ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPCO25

SOLEIL II BPMS DEVELOPMENT PROGRESS

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Abstract

SOLEIL II is the low emittance upgrade project for Synchrotron SOLEIL, targeting a natural emittance of ~ 80 pm · rad. The new lattice includes 196 Beam Position Monitors (BPMs), distributed in three different types depending on the vacuum chamber diameter. To optimize the BPM impedance, the button shape is conical. Electromagnetic and thermal simulations have been performed to validate the proposed designs. In parallel, button prototypes have been installed and tested on the existing machine to confirm the simulation results.

INTRODUCTION

The upgrade of the SOLEIL synchrotron aims at transforming the facility into a high-performance, fourth-generation light source. This upgrade is driven by significant photon beam properties improvement particularly in terms of brightness, coherence and stability. At the core of the SOLEIL II design is a non-standard MBA lattice: 7BA/4BA, enabling a substantial reduction in horizontal emittance from the current 3.9 nm · rad to 80 pm · rad. As a result of extensive miniaturization of the equipments. The vacuum chamber aperture is only 12 mm in diameter. This reduction demands high precision alignment and the use of advanced materials and mechanical design to minimize impedance and maintain beam stability [1].

SOLEIL II BPM SPECIFICATION

The BPM system for SOLEIL II is designed to meet stringent performance requirements in terms of resolution, stability and signal-to-noise ratio. Under nominal operating conditions, it will provide a fast acquisition resolution of 100 nm · rms within a bandwidth extending from DC up to approximately 2 kHz, as well as a turn-by-turn (TbT) resolution of 1 µm · rms. During commissioning, with beam currents as low as 0.1 mA. The system will still deliver a TbT resolution of 100 µm · rms. Across the full operating range from 0.1 mA to nominal current, the beam current dependence will be limited to 10 µm. In terms of absolute accuracy, performance will reach better than 500 µm before and 5 µm after beam-based alignment (BBA). Long-term stability will also be a critical feature, with drifts of measurement constrained to 500 nm over one day and 1 µm over one week.

BPM DESIGN

SOLEIL II baseline lattice includes 196 BPMs distributed along the storage ring. All BPMs are in the shadow of the synchrotron radiation with enlarged tapered section with respect to the vacuum chamber diameter. Depending on their location, BPM will have a different design (Fig. 1):

- BPM16-6 (144 units): achromat BPM with an inner diameter of 16 mm and button diameter of 6 mm including 16 BPMs welded onto dipole vacuum chamber.
- BPM20-7 (40 units): Nominal straight section (SS), or nearby long SS adaptative section BPM with an inner diameter of 20 mm and button diameter of 7 mm.
- BPM24-7 (12 units) : Long SS BPM with an inner diameter of 24 mm and button diameter of 7 mm.

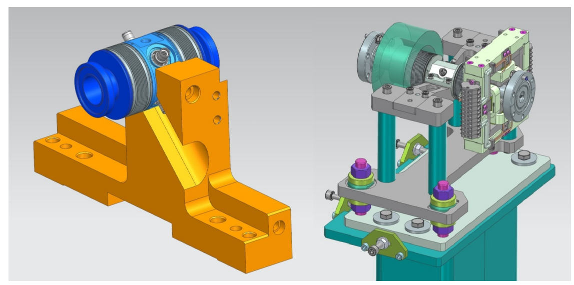

Figure 1: BPM16 for the arcs (left). Including bellows and flanges. The BPM length is only 74.2 mm. BPM20 for the nominal straight sections with Invar stand (right).In addition to the bellows, the block also includes a dedicated thin section to host a fast corrector.

Each BPM acts as a mechanically fixed reference within the vacuum chamber, mounted on dedicated supports attached either to the girder (in arc sections) or to the floor (in straight sections). To minimize thermal expansion, Invar is selected for supports in the straight sections, whereas water cooled steel structures are foreseen for the arcs, pending validation through thermal and vibration analysis. To reduce mechanical stress induced by the vacuum chamber, nearly all BPMs are positioned between two bellows. BPM chambers are fabricated from stainless steel and coated with a 10 µm copper layer to optimize beam impedance.

Bunch Length and Profile

SOLEIL II main operating mode is uniform filling with 416 bunches and a total beam current of 500 mA. 3rd harmonic cavity (HC) will be used to lengthen the bunches to approximately 50 ps · rms, resulting in a non-Gaussian longitudinal profile. This profile will produce a broader frequency spectrum than in the Gaussian case. In the case of a broad band resistive wall type impedance, simulations show that the total beam power loss will be equivalent to the one of a Gaussian bunch 15 % shorter (Fig. 2).

In the case of resonator-like impedances, such as those associated with trapped modes, the broader beam

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spectrum must be carefully considered. This situation occurs for SOLEIL II in the frequency range up to 20 GHz (Fig. 3). The assumption of equivalency with a 15 % shorter Gaussian bunch profile does not work in that case [2].

