Conclusions on FCC Availability Studies

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Reminder: LHC Availability in 2016-2017

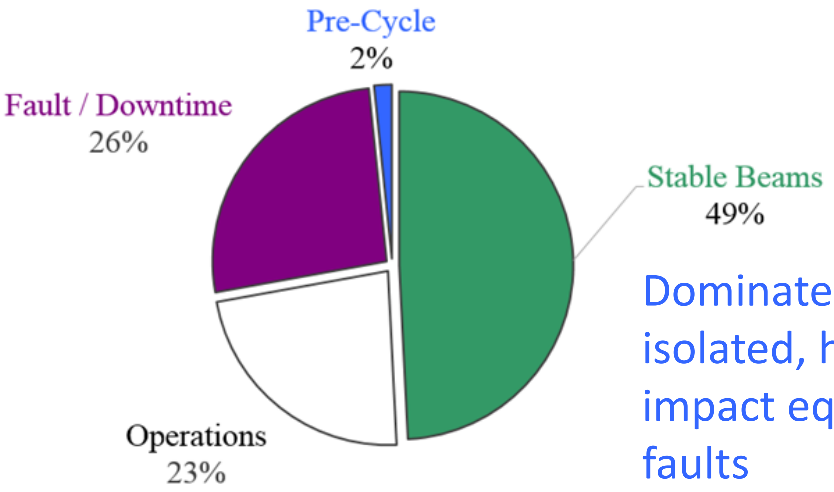
Proton run 2016

	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3
	= 3738.7

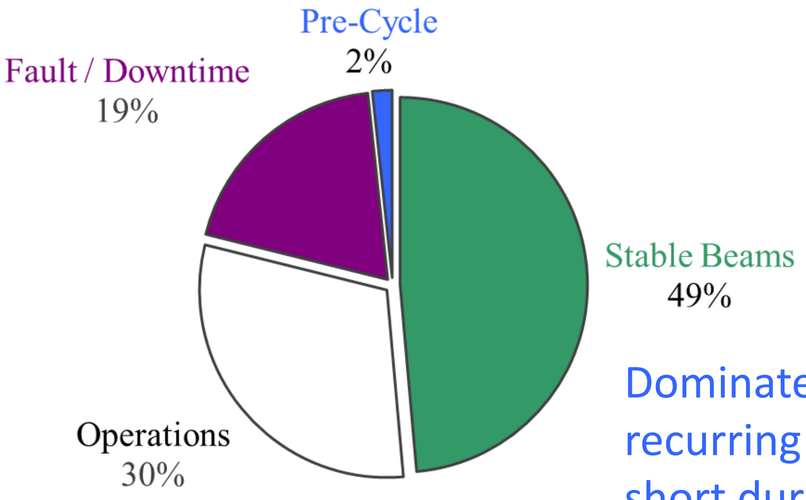
Availability
=
Operations + Stable Beams

Proton run 2017

	Duration [h]
Stable Beams	1633.9
Fault / Downtime	652.9
Operations	1018.1
Pre-Cycle	57.2
	= 3362.1

