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DEVELOPMENT OF A FAST BETATRON TUNE AND CHROMATICITY MEASUREMENT SYSTEM FOR COSY

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Abstract

A fast tune measurement is developed for the Cooler Synchrotron COSY at the Institut für Kernphysik of Forschungszentrum Jülich. Betatron oscillations of the beam are excited with a band-limited RF signal via a stripline kicker. Resonant transverse oscillations are then observed using capacitive beam position monitors (BPMs). Based on the bunch-by-bunch beam position data the betatron tune is determined. The usage of bunch-by-bunch data is characteristic of the new system. It allows for a discrete tune measurement within a few milliseconds, as well as continuous tune monitoring during beam acceleration. The high precision tune measurement also enables determination of the beam chromaticity. Therefore, the beam momentum is varied by means of the RF frequency and the subsequent tune change is determined. For routine use during beam operation and experiments, the developed method is integrated into the control system.

INTRODUCTION

The betatron tune and its dependence on the beam momentum (chromaticity) are central quantities of an accelerator. They must be monitored during operation to avoid instability causing resonances. This is especially important for experiments with polarized beams where additional spin tune resonances limit the polarization lifetime [1]. Such experiments are carried out by the Jülich Electric Dipole moment Investigations (JEDI) collaboration at COSY. Since the existing measurement procedures were not suited for routine monitoring and suffered from large beam losses, the need for a fast tune and chromaticity measurement system arose. In the following, the implementation of such a system, its capabilities and limits are presented.

EXCITATION OF BETATRON OSCILLATIONS

The betatron oscillations are excited with white noise in a suitable frequency band [2]. This excitation method has the benefit of being fast and thus causing no visible beam losses. For a typical tune of 3.5 to 3.7 at COSY, the excitation band ranges from 0.3 to 0.5 of the revolution frequency. A single tune measurement can be performed with only 25 ms of excitation.

The noise sequence is generated with an arbitrary function generator (AFG) upon trigger. Its duration, frequency band and power can be adjusted depending on the beam conditions. After splitting and amplification with four 150 W power amplifiers, the signal is applied to the beam via a stripline kicker.

In addition to the short time excitation for single tune measurements, the beam can also be continuously excited over several seconds, which allows tracking of the tune. To minimize the inevitable impact on the beam intensity in this case, the noise signal can be pulse-modulated. This also helps to clearly distinguish the pulsed tune signal from other spurious signals, and in principle allows for a repetitive background correction.

For beam momenta $p \gg 1$ GeV/c an alternative sinusoidal sweep excitation is implemented. While taking significantly longer, this allows to increase the power density, which otherwise would not be sufficient for such high energies.

BUNCH-BY-BUNCH DATA ACQUISITION AND PROCESSING

The excited transverse oscillations are measured using the existing COSY beam position monitors (BPMs), which underwent a major upgrade in 2017 [3]. Bunch positions are recorded every turn (bunch-by-bunch positioning) with the Libera Hadron [4] processor.

From the 29 available BPMs, the operator can chose those with the largest betatron function in order to improve the sensitivity to the beam oscillations. The bunch positions are acquired upon a measurement trigger and subsequently read out from the Libera Hadron's buffer.

Performing a discrete Fourier transform on the position data sampled at the revolution frequency yields the transverse frequency spectra as shown in Fig. 1. The accuracy of the measurement is improved by a background correction and filtering. Plausibility checks help to filter out incorrect measurements. The betatron sideband in the frequency spectrum is then fitted with a Gaussian, yielding the fraction $r = f/f_{\mathrm{rev}} \in [0, 0.5]$ for both planes. The absolute tune is calculated using the corresponding half-interval as pre-

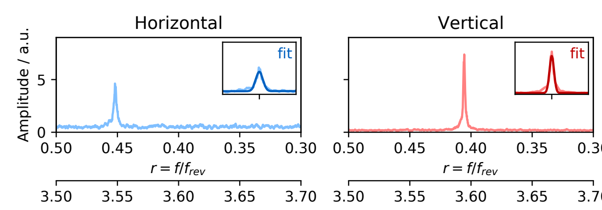

Figure 1: Frequency spectra of a tune measurement with Gauss fits: $Q_x = 3.5482 \pm 0.0015$; $Q_y = 3.5945 \pm 0.0009$.

