INVESTIGATIONS OF CAVITY INDUCED LONGITUDINAL COUPLED BUNCH MODE INSTABILITY BEHAVIOUR AND MECHANISMS*

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Abstract

The narrowband impedances of RF-resonators in a circular accelerator can drive coupled bunch mode instabilities (CBI), which might spoil the overall beam quality. Often the instability does not lead to beam loss, but to a severe degradation of the source brilliance, as e.g. in synchrotron light sources.

Investigations of longitudinal CBIs have been performed at the DELTA storage ring [1] with a single DORIS-type cavity for future comparision with the behaviour of a HOM-damped cavity to be tested at DELTA. This resonator has been developed and built within an EU-collaboration [2].The beam was deliberately driven into instability using the beam current, as well as the cavity temperature as individual parameters. At low energy (542 MeV) the longitudinal beam behaviour is completely dominated by instabilities, even for very low currents. At high energy (1.5 GeV) threshold currents between 30 and 75 mA have been detected for single higher order modes (HOM). The synchrotron sideband analysis shows a sattelite structure around the resonant mode. Numerical estimations including an FFT algorithm show that the fractional filling of the storage ring is responsible for this sideband structure.

INTRODUCTION

HOMs are induced by electrons passing the cavity. The electric field component of these resonating modes modulates the accelerating voltage for the individual bunches. The common model of these collective modes is the well known linear chain of coupled rigid oscillators oscillating at the same frequency f, but with a certain phase advance between each oscillator corresponding to the collective mode (coupled bunch mode, CBM).

A chain of n oscillators can exhibit n modes with a phase advance of $\varphi_k = \frac{2\pi}{n} \cdot k$, with $k = 0, \ldots, n-1$ indicating the mode. The time function of each oscillator is given by:

$$a_i(t) = \hat{a}_i \cos(2\pi f t + \varphi_k \cdot i).$$

In our case $a_i(t)$ is the longitudinal displacement of a rigid bunch when performing synchrotron oscillations. Observing the process at a fixed position, we obtain a phase modulated signal containing frequencies $f_{p,k}$

$$f_{p,k} = (pn + k + Q_s) f_0,$$

where f_0 is the revolution frequency, Q_s the synchrotune, k indicates again the mode of interest and $p \cdot n$ with $p = [-\infty, \infty]$ redisplays the circular character of the problem.

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The main damping mechanism of this oscillation is synchrotron radiation damping. If the frequency $f_{p,k}$ corresponding to a CBM is in the vicinity of a HOM this CBM can get unstable, if the rise time of the longitudinal instability exceeds the damping time. If one follows e.g. [3] the threshold current $I_b^{max}(f_{p,k})$ as a function of the longitudinal impedance $R_{||}(f_{p,k})$ at the edge of instability is given by:

$$I_b^{max}(f_{p,k}) = \frac{2EQ_s}{\tau_\epsilon e\eta} \frac{1}{f_{p,k} R_{\|}(f_{p,k})},$$

with E the beam energy, τ_ϵ the radiation damping time, η the momentum compaction factor and e the elementary charge.

The threshold impedances for a stored beam current of 1 mA to become unstable in DELTA at frequencies of 500 MHz and 3 GHz are listed in Table 1 for two energies. These numbers are easily exceeded by typical HOM shunt impedances of the DORIS-cavity.

DELTA characteristics are (high / low energy): E=1482 / 542 MeV, f_{RF}=499.8205 / 499.8385 MHz, f_s=$Q_s f_0$=15.8 / 27.5 kHz, τ_ϵ=4.2 / 89 ms, $\eta \approx 0.0053$, harmonic number h=192.

Table 1: Threshold impedances for a beam of 1mA at operation frequency and around cut-off frequency of beam tube.

f [MHz]	$R_{\|}$ @ 542MeV [kΩ]	$R_{\|}$ @ 1482MeV [kΩ]
500	50.6	1704.2
3000	8.4	284

Table 1 shows one big advantage of low energy measurements concerning HOM induced instabilities. Compared to high energy beams the threshold impedances are lower by two orders of magnitudes. The ability to investigate the CBM behaviour of a storage ring is therefore increased. For the EU-cavity tests this means, DELTA will not be able to run into an instablity at high energy, because all EU-cavity HOM shunt impedances are of the order of some kΩ, while the threshold impedances are some hundred kΩ. At low energy DELTA however is very sensitive to even small impedances, so a safe detection of the HOMs is expected.

EXPERIMENTAL SETUP

The beam power spectrum is measured at the four electrodes of a standard beam position monitor (BPM) of the storage ring DELTA. The four signals are fed through a network of 180° 3dB-hybrid couplers to generate a broadband sum and difference signal. The synchrotron sideband

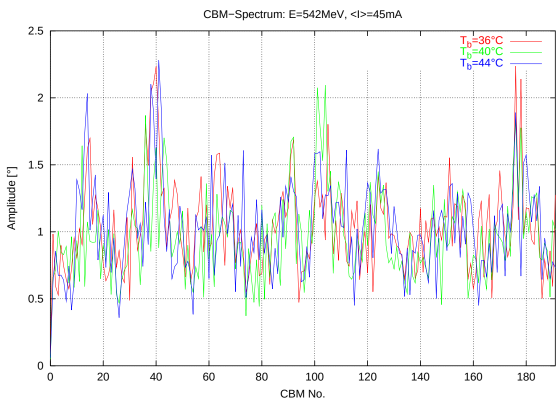

Figure 1: Low energy (542 MeV) spectra at $< I >\simeq 45$ mA and a cavity temperature of 36°C (red), 40°C (green) and 44°C (blue).

