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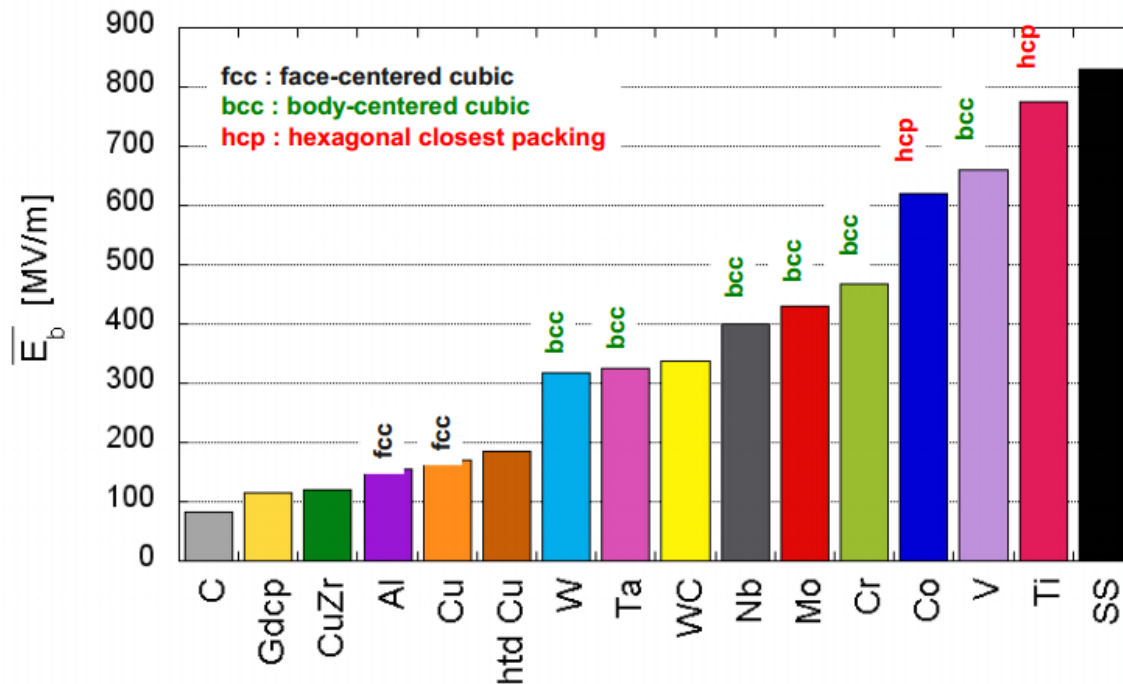
DC Spark Experiments

Nick Shipman, Sergio Calatroni, Tomoko Murunaka,
Walter Wuensch

Why study breakdown in a DC System for CLIC

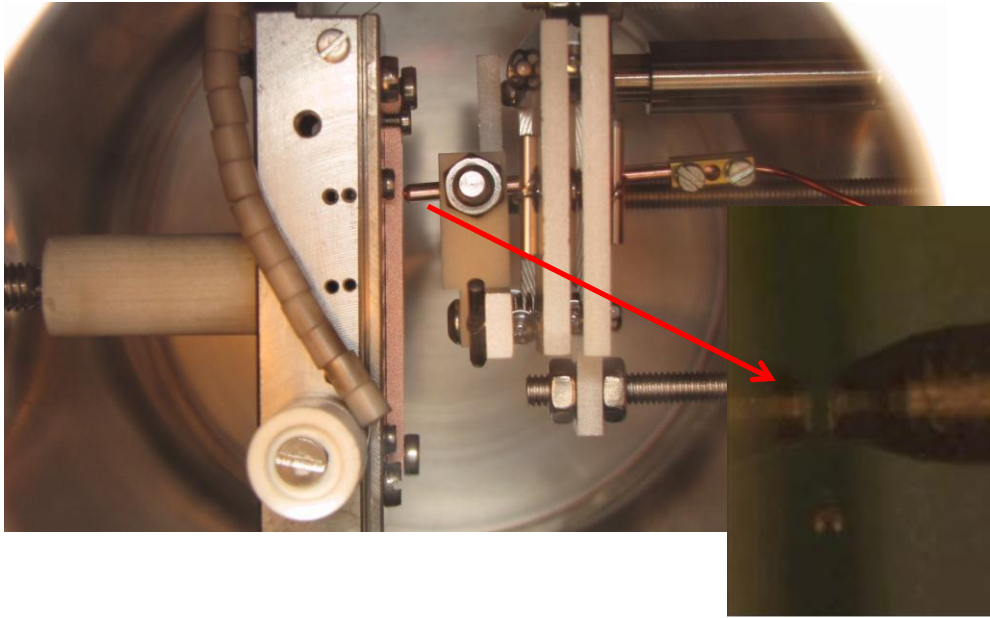
RF tests are expensive and time consuming. DC tests allow many more tests to be carried out.

The physics in DC tests is also simpler, no pulse surface heating, pre-breakdown magnetic fields etc. In order to understand the physics of RF breakdown, DC breakdown must be understood first!



For example it would never have been practically possible to get this lovely plot using only RF tests.

What are the CERN DC spark systems?



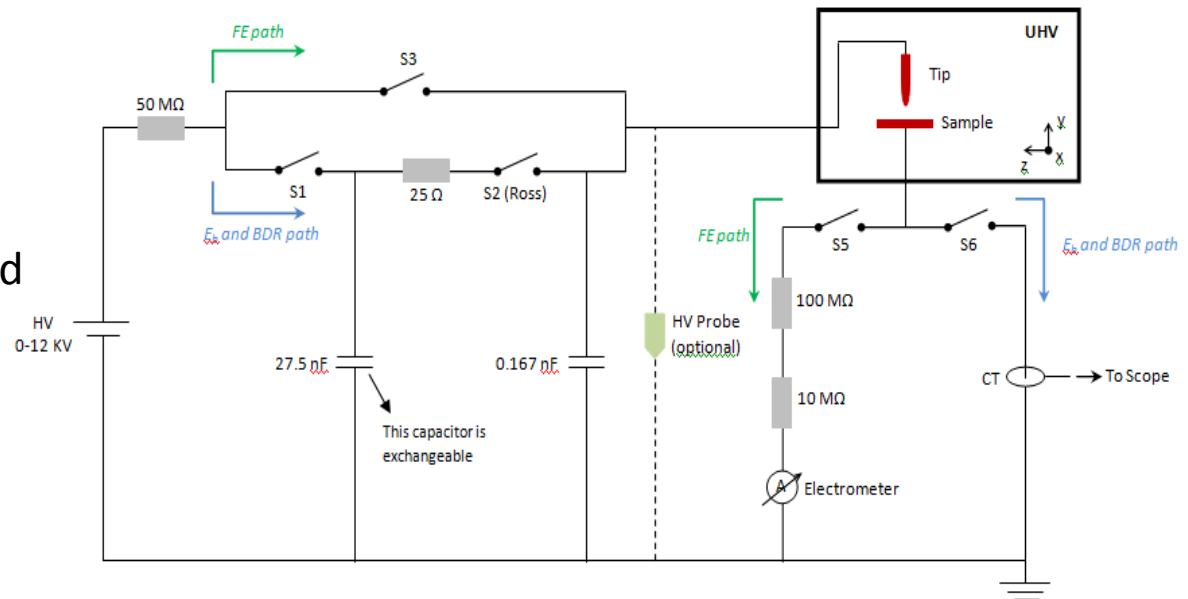
There are two systems which consist of an anode and cathode in a rod-plane geometry in ultrahigh vacuum.

The gap size can be varied but is typically 20 μ m.

The diameter of the anode is 2.3mm and has a rounded tip.

A high voltage can be applied to the tip using a mechanical relay.

By applying lower voltages and using a sensitive electrometer field emission currents can also be measured. These measurements enable us to calculate Beta.



Three limitations of the spark systems

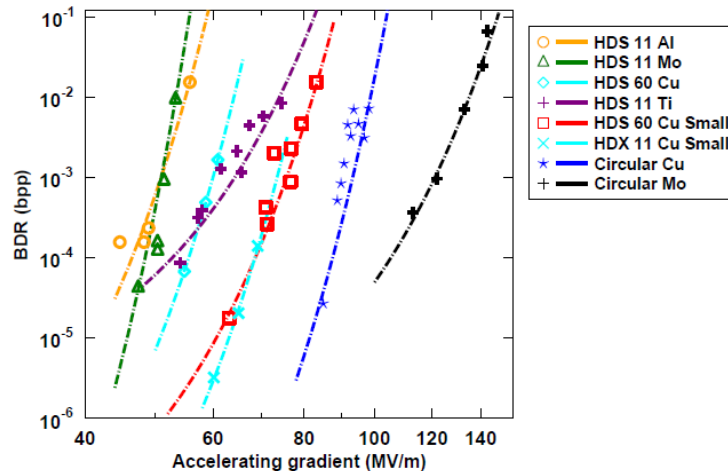
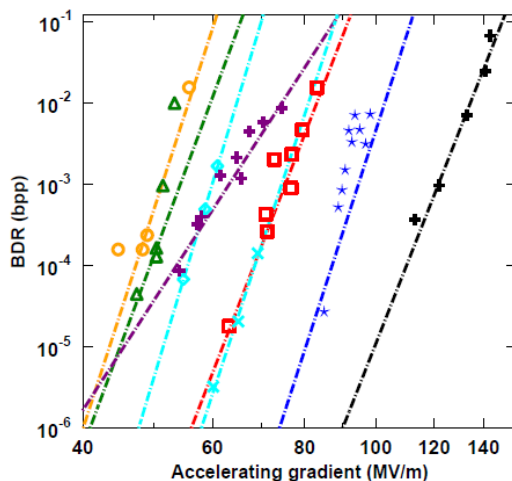
1. Low repetition rate
2. Only a small area of the cathode is exposed to high fields.
3. Slow, contact, measurement of the electrode gap

