INTENSITY THRESHOLDS FOR TRANSVERSE COHERENT INSTABILITIES DURING PROTON AND HEAVY-ION OPERATION IN SIS100

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INTRODUCTION

The SIS100 synchrotron is the central accelerator of the projected FAIR complex [1]. It should deliver high intensity proton and heavy-ion beams to the different FAIR experiments. Coherent transverse instabilities are a potential intensity-limiting factor in SIS100. In this contribution we give a summary of the different transverse coherent effects in intense bunched beams that can be expected in the SIS100. The weak head-tail instability is a major concern for the heavy-ion operation. We suggest that for the proton bunches it is different and the beam break-up instability should be considered, where a coasting-beam approach may be used for stability estimations. In order to support the applicability of this method for the beam parameters of our interest, particle tracking simulations are employed. The term "beam break-up" had been adopted from the linear accelerators despite the fact that in a linear system there is no reinforcing instability mechanism due to the lack of synchrotron oscillations. As we discuss here, this plays an important role in the similar instability is a synchrotron. Space charge is an important effect that, on the one hand, leads to the loss of Landau damping for a coasting beam, and on the other hand provides Landau damping of the head-tail eigenmodes.

COASTING-BEAM ESTIMATION

Within the coasting-beam approach we relate a part of a bunch with the current I_0 to the stability of a coasting beam with the same current and other characteristics, as the rms momentum spread $\delta_p = \delta p/p$. In a coasting beam, an impedance provides the complex tune shift

$$\Delta Q_{\rm coh} = \frac{I_0 q_{\rm ion}}{4\pi\gamma m c Q_0 \omega_0} i Z^{\perp}_{\rm ext} \,, \qquad (1)$$

where Q_0 is the bare betatron tune, m and $q_{\rm ion}$ are the mass and the charge of the beam particles and ω_0 is the revolution frequency. Hence, a real impedance provides an instability increment. The unstable spectrum in a coasting beam consists of the slow waves $f = (n - Q_0)f_0$, Landau damping due to the momentum spread is described by the chromaticity tune spread

$$\delta Q_\xi = |\eta(n - Q_0) + Q_0\xi|\, \delta_p \,, \qquad (2)$$

where $\xi = d\ln Q/d\ln p$ is the chromaticity and $\eta = -d\ln f_0/d\ln p$ is the slip factor. Coherent tune shifts which are still stabilized by the Landau damping can be presented using a stability diagram, Fig. 1.

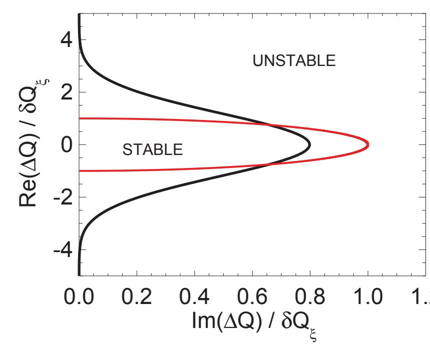

Figure 1: Stability diagram for a coasting beam. The black line: solution of the dispersion relation [2] for a Gaussian momentum distribution. The red line: the circle criterion $|\Delta Q|/\delta Q_\xi = 1$ [3].

A shift of the incoherent betatron tune due to space charge moves the incoherent spread away from the coherent frequency, which manifests in a shift of the stability curve downwards by $\Delta Q_{\rm sc}/\delta Q_\xi$. A beam can then get out of the stable area, the so-called loss of Landau damping. The characteristic space-charge tune shift $\Delta Q_{\rm sc}$ [4] corresponds to a transverse K-V distribution, in a rms-equivalent bunch with the Gaussian transverse profile the maximum space-charge tune shift is twice of this value, $\Delta Q^{\rm max}_{\rm sc} = 2\Delta Q_{\rm sc}$. A nonlinearity in space charge can improve stability properties [5], examples for SIS100 beams are given in [6]. In this work the accuracy of the estimations requires only the first-order, linear space charge effect.

