BEAM TESTS OF A STOCHASTIC SLOW EXTRACTION SYSTEM PROTOTYPE IN THE U70

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Abstract

The paper reports on development of a stochastic slow extraction (SSE) system prototype beam-tested during the 2004–5 MD runs of the 70 GeV proton synchrotron of IHEP–Protvino. Flat-topped 2–3 s long and smooth (r.m.s. AC-to-DC ratio < 0.3) spills were obtained. The scheme implemented has a few inventive features. Protons are forced into the 3-rd order horizontal resonance with a supplementary 200 MHz RF system driven by sum of a non-random RF carrier and an additive base-band low-pass phase noise. Waiting beam stack is kept coasting in a close outer vicinity of 200 MHz buckets, in the longitudinal phase half-plane opposite to that housing momentum image of extraction resonance. RF buckets are kept repopulated by inward diffusion from the outer stack. Shape of noise power spectrum is kept invariable (no conventional frequency sweeping is applied), magnitude of noise being controlled via a proportional DC-coupled feedback loop acquiring data from a beam loss monitor. Terminal travel to resonance is carried out via a fast trapped cyclic motion inside buckets. It drastically improves immunity of extraction to ripples in power supplies of beam optics. No mains harmonics are observed in the spills.

PREAMBLE

Prior Status of Slow Extraction from the U70

The conventional slow extraction has been and is being routinely employed in the U70 to feed external fixed-target experimental facilities with a 50–70 GeV beam.

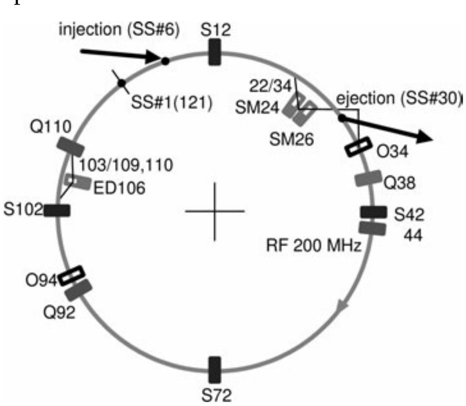

Figure 1: Slow extraction system in the U70.

Present layout of optical elements involved is shown in Fig. 1. Protons rotate clockwise. The slowly extracted beam passes through electrostatic wire deflector ED106, then traverses septum magnets SM24, 26, and ultimately leaves the machine through an exit window in straight section (SS) #30. Horizontal extraction resonance $3Q_x =$ $= 29$ is driven by four sextupoles S12, 72 and S42, 102. The beam is pushed towards the resonance with a steering quadrupole Q38 which action might be, optionally, supplemented by setting a linear decay of guide *H*-field.

Extracted beam current is monitored indirectly via a secondary-particle loss monitor LM106 located downstream of ED106, the first deflector along the beam trace.

By now, many efforts have been invested by the U70 extraction team to provide as long and smooth spills as possible [1]. Conditioning of power supplies feeding magneto-optical elements has seemingly resulted in approaching their feasible technical tolerances on ripples. A new decisive step to further improve the quality of spills was required. Such an opportunity is known [2] to be offered by going to a SSE scheme in which a drift (convection) mechanism of displacing protons to the extraction resonance is substituted by a diffusive transport. To this end, an auxiliary 200 MHz RF system located in SS#44 of the U70, see Fig. 1, was drafted to exercise control over beam extraction, instead of applying lens Q38.

The Classical SSE

The principle itself of the SSE was first put forward in [2]. It was then successfully proven in CERN [3, 4]. The classical implementation of this technique implies:

1. actually a lengthy spill lasting for 10 s – 10 h;
2. azimuthally uniform waiting beam;
3. controlled depletion of waiting stack with a sweeping edge of actuating noise power spectrum;
4. use of a dedicated “chimney” region [4] with an enhanced noise (and, hence, diffusion) around extraction resonance to squeeze beam profile tail locally.

