Reliability Requirements of the 11 Tesla Dipole Quench Protection System

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Reliability Requirements of the 11 Tesla Dipole Quench Protection System

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- Reliability Target
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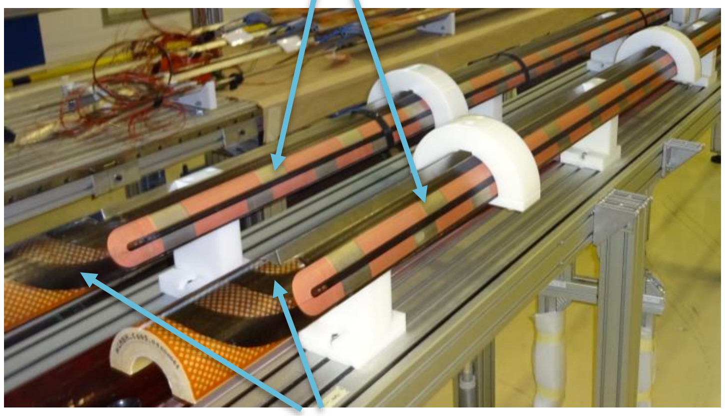
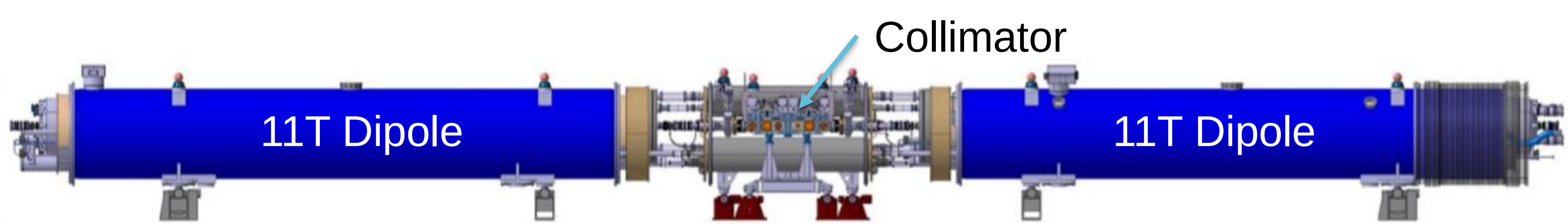
Introduction

- Two 11T dipole full assemblies will replace two main dipoles (MB) in the HL-LHC upgrade
- One 11T dipole full assembly contains two 11T dipoles and one collimator between them
- A new superconductor, niobium-tin (Nb_3Sn), is used for the 11T Dipole (The MBs use NbTi)
- The 11T dipole full assembly will be protected by quench heaters
  - 16 Quench Heater Discharge power Supplies (DQHDS)
  - Each DQHDS energizes one quench heater circuit with two quench heater strips





Introduction

- **In case of a quench, 14 oo 16 DQHDS have to fire the quench heater circuits correctly** in order to ensure the protection of the 11T Dipole

1. Question: Is the firing of the quench heaters at a quench event reliable enough?

- Analysis of the DYPQ rack of the main quadrupoles identified **the DQHDS entry (relay) as the most critical part** for not firing the heater strips

2. Question: Has an additional redundant trigger-line in the DQHDS a big impact on the system's reliability?

Reliability Target

1. Question: Is the firing of the quench heaters at a quench event **reliable enough**?

- Definition of the reliability target with the LHC risk matrix
- The LHC risk matrix determines the acceptable frequency of a specified failure mode on accelerator level

LHC risk matrix		Recovery						
		∞	year	month	week	day	hours	min.
Frequency	1 / hour							
	1 / day							
	1 / week							
	1 / month							
	1 / year							
	1 / 10 years							
	1 / 100 years							
	1 / 1000 years							

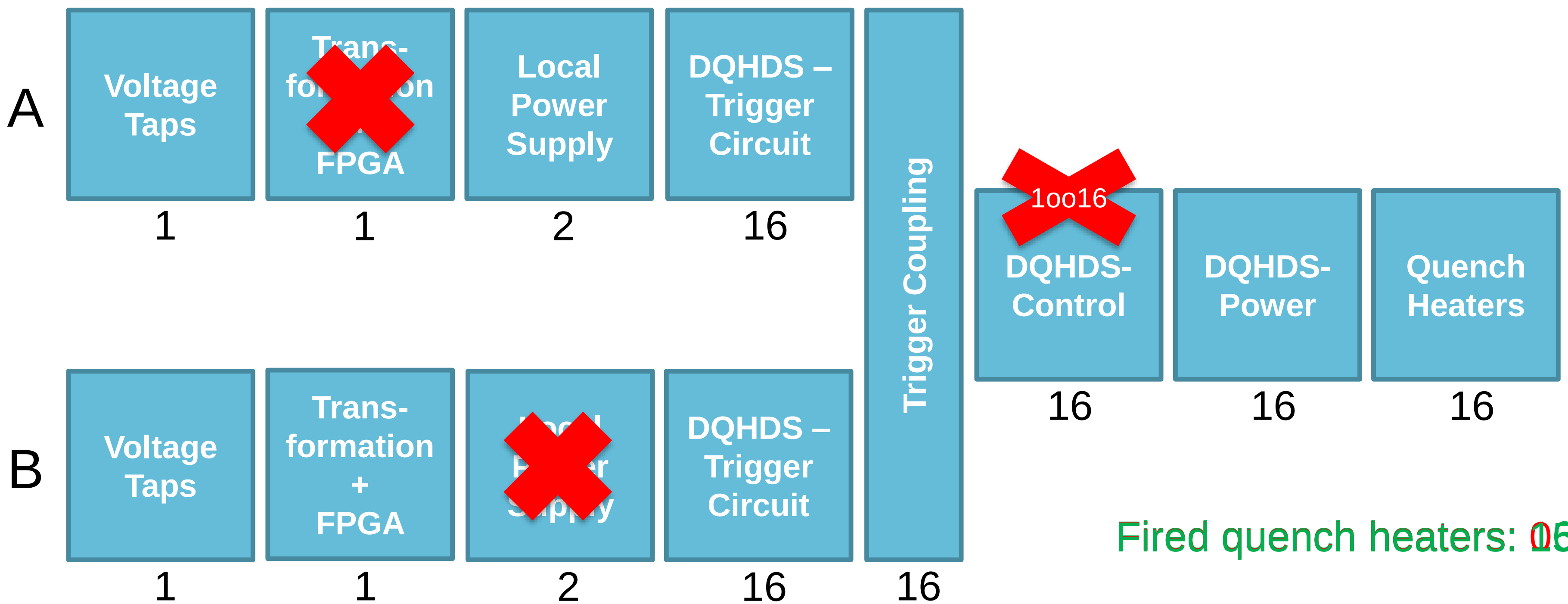
Presentation on RIRE approach: https://indico.cern.ch/event/756207/

