TRANSVERSE FEEDBACKS IN THE U70 PROTON SYNCHROTRON OF IHEP

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Abstract

To handle the adverse effect of transverse injection errors and resistive-wall instability in the U70, two frequency-band-separated feedback circuits are routinely employed. The first one is a narrow-band (around base-band DC) local end-to-end-analog circuit terminated by an electrostatic kicker. The second is a wide-band band-pass circuit with a variable (–10% ca) digital delay line and low-level DSP units and an electro-magnetic kicker. Both the circuits were subjected to a deep renovation during the recent 5 years, which provided a better control over transverse motion of the beam. The paper reports on technical solutions implemented, problem-oriented R&D studies, and beam observations.

INTRODUCTORY FORMULAE

In the U70, like in most of proton synchrotrons worldwide, coherent transverse beam motion, if any, is quieted by means of a relatively slow multi-turn deflecting coercion on beam. In this context [1], one can apply to a wave-to-wave cross-talk approach that involves propagating waves $\propto \exp(ik\Theta - i\omega t)$ of deflecting Lorentz force field strength (whose wave amplitude is $S_k(\omega)$) and electric dipole moment of the beam ($D_k(\omega)$). Here, k is an integer wave number, $\Theta \propto \omega_0 t$ is azimuth along the ring, ω_0 is angular rotation frequency of on-momentum particle, t is time.

Electro-dynamical properties of beam environment, either passive or active (e. g., of beam feedback circuits), are commonly described in terms of a transverse coupling impedance $Z_k(\omega)$, in Ohm/m, that is tacitly defined via

$$S_k(\omega) = i\beta\omega_0 Z_k(\omega) D_k(\omega)/L \qquad (1)$$

where L is orbit length, β is reduced velocity. This Eq. implies reflection symmetry $Z_{-k}(-\omega) = Z_k(\omega)^*$. Given *passive* components of the vacuum chamber (resistive wall, deflecting HOMs, etc.), $\omega \cdot \mathrm{Re} Z_k(\omega) \ge 0$.

Adopt, for definiteness, the upper betatron side-band convention with series $\omega \cong (k + Q)\omega_0$ where Q is betatron tune (about 9.8–9.9 in the U70). In this case, a coherent mode observable at a frequency line that probes $\mathrm{Re} Z_k(\omega) < 0$ turns unstable.

Hence, design goal for a perfect damping beam feedback is to impose *active* coupling counter-impedance with

$$Z_k^{(\mathrm{FB})}(\omega) = A_k^2 + i0 \qquad \text{at} \qquad \omega = (k + Q)\omega_0 . \qquad (2)$$

Because of a comb nature of beam transfer function one must tailor out the appropriate function $Z_k^{(\mathrm{FB})}(\omega)$ only in a close vicinity of the frequency line (lines) $\omega = (k + Q)\omega_0$ of interest, rather than globally over the entire ω-domain, which simplifies the task from the technical viewpoint.

Let a (short) pickup electrode PU be mounted at azimuth Θ_{PU} and a (short) transverse kicker K be at Θ_{K}, their separation azimuthally being $\Delta\Theta_{\mathrm{K-PU}} = \Theta_{\mathrm{K}} - \Theta_{\mathrm{PU}}$. Following Eq. 1, one can put down

$$Z_k^{(\mathrm{FB})}(\omega) = -iG(\omega)\exp(i\omega\tau - ik\Delta\Theta_{\mathrm{K-PU}}) . \qquad (3)$$

$\underline{G}(\omega)$ is in-out transfer function of electronics in the open feedback loop, reduced to units of Ohm/m,

$$G(\omega) = \frac{pc}{eJ_0}\left(\frac{\Delta y'_{\mathrm{K}}}{\Delta y_{\mathrm{PU}}}\right) = \frac{(El)_{\mathrm{K}}}{\beta (J_0 \Delta y)_{\mathrm{PU}}} = \frac{c(Bl)_{\mathrm{K}}}{(J_0 \Delta y)_{\mathrm{PU}}} . \qquad (4)$$

Here, y is transverse coordinate (vertical, horizontal), J_0 is average beam current, p is momentum, c is velocity of light, e is elementary charge, $(El)_{\mathrm{K}}$ and $(Bl)_{\mathrm{K}}$ are field strength integrals of electrostatic and magnetic kickers, optionally. Phase-frequency characteristic of $G(\omega)$ is assumed to have a vanishing slope averaged over the bandwidth. Time delay inherent in $G(\omega)$ (electronics + pure delay lines) is incorporated in the overall delay τ in Eq. 3.

