INSTABILITY STUDIES AND DOUBLE RF-SYSTEM OPERATION AT BESSY

E. Weihreter, A. Gaupp, H.G. Hoberg, W.-D. Klotz, P. Kuske, H. Lehr, R. Maier, G. Mülhaupt
Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung mbH (BESSY)
Lentzeallee 100, D-1000 Berlin 33

Abstract

Longitudinal multi-bunch oscillations are observed at the BESSY storage ring even with beam currents of 1-2 mA, although stored currents up to 970 mA can be achieved. With a double rf-system the threshold currents can be increased when operating the system in the tune splitting or in the 'Landau'-cavity mode. A longitudinal impedance of $|Z/n| \cong 12\ \Omega$ is obtained from bunchlength measurements. No transverse multi-bunch instabilities have been observed. This may be explained by Landau damping induced by the non-linear fields of the ions trapped in the beam.

Longitudinal Multi-Bunch Instabilities

BESSY is operated routinely at 750 MeV with h=104 bunches in the small emittance optics Metro[1], using a 500 MHz rf-system, although a 62.5 MHz subharmonic cavity has been installed recently (tab. 1). Longitudinal oscillations are observed as coherent phase-modulation signals with a broadband pick-up electrode, placed at a location with negligible dispersion. The signal spectrum consists of lines with the frequencies

$$f^{\pm}_{\mu,m} = nf_{rf} \pm (\mu f_\circ + mf_s) \qquad n=0,1,\ldots,\infty .$$

Here f_{rf} is the rf-frequency, $f_\circ$ the revolution frequency (4.8 MHz), and f_s the synchrotron frequency. Below 1 mA no sidebands are observed. Increasing the beam current, more and more coupled bunch modes with mode numbers $\mu=0,1,..,h-1$ are excited with characteristic unsymmetric sidebands around the harmonics of $f_\circ$. Above typically 10 mA all modes are present with nearly symmetric sideband amplitudes equal within 3 dB if averaged over longer times (fig. 1). The short time amplitude variations (10 msec) are about 10 dB. In addition to rigid bunch oscillations (m=1), quadrupolar (m=2), and sextupolar (m=3) shape modes are observed. Besides a more pronounced difference in the sideband amplitudes, this overall characteristic is also true for 13 bunch operation.

Tab. 1 Parameters of the BESSY Rf-System

	62.5 MHz	-Cavity-	500 MHz
Shunt impedance ($R_s = V^2/2P$) [MΩ]	0.6		3.
Quality factor	6000		30000
Rf-power [kW]	20.		35.
Harmonic number	13		104

The coupled bunch nature of the longitudinal motion has also been verified in time domain, using a fast oscilloscope, and operating the storage ring with 8 successive 500 MHz-bunches, the others being kicked out by a vertical knock-out system. The first bunch is stable up to 80 mA, while the others oscillate even at rather moderate currents. Thus the wake fields produced by the first bunch excites at least the second bunch, however it is damped out after one revolution period $T_\circ$=208 nsec. Longitudinal single bunch effects may only contribute to the sideband amplitudes at currents above 10 mA/bunch.

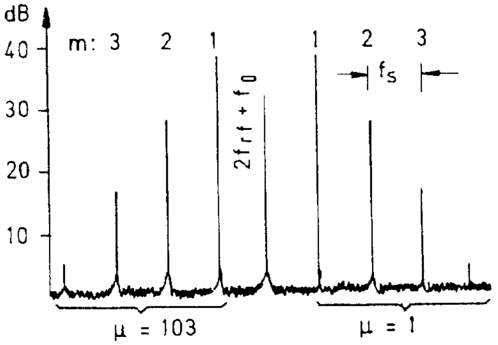

Fig.1: Synchrotron frequency sidebands

For some oscillation modes the sideband/rf-carrier intensity ratio I_s/I_{rf} is plotted in fig. 2. In the case of pure phase modulation this quantity represents the oscillation amplitude $\phi_\circ = 2\ I_s/I_{rf}$ of the respective mode. At low currents the amplitudes increase rapidly up to a constant value $\phi_\circ \cong 1°$ at about 50 mA. This typical behaviour has been observed for all modes, except the μ = 0 mode is always damped stronger (Robinson damping).

