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BEAM COUPLING IMPEDANCE OF THE MAIN EXTRACTION KICKERS IN THE CERN PS

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Abstract

In view of the High Luminosity (HL) upgrade of the LHC, the beam intensity must be doubled in the injector chain. To perform reliable beam dynamics simulations, the beam coupling impedance in the injectors, such as the Proton Synchrotron (PS), must be followed closely by including all contributing elements into the impedance model. The existing kicker magnets of the PS had been optimized for large kick strength and short rise/fall times, but not necessarily to minimise beam coupling impedance. Hence, unwanted beam induced voltage can build up in their electrical circuits, with an impact on the beam. The beam coupling impedances of the two main kicker magnets used for the fast extraction from PS, the KFA71 and KFA79, are extensively characterized in this study. In particular, electromagnetic simulation results for the longitudinal and transverse coupling impedance are shown. The critical impedance contributions are identified, and their effect on beam stability is discussed. Moreover, the impact of the cable terminations on the electromagnetic field pattern and possible mitigation techniques are presented, providing a complete impedance evaluation of the entire kicker installation.

INTRODUCTION

The KFA71 and KFA79 (Kicker Full Aperture) are the fast kickers, together with the septum magnet SMH16 (Septum Magnetic Horizontal) and a set of bumper magnets, involved in the extraction from PS towards SPS (Super Proton Synchrotron) and experimental areas. The extraction kicker system consists of twelve magnet modules which, due to space constraints, were split into two different devices: nine modules are located in a vacuum tank in section 71 (KFA71) and three in section 79 (KFA79) of the PS accelerator. These magnets were first installed in the 1970s [1], and they are nowadays part of the PS multi-turn extraction process, introduced in 2006 to split the beam transversely prior to extraction [2]. In the context of the multi-turn extraction, a measurement campaign of the beam coupling impedance of the PS kickers involved in the process was launched [3]. The impedance of two new kickers, KFA13 and KFA21, which consists of modules similar to those of the PS fast extraction kickers, were measured at that time.

Thereafter, in the framework of the PS machine impedance model and in view of the LHC Injectors Upgrade (LIU), the kickers were identified as the main source of broadband impedance, responsible for the longitudinal loss of Landau damping in the PS [4]. Due to mechanical modifications of the components over the years and due to the high computing resources required to analyse such complex geometries, the beam coupling impedance of the KFA71 and KFA79 was calculated in different iterations with the aim of keeping the PS impedance model updated [5, 6]. The two kicker magnets have been designed for the same functionality, therefore the complete characterization of the beam coupling impedance of the three modules magnet (KFA79) can be used as guiding case also for the nine modules magnet (KFA71). Longitudinal beam coupling impedance calculation results for the KFA79 were presented together with a mitigation solution to reduce the critical impedance contributions [7]. This completed the picture of the longitudinal beam coupling impedance of the KFA79 together with the transverse impedance results, and the study carried out on the nine modules kicker, the KFA71.

The objective of the present work was to present an up-to-date beam coupling impedance model of the PS extraction kickers KFA71 and KFA79, based on the longitudinal and transverse electromagnetic (EM) simulations results. In addition, the influence of the High-Voltage (HV) cables termination on the beam coupling impedance is here introduced and discussed for the KFA79.

ELECTROMAGNETIC CALCULATIONS

The kickers KFA71 and KFA79 are composed respectively by nine and three modules. Each module is a 15 Ω delay line consisting of an assembly of nine C-shaped ferrite cells, separated by aluminum alloy laminations (Fig. 1). Both kicker magnets have a similar layout, with the high voltage connectors of each module facing alternately towards the inside or outside of the PS ring. While the modules of the two kickers do not have exactly the same geometry, their assembly is comparable, with analogous impedance behaviour expected.

The EM calculations have been carried out by using the Wakefield solver in CST Studio Suite [8]. Both three dimensional (3D) geometries have been built in CST starting from previous models and by making use of the most recent drawings and CAD projects (Fig. 2). The three modules kicker, KFA79, is 0.89 m long, and it is assembled inside an octagonal vacuum tank, whereas the nine module magnet, KFA71, is 2.45 m long and it is contained in a round tank.

