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CAVITY IMPEDANCE REDUCTION STRATEGIES DURING MULTI CAVITY OPERATION IN THE SIS100 HIGH INTENSITY HADRON SYNCHROTRON*

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Abstract

The planned SIS100 heavy ion synchrotron at the GSI Helmholtzzentrum für Schwerionenforschung will possess twenty ferrite accelerating cavities in its final stage of extension. As at injection and at flat top during slow extraction of the planned acceleration cycles the RF voltage will be relatively low, not all cavities will be active in this part of operation. It is important to analyse the impact of the inactive cavities on the overall RF voltage and subsequently their implication on the longitudinal particle dynamics. Classical approaches for reducing the beam impedance consist of active detuning of the cavities to pre-described parking frequencies. The fact that two out of ten buckets have to stay empty in all SIS100 scenarios is of particular interest as additional frequency components appear in the excitatory beam current, which have to be considered when the cavity is detuned. Therefore multi-cavity particle tracking simulations, consisting of twenty cavities and their attached LLRF control systems, are carried out in order to analyse different possibilities to minimize the impact on the beam dynamics and emittance growth.

INTRODUCTION

Traditional approaches for handling significant beam current consist of detuning the cavity by shifting the resonance frequency via the eigenfrequency control loop in order to reduce its impedance. This is of particular importance for the planned SIS100 heavy ion synchrotron at GSI as especially during injection and extraction not all ferrite cavities are going to be active. The influence of these idle cavities on the beam quality remained an open question and it is unclear yet if special countermeasures are necessary. The fact that the SIS100 control loops will have to deal with empty buckets which will give rise to transient beam loading is of particular interest as the deployed ferrite cavities possess comparatively low quality factors. By blindly shifting inactive cavities near the arising sidebands one must expect negative impacts on the beam quality.

In the following we will analyze the impact of the resulting sidebands on the overall system dynamics and perform extensive numeric simulations on the impact of the chosen parking frequencies on the beam emittance growth.

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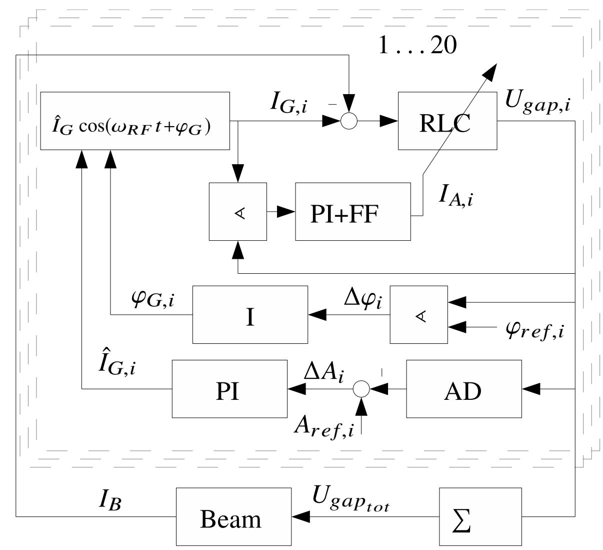

Figure 1: Block diagram of individual cavities with their control loops and beam dynamics.

SYSTEM SETUP: EXAMINED DYNAMICS

The focus of the present investigation lies on the longitudinal beam dynamics of the SIS100 synchrotron while the transversal dynamics are being neglected. Due to the time scale separation of both dynamics, they can be treated as uncoupled in good approximation [1]. Figure 1 shows the overall system under consideration. Each of the in total twenty ferrite acceleration cavities can be well modeled as an ideal lumped parallel RLC-circuit within it's operational range [1]. The underlying differential equation is given by

$$\ddot{U}_{\mathrm{gap},i} + \frac{1}{R_{p,i}C_p}\dot{U}_{\mathrm{gap},i} + \frac{1}{L_{p,i}C_p}U_{\mathrm{gap},i} = \frac{1}{C_p}\frac{d}{dt}\left(I_{G,i} - I_B\right).$$

