IFMIF Accelerator Facility RAMI analyses and the tools used

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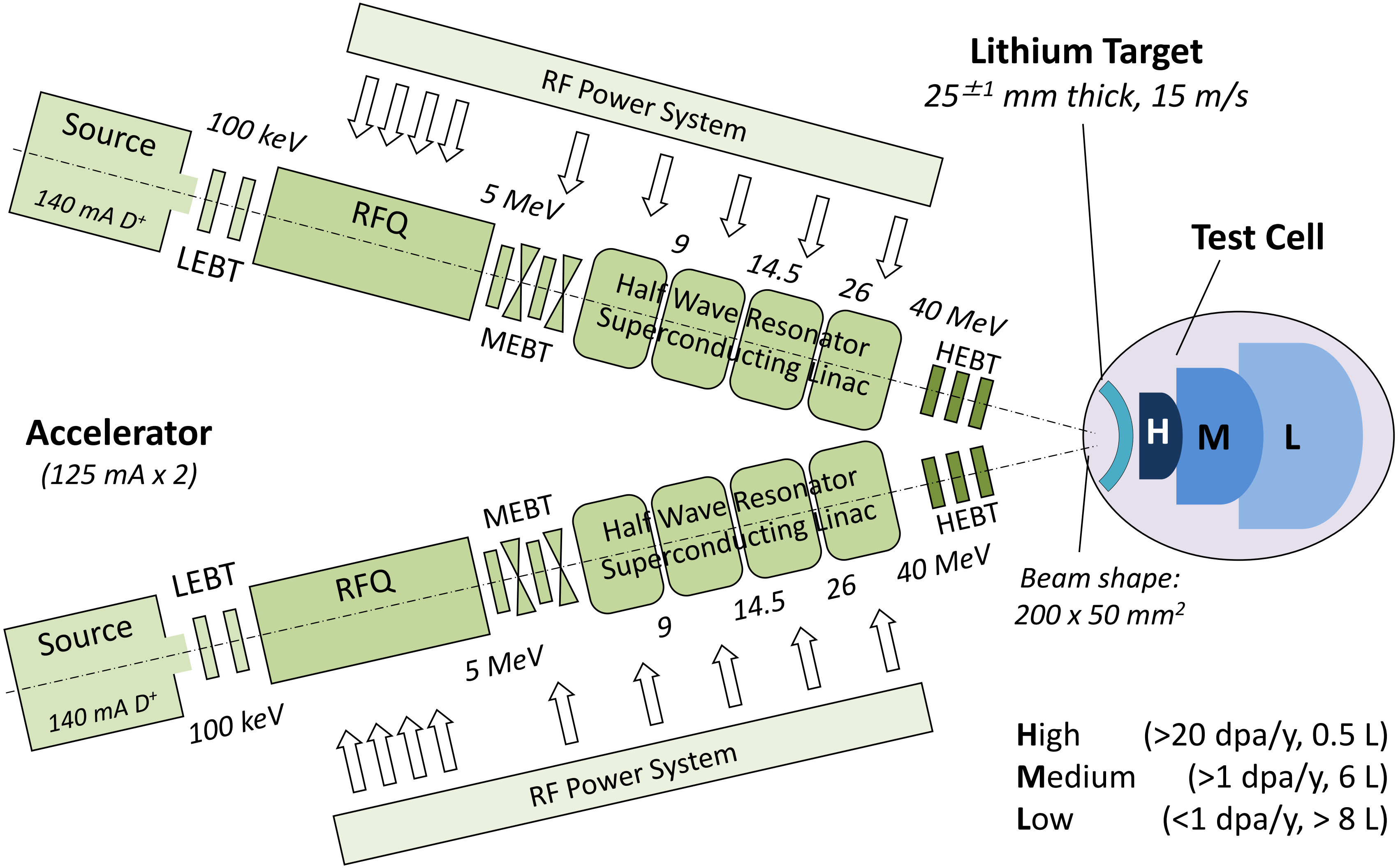
1. Introduction

IFMIF

- Stands for **International Fusion Materials Irradiation Facility**
- Its mission is to develop and qualify **radiation-resistant and low-activation materials** for future nuclear **fusion power plants**
- Will be a **high energy neutron source** with **high power** (10MW) and **huge flux** (20 to 40 dpa/fpy)
- Must produce high energy neutrons at sufficient **intensity** and **high availability** to find suitable materials for **design, licensing, construction and safe operation of fusion demonstration reactor (DEMO)**
- Is in the **engineering design phase**. Prototypes are being build (e.g. LIPAc, the Linear IFMIF Prototype Accelerator)

