



# **Missing energy analysis of vacuum breakdowns in a high-power X-band system**

**Mareike Wendelmuth**

# Scope of the thesis

## Outline

- **Investigate the missing energy during a breakdown**
- **Estimation of energy distribution during normal operation and during breakdowns**

## Motivation

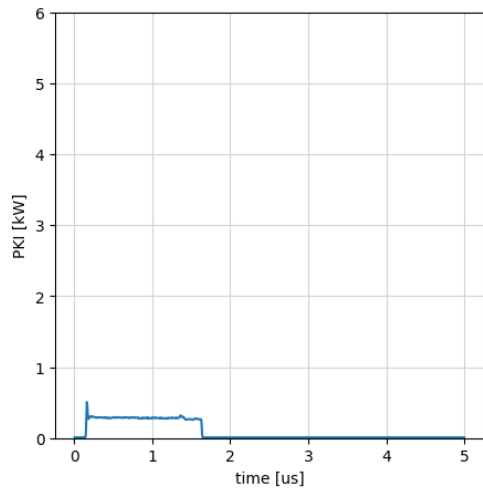
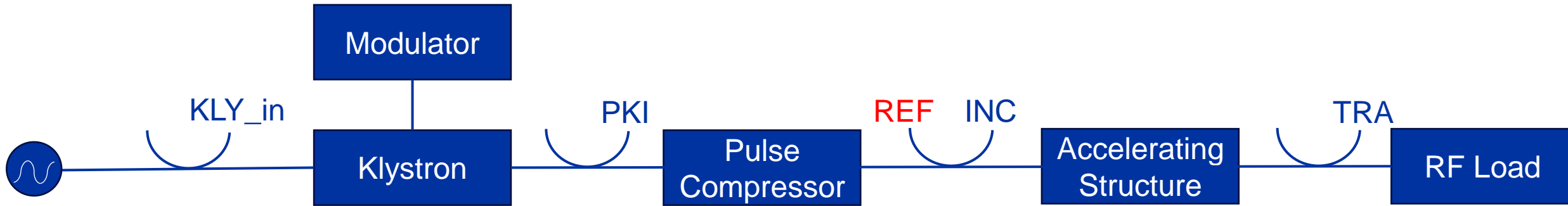
- **Breakdowns are still not fully understood**
- **Conditioning is interrupted after a breakdown**
- **In a real accelerator, not as many measurements are possible. This information can help for later operation**

# X-Band Facility

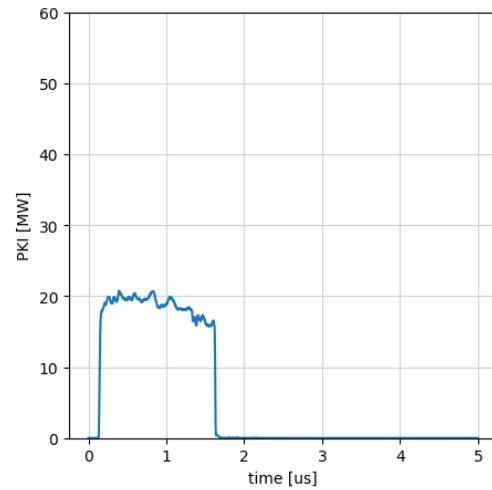
- Part of the CLIC research program
- Two test benches:
  - X-Box 2: One 50 MW Klystron
  - X-Box 3: Two 8 MW Klystrons
- Testing and conditioning of CLIC X-Band (11.994 GHz) structures
- Repetition rate of up to 50 Hz at X-Box 2 and 200 Hz at X-Box 3