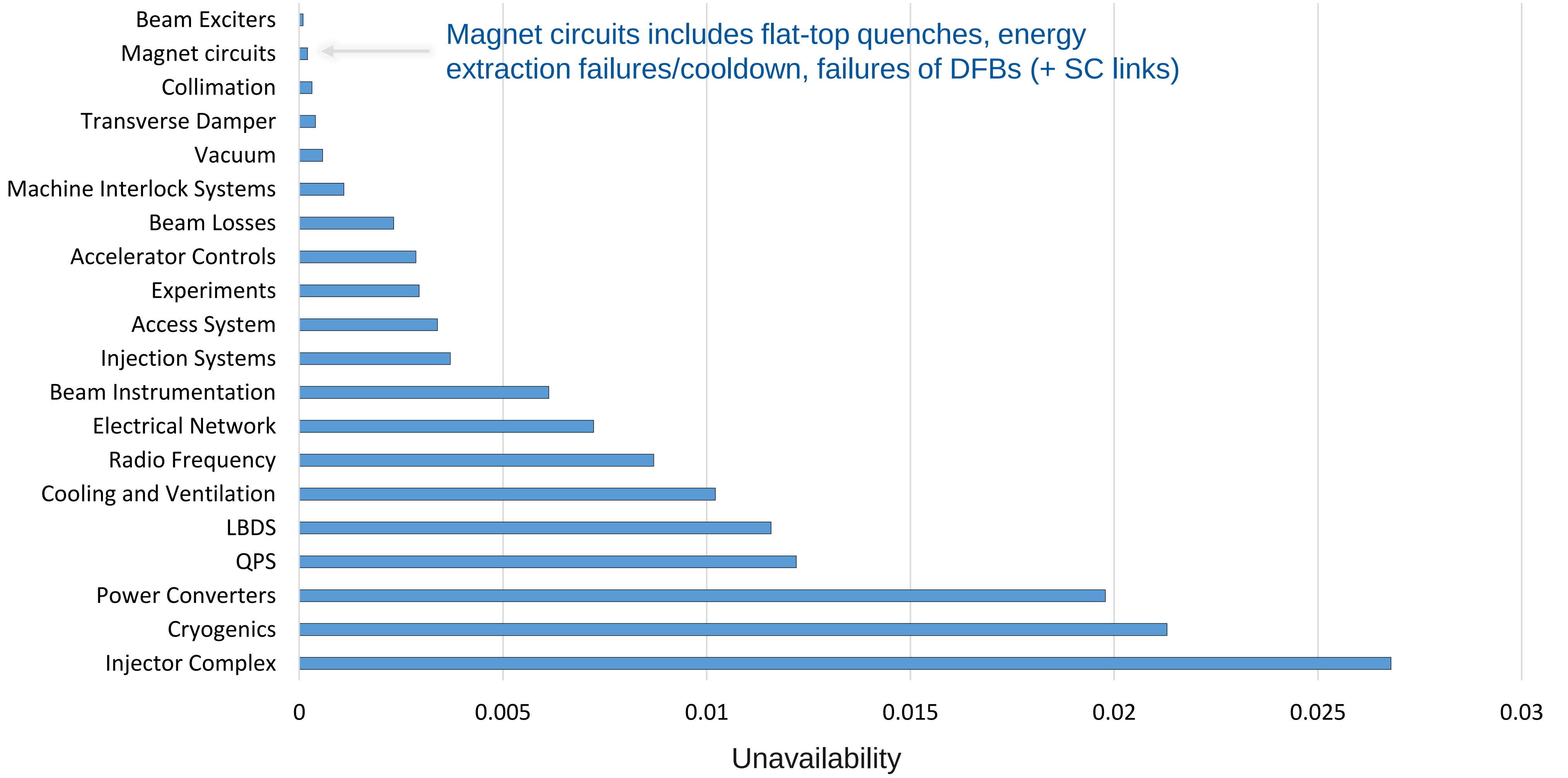


Dominated by few isolated, high impact equipment faults

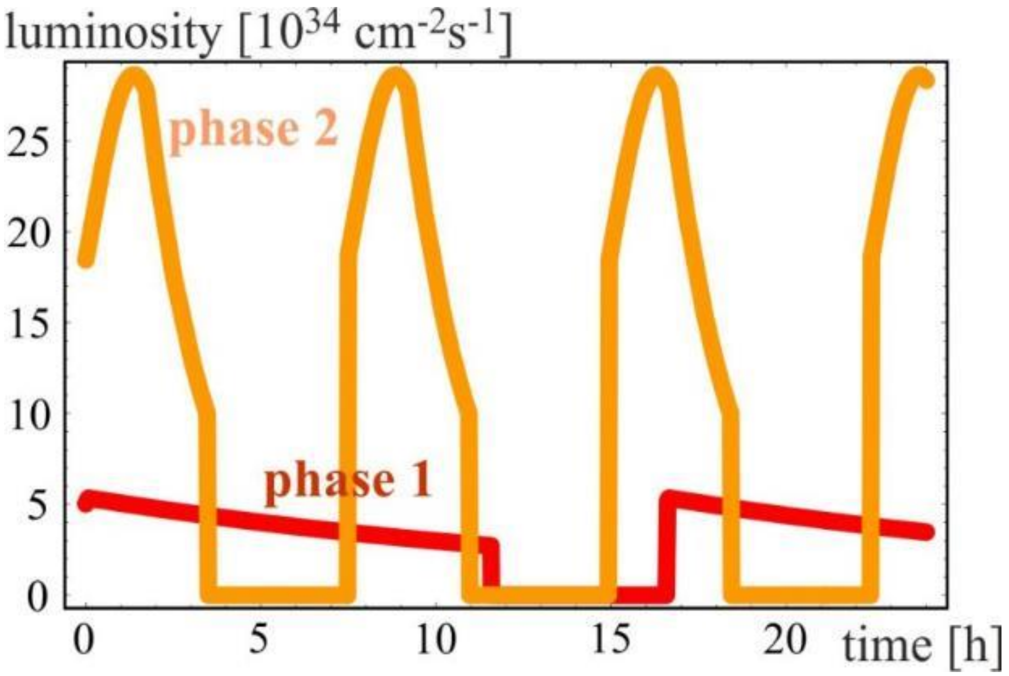


Dominated by recurring faults with short duration (16L2)

LHC System Unavailability: 2017



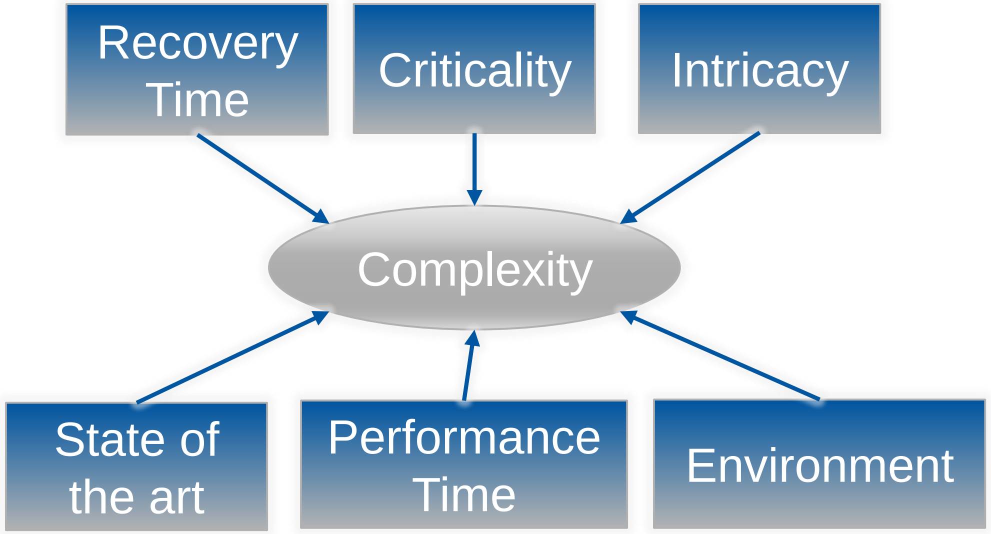
FCC Integrated Luminosity Production



- Reminder: 185-190 months dedicated to physics production during FCC lifecycle, divided in 5 ‘runs’ (2 phase 1 + 3 phase 2)
- Luminosity productions goals per run
  - **Phase 1**: 1.25 ab^{-1}
  - **Phase 2**: 5 ab^{-1}
- High-level goal: FCC is running with **70 % availability** (similar to LHC today) → max 30 % downtime allowed per year
- This goal is used to derive **availability targets for FCC systems**

Availability Allocation According to System Complexity

- Given high level availability goals for FCC, in the concept phase only a **top-down estimate of availability targets** for individual systems is possible
  - No final designs available
  - Estimates of system complexity required