The High Repetition Rate (HRR) System

Motivation behind the HRR system

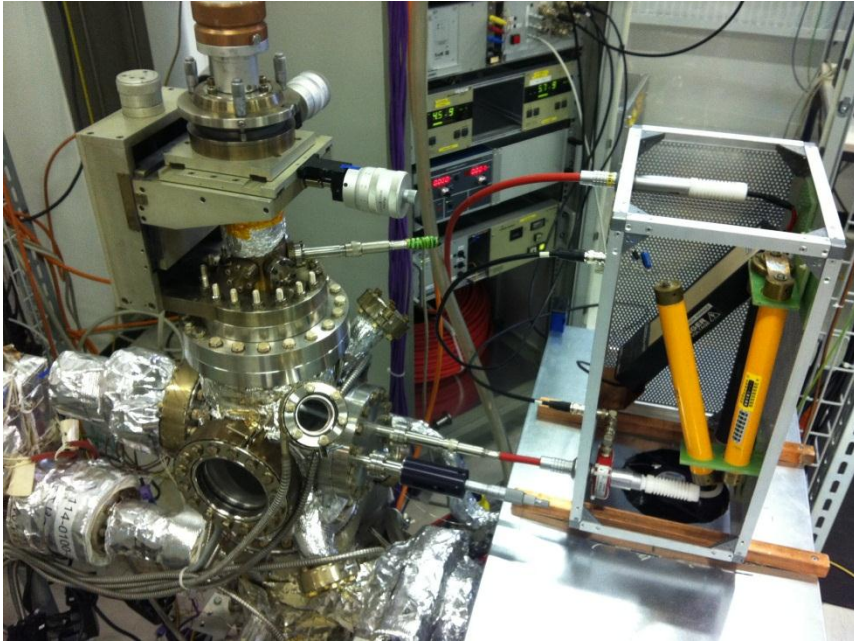
- CLIC is interested in the low breakdown regime $\sim 10^{-7}$ BDs/pulse/m.
- With the mechanical relay the maximum operating frequency is only 0.5Hz.
 - $10^7/0.5\text{Hz} \sim 7.7\text{months}$
- By using a solid state switch the HRR system can operate at 1kHz
 - $10^7/10^3\text{Hz} \sim 3\text{hours}$

$$BDR = Ae^{\varepsilon_0 E^2 \Delta V / kT}$$



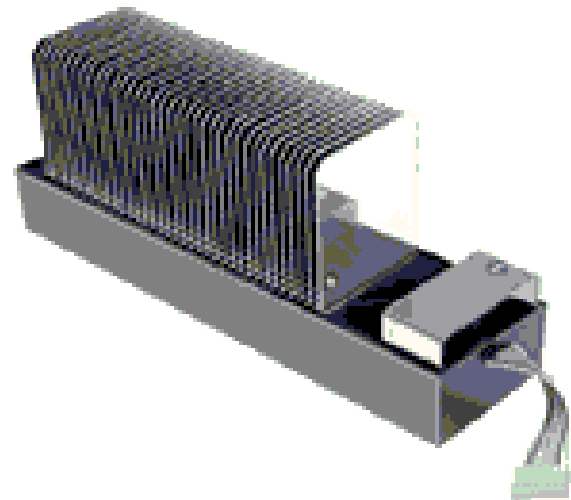
We should also be able to test the BDR vs. E scaling theory proposed by Fluyra Djurabekova .

The High Rep Rate System



The picture below shows the HRR system. The metal box housing the switch is placed as close as possible to the vacuum chamber to minimise stray capacitance.

The solid state switch used is the Behlke 181 25-B, which can operate at 1.8kHz handle an open voltage of 18kV and a peak current of 250 Amps.

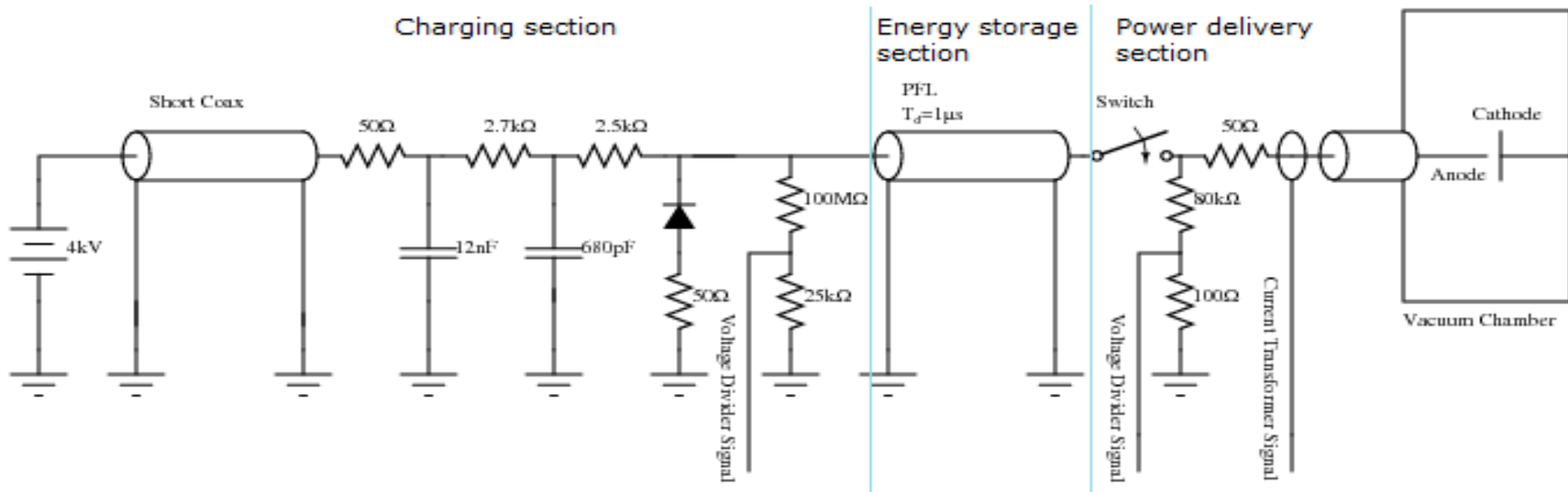


The High Repetition Rate System

Key Features

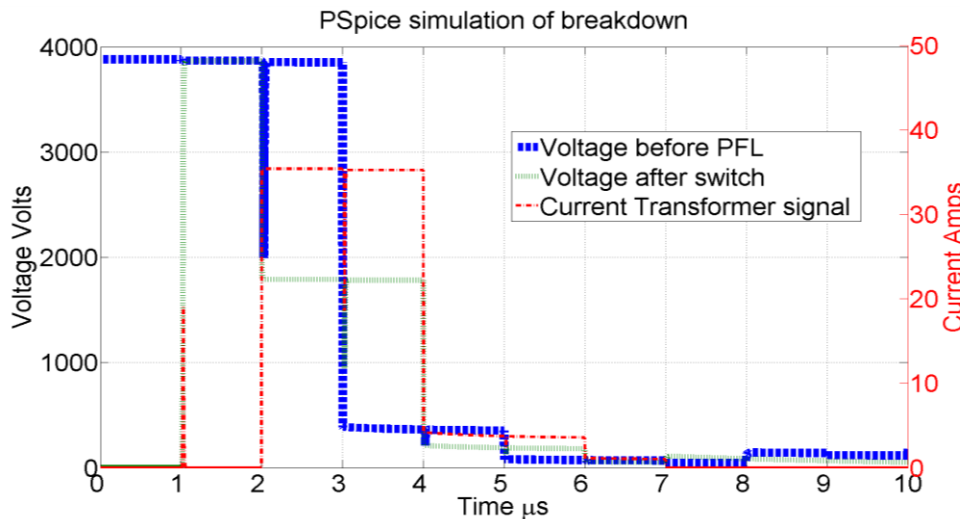
- Repetition rates of up to 1kHz
- Voltages up to 12kV (20um gap → 600 MV/m)
- High Bandwidth ≤ 10 ns
- Uses solid state switch
- Coaxial cables, and matched impedances used throughout
- Energy is stored on a 200m long spool of coaxial cable, the “Pulse Forming Line” or PFL.
- Replaces old 0.5Hz mechanical relay.

The High Rep Rate System

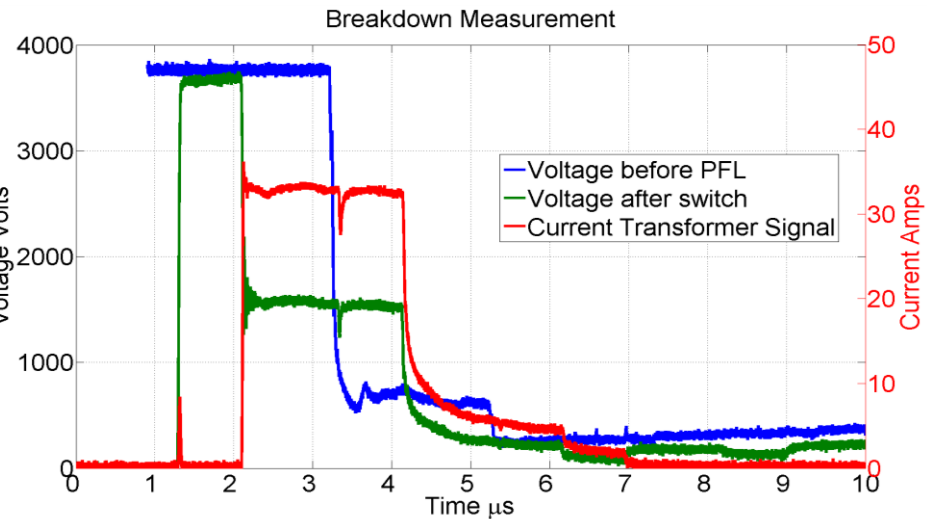


The circuit diagram of the HRR system. It can be thought of as consisting of three parts: the charging section; the energy storage section; and the power delivery section.

