

## LESSONS LEARNT AND MITIGATION MEASURES FOR THE CERN LHC EQUIPMENT WITH RF FINGERS

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### Abstract

Beam-induced RF heating has been observed in several LHC components when the bunch/beam intensity was increased and/or the bunch length reduced. In particular eight bellows, out of the ten double-bellow modules present in the machine in 2011, were found with the spring, which should keep the RF fingers in good electrical contact with the central insert, broken. Following these observations, the designs of all the components of the LHC equipped with RF fingers have been reviewed. The lessons learnt and mitigation measures are presented in this paper.

### INTRODUCTION

Despite the excellent performance of the LHC in 2011/12, the intensity ramp-up was perturbed by several instabilities [1] and beam-induced RF heating issues [2].

The problem mentioned above, with the so-called VMTSA modules, is revealed in Fig. 1. The left picture shows that the spring, which should keep the RF fingers in good electrical contact with the central insert, has been broken and therefore the bottom RF fingers fell down due to gravity. On the right picture the stainless-steel spring has been deformed and brazed to the CuBe (Copper-Beryllium) RF fingers with permanent deformation of the latter. The temperature reached has been estimated to be  $\sim 800 - 1000$  °C. Detailed simulation studies revealed that even a small gap of 0.5 mm could lead to huge power losses which are concentrated on the RF fingers and which could lead to this device failure [3].

After this observation, the decision was taken at the beginning of the 2012 run to review the design of all the components of the LHC equipped with RF fingers before the long shutdown in 2013/14 [4]. The outcome of this review is discussed in the present paper.

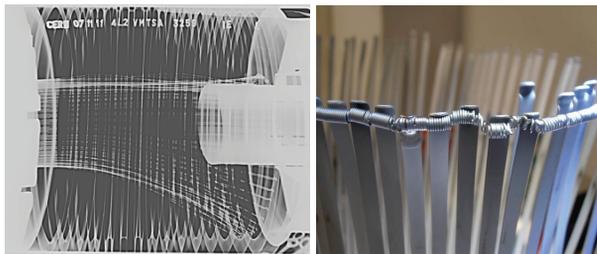


Figure 1: X-ray image of the nonconforming RF fingers of a VMTSA module (left) and stainless-steel spring deformed and brazed to some RF fingers (right).

### WHY DO WE NEED RF FINGERS AND/OR FERRITE TILES?

RF fingers are used to avoid having too large impedances (longitudinal or transverse) due to (big) changes of geometry for moving equipment, which can lead to (i) beam-induced RF heating (due to the real part of longitudinal impedance) and/or (ii) longitudinal or transverse beam instabilities (due to the real and/or imaginary parts of the longitudinal or transverse impedances). RF fingers' examples are shown in Fig. 2.



Figure 2: Example of (conforming) RF fingers for the VMTSA modules in 2011 (left) and for the PIMs (Plug-In Modules) (right).

If we take the particular example of the beam-induced RF heating issue, in the case of a sharp resonance impedance, i.e. when  $Q \gg f_r / (2 f_b)$ , assumed to fall exactly on an harmonic of the bunch frequency, the power loss is given by the simple formula

$$P_{loss} = I_{total}^2 \times 2R \times 10^{\frac{P_{dB}(f_r)}{10}}$$

where  $I_{total} = M I_b$  is the total beam current with  $M$  the number of bunches and  $I_b$  the bunch intensity,  $R$  the shunt resistance (i.e. the value of the impedance at the resonance frequency  $f_r$ ),  $P_{dB}$  the power in dB read from the longitudinal beam power spectrum (computed or measured),  $Q$  the quality factor of the resonance and  $f_b$  the bunch frequency. Assuming a total beam current of 1 A (the nominal LHC value is  $\sim 0.6$  A) and considering the theoretical longitudinal bunch spectrum of Fig. 3 (left) for an rms bunch length of 9 cm (similar to the LHC case in 2011 [5]), a sharp resonance of 5 k $\Omega$  (usual typical values are between few hundreds and few tens of thousands Ohms) at 1.4 GHz would therefore generate a power loss of 1 W. However, this result is very sensitive to the bunch length. It can be seen for instance from Fig. 3 (right), that dividing the bunch length by 2, i.e. going from 9 cm rms to 4.5 cm, would

increase the power loss by a factor  $\sim 2000$ , i.e. going from 1 W to 2 kW! Therefore, any (major) bunch length reduction should be considered with great care. In fact, in 2012 the bunch length was increased to  $\sim 10$  cm rms for beam induced RF heating reasons.

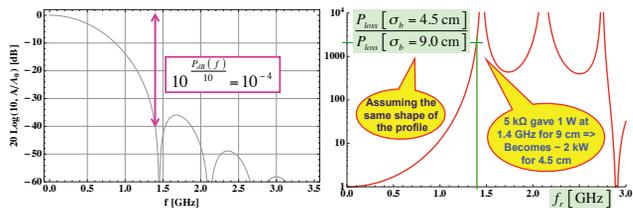


Figure 3: Theoretical longitudinal bunch spectrum (left) for the case of a LHC bunch in 2011 (9 cm rms bunch length) and power loss increase for the case of a bunch two times shorter (4.5 cm rms) assuming the same shape.

