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IMPEDANCE REDUCTION OF THE BEAM GAS IONIZATION MONITORS FOR THE CERN SPS

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Abstract

The beam gas ionization monitors (BGIs) are non-destructive instruments to measure the transverse beam profiles. With the goal to double the beam intensity in the injector chain for the High-Luminosity Large Hadron Collider (HL-LHC), any element contributing to the overall beam coupling impedance requires an in-depth impedance evaluation from the design stage. This paper presents the beam coupling impedance optimization and mitigation study of the beam gas ionization monitors for the Super Proton Synchrotron (SPS) at CERN. Detailed electromagnetic simulations of the 3D model were carried out already before the construction of the prototype. Consequently, geometrical modifications required for impedance mitigation were still possible and were investigated while keeping the functionality of the device. We present different mitigation measures as coatings, RF-fingers and the introduction of additional loss mechanisms to dampen resonances of the geometry. At last, a comparison of the instrument design before and after impedance reduction is shown.

INTRODUCTION

The BGIs are non-destructive transverse beam profile monitors in the circular accelerators at CERN. The beam ionizes the residual gas in the instrument. Then, the ionization image of the electrons are obtained through the particle detectors by the applied external magnetic field and a high DC voltage (Fig. 1). During the year end technical stop (YETS) 2023/24, two identical BGIs, one horizontal and one vertical were installed in the SPS ring to get the beam profile information in both transverse planes.

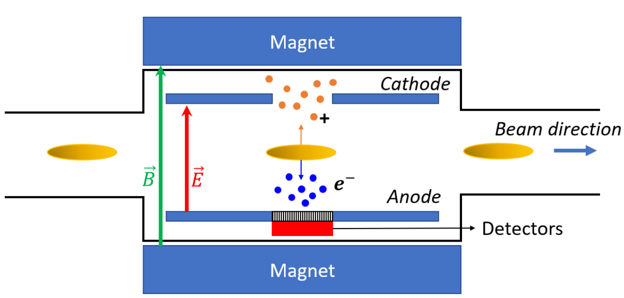

Figure 1: BGI working principle [1].

In this paper, the optimization of the beam coupling impedance of the new SPS-BGI by an extensive simulation campaign is described. Geometrical modifications and usage of coated materials have been used for the mitigation. The beam induced RF power loss calculations and the RF probe measurements of the prototype for benchmarking are presented as well.

SIMULATION STUDY

The simulation study was performed by using CST Microwave and Particle Studio [2], for which the original BGI design was simplified in complexity to allow longitudinal impedance simulations. RF fingers were changed to continuous strip lines to allow better geometry meshing. In addition, the outside mechanical parts were removed since they are out of the impedance calculation domain.

The original instrument design showed a significant number of resonances after the first set of simulations, as shown in Fig. 2. The largest peak was at 1.28 GHz with an impedance of 24 kΩ within the considered SPS beam spectrum up to frequency range of 1.5 GHz. Other resonances at 399 MHz, 656 MHz, 913 MHz and 977 MHz with lower magnitudes were observed. However, even lower resonance peaks could cause beam-induced heating when overlapping with components in the beam spectrum.

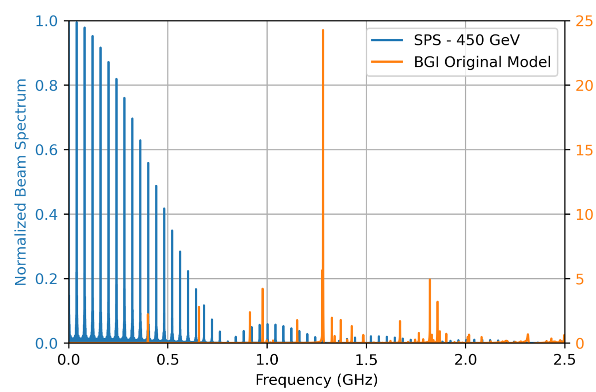

Figure 2: Real part of the longitudinal impedance of the BGI original model vs SPS beam spectrum for 450 GeV (Binomial distribution with 25 ns bunch spacing).

