ANALYSIS AND TESTING OF A NEW RF BRIDGE CONCEPT AS AN ALTERNATIVE TO CONVENTIONAL SLIDING RF FINGERS IN LHC

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Abstract

RF fingers are used as transition elements in beam vacuum line interconnections to ensure the continuity of the vacuum system wall within acceptable beam stability requirements. The RF fingers must absorb and compensate longitudinal, angular and transversal misalignments due to both thermal effects, during bake-out or cooldown processes, and mechanical movements during assembly, alignment, commissioning and operation phases. The new RF bridge concept is based on a deformable thin-walled structure in copper beryllium, which fulfils the above requirements without the need of sliding contacts. Mechanical tests have been carried out to characterize the response and the lifetime of such a component under different loading conditions. In addition, finite element models have been used to estimate the behaviour. The influence of different material grades and heat treatments on the reliability is presented. The paper includes a detailed analysis of the prototyping and testing phases that have led to a final design of the system, qualified on a dedicated test bench, for the collimator vacuum modules of LHC.

INTRODUCTION

RF fingers are a common component assuring the electrical continuity between adjacent vacuum chambers in high intensity beam accelerators. They are usually associated with an outer leak tight bellows and flanges to form a module. They have to assure this electrical function despite relative movements between the chambers.

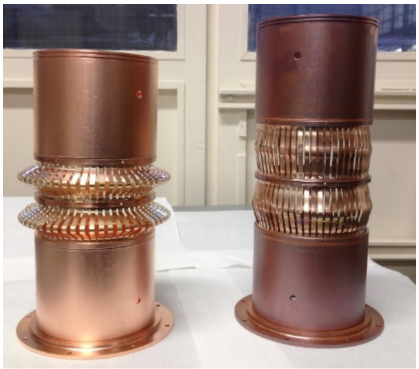

Figure 1: RF deformable bridges for LHC collimator vacuum modules, before and after thermomechanical tests.

New RF Bridge Concept

The new proposed design is based on a flexible and deformable thin wall element (0.1 mm) connected to the adjacent vacuum chambers. To avoid introducing large impedance, it is made out of copper alloy. The geometry is similar to a bellows with convolutions to compensate the displacements but with additional longitudinal slots to avoid circumferential compressive stresses and therefore, local buckling [1]. The slots divide the structure in multiple V-shaped convolutions (Fig. 1) that behave as basic structural components. Slot dimensions are similar to existing finger solutions. In the operation configuration, the convolutions are stretched and almost straight to reduce the impedance.

ANALYSIS OF CONVOLUTIONS

The convolutions have been analysed individually for different loading conditions and different material grades and tempers. The results are extrapolated to complete RF bridge geometries.

Geometric Analysis

A first analysis of the system has been focused on studying the geometric behaviour of one convolution. When the system is only extended, the geometry is well adapted to the movement and the dominating stress is flexural. If the system also includes a lateral displacement (combined movement) the extension tolerance is reduced and the most critical conditions appear when the lateral movement is made in the plane (Fig. 2). The convolution is then submitted to complex loading conditions combining bending, axial loading and twisting effect, with pre-eminence of both flexural and out-of-plane shear stress.

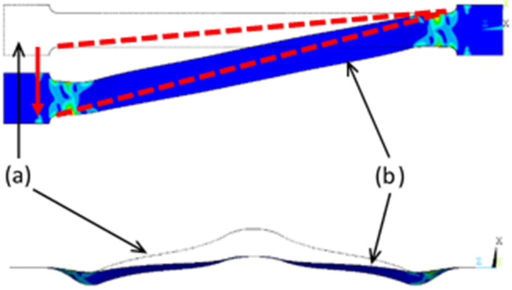

Figure 2: Effect of in-plane transversal movement (b) over a pre-extended convolution (a). Top and side views.

The criterion to fix the maximum displacements permitted on the convolutions is to limit the axial loading due to overextension. With this objective, the correlation between the extension movement, the lateral movement and the extension tolerance, has been obtained (Fig. 3).

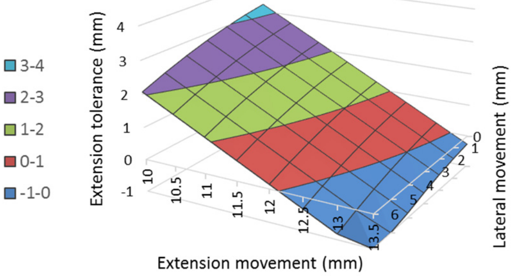

Figure 3: Extension tolerance of a convolution as a function of extension and in-plane lateral movements.

With an in-plane lateral movement of 6 mm, the maximum extension permitted is 12 mm. For axial behaviour, assuming 2 mm of lateral misalignment per convolution, the maximum extension permitted is 13 mm.