IFMIF Schemathic view



High	(>20 dpa/y, 0.5 L)
Medium	(>1 dpa/y, 6 L)
Low	(<1 dpa/y, > 8 L)

Main IFMIF requirements

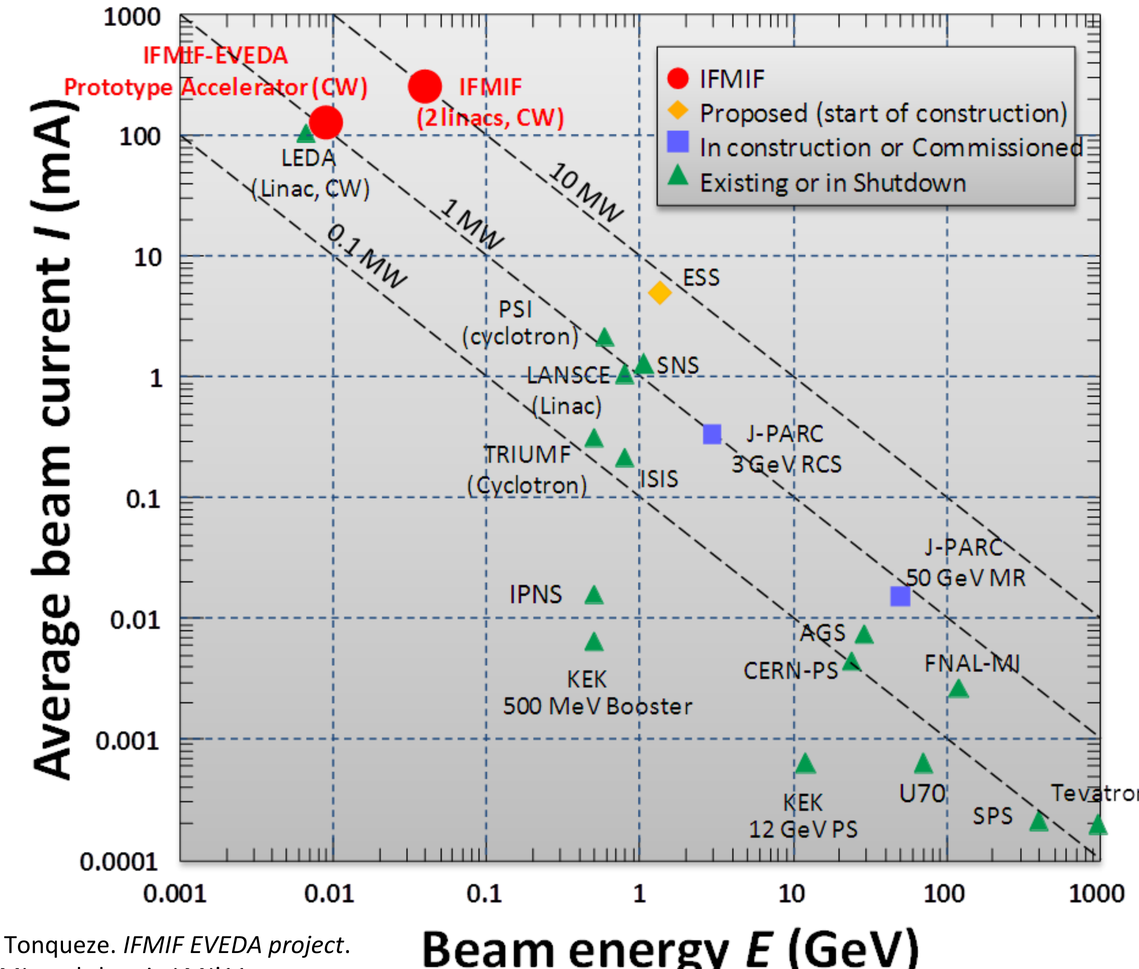
- **Neutron energy**: a broad energy peak near 14 MeV
- **Neutron flux**: 10^{18} n·s·m^{-2} at the high flux test module
- **Machine availability**: 70% of the total time

IFMIF accelerators

Deliver 250 mA of D^+ at 40 MeV in a continuous wave (CW)

- Very high intensity
- Very high space charge
- Very high power
- Very long RFQ
- **Very high availability requirements**