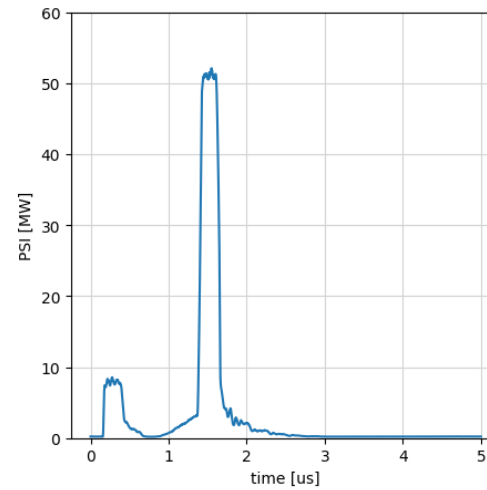
# X-Box2



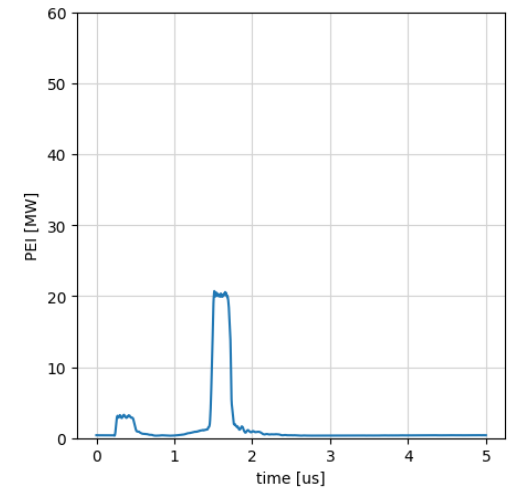
300 W  
1.5 us



20 MW  
1.5 us



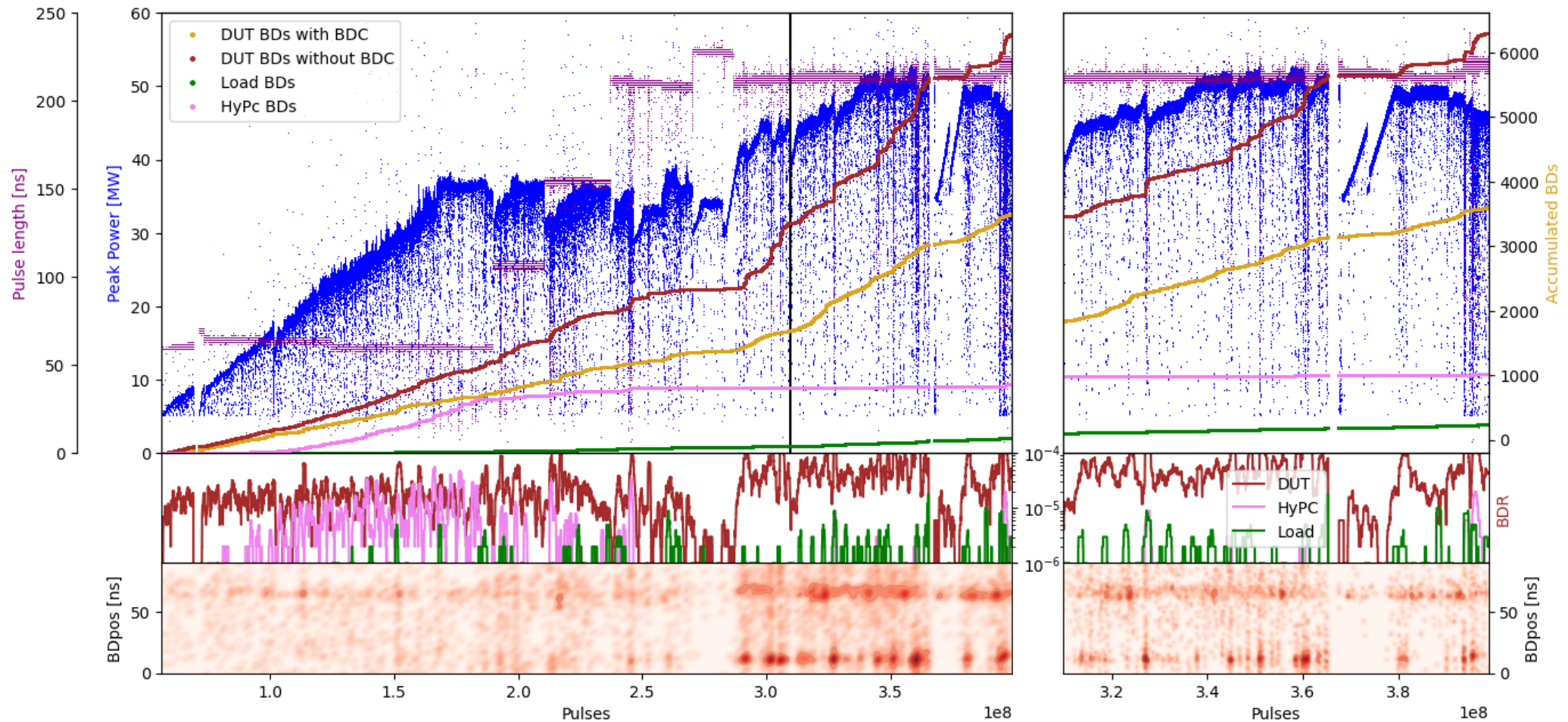
50 MW  
250 ns



20 MW  
250 ns

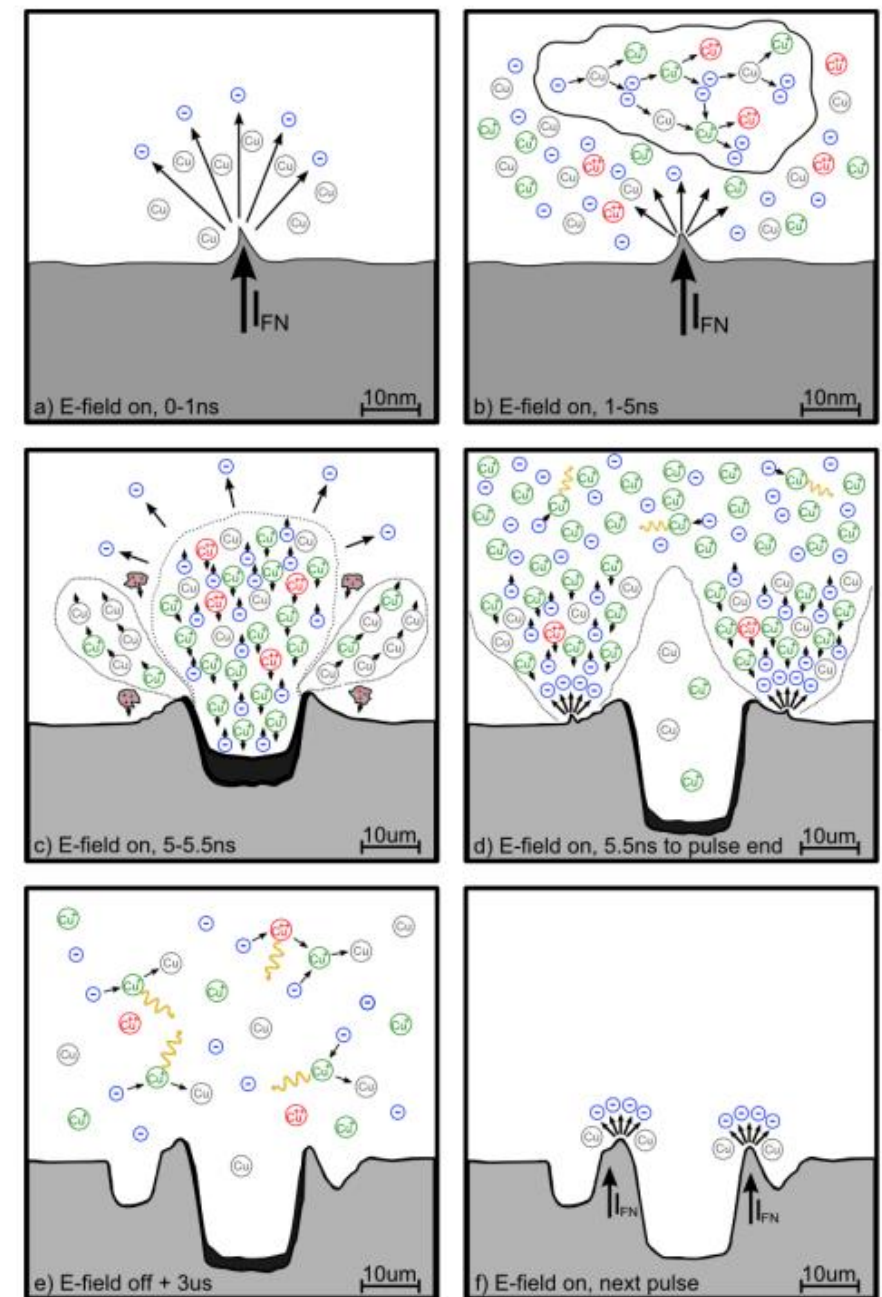


# Conditioning process of one structure



# Breakdown definition

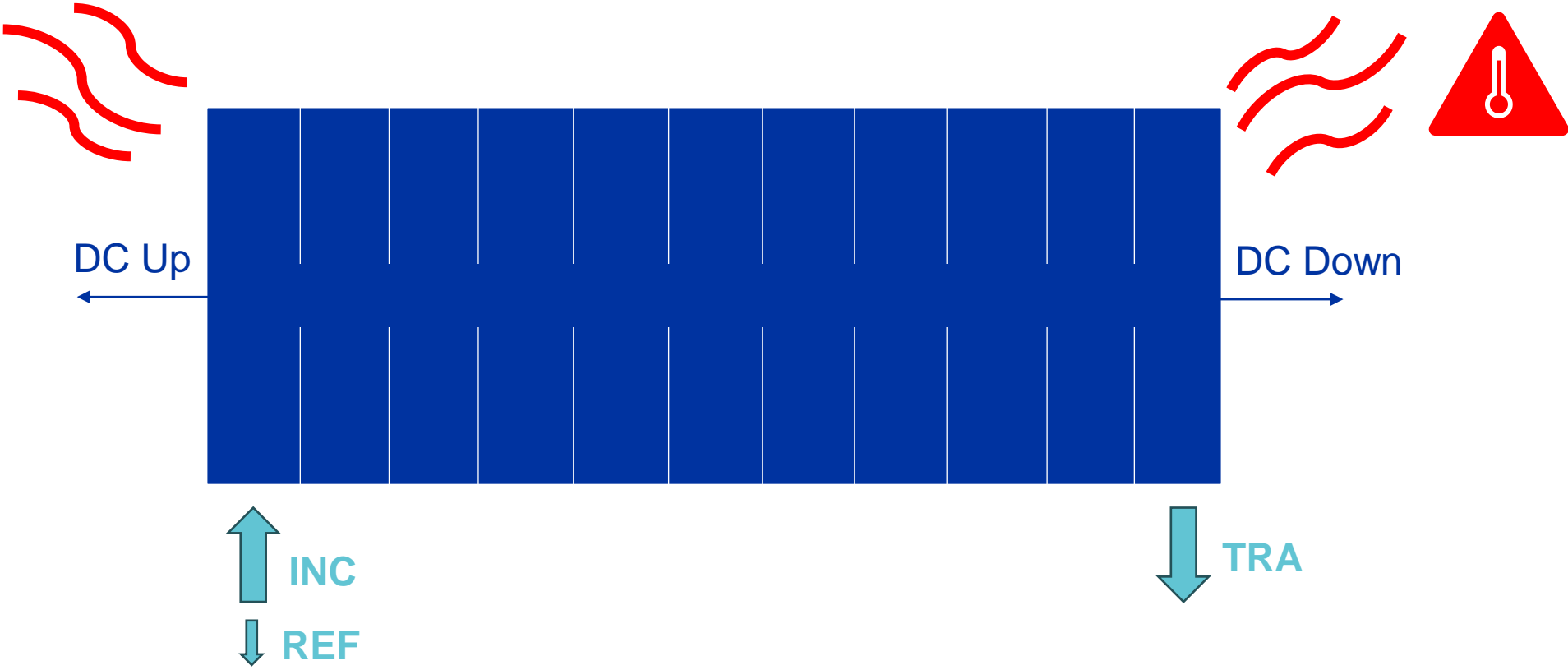
- Breakdowns are caused by emission of electrons, due to the large electric fields
- RF power reflected by occurring electric arc
- Damage on copper surface usually visible and cause to new breakdowns
- Breakdowns are part of the conditioning process



Picture taken from: J. W. Kovermann, "Comparative Studies of High-Gradient RF and DC Breakdowns," Ph.D. dissertation, RWTH Aachen University, 2010

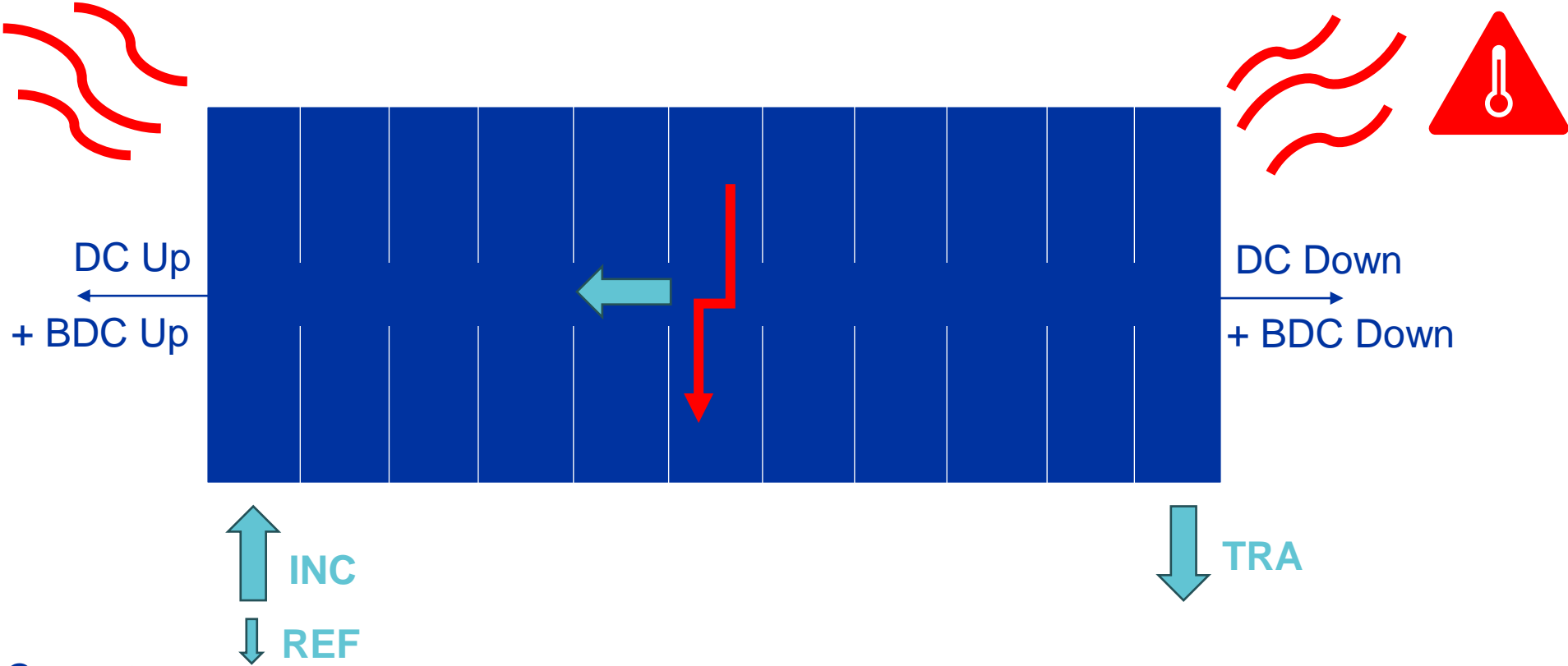
# Energy Distribution

$$\int INC = \int TRA + \int REF + Energy(DC_{up} + DC_{Down}) + Loss_{Heating}$$



# Energy Distribution Breakdown

$$\int INC = \int TRA + \int REF + Energy(DC_{up} + DC_{Down}) + LOSS_{Heating} + Energy(BDC) + Missing Energy$$

