Abstract

The current design of the RF power supply for the International Fusion Materials Irradiation Facility (IFMIF) is based upon tetrodes technology. Due to the improvement in the solid state amplifiers technology, the possibility of using this option for IFMIF is becoming a very competitive alternative presenting a priori several advantages in terms of availability, reliability and logistics. The current technology based on RF tetrodes chains leads no room for substantial improvements in terms of availability being the requirement for the RF system hard to achieve. On the other hand the solid state amplifiers technology opens from its concept several options to increase the system availability.

The principal goals of this paper are the use of RAMI (Reliability, Availability, Maintainability and Inspectability) analysis in the RF tetrodes design to led a future work to compare the availability, reliability and logistic performances for both alternatives.

The Project will consist in two parts: the development of a logistic support methodology and a specific study of the first part with an example related to the IFMIF facility.

First part: Develop a systematic procedure to study the logistic support required by any component of the IFMIF facility, focusing on the component’s effect in the availability of the whole facility

Second part: For the radiofrequency (RF) modules in the deuteron accelerator, study its logistic requirements and determinate the optimum quantity of the involved resources. It will comprise a research task of the requirements in the available documentation and a following task consisting in the simulation of the behaviour of the RF modules, in order to determinate the logistic support required.

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1. Glossary

1.1. List of Abbreviations

Module	Contains 2 RF chains. It is divided in two platforms: the MP and the CLP
MP	Main platform. It generates and accelerates the RF. Low level RF (LLRF), the pre-driver amplifier (Solid State), the driver amplifier (tetrode) and the final amplifier (tetrode). Control systems are also in this platform.
CLP	Circulator and Load platform. It consists of the circulator, the circulator load. It transmits the RF power from the MP to the accelerator, preventing the MP from the reflected RF power.
RF	Radiofrequency
PS	Power supply
LLRF	Low level RF
HV	High voltage
LV	Low voltage
RAMI	Reliability, Availability, Maintainability and Inspectability
IFMIF	International Fusion Materials Irradiation Facility
LSS	Logistic Support Study
LS	Logistic Support
MTBF	Mean Time Between Failures
WB	Work bench

2. Introduction

2.1. Project Objectives

The aim of the Logistic Support Study (LSS) is to help in the characterization of supportability factors. It offers a path to follow in order to identify and quantify the resources required for analysed system.
Based in the ILS (Integrated Logistic Support) methodology, the LSS comprises seven supportability fields:

- Life cycle cost
- Spares
- Personnel organization
- Training
- Technical manuals
- Tools and support equipment
- Support facilities

The term LSS is used instead of ILS & LSA in order to avoid misunderstandings: besides having the same purpose, the ILS & LSA has some fixed procedures which are not going to be done.

2.2. Project Scope of supply

The current project aim is to study the quantity of spare RF modules (hot and cold), the Technicians teams and the Work Benches to tune up the RF Modules

3. IFMIF

The implementation of this ambitious project requires a first phase called IFMIF EVEDA (Engineering Validation and Engineering Design Activities). It is aimed at providing the Engineering Design of IFMIF and at validating the key technologies of IFMIF through several prototypes. The main goal of the project is to deliver in a 6 year framework the Engineering Design File of IFMIF, enabling its rapid construction.

This design file will be validated thanks to the design, the manufacturing and the tests of 3 main prototypes: an accelerator (125mA/9MeV/CW), a 1:3 scale lithium target, the test cells of materials. The officially named for the accelerator prototype is Linear IFMIF Prototype Accelerator (LIPAc).

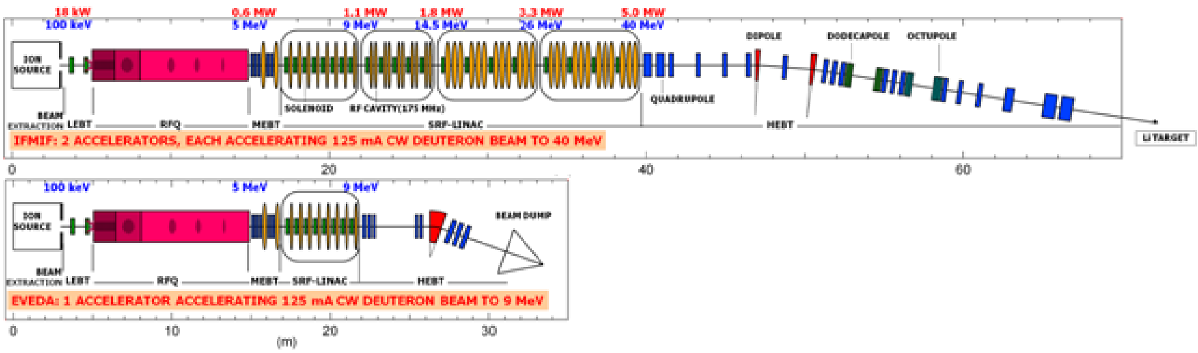

Figure 1: General layout of the IFMIF accelerators with comparison to the LIPAc [1].

The IFMIF is made up of 5 five different facilities, as mentioned above. Next there is a brief description of the main ones:

- Accelerator Facility
- Target Facility
- Test Facility

3.1. The accelerator

There are two accelerators each one produces a 40MeV, 125mA deuteron beam, directed to a common flowing lithium target. The lithium loop and lithium processing system are located below the main level of the facility. Each IFMIF accelerator is a sequence of acceleration and beam transport stages. The deuteron beam is produced and extracted from an Electron Cyclotron Resonance Ion Source (ECRIS) at 100keV. A Low Energy Beam Transport (LEBT) section guides the deuteron beam from the source to a Radio Frequency Quadrupole (RFQ). The RFQ bunches the beam and accelerates 125mA to 5MeV. The RFQ output beam is injected through a matching section called Medium Energy Beam Transport line (MEBT), which guides the beam up to the next accelerating system: Superconducting Radio Frequency linac (SRF), composed of four cryomodules totalizing 42 superconducting cavities and 21 solenoids, bring the beam energy to 40MeV, and finally a High Energy Beam Transport line (HEBT) guides and shapes the beam to produce a rectangular and uniform footprint at the level of the lithium target.

Injector

The IFMIF ion injector, consist of the ECRIS and the LEBT section. Different kinds of ion source have been studied, but the ion source finally selected is an Electron Cyclotron Resonance (ECR) at a frequency of 2,45 GHz at 875 Gauss and will deliver a deuteron beam of 140mA at 100keV in CW.

ECR sources are widespread applied in the accelerator facilities. Their major ability is to produce CW beams from a large variety of elements at useful intensities and good beam quality for nuclear and atomic physics research. The main characteristic of ECR sources is that the discharge in plasma is produced by RF power without cathodes. Therefore, only the source material injected into an ECR source is consumed. As a result, ECR sources can be operated continuously for long periods without interruption. Maintenance required on ECR sources is also minimal, consisting mainly of occasional repair of vacuum equipment, external ovens and electrical support equipment [2]. The ion source development and construction is based on a prototype called SILHI built by CEA-Saclay engineers.

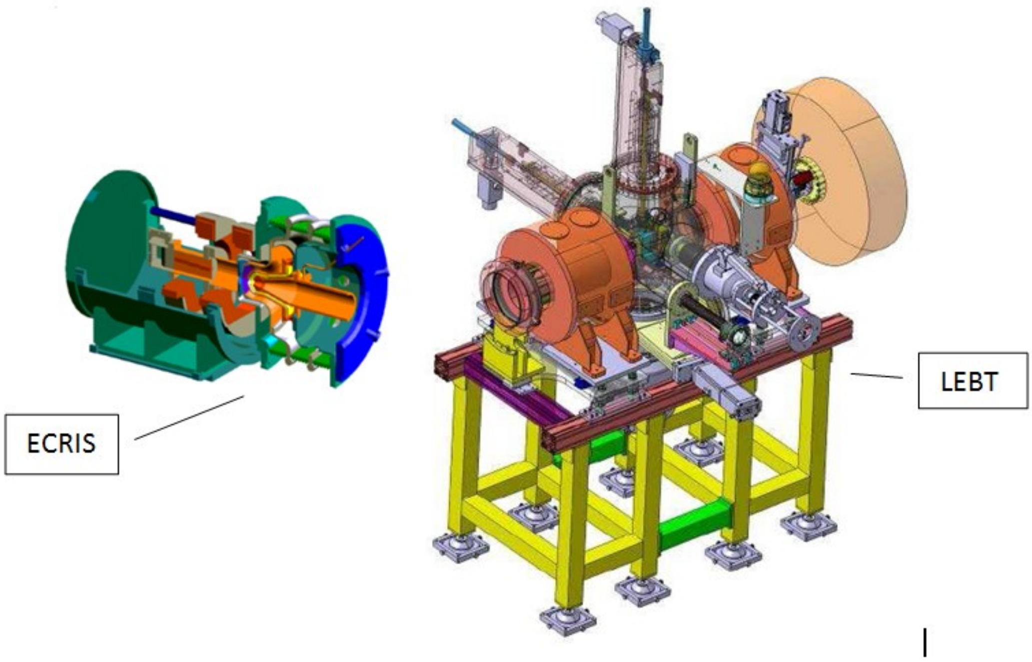

Figure 2: IFMIF ECR Ion Source and LEBT [2]

The Low Energy Beam Transport (LEBT) is essentially a pair of weak focusing magnets (solenoids) which have to match the beam to the RFQ input needs. This is necessary to provide optimal acceleration and to avoid activation of the RFQ. There is also a couple of quadrupoles or steerers which are optical elements used to focus the beam in the transverse directions if it deviate.

