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RF Contact Performance of LHC BPM Connections

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Summary

In this paper we compare measurements and numeric estimates of quality factors as well as impedances of fundamental and higher order modes (HOM) of cavity-like structures resulting from possible bad RF contacts of welded beam pipe flanges for LHC BPM connections.

Bad RF contacts may originate from length variations of the joined pieces after welding, in particular due to temperature changes. The impedance of this "microcavity" would add to the impedance budget of LHC.

1. Introduction

In this paper we present the calculation and measurement of quality factors as well as impedances of fundamental and higher order modes (HOM) of a cavity like structure resulting from RF contacts of welded beam pipe flanges. The results of numerical simulations and measurements using the coaxial wire method are compared.

The RF contact performance of LHC beam pipe connections may have to be taken into account for the LHC impedance budget. Here we consider the connections between a BPM(Beam Position Monitor) and a section of the beam pipe. The loss factor of RF contacts can normally be neglected, but this is true only for good RF contacts. If the RF contact is bad, a small gap forms at its location, and this may cause both power losses and instabilities, even if this gap is very small. The volume between the "RF contact" and the weld (cf. Figure 1) in this case is suspected to become a kind of cavity, capacitively charged by the narrow gap, and the impedance of this "microcavity" would add to the impedance budget of LHC. Bad RF contacts may originate from length variations of the joined pieces after welding, in particular due to temperature changes, since the structure is assembled at room temperature, and used at cryogenic temperature later on.

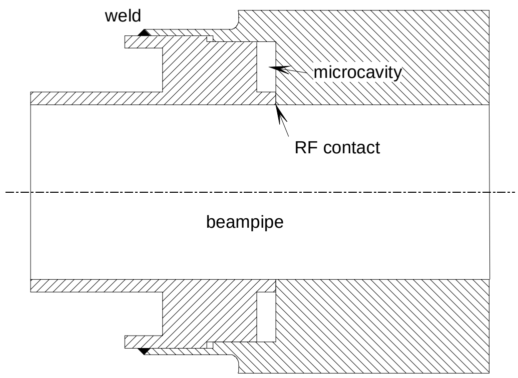

Figure 1: Beam pipe connection

We will compare the results of several simulations (time domain and frequency domain) with the measurement results.

2. Measurements

2.1. Measurement set-up

Impedance measurements were done on a beam position monitor (BPM) vacuum chamber with a RF contact, using an HP 8753D vector network analyser (VNA) and the coaxial wire method.

The coaxial wire method [1] is a convenient bench method for the simulation of charged particle beams. It is based on the assumption that a bunch of a highly relativistic beam has an electromagnetic field distribution very similar to that of a short pulse on a coaxial line (TEM field). For longitudinal impedance measurements, the set-up (cf. Figure 2) consists of a single conductor ("wire") in the center of the vacuum chamber, at the position of and replacing the beam. Here we used a copper plated inner tube in the stainless steel beam pipe. The radius of the inner tube is chosen here for practical reasons to have a coaxial line impedance of $Z_c = 50\ \Omega$ (D/d = 2.302), the same as the cables connected from the VNA to both ports, input and output.

Measurements were carried out in the frequency domain, in transmission and in reflection, and results are displayed in both time and frequency domain. The longitudinal impedance can be determined from the measured transmission coefficients S_{21} as

$$Z = \frac{2Z_C\left(1 - S_{21}\right)}{S_{21}}. \qquad (1)$$

Note that in (1) the scattering parameter S_{21} has to be used as a linear quantity and not in logarithmic format [dB], which is very common for VNA's.

