STUDIES OF LONGITUDINAL BUNCH-BY-BUNCH FEEDBACK FOR SOLEIL II

E. Kravishvili*[,1,2], Y.-M. Abiven[1], M. El Ajjouri[1], A. Gamelin[1], V. Gubaidulin[1], R. Nagaoka[1], J. Pham[1], L. Zhao[1], R. Sreedharan[1], T. Nakamura[3]
[1]Synchrotron SOLEIL, Saint-Aubin, France
[2]Université Paris-Saclay, Gif-sur-Yvette, France
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

In upgrading the present SOLEIL ring, it has been decided to introduce longitudinal bunch-by-bunch feedback (LFB) in addition to the already existing transverse feedback (TFB), because studies indicate that the new normal conducting fundamental RF cavities may excite longitudinal coupled-bunch instabilities (LCBI) due to their higher-order-modes (HOMs). SOLEIL II also plans to use bunch-lengthening harmonic cavities (HCs) to improve the Touschek lifetime, which may trigger complex LCBIs. The present study aims to develop an LFB system responsible for the longitudinal collective stability of the SOLEIL II beam. The theoretical calculation of the instability growth rate of the HOMs has been carried out, defining the preliminary performance requirements of the LFB. Among the three main parts of the system-detection, signal processing and kicking- the present work focuses on the development of the processing section and the paper also presents some design aspects of the kicker cavity along with a beam-based test converting the currently operating TFB system to LFB by utilizing the stripline as a longitudinal kicker.

INTRODUCTION

The SOLEIL II project aims to reduce the horizontal beam emittance to a value of 85 pm rad, which is almost 50 times smaller than that of the currently operating SOLEIL storage ring (see the related SOLEIL II parameters in Table 1) [1,2]. Achieving such a low emittance is highly challenging, and beam stability is therefore crucial. As to collective beam stability, at present, SOLEIL operates only with TFB, [3–5] since no LCBI has been observed so far. However, this may not be the case for SOLEIL II. An LFB system may become necessary because studies have shown that the main RF cavity could generate HOMs with a non-negligible risk of driving LCBIs [6,7]. Since LFB has never been operated at SOLEIL, an experimental study was carried out in the SOLEIL ring in which the existing TFB was converted in the longitudinal plane to gain experience [8]. Details of this experiment are presented in the first part of the paper. The development of an LFB system requires studies in several areas. First, it is necessary to investigate longitudinal coherent beam dynamics in SOLEIL II and identify all possible instabilities. Both theoretical and simulation-based studies must be performed to determine which HOMs are potentially dangerous and to evaluate their corresponding growth rates. These results define the minimum performance requirements for the LFB system. Preliminary results of the beam dynamics studies are presented in the second part of the paper. Once these requirements are established, the development of the LFB system can proceed. The system consists different important components, and two of them are signal processing and kicking [9]. Signal processing is performed using a scheme of Finite Impulse Response (FIR) filter. The development of the FIR filter for SOLEIL II is described in the third part of the paper. In the present study, we shall not describe the digital processors. Finally, one of the key aspects of the system is the stabilization of the beam with the correctly calculated and generated longitudinal kicks. The SOLEIL II longitudinal kicker design is based on the cavity developed at PSI for SLS 2.0 [10], which bases its original concept upon the waveguide overloaded cavity originally developed for DAΦNE [11,12], along with its unique extensions. Some future perspectives on the longitudinal kicker development for SOLEIL II shall be found at the end of the paper.

