INTENSE HEAVY-ION BUNCHES IN DUAL-HARMONIC RF SYSTEMS*

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Abstract

For the synchrotron's SIS-18 and SIS-100 (FAIR) a dual-harmonic RF system with the harmonic numbers $h_1 = 2$, $h_2 = 4$ and $h_1 = 10$, $h_2 = 20$ respectively is planned. Such systems flatten the bunch form and increase the bunching factor B_f therefore reducing the transverse space charge force. For high currents cavity beam loading and potential-well distortion will deform the flattened bunch shape and lead to phase shifts. Optimized settings for the difference between the two RF phases and for the synchronous phase of the main RF harmonic is an option to reduce these effects. In this contribution we will analyse the effect of optimized RF voltage amplitude settings to the matched bunch distribution in a dual-harmonic system for SIS-100 parameters and its influence to the optimized phase difference.

INTRODUCTION

Different waveforms and the stability of coherent synchrotron oscillations of Gaussian heavy ion distributions under space charge (SC) are described in [1] and [2]. There is shown that it reduces the RF voltage amplitude below transition energy and that it leads to loss of Landau damping. It is shown that beam loading (BL) caused by the real part of the impedance of the RF cavities can deform bunch shapes by energy loss to wake fields. This slows down the ions so that they center oneself at the back of the distribution.

The resistive part of any impedance in the synchrotron is responsible for the losses leading to phase shift and bunch form deformation by potential-well distortion (PWD) [3] both in single and dual-harmonic RF systems. This adds up to the BL of the RF cavities in the synchrotron SIS-100. The phase shift and beam distribution deformation can be described by the Haissinski equation [3] for Gaussian longitudinal ion distributions. The phase shift of a single harmonic RF system can be corrected by giving the RF voltage a synchronous phase Φ_{S1} as during acceleration. The beam distribution deformation cannot be corrected; it yet increases because of the accelerating bucket form.

This proceeding will concentrate on the description of the correction of phase shift and bunch form deformation caused by PWD in dual-harmonic RF systems. In [4] has been shown that for quality factors above about Q = 0.4 it is necessary to find an alternative method like an additional small RF voltage [3] or dual-harmonic RF systems with $\alpha \neq 0.5$. Here the behaviour of the α-factor and the connected correcting phases over the quality factor Q below

transition energy has been investigated also in comparison with the results for a constant α-factor.

PHASE SHIFT- AND BUNCH FORM DEFORMATION CORRECTION

For correcting phase shift and bunch form deformation a dual-harmonic RF system has to be applied as described by equation 1 where $\alpha = \frac{V2}{V1}$ and $\frac{h_2}{h_1} = 2$. V_1 and V_2 are the RF voltage amplitudes and h_1 and h_2 are their harmonic numbers. It reduces the SC effect by ion bunch flattening and increasing of B_f and makes it possible to countervail for the ion beam distribution deformation by adjusting the right phase difference between main and second RF harmonic $\Delta\Phi$ [4] as long as the quality factor Q of the impedance is low (broadband impedance). The phase shift correction is done as in a single harmonic RF system by adjusting the synchronous phase Φ_{S1} to the main harmonic.

$$V_{RF} = V_1(sin\Phi - sin\Phi_{S1} - \alpha(sin(\Phi_{S2} + \frac{h_2}{h_1}(\Phi - \Phi_{S1}) + \Delta\Phi) - sin\Phi_{S2}))$$

$$\Delta\Phi = \Phi_2 - \Phi_{S2} - \frac{h_2}{h_1}(\Phi - \Phi_S) \qquad (1)$$

In Figure 1 the red dashed curve shows the dual-harmonic beam distribution without PWD and SC impedance X_{SC} (defined in [5]) with the 1σ-bunch length of the main harmonic of 0.7 rad at injection energy (200 MeV/u) with $\alpha = 0.5$. The blue curve gives an example for an U^{28+} beam distribution deformation with the quality factor of the impedance Q = 0.1. Only PWD was observed with $N_b = 7.5 \times 10^9$ ions. Only PWD means that it was supposed that $X_{SC} = 0$. The beam interacts with the shunt impedance R_{Sh} of the longitudinal part of the resistive impedance (equation 2; ω_{RF}: resonance frequency of the impedance). The black line shows the result of the analytical solution for the slope at the potential free area of the dual-harmonic RF system using equation 3. It can be derived from the reduced Haissinski equation for the potential free region in a barrier bucket RF system because the potential free region in a dual-harmonic system is similar to this.