COHERENT STABILITY ANALYSIS

In our beam stability analysis we examine three bunch settings for the proton operation and two Uranium bunches. The parameters related to the transverse beam dynamics are listed in Table 1. During the proton accumulation at the injection energy, four bunches are stored for up to 1 sec. After multistage bunch merging, one bunch is formed and after $\approx$ 0.2 sec the acceleration starts. In the third scenario we consider the longitudinally shrunk proton bunch at the top energy. For the heavy-ion operation we consider one of the eight bunches during the accumulation (up to 1 sec) at the injection energy and the long "sausage" bunch with the barrier bucket at the top energy before compression.

Two main components of the SIS100 transverse impedance considered here are the Resistive-Wall impedance [7] of the SIS100 elliptical pipe, and the Broad-

Table 1: Overview of the SIS100 bunch parameters relevant for the vertical coherent stability as estimated for the Broad-Band Impedance (BB) and for the Resistive-Wall Impedance (RW) using the coasting-beam approach. For BB: $\Delta Q_{\rm cb}/\delta Q_\xi < 0.2$ and $\Delta Q_{\rm sc}/\delta Q_\xi < 0.5$ for all bunches. For RW: $\Delta Q_{\rm cb}/\delta Q_\xi < 0.5$ for all bunches.

	p^+ accumulation	p^+ before accel	p^+ top energy	U^{28+} injection	U^{28+} top energy
N_p per bunch	5e12	2e13	2e13	6.25e10	5e11
t_b	144 ns	442 ns	50 ns	342 ns	2600 ns
Q_s	4.9e-4	3.5e-4	6.3e-5	4.3e-3	
$q = \Delta Q_{\rm sc}/Q_s$	130	240	300	36	
Q_ξ, $\Delta Q_{\rm ht}$	616 , 25	616 , 8	4e4 , 72	33 , 19	
BB: $\Delta Q_{\rm cb}/Q_s$	10	18	140	0.13	
BB: $2n_{bb}$	290	900	100	700	
RW: $\Delta Q_{\rm cb}/Q_s$	2	30	4	head-tail	
RW: $\Delta Q_{\rm sc}/\delta Q_\xi$	3.7	2.3	0.3		2.2

Band impedance. Due to the lack of the corresponding impedance model for SIS100 at the moment, we adopt the results of the Broad-Band resonator measured [8] at the CERN PS synchrotron, which is a “similar” machine to SIS100. Hence, we assume $Q_{\rm T} = 1$, $f_r = 1$ GHz and $R_{\rm T} = 3\,{\rm M}\Omega/{\rm m}$. The beam break-up instability driven by this impedance has been repeatedly observed in PS [9].

For the SIS100 bunches the space-charge parameter values $q = \Delta Q_{\rm sc}/Q_s \gg 1$ which implies strong space charge. The chromatic frequency $Q_\xi = Q_0\xi/\eta$ is the position of the power spectrum of the $k = 0$ bunch eigenmode. The distance between the neighbor modes can be estimated [10] as $\Delta Q_{\rm ht} = 1/(f_0 t_b)$. We can conclude that the weak head-tail instability is not a danger for the proton bunches, since only the very high-order modes can couple to the RW-impedance, for example $k \sim 25$ for the proton bunch at the accumulations. The proton bunches are long regarding to the head-tail modes and their distance to the impedance in the spectrum. On the contrary, the Uranium bunch at the injection is short enough for the lower-order head-tail modes to couple to the RW-impedance. The mode with the largest growth rate is the $k = 4$ mode with the growth time of ≈ 200 ms. Interpolation of the results in [4] suggests that the mode $k = 4$ should be significantly stabilized by the Landau damping due to space charge only at $q \lesssim 14$, which is well below the nominal $q = 36$. Further studies are needed to solve the stability problem for this bunch, usage of the octupole magnets is an option.

