# EXPERIMENTAL OBSERVATION OF SPACE CHARGE EFFECTS IN TRANSVERSE BUNCH OSCILLATIONS IN THE SIS18 SYNCHROTRON

Vladimir Kornilov, GSI, Darmstadt, Germany
Oliver Boine-Frankenheim, GSI, Darmstadt, Germany and TU Darmstadt, Germany

## INTRODUCTION

Transverse coherent oscillations of bunches are routinely used in synchrotron or storage ring to measure different ring and beam parameters. The transverse offset of a bunch, averaged over the bunch length, can be recorded every single turn. The spectrum is then concentrated around the base-band $Q_{f0} f_0$, where $Q_{f0}$ is the fractional part of the betatron tune $Q_0$ and $f_0$ is the revolution frequency. Transverse bunch decoherence is a process of a turn-to-turn reduction of the total bunch offset signal after an initial bunch displacement. Incoherent shifts of the particles betatron frequency and of the synchrotron frequency modify the transverse spectrum and the bunch decoherence. We demonstrate that transverse space charge and nonlinear synchrotron oscillations are important to understand the decoherence signals and transverse spectra. Once the spectrum- and decoherence modifications are understood, they can be used to extract useful information about the bunches.

The characteristic space-charge tune shift is

$$\Delta Q_{\rm sc} = \frac{\lambda_0 r_p R}{\gamma^3 \beta^2 \varepsilon_\perp} , \qquad (1)$$

where $R$ is the ring radius, $r_p = q_{\rm ion}^2/(4\pi\epsilon_0 mc^2)$ is the classical particle radius, $\lambda_0$ is the peak line density, and $\varepsilon_\perp$ is the transverse total emittance. This tune shift corresponds to a transverse K-V distribution and is defined as the modulus of the negative shift. In a rms-equivalent bunch with the Gaussian transverse profile the maximum space-charge tune shift is $\Delta Q_{\rm sc}^{\rm max} = 2\Delta Q_{\rm sc}$. In the case of an elliptic transverse cross-section with the rms emittances $\varepsilon_y, \varepsilon_x$, the parameter $\varepsilon_\perp$ in Eq. (1) should be replaced by $\varepsilon_\perp = 2(\varepsilon_y + \sqrt{\varepsilon_y \varepsilon_x Q_{0y}/Q_{0x}})$, here for the vertical ($y$) plane. The parameter for the effect of space charge in a bunch is defined as $q = \Delta Q_{\rm sc}/Q_{s0}$, $Q_{s0}$ is the small-amplitude synchrotron tune.

## PHYSICAL MODEL

We use particle tracking simulations [1, 2] in order to investigate the combined effect of space charge and nonlinear synchrotron motion on transverse head-tail oscillations. A round transverse cross-section and a Gaussian transverse beam profile were used in the simulations in this work. In order to describe the bunch spectrum for arbitrary bunch length and space charge strength, simulation scans over different parameters have been performed. We suggest that the airbag bunch model [3] can be applied to the head-tail modes in a long Gaussian bunch,

$$\frac{\Delta Q_k}{Q_{s0}} = -\frac{q}{2} \pm \sqrt{\frac{q^2}{4} + k^2 q_*^2} , \qquad (2)$$

where $q_* = Q_{s*}/Q_{s0}$ is a characteristic parameter depending on the bunch length and the nonlinear synchrotron oscillations. In our case $q_*$ is used as a fitting parameter. Simulation results for practical usage are presented in Fig. 1, where $\sigma_z = L_{\rm rms} h/R$. These $q_*$ values can be included in Eq. (2) in order to estimate the space charge tune shift of the bunch eigenfrequencies for a given bunch length.

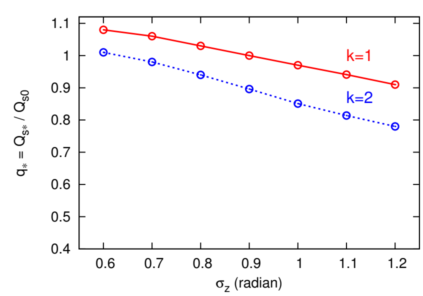


Figure 1: Summary of the simulation scans for the effect of the bunch length on the eigenfrequencies of the head-tail modes $k = 1$ and $k = 2$ with space charge.