- Complexity definition based on several factors

- Evaluation based on Geometric Allocation Method + DEMATEL procedure[1]
  - Accounts for system dependencies

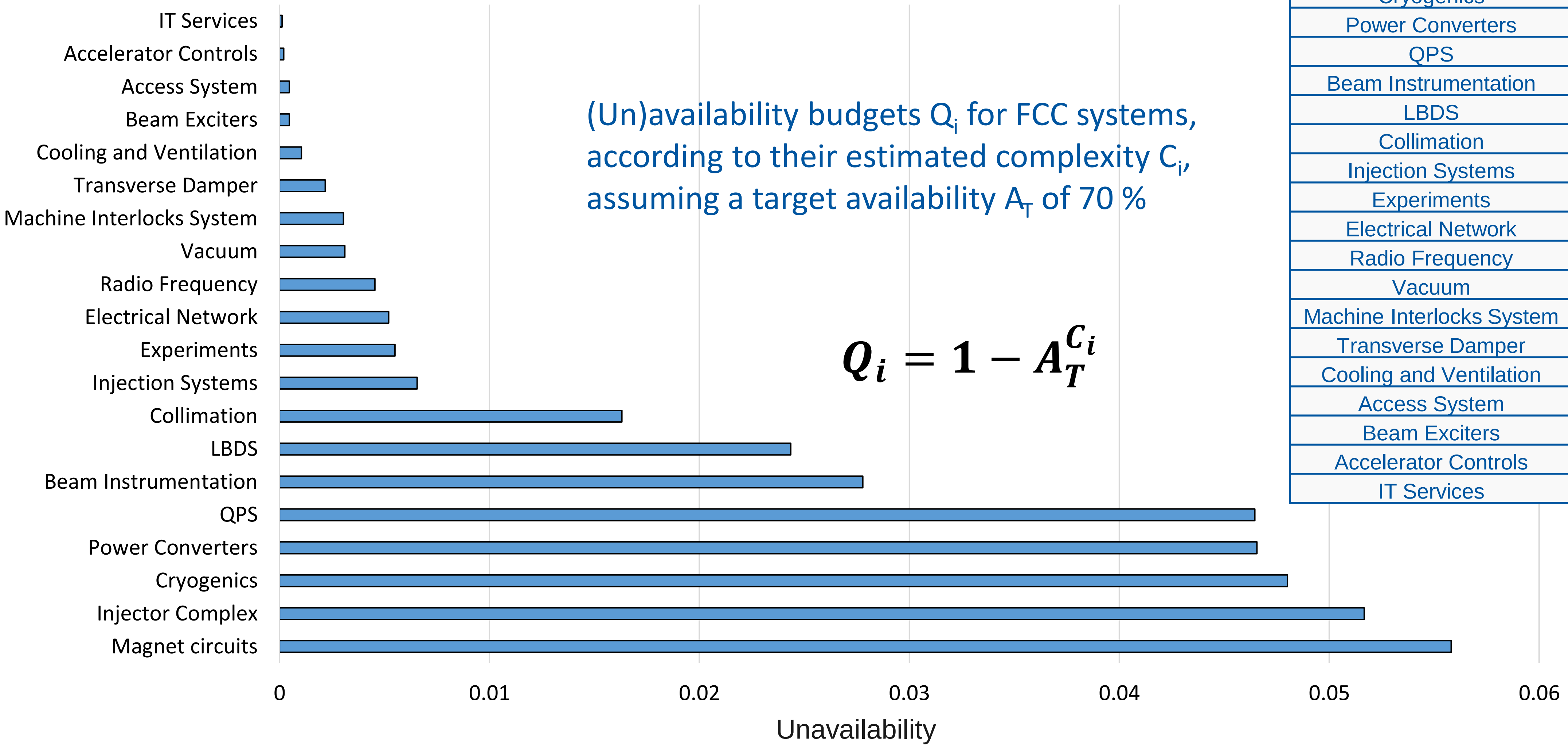
[1] O. Rey Orozco et al., "Availability allocation to particle accelerator subsystems by complexity criteria", International Particle Accelerator Conference, *Canada*, 2018, in preparation

FCC System Unavailability: Targets

System	Complexity [%]
Magnet circuits	16.1
Injector Complex	14.87
Cryogenics	13.8
Power Converters	13.37
QPS	13.34
Beam Instrumentation	7.9
LBDS	6.91
Collimation	4.61
Injection Systems	1.84
Experiments	1.54
Electrical Network	1.46
Radio Frequency	1.28
Vacuum	0.87
Machine Interlocks System	0.85
Transverse Damper	0.61
Cooling and Ventilation	0.29
Access System	0.13
Beam Exciters	0.13
Accelerator Controls	0.05
IT Services	0.03