The estimations for the BB-impedance are based on the Eq. (1) with the impedance parameters discussed above. $\Delta Q_{\rm cb}$ is the imaginary tune shift provided by the peak real impedance. The parameter $\Delta Q_{\rm cb}/Q_s$ shows that the instability is always faster than the synchrotron oscillations in the proton operation. The growth rate should also be compared with the characteristic frequency of particle sweeping through the instability wiggles in the bunch $2n_{bb} = 2f_r t_b$. Here we see that the latter is larger at the injection, which means that the synchrotron oscillations should partly decrease the instability growth rate. The instability is then not a pure beam break-up, it is affected by the synchrotron oscillations. At the top energy the instability is faster than $2n_{bb}Q_s$. The Landau damping mechanism is characterized by the chromatic tune spread Eq. (2) with the mode index $n = f_r/f_0$. According to $\Delta Q_{\rm cb}/Q_\xi$ for the BB-impedance the bunches are well within the stable area, compare Fig. 1. The space-charge tune shift should not cause the loss of Landau damping. In the case of the ion bunches the parameters are given to emphasize the dominant role of the synchrotron dynamics for the bunch at the injection; at the top energy the BB-impedance should not cause instability.

The instability under the RW-impedance is estimated under the assumption that the longitudinal wave length is equal to the bunch length, or n is equal to the integer just above the tune for longer bunches. First take a look at the proton operation. The beam break-up instability for all three bunches should be faster than the synchrotron oscillations, and it is also faster than the particle sweeping across the mode pattern, $2n_{rw} = 2$ in this case. The shift due to space charge is safe for the proton bunches before acceleration and at the top energy, but it is critical at the accumulation. The nonlinearity in space charge may have a stabilizing contribution. On the other hand, the coasting-beam estimation for the RW-impedance may be not accurate enough for a detailed prediction of the Landau damping. This should be clarified in further dedicated simulations. To some extent this is also true for the heavy-ion bunch at the top energy, with a difference that the space-charge tune shift is smaller and the coasting-beam estimation for a long barrier ($n_{rw} = 12$) seems to be more adequate than for a short bunch with $n_{rw} = 1$.

BEAM BREAK-UP SIMULATIONS

We use particle tracking simulations [11, 12] in order to investigate the thresholds of the beam break-up insta-

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bility. For this, we consider a bunch with the parameters similar to the SIS100 proton operation. In order to avoid a very high longitudinal resolution we apply a BB-impedance at 0.1 GHz, but the bunch is still long relating to the impedance and to the head-tail modes, $2n_{bb} = 30$, $Q_\xi = 280$, $\Delta Q_{\rm ht} = 24$. The instability growth rate for increasing beam intensity is presented in Fig. 2. The space-charge effect is not taken into account here. The imaginary tune shift $\Delta Q_{\rm cb}$ is given by Eq. (1), while Im(ΔQ) is the simulation result. Two cases are compared, the difference is given only by Q_s which means different δ_p, the corresponding Landau damping parameters δQ_ξ are indicated. Figure 3 shows results of simulations with the RW-impedance, here we compare two different chromaticity values, keeping the rest of parameters fixed. In both cases we observe a threshold intensity for a fast instability [Im(ΔQ) $>$ Q_s], the threshold correlates with the coasting-beam estimation δQ_ξ. With the BB-impedance the instability corresponds to $f_r = 0.1$ GHz, see the blue line in Fig. 4, while under the RW-impedance the instability wave relates to the bunch length, see the red line in Fig. 4. Above the threshold, the instability growth rate increases linearly with the intensity, and the instability is fast (with the BB-impedance Im(ΔQ)/Q_s=10) but the absolute value (Im(ΔQ)/$\Delta Q_{\rm cb}$ ≈0.2) shows the effect of the synchrotron motion ($2n_{bb} = 30$).