Unprecedented challenges



Source: Y. le Tonqueze. *IFMIF EVEDA project*. RAMI workshop in LMJ'11

IFMIF accelerators

- As a consequence of these challenges, **many design characteristics are contrary to a high availability performance**. Some examples are:
  - The design is **reluctant to accept failures**
  - Machine protection systems are **likely to stop the beam**
  - Cryogenic components need **large maintenance periods**
  - **Components activation** complicates maintenance actions

RAMI Specifications for IFMIF

Operational Availability requirements: 70% over calendar year

More than 30 years of operation. Exploitation plan: 24h/day

Scheduled Maintenance:

- Long shutdown: 20 days/year
- Short shutdown: 3 days/year

Inherent availability requirement: 75%

Accelerator Requirements

Inherent availability requirements for each IFMIF facility:

IFMIF Facilities	**Inherent availability requirements**
Tests Facility	96%
Target Facility	94%
Accelerator Facility	87%
Conventional Facilities	98%
Central Control System & Common Instr.	98%
TOTAL (product)	**75%**

Accelerator facility availability 87% refers to:

87% related to dpa (damage production) that both accelerators could produce in a determinate period

- If **both** accelerators are working: 100%
- If **one accelerator is not working** is assumed a 50% of availability
- If **none** are working: 0%

Definitions for the accelerator

- **Hardware availability (HA)**: fraction of time that the machine is available to produce beam over the scheduled operation time. Includes unscheduled repairs and all associated cool-down, warm-up and recovery times.

- **Beam Effectiveness (BE):** is the effective fraction of beam time actually delivering to the target facility. Include machine protection trips and beam degradation.

- **Beam availability (BA)** is the product of the hardware availability and the effective fraction of beam time. BA requirement = 87%

$$BA = HA \cdot BE$$

Availability allocation

Beam effectiveness was roughly calculated as 95.55%

- A preliminary rough assessment showed that, for each accelerator, the beam would be about 98% of the nominal intensity on average
- About 2.5% of the annual scheduled operation time is lost due to beam trips for each accelerator (comparative study)

Hardware availability requirement for each accelerator

$$HA_{A1} = HA_{A2} = \frac{BA_{AF}}{BE_{A1,2}} = 91.1\%$$

Allocation between IFMIF accelerator systems

Systems	HA requirement
Auxiliaries	99.4%
Diagnostics	99.8%
HEBT	99.2%
Injector	98.9%
MEBT	99.5%
RF System	98.2%
RFQ	98.6%
SRF Linac	97.2%
Accelerator	**91.1%**

Paper: "*RAMI analyses of the IFMIF accelerator facility and first availability allocation between systems*". E. Bargallo, et. al., Fusion Engineering and Design (2012)

Approaches for RAMI

Comparative studies

Gather information from other facilities. Compare it to results obtained with other approaches, have reference values, extrapolate for IFMIF and learn from other facilities (good practices, problems occurred…)

Analytical calculations

Fault tree models to analyze each accelerator system independently. Compare results with hardware availability requirements. Propose improvements to achieve the requirements. Specific probabilistic analyses.

Availability simulations

Monte Carlo simulation for the whole accelerator, considering beam parameters, maintenance policies and synergies between systems among others. Global availability results and beam parameters are obtained.

2. Analytical calculation

Analytical calculation models

- **Individual fault tree model** for each system using RiskSpectrum® PSA Professional
- Compare the results with the **Hardware availability requirements**
- Find **weak points of the design** and propose **improvements**
  - Importance/sensitive analysis
  - Parametric analysis
  - Time-dependent analysis
- **Many models were developed** to analyze different design options, possible improvements or different operation considerations.

Paper : *"Hardware availability calculations and results of the IFMIF accelerator facility"* E. Bargalló, et. al., Fusion Engineering and Design

