ESS RAMI analyses

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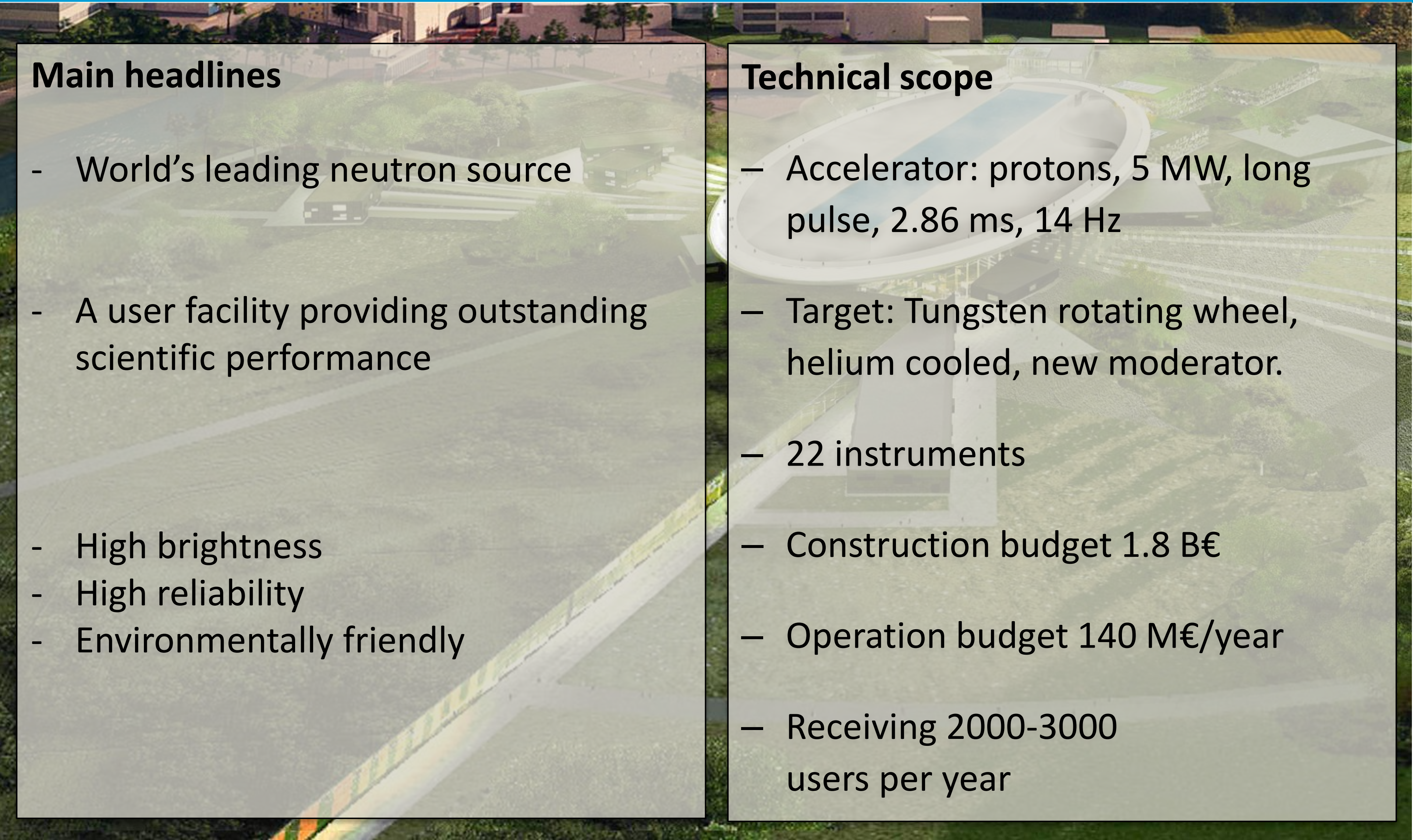
Reliability of Accelerators for ADS workshop
CERN, June 22, 2015

Outline

- The European Spallation Source
- ESS reliability and availability requirements
- Requirements allocation
- Beam degradation
- Accelerator RAMI analyses
- Conclusions
- Lessons learned

