BEAM COUPLING IMPEDANCE STUDIES ON THE LHC FP420 MULTI-POCKET BEAM PIPE PROTOTYPE*

F. Roncarolo†, R.B. Appleby, R.M. Jones
University of Manchester and Cockcroft Institute, Daresbury, England

Abstract

The LHC FP420 collaboration is assessing the feasibility of installing forward proton detectors 420m from the ATLAS and/or CMS interaction points. The latest prototype of a FP420 station consists of a modified LHC beam pipe in which two pockets hosting the detectors introduce an abrupt cross-section variation of the pipe. During the FP420 proposed operation, each station is moved towards the beam as close as 5 mm ($\approx 15\sigma_{\mathrm{x}}$). The impact on the LHC beam coupling impedance has been evaluated with a laboratory wire measurement and a suite of numerical simulations. In addition, we describe a proposed modification of the beam pipe design which minimizes the impedance of the resonances without compromising the FP420 detector signal to background ratio.

INTRODUCTION

The FP420 R&D collaboration converged on a final design [1] of the set of detectors that are proposed for complementing the LHC physics potential, by adding experiments in the forward regions starting at about 420 m from the high luminosity experiments ATLAS and CMS.

The final design considers, for every experimental region, two stations about 7 m apart, each of them equipped with a movable beam pipe (about 1 m long) that is intended to host the FP420 tracking and timing detectors behind the walls of specially machined indentations, referred to as beam pipe "pockets". A previous design studied at the beginning of 2007 (see RF studies in [2]) consisting of a 60 cm long pocket hosting both timing and tracking detectors, now has been changed to a multi-pocket design. The design change allows a more straightforward match of the mechanical tolerances and stability in addition to a simple cooling system for the different detector components that have to operate at different temperature. The new stations consists of two pockets of length $\mathrm{L_{P1}} = 20\,\mathrm{cm}$ and $\mathrm{LP_2} = 35\,\mathrm{cm}$ separated by a 8 cm normal beam pipe section, as shown in the double pocket prototype of Fig. 1.

The FP420 signal acceptance studies [1] require the detectors to be moved as close as 5 mm from the LHC circulating beam, in the inner side of the ring. As a consequence, as discussed in [2] for the single pocket design, one of the key issues to guarantee a safe and acceptable operation of the experiment, the impact of the movable beam pipe on the LHC beam coupling impedance needs to be assessed and minimized.

* Work supported by STFC, UK
† federico.roncarolo@cern.ch

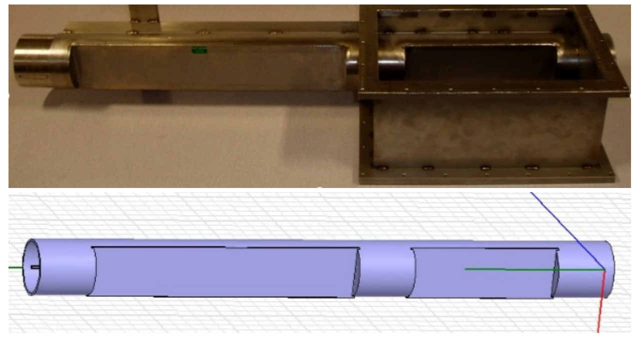

Figure 1: FP420 double-pocket prototype.

A near-beam detector as FP420 can potentially have an impact on the accelerator global resistive wall impedance (the effect is enhanced by the small gap between the beam and the beam pipe walls) and on the geometric part, due to the narrow band resonances that build up at any abrupt change of the beam pipe cross-section. In this paper we review such impedance effects for the latest FP420 multi-pocket design, by comparing the results of analytical and numerical simulations to laboratory measurements. The frequency band of interest is determined by the LHC beam spectrum, and this limits the upper limit to 3 GHz.

LONGITUDINAL BEAM COUPLING IMPEDANCE

The longitudinal impedance is in general related to the electromagnetic power exchange between the beam and its surroundings. Not only the beam stability can be compromised, but the power exchange represents a dangerous heat source and a potential disturbance to the detectors cooling and accuracy.

A series of numerical simulations were carried out using two commercially available codes, namely Ansoft HFSS [3] and GDFIDL [4].

HFSS was used to simulate the coaxial wire method described in [5] and discussed in [2], which consists of a thin wire that is stretched inside the Device Under Test (DUT) along the reference beam trajectory. The simulated (or measured) scattering parameter S_{21} of the resulting loaded transmission line, compared to the same quantity evaluated for a reference vessel (smooth beam pipe with same DUT initial diameter) allows the longitudinal impedance to be determined according to the well known 'log formula' $\mathrm{Z_L}(\omega) = -2\mathrm{Z_c}\ln[\mathrm{S_{21}^{DUT}}(\omega)/\mathrm{S_{21}^{REF}}(\omega)]$, where Z_c is the characteristic line impedance. All HFSS calculations are made with a finite elements method in the frequency domain.