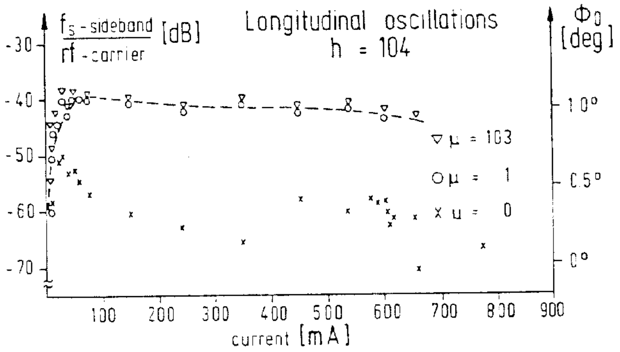

Fig. 2: Amplitudes of modes μ=0,1,103

With increasing oscillation amplitudes non-linear terms contribute to the effective acceleration voltage, leading to an equilibrium amplitude due to Landau damping, and thus allowing for stored currents up to 970 mA. There is no indication that the maximum current is limited by longitudinal instabilities. With an rf-power of 35 kW and the actual cavity/transmitter coupling factor, the Robinson stability limit is about 1000 mA. Thus, the maximum current seems to be limited by the available rf-power.

An attempt has been made to identify higher cavity modes as possible driving forces for distinct multi-bunch oscillations. For example in 13 bunch operation a mode of the 500 MHz cavity at 1744 MHz could be correlated with the μ=1 coupled bunch mode. With 104 bunches, however, a complete identification of all relevant cavity modes is hampered by the large number of possible coupled bunch

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modes and the low threshold currents. Since it would be practically impossible to damp out all these modes with selective antennas, other possibilities have been considered to combat longitudinal instabilities.

Tune Splitting Operation

When using the 62.5 MHz rf-system in addition to the 500 MHz main rf-system, it is possible to create different rf-voltage gradients for eight successive bunches, splitting up their synchrotron frequencies.

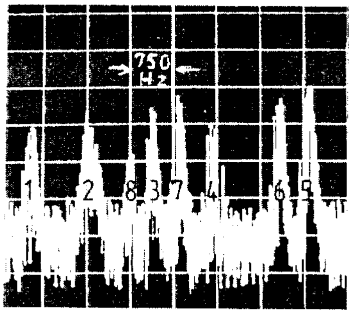


Fig. 3: Synchrotron frequencies of 8 successive bunches in the tune-splitting mode with cavity voltages

V_{500} = 230 kV

$V_{62.5}$ = 95 kV

Therefore these bunches no longer interact coherently and all oscillation modes are damped up to currents of about 25 mA, increasing the instability thresholds by a factor of 10. For higher beam currents, however, the synchrotron frequency spread (fig. 4) is of the order of the maximum frequency splitting between neighbouring bunches ($\Delta f \cong 500$ Hz), and the interbunch coupling can no longer be suppressed.

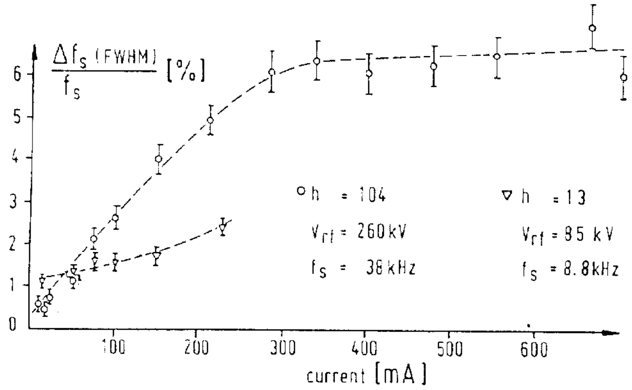
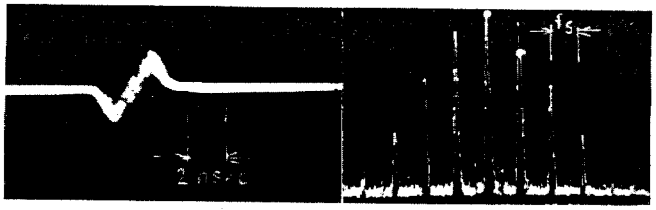