- **Critical failure mode of the QPS (top event):** 11T Dipole is unprotected at a quench event (≥ 3 oo 16 DQHDS do not discharge)
- **End effect:** 11T dipole damaged and adjacent magnets possible damaged
- **Recovery time (for the worst case):** In order of magnitude of years
- **Frequency:** Second green box from the top, since many other systems contribute to the same severity class

➔ **The probability that the top event occurs in 1000 years must not exceed 10 %**

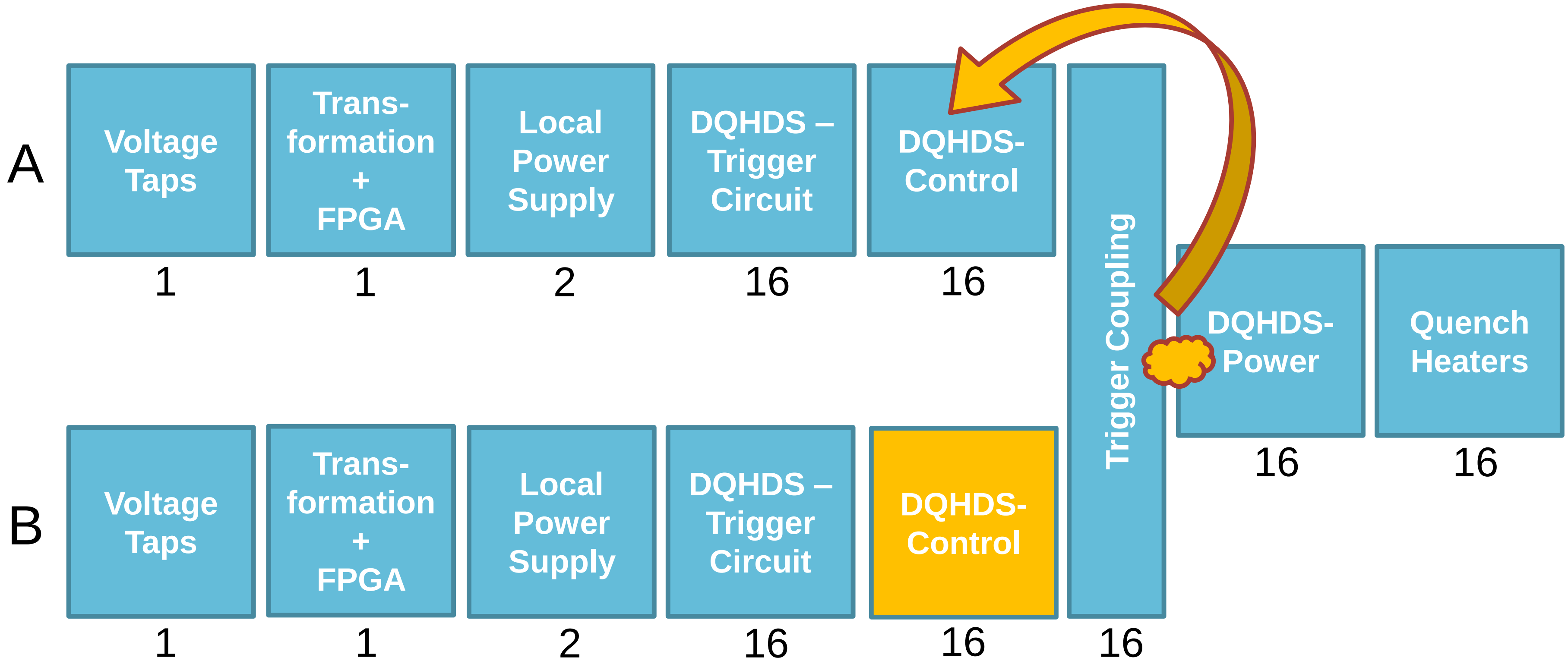
11T Quench Protection System

Version **Single** DQHDS-Control



11T Quench Protection System

Version **Double** DQHDS-Control



Failure Model

Failure behaviour

- Exponential failure distribution → **Constant failure rate**
- Failure rates are based on
  - operational data
  - specifications of the manufacturer
  - reliability prediction (MIL-HDBK 217Plus)