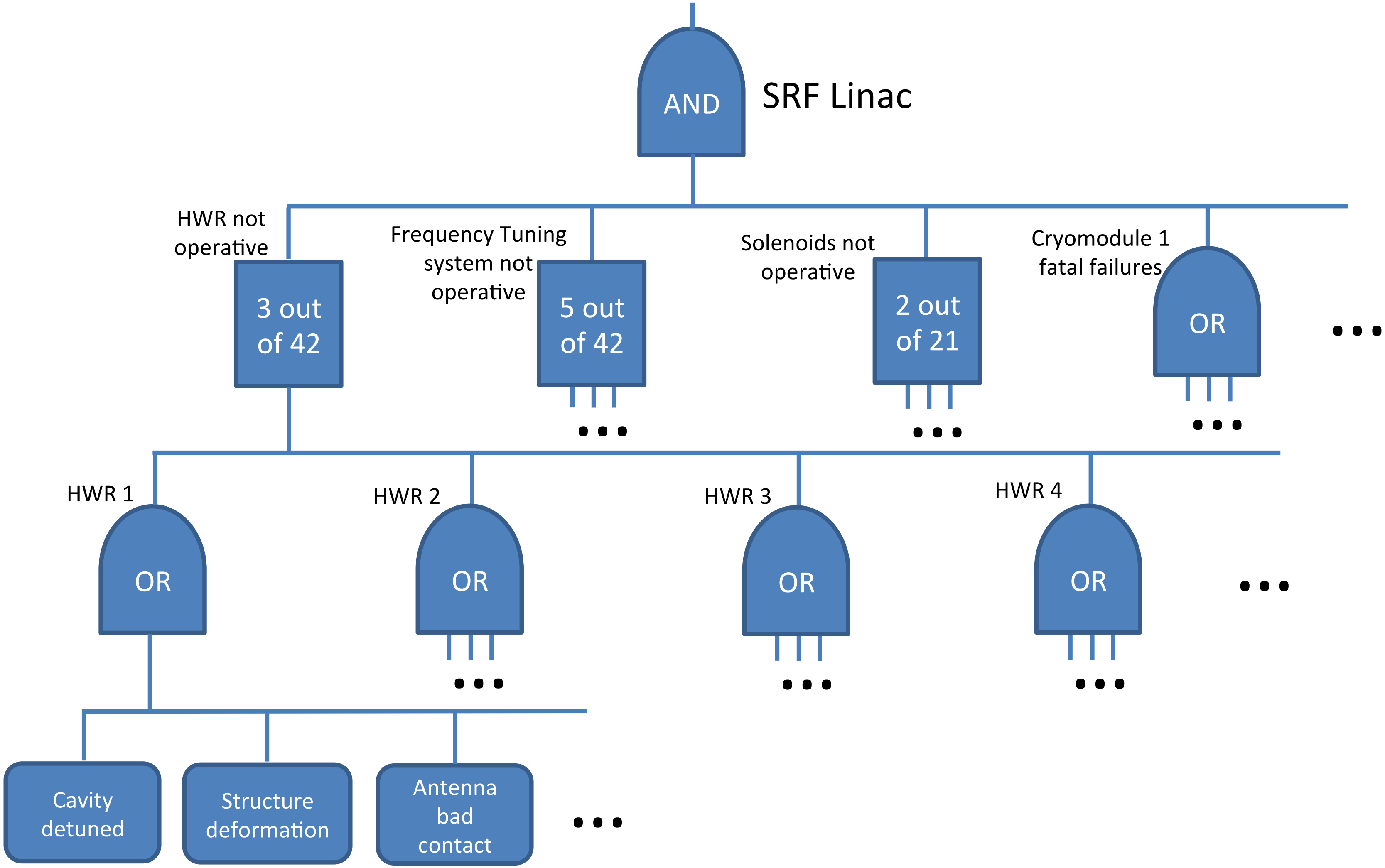
Example: SRF linac

- **Cryomodule refurbishments** will occur (7 from comparative study and 10.8 from the probabilistic analysis)
- **2.5 months for a single maintenance** activity (only 20 days of scheduled maintenance period)

- **Spare cryomodules** prepared to substitute the failed ones (20 days)
- **Failure acceptance** to perform corrective maintenance actions in the scheduled maintenance period

Case	Characteristics	SRF linac hardware availability
Case 1	- With hot spare cryomodules - Accepting beam degradation	98.07%
Case 2	- Without hot spare cryomodules - Accepting beam degradation	93.15%
Case 3	- With hot spare cryomodules - Not accepting beam degradation	88.20%
Case 4	- Without hot spare cryomodules - Not accepting beam degradation	81.80%