In the case without collective effects and without rf nonlinearities the bunch transverse oscillation amplitude decreases (decoherence) after a rigid kick, and appears again after $N_{\rm s} = 1/Q_{\rm s}$ turns (recoherence). Transverse space charge causes a betatron frequency shift, which depends on the particle transverse amplitude and on the longitudinal particle position in the bunch. The decoherence behaviour is thus very different from the linear decoherence. Figure 2 shows examples of the bunch oscillations after a rigid kick for three different values of the space-charge parameter. After the transition period of higher-order mode damping, the periodicity always corresponds to the frequency difference $\Delta Q = Q_{k=1} - Q_{k=0}$. Top plot: $q = 7, \Delta Q_{k=1} = 0.13\, Q_{s0}$ (periodicity 770 turns), middle plot: $q = 12, \Delta Q_{k=1} = 0.079\, Q_{s0}$ (periodicity 1270 turns), and for the bottom plot $q = 16, \Delta Q_{k=1} = 0.061\, Q_{s0}$ (periodicity 1640 turns). The low-intensity recoherence would have a periodicity of 100 turns for the same parameters ($Q_{s0} = 0.01$).

The key in understanding of the decoherence for a bunch with transverse space charge is the representation of the initial kick as a superposition of the bunch head-tail eigen-


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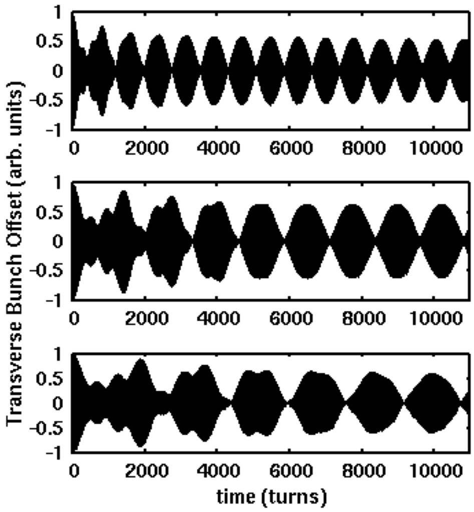


Figure 2: Transverse bunch decoherence from particle tracking simulations for a Gaussian bunch after a rigid kick.

modes, $A_0 = \sum_k a_k \exp\left(-i\frac{\chi_b \tau}{\tau_b} + i\phi_k\right)\overline{x}_k(\tau)$. The second key is the fact that the different eigenmodes are prone to Landau damping mechanisms, but with different intensity thresholds and damping rates. Landau damping due to the space charge tune spread along the bunch [4, 5, 6] is the most important mechanism in the beam parameter regime considered in the simulations of this work. In the presence of space charge especially the negative and the high-$k$ eigenmodes present in the initial kick are quickly suppressed, so that after a transition period a mixture of the survived eigenmodes continues to oscillate.

## EXPERIMENTAL RESULTS

Transverse decoherence experiments have been performed in the heavy ion synchrotron SIS18 at GSI Darmstadt. Bunches of $\mathrm{Ar}^{18+}_{40}$ ions were stored at the energy of 100 MeV/u, with $h = 4$, and kicked transversally with a kick duration of one turn. The Beam Position Monitors (BPMs) provide a higher quality signal in the vertical plane than in the horizontal one due to a smaller plate gap, thus we use the vertical BPM signals in the results presented here. The vertical bare tune was around $Q_0 = 4.31$ although it could vary for different intensities and machine parameters. SIS18 general parameters are: $R = 34.492$ m, $\gamma_t = 5.45$, $\xi \approx -1.4$.