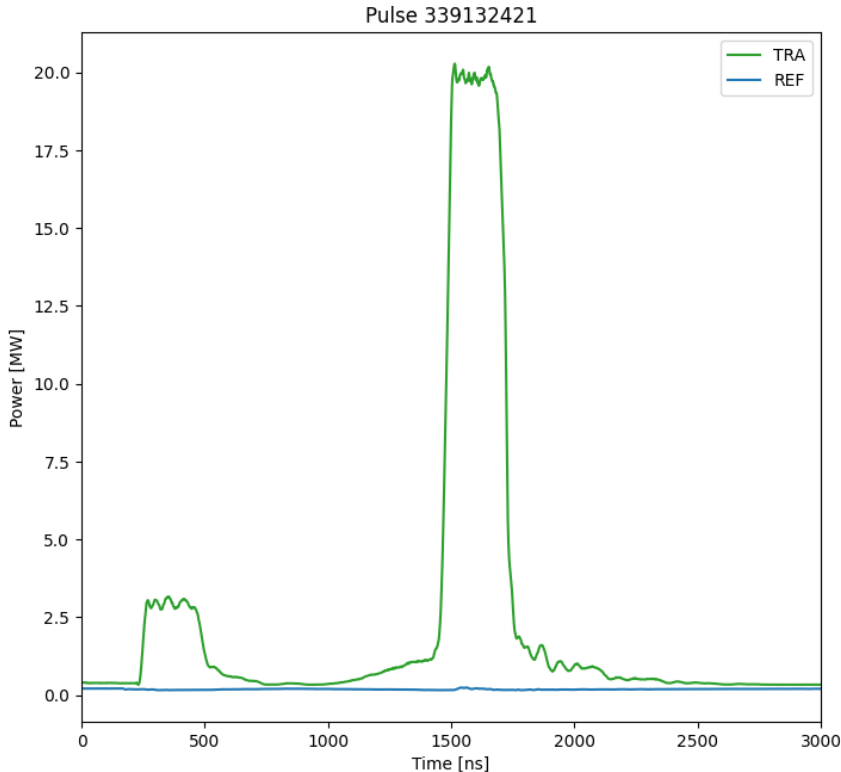


DC – Dark Current  
 BDC – Breakdown Current

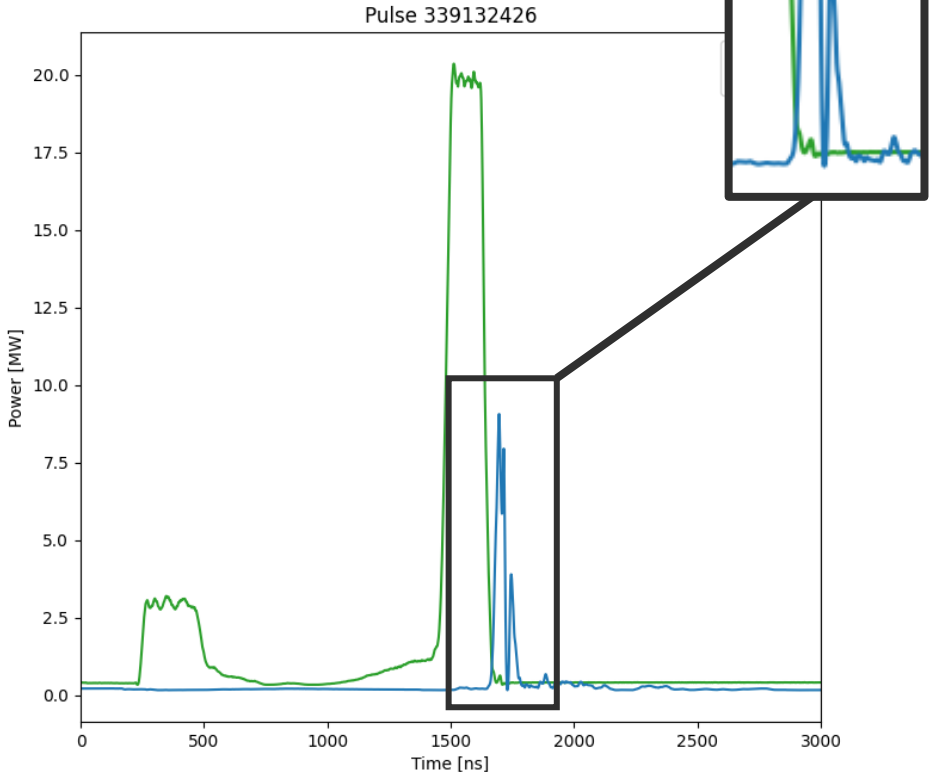


# Pulses

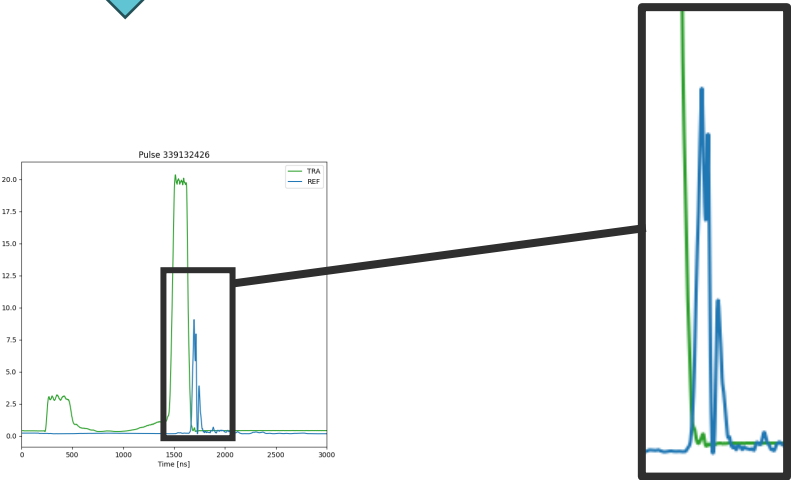
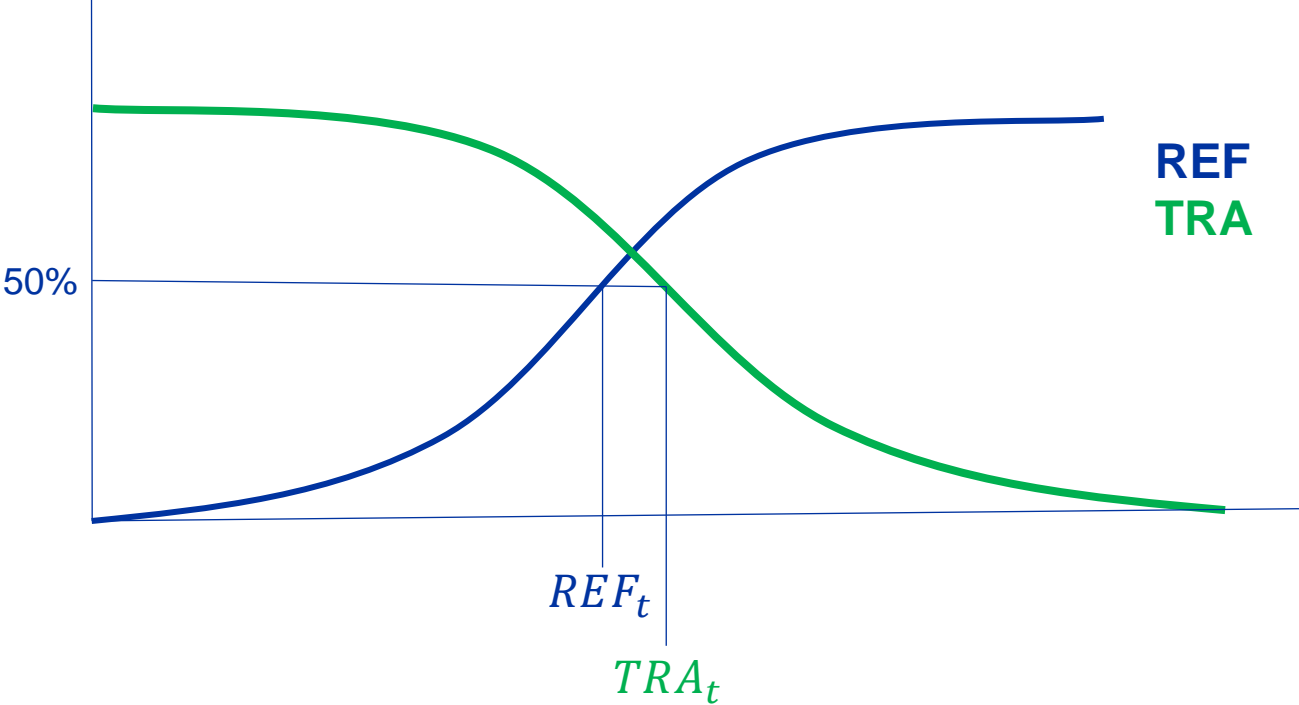
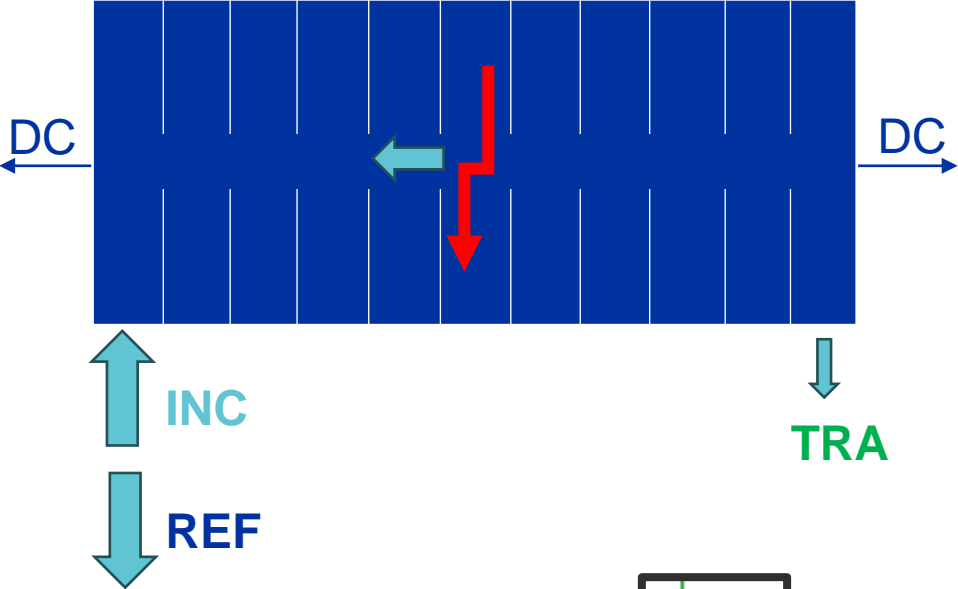
## Normal Pulse



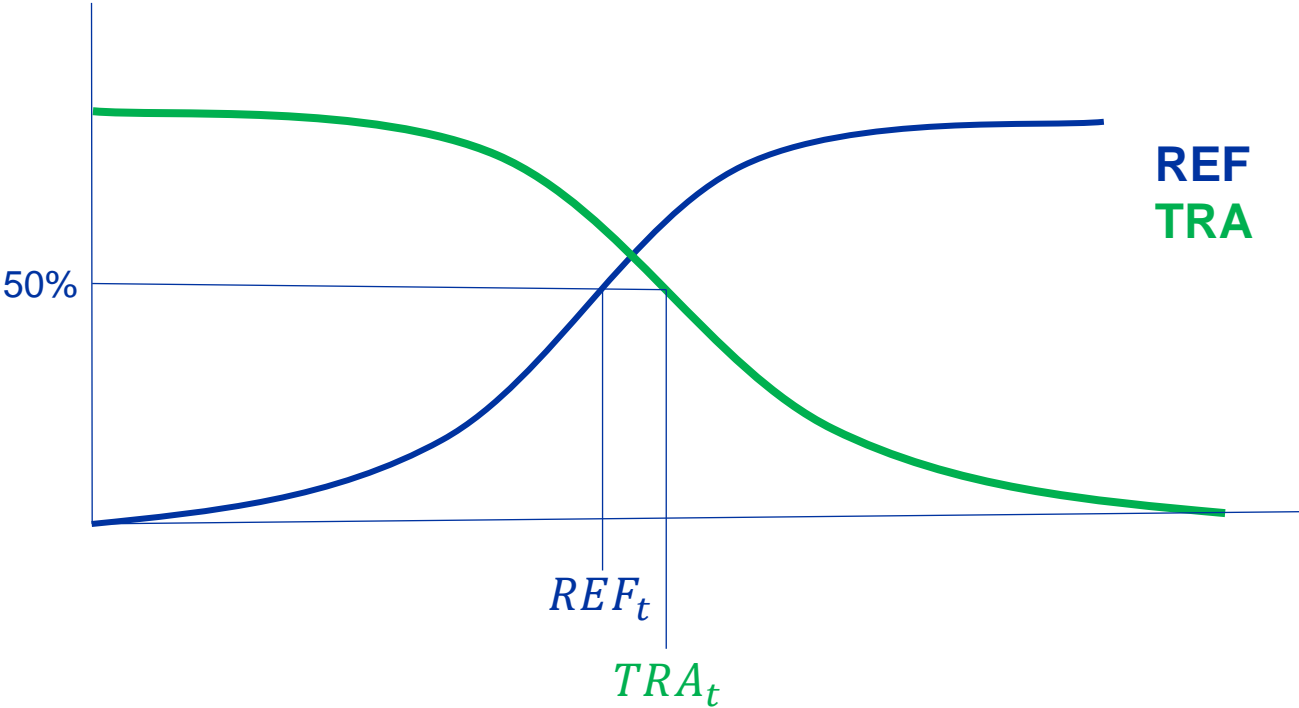
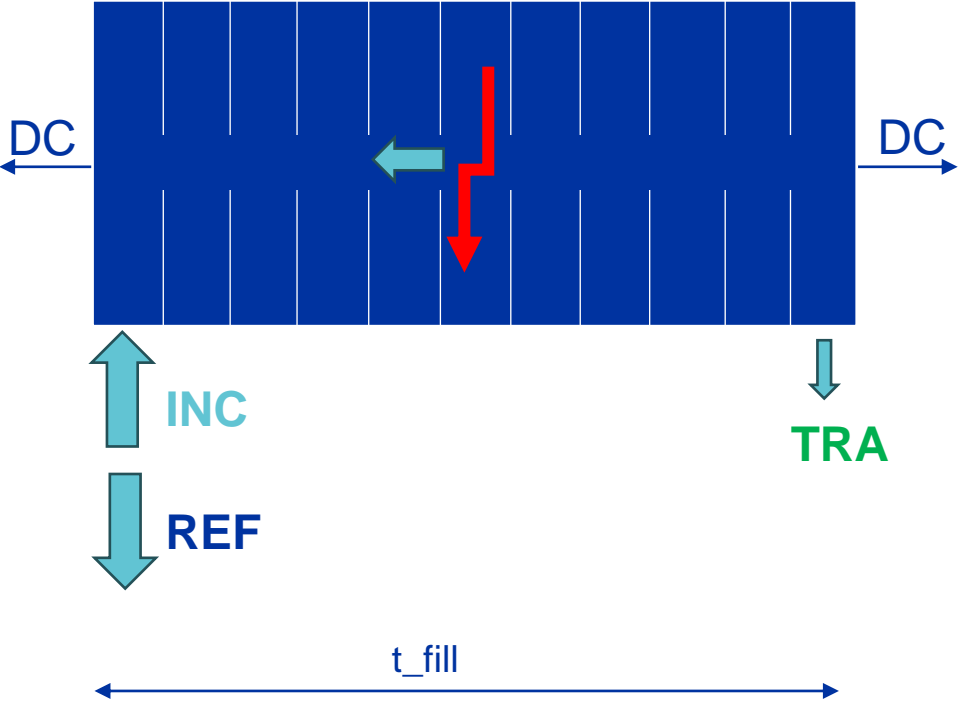
## Breakdown Pulse



# Structures – Breakdown Position



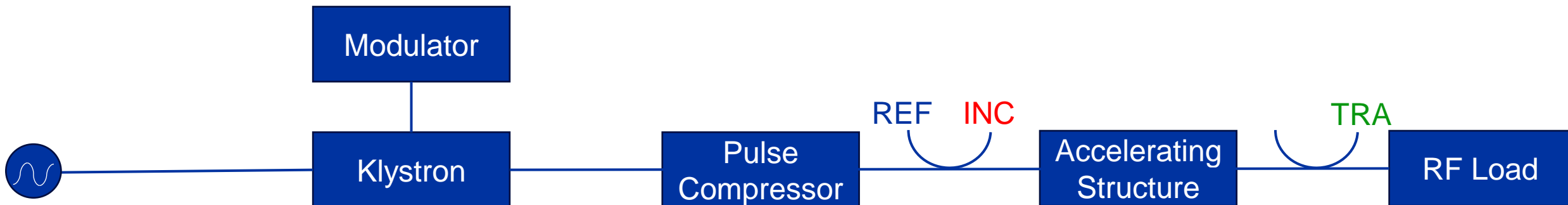
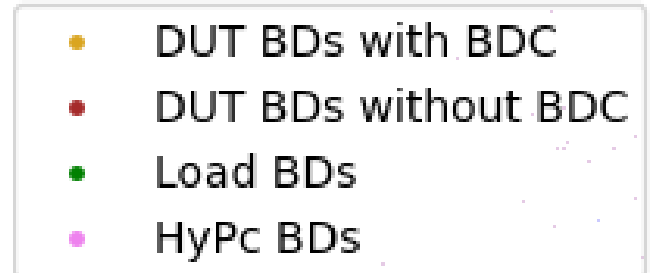
# Structures – Breakdown Position



$$\text{BD time} = \frac{REF_t - TRA_t - t_{fill}}{2}$$

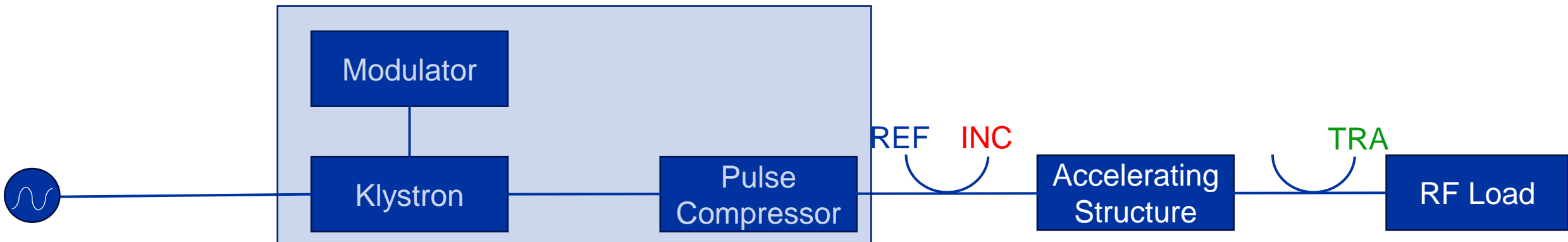
# Breakdown types

- **Flags are risen during operation**
- **Classification done later in Post-processing:**
  - HyPc BD: Breakdowns in the Hybrid part of the system
  - Load BD: Breakdown in the load after the structure
  - BD with BDC: Breakdown with detected Breakdown Current (BDC), larger than usual Dark Current (DC)
  - BD without BDC: Breakdown without Breakdown Current detection