The High Rep Rate System

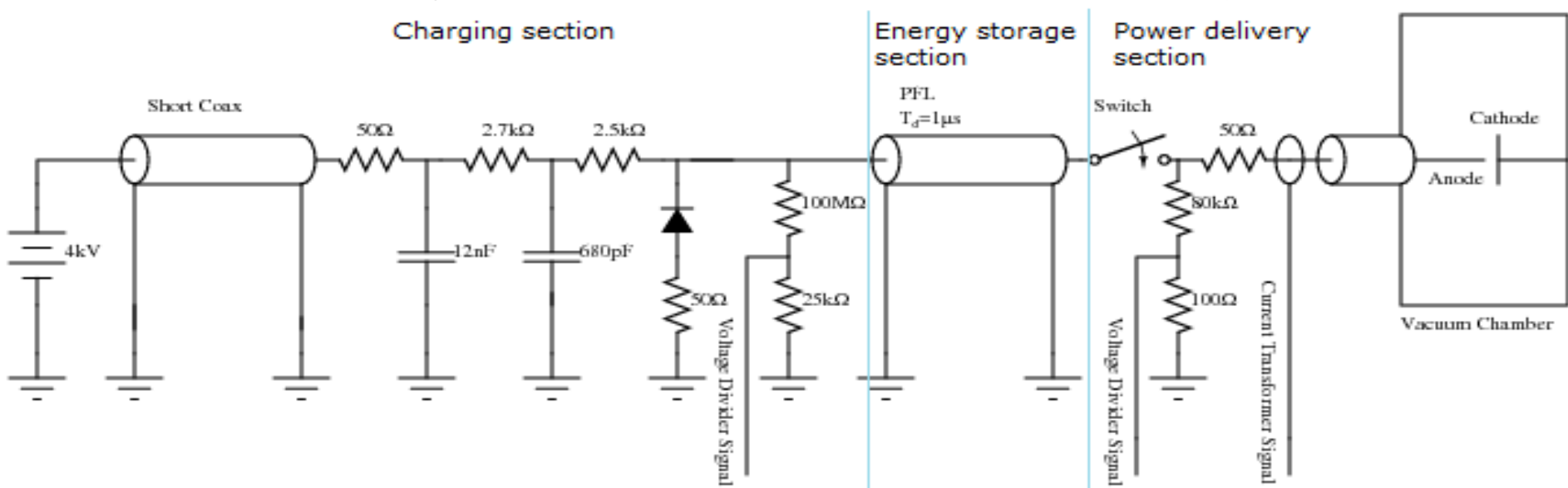
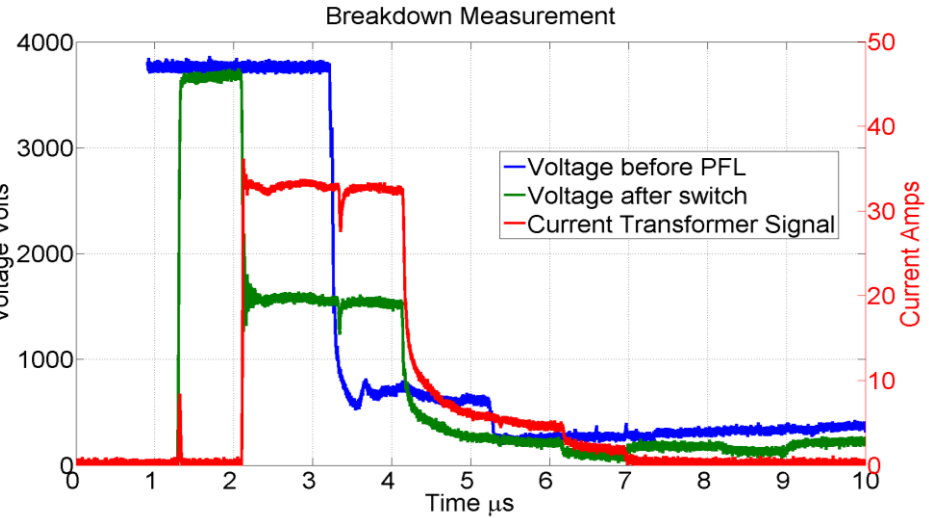
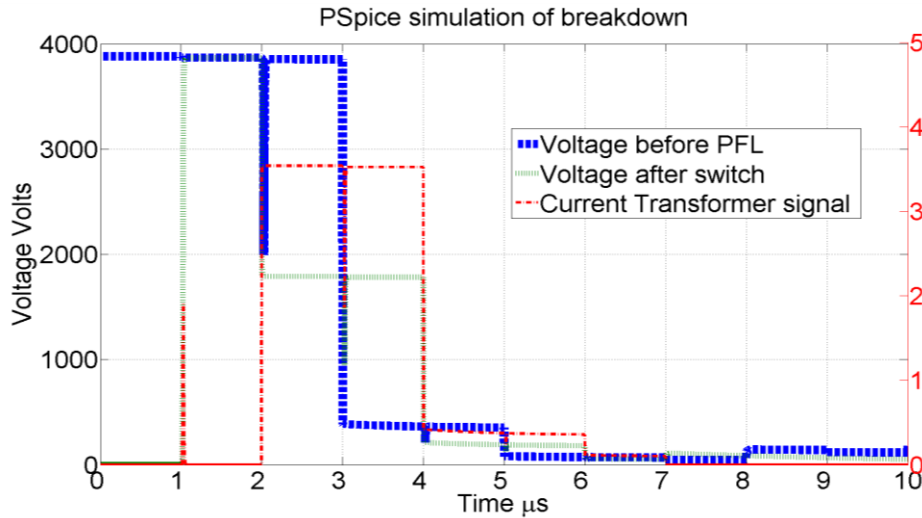


PSpice simulation of the HRR circuit during a breakdown. The switch is closed at 1 μs and the breakdown occurs at 2 μs .



Measured voltage and current signals in the HRR circuit during a breakdown. The switch is closed at 1 μs and the breakdown occurs at 2 μs .

The High Rep Rate System



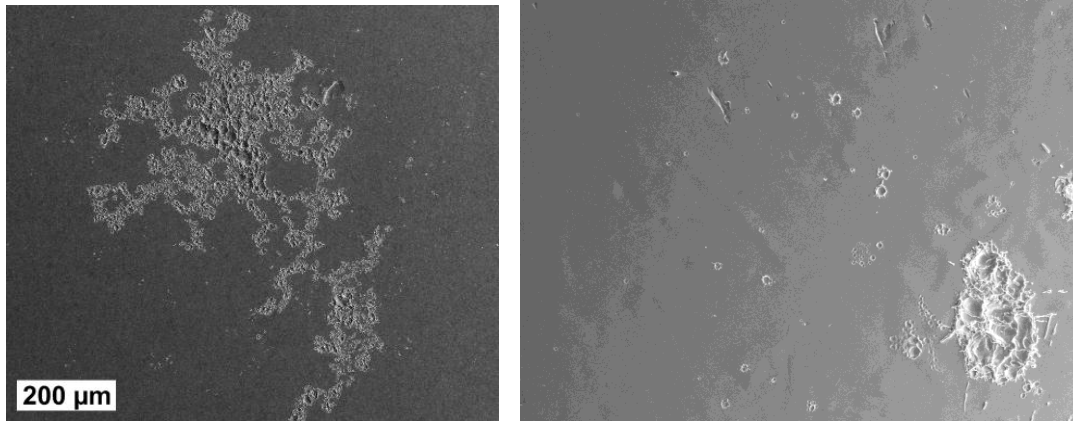
The Fixed Gap System

Motivation behind the fixed gap system

This fixed gap system solves two key issues...

1. There is no need to measure the electrode gap, it is fixed.
2. The surface area is very much larger, so hopefully breakdown will usually occur on “virgin” surface which hasn’t seen a breakdown yet.

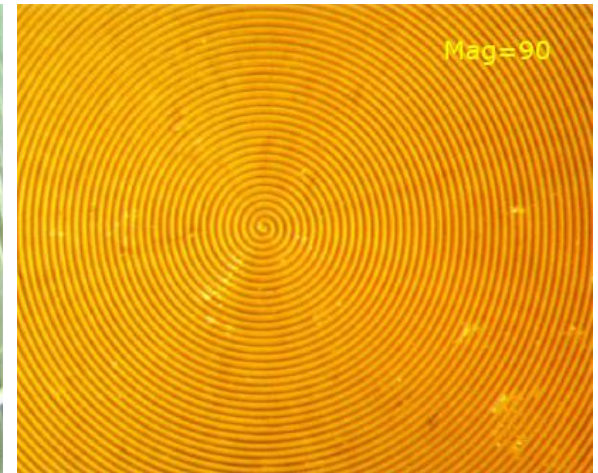
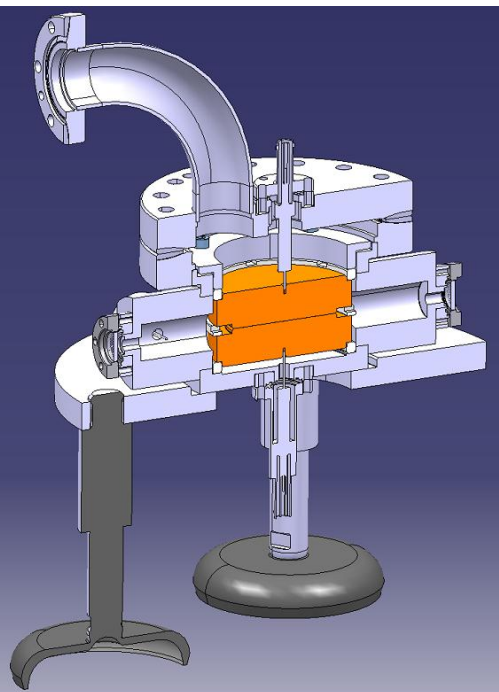
Also the system is very compact 30cm x 30cm. This will allow the whole system to be placed inside a 2T magnet we have at CERN, enabling us to study the effect an external magnetic field has on the BDR.



