Availability Modelling at CERN

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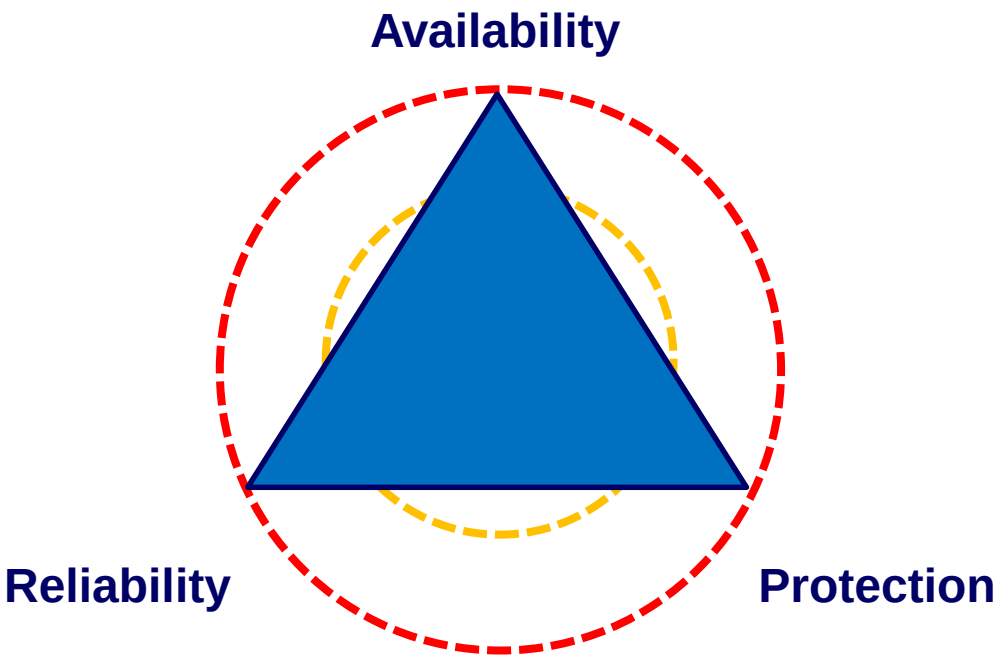
Motivation: Availability Modelling

- Reliability and Availability are *key performance indicators* for present and future accelerators (HL-LHC, CLIC, FCC, ADS)
- We need a way to predict the expected availability of these machines
- Very different machines (linear vs circular, hadron vs lepton, coupled with nuclear reactors!) + wide range of operating conditions to be covered

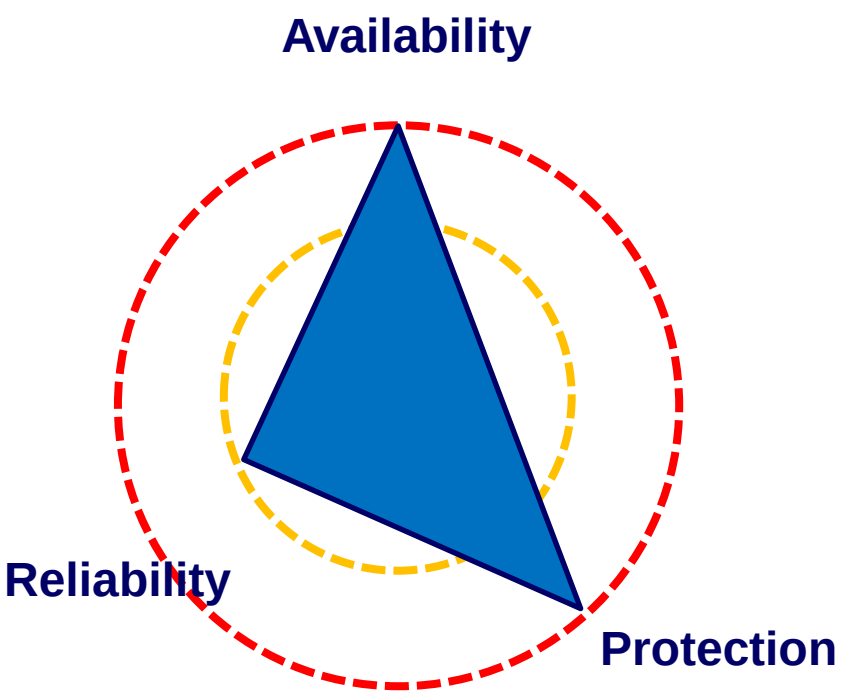
Requirements for Particle Accelerators



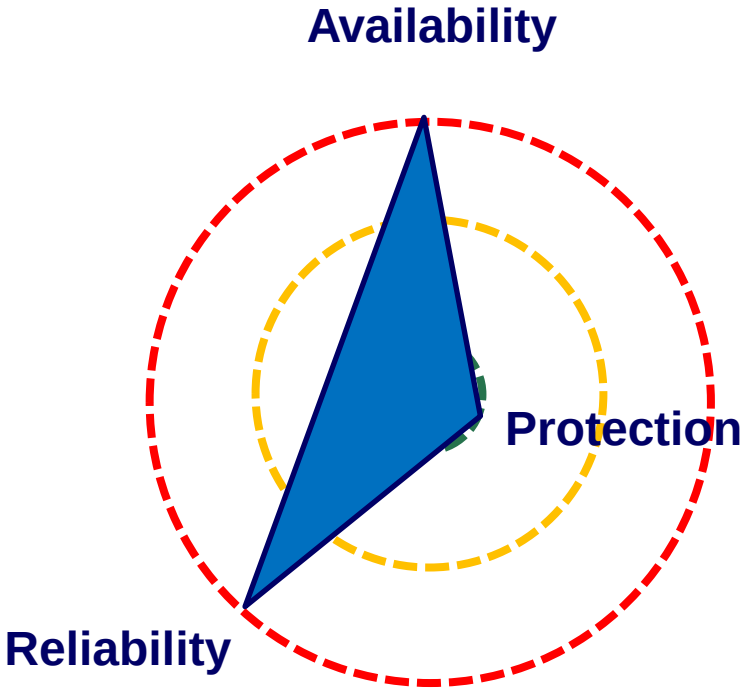
Low Importance
Relative Importance
High Importance