The European Spallation Source

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

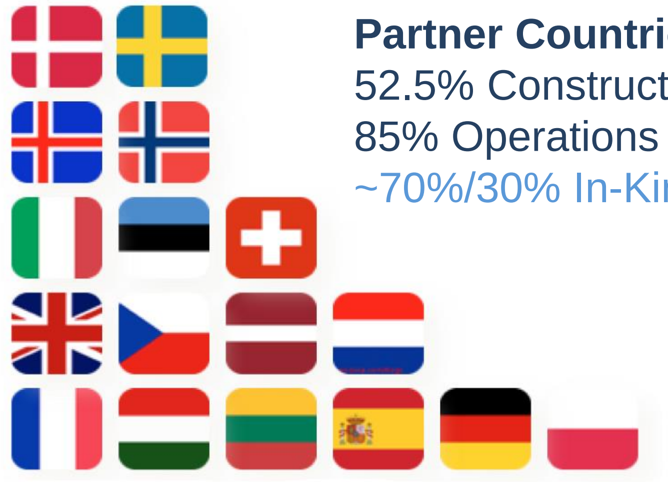
- Receiving 2000-3000 users per year

The ESS project

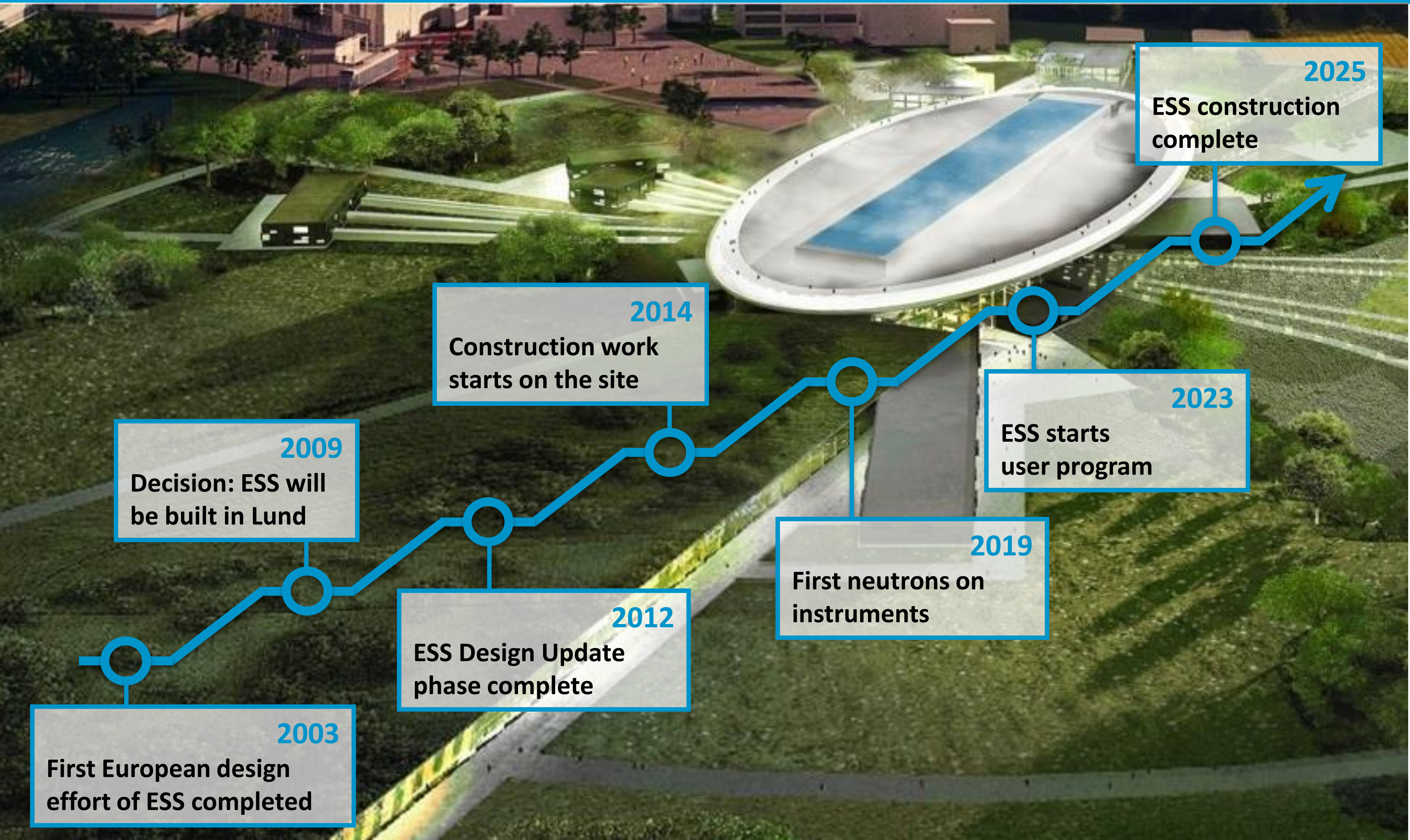
International collaboration

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

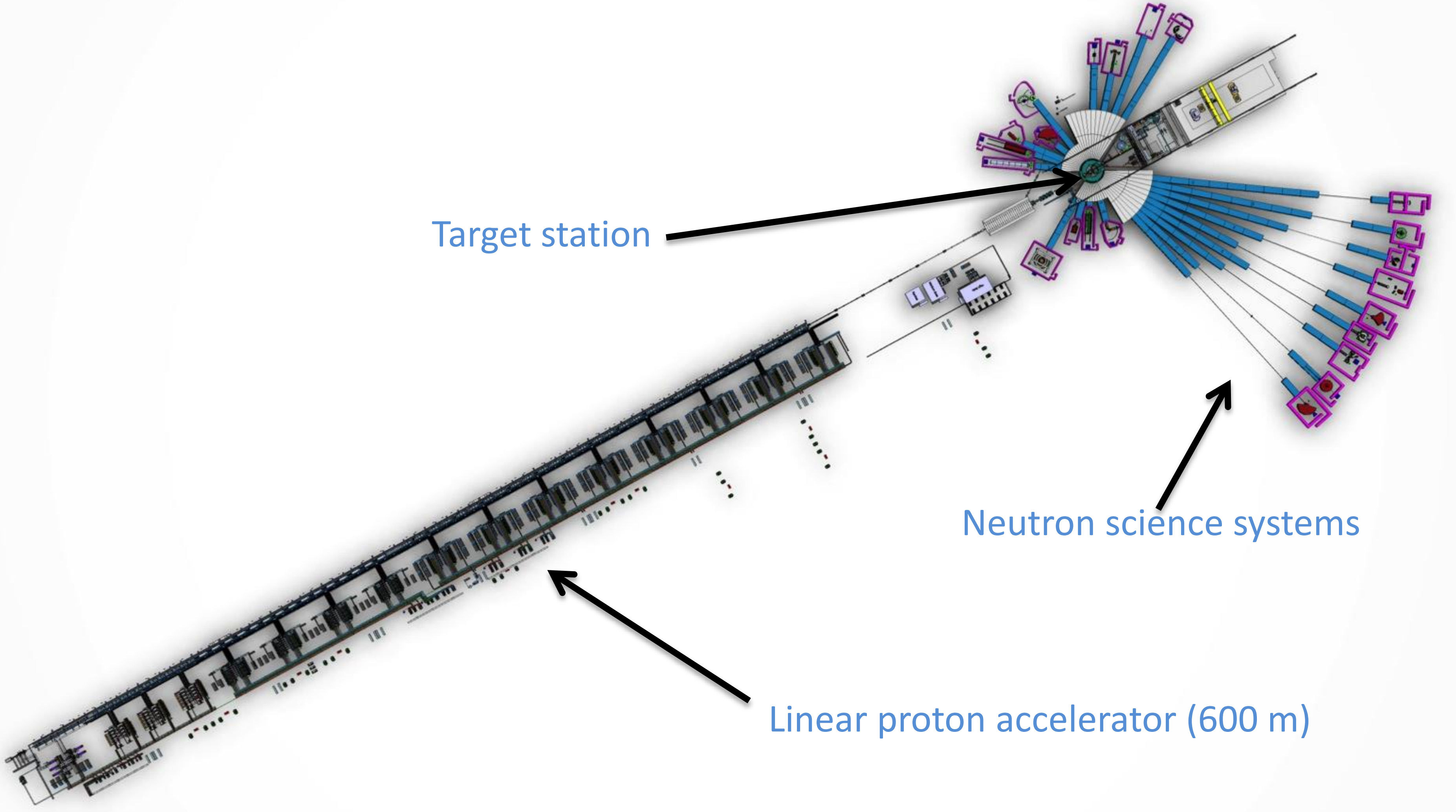
2019
First neutrons on instruments

2023
ESS starts user program

2025
ESS construction complete

Construction

ESS production of neutrons for science

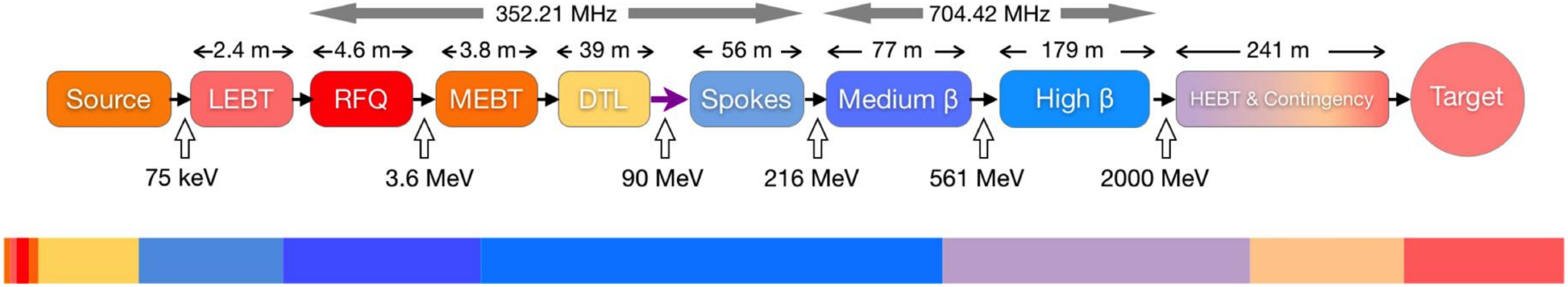


Target station

Neutron science systems

Linear proton accelerator (600 m)

