Effect of Mains Ripple Harmonics on Longitudinal Emittance of Bunches in the UNK

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Abstract

Features peculiar to longitudinal beam dynamics in the UNK are investigated when the mains ripple harmonics affect the beam via the guide magnetic field and the RF-voltage. The natural nonlinearity of synchrotron oscillations as well as the presence of an external beam control system are taken into account. The problem is of special importance for the UNK because of relatively low acceleration rate and low bucket-to-bunch ratio. Requirements to the feedback performances and to the level of perturbations of the magnetic and RF fields are obtained.

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Severe limitations on the longitudinal emittance ε are imposed in most large machines. Tolerances on ε should provide the highest possible luminosity in storage rings as well as keep out the losses of particles in accelerators with a high beam current.

For example, in order to reach the nominal luminosity at the IHEP Accelerating and Storage Complex (UNK) which is under construction now, the total growth of longitudinal emittance during acceleration from 65 GeV to 3 TeV should not exceed 25% of its initial value.

As for the UNK fixed-target operation mode, estimations have shown that 1% losses of design intensity might cause an overheating and subsequent quench of the superconducting magnets. Besides, the problem of emittance conservation is of special concern at the UNK because of its relatively low bucket-to-bunch ratio.

Of all disturbing factors affecting the longitudinal motion, a great deal of attention in last years was put to such strong effects as collective instabilities and noises of guide magnetic field and RF-voltage. All these would result in a more or less fast emittance growth. However, in view of extremely strict limitations imposed on ε at the UNK, one can not restrict himself exclusively to consideration of the effects mentioned. It is necessary to take into account all possible sources of the longitudinal emittance growth.

Some of perturbations caused by periodical pulsations of guide magnetic field $\Delta B/B$ and of radio-frequency $\Delta\omega_0/\omega_0$, are considered in this paper. Such pulsations occur due to the mains ripple which always persist in the magnet power supplies. Spectrum of these perturbations is a line one: its power density is concentrated at the mains angular frequency ω_1 and its higher harmonics $\omega_k = k\omega_1$, $k \geq 1$ are integers. Thus, perturbations of the following type are studied:

$$F(t) = F_m \sin(\omega_k t + \chi). \tag{1}$$

It is a rather complicated and expensive problem to suppress such perturbations in big machines. Therefore, it seems mandatory to estimate realistically the acceptable level of pulsations from the view point of their effect upon the longitudinal emittance.

While considering effect of the above perturbations on the longitudinal beam dynamics, it is customary to ignore nonlinearity of phase motion as well as presence of a feedback (e.g., see [1]). Usually, such simplifications are introduced for making the relevant equations tractable. However, this approximation is too rough, and seems to be applicable only for sufficiently short bunches. It is shown below that one should take into account the dependence of phase oscillation frequency on the amplitude to get more realistic results. Equations of longitudinal motion which include the above perturbations are written down as

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_s}\right) = \frac{eV}{2\pi}\left(\cos\phi - \cos\phi_s\right) \tag{2}$$

$$\frac{d\phi}{dt} = qK\omega_s\frac{\Delta E}{E_s} + \delta\omega_0 - q\alpha\omega_s\frac{\Delta B}{B}. \tag{3}$$

Here $\Delta E = E - E_s$ is energy deviation from the synchronous value, ϕ is RF phase of a particle, $eV\cos\phi_s$ is energy gain per turn, q is RF harmonic number, α is momentum compaction factor, ω_s is (angular) revolution frequency of a synchronous particle, $K = (\alpha\gamma_s^2 - 1)/(\gamma_s^2 - 1)$, γ_s is reduced synchronous energy.

Computer simulation was used to solve these equations. It should be noted that it is the longitudinal dipole mode which dominates whenever the resonant excitation is brought about by magnetic field and/or radio-frequency perturbations. Hence, a beam feedback should serve as a principal stabilizing factor. To get realistic results, we took this factor into account by using a simplified feedback model in which any excursion of the bunch center from the synchronous phase angle is corrected through the exponential law: $\Delta x(t) = \Delta x_0 \exp(-t/\tau)$, where Δx_0 is the bunch offset at $t = 0$.