Maintenance behaviour

- Some boxes **are monitored**
  → **Immediate failure detection and repair** (no hidden failures)
- Some boxes **are tested**
  → **Scheduled tests:** Periodic maintenance once per year
  1 LHC year ≙ 6000 hours (250 days with 24 hours per day)
  → **Quenches:** Periodic maintenance after every quench

Failure Model

required data to calculate the input for the model

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MIL-HDBK	MIL-HDBK	Operation	Operation	Operation
Failures [-]	10	1	-	-	-	0 (1)	90	10·10
Units [-]	22800	409	-	-	-	6000	6000	4928
Operation Time [LHC years]	7	3	-	-	-	7	7	7
MTBF [LHC years]	860	1250	33	50300	66500	42000	470	345
Maintenance	Immediate	Immediate	Immediate	Periodic	Periodic	Periodic	Immediate	Periodic

Failure Model

Quench Rate

1. Quench rate based on operational experience of the main dipoles (MB)

- 4 beam induced quench events per year for 1232 MB
- 5 magnets are quenched per quench event (4 adjacent magnets will also be quenched)

➔ $QR_{MB} = \frac{5 \cdot 4\ quenches/year}{1232\ MB} \approx 0.015\ \frac{quenches}{MB \cdot year}$

➔ $QR_{11T\ Full-Assembly} = 2 * QR_{MB} \approx 0.03\ \frac{quenches}{year}$

2. Conservative assumptions for the 11T dipole

➔ ≈ 0.3 quenches per year (* 10)

➔ ≈ 3 quenches per year (* 100)

➔ ≈ 30 quenches per year (* 1000)

Sequencing

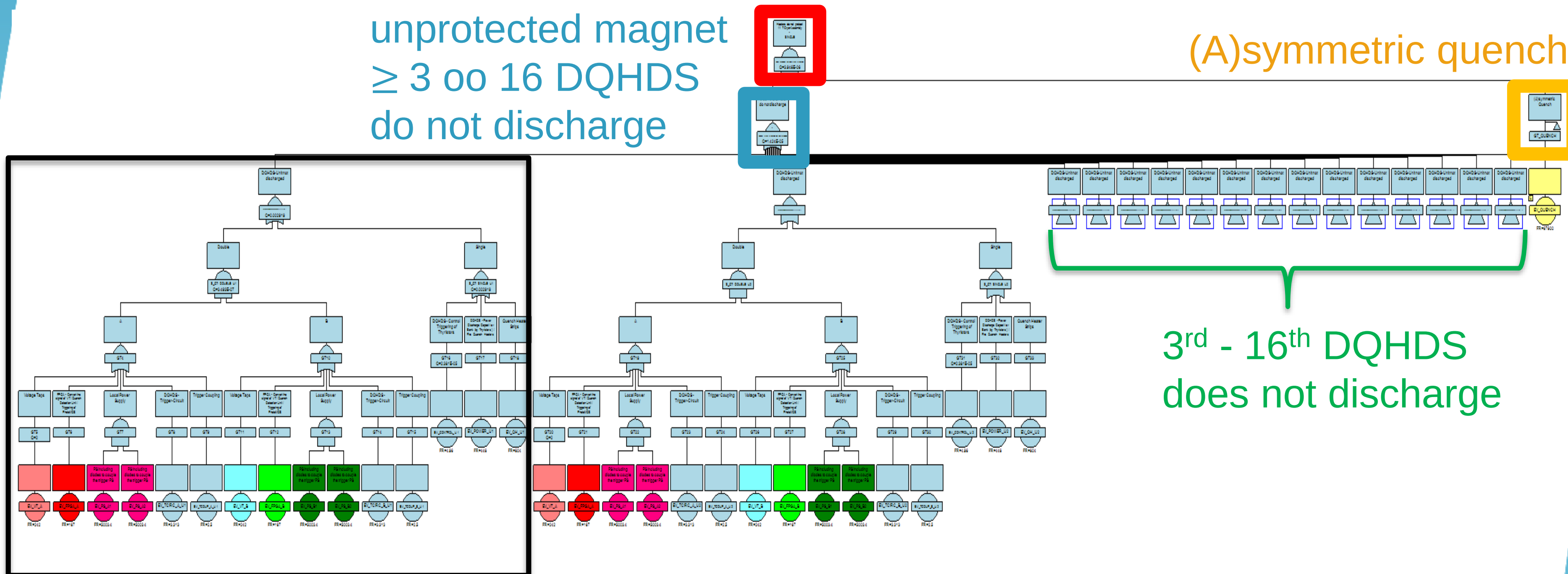
- A quench has to occur **after** the QPS went into a fault state

