BEAM-BASED INSTABILITY AND BUNCH-BY-BUNCH FEEDBACK CHARACTERIZATION AT SOLEIL

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Abstract

In the context of the ongoing SOLEIL II upgrade, a measurement campaign was conducted to characterize and understand the behaviour of single- and coupled-bunch instabilities, and the performance of transverse bunch-by-bunch feedback system at the present SOLEIL storage ring. This paper presents the keys results of beam current thresholds measurements; growth-damp measurements with resistive feedback. The most recent results constitute a snapshot of instabilities and bunch-by-bunch feedback performance at SOLEIL. These results are compared with an updated impedance model and past measurements. Our results provide guidance in designing the bunch-by-bunch feedback system for SOLEIL II.

INTRODUCTION

Synchrotron SOLEIL [1] is using a transverse feedback system based on that of the Spring-8 [2–4] for the storage ring. It was previously described [5, 6], notably in relation to characterisation and suppression of beam-ion instability [7–9]. Currently, SOLEIL is undergoing an upgrade towards a 4th-generation light source SOLEIL II [10–12], where a transverse feedback system will be required [13, 14]. We need to understand the capabilities of the current feedback system to guide the requirements and design of the future feedback system for instability mitigation in fourth-generation light sources [15].

Beam-based validation of impedance, instability and feedback modelling is a task relevant to many accelerator facilities [16–18]. The impedance model of the SOLEIL storage ring was recently updated [19] using an impedance modelling approach identical to the one for SOLEIL II [13, 20, 21].

Single- and multibunch operation modes of SOLEIL are described in Table 1.

Table 1: SOLEIL Operation Modes

Mode	N_{bunches}	I_{bunch} (mA)	Q_{bunch} (nC)
Uniform	416	1.2	1.4
Hybrid	312+1	1.4+5	1.7+6
8-bunch	8	12.5	14.8
Single-bunch	1	20	23.6

Experimental Setup

The feedback consists of dedicated BPMs, stiplines, RF frontends, a digital signal processor, and power amplifiers. It is set up every few months (after every machine restart) for a single-bunch regime, as it was identified in the past that this is the most demanding mode. After the set-up is verified by achieving the maximal required current in single- (20 mA) and multibunch regimes (500 mA) with open insertion device gaps (IDs). In all measurements, for feedback, a 5-tap FIR filter is applied to a signal with a phase corresponding to purely resistive feedback. All multibunch measurements were made with every rf bucket filled.

Threshold Measurements Beam or bunch current threshold is one of the most basic measures of the effective impedance of an accelerator. In a synchrotron light source, any instability will have a certain threshold current, where the growth time of the instability is slightly shorter than the damping time due to synchrotron radiation damping.

To measure the threshold current, we are gradually increasing the beam current until it is no longer possible to inject or until we start seeing an increase in beam emittance (measured with a pinhole camera). To avoid any instability triggered by an injection event, we inject with bunch-by-bunch feedback turned on and switch it off after the injection. This measurement is useful primarily for the operation team to know the current limits without bunch-by-bunch feedback. Thresholds can also be compared with analytical formulae or with tracking simulations.

Growth-damp measurement is more complex, and it allows for measuring the growth rate of an instability at a certain beam current (above the threshold) by switching the bunch-by-bunch feedback off for a short time window. After the feedback is switched back on, one can measure the damping rate provided by the feedback. All of these actions are done inside the acquisition window, where bunch-by-bunch data is recorded. This allows us to characterise the instability (measure the growth rate of each bunch, analyse the spectrum of bunch-by-bunch data), and measure the strength of the feedback system.

All measurements are automated using `Python` scripts.

