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ELECTROMAGNETIC DESIGN AND OPTIMIZATION OF DIRECTIVITY OF STRIPLINE BEAM POSITION MONITORS FOR THE HIGH LUMINOSITY LARGE HADRON COLLIDER

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Abstract

This paper presents the preliminary electromagnetic design of a stripline Beam Position Monitor (BPM) for the High Luminosity program of the Large Hadron Collider (HL-LHC) at CERN. The design is fitted into a new octagonal shielded Beam Screen for the low-beta triplets and is optimized for high directivity. It also includes internal Tungsten absorbers, required to reduce the energy deposition in the superconducting magnets. The achieved broadband directivity in wakefield solver simulations presents significant improvement over the directivity of the current stripline BPMs installed in the LHC.

INTRODUCTION

The High Luminosity upgrade for the Large Hadron Collider (HL-LHC) is scheduled to take place during the third long shutdown (LS3), when about 1.2 km of the present LHC ring will be modified. The upgrade aims at maximizing the integrated luminosity seen by the LHC experiments, with the aim of delivering $3000 fb^{-1}$ by mid 2030 [1]. The main change will be the installation of completely new magnets for the focussing triplet in the two high luminosity collision points (ATLAS and CMS).

Seven stripline BPMs on each side of the interaction region in points 1 and 5 are currently foreseen to be installed, located in the magnet interconnect from quadrupoles Q1 to Q5. They should provide the means to control the orbit of the two beams at the interaction point (IP) with a high resolution and stability.

As the two counter-rotating LHC beams are in the same vacuum pipe throughout this whole region the BPMs need to be able to distinguish one beam from the other. The degree to which the measurement of one beam can be decoupled from the other in a common BPM is known as the directivity and its optimisation is the subject of this paper.

STRIPLINE BPM

A transmission line (stripline) couples to the transverse electromagnetic (TEM) field of the beam. Stripline BPMs can measure two beams travelling in opposite directions and ideally their upstream and downstream ports should only be sensitive to incoming particles from a given direction. The directivity of a stripline is defined as the ratio of signal power at the upstream port to that at the downstream port in response to a bunched beam particle distribution. The directional stripline BPMs currently installed in the LHC achieve a typical broadband directivity of ~20 dB [2].

To illustrate how directivity affects the accuracy of a stripline BPM, the positioning error of beam 1 in the presence of beam 2 was calculated for different beam positions and different beam intensities for the current LHC stripline BPM (BPMSX) and a BPM with improved directivity (27dB). The results are shown in Table 1. When the two beams have equal intensity and position, the error is null. However, in the LHC the beams are physically separated before the IP up to 20 mm and the error in this case can reach more than 3% of the scale factor (~half radius) assuming the current LHC stripline, but which can be three times better if the directivity is improved by a factor of 2.

Table 1: Positioning Error of Beam 1 as a Function of the Position of Beam 2 (in mm) for the New and Current LHC BPM

Error [%]	***x*=0 new**	***x*=10 new**	***x*=0 current**	***x*=10 current**	**Intensity Ratio I_2/I_1**
***y* = 0**	0	1.22	0	3.55	1
***y* = 5**	0.66	0.6	1.92	1.87	1
***y* = 10**	1.34	0	3.99	0	1
***y* = -10**	1.34	2.56	3.99	7.51	1
***y* = -10**	0.6	1.31	2.09	3.93	0.5
***y* = -10**	2.57	4.92	7.2	13.79	2

The errors are more dramatic when the beam intensities are unequal. A factor of 2 difference in intensities leads to an error of nearly 14% for the current design, which can be reduced down to 4% with improved directivity.

These errors only apply of course if the two beams actually cross in the BPM. Both for the current LHC and HL-LHC layouts the BPM locations are chosen so as to maximise the arrival time difference between the two beams to minimise the impact of this imperfect directivity. Nevertheless the influence of one beam on the other is still observed, in particular for BPMs which could not be ideally located.

This work is therefore focused on the design of a new stripline BPM, optimizing the directivity to provide the best possible accuracy.