Radio Frequency Quadrupole

The RFQ will be the largest ever built, with 18 modules (~12.5m). It will accelerate the beam from 100keV to 5MeV while strongly focuses and bunches the DC beam from the injector as required for injection into the SRF. The aim of this pre-acceleration is the optimization of the SRF Linac section, which needs an input with this energy for taking profit of the 175 MHz frequency it is fed with.

The beam losses are directly related to the accelerator activation. The linac has been defined as a “hands on” maintenance system. Therefore a minimum beam loss at energies above ~ 1MeV are defined. There is no lower energy threshold for inducement of radioactivity when deuterons strike material, but confinement of beam losses as much as possible to under 1MeV (~10 times the injection energy) can be achieved with design and optimization techniques [3].

The RFQ cavity is an inherently robust structure that is expected to require little routine maintenance. During the 30 year lifetime of the facility, the RFQ will require to replace the first segment of the cavity due to excessive erosion of the vane tips from beam scrape-off. It is expected that this operation can be performed in the accelerator vault, during a scheduled maintenance period, with a minimum of accelerator disassembly.

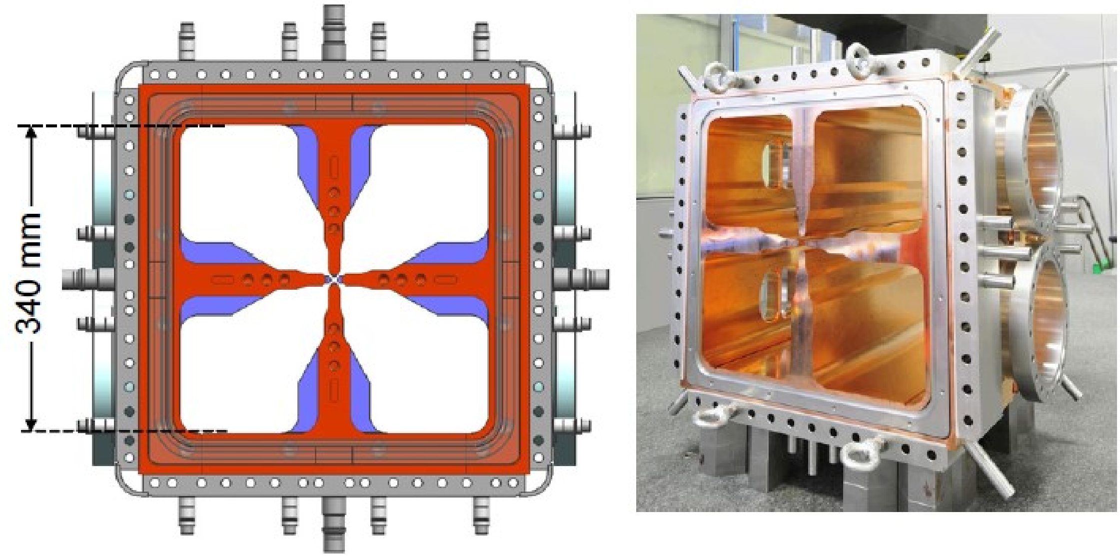

Figure 3: RFQ cavity prototype [4]

Medium Energy Beam Transport

MEBT focuses the beam in transverse with five quadrupoles (1triplet and 1 doublet) and in longitudinal with 2 buncher cavities. There is also a pair of collimators (scrapers) between the first and second magnet in order to absorb any deviation of the beam and properly matched into the SRF linac.

Superconducting Radio-Frequency Linear Accelerator

In the Comprehensive Design Report (CDR), published in 2004, the solution for the deuteron beam acceleration from 5 to 40MeV relies on a conventional structure, the Alvarez type Drift Tube Linac (DTL). However, all structures of this type have been developed for low intensity projects and operating in pulsed mode with rather low duty cycles, of the order of a few percents (SNS at Oak Ridge, J-PARC at Tokai, or LINAC4 at CERN). The extrapolation to the operation mode of IFMIF, which has to accelerate a high intensity beam in Continuous Wave (CW) mode, represents a real technological challenge. Consequently, an alternative solution, jointly proposed by CEA and CIEMAT, consists in using superconducting Half-Wave Resonators (HWR) since they could offer several advantages, especially a length reduction and significant plug power saving [5].
The SRF linac is the main and more complicated part of the accelerator. It is composed of 4 cryomodules, focuses the beam with solenoids and accelerates it with Half-Wave-

Resonator cavities up to the energy of 40MeV. A Half-wave resonator is a cavity made to match its measures with half the wavelength of the electric field in it. This way a resonance is generated and the amplitude is enhanced, and the energy associated to it (and transmitted to the particles) is much higher. The cryomodules have in total 21 solenoids and 42 resonators (operated at 4.2 K).

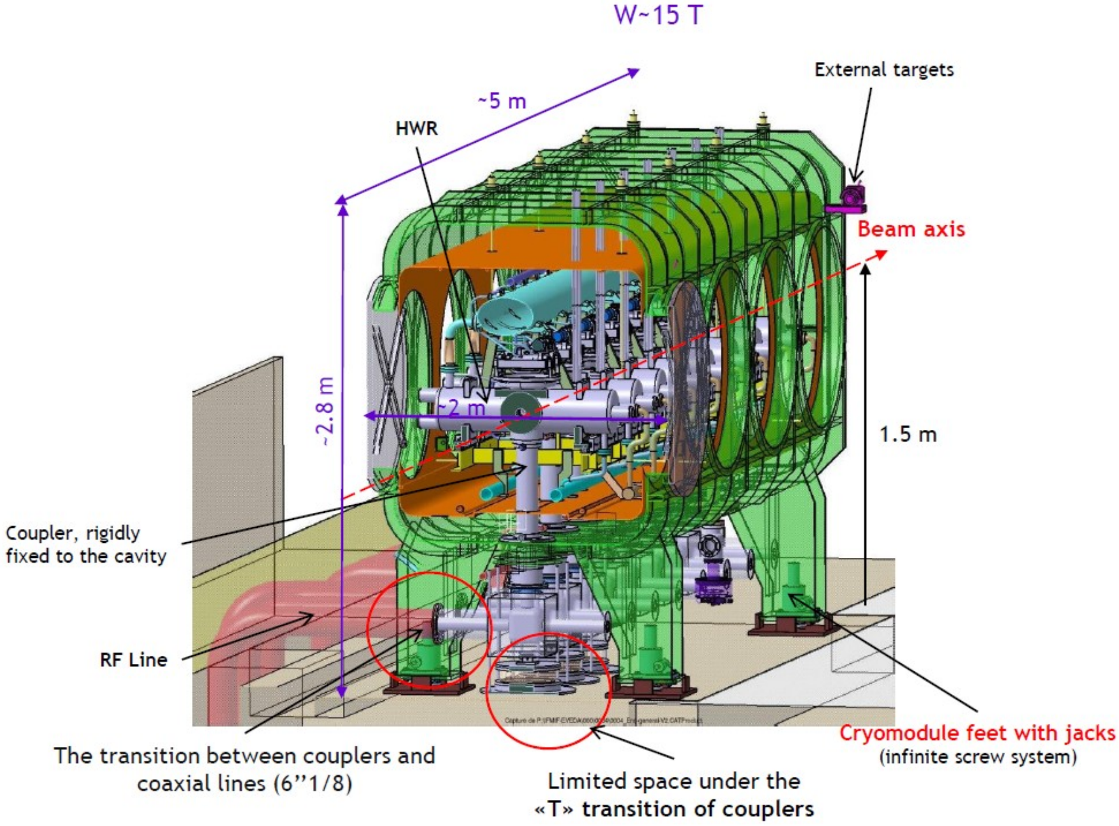

Figure 4: Overview of the cryomodule [6]

High Energy Beam Transport

Finally a HEBT line focuses the beam by means of quadrupoles and homogenizes the beam density by means of higher order multipoles, bends it by means of two dipoles and expands and matches it to the required rectangular and uniform footprint at the level of the lithium target.