RESULTS

Single-Bunch Case

Threshold Measurement Figure 1 demonstrates horizontal (left) and vertical (right) single-bunch instability thresholds measured at SOLEIL in different years. Simulation results were obtained with our code `mbtrack2` [22, 23]. More measurements were done in the vertical plane because the thresholds are lower and determine the feedback requirements. Transverse mode-coupling (TMCI) thresholds

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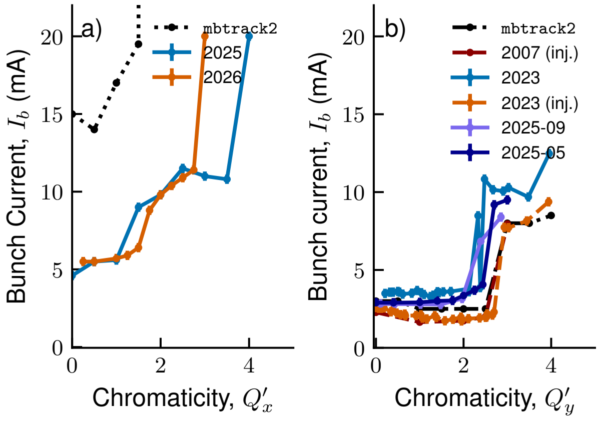

Figure 1: Horizontal (a) and vertical (b) single-bunch instability thresholds.

($Q'_{x,y} = 0$) were determined to be $I_{\text{tmci},x} = 4.6\,\text{mA}$ (simulation 15 mA). and $I_{\text{tmci},y} = 2.7\,\text{mA}$ (simulation 3.0 mA). The TMCI thresholds are in excellent agreement with the recent impedance model update [19] for the vertical plane. In the horizontal plane, the discrepancy between the simulation model and experiment is still large. Thus, either the simulation approach has missing elements or the impedance model is incomplete in the horizontal plane.

For vertical head-tail instability (HTI), the vertical threshold stays at $I_{\text{hti},y} \approx 3\,\text{mA}$ until $Q'_y \lesssim 2.5$. For $Q'_y > 2.5$, it jumps to $I_{\text{hti},y} \approx 10\,\text{mA}$. The jump is attributed to an increase in effective radiation damping strength for higher-order azimuthal head-tail modes [24]. For the vertical instability, we see a strong impact of the injection event on the measurement, similar influence of injection on instabilities was reported for some upgrade projects [25]. There is clearly an instability triggered by an injection that blows up the beam vertically. The beam blow-up can be eliminated by switching on transverse feedback. After the beam is stabilised, one can switch off the feedback, and the beam remains stable. This clearly links this blow-up to an injection event.

For horizontal head-tail instability, the threshold quickly increases to $I_{\text{hti},x} > 8\,\text{mA}$ with the increasing chromaticity $Q'_x > 2$. At $Q'_x \approx 3$, it is possible to inject up to 20 mA without horizontal feedback. In the SOLEIL case, the microwave instability (MWI) threshold was measured to be $I_{\text{mwi}} \approx 9.3\,\text{mA}$, which makes it harder to use horizontal emittance increase as a sign of horizontal head-tail instability.

Growth-Damp Measurement Figure 2 demonstrates a summary of growth damp measurements in a single-bunch mode. The growth time is obtained by doing an automatic exponential fit for all measurements. The damping time is obtained in the same manner by looking at the signal in reversed time. The spectrum of the instability in each case was broad, wider than the synchrotron tune sidebands. This is an indication that the observed instabilities are in the post-head-tail regime [26, 27]. The effect of chromaticity on growth times is moderate, with growth time (at 10 mA) increasing from 100 at $Q'_y = 0$ to 300 turns at $Q'_y = 2.5$. The measured damping time of the feedback is in the range of 10 turns to 50 turns with nominal feedback settings. The damping time is so short that it is challenging to obtain a good exponential fit of the signal over just a few tens of turns. In both cases, the observed dependency on the chromaticity is weak.

