Reliability and Availability of Particle Accelerators: Concepts, Lessons, Strategy

A. Apollonio
CERN Machine Protection Group (TE-MPE)
IPAC'18 – 04/05/2018
andrea.apollonio@cern.ch

Acknowledgements: TE-MPE Group, CERN Availability Working Group, Accelerator Fault Tracking team.

Accelerator Reliability Community

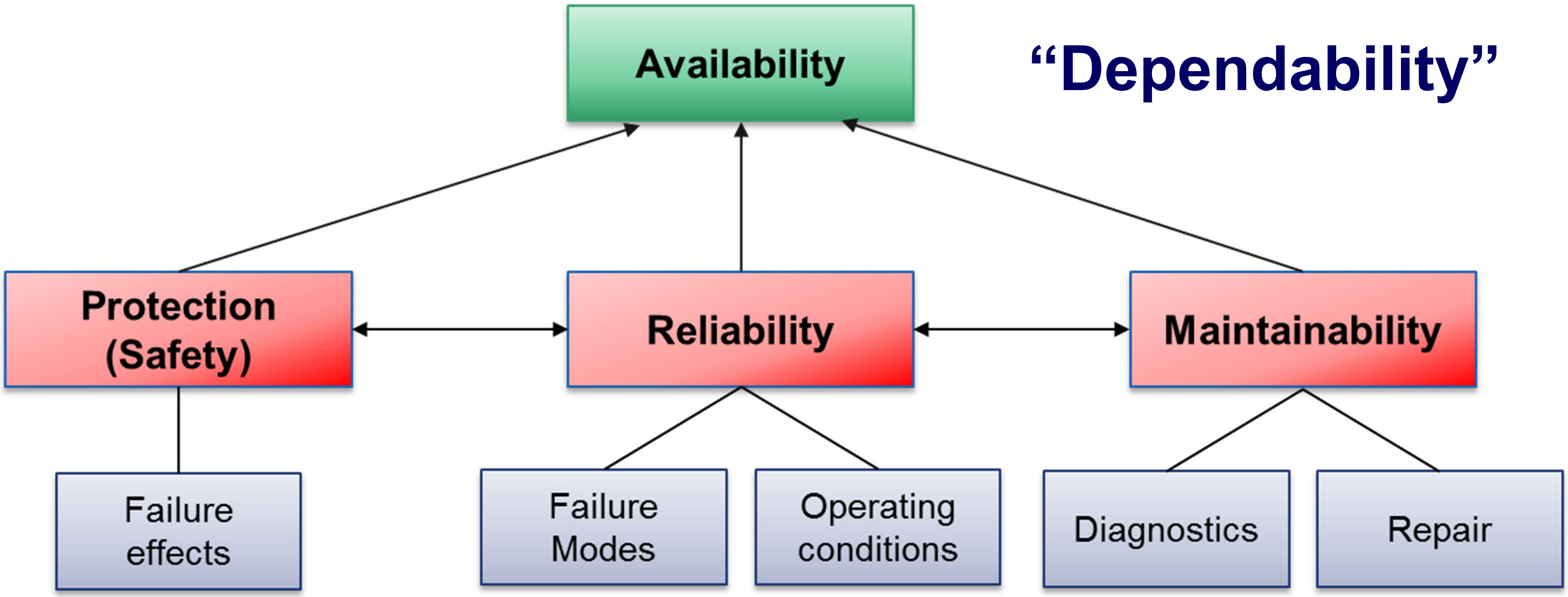
Canada = Particle Accelerator Community

Decades of experience designing accelerator systems without formal reliability engineering studies

Reliability Engineering applied to particle accelerators is a relatively new discipline, based on industry best practices and methods

Developed very consistently over the last years – why?

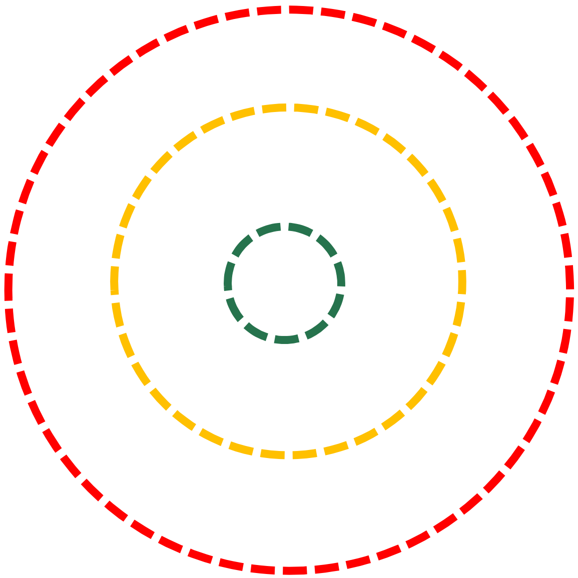
R-A-M-S(P)



NB: in the context of particle accelerators, we speak about 'Protection' rather than 'Safety', if no personnel is involved

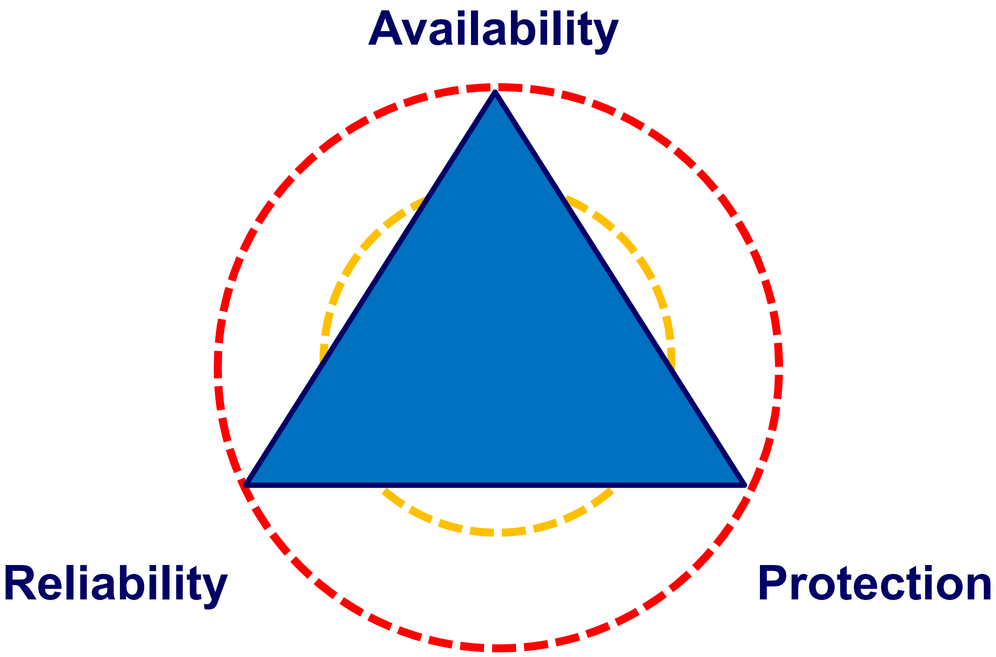
Discussions are ongoing in the particle accelerator community to tailor these definitions to different machines (Accelerator Reliability Workshop)

Requirements for Particle Accelerators



Low Importance
Relative Importance
High Importance

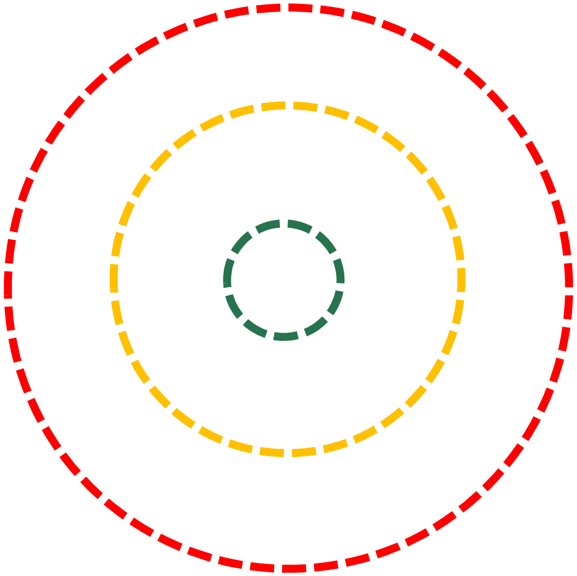
Requirements for Particle Accelerators



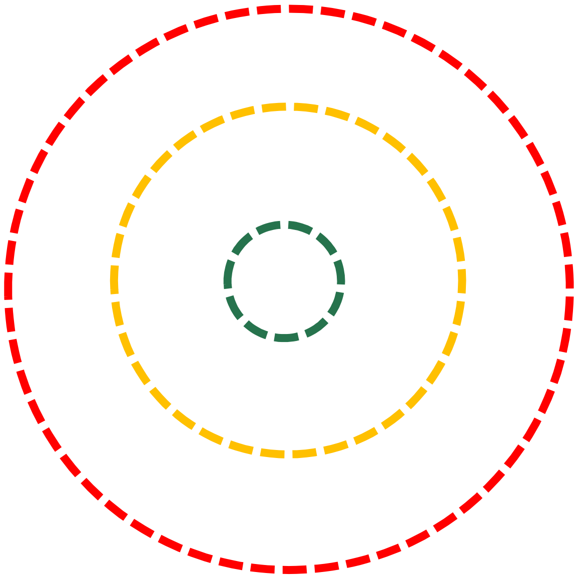
Low Importance
Relative Importance
High Importance

