BEAM INSTABILITY OBSERVATIONS AND ANALYSIS AT SOLEIL

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Abstract

The paper describes measurement and analysis of beam instability made at SOLEIL in comparison with the expectation using numerically estimated impedance budget. A multibunch beam is found to be under a strong influence of resistive-wall and fast beam-ion instabilities, in a way that largely depends on the local position in a bunch train. For a single bunch, the measured reactive impedance turns out to be larger by nearly a factor of two than calculated in all three planes. The roughness impedance due to NEG coating is assessed as a possible cause.

INTRODUCTION

SOLEIL is the French third generation light source ring commissioned in 2006 and starting its user operation this year. Due to reduced vertical chamber aperture around the machine, the resistive-wall (RW) and the geometric impedance was systematically evaluated and optimized 3D-wise at SOLEIL during the design stage, whose budget was then utilized to predict instability thresholds for multi and single bunches [1]. These theoretical calculations are compared with observed instabilities. As it was also anticipated, the electron beam in reality appears to be strongly affected simultaneously by the ions existing in the chamber.

MULTIBUNCH INSTABILITIES

General Aspect

Since the beginning of the commissioning, the transverse multibunch threshold was followed, vertically and horizontally, as a function of the beam filling and the chromaticity (Fig. 1).

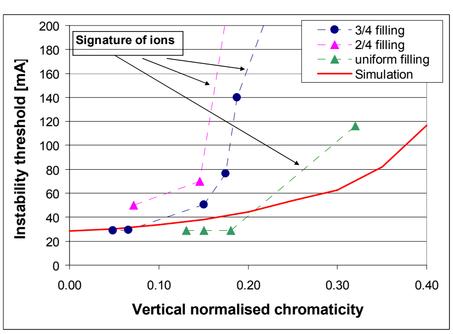

Figure1: Measured vertical multibunch instability threshold versus chromaticity.

Longitudinally, no coupled-bunch instability has been observed, as anticipated from the use of HOM-free superconducting SOLEIL cavities. The characteristics of the beam spectrum seen on a spectrum analyzer is that it exhibits transverse oscillation spectra with shapes typical to RW (Fig. 2 left) and beam-ion interactions (Fig. 2 right), whose degree depending upon beam conditions. With chromaticities close to zero, thresholds appeared at around 30 mA for different fillings vertically, in good agreement with the calculated RW threshold, where indeed RW spectra tended to show up.

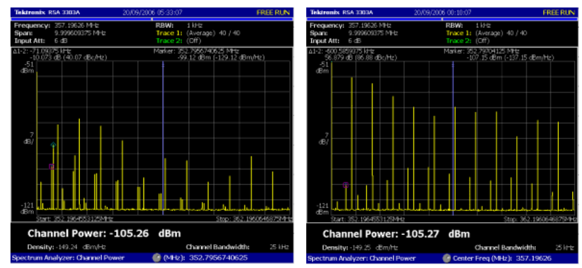

Figure 2: Spectra of vertically instable beam in 3/4th filling. Left: RW dominated. Right: Ion dominated.

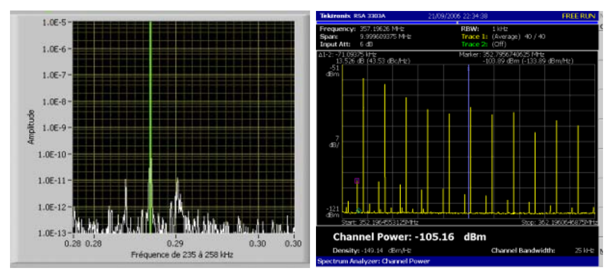

Figure 3: Observation of vertical m=-1 mode excitation in 3/4th filling. Left: Display of relative head-tail modes. Right: Global spectrum.

The rise of the threshold with increasing chromaticity was more pronounced for partial fillings (Fig. 1), where the spectra tended to be more beam-ion dominated. Although the stabilization of m=0 mode seemed to occur with smaller chromaticity values than expected, we could identify the excitation of m=-1 mode that takes over m=0, in accordance with the expectation (Fig. 3 left). Indeed, as anticipated, many sidebands appeared in such cases, due presumably to the latter being excited by the broadband (BB) impedance (Fig. 3 right). The unstable higher-order modes signify that for SOLEIL an alternative means such as feedback must be used to stabilize the beam. Although the observed trend was similar horizontally, with zero chromaticity the beam was instable at a current much lower than expected.

Analysis using Bunch by Bunch Feedback

The digital feedback system developed to combat the instability [2] later provided us with extremely useful diagnosis of the observed instabilities, with its bunch by bunch and turn by turn bunch position data. The instability was followed by switching off the feedback over typically a few milliseconds depending upon the growth rate, to follow the instability (Fig. 4). The evolution of vertical instability was followed in the standard 3/4th filling mode with zero chromaticity (Figs. 4-7) at different beam current. At 50 mA, the oscillation amplitude is observed to grow from the head to the tail of the bunch train in a way that reflects the beam current distribution (Fig. 5b).