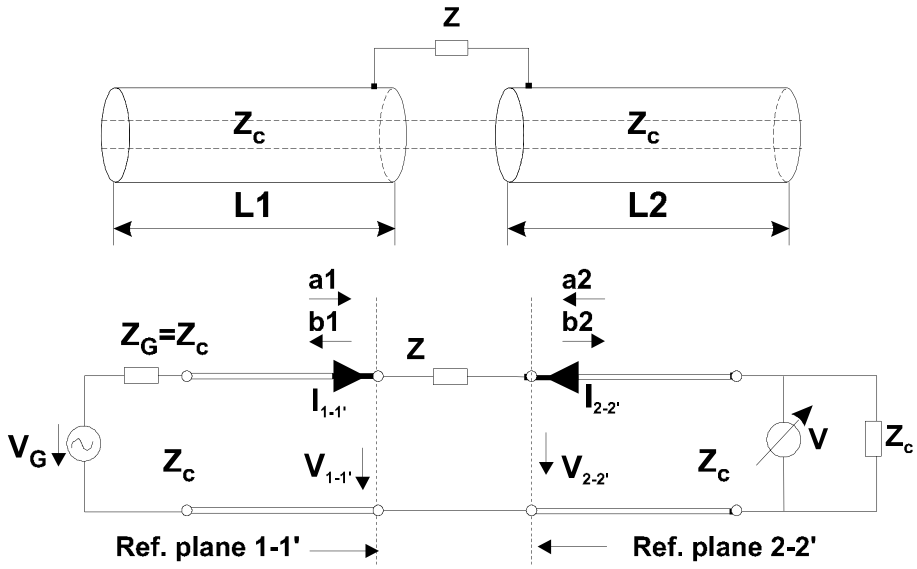

Figure 2: S-parameter measurement set-up for a single lumped impedance

An additional reflection measurement (display in time domain) allows to localise and identify the planes where the reflections occur: in the ports of the VNA, at the connectors or inside the actual device under test (DUT). Using this option, we can assure correct interpretation of the results.

2.2. Measurement results

The DUT shows up as an impedance of up to 60 Ω depending on the contact pressure. The first resonance may appear in a range of 1 to 3 GHz (also depending on the contact distance), i.e. well below the cut-off frequency of the beam pipe; for an empty pipe of 19 mm radius the cut-off frequency for the longitudinal mode of interest, TM_{01}, is f_c= 6.02 GHz.

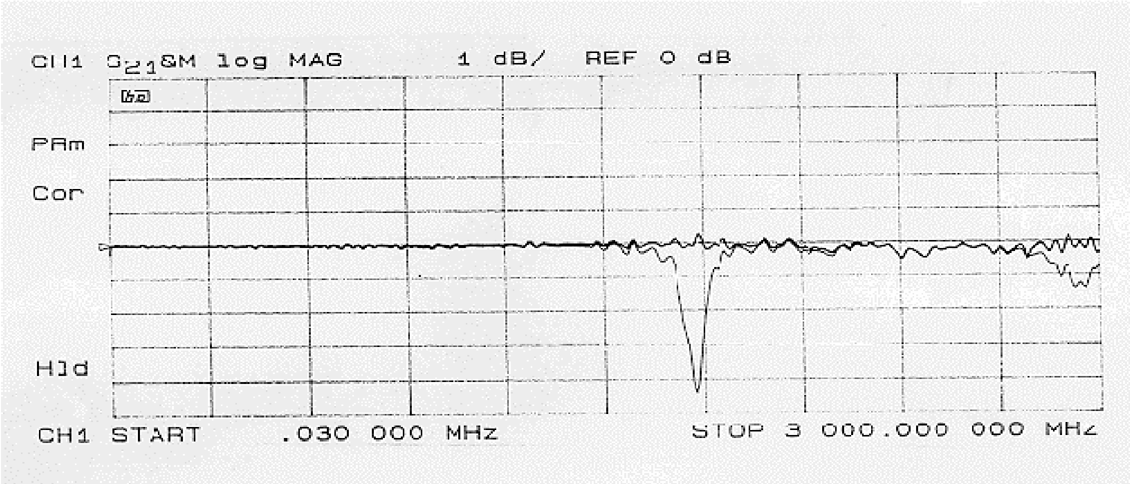

Figure 3: Network analyser output $|S_{21}|$ [dB] vs. Frequency [MHz]

It must be noted however that this is the cut-off frequency of an empty beam pipe with the same dimension, since the presence of the “wire” introduces the TEM mode with cut-off zero. The first higher order mode of the coaxial line is at 3.5 GHz and it corresponds to the TE_{11}.