Example: SRF linac



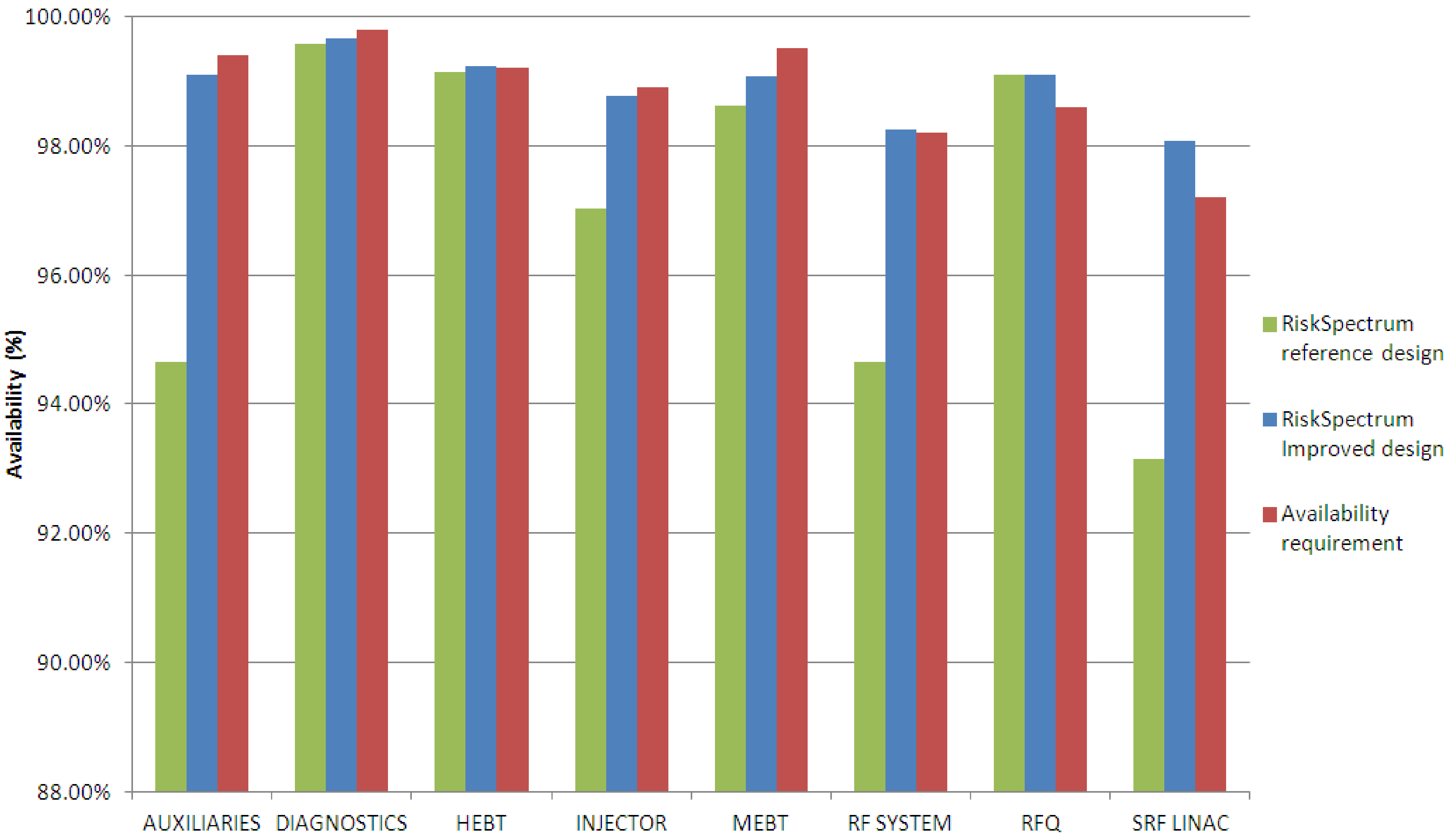
Example: RF system

- RF system availability **requirement is 98.20%**
- **Reference design tetrodes**:
  - Maximum availability achievable is **94.62%**
- **Solid state option**: relevant improvements:
  - Availability = **98.24%**. It has also less logistic performances and needs less manpower and spares
- Reliability, availability, maintainability and logistics studies were done for each design option
  - Very detailed fault trees with more than 7000 basic events and 600 gates
  - Specific logistic analysis (manpower, spares, workbench…)
  - Reliability solid state redundancy optimization…
- Results and comparison between designs:

	Tetrodes design	**Solid State design**
Max Availability	94.62%	98.24%
Initial cost	87,500k€	105,500k€
Replacement cost	7,400k€/year	2,500k€/year
Manpower cost	1,200k€/year	400k€/year
Cost at 30 years	344.8M€	191.8M€

Paper : "*Availability, reliability and logistic support studies of the RF power system design options for the IFMIF accelerator*" E. Bargalló, et. al., Fusion Engineering and Design 2012

