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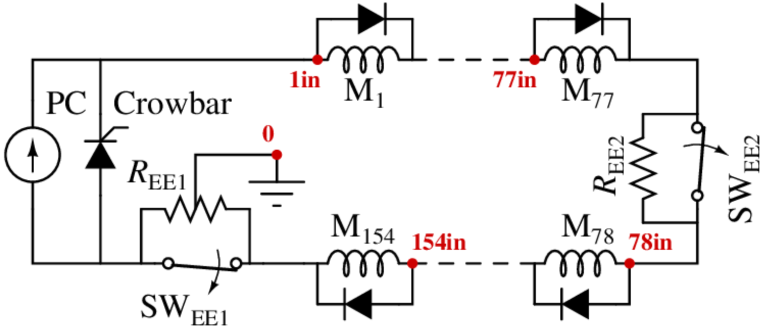
HL-LHC Energy Extraction Systems Reliability Study

Reliability and Availability Studies Working Group, 28 Oct 2021

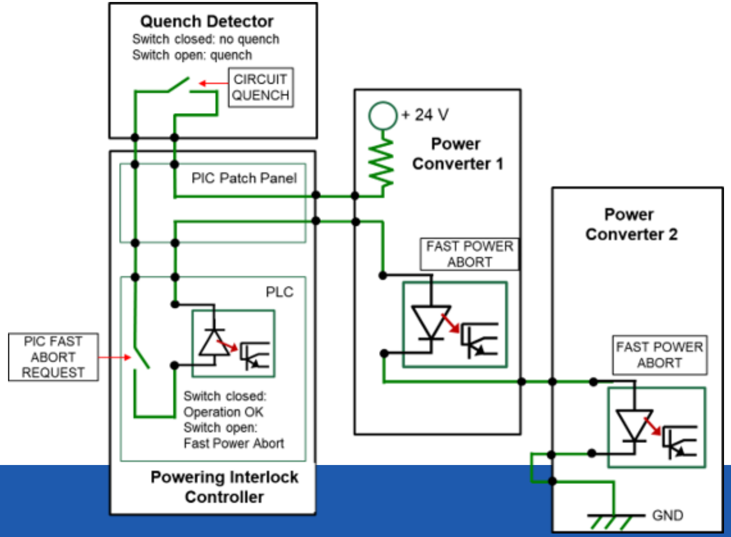
Andrea Apollonio, **Milosz Blaszkiewicz**, Thomas Cartier-Michaud, Bozhidar Panev

Energy Extraction

- Energy Extraction systems are used to extract energy stored in **superconducting magnets circuits** upon the detection of a **quench**.
  - After such an event is detected, the magnet's powering is **interrupted**, and the energy stored in magnets is **dissipated** through the resistors.
- The number of Energy Extraction systems in the LHC:
  - 202 for **600A** circuits,
  - 32 for **13kA** circuits.
- No critical system failure has been observed during the operation of the LHC. These systems have very stringent reliability requirements to **always ensure protection** of the circuits.

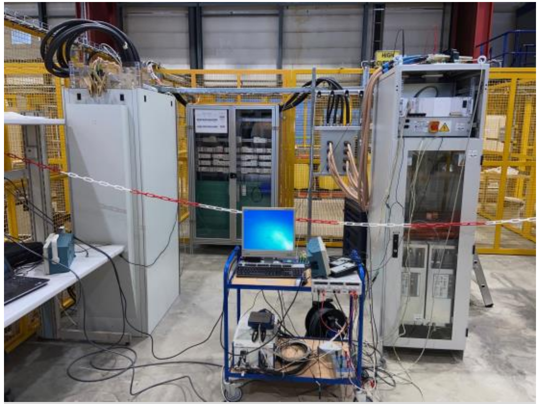


Example of EE systems for the main dipole circuits



Vacuum switches-based EE systems

- A new switching technology is introduced in the HiLumi EE systems (Collaboration between CERN-TE-MPE and DAE-Lodz, Poland – 2017)
- Two classes (2 kA and 600A) were developed and successfully tested.
- A pre-series of 8 systems was produced and tested. They will be used in clusters A, F and C in SM18.