Table 1: Some Relevant SOLEIL II Parameters

Energy	2.75 GeV
H-Emittance	85 pm.rad
Circumference	353.96 m
Longitudinal tune (with HC)	0.000 35
Long. radiation damping	12.1 ms

LFB EXPERIMENT

We conducted an LFB experiment primarily to provide the group with practical experience in the longitudinal feedback operation, which is not implemented at our facility. During the experiment, two striplines from the existing TFB system were used. One stripline was employed to longitudinally excite the beam, while the second was used for the feedback operation. For beam detection, sum signals from BPM electrodes was send to developed font-end electronics for the detection of the timing of the bunch. Two important aspects were addressed before the experiment. First, `GdfidL` [13] simulations were performed to determine the frequencies at which the existing striplines could efficiently excite the beam. Second, an FIR filter was configured to provide effective feedback. Each bunch is kicked by a quantity which is obtained by convolving its past longitudinal positions with

* elene.kravishvili@synchrotron-soleil.fr

the prepared FIR coefficients separately. In the transverse plane since the betatron oscillation is very fast only 5 turn data are enough, however the longitudinal oscillation takes much more time (the synchrotron tune is 0.005), therefore, to gather the relevant information of beam behavior, one needs as many as 200 turn data points in the SOLEIL ring. For this exact reason, the FIR filter was extended to a much higher number of taps and was prepared prior to the experiment.

Experiment and Results

After successfully exciting the beam with one stripline, the precise timing had to be found to damp the longitudinal oscillations with the kicks of the second stripline. This tuning was done with an oscilloscope, the screen capture of which is shown in Fig. 1. The two vertical dotted lines are respectively the kick and the bunch positions. However, the right dotted line can either be positioned at the beginning, the middle or at the end of the signal pass. The matching of a kick and bunch location determines the effectiveness of feedback. The three options were tested. The results happened to show in this particular setting that when the kick is applied at the beginning of the signal passage, it leads to antidamping when it is in the middle or the last part, the feedback is effective. These results can be seen on Fig.2.

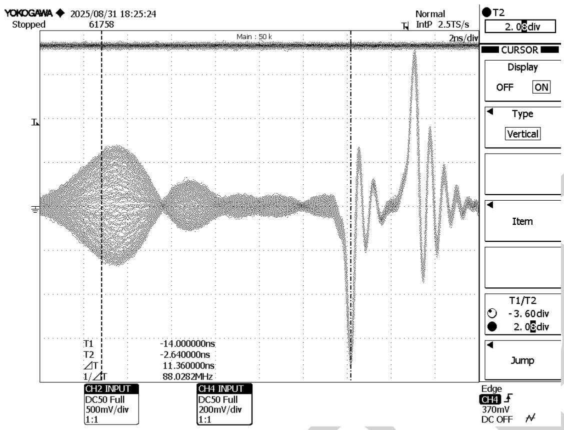

Figure 1: Oscilloscope trace used for timing adjustment in the single-bunch longitudinal feedback experiment. The left vertical dotted line marks the kicker signal arrival, and the right dotted line marks the bunch arrival at the selected observation point. The horizontal axis is time and the vertical axis is signal amplitude.

HOMs STUDIES

The primary motivation for the development of the FBL system is the mitigation of LCBIs possibly excited by HOMs of the 4 main RF cavities. Table 2 presents the most dangerous modes which may drive LCBIs. To evaluate their behavior, particularly their growth rates, both theoretical and simulation-based approaches should be employed. For the theoretical calculation of the growth rates, the well-known relation given in Eq. 1 was used, where τ_g is the instability growth time, I_0 is the beam current, E is the beam

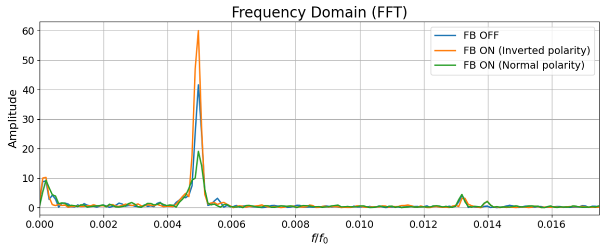

Figure 2: BPM signal FFT in three cases. Blue represents an excited beam with no feedback, while yellow and green show results when feedback is on.