NARROW-BAND FEEDBACK

It is a local system whose pickup, electrostatic kicker and signal-processing (analog) equipment are all housed in the same straight section SS#2 of the U70 lattice [2]. The system imposes a damping upon the dedicated spatial harmonic $-k_1 = [Q] + 1 = 10$ of beam perturbation where $[Q]$ is the integer part of Q. This harmonic is notable for the strongest destabilization by the resistive-wall wake.

The feedback signal-processing algorithm relies on tune Q being just below an integer value and reads

$$G(\omega) = -2\left(\frac{A}{1 - i\omega/\Delta\omega}\right)^2 \mathrm{HPF}(\omega) . \qquad (5)$$

Given (i) cut-off frequency (at –3 dB) of integrator circuit $\Delta\omega$ equal to $|k_1 + Q|\omega_0$, (ii) vanishing delay time $\tau = 0$, and (iii) negligible spatial separation $\Delta\Theta_{\mathrm{K-PU}} = 0$, Eq. 3 readily turns into a sought-for damping impedance of Eq. 2 at the frequency line $(k_1 + Q)\omega_0$ in question.

Last factor in Eq. 5 denotes a high-pass filter with a roll-off frequency $<< \Delta\omega$ that rejects a DC closed-orbit offset signal seen by the PU. Its higher-frequency translates at $\pm\omega_0$, $\pm 2\omega_0$, etc are safely smeared out by a cascade of two integrators in Eq. 5. The same mechanism suppresses residual self-excitation of the next neighbouring to k_1 base-band harmonic $k = -9$ that is inherently stable under the resistive-wall wake, with feedback off.

The system is in a routine service since 2007. Additional damping factor imposed is about 100 w. r. t. a natural decay time of harmonic k_1 due to de-coherence. Details of technical implementation are reported in [2].

WIDE-BAND FEEDBACK

Generalities

Conversely, it is a non-local wide-band band-pass system which uses two pickups, PU1, 2 at SS#107, 111 respectively, and an electro-magnetic kicker K at SS#90. In the U70, azimuth Θ of straight SS#*n* is ∝ 2π*n*/120.

The kick fed back to beam proceeds from a weighted sum of two beam signals red out from PU1 and PU2. Therefore, Eq. 3 now slightly modifies to

$$Z_k^{(\mathrm{FB})}(\omega) = -iG(\omega)\sum_{m=1,2} w_m \exp\left(i\omega\tau_m - ik\Delta\Theta_{\mathrm{K-PU}m}\right). \quad (6)$$

Here, three conditions to follow are set,

$$\tau_{1,2} = \Delta\Theta_{\mathrm{K-PU1,2}}/\omega_0\,, \qquad Q\Delta\Theta_{\mathrm{K-PU0}} = \frac{\pi}{2}(2j+1). \quad (7)$$

The first expressions equate beam time-of-flight to signal-processing in-out delay en routes PU1–K and PU2–K.

The rightmost of Eq. 7, where *j* is a positive integer, defines a virtual pickup denoted as PU0. Its location is set to an odd number of betatron quarter-wavelengths upstream of kicker K. In the U70, *j* = 16. With

$$G(\omega) = (-1)^j A^2\,. \quad (8)$$

$$\begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = \frac{1}{\sin Q\Delta\Theta_{\mathrm{PU2-PU1}}} \begin{pmatrix} \sin Q\Delta\Theta_{\mathrm{PU2-PU0}} \\ \sin Q\Delta\Theta_{\mathrm{PU0-PU1}} \end{pmatrix} \quad (9)$$

one gets Eq. 2 that is now effective for a whole set of frequency lines occurring inside the bandwidth of $G(\omega)$.

Suppression of closed-orbit offset signal at $\omega = k\omega_0$, with DC included, is accomplished via a variable electrical center of pickup biased with balance amplifiers. Supplementary option using a one-tap periodical (with a period ω_0) digital notch FIR filter in $G(\omega)$ was also tested.

Layout

Fig. 1 shows topological layout of the feedback circuit. Lengths of cables are such as to yield $\Delta\Theta_{B-A}/\omega_0 = \tau_{C-A}$ at injection flat-bottom. Component-by-component structure is sketched in Fig. 2. There are two identical channels servicing horizontal (H) and vertical (V) directions.

Low-level signal-processing electronics is taken out of the Ring Hall to the Main Control Room. High-power RF amplifiers are housed in the technological bld. #5/3. The equipment is interconnected with high-frequency cables having low attenuation and high temperature stability.