SSE from the U70

The SSE scheme implemented in the U70 diverts from the classical version in all the topics just listed:

1. shorter spills of a few second length and operation close to a short-time applicability limit of the stochastic technique as such;
2. nonlinear motion with a waiting beam coasting in a close outer vicinity of the empty 200 MHz RF buckets that also overlap the resonance;
3. stack depletion due to noise with a ramped magnitude and fixed-shape power spectrum extending over the entire frequency portrait of the beam stack;
4. use of much a stronger functional counterpart of a noisy “chimney” region — area of the fast finite cyclic motion inside RF buckets — to increase local speed of entering the resonance.

On the one hand, all these features are nothing but forced solutions imposed by < 4 s duration of extraction flat top, by non-availability of a longitudinal actuator other than the existing 200 MHz RF system, by its a bit out-of-dated low-level driving circuitry, by a need for a conservative and non-intervening modification of the latter, and a pressing demand for a low-budget solution.

On the other hand, the SSE scheme adopted for the U70 managed to turn around these constraints into profits. Say, immunity to coherent ripples was enhanced due to mixing protons inside the 200 MHz RF buckets prior to extraction and randomizing time of entering the resonance. Waiting beam stack is continuously smeared by the actuating noise thus facilitating cycle-to-cycle reproducibility of spills. Locus of a sink that absorbs diffusion in momentum is kept independent of betatron amplitude a_x, making stochastic spills insensitive to beam profile over a_x, etc.

Prerequisites for Beam Tests

Feasibility study for SSE from the U70 was published in [5, 6]. Mostly, it relies on theoretical and computational results of [7]. Important practical experience of applying noise to beam in the U70 was acquired during exercising RF noise gymnastics on injection flat-top to flatten bunch profiles [8]. Given this background, IHEP Directorate has endorsed experimental studies of the SSE. These were accomplished in the MD runs of the U70 in 2004–5.

OUTCOMES OF MD RUN, 2004

Beam intensity was (3–6)$\cdot 10^{12}$ p.p.p. (60 GeV). Only the so called *natural* spills governed by an invariable actuating noise were observed. By definition, they have got no flat top. Specifically, goals of the first MDs were [7]:

1. proof of principle and demonstration of workability;
2. observation of a static response of beam subjected noise excitation;
3. measurement of magnitudes and amplitude spectra of the spill ripples;
4. study of an in-out transfer performance of existing control channels in the 200 MHz RF system.

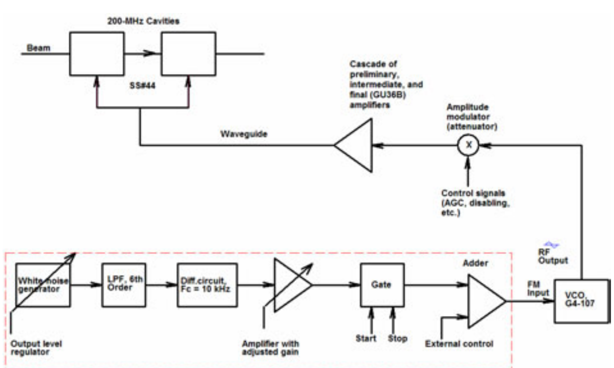

Figure 2: Block diagram of experimental setup #1.

Layout of the first, open-loop experimental circuit is shown in Fig. 2. The new purpose-built equipment is dashed around. It comprises a white base-band (phase) noise generator, a 6$^{\text{th}}$ order Butterworth low-pass filter, a differentiator for phase-to-frequency conversion upstream of a VCO FM input (compare spectra *2* and *3* in Fig. 3), a variable gain amplifier, a gate, and an adder.

Experimental data acquired with a digital oscilloscope LeCroy 9304 CM from the beam diagnostic DC current transformer (CT) and LM106 is shown in Figs. 4–7. The data is normalized during post-processing. Spill length is 1.89 s, 84% of beam being extracted stochastically.