These SEM pictures well illustrate the difference in experimental conditions in RF tests (Right) which even after 100s of hours of testing shows minimal surface modification compared to just 5 breakdowns in the present DC spark system (Left).

The Fixed Gap System

Despite the comparatively large size of the anodes, the system is very compact. Four antennas are included in the design to pick up the radiation from breakdowns.



The surface of the electrodes are 80mm in diameter and have a surface tolerance of $<1\mu\text{m}$. The picture on the right shows the high precision turning.

The Fixed Gap System

Key Features

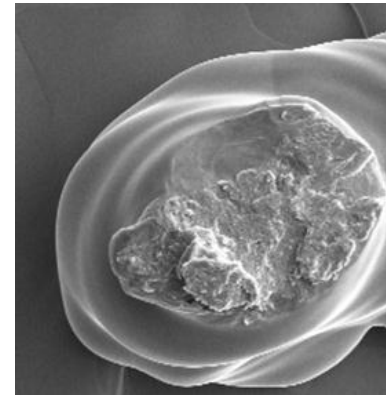
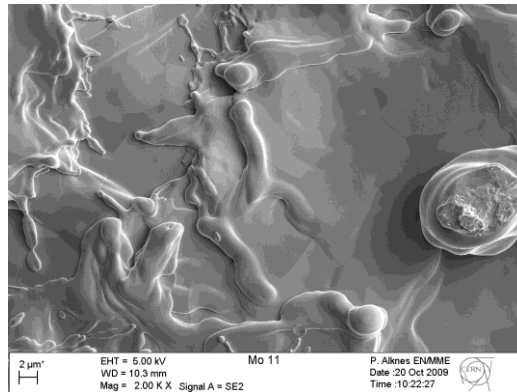
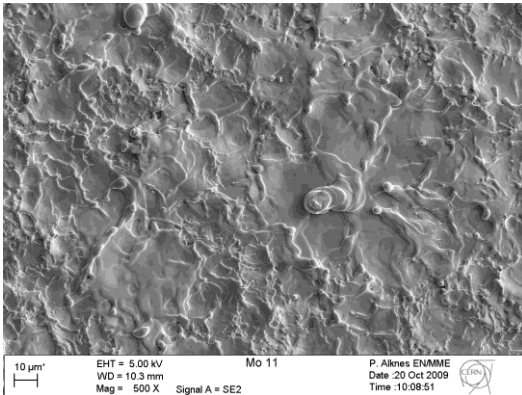
- Uses disc shaped electrodes with a large active surface area $\sim 50 \text{ cm}^2$
- Gap size is fixed eliminating the need for measurement.
- Gap size accurate to less than $1 \mu\text{m}$ across entire surface, even under large E-field stress (total forces of up to 500kg).
- 4 pick up antenna and 4 viewports
- Very compact, diameter $\sim 30\text{cm}$ height $\sim 30\text{cm}$.
- Electrodes are interchangeable.
- Ceramic spacer is interchangeable allowing different gap sizes to be selected.

Non-contact gap measurement

Motivation behind the non-contact gap measurement

For the “old” DC spark systems, a non-contact capacitive method has been developed to measure the electrode gap.

- This will avoid the need to touch the cathode avoiding any potential damage to delicate surface features which we may be interested in investigating.
- It will be automatic so it will also allow the gap to be measured more often and adjusted during an experiment if needed.

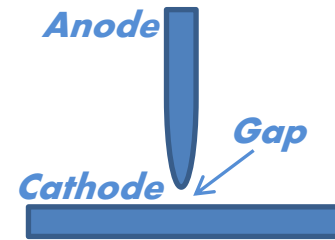


A SEM image shows jagged damage to the cathode. This must have been formed after the smoothed craters caused by breakdown, maybe by the contact gap measurement.

Non-contact gap measurement

Key Features

- For use with the tip and plane geometries of System 1 and 2, not needed for fixed gap system.



- Measures the absolute distance between the electrodes without them coming into contact.
- Relies on the accurate measurement of the very small capacitance between electrodes.
- A computer controlled stepper motor allows the measurement to be made automatically.
- Has been tested successfully in air and is now been installed on system II.

Results so far...

Measured Turn on Times

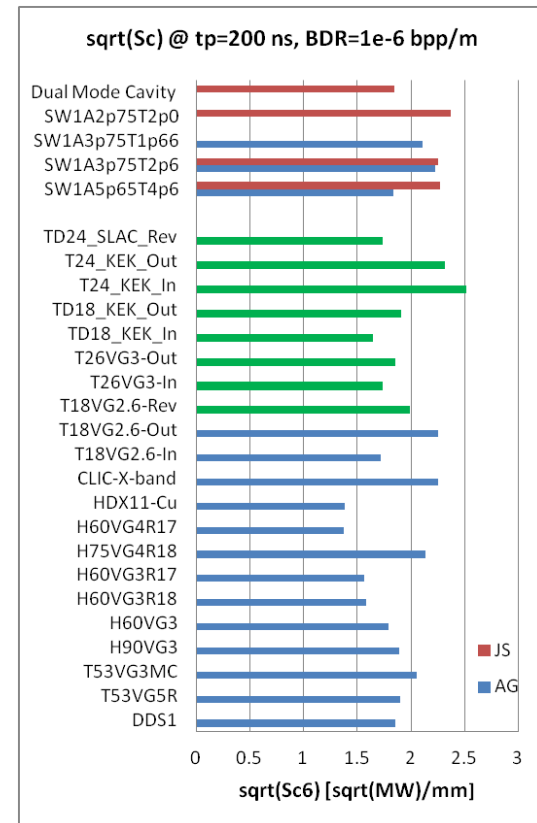
Firstly - why are we interested in turn on time?

RF tests indicate that low group velocity, and consequently narrow bandwidth structures are able to sustain much higher surface fields than high group velocity, large bandwidth, structures.

Further study has led to the idea that the process which governs the turn on time is the instantaneous power flow available to feed the breakdown during its onset.

In other words a high group velocity structure could more quickly replenish local energy density absorbed by a growing breakdown leading to faster turn on times.

An accurate measure of the rise time of breakdowns in the DC systems under electrostatic conditions is an essential precursor to understanding whether the transient response of RF systems to the breakdown currents determine breakdown limits.



For more background see references below

[1] C. Adolphsen 2005, "Advances in Normal Conducting Accelerator Technology from the X-Band Linear Collider Program", PAC 2005 pp.204-8.

[2] A. Grudiev, S. Calatroni and W. Wuensch 2009, "New local field quantity describing the high gradient limit of accelerating structures", PRSTAB, vol. 12, no. 10, pp.102001-1 -102001-9.

Secondly how we define the “Turn on time”

A simple transmission falling edge can be estimated by the following expression

$$\frac{E}{T} \approx (1 - \operatorname{erf} \alpha \tau) / 2,$$

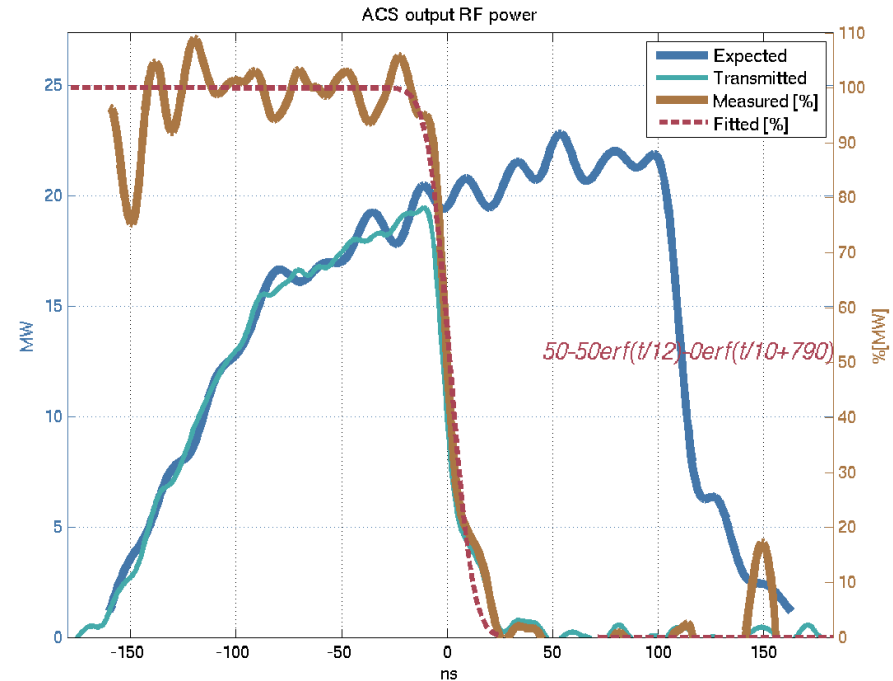
where τ is the time, α is a positive constant and erf is the error function:

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

The time $\tau = 0$ is the moment of the middle of the BD.