This also leads to a source of systematic error: the *Q* values deduced from the wire method may be systematically too low. Modes below the beam pipe cut-off, for example, can not lose energy by radiation through the beam pipe. They can however lose energy into the matched coaxial lines. Since we were mainly interested in demonstrating qualitatively the effect of poor RF-contacts and the range of resonant frequencies, the low *Q* readings are not a serious drawback. Anyway the quantity of interest, *R/Q* is supposed to be independent of *Q* (it only depends on the geometry).

Figure 3 shows the measured $|S_{21}|$ vs. frequency. The losses produced by the impedance of the RF contact when there is a gap can be seen in the $|S_{21}|$. The peak of losses, in this case is -4.3 dB, appears at 1.780 GHz. Extracting *Z* with (1) we obtain an impedance of 64 Ω. with a bandwidth of BW_{-3dB} = 30.76 MHz, the corresponding quality factor *Q* will be 57.8; thus the *R/Q* is about 1 Ω. We are not able to measure mechanically the size of the gap in this case but as it will be shown later (numerical results) the measured resonant frequency corresponds closely gap size of 0.05mm.

It is evident that the calculated values were obtained for a specific resonance below cut-off. It is possible to have another resonance and the values will be similar depending on the gap width when there is a bad RF-contact.

3. Numerical calculations

The computer program MAFIA [2] (Maxwell’s Equations using the Finite Integration Algorithm) was used for the numerical simulations. MAFIA is a set of codes used for the computed-aided analysis of radiofrequency structures. It includes distinct modules, for both time and frequency domain calculations, solving Maxwell’s equations using a set of finite difference equations for the electric and magnetic field vectors.

3.1. The wake potential and impedance

The wake potential and the impedance [3] describe the interaction of a bunch of charged particles in the accelerator with its environment. The various components of this environment are the vacuum chamber, cavities, bellows, dielectric pipes, and other kinds of obstacles the beam has to pass on its way through the accelerator. When the bunch interacts with a cavity, for example, there remain electromagnetic fields in the cavity which keep on "ringing" when the bunch has left, i.e. the bunch has lost energy into one or several cavity modes.

Regarding the wake potential, we can distinguish between two regimes, the transient regime due to short-range wake effects and the resonant regime due to long-range ones. For small distances *s*, measured from the head of the bunch in the opposite direction to the bunch velocity (cf. Figure 4), transient wake fields are dominant, while for $s >> \sigma$ the wake field is dominated by resonant effects due to several cavity modes ringing with their specific frequencies. We will use bunch length $\sigma = 5$ mm as a compromise between computation time and spectral coverage beyond 10 GHz.

