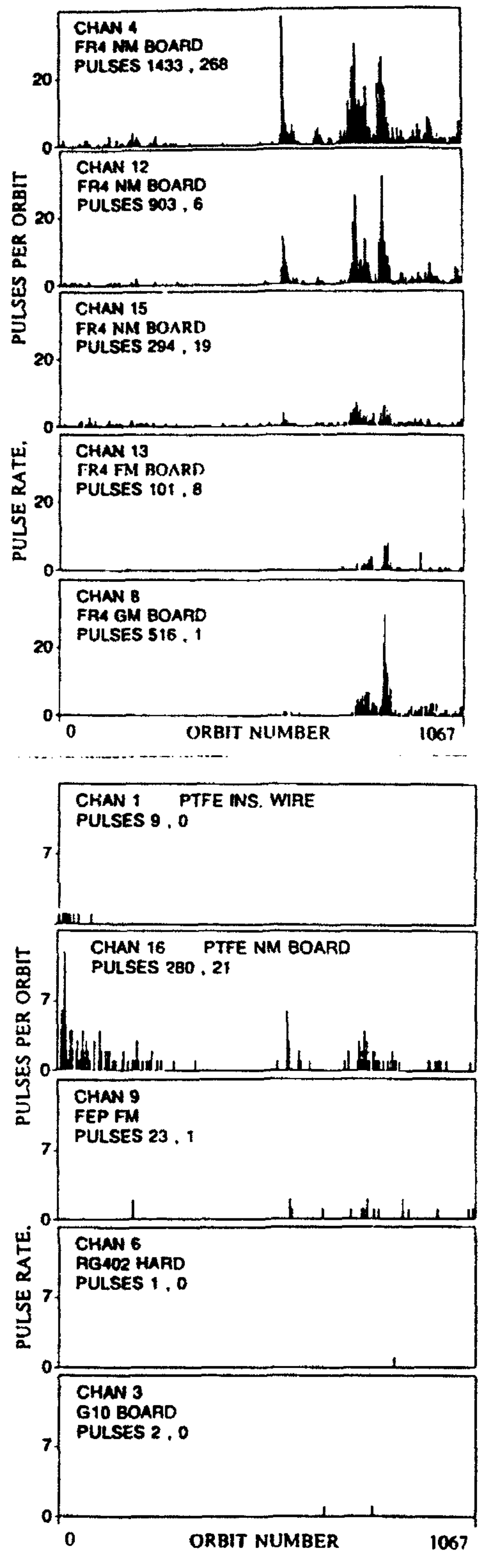

Fig. 2. Pulsing History of the Samples. The samples not shown never pulsed.

For those not familiar with the charge storage and pulsing properties of insulating materials, there are some similar ground testing results which provide a baseline for comparison. The results are compatible with the IDM results. The literature has been reviewed [4]. Additionally, a rich literature has developed concerning the fundamental physics of charge transport in insulators; we cite just three of the many examples [5-7]. TFE Teflon is known to rapidly become more conductive under irradiation [8]. FEP Teflon stores charge nearly "forever" [7] but does not pulse readily [1,9]. Fiberglass or other sharp protrusions are known to enhance pulsing rates in electrically stressed insulators [4,10].

Therefore, the physical basis for c, d, and f, above, are in the literature. Result f) is due to the fact that high electric fields strongly accelerate the pulsing rate. Result c) is due to the development of radiation-induced conductivity sufficient to leak off some of the incident electrons. Result d) is due to the high electric field strengths produced at the tips of the fiberglass needles. The remaining results, a, b and e may also be related to the form of the electric field, and are discussed below.

Dependence on Electron Flux

We have correlated the pulsing rate with power functions of the electron flux for orbits 575 through 1067. The power of the electron flux was varied from 0.001 to 1.5. The correlation coefficient was 0.49 at a power of 0.001, rose to 0.8 at a power of 0.25, and fell monotonically to 0.49 at a power of 1.5. Thus one may say that the pulsing rate, after orbit 575, varies as the fourth root of the electron flux.

There is evidence that the pulsing phenomena has changed. After orbit 575, the pulse rate per unit electron flux averages 5.8 times the pulse rate per unit flux prior to orbit 575.

Trends in Pulse Rates

We survey the statistically significant pulse rate data to see if other changes occurred. Fig. 3 shows scatter plots of the number of pulses in an orbit vs. the high energy electron fluence in the orbit. It is immediately obvious that there is not a tight relation between electron orbital fluence and the pulses per orbit. Some orbits with high flux produced only a few pulses. Orbits with ten or more pulses provide the best statistics.

Fig. 3 shows the four 100 orbit sequences wherein there were sufficient orbits with eleven or more pulses. To these orbits we fit the function $Y = a + bX$ (solid line), where:

Y = log of the number of pulses per orbit,
X = log of high energy electron fluence in the orbit, and
a and b are adjusted to the best least squares fit.