ESS Linac Parameters

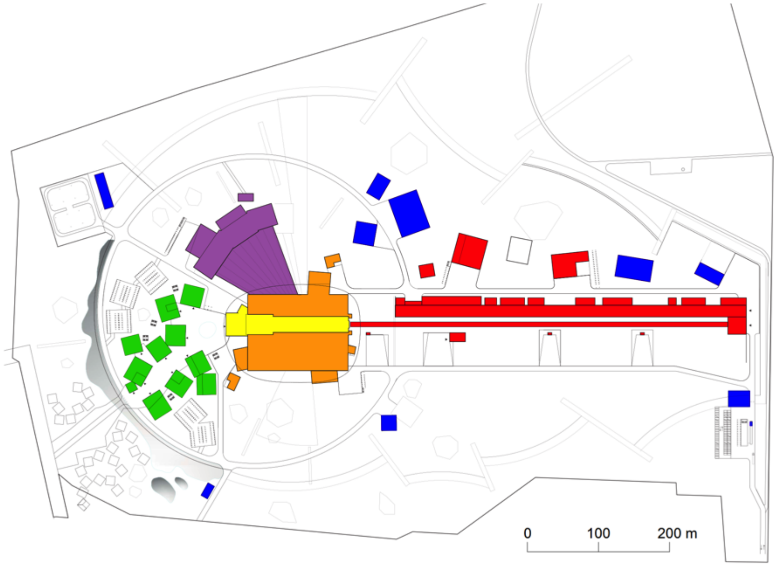

352.21 MHz
704.42 MHz

←2.4 m→ ←4.6 m→ ←3.8 m→ ← 39 m → ← 56 m → ← 77 m → ← 179 m → ← 241 m →

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

75 keV
3.6 MeV
90 MeV
216 MeV
561 MeV
2000 MeV

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



ESS reliability and availability requirements

Requirements before this study

ESS goal: 95% reliability/availability

- Not correctly expressed from the reliability point of view
- No technical reason behind it
- Implications in design were non-existent

Reliability and Availability at ESS

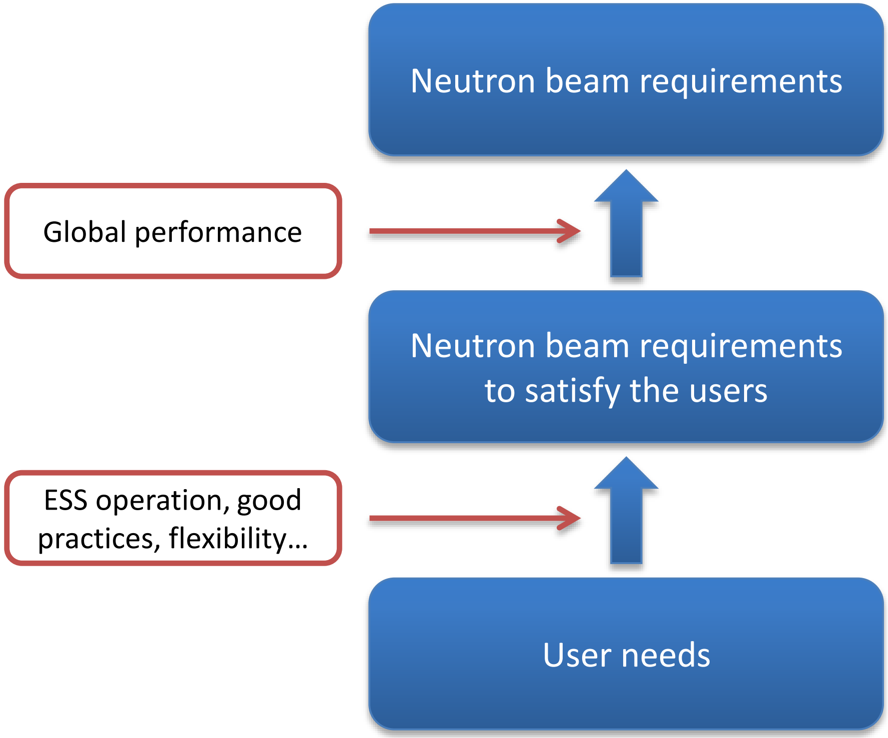
- **ESS goal**: science produced by the users
  - High brightness neutron beam
  - High reliability and availability of the beam

- **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

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



Neutron beam requirements

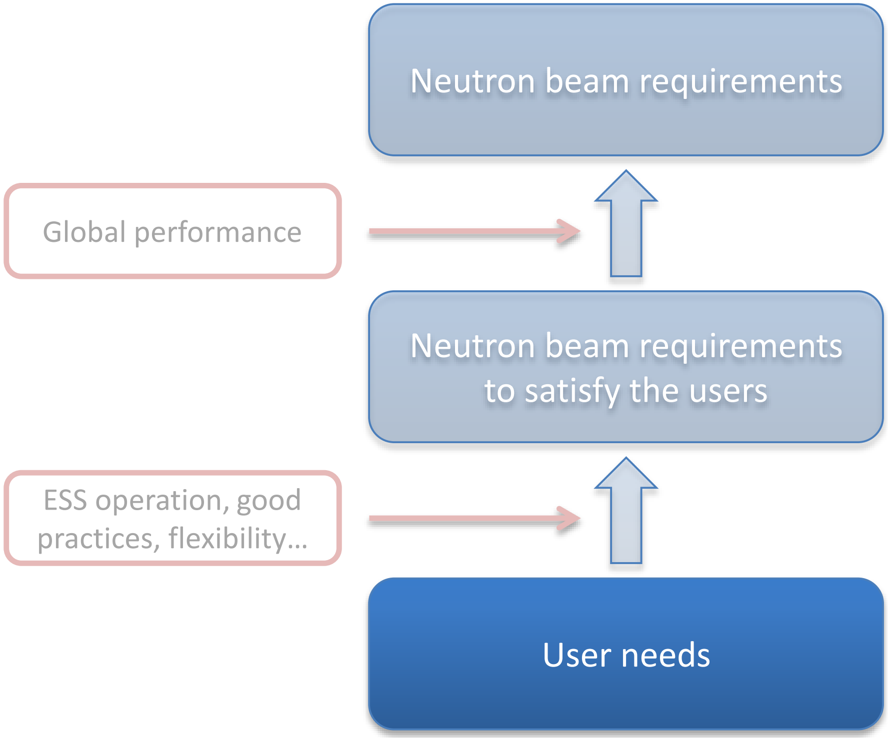
Global performance

Neutron beam requirements to satisfy the users

ESS operation, good practices, flexibility…

User needs

Neutron beam reliability and availability requirements



Neutron beam requirements

Global performance

Neutron beam requirements to satisfy the users

ESS operation, good practices, flexibility…

User needs

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:

Kinetic experiments

90% reliability for the duration of the measurement

Failure: Beam trip with a duration of more than 1/10th of the measurement length

Integrated-flux experiments

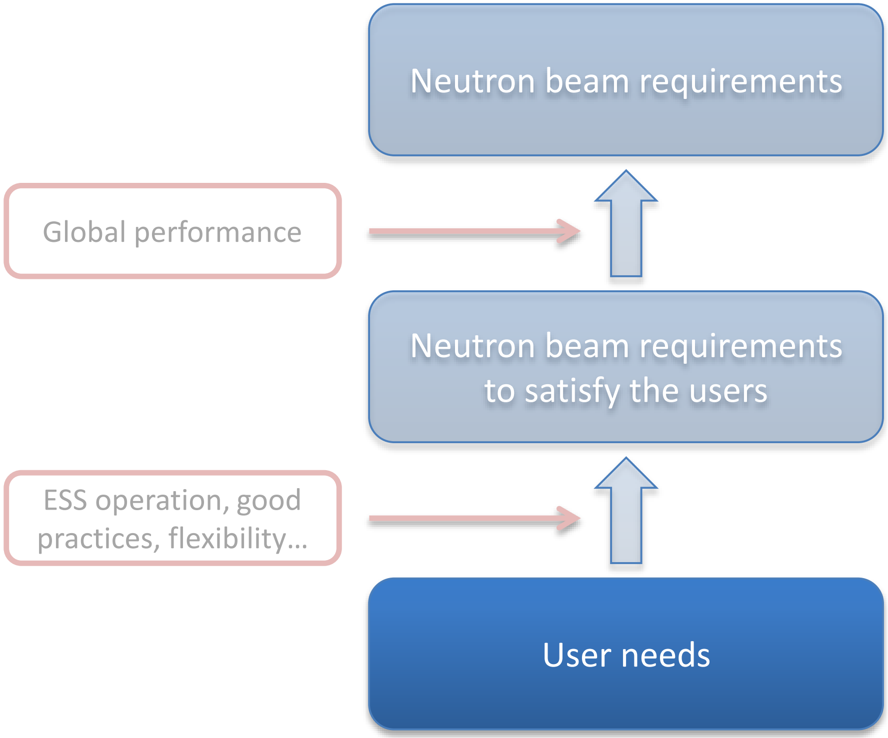
90% beam availability and **80% average beam power** for the duration of the experiments

Beam unavailable: power less than 50% for more than one minute

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



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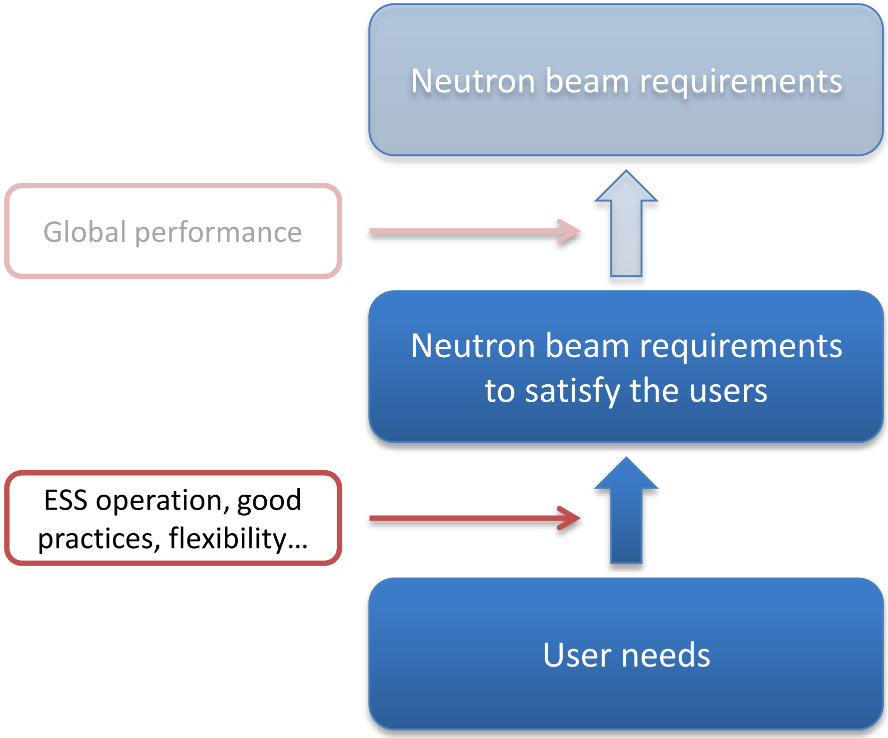


Neutron beam requirements

Global performance

Neutron beam requirements to satisfy the users

ESS operation, good practices, flexibility…

User needs

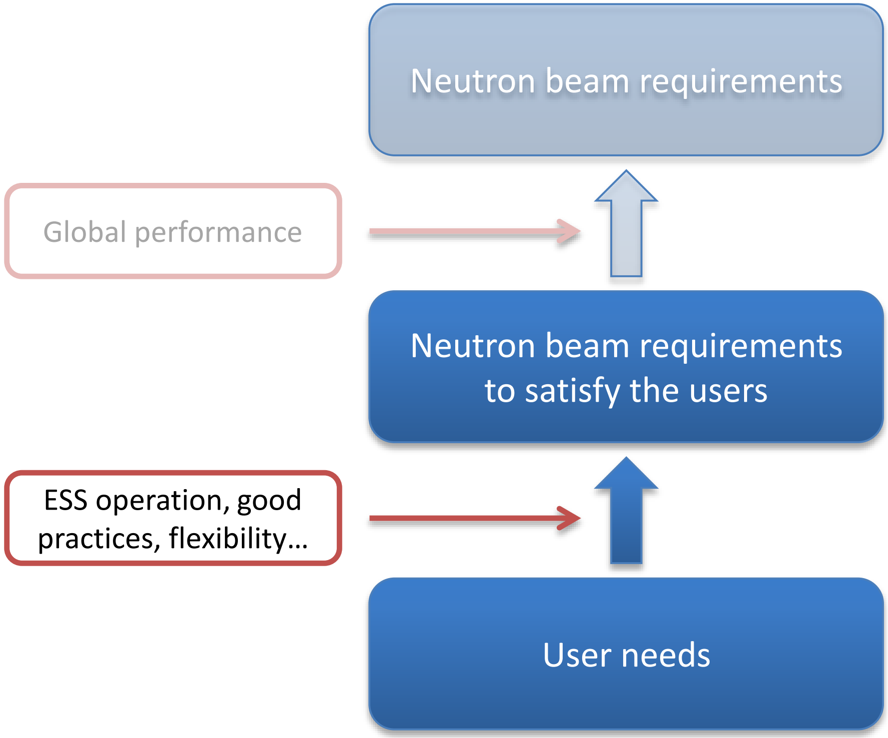
Neutron beam to satisfy the users

- 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:

Trip duration	Max. number of trips
1 second - 6 seconds	758 trips per day
6 seconds - 1 minute	136 trips per day
1 minute - 6 minutes	12 trips per day
6 minutes - 20 minutes	350 trips per year
20 minutes - 1 hour	99 trips per year
1 hour - 3 hours	33 trips per year
3 hours - 8 hours	17 trips per year
8 hours - 1 day	6.7 trips per year
More than 1 day	3.25 trips per year

Note: annual operation is assumed to be 200 days

Neutron beam reliability and availability requirements



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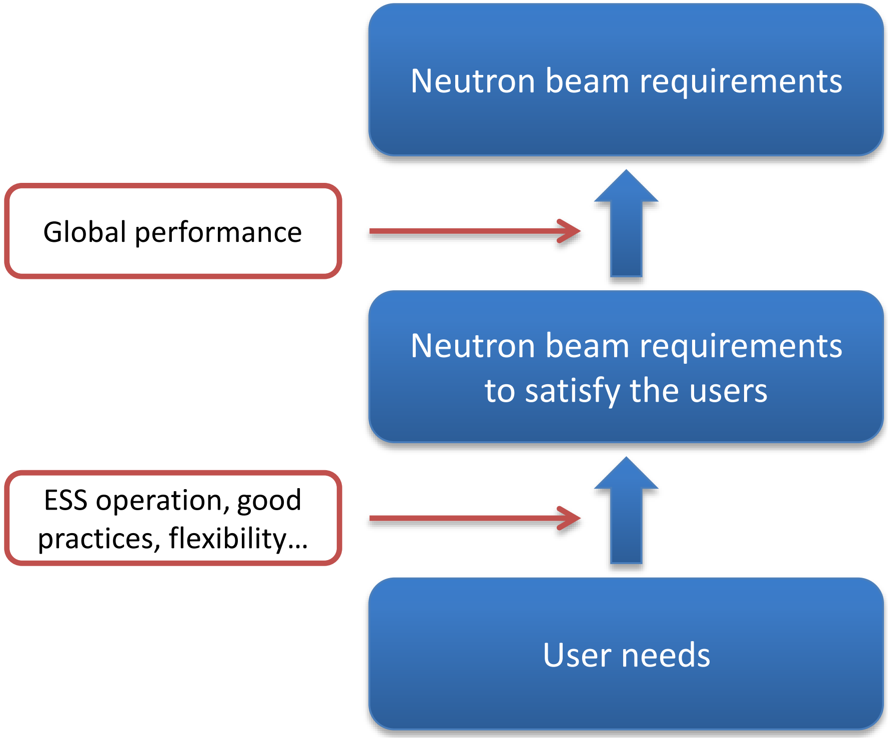


Neutron beam requirements

Global performance

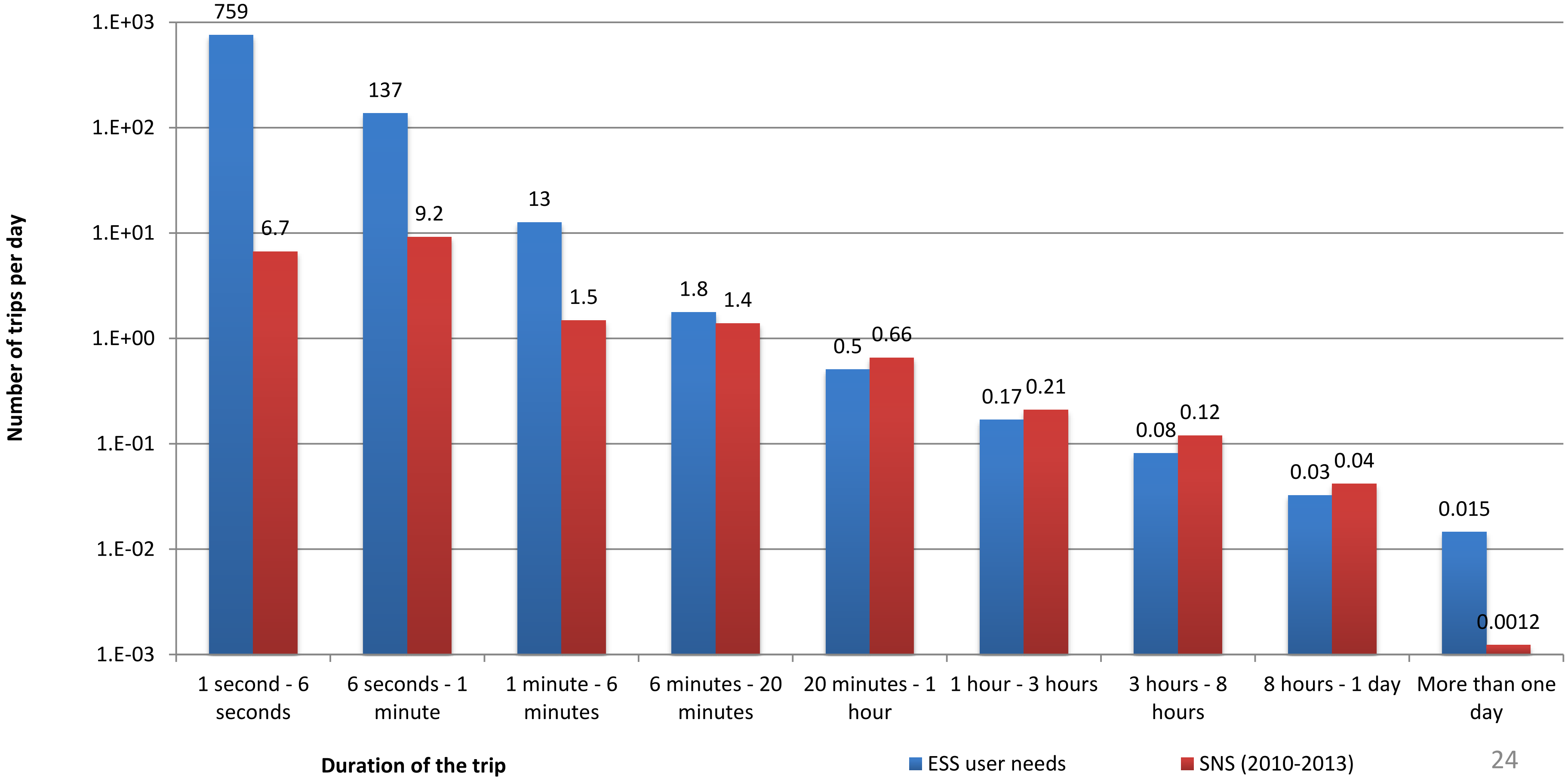
Neutron beam requirements to satisfy the users

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

Reduce the number of trips allowed

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

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

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

Downtime duration	Accelerator	Target	ICS	SI
1 second - 6 seconds	We can stop the proton source without further problems	No possible failures	No possible failures	No possible failures
6 seconds - 1 minute	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.			
1 minute - 6 minutes			Software, false trips or restart en electronic component	
6 minutes - 20 minutes	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.			
20 minutes - 1 hour		Instrumentation failure		Electric grid glitch? Change one line for the other…
1 hour - 3 hours	Fast maintenance on components outside the tunnel. Restart an electronic component, etc.		Component failure. Maintenance needed	
3 hours - 8 hours	Repair or replace a component or fast maintenance inside the tunnel.	Water cooling pump exchange		Components failure. Maintenance required
8 hours - 1 day				
1 day - 3 days	Major failure of a big component	Any hydrogen non-critical cooling system failure	Very rare	
3 days - 10 days				Very rare
more than 10 days	Big problem. E.g. repair cavity tuning system (15 days) Change cryomodule (2.5 months)…	Moderator failure		