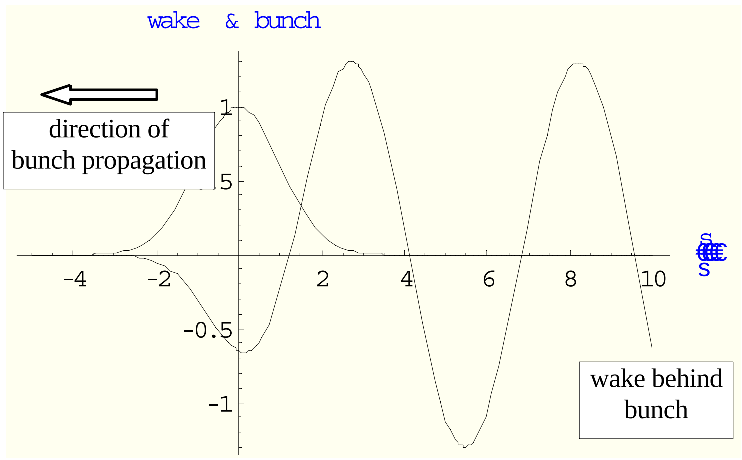

Figure 4: Typical longitudinal wake potential of a Gaussian bunch

Wake potential and impedance have similar meanings, both describing the coupling between the beam and its environment. The wake potential is the time domain description and the impedance is the frequency domain description, i.e. the impedance is the Fourier transform of the wake potential. The impedance often contains a number of sharply defined frequencies corresponding to the modes of the cavity, or the long range part of the wake potential. In particular below the cut-off frequency of the beam pipe there is a resonance for each cavity mode. In this case a formulation in the frequency domain is appropriate. Above the cut-off frequency a continuous spectrum of beam pipe modes contributes to the impedance. The high frequency components of the impedance correspond to the short range wake potential.

Real cavity modes are not ringing forever, since due to the finite conductivity of the cavity walls the field amplitudes decay slowly. This is generally described by the finite *Q* of the cavity modes.

In this paper we will compare the simulations with different gap sizes and different conductivities in the walls of the structure.

3.2. Time domain solver T2 versus frequency domain solver E

T2 is the time domain solver module of MAFIA which solves two dimensional initial-boundary-value problems assuming an axis symmetric structure. Several excitation methods are available, including waveguide modes, radiating dipoles and – in our case – particle beams.

For cavity-like structures with high Q, the evaluation with T2 is problematic since the long “ringing” would require long computation times, simulating typically at least Q RF periods. To keep the computation time reasonably low, we will introduce lower Q’s by artificially decreasing the surface conductivity by orders of magnitude.

The eigenmode solver E finds eigenfrequencies and the associated fields (eigenfields) for closed, lossless structures. Since the beam pipe is actually open at both ends, the E module is not suited for modes above the beam pipe cut-off. It can however be used for modes below cut-off if their field does not extend to the ends of the beam pipe. Once the eigenfields of the lossless structure are determined, Q values are determined later by a perturbation calculation.

We want to calculate the Q for the modes below beam pipe cut-off in both time domain and frequency domain. Comparing the results of E and the Fourier transformed results of T2 allows to calibrate the T2 results and verify their validity.

3.2.1. Frequency domain

In general the wall losses can be calculated approximately from the fields obtained for the modes established for a wall with infinite conductivity. The perturbation ansatz uses the magnetic field tangential to the metallic surface, so the surface current is given which causes losses in an equivalent surface resistance

$$R_A = \sqrt{\frac{\omega \, \mu}{2\kappa}} \, , \tag{2}$$

where ω is the frequency of the resonant mode, μ is the permeability and κ the conductivity of the wall material.

Given the frequency domain solution of the E module, MAFIA’s postprocessor, the P module, uses the expression

$$Q = \frac{\omega \, W}{P} = \frac{\omega \, W}{R_A \oint\!\!\oint_A |H|^2 \, \mathrm{d}\, A} \tag{3}$$

to calculate the Q, where W is the energy stored in this mode and P is the power loss in the cavity wall. For the impedance R we use

$$R = \frac{V^2}{2R} \, , \tag{4}$$

where V is the integral of the electric field along the particle's trajectory, i.e. along the axis.

Thus the calculation of quality factor is quite straightforward in frequency domain. In time domain however it is less evident how to obtain Q.

3.2.2. Time domain

For the calculation of Q in time domain we must calculate the wake potential function and determine Q graphically from its decay. The wake potential $V(s)$ at a distance s behind a point charge q traversing the structure is approximately given by

$$V(s) = -2q \sum_i k_i \cos(\frac{\omega_i}{c} s) e^{\left(-\frac{1}{2Q_i}\frac{\omega_i}{c}s\right)}, \tag{5}$$

where k_i is the loss parameter, i.e. the energy lost into mode i is $\Delta W_i = q^2 k_i$.