Fault Tree

Top event: unprotected magnet + quench

unprotected magnet
≥ 3 oo 16 DQHDS
do not discharge

(A)symmetric quench



3^{rd} - 16^{th} DQHDS
does not discharge

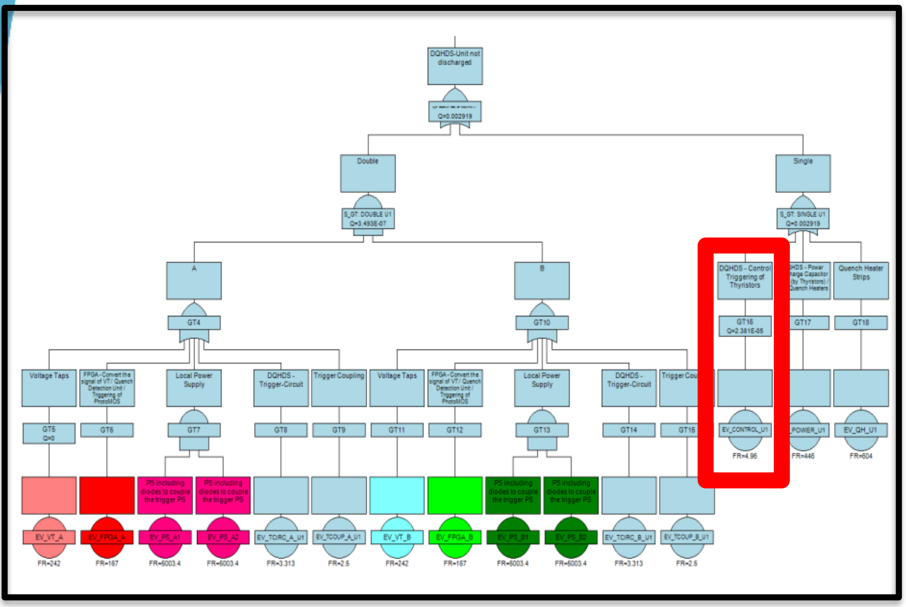
1^{st} DQHDS does
not discharge

2^{nd} DQHDS does
not discharge

isograph
Reliability Analysis Software

Fault Tree

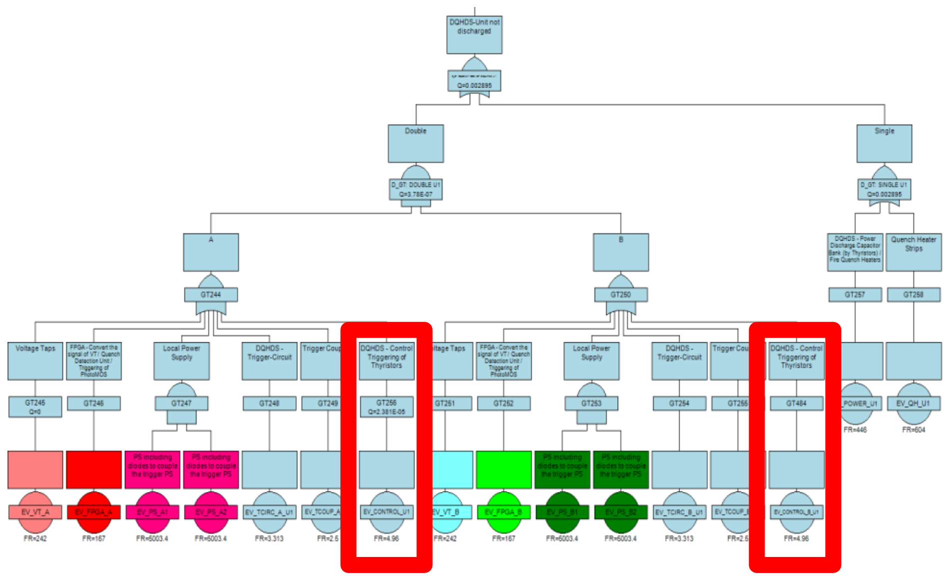
Version: **Single** DQHDS-Control



1 DQHDS-Control

1 DQHDS does not discharge

Version: **Double** DQHDS-Control



2 DQHDS-Control

1 DQHDS does not discharge

isograph
Reliability Analysis Software

Definitions

- **Unreliability**

Unreliability is the probability that a system or component **fails** during a **defined period of time** under given **functional and environmental conditions**

- **Failure**

Non-fulfilment of a function

- **Gain Factor**

Reduction of the system's unreliability between the **single** and **double** DQHDS-Control version

Results

Top event: Magnet unprotected + quench
Reliability target: Unreliability in t = 1000 years ≤ 10 %
Versions: Single ⇔ Double DQHDS-Control
Maintenance: Once per year (test) + after every quench

	Quench Rate (QR) per assembly	Unreliability for t = 1000 years Single [%]	Double [%]	Gain factor [-]
QR of MBs	$0.03\ \frac{quenches}{year}$	0.041	0.040	1.0250
	$0.3\ \frac{quenches}{year}$	0.21	0.20	1.0246
	$3\ \frac{quenches}{year}$	0.071	0.069	1.0249
	$30\ \frac{quenches}{year}$	0.00153	0.00150	1.0251

Results:

- The redundant trigger-line has a minor impact on the reliability of the system
- Quench rate (QR) has a huge impact on the unreliability
  - Low QR → System reliable
  - High QR → System reliable
  - Medium QR → Max. unreliability
- Best estimates of the QR

➔ The results meet the reliability target for both versions

Conclusions and Outlook

YES

1. Question: Is the firing of the quench heaters (14oo16) at a quench event reliable enough?

- Taking into account the best estimates of the quench rate, the calculated unreliability meets the specified reliability target
- The electronic hardware **is very reliable** not only **for low** but also **for high quench rates**
  - ➔ However, mechanical components wear out and the magnet is not designed for frequent quenches

BUT

2. Question: Has an additional redundant trigger-line in the DQHDS a big impact on the system's reliability?

NO

- The trigger-line in the DQHDS (DQHDS-control box) is very reliable
- The gain in reliability between the two configuration (single ⇔ double DQHDS-Control) is very limited