3.2. Target Facility

Every deuteron beam with a power of up to 5 MW (40MeV, 125mA) collides on a common beam footprint with a height of 50 mm and a width of 200 mm on a free surface of liquid Li flow of

25mm thickness. This may induce a reaction in which high energy neutrons are produced, in a range peaked around 14MeV. Typical reaction are: 7Li(d,2n)7Be, 6Li(d,n)7Be, 6Li(n,T)4He.

To avoid boiling and significant vaporization of the liquid Li even under a high power density of up to 1 GW/m2 (10 MW in the area of 50 mm x 200 mm) and a vacuum condition for the accelerators, a concept of liquid Li target flowing at high speed (15m/s) along with a concave channel increasing a boiling point due to a centrifugal force has been employed.

These facilities have to purify, chill and monitor the Li flux constantly, to prevent any radiological hazard, and structure erosion. Moreover, Li has to be perfectly isolated from air and water, to avoid combustion. Vacuum conditions around this system are designed to prevent this from happening [7].

3.3. Test Facility

The conceptual and engineering design of the IFMIF contemplates the Test Facility as three main parts: Test Cell (TC), Access Cell (AC), and Test Module Handling Cells (TMHCs). However this facility is still very susceptible to design changes.

Test cells provide the space for secure and reliable interaction of the deuteron beams, the lithium Target Assembly (TA) and the Test Modules (TMs).
Since materials inside and around the test cells will be highly activated, remote handling is needed for manipulation and maintenance operations. The range of temperatures also implies cryogenic system necessarily.

The Access Cell provides transport capacity, space and logistics for deposition of the Test Cell cover plate and shielding plugs. It is equipped with an infrastructure for the safe transfer of Test Modules and Target Assembly to and from Test Module Handling Cells.

The Test Module Handling Cells (TMHCs) are subdivided in a chain of cells according to their functions. Decontamination, heat removal and clean the specimens to be transported to the Post Irradiation Examination Facilities (PIE).

Depending on the damage level, the Test Modules (TM) are divided to three sections:

- High Flux Test Module (HFTM, > 20dpa/year),
- Middle Flux Test Module (MFTM, 1 ~ 20dpa/year)
- Low Flux Test Module (LFTM, 0.1~1dpa/year)

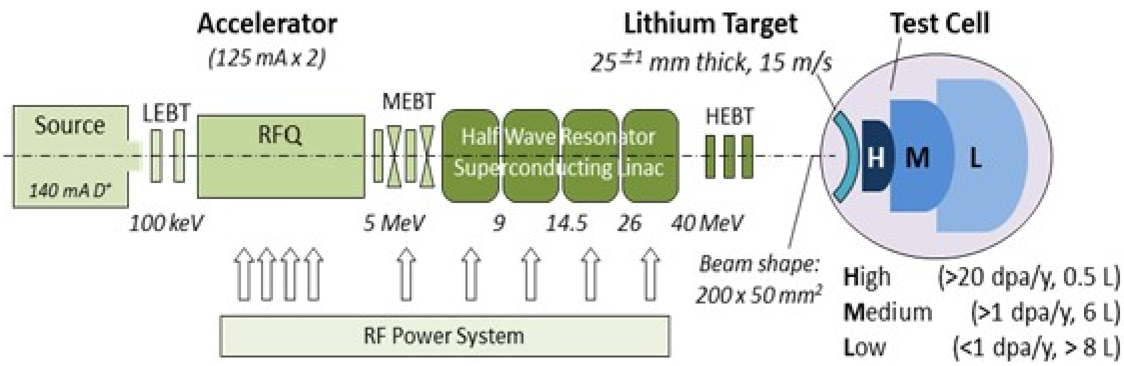

Figure 5: Schematic principle of IFMIF project [8].

3.4. Availability requirements

The operational availability requirement for IFMIF is 70%. This requirement is established for normal operation. However, during the first years of operation is foreseen that only one accelerator will be available until the commissioning of the second one is completed. No specific availability requirements have been established for this phase.

In the CDA [11] the availability budget was shared between the facilities inherent availability requirements taking into account 8 hours/week for the RF antenna replacements. As the RF antenna is not in the current design, the maintenance plan has been changed and the availability requirements have been updated.

In the current maintenance plan, one of the major restrictive components is the Boron nitride disks from the Injector. The Boron nitride disks have an expected life time of 400h [12]. This is the lowest lifetime of a component whose failure includes beam stop. A maintenance plan with two maintenance periods: a three days stop after six months of operation to change the disks (and other possible maintenance operations) and a long maintenance period to make the exhaustive maintenance and to replace the tests modules. This maintenance schedule is defined in the Maintenance Plan Document [13].

Therefore the scheduled maintenance plan for the annual campaign is the following:

- One long maintenance period of 20 days for general maintenance: mainly for maintenance in the lithium target facility and test modules replacement (including back-plate and modules change-out) and long term accelerator maintenance.
- One intermediate maintenance period of 3 days for short-term maintenance activities in the accelerator and other auxiliary and conventional systems. This maintenance period includes the replacement of boron nitride disks of the ion sources.

This new maintenance plan has changed the inherent availability requirements for each facility. The results of the new requirements are shown in the following table:

IFMIF RAMI specifications	Current requirements	Old requirements
Tests Facility	96%	97.5 %
Target Facility	94%	95.0%
Accelerator Facility	**87%**	**88.0%**
Conventional Facilities	98%	99.5%
Central Control System and Common Instr.	98%	99.5%
TOTAL (product)	**75%**	**80.7%**

Table 1: IFMIF inherent availability goals [13]

Availability requirements for the accelerator facility have changed from 88% to 87%. Therefore the requirement is lightly less restrictive. Nevertheless, it is a great challenge to achieve this availability requirement.

The 87% availability requirement for the accelerator facility is related to *dpa* (damage production) that both accelerators could produce in a determinate period. Taking into account this direct relation it has been assumed that [13]:

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

Due to these assumptions, the inherent availability for each accelerator should be the same (87%). Therefore, only one accelerator would be necessary to analyze. In consequence, only one injector it is studied. This concept could be expressed by these equations:

$$A_{Total\_accelerator} = 0,5 \cdot A_{accelerator\_1} + 0,5 \cdot A_{accelerator\_2}$$

$$A_{accelerator\_1} = A_{accelerator\_2}$$

$$A_{Total\_accelerator} = A_{accelerator\_1} = A_{accelerator\_2}$$

Where $A_{Total\_accelerator}$, is the total availability of the accelerator, $A_{accelerator}$ is the availability of one of the accelerators.

The requirements for IFMIF are given in terms of availability. No specific reliability requirement have been established, only the reliability requirements derived from availability ones. The mission of IFMIF is to produce a number of dpa in a period of time. In other words, to achieve a total facility operational availability of 70% in order to reach accumulated damage levels around 100 dpa in a few years of operation. According to this, an elevated number of shutdowns could be valid provided that the total down time is short enough. On the other hand, operation of IFMIF must be continuous to avoid the complications of annealing effects that occur in the case of intermittent irradiation. Therefore, IFMIF must be reliable as an availability requirement. However, a limited number of shutdowns or other restrictions involving reliability need to be considered [14].

4. Study planning

Before any other action, the first step to be done before any other task is to *understand* the system to support and to recognize the supportability factors that could be developed and, in consequence, studied.

Four tasks are suggested to be done:

1. **Use study:** the functions the system has to perform and in which environment.

2. **System functions and requirements:** how the functions are achieved and what the system requires to work.

3. **Identification of the required LS resources:** related to the system requirements, which supportability factors are involved in the system performance. If the system boundaries are not yet defined, it is a good moment to do so.

4. **LSS goals definition:** the supportability factors we are going to study in order to help the system achieve certain goals.

4.1. Tasks as per Logistics Support Study LSS

First of all a deep knowledge of the system to support is required. In that section the aim is to study the system, identify its LS needs and mark them as goals of the LSS.

Use study: which functions the system has to perform and in which environment.