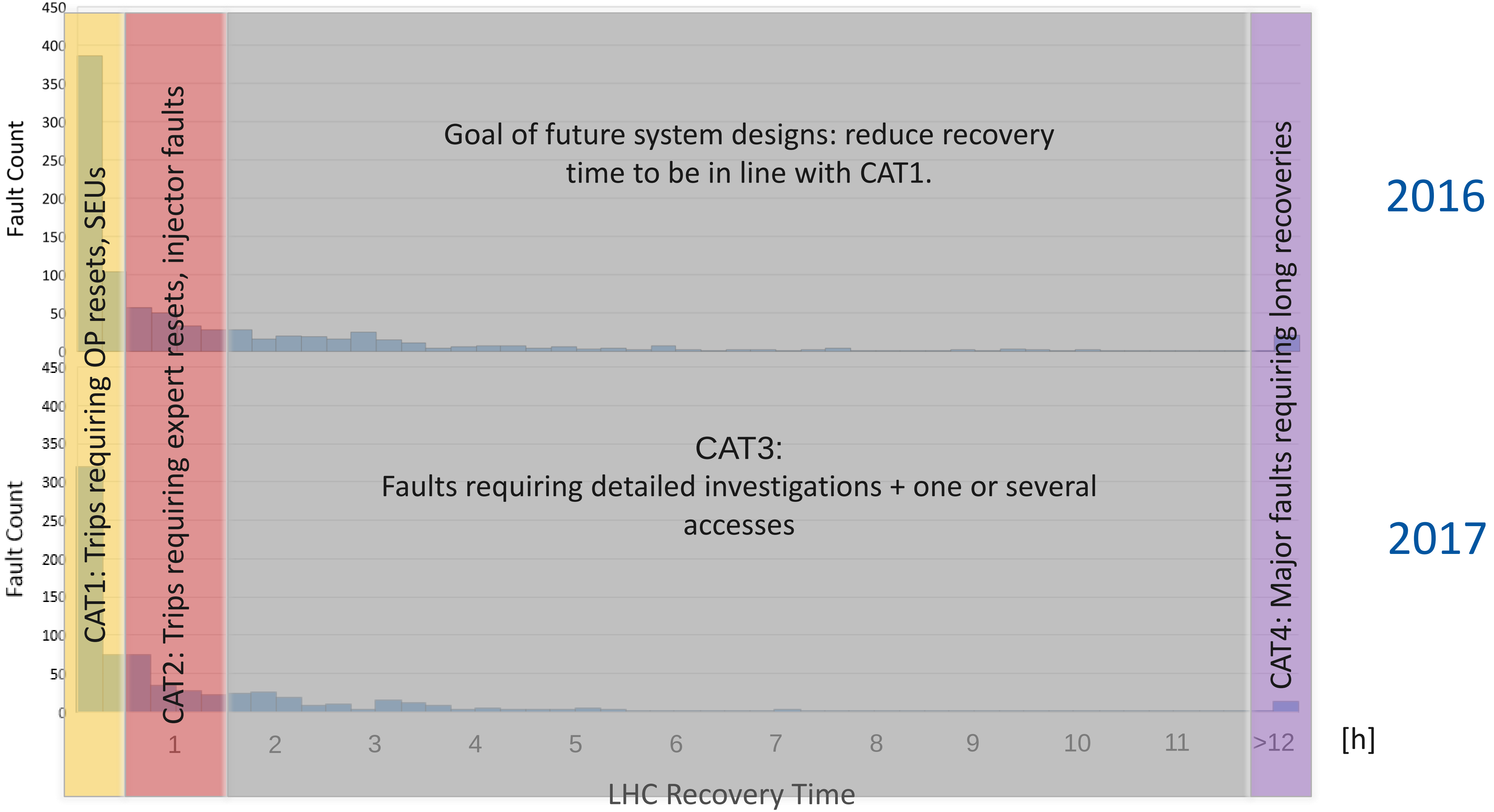
(Un)availability budgets Q_i for FCC systems, according to their estimated complexity C_i, assuming a target availability A_T of 70 %

$$Q_i = 1 - A_T^{C_i}$$



Availability Consideration for FCC Systems (1/2)

System name	LHC experience	FCC
Cryogenics	• Intrinsically long recovery times • Optimised configuration in 2016-2017 yielded excellent availability (only 4 cold compressor units) • Management of transient heat loads (injection/extraction) and e-cloud already a challenge at 6.5/7 TeV	• The number of cryogenics plants will increase from 8 to 10. • Higher heat loads and longer arcs will increase cooling power requirements • New compressor technology may improve reliability
Injector complex	• Availability is >90 % • Relatively high number of rejected injections due to insufficient beam quality	• Two options: LHC or superconducting SPS • In both scenarios: challenges associated to ageing of legacy equipment • Advanced beam quality diagnostics in the injectors is mandatory • Capital and operation costs + achievable availability should be considered
QPS	• Very complex and distributed system • Availability improved significantly over the years (remote diagnostics and resets) • Radiation tolerant design for quench detection systems	• Advanced quench detection techniques are under consideration • Based on present experience, expect over 100000 interlocks from QPS • Complexity will scale at least with the machine size
Power converters and magnet circuits	• 8 powering circuits for main dipoles • Most failures coming from corrector circuits • Radiation effects on electronics significantly contributing to the number of spurious beam aborts	• 100 powering circuits for dipoles due to protection requirements • Active energy extraction and energy recuperation technologies Unknowns = operational margins (quench levels of Nb_3Sn magnets, recovery time following quenches at 50 TeV)
Beam dump system	• 15 extraction kickers, 10 dilution kickers • No asynchronous dumps observed with beam from LHC start-up • Failure rate sharply increases with increasing voltage in the generators (10 switches per generator)	• 300 extraction kickers to limit generator voltage (2 switches per generator) • Design should allow tolerating the spurious firing of a single kicker • Prevent by design common cause failures for erratic triggers


Fault Count
Fault Count
450
400
350
300
250
200
150
100
50
0
CAT1: Trips requiring OP resets, SEUs
CAT2: Trips requiring expert resets, injector faults
Goal of future system designs: reduce recovery time to be in line with CAT1.
CAT3:
Faults requiring detailed investigations + one or several accesses
CAT4: Major faults requiring long recoveries
1
2
3
4
5
6
7
8
9
10
11
>12
[h]
LHC Recovery Time
2016
2017

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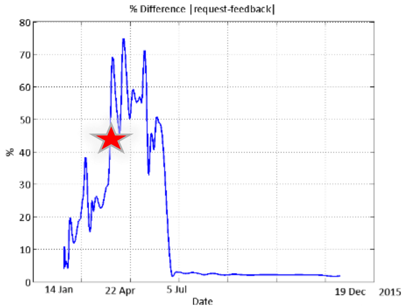
Breakdown of Recovery Time

