A STOCHASTIC SLOW EXTRACTION SCHEME FOR U70 SYNCHROTRON

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Abstract

Outcomes of a feasibility study for a low-budget stochastic slow extraction system in the U70 proton synchrotron of IHEP are reported. The existing 200 MHz (spill) RF system is to be employed as a longitudinal kicker. It will be driven by a sum of a non-random RF carrier plus an additive random amplitude-modulated signal — either quadrature or in-phase, or both. A few novel solutions to be implemented in the longitudinal diffusion technique that would force protons into the conventional 3-rd order transverse extraction resonance are foreseen so as to comply with the technical constraints inherent in U70. Getting a-few-seconds-long and high-quality spills is assessed as being viable with the system in question.

PREAMBLE

The concept itself of a stochastic (noise) slow extraction of beam from a proton synchrotron was pioneered in [1]. This principle was then subjected to a successful proof in the CERN PS machine where a 9 s long good-quality spill of 24 GeV protons had been demonstrated [2]. Subsequently, a very slow noise extraction of antiprotons from the LEAR storage ring was implemented; spill duration exceeding 1–2 h ca [3].

As is known since [1–3], the stochastic extraction scheme has a two-fold purpose of (i) yielding much a longer spill and (ii) ensuring far a better spill quality, i.e., getting a lower AC-to-DC ratio in extracted flux. This goal is scored by a changeover in a mechanism that forces beam into the transverse resonance. A headway relative motion of entire beam is substituted with an alternative, diffusive mechanism of beam transport. Power supplies feeding magnetic optics are turned to a sustained steady-state regime amenable to better conditioning technically. Edge of the extracting resonance band constitutes an “absorbing wall” that faces a thin close-by wedge-like end of beam distribution over momentum. Aftermaths of scraping such the beam by a waving sink, the spill ripples, are thus suppressed noticeably.

Reports [2, 3] disclose the conventional implementation of the noise extraction scheme in which:

1. Beam is kept uniform azimuthally.
2. Extracted diffusive flux is governed with a variable cut-off frequency of noise spectrum that is properly swept through beam frequency portrait.
3. Local enhancement of diffusion in a vicinity of extraction resonance is imposed with a dedicated “chimney” noise source having a peaked spectrum.

The scheme proposed for U70 diverts from these mainstream features, which is dictated, mainly, by constraints inherent in the machine and a demand for low-budget solutions.

SPECIFICS OF U70

For the time being, duration of extraction plateau in U70 is 2, 3, or 4 s at 70, 60, or 50 GeV, respectively. To this end, the noise extraction might only be implemented close to a short-time limit of the method, which imposes a few constrains on the technical options available.

Main accelerating system is operated at harmonic number $h = 30$, voltage amplitude $V_{RF} \le 400$ kV, and radio frequency 5.5–6.1 MHz. This RF system is ample to perform fast manipulations with beam, noise gymnastics included. Still, any residual 6 MHz structure of extracted beam is unacceptable. Use of the main RF system for the noise extraction purpose is thus prohibited.

The only option left for a longitudinal kicker is to use a supplementary (spill) accelerating system operated at $h = 990$, $V_{RF} \le 0.5$–1.0 MV, and 200 MHz. The amount of RF power thus installed is only marginally adequate to affect the coasting beam with a fractional momentum spread $\Delta p/p_0$ of around $\pm(1–1.5)\cdot 10^{-3}$. Therefore, to reduce time of diffusion to a few-second scale, one has to place beam center as close to resonance as possible at time $t = 0$.

Due to technical reasons, the 200 MHz RF system cannot be driven without a distinct non-random carrier. External noise may only be injected as an additive random amplitude-modulated signal, either quadrature or in-phase, or both simultaneously. The design goal is to gain a non-random voltage amplitude $V_{RF} = 0.5$ MV plus a random signal resulting in a peak-to-peak voltage excursion equivalent to ±1 rad in $\delta\varphi$ and/or ±1 in $\delta V_{RF}/V_{RF}$ (about a 10% surplus in average RF power consumed).