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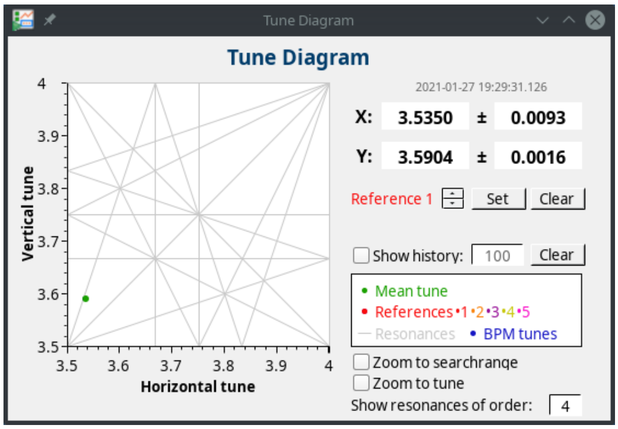

Figure 2: Tune diagram with working point (GUI screenshot).

dicted by model calculations. For the typical working point of COSY, this corresponds to $Q = 4 - r \in [3.5, 4]$.

FAST TUNE MEASUREMENT

With about 25 ms measurement time during excitation and again as much for the background measurement prior to excitation, a fast and quasi non-destructive tune measurement is performed. By computing the Fourier transform on 2^{13} sampled bunch positions, a resolution of 10^{-4} is achieved. Due to the width of the betatron sideband, the typical measurement uncertainty is in the order of 10^{-3} (see Fig. 1).

For regular use by the operating crew and experimentalists, the measurement routines are integrated into the COSY control system EPICS [5]. Thereby archiving of the measured data is enabled, as well as interaction with the MAD machine model [6]. Dedicated user interfaces (GUIs) are provided for control of the measurement parameters as well as to visualize the measurement results. This includes an interactive tune diagram (Fig. 2), which displays the working point alongside the tune resonance lines to be avoided and allows setting references.

CONTINUOUS TUNE MEASUREMENT

By continuously exciting the betatron oscillations, the tune can be tracked for several seconds. Therefore, a short-time Fourier transform (STFT) is used to compute the spectra as a function of time. The resolution in tune and time $\delta q \cdot \delta t = 1/f_{\text{rev}}$ is fixed by the revolution frequency. For a typical beam energy at COSY, resolutions of about 10^{-3} in tune and 1 ms in time can be achieved.

Figure 3 shows such a continuous tune measurement during bunching and acceleration. The fixed excitation band is chosen such, that the tune is visible throughout the complete measurement. As the revolution frequency increases, the excitation shifts from the betatron sideband at $1 - q$ to the one at q, partially overlapping halfway up the acceleration ramp. Since the excitation power is also kept constant, the tune signal becomes weaker as the beam gains momentum and drops when the second sideband is no longer excited. The transition of the tune from injection to flat top obtained by fitting the spectra is shown in the tune diagram in Fig. 3 (right).

CHROMATICITY MEASUREMENT

To measure the chromaticity, the beam's momentum is changed slightly and the resulting linear tune change is observed. The momentum is controlled with the RF cavity by a symmetric frequency sweep of typically ±0.3 ‰. Using the continuous tune measurement, the tune change ΔQ is determined. Therefore, a Gaussian with linear moving centroid is fitted to the normalized spectrograms. The corresponding linear frequency change Δf_{rev} is reconstructed at the same time from the bunch timestamps. With the slip factor η either from a MAD model calculation or separate