R-A-S(P) Requirements for Accelerators

Large-Scale Colliders

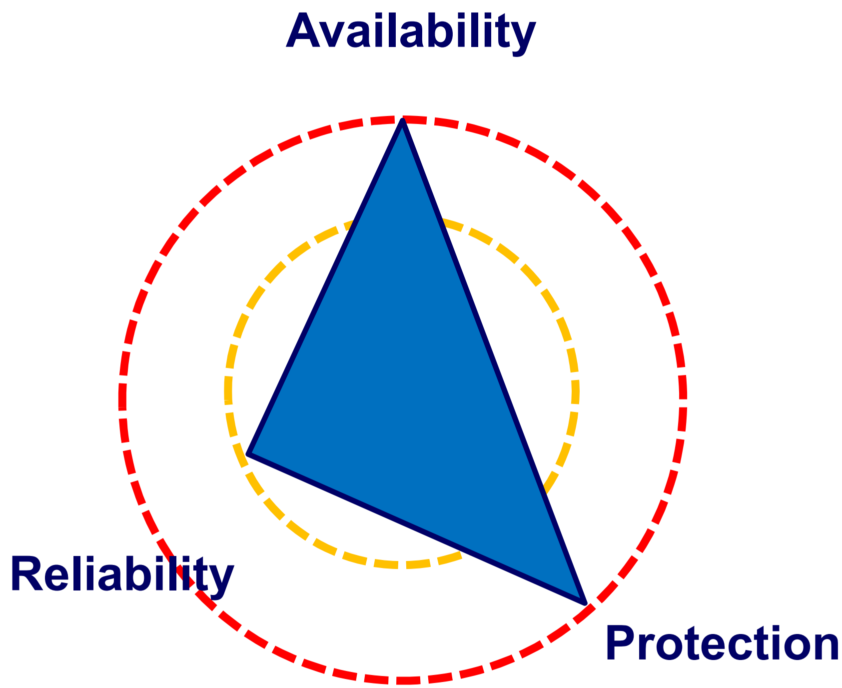


Synchrotron Light Sources

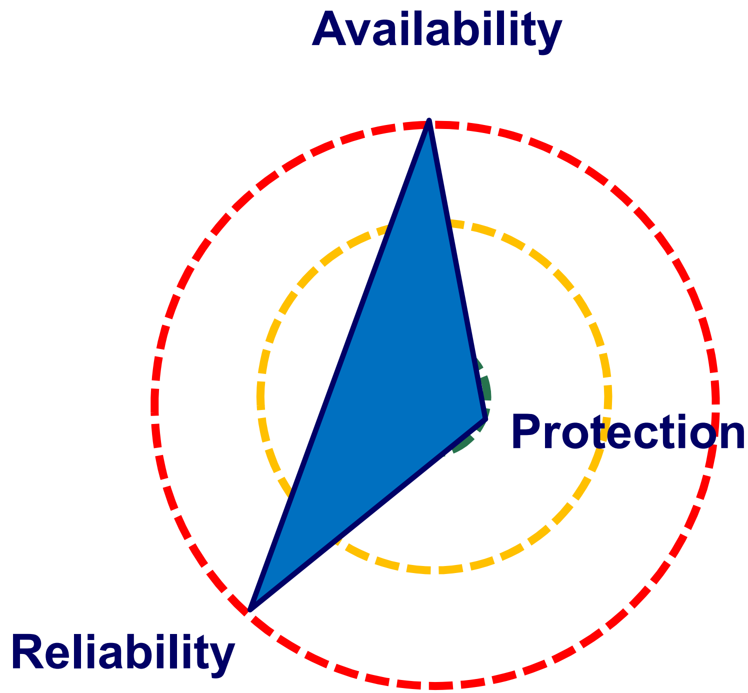


R-A-S(P) Requirements for Accelerators

Large-Scale Colliders

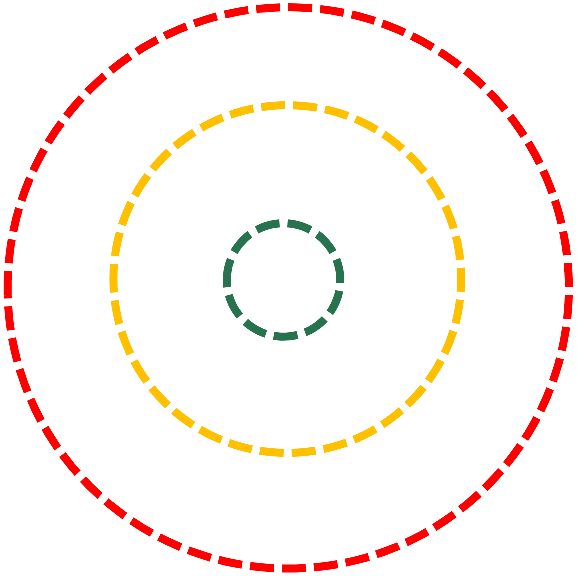


Synchrotron Light Sources

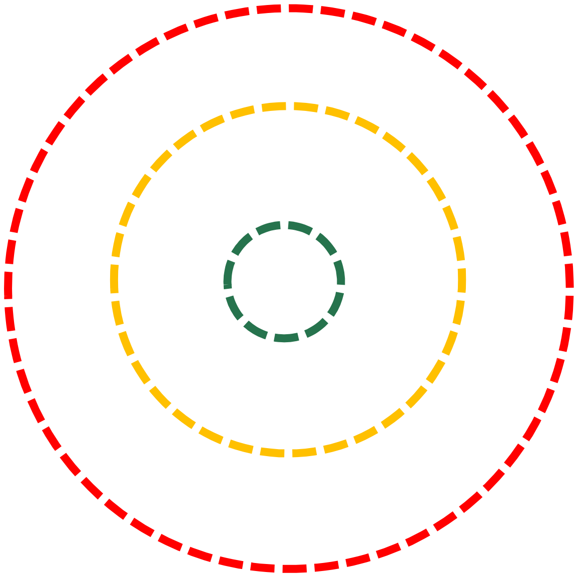


R-A-S(P) Requirements for Accelerators

Spallation Neutron Sources

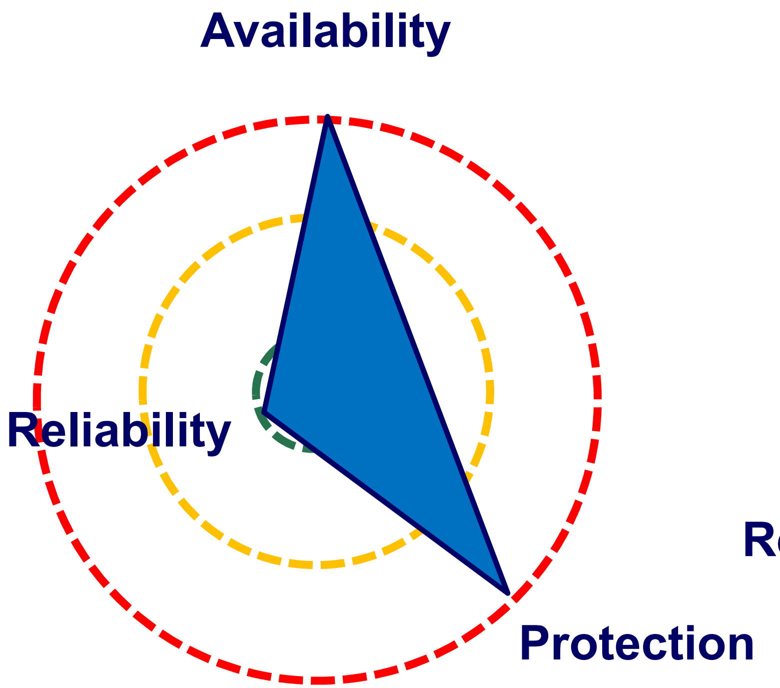


Accelerator Driven Systems

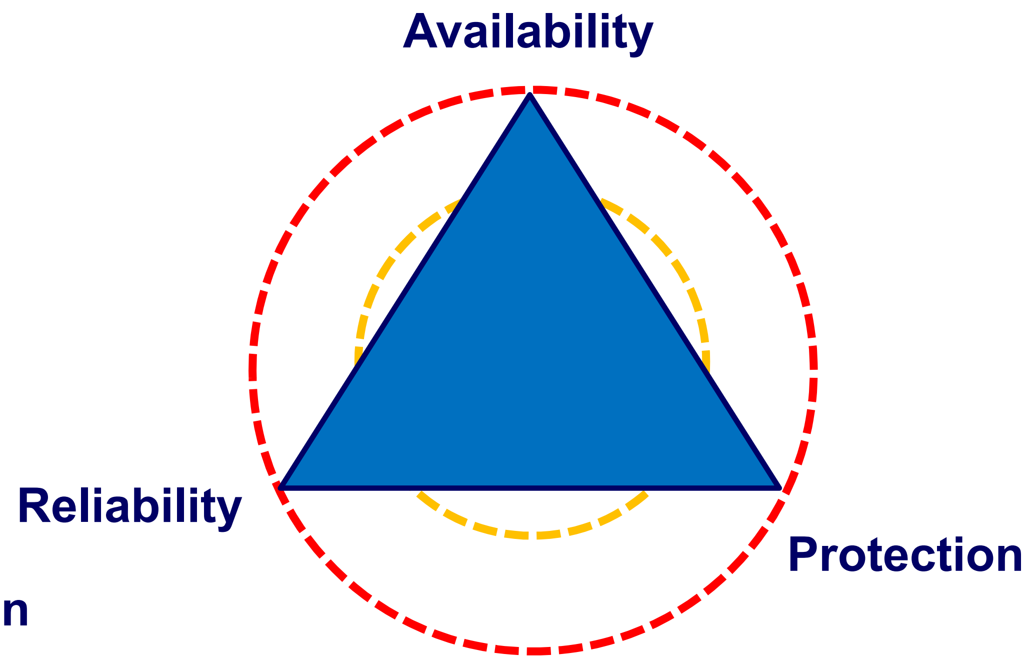


R-A-S(P) Requirements for Accelerators