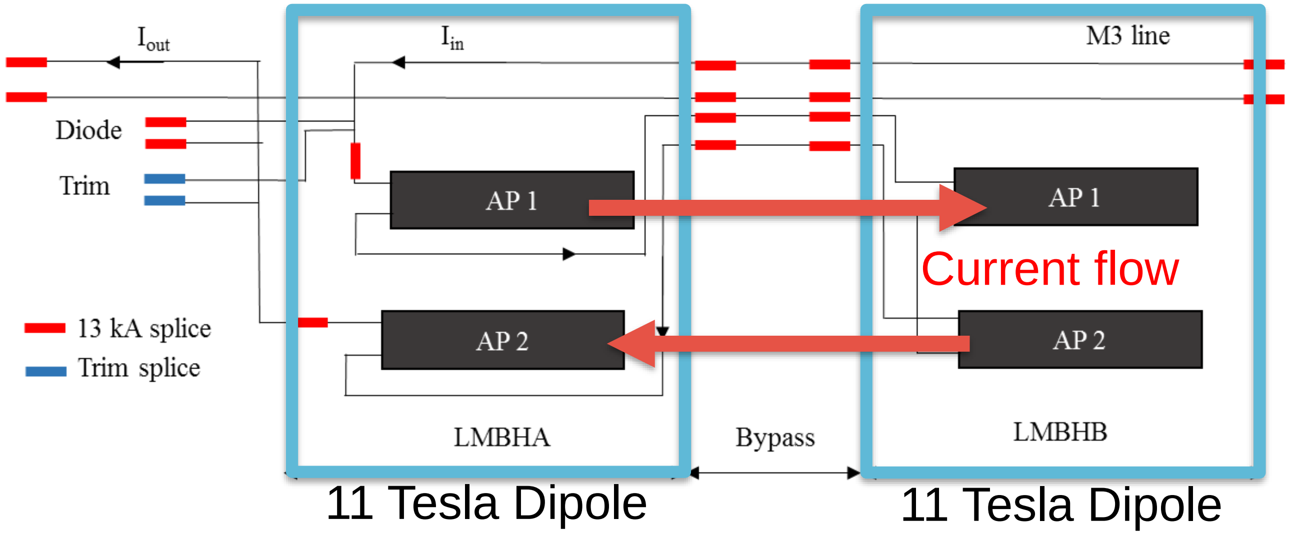
Outlook:

- The **quench rate needs to be determined more accurately**
- The **reliability requirements** of the 11T QPS will be completed following the RIRE procedure in order to **identify other critical failure modes** for the complete system

Thank you for your attention!

Assumption "14oo16 QHs must be fired to protect the magnet correctly" based on

11T dipoles are connected in series and protected together (1x Diode)



preliminary results		Nominal		1 circuit failure		2 circuits failure (worst case)	
		I_{nom}	I_{ult}	I_{nom}	I_{ult}	I_{nom}	I_{ult}
Current	kA	11.85	12.80	11.85	12.80	11.85	12.80
Quench integral	MA^2s	15.8	16.2	16.1	16.4	16.2	16.5
Hot spot temperature	K	320	342	327	349	333	356
Peak voltage to ground	V	245	340	570	680	950	1070
Peak turn to turn voltage	V	75	80	80	90	90	95

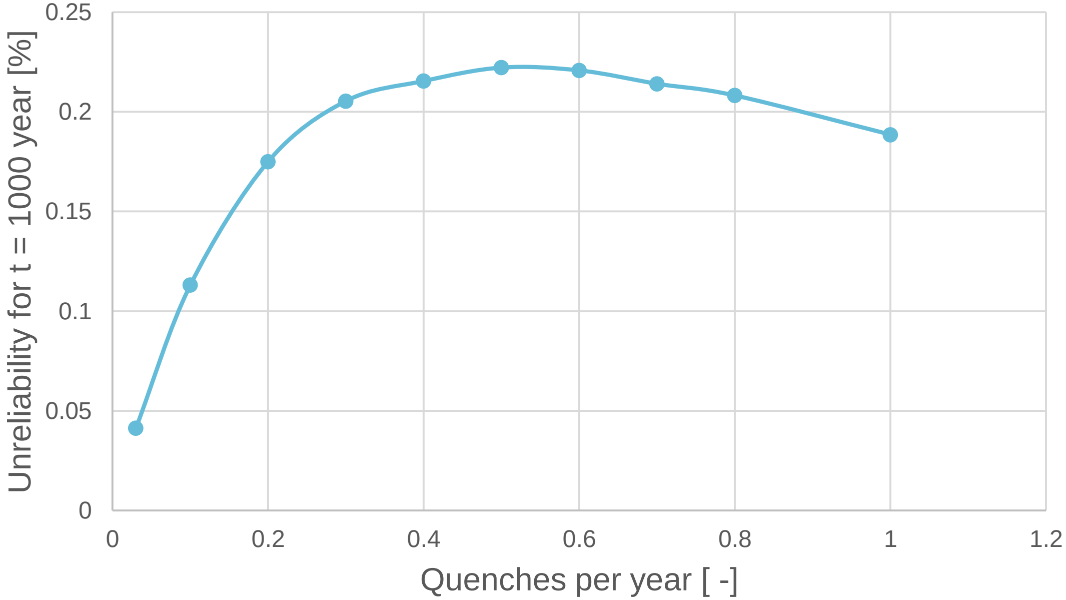
- ➔ hot spot temperature and peak voltage do not allow more circuit failures then two for both magnets
- ➔ hot spot temperature is independent of the location of the location of the circuit failures

See report:
11 Tesla Dipole – 11T Dipole Circuit – Powering and Protection (EDMS: 1764166)

Results

Top event:	Magnet unprotected + quench
Reliability target:	Unreliability in t = 1000 years ≤ 10 %
Versions:	Single ⇔ Double DQHDS-Control
Maintenance:	Once per year (test) + after every quench

Maximum of unreliability:



