RAMI OPTIMIZATION-ORIENTED DESIGN FOR THE LIPAC RF POWER SYSTEM

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) is currently under construction in Rokkasho (Japan). LIPAc will generate a continuous wave (CW) 9 MeV deuteron beam at 125 mA. It will serve to validate the final IFMIF accelerator concept and technologies. The radiofrequency (RF) power system is being integrated by CIEMAT (Spain) in collaboration with its partner companies and European institutes. LIPAc RF Power System design has been performed aiming high reliability, high availability and easy maintainability to address one of the most important requirements for IFMIF. The target of LIPAc tests is to validate the technologies and designs for the final phase of IFMIF. Several improvements in reliability, availability and maintainability have been implemented in the LIPAc RF Power System. These improvements are based on both, new technologies and new maintenance philosophy. The results of their first tests are shown in this paper.

INTRODUCTION

IFMIF will irradiate fusion structural materials under similar energy spectrum to the Fusion Neutron energy spectrum in order to test them under inner fusion reactor conditions. The data obtained from IFMIF are required for the building of the future DEMOnstration Fusion Reactor. Any delay in the IFMIF Program would directly delay the Fusion Program and the commercial application of Nuclear Fusion Energy.

Achieving the required dpa on the materials pivots on two parameters: deuteron current at the accelerator and irradiation time. Since IFMIF deuteron current is foreseen to be the maximum reasonably achievable (125mA per accelerator), the only way to speed up the program is by increasing the availability.

The RF Power System is the main active system of the accelerator. It is one of the largest systems and shares interfaces with most of the Accelerator Systems. Consequently, its availability highly impacts on the IFMIF's overall availability. An EFDA Report on technological options for the IFMIF RF Power System [1] was presented in 2007, assessing the use of solid state power amplifiers instead of tetrode based amplifiers. This report concluded that in the near future it would be advisable to develop a solid state alternative for the IFMIF amplifiers to take advantage of the inherent solid state availability characteristics. However, this technology was not ready for the LIPAc project due to the still low power MOSFET technology available in 2007.

Taking that into account, the first IFMIF RAMI (Reliability, Availability, Maintainability and Inspectability) studies [2] proposed a new availability target for the RF Power System for improving overall IFMIF availability: it should reach 98.2%. Two strategies have been followed for this purpose:

1. Improvements in the tetrode based LIPAc RF System.
2. Improvements in the solid state technology for a better performance and tighter fitting to this application.

LIPAc was then considered as a validating test bench for new proposals and new technologies devoted to improve the RF Power System availability.

AVAILABILITY FACTORS

All the developed improvements have been proposed following a RAMI optimization-oriented methodology. It consists of the continuous and iterated interaction between designers and RAMI engineers aiming at an enhanced availability. Since maximum operation time is defined by the characteristics of the critical components of the beam line, the RF Power System availability can be directly related to MDT (Mean Down Time). Two are the main MDT factors in which RF Power System can be improved:

1. MTBF (Mean Time Between Failures), which is mainly related to the reliability of the system.
2. MTTR (Mean Time To Repair), which is mainly related to the maintainability of the system.

THE LIPAC TETRODE BASED RF MODULE

Due to the high number of RF power chains at IFMIF (104), their high power levels (<220 kW each) and the high number of components required by the tetrode technology, the IFMIF RF power system reference design would have shown an unacceptable availability from the IFMIF's point of view.

An innovative solution was proposed in order to improve the availability: The RF Module [3]. This is a structure containing two complete RF chains, as shown in Fig. 1. All the components of both RF chains (except the HVPS) are on board. This daring design was developed by CIEMAT and its partner companies INDRA SISTEMAS and SEVEN SOLUTIONS. The full power tests of the amplifier demonstrated its capabilities, exceeding the foreseen. The achieved gain after the fine tuning is 25.4dB showing very high anode efficiency (73% at final amplifier). With 230kW CW RF output, the

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HVPS provides 11.6kV and 27A to the anode of the TH781. The output signal is a very clean sinusoidal wave, with 30 dBc harmonic rejection in the worst case.