Recovery Time

Identification



Diagnostics

Logistics

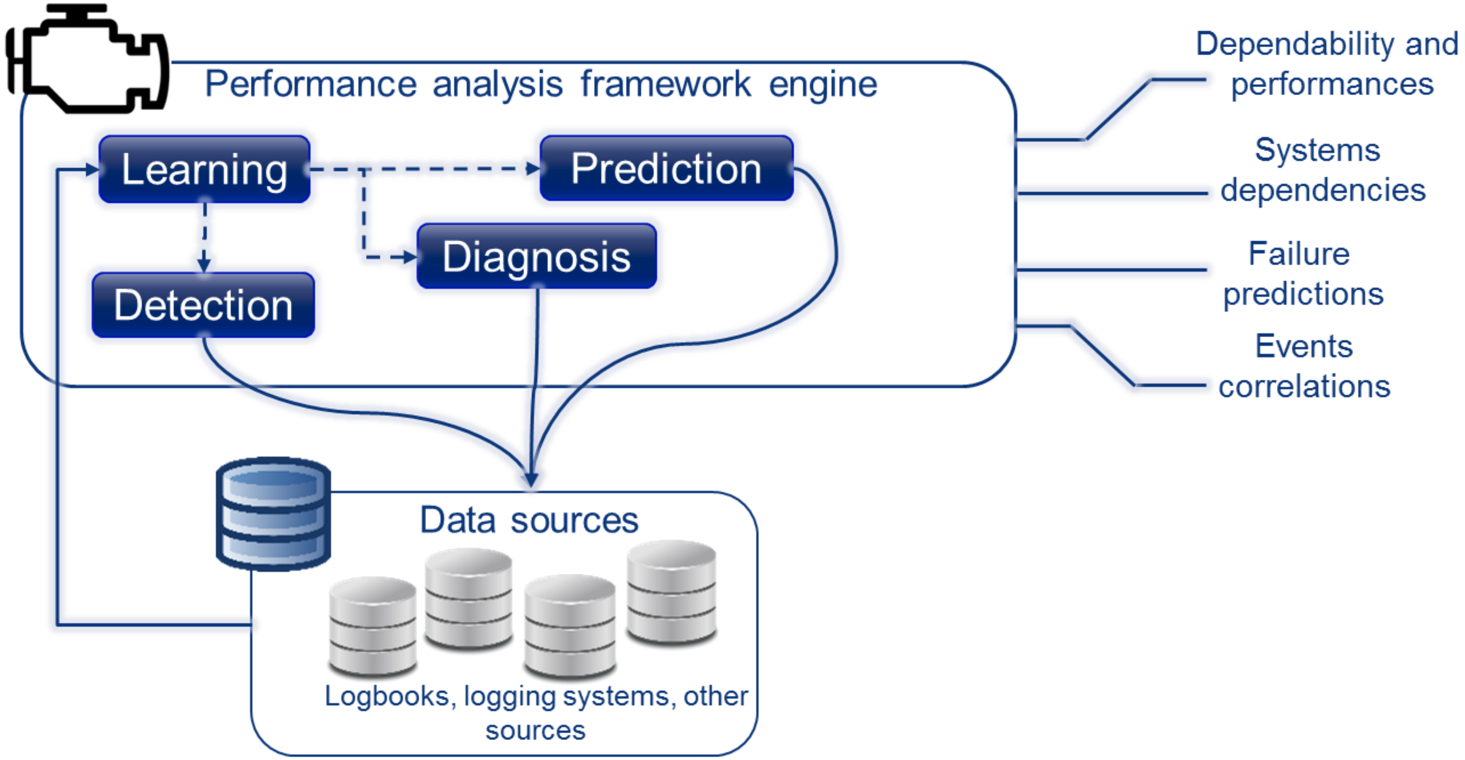
Repair

Machine learning for advanced diagnostics

Remote maintenance

Machine Learning Framework[1]

Complex and interdependent system of systems can profit from artificial intelligence and machine learning techniques to support operation, maintenance and consolidation activities



Machine learning allows to:

- Perform a root cause analysis when failures occur
- Perform predictive maintenance
- Support the coordination and evaluate the consequences of a planned intervention by providing the list of affected system
- Build prediction models for reliability and availability analyses

This framework is currently under development at CERN and being applied to some relevant use cases, as the extraction of the technical infrastructure functional dependencies and the analysis of electrical glitches

[1]U. Gentile and L. Serio, "A Machine-learning based methodology for performance analysis in particles accelerators facilities", *First International Conference on Electrical Engineering & Computer Science (EECS), IEEE*, 2017, accepted, in press.

Remote Maintenance – Current Solutions at CERN

The mission of tele-robotics at CERN: Ensuring safety of personnel improving availability of CERN's accelerators

Solutions for:

- Remote inspection for reconnaissance and RP measurements
- Telemanipulation: screwing/unscrewing, cutting, grasping etc.
- Research and developments in machine and deep learning, virtual reality, user friendly human robots interfaces and haptic devices
- Procedures and best practice for installation, dismantling and maintenance in highly activated areas

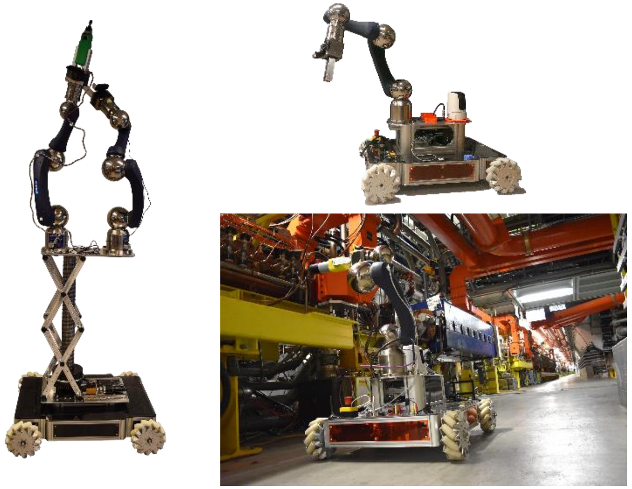
Train Inspection Monorail (TIM) for the LHC
For inspection and RP measurements