### SEVERAL DESIGNS FOR RF FINGERS

Depending on the need, several designs for the RF fingers have been adopted in the LHC. The first one uses the funneling concept and is used for the PIMs [6] as can be seen in Fig. 2 (right). However, this concept can be used only for the case of longitudinal movement and there can be possible issues with buckling and aperture restrictions. It is worth mentioning that the main reason to add some RF fingers for this particular case was to shield the distorted geometry of the bellows from the beam and avoid too strong an increase of the imaginary part of the longitudinal impedance, which could lead to a longitudinal beam instability by loss of Landau damping.

A second concept for the case of transversal displacement has been adopted for the VMTSA modules discussed above, which uses a spring (to be put at the extremity of the RF fingers where there is a groove, see Fig. 1 right) to keep the RF fingers together around a central insert. However, this concept might lead to possible issues with bad contacts and (large) gaps, in particular due to the elliptical shape (see Fig. 2 (left)), and therefore RF heating and potential aperture restrictions.

A third design was made with fixed extremities for the LHCb VELO (VERTex LOcator) (see Fig. 4 (left)) [7]. It seems to work very well and no problem was reported.

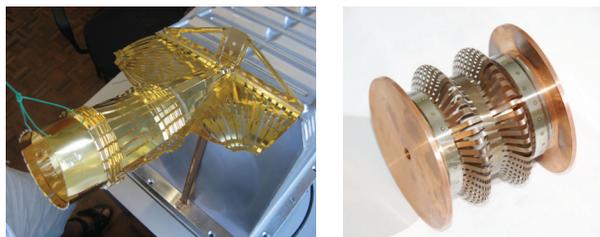


Figure 4: Wake-field suppressor for the LHCb VELO (VERTex LOcator) detector (left) and new design proposed by the CERN vacuum group with fixed extremities (to be operated in elongated position) (right).

A fourth design was recently proposed by the CERN vacuum team (see Fig. 4 (right)) using the similar concept

of having fixed extremities to avoid gaps [8]. The possible issue with such a device could be the potentially large imaginary part of the longitudinal impedance, if this equipment is not correctly elongated during operation (as in this case the device is electro-magnetically longer than mechanically due to induced current having to follow the convolutions, as for the PIMs without RF fingers discussed above) and if many such equipment are used.

Finally, a fifth concept using longitudinal sliding contacts has been used for the collimators (see Fig. 5) [9].

### Phase I Design Baseline

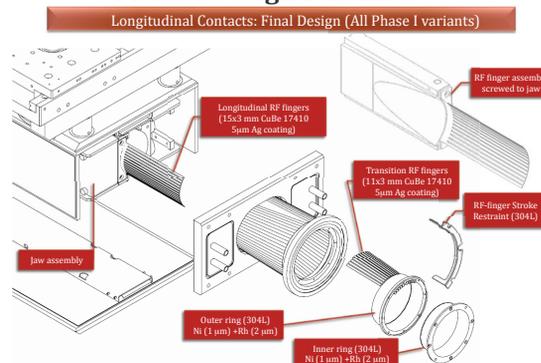


Figure 5: Longitudinal sliding contacts for collimators.

### POSSIBLE ISSUES WITH RF FINGERS

Good electrical contact requires (i) low surface roughness, (ii) soft metals (at least one) and (iii) no oxide layer at the surface. For the case of the PIMs, several requirements had to be met: (i) very low contact resistance (smaller than  $0.1 \text{ m}\Omega$ , i.e.  $3 \text{ m}\Omega$  per RF finger as there are 30 RF fingers in parallel), (ii) no cold welding, (iii) low friction and (iv) good formability properties. For the collimators, the considerations were: (i) the same as above with a possible higher contact resistance due to the smaller number of collimators with respect to the PIMs (smaller than  $1 \text{ m}\Omega$ ), (ii) ability to be baked out at  $250^\circ\text{C}$  for 1000 h, (iii) good thermal conductivity and (iv) wear after many cycles “open-close of the jaws” (1500 cycles  $\sim 4$  years). All these considerations have to be taken into account to make a proper design. The initial proposal for a first collimator prototype was made in 2003 using uncoated CuBe fingers sliding on C/C. The electrical contact resistance was found to be  $\sim 30 \text{ m}\Omega$ , whereas the specification was  $1 \text{ m}\Omega$ . A redesign was necessary (see next section) and the final design can be found in Fig. 5.

