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 im
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The phase error $\delta \phi$ itself comprises a few terms

$$\delta \phi = \delta \phi_{RF} + \int (\delta \omega_{RF}(t') - \alpha \delta B/B(t')) dt' \tag{3}$$

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

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

$$d^2 \psi/d\psi^2 + 2\lambda \cdot d\psi/d\psi + \psi = F,$$  

$$\lambda = \frac{1}{2} d\ln(M\Omega_0)/d\psi$$

being an instant adiabatic decrement. In the Booster, $|\lambda| < 0.01$ and phase advance in $\psi$ over a cycle is around $2\pi - 110$.

A peak detector monitors signal $P \propto N/(\phi^2)^{1/2}$ where $N$ is beam intensity, $\langle \phi^2 \rangle$ is variance of bunch distribution over $\phi$, and $\langle \phi^2 \rangle^{1/2}$ 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 $\delta P$, 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

$$d^2 y/d\psi^2 + 4y = f_i,$$  

where $f_i$ is a linear driving force.

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 eigenfrequency of coherent response $\nu$ to force $f_i$. Here, $\nu$ is a dimensionless frequency of oscillations w.r.t. $\psi$, time-dependence being $\propto \exp(-iv\psi(t))$.

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:

$$\delta V/V, \delta \phi_{RF}, \delta \omega_{RF}, \text{ and } \delta B/B,$$  
in priority order.

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

The observed scale of $|f_i| < 0.3$ 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 $|f_i(\psi)|$ and $|\gamma(\psi)|$ at around $|\nu| = 1$.

Fig. 3 demonstrates how dipole oscillations can drive a forced modulation in bunch length at the 1st harmonic of $\Omega_0$: bunches $1+2$ and $1+4$ represent two counter-phase snapshots 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 $\Omega_0$. 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 $\Omega_0$ 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.](image)

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.](image)

Figure 5: 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