On the other hand, GDFIDL enables simulations of not only the scattering parameters of the coaxial line structure, but also it enables to calculate the longitudinal (and transverse impedance) from the direct integration of the electromagnetic fields induced by a traveling line charge with the shape of a particle bunch. GDFIDL calculates the relevant wake fields in the time domain and coupling impedances are determined by FFT calculations.

The simulation results were meant to cross-check laboratory measurements at the Cockcroft Institute on a double pocket prototype. The measurements, based on the coaxial wire method mentioned above, were performed for setups corresponding to various FP420 positions, from parking (at about 15 mm for the beam) to data taking (at 3 mm). The hardware set-up and the accuracy on the wire position determination (within 0.5 mm) are discussed in [2].

The real and imaginary part of the longitudinal impedance $Z_L/n = Z_L/(f/f_0)$ (where f_0 is the particles revolution frequency) as simulated and measured, for a setup corresponding to FP420 in parking position, are shown in Fig. 2, where the frequency band 2.35 - 2.70 GHz is considered. At lower frequencies no resonances occur and at higher frequencies the LHC beam spectrum decays (i.e. the effective impedance becomes negligible).

The agreement between HFSS and the measurements (both based on the scattering parameters calculation) is excellent in terms of frequency and impedance magnitude. The residual discrepancies (below 5 MHz in f and 1 mΩ in Z_L/n) must be attributed to residual mismatch in the measured network and to not perfect meshing in the simulations. Differences between the nominal and real stainless steel resistivity may explain differences in the resonance amplitude and quality factor.

The GDFIDL simulations based on wake field calculations (blue line on the plots) are also in very good agreement with the measurements. The second resonance (at about 2.43 GHz) results at about 10 MHz lower frequency than measurements and HFSS. On the other hand the GDFIDL simulation with the wire method (green line) confirms the same mode frequency. It could be that the presence of the wires perturbs this particular mode, but this has not been confirmed by preliminary HFSS eigenmode simulations on the DUT with and without wire.

Both GDFIDL simulations give smaller resonance quality factors. This can be attributed to the chosen limited simulation time that limited the period on which the wake field was analyzed (if the wake field is not totally damped, narrow band frequency information is lost).

The experiment in the laboratory was repeated after tapering the beam pipe first and last indentation (the indentations in between the two pockets are very difficult to access after fabrication) with copper foils which provide a smoother transition for the wake fields at the pocket edges. Such foils were glued on the upper and lower part of beam pipe and pocket, leaving unchanged the volume that can possibly be traversed by the FP420 signal protons. In this way the signal/background ratio is not altered. The real part of Z_L/n with and without tapering, for a FP420 position in data taking is shown in Fig. 3. After tapering the maximum impedance is below 8 mΩ. A further decrease is expected if the tapering is implemented in between the two pockets too.

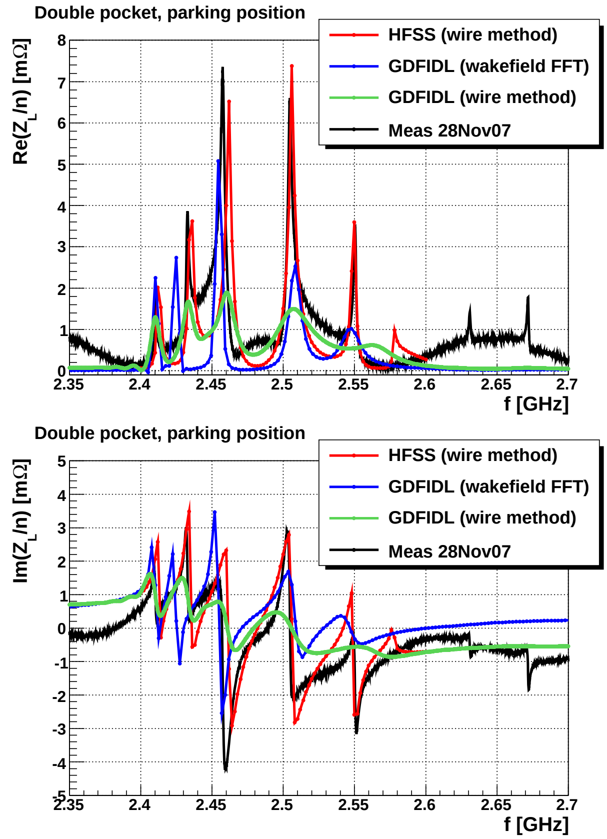

Figure 2: Longitudinal impedance of a FP420 double-pocket pipe in parking position calculated with simulations (HFSS and GDFIDL) and compared to laboratory experiments.

Transverse Impedance

Since the FP420 detectors are proposed to operate at a small distance from the beam, can potentially further increase the total LHC restive wall transverse impedance that is critical for coupled-bunch instabilities. Analytical calculations [1] showed that the contribution of a FP420 station results about two order of magnitude smaller than the one calculated when accounting for all the LHC collimators.