The effects of space charge has been studied using simulations with the model of a frozen electric field, i.e. a fixed potential configuration which follows the center of mass

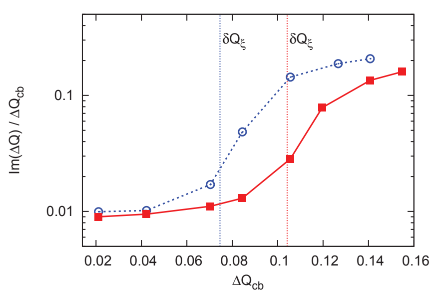

Figure 2: Particle tracking simulations: instability growth rate normalized by the coasting-beam estimation for the BB-impedance. δQ_ξ [Eq. (2)] is indicated by the corresponding colors. Blue: Q_s=2.5e-3; red: Q_s =3.5e-3.

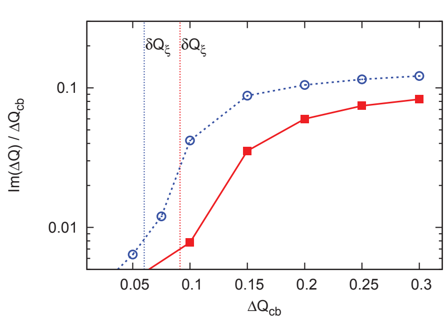

Figure 3: Simulation for the RW-impedance, Q_s=2.5e-3. Blue: $\xi = -1$; red: $\xi = -1.5$.

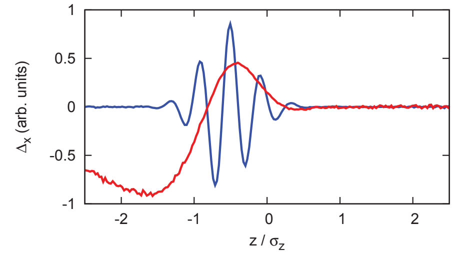

Figure 4: Typical bunch offset traces in the simulations for a beam break-up instability caused by the BB-impedance (the blue curve) and by the RW-impedance (the red curve).

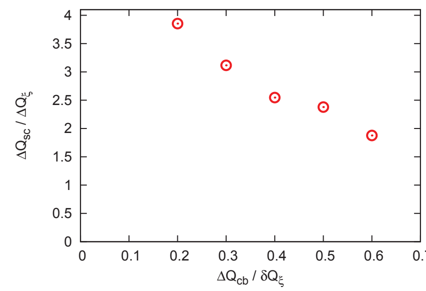

Figure 5: The threshold in the space-charge tune shift for the beam break-up instability as a function of the imaginary tune shift Eq. (1) provided by the BB-impedance.

for each bunch slice. This model is not adequate for the purpose of a detailed instability description, because under the beam break-up instability the transverse beam size changes. But, it may give a reasonable estimation for the instability threshold. The beam profiles are Gaussian longitudinally and transversally. Figure 5 shows the results of our simulation scans for the beam break-up instability under space charge. For each intensity (represented by $\Delta Q_{\rm cb}$) we perform simulations with the increasing space-charge tune shift $\Delta Q_{\rm sc}$ until the instability is triggered. We preliminary conclude that the effect of space charge on Landau damping is in a reasonable agreement to the coasting-beam model in its intensity dependence and in the absolute values for the space-charge tune shift.

REFERENCES

[1] FAIR Baseline Tech. Report (2006).

[2] A. Hofmann, CERN 95-06 v.1, p. 275 (1995).

[3] E. Métral, CERN-2005-006, p. 227 (2004).

[4] V. Kornilov and O. Boine-Frankenheim, Phys. Rev. ST Accel. Beams 13 (2010) 114201.

[5] V. Kornilov et al., PRST-AB 11 (2008) 014201.

[6] V. Kornilov et al., Proc. of IPAC2010.

[7] V. Kornilov et al., Acc-Note-2008-006, GSI (2008).

[8] R. Cappi et al., CERN-PS-89-39-PA, CERN (1990).

[9] S. Aumon et al., Proc. of HB2010, p. 681 (2010).

[10] F. Sacherer, CERN-77-13, p. 198 (1976).

[11] O. Boine-Frankenheim, V. Kornilov, Proc. of ICAP2006.

[12] G. Rumolo, F. Zimmermann, PRST-AB 5 (2002) 121002.