Measuring the envelope $\tilde{V}(s)$ of V at two distances s_1 and s_2 behind the charge (or short bunch), and assuming a single mode, results in

$$\tilde{V}(s_2) = \tilde{V}(s_1) e^{\left(-\frac{\omega}{2Q}\frac{s_2 - s_1}{c}\right)}, \tag{6}$$

thus Q can be determined from

$$Q = \frac{\omega}{2c} \cdot \frac{s_2 - s_1}{\ln \frac{\tilde{V}(s_1)}{\tilde{V}(s_2)}} . \tag{7}$$

The difficulty in time domain is that many modes contribute to $V(s)$ in (5), and they are not easily separated from each other in the time domain output, i.e. the single mode assumption which led to the simplified eqns. (6) and (7) is not always valid. The Fourier-transform of the data gives some indication of the eigenfrequencies of the contributing modes, but the observed line widths are dominated rather by the length of the investigated time window (limiting the resolution) and not related to Q. Extracting Q with (7) is not very precise in the presence of many modes.

For most simulations we used conductivity values smaller than that of copper to see the wake potential decay more rapidly. For copper conductivity, the Q values are too high to have a substantial decay within a time window dictated by computing time. The scaling of Q with κ is given in eqns. (2) and (3) above.

To show the dependence of Q on the gap size, several different gap sizes were investigated.

To investigate the properties of the structure rather than the bunch, the bunch length should be short. In the simulations we can only use a finite bunch length. We used a

Gaussian bunch $\propto e^{-\frac{1}{2}\left(\frac{s}{\sigma}\right)^2}$ with $\sigma = 5\,\text{mm}$ which is considered short enough for investigations well up to 10 GHz and beyond without a significant roll-off. The boundary conditions at the entrance and exit of the structure were set to “open”.

3.3. Results of numerical simulations

Figure 5 is a MAFIA plot of electrical field for the first resonance; with the chosen gap size of 0.2 mm, the resonance occurs at 3.6278 GHz. This plot confirms this to be the mode of interest with its field near the gap and not a spurious mode.