Pre-series unit under test

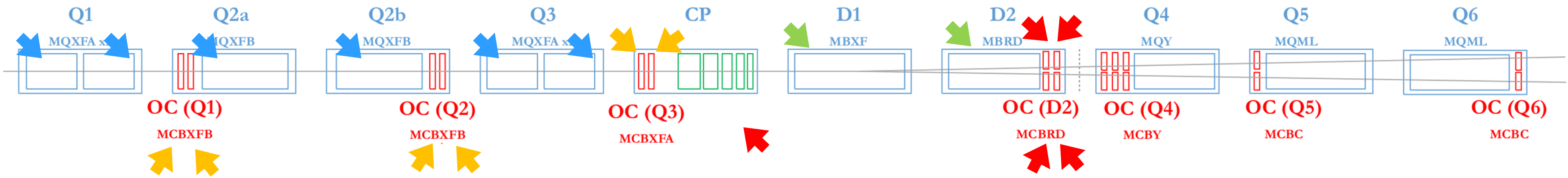
Cluster-F installation
2 x 2 kA EE systems

Slide content from: B. Panev “*Energy Extraction Systems - design and status*” presented in [11th HL-LHC Collaboration Meeting, CERN - 19-22 October 2021 · Indico]

Purpose of the study

- **Establish the reliability requirements for the system**
  - Deriving the target from LHC Risk Matrix
- **Development of a system reliability model**
  - Gathering reliability inputs (MTTF, etc.) about components
  - Use AvailSim4 to model advanced maintenance and repair strategies
- **Evaluating the system's compliance with the derived reliability target**
  - Probability of having an unprotected quench due to a failure of the Energy Extraction in the lifetime of the system
  - Probability of a failure on demand
  - Gathering additional insights and explanations for the results (e.g., root cause analysis, understanding the dynamics of the reliability behavior, etc.)

HiLumi Circuits Layout



Magnets	Protection	Number
Inter Triplet Quadrupole	CLIQ + QH	6×4
2kA orbit correctors	EE	6×4
600A and 200A high order correctors	EE	5×4
D1, D2	QH	2×4
TOTAL		$19 \times 4 = 76$

LHC Risk Matrix[1]

Recovery time

Frequency	[1m - 20m)	[20m - 1h)	[1h - 3h)	[3h - 6h)	[6h - 12h)	[12h - 24h)	[24h - 2d)	[2d - 1w)	[1w - 1M)	[1M - 1Y)	[1Y - 10Y)
1/H	U	U	U	U	U	U	U	U	U	U	U
1/Shift	U	U	U	U	U	U	U	U	U	U	U
1/Day	A	U	U	U	U	U	U	U	U	U	U
1/Week	A	A	A	A	U	U	U	U	U	U	U
1/Month	A	A	A	A	A	A	U	U	U	U	U
1/Year	A	A	A	A	A	A	A	A	U	U	U
1/10Years	A	A	A	A	A	A	A	A	A	U	U
1/100Years	A	A	A	A	A	A	A	A	A	★	U
1/1000Years	A	A	A	A	A	A	A	A	A	A	A

Data-driven risk matrices specify the acceptable failure frequency depending on the recovery time.

Matrix's value refers to HL-LHC superconducting circuits (including new inner triplets, D1, D2, and orbit correctors). This means that the reliability of all circuits combined must meet the target.

It is assumed that the frequency "one in hundred years" corresponds to no more than 10% probability of a single system failing in 100 years.

[1] EDMS **2647876 v.1,** https://edms.cern.ch/document/2647876/1

Deriving the reliability target for a single instance of the EE system

From the risk matrix:

$$R_{HL}(100\ years) > 0.9$$

Scaling to the lifetime of the system

$$R_{HL}(20\ years) > 0.9^{\frac{20}{100}}$$

Reliability target of HL Protection R_{HL}

$$R_{HL} = R_{IT}^{6\times4} \times R_{2kA}^{6\times4} \times R_{600A}^{5\times4} \times R_{D}^{2\times4}$$

$$R_{HL} = R_{subsystem}^{76} (*)$$

$$R_{HL} = 0.9^{\frac{20}{100}} \simeq 0.97914$$

$$R_{subsystem} = (0.9^{\frac{20}{100}})^{\frac{1}{76}} \simeq \mathbf{0.999723} = 1 - 2.7 \times 10^{-4}$$

