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CHARACTERIZATION OF THE LONGITUDINAL BEAM COUPLING IMPEDANCE AND MITIGATION STRATEGY FOR THE FAST EXTRACTION KICKER KFA79 IN THE CERN PS

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Abstract

In the framework of the High Luminosity Upgrade of the LHC (HL-LHC) the beam intensity from the injectors must be doubled while keeping longitudinal beam parameters unchanged. As such, high-quality beams with high intensities are required also from the Proton Synchrotron (PS). The beam coupling impedance plays a crucial role and mitigation measures must be taken to remain within a stringent impedance budget. Kicker magnets are important contributors to the overall broadband impedance of the PS. Moreover, the detailed study of kicker impedances revealed additional resonant modes which may be critical for the beam stability. The longitudinal beam coupling impedance for the fast extraction kicker KFA79 is presented in this study, and a solution to reduce the impedance of the critical resonant modes is introduced. Electromagnetic (EM) simulations have been performed to determine the impedance behaviour. Finally, the insertion of transition pieces between magnet modules is presented as a measure for mitigating the low frequency resonant impedance contributions.

INTRODUCTION

The kicker magnet KFA79 (Kicker Full-Aperture in straight section SS79) was installed in the CERN PS in the seventies [1]. Together with the fast kicker KFA71 (in SS71) and the septum magnet SMH16 (Septum Magnetic Horizontal in SS16), the KFA79 was built as part of the fast extraction process from PS towards experimental areas and is nowadays used towards the Super Proton Synchrotron (SPS), the AD machine and the n-TOF experiment. The fast kickers are also involved in the PS multi-turn extraction system [2].

The KFA79 is composed of three identical modules, each one containing nine ferrite cells. The connectors of each module (Fig. 1, right) face alternately towards the inside or outside of the PS ring (Fig. 2).

Every time a bunched beam passes through the accelerator, charges are induced in all conductive surfaces. In the case of cross sectional changes, e.g. along the beam pipe, or due to the installation of accelerator elements, these charges accumulate and will be the source of a resonance which is seen by the following bunch. The beam coupling impedance is defined as the integral over the normalised Fourier transform of the electromagnetic (EM) force along the particle trajectory [3].

The coupling impedance of the KFA79 was previously studied in the framework of the PS machine impedance model project [4]. In view of the LHC Injector Upgrade (LIU) project, a thorough survey allowed to refine the PS impedance model, and one of the main limitation for reaching higher intensities was identified in the coupled-bunch instabilities [5]. The requirements for the longitudinal impedance are defined by the sum of all impedance contributions during one turn. An analytical estimation based on shunt impedance R_s versus frequency provides a shunt impedance threshold for coupled-bunch instability [6]. For the PS, in the low frequency range ($f \lesssim 40$ MHz), the threshold for dipolar or quadrupolar modes is $R_s \lesssim 2$ kΩ. The requirement for an individual element, as a kicker, is to keep the impedance contribution to a minimum as well as to be optimized for their kick strength and rise/fall times. The 3D geometry of KFA79 was modelled in great detail to achieve maximum accuracy in the impedance behaviour [7]. However, the magnet geometry has been modified over the years, invalidating many of the previous impedance calculations.

The objective of this work was to produce an up-to-date 3D model of the kicker KFA79 and to calculate, with EM simulations, the longitudinal coupling impedance. Moreover, the aim was to analyze how the effects of impedance could be mitigated to improve beam stability and to reduce beam losses.

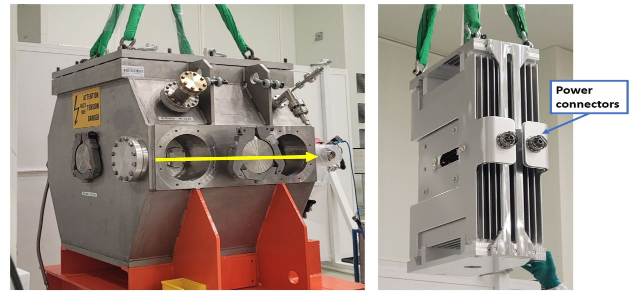

Figure 1: Outer view of the KFA79 vacuum tank with beam direction indicated by the yellow arrow (left) and extracted module (right).