# Breakdown types

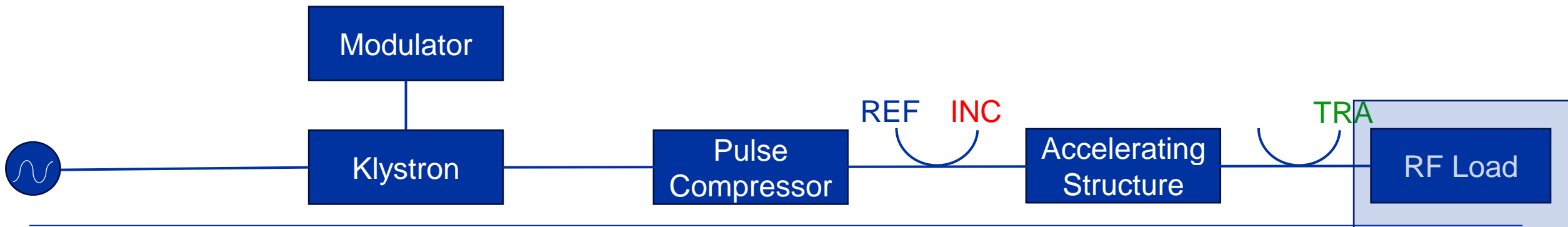
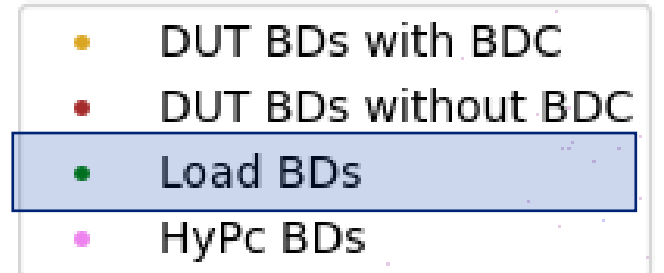
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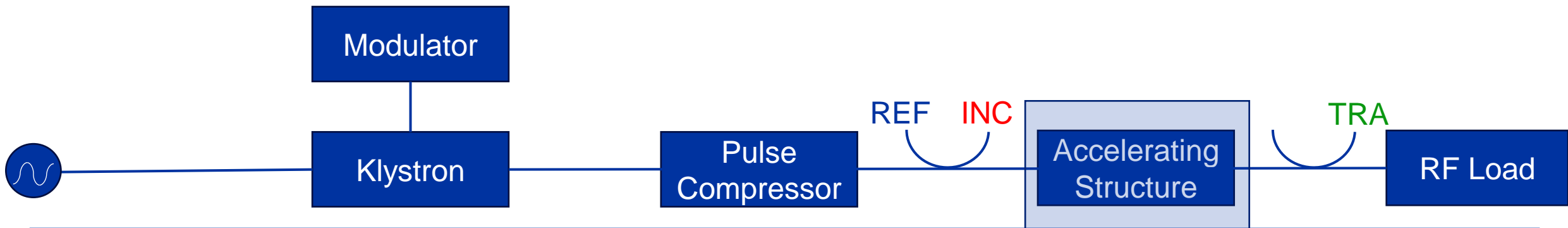
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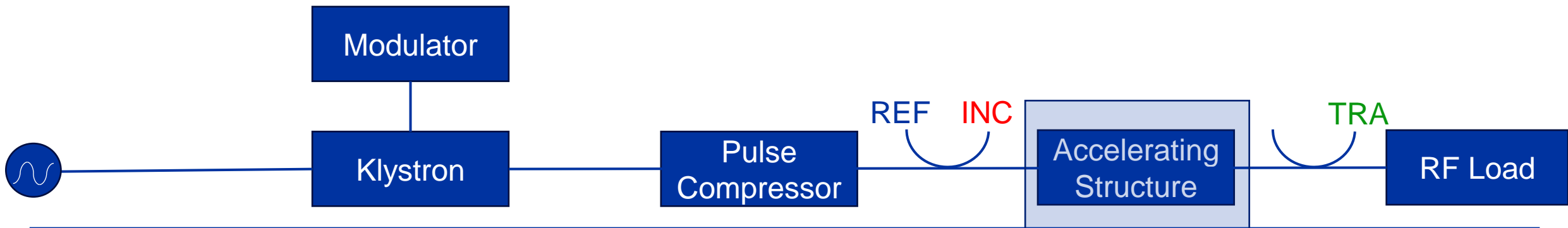
■	DUT BDs with BDC
●	DUT BDs without BDC
■	Load BDs
●	HyPc BDs



# Breakdown types

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  - **BD without BDC: Breakdown without Breakdown Current detection**

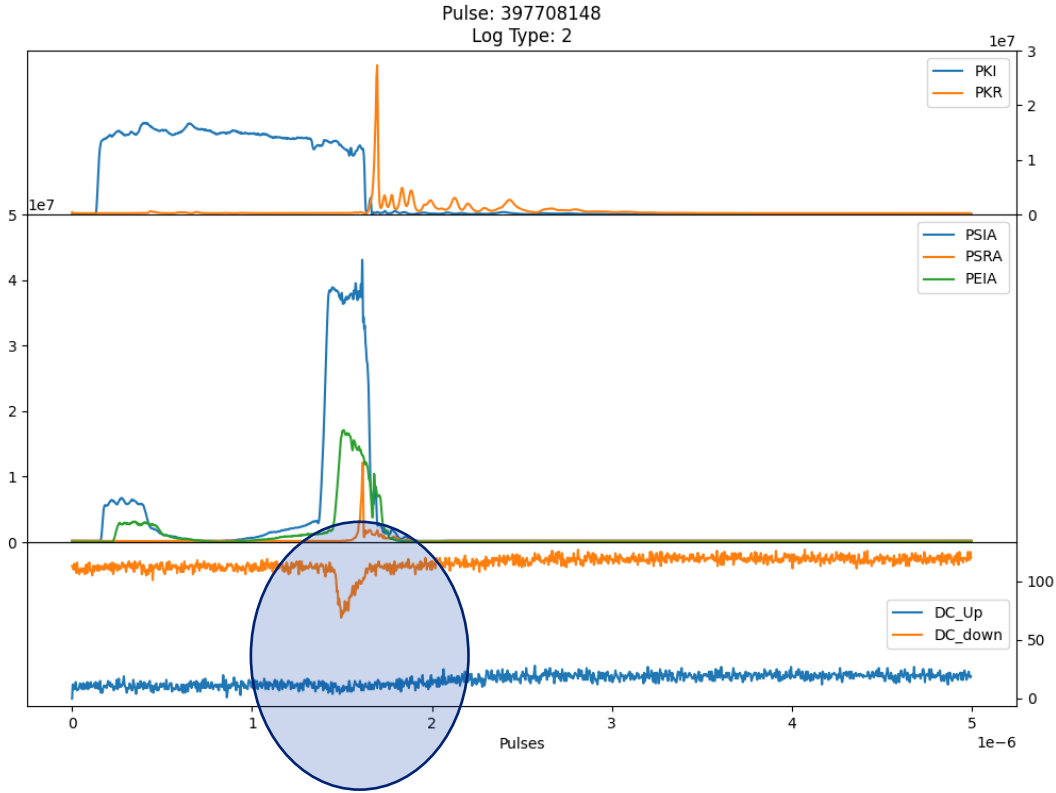
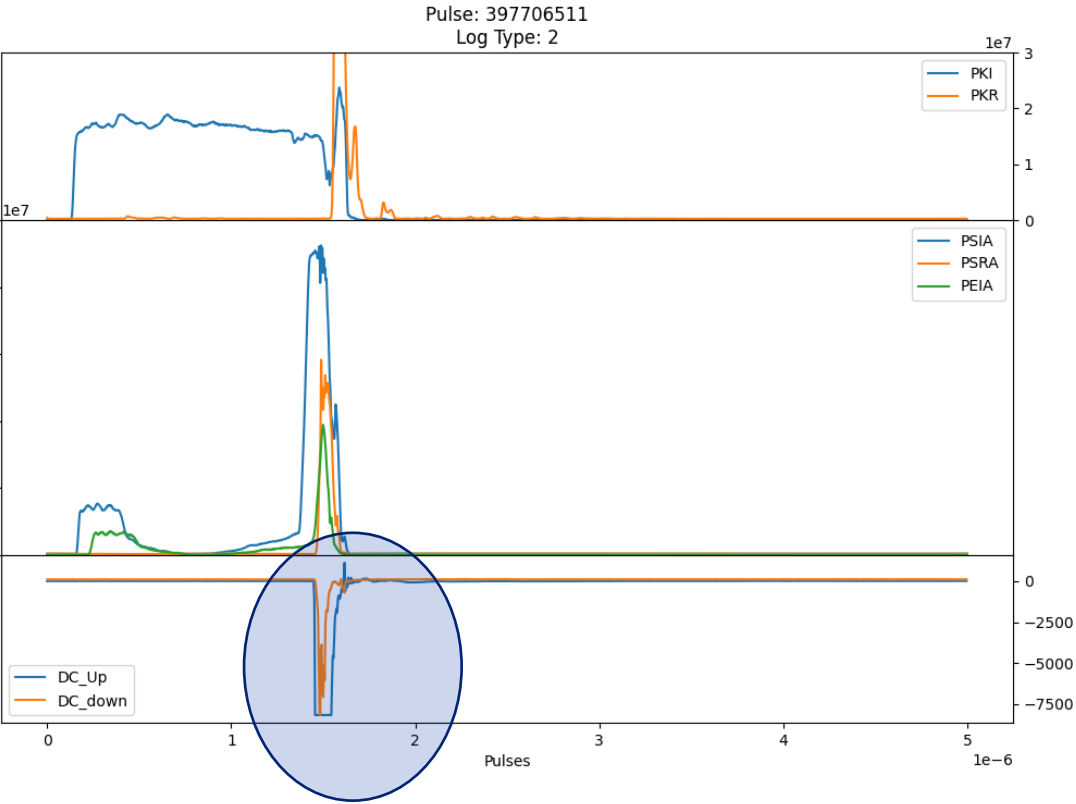
•	DUT BDs with BDC
•	DUT BDs without BDC
•	Load BDs
•	HyPc BDs



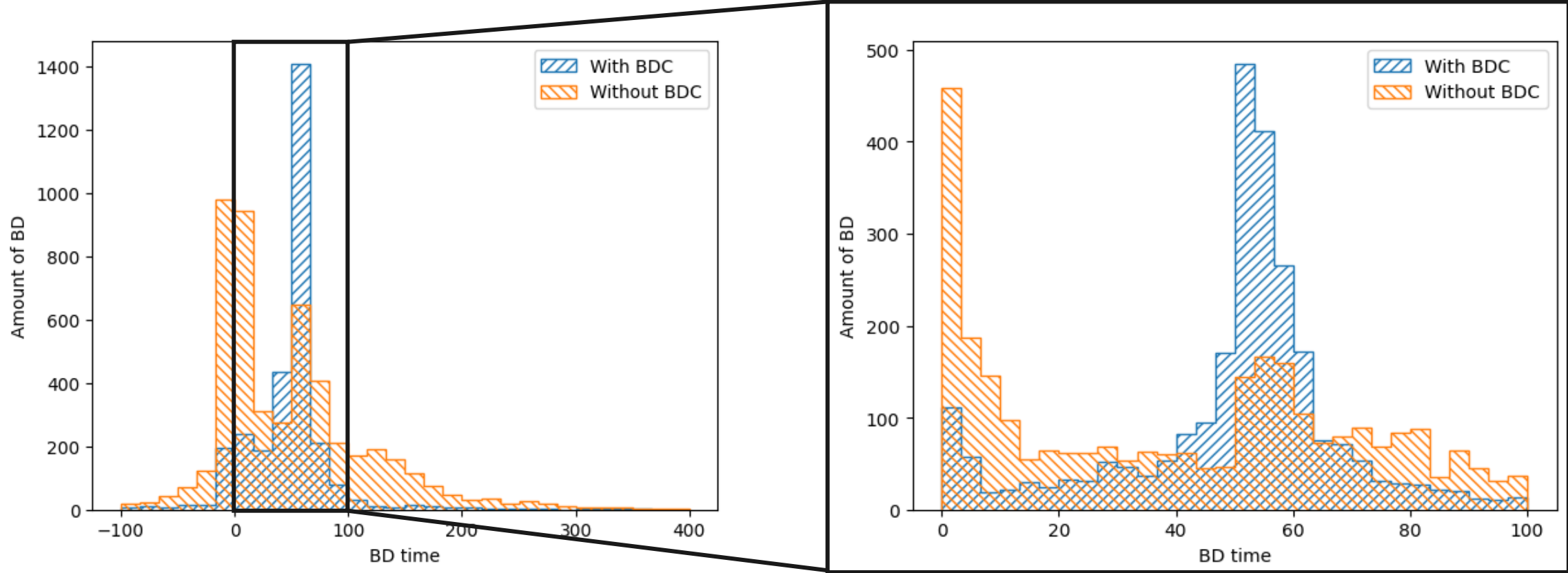
# Breakdown Types

## BD with Breakdown Current (BDC)

## BD without Breakdown Current (BDC)



# Position distribution of BD (XBox2)



-> BD with Breakdown Current (BDC) occur later in the structure than without BDC



# Missing Energy

$$\int INC = \int TRA + \int REF + Energy(DC_{up} + DC_{Down}) +$$
$$LOSS_{Heating} + Energy(BDC) + Missing Energy$$

