ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC51

MITIGATION OF BEAM COUPLING IMPEDANCE FOR THE WIRE SCANNERS IN THE CERN SUPER PROTON SYNCHROTRON

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Abstract

The beam wire scanners of the CERN Super Proton Synchrotron (SPS) experienced multiple failures of their carbon wires caused by the high-intensity beam during a very short period in April 2023. Different modifications of the existing instrument were therefore studied to reduce the beam-induced power without compromising its functionality nor negatively affecting the beam coupling impedance. Amongst these options were the implementation of ferrite absorbers, a change of the scanner mechanism and the installation of an RF coupler in the vacuum tank. In this paper, we introduce the electromagnetic simulation results for the installed ferrite loads and the RF coupler, as well as their impact on the on-axis beam impedance. The final improvement for the configuration to be installed during the end-of-year stop of the accelerator will be summarized.

INTRODUCTION

The Super Proton Synchrotron (SPS) measures almost 7 km in circumference and thus is the second-largest accelerator within CERN's accelerator complex. It is delivering particle beams to its own experiments, and it is also part of the injectors chain for the Large Hadron Collider (LHC).

The SPS operates with protons up to 450 GeV, and it is equipped in total with four rotational beam wire scanners (BWS), of which two scanners are reading the horizontal and the vertical planes, respectively [1]. The only difference between horizontal and vertical scanners is their orientation with respect to the beam. This type of BWS is used in different accelerators at CERN and in average, about 125k scans are recorded in a time frame of two years, during which only one wire broke so far [2].

In April 2023, the scanning carbon wires in all four BWS in the SPS broke almost simultaneously during a scrubbing run. More suprisingly, these failures took place while the wire scanner fork was in the so-called parking position, i.e. in the position farthest away from the beam. Details like the beam intensities reached during wire failures can be found in [3, 4]. The goal of this paper is to present the electromagnetic study that was carried out in the aftermath of the BWS failure, targeted to finding a mitigation to reduce the beam-induced power passing through the wire without impacting on either BWS functionality nor deteriorating the contribution of the wire scanners to beam coupling impedances.

SIMULATION MODEL

The EM-simulations of the SPS BWS were carried out with the simulation code CST [5] for eigenvalues and wake field simulations. Figure 1 shows a cut through of the model of the wire scanner geometry with the beam pipes attached and the wire fork visible.

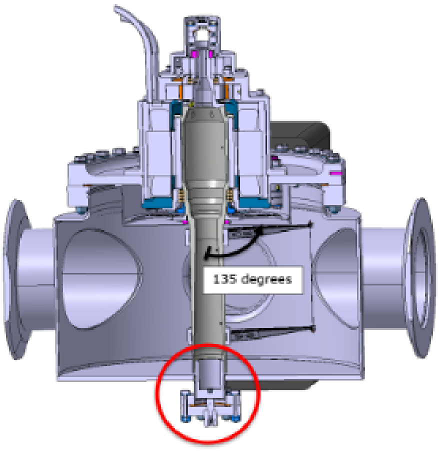

Figure 1: Illustrated model of the SPS Wire Scanner (BWS) with the fork rotated to 135 degrees from the parking position. In red is encircled the ceramic feed-through and capacitive coupler protruding into the rotational shaft of the BWS.

All four BWS were already equipped during the design phase with a ceramic feed-through to allow the installation of a capacitive rod coupler protruding into the BWS rotational shaft (see encircled area in Fig. 1). However, in the installed versions, the rod coupler was not implemented for reasons of simplifying the geometry, and because it was expected to be unnecessary from beam impedance point of view. During the consolidation phase, when RF-measurements were carried out before installation, the rod coupler was also needed to allow the measurement of certain modes which can otherwise not be measured from the access via the beam axis. Today, the existence of the ceramic feed-through made it possible to install a specially designed RF coupler, firstly to carry out RF-measurements of the induced beam spectrum in the wire scanners during operation, and secondly, as an option to attenuate potentially harmful modes.

MITIGATION STRATEGY

Figure 2 shows the simulation geometry built in CST [5] with the two ferrite tiles of TT2-111R [6]. The overall goal to avoid a wire breakage is to minimise wire coupling to the EM-fields in the BWS tank, such that the power deposited in the wire is reduced. However, from the point of beam coupling impedance on axis, the overall shunt impedance,

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R_{sh} must be kept reasonably low, and to avoid heating in the structure, resonances in the BWS tank are undesired and can be accepted only at frequencies that do not coincide with a beam spectrum harmonic. This might mean conflicting requirements: if we qualify a resonant build-up in the structure with the well-known quality factor Q, a higher Q-value gives sharper resonance peaks that are unacceptable within the beam spectrum, whereas a lower Q adds to the broadband contribution and might touch several beam spectrum lines. Hence, for the comparison of different mitigation options, at specific frequencies we take several parameters into account like shunt impedance R_{sh}, Q, and value for R/Q, the latter being a measure to determine the coupling between EM-fields and beam. To quantify the load which a specific mode deposits on the wire, we calculated the fraction of the overall losses on the carbon wire that the magnetic field of this mode contributes.