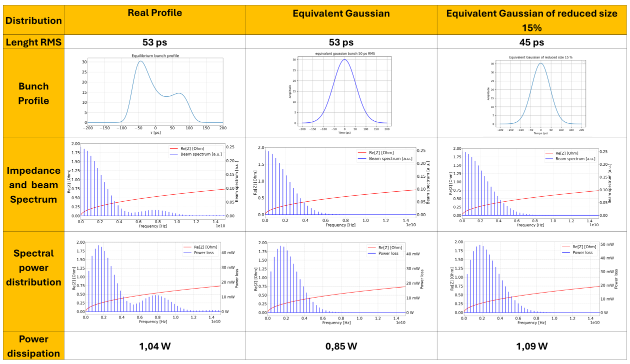

Figure 2: Theoretical example of a broad band impedance like resistive wall type. The non-Gaussian beam delivers the same amount of power as a Gaussian beam that's 15 % shorter.

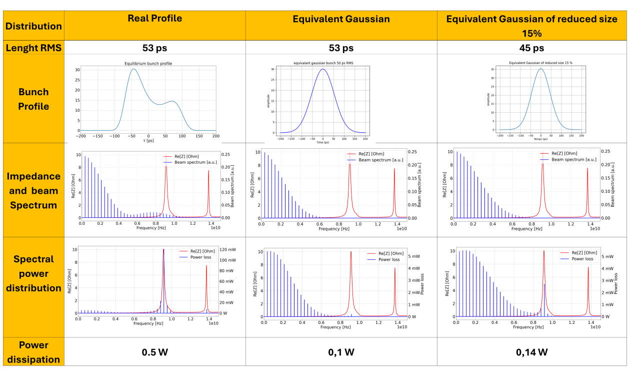

Figure 3: Theoretical example of a resonator-like impedance. The power dissipation for the the three cases: real profile, equivalent Gaussian and equivalant Gaussian shorted by 15 % . Equivalency with shorter Gaussian profile does not work in that case.

Another operating mode, referred to as the degraded mode, operates without HC and features shorter bunch lengths of approximately 10 ps · rms. This mode will be limited to a lower 300 mA beam current to mitigate heating problems.

Longitudinal Impedance Computing

High-fidelity electromagnetic and thermal simulations were performed on the full BPM blocks. These simulations considered the exact dimensions and material properties of buttons, flexible bellows, RF contacts, and complex assembly features such as welds, joint interfaces, and mounting supports. The aim was to analyze the 3D electromagnetic field distribution, including longitudinal impedance, to detect trapped or parasitic modes that could cause localized RF heating, thermal hotspots, or mechanical deformation (Fig. 4).

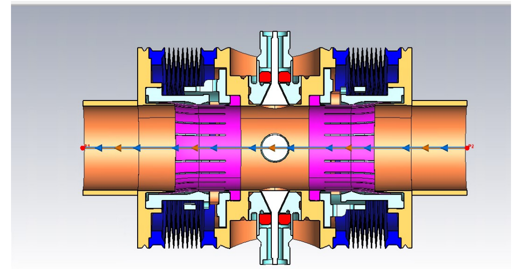

Figure 4: The CST model of the BPM16 with in blue the below, pink the RF fingers and in the white the real conical button [3].

Simulations reveal impedance peaks from trapped button modes at 25 GHz for BPM16-6 and 18 GHz for BPM20-7 and BPM24-7, related to the button diameter. Additionnel low frequency modes between 10 GHz and 15 GHz, not detected in preliminary simulations [4], are linked to the bellows and also vary with chamber diameter, showing that nearby structures may influence the wakefield impedance spectrum (Fig. 5).

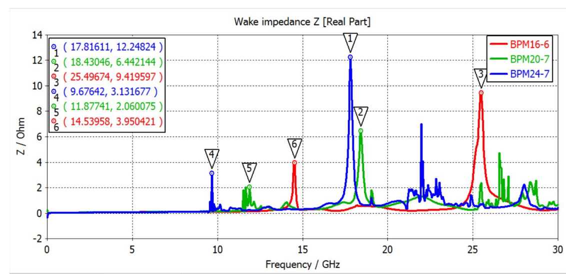

Figure 5: Real part of the wake impedance vs. frequency for three BPMs: BPM16-6 (red), BPM20-7 (green), and BPM24-7 (blue). Peaks near 25 GHz and 18 GHz are due to trapped modes in the buttons, while additional modes between 10–15 GHz arise from the bellows.

Power Dissipation

Power loss calculations indicate that, in the nominal operating mode with HC ($\sigma = 53$ ps rms), the dissipation is very limited, reaching at most 210 mW. In contrast, in the degraded mode without HC ($\sigma = 10$ ps rms), the losses are significantly higher, with values up to 2.4 W for the most affected BPMs (see Table 1).

Table 1: Calculated Power Loss on BPM Blocks for Nominal and Degraded Operating Modes

Power loss (W)	**BPM16**	**BPM20**	**BPM24**
Nominal mode ($\sigma = 53$ ps @ 500 mA)	0.14	0.21	0.21
Degraded mode ($\sigma = 10$ ps @ 300 mA)	1.6	2.0	2.4

In nominal mode, the contribution from the bellows is very small. In degraded mode, the stronger interaction with the beam arises both from the bellows and from the first trapped mode around the buttons (Fig. 6).