# Missing Energy

*Missing Energy =*

$$\begin{aligned}
 & \overset{\text{Measures}}{\int INC - \int TRA - \int REF} - \overset{\text{Measures}}{\text{Energy}(DC_{up} + DC_{Down})} - \\
 & \quad \underset{\text{Measures + Simulation}}{LOSS_{Heating}} - \underset{\text{Measures + Simulation}}{\text{Energy}(BDC)}
 \end{aligned}$$

# Missing Energy

## Simplified Analysis

**Missing Energy**

$$= \int INC - \int TRA - \int REF$$

$$- \text{Energy}(DC_{up} + DC_{down}) - LOSS_{Heating} - \text{Energy}(BDC)$$

$$[\text{Energy}(DC) + LOSS_{Heating}]_{BD\ Pulse} \approx [\int INC - \int TRA - \int REF]_{Normal\ Pulse}$$

**Missing Energy** Measures

$$= [\int INC - \int TRA - \int REF]_{BD\ Pulse} - [\int INC - \int TRA - \int REF]_{Normal\ Pulse} - \text{Energy}(BDC)$$

Estimation

## Precise Analysis

**Missing Energy** Measures

$$= \int INC - \int TRA - \int REF - \text{Energy}(DC_{up} + DC_{down}) - LOSS_{Heating} - \text{Energy}(BDC)$$

Measures + Simulation

Measures + Simulation

# Simplified Analysis

*Missing Energy*

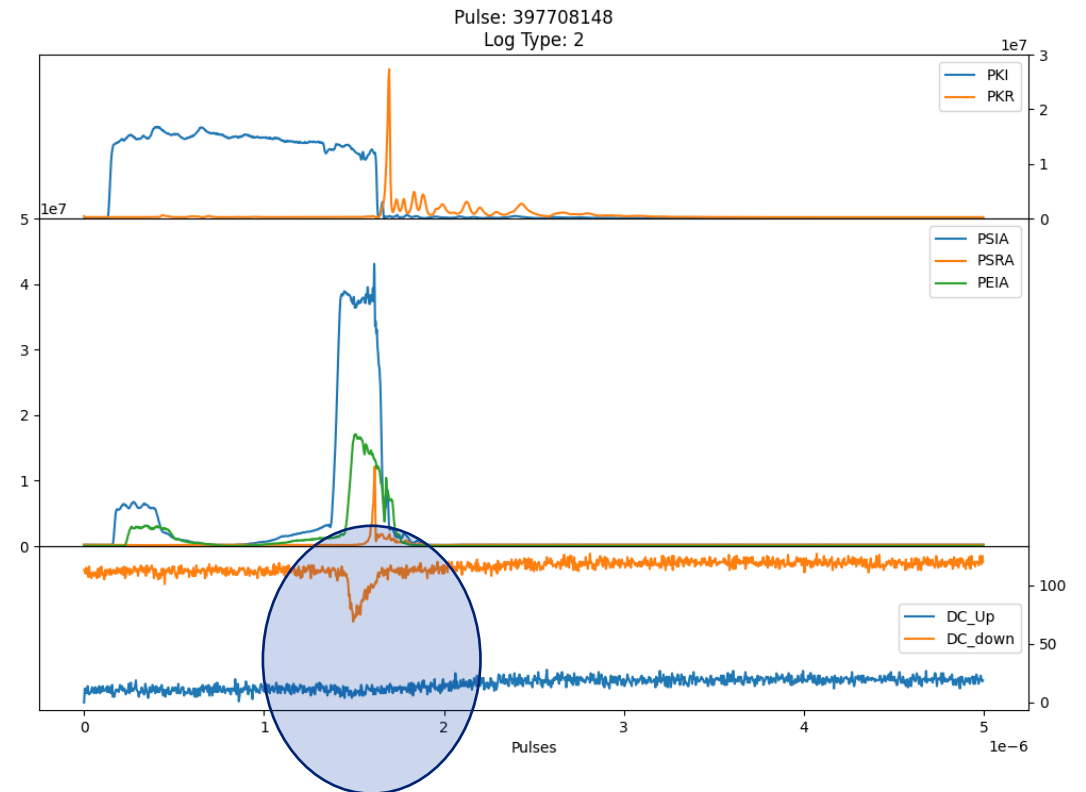
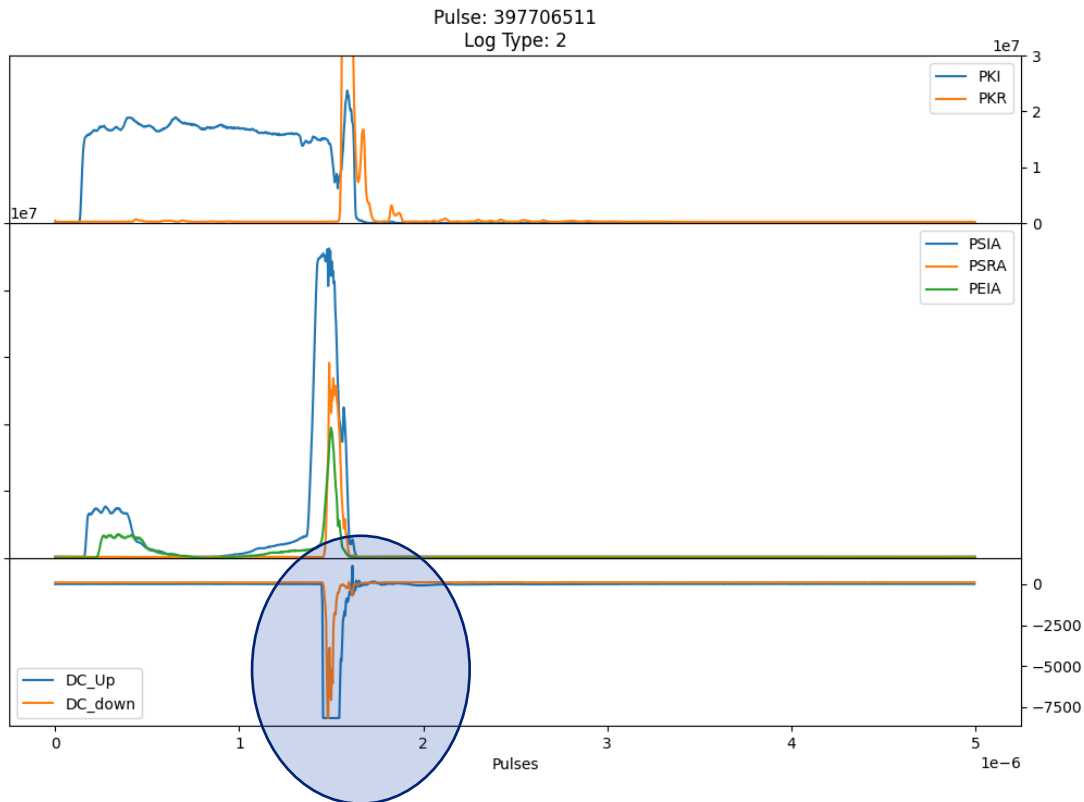
Measures

$$= \left[ \int INC - \int TRA - \int REF \right]_{BD\ Pulse} - \left[ \int INC - \int TRA - \int REF \right]_{Normal\ Pulse} - Energy(BDC)$$

Estimation

## BD with Breakdown Current (BDC)

## BD without Breakdown Current (BDC)



# Simplified Analysis

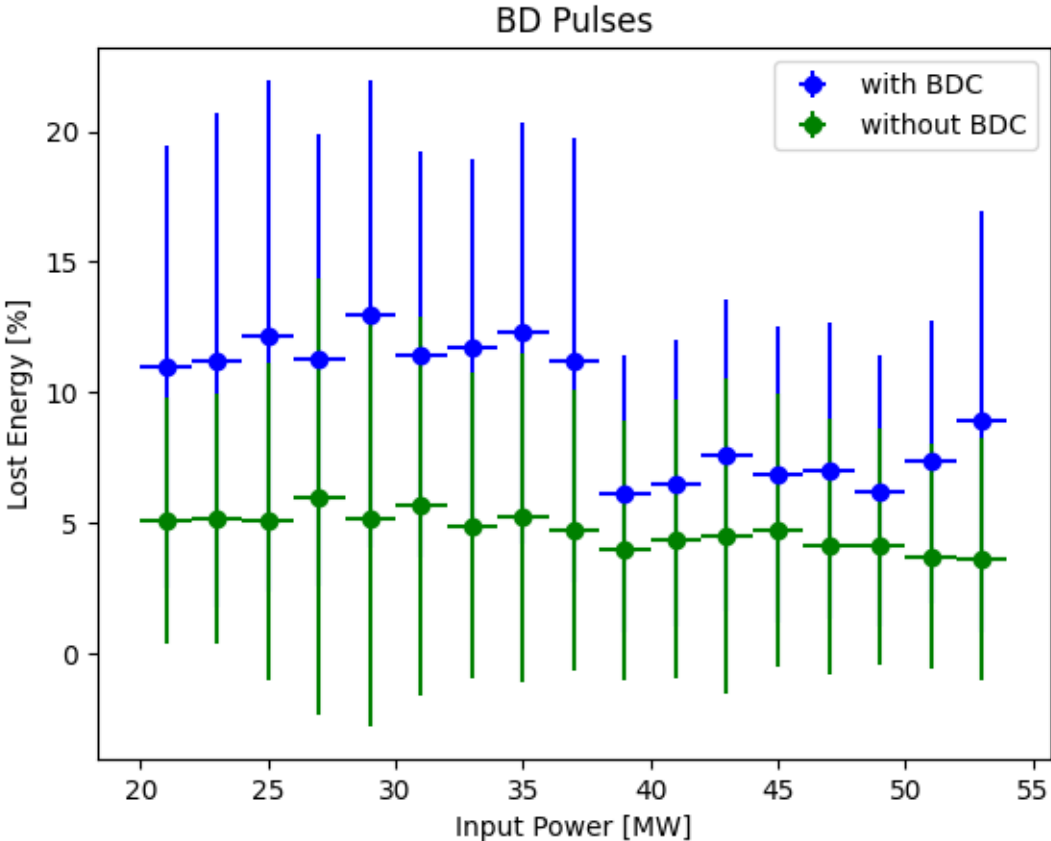
Measures

$$\begin{aligned}
 &= \left[ \int INC - \int TRA - \int REF \right]_{BD\ Pulse} \\
 - & \left[ \int INC - \int TRA - \int REF \right]_{Normal\ Pulse} \\
 & - \text{Energy}(BDC) \quad \text{Estimation}
 \end{aligned}$$

Measures

### Lost Energy

$$\begin{aligned}
 &= \text{Missing Energy} + \text{Energy}(BDC) \\
 &= \left[ \int INC - \int TRA - \int REF \right]_{BD\ Pulse} \\
 - & \left[ \int INC - \int TRA - \int REF \right]_{Normal\ Pulse}
 \end{aligned}$$

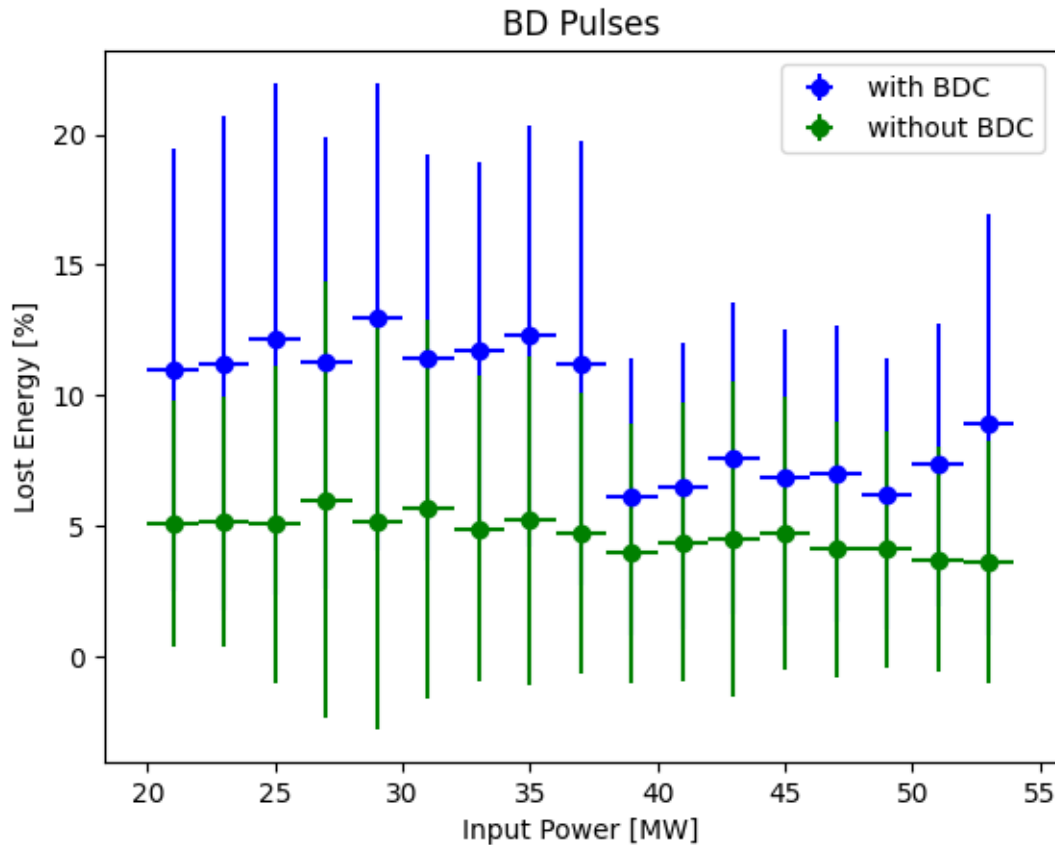




# Simplified Analysis

## Lost Energy

$$\begin{aligned}
 &= \text{Missing Energy} + \text{Energy}(BDC) \\
 &= \left[ \int INC - \int TRA - \int REF \right]_{BD\ Pulse} \\
 &\quad - \left[ \int INC - \int TRA - \int REF \right]_{Normal\ Pulse}
 \end{aligned}$$