Mechanical Analysis

Elasto-plastic simulations through Finite Element Models (FEM) have been made to estimate the behaviour of the convolutions and analyse the stress levels. For axial movement, the maximum stress levels are located on the crests of the convolutions, as the bending effect is maximum. For a combined movement, if an overextension is present or, as a general rule, if the in-plane lateral movement is bigger than 4 mm, the maximum stress levels are concentrated on small areas at the edges of the convolution roots.

Regardless of the maximum stress locations, most of the combinations included in Fig. 3 provoke material plastification. The accumulated plastic strain ($\Delta\varepsilon_p$) over a reverse cycle, as the driving parameter for the fatigue life estimation at low cycle regime, has been calculated for the alloys included in Table 1 (Fig. 4).

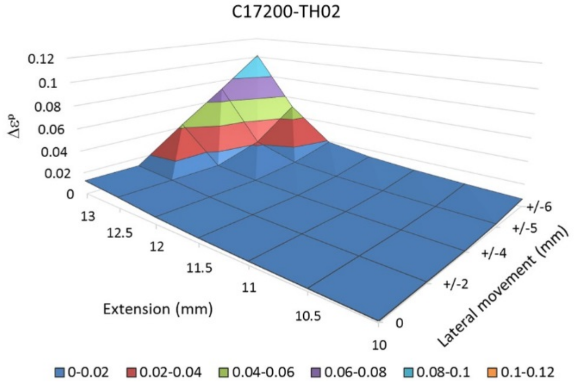

Figure 4: Accumulative plastic strain of a convolution in C17200-TH02 for different movement combinations.

In all cases, the behaviour is similar and well aligned with the above extension tolerance map. $\Delta\varepsilon_p$ values increase smoothly up to states where extension tolerances are near 0. From that point on, axial stress due to overextension becomes critic and makes $\Delta\varepsilon_p$ rapidly increase. The system becomes sensitive to small changes.

TESTS ON CONVOLUTIONS

Three material grades have been considered for analyses and mechanical tests: high strength copper beryllium alloys C17200-TD02 (alloy #1) and C17200-TH02 (alloy #2), and the high conductivity alloy C17410-TH02 (alloy #3). The TD02 condition refers to a cold worked (half hard) state, while the TH02 grade is an age hardened solution, after submitting TD02 to a standard heat treatment.

Alloy #2 acquires high strength values but shows low ductility properties. Alloys #1 and #3 share similar strength values with high ductility levels. At cryogenic conditions, these alloys increase strength and toughness, and retain excellent impact resistance with respect to room temperature conditions; improved mechanical behaviour is expected.

Table 1: Mechanical Properties of Alloys Analysed

Material	Temp [°C]	Young Modulus [GPa]	Yield strength [MPa]	Tensile strength [MPa]	Elongation [A%]	% IACS
C17200 -TD02	24	117	651	687	14.5	17
	-253	135[2]	750[2]	945[2]	45[2]	-
C17200 -TH02	24	130[2]	1140[2]	1354	4	25
	-253	145[2]	1230[2]	1640[2]	3.5[2]	-
C17410 -TH02	20	138[3]	626[3]	736[3]	18.7[3]	53.3
	-269	154[3]	740[3]	937[3]	37.5[3]	-

All alloys were analysed through FEM but only alloys #1 and #2 were tested as, out of all three, they provide the outermost ductile conditions. The effect of longitudinal and transversal rolling directions was also considered.

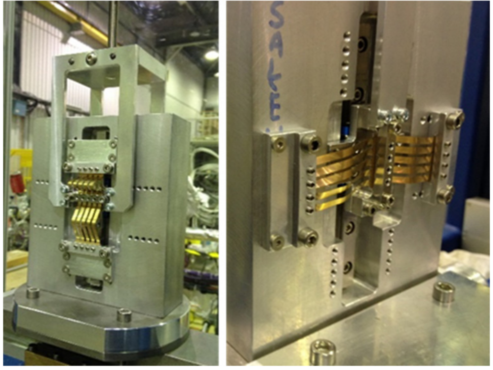

Figure 5: Test bench for mechanical tests.

Fatigue Tests

Fatigue tests were developed in a dedicated test bench (Fig. 5) over basic geometrical convolution items. Fatigue loads were applied at different reverse loading conditions, including longitudinal and in-plane lateral movements. In order to predict the lifetime of the solution for non-tested loading configurations, the results were traced out with the calculated $\Delta\varepsilon_p$ values and low-cycle fatigue curves were estimated for both alloys, by using the empirical Manson-Coffin approximation (Fig. 6).

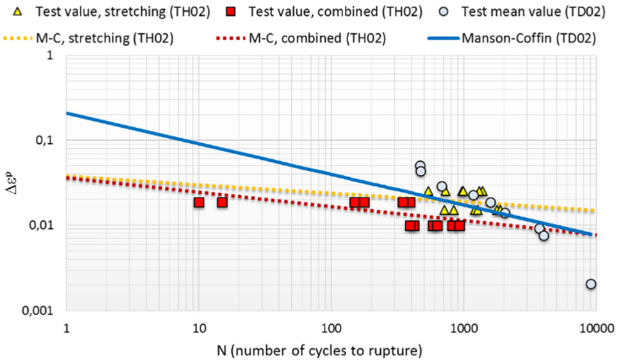

Figure 6: Fatigue curves of convolutions for alloys C17200-TD02 and C17200-TH02.

