UPGRADING LONGITUDINAL BEAM BEHAVIOR IN IHEP BOOSTER

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Abstract

Operation of 1.5 GeV fast-cycling Booster proton synchrotron of IHEP has been long hampered by unwanted oscillations in bunch length. To identify the reason of such beam behavior, a dedicated beam-dynamics research program has been initiated. The scope of this activity has covered a variety of the might-be mechanisms behind — coherent instabilities, malfunction of voltage amplitude feedbacks, quality of the voltage program, etc. Ultimately, phase loop encircling the VCO has been upgraded, which resulted in a noticeably suppressed scale of both, dipole and quadrupole oscillations of beam.

BEAM OBSERVATIONS

Coherent oscillations in bunch length were incidentally observed during routine operation of the machine. These were monitored as a distortion of bunch shape prior to beam transfer. The process was accompanied by an occurrence of asymmetry in longitudinal density distribution. This picture had a rather uncertain cycle-to-cycle recurrence. Each time, the beam conduct was subject to improving noticeably with finer tuning the initial value of radio-frequency in the Booster. Still, a mismatch with phase-plane trajectories of the accepting ring, U70, persisted. It hampered subsequent accumulation and acceleration of a high intensity beam in U70. To this end, a dedicated R&D program was launched to study beam longitudinal oscillations through the entire cycle and elaborate technical cures against oscillations in bunch length, specifically.

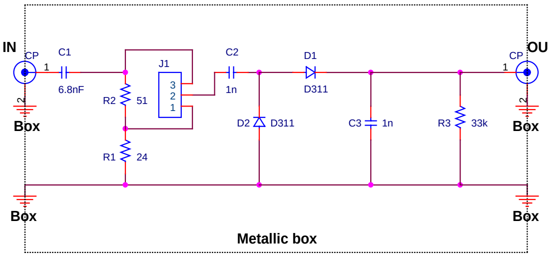

Figure 1: Circuit diagram of amplitude detector.

To monitor oscillations of bunch shape, a dedicated amplitude detector was developed (see Fig. 1). It is fed by a sum signal from an electrostatic beam-position pickup electrode servicing the closed-orbit measurements. Varying amplitude of the sum signal is a signature of bunch shape wavering, given no beam losses. Also, amplitude detection of the sum signal clears the readout off any effect of bunch c. o. m. longitudinal oscillations. Technical data of the detector is specified in Table 1.

The amplitude detector in question was used to diagnose bunch longitudinal oscillations under closed and open feedback loops (Fig. 2). Both, 1st and 2nd harmonics of synchrotron frequency were seen in the signals. The 2nd harmonic content was found to dominate in beam signals monitored under the open-loop configuration.

Table 1: Technical specification of amplitude detector

Input resistance	75	Ohm
Differential slope in a linear zone	1.8	
Suppression of 2 MHz at exit	–40	dB
Output load	1	MOhm
RF carrier frequency range	0.5–3	MHz
Bandwidth of AM signal	50	kHz
Peak amplitude of input RF voltage (depending on position of jumper *J*1)	15/45	V

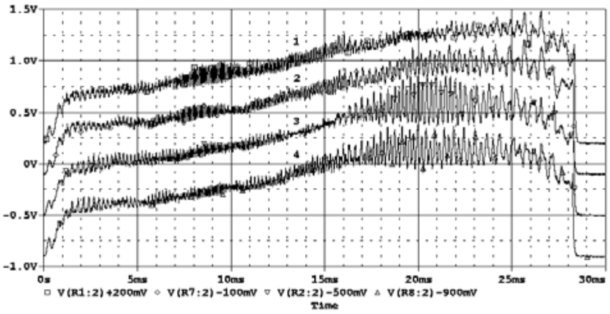

Figure 2: Beam peak current signal. Traces *1&2* — radial and phase feedbacks OFF; *3&4* — the feedbacks are ON.