The results of the fit are:

orbits 601-700; $a = -19.3$, $b = 1.80$, $-a/b = 10.7$,
orbits 701-800; $a = -18.3$, $b = 1.73$, $-a/b = 10.6$,
orbits 801-900; $a = -11.1$, $b = 1.12$, $-a/b = 9.91$,
orbits 901-1000; $a = -8.3$, $b = 0.85$, $-a/b = 9.76$.

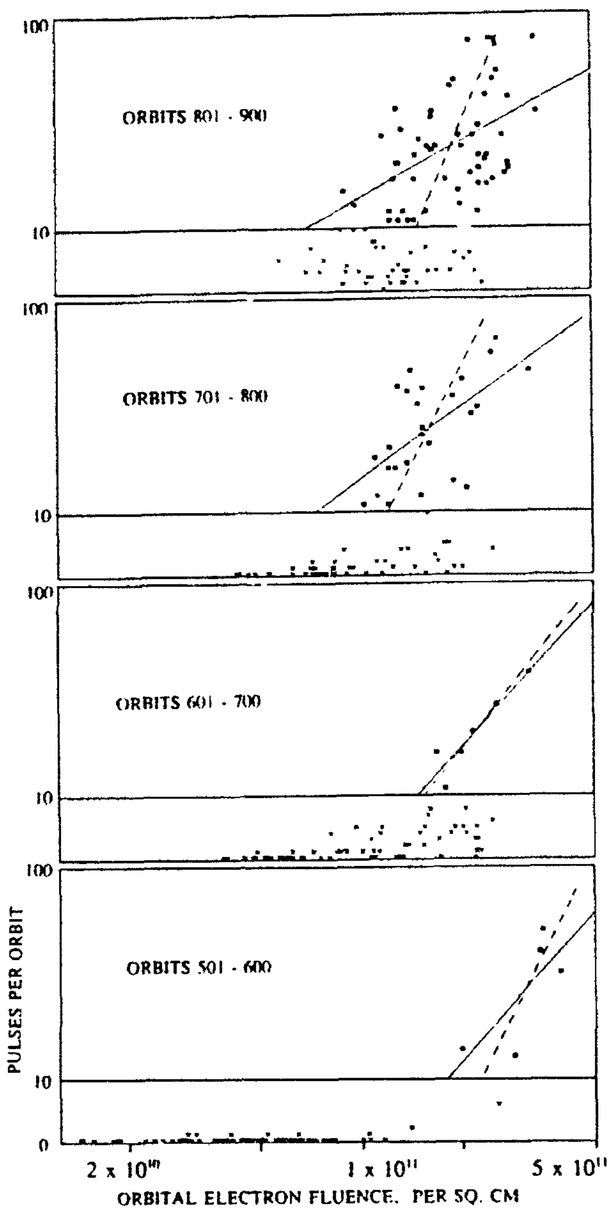

Fig. 3. Scatter Plots of Pulses per Orbit vs. Electron Fluence. The pulse count is linear for ten or fewer pulses, log for more than 10 pulses.

The dashed lines are least squares fits to $X = c + dY$. We refrain from comment at this time.

The fits to Fig. 3 show that the sample pulsing is changing in a consistent manner as time progresses.

1. The decay of b demonstrates that the pulse rate per unit flux is decaying with time.

2. The decay of -a/b indicates that the minimum flux required (at $Y=0$) to produce one pulse per orbit is also decaying. At first thought these two results might seem to be contradictory. However, laboratory testing provides the clues to "explain" this apparent contradiction [4].

It is well known that under constant high voltage stress, insulators produce fewer spontaneous partial discharges as time progresses. Perhaps a discharge site produces only one pulse under constant bias, and eventually all of the sites will have pulsed. Also as time goes on, the conductivity of insulators can either increase or decrease, depending on the generation of mobile charge carriers by radiation, or on the outgassing and trapping of mobile charge carriers, respectively. Perhaps the conductivity of our samples was decreasing so that changes in the space electron spectrum could more readily induce a new pulse by slightly increasing and/or changing the electric field profile in the insulator. Fig. 22 of Ref. 4 is an example that a small shift in the energy of the incoming electrons, without a change in flux, will produce many pulses in a sample which has ceased pulsing. Once a sample has been irradiated for a long time it may be that changes in the radiation produce most pulsing, continued steady irradiation may produce little pulsing. This phenomenon is similar to the well known partial discharge phenomenon in voids in insulators under 60 Hz AC stress.

This seeming contradiction impacts our ability to predict if pulses will occur on a spacecraft. On the one hand our pulse rate per unit flux seems to decay during a constant intensity irradiation. On the other hand the fluence needed to produce a pulse in one orbit is also decreasing. There are a number of phenomena even beyond those mentioned here that cause this to be a continuing dilemma. An exact prediction of pulse rates based on the high energy electron flux is not possible. Perhaps we can find a flux where pulsing is extremely unlikely, and shield to this level.