System functions and requirements: how the functions are achieved and what the system requires to work.

Identification of the required LS resources: related to the system requirements, which supportability factors are involved in the system performance. If the system boundaries are not yet defined, it is a good moment to do so. LSA 101 & 401

LSS goals definition: the supportability factors we are going to study in order to help the system achieve certain goals.

4.1.1. Use study and scope size. Related to LSA task 201

How, when and where the system will be used. Supportability factors identification, from the 7 categories? Information required, if not: assumptions!

4.1.2. Functional requirements specification. Related to LSA task 301

Deep study of the system to support

Funcions

Requeriments

(performances => EDR p32/ 38)

4.1.3. Identification of required LS resources. Related to LSA task 401

If the system boundaries are not yet defined, it is a good moment to do so. In the current project only the quantity of spare RF modules (hot and cold) and Technicans teams are going to be studied.

4.1.4. LSS goals definition

Te goal is simple: define quantity of spare RF modules (hot and cold) and Technicans teams.

4.1.5. Procedure

Data compilation of technical specifications. System model?

All data concerned with the system is required to perform a correct LSS. The most important technical specifications are those which concern lifetimes, MTBF, MTTR...

S&SRD – Supportability and Supportability Related Design factors. Related to LSA task 205

After the data compilation, the actions to be considered in order to improve LS.

Comparative analysis with similar systems or subsystems. Related to LSA task 203

All data concerned with the system is required to perform a correct LSS.

Standardization and compatibility study. Related to LSA tasks 202 and 402

Resources identification. It is interesting sharing “common” resources with other systems in the same facility whenever it is possible due to its minor cost; however it is necessary to take care of the effects it will cause to them and the risks that involves.

Support system alternatives. Some parts are related to LSA task 302

Generation and identification of the qualitative LS resources for each alternative. Which of the seven fields of the LS should be studied is defined in the goals.

4.1.6. Quantitative study. LS alternatives analysis and evaluation.

LS alternatives simulation.

It ends with the determination of quantitative LS resources. Problems and obstacles each LS alternative has to face are detected. If there are common problems or goals that are not achieved in all the alternatives => Iterative process, back to A and all tasks review.

We have to take into account that there are 2 or 3 kinds of RF modules

Evaluation of LS alternatives. Related to LSA task 303

The study of alternatives RF Modules vs. Solid State technology falls out of the scope of the current project.

4.2. Logistic Support Study (LSS) – Guide

The LSS has the main aim to define the logistics required for a system (or equipment, facility...) in order to allow its proper operation. Based in the LSA, defined in MIL-STD-1388-1A,

It is scheduled providing just one system, not for comparing different system alternatives and its supportability associated. However, it is not difficult to perform an analysis of alternatives.

The objectives of the system must be defined, the LS option chosen just helps to achieve that objectives.

The results should be presented following the LSAR requirements, described in MIL-STD-1388-2A

4.3. Study planning: develop a strategy

Once the goals to achieve with the LSS help are defined, it is time to plan the working route in two interconnected tasks:

1. **Define the resources:** The personnel, hardware... to develop the LSS. The information available of the system to support is an essential fact, so a previous research task is required in order to obtain a database from which the LSS would be performed.

2. **Schedule the work:** apart from the research task, there will be two more parts of the LSS, first a qualitative study and later on a quantitative study of the logistics involved in the support of the facility.

The qualitative part consists of a choice of the several activities that could be performed. According to the LSS goals proposed, not all the activities need to be performed.

4.4. The system to study

First model

Besides an expected life of 30 years for IFMIF, the simulation studies a period of 11 months. It results from considering that IFMIF is going to operate in annual cycles: an operation period of 11 months followed by a maintenance term of 22/30 days.

That period also fits with the tetrodes: although their expected operational lifetime is 18 months, it would be impossible to replace them during operation. In consequence, all the tetrodes are expected to be replaced during the maintenance stop.

4.4.1. RF system

The radio frequency (RF) system has to provide RF power at 175 MHz to 50 cavity inputs for each accelerator. These inputs will need different RF power: from 60kW for the low energy part, to 200kW for the high energy section.

The design of the RF system of the IFMIF accelerators has been done to improve the availability and reliability performances from the commencement. Several alternatives were analyzed and compared in terms of feasibility, cost and availability. Powerful diacrodes with splitters, tetrodes with different configurations and solid state technology were analyzed. The chosen solution for the prototype and for the IFMIF reference design is based on up to

200 kW RF power amplifiers configured in modular removable boards and up to 400 kW power supplies. Solid state amplifiers seemed to offer an excellent performance, but there was not enough knowledge to adopt this solution. Nevertheless, the cost and efficiency drawbacks of the solid state options are not true anymore due to transistor improvements since 2007. The output power per transistor was around 400W while nowadays it is around 1000-1200W. This increase of power implies a drastic reduction on the number of combination stages required for a given output power.

Current design: tetrodes

The current reference RF system design for the IFMIF accelerator facility is based on RF tetrodes chains in modular boards.

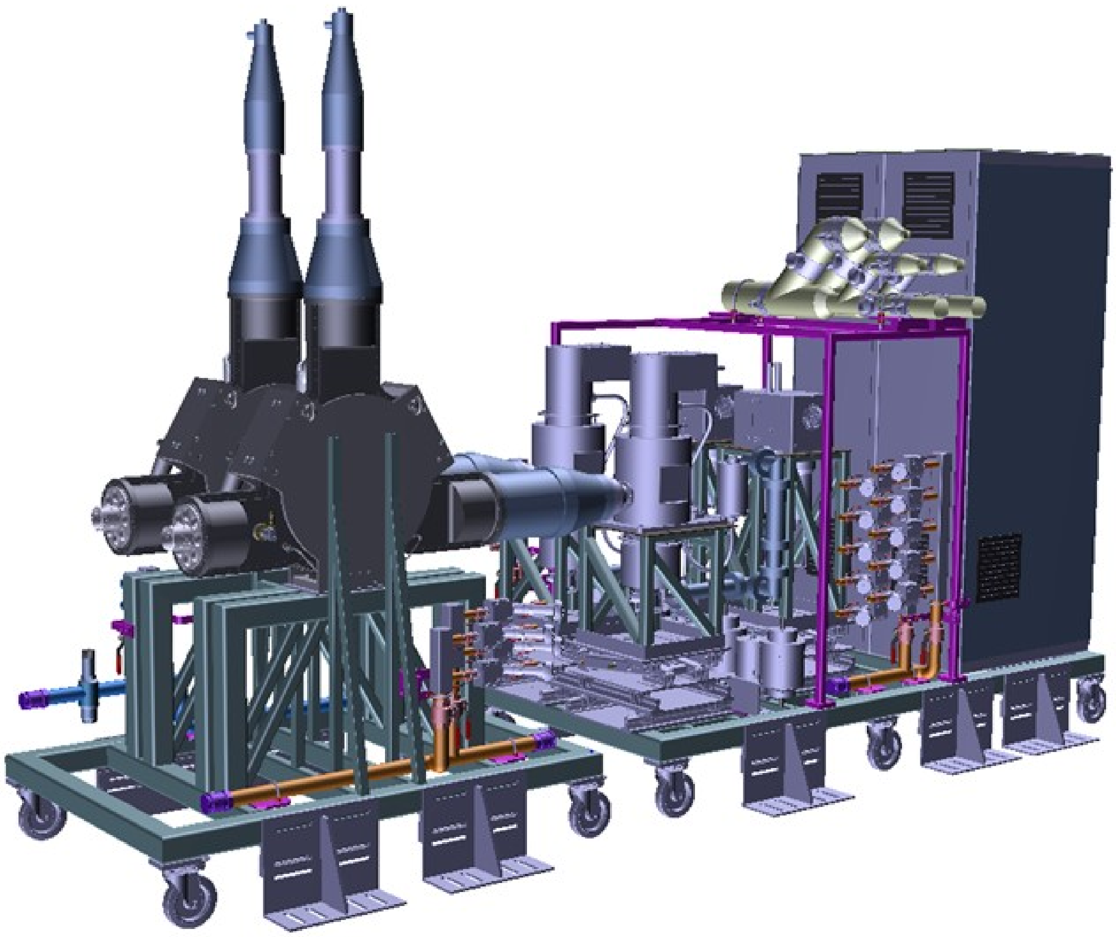

Fig.6 Circulators and RF chains boards.

