ESS reliability and availability approach

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Outline

• The European Spallation Source
• ESS reliability and availability requirements
• Requirements allocation
• Beam degradation
• Accelerator RAMI analyses
• Conclusions
The European Spallation Source
Main headlines

- World’s leading neutron source
- A user facility providing outstanding scientific performance
- High brightness
- High reliability
- Environmentally friendly

Technical scope

- Accelerator: protons, 5 MW, long pulse, 2.86 ms, 14 Hz
- Target: Tungsten rotating wheel, helium cooled, new moderator.
- 22 instruments
- Construction budget 1.8 B€
- Operation budget 140 M€/year
- Receiving 2000-3000 users per year
The ESS project

International collaboration

Sweden and Denmark:
47.5% Construction
15% Operations
100% Cash

Partner Countries:
52.5% Construction
85% Operations
~70%/30% In-Kind/Cash
Main milestones of the project

- **2003**: First European design effort of ESS completed
- **2009**: Decision: ESS will be built in Lund
- **2012**: ESS Design Update phase complete
- **2014**: Construction work starts on the site
- **2019**: First neutrons on instruments
- **2023**: ESS starts user program
- **2025**: ESS construction complete
ESS production of neutrons for science

- Target station
- Neutron science systems
- Linear proton accelerator (600 m)
ESS Linac Parameters

- Particle species: p
- Average power: 5 MW
- Energy: 2.0 GeV
- Current: 62.5 mA
- Peak power: 125 MW
- Pulse length: 2.86 ms
- Rep rate: 14 Hz
- Max cavity surface field: 45 MV/m
- Operating time: 5200 h/year
Reliability and Availability at ESS

• **ESS goal:** science produced by the users
  – High brightness neutron beam
  – High reliability and availability of the beam

• **Reliability and availability analyses goals:**
  – Translate users needs into technical requirements
  – Analyze the design to see if the requirements can be achieved
  – Propose changes if necessary
  – Give a global overview of the future operation of the machine in the design phase
ESS reliability and availability requirements
Reliability and availability requirements

- ESS requirements have been divided into:
  - **Neutron Source** requirements:
    - Accelerator
    - Target
    - Integrated Controls System (ICS)
    - Site Infrastructure (SI) (only conventional subsystems that could affect the neutron beam production)
  - **NSS** (Neutron Scattering Systems) requirements:
    - Instrument Systems (including Guide Bunker & Monolith Shroud),
    - Science Support Systems (SSS)
    - SI that supplies to the NSS subsystems.
Neutron beam reliability and availability requirements

Global performance

Neutron beam requirements to satisfy the users

ESS operation, good practices, flexibility...

User needs

Neutron beam requirements
Neutron beam reliability and availability requirements

User needs

ESS operation, good practices, flexibility...

Global performance

Neutron beam requirements to satisfy the users

Neutron beam requirements
Users at ESS

• A common effort was done to understand what the users need from the neutron beam reliability to perform their experiments

• People involved
  – instrument scientists
  – reliability experts
  – people with experience with users in similar facilities

• The outcome was the document “Experiments expected at ESS and their neutron beam needs” (ESS-0017709)
Users at ESS

- **ESS goal:**
  
  *At least 90% of the users should receive a neutron beam that will allow them to execute the full scope of their experiments.*

- **Neutron beam needs:**

<table>
<thead>
<tr>
<th>Kinetic experiments</th>
<th>Integrated-flux experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>90% reliability</strong> for the duration of the measurement</td>
<td><strong>90% beam availability</strong> and <strong>80% average beam power</strong> for the duration of the experiments</td>
</tr>
<tr>
<td><em>Failure: Beam trip with a duration of more than 1/10th of the measurement length</em></td>
<td><em>Beam unavailable: power less than 50% for more than one minute</em></td>
</tr>
</tbody>
</table>
RAMI for the users

- The **global ESS availability figure** is not the most important

- What is important for them is the **distribution of failures**:
  - Failures (or beam trips) of less than 1 hour can be easily accepted
  - Failures from 1 hour to 24 hours are the most problematic
  - Failures longer than some days will imply to reschedule the experiments (also happen in reactors)
  - Beam trips announcements would be very beneficial for the users
Neutron beam reliability and availability requirements

- Neutron beam requirements
- Global performance
- Neutron beam requirements to satisfy the users
- ESS operation, good practices, flexibility...
- User needs
Neutron beam reliability and availability requirements

Neutron beam requirements to satisfy the users

- Global performance
- ESS operation, good practices, flexibility...