R-A-S(P) Requirements for Accelerators

Large-Scale Colliders

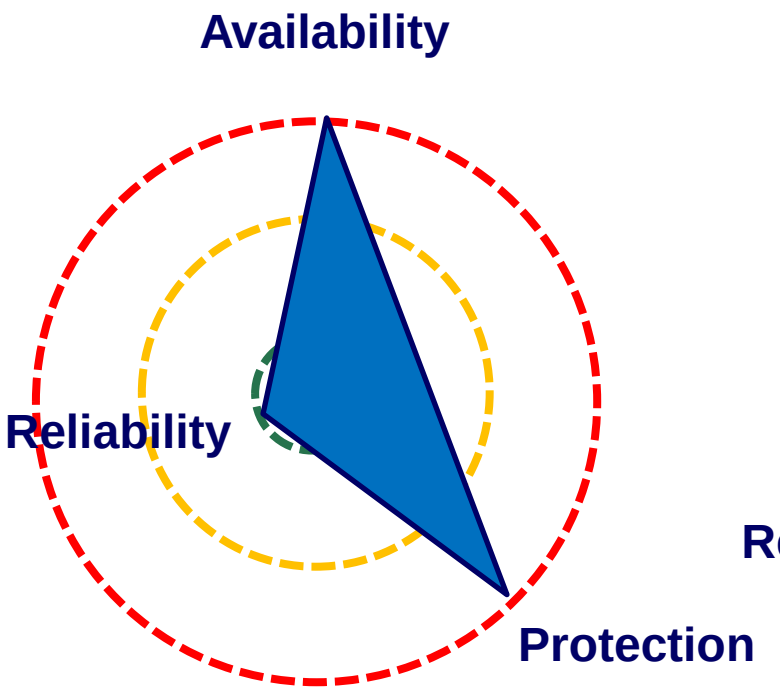


Synchrotron Light Sources

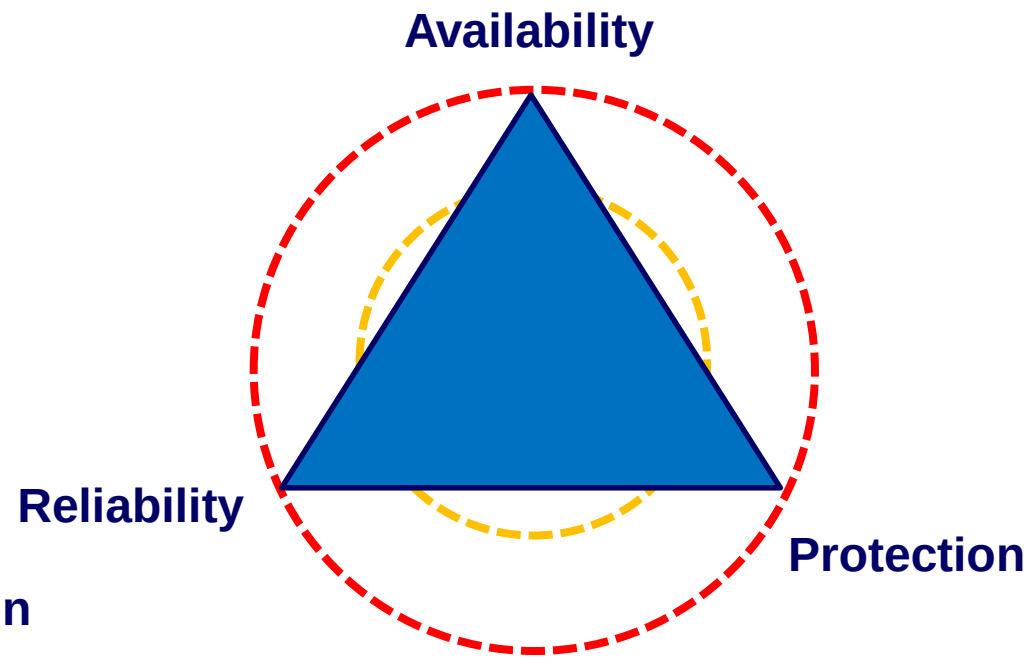


R-A-S(P) Requirements for Accelerators

Spallation Neutron Sources



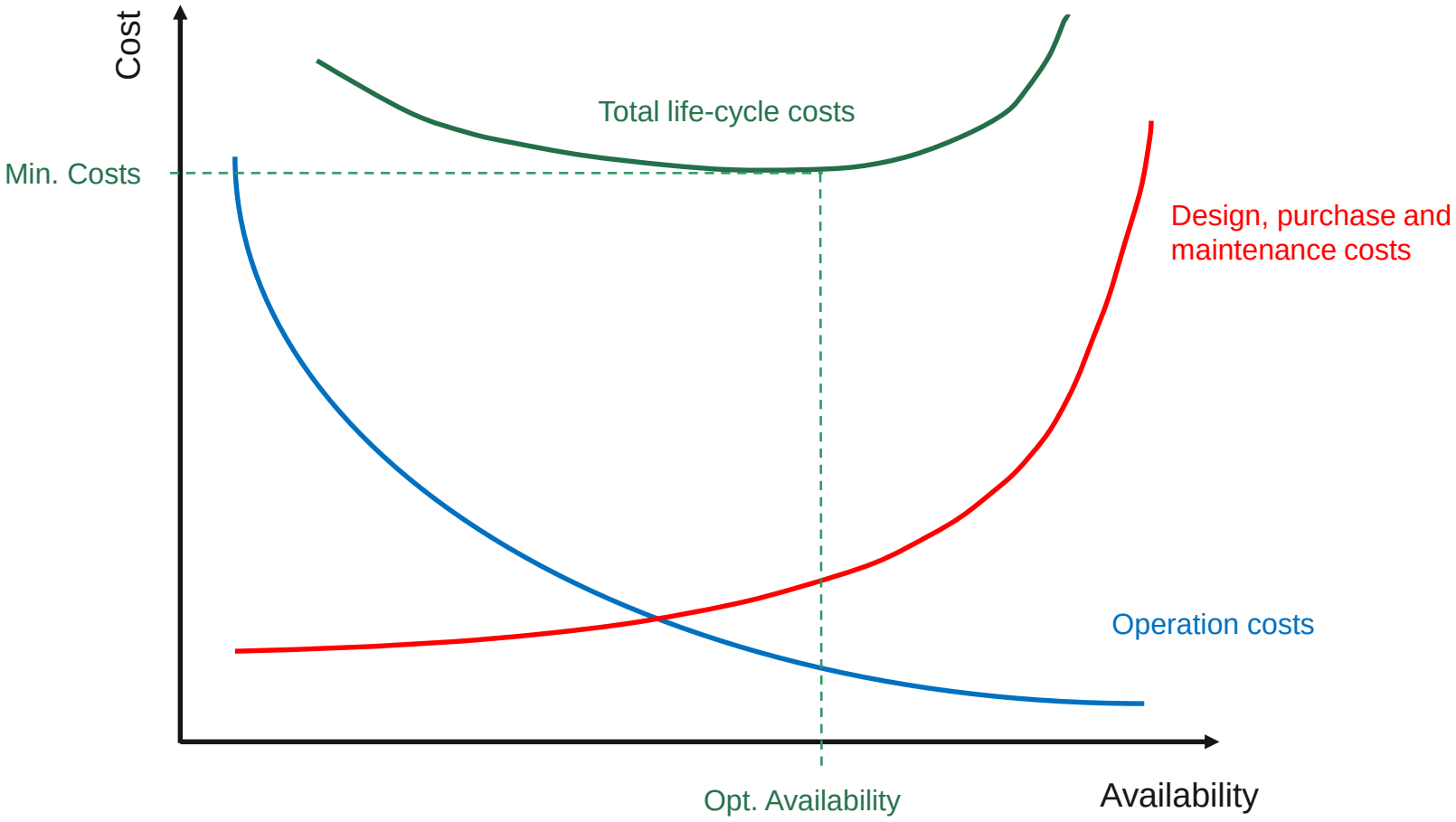
Accelerator Driven Systems



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

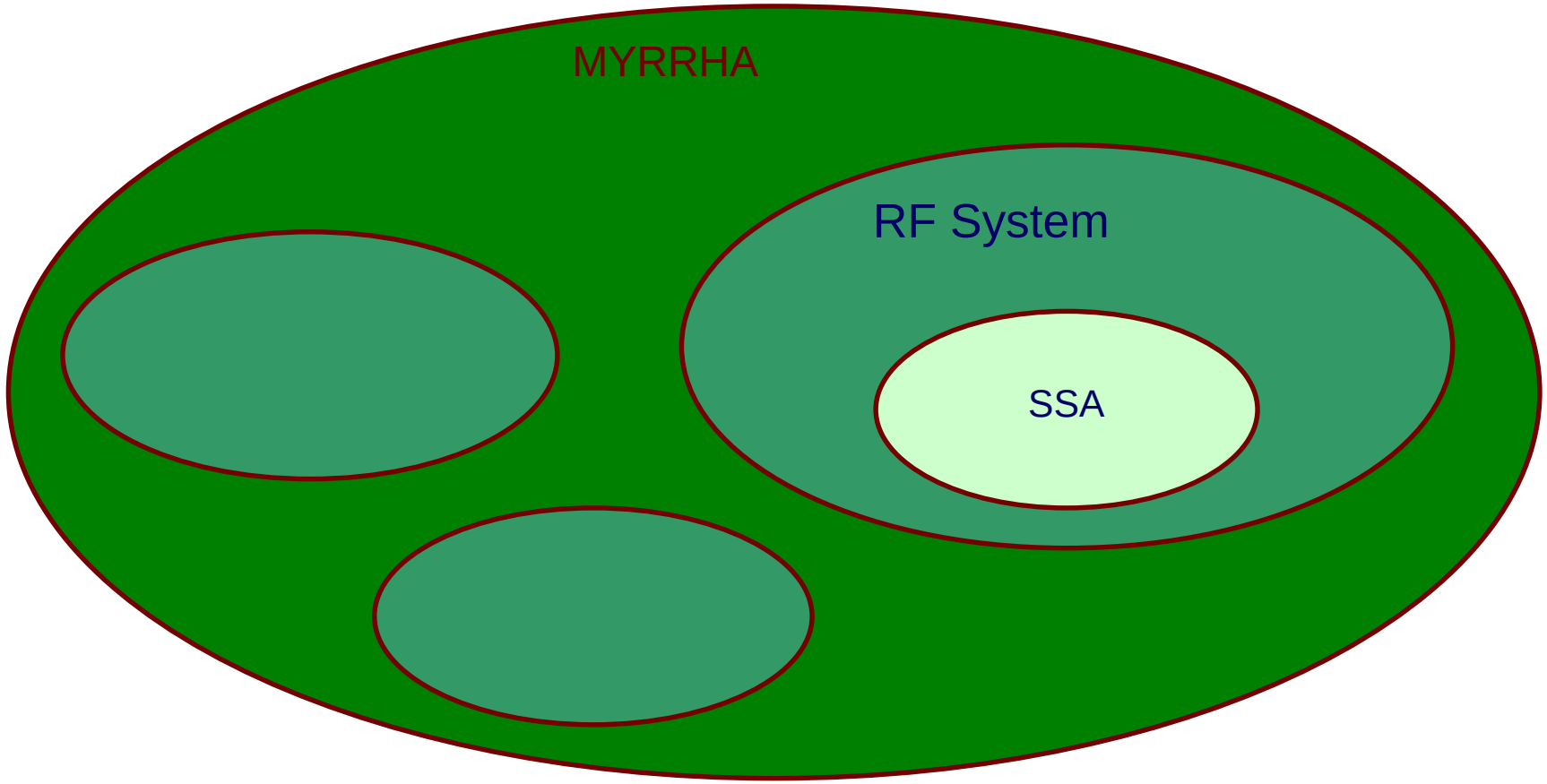
Costs, Reputation, Damage potential

Cost vs Availability



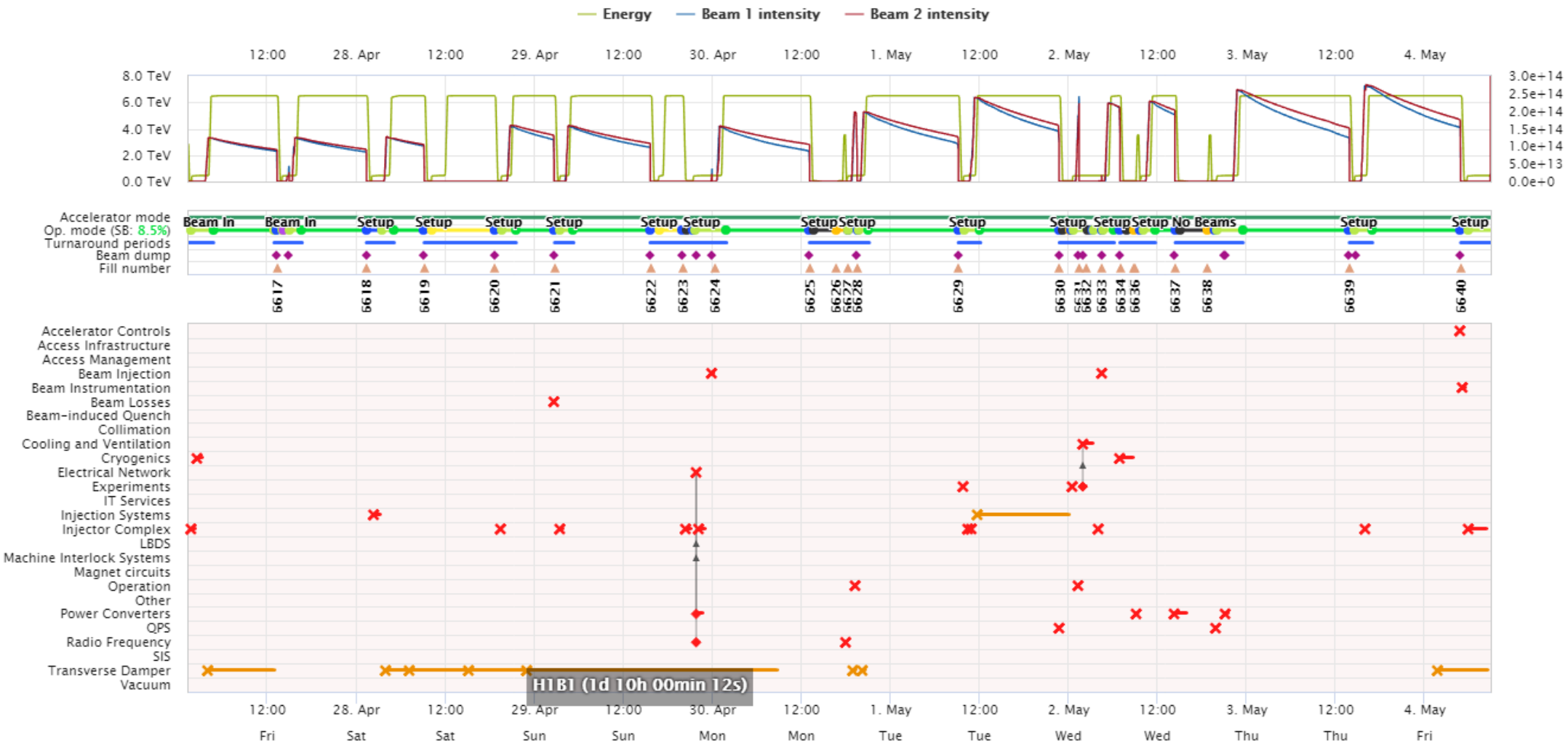
- Given a target performance reach (neutron fluence, number of patients treated, luminosity production, …), an optimal balance between capital costs and operation costs must be found
- This is an **absolute MUST** for the feasibility of next-generation machines

Abstraction Levels



- Availability models typically start from accelerator and system levels (repairable systems) and can go down to component level

What should we simulate? (LHC example)



We want to simulate accelerator operation: cycles, failures (phase-dependent), failure recoveries, impact of failures on accelerator parameters (degraded operation)

Availability Simulation Tools

Commercial software

Usually productivity oriented

Some accelerator specific needs are not considered/could not be modeled easily

ISOGRAPH

Special-made software

Availsim (the only software found at the time that explicitly target particle accelerators)

AVAILSIM 3.0

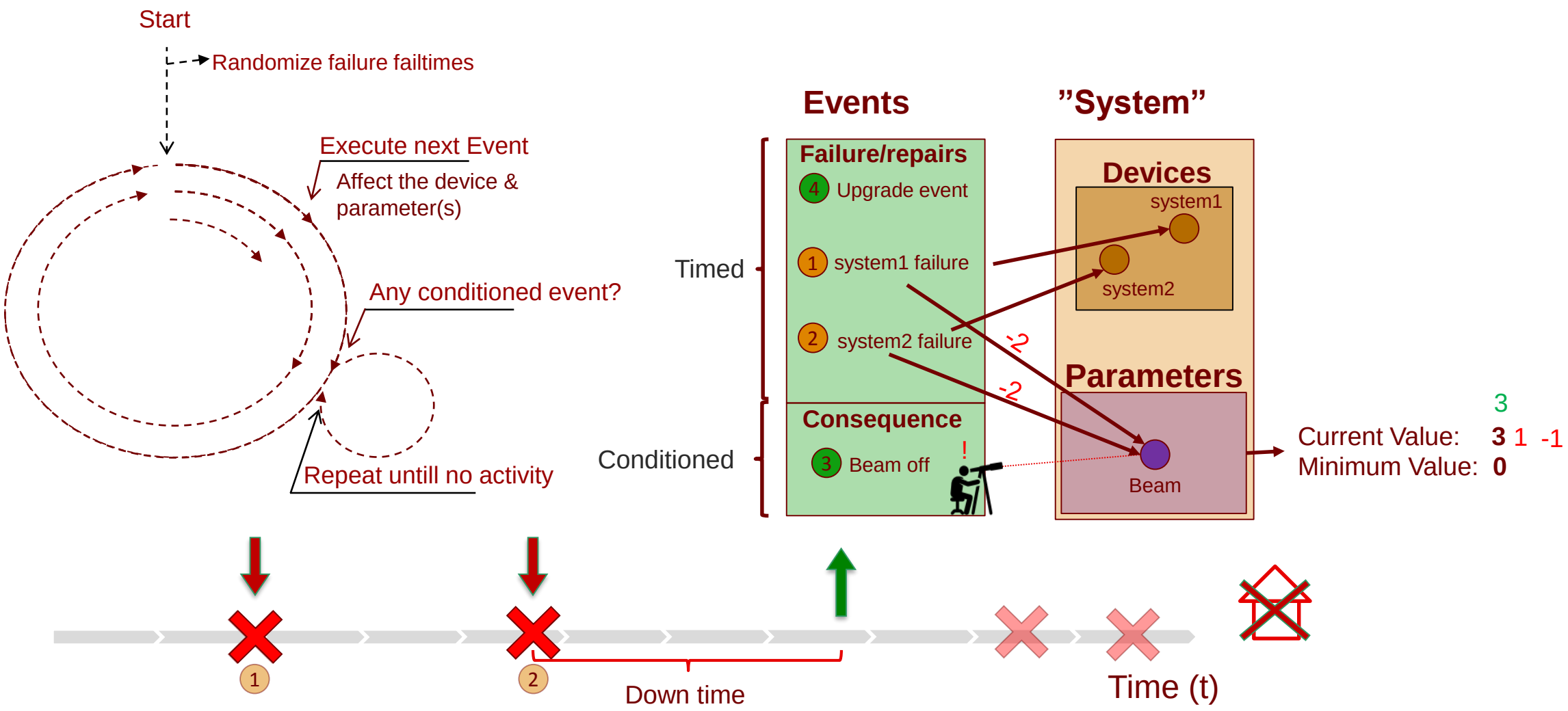
Availsim3

- Developed from scratch in Python 3 (no MatLab license)
- Object oriented
- Open sourced
- A simulation in discrete time that uses a so called ”three-phased” approach (Pidd, 1998)
  - Discrete Event Simulation (DES)
- Under continuous development and testing
- Adding accelerator driven features