Probabilistic analyses results



Probabilistic analyses results

- **Hardware availability** results obtained with RiskSpectrum
  - **Reference design 78.10%**
  - **Improved design 91.57%** (achieving the 91.10% required)
- These results were achieved as a result of the acceptance of operating with **beam degradation**
  - Requirements were done assuming that the mean intensity would be 98% of the nominal intensity (first rough estimation)
  - No easy way of calculating beam degradation with the probabilistic analysis
  - Considering number of failures and implication on the beam, a rough mean **intensity of 91%** was obtained

	Hardware availability	Beam effectiveness	Beam availability
Probabilistic improved design	91.57%	88.73%	81.25%
Requirement	91.10%	95.55%	87.00%

- In addition, no balance between BE and HA is possible

3. Availability simulation

AvailSim 1.0

- Is a **Monte Carlo simulation** developed by Tom Himel and other SLAC people for the ILC project.
- It **simulates the operation and maintenance** of an accelerator
- Main relevant features:
  - **Failure acceptance and beam degradation**
  - Include tuning and recovery times
  - Fix many things at once during an access
  - Include special characteristics of the accelerator (e.g. machine development)
  - Maintenance policies
  - Manpower and logistics analyses …
- An **adaptation** was necessary to simulate the IFMIF Accelerator:
  - Different inputs and outputs
  - Other parameters and goals
  - Different perspective (number of components…)

Paper : *"Availability simulation software adaptation to the IFMIF accelerator facility RAMI analysis"*
E. Bargalló, et. al., Fusion Engineering and Design

AvailSim 2.0

New features

- A **functions net** to model complex consequences in beam parameters
- “Realistic” **operation decisions**
- **Automatic simulation iterations** and statistical data treatment of the results
- Great detail in data outputs (history, component or system importance…) in **database format**
- **Maintenance policies**

  Possibility of not repairing all components in a maintenance period (not enough manpower, spares...)

Failure acceptance

- A lot of components' failure will stop the accelerator. But for some of them, a **retuning of components around can allow operation with degraded performance**
- The design is reluctant to accept failures: **nearly all failures will impose to reduce highly beam parameters**
- Operation limits:
  - Nominal **beam energy** is 40 MeV. The minimum energy acceptable for the users has been established at 39 MeV. Energy overhead is 1 MeV
  - **Beam shape** could be problematic for the target lithium loop. Some degradation is assumed to be acceptable in these studies
  - Operation with less **intensity** is accepted. Beam intensity is directly related to dpa (beam effectiveness) and to beam availability. Maintenance will depend on the degradation, the downtime to repair the component and the remaining time to the next scheduled maintenance period

