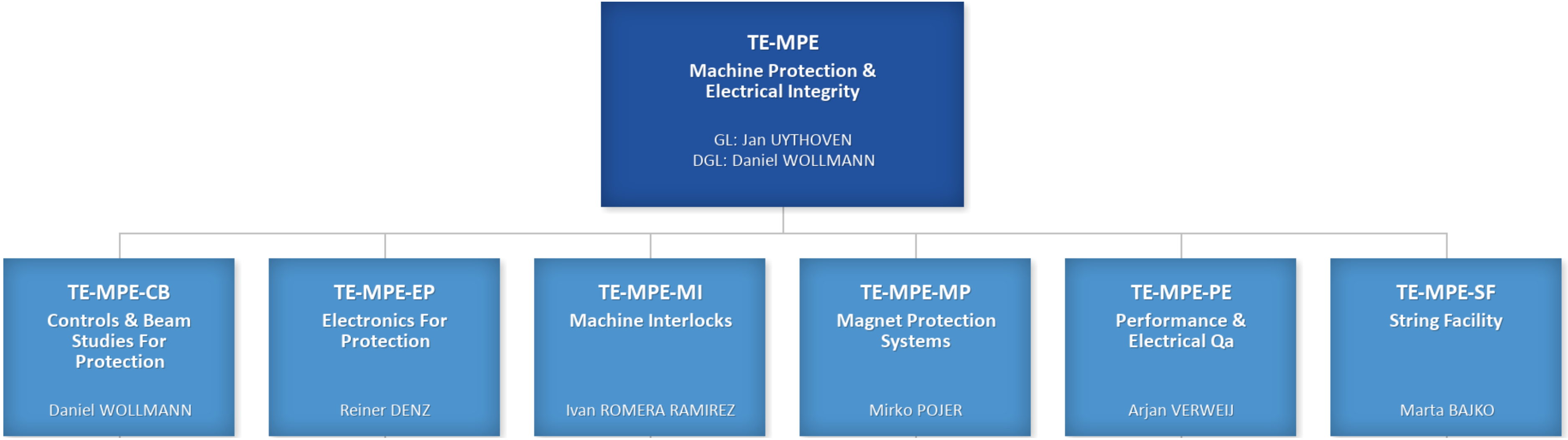

TE-MPE
Machine Protection & Electrical Integrity

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The MPE group supports the operation of CERN’s accelerators by developing, maintaining and operating **state-of-the art hardware and software technologies for magnet circuit protection and interlock systems.**

Energy stored in Magnet Powering System and Beam of the LHC

$E_{kin}(v = 27\text{ kn}) \approx E_{LHC\text{ main circuits}}(@6.5\text{ TeV})$

One LHC beam = 360 MJ = ?

The kinetic energy of a 200 m long train at 155 km/hour

M.Zerlauth - CAS 2021

Protection System Life-Cycle

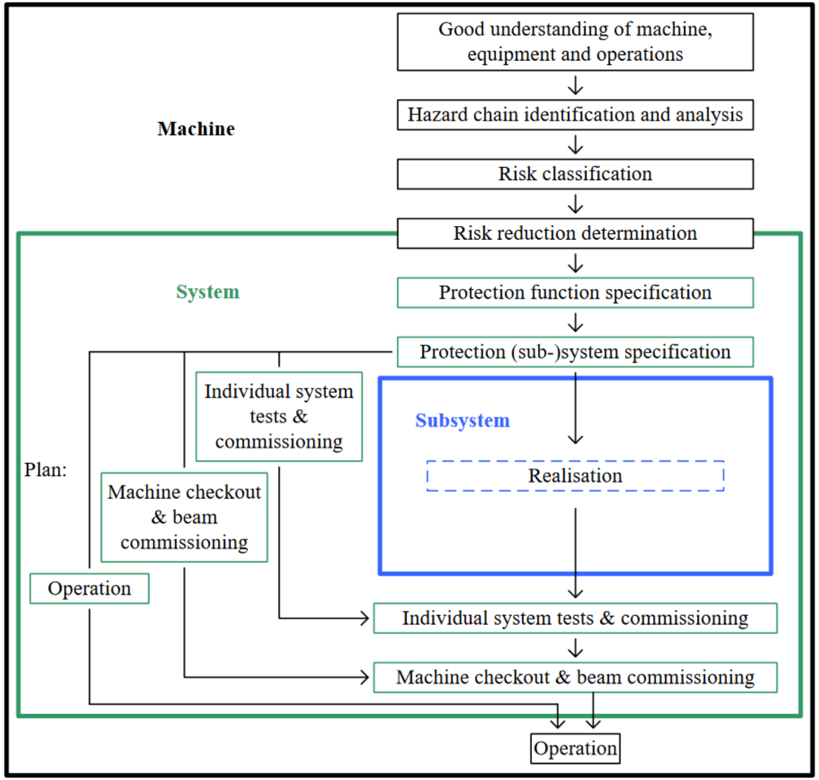
Risk and Machine Protection for Stored Magnetic and Beam Energies
Todd, B.; Kwiatkowski, M.