AvailSim Features

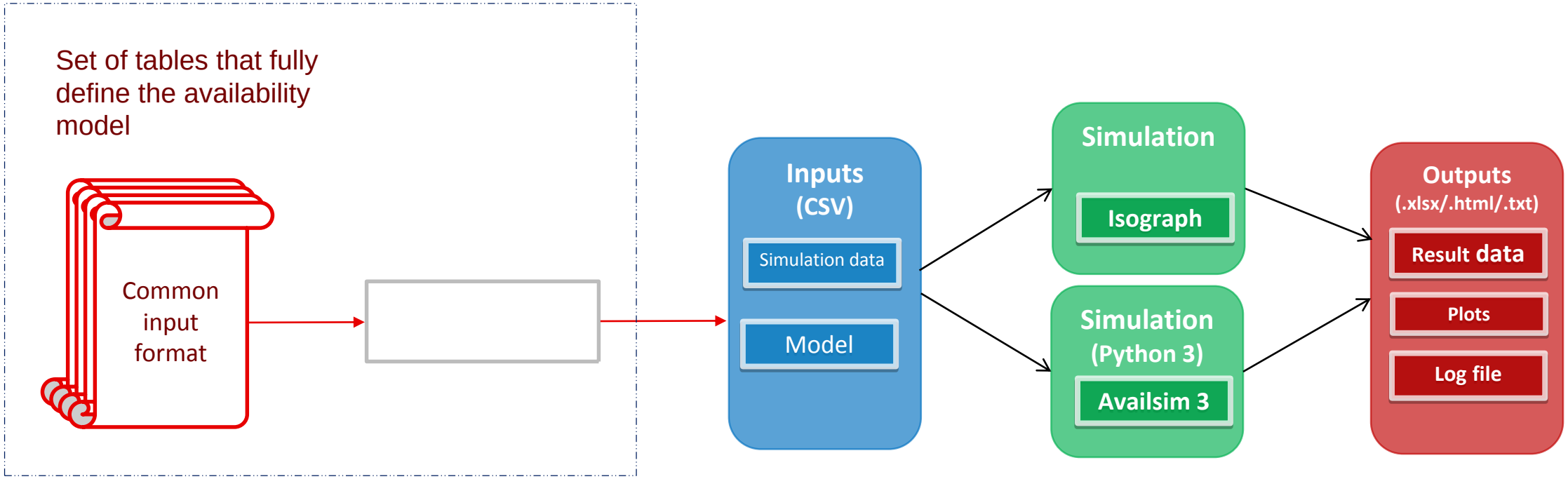
- **On-off site maintenance**
  - Remote interventions
  - Accessibility of equipment (tunnel, surface,…)
- **Repair strategies**, corrective maintenance when system fails (also ‘online’ repairs, e.g. RF serial redundancy in MYRRHA Linac)
  - Repair all failed components when accelerator fails
  - Repair only minimum number of components to bring the accelerator back in operation
  - Perform all repairs that fit in the longest mandatory intervention (LHC-like)
- **Spare management** → estimate number of spare parts required over accelerator lifetime
- **Phases and cycles** → model cycling operation of an accelerator + scheduled maintenance periods
- **Phase-dependent failure rates** → model system ‘stress’ under particular operating conditions

Quick and simple example



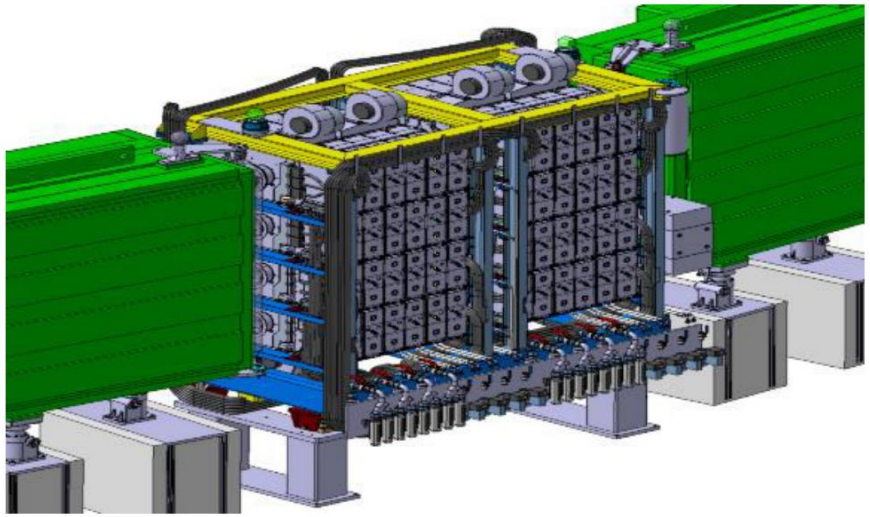
Availsim3

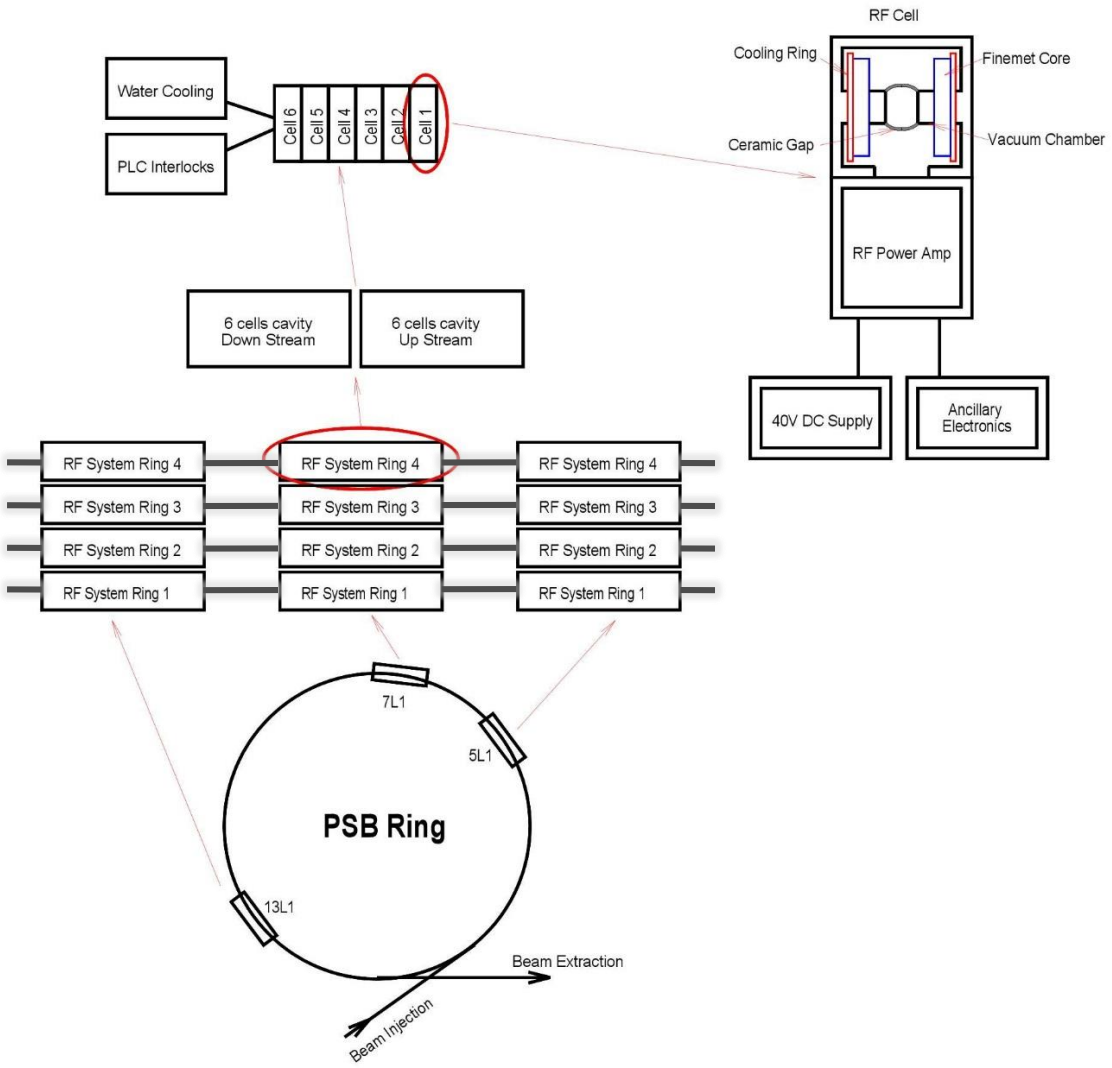
[Overview]



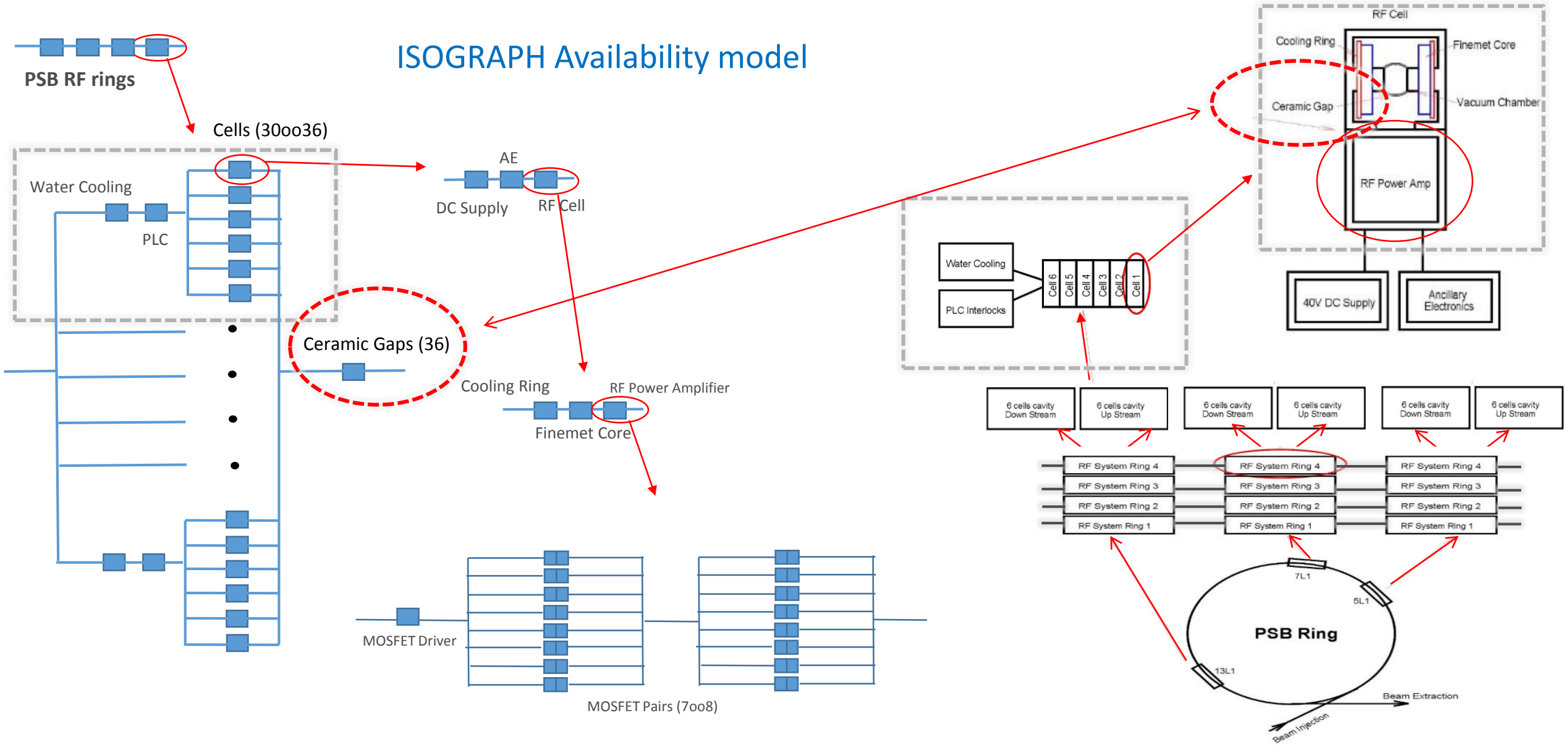
PSB RF System

- The **Proton Synchrotron Booster (PSB)** is made up of four superimposed synchrotron rings that receive beams of protons from the linear accelerator.
- Each synchrotron ring has its independent RF system.
- The **PSB RF system is upgraded** in the framework of the LIU (LHC Injectors Upgrade) project.





ISOGRAPH Availability model



Failure Rate Estimates

$$\lambda(t) = \frac{\text{Failures}}{\text{Total number of units still intact}}$$

TESTS
(Systems + Components)

Accurate results

Cost + Time

Accelerated lifetime tests (if applicable)

EXPERT ESTIMATES
(Systems)

Big uncertainties on boundary conditions

Good for known technologies

Good for preliminary estimates

STANDARDS*
(Components)

Very systematic

Boundary conditions taken into account

Technology advancements

IMPORTANT: The power of reliability analysis methods is not in the accuracy of failure rate estimates, but in the possibility to **compare architectures** and show the **sensitivity** of system performance on reliability figures

*Require dedicated calculations to derive system-level reliability (e.g. FT, RBD…see Miriam's talk)

Input Data- **MTTF**

Component	No. of components in the system	MTTF (years)	MTTF (h)	Data source
Water Cooling	24	10x24	2102400	Expert experience. Machine made up of 24 components failed ones in 10 years.
PLC Interlocks	24	22	200000	PLC MTTF=Its Power Supply MTTF Manufacturer data: Values from 200.000 to 980.000 hours
DC Supply	144	5	43800	Expert experience.
Ancillary Electronics	144	5	43800	Expert experience.
Cooling Ring	144	40x10x50	175E+6	Expert experience from PS. 1 ring failed in 40 years, 50 rings per cavity, 10 cavities
Finemet Core	144	10000/2	43.8E+6	Expert experience from various machines. One Finemet Core failed once each 10.000 years. The component is made up of two Finemet Cores
Ceramic Gaps (36)	4 (144/36)	20000/36	4.8E+6	Expert experience from various machines. One Ceramic Gaps fails ones each 20.000 years
Mosfets pair	4608/2	18600000/2	8.15E+10	Manufacturer data
Mosfets Driver	144	18600000	1.63E+11	Manufacturer data

Input Data – **Maintenance times**

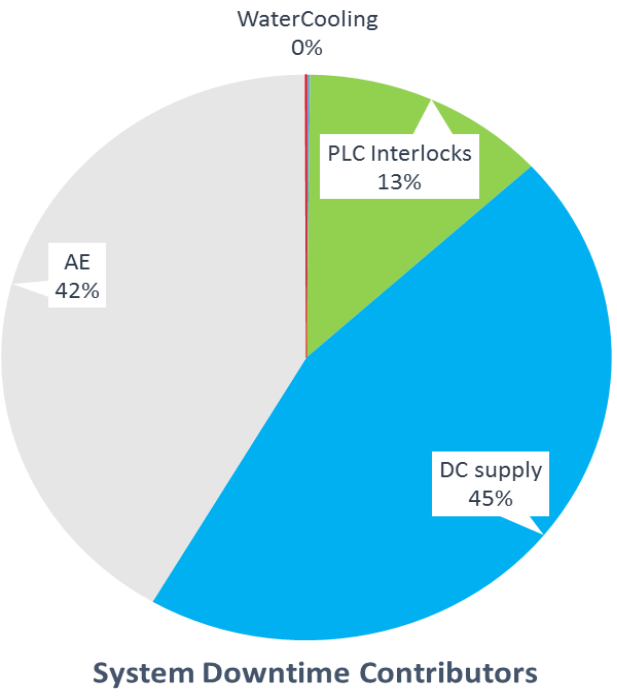
Operation / Planned Maintenance period	3 months (2190h)
Planned Maintenance time	48 hours
Lifetime	**6714 h (3 Operation phases and 3 PM phases)**

Operation 3 months	PM 48h	Operation 3 months	PM 48h	Operation 3 months	PM 48h

Results – **PSB RF System** Availability predictions

Availability = Availability is defined as the ratio between the operational time and total time.