For the first example of our decoherence measurements, Fig. 3 shows the turn-per-turn transverse bunch offset after the kick, and Fig. 4 demonstrates the spectrum of these bunch oscillations, the frequency on the horizontal axis is normalized by the bare synchrotron tune. The red line is for the spectrum of the whole bunch and shows mainly peaks of two modes which we can identify as the $k = 0$ mode and the $k = 2$ mode. If we calculate a Fourier transform for the bunch head, its spectrum (the blue line) clearly reveals other peaks, so that we can identify five head-tail modes, see Fig. 4. The spectrum is very different from the case without collective effects: the lines are not equidistant, the negative-modes ($k < 0$) are suppressed. The fact that the mode tune shifts are consistent with the space-charge model can be proved by calculating the space charge parameter,

$$q = \frac{k^2 q_*^2 - (\Delta Q_k / Q_{s0})^2}{\Delta Q_k / Q_{s0}} \,, \tag{3}$$

which corresponds to the model Eq. (2). The synchrotron oscillation parameter $q_*$ for the modes $k = 1$ and $k = 2$ is obtained from the results given in Fig. 1. $\Delta Q_k$ is the tune shift of the bunch mode from the measured spectrum. We summarize the space charge parameters $q$ obtained from the different eigenfrequencies of the spectra in Fig. 5. The values for the modes from Fig. 4 are shown in Fig. 5 with the blue circles, $q \approx 10$. Since this was a rather short bunch, $\sigma_z = 0.66$, the $q_*$-parameter was close to 1.0 and thus it was possible to estimate the space charge parameter for the $k = 3$ mode as well.

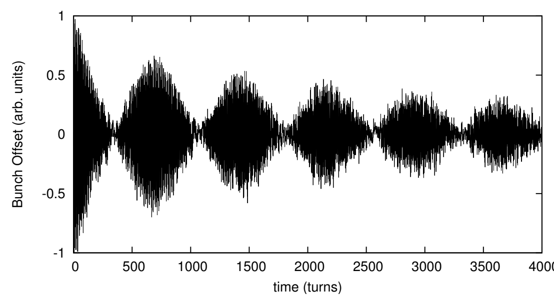


Figure 3: Time evolution of the bunch offset in the vertical plane at SIS18 after a transverse kick. The recoherence periodicity corresponds to the mix of the dominating head-tail modes $k = 0$ and $k = 2$ with $\Delta Q_{k=2} = 1.35 \times 10^{-3}$, giving the periodicity of 740 turns.

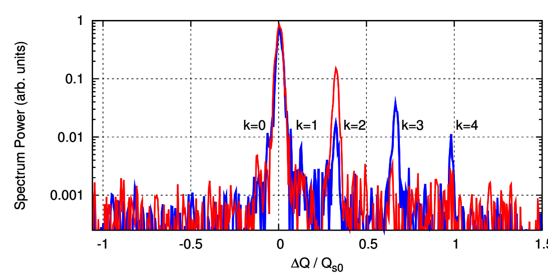


Figure 4: Transverse coherent spectrum for the bunch from Fig. 3, $Q_{s0} = 4.0 \times 10^{-3}$.

Figure 5 demonstrates a certain consistency between different head-tail modes for the space charge parameter, that, however, can not be expected perfect. The model Eq. (2) is based on the airbag [3] bunch which is a reasonable, but still an approximation for a Gaussian bunch [6]. The bunch spectra are also weakly affected by the facility impedances, image charges and nonlinear field components neglected in our analysis. Finally, in our simulations Gaussian bunch



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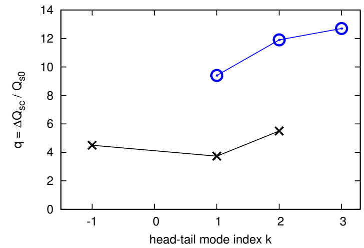


Figure 5: The space charge parameter determined from the coherent head-tail spectra of bunched beams in SIS18. Blue circles: Fig. 4; black crosses: Fig. 7.

profiles in the transverse and in the longitudinal plane have been assumed. It is a good, but not exact description for the bunches in the machine experiments.