BEAM DYNAMICS ISSUES

Here, p is momentum, p_0 is its reference value, $\omega(p)$ is rotational frequency (circular), $\varphi \propto h(\omega(p)-\omega_0)t$ is phase in RF rad, $\omega_0 = \omega(p_0)$, h is harmonic number (in the Booster, $h = 1$), t is time, φ_s is stable phase angle. By convention, energy gain per turn $\propto \cos\varphi_s$ ($\varphi_s > 0$ below transition), and $\varphi = 0$ for a reference particle.

Perturbed single-particle longitudinal oscillations obey, at small amplitudes, equation of motion that reads

$$M^{-1}\, d/dt\left(M\, d\varphi/dt\right) + \Omega_0^2\, \varphi = \Omega_0^2\, F\,. \qquad (1)$$

Here M is effective mass, Ω_0/ω_0 is longitudinal tune; F is reduced external force. Of major concern are the coherent oscillations in bunch length. To study them, consider

$$F = -\varphi\, f_1\,, \qquad f_1 = \delta V/V - \delta\varphi \cot\varphi_s \qquad (2)$$

where V is amplitude of accelerating voltage, δV and $\delta\varphi$ are amplitude and phase errors. For the high-accelerating-rate and fast-cycling machine in question (0.03–1.3 GeV in 30 ms), the two factors must be taken into account:

1. Varying $M = M(t)$ and $\Omega_0 = \Omega_0(t)$ resulting in a non-negligible adiabatic damping.
2. A large value of $\cot\varphi_s \le 0.5$–0.6 giving rise to a cross-talk effect of $\delta\varphi$ onto bunch length.

The phase error $\delta\varphi$ itself comprises a few terms

$$\delta\varphi = \delta\varphi_{RF} + \int^{t} \left(\delta\omega_{RF}(t') - \alpha\,\delta B/B(t')\right) dt' \qquad (3)$$

where $\delta\varphi_{RF}$ is the RF phase error proper, $\delta\omega_{RF}$ and δB are errors in radio-frequency $\omega_{RF} = h\omega_0$ and guide field B, α is momentum compaction factor.

Phase ψ of synchrotron oscillations is a natural cyclic variable of motion, $d\psi = \Omega_0\, dt$. In terms of ψ, Eq. (1) would convert into

$$d^2\varphi/d\psi^2 + 2\lambda\, d\varphi/d\psi + \varphi = F\,, \qquad (4)$$

$\lambda = ½ d\ln(M\Omega_0)/d\psi$ being an instant adiabatic decrement. In the Booster, $|\lambda| < 0.01$ and phase advance in ψ over a cycle is around $2\pi\cdot 110$.

A peak detector monitors signal $P \propto N/\langle\varphi^2\rangle^{1/2}$ where N is beam intensity, $\langle\varphi^2\rangle$ is variance of bunch distribution over φ, and $\langle\varphi^2\rangle^{1/2}$ is r. m. s. bunch length. The overall P signal is a sum of DC and AC components, $P = P_0 + \delta P$ where $P_0 \propto N(M\Omega_0)^{1/2}$ (adiabatic law) and $\delta P \propto NF$ (coherent signal). Technically, complementary filtering P through either LPF or HPF recovers either P_0 or δP, respectively.

On applying a method of moments to Eq. (4), $|F| << 1$, and opting for $y = \delta P/P_0$ as an observable, one arrives at

$$d^2 y/d\psi^2 + 4y = f_1\,. \qquad (5)$$

Eq. (5) may be shown [1] to hold true up to small terms $\propto 2\lambda^2/\nu^2$ in amplitude, $\propto 2\lambda/\nu$ in phase, and $\propto \lambda^2$ in eigen-frequency of coherent response y to force f_1. Here, ν is a dimensionless frequency of oscillations w. r. t. ψ, time-dependence being $\propto \exp(-i\nu\psi(t))$.

