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HORIZONTAL BEAM RESPONSE AT EXTRACTION CONDITIONS AT THE HEIDELBERG ION-BEAM THERAPY CENTRE

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Abstract

The Heidelberg Ion-Beam Therapy Centre's synchrotron makes use of the sextupole driven RF-KO method near the third-order resonance in order to slowly extract the beam that is delivered to the patients. The horizontal beam response of a coasting beam was studied experimentally and with simulations at extraction conditions in order to deduce regions of interest for an optimal excitation signal spectrum. Two narrow frequency regions were found were the beam reacts coherently. With these information an RF signal was proposed for the resonant slow extraction.

INTRODUCTION

The Heidelberg Ion-Beam Therapy Centre is a state-of-the-art facility capable of delivering four ion species of proton, ^{4}He, ^{12}C and ^{16}O and is equipped with the first heavy ion gantry worldwide. After the beam has reached it's final nominal energy in the synchrotron, it is slowly extracted by means of the sextupole driven RF-KO method [1, 2]. The horizontal tune is brought near a third-order resonance and this is actively fed further by resonance sextupoles. Under these conditions the beam's horizontal emittance is slowly blowed up with an external EM field. To ensure that the the extracted particle count remains constant, several techniques were implemented [3].

In this contribution the experimental data of the horizontal beam response of a coasting beam under extraction conditions and a simulation of it are presented. For the design of excitation RF signals for the slow extraction the typical approach was based on direct phenomenological studies (measurements and simulation) of the spill [4–7]. The study of the BTF at extraction conditions can aid to the design of the spectrum of the RF signal, since it can directly unveil the areas in frequency-space where the beam reacts coherently.

BTF MEASUREMENT

In this section the BTF measurement of a coasting carbon-ion beam $^{12}\mathrm{C}^{6+}$ with kinetic energy $E_{\mathrm{kin}} = 124.25\,\mathrm{MeV/u}$ is presented. The experimental setup for the measurement of the Beam Transfer Function (BTF) is shown in Fig. 1. Relevant parameters of the linear ion-beam optics can be found in Table 1. The tune values were infered from the BTF signal measured at extraction flattop with sextupole magnets off. The chromaticity of the machine was measured by introducing an offset on the end frequency of the accelerating cavity to produce a momentum offset and determining the tune shift through the BTF measurement with sextupole magnets off. The value presented in Table 1 is meant to be the specific chromaticity of the machine, namely $\xi = \frac{\Delta Q}{Q} / \frac{\Delta p}{p}$. The slip factor was determined from the experimental value of the synchrotron frequency f_S. The momentum-spread was infered from the width of the Schottky pick-up signal of the second harmonic of the revolution frequency.

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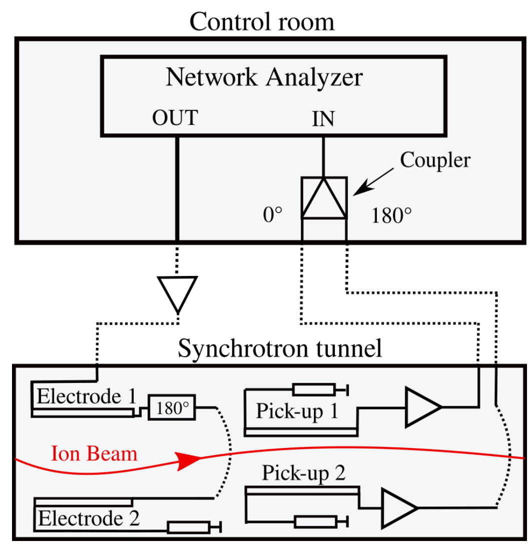

Figure 1: BTF experimental setup. The network analyzer (NA) generates an excitation signal and scans over a frequency span of interest. The response of the beam is then measured with two pick-up electrodes.

Table 1: Ion Optical and Beam Parameters of the HIT Synchrotron (The Momentum Spread is at FWHM)

Parameter	Symbol	Nom. Value	Meas. Value
Hor. tune	Q_x	1.67895	1.6795(1)
Ver. tune	Q_y	1.755	1.720(6)
Slip-factor	$\lvert\eta\rvert$	0.4766	0.44(2)
Hor. chroma.	ξ_x	-0.66	-0.72(6)
Mom. spread	σ_δ	-	$1.2{\cdot}10^{-3}$

After the beam has arrived to the nominal flattop energy, it is debunched and the tune is brought near the third order the resonance. Simultaneously the sextupoles are excited to the nominal strength for extraction, this corresponds for the resonance sextupoles to a strength of $k' = 0.9\,\mathrm{m}^{-3}$. This process lasts approx. 500 ms to ensure adiabaticity and that the

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particle distribution converges to a stationary distribution. In contrast to an ion-beam optics diagnostic run, the BTF at extraction conditions poses an additional challenge. Since the beam is prepared to be extracted, the dynamical aperture is considerably reduced, hence any external excitation leads easily to extraction (or beam loss) and thus spoils the signal. In order to recover a reasonable signal, the power of the external stimulus was dimmed such that particle loss during the measurement could be avoided.