energy, ν_s is the synchrotron tune, $Z(\omega)$ is the longitudinal impedance and α the momentum compaction factor, $\omega^{\pm}_{\mu,n} = (nM + \mu \pm \nu_s)\omega_0$ are the upper and lower synchrotron sideband frequencies, where M is the number of bunches, μ is the coupled-bunch mode number, n is the harmonic index, and ω_0 is the revolution angular frequency [14]. The corresponding analytical results are presented in Table 2. Finding their instability growth rates will help us evaluate a good value of shunt impedance required for the cavity kicker.

$$\tau_g^{-1} = \frac{e\alpha I_0}{4\pi E\nu_s}\left[\sum_{n=0}^{\infty}\omega^{+}_{\mu,n}Re[Z(\omega^{+}_{\mu,n})] - \sum_{n=0}^{\infty}\omega^{-}_{\mu,n}Re[Z(\omega^{-}_{\mu,n})]\right] \quad (1)$$

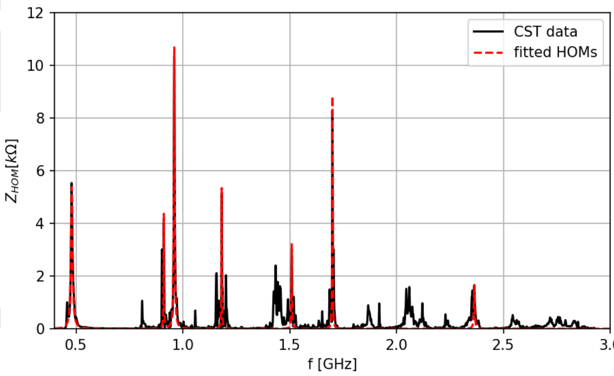

Figure 3: Longitudinal HOM impedance of the 4 main RF cavities expected for SOLEIL II, obtained from CST simulation. The solid black curve shows the CST result, and the red dashed curve shows the fitted HOM model used for instability analysis.

Table 2: Simulation Results of the Four Main RF Cavities HOMs in SOLEIL II Ring

Freq [GHz]	Q	Shunt imp. [Ohm]	Gr. rate [s^{-1}]	Gr. time [turns]
1.70	610	8826	324	2614
0.96	207	10 710	277	3057
1.18	453	5337	162	5228
0.91	354	4340	98	8642

mbtrack2 Studies of HOM-induced LCBIs

The main tool used for beam tracking is `mbtrack2` [15–17]. With it we can investigate instabilities caused by HOMs, as well as the beam's behavior with longitudinal feedback in order to determine the parameters required to damp the excitation. Figure 4 shows the evolution of the Courant–Snyder invariant for a simulated HOM in the SOLEIL II ring. In the simulation setup only the main cavities were included with the HOM driving an instability with a growth rate of 131.6 s^{-1}. The longitudinal radiation damping rate is included with a value of 85.5 s^{-1}. The fitted value of growth rate, corresponding to the difference of those two figures is 49.5 s^{-1}, which has 6.8 % relative error of analytical value. The simulation setup will incorporate HC in the future to reproduce the results corresponding to real case in SOLEIL II.

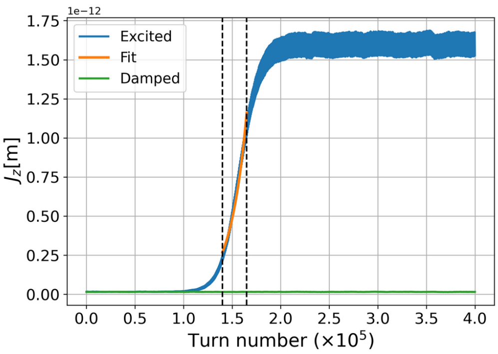

Figure 4: Simulated evolution of the longitudinal Courant-Snyder invariant as a function of turn number in `mbtrack2` for and unstable HOM case and the same case with longitudinal feedback (damping rate 211 s^{-1}). Blue: unstable beam without feedback, green: beam damped with LFB, yellow: exponential fit used to extract the instability growth rate.

