BEAM DYNAMICS IN SUPER-ACO WITH A NEW 500 MHz FIFTH HARMONIC RF SYSTEM[1]

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Abstract

A new 500 MHz fifth harmonic RF system has recently been installed on the Super-ACO storage ring with the goal of reducing bunch-length for Free electron laser (FEL) and time-resolved synchrotron radiation experiments. Bunches have been shortened by factors between 2 and 3.5. This is accompanied by several new coherent instabilities. In particular, a single-bunch transverse instability causing vertical beam dimension blow-up occurs for positive chromaticity at around 10 mA. This instability is highly sensitive to lattice non-linearity's but rather insensitive to chromaticity although very strong vertical chromaticity does at least partially cure it. Longitudinal coherent instabilities begin at less than 2 mA per bunch. They are manifested by complex bunch phase and shape oscillations at frequencies close to the synchrotron frequency and its harmonics as well as by low frequency (several hundred Hz) phase and length variations. We describe various experimental results concerning these phenomena, including double sweep streak camera bunch profile observations, as well as our attempts to understand them in terms of collective effects theory.

1 INTRODUCTION

The new 500 MHz fifth harmonic RF system which was installed on Super-ACO in early 1997 (see ref. [1] for a general description) has allowed us to obtain bunch shortening factors in the expected range of 2 to over 3. However this bunch length reduction has resulted in numerous new collective instabilities both in the transverse and longitudinal phase planes.

2 NORMAL MODE OBSERVATIONS (SINGLE 100 MHZ CAVITY)

Before describing experimental observations with the harmonic cavity in bunch shortening mode we will begin by quickly surveying the principal collective effects observed on Super-ACO in normal mode (before harmonic cavity installation or with the cavity detuned).

First a current limiting single bunch vertical instability (SBVI) is observed with a threshold of about 30 mA at nearly zero absolute vertical chromaticity ($\xi_z=0$) increasing to over 120 mA for $\xi_z=+2$. This instability has been attributed to the transverse mode-coupling (TMC) phenomenon[2].

Next non current limiting multibunch longitudinal instabilities (MBLI's) occur in 24 bunch mode with total threshold currents around 30 mA. These result in large amplitude phase oscillations (>1.5 ns) with many modulation sidebands present around all revolution harmonics.

In one and two bunch modes a series of longitudinal instabilities (LI's) occur which are manifested in the frequency domain by 2nd, 3rd and/or 4th order sidebands (the order refers to the approximate multiple of the synchrotron frequency) around revolution harmonics. Typically the thresholds are around 35, 40 and 50 mA/bunch respectively for the three orders although their exact values have varied somewhat. We believe that these LI's are essentially single bunch phenomena because the bunch current thresholds are very close for 1 and 2 bunch operation.

Finally measured bunch length as a function of current is presented in figure 1.

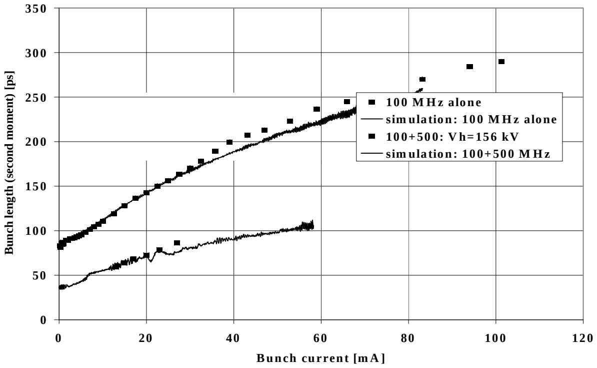

Figure 1: Super-ACO bunch length curves

3 BUNCH SHORTENING MODE OBSERVATIONS

In the bunch shortening mode the harmonic cavity is phased to increase the RF focusing slope and excited to a voltage between 30 and 300 kV. This corresponds to synchrotron frequencies between 20 and 42 kHz.

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3.1 Transverse

One of the most marked phenomena observed in this mode is a new SBVI with 2 regimes which we will refer to respectively as NSBVI-I and NSBVI-II.

