DEPENDABILITY STUDIES FOR CERN PS BOOSTER RF SYSTEM UPGRADE

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Abstract

Radio frequency systems are a vital part of almost all accelerators. The request for a higher beam brightness from the injector chain of CERN's Large Hardon Collider, as demanded by the future High-Luminosity program, has motivated, among many other upgrades, the construction of new RF equipment in the PS Booster. Because availability and reliability have an important impact on the luminosity production in a collider environment, dependability studies have been performed on the new design of the RF system assuming different maintenance strategies. This paper will present the model, made with the commercial software Isograph, for dependability studies. In addition, a comparative study will be presented between the results obtained from Isograph and from an analytical analysis.

INTRODUCTION

The accelerator complex at CERN is a succession of machines that accelerate particles to increasingly higher energies until the Large Hadron Collider (LHC), the last element in the chain. The second accelerator in the chain, the PS Booster (PSB), is made up of four superimposed synchrotron rings that receive beams from the linear accelerator LINAC-2 and accelerate them for injection into the Proton Synchrotron (PS). Each PSB synchrotron ring has its independent Radio Frequency equipment (RF System).

The request for a higher beam brightness in the injector chain, as demanded by the future High-Luminosity program, has led to new requirements for the machines. These requirements have motivated, among many others, the upgrade of the RF System in the PSB [1].

The increasing complexity of the PSB RF System makes dependability studies of crucial importance in order to assess whether the requested high availability would be achieved. Two different methods were developed to estimate the PSB RF System availability and reliability: one based on the commercial software Isograph [2] and the other, an analytical model based on Boolean system probability theory. A comparison of the different tools for availability modelling can be found in [3].

THE PSB RF SYSTEM

Design and Component Dependencies

Each PSB synchrotron ring has its independent RF system as shown in Figure 1. Each Ring RF system is made up of 36 cells from which 30 need to be operational for the RF System to be available. Groups of 6 cells depend on one Water Cooling system and one PLC Interlocks system.

Each Cell is made up of three components: DC Supply, Ancillary Electronics and RF Cell.

Each RF Cell is made up of five components: Cooling Ring, Magnetic Alloy (MA) Core, Ceramic Gap, Vacuum Chamber and RF Power Amplifier. While the Vacuum Chamber failures are negligible, in case of a Ceramic Gap component failure, the whole ring (and in practice also the whole PSB) will be out of service.

An RF Power Amplifier is made up of 32 MOSFET arranged in 2 groups of 8 MOSFET pairs in parallel and one MOSFET Driver. 7 pairs out of 8 pairs need to be operational from each group of 8 MOSFET pairs for the RF Power Amplifier to be operational. If one MOSFET of a MOSFET pair fails the pair of MOSFET is out of service.

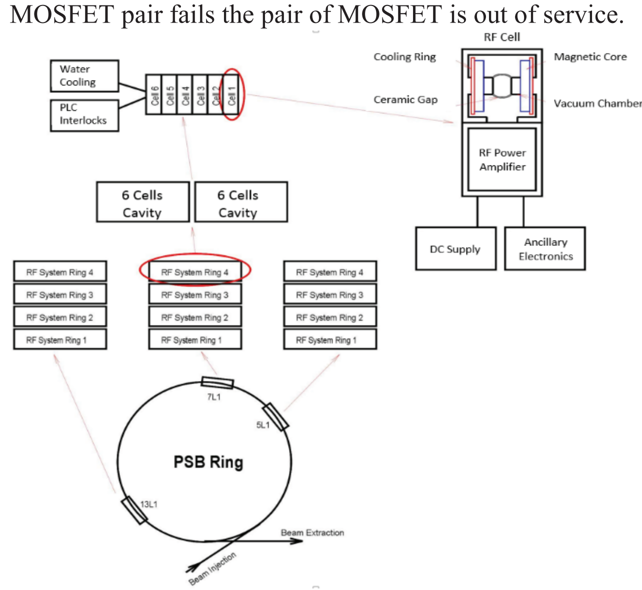

Figure 1: PSB RF System components

DEPENDABILITY STUDIES

Isograph Model

Isograph Availability Workbench RF System availability and reliability predictions have been performed using the Isograph Availability Workbench commercial software. Reliability Block Diagrams (RBD) are used to model the RF system dependencies. The RBD is made of blocks, which represent the components and subsystems of the RF System, connected in parallel or in series. A failure model is assigned to each block and different maintenance strategies have been defined. Components are assumed to follow an exponential failure distribution. The assumed values, based on expert judgement, for each

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component failure mode, Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR), are shown in Table 1. Note that if only one Ceramic Gap fails, the whole ring will be out of service. For this reason, one reliability block in series with the ring models 36 Ceramic Gaps, one for each cell in the ring. Hence, there are 4 reliability blocks each representing the failure behaviour of 36 Ceramic Gaps.