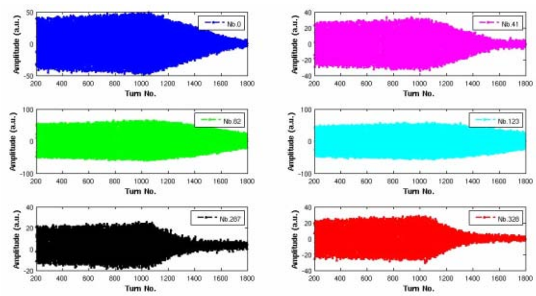

Figure 4: Observed envelops of centre of mass bunch oscillations via transverse feedback.

The oscillation phase evolves smoothly across the bunch train, with the phase shift between adjacent bunches being ~0.9 deg, which is nearly what expected from the strongest RW mode (Fig. 6a, dark blue). At 100 mA, a significant change appears in the bunch oscillation amplitude, with a rapid quasi-periodic variation along the train (Fig. 5c). A similar structure appears on the phase evolution, while the overall slope is still not much different from 50 mA (Fig. 6a, pink). At 250 mA, a dramatic change occurs on the phase where the phase shift per bunch jumps to ~40 deg (Fig. 6a, light blue), constantly across the entire bunch train, while the distribution of the oscillation amplitude remains similar to 100 mA (Fig. 5d).

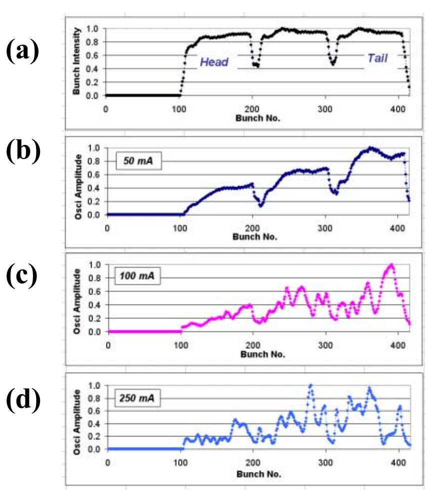

Figure 5: Measured vertical instability in 3/4th filling. Top: Current along a bunch train. Lower three: Oscillation amplitude versus bunch train at 50, 100 and 250 mA.

On the instability growth rate, a large bunch dependent variation appears from 100 mA onwards, although on the average, it increases quasi linearly with beam current, with a slope not far from what expected from the RW instability (Fig. 6b). These observations furthermore support the idea of the mixture of RW and beam-ion instabilities. In all cases, the instability seems to be initialized by the 1/4th of the beam gap. Measurement made in 1/4th filling finds these aspects to be more pronounced for a given beam current, indicating the bunch current dependence of the phenomena, which in turn suggests the presence of fast beam-ion instability.

It may be worth noting that with the gradual improvement of the vacuum in the machine, it became apparently more difficult to encounter RW dominated instability. Namely, it appears as the threshold of the fast beam-ion instability in the tail of a bunch train became lower than that of the RW instability. Whether worse vacuum could trigger the RW instability via enhanced beam-ion interactions is a point that needs to be verified with full numerical studies.

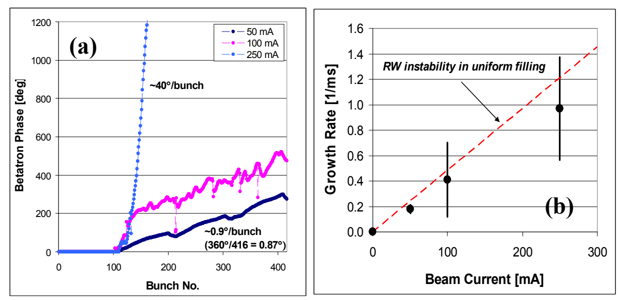

Figure 6: Left: Phase of vertical bunch oscillations measured at 50, 100 and 250 mA in 3/4th filling. Right: Measured average vertical growth rate versus beam current and that expected from RW instability.

Development of a Multibunch Tracking Code

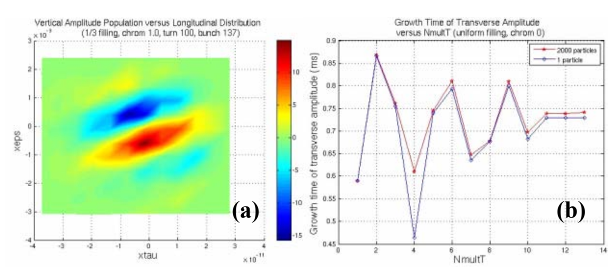

Figure 7: Impact of multi-turn effect on the instability growth rate (left) and bunch internal motion (right).