The fall time from 90% to 10% can be explicitly found

$$\begin{aligned} \gamma_{90 \rightarrow 10} &= \frac{2}{11\alpha} \operatorname{erf}^{-1} 0.8 \\ &\approx \frac{1.812}{\alpha} \end{aligned}$$



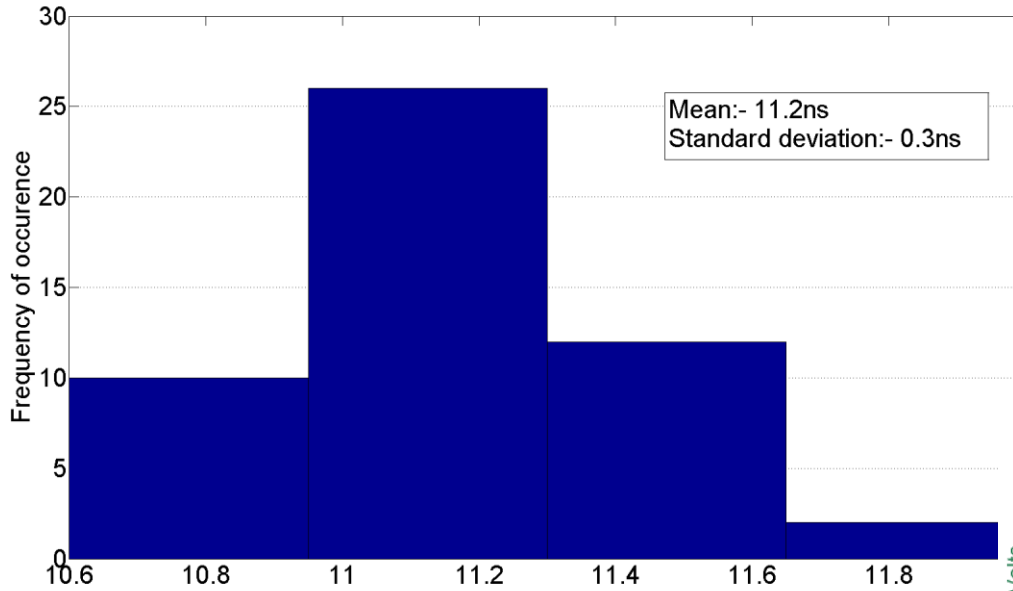
What we measure:-

- DC - voltage fall time
- RF - transmitted power fall time

Courtesy of Alexey Dubrovskiy

DC Spark System Turn on Time

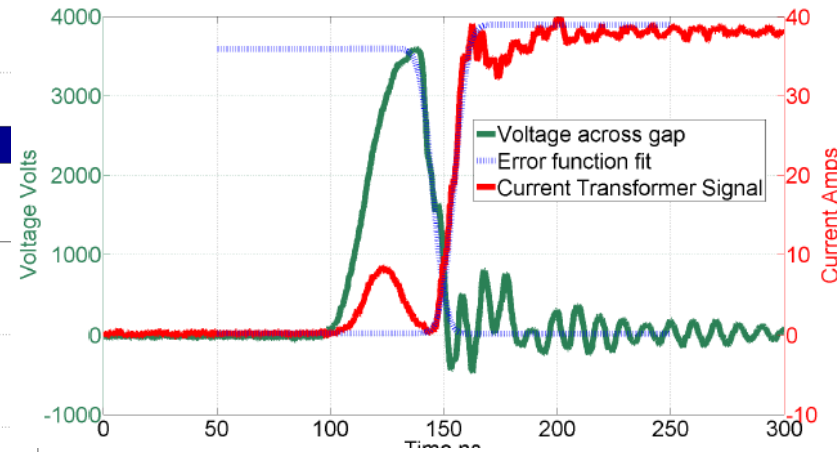
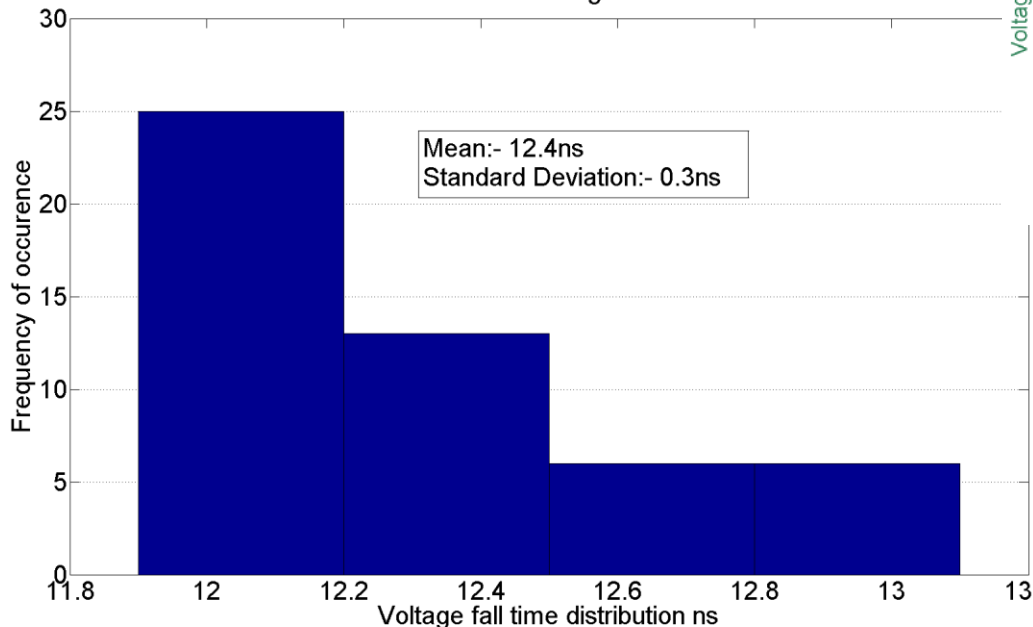
Distribution of current rise times



Sample size = 50

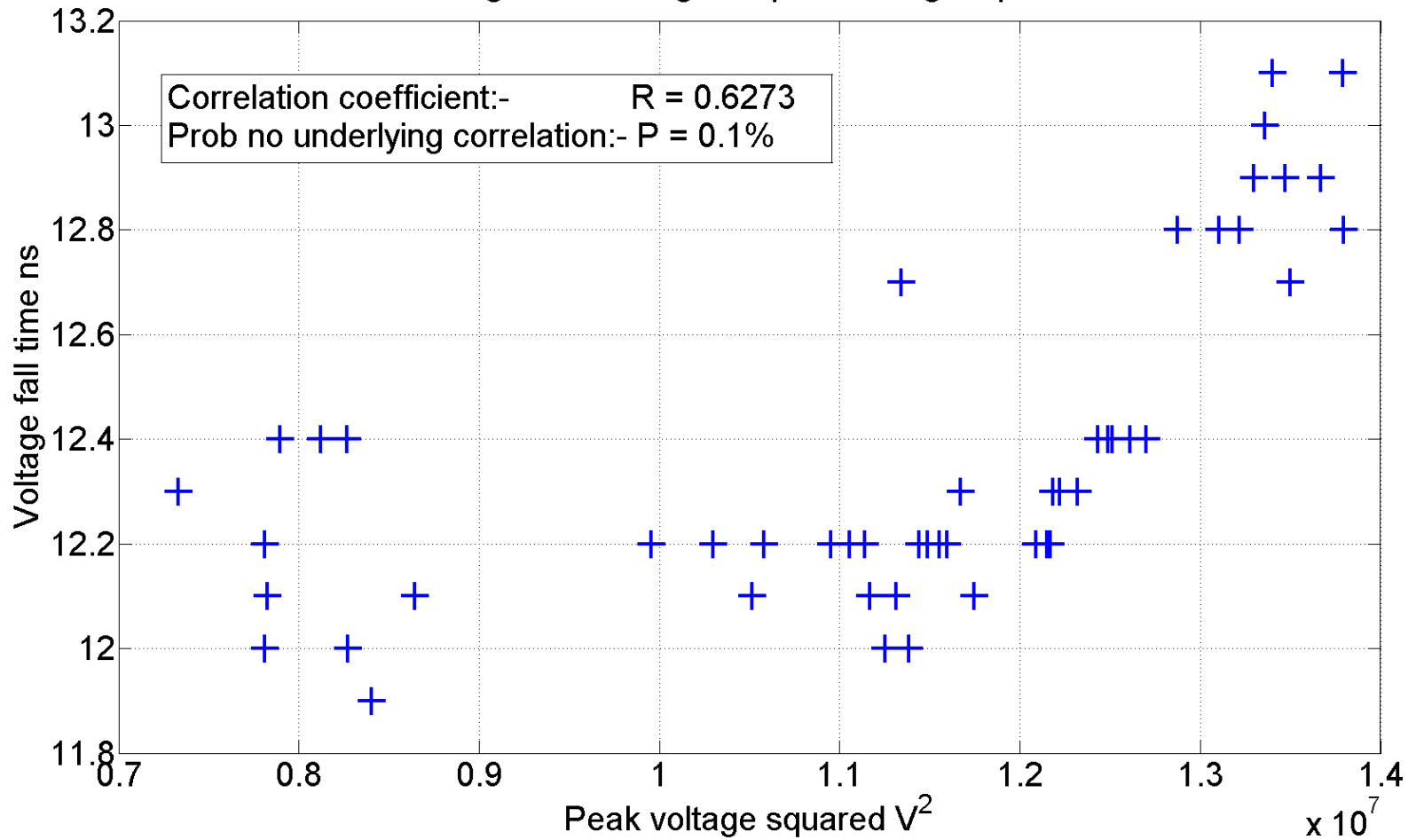
The spread in voltage fall times (and current rise times) is extremely small compared to the RF case.

Distribution of voltage fall times



The measured current rise time always shorter than voltage fall time due to initial charging current overlap.