One simulation run takes more than one day given the amount of components and redundancy in the RF System.

Lifetime and Maintenance strategies The mission time of the RF system is set to 9 months, i.e. one operational year, and is divided in three operational phases and three maintenance phases. After each three months of Operation a scheduled maintenance of 48 hours is performed.

Two maintenance types have been defined:

- Corrective Maintenance (CM): Maintenance done in all failed components only when the RF system is not available any more due to components failures.
- Planned Maintenance (PM): Scheduled maintenance of all failed components after each operational phase. PM time is not taken as RF system downtime.

We assumed that during maintenance components will not experience failures.

A small variant of the CM strategy (CM2) was also implemented in which PLC Interlocks, DC Supply and Ancillary Electronics are repaired immediately even if the system is in service. This has been considered because these components are accessible without affecting the system operation.

Table 1: Components Failure Data

Component	No. components	MTTF(h)	MTTR(h)
Water Cooling	24	2102400	2+4
PLC Interlocks	24	200000	2+4
DC Supply	144	43800	2+4
Ancillary Electronics	144	43800	2+4
Cooling Ring	144	175E+6	72
MA Core	144	43.8E+6	72
Ceramic Gaps (36)	4 (144/36)	4.8E+6	72
MOSFET pair	4608/2	8.15E+11	2+4
MOSFETs Driver	144	1.63E+11	2+4

Analytical Model

The PSB RF System analytical model is based on Boolean system probability theory to model system dependencies [4]. The model follows a bottom to top approach, i.e., the RF System availability and reliability functions are calculated from components availability and reliability functions. Components failures follow also an exponential distribution. Parameters are shown in Table 1.

Planned Maintenance phases are not modelled in this case. As in the Isograph model, the system is a good as new after each PM and PM time is not considered as RF System downtime. Hence, the analytical results are considered at time 3 months, just before the PM phase, to be comparable with the ones obtained from the Isograph model.

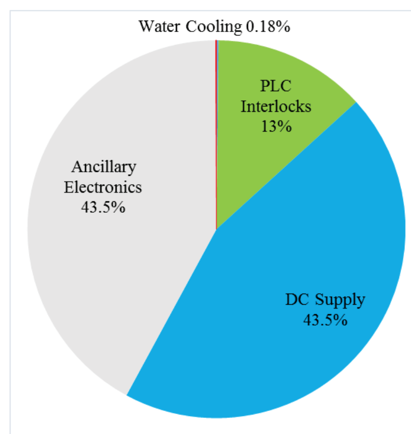
A One-at-a-time sensitivity analysis has been also implemented in the RF System analytical model. Moving one component failure rate and keeping the others at their nominal value to show the effect this produces in the RF System model output parameters.

RESULTS

Isograph Model

PSB RF System Availability Predictions The PSB RF System is expected to fail once during a mission due to components failures. The downtime and MTTR of the system are around 6 hours, which mainly correspond to the repair time of components with repair time of 6 hours, as will be shown in the next subsection. The mean availability of the system is evaluated as 99.9%, which in other words means that 99.9% of the time the system will be operational. Major contributors to System Downtime are DC Supply, Ancillary Electronics and PLC Interlocks as shown in Figure 2.

Figure 2: Contributions to the 6.68h of RF System Downtime (CM)



PSB RF System components Availability Predictions Estimated failures (F) and downtime per component type are shown in Table 3. Components that, although failed, do not stop the system from operating, remain failed until the next CM or PM maintenance. Hence, their mean downtime (MDT) is bigger than their repair time. Conversely, if a Ceramic Gap fails the system will be out of service. That's why, the Ceramic Gap MDT per failure is the same as its repair time. This is a direct consequence of the maintenance strategies considered.

PSB RF System Spares Predictions Last column of Table 3 shows the total spares needed during one Operational year, divided in Operation phases and PM phases. As expected, the largest number of spares will be needed during PM phase.