By virtue of (2), (3) and (5) one thus gets an extended list of external factors to be inspected for being a cause of oscillations in bunch length:

$$\delta V/V, \quad \delta\varphi_{RF}, \quad \delta\omega_{RF}, \quad \text{and} \quad \delta B/B,$$

in priority order.

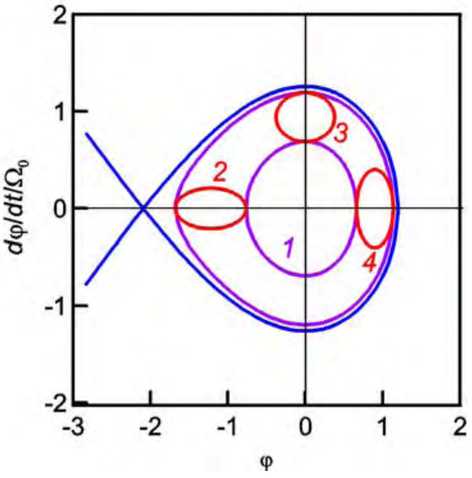

Figure 3: Mechanism of coupling a c. o. m. motion to an accompanying bunch length modulation, at $\varphi_s = \pi/3$ or $\cot\varphi_s = 1/3^{1/2} = 0.58$. Ellipses *2*, *3* and *4* encircle the equal phase-plane areas.

On post-processing a digitally acquired record $\{t_i, P(t_i)\}$ to $\{\psi_i, y(\psi_i)\}$, smoothing and differentiating y over ψ via a finite-difference technique, on can use Eq. (5) to filter free oscillations out of y and estimate a magnitude and spectrum, over ψ, of the reduced driving force f_1, (2), (3).

The observed scale of $|f_1| < 0.3$ was not supported by a straightforward measurement of ripples in $\delta V/V$. It has cleared amplitude-related circuits out of suspicion. At the same time, the attention was drawn to a visible excess in dipolar content of $|f_1(\nu)|$ and $|y(\nu)|$ at around $|\nu| = 1$.

Fig. 3 demonstrates how dipole oscillations can drive a forced modulation in bunch length at the 1st harmonic of Ω_0: bunches *1+2* and *1+4* represent two counter-phase snap-shots of the c. o. m. oscillations; bunch *1+4* being shorter than *1+2*. On the contrary, free oscillations of the bunch length (due to bunch portrait mismatch about the phase-plane trajectories) would have proceeded at the 2nd harmonic of Ω_0. Both the oscillations are readily seen through the amplitude detector.

Therefore, in an operation under closed and properly tuned feedback loops one would have observed a simultaneous suppression of both, 1st and 2nd harmonics of Ω_0 in the observed signal spectra. With this motivation in mind, the further research efforts were diverted towards phase-frequency and radial feedback circuits around the VCO.

FEEDBACK LOOPS

Major components of a feedback circuit are phase and radial transducers. They convert input higher-frequency signals from beam and accelerating voltage into low-pass base-band control signals proportional to radial and phase offsets of the bunch.

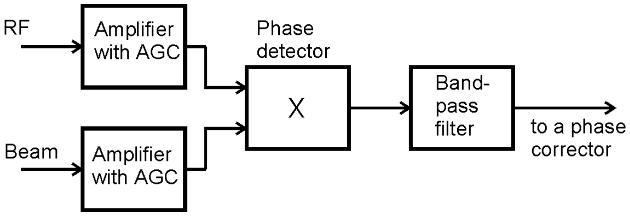

Figure 4: Block diagram of a phase detector.

Both, phase and radial paths contain correcting circuits that tailor out proper amplitude- and phase-frequency responses ensuring stability of the closed-loop configuration against self-excitation. Slopes of the modulation curves are:

50 kHz/V	in the band 0.1–100 kHz	(phase loop)
10 kHz/V	0–100 kHz	(radial loop)

A careful tuning of the feedback loops has revealed that the existing phase transducer could not attain adequate damping of bunch dipole oscillations. To this end, it was replaced with a modernized module of a phase detector (see Fig. 4) similar to that employed in the main PS U70 [2]. Naturally, the relevant amplitude- and phase-frequency transfer functions were adjusted so as to comply with the particular parameters of beam longitudinal motion in the Booster. Figs. 5 and 6 plot the major performance data on the thus updated phase detector.