Design description

The RF system of each accelerator is composed by 32 chains of 200kW and 18 chains of 105kW. Each chain has a circulator and a dumb. The chains have been installed in removable modular boards by pairs, leaving 16 modules of 200kW, 9 modules of 105kW and 25 circulator platforms for each accelerator.

Each chain consists of a Low Level RF, a pre-driver amplifier (a 400W Solid State amplifier), a driver amplifier (TH561 Tetrodes) and a final power amplifier (TH781 Tetrodes). Each module is composed by two chains, the power supplies, the control and protection systems, and the common auxiliaries. The High Voltage Power Supplies for the TH781 tetrodes anode placed outside the removable platform. More detailed description can be found in [14].

Cycle

The first 50 MP which will operate enter directly to the accelerator. Some of them are considered to enter as hot spares, as much as the capacity of the SetUpWB. The rest go to the warehouse as cold spares, which are subjected to a limited life of 30 days. If a module had spent more than 30 days as cold spare, their tetrodes need to be set up: it will be sent to the maintenance facility. For that reason it is not desired to have unnecessary MP spares.

Once a module fails, it is sent to a temporary buffer where it will wait for a free workbench. When there is a free workbench, the MP is installed there in order to be repaired.

5. Qualitative study

It is planned in the following steps [9]:

1. **Data compilation:** as it was said before, it is the starting point. All data concerned with the system is required to perform a correct LSS. The most important technical specifications are those which concern lifetimes, MTBF, MTTR...

2. **S&SRD – Supportability and Supportability Related Design factors:** the actions to be considered in order to support the system and the identification of the required resources.

3. **Comparative analysis with similar systems or subsystems**.

4. **Standardization and compatibility study:** although it is risky, it can simplify the support activities.

5. **Support system alternatives:** generation of qualitative LS solutions. Involving no calculations, a model of the alternative with its related data is needed.

5.1. RF modules

One of the major concerns of this design is the tetrodes lifetime. Filament lifetime is the cause of the short tetrodes lifetime. The time required to obtain a new tetrode from the manufacturer is around 9 months for the TH781, and 6 months for the TH561. It is fundamental to plan properly the spares logistics.

It is assumed that the minimum lifetime is 10,000h for both TH781 and TH561 tetrodes. In order to not decrease the unavailability of the accelerator for the short lifetime of the tetrodes, it is planned that all the tetrodes will be replaced in the long maintenance period, after more than 8000 hours of operation. This means to replace 200 tetrodes in 20 days; which is challenging.

6. Quantitative Study

The LS alternatives analysis and their evaluation [10].

1. LS alternatives simulation: it ends with the determination of quantitative LS resources. Problems and obstacles that each LS alternative has to face are detected.

2. Evaluation of LS alternatives: comparative study of the results obtained in the previous task. It ends with the selection of the worthiest alternative according our criteria.

If there are unacceptable common problems or goals that are not achieved in all the alternatives, as an iterative process it is required to go back to the qualitative study and make corrections in the work done.

6.1. Supportability tasks

They are divided in three groups: platforms replacement in the RF power supply area, platforms maintenance and components repair.

In-site module repair: when there is no RF feed, the accelerator is not working properly. It is the most critical task as it affects directly to the system availability. As most of the platforms repair tasks require long time, a basic diagnosis determines its length and if it is worthy to do the repair actions in-site. It only will happen when the repair actions are shorter than the platform replacement.

Offsite module repair: when a failed platform is extracted, it is conducted to the RF modules maintenance facility buffer. There, when there is a workbench available, it is tested and repaired. The four tetrodes are replaced.

Components repair: most of them are not going to be able to be re-used. From the repairable ones, only the tetrodes are going to be analysed. The tetrodes are the most expensive components and the ones that require a longer and a more specific maintenance (set up).

Platform replacement: extraction and insertion

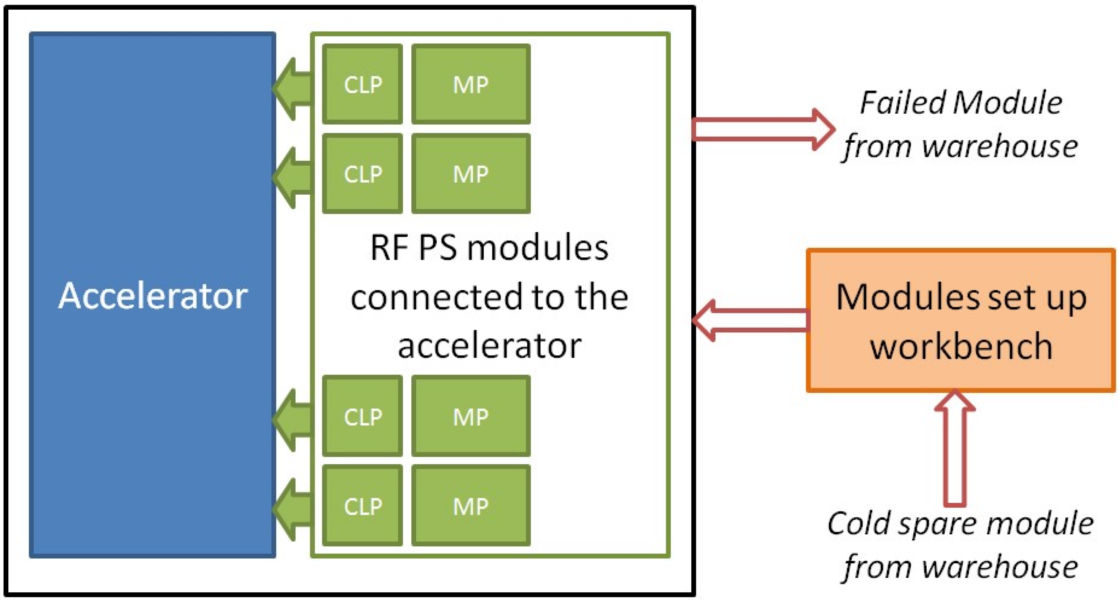

Image 7 – RF platforms cycle inside the RF PS facility

In order to optimise the time required, the required tasks are listed below:

Task	Time (min)	Comments
Preliminary diagnosis	5	
Basic diagnosis	30	Its performance depends on the preliminary diagnosis
RF & HV power supply cut	7	
Coaxial line disconnection	25	
Filament PS cut	8	
LV PS disconnection	10	
Control wires disconnection	10	All the wires together in a bus would shorten that task
LLRF wires disconnection	10	
Water cooling cut & disconn.	20+10 (?)	(Time required?)

Task	Time (min)	Comments
Air cooling shutdown & disconn.	10	
Platform unfasten	20	
Platform extraction	25	A temporary buffer close to the RF facility would reduce those times. 20 and 25 minutes to extract and insert the MP platform?
"Hot spare" transport from warehouse	40	
New platform insertion	20	
New platform fasten	20	
Coaxial line connection	25	
Control and LLRF wires connection	10	<u>It should take more time to connect rather than to disconnect.</u> All the wires together in a bus would shorten that task
LV wires connection	10	
Connect and start water cooling	10	
Connect and start air cooling	8	
Filament switch on	8+30 (?)	
Sequential HV switch on	5	
In-line set up	30	

Table 2 –Main platform replace tasks and duration. Times were provided by CIEMAT.

However, some tasks could be done simultaneously improving considerably the downtime of the accelerator. Later, a Gantt diagram can be done and the action of replace a platform, optimized.