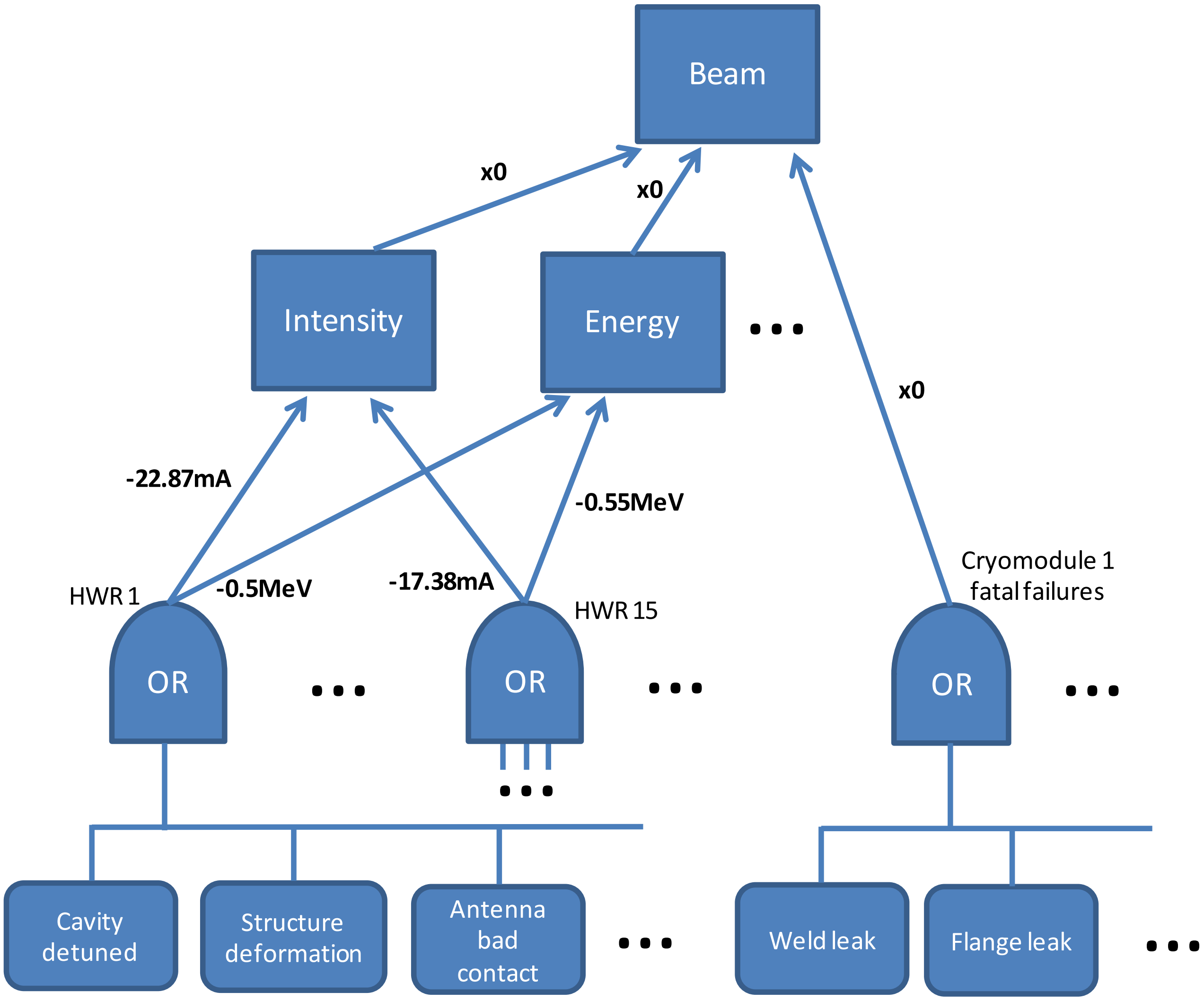
Failure acceptance

- Components which failure can be accepted if the accelerator is properly retuned and beam parameters reduced are:

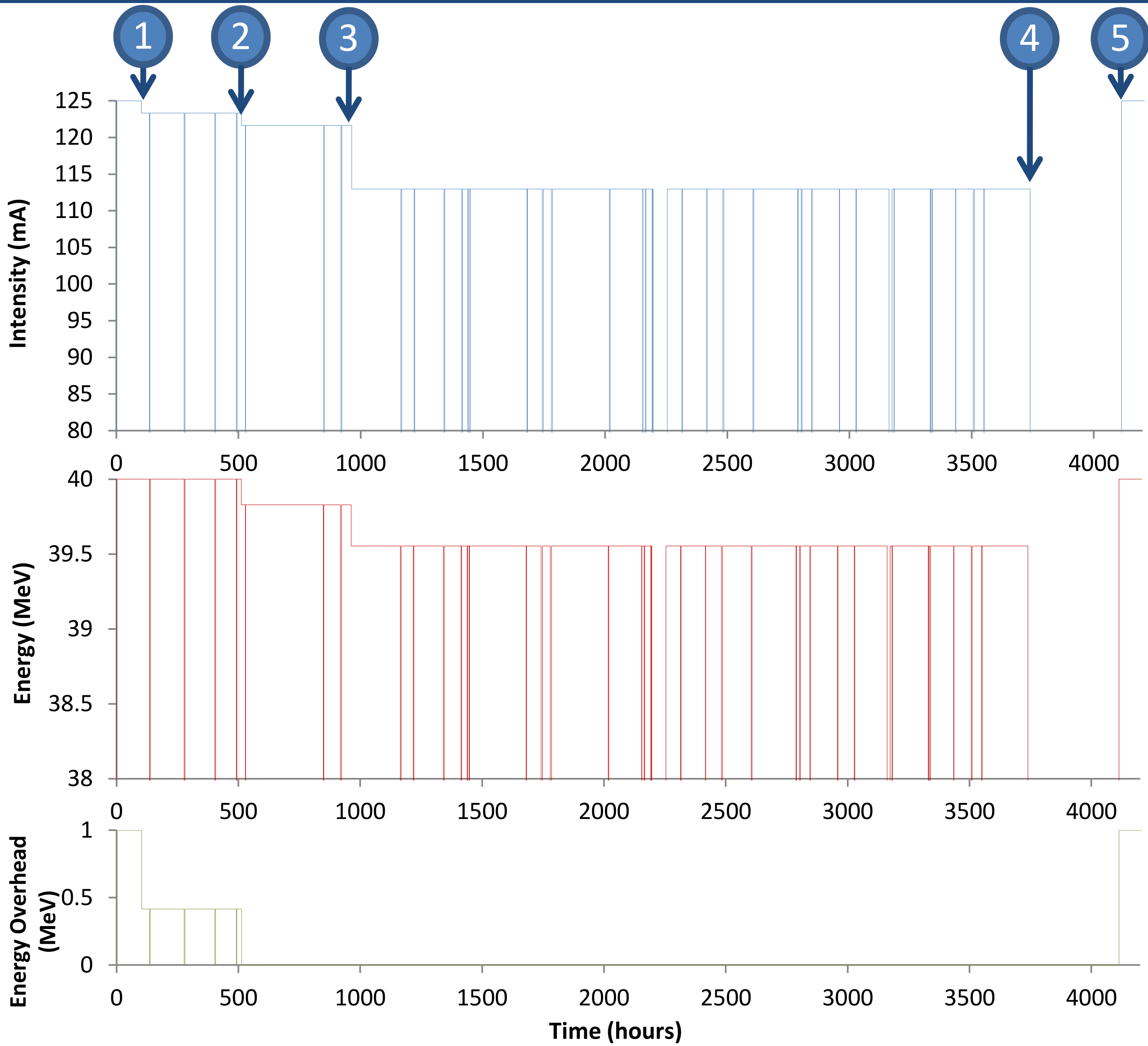
System	Component and kind of failure	Number of failures	Maximum intensity	Energy reduction	Beam shape degradation
SRF Linac	Cavity failure	First	Depending on the position	- E of the failed cavity	No
		Second or more	Depending on the positions	- E of the failed cavities	No
	Tuning system	First	Depending on the positions/2	- (E of the failed cavity/2)	No
		Second or more	Depending on the positions/2	- (E of the failed cavities/2)	No
	Solenoid	First	100 mA	- E of the switched off cavity	No
		Second	62.5 mA	- E of the switched off cavities	No
	Steerer	One per plane per cryomodule	115 mA	No	No
MEBT	Quadrupole	One	87.5 mA	No	No
	Steerer	One per plane	115 mA	No	No
HEBT	Quadrupole in a triplet	One per triplet	87.5 mA	No	Yes
	Steerers	Three failures per plane, non consecutive	115 mA	No	No
	Multipoles	One or more	125 mA	No	Yes