Telemax and Teodor for inspection and telemanipulation

ISOLDE and MEDICIS robots for targets exchange

Radioactive samples fine handling

CERNbot for inspection and telemanipulation



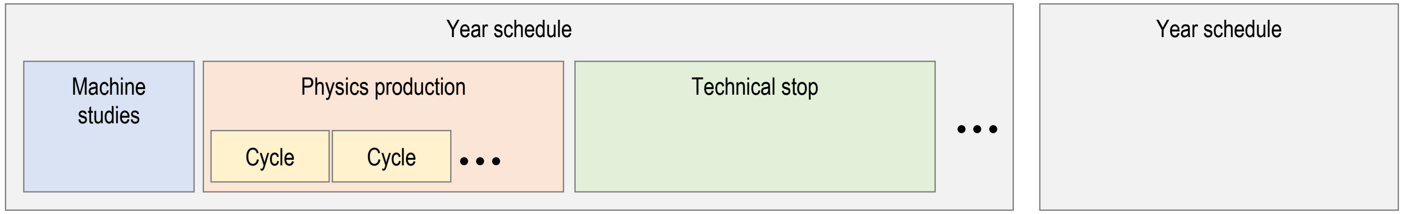
CRANEbot for accessing "complicated" areas

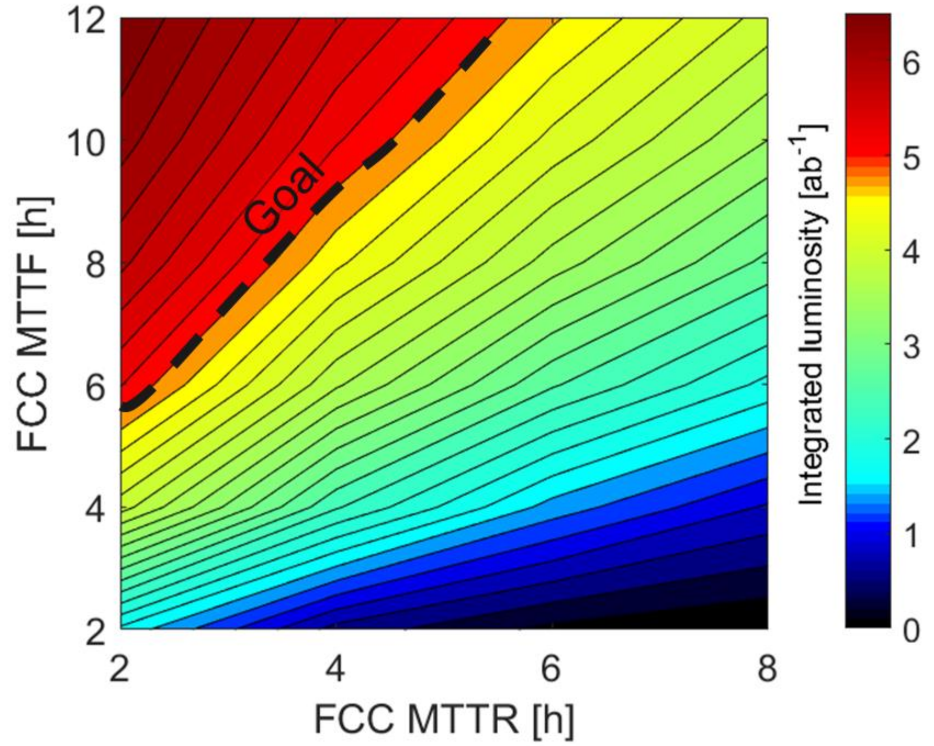
Virtual reality for intervention preparation

M. Di Castro, A. Masi, "Robotics Inspections, maintenance and early interventions for the FCC", FCC Week, Thursday, 2018 https://indico.cern.ch/event/656491/contributions/2938741/.