➔ The unreliability for t = 1000 years is maximal (0.222 %) for **0.5 quenches per year**

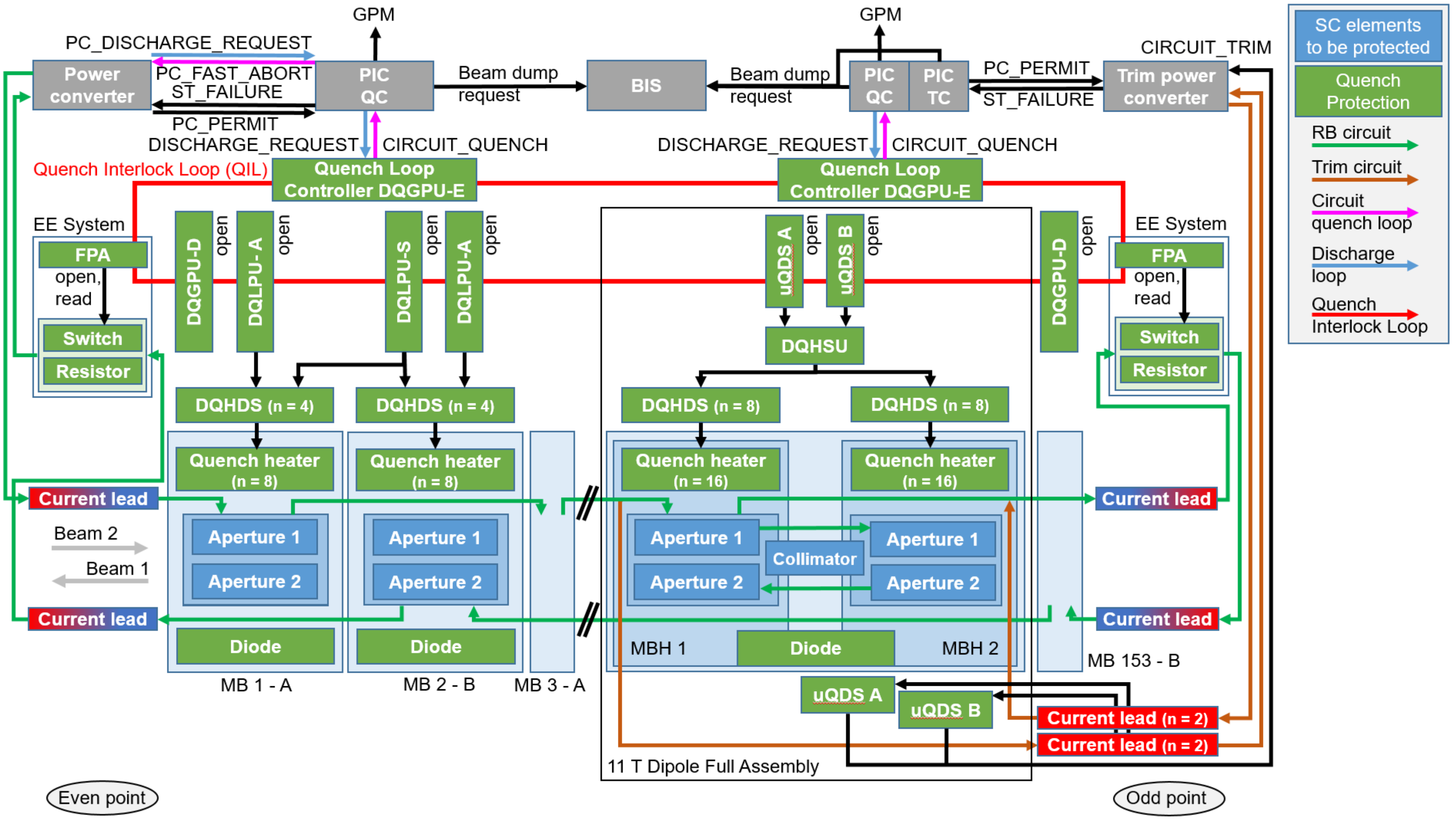
Results

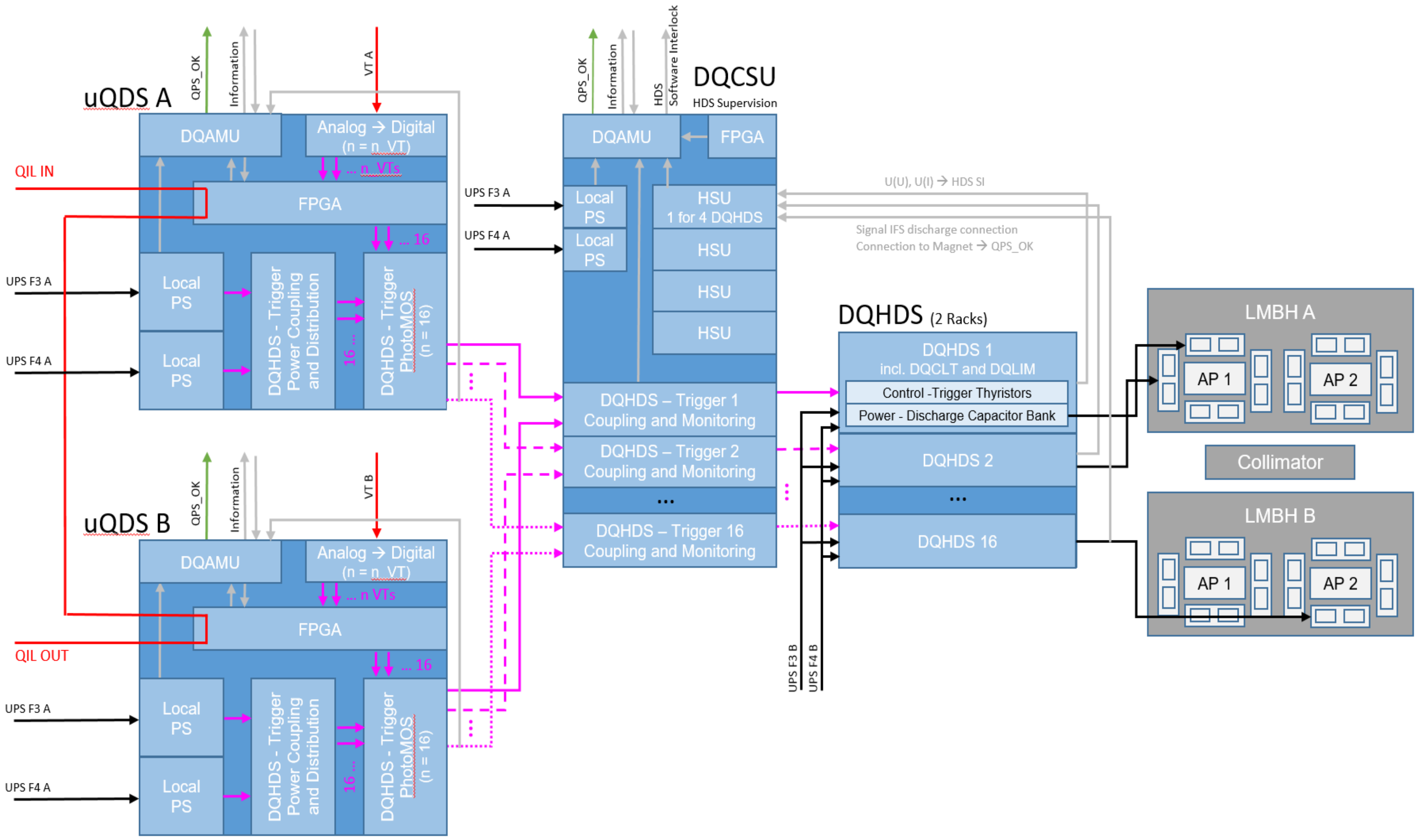
Top event: Magnet unprotected + quench
Reliability target: Unreliability in t = 1000 years ≤ 10 %
Versions: Single ⇔ Double DQHDS-Control
Quench rate: 0.3 quenches per year for the assembly

Influence of the maintenance frequency on the reliability:

Periodic Maintenance (PM)	Unreliability for t = 1000 years Single [%]	Double [%]	Gain factor [-]
PM every 0.5 years	0.037	0.036	1.025
PM every year	0.21	0.20	1.025
PM every 2 years	0.88	0.86	1.025
PM every 3 years	1.76	1.72	1.025
PM every 5 years	3.54	3.45	1.024

Results:
- Periodic maintenance has a huge impact on the unreliability
- The results meet the reliability target for all PM frequencies


GPM
PC_DISCHARGE_REQUEST
Power converter
PC_FAST_ABORT
ST_FAILURE
PC_PERMIT
DISCHARGE_REQUEST
CIRCUIT_QUENCH
PIC QC
Beam dump request
BIS
Beam dump request
GPM
PIC QC
PIC TC
PC_PERMIT
ST_FAILURE
CIRCUIT_TRIM
Trim power converter
DISCHARGE_REQUEST
CIRCUIT_QUENCH
Quench Interlock Loop (QIL)
Quench Loop Controller DQGPU-E
Quench Loop Controller DQGPU-E
EE System
FPA
open, read
Switch
Resistor
DQGPU-D
open
DQLPU-A
open
DQLPU-S
open
DQLPU-A
open
uQDS A
open
uQDS B
open
DQHSU
DQGPU-D
open
EE System
FPA