Sensor and Actuator

Beam-position sensors are stations of skew-cut electrostatic pickup electrodes followed by front-line electronics that matches pickup impedance to wave impedance of the cable traces. The pickups are mounted in straights SS#107 and 111, the latter being shown in Fig. 3 (left). Their technical performance data is reported in [2]. The difference signal is acquired and low-pass filtered (6.3 MHz cut-off at –3 dB) in the front-end electronics.

The feedback actuator is a fast electro-magnetic beam kicker (deflector) comprising a pair of air coils. Its performance data is specified in Table 1.

The kicker is installed in SS#90, refer to Fig. 3 (right). The same straight houses an auxiliary beam pickup, which is used to trim and control, mainly, the digital delay line performance. The goal for such a crucial control is to ensure simultaneous arrival to SS#90 of a bunch itself and of its signal delayed over the entire feedback path.

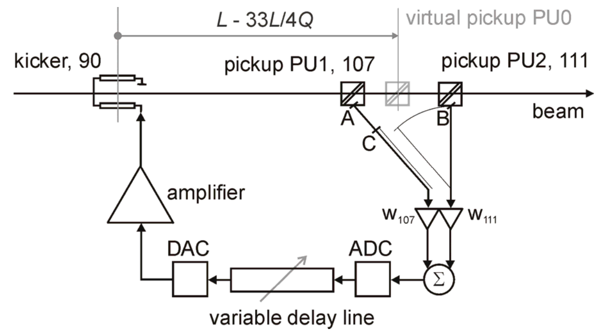

Figure 1: Layout of the wide-band feedback.

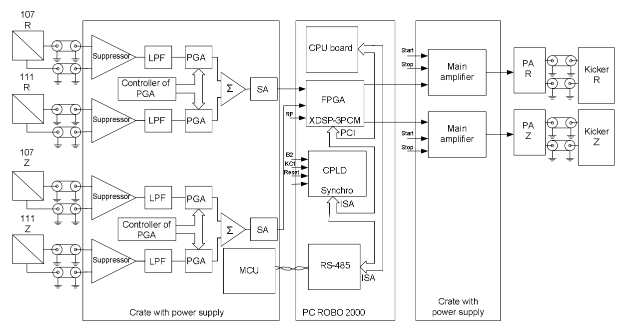

Figure 2: Block diagram of the wide-band feedback.

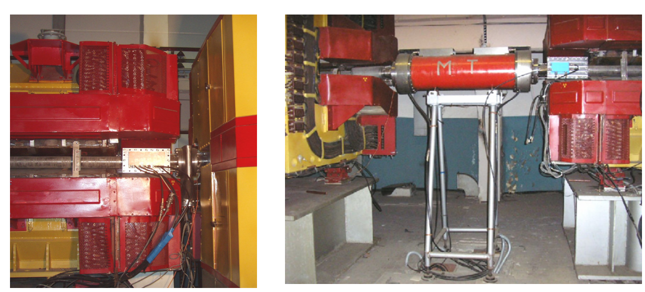

Figure 3: Pickup station (left). Electro-magnetic beam kicker followed by an auxiliary in-situ beam pickup (right).

Table 1: Performance data of kicker and amplifier

Length of a dipole coil	1.1	m
Coil inductance	0.6	μH
Ratio of *B*-field to current	6.5	μT/A
In/Out resistance of amplifier	75/37.5	Ohm
Max input voltage, peak-to-peak	1	V
Max output current	5	A
Bandwidth at –3 dB	0.1–15	MHz

Low-Level Signal Processing

The key technical problem behind this feedback is to comply with the leftmost of Eq. 7 under a varying rotation frequency $\omega_0/2\pi$= 183.9–202.0 kHz. Historically, a 1 km long hank of cable performed this task. During renovation this outdated solution was substituted by a digital delay line clocked at the 16th harmonic of acceleration frequency $\omega_{RF}/2\pi$ = 5.516–6.062 MHz.

Core of the digital system constitutes a signal-processing module XDSP-3PCM whose structure is shown in Fig. 4. It is an AT-size motherboard mounted via PCI bus into an industrial computer ROBO-2000. There are two 12-bit ADC and DAC embracing the FPGA programmable logical matrix available. The latter device implements the prescribed signal-processing algorithms, of which the simplest one being a mere delay of a signal.