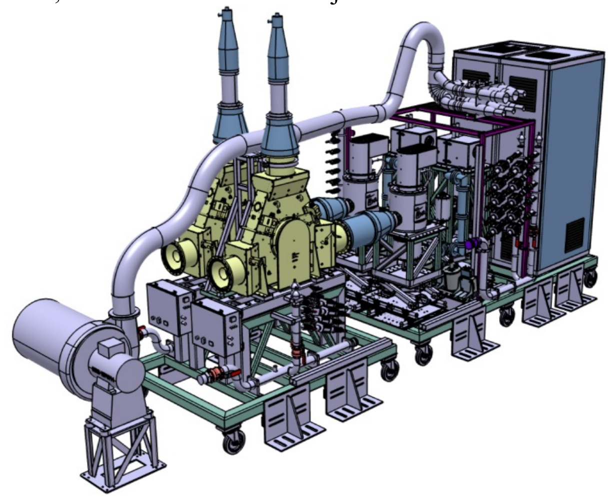

Figure 1: Tetrode based RF Module.

The new design has been developed following the performance and availability requirements under coordination with the IFMIF RAMI team leading to an improved availability design.

AVAILABILITY IMPROVEMENTS ON THE RF MODULE

Four availability improvements have been included in the Tetrodes RF Module design:

1. Removable platforms (R): It is a technological innovation that mainly impacts on MTTR
2. Modular design (M): It is a technological innovation that mainly impacts on MTTR
3. Enhanced control systems (E): These are two technical innovations that mainly impact on MTBF
4. SMART SPARE concept (S): A new concept in maintenance management that mainly impacts in MTTR

Removable Platforms

All the components of the RF Module are installed on board of two wheeled platforms:

1. The main platform that contains auxiliary systems and amplifiers
2. The circulators platform that contains the circulators and their stability control systems

As shown in Figure 2, a very innovative arrangement based on the said platforms lets each failed RF Module to be easily replaced in less than 4 hours, leading to a limited time to repair impacting on MTTR and therefore on MDT.

Modular Design

A fully modular design has also been implemented. This modular design consists of three levels of modularity: platform level, subsystem level and component level.

This innovation consists of a decision table that leads the maintenance technician to select the level of intervention following a protocol:

1. After the failure the technicians will take a maximum of a predefined time for diagnostic.
2. If the failed subsystem is identified before this time, the diagnosis continues in lower level (subsystem's level) and so on up to component level.
3. If the failed subsystem is not identified, the intervention is made at the platform level, so the whole platform is replaced by a spare one. Same procedure would be applied for lower levels.

All the steps of the protocol must be defined with a maximum time for diagnostic and also for repairing. In case that the whole time to repair at the level of component or subsystem is expected to be longer than the time needed for the platform replacement (4 hours), the head of the maintenance team could decide to replace the platform instead of repairing it. This ability improves the MTTR reducing the MDT.

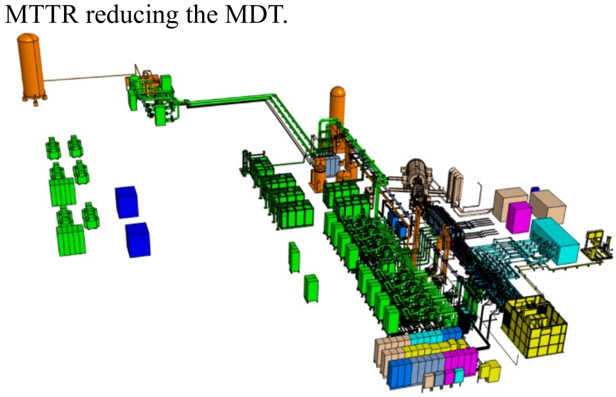

Figure 2: LIPAc (RF Power System in green).