The dispersive behaviour of the ferrite material 8C11 [9] has been included by importing measured values of the mag-

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netic permeability as a function of frequency [10]. Due to the high geometrical complexity of the components, the simulation settings were chosen to achieve a compromise between good resolution in the desired frequency range and reasonable computational time.

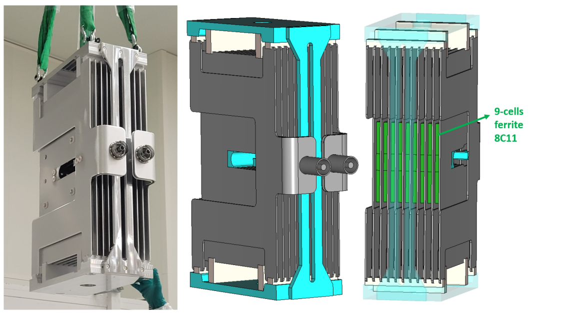

Figure 1: Photo (left) and 3D geometry (right) of a single module of the kicker magnet KFA79, with the assembly of aluminum alloy plates and nine cells of ferrite.

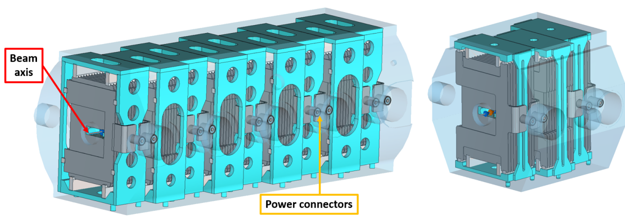

Figure 2: 3D model of the KFA71 (left) and KFA79 (right).

Longitudinal Beam Coupling Impedance

To calculate the longitudinal beam coupling impedance a gaussian particle beam with an rms bunch length of 65 mm has been defined, in the Wakefield solver. This was chosen to obtain a good resolution up to 1.5 GHz, frequency range of the PS beam spectrum. The background material has been considered as the one of the tank walls, stainless steel, with electrical conductivity of $\sigma = 1.37 \times 10^6$ S/m. Perfect electric boundaries (PEC) have been set in the horizontal and vertical direction, while an open boundary has been selected along the longitudinal beam axis. For the case of longitudinal beam coupling impedance calculation, the wakelength has been considered long enough to ensure a complete convergence of the wake potential and impedance peaks with saturated amplitude. The main simulation settings are summarized in Table 1.

The impedance of the kickers shows a broadband behaviour, directly proportional to the number of ferrite elements and with a resonant frequency around 600 MHz (Fig. 3). As expected, with KFA71 containing three times more ferrite elements than the KFA79, the impedance amplitude is three times larger than that of the KFA79. The longitudinal beam coupling impedance of the KFA71 has a maximum amplitude of 5.6 kΩ for a resonant mode at 665 MHz, above the main part of the beam spectrum in the PS.

Table 1: Main parameters of CST Wakefield simulations for the longitudinal beam coupling impedance calculation of KFA71 and KFA79.

	KFA71	**KFA79**
Bunch length rms [mm]	65	65
Wakelength [km]	2	1
Max frequency [GHz]	1.58	1.58
Mesh-cells (hexahedral)	18.9×10^6	19.8×10^6

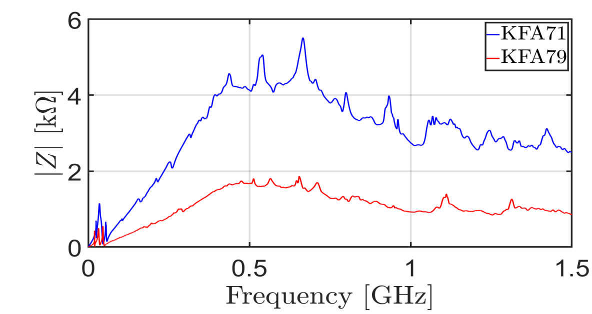

Figure 3: Magnitude of the longitudinal beam coupling impedance for frequency up to 1.5 GHz of both the PS extraction kickers (KFA71 in blue, KFA79 in red).