- **With Breakdown Current (BDC), about 8-10% of the energy is lost**
  - Lost in BDC
  - Lost in additional heating of the breakdown location
- **Without BDC, about 5% of the energy is lost**
- **Thesis: 5% of the energy is lost within the structure during a breakdown, not seen in BDC**

# Missing Energy

## Simplified Analysis

$$\begin{aligned}
 & \textit{Missing Energy} \\
 &= \int INC - \int TRA - \int REF \\
 &- \textit{Energy}(DC_{up} + DC_{down}) - \textit{LOSS}_{Heating} \\
 &- \textit{Energy}(BDC)
 \end{aligned}$$

$$[\textit{Energy}(DC) + \textit{LOSS}_{Heating}]_{BD\ Pulse} \approx [\int INC - \int TRA - \int REF]_{Normal\ Pulse}$$

$$\begin{aligned}
 & \textit{Missing Energy} \quad \text{Measures} \\
 &= [\int INC - \int TRA - \int REF]_{BD\ Pulse} \\
 &- [\int INC - \int TRA - \int REF]_{Normal\ Pulse} \\
 &- \textit{Energy}(BDC) \quad \text{Estimation}
 \end{aligned}$$

## Precise Analysis

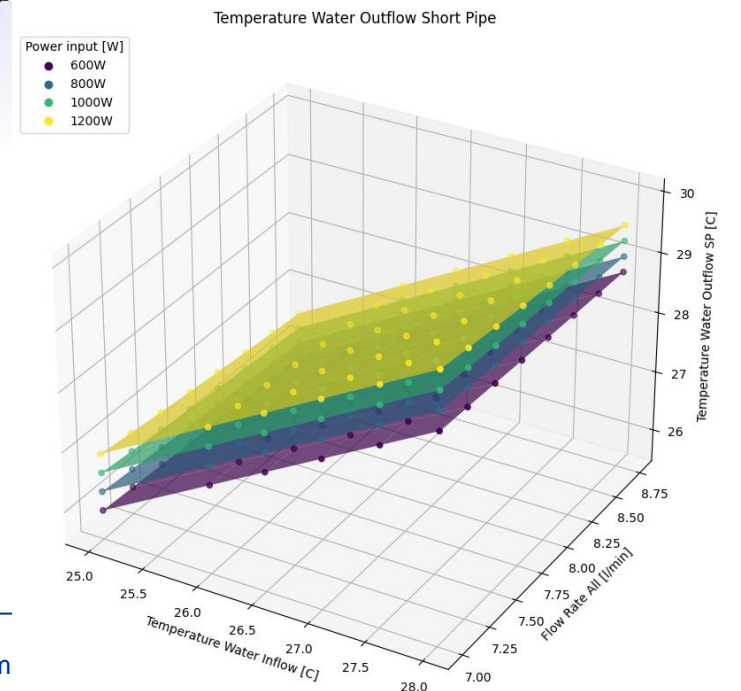
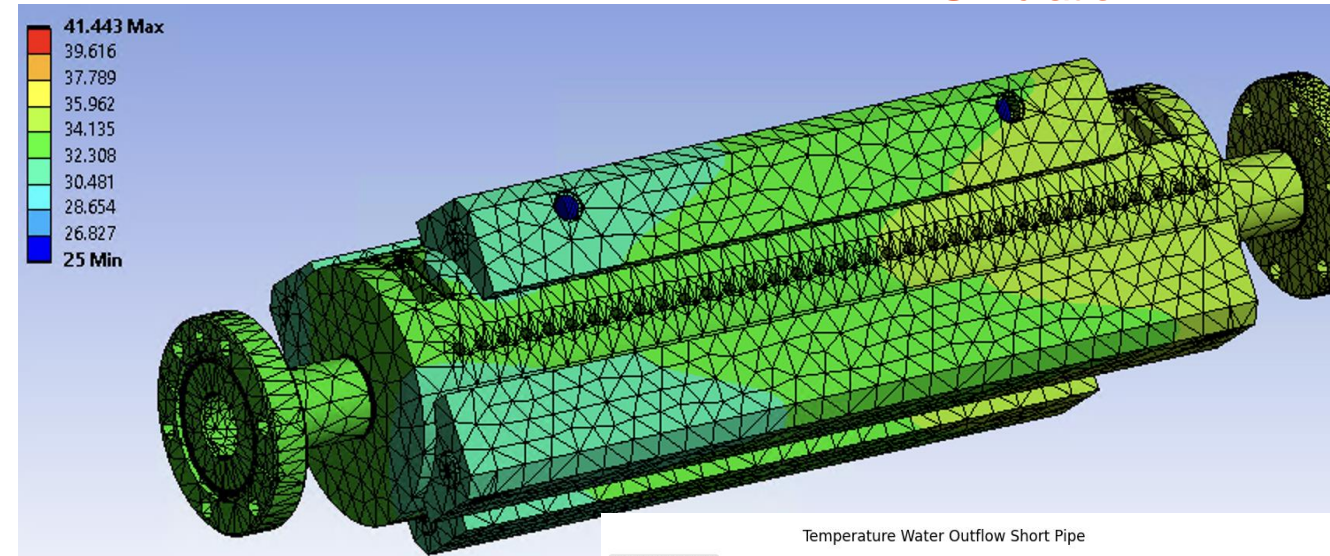
$$\begin{aligned}
 & \textit{Missing Energy} \quad \text{Measures} \\
 &= \int INC - \int TRA - \int REF \\
 &- \textit{Energy}(DC_{up} + DC_{down}) - \textit{LOSS}_{Heating} \\
 &- \textit{Energy}(BDC) \\
 & \quad \text{Measures + Simulation} \quad \text{Measures + Simulation}
 \end{aligned}$$

# ANSYS Heat analysis

- **Heat simulation of structure:**
  - Linear behavior of temperature change of Structure Surface and Water
- **Implementation of water temperature measurements:**
  - Calibration at no input power
  - Uncertainty of 0.3C at sensors
  - Verification of Simulation to be done

$$\text{Missing Energy} = \int \text{INC} - \int \text{TRA} - \int \text{REF} - \text{Energy}(DC_{up} + DC_{down}) - \boxed{\text{Loss}_{\text{Heating}}} - \text{Energy}(BDC)$$

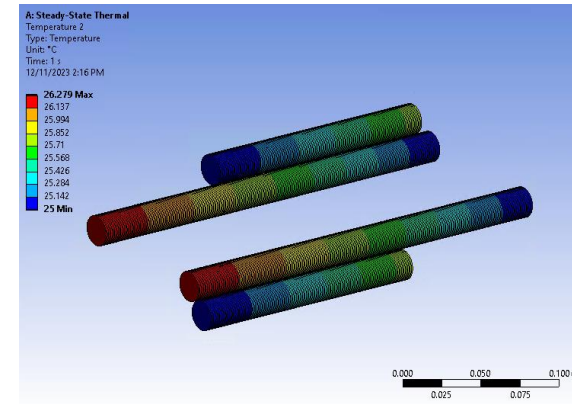
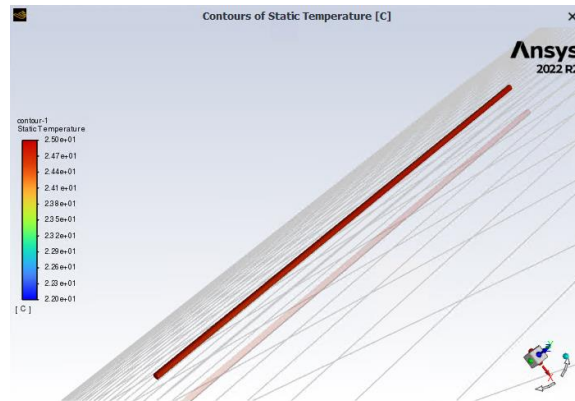
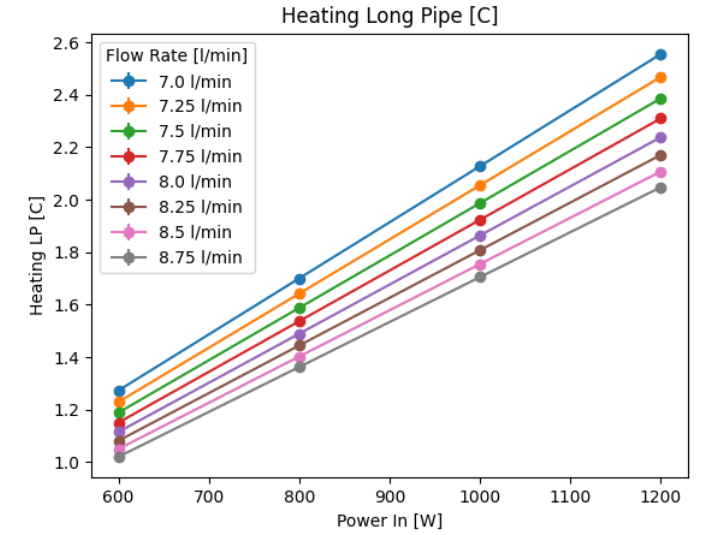
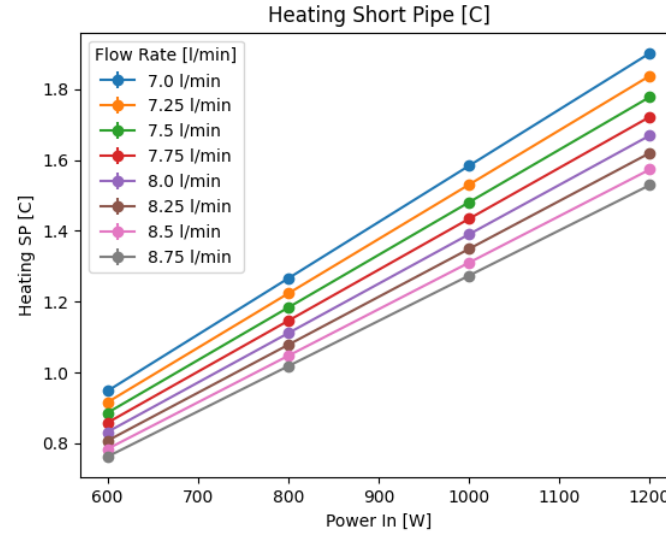
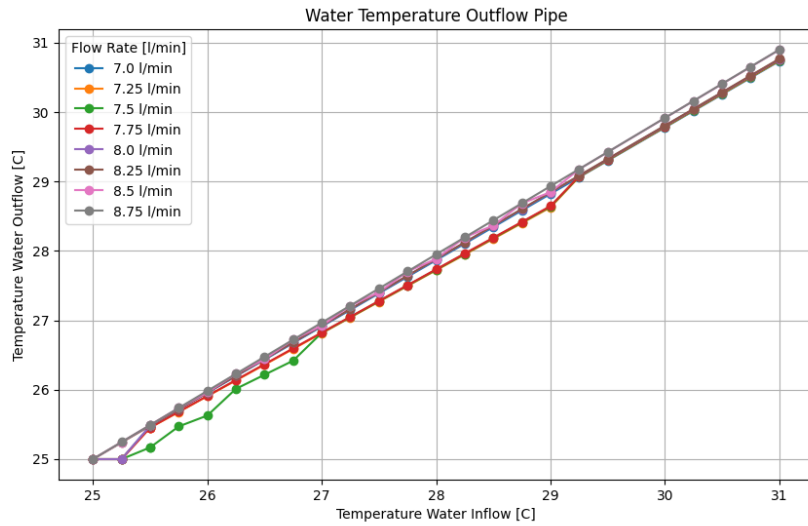
Measures +  
Simulation



# ANSYS Heat analysis

$$\text{Missing Energy} = \int INC - \int TRA - \int REF - \text{Energy}(DC_{up} + DC_{down}) - \boxed{\text{Loss}_{\text{Heating}}} - \text{Energy}(BDC)$$

