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TRANSVERSE EXCITATION AND APPLICATIONS FOR BEAM CONTROL

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Abstract

Transverse excitation of stored particle beams is required for a number of applications in accelerators. Using a time-varying, transverse electric field with a dedicated frequency spectrum, the amplitude and coherence of betatron oscillations can be increased in a controlled manner. This allows for determination of the betatron tune from turn-by-turn position measurements, control of transverse beam shapes, as well as extraction of stored beams. For studies of beam excitation, a custom signal generator is being developed. It is based on software-defined radio (SDR) which allows for configurable signal characteristics and tuneable spectra. This approach enables usage for multiple applications in beam diagnostics and control. To determine appropriate excitation spectra, studies of particle dynamics in presence of excitation are being carried out. Nonlinear fields are also incorporated to account for beam extraction conditions, which affects frequency spectra of beam motion due to detuning effects.

PARTICLE DYNAMICS SIMULATIONS WITH SIMPLIFIED MODEL

To study the effect of excitation on the dynamics of particles in a circular accelerator, a simplified model is used. In this model, the linear ion optics are described by a linear transfer map with machine tune q. Nonlinear contributions are condensed in a single virtual sextupole magnet in thin-lens approximation, which drives a 3rd order resonance hence allowing to model conditions typical for beam extraction. A dipole kicker excites the transverse betatron oscillations with a dedicated, time-dependent kick. The particle motion is studied in 2D (flat beam approximation) with zero chromaticity. By making use of normalized phase space coordinates $X = \sqrt{2J}\cos(\theta)$ and $X' = -\sqrt{2J}\sin(\theta)$ as well as normalized kick strengths, the simulation is independent of local twiss parameters.

The simulations presented in this paper use a machine tune of $q = r + d$ with small distance $d = -0.003$ to the resonance $r = 2/3$, but the results are valid for the $1/3$ resonance as well. The 3rd order resonance is driven by a sextupole with normalized strength $S = -0.45\,\mathrm{m}^{-1/2}$. The free particle dynamics of such a system is well described by the Kobayashi theory [1] with Hamiltonian:

$$H = 3\pi d\left(X^2 + X'^2\right) + \frac{S}{4}\left(3XX'^2 - X^3\right)$$
$$H_{\mathrm{sep}} = (4\pi d)^3 / S^2 \qquad (1)$$

The equipotentials of H are shown in Fig. 1 (left).

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SINUSOIDAL EXCITATION

We consider a dipolar deflector with a time-variant, sinusoidal transverse field. A traversing particle experiences a kick $\Delta X' = K\sin(2\pi f_{\mathrm{ex}} t)$ where $K = -k_0 l\sqrt{\beta_x}$ is the normalized strength of the deflector and f_{ex} the excitation frequency. A typical use case of such a sinusoidal excitation is a beam transfer function (BTF) measurement [2] of a linear machine, where the beam response is measured as function of the excitation frequency. In the case of linear dynamics, this allows to determine the resonant tune.

Beating

If the excitation frequency f_{ex} is near but different from the betatron oscillation frequency $f_{\mathrm{q}} = qf_{\mathrm{rev}}$, a beating can be observed, leading to large transverse beam oscillations, where f_{rev} denotes the revolution frequency. In linear beam dynamics this beating motion is simply the consequence of the superposition of the two oscillating terms which are periodically in and out of phase. This leads to a period in- and decrease of the particle oscillation energy at the beating frequency $|f_{\mathrm{q}} - f_{\mathrm{ex}}|$, causing the beam to spiral in- and outwards in phase space. The particle oscillation energy is thereby quantified by the value of the Hamiltonian H.

For nonlinear dynamics and excitation in the vicinity of the driven 3rd order resonance however, detuning with action J and angle θ plays a major role [3,4]. In this case, the betatron oscillation frequency and therefore its phase advance

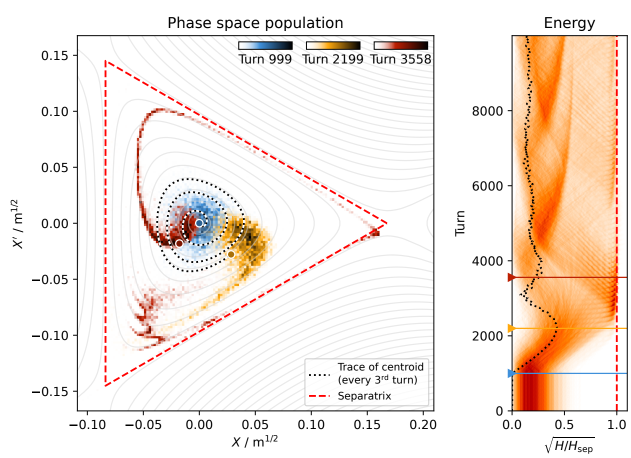

Figure 1: Particle beam dynamics during sinusoidal excitation with frequency $f_{\mathrm{ex}}/f_{\mathrm{rev}} = 0.6641$. The excitation with strength $K = 10^{-4}\,\mathrm{m}^{-1/2}$ starts in turn 1000. The color shading represents particle density; the dotted black line the centroid motion; and the red dashed line the separatrix. Left: Phase space image for three distinct turns and trace of centroid in between. Right: Energy according to Eq. (1).