PROCESSING: FIR

For the signal processing the filter used will be time domain FIR filter which scheme was developed at SPring-8 [18–20]. It defines the value of the required kick for stabilizing the beam by multiplying and summing up the coefficients and beam position data at each turn for each bunch separately. Coefficients are defined by specifying the working point, which in our case is the synchrotron tune, as well as the required tap numbers. To observe the feedback response, one should see its transfer function shown in Eq. 2, whose magnitude and phase correspond to the feedback gain and phase, respectively. a_k are the FIR filter coefficients for k-th previous turn position, N is the number of taps, $|H(\omega)|$ is the magnitude of the filter and $arg(H(\omega))$ is the phase of the filter.

$$H(\omega) = \sum_{k=0}^{N-1} a_k e^{-j\omega k} \tag{2}$$

For operation with feedback, tune acceptance is an important value. During operation, the tune can vary slightly due to insertion devices and since the feedback coefficients are predefined for a specific working point, the filter response may be degraded. To guarantee stability, the filter response should remain flat around the synchrotron tune. Here lies the difficulty in the longitudinal plane, because the synchrotron oscillation is very slow and the tap number should be quite large to get the beam behavior during one complete synchrotron oscillation. As the tap number increases, the peak of the response function becomes narrower. However, the filter scheme provides flexibility to shape the response according to the requirements, including flattening it by imposing conditions on higher-order derivatives at the tune value. By applying these conditions and increasing the order, the response becomes flatter and makes the operation more robust, as shown in Fig. 5.

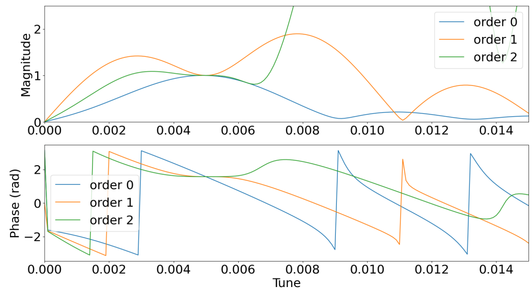

Figure 5: Behavior of magnitude and phase response for different orders of the filter.

CAVITY KICKER DESIGN

Since the feedback system operates bunch-by-bunch, the kicker should be designed to provide efficient energy transfer while maintaining a very fast response. We chose a cavity kicker as opposed to a stripline, as widely used in many other machines. The original design was developed in Frascati [11, 12], while SLS 2.0 upgraded the kicker by introducing the nose cones for more efficient kick and HOM dampers which were not included in the original design [21]. This design will serve as the basis for the SOLEIL II kicker.

CONCLUSION

The development of an LFB system has been launched for SOLEIL II. A beam-based experiment was conducted to gain experience with LFB in the SOLEIL ring by converting TFB to LFB. The computational tool to simulate feedback with the FIR filter is the `mbtrack2` code. The cavity-kicker design is based on the SLS 2.0 concept and is still at a preliminary stage.

ACKNOWLEDGEMENTS

The authors would like to thank the help of G. Rehm (HZB) on the evaluation of DLS-MBF processors and M. Dehler (PSI) on the cavity kicker design.

REFERENCES

[1] A. Nadji and L. S. Nadolski, “Upgrade Project of the SOLEIL Accelerator Complex”, *Synchrotron Radiat. News*, vol. 36, no. 1, pp. 10–15, 2023. doi:10.1080/08940886.2023.2186661

[2] J. Susini *et al.*, “A brief introduction to the Synchrotron SOLEIL and its upgrade programme”, *Eur. Phys. J. Plus*, vol. 139, p. 80, 2024. doi:10.1140/epjp/s13360-024-04872-2

[3] R. Nagaoka *et al.*, “Performance of bunch by bunch transverse feedback and evolution of collective effects at SOLEIL”, in *Proc. PAC'09*, Vancouver, BC, Canada, May 2009, paper TH6REP079.

[4] V. Gubaidulin, M. El Ajjouri, A. Gamelin, R. Sreedharan, and S. Thakur, “Beam-based Instability and Bunch-by-Bunch Feedback Characterization at SOLEIL”, presented at IPAC'26, Deauville, France, May 2026, paper WEP5106, this conference.