Spallation Neutron Sources



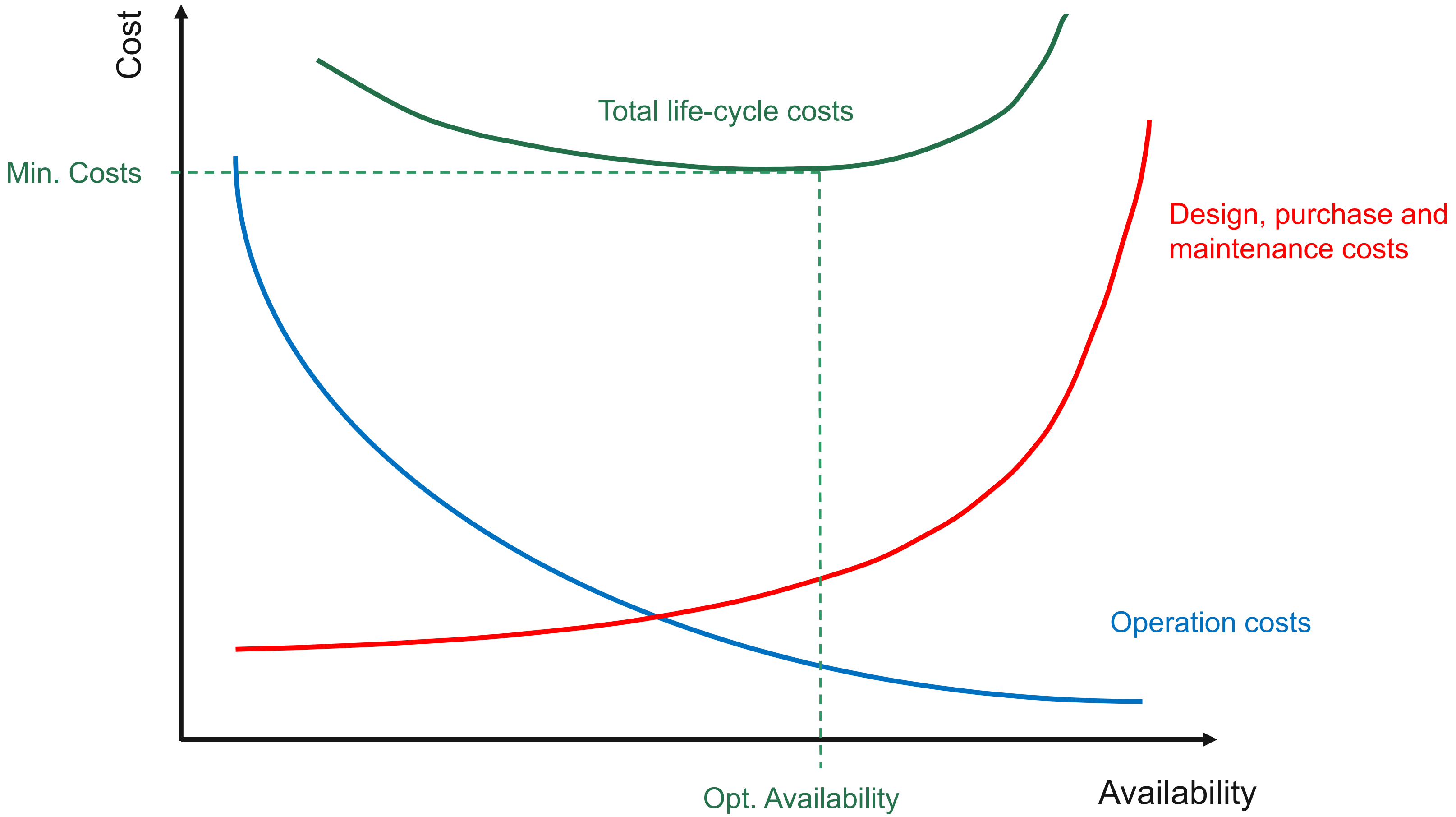
Accelerator Driven Systems



Why is availability a concern for the scientific output of all facilities?

Costs, Reputation, Damage potential

Cost vs Availability

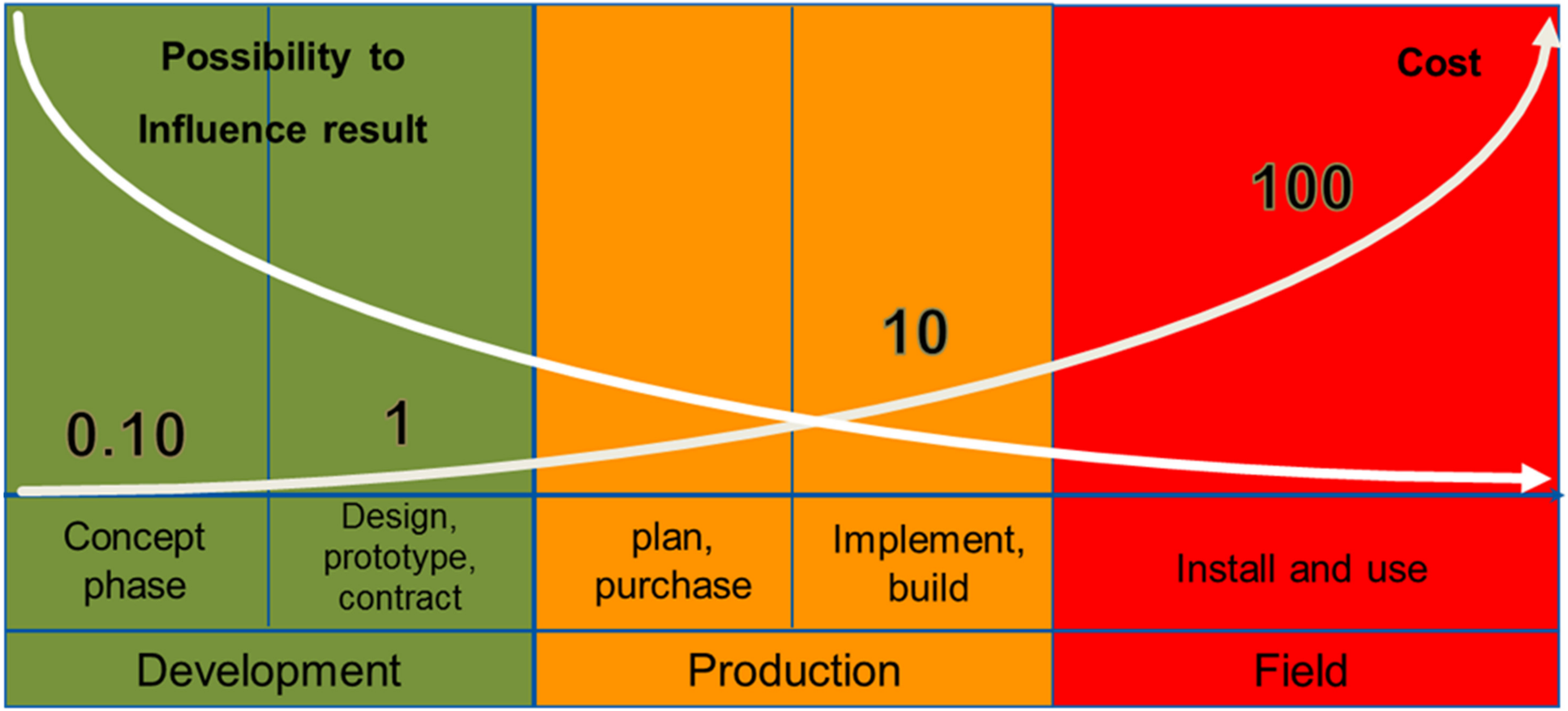


- Given a target performance reach (neutron fluence, number of patients treated, luminosity production, …), an optimal balance between capital costs and operation costs must be found
- This is an **absolute MUST** for the feasibility of next-generation machines

Dependability Studies: if yes, when?