Requirements allocation

- The result of the preliminary allocation is the following:

Downtime duration	Accelerator	Target	ICS	SI
1 second - 6 seconds	120 per day	-	-	-
6 seconds - 1 minute	40 per day	-	-	-
1 minute - 6 minutes	4.8 per day	-	40 per year	-
6 minutes - 20 minutes	1.7 per day	-	10 per year	-
20 minutes - 1 hour	90 per year	2 per year	4 per year	3 per year
1 hour - 3 hours	29 per year	1 per year	2 per year	1 every 2 years
3 hours - 8 hours	15 per year	1 every 2 years	1 every 2 years	1 every 2 years
8 hours - 1 day	5.5 per year	1 every 2 years	1 every 5 years	1 every 3 years
1 day - 3 days	2.3 per year	1 every 2 years	-	1 every 10 years
3 days - 10 days	1 every 5 years	1 every 20 years	-	-
more than 10 days	3 every 40 years	1 every 40 years	-	-

Beam power degradation

Beam power degradation

EUROPEAN
SPALLATION
SOURCE

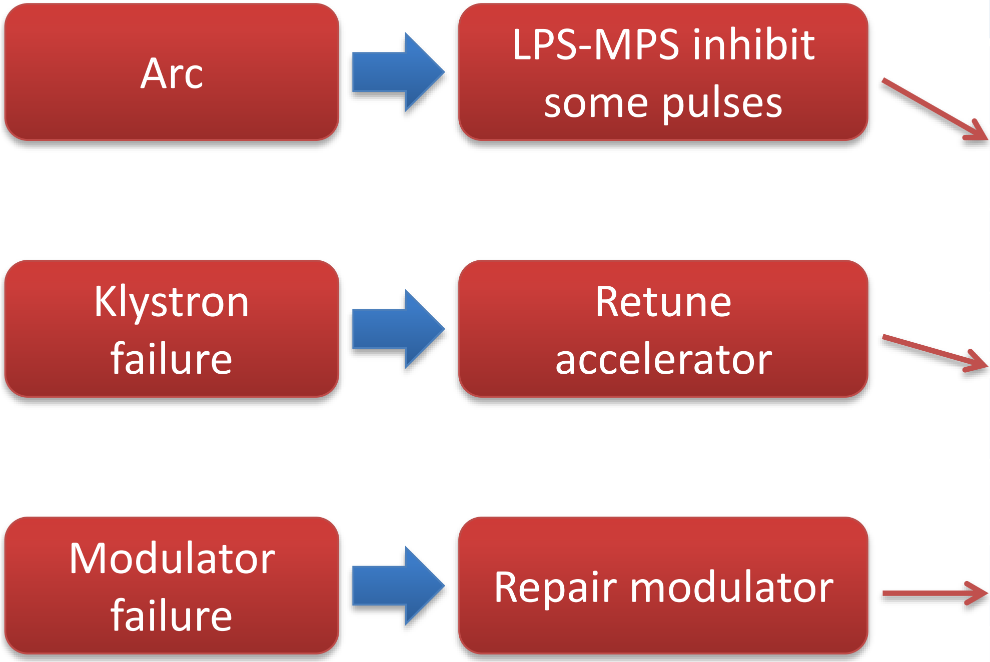
It is possible to decrease proton beam power to 50% of the scheduled beam power without considering it a beam trip. However, the average proton beam power over 10 days shall be higher than 80% of the scheduled beam power.

- Some accelerator and target failures may imply to reduce proton beam power instead of stopping the beam:
  - En 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

Downtime duration	Accelerator
1 second - 6 seconds	120 per day
6 seconds - 1 minute	40 per day
1 minute - 6 minutes	4.8 per day
6 minutes - 20 minutes	1.7 per day
20 minutes - 1 hour	90 per year
1 hour - 3 hours	29 per year
3 hours - 8 hours	15 per year
8 hours - 1 day	5.5 per year
1 day - 3 days	2.3 per year
3 days - 10 days	1 every 5 years
more than 10 days	3 every 40 years

It will depend on many things:

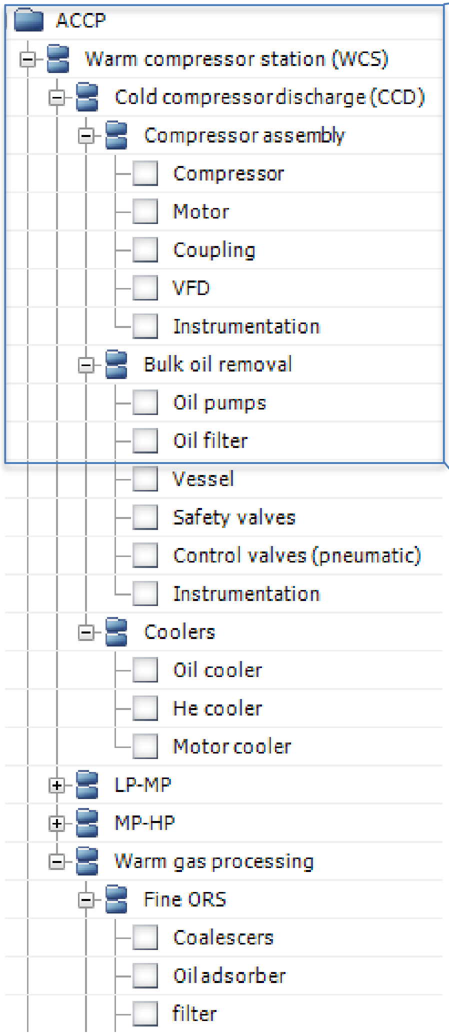
- Manpower
- Spares
- Access time
- Cavity affected
- Retune time
- …

FMEA (Failure Mode and Effect Analysis)