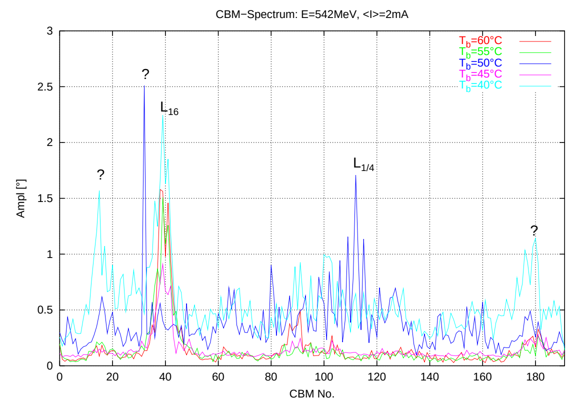

Figure 3: Low energy (542 MeV) spectra at cavity temperatures between 60°C (red) and 40°C (cyan) in steps of 5°C at $< I >$=2 mA. Mostly the same modes are involved, but with different amplitudes.

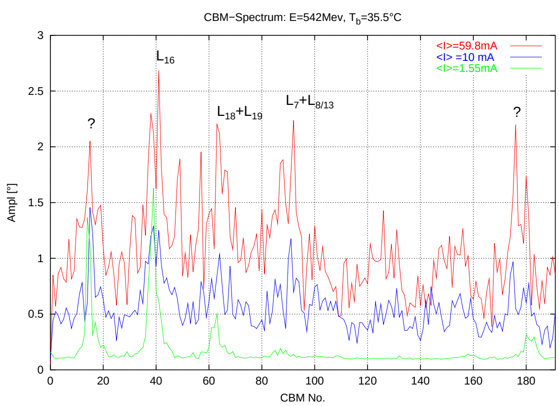

Figure 2: Low energy (542 MeV) spectra at a cavity temperature of 35.5°C and stored beam currents of $< I >$=59.8 mA (red), $< I >$=10 mA (blue) and $< I >$=1.55 mA (green).

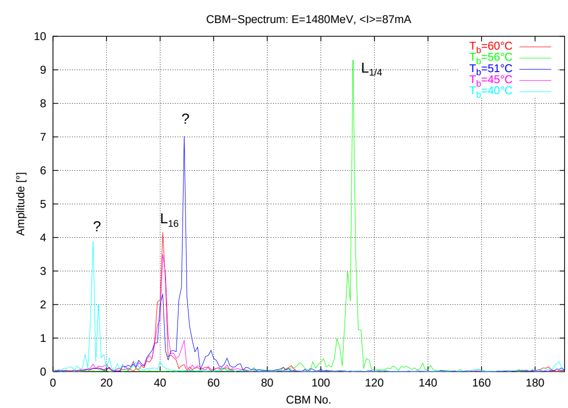

Figure 4: High energy (1482 MeV) spectra at cavity temperatures between 60°C (red) and 40°C (cyan) in steps of 5°C at $< I >$=87mA. Again nearly the same modes as at low energy are involved.

spectra are scanned in the usual manner [4] by a spectrum analyser. The center frequency is stepped between 500 and 750 MHz by 2.6 MHz (span 80 kHz, bandwidth 1 kHz, 10 times averaging). With this settings one scan takes approx. 18 min.

MEASUREMENTS & RESULTS

Measurements have been made at E=542 MeV and 1482 MeV and different stored beam currents. As parameter the cavity temperature was stepped between $35/40$°C and 60°C in steps of 5°C to allow a variation of HOM frequencies w.r.t. the operating frequency to get a different instability behaviour. The structure of the beam filling was monitored with a fast oscilloscope, again at a BPM, to ensure a homogeneous 144 out of 192 bunch (DELTA standard) pattern.

First the measurements were made at E=542 MeV, starting at a relatively high current of I=60 mA. It became obvious (figure 1), that at those high currents and all cavity temperatures hardly any structure is visible, nor could these synchrotron sideband structures easily be dedicated to specific CBMs. At this high current levels several resonant CBMs are well above threshold and show a complicated broadband structure. With decay of current more and more structure evolves (figure 2). The existence of excited modes could be proven down to currents of 0.9 mA, this is already near detection limit of our setup. No threshold could be determined. The major mode is excited around CBM 39-41, which is present at all temperatures, but with different amplitude, followed by CBM 15-17, 61-68 and 89-92 (see figure 3). There are also non-temperature dependent modes. The sources of these longitudinal impedances is not yet explained.