Magnets	Protection	Number
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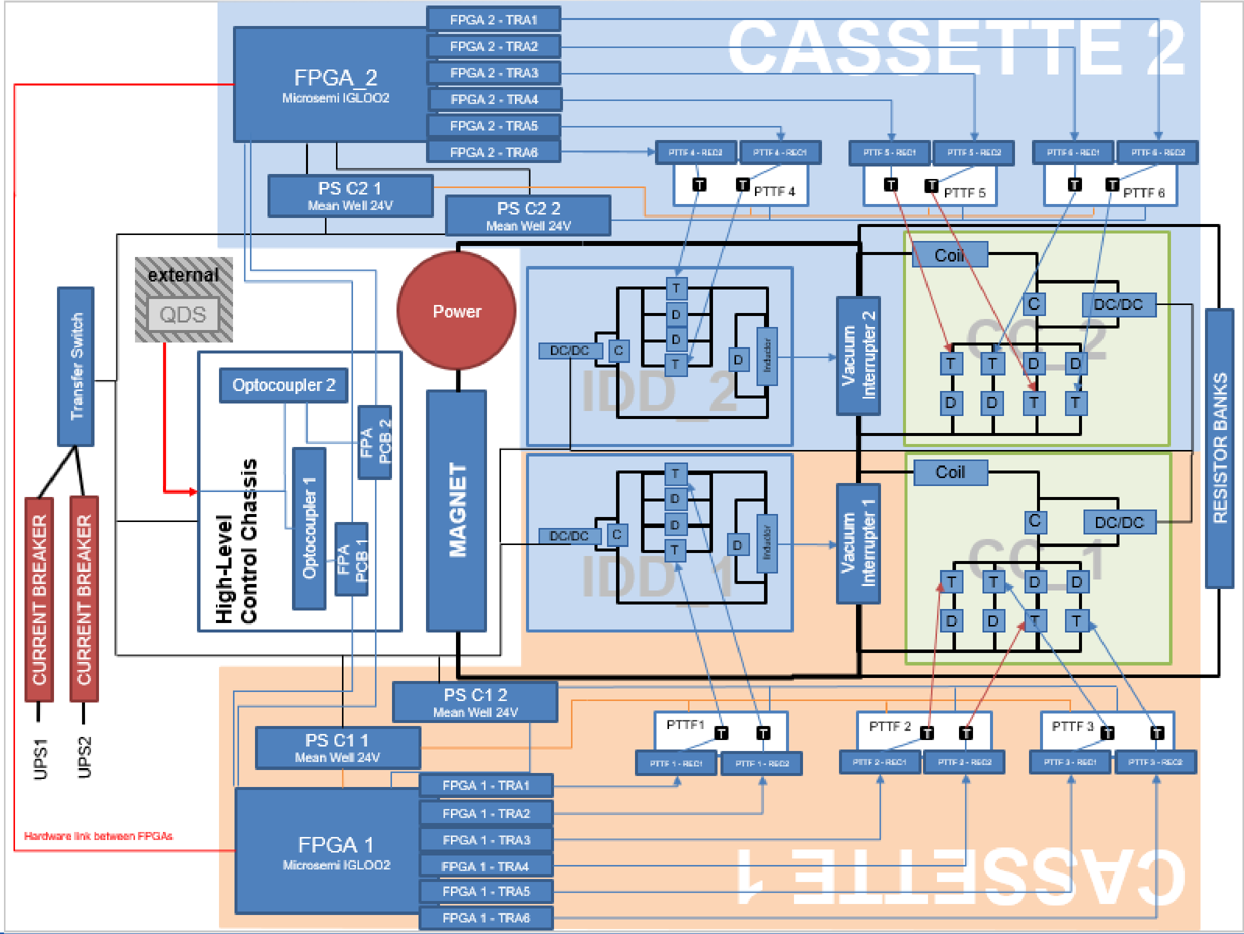
* Implicit assumption: all systems are expected to meet the same reliability