<u>Platform repair</u>

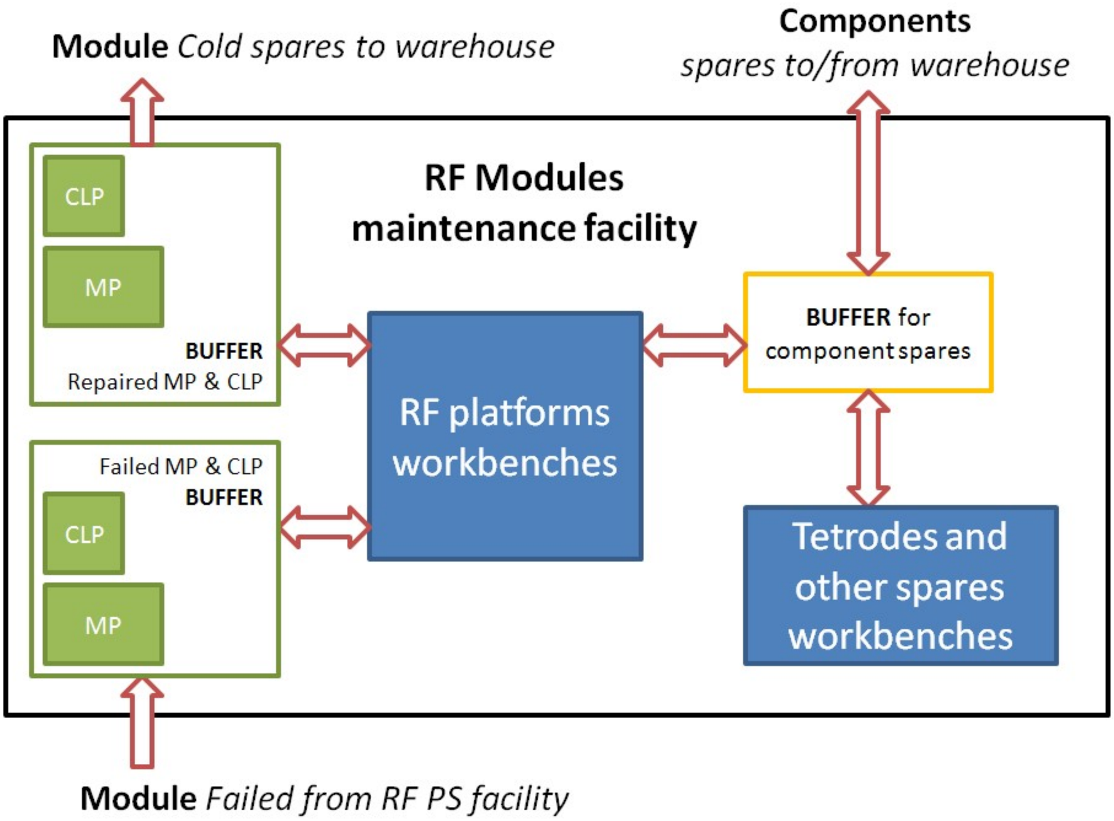

Image 8 – RF platforms maintenance facility

Actions to perform in order to repair a platform (CLP or MP):

Task	Time (min)	Comments
CLP		
CLP transport from buffer 1 to buffer 2	30	
CLP transport from buffer 2 to workbench	5	
CLP fasten to workbench	20	
Diagnosis hardware connection and start	15	
Water cooling check	10	
Water hoses repair	30	
Problem detection	40	
Circ Load replacement	60	
Bidirectional Coupler replacement	80	
Circulator replacement	110	
Electric wires/sensors replacement	30	
Coax line replacement	50	
CLP check	10	
CLP unfasten	20	
CLP transport to warehouse	30	

Task	Time (min)	Comments
MP		
MP transport from buffer 1 to buffer 2	30	
MP transport from buffer 2 to workbench	5	
MP fasten to workbench	20	

Diagnosis hardware connection and start	30
Air cooling check	10
Air pipes repair	60
Water cooling check	20
Water hoses repair	40
Problem detection	60
Generic rack electronic unit reset	10
General rack electronic unit replace	60
Electric wires/sensors replacement	20
Tetrode extraction (4 tetrodes)	40
Tetrode insertion (4 tetrodes)	60
Coax line replacement	120
MP check	20
MP unfasten	30
MP transport to warehouse	30

Table 3&4– CLP and MP repair tasks and duration. Times were provided by CIEMAT. (Buffer 1, RF PS facility. Buffer 2, RF modules maintenance facility).

In my proposal, all failed component will be replaced by a new/repaired one, the idea is not to have dead times in the platforms workbench. It is going to be considered, in the next section, the evolution of the tetrode maintenance.

Components maintenance

Tetrodes maintenance

Task	Time (min)	Comments
Workbench set up	15	Is it required?
Transport from buffer	20	Could TH561 & TH781 be set up at the same workbench? Or the 4 tetrodes of a MP will be set up at the same time?
Fixing to workbench	15	
Air cooling connection	10	
Water cooling connection	15	
PS connections	5	Are diagnosis elements required, such as temp. sensors?
Connections check	10	
Tetrode set up	2880	2 days
Set up check	15	
PS disconnect	5	
Cooling time	60	Is it required?
Water cooling disconn.	15	
Air cooling disconnection	10	
Workbench unfasten	15	
Transport to buffer	20	Does it require special conditions?
New tetrode delivery time	270 days	

Table 5 – Tetrodes maintenance. All times are assumptions

Tetrodes failure

- TH781 tetrodes failure rate will be modeled with a lognormal distribution with a mean value of **3.9e-5 h-1** and an error factor of 10.

- TH561 tetrodes will have better reliability parameters due to the lower power and lower operation conditions under design normal operation. FR is a lognormal with a mean value of **1.95e-5 h-1** and an error factor of 10

6.2. Failures in our study

After summing up all the possible failures, we have considered two kinds of failures:

- Small failure: with a probability of 0,0382% hourly, the damaged RF module requires 2 hour of maintenance on site by 1 team of two technicians

- Big failure: with a probability of 0,0287% hourly, the damaged module requires to be replaced by 2 teams of 2 technicians. A hot spare is required

6.3. Model for study: functions

We consider the accelerator is working if the sum of all the modules are working. Otherwise it remains inoperative

6.3.1. Failure (Trep) repair time – Sets a failure in an RF module

If $Accelerator_i(t\text{-}1) = 1$ *(the accelerator "i" is working)*
    If $random_{ij}(t) > 0.000669$ *(the random number is above the probabilistic FR)*
        If $random_{ij}(t) > 0.000287$ *(the random number is above the big failure)*
            $Repair\_time_{ij}(t) = 2$ *(repair is required, but not replacement)*
        Else if
            $Repair\_time_{ij}(t) = 5$ *(big failure, replacement required)*
        End if
    Else if
        $Repair\_time_{ij}(t) = 0$
    End if
Else if
    $Repair\_time_{ij}(t) = 0$
End if

6.3.2. Technician available

If free_technician$_{ij}$(t-1) > 0 *(there is a technician working in the module)*
If Repair_time$_{ij}$(t-1) > 1 *(the module still requires some repair work)*
Free_technician$_{ij}$(t) = free_technician$_{ij}$(t-1)
Else if *(the repair work ended just now)*
Free_technician$_{ij}$(t) = 0
If random$_{ij}$(t) > 0.000287 *(the random number is above the big failure)*
Repair_time$_{ij}$(t) = 2
Else if
Repair_time$_{ij}$(t) = 5
End if
Else if
Repair_time$_{ij}$(t) = 0
End if
Else if
Repair_time$_{ij}$(t) = 0
End if

Module spare availability
(We proceed to change the failed module if there is an spare module available)

If waiting_for_spare_module$_{ij}$(t-1) = 1 (We have a reserved module)

If technician$_{ij}$(t-1) > 0 *(there is a technician working in the module)*
If Repair_time$_{ij}$(t-1) > 1 *(the module still requires some repair work)*
technician$_{ij}$(t) = technician$_{ij}$(t-1)
Else if (the repair work ended just now)
technician$_{ij}$(t) = 0
If random$_{ij}$(t) > 0.000287 *(the random number is above the big failure)*
Repair_time$_{ij}$(t) = 2
Else if
Repair_time$_{ij}$(t) = 5
End if
Else if
Repair_time$_{ij}$(t) = 0
End if
Else if
Repair_time$_{ij}$(t) = 0
End if

6.3.3. Time required to have the module ready to operate in case of failure

If repair_time_required$_{ij}$(t-1) = 0 *(the module was able to work)*
    If waiting_for_spare_module$_{ij}$(t) = 1 *(the module failed, requires a spare and it is available)*
        If free_technician$_{ij}$(t-1) = 2 *(there are enough technicians available to perform the reparation required)*
            repair_time_required$_{ij}$(t) = 5 *(the module starts being replaced)*
        Else if
            repair_time_required$_{ij}$(t) = 9 *(the module remains failed without repair actions)*
        End if
    Else if
        If waiting_for_spare_module$_{ij}$(t) = 9 *(the module failed, requires a spare but it is not available)*
            repair_time_required$_{ij}$(t) = 9 (the module remains failed without repair actions)
        Else if
            repair_time_required$_{ij}$(t) = Repair_time$_{ij}$(t) *(the module is already being repaired)*
        End if
    End if
Else if
    If waiting_for_spare_module$_{ij}$(t) = 1 *(the module is already failed without being repaired but a spare is available)*
        If free_technician$_{ij}$(t-1) = 2 *(there are enough technicians available to perform the reparation required)*
            repair_time_required$_{ij}$(t) = 5 *(the module starts being replaced)*
        Else if
            repair_time_required$_{ij}$(t) = 9 *(the module remains failed without repair actions)*
        End if
    Else if *(the module has just failed but does not require a spare)*
        If free_technician$_{ij}$(t-1) > 0 *(there are enough technicians available to perform the reparation required)*
            repair_time_required$_{ij}$(t) = repair_time_required$_{ij}$(t-1) - 1
        Else if
            repair_time_required$_{ij}$(t) = repair_time_required$_{ij}$(t-1) *(the module remains failed without repair actions)*
        End if
    End if
End if