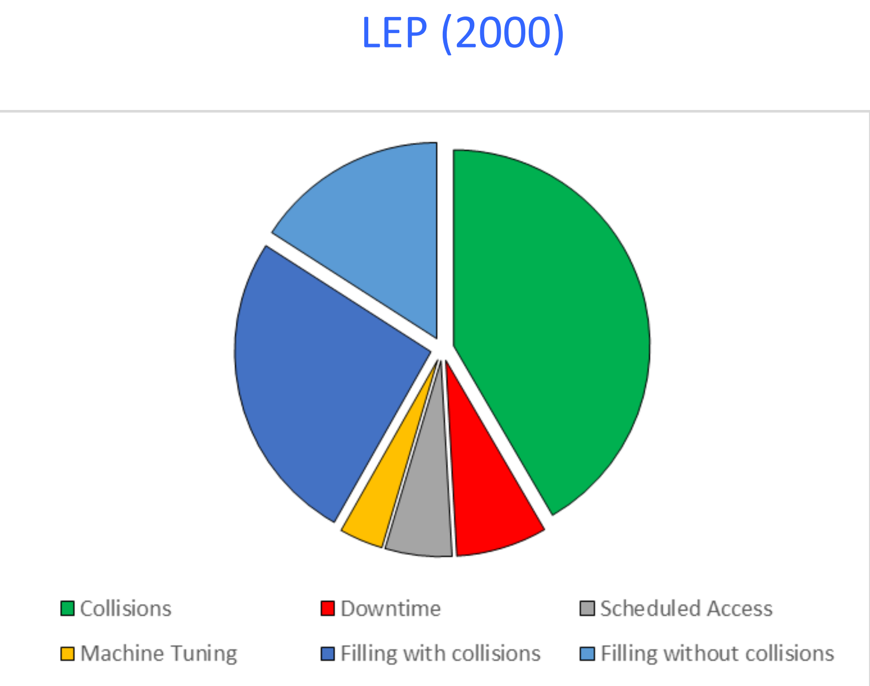
Conclusions on Modelling Approach

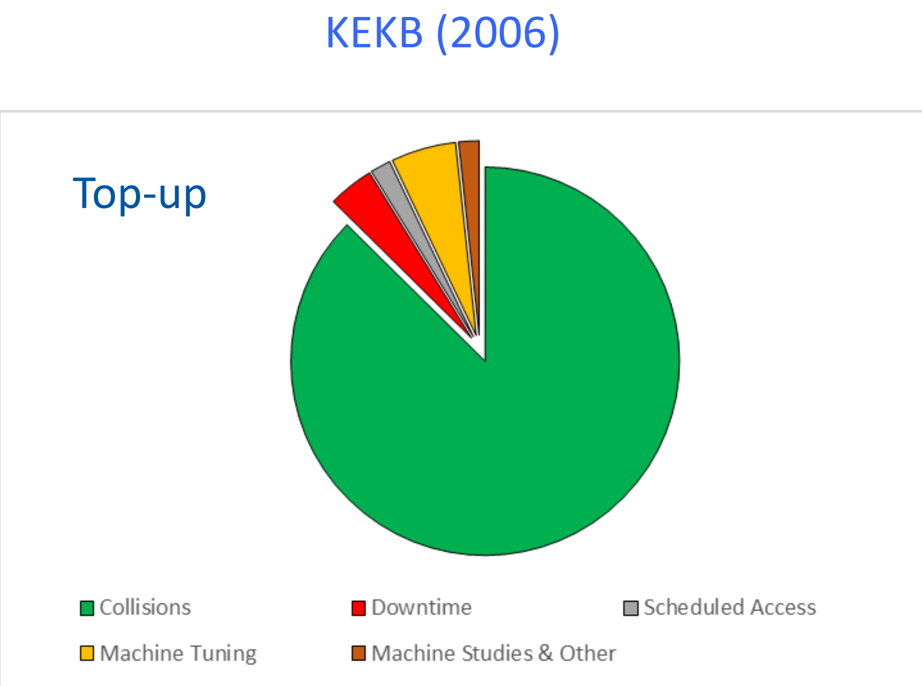
- **Monte Carlo simulations** of accelerator operation:
  - Accelerator cycles, faults and luminosity production
- Fault tree description of system availability/reliability:
  - Failure rates + repair times
- Requires **accurate data** for meaningful predictions, not always available to the desired level of detail
- **Fault Tracking** of comparable operating accelerators is fundamental for accurate performance predictions of future machines

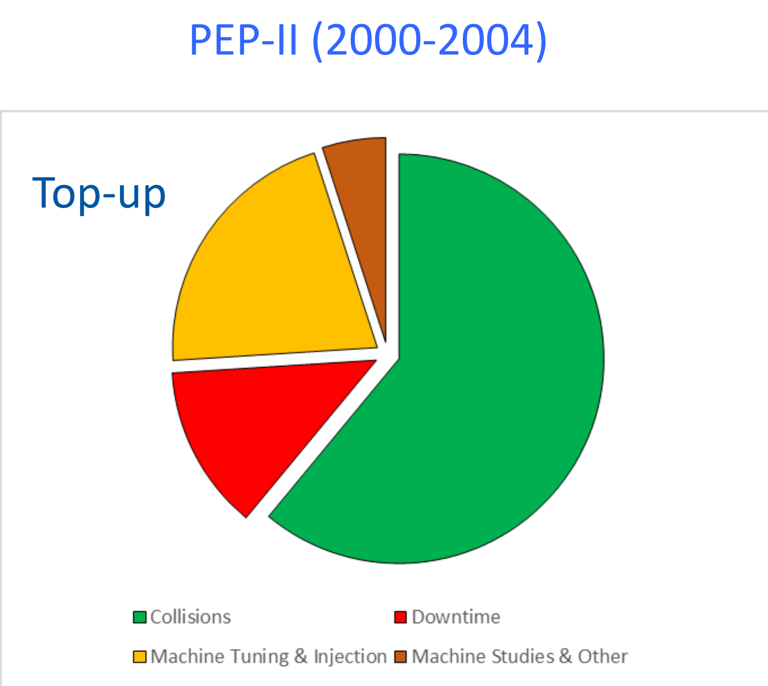




Lepton Machines – Performance Review







- Based on experience with previous machines, assuming operation with top-up injection, FCC-ee can target 90 % time with collisions

Conclusions

- Top-down allocation of system availability requirements: **targets set for individual system availability**, including complexity scaling for FCC technologies
  - Expected downtime drivers: magnet circuits and injector complex

- Recommendations for future activities and R&D:
  - Study reliability of proposed **magnet circuit configurations** (protection vs complexity vs availability)
  - Identify best **injector option** for FCC (cost vs complexity vs availability)
  - Explore potential of **machine learning** for advanced fault diagnostics and **remote maintenance** to reduce intervention times
  - Invest in **availability modelling** and simulations for performance predictions
  - Invest in **fault tracking** of operating accelerators for consistent record of their performance

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Thanks a lot for your attention!

Factor	Recovery time	Criticality	Intricacy	State of art	Performance time	Environment
Scoring scale	10: highest recovery time 1: lowest repair time	Scale from 1 to 10 10: many interlock channels associated 1: few interlock channels associated	Scale from 1 to 10 10: highly intricate system 1: less intricate system	1: Innovative 0.67: existing 0.33: established	1: whole mission time 0.67: Continuous and long times 0.33: instantaneous	1: highly radioactive 0.67: average radioactive 0.33: low radioactive
Accelerator Controls	2	2	2	0.33	1	0.33
Access System	5	2	3	0.33	1	0.33
Beam Exciters	3	2	4	0.67	0.33	0.67
Beam Instrumentation	5	8	9	1	0.67	0.67
Collimation	5	5	6	1	0.67	1
Cooling and Ventilation	7	2	3	0.33	1	0.33
Cryogenics	10	5	8	1	1	0.67
Electrical Network	8	4	5	0.33	1	0.33
Experiments	3	2	10	1	0.67	1
Injection Systems	5	4	7	0.67	0.67	0.67
Injector Complex	8	7	10	1	1	0.67
IT Services	2	2	2	0.33	0.67	0.33
LBDS	7	6	10	1	0.67	0.67
Machine Interlocks System	3	4	5	0.67	0.67	0.67
Magnet circuits	10	8	10	1	0.67	0.67
Power Converters	5	10	9	1	0.67	1
QPS	5	10	9	1	0.67	1
Radio Frequency	5	4	5	0.67	0.67	0.67
Transverse Damper	3	2	6	1	0.67	0.67
Vacuum	5	5	5	0.33	0.67	0.67

