

OBSERVATION OF SPACE CHARGE EFFECTS ON TUNE AT SIS-18 WITH NEW DIGITAL BASE BAND TUNE MEASUREMENT SYSTEM*

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Abstract

To achieve a high current operation close to the space charge limit, a precise tune measurement during a full accelerating cycle is required. A tune measurement system was recently commissioned at GSI synchrotron SIS-18, which allows evaluation of tune using digital position data. Using this system, the space charge effects were observed by correlating the current levels to tune shifts in the GSI SIS-18. The experiment was conducted at injection energy of 11.4 MeV/nucleon using a $^{238}_{92}\text{U}^{73+}$ ion beam with stored number of particles from $2.5 \cdot 10^7$ to $2.5 \cdot 10^9$. A significant broadening of the tune spectrum in dependence of the stored number of particles was detected. This proves the reliability of this measurement method for bunched beams and opens the possibility of detailed beam physics investigations.

INTRODUCTION

High current operations at injection energies in hadron accelerators lead to large tune shifts which can result in emittance blow up or loss of particles. Emittance blow up is not desirable for storage rings or accelerators, thus it is very important to station frozen tune at appropriate point in resonance diagram.

A new system has been commissioned at GSI for position and tune measurements. It consists of three distinct parts; A band-limited exciter which provides power to excite coherent betatron oscillations in the bunched beam. Fast ADCs digitize the BPM signals at 125 MSa/s and the post processing electronics integrate the data bunchwise to acquire one position value per bunch. Subsequently the baseband tune is determined by Fourier transformation of the position data. One tune value can be calculated typically from 256 turns to 4096 turns based on the investigation needs.

The first objective of this work is to observe the space charge effects on the tune at SIS-18 injection energies. By space charge effects we mean both the effects of self fields and image charges often termed as incoherent and coherent tune shift respectively. Incoherent tune shift is caused by the interaction of individual charged particles in the beam. Since incoherent tune shift causes a spread in the tune spectrum, the term “tune spread” has been interchangeably used for refer this effect throughout this report. Coherent tune

shift stems from the boundary conditions, e.g. the beam pipe and all other devices in the beam pipe surrounding the charged ion beam [1]. The second objective is to see the influence of noise excitation on various beam parameters like tune spectrum, emittance and life time.

METHODS

This section highlights the working of the tune measurement system as a whole, and then explains the working principle of tunable noise generator in further detail.

TOPOS: Tune Orbit Position Measurement System

TOPOS is the tune, orbit and position measurement system established in SIS-18 at GSI [2]. Figure 1 gives an overview of the fragment of TOPOS used for tune measurement.

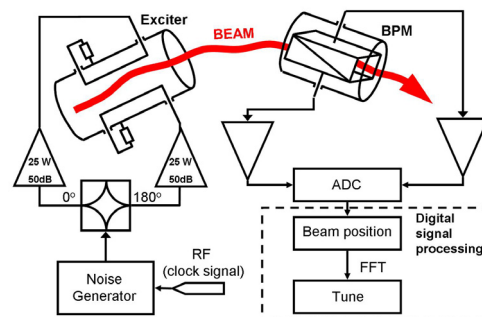


Figure 1: TOPOS: Tune measurement system.

Particles revolve in an accelerator with unrelated phases due to finite injection time and momentum spread, and thus the barycentre of a bunch of particles does not provide any information on the transverse movement of the individual particles. Thus beam excitation is needed to make the motion of particles coherent, and capture the transverse movements for tune measurement. A band limited noise exciter is employed to give this excitation. The advantages of this exciter are: lower continuous power is transferred to the beam causing minimal disturbance to the beam parameters; It can be used throughout the ramp for continuous monitoring of the tune [3, 4]. A tunable noise generator synthesizes a frequency centered at the baseband tune frequency and twice the span of maximal expected tune spread (Eq. 1). It is modulated by the revolution frequency f_0 and fed to

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the exciter through a fixed gain amplifier. Then the excited beam signal is measured by a shoe-box type pick-up [5] in both horizontal and vertical planes. This signal is digitized for both planes and further processed in an FPGA in real time to get one position data per bunch using an algorithm described in [6]. The position data is transferred to concentrator PCs where FFT is calculated and fractional tune is displayed in the main control room. The measurement system has been designed to cater the need for a future tune control system which should be reasonably fast, in either case of a feed-back or a feed-forward system. More details on the system can be found in [4].

