DETERMINATION OF THE ACCEPTANCE OF SIS-18 USING AN RF VOLTAGE

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Abstract

The present heavy ion synchrotron SIS-18 will be upgraded to be used as a booster for further synchrotrons being part of the FAIR project underway at GSI. We present a technique for measuring the acceptance of an accelerator based on the measurement of particle loss. We use in SIS-18 a pseudo-stochastic RF voltage to transversally excite a coasting heavy ion beam. The resulting transverse beam growth leads to particle loss when the beam width exceeds the limiting aperture. The acceptance is determined from the measured time evolution of the beam current.

INTRODUCTION

The need for measuring the SIS-18 acceptance arises from the usage of SIS-18 as a booster within the FAIR project [1, 2] including regular high-current operation. In this regime, an uncontrolled beam loss in the pipe can lead to vacuum degradation and irradiation of the machine. A precise knowledge of the acceptance will help to optimise SIS-18 to reduce particle loss.

Our method is based on diffusion driven by a pseudo-stochastic RF voltage applied to an ion beam in SIS-18. Several experiments, which used diffusion, had been performed at different accelerators to measure the acceptance or the dynamic aperture. Here, the time required for the beam edge to reach the aperture was measured, see e.g. [3, 4]. The estimation of this time is difficult as a detailed knowledge of the initial beam width is necessary. In order to avoid this uncertainty we study the time evolution of the particle loss after the beam edge has reached the aperture of the accelerator. The determination of the acceptance from the beam loss is easier because beam loss is essentially determined by stochastic dynamics. It can be shown that a pseudo-stochastic transverse RF voltage generates particle diffusion which transforms any arbitrary initial particle distribution into a distribution described by a Bessel function J_0 [5]. After the beam profile has reached this asymptotic shape, the time evolution of the beam current does no longer depend on the initial particle distribution. That enables us to determine the acceptance of SIS-18 by measuring the particle loss and comparing it to the results of a numerical model.

DETERMINATION OF THE ACCEPTANCE

Procedure

To determine the acceptance ϵ_{lim} of SIS-18, the ion beam is accelerated to the extraction energy. After that, the process of RF excitation starts using a BTF exciter implemented in the ring. When the beam width exceeds the limiting aperture, particle loss starts and is measured using a slow transformer. The time resolution is 2.5 ms. During the excitation, the energy is kept constant.

To obtain information about the acceptance, the particle loss is modelled with a tracking algorithm. The lattice parameters are calculated using the MAD-X code. The acceptance is found by applying a trial-and-error procedure, wherein the computation of the particle number as a function of time is repeated with the acceptance varied until a curve for the time dependent particle number is found which best fits the corresponding measured curve for the beam current.

Tracking Model

In our model, the particles are tracked through the lattice of the synchrotron, where they get in each revolution a time dependent momentum kick as generated by the BTF exciter which is acting in only one plane. Here, we use the approximation of a linear lattice. Hence, the transformation of the phase space coordinates of a particle during a revolution is

$$\vec{z}_{p,n+1} = M \cdot \vec{z}_{p,n} + \Delta\vec{z}^{\,\prime}_{p,n}, \tag{1}$$

where $\vec{z}_{p,n}$ is the vector of the phase space coordinates of the pth particle at the end of the nth revolution, M is the one turn map of the lattice, and the vector $\Delta\vec{z}^{\,\prime}_{p,n}$ contains the momentum kick due to the RF field acting onto the pth particle after the nth revolution. The RF field is approximately the same for every particle in one revolution.

The map M is

$$\begin{aligned} M &= M(\mu_p) \\ &= \begin{pmatrix} \cos\mu_p + \alpha\sin\mu_p & \beta\sin\mu_p \\ -\frac{1+\alpha^2}{\beta}\sin\mu_p & \cos\mu_p - \alpha\sin\mu_p. \end{pmatrix}. \end{aligned} \tag{2}$$

The parameters α and β in equation (2) denote the Twiss functions at the location of the exciter. They were calculated by means of the MAD-X code. $\mu_p = \mu + \xi\delta_p 2\pi\nu$ is the phase advance for a full revolution of the pth particle, which depends on the momentum deviation δ_p of the particle. The initial particle coordinates are chosen according to a bi-Gaussian distribution in the transverse phase space plane considered and to a momentum Gaussian distribution.

We made a test of this model against the analytical model described in [5]. The momentum kicks are taken according to "white noise". That means, the momentum kick given to a particle is statistically independent of the momentum kicks to every other particle in the same revolution and to every kick to the particle considered in each other revolution.