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Availability Consideration for FCC Systems (2/2)

System name	LHC experience	FCC
Electrical network	Unavailability mainly due to: • Isolated, high impact events (e.g. 18 kV transformer in 2016) • Electrical glitches resulting in spurious beam dumps.	• FCC will have 3 connections (vs 1 for the LHC) for electrical supply • Electrical infrastructure is expected to scale with the size of the machine • Power dip reduction system may resolve the fluctuation issues.
C & V	• No major problems observed for LHC	• Complexity will scale with the machine size • Constraints for periodic maintenance of cooling towers
RF	• 16 cavities in 4 cryomodules powered by 16 klystrons	• 40 cavities in 10 cryomodules powered by 40 klystrons
Injection Systems	4 kickers and 20 m of septum magnets per beam	40 kicker magnets and 90 m of septum magnets per beam
Beam Instrumentation	• 4000 BLMs, few spurious dumps per year • Very few problems with other beam instruments	• Complexity is expected to scale with the size of the machine
Beam Losses	• Instabilities: no major problems with beam instabilities (beam-beam, impedance, …), running with high octupole current • UFOs: rate strongly depends on machine conditioning; large UFOs can lead to magnet quenches, significant impact of beam energy	• Assumption: no major problems with instabilities • UFO generation mechanism understood and solved
Vacuum	• Very few vacuum issues observed	• Complexity is expected to scale with the size of the machine • Synchrotron radiation requires new beam pipe design

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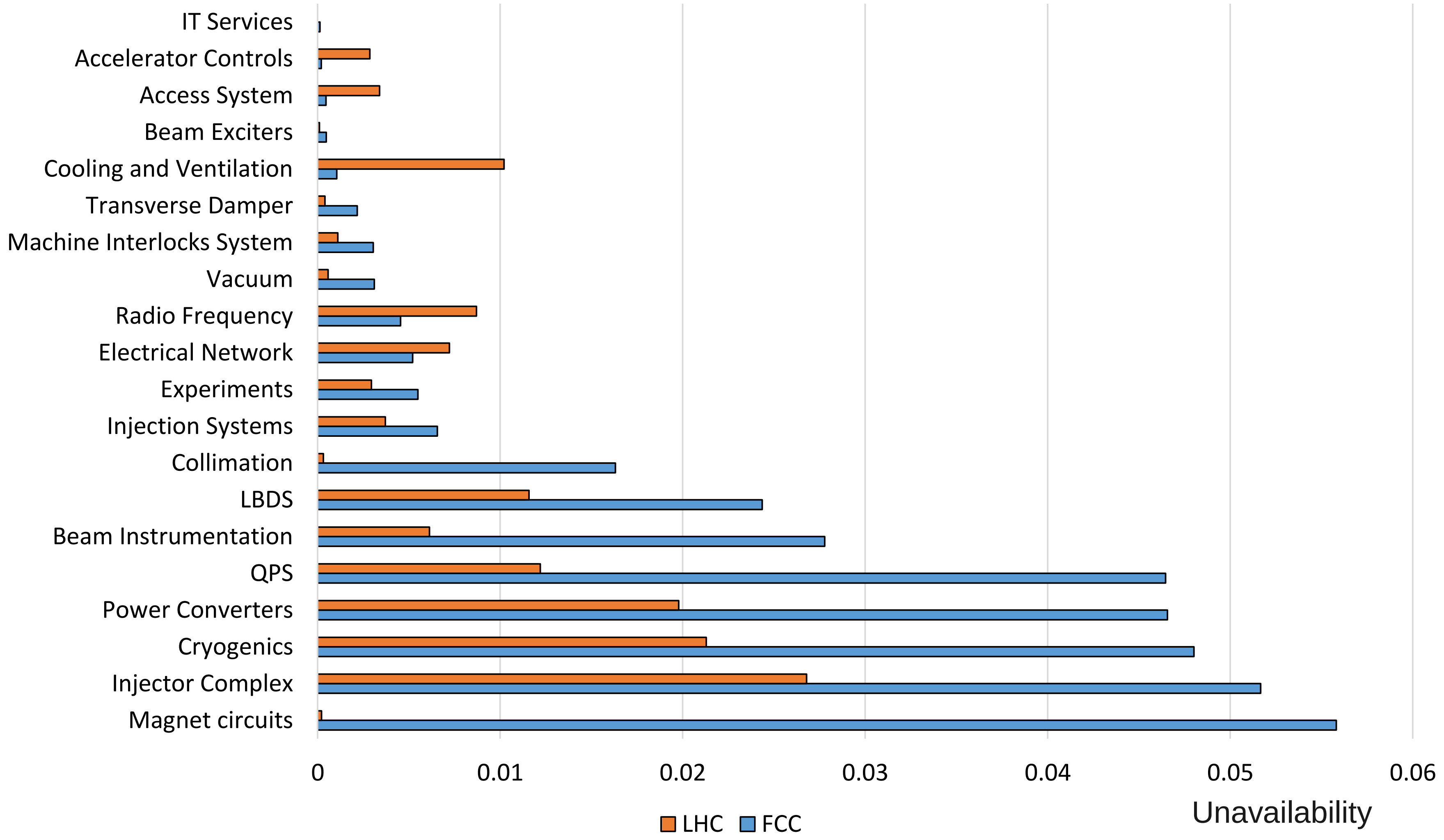
LHC and FCC System Availability: Comparison



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