No. of system failures	Downtime (h)	MTBO(h)	MTTR(h)	Mean Availability	Availability at Lifetime
1.077	**6.7**	**6234.3**	**6.2**	**99. 9%**	100%



Contributors to system downtime:

- DC Supply and Ancillary Electronics (86%)
- PLC Interlocks (13%)
- Water Cooling (0.2%)
- Ceramic Gaps (0.05%)

System in operation after LS2 and close follow-up of performance with AFT

Conclusions

- Reliability and Availability are *key performance indicators* for present and future particle accelerators (ADS!)

- Reliability and Availability prediction tools and methods developed at CERN over the years
  - Actively used to assist system designs (see also Miriam's talk) and predict performance of future accelerators/projects
  - Methods and tools are generic, can be applied to any accelerator/system, CERN is willing to share its experience

Thanks!

Accelerator Fault Tracker: What is it?

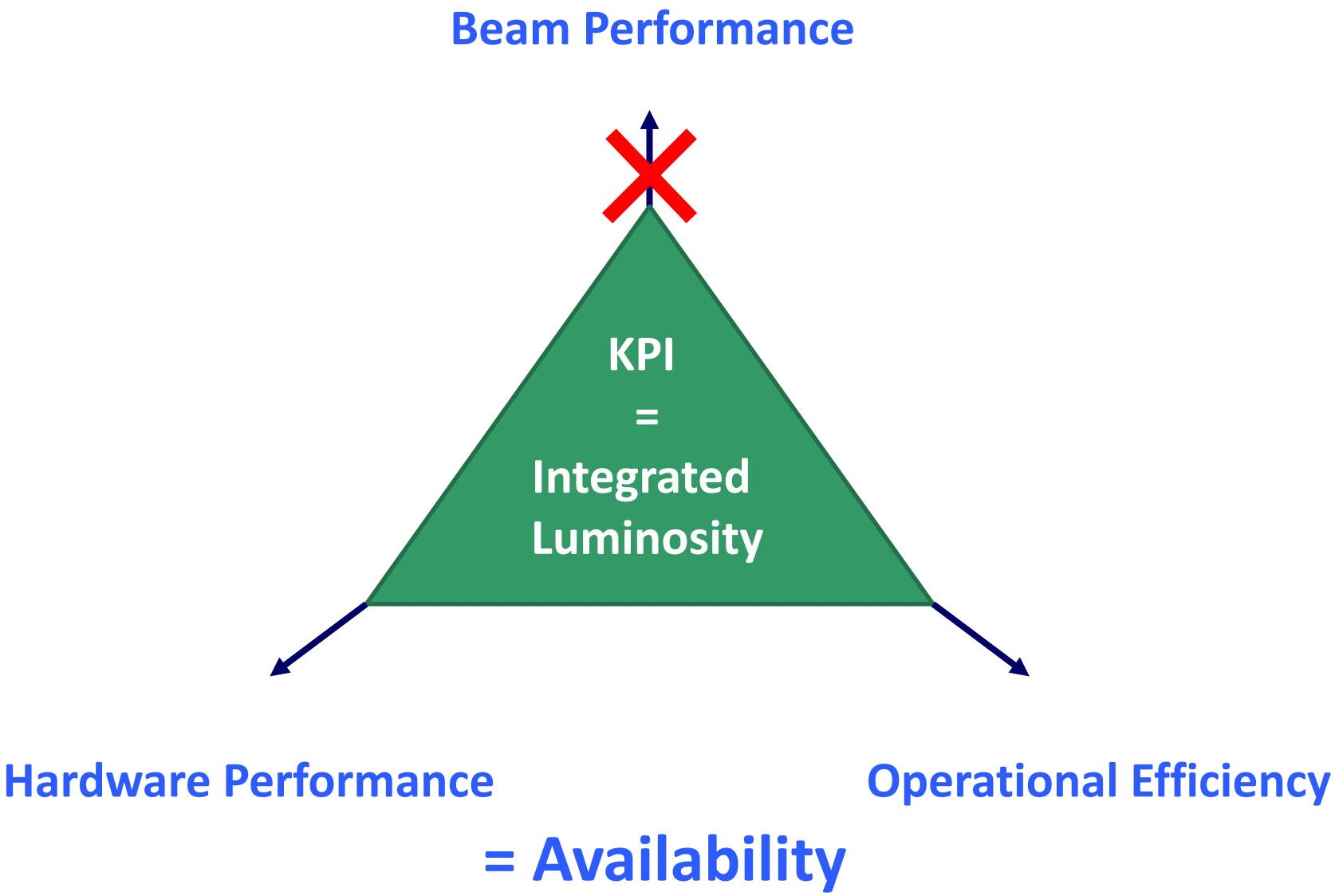
Operators register faults – providing a very **broad overview** of accelerator behavior, but **lacking details** for system improvements

AFT is a **software application** to:

Ensure consistent and objective fault tracking for the CERN accelerator complex

System experts register faults via dedicated tools (Jira, AMMSs, Excel, etc.) that are not easily shared – resulting in a **very detailed system specific view**, but **lacking information on overall accelerator impact**

AFT: Why was it invented?



AFT: What does it do?

Fast, powerful and objective reporting on accelerator performance

Enabling to:

Prioritize consolidation activities according to impact on availability

Maximize return of investment given allocated budget constraints

Provide **input for modelling** of accelerator projects

AFT History…

2012

LHC Availability Working Group (**AWG**) launched (chairs: B. Todd, L. Ponce, sc. Secretary: A. Apollonio), reporting to LHC Machine Committee

2013

Accelerator Fault Tracker (**AFT**) proposed to have objective view of LHC availability
B. Todd / L. Ponce / A. Apollonio together invented Cardiogram data view
C. Roderick joined as partner from Controls

2014

AFT project launched (combined BE-CO, BE-OP and TE-MPE initiative)

2015

AFT extensively used for LHC availability data analysis and predictive models of accelerator performance

2016

AWG periodic LHC reporting using AFT data
CERN Machine Advisory Committee recommendation: extend AFT to entire CERN complex

2017

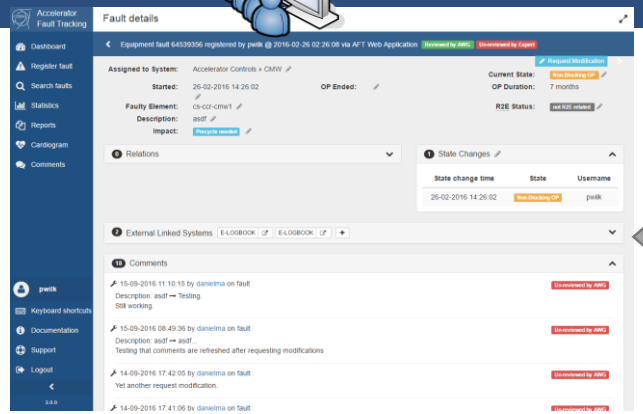
AFT extensively used for CERN-wide availability data analysis

2018

AWG began periodic reporting for injectors using AFT data
LHC = B. Todd / A. Apollonio / D. Walsh, Injectors = A. Apollonio, A. Niemi

On-going developments (BE-CO), with requirements from AWG, BE-OP and several ATS equipment groups

AFT High-Level Overview



ANGULAR TypeScript

Web application: browse, edit and analyse fault data.

REST API

Spring JPA

ORACLE AFT DB

Storing fault data plus filtered data coming from other systems to be correlated with fault details

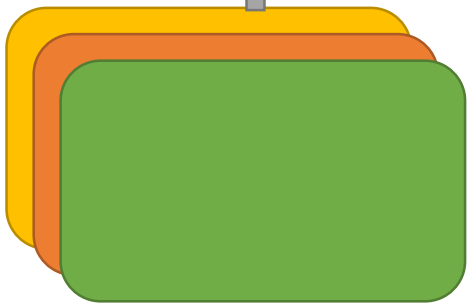
AFT server

Spring Boot

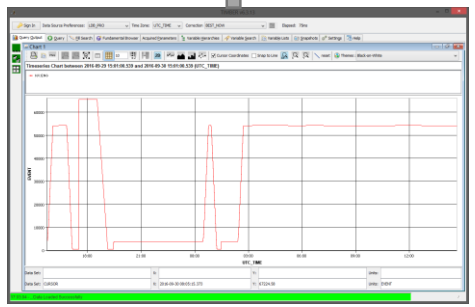
REST APIs

RMI (*REST soon*)

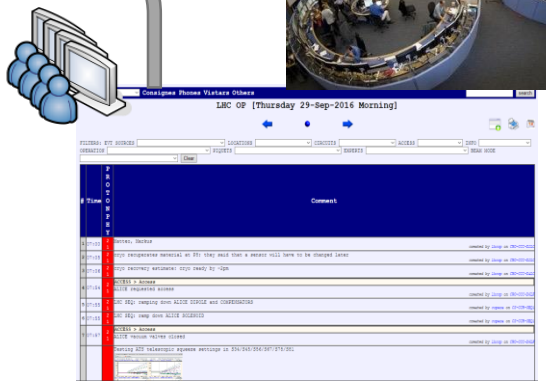
Logging Client (Java)



Layout (faulty elements), ASM (schedule data)

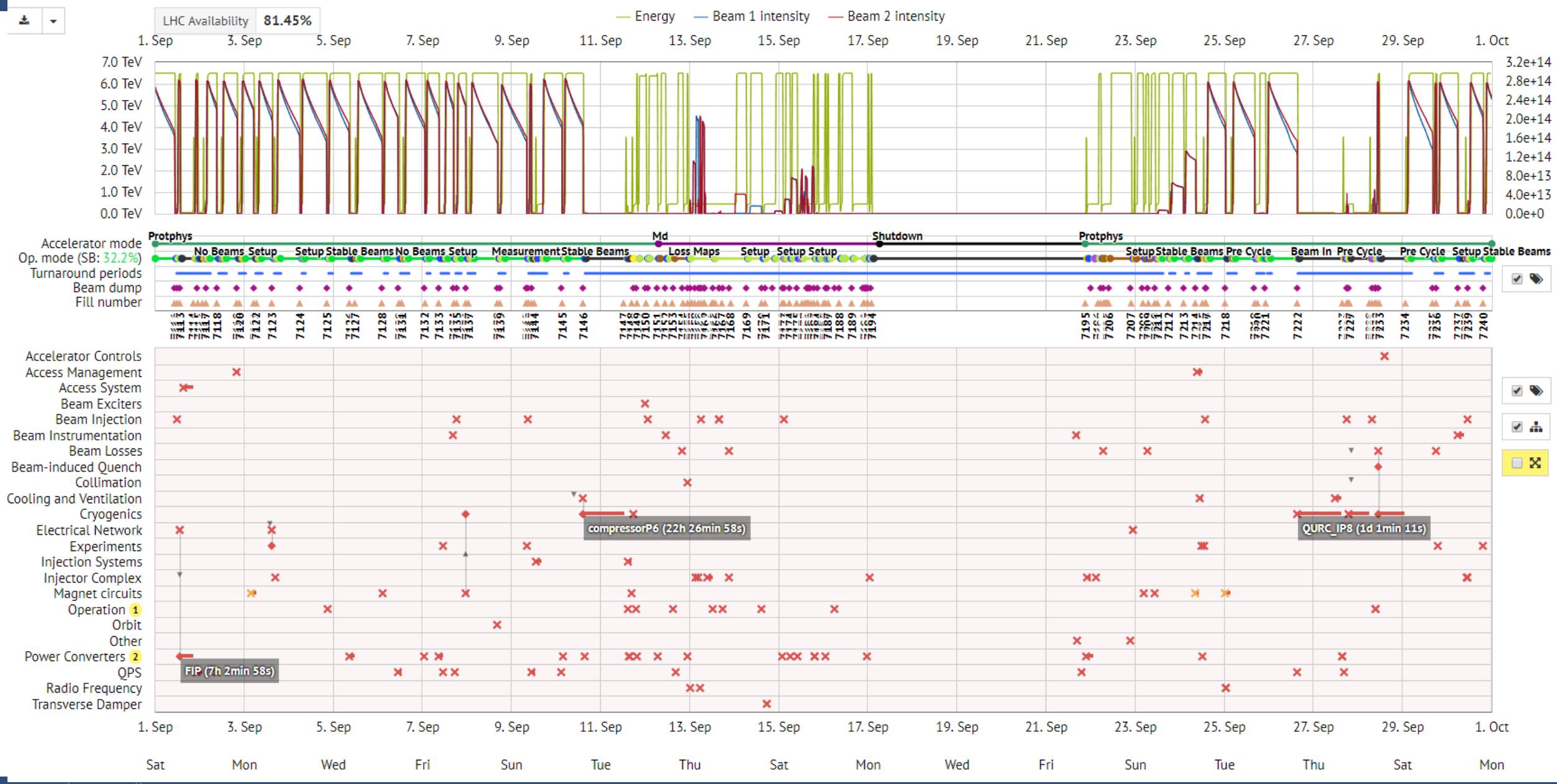


Logging System (archived data) – machine info (beam modes etc.)