Prof. Dr. B. Bertsche, Dr. P. Zeiler, T. Herzig, IMA, Universität Stuttgart, CERN Reliability Training, 2016

- Product Lifecycle: 'Power-of-10 Law'



- The earlier reliability constraints are included in the design, the more effective the resulting measures will be

Today: Dependability Studies

Concept Phase	**Technology Feasibility Assessment**
Design Phase	**Technology Definition and Implementation**
Exploitation Phase	**Technology Field Use & Optimization**
Upgrade Phase	**New Technology Definition and Implementation**

Reliability Studies

Future: Dependability Studies

Reliability Studies

Concept Phase — Technology Feasibility Assessment

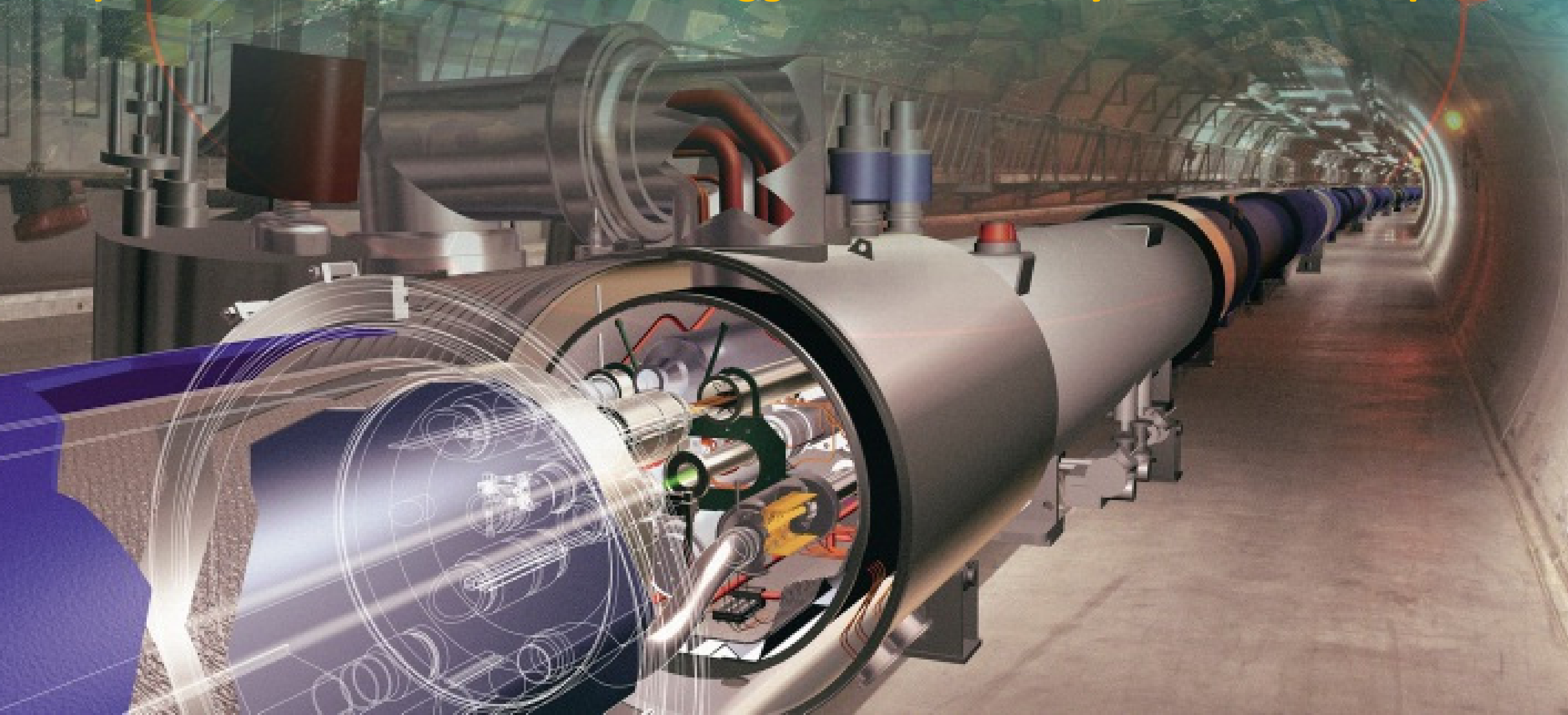
Design Phase — Technology Definition and Implementation

Exploitation Phase — Technology Field Use & Optimization

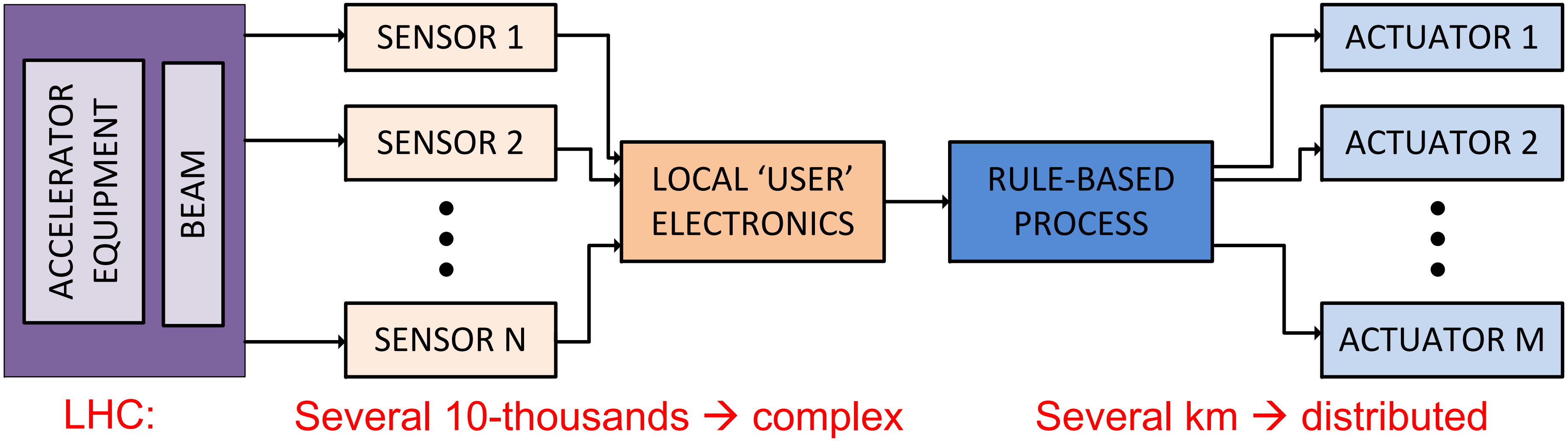
Upgrade Phase — New Technology Definition and Implementation

Reliability and Protection Analyses: LHC was a Game Changer

First particle accelerator with damage potential beyond repair
Requirement 1: Must have Machine Protection Systems (MPS)
Requirement 2: MPS must meet very strict reliability requirements
Requirement 3: MPS must not trigger unnecessary beam interruptions