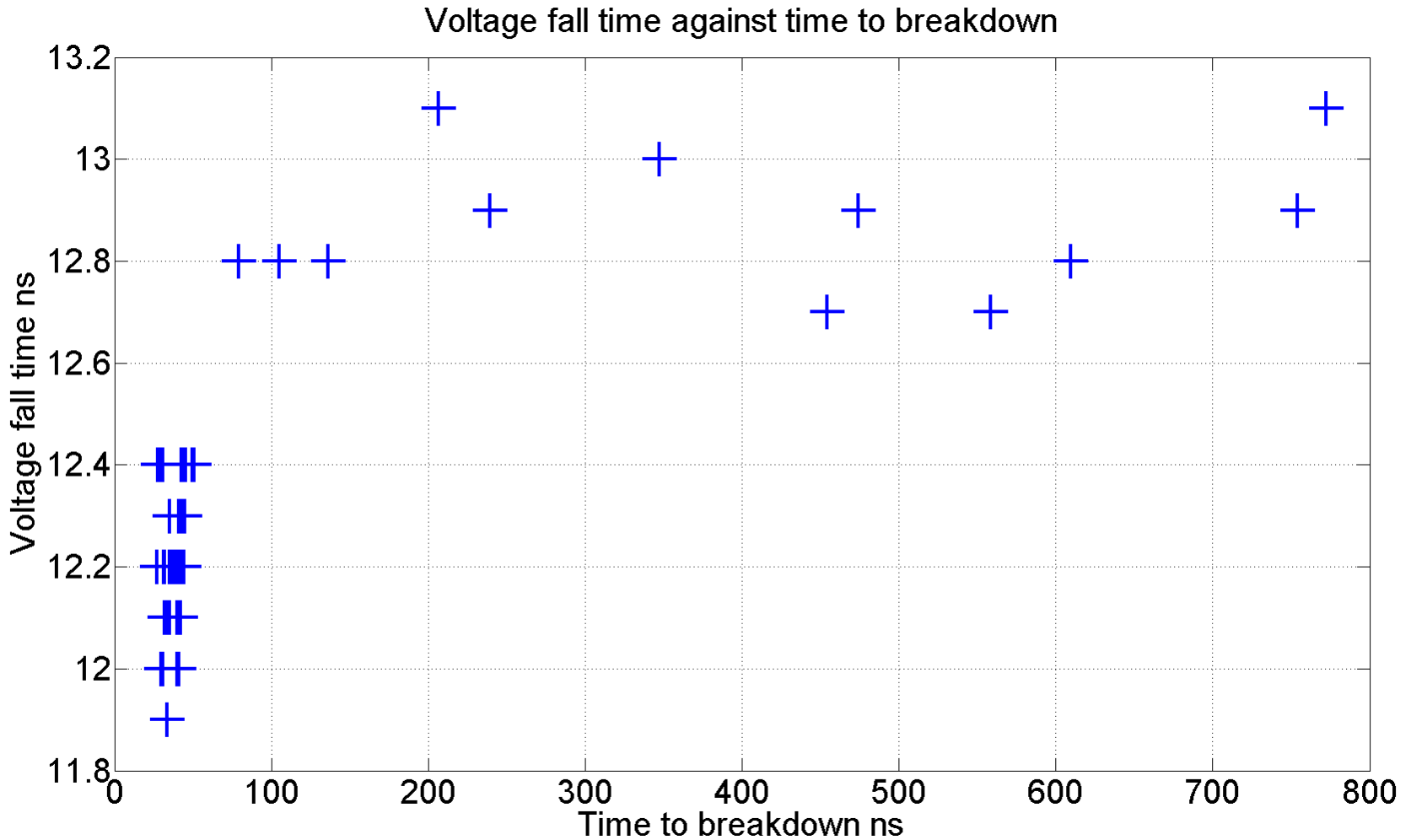
Voltage fall time against peak voltage squared



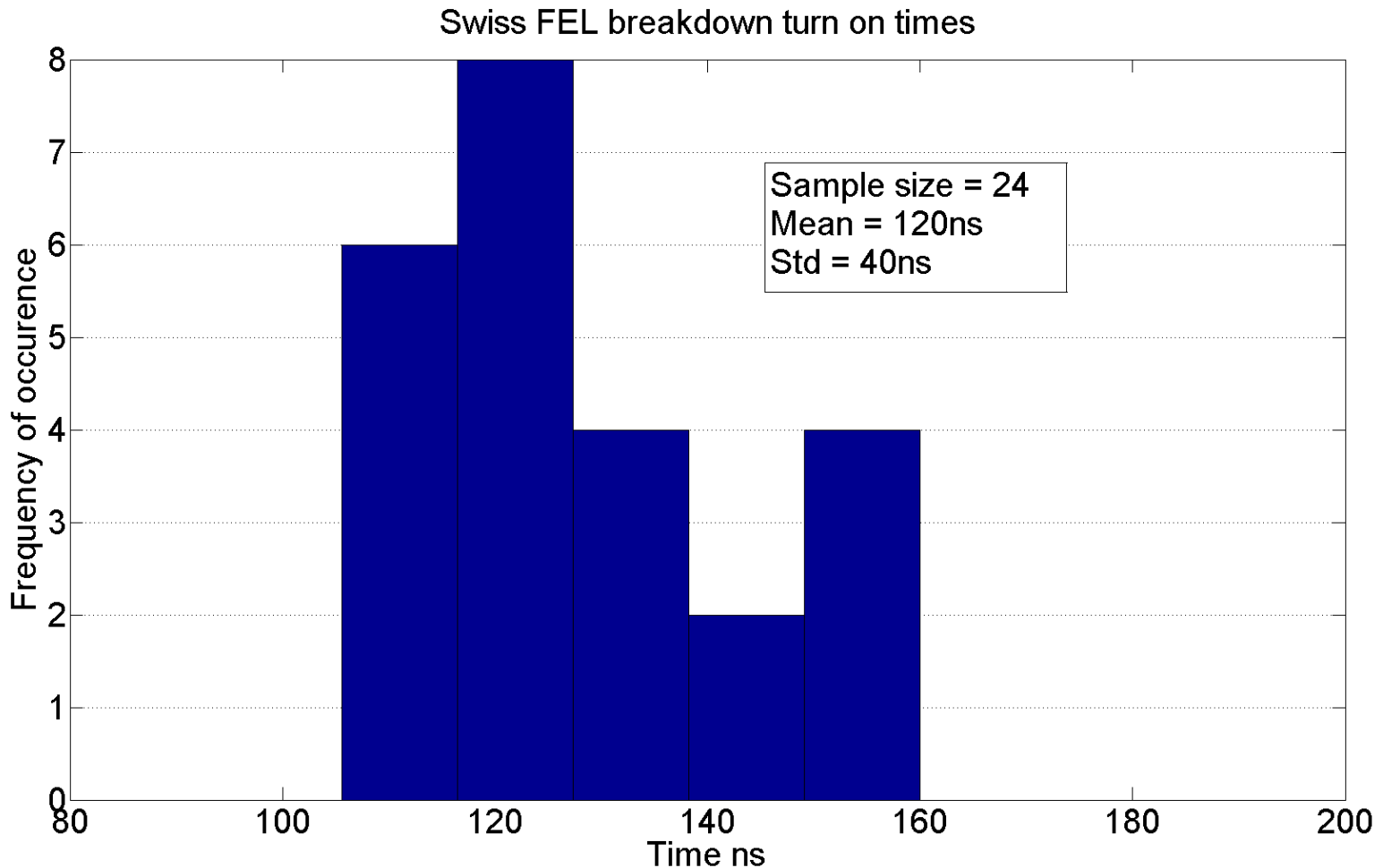
The power supply was always set at 4kV. However a breakdown often occurred before the voltage across the gap had reached this value.

The higher the gap voltage immediately before breakdown the longer the slope.

I had not expected to see any correlation as I expected the tiny variation in breakdown times to be dominated by noise or error.

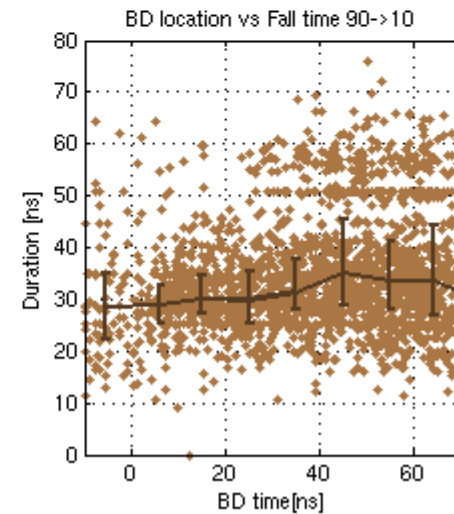
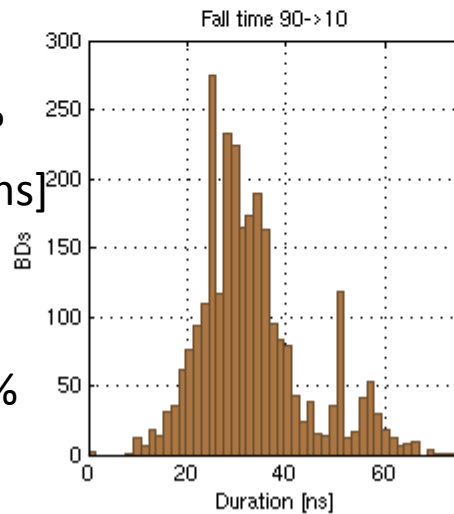
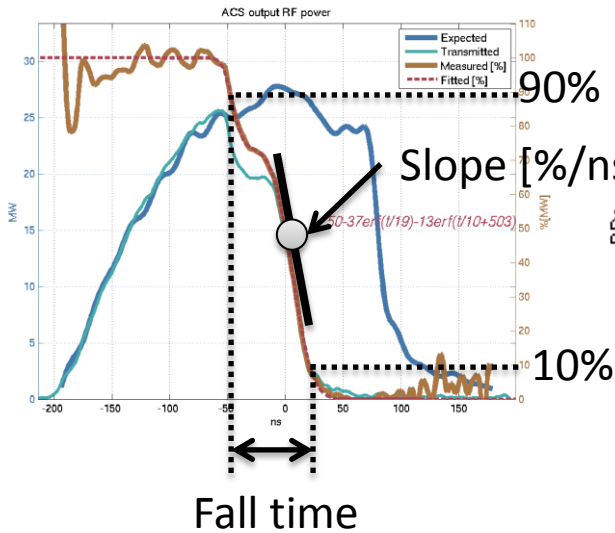
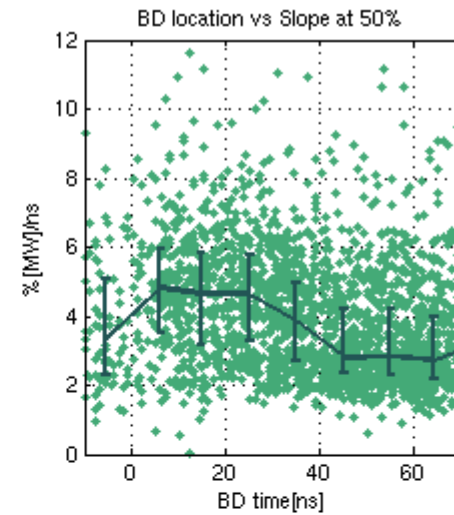
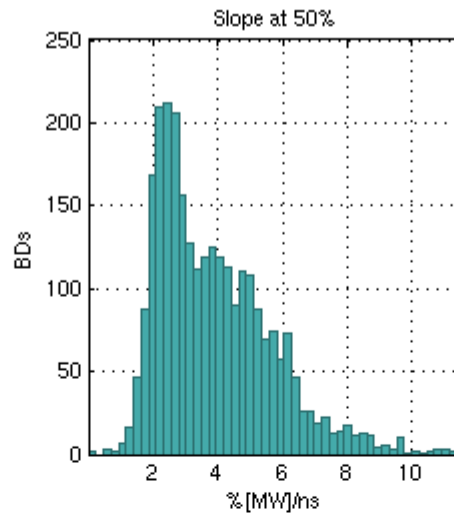
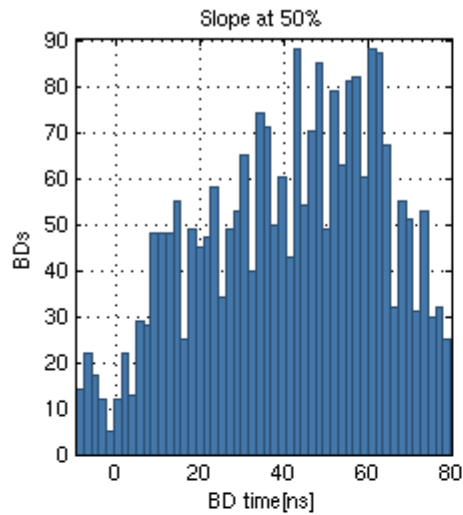