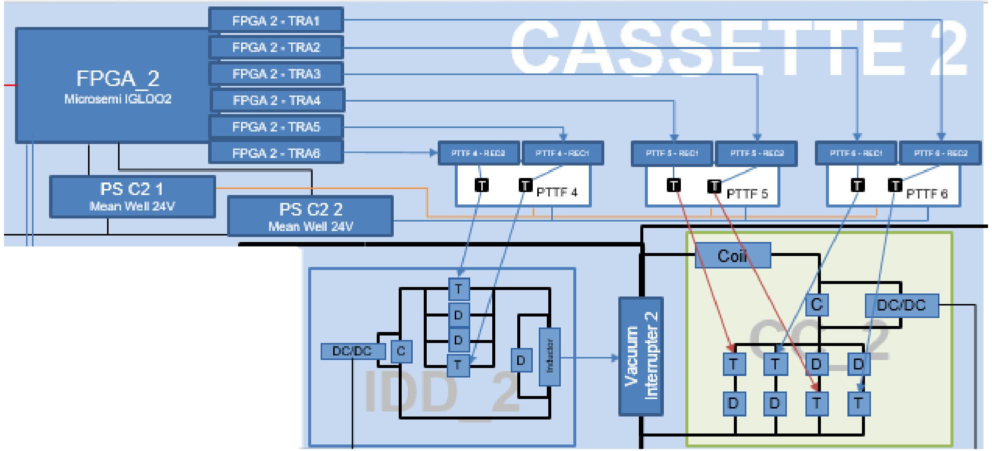
Energy Extraction Block diagram

- Redundant power source components in both cassettes
- Communication channels from FPGA to Inductive Dynamic Driver (IDD) and Counter Current (CC) mechanism .
- Two redundant lanes inside the High-Level Control Chassis (HLCC).
    - **Completed a hybrid component/block level analysis**
- Temperature of 45°C inside the rack (operating), 25°C (non-operating).



Monitoring and MRUs

- Active and passive monitoring
  - **Active:** failures are visible immediately
  - **Passive:** completed through data dumps to Post Mortem database
  - Non-monitored blind failures
- Minimal Replaceable Units (MRU)
  - Physical object being replaced upon a failure of any element within the object
  - Replacement of the unit removes blind failures
- Fail-safe behaviour



Cassette – single Minimal Replaceable Unit in Energy Extraction systems

Failure rate estimations for individual components

Inductive Dynamic Driver (IDD) and Counter Current (CC)

Inductive Dynamic Driver

Component name	FIT	MTTF [10^6 h]	Detection	Ref [see appendix]
AnXon AXCT27410K152DA, 410 uF, 1500 Vdc	30	33	Detectable	[1] - Datasheet
POWEREX T7H8167504DN, 750 A / 10.5 kA / 1.6 kV / 150 A/µs	138	7	Blind	[2] - Producer
LAMINA D61-250-18-NO, 250 A / 1.8 kV / 5.5 kA/µs	9	111	Blind	[3] – MIL-HDBK-217F (25 C)
LAMINA D22-10-16, 10 A/ 1.6 kV / 250 kA/µs	9	111	Blind	[3] – MIL-HDBK-217F (25 C)
Proton-Electrotex TFI343-630-15-77-N, 630 A / 10.5 kA / 1.5 kV / 2 kA/µs	20	50	Blind	[4] - Producer
NORATEL FR60B-660230, 40 VA, 4/5.2 kV AC RMS	12	83	Detectable	[3] – MIL-HDBK-217F (25 C)

Counter Current

Component name	FIT	MTTF [10^6 h]	Detection	Ref [see appendix]
AnXon AXCT27410K152DA, 410 uF, 1500 Vdc	30	33	Detectable	[1] - Datasheet
LAMINA D63-400-26, 400 A / 5.5 kA / 2.6 kV / 5.5 kA/µs	9	111	Blind	[3] – MIL-HDBK-217F (25 C)
NORATEL FR60B-660230, 40 VA, 4/5.2 kV AC RMS	12	83	Detectable	[3] – MIL-HDBK-217F (25 C)
Proton-Electrotex TFI343-630-15-77-N, 630 A / 10.5 kA / 1.5 kV / 2 kA/µs	20	50	Blind	[4] - Producer