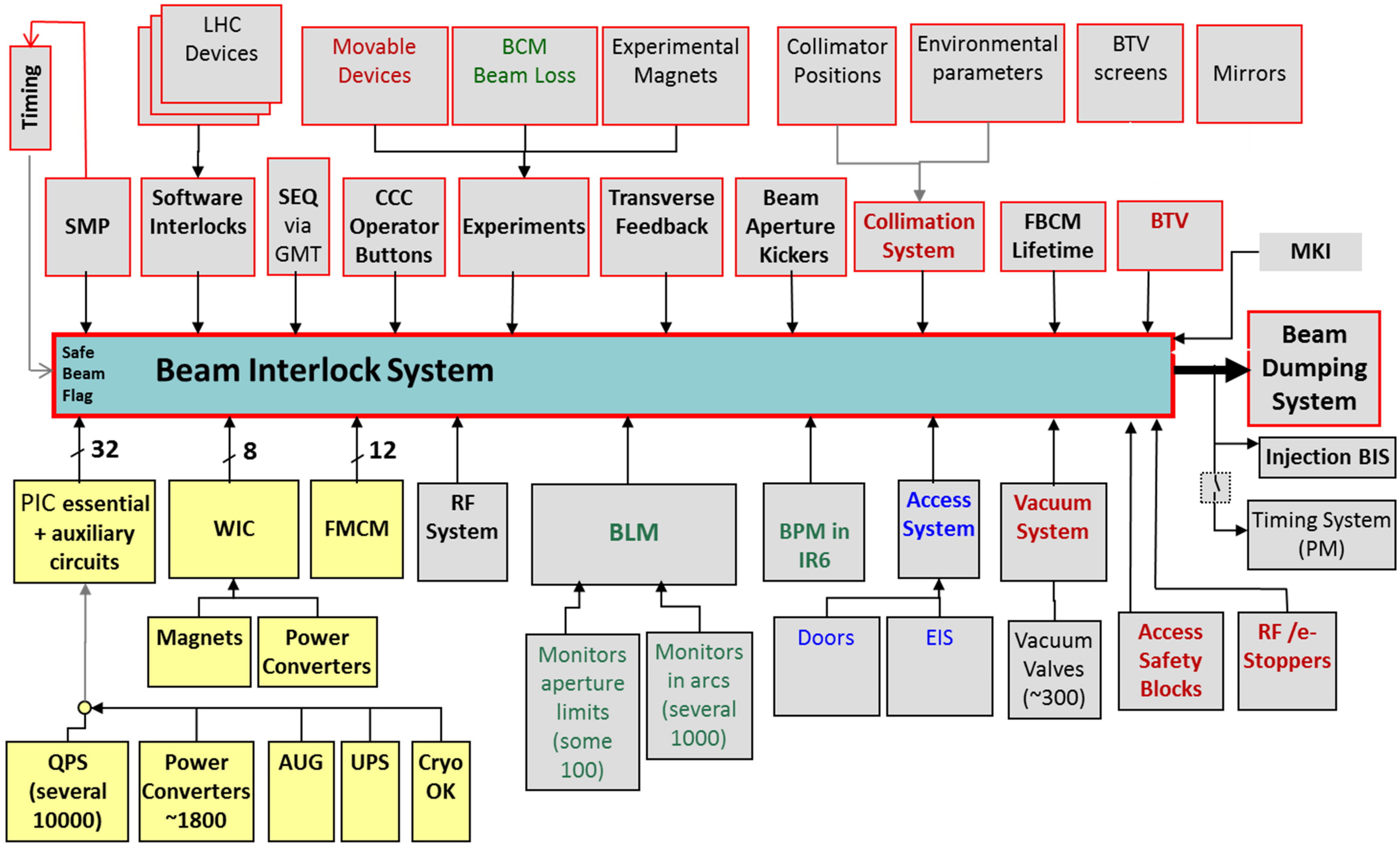
Machine Protection: Interlocks



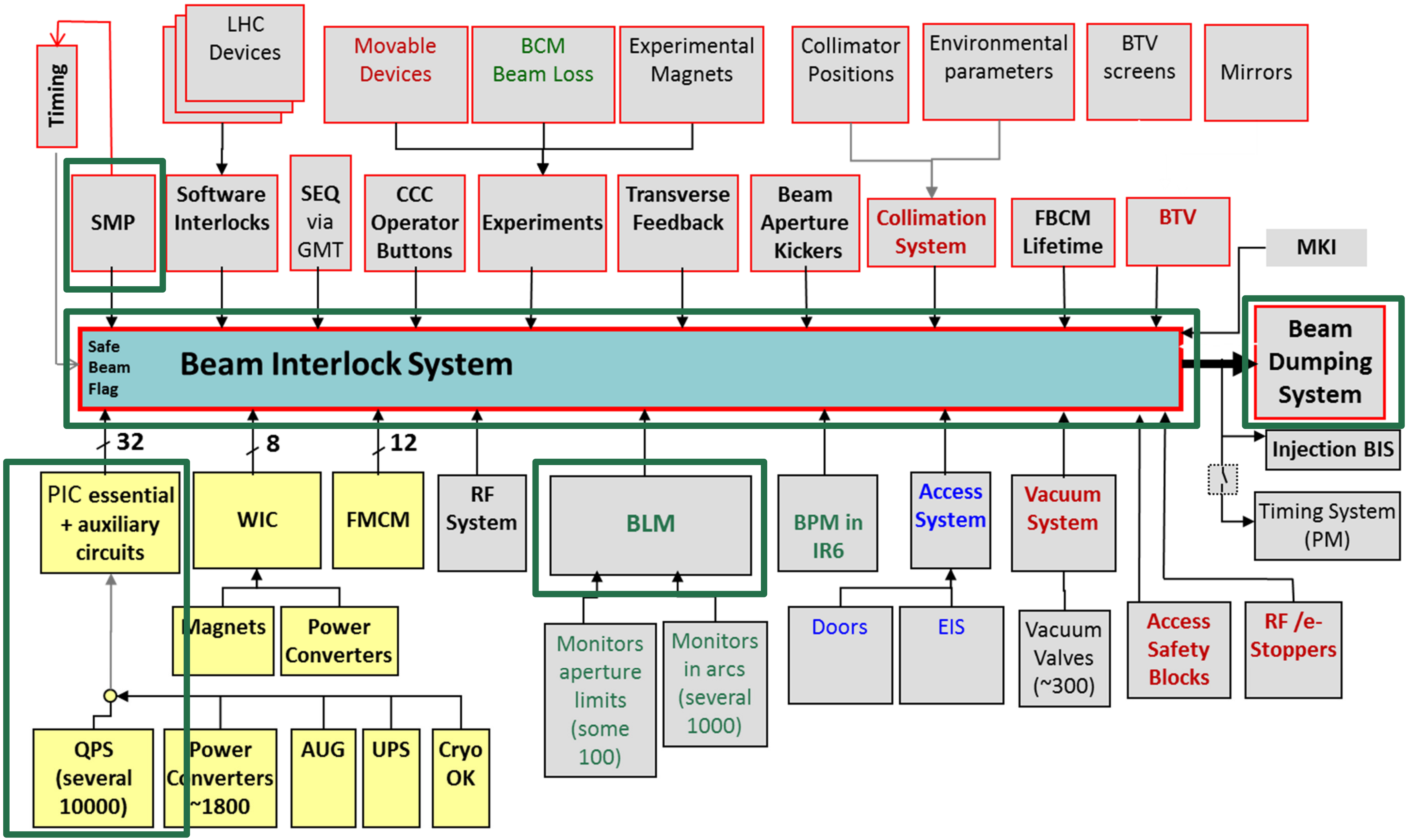
- Perform **controlled removal** of beams in case of failures:
  - Circular accelerators (e.g. LHC): Beam dump (100 µs – ms)
  - Linear accelerators (Linac4, ESS): Beam stop (1-10 µs)

- Improve availability by preventing consequences of severe failures
- Affect availability by triggering unnecessary ('false') beam aborts

LHC Machine Protection Layout



LHC Machine Protection Layout



- Quantitative reliability analyses performed for protection-critical systems
- Inspired by European Standards for safety-critical electronic systems

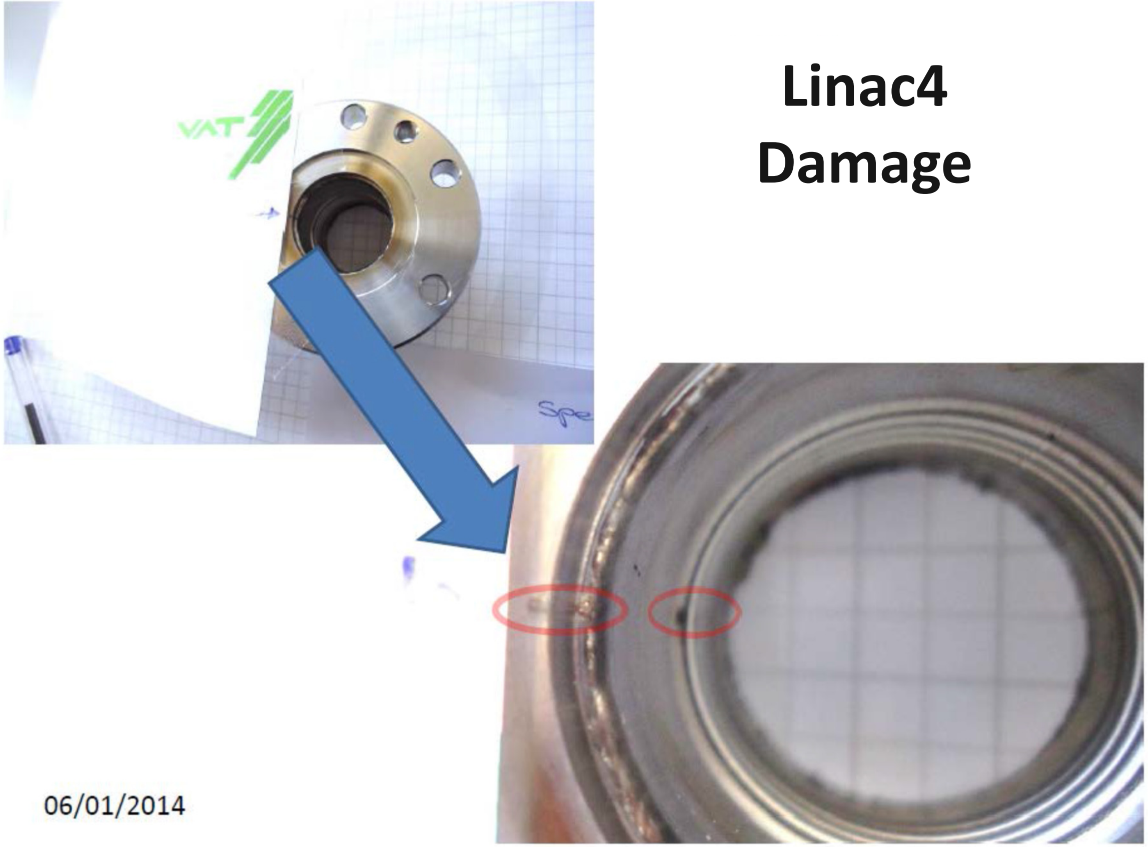
Does It Work? (LHC)

Since the beginning of LHC operation (2010):

0 beam-related accidents
(achieved: high level of protection)

Few unnecessary beam aborts caused by MPS per year
(observed: low impact on availability, mostly related to radiation effects on electronics)

Does It Always Work? (Linac4)