Critical systems follow defined life-cycle

- Ensures that risks are mitigated
- Inspired by IEC 61508 and adapted for CERN context

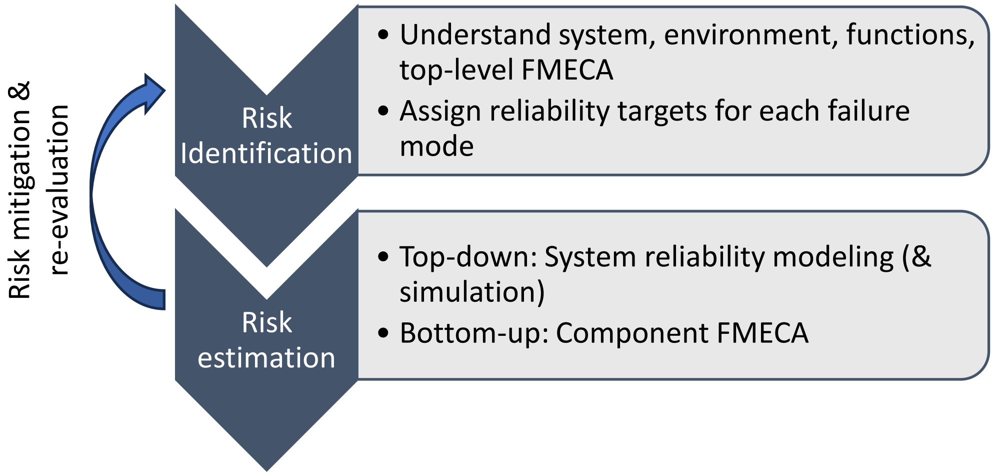
Slides show sub-set of life-cycle on examples of

- Reliability analysis
- Reliable firmware & software development



Machine
Good understanding of machine, equipment and operations
Hazard chain identification and analysis
Risk classification
Risk reduction determination
System
Protection function specification
Protection (sub-)system specification
Plan:
Individual system tests & commissioning
Machine checkout & beam commissioning
Operation
Subsystem
Realisation
Individual system tests & commissioning
Machine checkout & beam commissioning
Operation

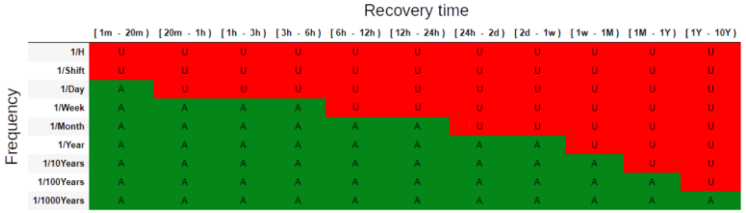
Reliability Analysis



- Understand system, environment, functions, top-level FMECA
- Assign reliability targets for each failure mode

- Top-down: System reliability modeling (& simulation)
- Bottom-up: Component FMECA

LHC Risk Matrix – common definition of reliability targets:



Frequency \ Recovery time	[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	A	U
1/1000Years	A	A	A	A	A	A	A	A	A	A	A

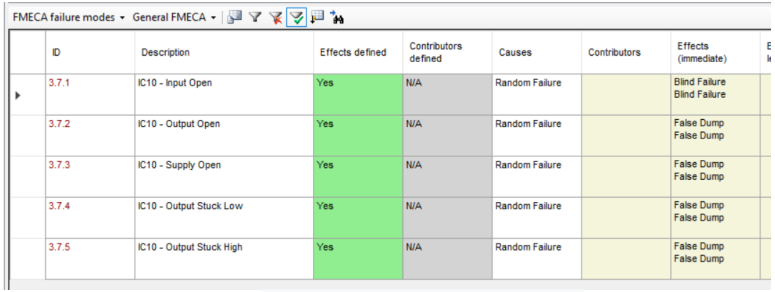
In-house developed open-source MC simulation tool:

AvailSim4

Project ID: 131878

https://gitlab.cern.ch/availsim4/

Reliability toolkit (FTA, RBD, FMECA, Weibull, …):



	ID	Description	Effects defined	Contributors defined	Causes	Contributors	Effects (immediate)
▸	3.7.1	IC10 - Input Open	Yes	N/A	Random Failure		Blind Failure Blind Failure
	3.7.2	IC10 - Output Open	Yes	N/A	Random Failure		False Dump False Dump
	3.7.3	IC10 - Supply Open	Yes	N/A	Random Failure		False Dump False Dump
	3.7.4	IC10 - Output Stuck Low	Yes	N/A	Random Failure		False Dump False Dump
	3.7.5	IC10 - Output Stuck High	Yes	N/A	Random Failure		False Dump False Dump

isograph

Well-established process. Areas of research interest:

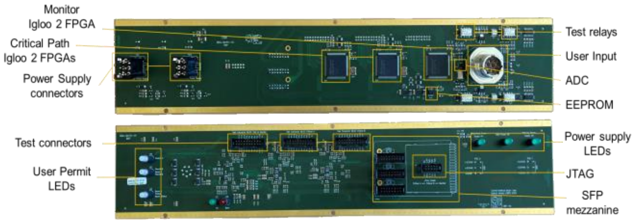
- Integrating critical soft-/firmware assessment into the overall reliability assurance process
- Formalize reliability modeling process further to allow for automatic model generation and property checking.
- Maintaining & re-using system reliability models across the life cycle with monitoring and test data for early corrective actions

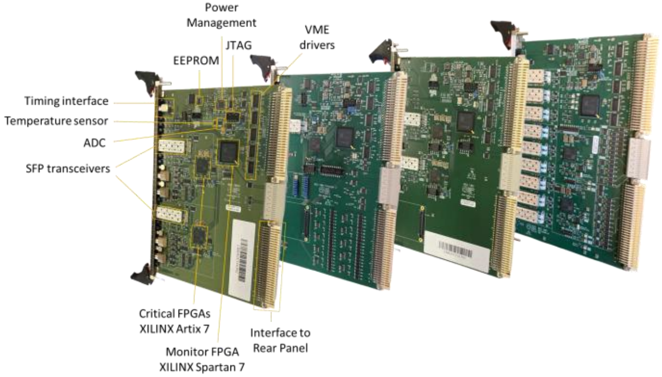
Development and testing of critical firmware – Example of the Beam Interlock System

- The BIS is the backbone of the machine protection system at CERN based on FPGAs
- Numerous firmware images to develop, build, test and maintain
- Each BIS board implements continuous integration based on GitLab CI/CD
- Heavy use of dockers to simulate and synthesize the code
- Several jobs are run for performing functional tests
  - Linter (static checks on the VHDL code)
  - Simulation (unit and top-level tests)
  - Synthesis
- In addition, system-level tests are run with CI on a dedicated test platform
  - 108h of automated tests per week

File type	Number of lines
VHDL	74k (60k without comments and empty lines) 7k are not ours
Bash	6k
TCL	14k
XDC/PDC/SDC	5k
Python	19.5k
CSV	6.2k
Total	**> 120k**