Tunable Band Limited Noise Excitor

The tunable noise generator takes the accelerating rf using a frequency tracker as the input from which it generates the sine waveform at baseband tune frequency given by the relation $f_t = \frac{Q_f * f_{rf}}{h}$ where h is the number of bunches in the ring and Q_f is the fractional tune. This frequency is then modulated by the output of pseudo random noise direct digital synthesizer (PRN-DDS) causing sudden phase jumps at regular intervals depending on the set tunable noise bandwidth. Figure 2 shows the output spectrum generated by noise generator.

The noise excitor can supply total power between 0.25 W to 160 W after amplification to the beam [7]. The power transferred to the beam can be best defined in terms of power spectral density (PSD [W/Hz]). The kick provided to particles is directly proportional to the noise PSD and inversely proportional to beam rigidity. The distance between horizontal exciter plates is three times larger than vertical excitation plates, which means that less power is needed to provide the same kick in vertical plane.

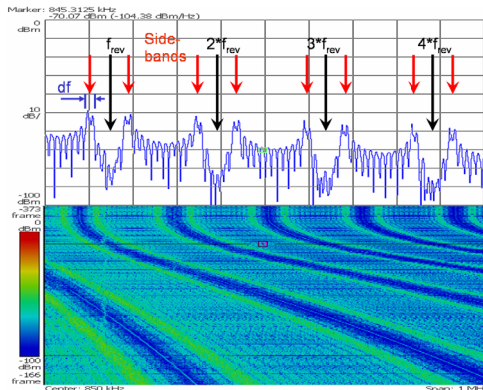


Figure 2: Noise output spectrum changing with rf during ramping.

Experimental Conditions

Experiments were done using U^{73+} beam at 11.4 MeV on injection flat top for 1 s. The experiment was repeated at decreasing intensities of stored ions from $2.7 \cdot 10^9$ to

$2.5 \cdot 10^7$. At each intensity level, several measurements were done with different levels of noise excitation ranging from 0.025 mW/Hz to 3 mW/Hz in both planes. The beam current was measured using beam current transformer and transverse beam profile was measured using Ionization profile monitor [8].

Tune Spread Calculations

Rough estimates of space charge effects on the tune spectrum are made assuming transverse and longitudinal gaussian beam distribution and some further simplifications [9]. The incoherent and coherent tune shifts are then given by Eq. 1 and 2 respectively.

$$\delta Q_{inc} = \frac{r_0 I R \langle \beta_y \rangle}{ec\beta^3 \gamma^3 a^2} \quad (1)$$

$$\delta Q_{coh} = \frac{\pi^2 r_0 I R \langle \beta_y \rangle}{8ec\beta^3 \gamma h^2} \quad (2)$$

where:

$r_0 = \frac{e^2}{4\pi\epsilon_0 m_0 c^2}$ is the proton radius; I is the peak current in the ring; Radius of the ring $R = 34.4$ m; Average beta function $\langle \beta_{x,y} \rangle = 8, 10.5$ m of the ring in horizontal and vertical planes respectively; e is the electric charge; c is the speed of light; Relativistic beta function $\beta = 15.5\% \cdot c$; Relativistic lorentz factor $\gamma = 1.01$; 1σ beam radius $a_{x,y} = 9, 6$ mm; Radius of the beam pipe $h = 50$ mm;

All the above parameters are given at injection energies and were almost constant during our experiment. After inserting the values of the mentioned parameters at the highest current $I = 15.1$ mA in Eq. 1 gives us $\delta Q_{inc,h}(1\sigma) = -0.005$ and $\delta Q_{inc,v} = -0.017$. The schematic in Fig. 3 shows the expected effects of incoherent and coherent tune shifts. This schematic is for demonstration of space charge effects and does not represent actual values.