Linac4 Damage

06/01/2014

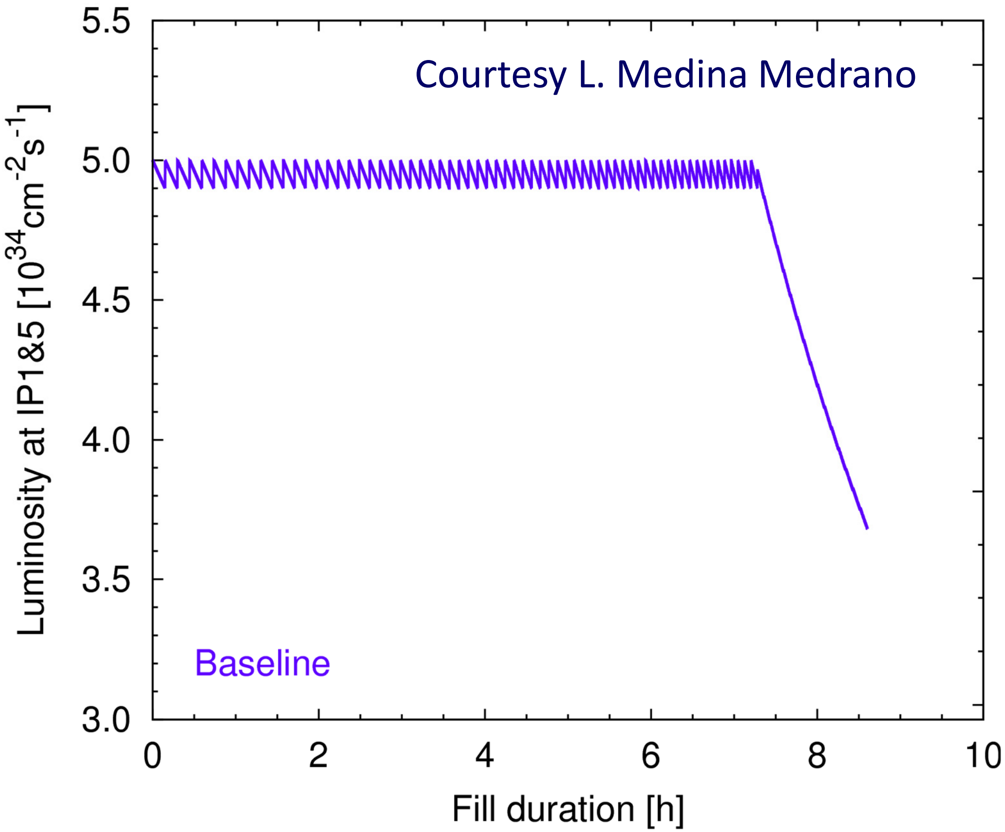
1) Severe misalignment in the low-energy section
2) Optics that favoured amplification of this misalignment (test)
3) Phase advance such that the loss occurred on the “wave” of the bellow (200 μm) and it is an aperture limitation

Accidents might occur due to a combination of different factors (change of boundary conditions, non-standard operation, design flaws, human errors, timing constraints…)

Availability: HL-LHC is a Game Changer

Explicit Integrated Luminosity Production Goal

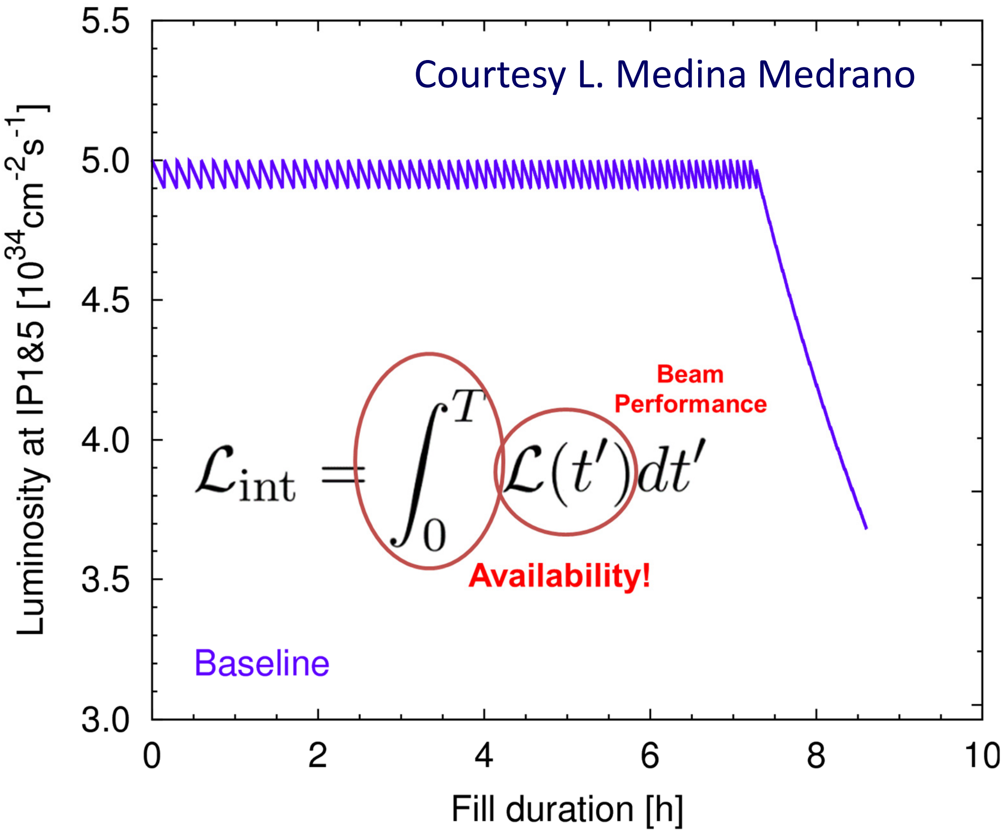
3000 fb^{-1} over HL-LHC Lifetime



Availability: HL-LHC is a Game Changer

Explicit Integrated Luminosity Production Goal

3000 fb^{-1} over HL-LHC Lifetime

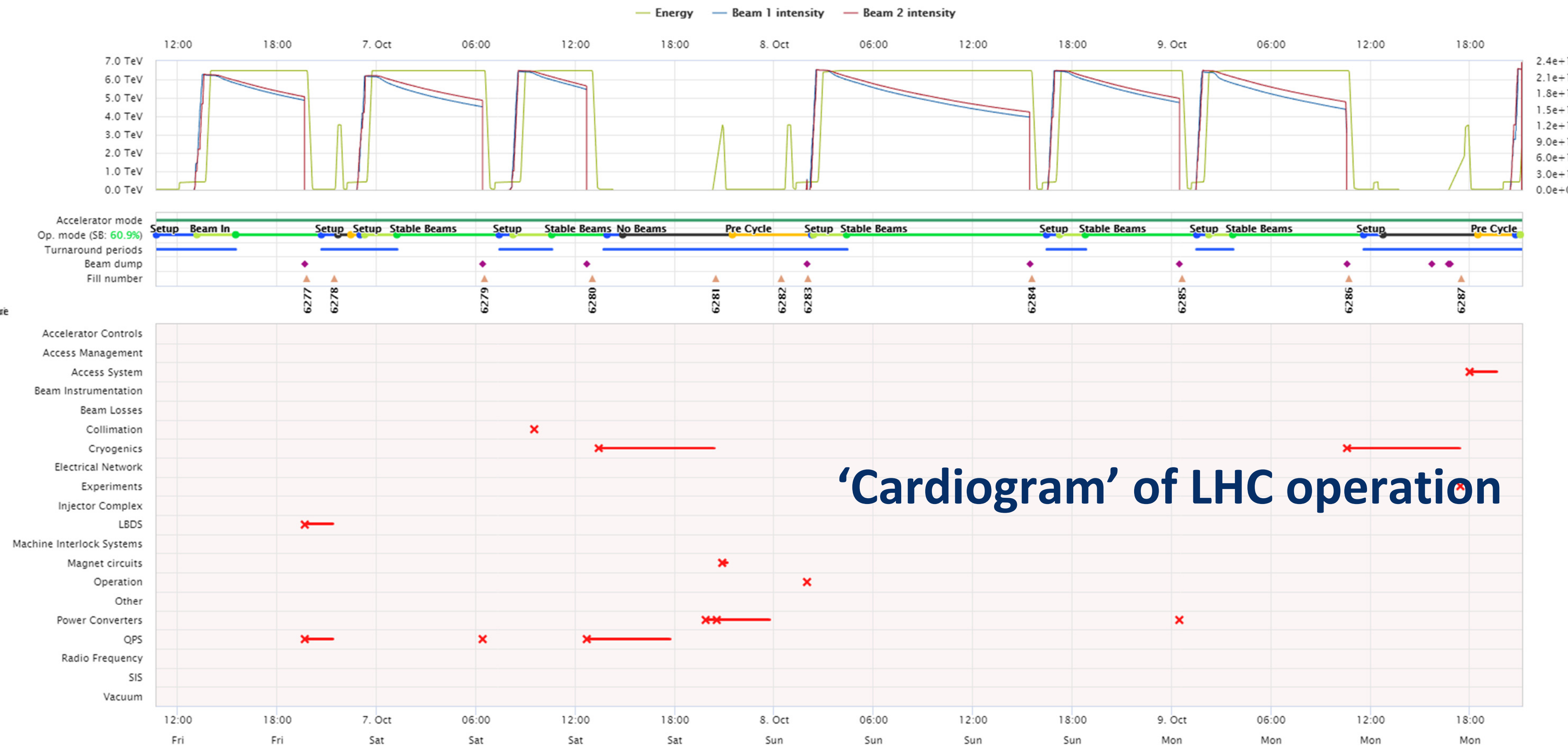


The adoption of luminosity levelling shifts the focus on increasing availability to increase luminosity production