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ELECTROMAGNETIC SIMULATIONS

The new simulation model was built starting from drawings and from the CAD model of the kicker. Most of the changes implemented to the kicker geometry, with respect to the original one, were carried out to allow an improved manufacturing process. These changes mainly involved modifying the vacuum tank from its round shape to straight profiles as well as making some modifications to the assembly of the individual modules. The 3D model used for EM calculations is shown in Fig. 2.

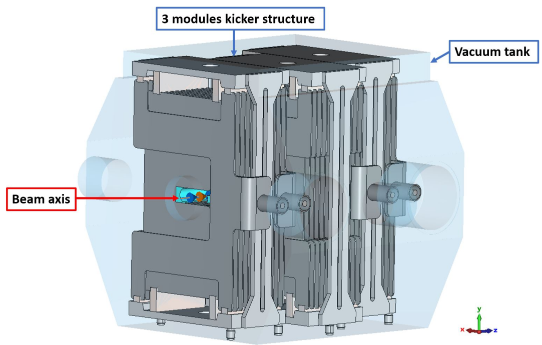

Figure 2: New 3D model of KFA79 used for EM calculations. The vacuum tank (light blue) is made transparent to see the kicker modules (gray).

The module of each magnet consists of aluminium alloy plates electrically connected alternately to high voltage or to ground. C-shaped 8C11 ferrite blocks [8] are inserted between the plates, and ceramic isolating combs are used as supports to hold the plates assembly in place. The entire assembly, including the ceramic combs and plates, is mounted onto an aluminum alloy support frame. The magnet modules are electrically grounded via steel legs that are in contact with the tank.

The entire geometry was modelled in the electromagnetic simulation code CST [9]. The calculation of the longitudinal impedance was carried out by using the wakefield solver. Figure 3 shows the predicted longitudinal beam impedance of the kicker KFA79 versus frequency up to 1.6 GHz. The impedance increases to 1.7 kΩ up to 500 MHz, with a peak of 1.8 kΩ around 650 MHz, it then generally decreases until the end of the considered range of frequency. The envelope of the impedance curve represents the so-called broadband behavior and it is directly caused by the ferrites. Three resonances, at 19.7 MHz, 32.3 MHz and 45.5 MHz, are excited by the beam inside the vacuum tank and between the modules (Fig. 4). Their shunt impedance is in the order of several hundred ohms. These resonances can be critical for the stability of the beam because they could be located in correspondence with the beam spectrum lines and generate induced voltage contributions. Therefore, a complete understanding of their origin was the main focus of investigation.

The electric field was calculated from the wakefield simulation by using field monitors at the frequencies of interest. The electric field distribution allowed to identify the location of the critical resonances in the low frequency range. An example of E-field monitor for the impedance peak at 19.7 MHz is shown in Fig. 5. The E-field monitors from the three low frequency peaks revealed resonances building up between the side walls of the vacuum tank and the ground plates of the modules at the extremities. A large E-field intensity was also seen between the ground plates of two consecutive modules.

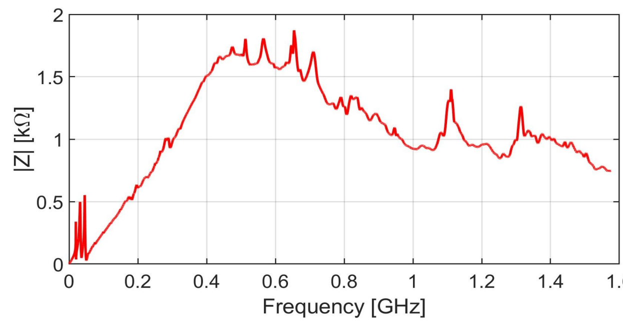

Figure 3: Predicted longitudinal beam coupling impedance of the kicker KFA79. The plot shows the critical resonances below 100 MHz, as well as the overall broadband impedance contribution.