Contrary to betatron motion, it is typical that the phase oscillation frequency either decreases adiabatically during acceleration, or changes rapidly, say, in $10 - 20$ phase oscillation periods, in going from injection to acceleration. Thus, in fact, the bunch crosses the longitudinal resonance at the mains harmonics. However, it is convenient, for a while, to assume that the bunch is crossed by the resonance, perturbation frequency ω_k being varied and phase oscillation frequency Ω_s being kept constant. It seems to be justifiable for it is a relative variation of ω_k w.r.t. Ω_s, or vice versa, which is actually of importance. In this case the bucket's shape and area, the equilibrium bunch length, its energy and other parameters are kept constant, which allows one to find out a few generalized qualitative results.

Fig. 1 shows the relative growth of the smeared longitudinal emittance $\varepsilon/\varepsilon_0$ against $t_r = t/T_s$ where t_r is a time interval during which frequency ω_k of external perturbation occurs within incoherent frequency spread in the bunch, $T_s = 2\pi/\Omega_s$ is a small-amplitude phase oscillation period. Magnetic field perturbation corresponds to Eq.1 with $F_m = (\Delta B/B)_m = 1 \cdot 10^{-5}$; bucket-to-bunch ratio is $S/\pi\varepsilon = 2.4$. The calculations were carried out for circulating beam whose $\cos\phi_s = 0$. Phase oscillation frequency Ω_s is kept constant while perturbation frequency ω_b increases linearly so as to pass through the entire incoherent frequency spread within the bunch. The results are obtained for the linear (curve 1) and sinusoidal RF-voltage wave-form (curve 2) without a feedback. It is evident from Fig. 1 that linear approximation can result in an unduly severe limitations on the level of perturbations.

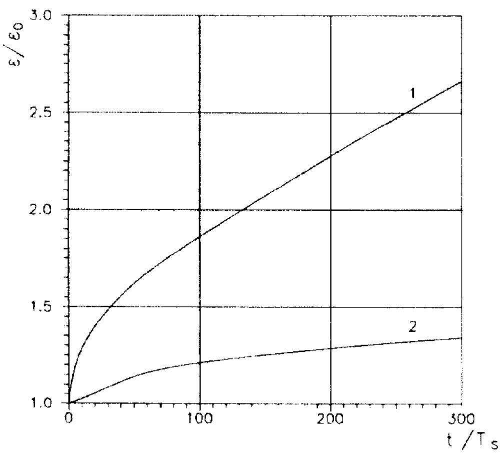

Figure 1: Emittance growth for the linear (curve 1) and sinusoidal (curve 2) RF-voltage wave-form.

The above said is especially actual for the UNK where bucket-to-bunch ratio is as low as $S/\pi\varepsilon \leq 2 - 3$. It follows from the previous example that realistic tolerances on $(\Delta B/B)_m$ and other perturbations can be obtained only with the nonlinearity of the phase motion taken into account.

The analogous graph for $\varepsilon/\varepsilon_0$ in nonlinear case is shown in Fig. 2. This time, the effect of feedback is taken into account. The curves are obtained for various values of the damping time constant τ/T_s ($\tau \to \infty$ stands for feedback being off). A strong damping effect of the feedback is clearly seen. It should be noted, the feedback is less effective for bunches with a frequency spread because, as is evident, in linear case oscillations would be quickly suppressed to zero on having passed through the resonance.

In order to get more detailed information on the emittance growth and the corresponding tolerances on $(\Delta B/B)_m$ and τ, one should use parameters of a particular machine and simulate the real process of acceleration. Let us now consider the case when UNK operates as a 600 GeV accelerator (U–600). In this mode of operation $\Omega_s/2\pi$ will cross the mains 2-nd harmonic 100 Hz twice. Firstly, in going from injection to acceleration $\Omega_s/2\pi$ increases rapidly (in $\sim (10-20)T_s$) from 96 Hz to 128 Hz. Secondly, during acceleration in energy range of 110–170 GeV adiabatic decrease of $\Omega_s/2\pi$ results in much slower (in $\sim 250T_s$) crossing 100 Hz harmonic. Results for the last, much more dangerous, case are shown in Fig. 3 where the dependence of $\varepsilon/\varepsilon_0$ on the amplitude of the magnetic field pulsations $(\Delta B/B)_m$ is presented for various τ.