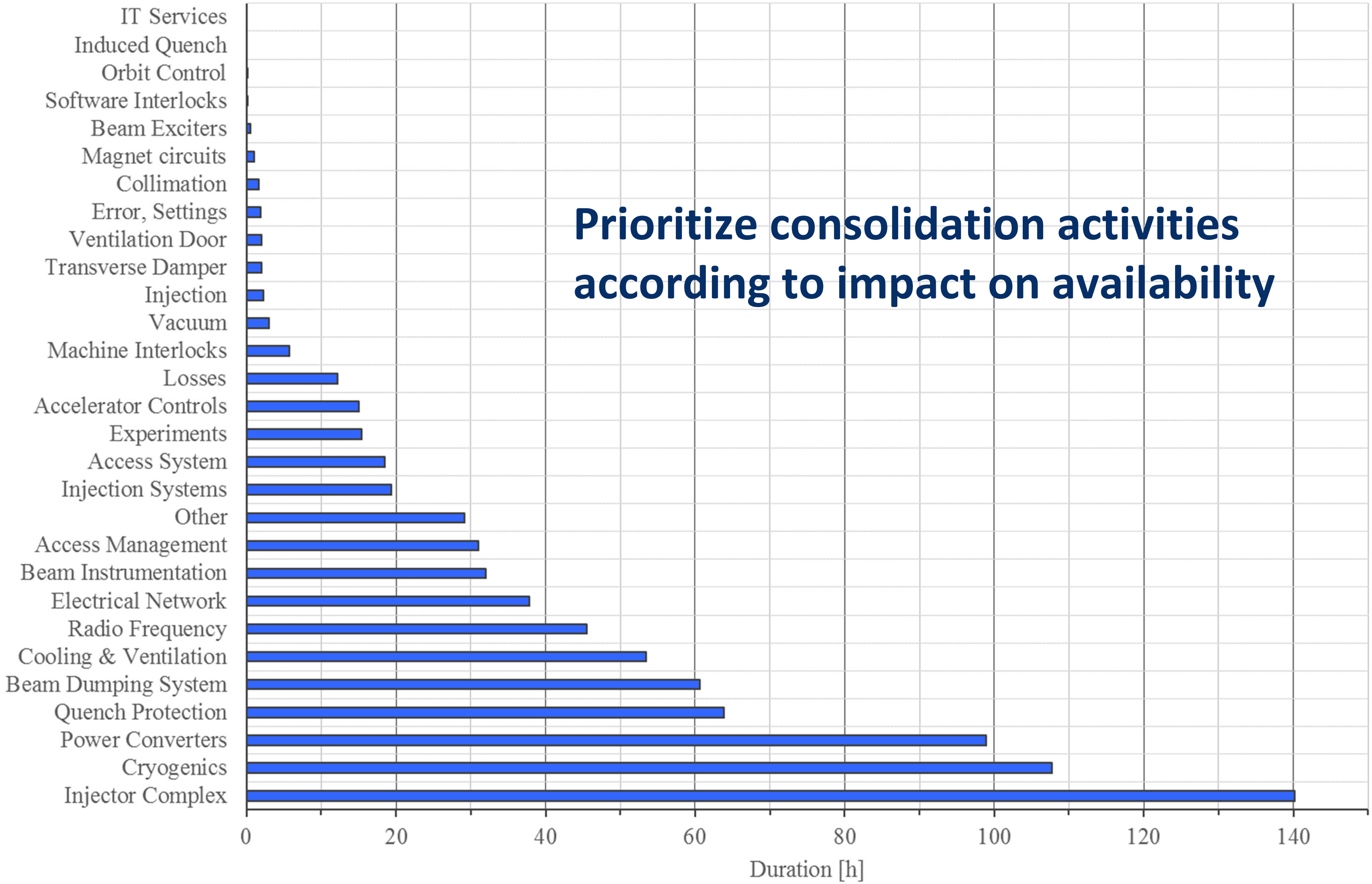
STEP1: Measure availability
STEP2: Predict performance (model) as a function of availability

Step 1: Failure Tracking At CERN

- Since 2015 at CERN, **Accelerator Fault Tracker** in use to keep consistent records of accelerator system reliability and availability during LHC lifetime
- Used to estimate system failure rates and recovery times
- Consolidated over 3 years of operation, now widely accepted by system experts