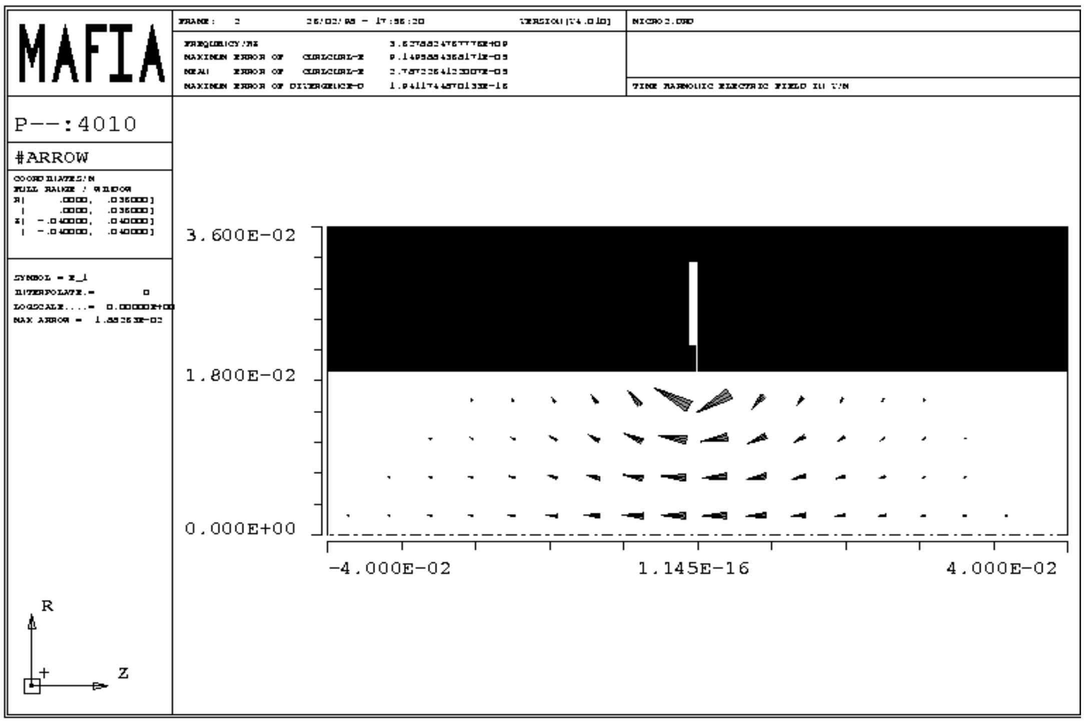

Figure 5: Electric field [V/m] of the fundamental mode near the gap.

In both frequency and time domain, if the gap width decreases, the resonant frequencies below cut-off and the quality factors also decrease (see Table 1). In the limiting case (without gap), the discontinuity disappears as well as the associated resonance. The *R/Q*

Gap [mm]	Freq [GHz]	*R/Q* [Ω]	Q (κ= 5.8e4 S/m)	Q_{inox} (κ= 11.6e5 S/m)
0.05	1.8162	0.968	17.53	78.403
0.1	2.7278	1.331	21.312	95.2
0.2	3.6278	1.759	25.229	112.829
0.4	4.3488	1.932	26.11	116.8

Table 1: Frequency domain results

and resonant frequency in all E simulations is in a range of 0.968 Ω and 1.816 GHz for 0.05 mm width gap to 1.9 Ω and 4.34 GHz for 0.4mm width gap. Note that the data for a gap width of 0.05 mm correspond reasonably well to the measurement results shown in Figure 3, both in terms of *Q* values and *R/Q* as well as the resonant frequencies. However for the smallest gap size considered, the MAFIA result may be questionable as the number of mesh lines across the gaps amounts only two. A larger number would lead to an unacceptable increase in memory and computer-time requirements. As expected, the length of the total structure (beam pipe) does not influence the results of resonance frequency and quality factor calculations. But for the same mesh size a longer structure requires more computer time.

In the following figures, the T2 results for the geometry with a gap width of 0.1 mm are