The sweep time of the investigated frequency span around the betatron resonance was set to ten seconds and equal for all shots. The investigated frequency span $f \in [18.0479, 18.0979]$MHz was scanned in 701 frequency steps. The read-out of the stored current was used to monitor and confirm that no beam loss was present during the measurement. The measured signal is illustrated in Fig. 2.

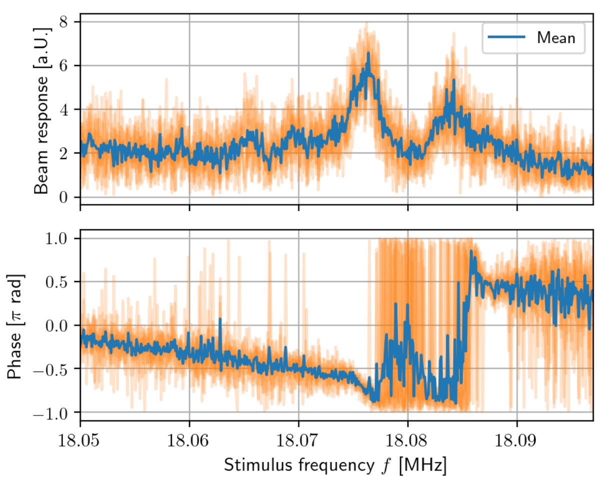

Figure 2: Measured horizontal beam response at extraction conditions. Orange background: Overlapp of eight different shots. Blue solid curve: Mean value of the eight recorded shots.

The beam response (see Fig. 2 upper panel) shows clearly two regions where the beam reacts coherently to external periodic excitations. This result is in complete agreement with previous studies [4]. Since the measurement had to be performed with a dimmed excitation signal to avoid beam loss, the recorded signal was at background noise level. Note that the beam response is in linear scale. By averaging over many shots the background noise contribution can be suppressed, as it is illustrated by the blue solid curve in Fig. 2. The phase (see Fig. 2 lower panel) appears to show a jump near the position of the peak nearest to the third order resonance $f_{\text{res}} = 18.1$ MHz. The apparent phase jumps in the frequency region from $f \in [18.075, 18.085]$ MHz come from the equivalence of an additive degree of freedom of 2π; the signal jumps from $-\pi$ to π and viceversa.

In the next section the simulation of the BTF measurement will be presented.

Table 2: Parameters for the Simulation of the BTF Measurement

Parameter	Value
N particles	10^4
Turns(recorded)	2600(325)
Max. kick	2.5 µrad/turn
Tune span	[1.6679, 1.6841]
Tune steps	200
$\varepsilon_{x,y}$ (rms)	2 mm mrad

BTF SIMULATION

The BTF measurement was simulated under extraction conditions, where a bunch of particles was tracked turn-by-turn while externally excited by a harmonic stimulus with a frequency (tune) range near the betatron resonance. To start, an initial particle distribution, whose transversal probability density function reads

$$\rho(\vec{x}) = \frac{1}{\sqrt{2\pi\varepsilon}} \exp\left(\vec{x}^T \Sigma \vec{x}\right), \qquad \Sigma = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \quad (1)$$

where α, β, γ are the corresponding ion-beam optical functions from the Courant-Snyder parametrization and the emittance ε for each transversal plane, was tracked for 10^4 turns under extraction conditions (with nominal sextupole fields for extraction) in order to recover a stationary distribution. This stationary distribution was excited externally over a tune region of interest (see Table 2) over 2600 turns for each sampled tune step. Relevant parameters of the simulation can be found in Table 2. The simulation was performed with the MAD-X tracking module [8]. The momentum-spread was the same as in Table 1.

For the analysis of the simulated data the considerations described in [9, 10] were implemented. In principle, the region corresponding to the core maintains the same particle density such that for a coasting beam the core delivers a simple DC signal to the pick-up electrodes. In contrast, the particle density outside of the core (which form the so called lunettes [9]) shows a more significant change over time due to the external harmonic excitation, thus the AC signal measured at the pick-up electrodes is mostly given by this density modulation. On top of this, the stripline Schottky pick-up electrodes' non-linear sensitivity enhance the contribution of particles with higher amplitudes to the measured signal.