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STRIPLINE BPM DESIGN

In the new HL-LHC triplet cryostat design, the inner diameter of the cold bore is 138 mm, which is significantly larger than that of the current LHC [3]. Inside the cold bore, there is a beam screen to shield the cold bores from synchrotron radiation and heating due to the beam image current. In addition the beam screen will be equipped with Tungsten-INERMET180 absorbers to catch collision debris, to minimise the energy deposition in downstream magnets. These absorbers will come in two variants: 16 mm thick to be installed inside the Q1 and 6 mm thick to be installed from Q2 to D1. The beam screen will therefore have an octagonal shape to maximise aperture and accommodate the tungsten shielding (Fig. 1).

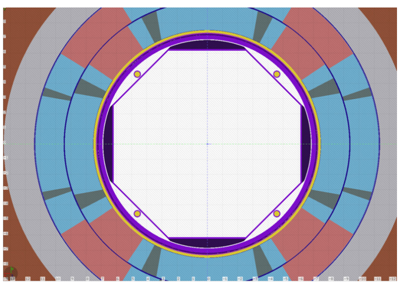

Figure 1: HL-LHC Q2 and beam screen cross-section.

The stripline beam position monitors will be mounted between two beam screen segments and will also need to accommodate tungsten shielding.

Maintaining a high degree of directivity in a stripline BPM requires the velocity of the beam and that of the signal to be well matched, with the stripline impedance corresponding to the termination impedance. The coupling between striplines also needs to be minimized [4]-[8].

Extensive full-wave electromagnetic simulations using CST Particle Studio have been performed with the aim of redesigning the electrode shape and redesigning the transitions between the electrode and coaxial connector to minimize return loss, while fitting these electrodes into the larger diameter pipe with absorbers. The stripline electrode is 120 mm long, and has a characteristic impedance of 50 Ω.

Wakefield simulations with the current electrode designs fitted into a 148 mm pipe shown in Fig. 2, with and without 16 mm thick Tungsten-INERMET180 absorbers (modelled as a lossy metal with an electric conductivity of 1.2e7 Sm^{-1}) showed a reduction in the signal of 30% in the presence of the tungsten (Fig. 3) which can be explained by the field distributions due to the positioning of the tungsten blocks within the vacuum pipe and near the retracted electrodes. This signal reduction should not be an issue for the BPM processing electronics.

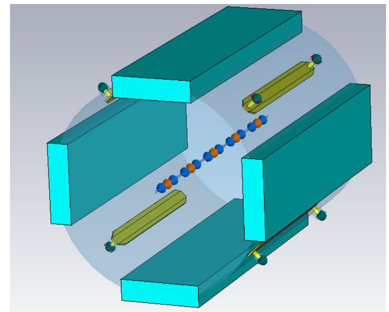

Figure 2: BPM with current electrode design and 16 mm tungsten blocks.

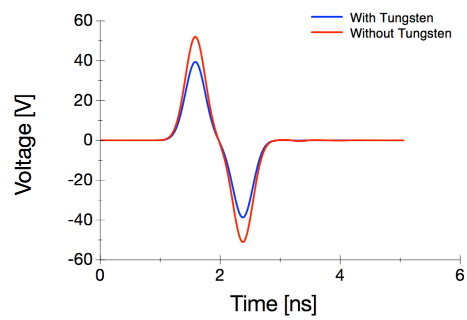

Figure 3: Signal with and without tungsten absorbers.

Optimization of Stripline to Coaxial Transition

CST Microwave Studio Time-Domain Reflectometry (TDR) analysis of different transition curvatures was performed to optimise the stripline to coaxial transition. Three transitions with different smoothness factor and their corresponding TDR results are shown in Fig. 4 and Fig. 5 respectively. The optimal transition is shown in Fig. 4a, giving an almost perfect match to 50 Ω as shown in Fig. 5.