Since $V_{RF} \ne 0$, there would be 200 MHz buckets present in the longitudinal phase plane. Bandwidth of cavities comprising the 200 MHz RF system is about ±10 kHz (at –3 dB). Full frequency spread at base of beam near harmonic $h = 990$ of rotational frequency ω_0 is 4–6 kHz. Therefore, frequency portrait of beam is destined to occur close to the discrete frequency line of 200 MHz, and phase-plane portrait of beam must be located close to, still beyond of, the 200 MHz buckets. The waiting beam will thus be non-uniform azimuthally, although not yet bunched. The protons would circulate in a close outer vicinity of RF buckets, in a region of a strong nonlinearity of longitudinal motion.

This constitutes the major distinction of the stochastic extraction scheme intended for U70, as compared to the conventional one. Another specific feature is to apply a simpler way to shape the extracted beam pulse. A fixed-shape power spectrum with a controlled magnitude will be employed to that end. Local enhancement of diffusion toward resonance will be attained, in part, by the inherent upsurge of diffusion coefficient D at separatrix.

GENERAL LAYOUT

Fig. 1 illustrates the extraction scheme in general, all numerical notations being explicated in Table 1. Letter p denotes momentum; p_0 is that at the central orbit where reference particles (centers of empty buckets) rotate, $\omega(p)$ is rotational frequency (circular), $\omega_0 = \omega(p_0)$ is its reference value, A_x and σ_x are horizontal amplitude and its r.m.s. value, Q_x is betatron tune, $\varphi = h(\omega(p) - \omega_0)t$ is phase in RF radians. Concentric curves sketch contour plot of beam distribution function in plane $(A_x, (p-p_0)/p_0)$.

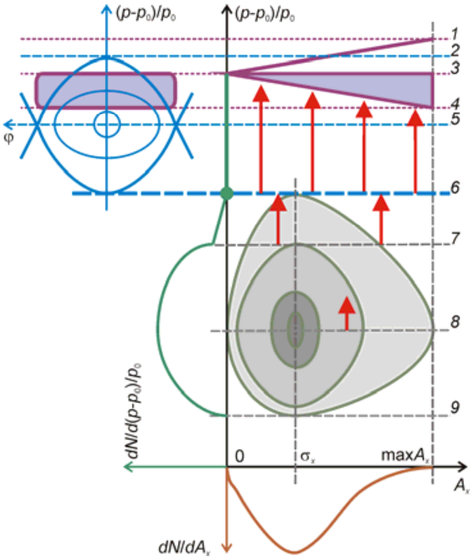

Figure 1: Steinbach diagram of extraction scheme

Table 1: A legend to Figs. 1 and 2

#	Explication
3	Center of resonance $3Q_x = 29$. Extraction of particles with betatron amplitude $A_x = 0$.
1, 4	Extraction of particles with maxA_x.
1–3, 3–4	Two half-bandwidths of the resonance.
3–4	Operating half-bandwidth with $Q_x > 29/3$.
5	Momentum of a reference particle of a 200 MHz bucket. Central orbit.
2–6	Momentum size of a 200 MHz bucket.
8	Beam center.
7–9	Beam core. A slow diffusive transport.
7–6	Buffer layer (beam halo). A fast diffusive transport. Low density.
6–3(4)	A very fast transport via synchrotron oscillations.
6	“Absorbing wall” for a boundary-value problem of diffusion over momentum.

Image *1–4* of extraction resonance $3Q_x = 29$ is always placed above central orbit *5* (outer radii in U70). Prior to extraction, the beam is de-bunched around a lower orbit *8*. Gap *6–7* is left between waiting beam edge and empty RF buckets so as to rule out any premature extraction due to uncontrolled ripple of *6*, or *3*, respective to beam center *8*.

The operating half-bandwidth *3–4* of the resonance is overlapped wholly by the bucket upper halve *2–5*. The bucket itself constitutes a trap that: (i) locks protons in resonance allowing for cyclic re-entering it, if required, (ii) mixes protons with various A_x due to randomised initial phases and strong non-linearity of incoherent synchrotron motion, and (iii) increases local speed of entering the resonance.

The diffusive flux is directed all way upwards in plane $(A_x, (p-p_0)/p_0)$. It does not affect beam distribution over A_x. There are 3 regions involving various beam transport mechanisms:

1. A very slow diffusion in *7–9* that gradually feeds the extraction and, incidentally, smears out and unifies beam distribution over $(p-p_0)/p_0$.
2. An appropriately increased diffusion in *6–7* that dilutes beam density towards sink *6* so as to decrease the extraction ripple.
3. A fast transfer of protons in *2–6* towards resonance *1–4* via conventional synchrotron oscillations.