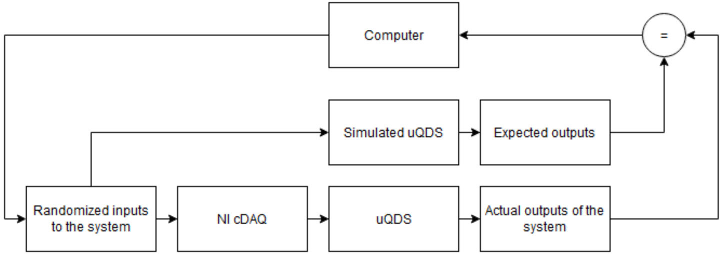
TE-MPE Technical Meeting #200





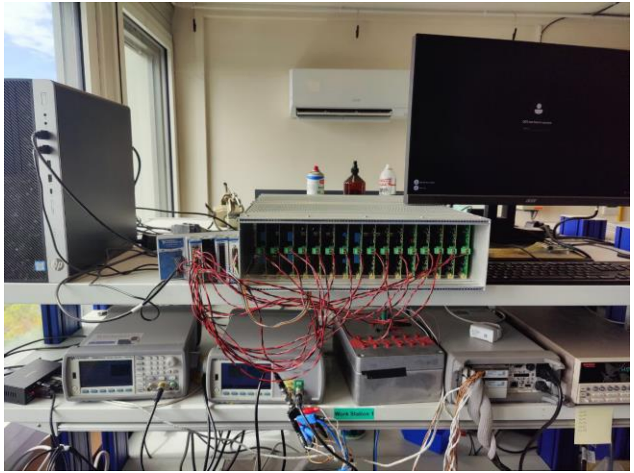
A. Colinet et al., "Testing aspects of the Beam Interlock System prior to installation in the accelerator", *IPAC24*

Development and testing of critical firmware – Example of the Quench Detection System (QDS)



The QDS measures voltages across superconducting magnet coils to detect when superconductivity is lost.

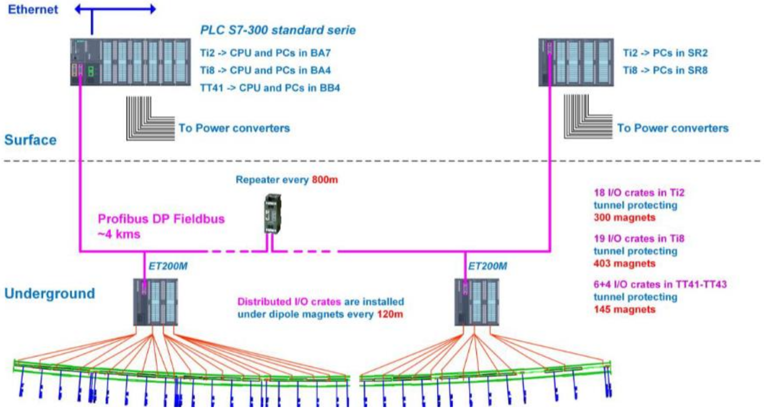
- Essential part of superconducting magnet protection
- Performs real time digital signal processing on FPGAs (filters, gain/offset correction)
  - Neural Networks with formally verified properties may prove interesting for real time digital signal processing task in future
- Large parameter space due to continuous inputs and detection thresholds → testing based on randomized sampling
  - Testing of every protection scheme for the various magnets, using a NI cDAQ to set the inputs to the system and read its outputs.
  - A python script generates a Montecarlo simulation of the system: it randomizes a set of (continuous) inputs and compares the outputs with the expected results. During the test we also randomise the protection parameters (voltage thresholds, etc) to sample the parameter space.
  - Critical firmware is modular & requires a modular testbench.

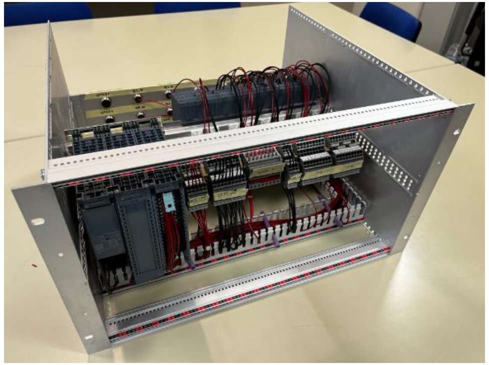


Development of critical PLC code – Warm and Cold Magnet Interlock Controllers (WIC/PIC)

- **“Slow” interlock systems often based on PLCs**
  - Based on well-defined state machines
  - Strict configuration process from a common database

- **Development of critical code for new generation of WIC/PIC systems in collaboration with BE-ICS**
  - Apply formal methods (PLCverif)





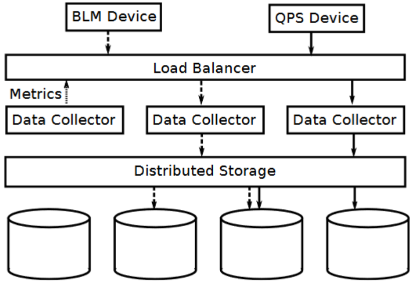
Software Development - Diagnostics and Automated Testing of Deployed Protection Systems

Software development based on high code-quality standards and extensive testing:

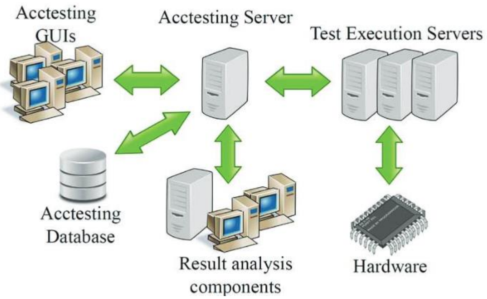
- **Static code analysis performed with SonarQube**
- **Different levels of testing**
  - **unit tests** to ensure the correctness of each unit of code
  - **integration tests** to validate the integration of components together
  - **user acceptance tests** to validate features
- **Use of staging environments and a hardware testbed copying a sector of the LHC**

Additional model and property checking tools may be interesting to explore.

PostMortem: ensure integrity of protection systems after every LHC beam dump



AccTesting: automatize repeating machine commissioning steps



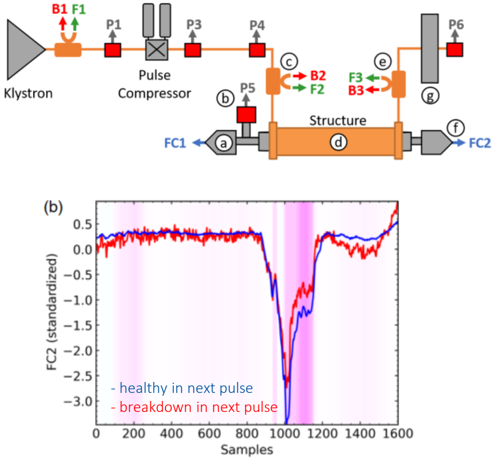
Summary

- The MPE group provides state-of-the art hardware (FPGAs & PLCs) and software technologies for magnet circuit protection and interlock systems.
- Critical systems follow a protection life cycle, which includes a top-down & bottom-up reliability analysis
- Reliability of critical firmware and software is ensured via extensive testing at multiple levels and environments, staging/CI & validation.
- Generally interested to test additional software modeling and verification tools

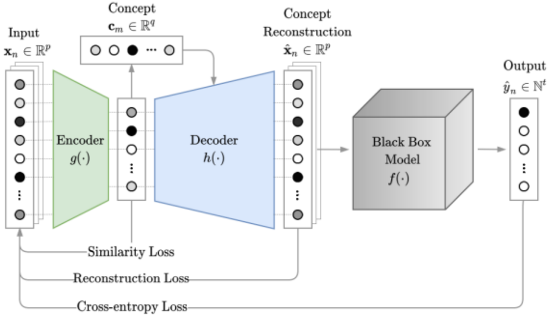
Back-up slides

Interpretable Machine Learning for Predictive Maintenance

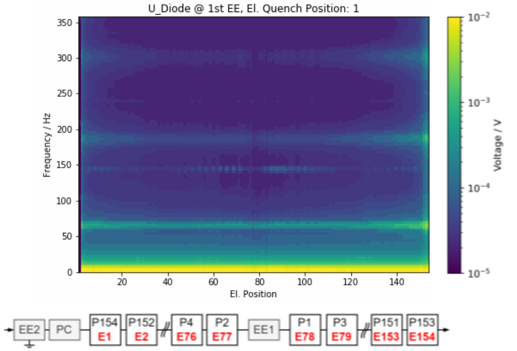
Explainable Machine Learning for Breakdown Prediction in **High Gradient RF Cavities**