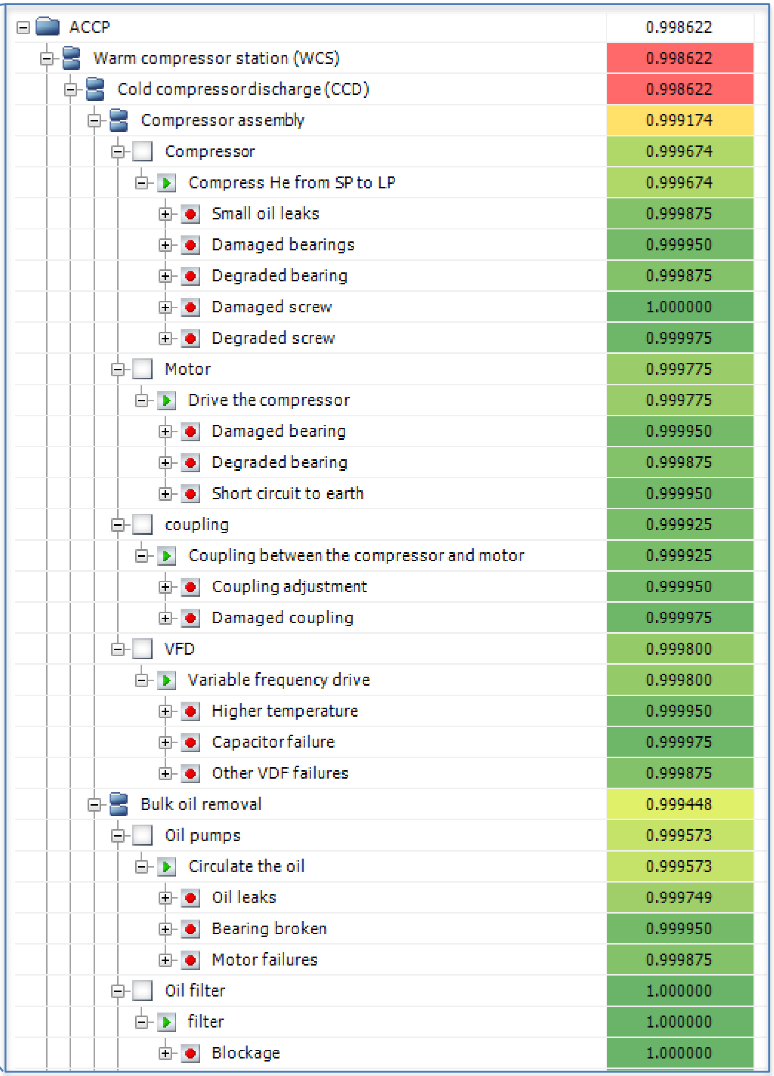
						Consequences			Reliability					Maintenance						
Level	**Component**	**Number of component**	**Function**	**Failure mode**	**Possible causes**	**Locally**	**Next level**	**On the Beam**	**Random (data)**	**Random (level)**	**Lifetime (data)**	**Lifetime (level)**	**On demand**	**Corrective actions**	**Preventive actions**	**Spares and tools**	**Access time (h)**	**Time to repair (h)**	**Time to restart locally (h)**	**Time to restart next level (h)**
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?	Mesure vacuum	No signal/wrong signal	Random failure	No vacuum data at one point	If X gauges fail, we can't measure the vaccum	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

EUROPEAN
SPALLATION
SOURCE

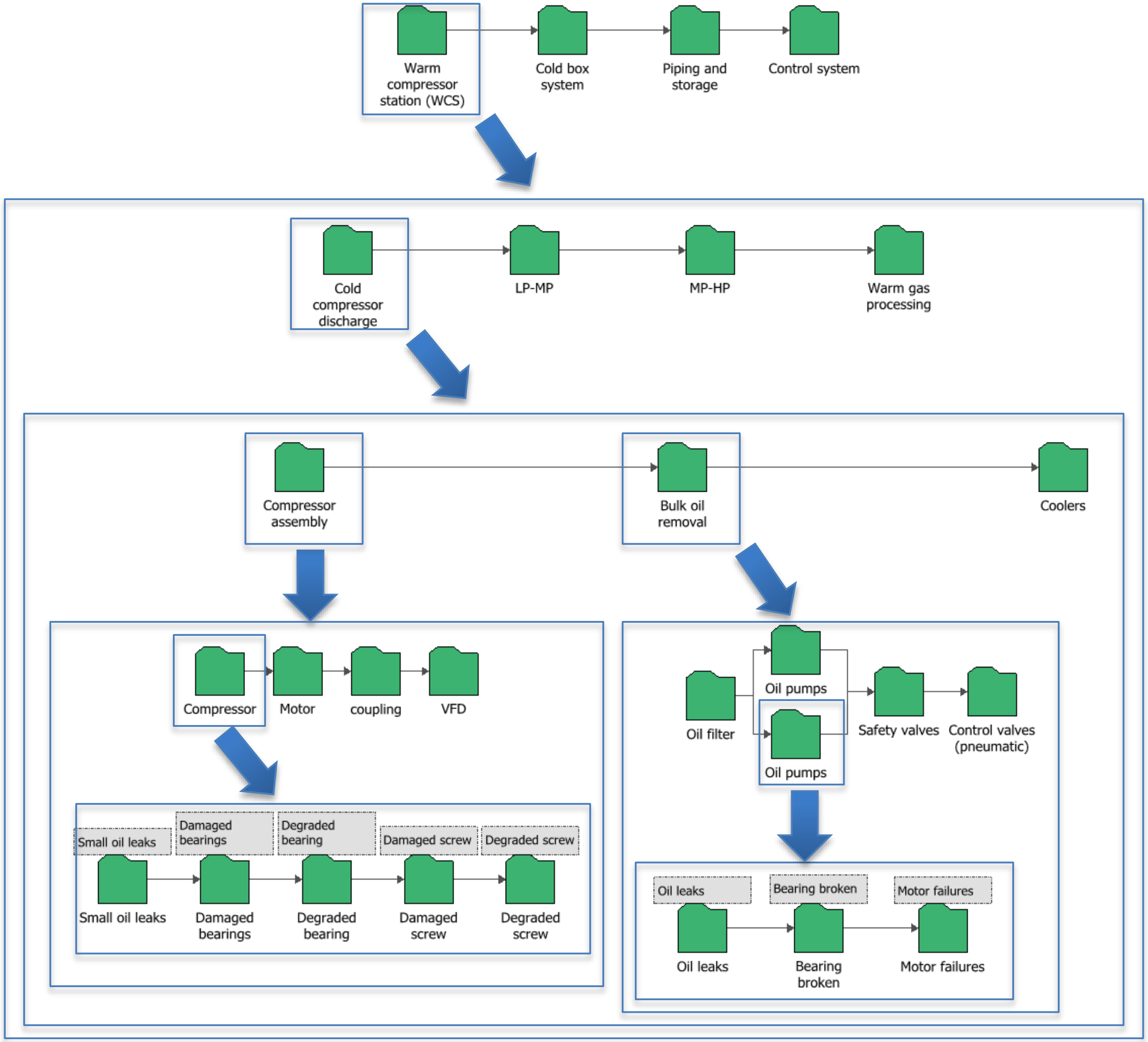


- ACCP
  - Warm compressor station (WCS)
    - Cold compressor discharge (CCD)
      - Compressor assembly
        - Compressor
        - Motor
        - Coupling
        - VFD
        - Instrumentation
      - Bulk oil removal
        - Oil pumps
        - Oil filter
        - Vessel
        - Safety valves
        - Control valves (pneumatic)
        - Instrumentation
      - Coolers
        - Oil cooler
        - He cooler
        - Motor cooler
    - LP-MP
    - MP-HP
    - Warm gas processing
      - Fine ORS
        - Coalescers
        - Oil adsorber
        - filter