Typical time scale of beam transport in between *7–9* and *6–7* is commeasurable to the spill duration (a few s, fractions of a s). On the contrary, synchrotron oscillations in *2–6* and extraction itself in *2–4* are accomplished in a time scale of 1–5 ms. Quite a distinct time scales involved allow for treating line *6* as an “absorbing wall” for a boundary-value problem of diffusion over momentum. Footprint of this “wall” does not depend upon A_x, and a single solution for the diffusion equation would represent all amplitudes A_x thus facilitating a straightforward control over the noise extraction procedure.

To some extent, the scheme resembles extraction of a 200 MHz bunched beam with a stationary resonance. The 2π-long bunches are continuously re-populated by diffusion into the RF bucket from the outer beam stack.

BEAM DYNAMICS

Fig. 2 plots calculated disposition of empty bucket and beam in phase plane $(\varphi, \xi = -d\varphi/dt)$, $\xi \propto (p-p_0)/p_0$ on extraction plateau of U70. Beam energy is 60 GeV, momentum spread prior to de-bunching is $\Delta p/p_0 = \pm 1 \cdot 10^{-3}$, $V_{RF} = 0.5$ MV, small-amplitude synchrotron frequency $\Omega_0/2\pi = 0.76$ kHz, horizontal chromaticity $\chi_x = -15$, resonance half-bandwidth *3–4* for maxA_x is $\delta Q_x = 8 \cdot 10^{-3}$. This is a realistic data set for U70.

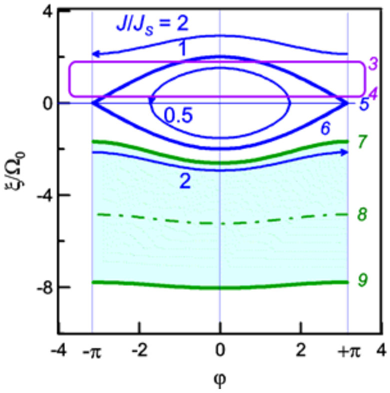

Figure 2: Phase-plane portrait of beam and empty RF bucket at $t = 0$. Refer to Table 1 for notations

Let J denote a longitudinal action variable acquiring the value of $J_S = 8\Omega_0/\pi$ at separatrix. Diffusion proceeds along J-axis, under a diffusion coefficient $D = D(J)$ which is tailored out with an externally controlled noise spectrum $P(\Omega)$. Technique to calculate $D(J)$, both inside and beyond RF buckets, and a custom-made computer code to solve diffusion equation with the Finite-Element Method are documented in [4]. Noise-related experimental beam studies at U70 to verify results of [4] are reported in [5].

Curve *1* in Fig. 3 shows a plot of a tentative operational $P(\Omega)$, a phase noise. The relevant $D(J)$ is given by curve *1* in Fig. 4. The non-trivial branch of $D(J)$ must not extend beyond the outer edge of the waiting beam (curve *3* in Fig. 4) so as to ensure, mostly, the one-directional diffusion towards the bucket. $D(J)$ exhibits an inherent integrable divergence at $J = J_S$ that would favorably enhance diffusion locally. Curves *2* in Figs. 3, 4 demonstrate how to put forth more control over beam density at the inner beam edge to further suppress extraction ripple.

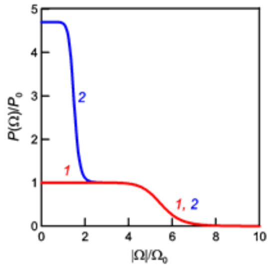

Figure 3: Noise spectra, *1* and *2*

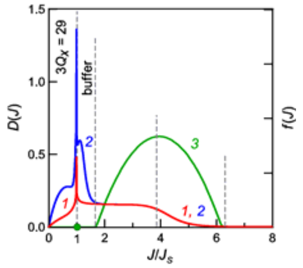

Figure 4: Diffusion coefficient, *1* and *2*. Beam profile $f(J, t = 0)$, curve *3*