While the capacitance $C_p = 740\,\mathrm{pF}$ is nearly constant, both the inductance and the resistance show a time varying behavior. The resistance $R_{p,i} \in [2\,\mathrm{k\Omega}, 3\,\mathrm{k\Omega}]$ can be modeled as a nonlinear function depending on the individual gap voltage and resonance frequency, whereas the inductance $L_{p,i}$ is dominated by the bias current given by the resonance frequency control loop [2],[3]. The low level RF (LLRF) control loops consist of the aforementioned resonance control loop given by a PI controller augmented with a feed forward path, the amplitude control loop, which is as well given by a linear PI controller, and finally the cavity synchronization loop which is a simple integral controller. Both the

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amplitude- (AD) and phase-detector (PD) are idealized and modeled by a sine fitting algorithm [4].

The input to each cavity is the generator current $I_{G,i}$ which is a single harmonic RF signal whose amplitude and phase are given as the outputs of the LLRF controls. The total gap voltage, as seen by the beam, is the sum of the twenty gap voltages of each individual cavity, while the beam current acts as a disturbance on the driving signal of each single cavity. Hereby both, cavity and beam dynamics are coupled. Furthermore, also the single cavities are coupled as well. A disturbance in one cavity may influence also the other cavities in the ring through the beam dynamics and its current. Finally the beam dynamics are modeled by a macro particle tracking simulation.

It is important to note, that the LLRF control loops only act on the RF frequency component they are tuned to. In addition they are without further measures not able to actively damp the cavity in the case that the induced gap voltage by the beam is higher than the commanded gap voltage, making cavities running idle especially sensitive to beam loading. Other signal components are only damped by the system dynamic of the cavity, which depends significantly on the quality factor $Q_i = R_{p,i} C_{p,i} \omega_{RES}$.

SIDEBANDS DUE TO EMPTY BUCKETS

Under the assumption that the beam current of a single bunch (SB) can sufficiently precise be modeled by a Gaussian pulse, the Fourier transformed signal of its bunch current can be stated as

$$I_B^{SB}(\omega) = \hat{I}_B \sigma \sqrt{2\pi} \exp\left(\frac{-(\omega\sigma)^2}{2}\right),$$

with $\hat{I}_B$ being the peak current and σ the standard deviation, which usually lies in the interval corresponding to 40 to 60 degrees. By addition of the single bunches to a bunch train (BT) and by sampling with a Dirac comb one obtains the Fourier transformed signal of the whole orbiting bunch train [5]

$$I_B(\omega) = \left[I_B^{SB}(\omega) \cdot \sum_{l=1}^{h} \mu_l \exp\left(-\mathrm{j}\omega l T_{RF}\right) \right] \sum_{k=-\infty}^{\infty} \delta(\omega - k\omega_R).$$

Herein T_{RF} is the RF periodic time, μ_l is either one or zero depending on whether bucket number l is filled or empty and h is the harmonic number specified by $h = T_R/T_{RF}$, with T_R being the revolution time of the whole bunch train.

Figure 2 shows the Fourier coefficients of a revolving bunch train both for the case that all ten buckets are filled and the case that two adjacent out of ten buckets stay empty. Whereas no sidebands occur in the first case (red), it can be observed that with empty buckets (blue) this is no longer the case. Instead, the frequency components only disappear at particular frequencies given by

$$\omega_n = \left(n - \frac{1}{2}\right) \omega_{RF},\ n \in \mathbb{N}_{>0}. \qquad (1)$$