Where breakdowns occur very early the voltage across the gap is still charging up resulting in an increase in fall time.
 Once the voltage across the gap is fully charged there is no discernible difference in the voltage fall time.



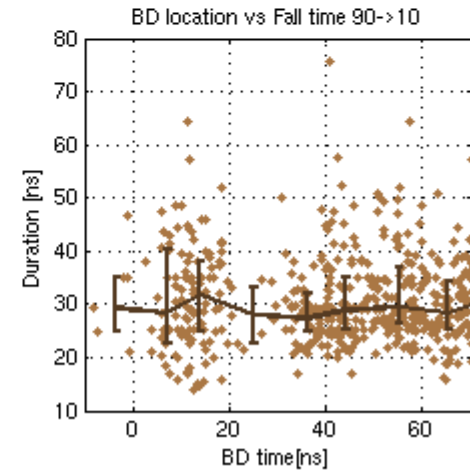
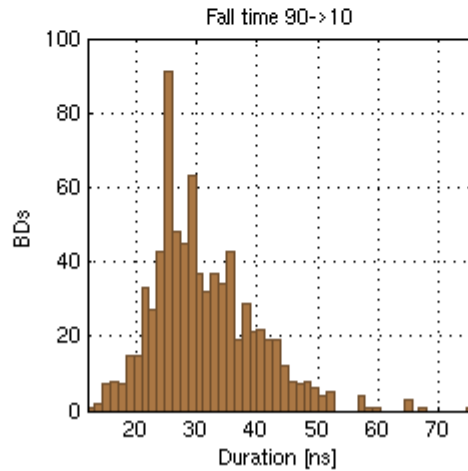
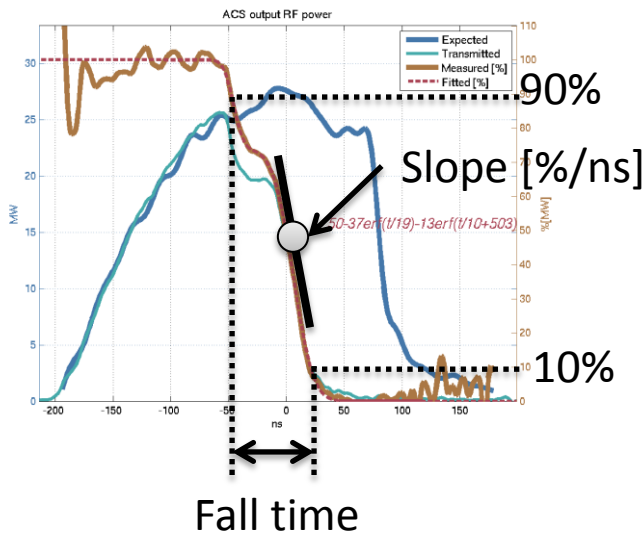
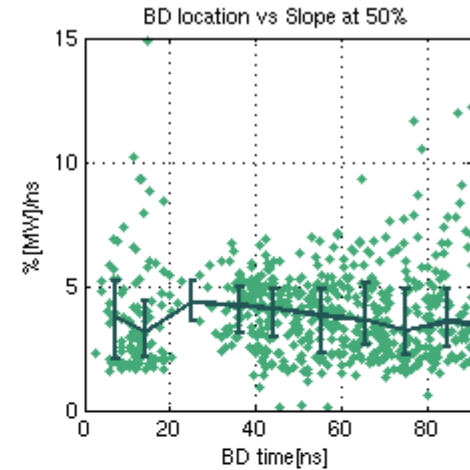
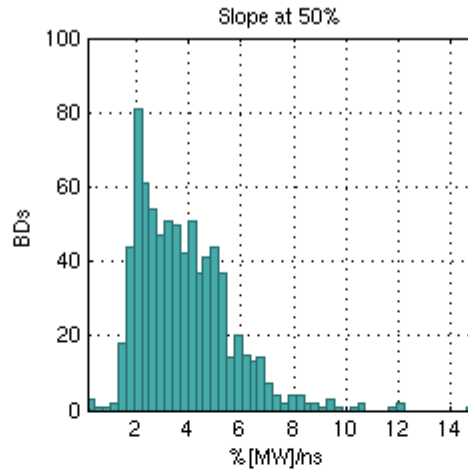
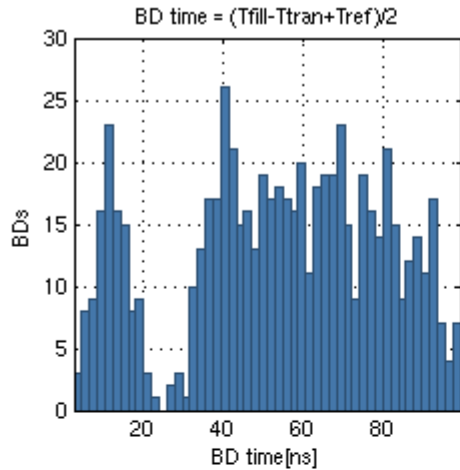
The Swiss FEL turn on times are much longer than in the DC case and the variation is much greater, this is keeping with other RF breakdown turn on time measurements.

