HIGH-INTENSITY EFFECTS IN THE FAIR SYNCHROTRONS

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Abstract

Beam loss and emittance increase due to nonlinear resonances, space charge and coherent instabilities are some of the main concerns for the high-intensity operation of the FAIR synchrotrons. In this contribution we review recent theoretical and experimental results related to high intensity effects in the FAIR synchrotrons and possible cures.

INTRODUCTION

The FAIR synchrotrons, SIS18 and the planned SIS100, will be operated with medium energy, intense heavy ion beams of low momentum spread. In addition intense proton beams for anti-proton production will be accelerated. However, in the present review we will focus on uranium beams. The range of bunch lengths and bunch profiles during a typical cycle covers dc beams, long dc-like bunches in barrier buckets, long bunches in single and in dual rf waves [1]. Before extraction, the bunches are converted into a single, short (50 ns) bunch. The required accumulation times in SIS100 are of the order of 1s. The maximum transverse space charge tune shift ranges from $\Delta Q = -0.25$ during accumulation up to -1 at the end of the fast bunch compression in SIS-100. The large variation in the bunch forms and length together with space charge and impedances effects, acting over long time scales poses a challenge to the estimation of beam loss and instability thresholds.

BEAM LOSS DUE NONLINEAR RESONANCES AND SPACE CHARGE

The fine-tuning of the SIS-100 working point has been undertaken using DA calculations for different scenarios of SIS-100 operations [4]. The DA is defined here as the radius (in normalized coordinates) of the largest circle in-scribed inside the domain of stable initial conditions. For the sake of computer time we are only calculating the short-term DA using 1000 turns. As customary we express the DA in terms of the beam σ, which is defined at injection energy (200 MeV/u) by our reference rms emittance of 12.5 mm mrad (in horizontal plane). The simulations are per-formed within the MICROMAP library developed at GSI, which has been benchmarked for long-term loss with experiments at the CERN Proton synchrotron [3]. For the calculation of the dynamic aperture (DA) in the plane of working points we account for (1) systematic multipoles with error assumptions for super-conducting dipoles, (2) systematic multipoles from quadrupole magnets, (3) misalignment errors of quadrupole magnets to model closed orbit errors at an accepted level. In Fig.1 a DA simulation scan together with the standard working point is shown. For realistic beam loss calculations for a given working point we perform long-term tracking (105 turns) studies for a bunch including 'frozen' space charge, chromaticity and realistic beam distribution function with truncated tails. These simulations show that beam survival of about 90% should be possible even for full intensity. This requires a) closed orbit errors should be corrected to the1/1.6 mm rms tolerance (vertical/horizontal) assumed in the simulations, b) random magnet field errors should not exceed the values adopted in the simulations somewhat arbitrarily, c) flexibility should be kept for the ultimate choice of working point to take into account the actually measured strength of near-by nonlinear resonances. Compensation – at least partial – may be needed, d) a double-harmonic RF system during the injection plateau should be considered to raise the bunching factor from 0.33 to about 0.5; this would clearly cause a corresponding reduction of space charge and momentum spread and reduce loss.

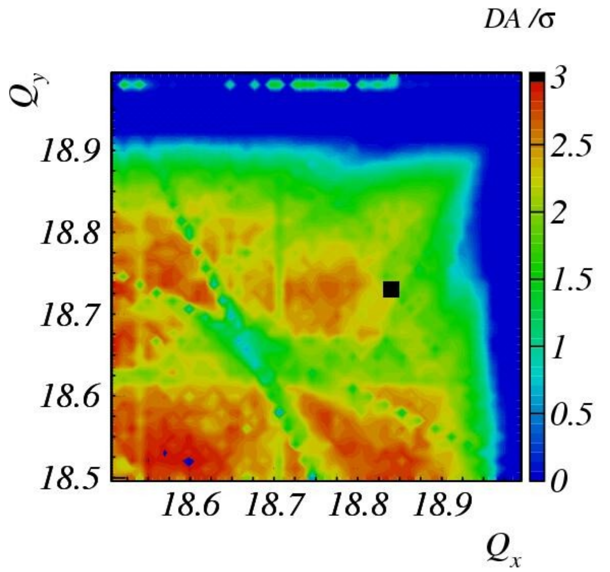

Figure 1: Result of 1000-turn DA scans with reference random errors. Black marker: proposed standard working point.