The response of the tested alloys is different. The most ductile one (alloy #1) reveals a slower fatigue crack propagation rate, and the lifetime is well correlated with $\Delta\varepsilon_p$ values for all loading conditions. Alloy #2 shows different behaviours depending on the type of load. In all

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cases, the system is very sensitive to an overextension, especially when combined with a twisting effect (combined load).

Regarding the rolling direction effect, when only axial and bending loads are present, lifetime differences between parallel and perpendicular rolling directions are usually under 10%. On the contrary, when a twisting effect is also present, lifetime differences of up to 30% are observed. In all cases, as expected, the parallel rolling direction gives better results than the perpendicular one.

Thermal and Tensile Tests

The effect of the bake-out processes over the alloy C17200-TD02 was assessed by submitting it to baking tests at different temperature and exposure time conditions. Further tensile tests enabled to obtain the mechanical properties of the samples tested. The main conclusion is that the alloy starts age hardening at temperatures lower than 250 °C [4]. At 180 °C, with an exposure time of 100 h, the tensile strength increases up to 832 MPa, remaining the elongation at the same level (14.5%). Instead, if the exposure time is 500 h, the tensile strength continues to increase (up to 960 MPa) but the elongation is reduced to 4% (as for TH02 grade). The results show a tendency to have a final TH02 grade by increasing the exposure time.

LHC COLLIMATOR VACUUM MODULE

Design Solution

The collimator vacuum modules of LHC are attached to room temperature collimators which can be placed at three different working positions: centred with respect to the beam, or displaced laterally to +10 mm or -10 mm. The lateral movements are compensated by the combination of 2 sets of convolutions in series. The structure is nominally extended to +22 mm and the system is bakeable at 250 °C (see Fig. 7).

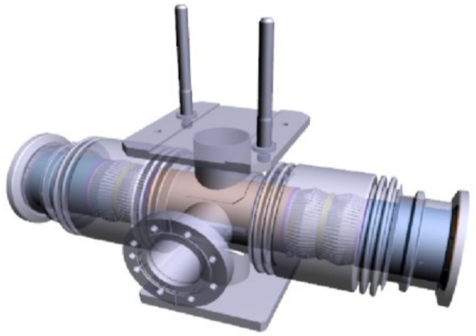

Figure 7: RF bridge solution in a LHC collimator ‘double bellows’ module.

Prototypes and Tests

Four initial prototypes, two in C17200-TD02 and two in the TH02 grade, were manufactured and tested with the aim to validate the joining solution of the deformable strip to the insert, and to corroborate the mechanical analyses and tests of the convolutions. The components were submitted to different fatigue load combinations, and satisfactory and coherent results were obtained. Additionally, one TH02 module was submitted to a tensile test to assess its behaviour until rupture (Fig. 8), which occurred at the level of the welding joint at 407 MPa.

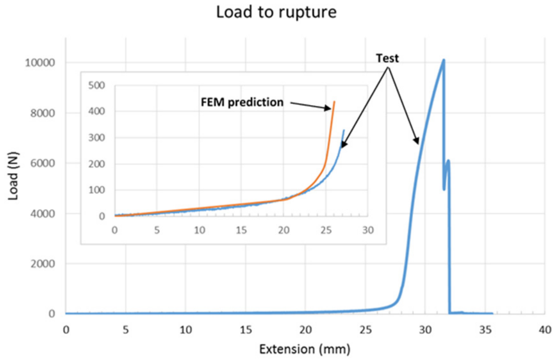

Figure 8: Rupture test of a RF bridge in C17200-TH02.

In a second phase, two final RF bridge prototypes for the LHC collimator vacuum modules were manufactured in C17200-TD02 and tested (Fig. 1). The overall constructive solution was validated and thermo-mechanical tests were developed, combining bake-out processes with series of combined fatigue loads at maximum design values (+24 mm of extension and ±12 mm of lateral movement), without convolution breakage. The number of bake-out processes was eight, accumulating a total of 1000 h at 200 °C, and the number of mechanical cycles, more than 350.

CONCLUSIONS

Extensive analyses and tests have been performed for a new RF bridge concept, firstly at the convolution level, as basic structural item, and lately on a proposed structure solution for the LHC collimator vacuum modules. The mechanical limits have been defined, and the behaviour and the expected lifetime are now predictable. Different material grades have been studied and their constraints analysed. Out of them, ductile alloys are preferred due to their lower sensitivity to geometric non-conformities and their better behaviour against combined loads.

A prototype solution for the LHC collimator modules has been successfully tested, and qualified on a dedicated test bench. The manufacture of a final mock-up prototype for a collimator ‘double bellows’ module is on-going.

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