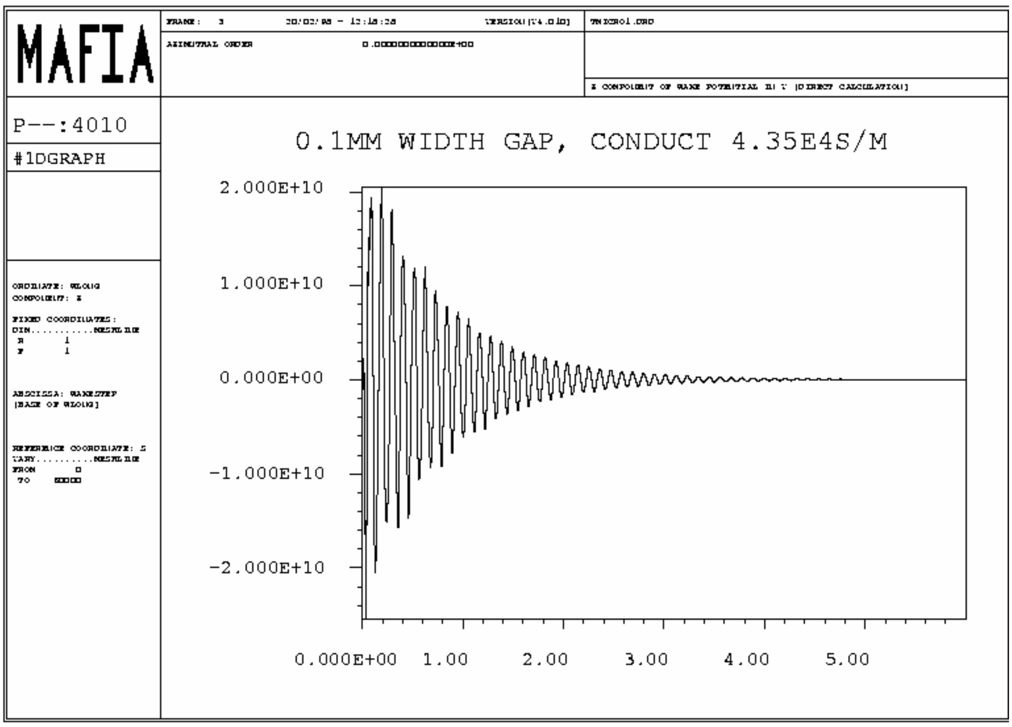

Figure 6: Wake potential [V] in the beam pipe vs. distance *s* [m].

shown. Figure 6 shows the wake potential in V/m as function of the distance *s* in meters. Figure 7 is the FFT (Fast Fourier Transform) plot of these time-domain data; it shows the longitudinal impedance times *c* in Ω m/s versus frequency/*c* in 1/m (wave number).

There are no systematic differences to be expected between time and frequency domain calculation, except for the different boundary conditions. The closed structure used in frequency domain could lead to higher *Q*'s.

The resolution of the mesh is of capital importance to obtain reasonable results in time and frequency domain. Extraction of *Q*-values from the (time domain) longitudinal wake potential is subject to reading uncertainties (error bars). We experienced numerical problems with the *Q* calculation depending on the conductivity of the material. For small gaps and small conductivity ($\kappa < 5.8\ 10^4$ S/m) time and frequency domain results agree

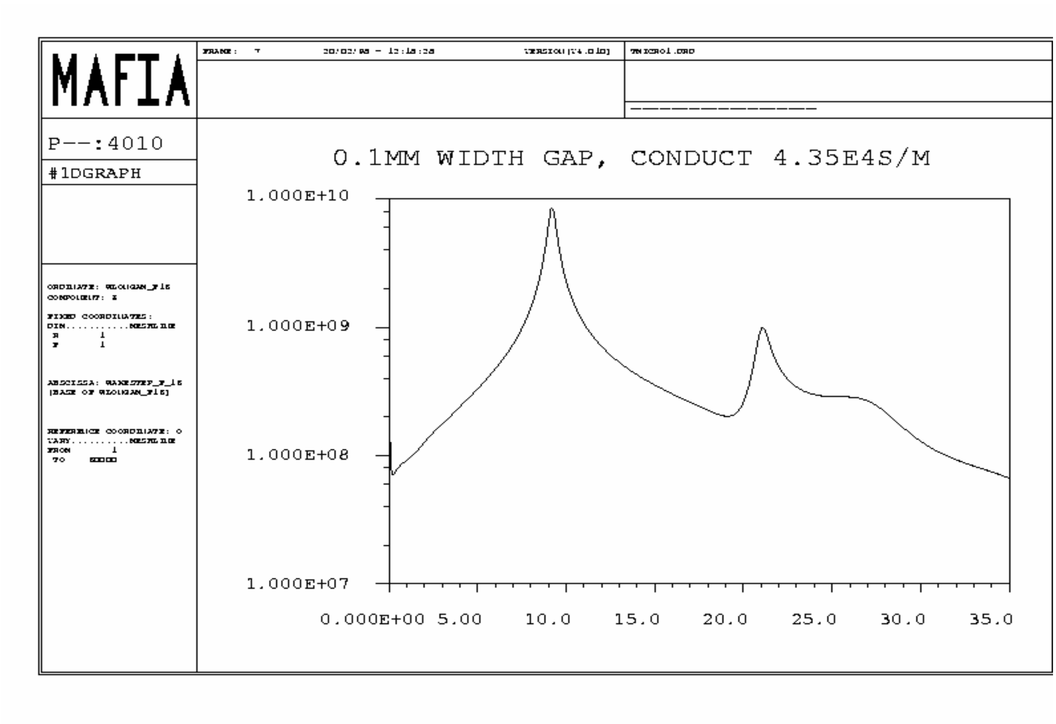

Figure 7: Fourier transform of the wake potential

well. For larger values of the conductivity, the simulation results of time domain and frequency domain start to diverge.