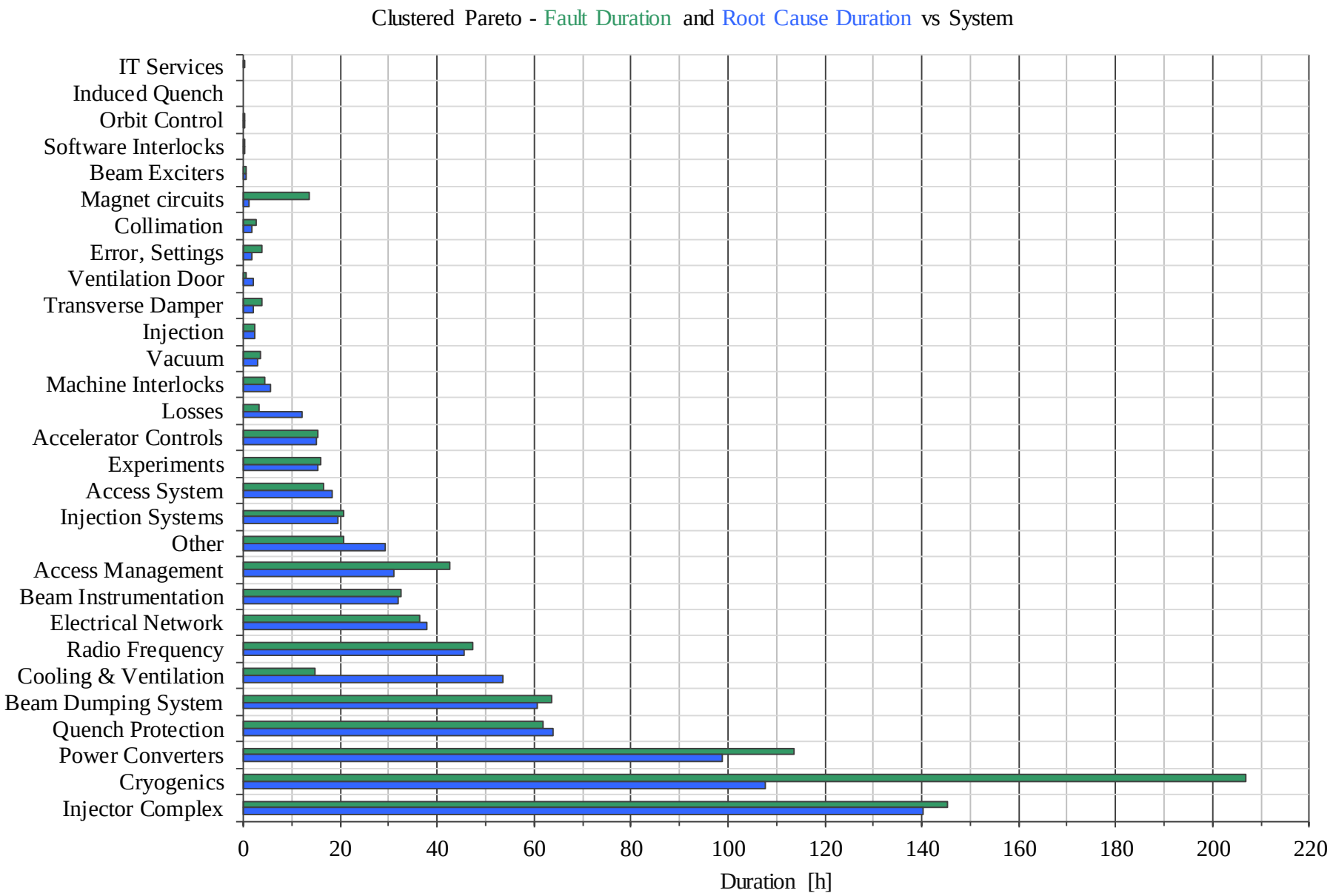


eLogbook – basic fault data from Operators

Cardiogram of LHC Operation



Objective view of 2017 LHC System Downtime



System Viewpoint =
Integrated fault time logged

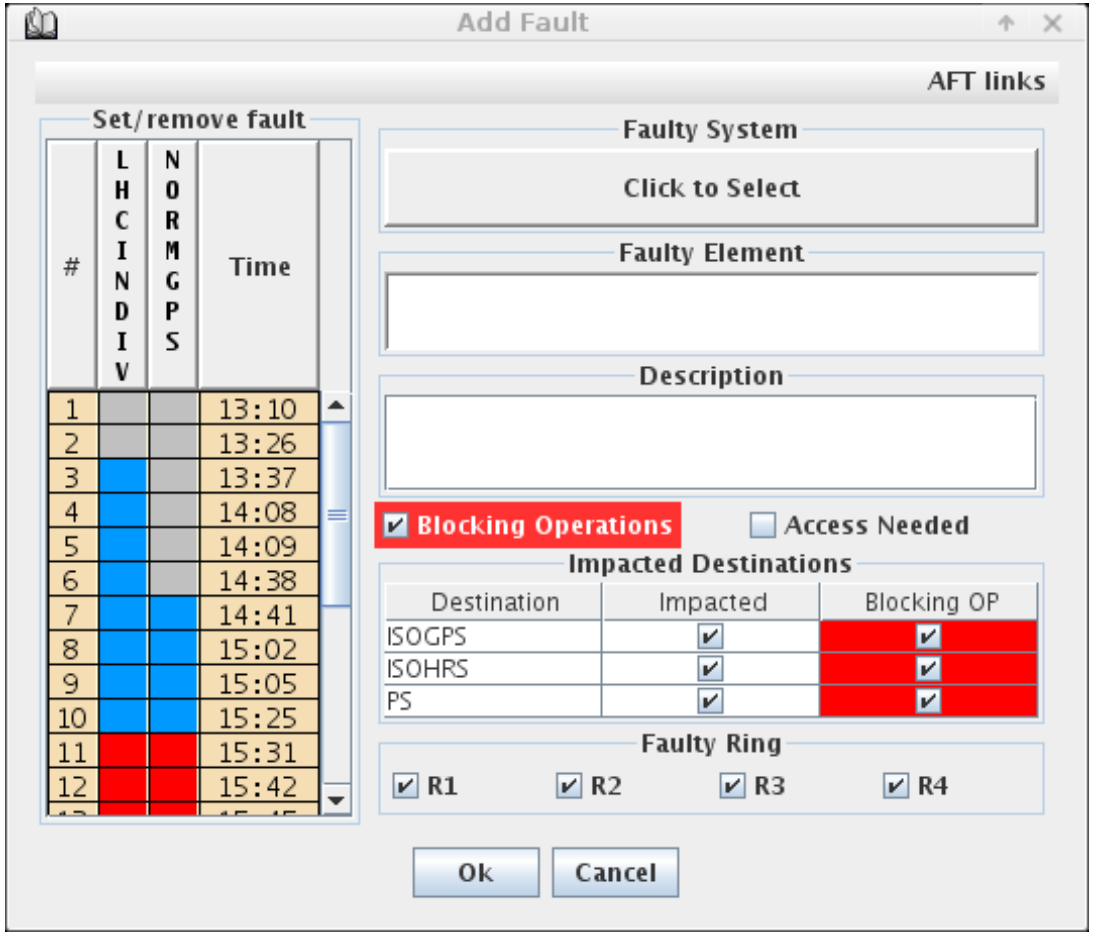
Operations Viewpoint =
Corrects for dependencies
parent / child / shadow

AFT LIVE DEMO

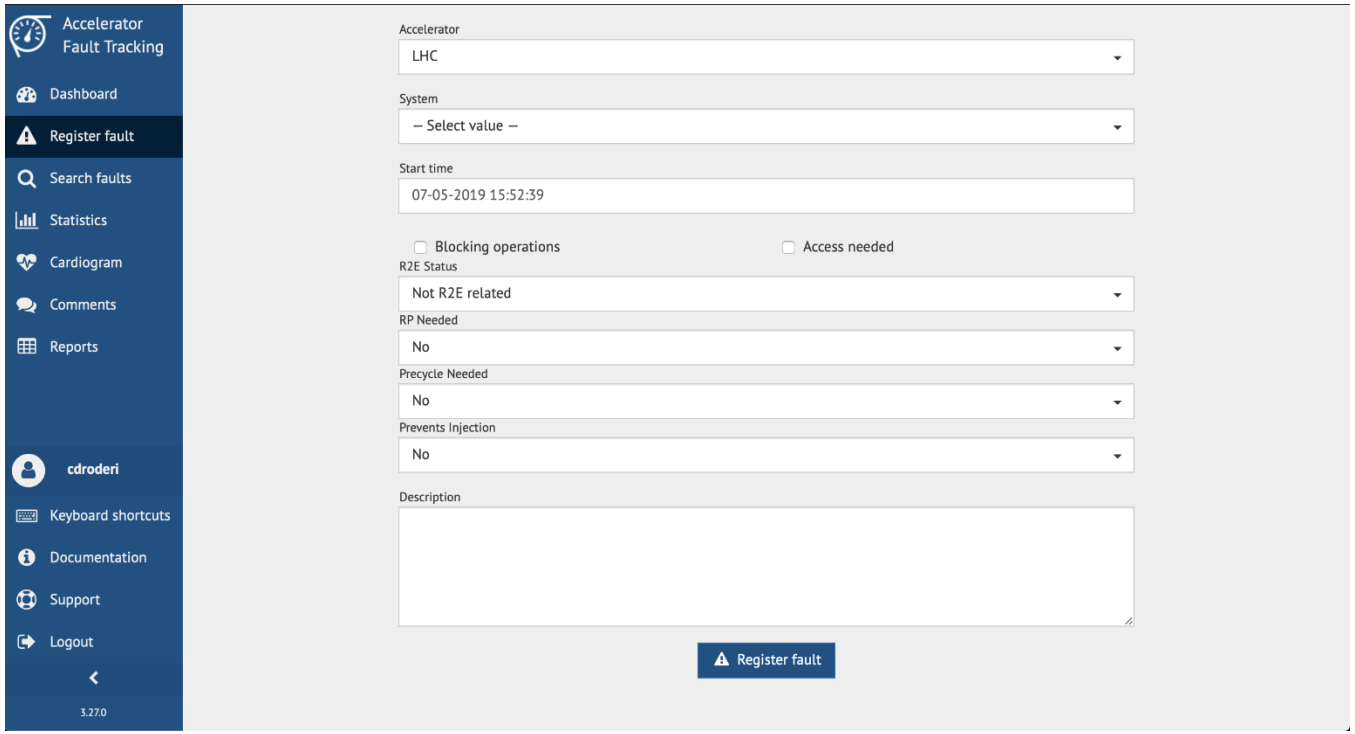
aft.cern.ch

Fault Registration

Operators use existing E-Logbook Tool



AFT Web application also available



In both cases – the fault capture is intended to be as simple as possible

Customisable Event Details

LHC Equipment fault registered by lhcop @ 05-07-2018 03:22:46 via LHC Logbook AWG Reviewed Expert Reviewed

Review Status

05-07-2018 00:20

05-07-2018 00:22 OP Ended after 1min 50s

Basic Information

Basic Information

System
Electrical Network » Distribution

Effective Duration
05h 40min 21s

Description
Large electrical glitch

Display Label

Access Needed
No

Labels
TIOC

Impact
RP Needed No Precycle Needed Yes
Prevents Injection No

R2E Status
NOT_R2E_RELATED

System-specific Properties
TI Fault Type none TI Major Event Id none

Attributes

Details and History

1 Faulty Elements

Name (#Faults, duration)	Type (#Faults, duration)	Description
BEH (4 faults, 03min 06s)	BUILDING (22 faults, 18h 35min 55s)	SOUS STATION ELECTRIQUE POSTE 400KV

Enter / select one or more faulty elements related to this fault

Event Dependencies

9 Relations

is parent of
- LHC Power Converters (04min 27s) OP Ended
- PSB Power Converters (16min 15s) OP Ended
- PSB Power Converters (16min 15s) OP Ended
- LHC Radio Frequency » Hardware (03h 51min 58s) OP Ended
- PSB Power Converters (16min 15s) OP Ended
- LHC Cryogenics » Users » Quench (01h 46min 30s) OP Ended
- LHC QPS » Hardware (04h 36min 42s) OP Ended
- PSB Vacuum » Hardware (05h 39min 31s) Cancelled
- PSB Power Converters (16min 15s) OP Ended

17 Activity

Comments | Modification requests | History

12 older entries hidden

24-07-2018 16:46:29 by aapollon
Fault marked as AWG Reviewed

21-09-2018 17:36:10 by cdroderi

History of changes

3.23.1

Customisable Event Details

LHC Equipme

05-07-2018 00:20

Basic Information

System
Electrical Network » Distribution

Effective Duration
05h 40min 21s

Description
Large electrical glitch

Display Label

Access Needed
No

Labels
TIOC

Impact
RP Needed No Precycle Needed Yes
Prevents Injection No

R2E Status
NOT_R2E_RELATED

System-specific Properties
TI Fault Type none TI Major Event Id none

Attributes

PSB Equipment fault registered by psbop @ 31-05-2018 14:43:33 via PSB Logbook AWG Reviewed Expert Review

31-05-2018 14:27

Basic Information

System
Electrical Network » Distribution

Effective Duration
0s

Description
Electrical Glitch

Display Label

Access Needed
No

Labels
TIOC

Impacted Destinations
PS

Affected Rings
Ring 1 Ring 2 Ring 3 Ring 4

Timing User ZERO Destination BDUMP
Mapped Cycle ---ZERO---

System-specific Properties
TI Fault Type Glitch TI Major Event Id 57706

Faulty Elements

Relations

is parent of
PSB Power Converters (17min 12s) OP Ended
PSB Power Converters (18min 45s) Cancelled
PSB Power Converters (17min 12s) Cancelled
PSB Power Converters (17min 12s) OP Ended
PSB Injector Complex » No Beam » Linac2 (15min 05s) OP Ended
PSB Power Converters (17min 12s) OP Ended

Activity

Comments Modification requests History

31-05-2018 14:43:33 by becodev
Fault registered by psbop.