In the low frequency range, up to about 60 MHz, where the beam spectrum is strongest, both kickers show three resonances each (Fig. 4). In particular, the KFA71 has a resonant mode at 35.6 MHz with an amplitude of about 1 kΩ. Such large resonances can lead to coupled bunch instabilities [11] and to beam energy losses. It is therefore important to reduce their magnitude.

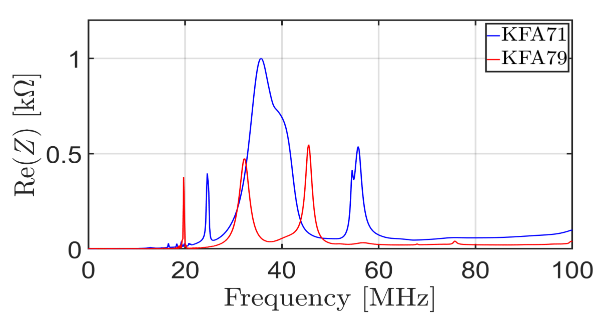

Figure 4: Real longitudinal beam coupling impedance up to 100 MHz (KFA71 in blue, KFA79 in red). Three critical resonant modes are predicted for both kickers.

Transverse Beam Coupling Impedance

For the transverse beam coupling impedance simulations, the rms bunch length was reduced to 40 mm in order to increase the frequency range of interest up to 2.5 GHz and to include the tail of the broadband behaviour.

Both dipolar and quadrupolar component have been computed for the horizontal and vertical directions.

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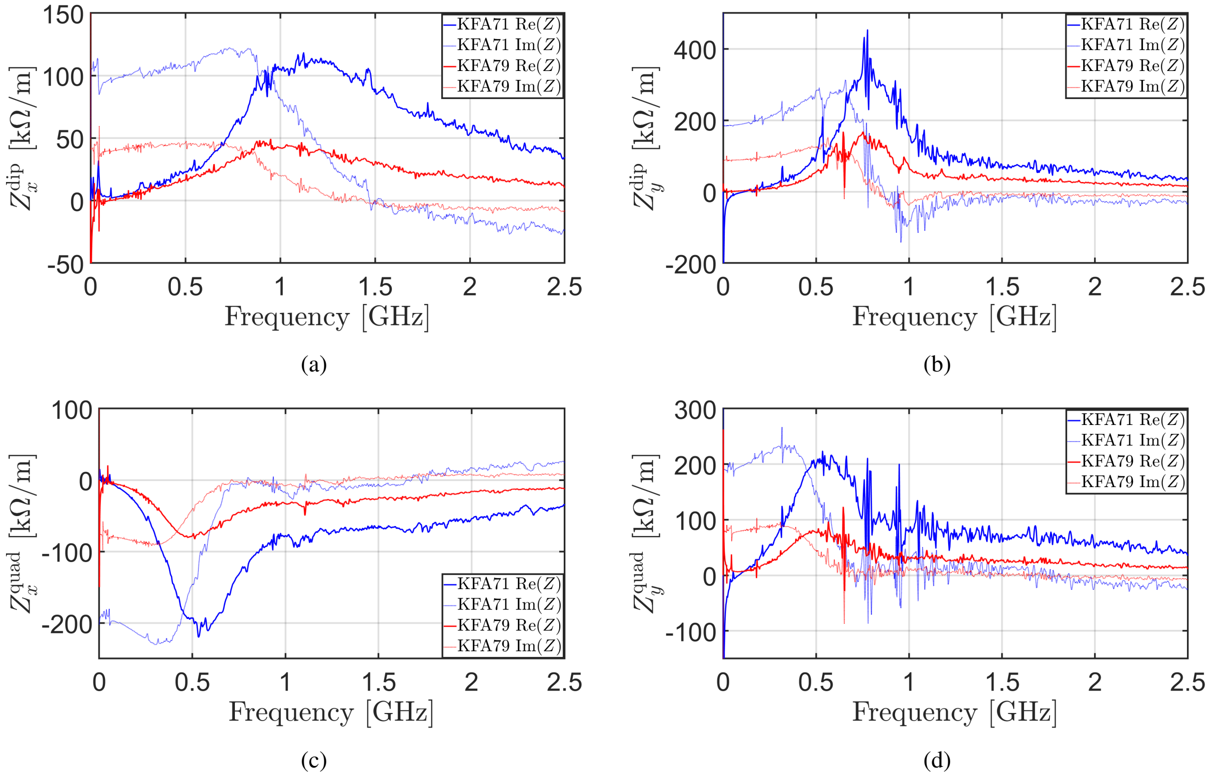