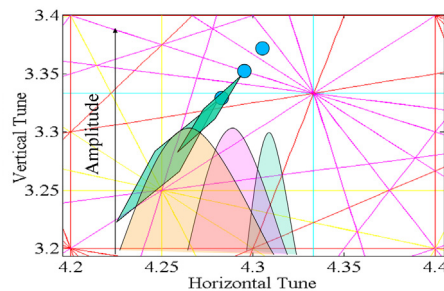


Figure 3: Schematic showing the expected combined effect from coherent and incoherent tune shifts.

RESULTS AND DISCUSSION

In this section the comparison of observed tune shifts with expected values are presented. It is important to determine the tolerance of beam excitation against significant beam losses or emittance growth. Thus, dependence of

beam life time on intensity and noise excitation was investigated. Beam profile was monitored throughout the experiment to observe the evolution of emittance growth with increase in noise excitation.

Beam Life Time

Figure 4 shows the current decay curve at different noise excitations at $2.7 \cdot 10^9$ and $1.5 \cdot 10^9$ injected ions.

The beam life time is obtained using the relation

$$\tau_{beam} = \frac{1}{\ln \frac{N_{max}}{N_{end}}} \quad (3)$$

where N_{max} is the initial number of particles and N_{end} is the particles remaining at the end of measurement. Figure 5 shows the effect of noise excitation on the beam life time at two different beam current levels. Beam life time is a function of various parameters; Ion induced desorption, beam intensity, noise excitation and tune. The focus of investigation here is the effect of noise excitation on the beam life time. The life times are found to be shorter than expected from the previous measurements [11]. Since the life times are of the same order as measurement times 1 s, it needs to be taken into account for evaluation of the tune.

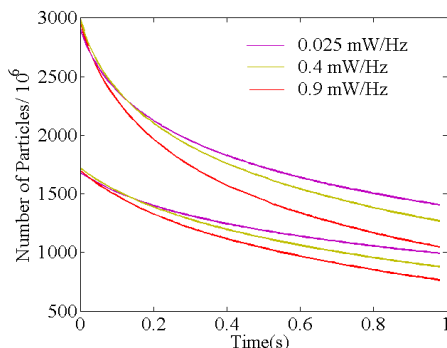


Figure 4: Beam life time at $2.7 \cdot 10^9$ particles (upper curves) and $1.5 \cdot 10^9$ particles (lower curves) with three different levels of noise excitation in each of them.

Tune Shift Observation

The tune evaluations shown below are done 600 ms after injection, so as to avoid significant decrease in beam current during 200 ms. A vertical tune shift was observed with increasing current as shown in Fig. 6. The spectrum shown is an average of twenty FFTs made over 512 turns. It is measured at three different current levels ranging from $4 \cdot 10^8$ to $20 \cdot 10^8$ stored particles. The expected and measured tune spread (1σ) due to space charge are calculated in Table 1. Tune spread due to space charge for lower currents are shadowed by the chromatic tune spread. Chromatic tune spread is present because of uncompensated chromaticity and momentum spread of the particles. Chromatic tune spread is found to be approx. 0.004 and 0.01

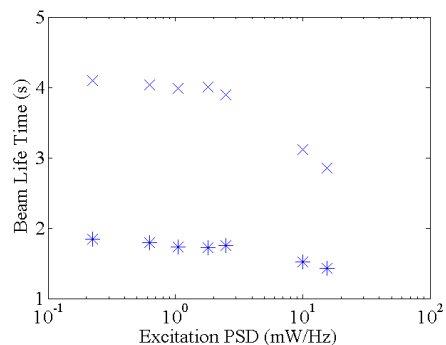


Figure 5: Lower plot (with *): Life times with increasing noise excitation levels using the injection current levels for N_{max} ; Upper plot (with X): Life times with increasing noise excitation using the current levels 0.5 s after the injection as N_{max} .

for horizontal and vertical planes respectively. The set tune was centered at 0.260 but the observed tune was centered at 0.262. This difference in the set and actual tune is attributed to discrepancies in GSI machine model with respect to the real accelerator, see e.g. [6].