31-05-2018 14:43:33 by copera
Fault state Blocking OP added starting at 31-05-2018 14:27:55.

31-05-2018 14:54:04 by copera
Fault state OP Ended added starting at 31-05-2018 14:43:00.

31-05-2018 15:13:00 by bettina1
Fault marked as AWG Reviewed

12-06-2018 16:30:01 by rledru
Description changed from "Electrical Glitch" to "Emergency stop".

12-06-2018 16:30:21 by rledru

Alarm and Interlock Systems

- Alarm systems are mostly used for diagnostics of faults (accelerators + technical infrastructure)
  - Requires accurate configuration
  - Easier to use in smaller machines
  - Direct interface with operators to identify faults
  - Today not in use for LHC, too many alarms, practically unmanageable

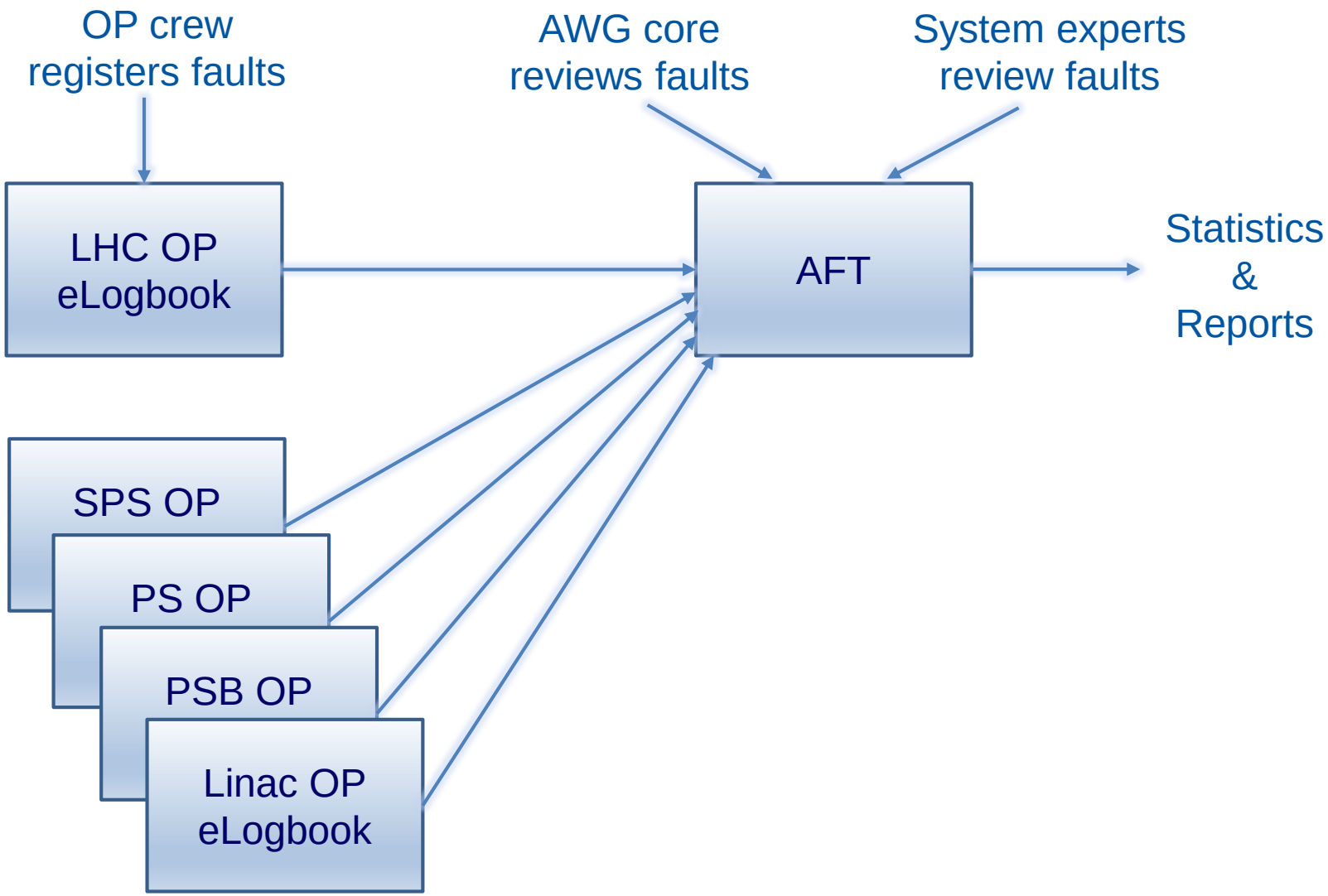
- Interlock systems are used for machine protection
  - Cannot be bypassed by operators
  - Reaction time (LHC) ~100 us
  - Also provide accurate fault diagnostics via the post-mortem system
  - Absolutely vital for LHC operation, extremely stringent reliability requirements

A Data-Driven Approach

AFT is largely **data-driven** – based on configuration data stored in a relational model. This includes definitions of:

- Accelerators (facilities)
- Accelerator Specific Fault Properties
  (e.g. affected ring for the CERN PSB, LHC R2E status, etc.)
- Accelerator Systems
- Accelerator System Responsibles
- Accelerator System Specific Fault Properties
  (e.g. Technical Infrastructure Failure Modes, Electrical Network distribution site locations, Controls JIRA issue keys) etc.
- Etc.

Fault Registration Workflow



Background

Complete & Consistent Tracking will allow to identify:

- Problems as early as possible

  ☞ allowing for timely mitigation

- Key issues which *will* limit performance of accelerators or equipment (Run3, HL-LHC, …)

Aim: Increase availability, both short and long-term, by dealing with issues ASAP

Track faults in two areas:

1. Directly affecting accelerator operation – identify root causes
2. Equipment faults independently of immediate impact on accelerator operation

Current Status

AFT is the common source for regular performance reporting:

Weekly Facilities Operation Meetings, LHC Machine Coordination meetings, Post Technical Stops, Annual Performance workshops (Evian) etc.

Steadily providing new features and improvements

>450 users (~250 regular users)

Extension foreseen to cover SPS North Experimental Area from 2020 onwards

Roles and Privileges

All access requires a login via CERN Single Sign On.

Your role dictates what you can do inside AFT.

Roles use RBAC (Role Based Access Control).

Main Roles:

AWG Members (Availability Working Group) &
Machine Supervisors: *power users*, responsible for overall data quality, arbitrating between operators and equipment groups, producing periodic reports.

Operators: responsible for initial data entry / edition.

System Experts: responsible for validating and completing data for faults assigned to their system(s).

Other users: have read access, are able to comment etc.

Fault Review Process

AWG members and Machine coordinators meet periodically (weekly for the injectors) to review the faults:
completing missing data, ensuring consistency across the machines, and adding relationships between the faults where applicable.

System Experts are notified of new faults either immediately after they are assigned or periodically (weekly) according to the system experts preferences.

- Invited to review the faults assigned to their system - essentially acknowledging the fault.
- Able to update certain attributes.
- Can request modification of remaining attributes by AWG (e.g. change of times, states, re-assignment to another system etc.).

Workflow behind, whereby the AWG/Machine Coordinators are able to see and accept / reject modification requests.
This is the best / easiest way to work - i.e. don't just send mails or make comments asking for things to be re-assigned.

Conclusions / Personal remarks

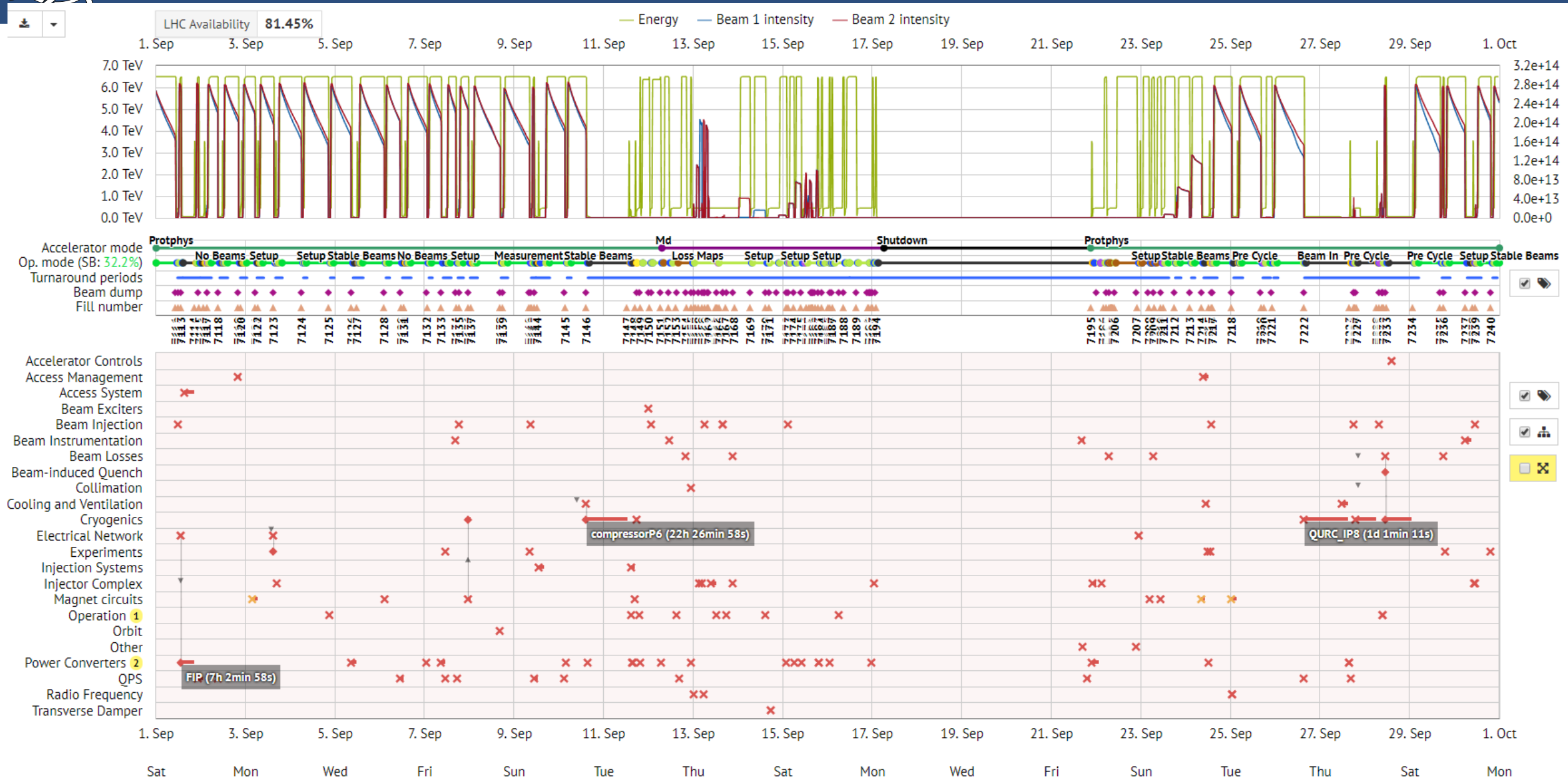
Raising awareness of the importance of fault tracking and fault follow-up in the organization is fundamental