To account for this phenomenon, the particles inside a region of $x_{\text{cut}} \in [-2.1\sigma_x, 2.1\sigma_x]$ were masked-out and the remaining particles were considered for the calculation of the center of charge. σ_x refers to the horizontal spatial standard deviation of the initial particle distribution (with no external harmonic excitation). The dependency of the simulated signal as function of the parameter x_{cut} is illustrated in Fig. 3. Without this consideration the simulated BTF signal peaks more prominently at the nominal tune value (zero amplitude betatron frequency) and the second peak is considerably overshadowed and shifted away from the resonance. Note

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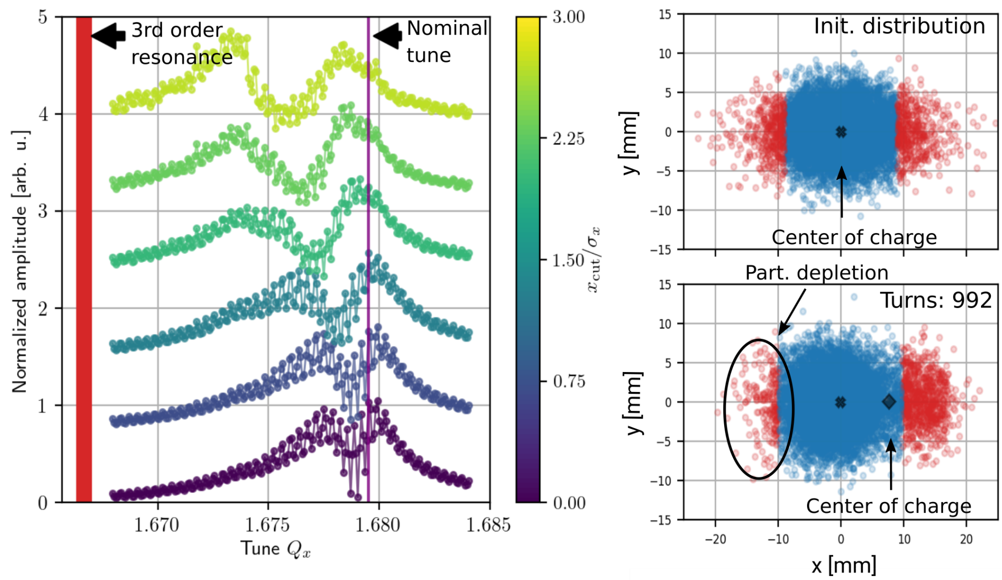

Figure 3: Horizontal beam response as function of the cutoff parameter.

that the splitting behaviour of the simulated signal is always present. There is no trivial way of determining from *a-priori* considerations the cutoff region.

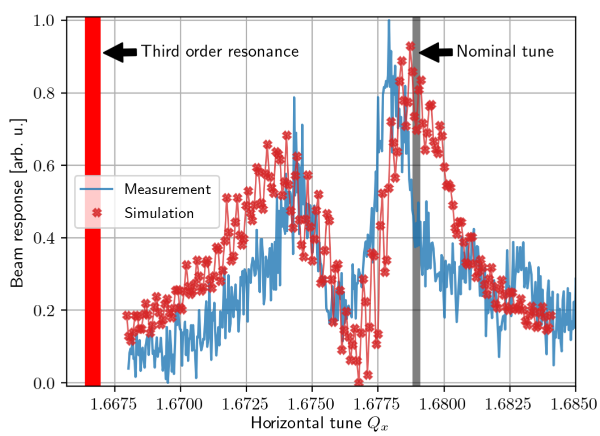

Figure 4: Horizontal beam response.

The result of the simulation and a comparison to the measured signal are illustrated in Fig. 4. From the BTF two regions of interest can be recognized. The tune regions appear to be sharply localized such that narrow bands would suffice for driving the beam's coherent response efficiently. Other tune regions appear to have a weaker influence on the beam response at extraction conditions at HIT. Therefore an excitation signal for the emittance blow-up scheme has to carry mainly frequencies in its spectrum that cover these two regions of interest.

SUMMARY AND CONCLUSION

In this contribution the measurement of the BTF of a coasting carbon ion beam E_{kin} = 124.25 MeV/u and relevant ion beam optics and beam parameters were presented. The signal showed two frequency regions at which the beam reacts coherently. The BTF measurement was simulated under extraction conditions. Considering the Hereward effect [9] together with the non-linearity of the strip-line pick-up sensitivity, the simulation and the measurement agree well with each other. With this information an excitation RF signal for the slow RF KO extraction can be designed, such that the frequency regions, where the beam reacts coherently strong, are covered by the signal's spectrum.

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