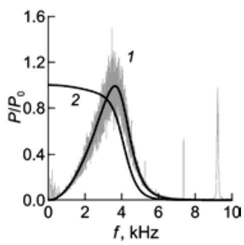

Figure 3: Measured noise power spectrum at FM input to the VCO (*1*). Equivalent spectrum of phase noise at beam (*2*).

Random signal with a spectrum shown in Fig. 3 and 10 mV peak-to-peak magnitude at FM input to the VCO drives phase noise of $1\cdot 10^{-6}$ rad^2/Hz ca at beam, in the frequency band 0–4.2 kHz (–3 dB).

A compromise boundary frequency to separate between DC and AC fractions of the spill signal spectra was found to be 10 Hz at –3 dB.

Quality of spills observed was promising, showing no coherent harmonics multiple of the mains 50 Hz. There were no negative spill overshoots resulting in extraction cutoffs. No useful content in spill spectra beyond 500 Hz (at base) was diagnosed.

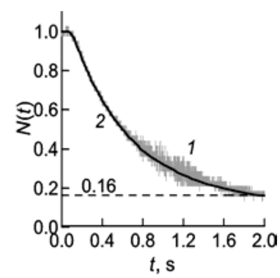

Figure 4: Signal from a DC CT (*1*), waiting beam intensity, norm-ed. Trace *2* is a running integral under ragged curve *1* in Fig. 5.

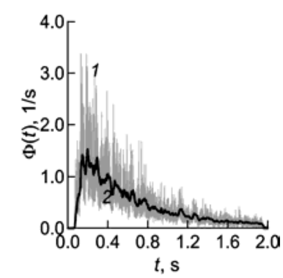

Figure 5: Signal from the LM106 (*1*), the slowly extracted spill rate, norm-ed. Trace *2* — its DC fraction (0–10 Hz @ –3 dB).

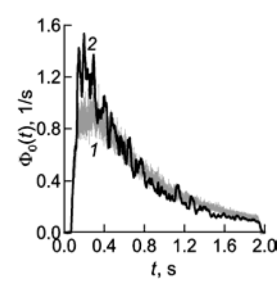

Figure 6: DC component of a *natural* spill (*2*), the same as trace *2* in Fig. 5. Statistical average over 32 machine cycles (*1*).

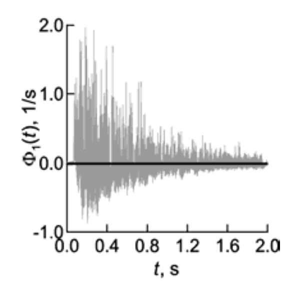

Figure 7: AC component (ripple) of a *natural* spill. Its envelope is proportional to DC signal from Figs. 5, 6.

Cycle-to-cycle reproducibility of stochastic spills was found to be insufficient to allow for use of a function generator to ramp the noise. To this end, more flexible and adaptive feedback schemes to control spills were adopted.

In general, power, linearity and dynamical range of phase–frequency modulation circuit in the 200 MHz RF system were all found adequate to ensure stochastic extraction of 80–90% of beam in 2–3 s and longer [7].

OUTCOMES OF MD RUN, 2005

During preparations to the MD-2005, major efforts were spent to develop a dedicated feedback circuit to flatten and smooth out the stochastic spills. The circuit had to control a system which is neither linear nor time-invariant — beam subjected to a ramped actuating noise.

A deeper insight into the system dynamics, its tuning procedure and future beam observations was gained by developing a sound equivalent circuit model of the stochastically extracted beam. Such a beam happens to be well modeled with a (single-pole) non-periodic serial *RLC* network where a fixed pre-charged capacitance *C* is discharged through the *RL* branch whose variable resistance *R* and inductance *L* are both varied by a feedback loop that acquires the discharge current signal [8].