6.3.4. Module Working

If repair_time_required$_{ij}$(t) = 0 *(the module is working or is ready to work)*
    Module_working$_{ij}$(t) = 1
Else if
    Module_working$_{ij}$(t) = 0
End if

6.4. Assumptions

Assumptions

- The RF power of the IFMIF accelerator is supposed to be feed by RF chains. These chains are going to be placed in pairs (two by two) in wheeled modules, seeking the highest availability: as it allows offsite maintenance of the RF chains.
- The modules are divided in two platforms: the MP, which holds up most of the components with high failure rates, and the CLP, which only hosts passive components and has a much lower failure rate.
- Circulator and load platforms, as they only host passive components, are not supposed to fail.
- In order to affect as less as possible to the system availability, when an RF chain fails a **preliminary diagnosis** is performed in order to determine if the failure is important enough to proceed directly with the module extraction.
- If the preliminary diagnosis has not concluded with the module extraction, a **basic diagnosis of a maximum 30' length** is carried out in order to determine if the required reparation is going to be shorter than the module replacement. After 30' and without a resolution, the module is extracted anyway.
- Different main platforms, MP (16, 105 or 220 kW), have the same maintenance requirements and only differ in its internal components.
- Every time a MP is extracted, the four tetrodes are changed to proceed with its set up.
- There are no time differences between the 2 accelerators.

We assume that there is only one RF modules maintenance facility, shared by the two accelerators. It allows that every RF platform can be used indistinctly in both accelerators.

- All electric PS, sensors and water cooling of the CLP comes from the MP, the only interaction of the CLP with another system is the RF output to the accelerator and its fastening screws.
- Except for the tetrodes, the rest of component spares are considered to be “hot spares” without set up time.
- MP pre-insertion set up: it is required in order to determine its power output.

6.5. Simulation

From the data and functions in the points above, the system was simulated with MS Excel macros and Lanner’s WITNESS software. Last software was found useful in developing the system at small scale but lacked the power to run the calculations.

As results at small scale were similar in both softwares, only MS Excel was used to run the full-scale simulations. Each simulation was run for 1600 cycles of operation. The approach was to simulate the limit of each variable in order to achieve the minimum turndown of the accelerator. A total of 19 scenarios were considered as per table 6.

Scenario	Technician teams	Spares 105	Spares 220	WB for Hot Spares
1	2	6	7	3
2	3	6	7	3
3	4	6	7	3
4	5	6	7	3
5	6	6	7	3
6	6	2	7	3
7	6	3	7	3
8	6	4	7	3
9	6	5	7	3
10	6	6	7	3
11	6	6	2	3
12	6	6	3	3
13	6	6	4	3
14	6	6	5	3
15	6	6	6	3
16	6	6	7	3
17	6	6	7	1
18	6	6	7	2
19	6	6	7	3

Table 6 – Simulated scenarios

This resulted in the following availability of the RF modules

Scenario	Tech.	Sp. 105	Sp. 220	WB HS	Avail. % Acc1		Avail. % Acc2		Avail. % Total Acc	
					Mean	σ	Mean	σ	Mean	σ
1	2	6	7	3	94,296	2,298	94,315	2,258	94,305	1,689
2	3	6	7	3	94,470	2,210	94,471	2,212	94,470	1,564
3	4	6	7	3	94,510	2,147	94,604	2,106	94,557	1,506
4	5	6	7	3	94,487	2,188	94,618	2,108	94,553	1,505
5	6	6	7	3	94,625	2,110	94,545	2,162	94,585	1,504
6	6	2	7	3	94,064	5,460	93,972	6,070	94,018	4,638
7	6	3	7	3	94,513	3,059	94,505	2,526	94,509	1,974
8	6	4	7	3	94,572	2,227	94,548	2,085	94,560	1,543
9	6	5	7	3	94,562	2,090	94,525	2,136	94,543	1,523
10	6	6	7	3	94,465	2,189	94,528	2,175	94,496	1,552
11	6	6	2	3	92,118	12,305	92,514	11,428	92,316	9,282
12	6	6	3	3	94,196	5,308	94,556	3,068	94,376	3,375
13	6	6	4	3	94,507	2,136	94,526	2,156	94,516	1,496
14	6	6	5	3	94,577	2,174	94,633	2,216	94,605	1,593
15	6	6	6	3	94,493	2,229	94,580	2,170	94,536	1,538
16	6	6	7	3	94,604	2,214	94,518	2,085	94,561	1,525
17	6	6	7	1	94,572	2,232	94,638	2,179	94,605	1,521
18	6	6	7	2	94,528	2,113	94,515	2,191	94,522	1,496
19	6	6	7	3	94,593	2,241	94,544	2,182	94,568	1,565

Table 7 – Accelerators availability

This resulted in the following availability of the RF modules

Scenario	Tech.	Sp. 105	Sp. 220	WB HS	Repl. 105	Repl. 220	TH781	TH561	Replac #
					Anual	Anual	Anual	Anual	Anual
1	2	**6**	**7**	3	39,480	71,070	9,050	4,580	258,260
2	3	**6**	**7**	3	40,380	69,820	9,490	4,480	258,480
3	4	**6**	**7**	3	40,940	69,380	9,890	4,870	259,060
4	5	**6**	**7**	3	39,950	71,340	9,530	4,850	258,040
5	6	**6**	**7**	3	39,610	70,630	9,760	5,060	257,230
6	6	**2**	**7**	3	40,720	70,570	9,410	4,670	258,590
7	6	**3**	**7**	3	40,260	70,640	9,280	4,680	258,500
8	6	**4**	**7**	3	40,440	70,110	9,660	4,410	258,350
9	6	**5**	**7**	3	39,630	71,050	9,950	4,130	259,110
10	6	**6**	**7**	3	40,620	71,570	9,810	4,780	259,900
11	6	**6**	**2**	3	38,150	68,630	9,200	4,760	249,560
12	6	**6**	**3**	3	39,190	70,370	9,340	4,840	255,430
13	6	**6**	**4**	3	40,260	71,400	9,520	4,710	259,810
14	6	**6**	**5**	3	39,320	69,900	8,770	4,290	257,380
15	6	**6**	**6**	3	40,070	71,760	9,240	4,900	257,700
16	6	**6**	**7**	3	39,250	71,640	9,630	4,650	257,560
17	6	**6**	**7**	1	39,830	69,800	9,080	4,970	256,190
18	6	**6**	**7**	2	39,920	71,620	8,870	4,610	259,650
19	6	**6**	**7**	3	39,740	71,540	10,290	4,530	257,320

Table 8 – Replacement of RF Modules, necessity of tetrodes and total replacements

And the necessity of Technician teams (two technicians/team) by their occupation %:

Scenario	Tech.	Sp. 105	Sp. 220	WB HS	Tecnicians occupation %	
					Mean	σ
1	**2**	6	7	3	22,602	9,375
2	**3**	6	7	3	15,336	6,434
3	**4**	6	7	3	11,472	4,726
4	**5**	6	7	3	9,198	3,728
5	**6**	6	7	3	7,710	3,141
6	**6**	2	7	3	7,896	3,567
7	**6**	3	7	3	7,656	3,171
8	**6**	4	7	3	7,731	3,154
9	**6**	5	7	3	7,678	3,057
10	**6**	6	7	3	7,682	3,206
11	**6**	6	2	3	8,237	4,584
12	**6**	6	3	3	7,729	3,410
13	**6**	6	4	3	7,693	3,163
14	**6**	6	5	3	7,582	3,198
15	**6**	6	6	3	7,762	3,225
16	**6**	6	7	3	7,631	3,159
17	**6**	6	7	1	7,733	3,077
18	**6**	6	7	2	7,737	3,184
19	**6**	6	7	3	7,685	3,214