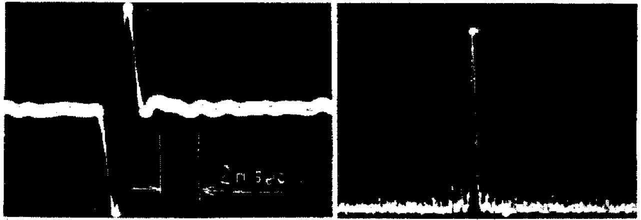
Fig.4: Synchrotron frequency spread

Operation with a 'Landau'-Cavity

Also when operating the storage ring with 13 bunches (f_{rf}=62.5 MHz) all longitudinal modes are excited above a current threshold of 10 mA (I_{max}=340 mA). An attempt has been made to suppress the longitudinal oscillations by operating the 500 MHz-resonator as a 'Landau'-cavity: with a suitable choice of the rf-voltage V_{500} and the phase ϕ relative to the 62.5 MHz main rf-system, a zero gradient of the accelerating voltage can be achieved. One obtains a very long bunch (up to 1.4 nsec) and a broad distribution of synchrotron frequencies within the bunch, so the electrons no longer oscillate coherently. Up to currents of 35 mA all multi-bunch oscillation modes can be suppressed by manual control of V_{500} and ϕ. For larger currents these parameters are affected by the interaction of the beam with the high shunt impedance of the 500 MHz cavity. This has also been observed at SOR[2] and PETRA[3]. An adequate feedback-loop for the dynamic control of V_{500} and ϕ is not yet available. However, even with the 500 MHz-cavity being passive, an approximate 'Landau'-operation mode can be established. The beam induced voltage in the passive resonator can be set by the cavity tuning. Although the phase of this voltage relative to the beam is no longer a free parameter as in the case of the active cavity, currents up to 220 mA can be stored without any longitudinal motion (fig. 5).



Tuner position 38 mm: all multi-bunch modes and many bunch shape modes are excited.



Tuner position 20 mm: all modes are damped, beam is stable in longitudinal direction.

Fig. 5: Beam signal in time domain (left) and frequency domain (right)

Bunchlength and Longitudinal Impedance

In single bunch operation with the 62.5 MHz system no coherent oscillations have been observed up to currents of 100 mA. Therefore bunchlength measurements have been performed in this mode, registrating the signal of a small pick-up electrode with a sampling technique[4]. Above a threshold of $I \cong 3$ mA the data indicate a $I^{1/3}$ -behaviour of the bunchlength as predicted by turbulent bunchlengthening.

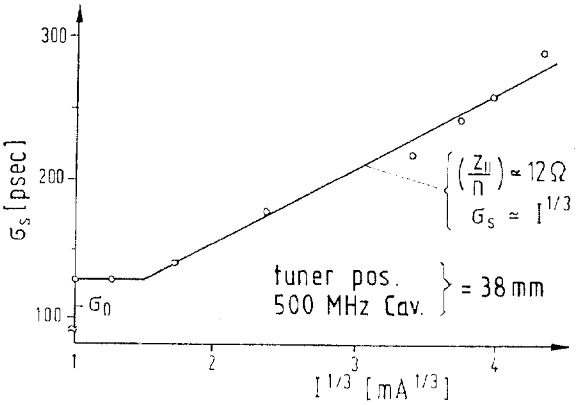


Fig.6: Bunchlength in single-bunch operation

As a result a longitudinal impedance of the vacuum chamber of $|Z/n| \cong 12\ \Omega$ is obtained.

At low currents the bunch is influenced by potential well distortion, showing a slight increase in σ_s as compared to the natural bunchlength σ_o = 108 psec. The bunchlength also depends on the tuning of the passive 500 MHz resonator (fig.7), which modifies the effective potential. For capacitive tuning the bunch is shortened wereas for inductive tuning bunchlengthening is obtained, thus allowing for a simple method to control the bunchlength.