Measures + Simulation

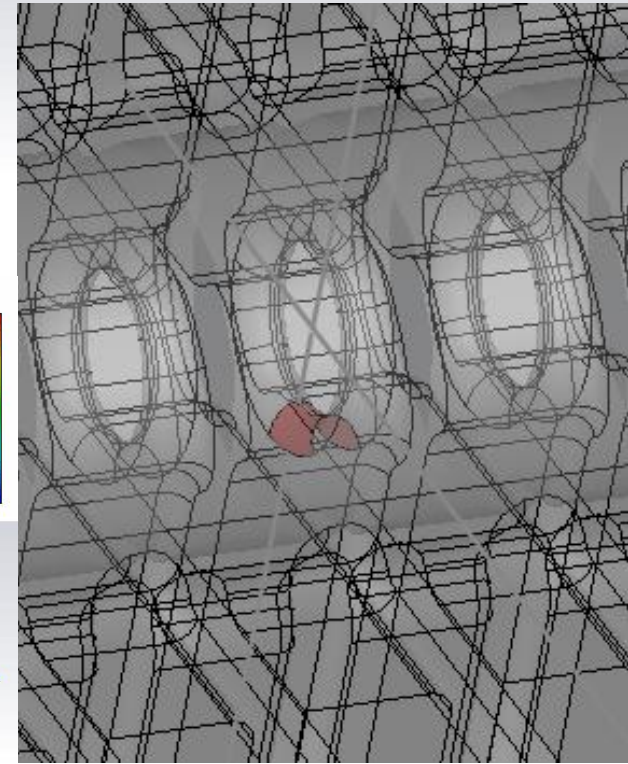
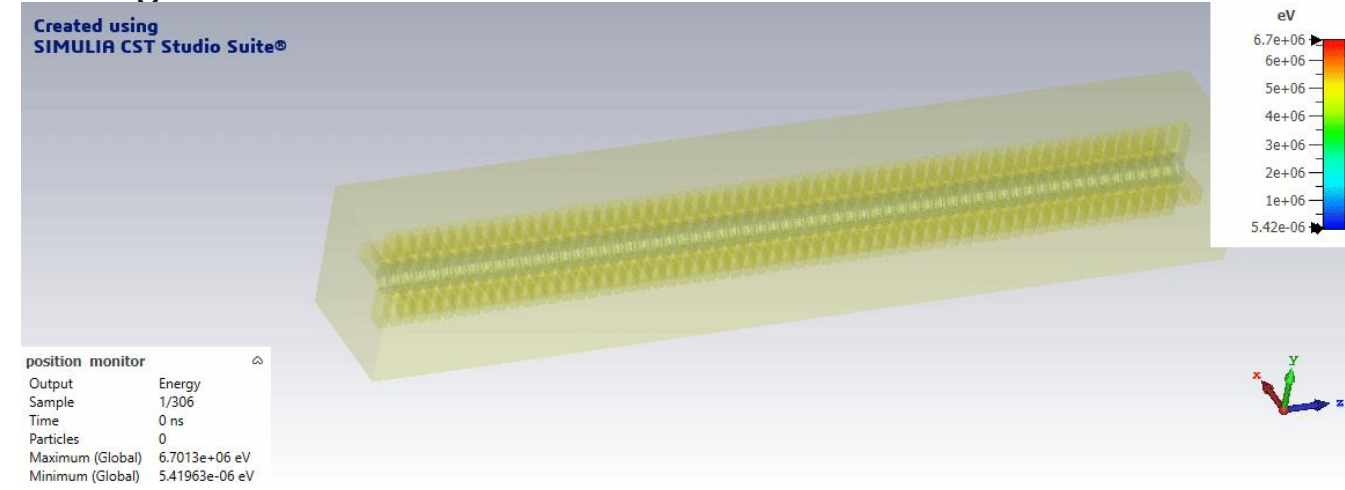
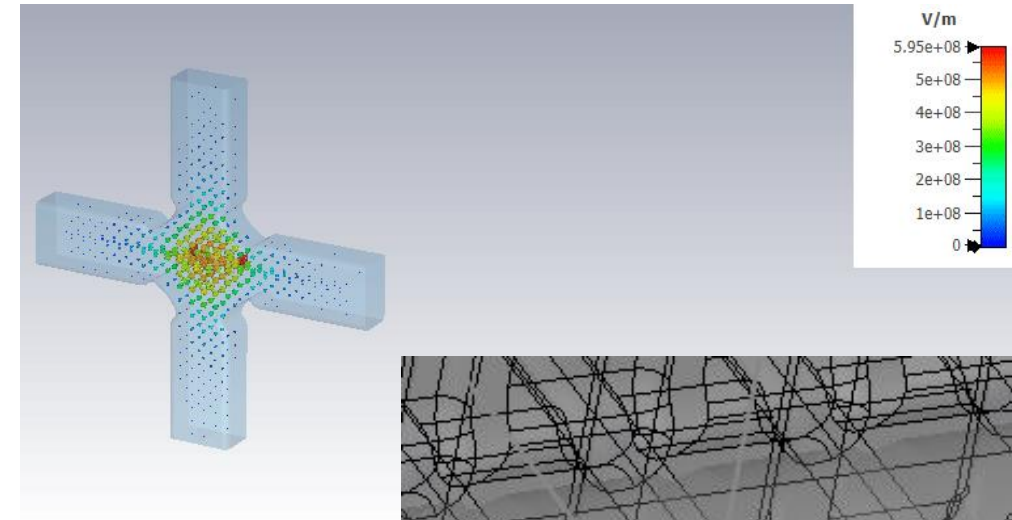


# CST Analysis

$$Missing\ Energy = \int INC - \int TRA - \int REF - \boxed{Energy(DC_{up} + DC_{down})} - LOSS_{Heating} - \boxed{Energy(BDC)}$$

Measures + Simulation

- **Simulation of Dark Current:**
  - Eigenmode simulation of one cell, repetition 61 times for PIC simulation
- **PIC:**
  - Emission at 1/8<sup>th</sup> of one iris
  - Measurement at each iris
  - Repetition for different gradients

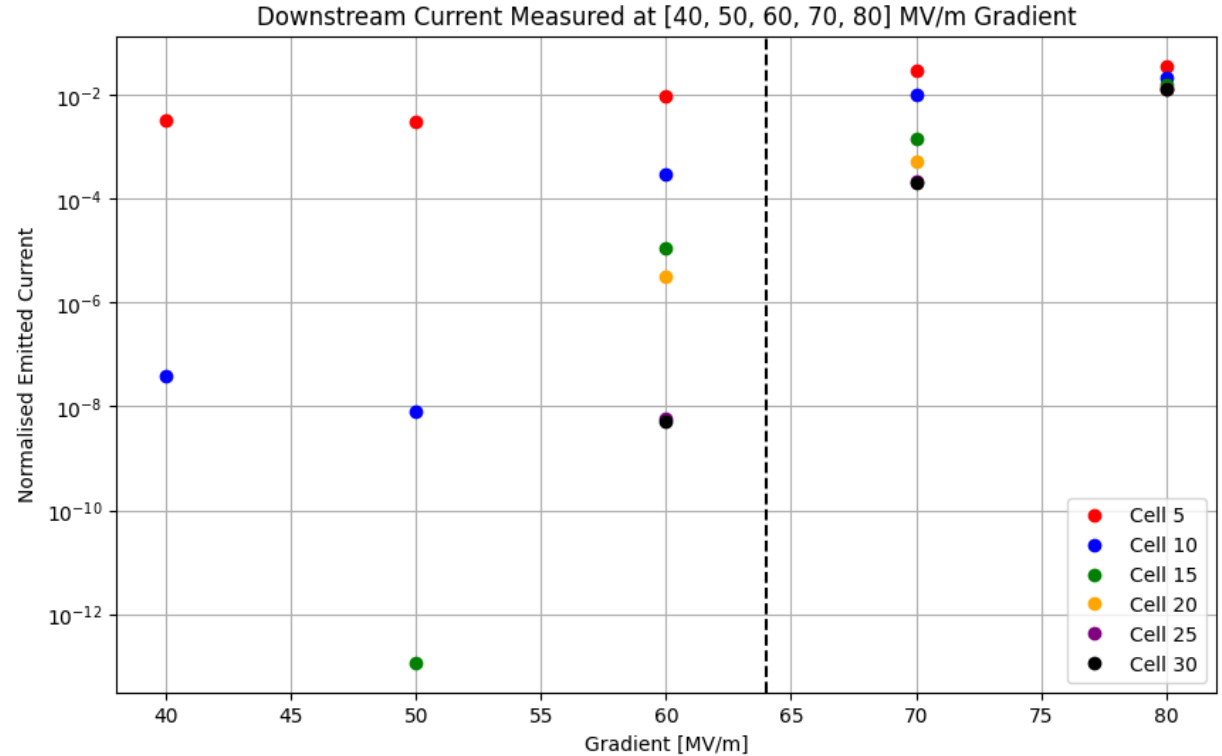
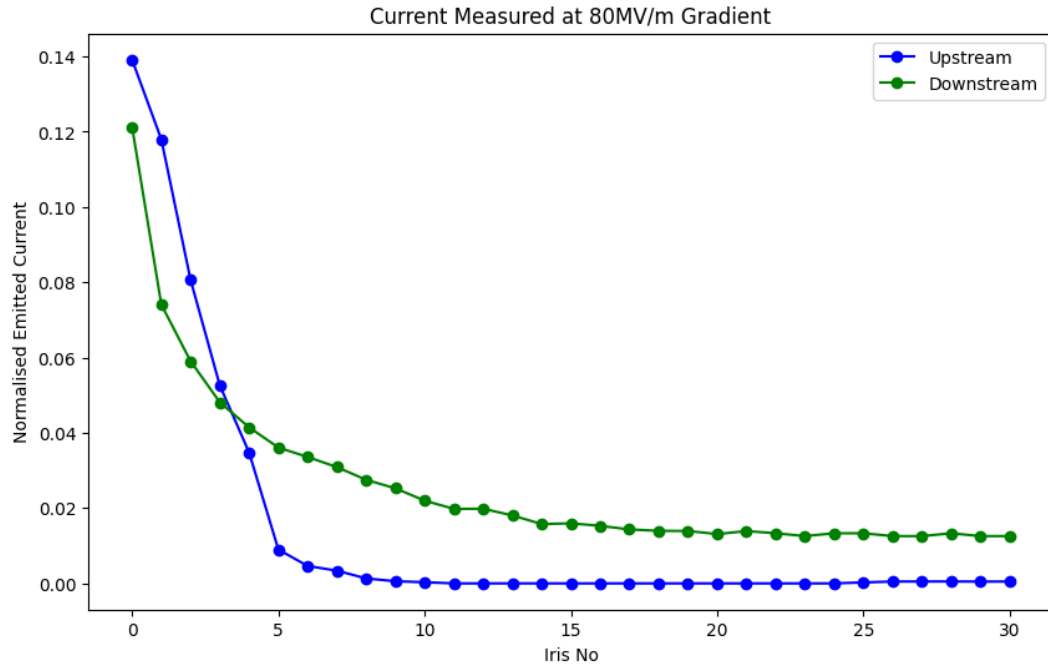




# CST Analysis

$$\text{Missing Energy} = \int INC - \int TRA - \int REF - \boxed{\text{Energy}(DC_{up} + DC_{down})} - \text{Loss}_{\text{Heating}} - \boxed{\text{Energy}(BDC)}$$

Measures +  
Simulation



About 2.6% of emitted current reaches downstream faraday cup

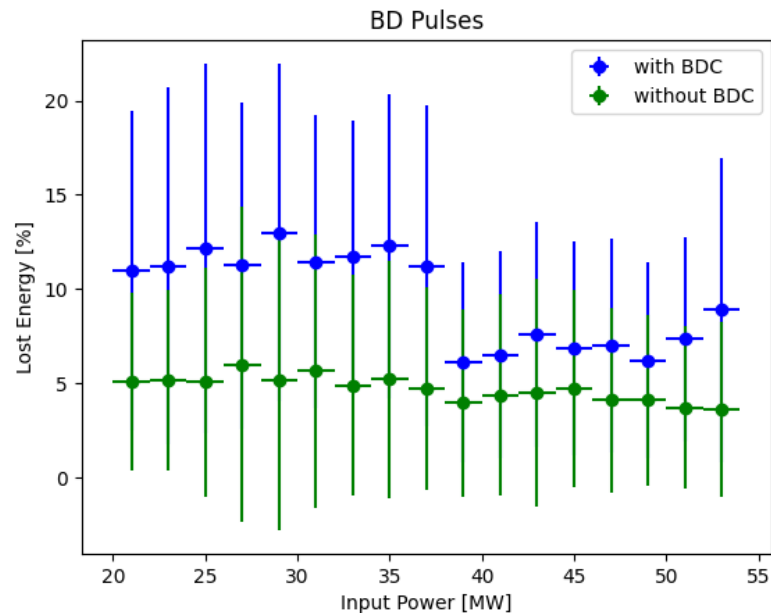
About 1.4% of emitted current reaches upstream faraday cup