Table 9 – Technicians occupation %

And the necessity of Work Benches to tune up the RF Modules

Scen.	Tech.	Sp. 105	Sp. 220	WB HS	WB 1 occ %		WB 2 occ %		WB 3 occ %	
					Mean	σ	Mean	σ	Mean	σ
1	2	6	7	**3**	34,452	12,223	12,738	10,331	3,418	5,894
2	3	6	7	**3**	30,599	11,635	10,010	8,727	2,035	4,412
3	4	6	7	**3**	30,641	11,483	10,163	8,836	1,874	4,047
4	5	6	7	**3**	30,369	11,553	10,160	8,480	1,978	4,302
5	6	6	7	**3**	31,038	11,314	9,857	8,723	1,883	4,272
6	6	2	7	**3**	30,824	11,348	10,029	8,803	1,963	4,083
7	6	3	7	**3**	30,584	11,687	9,950	8,834	1,868	4,123
8	6	4	7	**3**	30,737	11,493	10,179	8,805	1,957	4,306
9	6	5	7	**3**	30,603	11,143	10,038	8,706	1,898	4,087
10	6	6	7	**3**	30,490	11,552	10,110	8,805	1,978	4,160
11	6	6	2	**3**	29,685	11,579	9,509	8,292	1,868	4,116
12	6	6	3	**3**	30,438	11,393	10,094	8,848	1,901	4,139
13	6	6	4	**3**	30,501	11,432	10,218	9,045	1,922	4,158
14	6	6	5	**3**	30,246	11,617	9,920	8,791	1,804	4,081
15	6	6	6	**3**	30,974	11,796	10,259	8,971	1,876	4,028
16	6	6	7	**3**	30,450	11,683	9,932	8,572	1,926	4,187
17	6	6	7	**1**	42,913	18,505	0,000	0,000	0,000	0,000
18	6	6	7	**2**	31,794	11,910	11,107	10,042	0,000	0,000
19	6	6	7	**3**	30,738	11,726	10,049	8,706	1,880	4,106

Table 10 – Work Benches occupation %

It results that up to a value, more resources do no mean a better availability due to the time required to repair the system cannot be reduced. So the resources considered necessary are:

- 4 technicians teams of 2 technicians per shift.
- 4 RF modules of 105 MW
- 6 RF Modules of 220 MW
- 3 workbenches to tubne up the RF Modules (suitable both for two powers)

So it is simulated the system with the resources considered.

Avail. % Acc1		Avail. % Acc2		Avail. % Total Acc		Repl. 105	Repl. 220	TH781	TH561	Replac #
Mean	**σ**	**Mean**	**σ**	**Mean**	**Mean**	**Anual**	**Anual**	**Anual**	**Anual**	**Anual**
94,593	2,241	94,544	2,182	94,568	1,565	39,74	71,54	10,29	4,53	257,32

Table 11 – Accelerators availability and Replacement of RF Modules, necessity of tetrodes and total replacements

Tecnicians occupation %		WB 1 occ %		WB 2 occ %		WB 3 occ %	
Mean	**σ**	Mean	**σ**	Mean	**σ**	Mean	**σ**
14,222	6,449	30,738	11,726	10,049	8,706	1,880	4,106

Table 12 – Technicians occupation % and Work Benches occupation %

Conclusions and Future Work

As an iterative process, there are no final results in an LSS until they meet with the aimed goals. If the results are not the desired ones, some actions of the LSS should be reconsidered: the planned goals or more logistics activities should be considered.

In order to help with the future implementation of the resultant logistics requirements and being aware of the inexistence of ideal solutions, during the LSS some future problems related with the support implementation will be detected. At least, a brief description of these difficulties is going to be very helpful at the time they will be faced.

RF modules reliability model

The reliability analysis use fault tree models to find out the probability of having a determinate failure in the RF system. Each RF module model is composed by 267 basic events and 25 gates.

The circulator platforms will fail, on average, 3.3 times per year. The RF main platform will fail around 137 times per year, 78 of them could be repaired online, and 59 will require the change of the whole module. In the case that the module will need to be changed, different actions should be performed depending on the cause of the failure. Availability and logistic analysis were performed based on these results.

RF system availability calculation

A very detailed model with 7772 basic events and 620 gates has been used to evaluate the availability of the current design of the RF system. The inherent availability result obtained was 94.4%. This result does not achieve the requirement of 98.2% for the RF system.

Power supply system does not have redundancies in the current design. Nevertheless, a design similar to the one done in ESRF [12], in which a switching board connects a redundant power supply in case of a failure, could be performed to improve the availability. The maximum availability achievable taking into account some plausible redundancies would be 94.62%, less than the availability requirement.

Maintenance and logistic analysis

This analysis consists in evaluate the maintenance actions to be performed, the resources needed and their impact in the availability.

Tetrodes

Taking into account the spares modules, the replaced modules, the failed tetrodes, and the limited lifetime, the recommended quantity of tetrodes is:

- TH781: 115 cold spares and 6 hot spares in RF Modules
- TH561: 110 cold spares and 4 hot spares in RF Modules

Modules

Logistic performance of modules replacement, repair and set-up has been studied. Simulations with different configurations and parameters have been done to determine the number of resources that affect the minimum to the accelerator availability.

The result of the analysis showed that 4 workers must be the whole time available to face the mean 260 maintenance operations that will occur every year to the RF system modules. About 110 operations will consist of replacement of failed modules, with the consequent repair operations in the workbench. In order to perform modules repairs, tetrodes set-up, hot spares preparation and other regular activities, more than 11,000 men-hours will be needed. Three shifts of two men are recommended.

A minimum of four 105kW spares and five 200kW spares are necessary to not affect the availability. Three module repairing workbench are recommended with 6 workers at three shifts, if two shifts were preferred, more spares and workbench would be advised. Two hot spare modules workbench for the 105kW and three for the 200kW are recommended.

Result

	Tetrodes
Availability	94.62%
Initial cost	43,750k€
Replacement cost	7,400k€/year
Manpower cost	1,200k€/year
Cost at 30 years	301M€

Future work

Now the other major goal is to study the Solid State alternative to the RF Modules. This alternative uses several modular solid state power amplifiers (SSPA) of about 1kW to supply the desired RF power to each cavity. Each power chain of IFMIF could have the exactly necessary power, with significant savings in installation costs.

The technology to combine these “low” SSPA to achieve high power output does not present major difficulties being used often in the industry. In fact, this technology is being used in other accelerator facilities like SOLEIL with an amplifying power per chain of 180kW [16] and ESRF with 150kW [17].

Acknowledgements

This project would not have been possible without the collaboration of my directors, Javier Dies and Carlos Tapia, and the other people working on FEEL during last year, José Carlos Rivas, Javier Abal and especially EWnric Bargalló, who has worked shoulder to shoulder in each and every step of it, having an essential feedback that brought to this result. Also thank the Transports Deparment for his uncalculable help in building the simulation.

To my family and friends.

Environmental impact

This project is just a theoretical paper without any experiment being carried out. The only impact is the energy consumed by the computer and the printing of the Memory, draft papers and the other printings in order to read them carefully.

It took 4 months to develop all the system at the FEEL laboratory using a desktop computer. Considering 8h a day in a five days week, it results in 640h. A standard computer consumes 220Wh and a screen 90 Wh. It sums a total of 198,4kWh.

To write the memory it took me 2 months at 4 hours daily plus 4 weekends at a rate of 5 hours/day. I used my laptop which consumes 120 Wh. It results in 240h consuming 28,8 kWh.

I used approximately 50 draft papers, printed around 250 sheets (2 sides and 2 pages per side) and the memory is about 60 pages per 2 copies. It results in 420 sheets of paper. Due to the fact that no recycled paper was available at the moment of printing, all paper used was non recycled paper.

Total consumption:

- 227,2 kWh
- 420 sheets of paper

Considering the emissions per kWh in Spain in 2011 were 0,33 kg/CO_2 [18] and that to produce a sheet of paper (A4) is 0,015 kg/CO_2 [19]. It results:

- 227,2 kWh · 0,33 kg/CO_2 = 74,97 kg/CO_2
- 420 sheets of paper · 0,015 kg/CO_2 = 6,30 kg/CO_2

The total amount of CO_2 emitted is 81, 27 kg.

PROJECT BUDGET

As commented in the environmental impact point, this project is just a theoretical paper without any experiment being carried out.

The only cost to be considered is the manpower invested on it. The computers use was minimal considering its lifetime and the electricity or the paper used is a millesimal part of the consumption at the ETSEIB.

Taking in account that the estimated amount of time spent working in the project is 640 h, it results in 80 days at a rate of 8h/day and means 3,64 months at a rate of 22 working days per month. Being done most of the project on 2012, the minimum wage in Spain for thet year was 641.4 €/month [20]. It results in an economic impact of 2.334,70 €.

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