LHC System Downtime in 2017

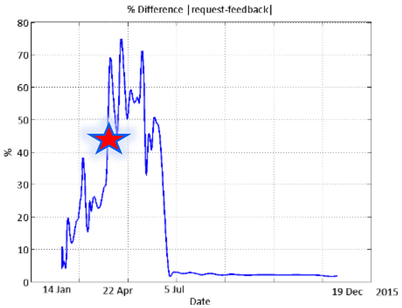


Prioritize consolidation activities according to impact on availability

Maintainability: Failure Duration

Failure Duration

Identification



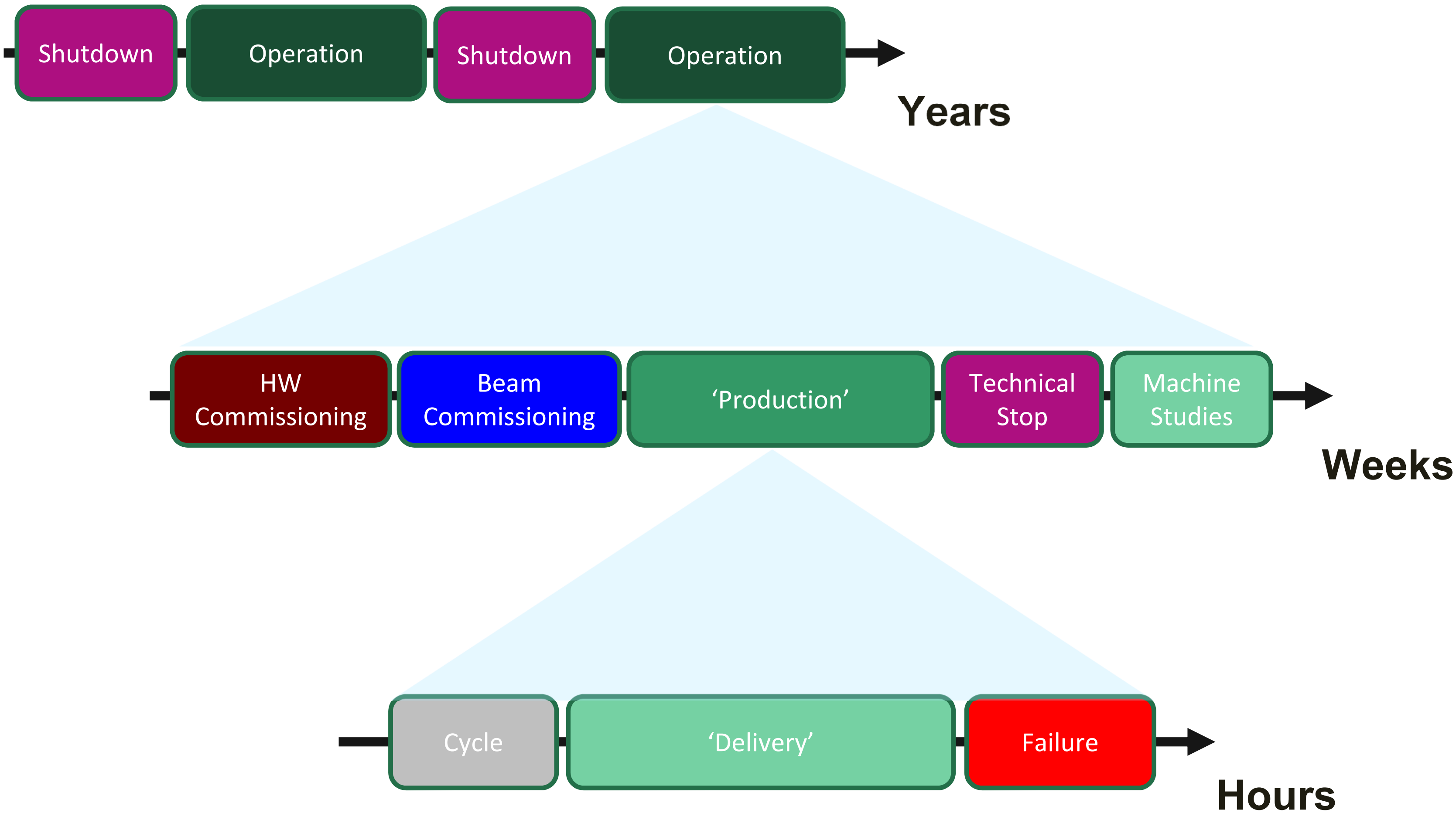
Diagnostics

Logistics

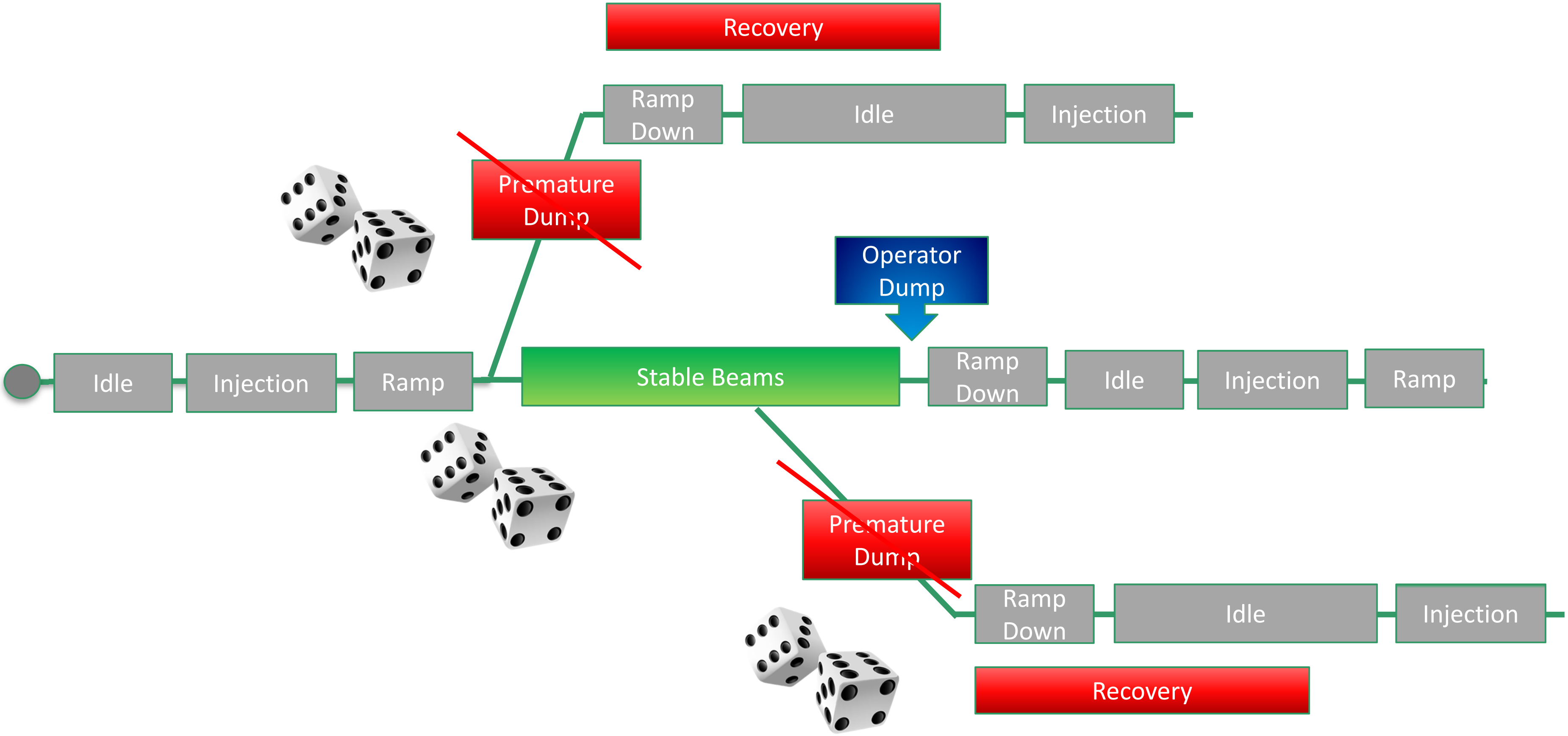
Repair

- **Accelerator specific**: some time might be required to recover nominal operating conditions (e.g. beam-tests, source stabilization, magnetic pre-cycles,…)
- Optimising accelerator **maintainability** will be fundamental for future large-scale machines

Step 2: From Data to Models



Monte Carlo Simulation Concept

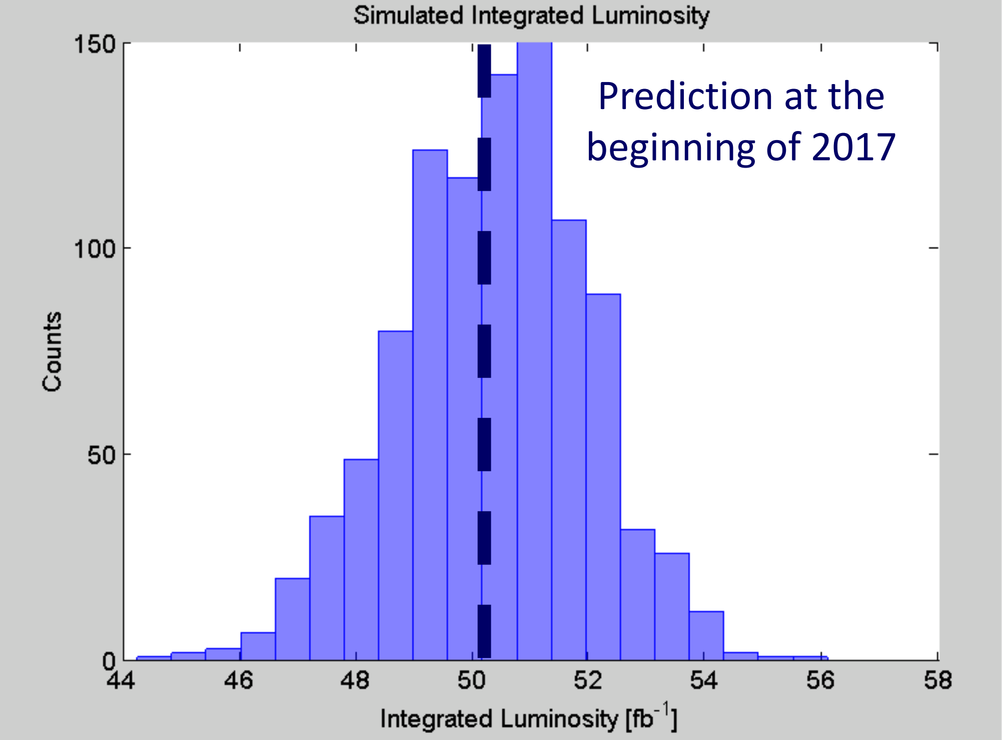


Random failures (phase specific) + random recovery times

2017 Integrated Luminosity Prediction

- 6.5 TeV
- 134 days of p-p operation
- 2016 fault distributions
- 2017 beam parameters (estimated at the beginning of 2017)

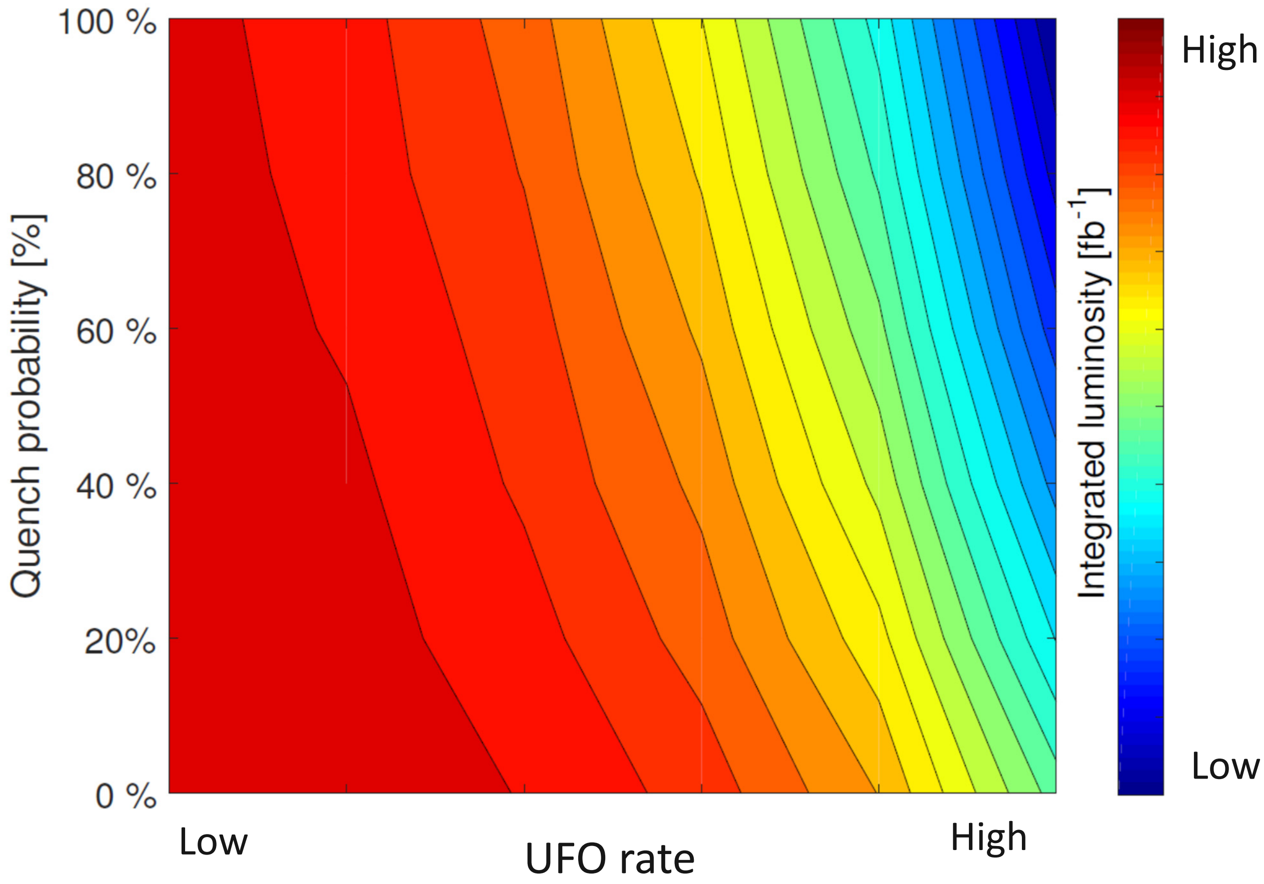
- Achieved in 2017: Integrated Luminosity = 50 fb^{-1}



- Observed failure modes in 2017 different than in 2016, but overall similar achieved availability + good guess of beam parameters
- **Important**: order of magnitude of the results is correct → realistic prediction of integrated luminosity (validated for several years of LHC operation)
- **More important**: possibility to simulate impact of different scenarios on luminosity production

Application: Protection vs Availability

Dust macro-particles interacting with the beam (UFOs)
Losses are detected by Beam Loss Monitors (BLMs)
Premature beam dumps + (in some cases) a magnet quench
Thresholds of BLMs should be optimized to limit impact on operation



Outlook

- Achieving high **availability will be a key requirement** for the success of next-generation particle accelerators and needs to be pursued from early design phases

High Reliability and Protection

High Maintainability

Redundancy
Fault Tolerance

Failure Prediction
Advanced Diagnostics

Robotic Maintenance

TOTAL AVAILABILITY

(B. Todd, R. Schmidt, L. Felsberger)

Conclusions