TRANSVERSE IMPEDANCE SPECTRUM

The thin resistive beam pipe together with the injection/extraction kicker modules represent the most important impedance contributions in SIS-18 and SIS-100. The beam pipe impedance affects the coherent betatron sidebands between ≈50 kHz and 1 MHz, depending on the machine tune. In order to reduce eddy current effects, the stainless steel beam pipe in the SIS 18 magnets is only 0.3 mm thick. The skin depth is 1 mm at the injection energy of 11.4 MeV/u. For the stainless steel beam pipe in the planned SIS 100 magnets, a wall thickness of a few 0.1 mm will be required. In addition to the large impedance contribution of a thin beam pipe at low frequencies also the shielding effectiveness of the pipe is of importance [5]. For low frequencies structures behind the wall can contribute to the impedance. The impedance of the ferrite-loaded kickers can be divided into two parts [6]. Below frequencies ≈ 50 MHz the horizontal impedance is dominated by the external circuit. Above ≈ 200 MHz the Ferrite contribution dominates. For coasting beams and for long bunches we are concerned about transverse impedances below ≈ 50 MHz . Fig. 2shows the calculated transverse impedances (real parts) of the resistive wall and of the kickers in SIS 18 for 200 MeV/u beam energy. Because the beams in the FAIR synchrotrons typically fill a large fraction of the pipe, the dominant imaginary impedance contribution is expected to arise from the image currents. The corresponding space charge impedance is

$$Z_{\perp}^{sc} = -i\frac{Z_0 R}{\gamma_0^2 \beta_0^2 b^2} \quad (1)$$

with the ring radius R, the beam pipe radius b, the relativistic factors β_0 and γ_0. The effect of electron clouds can be cast into a transverse impedance (see [7]) for a known neutralization factor. For the plot in Fig. 2 the neutralization factor η_e has been estimated as 0.01 based on rough estimates. The expected major source of electrons in SIS¬18 and SIS-100 at injection energy will be the ionization of the residual gas by U28+ projectile ions. Detailed studies of the electron cloud buildup and of the interaction with long bunches at medium beam energies will be studied in the near future.

TRANSVERSE COHERENT INSTABILITIES

Our studies focus on instabilities driven by the resistive wall impedance, which has the largest contribution at small frequencies. For coasting beams the space charge tune shift makes the Landau damping due to momentum spread inefficient. Fig. 3 shows the stability contour together with different beam parameters in SIS-100. It can be seen that especially during injection transverse dipole oscillations are unstable. The growth rate is of the order of a few ms only. Increasing the momentum spread for stabilization is not an option because of the rf bucket acceptance in SIS-100. The nonlinearity of the transverse space charge force can enhance the stability boundary. Detailed studies [8] showed that the combination of octupoles, creating additional tune spread, and nonlinear space charge can lead to a sufficient stabilization. In these studies results obtained from a dispersion relation for nonlinear Landau damping, were compared with particle tracking simulations. It was found that the role of nonlinear space charge is decisive for stability predictions in SIS-100 and that octupoles may stabilize dipole instabilities during accumulation in SIS-100. The effect of the octupoles on the dynamic aperture and the corresponding beam loss is still subject of ongoing studies. The coasting beam instability threshold represents a conservative estimate for the long bunches in SIS-100.

Due to finite bunch length effects and due to the variation of the space charge tune shift along the bunch we expect an increase in the instability boundary. In addition image currents and the resulting coherent tune spread along the bunch can damp dipole oscillations. Using the theory of Sacherer, ignoring space charge and image current effects, we predict a fast (< 100 ms) single-bunch head-tail instability excited by the resistive-wall impedance at injection energy in SIS-100. The mode structure and influence of chromaticity on head-tail modes is discussed in Ref. [9]. Simulation studies of head-tail modes in SIS-100bunches, including space charge, image currents and nonlinear synchrotron motion are still ongoing. In theses studies we use the two different simulation codes PATRIC, developed at GSI and HEADTAIL, developed at CERN.

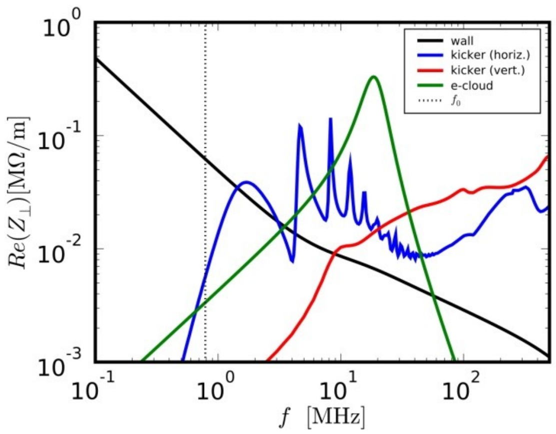

Figure 2: Transverse impedance spectrum in SIS-18 (real part).