A set of geometrical changes were applied to the instrument. In the original model, the RF fingers were placed only at the bottom part of the instrument and the back part of the holders was not connected to the chamber, as illustrated in Fig. 3. Thus, the chamber was shortened to contact the holders and the holders were fully covered by the RF fingers. The source of the resonance peak at 1.28 GHz was identified as the protruding parts of the stainless-steel cathode (Fig. 4). As a mitigation measure, in addition to RF fingers, the instrument holders were moved outwards to suppress the protruding edges from the cathode. These changes were

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effective to create a small frequency shift and to lower the resonance amplitude from 21 kΩ to 7 kΩ.

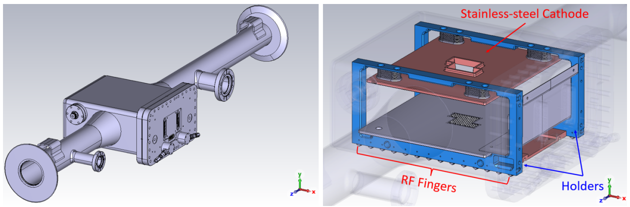

Figure 3: BGI chamber with 84 mm (tapered to tank, left) and 120 mm (straight to tank, right) diameter beampipes.

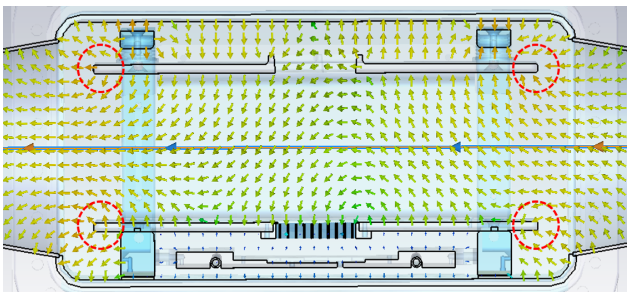
Figure 4: Protruding parts of the stainless steel cathode(dashed red circles) as a source of the resonance peak at 1.28 GHz.

Normally, as a standard measure, abrupt changes in cross-section of vacuum chambers are not acceptable. However, in this case, implementing straight beampipes instead of tapered ones (Fig. 5) was more convenient for both horizontal and vertical integrations with surrounding elements in the SPS ring. After those geometrical changes, the longitudinal impedance of the instrument was reduced significantly, as plotted in Fig. 6.

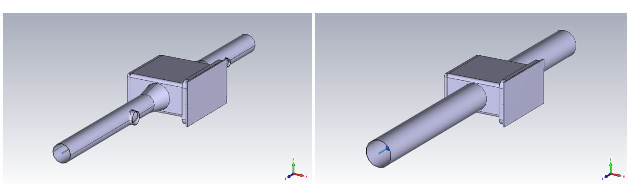
Figure 5: BGI chamber with 84 mm (tapered to tank, left) and 120 mm (straight to tank, right) diameter beampipes.

The resonances below 1 GHz still must be mitigated since they are prone to cause beam-induced heating. To overcome this, coated materials had been considered [3]. A titanium coated ceramic (Alumina) rod with 10 Ω/sq resistivity was added between the holders to mitigate the resonances in the range of 645 to 690 MHz. The rod was placed at the down part of the holders since its thin film coating should not be exposed directly to a high intensity beam. The cathode material was changed to ceramic (Macor) with a non-evaporated getter (NEG) coating. In order to obtain the best coating resistivity on impedance reduction, several NEG coatings had been studied on the ceramic cathode by the 'thin panel' approximation in the CST Wakefield Solver (Fig. 7).

We also tested different coating sample thicknesses at the laboratory to achieve the best performance. All the coating

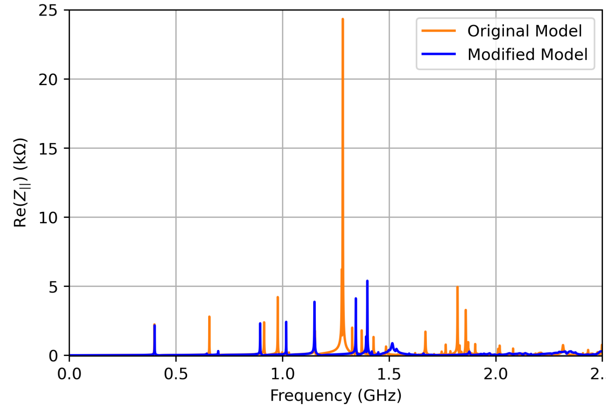

Figure 6: Real part of the longitudinal impedance of the BGI original vs modified model.