User needs
Neutron beam to satisfy the users

• Taking into account:
  – Specific needs for Kinetic and for Integrated-flux experiments
  – Good practices and the operational flexibility described in the users’ document. E.g. start 4 hours later, use optional study days, etc.

• The following neutron beam requirements were obtained:

<table>
<thead>
<tr>
<th>Trip duration</th>
<th>Max. number of trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second - 6 seconds</td>
<td>758 trips per day</td>
</tr>
<tr>
<td>6 seconds - 1 minute</td>
<td>136 trips per day</td>
</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>12 trips per day</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>350 trips per year</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td>99 trips per year</td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td>33 trips per year</td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>17 trips per year</td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td>6.7 trips per year</td>
</tr>
<tr>
<td>More than 1 day</td>
<td>3.25 trips per year</td>
</tr>
</tbody>
</table>

Note: annual operation is assumed to be 200 days
Neutron beam reliability and availability requirements

Neutron beam requirements

Global performance

ESS operation, good practices, flexibility...

User needs
Neutron beam reliability and availability requirements

Neutron beam requirements

Global performance

Neutron beam requirements to satisfy the users

ESS operation, good practices, flexibility...

User needs
ESS users needs compared to SNS operation

Comparison of ESS users needs with data recorded during operation at SNS (beam trips and downtime from fiscal years 2010 to 2013 - data sent by Charles C. Peters and George Dodson)
### ESS neutron beam trips requirements

<table>
<thead>
<tr>
<th>Trip duration</th>
<th>Max. number of trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second - 6 seconds</td>
<td>120 trips per day</td>
</tr>
<tr>
<td>6 seconds - 1 minute</td>
<td>40 tips per day</td>
</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>5 trips per day</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>350 trips per year</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td>99 trips per year</td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td>33 trips per year</td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>17 trips per year</td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td>6.7 trips per year</td>
</tr>
<tr>
<td>1 day - 3 days</td>
<td>2.9 trips per year</td>
</tr>
<tr>
<td>3 days - 10 days</td>
<td>1 every 4 years</td>
</tr>
<tr>
<td>more than 10 days</td>
<td>1 every 10 years</td>
</tr>
</tbody>
</table>

**Reduce the number of trips allowed**

**Divide the “more than 1 day” bin into 3 bins**
Requirements allocation
Requirements allocation

- A first allocation of the requirements was done following two methodologies:
  - Comparison with SNS distribution of failures (with the necessary assumptions)
  - Expert opinion, failures tracking and possible downtime for different systems

<table>
<thead>
<tr>
<th>Downtime duration</th>
<th>Accelerator</th>
<th>Target</th>
<th>ICS</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second - 6 seconds</td>
<td>We can stop the proton source without further problems</td>
<td>No possible failures</td>
<td>No possible failures</td>
<td>No possible failures</td>
</tr>
<tr>
<td>6 seconds - 1 minute</td>
<td>Maybe the source could accept to be in standby for more time or it could be faster to come back or the ramp-up takes longer. Possible accelerator tuning time if a cavity fails and we have to retune.</td>
<td>No possible failures</td>
<td>Software, false trips or restart or electronic component</td>
<td>No possible failures</td>
</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>Typical time if something happen and the operator has to do changes in the configuration or any operator action. Restart proton source, ramp-up etc.</td>
<td>Instrumentation failure</td>
<td>Component failure. Maintenance needed</td>
<td>Electric grid glitch? Change one line for the other…</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>Fast maintenance on components outside the tunnel. Restart an electronic component, etc.</td>
<td>Water cooling pump exchange?</td>
<td>Components failure. Maintenance required</td>
<td>Components failure. Maintenance required</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>Repair or replace a component or fast maintenance inside the tunnel.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 day - 3 days</td>
<td>Major failure of a big component</td>
<td>Any hydrogen non-critical cooling system failure</td>
<td>No possible failures</td>
<td>Very rare</td>
</tr>
<tr>
<td>3 days - 10 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>more than 10 days</td>
<td>Big problem. E.g. repair cavity tuning system (15 days) Change cryomodule (2.5 months)…</td>
<td>Moderator failure</td>
<td>No possible failures</td>
<td>Very rare</td>
</tr>
</tbody>
</table>
The result of the preliminary allocation is the following:

<table>
<thead>
<tr>
<th>Downtime duration</th>
<th>Accelerator</th>
<th>Target</th>
<th>ICS</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second - 6 seconds</td>
<td>120 per day</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6 seconds - 1 minute</td>
<td>40 per day</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>4.8 per day</td>
<td>-</td>
<td>40 per year</td>
<td>-</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>1.7 per day</td>
<td>-</td>
<td>10 per year</td>
<td>-</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td>90 per year</td>
<td>2 per year</td>
<td>4 per year</td>
<td>3 per year</td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td>29 per year</td>
<td>1 per year</td>
<td>2 per year</td>
<td>1 every 2 years</td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>15 per year</td>
<td>1 every 2 years</td>
<td>1 every 2 years</td>
<td>1 every 2 years</td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td>5.5 per year</td>
<td>1 every 2 years</td>
<td>1 every 5 years</td>
<td>1 every 3 years</td>
</tr>
<tr>
<td>1 day - 3 days</td>
<td>2.3 per year</td>
<td>1 every 2 years</td>
<td>-</td>
<td>1 every 10 years</td>
</tr>
<tr>
<td>3 days - 10 days</td>
<td>1 every 5 years</td>
<td>1 every 20 years</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>more than 10 days</td>
<td>3 every 40 years</td>
<td>1 every 40 years</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Beam power degradation
It is possible to decrease proton beam power to 50% of the scheduled beam power without considering it a beam trip. However, the average proton beam power over 10 days shall be higher than 80% of the scheduled beam power.

- Some accelerator and target failures may imply to reduce proton beam power instead of stopping the beam:
  - An event that would reduce the beam power to 50% of the scheduled power could have a maximum duration of about 4 days.
  - The scheduled beam power could be reviewed every two weeks in case of a permanent degradation.

- User community: users will always prefer beam availability to beam power.
Accelerator RAMI analyses
Failure examples

- Arc
  - LPS-MPS inhibit some pulses
- Klystron failure
  - Retune accelerator
- Modulator failure
  - Repair modulator

It will depend on many things:
- Manpower
- Spares
- Access time
- Cavity affected
- Retune time
- ...

<table>
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<tbody>
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</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>4.8 per day</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>1.7 per day</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td>90 per year</td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td>29 per year</td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>15 per year</td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td>5.5 per year</td>
</tr>
<tr>
<td>1 day - 3 days</td>
<td>2.3 per year</td>
</tr>
<tr>
<td>3 days - 10 days</td>
<td>1 every 5 years</td>
</tr>
<tr>
<td>more than 10 days</td>
<td>3 every 40 years</td>
</tr>
</tbody>
</table>
## FMEA (Failure Mode and Effect Analysis)