Figure 5: Real and imaginary part of the transverse dipolar horizontal (a) and vertical (b) and quadrupolar horizontal (c) and vertical (d) beam coupling impedance of KFA71 (blue) and KFA79 (red).

The horizontal and vertical offsets between beam and integration path have been chosen small enough (less than 10% of the dimensions of the rectangular beam aperture, 147 mm and 53 mm respectively), in order to guarantee the validity of the linear approximation of the wake functions [12]. The mesh density has been locally increased in the region of beam and integration path to ensure at least three mesh cells between the two lines. The main simulation settings for the transverse beam coupling impedance calculations are summarised in Table 2.

Table 2: Main parameters of CST Wakefield simulations for the transverse beam coupling impedance calculations for KFA71 and KFA79.

x_{off} = 6.5 mm y_{off} = 2.5 mm	**KFA71**	**KFA79**
Bunch length rms [mm]	40	40
Wakelength [m]	100	300
Max frequency [GHz]	2.5	2.5

The four transverse components were computed by applying the relation [12]:

$$Z_u^{\mathrm{dip/quad}} = -\frac{Z_u(\omega) - Z_u^0(\omega)}{u_{s/t}}. \quad (1)$$

The index u takes the values x, y for each of the two transverse planes under consideration, with $x_{s/t}$ and $y_{s/t}$ denoting the horizontal and vertical displacement of the source/test particle, respectively. The parameter $Z_u(\omega)$ is the transverse impedance component computed in CST by shifting either the source or the test particle by a certain offset and $Z_u^0(\omega)$ is the transverse impedance component, which is independent of the particles' offsets. Equation (1) is valid under the assumption of absence of coupling between the two planes and a transverse displacement small enough so that second and higher order terms are considered negligible [13].

As predicted by theory, in the case of a rectangular beam pipe [14], the dipolar x and y component differ by about a factor of two (Fig. 5a-5b). Moreover, the two quadrupolar components have the same amplitude but opposite sign (Fig. 5c-5d).

Focusing on the low frequency range, up to 100 MHz, the horizontal dipolar impedance component, as well as the horizontal and vertical quadrupolar ones, reach values up to 30 kΩ/m. In addition, oscillations for vertical dipolar and quadrupolar impedance are visible below 1 GHz. In order to better quantify the unwanted modes at low frequency and to exclude simulation artifacts, the simulation could be refined in terms of number of mesh cells and wakelength to obtain a better resolution in the frequency range of interest.

Both the real and imaginary parts of the transverse impedances are necessary for transverse dynamics studies to understand their impact on the instability growth rate or betatron frequency spread.

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IMPEDANCE CALCULATION INCLUDING CABLE TERMINATIONS

Each kicker module is powered by a high-voltage (HV) pulse generator, connected to the module via two parallel 30 Ω transmission cables. When the module is not being pulsed to extract beam, the main switch thyratron (Fig. 6) is in the off-state: hence, the main thyratron, end of the transmission cables, is effectively open circuit. The output of each module is connected, via two parallel 30 Ω transmission cables, to a 15 Ω resistive termination (Fig. 6). Previous studies point out how the beam coupling impedance response depends strongly on the cables, and how they are terminated [15]. Therefore, it is important to measure and simulate a kicker module in the same configuration as it is in the accelerator, by including all the pulse power connections.