open, read
Switch
Resistor
DQHDS (n = 4)
DQHDS (n = 4)
DQHDS (n = 8)
DQHDS (n = 8)
Quench heater (n = 8)
Quench heater (n = 8)
Quench heater (n = 16)
Quench heater (n = 16)
Current lead
Aperture 1
Aperture 2
Aperture 1
Aperture 2
Aperture 1
Collimator
Aperture 2
Aperture 1
Aperture 2
Current lead
Beam 2
Beam 1
Current lead
Diode
Diode
MBH 1
Diode
MBH 2
Current lead
MB 1 - A
MB 2 - B
MB 3 - A
MB 153 - B
uQDS A
uQDS B
Current lead (n = 2)
Current lead (n = 2)
11 T Dipole Full Assembly
Even point
Odd point
SC elements to be protected
Quench Protection
RB circuit
Trim circuit
Circuit quench loop
Discharge loop
Quench Interlock Loop


uQDS A
QPS_OK
Information
VT A
DQAMU
Analog → Digital
(n = n_VT)
... n_VTs
QIL IN
FPGA
... 16
UPS F3 A
UPS F4 A
Local PS
Local PS
DQHDS - Trigger Power Coupling and Distribution
16 ...
DQHDS - Trigger PhotoMOS (n = 16)
uQDS B
VT B
QIL OUT
DQCSU
HDS Supervision
HDS Software Interlock
FPGA
HSU
1 for 4 DQHDS
HSU
HSU
HSU
U(U), U(I) → HDS SI
Signal IFS discharge connection
Connection to Magnet → QPS_OK
DQHDS – Trigger 1 Coupling and Monitoring
DQHDS – Trigger 2 Coupling and Monitoring
...
DQHDS – Trigger 16 Coupling and Monitoring
DQHDS (2 Racks)
DQHDS 1
incl. DQCLT and DQLIM
Control -Trigger Thyristors
Power - Discharge Capacitor Bank
DQHDS 2
DQHDS 16
UPS F3 B
UPS F4 B
LMBH A
AP 1
AP 2
Collimator
LMBH B