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per 3 turns is no longer constant, but continuously changes as the particle moves in phase space according to:

$$q_{3\text{-turn}} = \frac{1}{2\pi}\frac{\partial H}{\partial J} = 3d - \frac{3S}{8\pi}\sqrt{2J}\cos(3\theta) \qquad (2)$$

Figure 1 shows results of a particle tracking simulation of a Gaussian beam of 10^4 particles with sinusoidal excitation near the driven 3rd order resonance. The centroid of the particle beam initially shows the beating motion with in- and decreasing oscillation energy and spiraling motion in phase space described above. However, the beating is damped after a few periods. This is caused by a spread in beating frequency due to the tune spread originating in the various detuning effects. In addition, filamentation of the beam leads to a broad coverage of amplitudes and angles in phase space, leading to further stabilisation of the centroid motion.

The distribution of particles during excitation is not uniform. While a majority of particles stay close to or return towards the center of phase space, and thus does the centroid, few particles gain large amounts of energy and eventually become unstable. The phase space image reveals that the beam is strongly stretched, forming a tail that reaches to the separatrix and eventually filaments towards smaller amplitudes again. This behaviour can be understood as follows: the spiraling and beating motion affects the phase advance per turn due to detuning with amplitude and phase. With the phase advance constantly changing, the relative phase between particle motion and excitation is modulated, which feeds back on the beating motion. As a consequence, the evolution of the beam distribution strongly depends on the exciting frequency and phase.

Nonlinear Resonant Region

To understand the effect of sinusoidal excitation at different frequencies on the particle motion, the simulations have been repeated for different values of f_{ex}. The distribution of the resulting motion in frequency and energy is depicted in Fig. 2. In addition, the narrowly band-filtered magnitude response along f_{ex} corresponding to the diagonal in the frequency spectra is shown. Excitation away from the machine tune shows a small transverse energy distribution corresponding to the initial values of the Hamiltonian of the system. In this case, the beam performs a forced oscillation as a whole and there is no net energy or emittance increase if the excitation is switched on adiabatically [5]. The frequency analysis of the single particle motion shows two distinct frequency components corresponding to the forced oscillation and the non-excited motion, which differs from q due to the amplitude detuning.

A sinusoidal excitation near the betatron tune resonance shows a strong effect on the transverse oscillation energy, which is apparent in Fig. 2 (left) as a large spread in values of H covered by the beating motion. This resonant region includes a range of excitation frequencies from $N \pm q$ ($N \in \mathbb{N}$) towards the direction of the driven 3rd order resonance. The range of frequencies is related to the tune spread due to detuning with amplitude and phase, which already applies to the single particle case since it is directly connected to the spread in H due to the beating and sprialing motion in phase space as described above. The beating in this region is not simply a consequence of the superposition of two oscillating motions as in the off-resonant case. Instead, the phase of particle motion is correlated to the phase of excitation, with the phase difference (slowly) oscillating within 0 and 180 degree. The slow speed of this oscillation allows energy transfer between the exciting field and the particle and hence the energy modulation is very strong in this region. For a certain frequency the particle even reaches the origin of phase space where H reaches zero. For another excitation frequency closer to the resonance, the spiraling motion reaches the separatrix. Only at this frequency particles become unstable and are lost. The detuned betatron frequency lies in between at $f/f_{rev} \approx 0.336$.

The frequency analysis in the resonant region shows a broad spectrum with a comb-like structure. These additional frequency components can be identified as the beating sidebands; their spacing corresponds to the frequency of

