

ON THE RELIABILITY ORIENTED OPTIMISATION OF THE LHC INTERCONNECTIONS

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Abstract

To achieve the maximum beam energy in the LHC the accumulated length of spatial zones, dedicated to the interconnections between the main cryo-magnets, has been limited to 3 % of the total magnetic length in the Arcs and Dispersion Suppressors. Such a low ratio leads to a very compact design of systems and sub-systems situated in the LHC interconnections. The requirements concerning reliability of the LHC interconnections are very tight since the availability of the collider for physics can not be compromised. The failure modes taken into account in the LHC interconnections are grouped into 4 categories: material failures, structural failures, fatigue failures and electrical failures. A concept of reliability oriented parametric optimisation of the LHC interconnections is presented.

- structural failures – local and global instabilities leading to excessive local deformations of the expansion joints or misalignment of the magnets,
- fatigue failures leading to propagation of fatigue cracks and causing leaks in the beam or the insulation vacuum,
- failure of splices of the superconducting bus-bars resulting in the malfunction of the main or the corrector magnets.

In the present paper a concept of reliability oriented parametric optimisation of the LHC interconnections is presented. A global availability of the LHC interconnections is assumed at the level of 99.5 %. It is based on the assumption of one short intervention (10.5 days) over 10 years of LHC operation (200 days a year) due to a failure in the interconnection system.

1 INTRODUCTION

Optimum design of the modern lepton and hadron storage rings requires minimization of space of the interconnection zones when compared to the accumulated magnetic length of the main FO-DO quadrupoles and the bending dipoles. The ratio of non-magnetic to magnetic zones in the LHC Arcs and Dispersion Suppressors is close to 3 %. This implies an extremely compact design of systems and sub-systems located in the interconnections [1] like: bellows expansion joints, splices of the superconducting bus bars, RF contacts etc. The compactness has been enhanced by the two-in-one specific magnet configuration in the LHC. In order to cope with the space limitations a deliberate choice, backed by a mathematical optimisation, was made and the LHC bellows expansion joints work in highly inelastic regime called low-cycle fatigue. All deformation developed during cool-down and warm-up of the collider is localised in the interconnections (the accumulated value of thermal contraction approaches 70 m for LHC Arcs and DS). Therefore, the requirements concerning the reliability of the LHC interconnections were strongly increased. When compared to the conventional magnets (LEP) the possible failure modes of the interconnections between the superconducting magnets (LHC) become more complex. The failure modes taken into account in the LHC interconnections are grouped into 4 categories:

- material failures - comprising magnetic permeability failure, resulting from the phase transformations in stainless steel at cryogenic temperatures, and evolution of ductile damage,

2 APPORTIONMENT OF THE RELIABILITY LEVELS

Since in the LHC interconnections there are 3 main systems that might fail: mechanical compensation system (bellows expansion joints), electrical connections (superconducting bus-bars) and beam image current continuity system (fixed and sliding RF contacts) it is assumed that the expected availability is apportioned to each system on an equal basis. Thus, the expected availability amounts to 99.8 % for either of them. Given the number of interconnections in the LHC Arc and DS zones (1618) the apportioned availability per one interconnect is fixed to 99.9999 %.

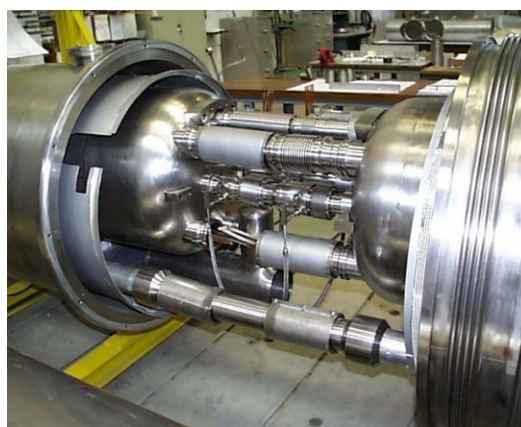


Figure 1: LHC interconnections

The apportionment of the reliability levels to subsystems and components in each LHC interconnect corresponds to the reliability categories presented in Table 1. As an

example, allocation of these categories to the standard LHC dipole/dipole interconnect is shown in Table 2. Lower categories (0-4) are reserved for the whole interconnect and the sub-systems whereas the higher categories (5-9) are reserved for the components. For instance, a typical reliability level allocated to the RF-contact module is equal to 99.999999 % (category 6).