Enhanced Control Systems

A highly flexible and programmable set of control systems has been implemented for the LIPAc RF Power System. These reliability improvements consist of:

1. Enhanced management of faults and arcing.
2. Ability of adaptive and predictive maintenance.

Two main control systems perform this innovation:

1. PSYS (tetrode protection system), which is an intelligent system based in FPGA and fast electronics collaborating with analogic power electronics, developed in collaboration with INDRA SISTEMAS.
2. LLRF (Low Level RF). Fully digital and empowered by "White Rabbit", this innovative system developed in collaboration with SEVEN SOLUTIONS, is able to improve the signal quality for a better reliability.

This set of enhanced control systems is supposed to reduce at least the 10% of failures by year.

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The SMART SPARE Concept

Unlike a conventional hot spare, a SMART SPARE is a spare that is ready for being installed in every position independently of the local required settings, by means of:

1. An evolving database containing a set of parameter for each RF line.
2. A devoted test bench ready to upload the data and to set the spare RF module just before being installed.

By this way the SMART SPARE arrives to the replacing position almost ready to start working and a very short time is required for fine tuning. This new concept reduces the platform replacing MTTR in around 30 minutes and reduces the spare needs.

IMPACT ON AVAILABILITY

Four improvements [4] have been included in the RF Module design aiming a better availability. Starting from the whole availability model developed for IFMIF (see Table 1) a simplified model with only the RF amplifiers was performed by Reliasoft Blocksym® RAMI modelling software (see Table 2).

Table 1: Results of the Whole IFMIF RAMI Model

Failure	***Failures/year***	**MDT**
w/ Main Platform replacement	59	4h
w/o Main Platform replacement	78	2
w/ Circulators Platform Replacement	3.4	5

The starting point includes the removable platforms, modularity and enhanced control systems resulting in a 95.2 % of availability. The simplified model is used to understand the behaviour of each improvement isolated from the rest of the system. The study of their impact is featured removing each improvement and calculating the new availability.

Table 2: Results of the Simplified RAMI Model

Simplified Model	**Characteristic**	**Estimated Availability**
R+M+E	Starting Point	95.2%
M+E	No platform replacement MDT=10h	91.3%
R+E	All failures w/ platform replacement	93.5%
R+M	10% additional failures	94,8%
R+M+E+S	MDT-30 minutes (tuning time saved)	95.6%

SOLID STATE ALTERNATIVE

Currently available solid state technology wouldn't be enough for IFMIF RF System since it would require a hundred of 200 kW CW 175MHz RF amplifiers with the following specifications:

- Higher overall efficiency than currently available
- Higher power amplifiers (> 200 kW CW)
- Higher availability (virtually 100%)
- High signal quality

This design requires, enhanced amplifier technology and enhanced combining systems. Two 16 kW SSPA have been developed in collaboration with Broad Telecom BTESA. In parallel, a cavity combiner is being tested at CIEMAT (see Figure 3).

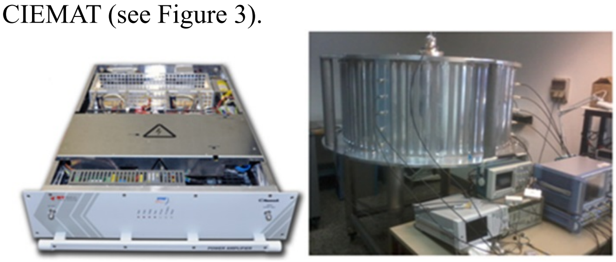

Figure 3: Enhanced solid state solutions.

A new validating experiment is being prepared for a one MW SSPA with competitive efficiency and signal quality. The current design is virtually 100% available due to the addition of high individual reliability, hot swapping of the basic amplifiers, and degraded modes, which allow very flexible redundancy. With a reasonable level of redundancy the estimated availability is 98.2%.

CONCLUSION

The maximum achievable availability for a RAMI-optimized tetrode-based IFMIF RF system was estimated in 95.6% including all the proposed improvements.

An LDMOS based solid state RF amplifier technology requiring improvements for being applicable to IFMIF have been developed resulting in an estimated availability of 98.2%.

ACKNOWLEDGMENT

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