For example, from simulations, the BWS geometry as installed (without the RF coupler) gives only small contributions for frequencies below 800 MHz, but a high shunt impedance and a high Q-value for the critical frequency of 807 MHz (see red traces in Fig. 3, top: Q-values, bottom: shunt impedance R_{sh}). The installation of two ferrite tiles directly underneath the BWS fork gives a considerable reduction of both R_{sh} and Q-values (blue traces). Other resonances are expected at frequencies around 1.1 GHz and 1.2 GHz. To mitigate these resonances in addition, several options of using a damping ferrites were studied (see next section).

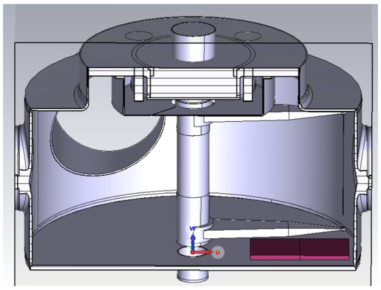

Figure 2: Simulation geometry with two tiles of damping ferrites (red) installed underneath the BWS fork to reduce the load on the wire.

Several mitigations with the goal to reduce the load on the scanning wire were tried besides the use of damping ferrites. These included the change of the fork position, a reduction of the fork height and a modification of the fork material. All of them were mostly leading to frequency shifts of the resonance peaks which are intrinsically building up in the BWS tank. It was therefore concluded, that the introduction of a new loss mechanism is required to dampen these resonances. Consequently, a number of different options for placing damping ferrites in the BWS tank were simulated to get a good understanding of the resulting field patterns and the overall damping effectiveness. The use of the damping ferrite TT2-111R from TransTech Inc. [6] was decided as this ferrite has been deployed in other installations at CERN before and thus was readily available. It also had already passed all required tests for vacuum compatibility in the SPS. Table 1 gives a comparison of the geometry with and without the insertion of two ferrite tiles of TT2-111R. From the values shown, already the insertion of two ferrite tiles appears promising, hence this mitigation method continued including a heating study [4] on the ferrites as well as considering the overall beam coupling impedance on axis.

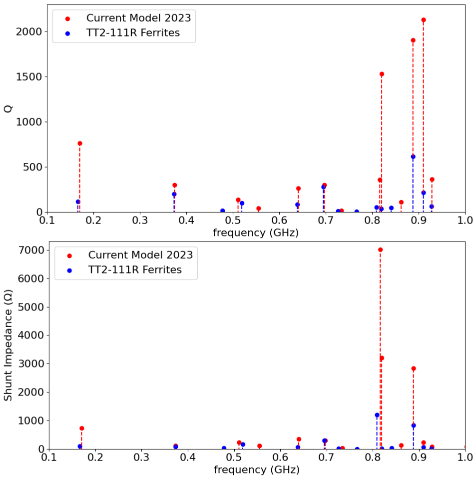

Figure 3: Simulated Q-values and R_{sh} for the BWS with (blue) and without (red) mitigation option of installing two tiles of damping ferrites underneath the BWS fork to reduce the load on the wire.

Table 1: Resonance Mitigation by Installing Two Tiles of Damping Ferrites, Compared to Unmodified Geometry

	f [MHz]	R_{sh} [Ω]	Q	R/Q [Ω]	% of loss on the wire
no ferrites	807	10381	1233	8.3	34
2 tile case	806	149	19	7.7	1.4

MITIGATION RESULTS

Since the ferrite tiles are impacting the magnetic field distribution due to their permeability, obviously the insertion of more ferrite tiles will cause a larger damping. However, the example of three and four ferrite tiles in different positions shows that also their positioning is important. Figure 4 shows the cross-sections of the BWS simulation models with 3, 4, 5, and 6 ferrites in the tank. The calculated average magnetic fields on the wire surface are shown in Fig. 5 for two different frequency ranges (around 160 MHz, respective 700 MHz) for the cases shown in Fig. 4, and compared to BWS without ferrites. A comparison of the four tiles arranged along the vacuum pipe and arranged around the fork shaft (4 tiles, V2) shows a frequency shift of the different resonances towards lower frequencies in the relevant frequency ranges, whereas the gain in reducing the average field on the wire is not significant. Additionally shown are the results for the other ferrite options which are giving a

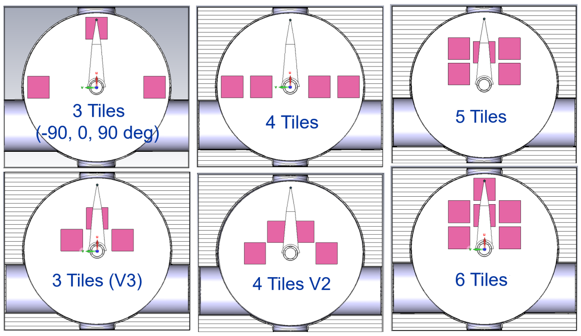

Figure 4: Cross-section of the simulation model of the SPS BWS with different ferrite distributions in the tank.