The the U–600 bucket-to-bunch ratio at the start of acceleration is as small as $S/\pi\varepsilon \approx 1.8$. Therefore, it is assumed that emittance growth after a single crossing of the resonance (due to one type of perturbation, say, $(\Delta B/B)$) should not exceed 2%. As is seen from Fig. 3, to meet this demand without feedback it is necessary to provide perturbation amplitude $(\Delta B/B)_{m2}$ which corresponds to the mains 2-nd harmonic amplitude being $\lesssim 1 \cdot 10^{-7}$. At the same time with $\tau = 0.5T_s$ this tolerance becomes 70 times more free: $(\Delta B/B)_{m2} \lesssim 7 \cdot 10^{-6}$. It is evident hereof, and the simulation proves it, that this condition provides almost ideal (i.e. without any emittance growth) crossing of the mains 2-nd harmonic during the short period between injection and acceleration.

It should be noted that the relevant tolerance on the amplitude of the radio-frequency pulsations can be readily obtained from the simple relation

$$(\Delta\omega_0/\omega_0)_m = \alpha\,(\Delta B/B)_m \tag{4}$$

which follows immediately from Eq.3. The corresponding amplitude of the RF-phase pulsation is

$$(\delta\phi)_m = \frac{\omega_0}{\omega_k}\left(\frac{\Delta\omega_0}{\omega_0}\right)_m \tag{5}$$

One can now summarize tolerances on the perturbations due to mains ripple at the 100 Hz harmonic for the U–600 as:

$$\begin{aligned} (\Delta B/B)_{m2} &\lesssim 7 \cdot 10^{-6} \\ (\Delta\omega_0/\omega_0)_{m2} &\lesssim 3.5 \cdot 10^{-9} \\ (\delta\phi)_{m2} &\lesssim 0.4^\circ \end{aligned} \tag{6}$$

The adiabatic decrease of phase oscillation frequency (as well as of frequency spread) at 600 GeV results in: $\Omega_s/2\pi \approx 55$ Hz and $\Delta(\Omega_s/2\pi) \approx 2.5$ Hz. Thus, formally, there is no crossing of the basic mains harmonic 50 Hz. However, frequencies Ω_s and ω_1 are quite close to yield a beating of oscillation amplitudes. If $(\Delta B/B)_m$ is large enough, some peripheral particles can fall into resonance with consequent growth of ε. Besides, some undesirable side effects can happen, say, beam modulation during slow extraction. Calculations show that feedback with $\tau/T_s \lesssim 0.5$ would suffice to avoid any emittance growth unless $(\Delta B/B)_m \gtrsim 1 \cdot 10^{-5}$. This condition can easy be met.

As far as operation mode of a 3000 GeV accelerator (UNK–3000) is concerned, the basic mains harmonic 50 Hz is the only one to be crossed at the superconducting ring. There is no resistivity in the superconducting coils. Hence, suppression of $(\Delta B/B)$-perturbations is much easier a problem as compared to conventional magnets. As for perturbations of RF, tolerance of Eq.6 provides $\varepsilon/\varepsilon_0 \lesssim 1.1$ which is enough in view of the better (compared to U–600) bucket-to-bunch ratio $S/\pi\varepsilon \approx 3$.

In a collider mode of operation, the 100 Hz harmonic is to be crossed in the 1-st ring while 50 Hz harmonic — in the 2-nd one. In the first case the acceleration rate is slower than in U–600, but the lower ratio ($S/\pi\varepsilon \approx 1.5$) yields stronger nonlinearity of phase oscillations. As a result the tolerances of Eq.6 are applicable for the collider mode as well. In the 2-nd case (crossing 50 Hz) the same tolerances would provide only $\varepsilon/\varepsilon_0 \lesssim 1.2$. Actually, it would be enough in view of large ratio $S/\pi\varepsilon \approx 5.5$. But contrary to all previous cases there is now a possibility to increase sharply the rate of the resonance crossing. To provide this, it is necessary to lower peak RV-voltage from 20 MV down to 12 MV, which should be done at ~1300 GeV when Ω_s = 59 Hz is still far enough from the resonance. During the time interval t_v it abruptly decreases to 46 Hz, the bucket-to-bunch ratio being acceptable: $S/\pi\varepsilon \approx 4$. Fig. 4 shows dependence of the emittance grows vs. t_v for various $(\Delta\omega_0/\omega_0)_{m1}$. The damping time is $\tau = 0.5T_s$. It can be seen that if $t_v \sim (4 \div 8)T_s$ we obtain the tolerances $(\Delta B/B)_{m1} \lesssim 0.7 \div 1.0 \cdot 10^{-5}$ and $(\Delta\omega_0/\omega_0)_{m1} \lesssim 3.5 \div 5.0 \cdot 10^{-9}$ which are easy to meet. The corresponding emittance growth $\varepsilon/\varepsilon_0 \lesssim 3 \div 4\%$.