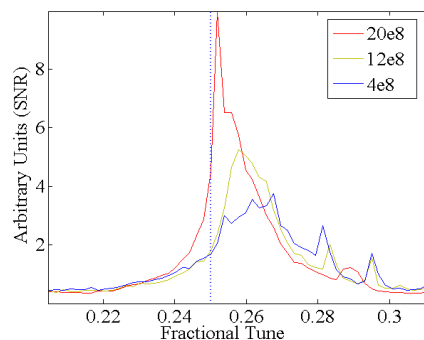


Figure 6: Increase in tune spread with increasing current. The line at $Q_y = 0.25$ depicts the fourth order resonance.

Table 1: Expected And Measured Tune Spread (rms)

Number of Particles	$20 \cdot 10^8$	$12 \cdot 10^8$
Expected $Q_{x,inc}$	0.005	0.003
Measured $Q_{x,inc}$	0.004	0.004
Expected $Q_{y,inc}$	0.017	0.010
Measured $Q_{y,inc}$	0.021	0.012

An appropriate choice of FFT size is based on the investigation needs. For example, during acceleration cycles monitoring of small changes in tune could be a requirement, which calls for smaller FFT sizes. However in case of stationary beam parameters, higher resolution in tune spectrum may be needed. Figure 7 shows the spectra for 40960 position values with different FFT sizes followed by averaging over entire position values. Tune spectra with

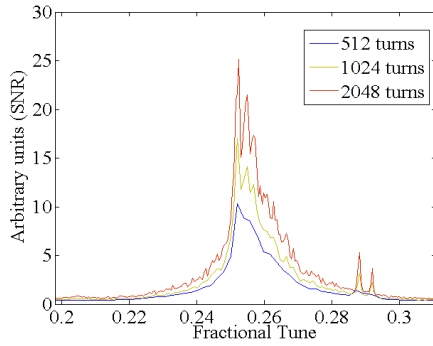


Figure 7: Tune spread measurement with different FFT lengths for 40960 turns for $20 \cdot 10^8$ stored ions and noise excitation PSD of 0.4 mW/Hz.

longer FFT size allows better frequency resolution, while shorter FFT size allows more averaging for same number of values to get a less noisy spectra.

Influence of Noise Power on Tune Spectra

Figure 8 demonstrates the influence of noise power on vertical tune spectra. Each tune spectrum is cut at a certain fraction of peak value to remain above the noise level, and 1σ tune spectrum width is calculated from it. The tune spread at 15% and 20% cut of peak value is plotted in Fig. 9. Tune spread is found to be independent of the power of noise excitation within the depicted range. The other observation in Fig. 8 is that the SNR improves significantly in the depicted range of noise excitation and this was also observed during tune measurements while ramping [4]. This proves the applicability of this method of tune measurement.

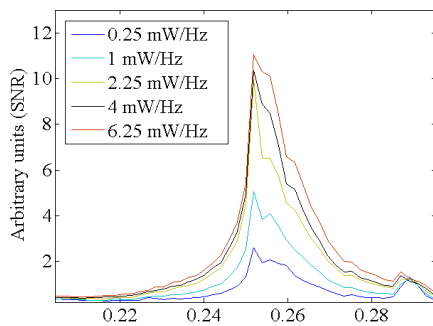


Figure 8: Vertical tune spread at increasing noise excitation levels, we observe negligible change in the spectrum but significant improvement in SNR.

Excitation Influence on Emittance

The effect on vertical and horizontal beam profile at different levels of noise excitation after 500 ms on injection

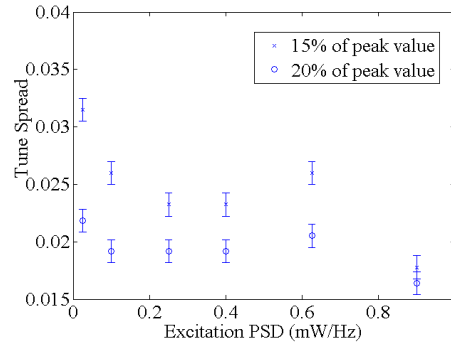


Figure 9: Rms tune spread measured at 15 and 20% cut with respect to peak value. The error bar signifies the frequency bin size.

flat top is shown in Fig. 10 and 11. No increase in emittance with increasing excitation in either planes was observed. This behaviour hints the effect of proximity to a fourth order tune resonance, which could lead to quick particle losses (within few hundred turns). Beam profiles are measured in IPM by averaging over 0.5 ms (100 turns), thus no changes in the width of beam profile are visible. On the other hand uniform continuous decline in profile amplitude depicts the uniform particle losses.