ACCP	0.998622
Warm compressor station (WCS)	0.998622
Cold compressor discharge (CCD)	0.998622
Compressor assembly	0.999174
Compressor	0.999674
Compress He from SP to LP	0.999674
Small oil leaks	0.999875
Damaged bearings	0.999950
Degraded bearing	0.999875
Damaged screw	1.000000
Degraded screw	0.999975
Motor	0.999775
Drive the compressor	0.999775
Damaged bearing	0.999950
Degraded bearing	0.999875
Short circuit to earth	0.999950
coupling	0.999925
Coupling between the compressor and motor	0.999925
Coupling adjustment	0.999950
Damaged coupling	0.999975
VFD	0.999800
Variable frequency drive	0.999800
Higher temperature	0.999950
Capacitor failure	0.999975
Other VDF failures	0.999875
Bulk oil removal	0.999448
Oil pumps	0.999573
Circulate the oil	0.999573
Oil leaks	0.999749
Bearing broken	0.999950
Motor failures	0.999875
Oil filter	1.000000
filter	1.000000
Blockage	1.000000

Reliability Block Diagram



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 (pre-amplifiers and bunchers)
- DC magnets vs. Pulsed magnets
- Selection of reliable arc detectors
- …

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).
  - **MIL standard** for modulators reliability analyses
  - …

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

Lessons learned

Before starting the analyses

Clear goals

Maybe not only reliability or availability figures… integrated flux, production, beam “useful” for experiments…

Understand the real need from the project to push for reliability
- Is it technical or political?
- A requirement or an ideal goal

You should know what to analyze

- Catastrophic events
- Beam trips (“normal” behavior)
- Failure of components

If you care about downtime

Good idea of how the machine is going to operate

Beam dump, inhibit pulses, ramp-up, machine flexibility…

Functional analysis and interface requirements

Consequences of failures on one system to the other...
(e.g. cryoplant and cryomodules, CF and accelerator, etc.)

Good reliability data

Important for any analysis

Other things to consider

- Safety and protection can be on the other side of the balance
- Schedule can be your friend: Preventive maintenance
- Watch out spares and logistic times
- Machine flexibility can change the whole picture

Other considerations

Be sure that RAMI analyses are coupled with the design/purchase…

- Technology and components selection
- Contracts with companies and collaborators
- People usually think that they know about reliability
- …

Testing, commissioning and preparation for operation

- We will be there at some moment!!!

Accelerator Reliability Community

- New platform: Confluence wiki page
  - Common nomenclature
  - Exchange information
    - Operational data
    - Reliability data
    - Problems occurred
    - Software used…
  - Start discussions (open or private)
  - Questions to the community
  - Contact people
  - Links to workshops
  - …

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

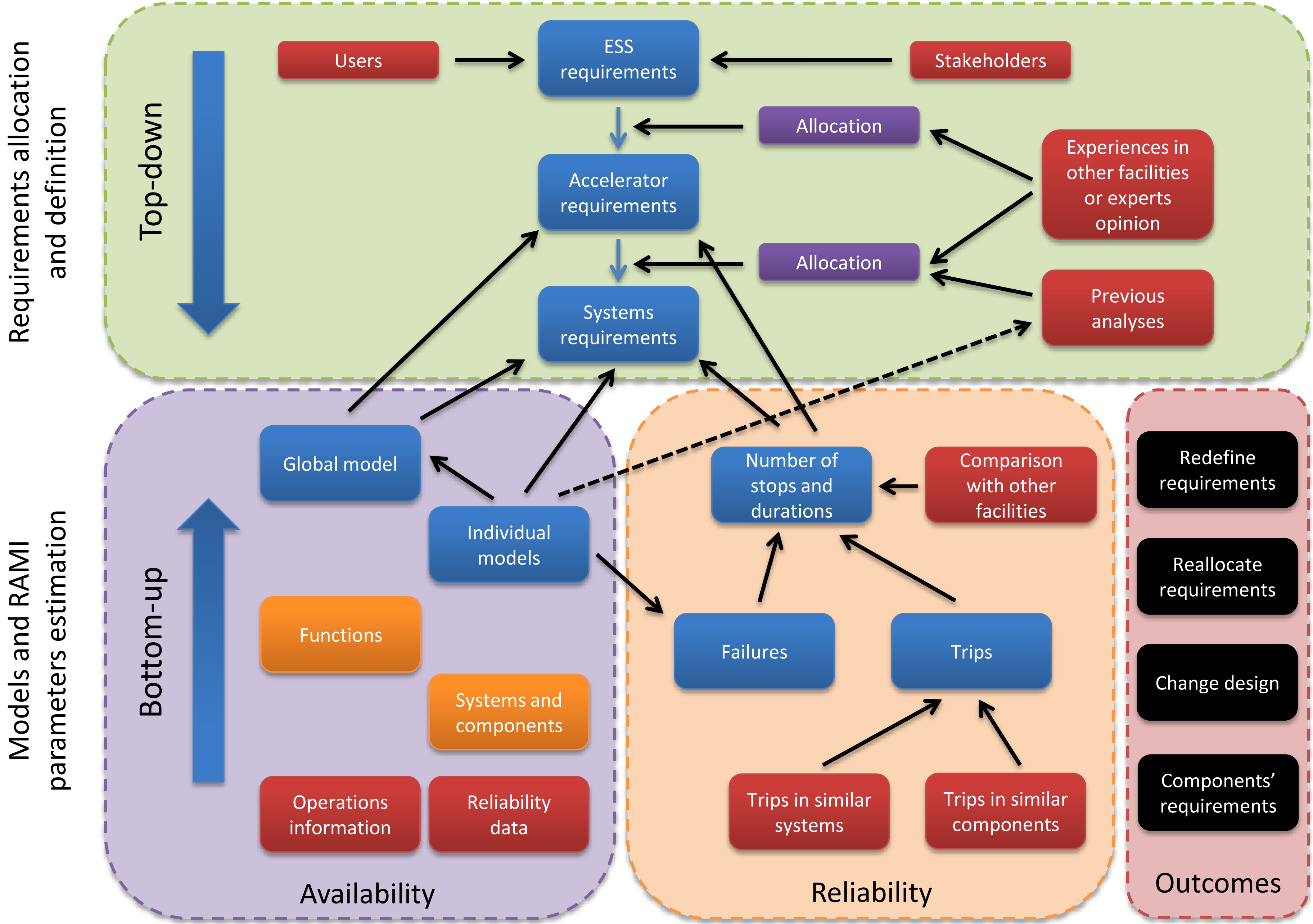
- **Availability**:

$$Availability = \frac{Uptime}{Scheduled\ uptime}$$

- **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



Requirements allocation and definition

Top-down

Users

ESS requirements

Stakeholders

Allocation

Accelerator requirements

Experiences in other facilities or experts opinion

Allocation

Systems requirements

Previous analyses

Models and RAMI parameters estimation

Bottom-up

Global model

Individual models

Functions

Systems and components

Operations information

Reliability data

Availability

Number of stops and durations

Comparison with other facilities

Failures

Trips

Trips in similar systems

Trips in similar components

Reliability

Redefine requirements

Reallocate requirements

Change design

Components' requirements

Outcomes