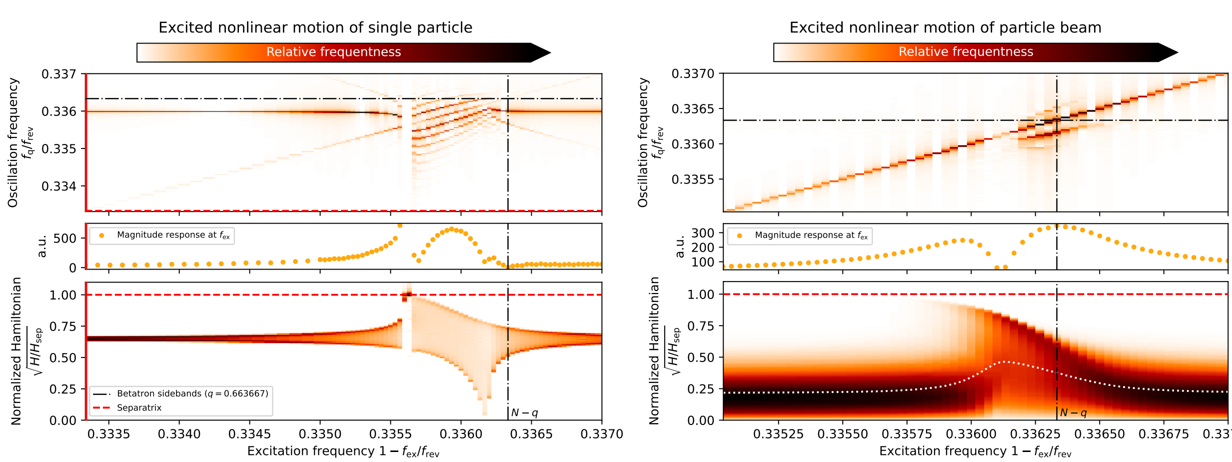

Figure 2: Frequency spectra, magnitude response and energy distribution of a single particle (left) and a Gaussian beam (right, 10^4 particles) over 5×10^4 turns during sinosoidal excitation with $K = 5\times10^{-5}\ \mathrm{m}^{-1/2}$ near driven 3rd order resonance.

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beating motion. The energy of transverse oscillations is thereby distributed into these sidebands, which for certain values of f_{ex} are even dominant over the oscillation energy at the excitation frequency. For a BTF measurement this means, that the magnitude response shows a dip in the resonant region, which has already been experimentally observed [4].

Even for a particle beam (Fig. 2, right) consisting of many particles with different initial phase space coordinates and different detuning, the basic properties of this resonant region remain visible: The largest value of the Hamiltonian is reached at an excitation frequency much closer towards the $2/3^{rd}$ resonance, where particles can become unstable and be extracted. However, only few particles have such a large oscillation energy while most remain at small amplitudes (meaning that the beam emittance remains small). In the frequency spectra of the centroid motion, only the forced oscillation is coherent, while the non-excited incoherent motion is not visible. Nonetheless, the beating sidebands in the resonant region can still be observed. Likewise, the spectral power in a narrow band around the exciting frequency is reduced at a certain excitation frequency $f_{ex} \approx 0.3361$ compared to the surrounding frequencies.

BEAM EXCITATION SIGNAL GENERATOR

For excitation of transverse oscillations, a software based signal generator is being developed at GSI. Besides experimental studies of excitation mechanisms, the device can also be used for regular tune and chromaticity measurements or Radio Frequency Knock Out (RF-KO) extraction. For this purpose, an universal software radio peripheral (USRP) with 2 RF in- and outputs each and several general purpose input/outputs (GPIOs) is used (Fig. 3). Such hardware has already been successfully used for beam studies of RF-KO extraction at the Heidelberg Ion Therapy Center (HIT) [6]. The device converts the analog signals to digital samples while streaming the data to an industrial PC and vice verca. Digital signal processing (DSP) is implemented on the PC using the open source GNU Radio framework [7].

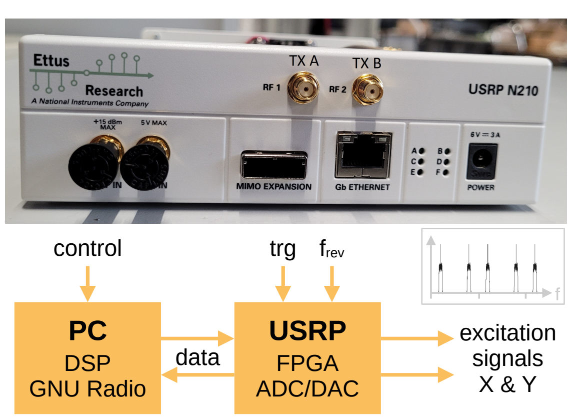

Figure 3: USRP hardware and schema for signal generation

This allows for a large flexibility in signal processing and generation at comparatively low costs and short realization times.

The excitation waveform is generated in baseband at a sampling rate of 333 kS/s. Presently, 4 basic signal types are implemented: single frequency sinusoid, bandlimited white noise, random binary phase shift keying and frequency chirp. Bandwidth and signal level of the excitation signals are adjustable at run-time according to the requirements. The narrow-band signal is up-sampled to 10 MS/s and shifted to the betatron oscillation frequency at $f_{ex} = (h \pm q) f_{rev}$, where $h \in \mathbb{N}$ is the harmonic. For the horizontal and vertical plane, two independent signals can be produced at a betatron sideband corresponding to the respective tunes.

For excitation during the acceleration ramp an RF reference signal connected to one of the USRP's inputs provides the revolution frequency f_{rev} and thus defines the location of the sidebands.

For the initial data processing flowgraph, the delay was non-deterministic and ranging from 20 ms up to several 100 ms, including dropouts in the produced signals due to buffer underruns. Significant effort was put into reducing the digital signal processing and transmission delay to overcome this issue. A custom implementation for data flow control was able to significantly reduced and stabilize the delay in the long-term. The signal delay between RF reference input and excitation output achieved is 2.05(17) ms, which even for the highest acceleration ramping speed of 8 MHz/s results in a deviation of only 5 kHz at a typical tune of 0.3, which is within the margin covered by the excitation bandwidth needed to account for tune variations. The delay between trigger and start of the excitation signal is 1.89(34) ms, which is small compared to the typical duration of excitation used. In nutshell, the performance achieved with a DSP based solution is sufficient for usage as excitation generator in the GSI/FAIR accelerator environment.

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