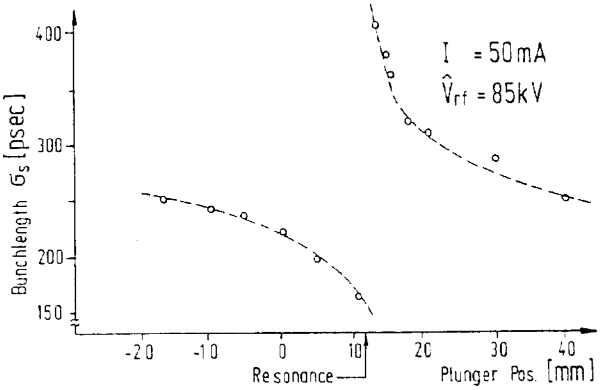


Fig.7: Bunchlength as a function of the passive 500 MHz cavity tuner position

Transverse Instabilities

During injection occasionally individual bunches have been observed to drop out in h = 13 operation and in very rare cases also with 104 bunches. This limitation could always be overcome by changing the sextupole setting. In the Metro optics the chromaticities are negative (ξ_x=-12,ξ_z=-2), so this observation can be attributed to the head-tail effect. With adequate sextupole settings the head-tail thresholds are above 12 mA and 100 mA per bunch for h = 104 and h = 13 operation,respectively.

Surprisingly, no transverse multi-bunch oscillations have been observed. A possible explanation is the presence of ions collected by the beam, which gives additional Landau damping for the transverse motion due to the non-linear fields produced by the ions. Estimates of critical masses based on a current ion trapping model[5] indicate that ions should always be trapped, even with a single bunch.

To verify the presence of ions, tune shifts have been determined as a function of beam current, measuring the betatron frequencies after transverse excitation. For the tune shifts in single bunch operation shown in fig. 9, the response of the beam has been detected by a photomultiplier behind a slit, placed in the tail of the synchrotron radiation distribution. The signal sensitively depends on the excitation amplitude, which has to be chosen as small as possible in order not to perturb or kick out the ions. In both transverse planes, the tune-shifts are positive, as expected for ion-induced fields. This is also true for fillings with 13 and 104 bunches although relatively high excitation levels have been used here.

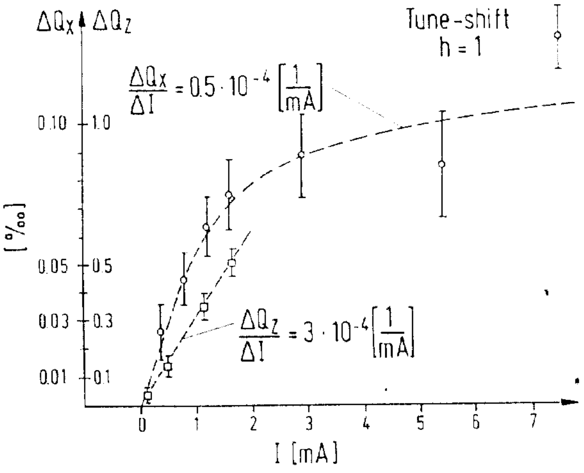


Fig.8: Tune shifts in single bunch operation

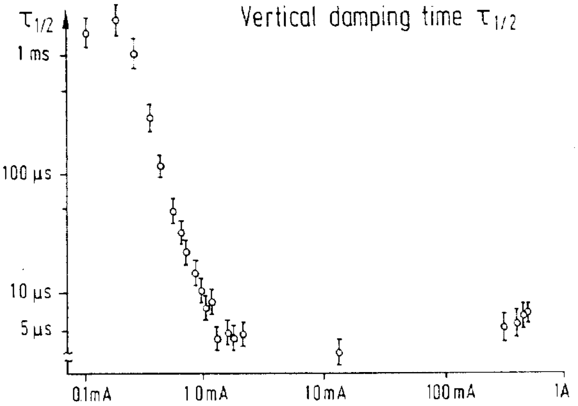


Fig.9: Vertical damping time in multi-bunch operation (h=104)

In all cases we observe a significant broadening of the betatron frequency distributions with increasing beam current (e.g. Δf =1 MHz at 500 mA). A direct measurement of the vertical damping time of coherent betatron oscillations (fig.8) also shows a strong decrease in damping time when the current is increased from 0.1 to 1 mA. It is not yet possible to relate the experimental tune spread and damping time results in a consistent quantitative way. Nevertheless, we think that, although the present data are still preliminary, the qualitative picture of Landau damping induced by the non-linear fields of the ion distribution may explain the absence of transverse coherent oscillations.

References

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