A second test concerns the influence of the chromaticity. We find that the tune spread caused by the momentum spread plays an important in the diffusion process if an RF signal is used. A linear growth of the beam emittance in time is typical of diffusion. We retrieve it only if the chromaticity ξ is large enough, as one can see in Fig. 1 for the case of the vertical chromaticity ξ_y. Furthermore, we found that the slope of the emittance is not further modified for $|\xi_y| > 0.1$.

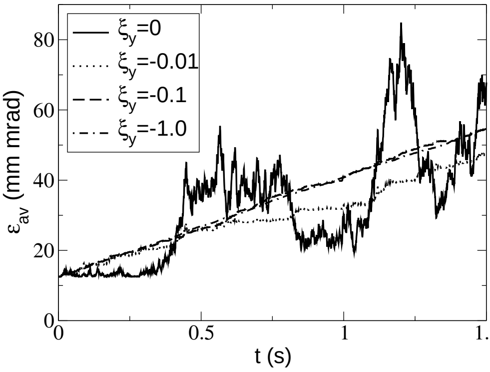

Figure 1: Time evolution of the beam emittance depending on the chromaticity. For $|\xi_y| > 0.1$ the growth of the emittance does no longer depend on ξ_y. Consequently, the curves for $\xi_y = -0.1$ and $\xi_y = -1.0$ are approximately identical.

RF Signal of the Exciter

The BTF exciter consists of two parallel plates with the distance d_0 in between. The electric RF field $E(t)$ between the plates is approximately homogeneous and caused by the RF voltage [6]

$$U(t) = U_a \sin(2\pi f_C t + \phi_0(t)), \tag{3}$$

where f_C is the carrier frequency being adjusted to the fractional part of the betatron frequency. ϕ_0 is a phase jumping between the values $0, \pi$ with a probability of 50 % and the time $T_S = 1/f_S$ between two possible jump times. The phase jumps are assumed to occur instantaneously. At least, the condition $\Delta t \approx 1/|\dot{\phi}_0| \ll 1/(2\pi f_C)$ for the time necessary for a jump to occur is fulfilled. Therefore, the effective voltage is approximately given by

$$U_{eff} = \sqrt{\frac{f_C}{2\pi} \int_0^{1/f_C} U^2(t)\,\mathrm{d}t} = \frac{U_a}{\sqrt{2}}. \tag{4}$$

f_S is the half width of the corresponding power spectrum,

$$P(f) \propto \frac{\sin^2[\pi(f - f_C)/f_S]}{[\pi(f - f_C)/f_S]^2}. \tag{5}$$

To excite all particles, f_S must be large enough to cover the the range of the betatron frequency caused by the momentum spread. Its RMS value is given by

$$\Delta\nu_{rms} = \xi\sigma_p 2\pi\nu, \tag{6}$$

where ξ is the chromaticity, ν is the tune, and $\sigma_p = (\Delta p/p)_{rms}$ is the RMS relative momentum uncertainty.

The sinusoidal voltage generates a momentum kick with a sinusoidal time behaviour. Its amplitude is given by

$$\Delta y_a^{'} = \frac{q E_a \Delta t}{p}, \tag{7}$$

where q is the ion charge, $E_a = U_a/d_0$ is the amplitude of the electric field strength, p is the momentum, and Δt is the time necessary for the ion to pass through the exciter. Using $q = Ze$, $\Delta t = \beta_0 c/l_0$, and $p = A m_u c \beta_0 \gamma_0$, this equation can be rewritten to

$$\Delta y_a^{'} = \frac{1}{m_u c^2 \beta_0^2 \gamma_0} \frac{Z}{A} \frac{U_a l_0}{d_0}. \tag{8}$$

Here, $m_u c^2 = 931.5$ MeV is the rest energy of a nucleon, β_0, γ_0 are the relativistic factors, $l_0 = 750$ mm is the length of the exciter, and Z, A are charge state and mass number of the ions. The transverse distance between the plates d_0 is 200 mm horizontally and 70 mm vertically.

RESULTS

Horizontal and vertical acceptance were measured in separate experiments.

In a first step, only the vertical acceptance could be measured [7]. Here, a Ta^{61+} beam initially consisting of 10^9 ions has been used at the extraction energy $E = 100$ MeV/u. The working point was $(\nu_x, \nu_y) = (4.17, 3.29)$. RF signals with amplitude voltages $U_a = 14$ V and $U_a = 28$ V were applied, where only the larger voltage caused a sufficiently large beam loss which could be evaluated. Additionally, measurements with $f_S = 0.01/T_0$ and $f_S = 0.005/T_0$ were performed. The usage of the broader power spectrum led to to the value $\epsilon_{lim,y} = 46$ mm mrad, the measurement with the smaller spectral width gave $\epsilon_{lim,y} = 45$ mm mrad. Both values of the vertical acceptance are very similar although they were obtained for different levels of spectral power density in the centre of the spectrum what we consider as a sign for consistency and the robustness of the method.