The high energy measurements at E=1482 MeV were performed starting at I_{max}=100 mA (see figure 4). During the data taking a mean current of $< I >\simeq 87$ mA was stored in the ring. Typically threshold currents of 70-75 mA were necessary to drive instabilities at all temperatures. At high temperature ($55°\mathrm{C}$) the HOMs L_1 and L_4 at 778 and 1275 MHz drive the instability down to currents of 30-35 mA. The high energy sideband spectra above threshold show quite the same behaviour as the low energy spectra at very low current and detection limit. All of them exhibit a sattelite structure, that is clearly connected to a resonant excited CBM.

In contrast to the simple model of rigid oscillators in an 100% filled storage ring, fractional filling modifies the beam power spectrum and its transient beam loading modulates the eigenfrequencies of the bunches, giving rise to Landau damping combined with enhanced stability. In the case of DELTA with its 144/192 filling the frequency spread amounts to 35 Hz at 100 mA and $\hat{U}_{RF}$=350 kV, which could be measured in good agreement with numerical calculations. Following the estimations in [5], the additional Landau damping is considered as small in DELTA. Numerical investigations have been performed to clarify the observed sideband structure. To allow more than one collective oscillation, two independent subbunches "1" and "2" per RF-bucket n have been implemented. Let these macro particles have different phase advances according to their CBM. They generate the beams time function $S_{1,2}(t)$:

$$S_{1,2}^{(n)}(t) \propto \mathrm{e}^{-\left[t-\tau_0 \sin\left(2\pi(f_s+\mathrm{d}f\frac{n}{h-1})t+\varphi_k n\right)\right]^2/2\sigma^2} + \mathrm{e}^{-\left[t-\tau_0 \sin\left(2\pi(f_s+\mathrm{d}f\frac{n}{h-1})t+\varphi_l n\right)\right]^2/2\sigma^2},$$

k and l denote the collective mode, $\mathrm{d}f\frac{n}{h-1}$ is a frequency shift of the macro particles w.r.t. the leading bunch of the train to reproduce a frequency distribution (n=$[0, h-1]$).

Numerical simulations were made by generating this time signal of the circulating beam and applying a FFT to this function (resolution $\approx$ 2kHz). The generated spectra were analysed and show that the main contribution to the sattelite structure originates from the fractional filling of the ring. The sidebands exhibit a sinc-function like behaviour (figure 5). Within the scope of this model the spectrum was reproduced reasonably. To investigate if this sattelite structure could also be achieved by only applying a frequency spread, a homogeneously filled ring was simulated. Figure 6 shows that extremely large frequency shift are necessary to gain a comparable structure.

SUMMARY

The storage ring DELTA was characterised concerning longitudinal collective mode instabilities with a single DORIS cavity installed. A simulation code for mode spectra of those instabilities was implemented explaining the observed sattelite structure. With subbunching and fractional filling a reproduction of a spectrum could be achieved, while the effect of frequency spread due to fractional filling was comparatively small. DELTA seems to be well prepared for the upcoming test of the HOM-damped EU-cavity.

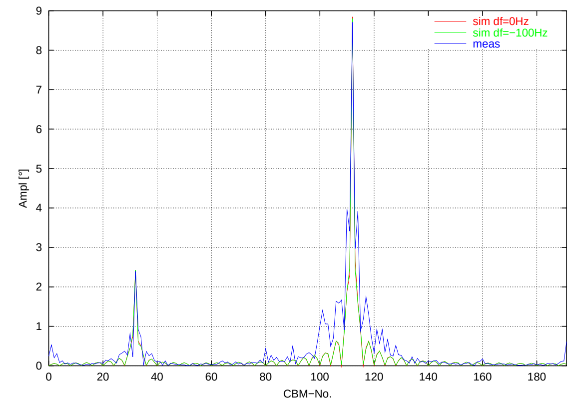

Figure 5: Simulated (red/green) and measured (blue) CBM spectra of a 144/192 filled ring oscillating at two collective modes and allowing a frequency shift of $\mathrm{d}f = -100\mathrm{Hz}$ (green) and without shift (red). The simulated spectra are nearly congruent.

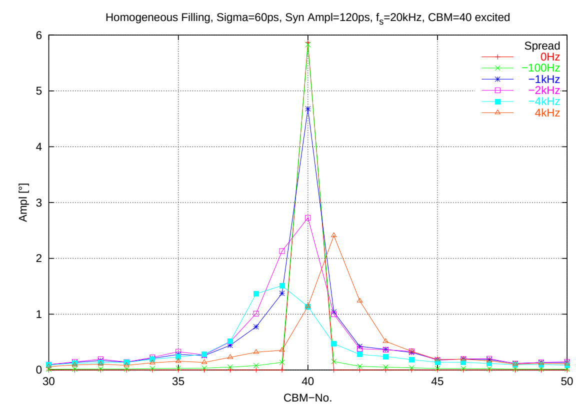

Figure 6: Simulated CBM spectra of a homogeneously filled ring with different overall frequency shifts (from red to orange: 0Hz, -100Hz, -1kHz, -2kHz, -4kHz, 4kHz). To gain a strong sattelite structure very large frequency shift are necessary. Remarkably those shifts moved the CBMs maximum amplitude.

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