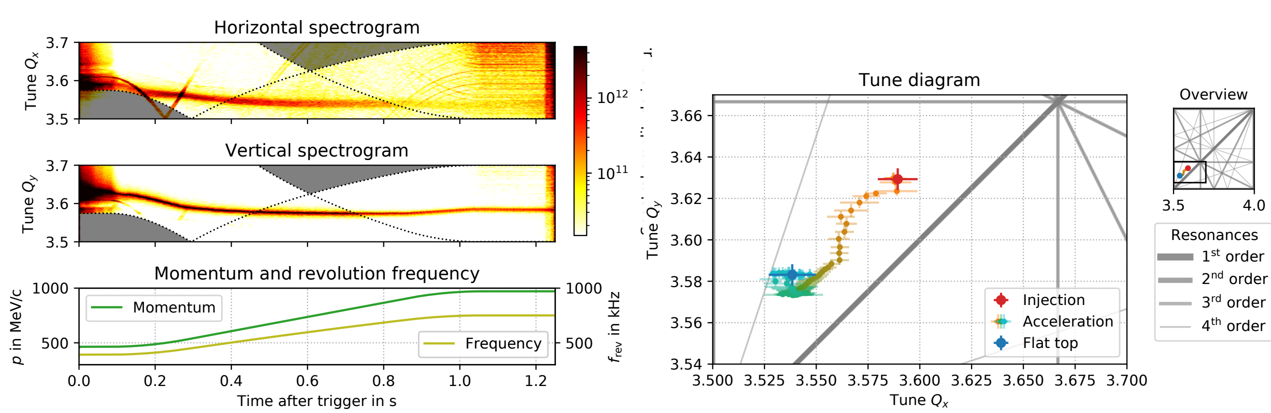

Figure 3: Tune measurement during bunching and acceleration of a deuteron beam from 460 MeV/c (injection) to 970 MeV/c (flat top). Left: Frequency spectrograms with the tune visible as bold line. The excitation frequency band from 0.3 to 0.5 · 750 kHz is indicated by dashed lines; shaded regions are not excited. The momentum ramp is shown in the bottom plot. Right: Evolution of the tune during the acceleration in the tune resonance diagram.

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measurement, the chromaticity is calculated:

$$\xi = \frac{\Delta Q}{\Delta p/p} = \eta \frac{\Delta Q}{\Delta f_{\mathrm{rev}}/f_{\mathrm{rev}}}$$

Figure 4 shows a screenshot of the operator GUI, displaying the linear frequency and tune changes as function of time as well as the fit results and determined chromaticity.

By performing the STFT over chunks of 2^{13} bunch positions, a resolution in tune of 10^{-4} is achieved. With a sweep time of about 0.5 s to 1 s, the linear fits are calculated over 50 to 100 spectra. This allows to determine the chromaticity with a typical uncertainty of 0.5 units.

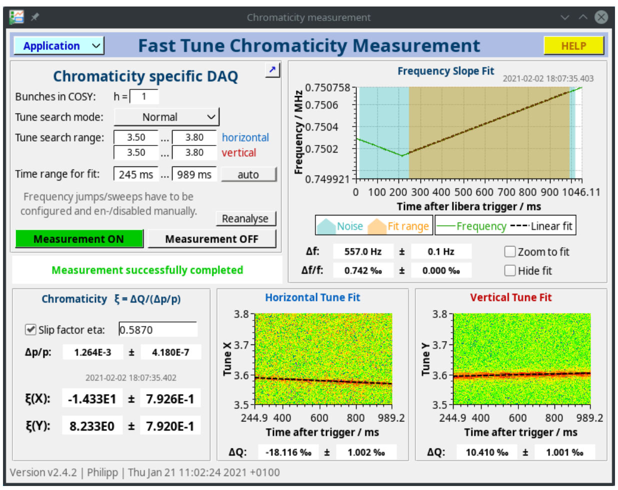

Figure 4: Chromaticity measurement (GUI screenshot).

CONCLUSION

The development of a fast tune measurement system for COSY started in 2019 [7]. Since the initial version, many improvements were made and new features were added: In addition to the noise excitation using a fixed frequency band, a sinusoidal sweep excitation mode for high beam energies was implemented. A continuous tune measurement was developed, allowing to track the evolution of the tune, e.g. during the acceleration ramp. Based on the tune tracking, a chromaticity measurement was realized by sweeping the beam momentum with the RF frequency and observing the linear tune change.

In the future, it is planed to extend the BPM based tune measurement to unbunched beams by directly analysing the pick-up signal (ADC data) provided by the Libera Hadron. The feasibility of this approach has already been confirmed and can be implemented.

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