Failure Model

Voltage Taps (**1 of 2**):

- Failures: 5 – 10
  - Excluding ≈ 100 weak VTaps failures (increased resistance in the wire)
    → No risk for the magnet, as long the VTap is checked with the redundant VTaps:
- Units: 22800 VTs
  - 12 VTaps per MB and 20 VTaps per MQ
- MBH: 37 VTaps per MBH – cryo assembly (19 uQDS A, 18 uQDS B)
  - Pessimistic assumption: All VTaps have to work in order to detect a quench

$$\rightarrow FR_{VTap\ Box} = FR_{VTap} \cdot \frac{n\_VTaps\ of\ MBH-cryo\ assembly}{2} = FR_{VTap} \cdot \frac{37}{2}$$

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MIL-HDBK	MIL-HDBK	Operation	Operation	Operation
Failures [-]	10	1	-	-	-	0 (1)	90	10·10
Units [-]	22800	409	-	-	-	6000	6000	4928
Operation Time [LHC years]	7	3	-	-	-	7	7	7
MTBF [LHC years]	860	1250	33	50300	66500	42000	470	345
Maintenance	Immediate	Immediate	Immediate	Periodic	Periodic	Periodic	Immediate	Periodic

required data to calculate the input for the model

Failure Model

FPGA (**1 of 2**):

- Functions
  - Convert the voltage signal of the voltage taps
  - Quench Detection System
  - Triggering of the PhotoMOS
- Comparable board in LHC:
  - 1 FPGA + 4 input channels: 1 failure of 1636 boards in 609 days of operation

  → MBH: 1 FPGA with max. 16 input channels: $FR_{new\ Board} = FR_{old\ Board} \cdot 4$

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MIL-HDBK	MIL-HDBK	Operation	Operation	Operation
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required data to calculate the input for the model

Failure Model

Local Power Supply (**1 of 4**):
- New PS → no operation data available
- Manufacturer: MTBF = 200,000 h (other alternatives show higher values)

- Coupling of the power supplies for the trigger circuit:
  - 2 Diodes: Low Frequ, Schottky → Prediction with MIL-HDBK
- Monitoring:
  - Each local PS is monitored before the coupling
    → Failure of a single local PS is detectable

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trig… Cir…	Trigger	DQHDS	DQHDS	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MI… HD…			…n	Operation
Failures [-]	10	1	-					10·10
Units [-]	22800	409	-	-				4928
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MIL-HDBK:
- Classification
  - Category: Diode, relay, transistor, etc.
  - Type: Type of diode, type of relay, etc.
  - Quantity
    → huge influence on FR
- Default values for other parameters
  - e.g. temperature, cycling rate, etc.
    → minor influence on FR

required data to calculate the input for the model

Failure Model

DQHDS Trigger Circuit (**1 of 16**):
- 1 PhotoMOS (Solid State Relays)
  → Prediction with MIL-HDBK
- 1 Resistor to monitor the current while triggering the DQHDS - unit
  → Prediction with MIL-HDBK

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
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required data to calculate the input for the model

Failure Model

Trigger Coupling (**1 of 16**):
- 2 Diodes: LowFreq, Gen Purpose
  → Prediction with MIL-HDBK

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MIL-HDBK	MIL-HDBK	Operation	Operation	Operation
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Maintenance	Immediate	Immediate	Immediate	Periodic	Periodic	Periodic	Immediate	Periodic

required data to calculate the input for the model

Failure Model

DQHDS Control (**1 of 16**):
- Failures: 0
  - No failures in 9 years operation (including 2 years for LS1)
  - Assumption: First failure will occur tomorrow

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
Source	Operation	Operation	Manufact. + MIL-HDBK	MIL-HDBK	MIL-HDBK	Operation	Operation	Operation
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required data to calculate the input for the model

Failure Model

DQHDS Power (**1 of 16**):
- Failures: 90 https://wikis.cern.ch/pages/viewpage.action?pageId=103441547
  - 90 failures in total
  - 65 failures of the mains switch (excluding mains switch failures of the old type)
- Failure Accelerator Fault Tracker von Reiner (2015 – 2018)
  - 842 operation days
  - DQHDS Failures: 8
  - F3 Failures: 3

Box / Attribute	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
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required data to calculate the input for the model

Failure Model

Quench Heater Circuit (**1 of 16**):
- 1 QH circuit consists of 2 QH strips for the MB and the MBH

- Failures: 10 MB-QH failures during the period from October 2007 to May 2016
- Units: $1232\ MB \cdot 4\ QH\ circuits \cdot \frac{2\ QH\ strips\ per\ circuit\ for\ MB}{2\ QH\ strips\ per\ circuit\ for\ MBH} = 4928\ units$
- This period includes
  - Commissioning and re-commissioning
  - Quench trainings
  - LHC operation at 3.5 TeV and at 6.5 TeV
- MBH: Pessimistic Assumption: $FR_{MBH} = FR_{MB} \cdot 10$

Attribute \ Box	Voltage Taps	FPGA	Local Power Supply	DQHDS Trigger Circuit	Trigger Coupling	DQHDS Control	DQHDS Power	Heater Strips
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