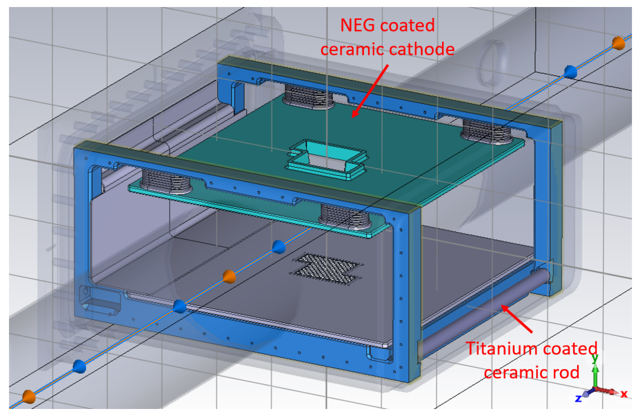

Figure 7: Final simulation model of the inner geometry of the BGI equipped with coated ceramic cathode and rod.

options studied were effective to mitigate the resonances up to 2.5 GHz. The cathode coating resistivity of 1 kΩ/sq option was retained since the produced test sample showed repeatability and the impedance reduction in the overall spectrum is better than the other resistivities especially below 1 GHz (Fig. 8).

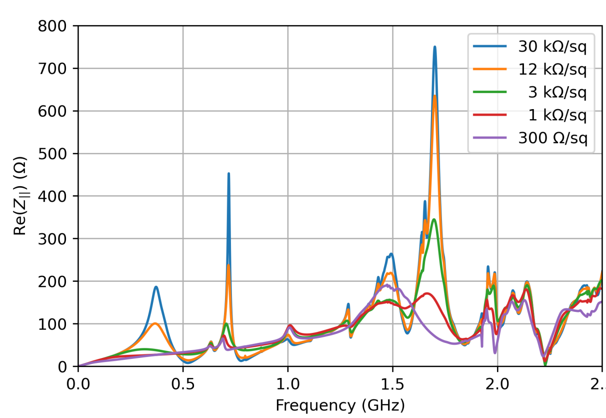

Figure 8: Real part of the BGI longitudinal impedances with damping rod and different resistivities of the cathode coatings.

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BEAM-INDUCED RF POWER LOSS

The beam-induced RF power loss has been evaluated by the Eq. 1 where $Z_{\|}$, p, ω_o and $\tilde{I}$ denotes longitudinal impedance, harmonic number, revolution frequency and the Fourier Transform of the beam current, respectively [4].

$$P_{loss} = \sum_{p=-\infty}^{\infty} Re[Z_{\|}(p\omega_o)]|\tilde{I}(p\omega_o)|^2 \quad (1)$$

A tool based on the Beam Longitudinal Dynamics (BLonD) [5] code was used for the calculations. The final BGI model has been verified for both SPS energies 26 GeV and 450 GeV of the HL-LHC beam parameters [6] for different bunch lengths (4σ) as shown in Fig. 9. RF power loss increased for shorter bunch lengths in both cases, as observed in Fig. 10.

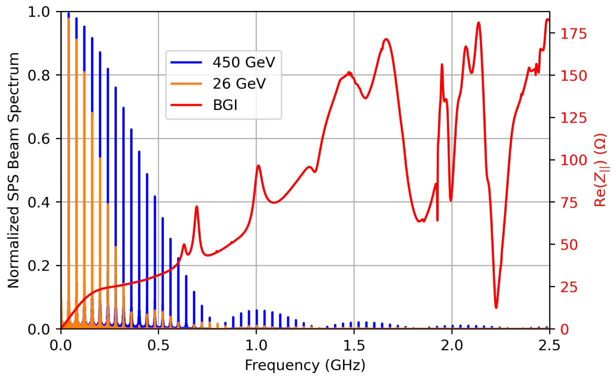

Figure 9: SPS beam spectra for 26 GeV (4σ = 3.4 ns) and 450 GeV (4σ = 1.65 ns) and BGI final model impedance.