Table 1: Reliability categories

R(t) is function of importance and accessibility of system	Category	R(t) [%]	Category	R(t) [%]
	0	99.9999	5	99.999998
	1	99.99995	6	99.999999
	2	99.99998	7	99.9999995
	3	99.99999	8	99.9999998
	4	99.999995	9	99.9999999

Table 2: Standard LHC MB-MB interconnect

Sub-system: interconnection line	Nr of lines	Reliability per line [%]	Reliability category
Beam vacuum lines	2	99.999995	4
Main cryogenic & bus-bar lines	3	99.99999	3
Heat exchanger line	1	99.99999	3
Auxiliary bus-bar line	1	99.99998	2
Cold feet / beam screen cooling line	1	99.99998	2
Thermal shield line	1	99.99998	2
Vacuum vessel sleeve (envelope)	1	99.99995	1

3 FAILURE MODES

The failure modes of the LHC interconnections are directly related to their principal functions: continuity of the beam and insulation vacuum, transfer of helium through the pressurized channels, continuity of the power supply (main and auxiliary bus-bars), continuity of the RF system, continuity of the thermal shielding etc. The most critical failure modes are presented below.

3.1 Material failures

The material failures reflect low temperature behaviour of stainless steel comprising evolution of damage and plastic strain induced martensitic transformation ($\gamma \rightarrow \alpha'$). The first leads to an inadmissible increase in the density of micro-damage and to fatigue crack propagation. The second phenomenon initiates presence of the ferro-

magnetic α' phase in the austenitic γ matrix. Such a bi-phase material may show a very high level of magnetic permeability, called magnetic failure. A combination of damage failure and magnetic failure constitutes a criterion enabling the evaluation of the allowable number of thermo-mechanical cycles:

$$N_f = F_N(D, \mu(\xi)) \quad (1)$$

where N_f, D, μ, ξ denote the number of cycles to failure, the damage parameter, the magnetic permeability and the volume fraction of martensite, respectively.

3.2 Structural failures

The structural failures consist in the local and the global instabilities in the interconnections under pressure loads [2]. These instabilities (bifurcation buckling), related to the presence of the bellows expansion joints, are classified in the following groups:

- local failures of the expansion joints (squirm),
- semi-local failures of the interconnects (transverse instabilities of interconnection lines),
- global instability of a portion of the collider involving more than one interconnect.

The coupling between the thermo-mechanical cycles (cool-down and warm-up) and the local/global instabilities leads to a criterion limiting the life of the interconnections [3]. An essential impact is attributed to the imperfection field (initial misalignment of the magnets).

3.3 Fatigue failures

Fatigue failures are generally associated with the effect of the thermo-mechanical and quench cycles on the components in the LHC interconnections. The families of components particularly exposed to the fatigue failures are bellows expansion joints, RF contact fingers, bus-bar splices, seals etc. The fatigue failures are predicted by analysing the evolution of inelastic strains and related micro-damage in the above listed components. Also, accelerated life testing programs permit experimental verification of the number of cycles to failure and of the relevant reliability levels [2].

3.4 Electrical failures

Electrical failures are related to the splices of the superconducting bus-bars and may result in the malfunction of the main or the corrector magnets [4]. They are classified in the following way:

- failures that violate the logic of the electrical scheme (connection errors),
- failures that violate the continuity of the electrical scheme (lack of connection),
- failures related to the quality of connections (electrical resistance at cold).

In the design and optimisation process the latter has an important role since the accumulated dissipation of energy in all the interconnection splices contributes to the thermodynamic budget of the collider.

4 RELIABILITY AND COST ORIENTED OPTIMISATION

4.1 Survival probability

In order to illustrate analysis of the survival probability of the components of the LHC interconnections two examples are chosen: the RF-contact bellows expansion joint (beam vacuum interconnections) and the splices of the spool piece powering bus bars. For the bellows the “survival probability” is defined as the probability that the unit will survive 50 thermo-mechanical cycles (Fig. 2).