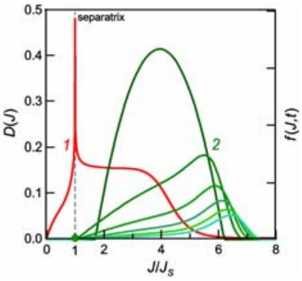

Figure 5: Diffusion coefficient, *1*. Evolution of beam profile, *2*, at $t_1 = 0(50)250$

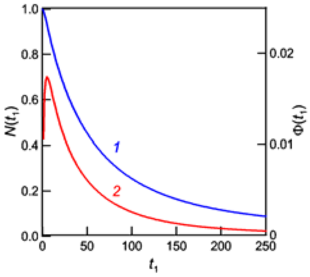

Figure 6: Beam intensity, *1*. Extracted flux, *2*

Figs. 5, 6 show solutions of the diffusion equation. Variable t_1 denotes a natural, diffusion time introduced as $t_1 = t\,\Omega_0^2\,P_0$ where P_0 is a reference value of $P(\Omega)$, and $[t_1] = 1$. Natural decay $N(t_1)$ of the waiting beam subjected to time-invariant noise $P(\Omega)$ occurs in line with curve *1* in Fig. 6. Curve *2* in Fig. 6 shows the natural shape $\Phi(t_1)$ of the extracted beam pulse. It has not got any visible flattop demanded by beam consumers. To flatten the spill, one has to vary the noise spectrum by going to a time-varying function $P(\Omega)G(t)$ where $G(t) \geq 1$ is the appropriate noise-magnitude enhancement factor. There exists a regular way [6] to find $G(t_1)$ proceeding from the generic laws $N(t_1)$ and $\Phi(t_1)$ for $G = 1$ plotted by curves *1*, *2* in Fig. 6.

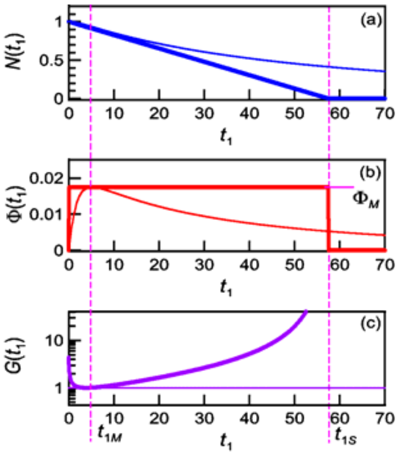

Figure 7: Flattening the spill pulse

Figs. 7 show how to get a flat-topped spill. Its asymptotic length is $t_{1S} = N(0)/\max\Phi(t_1)$ and $G(t_{1S}) = \infty$, which is not feasible technically — $G(t_1)$ must saturate at $G_M > 1$ as dictated by acceptable variance of noise with spectrum $P(\Omega)G_M$. In its turn, the value of G_M sets the upper limit to a fraction of beam intensity extractable under the flattop.

Design figures for U70 are $G_M = 15$; phase noise with $P_0 G_M = 12\cdot10^{-6}$ rad^2/Hz; 85% of beam extracted under 2.7 s long flat spill; peak-to-peak random voltage excursion about ±1 rad of 200 MHz voltage, by end of a spill.

Fractional amplitude of ripple in Φ, in response to a sinusoidal waving with amplitude a and circular frequency ω of bucket/resonance respective to beam center, is

$$\left|\delta\Phi/\Phi\right| \leq 3\,\omega\, t_S\,\left(a/A\right)^2 /\Gamma G\ .$$

Here, t_S is spill length in s, A is beam foot size in units of $[a]$, $\Gamma \geq 1$ is a factor of local enhancement of $D(J)$ around $J = J_S$ (compare *1*, *2* for $J/J_S \in [1; 1.5]$ in Fig. 4), G is a factor of temporal enhancement of both $P(\Omega)$ and $D(J)$, see Fig. 7c. Estimated value of $|\delta\Phi/\Phi|$ is ≤ 0.1–0.01 ca.

SUMMARY

The proposal looks feasible and relies on the existing capital equipment of U70. Its implementation calls for a low-budget funding. The scheme promises yielding better and longer spills that would upgrade functionality of U70.

More details on the subject matter can be found in [6].

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