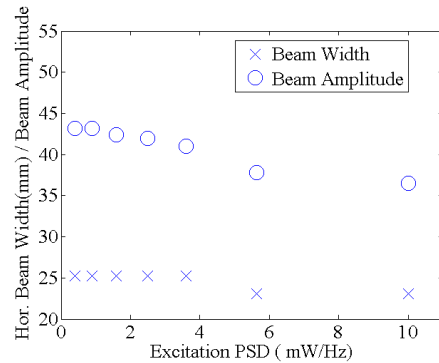


Figure 10: Horizontal beam profile width and amplitude at different noise levels after 500 ms on injection flat top.

The effect of noise excitation on emittance during one machine cycle taken every 100 ms is shown in Figs. 12, 13 below. Here we observe no increase in vertical emittance while the horizontal emittance actually reduced with time. The plausible explanation to this behaviour is the same as previous subsection.

SUMMARY AND OUTLOOK

An increase in tune spread with increase in intensity at injection energy for U^{73+} at SIS-18 is observed which matches well with the theoretical value. The tune spectrum is found to be independent of noise excitation power while its SNR improves with increasing noise excitation. The dependence of beam life time on intensity and noise

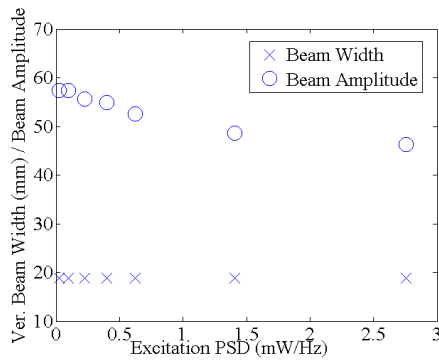


Figure 11: Vertical beam profile width and amplitude at different noise levels after 500 ms on injection flat top.

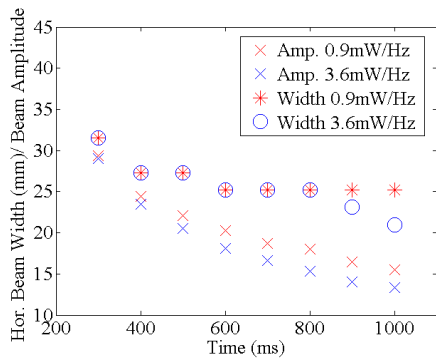


Figure 12: Horizontal beam profile width and amplitude at the interval of every 100 ms in the same machine cycle.

excitation is also observed. For these particular experimental conditions, no changes in emittance with different noise excitations are observed. The vertical tune was stationed close to fourth order resonance which can explain the constant emittance and small beam life times, though this is still under discussion. Since certain parts of the results have not been fully understood, the next step would be to investigate and validate the present results for higher currents preferably with FAIR reference ion U^{28+} and Ar^{18+} . Fi-

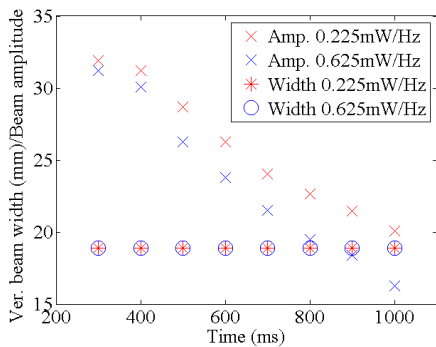


Figure 13: Vertical beam profile width and amplitude at the interval of every 100 ms in the same machine cycle.

nally, this experiment throws a positive light on the usability of this method to continue with further beam physics experiment.

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