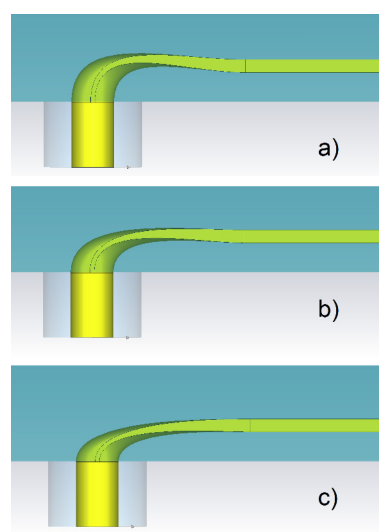

Figure 4: Stripline-to-coaxial transition shapes.

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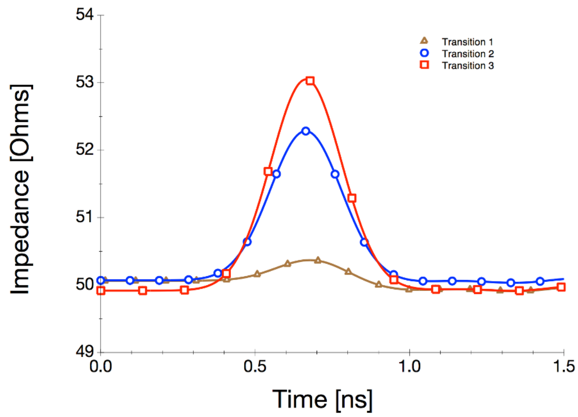

Figure 5: Stripline-to-coaxial transition TDR simulations.

Directivity

Voltage signals at the upstream and downstream ports, for the configuration in Fig. 4a, in time and frequency domains are presented in Fig. 6 and Fig. 7 respectively. The peak values of voltages at the upstream and downstream ports are 54.5V and 2.4V respectively. The broadband directivity achieved is therefore 27 dB. Directivities for current and new BPM in different frequency bands are shown in Table 2.

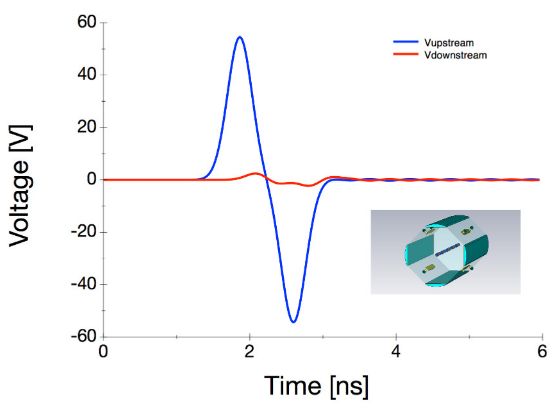

Figure 6: BPM time response.

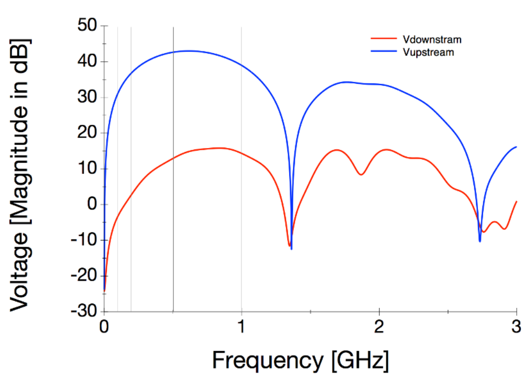

Figure 7: BPM frequency response.

Table 2: Directivity of the Current and New BPM in Different Frequency Bands

Frequency [MHz]	**Directivity**	
	Current BPM [dB]	**New BPM [dB]**
100	27	34
200	28	34
500	24	30
1000	14	24

CONCLUSION

The preliminary electromagnetic design of the stripline BPM for HL-LHC has been presented. The new electrode and transition designs have shown a good impedance match, resulting in a broadband directivity of 27 dB. Directivity improvement was achieved in all frequency bands. This preliminary BPM design will be further improved through additional simulations, while including more detail from manufacturing and mechanical integration constraints.

ACKNOWLEDGEMENT

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