$$Z_{Sh||} = \frac{R_{Sh}}{1 + iQ(\frac{\omega}{\omega_{RF}} - \frac{\omega_{RF}}{\omega})} \qquad (2)$$

$$Z_{Sum||} = Z_{Sh||} - iX_{SC}$$

$$\lambda_\tau = \frac{\lambda_0}{1 + \alpha_R N_b \lambda_0 \tau}$$

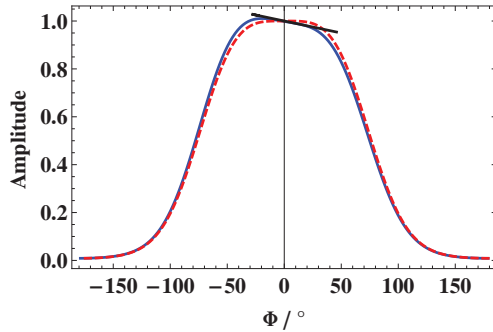$$\alpha_R = \frac{e^2 \beta^2 E_0 R_S}{\eta T_0 \sigma_E^2} \tag{3}$$

Figure 1: U^{28+} distribution in SIS-100 without (dashed red) and with (blue) PWD for Q = 0.1 and analytically determined slope (black) with $N_b = 7.5 \times 10^9$ ions.

For higher ion intensities the further evaluation of the bunch form distribution deformation was shown in [4]. For higher quality factors $Q > 0.4$ no phase shift correction by adjusting only the synchronous phase of the first harmonic is possible any more. With quality factors $Q > 1.0$ phase shift corrections are possible again but for $\alpha = 0.5$ no flattened bunch form is reachable as can be seen in Figure 2. In Figure 3 it can be seen that α has to be changed in addition to the synchronous phase Φ_{S1}. In Figure 4 and Figure 5 for $N_b = 9.3 \times 10^{10}$ it is shown that for $\alpha = 0.58$ and about the same correcting phases to the $\alpha = 0.5$ case the bunch form can be flattened again and the phase shift is compensated.
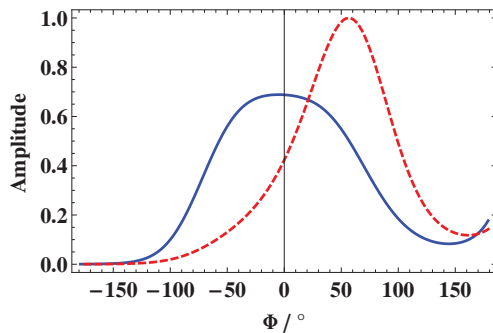

Figure 2: Bunch form of a U^{28+} distribution with $N_b = 9.3 \times 10^{10}$ ions, Q = 15 and $\alpha = 0.5$.

QUALITY FACTOR Q AND INTENSITY DEPENDENCY OF THE CORRECTION

As an example it is demonstrated that with variable α (α var) the absolute values of the phase difference $\Delta\Phi$ and synchronous phase Φ_{S1} for Q = 0.1 must be higher as for $\alpha = 0.5 =$ const. to correct bunch form deformations and
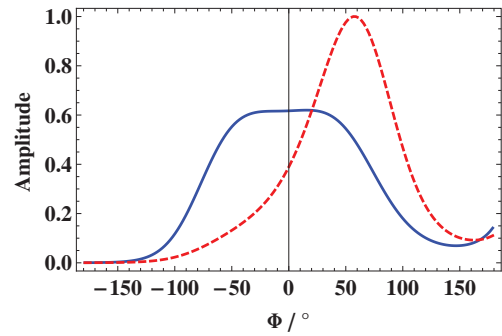
Figure 3: Bunch form of a U^{28+} distribution with $N_b = 9.3 \times 10^{10}$ ions, Q = 15 and $\alpha = 0.58$.

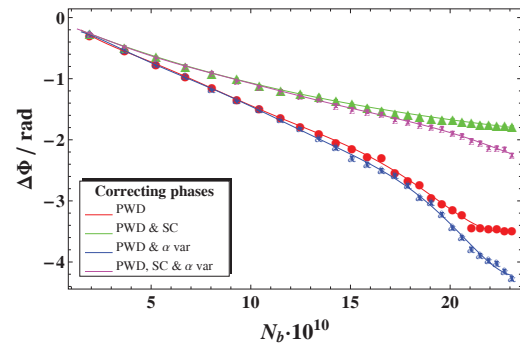phase shifts caused by PWD and BL as is shown in Figure 4 and Figure 5.

Figure 4: Development of the phase difference $\Delta\Phi$ between the two RF harmonics to correct for bunch form deformation over U^{28+} intensity for Q = 0.1. The solid lines are the polynomial fits of seventh order.
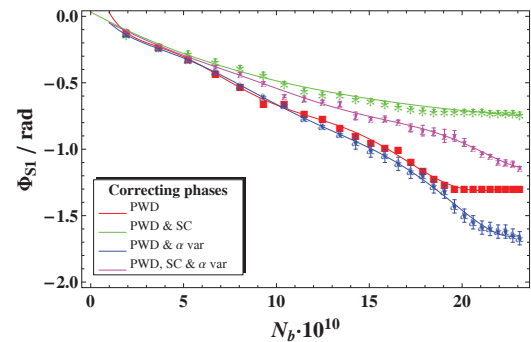

Figure 5: Development of the synchronous phase Φ_{S1} for phase shift corrections of the first RF harmonic over U^{28+} intensity for Q = 0.1. The solid lines are the polynomial fits of seventh order.