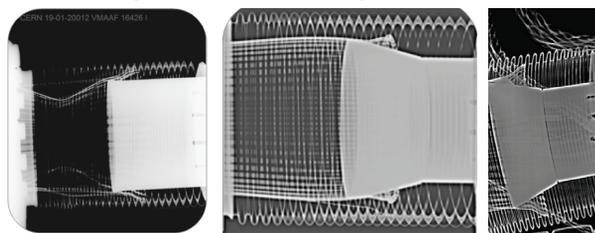


Figure 6: Examples of nonconformities in the LHC in 2012 revealed by X-rays.

Finally, when dealing with devices with RF fingers, the installation is always a delicate process and sufficient time should be devoted to avoid major issues during beam operation. A total of 1800 X-rays have been taken and 92 nonconformities (i.e.  $\sim 5\%$ ) were found (see Fig. 6).

## GUIDELINES FOR RF FINGERS

The RF fingers should be made of CuBe (whose grade is very important in case of bake-out as for the collimators, in which case it should be C17410) for several reasons: high conductivity, good adhesion of coatings, weldability by e- beam, good formability properties, low magnetic permeability (low content of Ni, but contains Co – small enough amount for the radioprotection, but in fact more than Be...), higher elasticity than Cu alone, etc. However, even though CuBe is a good conductor it still has too an high surface impedance and a coating is needed to increase the surface conductivity, reduce the contact resistance and avoid cold welding. Two solutions can be adopted to avoid cold welding. The first consists of putting a diffusion barrier between the two metals (i.e. an oxide layer), but this is bad for the electrical contact. The second consists of choosing metals with low solubility. This solution has been adopted and the best materials' pair is Au-Rh (as they are the best enemies, leading to almost no solubility). The pair Ag-Rh is also quite similar.

As concerns the contact resistance, with a plating of the CuBe RF finger with Au and a plating of the base material (Cu) of Rh, the resistance was measured to be  $\sim 3\text{ m}\Omega$  for 1 RF finger (i.e.  $\sim 0.1\text{ m}\Omega$  for 1 PIM). Note that it was measured to be  $\sim 35\text{ m}\Omega$  for the baseline Ag / SS contacts (i.e.  $\sim 1.2\text{ m}\Omega$  for 1 PIM). The use of Ag instead of Au led to  $\sim 2\text{ m}\Omega$  but Au was chosen for the PIMs to avoid cold welding. Finally, the contact surface on the insert should be electro-polished before putting the Rh coating.

As concerns the bake-out for the collimators (at  $250^\circ\text{C}$ ), Au cannot be used at this temperature because of the diffusion of Cu into Au and the subsequent disappearance of the Au layer. The same problem occurs with Ag but at a higher temperature and therefore Ag replaced Au for the collimators.

For the MKI injection kickers, stainless-steel (instead of CuBe), but still Au plated, is used for the RF fingers because of the bake-out, which is performed at  $\sim 300^\circ\text{C}$ , which, with CuBe, would lead to a very small residual elasticity of  $\sim 20\%$  only.

Finally, any gap should be avoided, as it can be fatal (depending on the real geometry) [3].

## GUIDELINES FOR FERRITE TILES

If RF fingers cannot be used or in case of nonconformities, some trapped modes might be created and ferrite tiles can be used to damp these modes. The ferrite should be put at (or close to) the maximum of the magnetic field of the mode to be damped (at the metallic wall), which is deduced after detailed electro-magnetic

simulations, assuming known electro-magnetic properties of the ferrite. The ferrite should not be seen directly by the beam (if possible) and depending on the frequency of the mode to be damped, the ferrite type and thickness need to be optimized. Furthermore, the ferrite should be compatible with UHV (Ultra High Vacuum) and even if the ferrite will considerably reduce the power loss (by lowering the quality factor  $Q$  of the resonance, while keeping  $R / Q \sim \text{constant}$ ), the remaining power loss will be absorbed by the ferrite which will heat and might reach its Curie temperature (and therefore lose its damping properties) if the heat transfer is not optimized. A figure of merit for the maximum RF induced power on the ferrite before the Curie temperature is reached is discussed in Ref. [10].

## CONCLUSIONS

A lot of experience has been accumulated over the past decades for the use of RF fingers and/or ferrite absorbers. Several designs of RF fingers are used in the LHC depending on the requirements. Some have been studied in great detail, which took time but it paid off. All the double-bellow VMTSA modules, which experienced some RF heating issues in 2011, will be removed during the long shutdown in 2013/14 and will therefore not be a potential worry anymore. All the 92 (i.e.  $\sim 5\%$ ) identified nonconformities in warm modules will also be repaired during the shutdown. For all the cases studied, no impedance issues could be identified for conforming RF fingers. No showstopper is therefore expected for future operation with higher intensities but the top priority should be to try and achieve robust mechanical designs to keep the contacts of all the RF fingers (e.g. with funnels as for the PIMs, or using fixed extremities) and to do a very careful installation. The major problem could come from the possible use of bunches much shorter than nominal for future operation. In such a case, many careful checks must be performed due to the extreme sensitivity of RF heating to bunch length.

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