Results obtained when considering CM2, compared to the nominal maintenance strategies, are shown in Table 2. While the expected number of component failures remains the same, the variation of the corrective maintenance strategy has its main impact on the RF System failure and downtime predictions. Within this new scenario, the probability of failure of the RF System during an Operational year is negligible. The downtime of the system is expected to be 0.5h and the MTTR is around 8.5h, due to larger relative contribution of failing components with higher repair times than 6 hours, as it is observed in the contributions to system downtime in Figure 3. This decrease in system downtime and failure probability gives an availability of almost 100%. As the components failures, the number of spares needed remains the same, but the majority of them are needed during Operation and not in the PM phases.

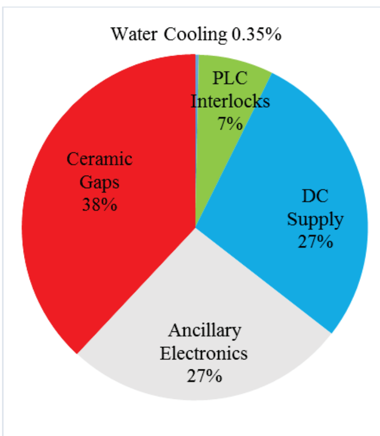


Figure 3: Contributors to the 0.5h of RF System Downtime (CM2).

Table 2: RF System Availability Predictions

RF System	F	MDT (h)	MTTR (h)	Availability
CM	1.07	6.68	6.2	99.90%
CM2	0.06	0.5	8.6	99.99%

Analytical model

PSB RF System Reliability The probability of the system to perform its required function at time just before PM (3 months) is 61%. This means that, with 61% of probability no intervention will be needed between two PM phases. The MTTF of the system is 2442h (102 days). Hence, the system is most likely to fail just after a PM phase.

The PSB RF System reliability sensitivity analysis to components failure rates shows the components with more impact on system reliability and MTTF: Ancillary Electronics, DC Supply and PLC Interlocks. Whereas MOSFETs have very small impact. Improving or degrading a component quality in a small area around its nominal failure rate, the RF System reliability will be between 50% and 70% and the MTTF between 2750h and 2000h. The sensitivity analysis also shows the effect a component aging could have on the system reliability. For example, a degradation of the Water Cooling failure rate by a factor of 10, will lead to a decrease of the RF System Reliability from 61% to 50%.

PSB RF System Availability The fraction of operational time that can be used for production is evaluated as 99.92%.

The PSB RF System availability sensitivity analysis to components failure rates shows the components with more impact in system availability: Ancillary Electronics, DC Supply and PLC Interlocks. Improving or degrading a component quality in a small area around its nominal failure rate, does not affect the RF System availability.

Table 3: RF System Components Availability Predictions Calculated Using the Isograph Model

Component	F	MDT per failure	Spares Predictions	
			Operation	PM
Water Cooling	0.06	240.2	0.06	0.006
PLC Interlocks	0.76	203.03	0.7	0.07
DC Supply	18	954.1	4.5	13.5
Ancillary Electronics	18	954.1	4.5	13.5
Cooling Ring	0.004	980.6	0	0.004
MA Core	0.02	1079.3	0.005	0.014
Ceramic Gaps (36)	0.003	72	0.03	0
MOSFET pair	0	0	0	0
MOSFETs Driver	0	0	0	0

CONCLUSIONS

The results obtained from the Analytical model go in line with the ones obtained from Isograph. Further verification of the Analytical model could lead to a faster method for availability and reliability calculations.

The main results obtained are:

- The RF system mean availability is 99.9%
- The expected number of times the RF system will fail during one operational year is one.
- The components contributing most to system downtime are Ancillary Electronics, DC Supply and PLC Interlocks.
- The impact of components failures on the PSB RF System is minor due to the implemented redundancy.
- If the Ancillary Electronics, DC Supply and PLC Interlock components are repaired as soon as they fail, the system failures during one operational year can be neglected.

Results could help in deciding maintenance strategies for the RF System and predictions on spares needed, maintenance cost and required personal.

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REFERENCES

[1] M.M. Paoluzzi, S. Albright, M.E. Angoletta, L. Arnaudon, *et al.*, "Design of the new Wideband RF System for the CERN OS Booster", 7th International Particle Accelerator Conference 2016, Busan, Korea, this conference.

[2] Isograph, `http://www.isograph.com`

[3] O.Rey Orozco, E. Bargalló, A. Nordt, A. Apollonio, R. Schmidt, "Reliability and Availability Modelling for Accelerator Driven Facilities", 5th International Particle Accelerator Conference 2014, Dresden, Germany.

[4] B.Bertsche, "Reliability in Automotive and Mechanical Engineering", Springer-Verlag Berlin Heidelberg, 2008, chap. 2 , pp. 70-76.