For quality factors $Q \geq 0.1$ the change of the α-factor for the beam deformation correction is intensity dependent like for the correcting phases. The voltage amplitude relationship α increases for increasing intensity. The development of α can be fitted by a polynomial of seventh order. For $X_{SC} = 0$ there is a reversal point in the development of α

over the quality factor Q. α increases with increasing intensity and with decreasing quality factor Q till Q = 0.6. Then α decreases with further decreasing quality factor. With Q $\lesssim$ 0.1 the value α = 0.5 = const. over the intensity. This can be seen in Figure 6. For $X_{SC} \neq 0$ there is no reversal point. With decreasing Q the value of α decreases against the limit value α = 0.5 over the whole intensity range as can be seen in Figure 7.
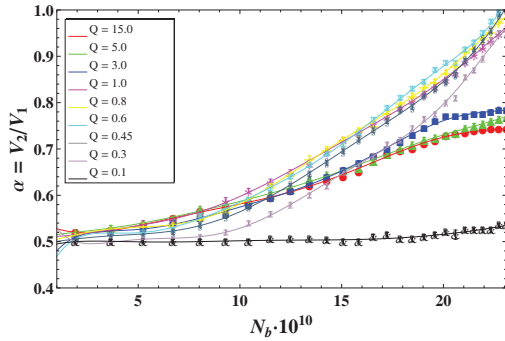

Figure 6: Development of α over the U^{28+} intensity with $X_{SC} = 0$. Q = 0.6 is a reversal point for the development of α over Q as explained in the text. The solid lines are the polynomial fits of seventh order.
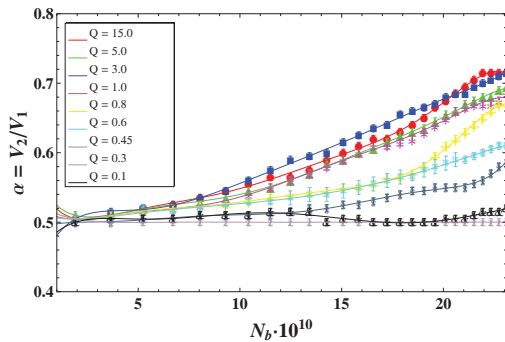

Figure 7: Development of α over the U^{28+} intensity with $X_{SC} \neq 0$. Here is no reversal point in the α development over Q. The solid lines are the polynomial fits of seventh order.

As can be seen in Figure 8 and Figure 9 the phases $\Delta\Phi$ and Φ_{S1} decrease with decreasing Q. Their absolute values increase with increasing intensity N_b. Including the SC impedance the correcting phases decrease compared to the shown curves. These figures are not shown here.

CONCLUSION

Bunch form deformation and phase shift are correctable below $Q < 0.45$ if α = 0.5 = const. With α changing over intensity from $0.5 \leq Q \leq 1.0$ they are correctable for every quality factor Q. These corrections decrease the RF voltage amplitude as the SC impedance itself. Therefore the necessity for the correction should be avoided which means that the real part impedance has to be as low as possible.
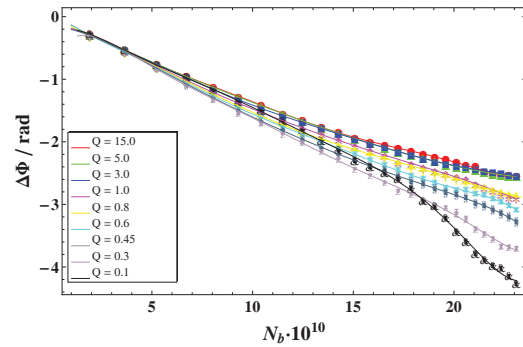

Figure 8: Development of the phase difference $\Delta\Phi$ between the two RF harmonics to correct for bunch form deformation over U^{28+} intensity for different quality factors Q. The solid lines are the polynomial fits of seventh order.
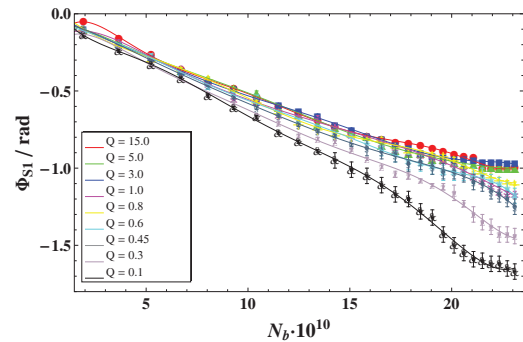

Figure 9: Development of the synchronous phase Φ_{S1} for phase shift corrections of the first RF harmonic over U^{28+} intensity for different quality factors Q. The solid lines are the polynomial fits of seventh order.

But this increases the power requirements for the cavities and therefore their costs. SC itself simplifies the corrections because it lengthens the ion distribution and therefore reduces BL and PWD. Curves for these corrections can be given for control systems but they are SC and quality factor Q dependent. So both values have to be known to choose the right curves.

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