To be able to investigate the instability by taking well into account the beam filling dependence, a code has been developed that tracks multi bunches where each bunch consists of thousands of particles (Fig. 7a). The scheme consists of a master and slave structure using *pvm*, in which each slave firstly transforms particles within a bunch with intra bunch forces in the conventional one turn approximation. Centre of mass motions are then deduced and sent to the master, which collects the information over all bunches and stores over multiple turns. Secondly, each slave applies long range RW forces to particles in a bunch, by respecting the distance between bunches over multi turns (Fig. 7b). The feasibility of including ion clouds into the code is being studied in order to simulate the observed fast beam-ion interactions.

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SINGLE BUCNH INTABILITIES

The measured transverse mode coupling instability (TMCI) threshold turned out to be lower than the expected by nearly a factor of two both vertically and horizontally (Fig. 8). It signifies underestimation of the effective imaginary impedance, composed of RW and BB impedance, by the same factor. In the horizontal plane, the coherent detuning is seen to be largely cancelled by the incoherent tune shift arising from the chamber cross section asymmetry. In deducing the coherent detuning, the incoherent tune shift is subtracted in both planes.

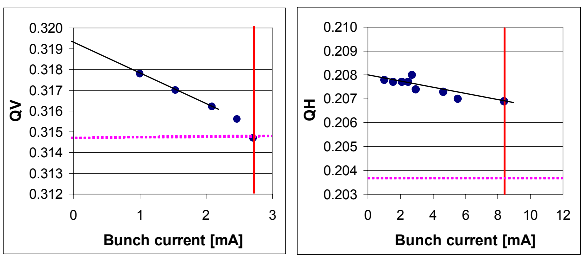

Figure 8: Measured dipole detuning. Left: Vertical. Right: Horizontal. Red line: TMCI threshold. Pink line: One synchrotron tune separation from the zero current tune.

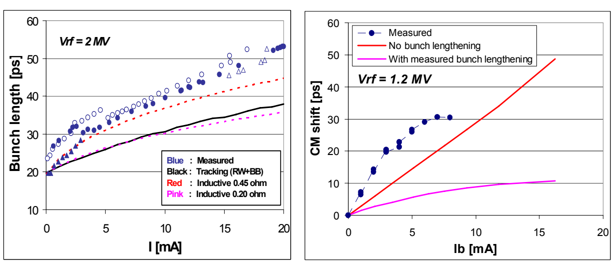

Figure 9: Bunch lengthening (left) and synchronous phase shift (right) measured with a streak camera.

The bunch lengthening and the synchronous phase shift were measured with a streak camera as a function of single bunch current (Fig. 9). Again, the measured values are larger than the expectation. In particular, the fit of the measured bunch lengthening with a purely inductive model requires the impedance of ~0.45 Ω, which is roughly a factor of two above $|Z/n|_{eff}$ = 0.2 Ω of the impedance budget. Note that the lengthening due to the purely inductive impedance of 0.2 Ω agrees well with the tracking result using the impedance budget (Fig. 9). On the other hand, the discrepancy on the synchronous phase shift may well be due imprecise evaluation of resistive impedance at high frequencies.

There are reports showing that NEG coating on Al chambers creates granular surface. Besides, an anomalous increase of the reactive impedance was measured in Elettra when NEG coated Al chambers were installed [3]. In fact, if we assume 1 μm of granular variations on the surface of our NEG coated Al chambers, as measured at the ESRF on one of their chambers [4] (Fig. 10a), the observed discrepancy on the imaginary impedance could be explained using the model proposed by K. Bane et al [5]. On the other hand, analysis of SOLEIL Al chamber indicated that, the surface roughness is ~0.3 μm in rms azimuthally and much less in the direction of beam circulation, reflecting the extrusion (Fig. 10b). Moreover, at SOLEIL, the coating thickness was reduced to 0.5 μm for precaution. The electron microscope on sample coupons found no degradation of the roughness after coating (Fig. 10c). To evaluate the roughness impedance the model proposed by G. Stupakov that employs the small angle approximation [6] is suited for such surface instead of the above model. Taking into account directivity of the roughness, the model predicts that the roughness impedance is totally negligible.

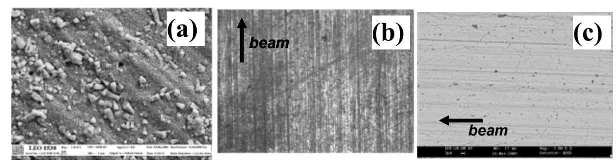

Figure 10: Surface of a NEG coated Al chamber (left) measured at the ESRF [4]. Surface of a SOLEIL Al chamber before (middle) and after (right) NEG coating.

CONCLUSION

With additional diagnostics that became available using the bunch by bunch transverse feedback system, it was confirmed that the beam is under a strong influence of fast beam-ion interactions, on top of the impedance effects. Better understanding of the dynamics is required for the good control of beam instability, as a function of the beam filling and vacuum conditions. The origin of discrepancy on the reactive broadband impedance (measured versus calculated) must be pursued.

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