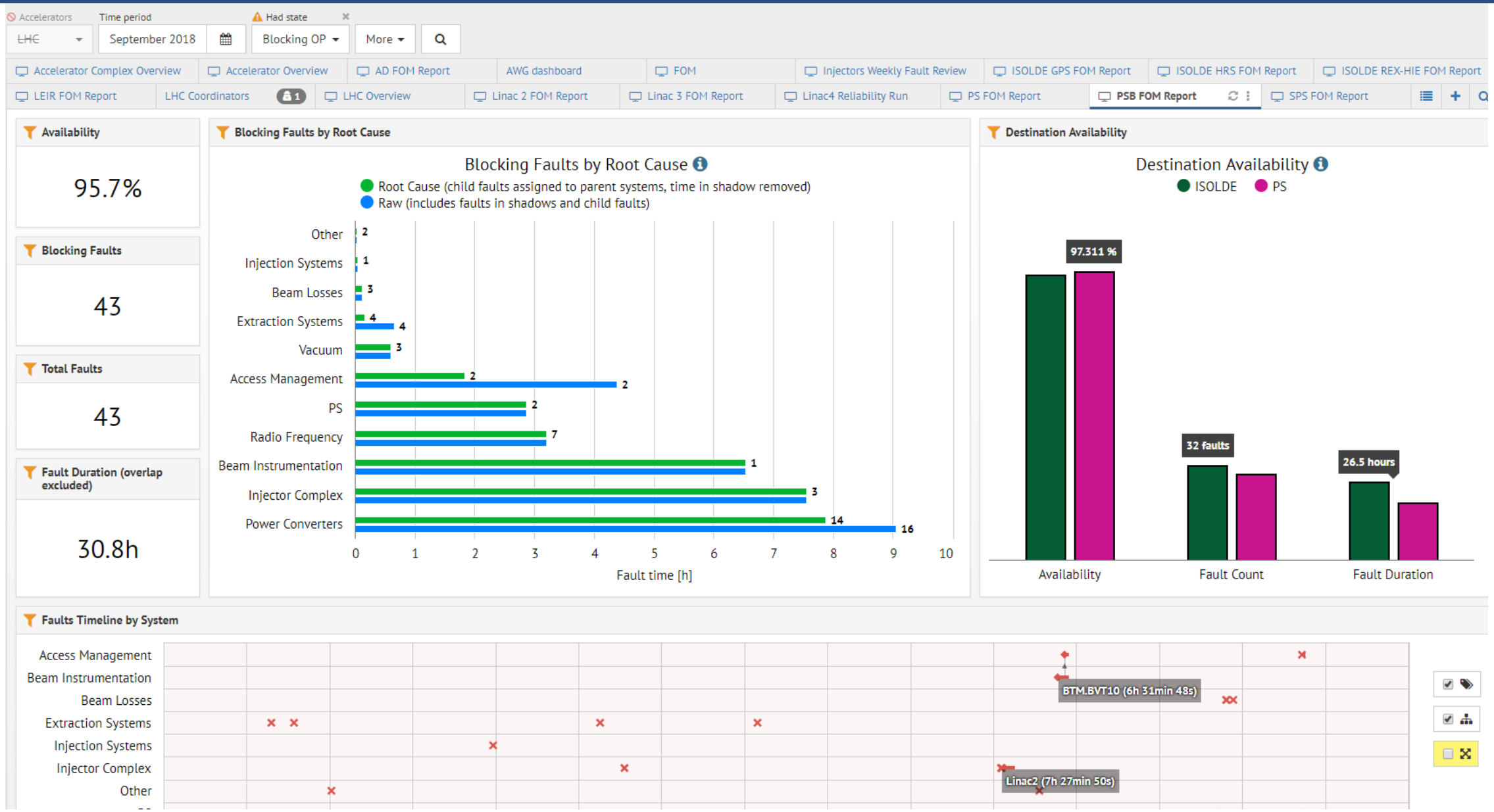
Make fault tracking credible, objective and visible to all accelerator experts

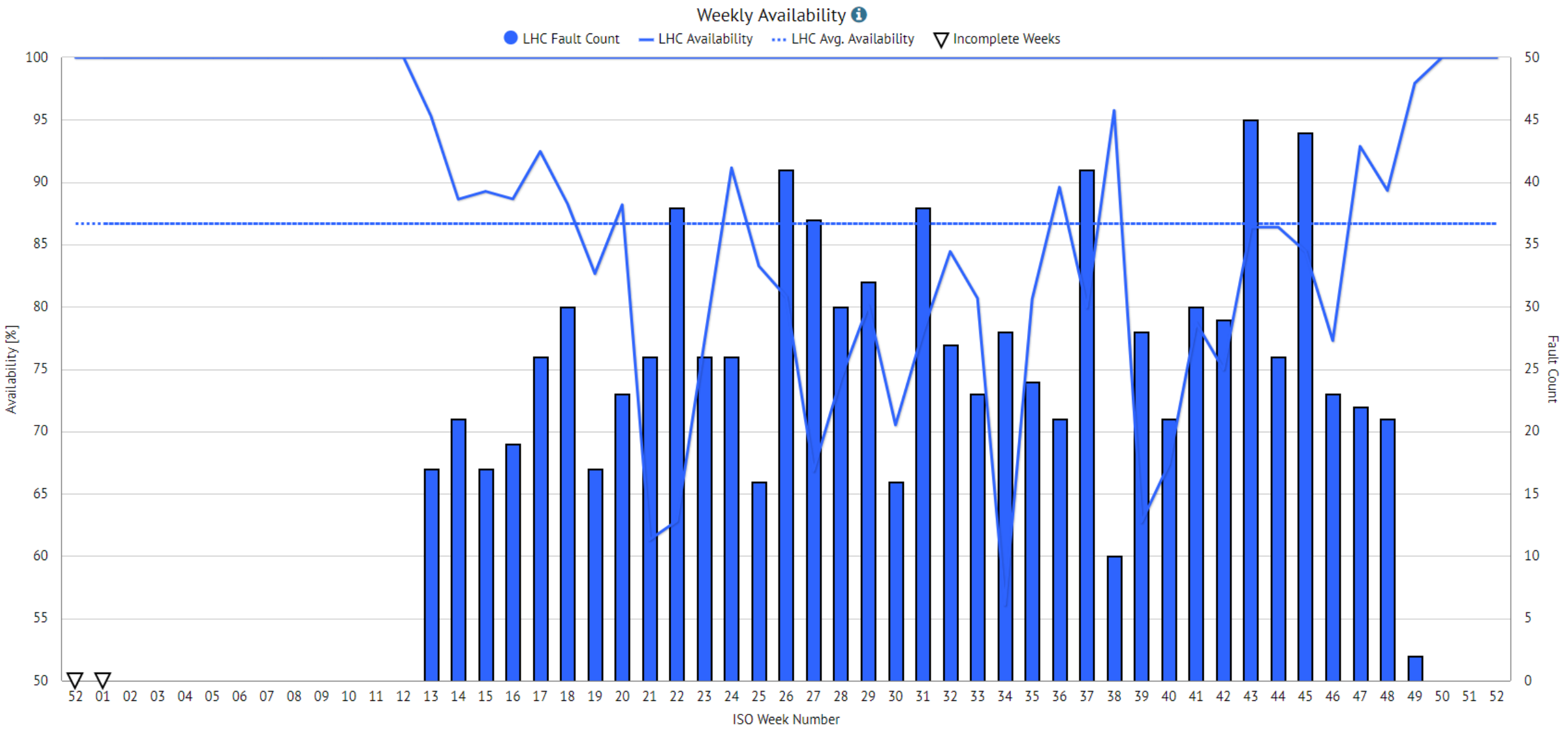
Establish a clear workflow for fault registration and review, involve operations, technical experts, management

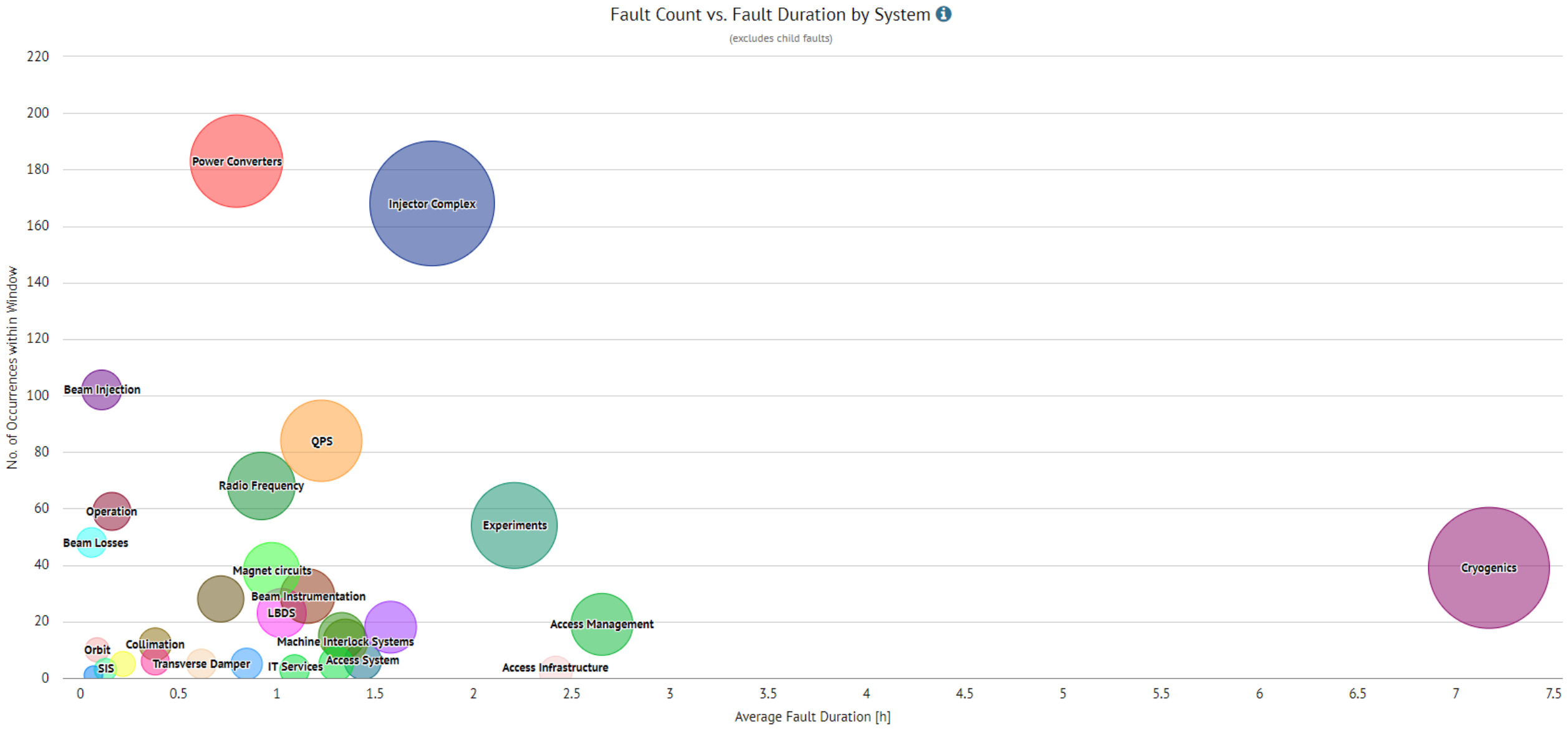
Automatic fault registration is the dream…may be not so easy in some cases

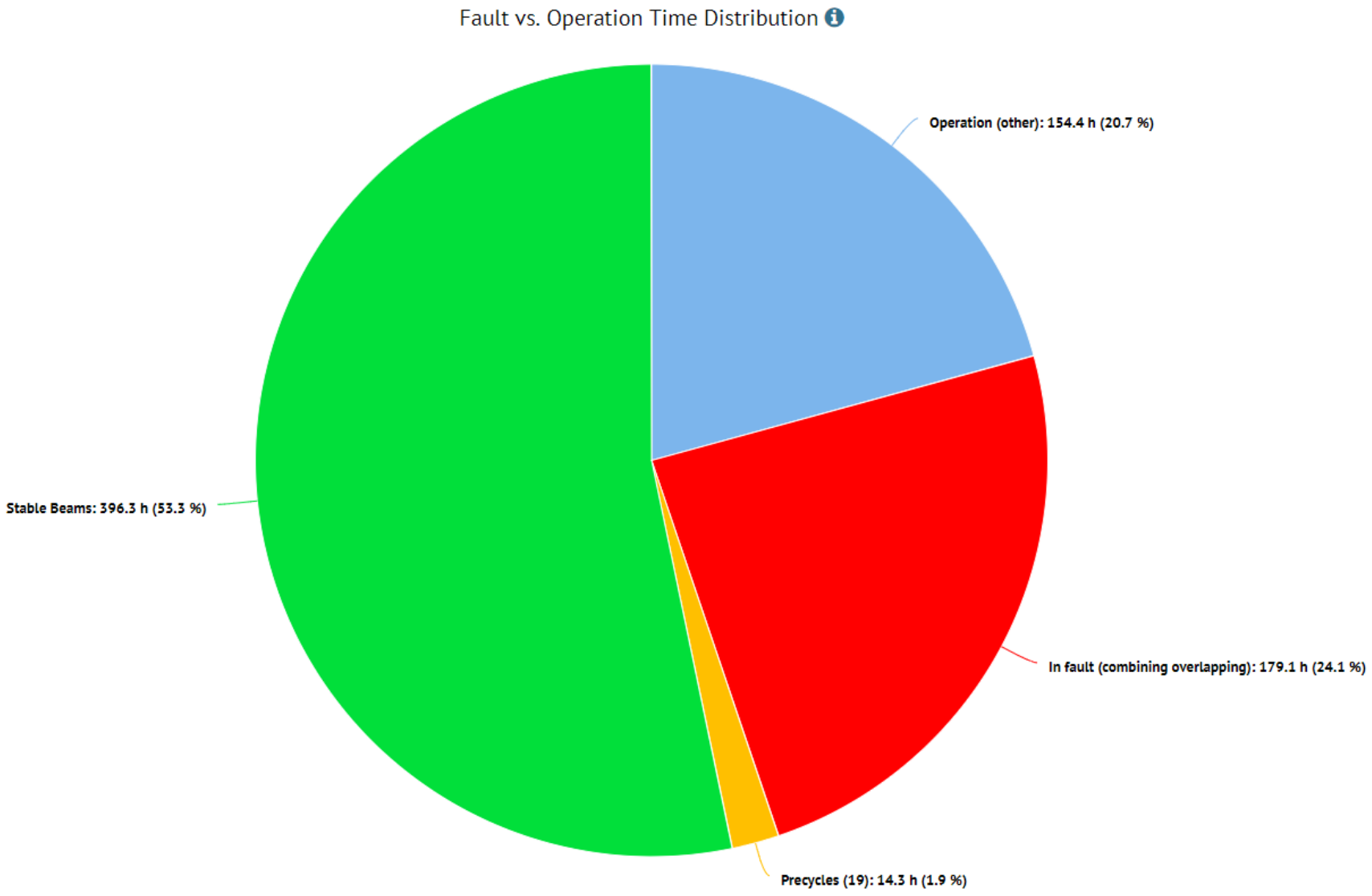
Takes time…(several years, if not implemented from the beginning)