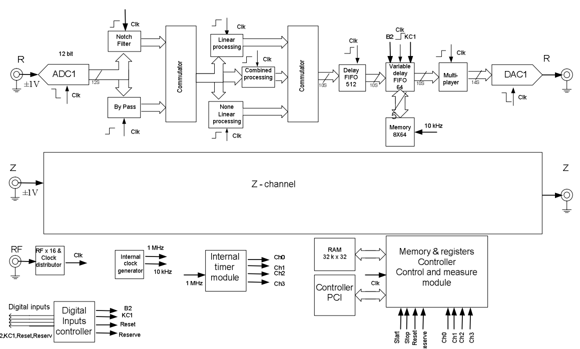

Figure 4: Block diagram of the XDSP-3PCM module.

Host processor of the ROBO-2000 computer executes Read-Write operations with service data sets that, say, govern variable gains of outer differential amplifiers whose microcontrollers acquire data through a serial optically isolated interface RS-485.

Easy implementation of variable delays is not the only profit gained on going to the DSP. Indeed, various algorithms to tailor out the feedback signal can now be accomplished by means of a straightforward high-level language coding of the DSP board free of hardware changes.

Table 2: Feedback modes

	A: linear	B: “bang–bang”
Feedback, n is turn no.	$\Delta y_n = -Ay_{n-1}$, gain $A > 0$	$\Delta y_n = -B \operatorname{sgn} y_{n-1}$ kick level $B > 0$
Decay law	$y_n = y_0 \exp(-An)$	$y_n = y_0 - Bn \operatorname{sgn} y_0$ unless turning bi-polar
Decay time in turns	$\frac{1}{A}$	$\frac{\lvert y_0 \rvert}{B} = \frac{\lvert y_0 \rvert}{\max \lvert y \rvert} \frac{1}{A}$
Ultimate at $n \to \infty$	$y_n \to 0$	$y_n \neq 0$, beating with $\lvert y_n \rvert < B$

To this end, we have tried not only a conventional linear (proportional) feedback presented conceptually in row A of Table 2. A faster non-linear regime (row B) responding to a sign of bean offset by the utmost deflection yielded by the kicker was also tested. Regime B shortens the initial decay time of beam oscillations by a factor equal to a ratio of factual initial offset magnitude $|y_0|$ to a peak linear dynamic range max $|y|$ of the feedback circuit in mode A.

As is known, contrary to linear feedback A, mode B cannot settle beam offset to zero ultimately. Therefore, a combined regime A-B with a user-selectable toggling threshold in between the two modes was adopted for a routine service. It naturally combines advantages of both the modes (shadowed cells in Table 2) and ensures a noticeably faster damping of transverse coherent motion.

Beam Observations

Since the 2nd run of 2008, the digital wide-band feedback of the U70 is in a test operation. Outcomes of its commissioning are shown in oscillograms of Figs. 5–7.

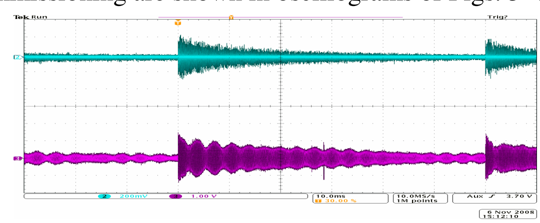

Figure 5: Natural decay (time 50 ms) of horizontal injection error with feedback off. Lower trace is the 10th harmonic of beam signal. Bunch-to-bunch gap is 60 ms.

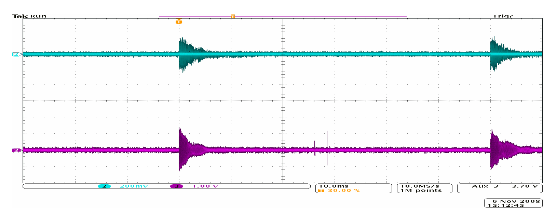

Figure 6: Forced decay (time 2–3 ms) with feedback on in a linear mode A.

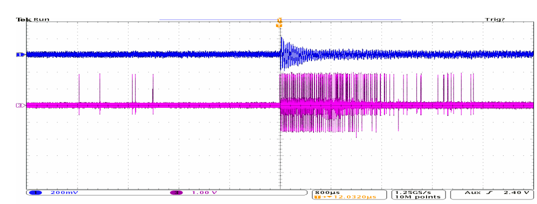

Figure 7: Forced decay (time 1 ms ca) with feedback on in a combined mode A-B. Lower trace shows driving current sent to the kicker.

CONCLUSION

The two transverse beam feedbacks in the U70 are well effective and shorten damping time by a factor of 100 for the narrow-band, and 20–25 (linear mode A) or 50 (combined mode A-B) for the digital wide-band circuits.

REFERENCES

[1] S. Ivanov, Preprint IHEP 97–64, Protvino, 1997.
[2] O. Lebedev et al, Proc. of RUPAC-2008, Zvenigorod, 2008, p. 21–23.