# Summary

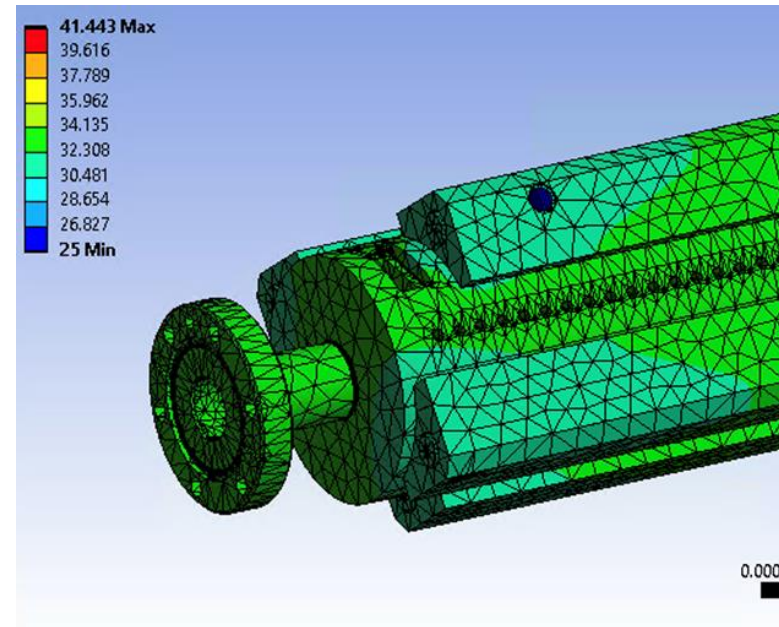
## Missing Energy

$$= \int INC - \int TRA - \int REF - Energy(DC_{up} + DC_{down}) - LOSS_{Heating} - Energy(BDC)$$

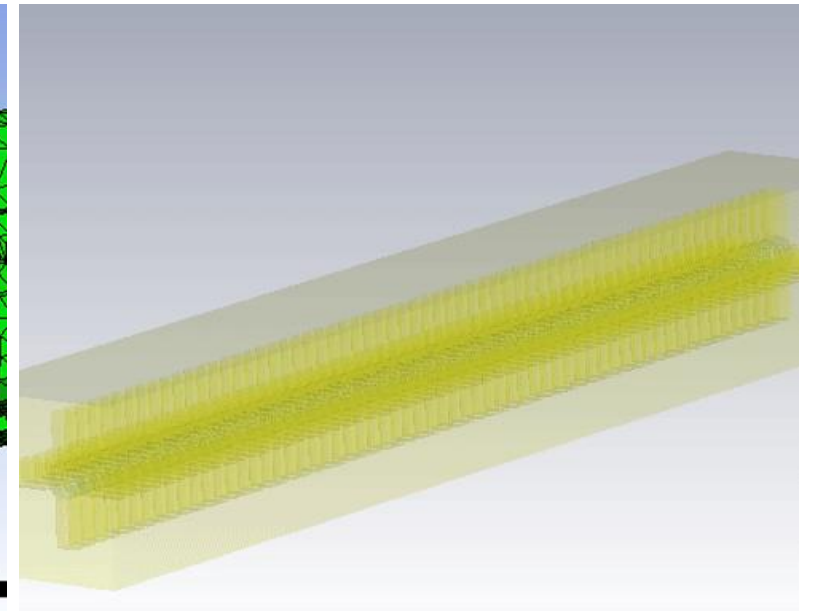
## Data Analysis



## Heat Analysis



## Dark Current Analysis



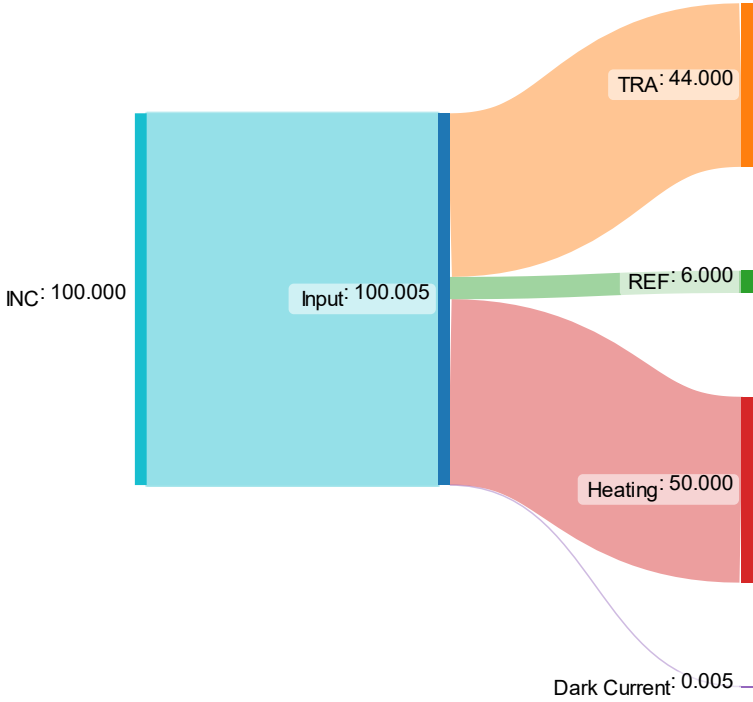
# Thank you for your attention

**Thanks to the complete X-Box team**



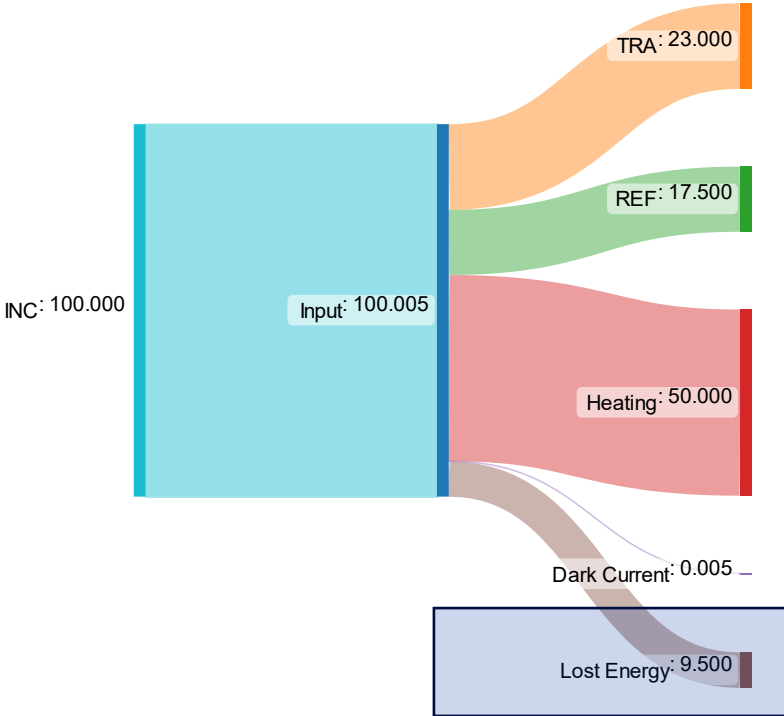
# Energy Distribution

## Normal Pulse



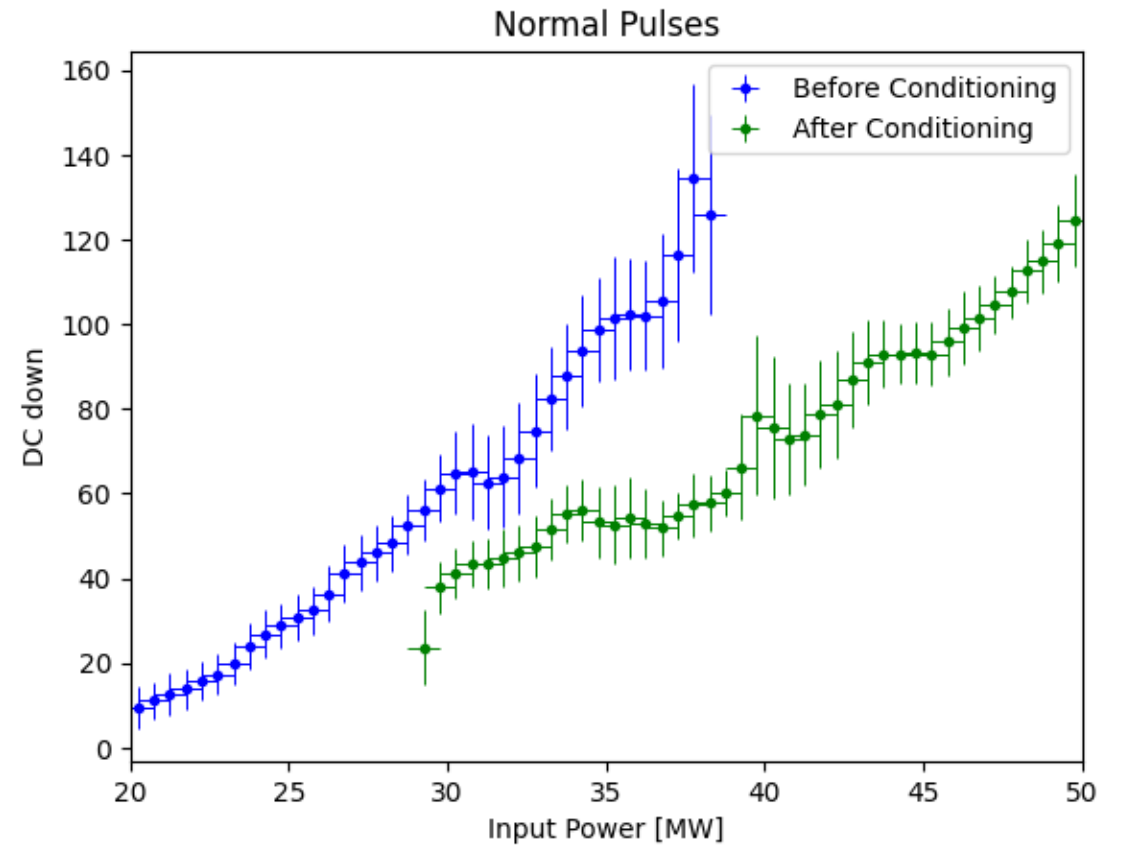
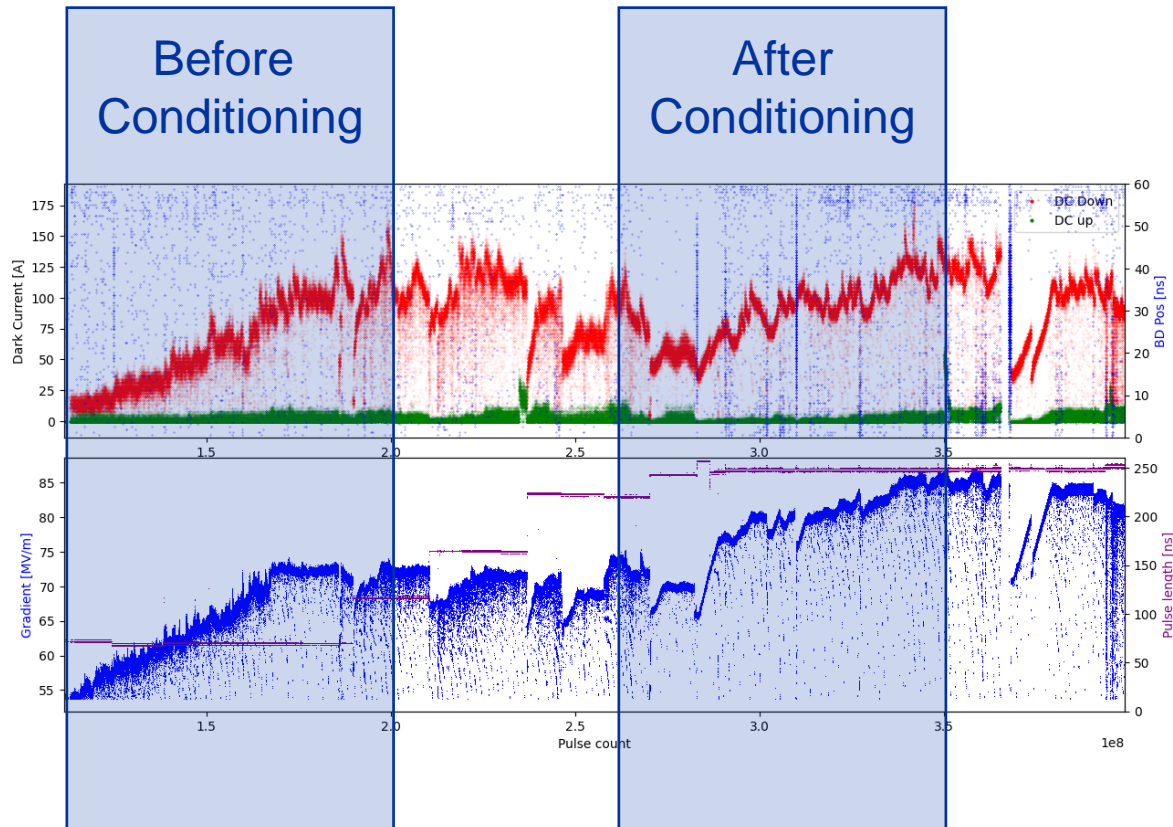
Made with SankeyMATIC

## BD Pulse



Made with SankeyMATIC

# Distribution of DC



# BD time

$$\text{BD time} = \frac{REF_t - TRA_t - t_{fill}}{2}$$

- $TRA_t$ : Time when the transmitted signal drops and starts to be reflected
- $REF_t$ : Time when the reflected signal rises
- $t_{fill}$ : Filling time of the Structure. Precise filling time brings errors and an absolute time of 60ns is used

# BD type definition X-Box 2

- **Flags are risen during operation**
- **Division done later in Post-processing:**
  - HyPc BD: Breakdowns in the Hybrid part of the system
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