Example or Prototype? Learning Concept-Based Explanations in Time-Series

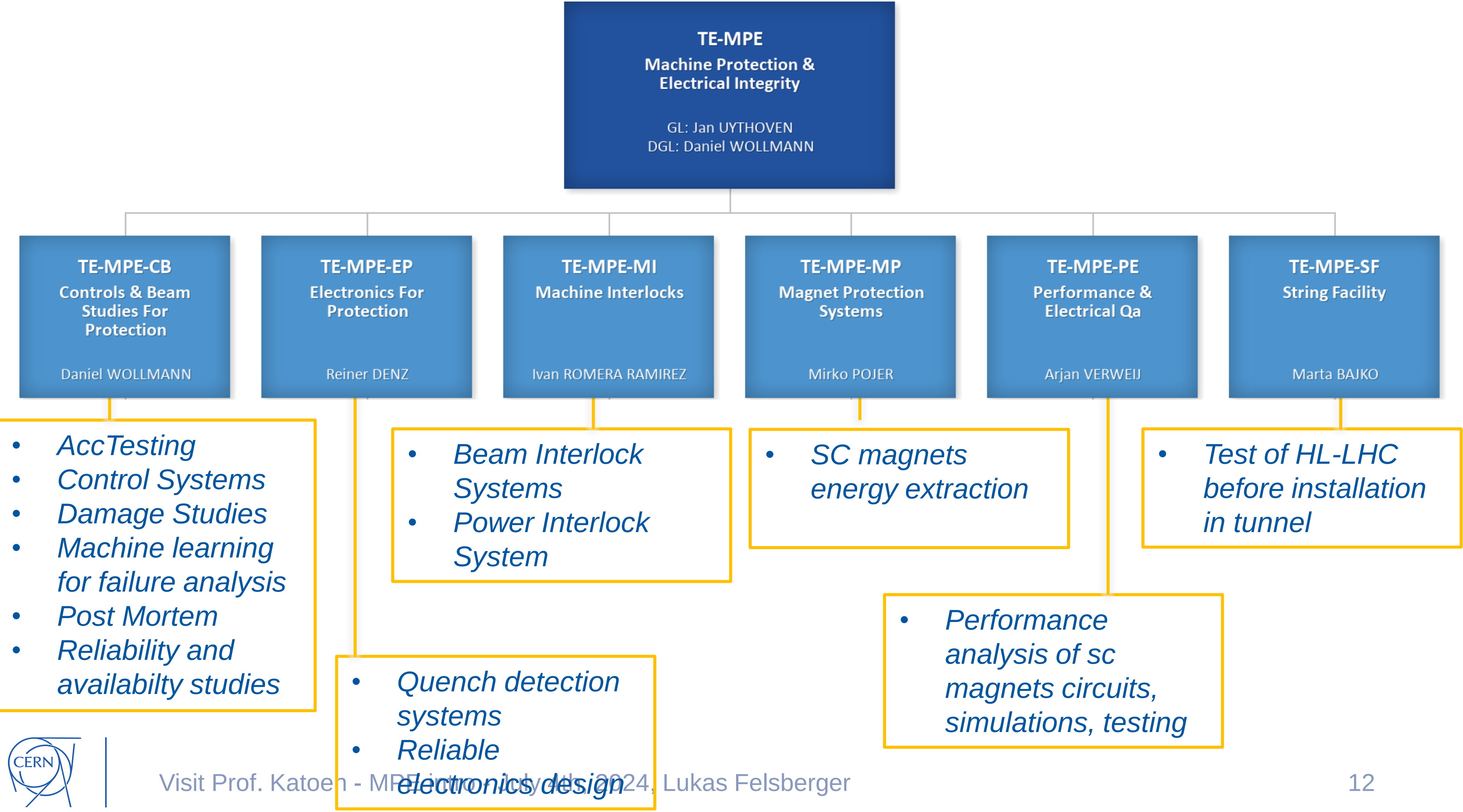


Interpretable Anomaly Detection in the **LHC Main Dipole** Circuit with Non-negative Matrix Factorization



C. Obermair

Aim is to reduce unplanned downtime of systems and improve diagnostics (faster repair).



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- *AccTesting*
- *Control Systems*
- *Damage Studies*
- *Machine learning for failure analysis*
- *Post Mortem*
- *Reliability and availabilty studies*

TE-MPE-EP
Electronics For Protection
Reiner DENZ

- *Quench detection systems*
- *Reliable electronics design*

TE-MPE-MI
Machine Interlocks
Ivan ROMERA RAMIREZ

- *Beam Interlock Systems*
- *Power Interlock System*

TE-MPE-MP
Magnet Protection Systems
Mirko POJER

- *SC magnets energy extraction*

TE-MPE-PE
Performance & Electrical Qa
Arjan VERWEIJ

- *Performance analysis of sc magnets circuits, simulations, testing*

TE-MPE-SF
String Facility
Marta BAJKO

- *Test of HL-LHC before installation in tunnel*

Reliability and Availability Working Group

RAWG is an advisory body in the reliability domain

- Promote common tools and standards
- Accelerator Fault Tracking
- Building internal and external collaborations