NSBVI-I :

The first regime presents a threshold close to 10 mA/bunch which is independent of the charge configuration (1 bunch, 2 equidistant bunches, 2 adjacent bunches). It is manifested by a vertical excitation of the beam image as well as by a self-excited line in the transverse beam spectrum at a frequency slightly above that of the vertical tune (ν_z). This frequency does not correspond to that of a head-tail mode even taking into account the current variation of the frequencies of these modes. The amplitude is not constant but oscillates at low frequency. No parameter (tunes, chromaticity, transverse non-linearity's, harmonic voltage) has been found to change significantly the threshold current which always lies in the 8 to 10 mA range. However some of these parameters strongly influence the intensity of the instability and can under certain circumstances render it undetectable. In particular the instability has never been observed for harmonic voltages below about 32 kV, corresponding to a synchrotron frequency of 20 kHz. Note that the synchrotron frequency in the normal mode is 14 kHz, therefore well below this threshold.

The state (open or closed) of the 4 Super-ACO undulators strongly influences the behaviour of the instability. When all 4 undulators are closed, we observe a very large vertical beam blow-up (roughly a factor of 10 compared to a flat beam). In the FEL configuration, with only 1 undulator closed, this blow-up is only about a factor of 3 with regard to a flat beam. Finally when all the undulators are open, the instability has never been observed.

We adopted the working hypothesis that the effect of the undulators might be due to the effective vertical octupolar component which they introduce[3]. If this component is opposite in sign to that of the machine, the presence of undulators would tend to reduce the overall octupolar component and thus the non-linear tune spread, leading to less Landau damping and a greater tendency to instability. Unfortunately the natural octupolar components of the machine are not well known.

In order to test this hypothesis semi-quantitatively we installed an octupolar lens on the machine and observed beam behaviour as a function of its excitation level and of undulator configuration. The octupole strongly influences beam behaviour, allowing stabilisation with 4 undulators. However it could not destabilise the beam without undulators. A detailed analysis of these results has led to the conclusion that there exists a set of octupolar coefficients for the machine which are compatible with the experimental observations and the stated hypothesis.

Although these results help to understand the effect of undulators on the instability, they give no indication as to its physical origin. With regard to this point we dispose of the following additional information. The existence of the instability is independent of beam charge sign (normally e^+). Nor does it depend on the presence of non-zero dispersion in the harmonic cavity. It is also insensitive to the absolute value of tune, on both sides of the integer. However the distance to the coupling resonance (ν_z- ν_x) does appear to influence the intensity of the instability although in a way that is difficult to define. Finally the instability is insensitive to chromaticity for values between 0 and +2.5. It does however disappear for very strong chromaticities (on the order of 5) but this effect may be due to a change in tune spread due to the very strong sextupole excitation rather than to the chromaticity as such.

These results permit to exclude several mechanisms, such as an interaction between the beam and extraneous charged particles, a synchro-betatron instability or an instability due to the narrow band resistive wall impedance. Finally the relative insensitivity to chromaticity renders an explanation in terms of azimuthal head-tail modes problematic.

At present the origin of this instability remains mysterious. Our only means of combating it is a very strong increase in vertical chromaticity but this results in a reduction in dynamic aperture and thus in beam lifetime.

NSBVI-II :

The second regime appears at a threshold current close to 30 mA/bunch. Its principal characteristic is that the mode head-tail -1 (ν_z- ν_s) becomes self-excited. This regime appears to correspond to the mixing of the 0 and -1 head-tail modes. At a current of 40 mA, the two lines become indistinguishable and injection saturates. In this situation increasing the vertical chromaticity from 2.5 to 4 leads to a sudden separation of the two lines and a calming of the instability giving place to NSBVI-I.

These observations seem compatible with the TMC mechanism already observed on Super-ACO in normal mode. The only difference is the need for somewhat higher chromaticities in order to calm the instability at a given current.

