Availability Modelling at CERN

21 May 2019

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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

Availability

Reliability

Protection

Low Importance
Relative Importance
High Importance
R-A-S(P) Requirements for Accelerators

Large-Scale Colliders
- Availability
- Reliability
- Protection

Synchrotron Light Sources
- Availability
- Reliability
- Protection
Why is availability a concern for the scientific output of all facilities?
Costs, Reputation, Damage potential
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.
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)
Availibility Simulation Tools

Commercial software
- Usually productivity oriented
- Some accelerator specific needs are not considered/could not be modeled easily

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

ISOGRAPH

AVAILSIM 3.0
• 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

Start
- Randomize failure failtimes
  - Execute next Event
    - Affect the device & parameter(s)
      - Any conditioned event?
        - Repeat until no activity

Events
- Timed
  - Failure/repairs
    - Upgrade event
  - Conditioned
    - system1 failure
    - system2 failure

Parameters
- Beam
  - Beam off
- Devices
  - system1
  - system2

Consequence
- Beam off

Failure/repairs
- Upgrade event
- system1 failure
- system2 failure
- Beam off

Time (t)
- Down time

Current Value: 3
Minimum Value: 0

Availsim3

[Overview]

Set of tables that fully define the availability model

Common input format

Inputs (CSV)
- Simulation data
- Model

Simulation
- Isograph

Simulation (Python 3)
- Availsim 3

Outputs (.xlsx/.html/.txt)
- Result data
- Plots
- Log file
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

PSB RF rings

Cells (300x36)

Water Cooling

PLC

Ceramic Gaps (36)

AE

DC Supply

RF Cell

Cooling Ring

RF Power Amplifier

Finemet Core

MOSFET Driver

MOSFET Pairs (70x8)

Cooling Ring

Ceramic Gap

Vacuum Chamber

RF Cell

Finemet Core

PLC Interface

40V DC Supply

Ancillary Electronics

Odei Rey Orozko

April 2016 -- LIU-PSB WG meeting

LIU
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

<table>
<thead>
<tr>
<th>Component</th>
<th>No. of components in the system</th>
<th>MTTF (years)</th>
<th>MTTF (h)</th>
<th>Data source</th>
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<tr>
<td>Water Cooling</td>
<td>24</td>
<td>10x24</td>
<td>2102400</td>
<td>Expert experience. Machine made up of 24 components failed ones in 10 years.</td>
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<tr>
<td>PLC Interlocks</td>
<td>24</td>
<td>22</td>
<td>200000</td>
<td>PLC MTTF=Its Power Supply MTTF. Manufacturer data: Values from 200.000 to 980.000 hours</td>
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<td>144</td>
<td>5</td>
<td>43800</td>
<td>Expert experience.</td>
</tr>
<tr>
<td>Ancillary Electronics</td>
<td>144</td>
<td>5</td>
<td>43800</td>
<td>Expert experience.</td>
</tr>
<tr>
<td>Cooling Ring</td>
<td>144</td>
<td>40x10x50</td>
<td>175E+6</td>
<td>Expert experience from PS. 1 ring failed in 40 years, 50 rings per cavity, 10 cavities</td>
</tr>
<tr>
<td>Finemet Core</td>
<td>144</td>
<td>10000/2</td>
<td>43.8E+6</td>
<td>Expert experience from various machines. One Finemet Core failed once each 10.000 years. The component is made up of two Finemet Cores</td>
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<tr>
<td>Ceramic Gaps (36)</td>
<td>4 (144/36)</td>
<td>20000/36</td>
<td>4.8E+6</td>
<td>Expert experience from various machines. One Ceramic Gaps fails ones each 20.000 years</td>
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<td>Mosfets pair</td>
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<td>186000000/2</td>
<td>8.15E+10</td>
<td>Manufacturer data</td>
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<tr>
<td>Mosfets Driver</td>
<td>144</td>
<td>18600000</td>
<td>1.63E+11</td>
<td>Manufacturer data</td>
</tr>
</tbody>
</table>

April 2016 -- LIU-PSB WG meeting

Odei Rey Orozko
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)
Availability = Availability is defined as the ratio between the operational time and total time.