[5] R. Nagaoka *et al.*, “Operational status of the transverse bunch by bunch feedback system at SOLEIL”, in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper WEPEB029.

[6] A. Gamelin, V. Gubaidulin, M. B. Alves, and T. Olsson, “Semianalytical algorithms to study longitudinal beam instabilities in double RF systems”, *Phys. Rev. Accel. Beams*, vol. 28, no. 5, p. 054401, 2025. doi:10.1103/PhysRevAccelBeams.28.054401

[7] A. Gamelin *et al.*, “Double RF system design using normal conducting passive harmonic cavity for SOLEIL II”, presented at IPAC'26, Deauville, France, May 2026, paper WEP5091, this conference.

[8] A. F. D. Morgan, M. G. Abbott, and G. Rehm, “First experiences with the longitudinal feedback system at Diamond Light Source”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1947–1950. doi:10.18429/JACoW-IPAC2017-TUPIK114

[9] M. Lonza and H. Schmickler, “Multi-bunch feedback systems”, CERN, Geneva, Switzerland, CERN Yellow Report CERN-2014-009, 2016. doi:10.5170/CERN-2014-009.503

[10] M. Dehler, “Kicker design for the ELETTRA/SLS longitudinal multi-bunch feedback”, in *Proc. EPAC'02*, Paris, France, Jun. 2002, pp. 2070–2072.

[11] R. Boni, A. Gallo, A. Ghigo, F. Marcellini, M. Serio, and M. Zobov, “A Waveguide Overloaded Cavity as Longitudinal Kicker for the daphne bunch-by-bunch Feedback System”, *Part. Accel.*, vol. 52, pp. 95–113, 1996.

[12] R. Boni, F. Caspers, A. Gallo, G. Gemme, and R. Parodi, “A broadband waveguide to coaxial transition for high order mode damping in particle accelerator RF cavities”, *Part. Accel.*, vol. 45, pp. 195–208, 1993.

[13] W. Bruns, “GdfidL: A Finite Difference Program with Reduced Memory and CPU Usage”, in *Proc. PAC'97*, Vancouver, Canada, May 1997, paper 9P118, pp. 2651–2653.

[14] A. W. Chao, “Coherent instabilities of a relativistic bunched beam”, *AIP Conf. Proc.*, vol. 105, pp. 353–523, 1983. doi:10.1063/1.34238

[15] A. Gamelin, W. Foosang, and R. Nagaoka, “mbtrack2, a collective effect library in Python”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 282–285. doi:10.18429/JACoW-IPAC2021-MOPAB070

[16] A. Gamelin, W. Foosang, N. Yamamoto, V. Gubaidulin, and R. Nagaoka, MBTRACK2, Synchrotron SOLEIL, Dec. 2024. doi:10.5281/zenodo.10871039

[17] N. Yamamoto, A. Gamelin, and R. Nagaoka, “Investigation of longitudinal beam dynamics with harmonic cavities by using the code mbtrack”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 178–180. doi:10.18429/JACoW-IPAC2019-MOPGW039

[18] T. Nakamura, “Transverse and longitudinal bunch-by-bunch feedback for storage rings”, in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr.–May 2018. doi:10.18429/JACoW-IPAC2018-TUZGBD2

[19] T. Nakamura, “Bunch by bunch feedback systems review”, in *Proc. IBIC'24*, Beijing, China, Sep. 2024, p. 6. doi:10.18429/JACoW-IBIC2024-WECI1

[20] T. Nakamura, S. Daté, K. Kobayashi, and T. Ohshima, “Transverse bunch-by-bunch feedback system for the SPring-8 storage ring”, in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, pp. 2649–2652.

[21] M. Dehler, G. Scrimali, M. Lonza, R. Fortunati, and S. Dordevic, “Fast kickers for bunch by bunch feedbacks at SLS 2.0 and ELETTRA”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4817–4819. doi:10.18429/JACoW-IPAC2023-THPL149