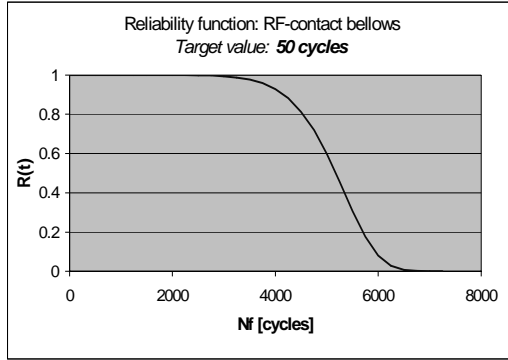


Figure 2: Reliability of the RF-contact bellows

In the case of spool piece powering bus-bars the “survival probability” is defined as the probability that the electrical resistance of splices will remain below the target value of 18 nΩ (Fig. 3). In both cases the assumed reliability levels (99.99995 %, 99.99999 %) have been reached.

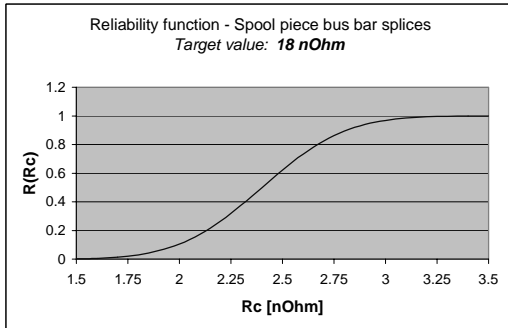


Figure 3: Reliability of the spool piece bus-bar splices

4.2 Optimisation algorithm

Since the enhancement of the reliability/stability results in an increase of performance but also the cost of the interconnections, a stable proportion (parity) between both functions is established and a maximum of the combined design objective is searched in the optimisation domain (Fig. 4). The following formulation of the reliability oriented optimisation with the mixed stability (S)/cost (Q) design objective is applied to the LHC interconnections:

- the objective function:

$$\max[\min(\mu_1(1/Q) + \mu_2 S)] \quad (2)$$

- the equality constraints:

$$L_{arc} = const$$

$$N_{seg} = const \quad (3)$$

- the inequality constraints:

$$P(\underline{x})|_{\Omega} \leq p_0 \quad (4)$$

$$P[\max(\delta_i, i=1, n) > \delta_{ad}] \leq p_1; f(\delta_i) = f_0 \quad (5)$$

$$P[\max \sigma_{eq}|_{\Omega} > \sigma_{ad}] \leq p_2 \quad (6)$$

$$P[(N_f)_j < N_0] \leq p_3; j=1, n_c \quad (7)$$

$$P[(P_{buct})_j < P_{j0}] \leq p_4; j=1, n_c \quad (8)$$

- the random variables:

$$\underline{x} \rightarrow (x_1, x_2, \dots, x_n, \dots, x_N) \quad (9)$$

where P denotes the probability of failure and p_i its limiting value. The objective is to maximise the combined design function under the constraints of constant length of the accelerator arc L_{arc} , constant number of segments N_{seg} (magnets + interconnections) and under the corresponding inequality constraints (reliability, transverse displacements, stresses, fatigue life and local stability).

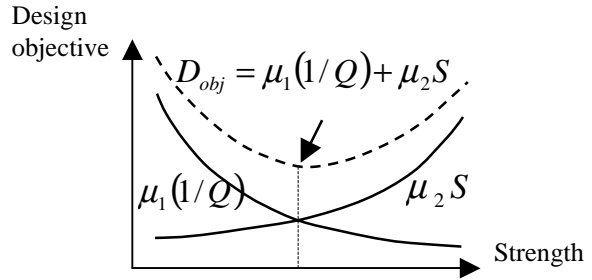


Figure 4: Mixed design objective: stability (S)/cost (Q)

As a result of the optimisation all the reliability targets were reached at a minimum cost. At present the interconnections are being tested at CERN in the LHC prototype – String 2.

5 REFERENCES

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