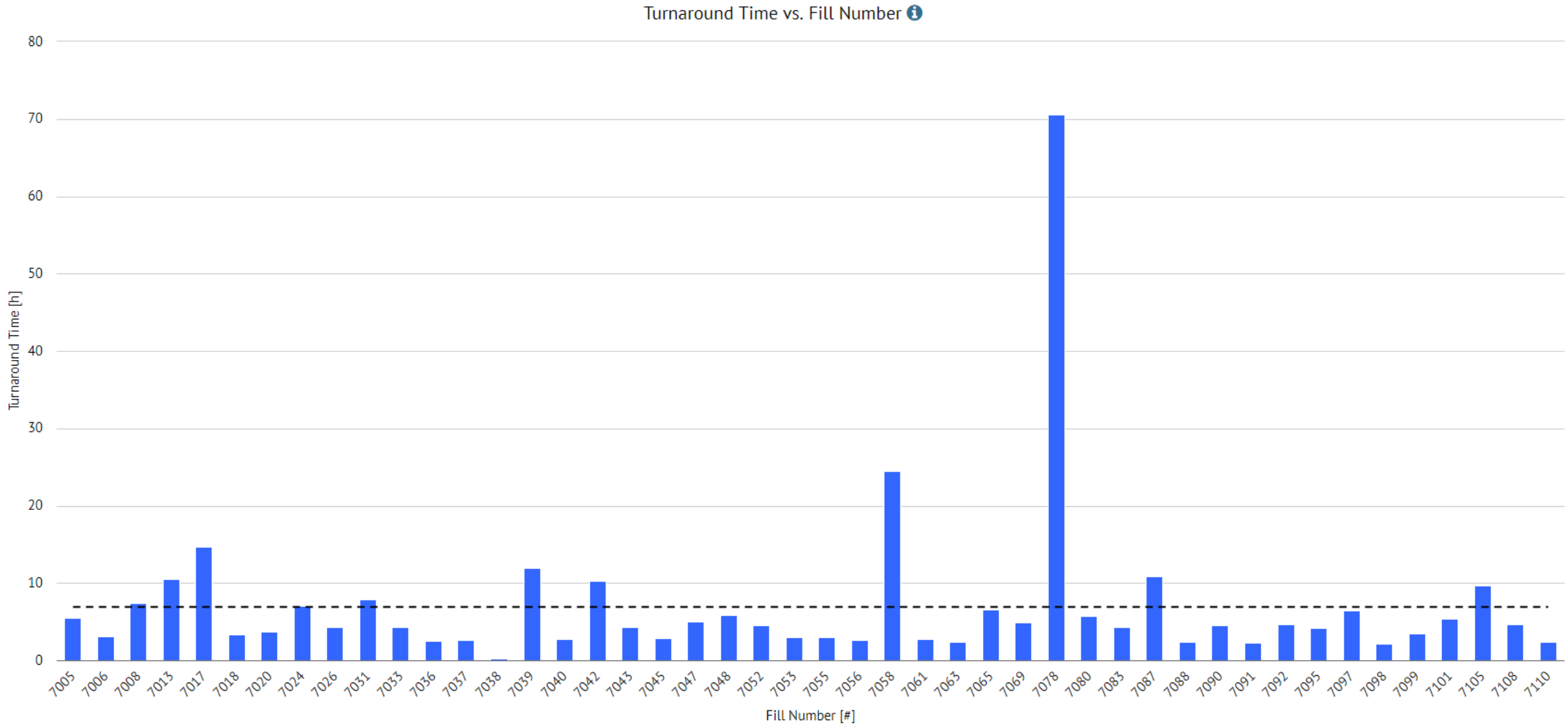

LHC Availability 81.45%
Energy
Beam 1 intensity
Beam 2 intensity
1. Sep
3. Sep
5. Sep
7. Sep
9. Sep
11. Sep
13. Sep
15. Sep
17. Sep
19. Sep
21. Sep
23. Sep
25. Sep
27. Sep
29. Sep
1. Oct
7.0 TeV
6.0 TeV
5.0 TeV
4.0 TeV
3.0 TeV
2.0 TeV
1.0 TeV
0.0 TeV
3.2e+14
2.8e+14
2.4e+14
2.0e+14
1.6e+14
1.2e+14
8.0e+13
4.0e+13
0.0e+0
Accelerator mode
Op. mode (SB: 32.2%)
Turnaround periods
Beam dump
Fill number
Protphys
Md
Shutdown
Protphys
No Beams
Setup
Setup
Stable Beams
No Beams
Setup
Measurement
Stable Beams
Loss Maps
Setup
Setup
Setup
Setup
Stable Beams
Pre Cycle
Beam In
Pre Cycle
Pre Cycle
Setup
Stable Beams
Accelerator Controls
Access Management
Access System
Beam Exciters
Beam Injection
Beam Instrumentation
Beam Losses
Beam-induced Quench
Collimation
Cooling and Ventilation
Cryogenics
Electrical Network
Experiments
Injection Systems
Injector Complex
Magnet circuits
Operation 1
Orbit
Other
Power Converters 2
QPS
Radio Frequency
Transverse Damper
compressorP6 (22h 26min 58s)
QURC_IP8 (1d 1min 11s)
FIP (7h 2min 58s)
Sat
Mon
Wed
Fri
Sun
Tue
Thu
Sat
Mon
Wed
Fri
Sun
Tue
Thu
Sat
Mon


Accelerators
Time period
Had state
LHC
September 2018
Blocking OP
More
Accelerator Complex Overview
Accelerator Overview
AD FOM Report
AWG dashboard
FOM
Injectors Weekly Fault Review
ISOLDE GPS FOM Report
ISOLDE HRS FOM Report
ISOLDE REX-HIE FOM Report
LEIR FOM Report
LHC Coordinators
LHC Overview
Linac 2 FOM Report
Linac 3 FOM Report
Linac4 Reliability Run
PS FOM Report
PSB FOM Report
SPS FOM Report
Availability
95.7%
Blocking Faults
43
Total Faults
43
Fault Duration (overlap excluded)
30.8h
Blocking Faults by Root Cause
Blocking Faults by Root Cause
Root Cause (child faults assigned to parent systems, time in shadow removed)
Raw (includes faults in shadows and child faults)
Other
Injection Systems
Beam Losses
Extraction Systems
Vacuum
Access Management
PS
Radio Frequency
Beam Instrumentation
Injector Complex
Power Converters
Fault time [h]
Destination Availability
Destination Availability
ISOLDE
PS
97.311 %
32 faults
26.5 hours
Availability
Fault Count
Fault Duration
Faults Timeline by System
Access Management
Beam Instrumentation
Beam Losses
Extraction Systems
Injection Systems
Injector Complex
Other
BTM.BVT10 (6h 31min 43s)
Linac2 (7h 27min 50s)


Weekly Availability
LHC Fault Count
LHC Availability
LHC Avg. Availability
Incomplete Weeks
Availability [%]
Fault Count
ISO Week Number
100
95
90
85
80
75
70
65
60
55
50
50
45
40
35
30
25
20
15
10
5
0
52 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52

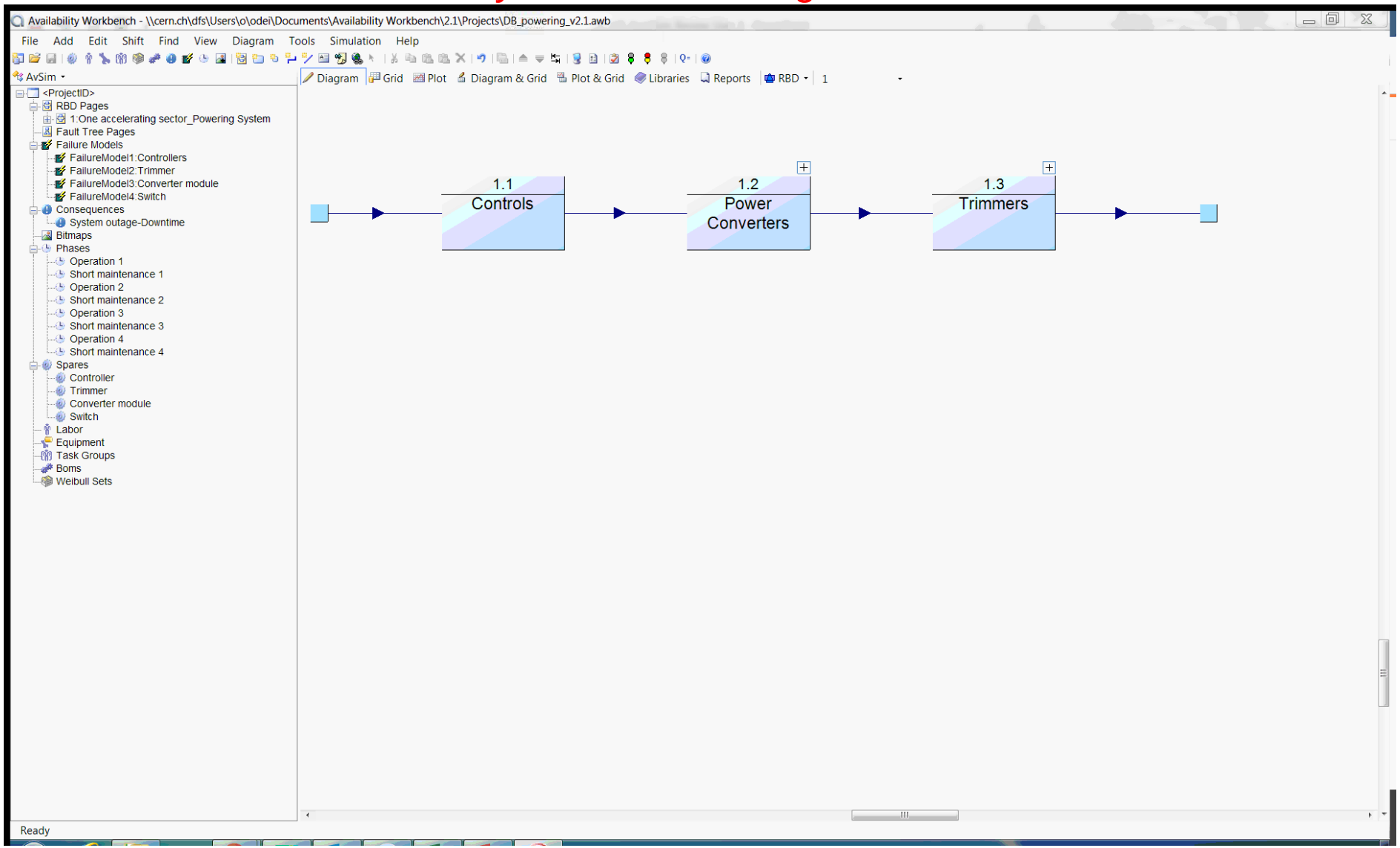

Fault Count vs. Fault Duration by System
(excludes child faults)
No. of Occurrences within Window
Average Fault Duration [h]
0
20
40
60
80
100
120
140
160
180
200
220
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Power Converters
Injector Complex
Beam Injection
QPS
Radio Frequency
Operation
Beam Losses
Experiments
Cryogenics
Magnet circuits
Beam Instrumentation
LBDS
Access Management
Machine Interlock Systems
Orbit
Collimation
SIS
Transverse Damper
IT Services
Access System
Access Infrastructure


Fault vs. Operation Time Distribution
Operation (other): 154.4 h (20.7 %)
Stable Beams: 396.3 h (53.3 %)
In fault (combining overlapping): 179.1 h (24.1 %)
Precycles (19): 14.3 h (1.9 %)


Turnaround Time vs. Fill Number
Turnaround Time [h]
80
70
60
50
40
30
20
10
0
7005
7006
7008
7013
7017
7018
7020
7024
7026
7031
7033
7036
7037
7038
7039
7040
7042
7043
7045
7047
7048
7052
7053
7055
7056
7058
7061
7063
7065
7069
7078
7080
7083
7087
7088
7090
7091
7092
7095
7097
7098
7099
7101
7105
7108
7110
Fill Number [#]

The CLIC Drive Beam Quad powering System: Isograph

Only one accelerating sector!



x 48

The CLIC Drive Beam Quad powering System: AvailSim

Facility	Element	Name	Parent	Component Code	Instances	Location	Impacted System	DeviceType	Failure Behaviour Logic
CLIC	Compound	**DB QD powering**	ROOT	DB-QD	1				AND
CLIC	Compound	**Sector**	**DB QD powering**	Sector	48				AND
CLIC	Basic	**Controls**	**Sector**	Controls	1	Tunnel	Controls	Controls	
CLIC	Compound	**Power Converters**	**Sector**	PC	1				AND
CLIC	**Compound**	**4-modules PC**	**Power Converters**	4mod	12				AND
CLIC	Compound	4module	**4-modules PC**	4mod	1				AND
CLIC	Basic	Module	4module	M	4	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	**4-modules PC**	4mod	1	Tunnel	Power Converters	Controls	
CLIC	**Compound**	**3-modules PC**	**Power Converters**	3mod	16				AND
CLIC	Compound	3module	**3-modules PC**	3mod	1				AND
CLIC	Basic	Module	3module	M	3	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	**3-modules PC**	3mod	1	Tunnel	Power Converters	Controls	
CLIC	**Compound**	**2-modules PC**	**Power Converters**	2mod	2				AND
CLIC	Compound	2module	**2-modules PC**	2mod	1				AND
CLIC	Basic	Module	2module	M	2	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	**2-modules PC**	2mod	1	Tunnel	Power Converters	Controls	
CLIC	Compound	**Trimmers**	**Sector**	T	1				ACTIVE(810,830)
CLIC	Basic	Trimmer	Trimmers	Trimmer	830	Tunnel	Power Converters	Trimmer	