Failures acceptance and degradations analyses have been made jointly by the beam dynamics team, accelerator system designers and the RAMI team.

AvailSim: events and functions



AvailSim example



1- Cavity frequency tuning system in cryomodule 4 not operative. Intensity to 123.3 mA and energy overhead reduced in 0.6 MeV

2- A failure in another frequency tuning system in cryomodule 4 leads to reduce intensity to 121.6 mA. Energy overhead is consumed and beam energy decreased to 39.8 MeV

3- Cavity in cryomodule 2 became not operative. Intensity to 112.9 mA and energy to 39.6 MeV

4- Solenoid in cryomodule 3 not operative. Intensity should be 101.5 mA but it is too much degradation. Maintenance starts.

5- Restart operation after 16 days with nominal beam parameter.

Availability simulation results

Many results can obtained in AvailSim.

The most relevant are:

Parameter	Reference design	Improved design
Accelerator operating	210,331 hours	224,655 hours
Accelerator down (unscheduled)	35,908 hours	21,405 hours
Scheduled maintenance	16,560 hours	16,740 hours
Operational availability	80.03%	85.48%
Hardware availability	85.42%	91.30%
Vault access time	17,508 hours	10,889 hours
Times the vault has been accessed	164 times/year	125 times/year
Maintenance extended	352 hours	535 hours
Downtime used for scheduled maintenance	940 hours	548 hours

Simulation vs. Analytical results

Comparing the results obtained with RiskSpectrum and with AvailSim for the improved design models:

- **RiskSpectrum** calculates the Hardware Availability of the systems **without considering if the degradation** in the beam parameters is too high
- **AvailSim balances in a more realistic way** the Hardware availability and the Beam effectiveness

Software	Hardware availability	Beam effectiveness	Beam availability
AvailSim	90.75%	93.48%	84.83%
RiskSpectrum	91.57%	88.73%	81.25%
Requirement	91.10%	95.55%	87.00%

4. Conclusions

Conclusions

- Riskspectrum was a good tool for detailed analyses of individual systems and helped in the identification of possible improvements in the individual systems
- AvailSim allows to understand in a better way the global picture of the operation, failures and maintenance of the machine.
- The two methods were complementary and contributed very positively