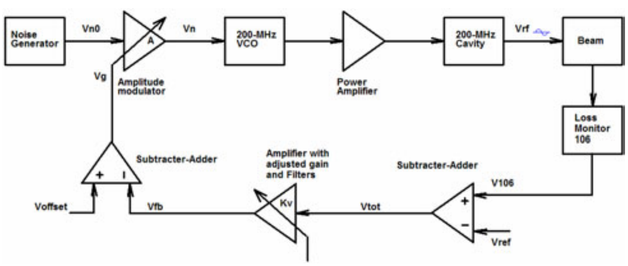

Figure 8: Block diagram of experimental setup #2.

Layout of the second, closed-loop experimental circuit is shown in Fig. 8. It is a development of the setup shown in Fig. 2. Proportional DC-coupled feedback is closed en route "voltage readout V_{106} from the LM106 — amplitude modulation of the random carrier V_{n0}".

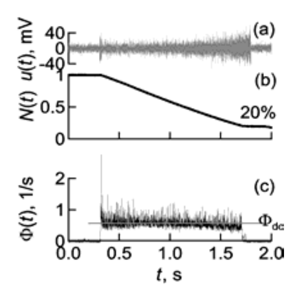

Figure 9: Experimental plots: (a) random voltage; (b) waiting beam population; (c) spill rate.

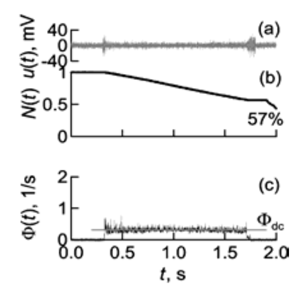

Figure 10: Experimental plots. Refer to Fig. 9 for explications.

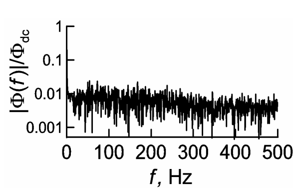

Figure 11: FFT amplitude spectrum of the spill signal shown in Fig. 9c.

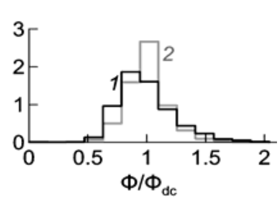

Figure 12: Histograms of ripple overshoot distribution for the signals from Figs. 9c (*1*) and 10c (*2*).

Closing the feedback circuit with the proper reference, V_{ref} and offset, V_{offset} voltages resulted in flat extraction spills sustained at a controlled rate, see Figs. 9, 10. Beam intensity was $(2–5)\cdot 10^{12}$ p.p.p. (50 GeV). Extrapolation of the spill signal shown in Fig. 10b indicates that 80% of beam could have been extracted in a 2.6 s long spill that is a design figure from the feasibility pre-study [5, 6].

Again, no coherent harmonics, multiple of the mains 50 Hz, were observed, see Fig. 11. The ripple amplitude spectrum is flat and runs at – (40–45) dB w. r. t. DC over 5–500 Hz frequency range. Spill overshoot distribution, Fig. 12, confirms good quality of the stochastic extraction. Spill ripple signal looks like a Gaussian white noise.

More details of the SSE system feedback design and outcomes of the beam observations are reported in [8].

SUMMARY

The SSE scheme for the U70 proton synchrotron has been experimentally tested in 2004–5 on a system prototype. It appeared to be well understandable, serviceable, and easy to control. It complies with both the requirements to and the capabilities of the U70 machine. It has been confirmed that the DC-coupled proportional feedback system fed by the extracted beam signal is able to yield flat-topped spills and maintain their ripple low.

The U70 is thus acquiring an extraction system with new performance capabilities. It possesses a few properties important for the beam users and provides longer spills, higher quality of their time structure, and good reproducibility of spills during the machine cycles.

The SSE system is expected to extend functionality of the U70 machine for external fixed-target experiments.

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