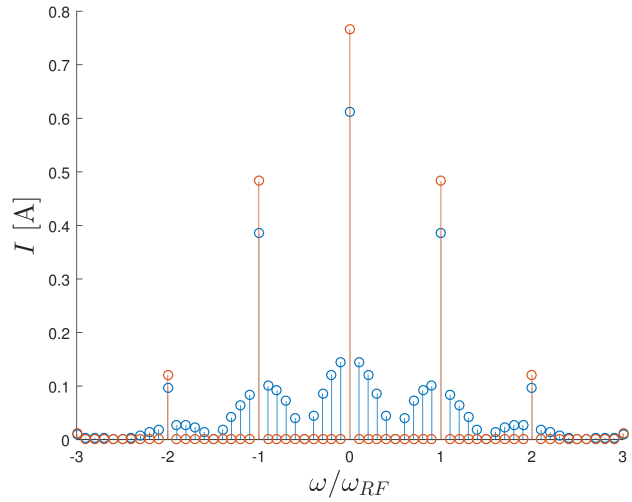

Figure 2: Fourier coefficients of the revolving bunch train in the case of eight of ten filled buckets (blue) and ten out of ten filled buckets (red).

Table 1: Main Cycle Values, Extract from [6]

Parameter	Value	Dimension
ion mass	238.05078	amu
number of ions	5×10^{11}	
injection energy	197.57	MeV/u
extraction energy	2700	MeV/u
RF frequency	1.56 - 2.67	MHz
gap voltage (max)	372.53	kV
synchronous phase (max)	59.28	deg
ramping rate (max)	4	T/s
momentum compaction	0.005	

Due to symmetry this result still holds true, if an even number of buckets stays empty as e.g. during injection. Clearly a detuning strategy of the cavity based on shifting of the resonance frequency has to make sure that no parasitic sideband frequencies are amplified and consequently the frequencies given by (1) are natural candidates as parking frequencies for inactive cavities.

The main difference between the individual frequencies is the slope of the amplitude of the adjacent sidebands. For example a resonance frequency corresponding to ω_3 seems to be very promising from the point of view of beam quality, as the frequency components both to the left and right are relatively low. This fact is of particular interest for a cavity with a low quality factor Q. However, one has to keep in mind that the bias systems of the ferrite cavities do not usually cover such a broad range of frequencies. Therefore practical applications will mainly have to concentrate on ω_1 and ω_2.

SIMULATION OF AN $^{238}U^{28+}$ CYCLE

In order to validate and quantify the previous results, particle tracking simulations of an SIS100 $^{238}U^{28+}$ extremal cycle are performed. The main cycle values are summa-

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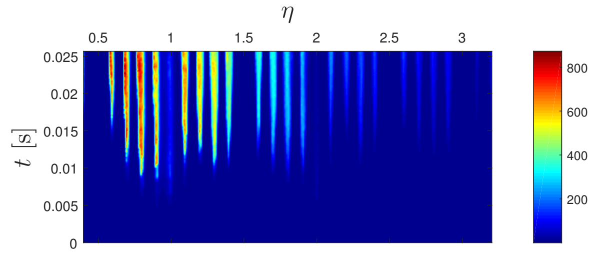

Figure 3: Devolution of the performance measure J in dependence of η and t.

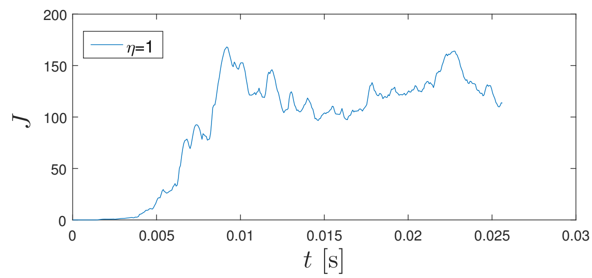

Figure 4: Devolution of J for $\eta = 1$.

rized in Table 1. This particular ramp leads to considerable beam loading, as at injection from SIS18 to SIS100 the beam current has a peak value of about 1.7 A, which increases up to 9 A during acceleration. In the course of the bunch to bucket transfer from SIS18 into the SIS100, the bunches are injected pairwise until eight out of ten are filled. During this phase only two cavities are active, delivering a combined gap voltage of 30.55 kV. As each of the twenty ferrite acceleration cavities will be able to supply a maximum gap voltage of 20 kV, the cavities will be turned on successively until the maximal acceleration voltage of 372.53 kV is reached. For each bucket i the RMS-emittance is calculated by