Falling edge duration - TBTS



Slide courtesy of Alexey Dubrovskiy

Falling edge duration - KEK



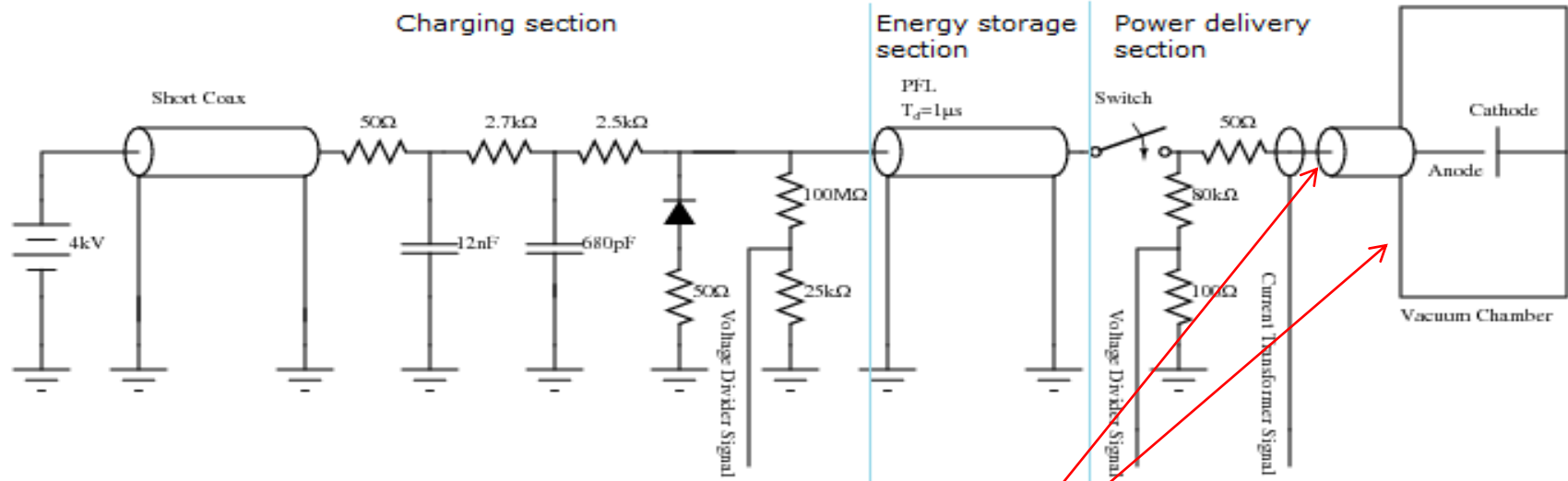
Slide courtesy of Alexey Dubrovskiy

Summary of turn on times

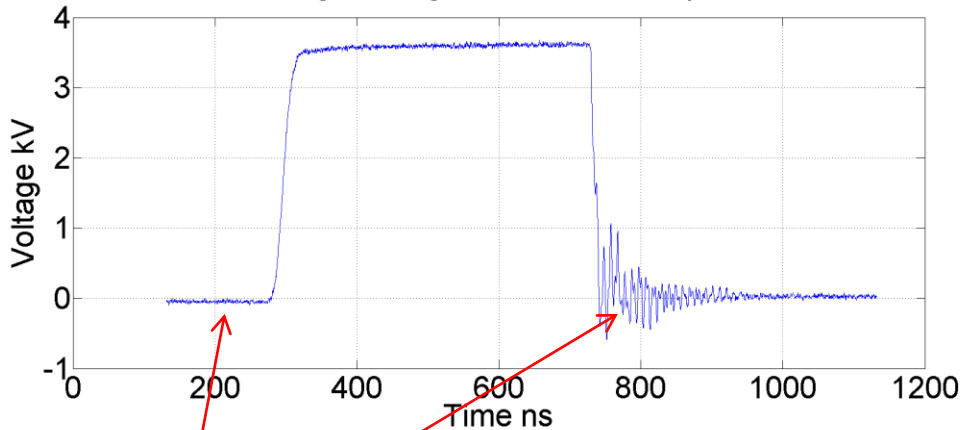
Test	Measurement	Result
Simulation		0.25ns
New DC System	Voltage Fall Time	12-13ns
Swiss FEL (C-Band)	Transmitted Power Fall Time	110 - 140ns
KEK (X-Band)	Transmitted Power Fall Time	20-40ns
TBTS (X-Band)	Transmitted Power Fall Time	20-40ns

Results so far...
Measured Burning Voltages

Measured Burning Voltages



Voltage during breakdown example 1

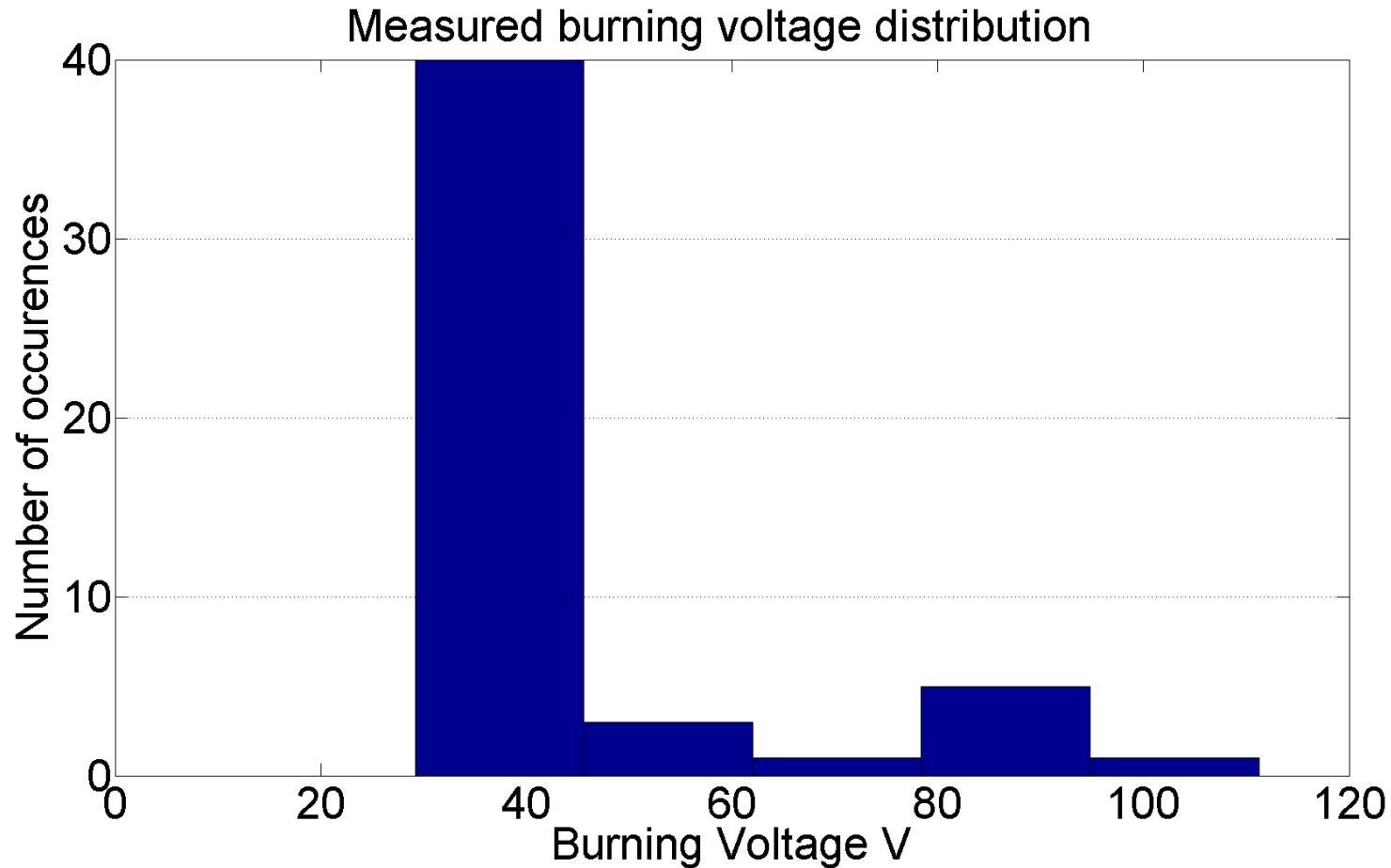


The burning voltage was measured across here.

It is the “steady state” voltage across the plasma of a spark during a breakdown at which point most of the voltage is dropped across the 50 Ohm resistor. It is a property of the material.

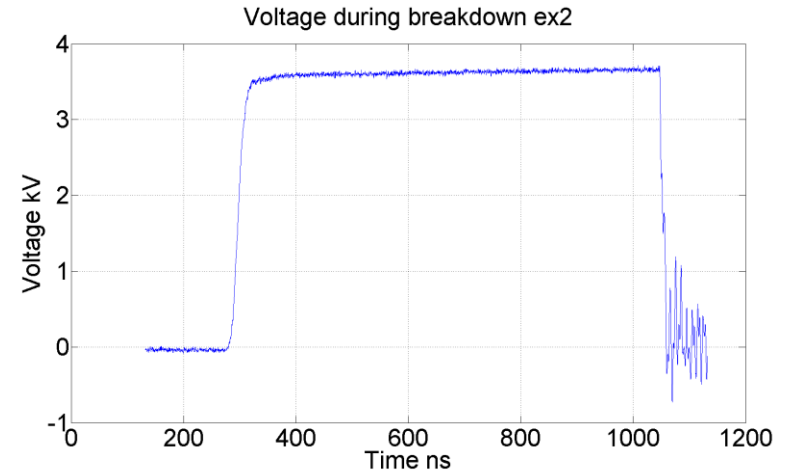
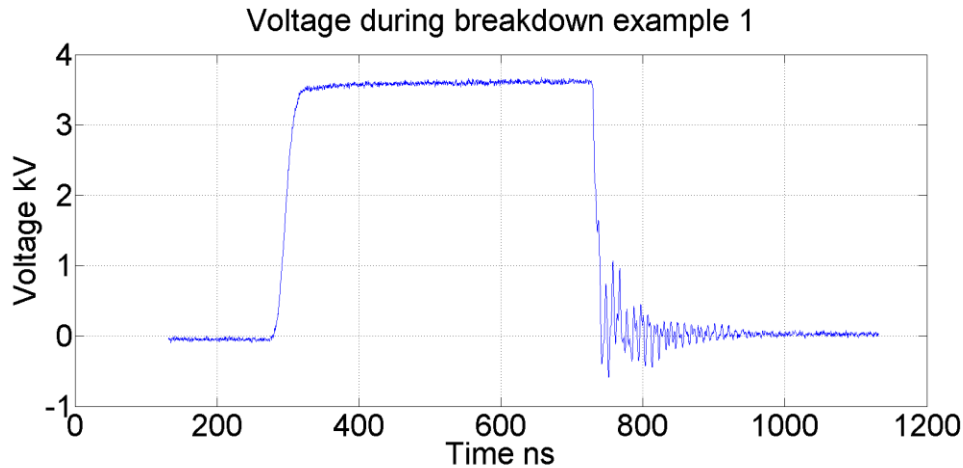
Subtract average voltage with switch closed from Average voltage during breakdown after initial voltage fall.

Measured Burning Voltages



The literature gives a value for the burning voltage of clean copper of $\sim 23\text{V}$. This is lower than what I have measured so far in the DC spark system. But I have not measured or corrected for the short circuit resistance of cables etc.

Burning Voltages



- Depending on when the breakdown occurs there is sometimes a paucity of data points with which to make the average needed to acquire the burning voltage value.
- It is these cases which are responsible for the higher values of burning voltages seen on the histogram.
- This may suggest that the plasma burning voltage starts high and then settles to a lower value later. This will be investigated further.
- The nature of the oscillations will also be investigated further, they could either be due to an LC type ringing in the powering system or due to plasma oscillations in the Arc.

Future Plans

Future Plans

- Use HRR system to obtain BDR vs. E graph for the fixed gap system.
- Investigate how BDR changes when the fixed gap system is placed in an external magnetic field ($\sim 2\text{T}$)
- Measure fixed gap system turn on times. Investigate correlation with gap size. Compare antenna signals to voltage fall times.