In Figure 8 we plotted the Q of the dominant mode versus conductivity κ. The expected dependence is, according to eqns. (2) and (3), a proportionality to $\sqrt{\kappa}$. For the time domain data however, we first observed an apparent, but inexplicable proportionality to κ. This could later be identified as related to a poor mesh solution. With an appropriate mesh size, the time and frequency domain Q values agreed well.

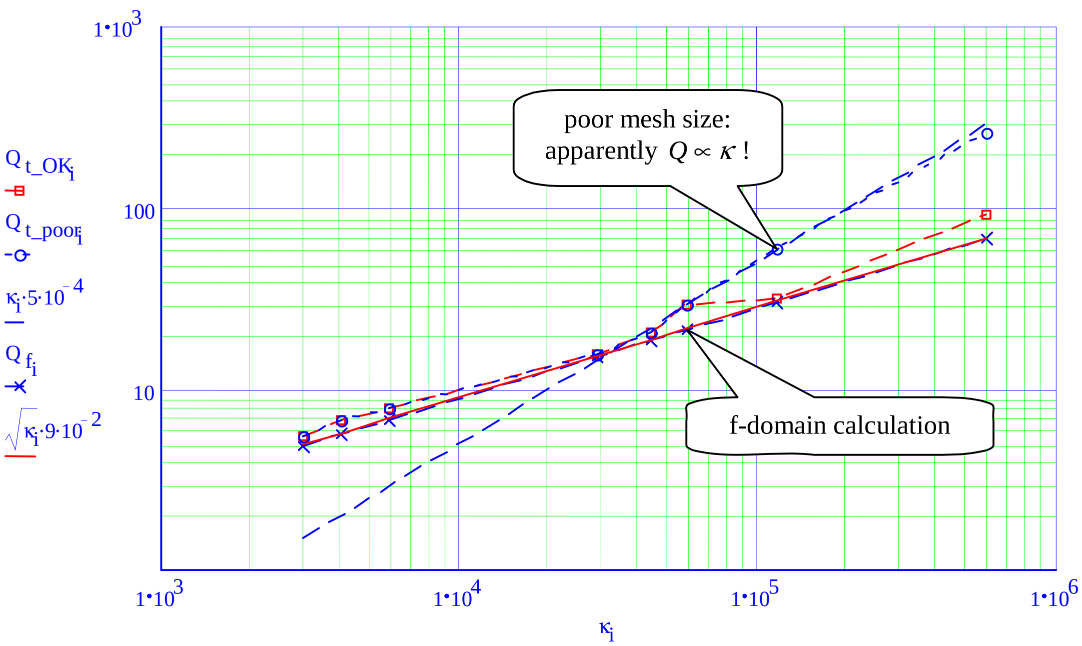

Figure 8: Q values calculated for different conductivities, comparing time and frequency domain data

4. Conclusion

The RF contacts (calculated in a pessimistic way assuming a beam pipe with a gap several times larger than in reality) are not very dangerous for the beam stability and heat loss of the LHC provided the gap width is kept below ~ 0.1mm. This can be achieved by welding the BPM tube to the LHC beam pipe maintaining about 1000 N mechanical pre-stress.

The numerical time domain and frequency domain simulations (longitudinal impedance only) are mutually in good agreement within limitations due to the mesh resolution and the poor precision of the *Q*-values obtained from the wake potential graphs.

The data obtained by numerical simulations using MAFIA in the time and frequency domain are consistent with network analyser measurements in terms of resonance frequencies and *R/Q* values. Assuming a stainless steel beam pipe at room temperature we would expect *Q* values of about 92 for the “microcavity”.

5. Acknowledgements

I would like to thank E. Jensen for his help solving simulation problems, F. Caspers and E. Jensen for many fruitful discussions and G. Schneider (LHC-VAC) for providing the mechanical test pieces.

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