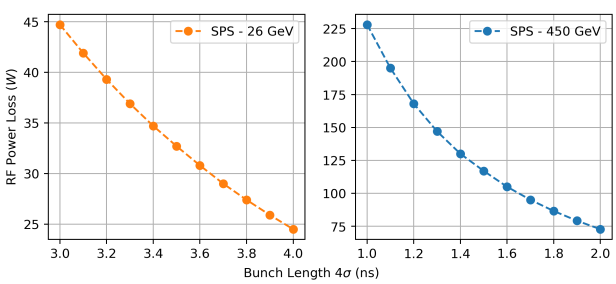

Figure 10: Beam-induced RF power loss of BGI final model for different bunch lenghts (4σ) at 26 GeV (left) and 450 GeV (right) in the SPS.

RF MEASUREMENTS

In order to confirm the validity of the simulated and implemented impedance reduction, first RF measurements had been performed with the manufactured BGI chamber which was equipped with a NEG coated ceramic (Macor) cathode and a titanium coated ceramic (Alumina) rod, as illustrated in Fig. 11. The cathode coating was measured with non-uniform resistivity of 600 Ω/sq on the down side and 1.8 kΩ/sq on the upper side. Furthermore, the rod was coated with a resistivity of 10 Ω/sq. No resonances were detected during the reflection (S_{11}) and transmission (S_{21}) measurements.

In addition, to confirm the impedance mitigation effect of the coatings, a set of RF measurements was performed with

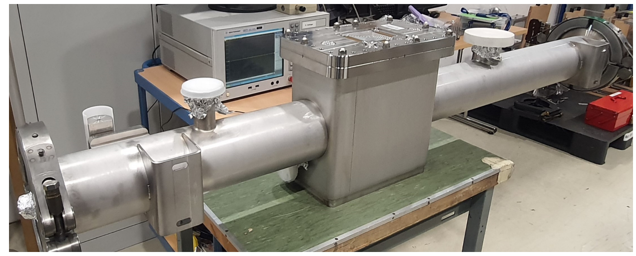

Figure 11: BGI chamber with coated cathode and rod.

a benchmark model of the BGI tank without beampipes. For this purpose, the simulation model was created for calculations with CST Eigen Solver. A loop type probe was built to allow reflection (S_{11}) measurements on the small flange openings in the lower part of the tank, as shown in Fig. 12.

Due to the change of the shape of the tank, different resonant modes emerged compared to the real instrument. Nevertheless, a comparison of the eigenmodes of this model was possible with uncoated parts (ceramic cathode and no rod) and confirmed by observing the field patterns obtained from the eigenmode simulation (Table 1). During the measurement of the model with coated cathode and rod, it was determined that all the previously measured modes were removed below the detection level [7].

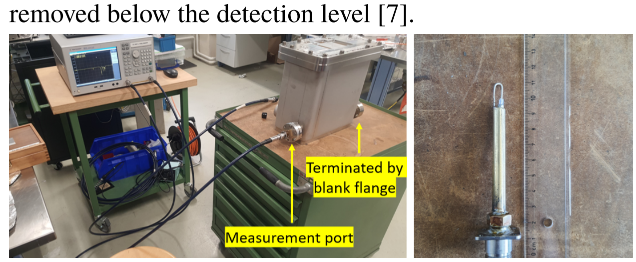

Figure 12: Benchmark model without beampipes (left) and probe (right).

Table 1: Simulated and Measured Resonant Frequencies of the Model with Uncoated Parts

f_{sim}[GHz]	0.717	1.11	1.308	2.327	2.355
f_{test}[GHz]	0.714	1.09	1.312	2.328	2.352

CONCLUSION

In this contribution, the impedance mitigation of the new SPS-BGI design is presented. A significant amount of resonances has been removed successfully before the final mechanical design. The studied model was benchmarked with RF tests. Since the heating may be observed due to the doubled beam intensity and the usage of coated materials, monitoring of the instrument temperature is suggested.

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