| Level | Component | Number of component | Function | Failure mode | Possible causes | Locally | Next level | On the Beam | Random (data) | Random (level) | Lifetime (data) | Lifetime (level) | On demand | Corrective actions | Preventive actions | Spares and tools | Access time (h) | Time to repair (h) | Time to restart locally (h) | Time to restart next level |
|-------|-----------|---------------------|----------|--------------|----------------|---------|------------|------------|--------------|---------------|----------------|----------------|----------------|-------------|----------------|--------------------|----------------|----------------|----------------|----------------|------------------|
| 1     | Vacuum system | 1 |               |             |               |               |         |            |            |               |               |                |                |            |                |                    |               |                 |                 |                 |                  |
| 2     | Vacuum beam pipe | 1 | Vacuum not good for operation |             |               |               |         |            |            |               |               |                |                |            |                |                    |               |                 |                 |                 |                  |
| 3     | Ion source | 1 |               |             |               |               |         |            |            |               |               |                |                |            |                |                    |               |                 |                 |                 |                  |
| 4     | Turbo pump | 4 | Pump vacuum from ion chamber | Random mechanical problem | Random failure | Pump not operative | 3 out of 4 must be operative otherwise the vacuum is not good enough | No beam | 3 | Replace pump | Pump | 4 | 1 | 3 | 2 |
|       |           |       | Mechanical wear out | Wear out | Pump not operative | 3 out of 4 must be operative otherwise the vacuum is not good enough | No beam | 3 | Current sensor. Replace pump | Pump | 4 | 1 | 3 | 2 |
|       |           |       | Power supply failure (controller) | Random failure | Pump not operative | 3 out of 4 must be operative otherwise the vacuum is not good enough | No beam | 3 | Replace controller | Controller | 0 | 1 | 0.1 | 0.5 |
| 4     | Multi roots | 2 | Pump vacuum from ion chamber | Random mechanical problem | Random failure | Pump not operative | 1 out of 2 must be operative otherwise the vacuum is not good enough | No beam | 3 | Replace pump | Pump | 4 | 1 | 3 | 2 |
|       |           |       | Mechanical wear out | Wear out | Pump not operative | 1 out of 2 must be operative otherwise the vacuum is not good enough | No beam | 4 | Current sensor. Replace pump | Pump | 4 | 1 | 3 | 2 |
| 4     | Valves (not gate valve) | 8 | Isolete pump from beam vacuum for maintenance | Vacuum leak | Random failure | Air in beam pipe | Lose vacuum | No beam | 4 | Replace valve | Valve | 4 | 1 | 3 | 2 |
| 4     | Gauge | 6? | Measure vacuum | No signal/wrong signal | Random failure | No vacuum data at one point | If X gauges fail, we can't measure the vacuum | No beam (or maybe we can always continue if there are no loses detected by the BLM?) | 3 | Replace failed gauges | Gauge | 4 | 1 | 3 | 2 |
| 3     | RFQ | 1 |               |             |               |               |         |            |            |               |               |                |                |            |                |                    |               |                 |                 |                 |                  |
| 4     | Turbo pump | 8 | Pump vacuum from beam pipe | Random mechanical problem | Random failure | Pump not operative | 2 out of 3 must be operative otherwise the vacuum is not good enough | No beam | 3 |               |                |            |                |            |                    |                |               |                 |                 |                 |                  |
|       |           |       | Mechanical wear out | Wear out | Pump not operative | 2 out of 3 must be operative otherwise the vacuum is not good enough | No beam | 3 |               |                |            |                |            |                    |                |               |                 |                 |                 |                  |
|       |           |       | Power supply failure | Random failure | Pump not operative (one ?) | Bad vacuum | No beam | 2 |               |                |            |                |            |                    |                |               |                 |                 |                 |                  |
|       |           |       | Controls failure | Random failure | Pump not operative | 2 out of 3 must be operative otherwise the vacuum is not good enough | No beam | 4 |               |                |            |                |            |                    |                |               |                 |                 |                 |                  |
### FMEA Import to ReliaSoft

<table>
<thead>
<tr>
<th>Component</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm compressor station (WCS)</td>
<td>0.998622</td>
</tr>
<tr>
<td>Cold compressor discharge (CCD)</td>
<td>0.998622</td>
</tr>
<tr>
<td>Compressor assembly</td>
<td>0.999174</td>
</tr>
<tr>
<td>Compressor</td>
<td>0.999574</td>
</tr>
<tr>
<td>Motor</td>
<td>0.999560</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.999980</td>
</tr>
<tr>
<td>Damaged bearings</td>
<td>0.999875</td>
</tr>
<tr>
<td>Degraded bearing</td>
<td>0.999575</td>
</tr>
<tr>
<td>Damaged screw</td>
<td>0.999975</td>
</tr>
<tr>
<td>Oil pumps</td>
<td>0.999995</td>
</tr>
<tr>
<td>Oil filter</td>
<td>0.999925</td>
</tr>
<tr>
<td>Vessel</td>
<td>0.999995</td>
</tr>
<tr>
<td>Safety valves</td>
<td>0.999875</td>
</tr>
<tr>
<td>Control valves (pneumatic)</td>
<td>0.999875</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0.999800</td>
</tr>
<tr>
<td>Coolers</td>
<td>0.999800</td>
</tr>
<tr>
<td>Oil cooler</td>
<td>0.999800</td>
</tr>
<tr>
<td>He cooler</td>
<td>0.999800</td>
</tr>
<tr>
<td>Motor cooler</td>
<td>0.999800</td>
</tr>
<tr>
<td>LP-MP</td>
<td>0.999570</td>
</tr>
<tr>
<td>MP-HP</td>
<td>0.999573</td>
</tr>
<tr>
<td>Warm gas processing</td>
<td>0.999749</td>
</tr>
<tr>
<td>Fine ORS</td>
<td>0.999875</td>
</tr>
<tr>
<td>Coalescers</td>
<td>1.000000</td>
</tr>
<tr>
<td>Oil adsorber</td>
<td>1.000000</td>
</tr>
<tr>
<td>filter</td>
<td>1.000000</td>
</tr>
</tbody>
</table>
Consequences of RAMI in the design