Failure rate estimations for individual components

Pulse Train Thyristor Firing (PTTF) units and other

	Component name	FIT	MTTF [10^6 h]	Detection	Ref
PTTF	Wurth Electronik 750315240, 1A, 5 kVrms/minute	12	83	Blind	[5] - Producer
PTTF	Broadcom HFBR-2522Z, 1 MBd	769	1.3	Blind	[6] - Producer

	Component name	FIT	MTTF [10^6 h]	Detection	Ref
Other	Broadcom HFBR-1532Z, 1 MBd	833	1.2	Blind	[6] - Producer
Other	Broadcom HFBR-1533Z, 40 kBd	833	1.2	Blind	[6] - Producer
Other	Broadcom HFBR-2533Z, 40 kBd	769	1.3	Blind	[6] - Producer
Other	Microsemi IGLOO2 M2GL005-TQG144I	3.2	311	Detectable	[7] - Producer
Other	Mean Well DR-15-24, 24V DC, 0.63 A DC	853	1.2	Detectable	[8] - Producer
Other	Circuit Breaker (no-name)	16.3	61	Detectable	[9] – Inner Triplet Study
Other	Siemens VS 17005 - vacuum interrupter	2.3	428	Blind	[4] - Producer

To be revisited in the next slide

Vacuum interrupter MTTF

- A further study of the available literature in the field of vacuum interrupters reliability revealed some additional information regarding the entire class of these devices: in a white paper, Renz et al. show a figure estimating Siemens VI MTTF at **45,000 years**.
- Technical note on the Siemens website provides an updated value of **57,000 interrupter years** (i.e., more than **400 mln hours**).
- Finally, the search was concluded with a documents obtained from Siemens' representative, which states that their MTTF estimation for the specific interrupter (only) is **428 mln hours**.

Other model assumptions

- Spring as a mechanical element of the vacuum interrupter
  - Not explicitly included in the model, since considered **fail-safe**.
  - Additional simulations performed with conservative approach to the mode's effects which show that system still meets the target.
- Transfer switch, UPS – no failures
  - **Fail safe**: lack of power triggers an extraction of energy.
- Failures of the **Quench Detection System** are not included in the model
  - Their contribution can be added analytically based on previous estimates derived from experience.
- **Optical fibers**
  - Only qualitative statements available from the EL experts; fibers not expected to fail if correctly installed (failures detected during commissioning) and thus not included in the model.
- Coil, inductor of IDD and CC and resistors
  - Not included in the models following expert's feedback

AvailSim4 – introduction

- Monte Carlo (MC, stochastic simulation methods)
  - Three-phased Discrete Event Simulation for evaluating instances of the system lifetime.
- High flexibility in terms of defined system parameters:
  - Customizable failure modes:
    - Frequency and repair times described using **probability distributions.**
    - Two types of failures: **blind** and **detectable** (active monitoring).
  - Periodic **inspection events** – detecting and removing blind failures for selected components.
  - Advanced component tree structures:
    - **Minimal Replaceable Units** (MRU).
    - **Failure dependencies** shared between different parts of the architecture tree.
  - **User-defined phases** to reflect system's changing environment.
  - **Root Cause Analysis** (RCA) feature for more detailed examinations.