stronger damping, including the case of 5 tiles which was finally chosen. We calculated the longitudinal beam coupling impedance of the original BWS (no ferrites, no RF coupler) and compared this with the damping solution of 4, 5, and 6 tiles for the frequency range of consideration with f_{max}= 1.5 GHz, as is shown in Fig. 6. The zoom on the impedance shows the damping of the modes at 170 MHz, and from 600 to 700 MHz, as well as the most critical modes at 800 MHz and 1.2 GHz. In particular, the forest of modes around 1.2 GHz, are damped almost equally well by the three options mentioned. The mode at 800 MHz is considered critical as it is still within the beam spectrum of the SPS.

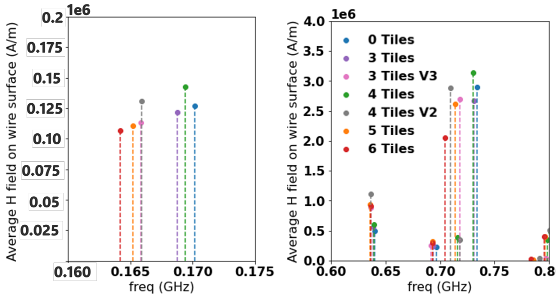

Figure 5: Calculated average magnetic field on the wire surface for two frequency ranges for the cases shown in Fig. 4, and compared to the case without ferrite. Low frequency range (left), and the band of the largest resonances (right).

Figure 6 gives a comparison of the calculated longitudinal impedances of the original BWS and with different number of ferrite tiles installed. The simulations show that changing from four tiles arranged around the fork shaft (4 tiles, V2) to five tiles gives a considerable better damping at around 800 MHz. However only little improvement can be obtained by adding one more tile. Furthermore, it was observed that placing six tiles underneath the fork lead to a concentration of magnetic field in the position of the wire and thus results in a local field enhancement instead of further reducing the power deposited on the wire. Figure 7 shows the combined option of installing 5 ferrite tiles in addition with a capacitively coupled rod protruding into the BWS shaft is giving the best results, and has been chosen for the final installation.

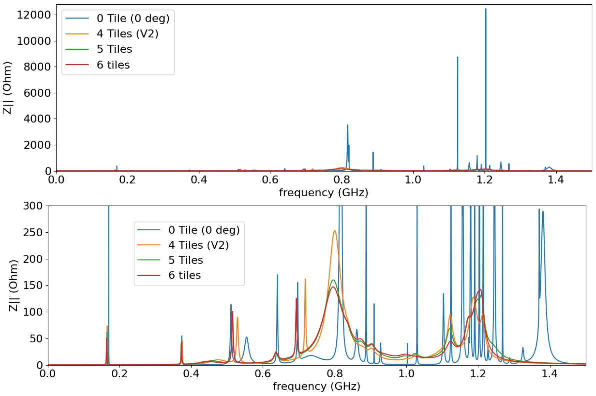

Figure 6: Calculated longitudinal impedance of the BWS in the original situation (no ferrites), and with 4, 5, 6 ferrite tiles inserted, following the configurations shown in Fig. 4.

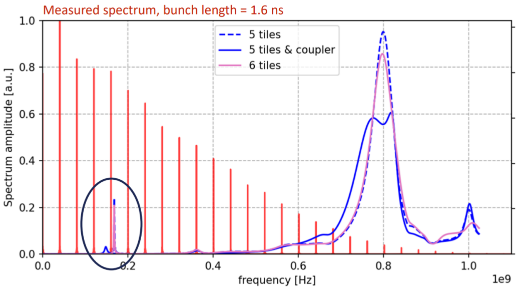

Figure 7: Comparison of calculated longitudinal impedance of the BWS with mitigation solutions of 5 and 6 tiles, as well as the final solution with 5 tiles and the installed RF rod coupler. Also shown is the measured bunch spectrum for a bunch length of 1.6 ns.

CONCLUSION AND OUTLOOK

Simulations of different ferrite tile configurations were carried out, and beam tests during 2023 operation confirmed that an optimal mitigation consists of a combination of inserting five ferrite tiles in the BWS tank together with the installation of an RF coupler. The RF coupler consists of a capacitively coupled rod installed via a ceramic feed-through that is protruding into the BWS shaft and is on the outside connected to a 50 Ω coaxial line. It could be demonstrated that this combined option allows to remove a significant amount of power from the BWS tank. As an additional feature, the RF rod coupler was connected to a spectrum analyser and thus provides the possibility to record the beam-induced power spectrum. It will also help to detect potential wire breakage hazards in the future (see [3, 4] for details).

ACKNOWLEDGEMENTS

The authors would like to thank R. Calaga for carrying out RF measurement of the beam spectrum in the BWS with the RF coupler as well as B. Salvant and C. Zannini for fruitful discussions and W. Andreazza for providing the BWS for RF measurements.

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