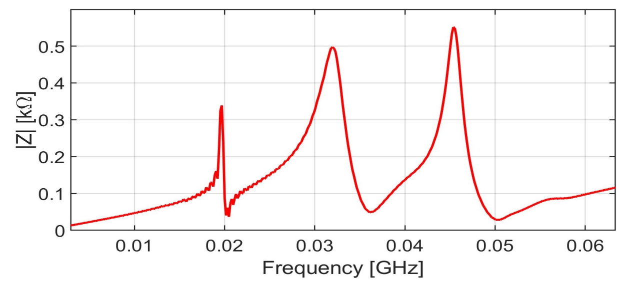

Figure 4: Zoom in the low frequency range of the predicted longitudinal coupling impedance of the kicker KFA79. The plot shows the three critical resonances respectively at 19.7 MHz, 32.3 MHz and 45.5 MHz.

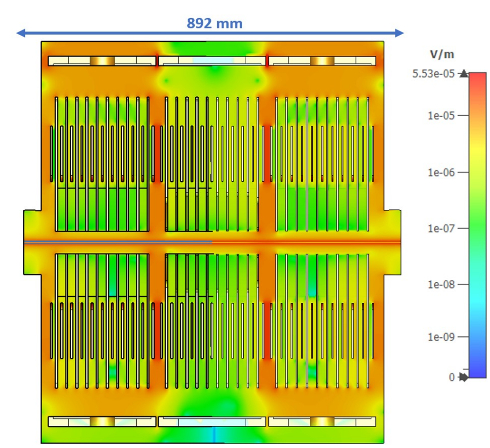

Figure 5: Side view of the kicker KFA79 showing the electric field distribution at 19.7 MHz. The largest E-field intensity identifies the resonance building up between the magnet modules.

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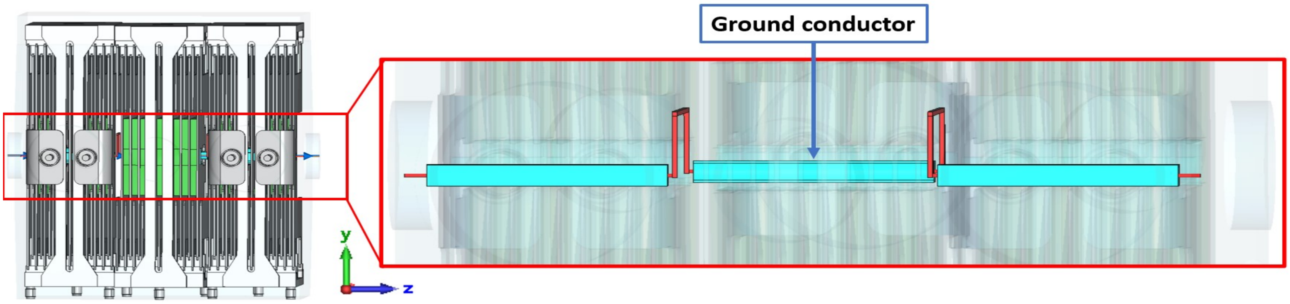

Figure 6: KFA79 kicker model with the inclusion of transition pieces. Ferrite elements (green) are visible in the left picture and transition pieces (red) as well as module's ground conductors (light blue) in the zoom-in picture on the right.