$$\pi\epsilon_i = \pi\sqrt{\sigma_\tau^2\sigma_W^2 - \sigma_{\tau,W}^2},$$

where τ and W are the canonical conjugate phase space coordinates namely the time and energy deviation of each particle, with respect to the reference particle. Based on the individual emittances of the eight filled buckets, we calculate the following dimensionless performance measure, which corresponds to the maximal emittance increase of the single buckets

$$J(t) = 100 \cdot \left\|\Delta\epsilon_i(t)/\epsilon_i^0\right\|_\infty, \text{ with } \epsilon_i^0 := \epsilon_i(t=0),$$

where $\|\cdot\|_\infty$ denotes the supremum norm. The shifting of the resonance frequency is accomplished by the feed forward path of the resonance control loop, whose dynamics have been neglected. While this is a very restrictive assumption, it allows to determine a theoretical limit of emittance growth when using this impedance reduction strategy. Figure 3 shows the growth of J plotted over the time t and the ratio of the parking frequency ω_p to the RF frequency given by $\eta = \omega_p/\omega_{RF}$. It can be observed, that the side bands

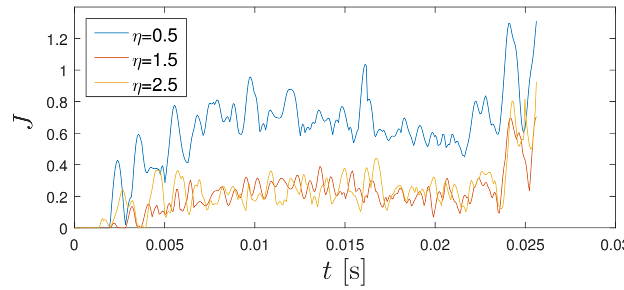

Figure 5: Devolution of J for $\omega_1, \omega_2, \omega_3$.

lead to significant emittance growth, if the inactive cavities are shifted to inadequate frequencies. Additionally the sidebands seem to have a more negative impact on the beam quality, even though their amplitudes are clearly below the integer harmonics. Figure 4 shows the growth of J if the cavities are not detuned, which leads to an unstable beam with an emittance growth of more than 150 percent. The decrease of the RMS-emittance arises due to loss of particles during the injection phase. In contrast the development of J is depicted in Figure 5 for the case that the cavities are tuned to the proposed parking frequencies. The maximal emittance growth stays now below 1.4% despite the high beam current.

CONCLUSION AND OUTLOOK

The existence of empty buckets restricts the degree of freedom on limiting the cavity impedance by detuning to some disjoint particular frequencies. As a consequence the detuning strategy from SIS18 may not be deployed unchanged in SIS100. The presented results are based on the assumption of a Gaussian beam current. Especially during slow extraction this simplification is not justified. Future research will have to focus on validating the planned control architecture during this ramp phase. Feed forward compensation of the beam current might offer a promising endorsement in order to guarantee high beam qualities.

REFERENCES

[1] H. Klingbeil, U. Laier, D. Lens, "Theoretical Foundations of Synchrotron and Storage Ring RF Systems", Springer, 2015.

[2] C. Spies, U. Hartel, M. Glesner, "Dynamics of Ferrite Cavities and their Effect in Longitudinal Dipole Oscillations", proceedings of ICAP2012.

[3] H. König, "Detailed Specification on the SIS100 Acceleration System for FAIR", Tech.rep.GSI, 2013.

[4] P. Händel, "Properties of the IEEE-STD-1057 Four-Parameter Sine Wave Fit Algorithm", IEEE Transactions on Instrumentation and Measurement, Vol.49, No.6, December 2000.

[5] D. Mihailescu-Stoica, D. Domont-Yankulova, D. Lens and H. Klingbeil, "On the impact of empty buckets on the ferrite cavity control loop dynamics in high intensity hadron synchrotrons", IPAC'17, Copenhagen, May 2017.

[6] D. Ondreka, H. Liebermann, "SIS100 Cycles 3.0", Tech. rep. GSI, 2016.