In the second example we demonstrate a longer bunch ($\sigma_z = 1.2$), the decoherence is dominated by a mixture of the $k = 0$ mode with the $k = 1$ mode; the bunch oscillations are shown in Fig. 6, the spectrum is shown in Fig. 7. The horizontal chromaticity was partly compensated, by a half of the natural value, the associated nonlinearities probably contributed to establishing of the longer bunch and to a stronger damping of the $k = 2$ mode. The recoherence is thus quite slower, nearly one and a half thousand turns, which is given by the frequency of the $k = 1$ mode in a good agreement with the bunch spectrum. Another outstanding feature of this spectrum is the clear presence of the $k = -1$ mode, with the frequency shifted strongly downwards in a very good agreement with the space-charge model, see black crosses in Fig. 5. In part, the presence of the $k = -1$ mode was probably possible due to rather moderate space charge $q \approx 4.5$ in this case.

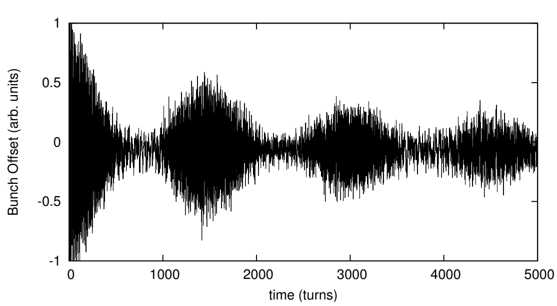


Figure 6: The bunch offset in SIS18 after a transverse kick. The recoherence periodicity corresponds to the mix of $k = 0$ and $k = 1$ with $\Delta Q_{k=1} = 0.68 \times 10^{-3}$, giving the periodicity of 1470 turns.

The space-charge parameter $q = \Delta Q_{\rm sc}/Q_{s0}$ can be additionally estimated using Eq. (1) and the measured bunch parameters. The particle number and the bunch length could be measured with a reasonable accuracy. The transverse beam radius, which enters the space-charge tune shift as squared ($\varepsilon_y = a_y^2 Q_{0y}/R$, $a_y$ is the vertical rms radius) and is thus especially important, could not be determined with a satisfactory precision, as it was also the case in the

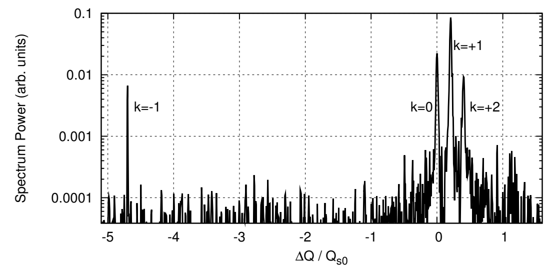


Figure 7: Transverse coherent spectrum for the bunch from Fig. 6, $Q_{s0} = 3.24 \times 10^{-3}$.

previous coasting-beam measurements [7] at SIS18. An estimation for the bunch presented in Figs. 3, 4: the transverse rms emittances were $\epsilon_y = 6.2\times10^{-3}$ mm mrad, $\epsilon_x = 8.4\times10^{-3}$ mm rad, number of ions per bunch was $5.1\times10^9$. Using these parameters and the rest of parameters, we obtain from Eq. (1) $q_{\rm est} \approx 7$. The bunch from Figs. 6, 7: $\epsilon_y = 5.5\times10^{-3}$ mm mrad, $\epsilon_x = 6.6\times10^{-3}$ mm rad, $4\times10^9$ ions per bunch, Eq. (1) gives $q_{\rm est} \approx 4.8$.

## CONCLUSIONS

The transverse decoherence and coherent eigenspectra in long bunches with space charge have been studied using measurements at the SIS18 heavy-ion synchrotron and particle tracking simulations. A model Eq. (2) for the combined effect of space charge and nonlinear synchrotron oscillations has been formulated, with the fitting parameter $q_*$ obtained from the particle tracking simulations for the low-order head-tail modes.

The transverse decoherence in bunches with space charge has been observed experimentally and quantitively explained, using simulations and analytic models. The space charge parameter $q$ has been determined from the bunch spectra for different head-tail modes, Fig. 5. With increasing bunch length we observe that nonlinear synchrotron oscillations modify the head-tail mode frequencies. The bunch decoherence always corresponded to the mix of the dominating modes, in our case the $k = 0$ and $k = 1$ modes or the $k = 0$ and $k = 2$ modes.

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