Table 1: Main Experimental Parameters

General:	
Circumference of SIS-18 C	216.72 m
Working point ν_x, ν_y	$4.17, 3.29$
Initial ion number $N_p(0)$	$\sim 10^9$
Particle energy E	100 MeV/u
Revolution time T_0	1.683 μs
RMS momentum width σ_p	$5.0 \cdot 10^{-4}$
Exciter length l_0	750 mm
Vertical measurement	
Ion	Ta^{61+}
Measuring time t_{max}	≈ 1.8 s
Revolution number n	$\sim 10^6$
Vertical exciter plate distance d_0	70 mm
Effective exciter voltage U_{eff}	10 V and 20 V
Width of power spectrum $f_S \cdot T_0$	0.005 and 0.01
β_y at exciter position	7.0 m
α_y at exciter position	0.15
Vertical chromaticity $\xi_{y,nat}$	-1.4647
Horizontal measurement	
Ion	Ar^{18+}
Measuring time t_{max}	≈ 6.5 s
Revolution number n	$\sim 3.5 \cdot 10^6$
Horizontal exciter plate distance d_0	200 mm
Effective exciter voltage U_{eff}	70 V
Width of power spectrum $f_S \cdot T_0$	0.05 and 0.1
β_x at exciter position	15.0 m
α_x at exciter position	-1.56
Horizontal chromaticity $\xi_{x,nat}$	-1.4647

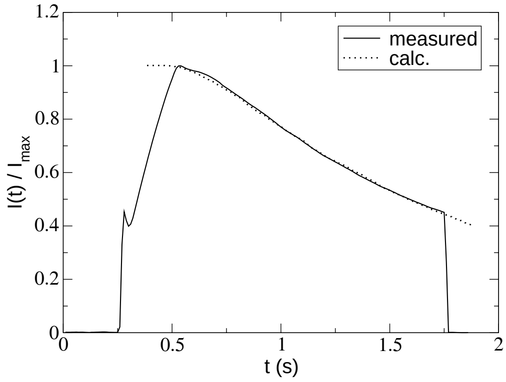

Figure 2: Normalised current measured and calculated for $E = 100$ MeV/u, $U_a = 28$ V, $f_S = 0.01/T_0$, and $\epsilon_{lim} = 46$ mm mrad.

A measured and a calculated curve determined for $f_S = 0.01/T_0$ are shown in Fig. 2. Within an error analysis, the maximum uncertainty for ϵ_{lim} is estimated to 13 %.

First measurements of the horizontal acceptance have been done with an Ar^{18+} beam. Here, the same scheme, working point, and energy were chosen. An important difference is the horizontal distance between between the exciter plates, $d_0 = 200$ mm, which is about three times the vertical distance. Therefore, the horizontal electric RF field strength is three times smaller than that in vertical direction for the same voltage. To compensate that, a voltage having the maximum possible amplitude $U_a = 100$ V what is about three times the voltage used for the vertical measurements. Furthermore, the width of the spectral power spectrum has been increased to make the RF signal more similar to white noise. So, $f_S = 0.05/T_0$ and $f_S = 0.1/T_0$ have been used. For that reason, a much smaller emittance growth is achieved because it scales with the spectral power density close to the tune which is $\propto 1/f_S$. The increase of the measurement time interval to 6 s is not sufficient to reach the same amount of beam loss as in the vertical measurements. Finally, only the measurements with the narrow power spectrum delivered evaluable curves for the beam current. Nevertheless, the best agreement between measured and calculated beam current has been reached for an acceptance $\epsilon_{lim} = 175$ mm mrad what is reasonable.

CONCLUSIONS

We applied an RF voltage to determine the acceptance of the GSI heavy ion synchrotron, SIS-18. The excitation of the beam by the RF field led to an increase of the beam size and to a reduction of the beam current after particles had started to hit the aperture. We measured the decrease of the beam current and extracted the acceptance from it to remove the dependency of the measured data on the initial beam width. For the evaluation of the experimental data we used a tracking method.

In a first step we measured only the vertical acceptance, where we obtained reasonable results in good agreement to each other obtained for different parameters. The latter is a sign for consistency and, so, for the reliability and robustness of the method.

The measurement of the horizontal acceptance is still in a preliminary stage. First results are reasonable.

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