We draw a line above all the data which, when projected to the fluence axis, provides the maximum fluence per orbit which did not produce a pulse on the IDM samples. In order to avoid insulator pulsing, one might wish to avoid fluxes exceeding this level by the use of shielding. This fluence occurs at 2×10^{10} electrons per cm^2-orbit. The average electron flux during this 10 hour orbit is 5.5×10^5 electrons per sec-cm^2. Fluxes below this level are not likely to produce more than a few pulses per year. We found the same guideline in an earlier report [1]. However, this is not a guaranteed rule. The scatter plots show that the low flux orbits which produced no pulsing occurred early in the mission. The least squares fit lines at later orbits indicate that pulsing at even this low electron fluence is a possibility. Long exposure in space seems to have made the samples more sensitive.

Electric Fields

We achieve a significant improvement in our understanding of the pulsing phenomena by calculating the electric fields in the insulators. The fields can best be estimated for sample (channel) 8 where the boundary conditions are best known. We use a computer code [11] which has been well tested in the laboratory [4] to estimate the electric fields in the geometry of sample 8. We have recently tested it against the data of Zahn et. al. [12] with reasonable results for electric field strength.

We irradiate the sample, using the computer code to simulate it, with a series of monoenergetic beams to model the space spectrum which impacts our samples. The intensity of each beam is weighted according to a space-like E* form. At the low energies the intensity is attenuated and the energy is lowered by absorption in the 0.02 cm thick aluminum cover sheet. The effect of the cover sheet has been determined based on published data [13] and is in the process of publication elsewhere. Fig. 4 shows the simulated electric field strengths at the front and back electrodes for two dark conductivity levels (1/ohm-cm) and a coefficient of radiation induced conductivity of 10^{-17} (sec/ohm-cm-rad).

Note that the electric fields in sample 8 did not achieve the magnitude of 10^4 V/cm that is necessary [4] to begin pulsing until several months into the flight. This is what actually happened in sample 8 as described by Fig. 2.

The samples with floating surfaces (types 1, 2, 5-7 in fig. 1) are more difficult to model and we are proceeding with that now. Until then, we are uncertain about the magnitude of the surface voltage on all of the floating surface samples. We can use the pulse data to determine rough order of magnitudes for the changes in surface voltage which occurred during the pulses.

Assume a five nanosecond triangular pulsewidth [2], fifty volts on fifty ohms. Such a pulse produces a charge transfer of 2.5 nanocoulombs. The capacitance of the front surfaces of samples 4 and 12 to ground is 40 pF. The change in surface voltage during a pulse is therefore roughly 2.5 nC/40 pF = 62 Volts. This seems to be rather small considering that MeV electrons were involved in creating the charged insulator.

Considering the laboratory tests with 20 keV electrons and the scaling laws of Balmain [14], this low voltage (62 V) indicates that either IDM pulses never substantially lowered the voltage of the surfaces, or the surfaces were never charged more than several hundred volts. Pulses from samples irradiated by 10 to 50 keV electron beams in the lab almost always experience substantial collapse of the surface voltage, at least several kV, during a pulse. We don't know why these MeV irradiated samples in space and on the ground [1] produce only small surface voltage decay. We hope to model this feature using the computer code.

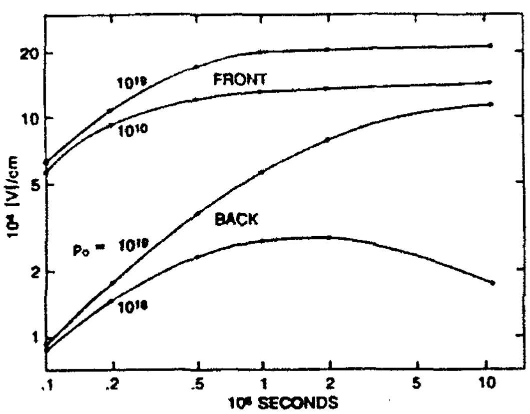

Fig. 4. Calculation of Electric Field Profile in Sample 8 for Typical E^{-4} Electron Energy Spectrum at Several Times.

Conclusions

1. Spontaneous pulsing of electrical insulation is common in the space electron belts when the electron flux at the surface of the insulation exceeds five nanoamperes per square meter. The pulsing rate is crudely proportional to the electron flux above this level.

2. We see no evidence for proton-induced pulses, but this is due to the overwhelming strength of the electron fluxes. Proton effects, if any, would be measurable only by samples confined to the proton belts.

3. The pulsing statistics have changed over the 14 month exposure. During the first seven months, the pulsing built up and decayed slowly as the satellite entered and exited the electron belts. The time constant was roughly ten hours. After the seventh month the time constant had decayed to an hour or less.

4. Only about ten percent of the pulses exceeded 50 volts on 50 ohms.

5. The TFE Teflon ceased pulsing after extended exposure to radiation, of the order 10^6 rads.

6. Seven months were required to bring the samples up to maximum steady state electric field intensity. After this time the pulse rate averaged almost six times more than during the first seven months, on a per unit electron flux basis.

7. The relationship between pulse rate and electron flux is weak. We correlated the pulses per orbit with the electron fluence per orbit. The pulsing history for all samples summed together correlates best with the 0.25 power of the electron flux.

8. After steady state electric field strength is achieved, the number of pulses per unit electron flux appears to decrease slightly.

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