3.2 Longitudinal

Measurements of bunch length as a function of current made with a dual sweep streak camera (DSSC) for an harmonic voltage of 156 kV are shown in figure 1. Unfortunately when observed as a function of time the bunches oscillate in a complex fashion. On a several ms timescale, one observes semi-periodic low-frequency oscillations (LFO's) of 1st, 2nd, 3rd and 4th bunch profile moments. The most commonly observed waveform shape is sawtooth-like. Usually risetimes are much faster than falltimes. Frequencies vary between several tens of Hz and about 300 Hz. The amplitude of LFO's varies widely as a function of bunch current and harmonic voltage. Second moment variations typically range from 5 to 20 % and bunch centroid phase variations from 3 to 30 ps.

On a faster time scale we observe high frequency oscillations (HFO’s), with frequencies close to multiples of the synchrotron frequency. Many different forms of oscillation have been observed but most are difficult to categorise. Some forms seem to suggest phase oscillations of parts of the bunch within an envelope which does not oscillate. For currents above about 8 mA/bunch, these rapid oscillations are sporadic, appearing on some DSSC images but not on others. We believe that this sporadic nature is related to the LFO’s but the large difference in time-scale has not allowed a straightforward confirmation of this hypothesis. Below this "inverted" threshold HFO’s are present constantly, although their forms and amplitudes still oscillate, and their amplitudes are somewhat larger than for slightly higher currents. The LFO’s remain present however. The oscillations remain persist at least until 2 mA/bunch. However for 20 μA/bunch the beam is stable.

Longitudinal beam spectra typically show ill-defined sidebands covering frequencies up to about 80 kHz from the revolution harmonics but with broad double-peaked maxima near 1 and 2 times the synchrotron frequency. The lower frequency peak of the first order side-band often corresponds to the frequency of those HFO’s which present internal phase oscillations while the second peak is close to the theoretical synchrotron frequency. The difference between these two peaks varies but is of the order of several kHz.

For harmonic voltages above about 150 kV, the amplitude of both HFO’s and LFO’s tend to increase markedly and the first and second order sidebands become much more strongly excited.

The observed longitudinal phenomena are clearly very complex. We have attempted to present a broad summary of observed behaviour. Although this general description seems quite reproducible many details of the phenomena vary significantly from run to run in ways which are currently not well understood. Although we believe that these phenomena are predominantly single-bunch in nature, their lack of complete reproducibility would tend to suggest that narrow-band machine impedance's may also play a role.

4 LONGITUDINAL SIMULATION RESULTS

We have used an FFT based longitudinal particle in cell code in an attempt to understand the nature and origin of the observed longitudinal instabilities. This of course requires knowledge of the longitudinal machine impedance. In order to obtain a rough preliminary impedance model we have made impedance calculations with ABCI[4] on 2D approximations to some of the major discontinuities of the Super-ACO vacuum chamber. The main contribution included in this model is that of the 16 circular pumping chambers located between elliptical beam pipes, 2 of which occur in each straight section.

Simulations performed with this impedance model give reasonable agreement to the bunch lengthening curves (fig. 1). Note that because of the uncertainty in passing from 2D to 3D results, a single overall scaling factor close to 1 was applied to the impedance used in these simulations in order to fit the low current bunch length of the 100 MHz curve. In addition, certain features of the observed instabilities such as low current thresholds, doubled synchrotron frequencies and partial phase oscillations are also reproduced. Agreement is currently best for currents below the 8 mA/bunch inverted threshold.

5 CONCLUSIONS

From a practical standpoint the phenomena we describe can represent a significant problem for FEL operation. Nonetheless because of the stabilising effect of the FEL on the electron beam, stable FEL operation as a user light source has been achieved for harmonic voltages up to 150 kV with bunch shortening factors up to 2 and significant gains in performance compared to normal mode operation[5]. FEL operation is also possible, though currently less stable, at voltages up to the 300 kV maximum with bunch shortening factors close to 3.

From a theoretical point of view the observed instabilities possess many unusual characteristics, such as very low threshold currents, inverted thresholds and insensitivity to parameters in very broad ranges which make their comprehension difficult in terms of the usual concepts of coherent effects theory. We hope that further progress on simulations, using more refined (hopefully 3D) impedance models will lead to insight into the mechanisms of these phenomena.

REFERENCES

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