IMPEDANCE MITIGATION

The identification of the source and location of critical impedance contributions led to an investigation of potential solutions for mitigation. The primary objective was to dampen the impedance peaks in the low frequency range. This could be achieved by providing a conductive path for the passage of induced currents in regions where the electric field was contributing the most. To this aim, an electrical connection from the tank's left wall (beam in) to the right one (beam out), passing via the modules' ground conductors was inserted. The 3D model was updated to include copper bars and rods, creating a conductive path between the tank and the module's ground plates (Fig. 6). As a first iteration, the idea was to keep an electromagnetic symmetry in the structure by placing the copper transition rods in correspondence of the beam vertical coordinate. However, the central module is flipped with respect to the horizontal and therefore its ground conductor is not aligned along the x-axis with the other two. Transition copper bridges, surrounding the beam chamber, were added in the model to overcome this problem. The 3D model, including the above mentioned modifications, was simulated using CST wakefield solver. The longitudinal beam coupling impedance is compared for both cases, with and without the insertion of transition pieces in Fig. 7.

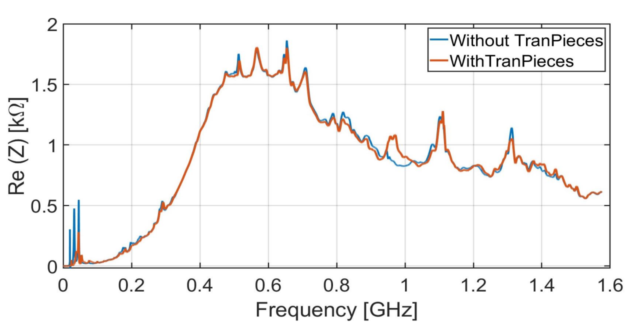

Figure 7: Predicted longitudinal beam coupling impedance of the kicker KFA79 with (red) and without (blue) the inclusion of transition pieces.

The plot of the real part of the impedance allows to directly compare the values of the shunt impedance for both cases. The results indicate that the three low frequency peaks are considerably attenuated with the inclusion of transition pieces (Fig. 8).

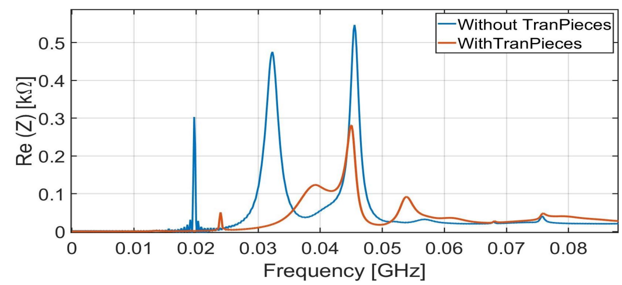

Figure 8: Zoom in the low frequency range of the longitudinal beam coupling impedance of the kicker KFA79 with (red) and without (blue) the inclusion of transition pieces.

The overall broadband behaviour remains unaffected by the geometrical modification, and it is a direct consequence of the kickers design and functionality. The inclusion of conductive transitions is therefore confirmed to be beneficial in mitigating the impact of low frequency resonances. The mechanical design and implementation of the transition pieces is currently being discussed in order to obtain a technically feasible solution.

CONCLUSION AND OUTLOOK

A new simulation model of the PS fast-extraction kicker KFA79 was created starting from original drawings and from the CAD model. The kicker beam coupling impedance was obtained through EM calculations, by using the CST wakefield solver. Three resonances have been found in the low frequency range and they have been identified as possibly critical for the beam stability. A careful analysis of the field distribution at the frequencies of interest allowed to identify a means of mitigation for these resonances. The inclusion of transition pieces connecting the ground plates of adjacent modules and the outer ground plate of the first and third modules to the tank shows a very good reduction in the kicker beam coupling impedance and therefore a good contribution to the overall reduction of coupled-bunch instabilities. A mechanically feasible implementation is currently being discussed. Radio-frequency measurements will allow to complete the picture of the longitudinal coupling impedance of the KFA79 kicker. Furthermore, the characterization of the coupling impedance of the KFA79 will serve as guiding example for extending the study to the other PS extraction kicker, the KFA71.

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