<table>
<thead>
<tr>
<th>No. of system failures</th>
<th>Downtime (h)</th>
<th>MTBO(h)</th>
<th>MTTR(h)</th>
<th>Mean Availability</th>
<th>Availability at Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.077</td>
<td>6.7</td>
<td>6234.3</td>
<td>6.2</td>
<td>99.9%</td>
<td>100%</td>
</tr>
</tbody>
</table>

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?

Beam Performance

KPI = Integrated Luminosity

= Availability

Hardware Performance

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

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

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

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

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

AFT extensively used for CERN-wide availability data analysis

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

**AFT server**

- Spring JPA
- REST API
- RMI (REST soon)

**Logging System** (archived data)
- Machine info (beam modes etc.)

**eLogbook** – basic fault data from Operators

**Layout** (faulty elements), **ASM** (schedule data)

**Web application**:
- Browse, edit, and analyse fault data.

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

**ANGULAR TypeScript**

- Web application: browse, edit and analyse fault data.
Cardiogram of LHC Operation
Objective view of 2017 LHC System Downtime

Clustered Pareto - Fault Duration and Root Cause Duration vs System

System Viewpoint = Integrated fault time logged

Operations Viewpoint = Corrects for dependencies parent / child / shadow
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

Basic Information
- System: Electrical Network ➔ Distribution
- Effective Duration: 05h 40min 21s
- Description: Large electrical glitch
- Display Label: Large electrical glitch
- Access Needed: No
- Labels: TIOC
- Impact: RP Needed: No, Prevents Injection: No
- R2E Status: NOT_R2ERELATED
- System-specific Properties: TL Fault Type: none, TL Major Event Id: none

Faulty Elements
- Name (#Faults, duration): BDH (Q 4 faults, 03min 06s)
- Type (#Faults, duration): BUILDING (Q 22 faults, 18h 35min 55s)
- Description: SOUS STATION ELECTRIQUE POSTE 400KV

Event Dependencies
- is parent of:
  - LHC Power Converters (04min 27s)
  - PSB Power Converters (16min 15s)
  - PSB Power Converters (16min 15s)
  - LHC Radio Frequency ➔ Hardware (03h 51min 35s)
  - PSB Power Converters (16min 15s)
  - LHC Power Converters (04min 27s)
  - LHC Cryogenics ➔ Quench (01h 46min 30s)
  - LHC QPS ➔ Hardware (04h 36min 42s)
  - PSB Vacuum ➔ Hardware (05h 39min 31s)
  - PSB Power Converters (16min 15s)

Activity

Review Status
- AWG Reviewed
- Expert Reviewed

Details and History

History of changes
- 24/07/2018 16:46:29 by apollonio
  - Fault marked as: AWG Reviewed
- 24/07/2018 17:35:50 by corradini
  - 12 older entries hidden
Customisable Event Details

Attributes
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 Responsibilities
- 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

- OP crew registers faults
- LHC OP eLogbook
- AWG core reviews faults
- System experts review faults
- AFT
- Statistics & Reports
- SPS OP
- PS OP
- PSB OP
- Linac OP eLogbook
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)
**Availability**

95.7%

**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: 2
- Injection Systems: 1
- Beam Losses: 3
- Extraction Systems: 4
- Vacuum: 1
- Access Management: 2
- PS: 2
- Radio Frequency: 7
- Beam Instrumentation: 1
- Injector Complex: 3
- Power Converters: 14

**Fault Duration (overlap excluded)**

30.8h

**Destination Availability**

- ISOLDE: 97.311%
- PS: 82 faults, 26.5 hours
The CLIC Drive Beam Quad powering System: Isograph

Only one accelerating sector!
### The CLIC Drive Beam Quad powering System: **AvailSim**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Element</th>
<th>Name</th>
<th>Parent</th>
<th>Component Code</th>
<th>Instances</th>
<th>Location</th>
<th>Impacted System</th>
<th>DeviceType</th>
<th>Failure Behaviour Logic</th>
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<td>DB QD powering</td>
<td>ROOT</td>
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<td>1</td>
<td>DB-QD</td>
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