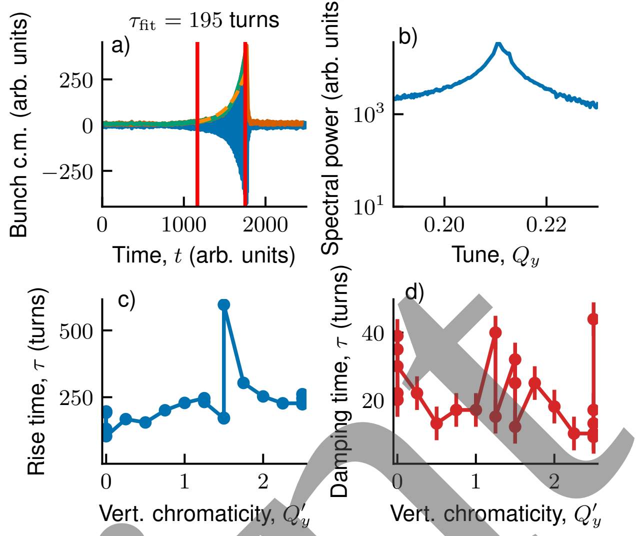

Figure 2: a) An example of measured beam c. m. offset and fitted growth time; b) An example of a bunch spectrum during the measurement; c) Fitted instability growth time against vertical chromaticity; d) Fitted feedback damping time against vertical chromaticity.

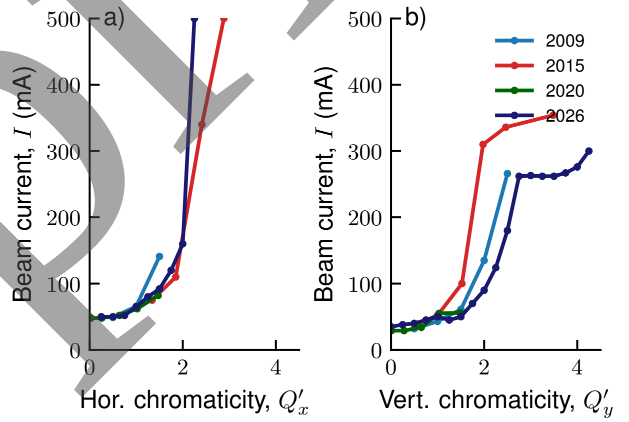

Figure 3: Horizontal (a) and vertical (b) coupled-bunch instability threshold at SOLEIL with open IDs configuration.

Multibunch Case

Threshold Measurement Figure 3 demonstrates coupled-bunch instability thresholds (left: horizontal, right: vertical) for different chromaticities. At zero chromaticity, the horizontal coupled-bunch instability (TCBI) threshold is $I_{\text{tcbi},x} \approx 48\,\text{mA}$ (simulation $\approx 70\,\text{mA}$) and the vertical one is $I_{\text{tcbi},y} = 29\,\text{mA}$ (simulation $\approx 31\,\text{mA}$) with open

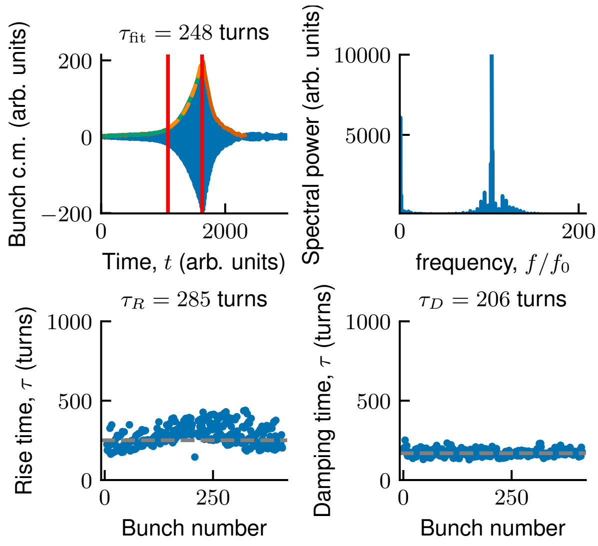

Figure 4: a) Example of growth-damp beam position signal with fitted growth time; b) Typical spectrum of vertical beam oscillations; c) Fitted growth times for every bunch; d) Fitted damping times for every bunch.