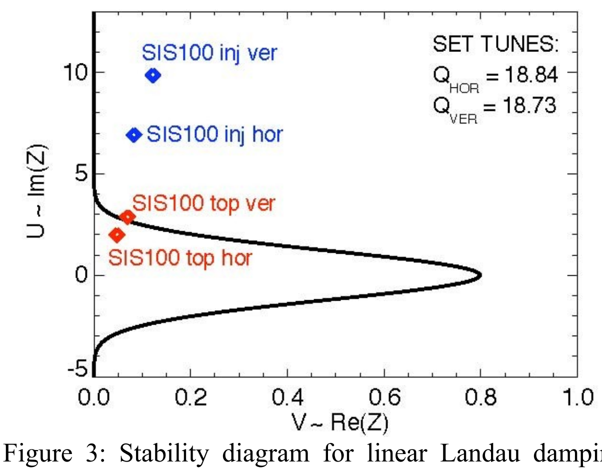

Figure 3: Stability diagram for linear Landau damping due to momentum spread and chromaticity. The region enclosed by the curve and by the U-axis is the stable area. Impedances, which correspond to the resistive wall for four beam parameters in SIS-100 are shown, for the injection energy (inj) and after acceleration (top), for the horizontal and for the vertical plane.

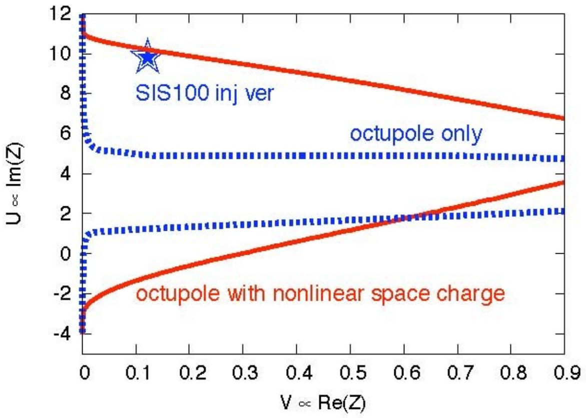

Figure 4: Stability diagram for nonlinear damping. Regions enclosed by the curves and by the U-axis are the stable areas. Blue curve: only effect of octupole magnets is taken into account; red curve: combination of these octupoles with nonlinear space charge (waterbag distribution). The star indicates the resistive wall impedance for a SIS100 beam at the injection energy in the vertical plane.

LONGITUDINAL BUNCH MANIPULATIONS

The rf cycle in the SIS-18/SIS-100 accelerator chain contains a number of critical steps. During all the rf manipulations longitudinal space charge and cavity beam loading effects are important. The tolerable phase space dilution factor for the total rf cycle including all bunch manipulations is 2-3. It is foreseen to inject two SIS-18 bunches into matched SIS-100 rf buckets. The resulting injection transients induced by beam loading will be actively damped. After injection of eight bunches from SIS-18 the acceleration ramp starts. The matched bunch and bucket boundaries including space charge and beam loading were obtained from the theory presented in [10]. After acceleration, the eight bunches will be rebunched into a long barrier rf bucket. In the barrier bucket beam loading will lead to modifications of the bunch form. Here we assume that only the barrier rf cavities are visible and all other rf systems are shorted. If necessary a dedicated feedback for the barrier rf operation will be installed. The perturbed bunch forms in the barrier bucket are obtained from [11] assuming a Gaussian beam distribution. It is interesting to note that space charge has a beneficial effect on the bunch form. It removes part of the bunch form asymmetry caused by the beam loading effect. The rf barrier walls will be moved in order to pre-compress the bunch within 200 ms. Simulation studies indicate that the bunch area increases by 10% during pre-compression, which is tolerable. After the barrier bucket pre-compression the bunch compressor rf voltage is switched on. This process has been studied in detail including the effect of beam loading and space charge. The compressed bunch distribution is shifted downwards in momentum by -0.8% due to cavity beam loading. This shift should be corrected during the rotation by a fast rf phase control system.

CONCLUSIONS

Space charge and impedance effects play a major role in the existing SIS-18 synchrotron and in the planned SIS-100. For the design working point we estimated the beam loss due to nonlinear resonances and space charge in SIS-100 after 1 s. Alternative working points are still under discussion. The main transverse impedance sources are the resistive wall, kickers and possibly electron clouds. For the resistive wall we obtained the stability boundaries for transverse dipole oscillations in SIS-100 including the effect of nonlinear space charge and octupoles. Octupoles are a potential cure for transverse beam instabilities in SIS-100. The effect of space charge and image currents on head-tail modes in long bunches are still being studied. The rf cycle is being optimized for low phase space dilution using analytic estimates as well as simulation studies.

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