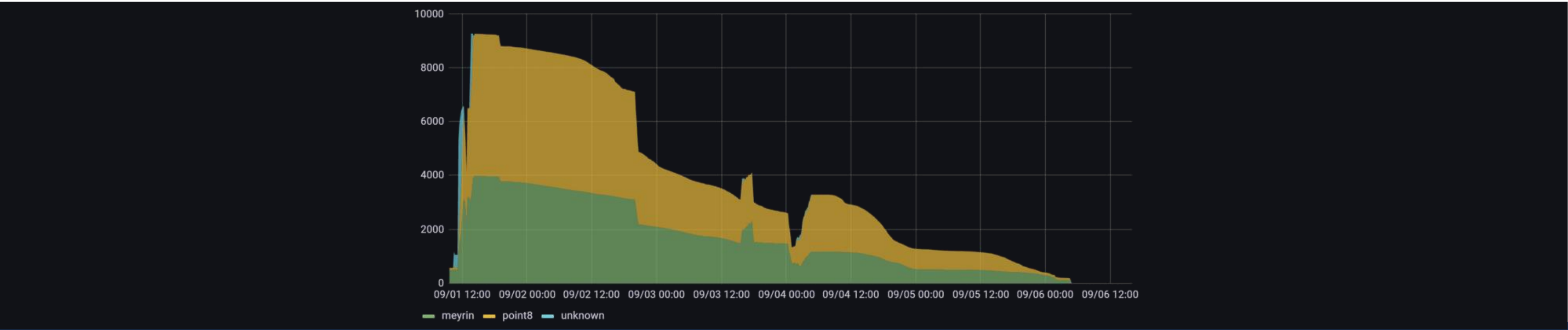
AvailSim4 – more advanced features

- Works well both **locally**, on a user's computer, and on a **computing cluster**, with specialized module for HTCondor cluster support.
- **Rare nature of the events** of interest (expected order of magnitude of the failure probability below 10^{-6})
- More intricate system behaviours modelled through configurations of artificial failure modes and MRUs.

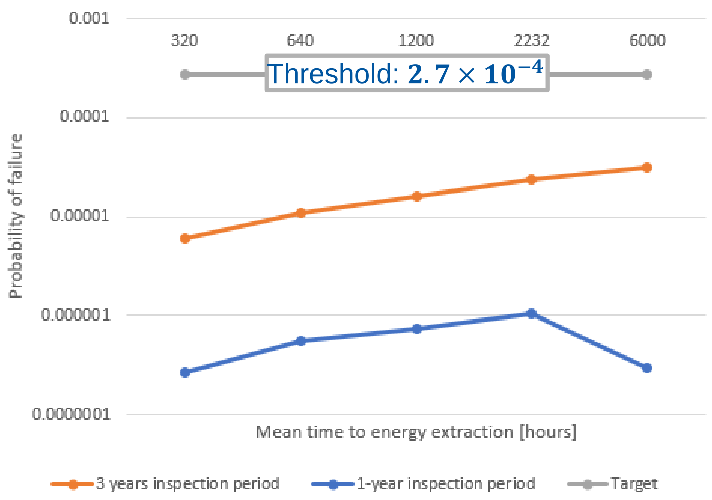
- Gitlab: Availsim4 · GitLab (cern.ch) (access available on request or via AccPy distribution's pip)

EE System Reliability simulations in AvailSim4

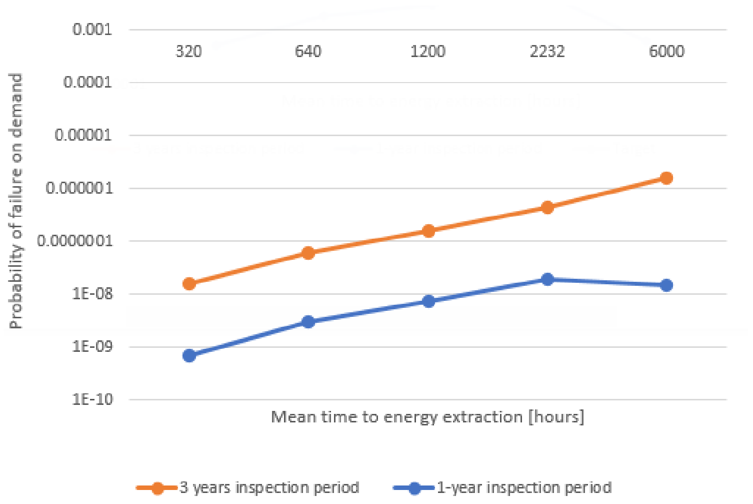
- For Energy Extraction reliability study, we completed several HTCondor campaigns of iteratively-improved model:
  - Final run comprised 20 separate configurations: with or without spring failure mode, 1- or 3-years inspection interval and 5 values of mean time to energy extraction.
  - Eventual number of model evaluations (accuracy of the prediction) varies per configuration from 2 to 10 million. Factors of practical nature played a major role in this aspect.