IDs. Around a chromaticity of $Q'_{x,y} \gtrsim 2$, the threshold starts to increase significantly $I_{\mathrm{tcbi},x} \gtrsim 300\,\mathrm{mA}$ and $I_{\mathrm{tcbi},y} \approx 260\,\mathrm{mA}$ to 300 mA. Disagreement of vertical thresholds in the vertical plane can be due to beam-ion instability at higher beam currents. With operational chromaticity values, transverse feedback is required in both planes to suppress coupled-bunch instabilities.

Growth-Damp Measurements Figure 4 shows an example of growth time fit of a particular bunch (a), typical beam oscillation spectrum (b), example of measured growth time for each bunch (c), and example of measured damping time of each bunch (d). In all measured instabilities, all bunches had very similar growth times and feedback damping time was also found to be independent of the bunch index. Also, in all cases, the dominant coupled bunch mode, as can be seen in Fig. 4 (c), is $f = (103 - Q_y) f_0$ instead of the typical resistive wall mode $f = (1 - Q_y) f_0$. The observed mode corresponds to beam-ion instability [14] driven by H_2^+ ion, which for SOLEIL lattice will excite revolution harmonics $f/f_0 \approx 70$ to 120.

Figure 5 summarises the obtained instability growth times and feedback damping times over the measurement campaign. The growth time of the instability depends on chromaticity and increases from $\tau \approx 200$ turns at $Q'_y = 0$ to $\tau \approx 1200$ turns at $Q'_y = 2$. The growth rate was measured at different total beam currents. We found that instability growth time follows a scaling law $\tau \propto I_{\mathrm{beam}}^{3/2}$, which corresponds to beam-ion instability scaling [8]. Together with the observed spectrum, this allows us to conclude that in a uniform filling pattern at SOLEIL, a beam-ion instability can be routinely observed at high beam currents without a bunch-by-bunch feedback system. In most measurements, the typical feedback damping time is around $\tau_{\mathrm{fb}} \approx 50$ turns to 100 turns for $Q_y < 2$ and the dependency on chromaticity is rather

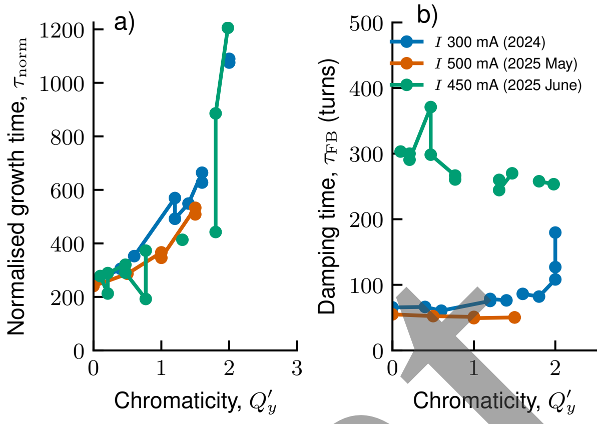

Figure 5: Results of growth-damp measurements. a) Instability growth time (scaled) for different chromaticity values; b) Bunch-by-bunch feedback damping time at different chromaticities and different machine runs.

weak until the beam oscillation is expected to shift to a higher-order head-tail mode. In one series of measurements, the damping time was significantly worse ($\tau_{\mathrm{fb}} \approx 300$ turns) than in the others. This can be attributed to the difference in the feedback setting, as the damping time is not yet systematically measured at machine restart.

CONCLUSION

Many factors influence the threshold measurement: transient effects at injection, presence or absence of various feedbacks (orbit feedback, tune feedback, noise, etc). It is expected that the beam is sensitive to different kinds of perturbations when it is close to the instability threshold.

Coupled-bunch instability at $I_{\mathrm{beam}} > 300\,\mathrm{mA}$ is identified as beam-ion instability driven by H_2^+. The transverse feedback system successfully suppresses this instability at SOLEIL, confirming that it is possible to suppress beam-ion instability for SOLEIL II using transverse feedback [14] even without any ion clearing gap.

The feedback damping times achievable today are in line with or faster than the ones required for SOLEIL II [13]. The feedback damping time also decreased by a factor of two for coupled-bunch instability, likely because the observed coupled-bunch instability is at a very high revolution harmonic.

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