- Cryoplant warm-up: from 6 months to 3 years
- RF Interlock PLC’s: more reliable solutions
- Tetrodes vs. Klystrons for the spokes in different configurations
- Solid State amplifiers configuration for the bunchers
- DC magnets vs. Pulsed magnets
- Selection of reliable arc detectors
- ...

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Other related activities

• Many related activities are being done. Some examples are:
  – Beam physics studies to determine degraded modes of operation and flexibility of the machine are being done.
  – Link between MPS, LPS and accelerator performance in order to allow a good protection of the machine without affecting the overall operation.
  – Operation and maintenance plans with accelerator start-up and ramp-up procedures (users, schedule power and calendar...).
  – Risk analyses (e.g. warming-up cryomodules).
  – ...
Conclusions
Conclusions

• Work is advancing in the right direction

• Requirements and preliminary allocation are done

• Comparisons with other facilities show that the requirements will be difficult to achieve: an important effort is needed
  – Perform RAMI analyses (more focus on the weak spots)
  – Include RAMI requirements where needed
  – Consider RAMI in the design decisions
Thanks for your attention!
Back-up slides
Organization

**XFWG on reliability**

- **Accelerator**
  - Enric Bargalló
  - Andreas Jansson
- **Target**
  - Eric Pitcher
- **Instruments and science**
  - Ken Andersen
  - Arno Hiess
  - Robert Connatser
- **ICS**
  - Annika Nordt
- **Site infrastructure**
  - Ronny Sjöholm
- **Systems engineering**
  - Johan Waldeck

**RAMI group**

- **Accelerator**
  - Enric Bargalló
- **Target**
  - Alex Garcia (partially)
- **Instruments and science**
  - Peter Sångberg (only coordination)
- **ICS**
  - Student?
- **Site infrastructure**
  - Björn Yndemark (partially)
Requirements assumptions

• These requirements do not apply to the commissioning phases of the subsystems or to the initial operations.
• There are enough scheduled maintenance periods to allow for proper preventive maintenance.
• Proton beam power has been set as the parameter that defines the degraded modes of operation and limits from the user perspective. This allows an easy interpretation for Target, Accelerator and NSS.
• The cascade effects of the failures on one system to the neutron beam availability will be accounted to the system that caused the failure. This can have a major impact in subsystems that supply others. The consequence of failures will take total ESS downtimes (e.g. a few minutes electrical power blackout will imply several hours of downtime for ESS) into account.
• Negligibly small neutron spectrum changes are expected when the accelerator reduces its power to 50% of its nominal value. It is assumed that will not affect the experiments.
• No catastrophic events coming from outside ESS are considered in the requirements.
• Internal fire and other catastrophic events are not included in this analysis. It is considered that the corresponding responsible teams will reduce their probability and consequences.
• Problems that occur in the maintenance periods are not considered in these analyses. Those problems might be analyzed, but are not in the scope of the current document.
• Human reliability related problems should also be included when relevant.
RAMI definitions

• **Reliability**: Probability of success over a certain period of time

  _E.g. probability that the proton beam will not have any trip for one hour_

• **Availability**: 

  \[
  Availability = \frac{Uptime}{Scheduled\ uptime}
  \]

• **Maintainability**: capability of performing maintenance to a system or component.

• **Inspectability**: capability to inspect, test and monitor a system and its possible failures.
A. Estimate accomplishment of requirements

- Users
- Stakeholders
- Allocation
- Experiences in other facilities or experts opinion
- Previous analyses

Top-down

Requirements allocation and definition

- ESS requirements
- Accelerator requirements
- Systems requirements

Bottom-up

Models and RAMI parameters estimation

- Global model
- Individual models
- Functions
- Systems and components
- Operations information
- Reliability data

Availability

- Number of stops and durations
- Failures
- Trips in similar systems

Reliability

- Comparison with other facilities
- Trips
- Trips in similar components

Outcomes

- Redefine requirements
- Reallocation requirements
- Change design
- Components’ requirements