The tolerances on $(\Delta B/B)_m$, $(\Delta\omega_0/\omega_0)_m$ and $(\delta\phi)_m$ are shown in the table below for all operation modes of the UNK. The results are obtained for the damping time constant $\tau = 0.5T_s$. Such a feedback is feasible in principle (e.g. see [2], [3], [4]), and now various schemes applicable for the UNK are being studied.

Table 1. Tolerances on perturbations of magnetic field, RF and RF-phase at the UNK ($\tau = 0.5T_s$)

Mode	ω_k, Hz	$\Delta B/B$ $\cdot 10^{-6}$	$\Delta\omega_0/\omega_0$ $\cdot 10^{-9}$	$\delta\phi_m$	$\varepsilon/\varepsilon_0$ $\sum$
U–600	100	7.0	3.5	0.4°	1.04
	50	7.0	3.5	0.8°	1.04
U-3000	50	3.5	3.5	0.8°	1.10
Colli-	100	7.0	3.5	0.4°	1.10
der	50	3.5	3.5	0.8°	$\leq$1.08

1 REFERENCES

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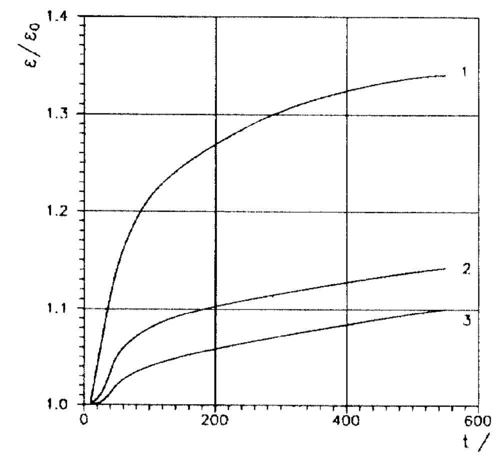

Figure 2: Emittance growth in presence of feedback; curves 1,2,3 correspond to τ/T_s =∞, 1.0 and 0.5.

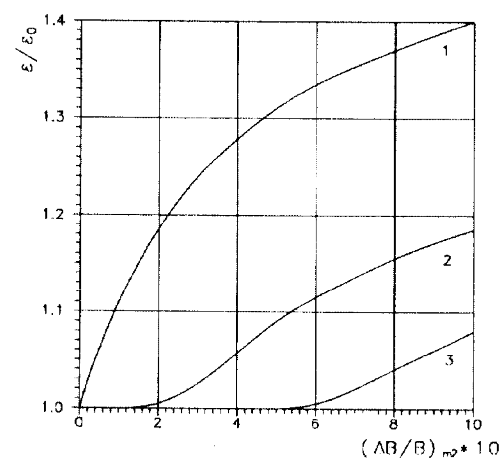

Figure 3: Crossing 100 Hz resonance at the U–600 during acceleration; curves are marked as in Fig. 2

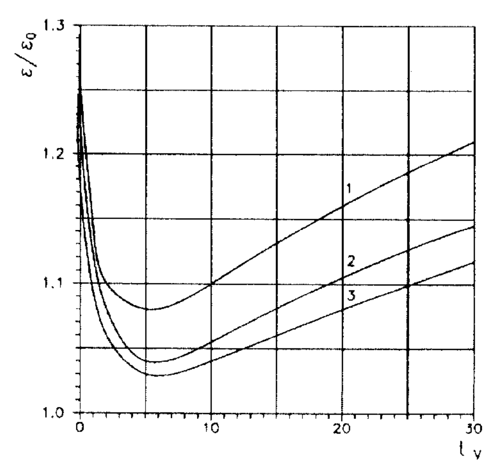

Figure 4: Fast crossing of resonance at 50 Hz in the collider mode. Curves 1,2,3 correspond to $\Delta\omega_0/\omega_{0m} = 7.5 \cdot 10^{-9}$, $5.0 \cdot 10^{-9}$ and $3.5 \cdot 10^{-9}$.