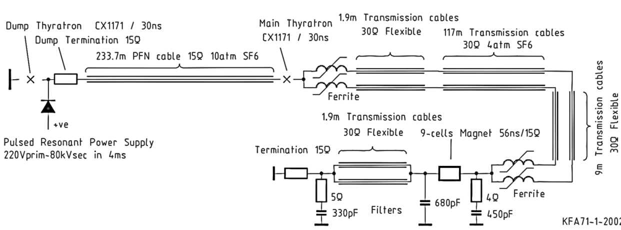

Figure 6: Circuit schematic of a magnet module unit. The output of each module, indicated as "9-cells magnet", is connected to a 15 Ω resistive termination [16].

To mimic the measurement setup, a simulation of a single stretched wire measurement has been carried out in CST. The 3D model includes the full KFA79 kicker, with three modules, a 0.5 mm diameter copper wire at the beam path, and two matching resistors of 220 Ω inserted at the two ends of the stretched wire. The Frequency Domain (FD) solver has been used to compute the scattering parameters. In particular, the transmission parameter, S_{21}, is of interest because it directly gives information on the longitudinal beam coupling impedance. The input and output power connectors of each of the three modules have been selected as waveguide ports, obtaining an eight ports component.

In CST studio suite, an environment called CST design studio, allows to manage simulation projects, enabling the integration of a lumped element circuit model with a 3D electromagnetic simulation. By using a schematic modeling, the cable terminations could be added to the 3D geometry. Different cable terminations have been tested for the output power connectors in order to check the influence on the scattering parameter S_{21}.

Two external ports, at the kicker beam-input and output, were included to excite the structure. For each module, all the input power connectors have been connected to an ideal open transmission line (main switch thyratron in off-state), while the output power connectors have been terminated either with 15 Ω resistors (actual situation), with ideal open transmission lines or with short circuits. The results for the three cases in the low frequency range, are shown in Fig. 7. The plotted S_{21} parameter is changed substantially by

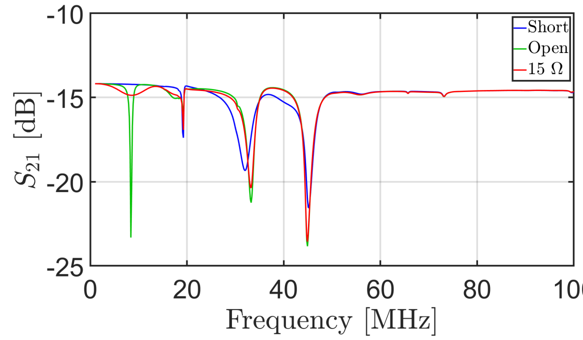

Figure 7: Magnitude of simulated S_{21} parameter versus frequency up to 100 MHz with different electrical cable terminations: short circuit in blue, ideal open transmission line in green and 15 Ω resistor in red.

modifying the cable termination. In particular, in the case of an open transmission line, the scattering parameter presents an additional notch around 8 MHz, while in the other two cases the first notch is at ~19 MHz. Hence, the cables and their terminations have a large influence on the longitudinal impedance behaviour in the low frequency range, as they affect the longitudinal beam coupling impedance by shifting the resonant frequency and by changing the amplitude of the modes. Stretched wire measurements on the kicker magnet, including proper cable terminations, are planned to give a final confirmation of these results.

CONCLUSION AND OUTLOOK

The longitudinal and transverse beam coupling impedances for both the PS extraction kickers, KFA71 and KFA79, have been simulated and the critical impedance contributions have been discussed. The results will be benchmarked by performing wire measurements to confirm the impedance model. A study of possible mitigation solutions has already started and their implementation will be needed to tackle the critical impedance peaks. The transverse impedance results are important to update the transverse dynamics simulations with the most recent impedance model. By weighting the transverse impedance with the β-function at the location of the kickers, more information on transverse instabilities can be deduced. Finally, the transmission cable terminations highly influences the beam coupling impedance. Therefore, transmission cables with their proper terminations are included in the simulations and will also be part of the measurement setup.

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