Loss Factor

The coaxial wire method can be applied to calculate the loss factor k by means of time domain measurements [6]. The method consists in transmitting a pulse down the wire stretched inside the DUT with a Gaussian pulse resembling the longitudinal shape of a particle bunch. By comparing

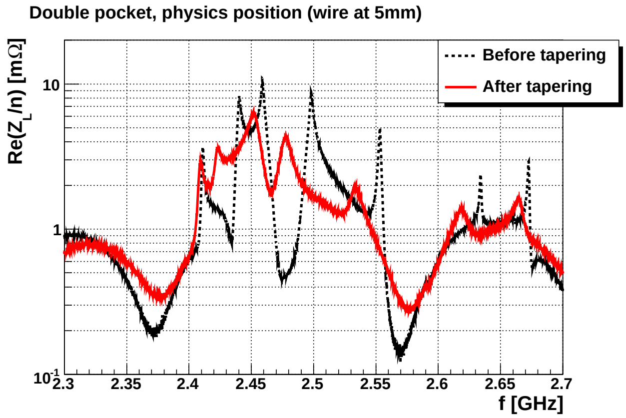

Figure 3: Longitudinal impedance of a FP420 double-pocket pipe in data taking position, as measured with and without copper tapering (see text).

the resulting pulse shape $\mathrm{i_m(t)}$ with that of a pulse $\mathrm{i_m(0)}$ that is transmitted through a reference vessel, the amount of energy that a bunch will lose passing through the DUT can be estimated, according to:

$$k = \frac{2Z_c \int i_0(t)[i_0(t) - i_m(t)]dt}{[\int i_0(t)dt]^2} \qquad (1)$$

where $\mathrm{Z_c}$ is the characteristic line impedance. The Gaussian pulse as measured for the reference vessel and for different wire positions inside the double pocket beam pipe are shown in Fig. , while the resulting loss factors are shown in Fig. 4.

CONCLUSIONS AND OUTLOOK

The longitudinal coupling impedance of the FP420 double pocket stations is dominated by a narrow band component with significant modes from 2 to 3 GHz and it has been characterized by means of laboratory measurements and numerical calculations that result in good agreement. The small impact on the LHC impedance budget will be even smaller after implementing the next design entailing tapering foils at the pockets indentations. The stretched wire technique has been successfully used for determining the characteristic loss factor. This quantity, after scaling for the real LHC bunch shape can be used for predicting the amount of energy lost by the beam on the FP420 beam pipe walls. Analytical calculations not discussed here, based on classical and novel theories [8] assess the transverse resistive wall impedance of a station at 5 mm from the beam to be about two order of magnitude smaller than the one calculated when accounting for all the LHC collimators [7].

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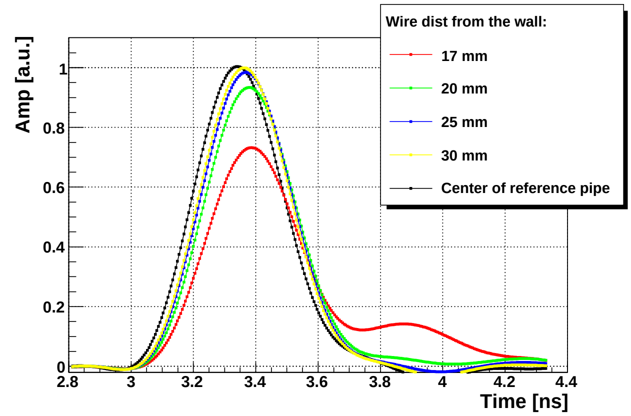
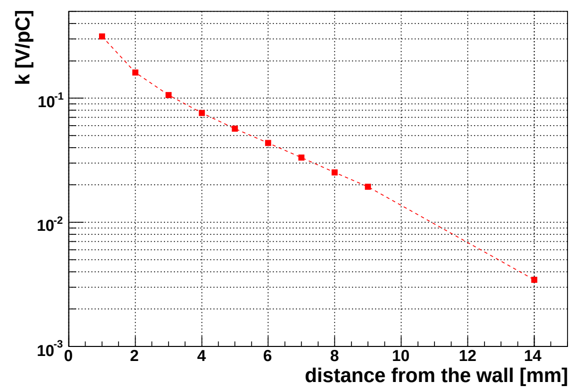


(a)



(b)

Figure 4: Time domain measured pulses (a) and calculated loss factors (b) for different wire distances from the wall.

REFERENCES

[1] M. Albrow et al., hep-ex/0806.0302

[2] F.Roncarolo et al., "Beam Coupling Impedance Simulations and Measurements for the FP420 Detector", Proceedings of PAC07

[3] Ansoft Corporation, URL: http://www.ansoft.com/

[4] GdfidL, URL: http://www.gdfidl.de/

[5] V.G. Vaccaro, "Coupling Impedance Measurements", INFN/TC-94/023 (1994)

[6] M. Sands, J. Rees, SLAC - TN-05-051

[7] E.Metral et al., "Transverse impedance of LHC collimators", Proceedings of PAC07

[8] E.Metral et al., "Resistive-Wall Impedance of an Infinitely Long Multi-Layer Cylindrical Beam Pipe", Proceedings of PAC07