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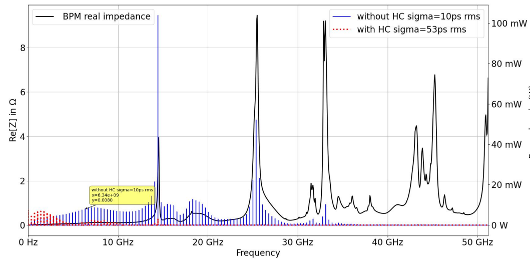

Figure 6: The spectral distribution of power dissipated in the BPM16-6 with HC (red) and without HC (blue). The black curve shows the real part of the longitudinal impedance.

Thermal Simulation

Thermal simulations of the three BPM types were carried out for two power scenarios. Under normal operation ($\sigma = 53$ ps, 500 mA), the temperature rise was limited to less than 1 °C at 23 °C with natural convection of $10\,\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}$(Fig. 7). In degraded mode ($\sigma = 10$ ps, 300 mA), the maximum increase reached about 7 °C. Although BPM16 is equipped with a water-cooling system, this was not included in the analysis. In all cases, the thermal behaviour remains compatible with BPM stability and integrity.

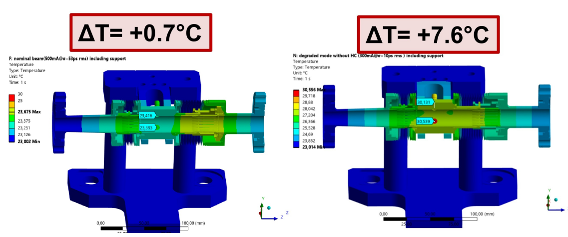

Figure 7: Thermal simulations of BPM20-7 using Ansys software [5]: nominal mode (left) and degraded mode (right).

BUTTON PROTOTYPE TESTING

Based on an initial button design with 5 mm diameter, two different commercial companies have produced batches of 20 units. To validate the simulation results and buttons manifacturing, the feedthroughs from both batches were installed in a dedicated vacuum chamber on the current machine. One batch has been withdrawn after leakage problems during the soldering and bake-out phase [6]. The buttons are positioned at a distance of 8 mm from the beam, as will be the case for SOLEIL II. Thermal and wake simulations were carried out using the SOLEIL beam parameters to determine the maximum temperatures to be reached (Fig. 8).

The measured temparture all along of chamber and button pin values are 15 % in average lower than simulation prediction. This difference is likely due to an underestimation of heat exchange with the environment in the simulations. At a

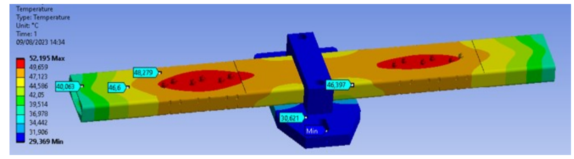

Figure 8: Thermal simulation of the test chamber the maximum temperature obtained for 500 mA is 52 °C

beam current of 500 mA, the maximum measured temperature is 47.6 °C (52 °C in the simulations).

The RF measurement was performed using a 32 m cable with 4 dB attenuation at 352 MHz and an additional15 dB attenuator. Single-bunch measurements confirmed that the pick-up voltages matched the CST simulations. At a beam current of 500 mA, the collected signal reached −5 dBm, in good agreement with the analytical prediction of −7 dBm. Long-term monitoring showed no anomalies or multipactor activity, demonstrating stable RF performance. Linearity tests with beam bumps further exhibited a predictable response within ±1 mm in both planes (Fig. 9).

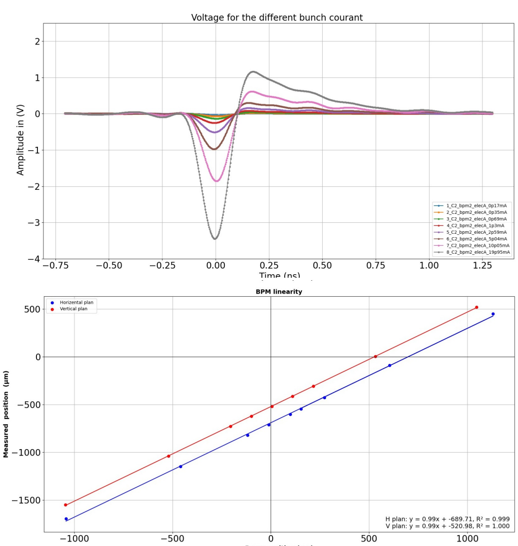

Figure 9: pick up signal in single bunch for different current level(top), vertical and horizontal curve linearity (bottom).

CONCLUSION

The BPM simulations are nearly complete, and the thermal simulations indicate an acceptable temperature rise of +0.5 °C in nominal operational mode. Thermal measurements on the real chamber confirm that the simulation methodology provides accurate predictions. The collected signal aligns with theoretical calculations.

Three batches of 6 mm buttons with improved designs are under production. They will be tested intensively to bake-out to validate possible manufacturers. Validation of laser welding on CuCrZr (for BPMs integrated) on the bending magnet vacuum chamber) will also be done.

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