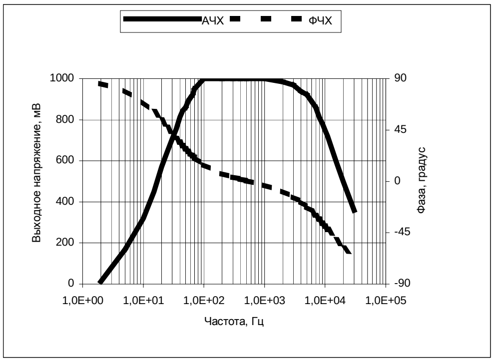

Figure 5: Amplitude- and phase-frequency transfer functions of the phase detector. Frequency in Hz, voltage in mV, phase in deg.

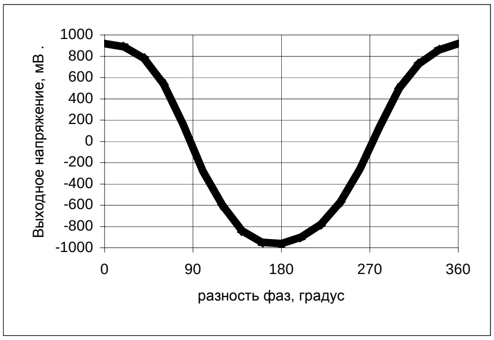

Figure 6: Sensitivity of phase detector. Abscissa — phase difference in deg, ordinate — output voltage in mV.

EXPERIMENTAL DATA

The updated phase feedback loop around VCO was tested with beam during the autonomous run of the Booster in the spring of 2004. A proper tuning of the phase loop has allowed suppressing oscillations in bunch c. o. m. Simultaneously, coherent oscillations in bunch length apparent at frequencies around Ω_0 and $2\Omega_0$ were suppressed as well.

Fig. 7 shows an example of the feedback operation. There, a jump in RF phase is driven with a fast-pulsed offset in radio-frequency. The consequent oscillations in bunch length (or peak density of a bunch) were then observed and got rid of. Similar procedures were reiterated at various time instants so as to optimize the feedback performance through the entire accelerating cycle.

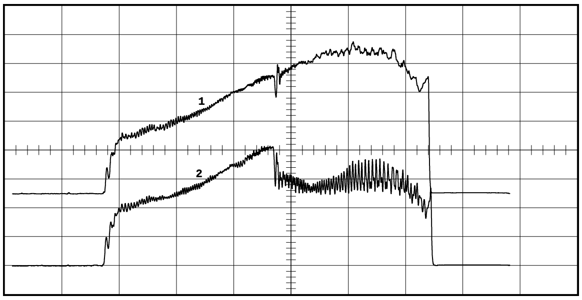

Figure 7: A signal from the amplitude detector, phase jump at *t* = 15 ms. Trace *1* — phase feedback ON; *2* — OFF. Sweep rate = 5 ms/division.

CONCLUSION

Thus, goals of the R&D program were attained. It was found and proved that bunch-length oscillations in the Booster were, dominantly, an accompanying effect of dipole oscillations due malfunctioning phase feedback loop. Root of the problem was spotted, corrected and beam behavior in the Booster was improved noticeably.

REFERENCES

[1] S. Ivanov and O. Lebedev, “A Study of Bunch-Length Oscillations in the Booster”, Internal Report (unpublished), IHEP, Protvino, 2003.

[2] Yu. Ivanov and A. Kuz’min, “A System to Control Frequency of Accelerating Voltage by Beam Data”, PTE, #4, 1962.