Reliability estimations - one system



Probability of having an unprotected quench within 20 years of operation

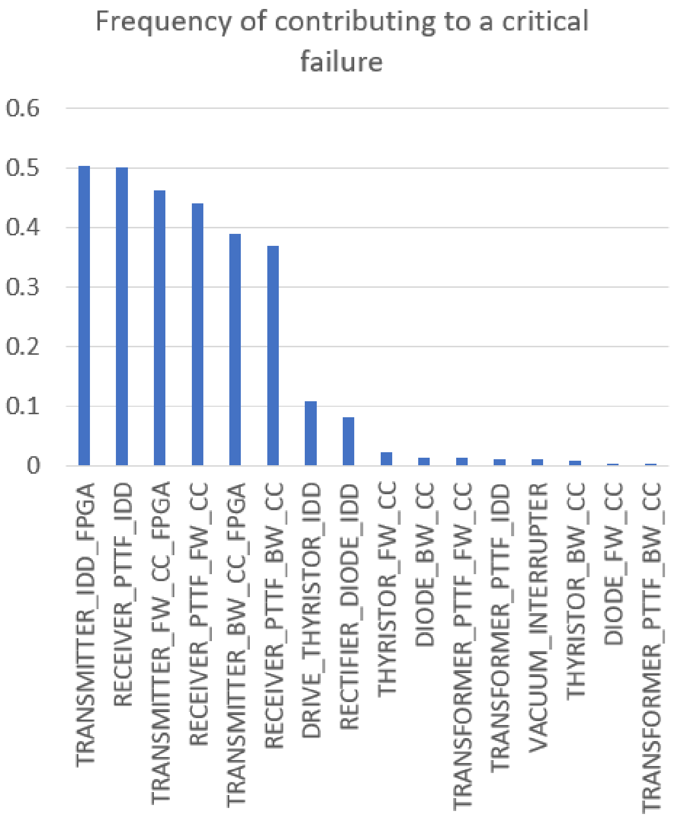


Probability of failure on demand

Even with 3-years inspection interval, the reliability target is met

Root cause analysis

- There is **no single point of failure** in the model.
- All critical failures are caused by a combination of failures in both redundant paths.
- Optical communication components are most frequent contributors to critical failures.
- Rectifier diode is present in 8% of all critical failures (single point of failure for an IDD)
- Thyristors and transformers have a higher MTTF, so they appear less often as causes for a failure, but they appear in combination with a failure in optical fiber components



Probability of failure on demand (quench) for HL-LHC protection systems

Symbol	QDS	QH	CLIQ	**EE**
Protection Layer	Quench Detection Systems (including voltage taps)	Quench Heater Circuits	CLIQ	**Energy Extraction**
D1/D2	$\mathbf{10^{-6}}$	$\mathbf{1.2 \times 10^{-7}}$ (P < 2oo4 QHs)	Not present	**Not present**
IT (@low current)	$\mathbf{10^{-6}}$	$\mathbf{2.8 \times 10^{-8}}$ (P < 4oo8 QHs)	Not present	**Not present**
IT (@high current)	$\mathbf{10^{-6}}$	$\mathbf{2.3 \times 10^{-6}}$ (P < 5oo8 QHs)	$\mathbf{8.7 \times 10^{-5}}$	**Not present**
Corrector (600A and 2kA)	$\mathbf{10^{-6}}$	Not present	Not present	$\mathbf{1.6 \times 10^{-6}}$

Green = simulations
Blue = estimations based on historical data (of the present system)

Conclusions

- **System meets the reliability target with the presented assumptions**
- The design is highly reliable due to **extensive redundancy**, **fail-safe mechanisms** and **active monitoring** of some components.
- Overall reliability improves also due to the **chosen repair strategy** (replacement of the entire cassette in case of a detected failure).
- Detecting failures of inside IDD or CC (not monitored – blind failed) is likely to **improve system's reliability** even further.
- Reliability tests in the future will help **building further confidence** in the obtained results.

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