INVESTIGATION AND CURES OF SELFBUNCHING AT SLOW EXTRACTION OF BEAM FROM PROTON SYNCHROTRON U-70

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Abstract

Computer simulation as well as experimental study of selfbunching at frequency of ~ 5 MHz during the slow extraction of beam from the U – 70 were continued. The selfbunching takes place due to interaction of the beam with the passive accelerating cavities and leads to bad quality of the extracted beam. Its threshold is abnormally low due to the filament structure of the drifting bunches. The methods are described which have been proposed and realized in practice to cope with the selfbunching. The main instrument for this is the existing 200 MHz RF station. The filament structure of the beam is destroyed and the uniform momentum distribution of particles is formed due to the modulated voltage created by this station. The results of the computer simulation for the beam population up to $3 \cdot 10^{13}$ protons are shown.

Longitudinal instability – selfbunching of the drifting beam occurs in the proton synchrotron U–70 at the upper flat top of magnetic field during the slow extraction. It happens at frequency of ~ 5 MHz and is seen at intensities almost an order lower then follow from the well-known Keil–Shnell criterion [1]. This problem was investigated with the help of the modernised computer code LONGIT using the macroparticles method [2].

Earlier [3] we studied the U–70 beam with the total intensity of $N = 1\times10^{13}$ protons. The beam in the phase space coordinates "RF phase – energy" is shown in Fig. 1a, b, c at the moments of 25, 150, and 650 ms after switching off the RF voltage. Fig. 1a shows the specific striplike (filament) structure of the drifting beam. The beam would keep such a structure for an infinitely long time in the absence of perturbations. But acting of the voltage, induced in the accelerating cavities, becomes essential in about 15 ms after the drift has started.

Local momentum dispersion of particles at the central parts of the bunches decreases gradually during the drift and at some moment it becomes smaller then the vertical dimension of the parasitic separatrixes. The particles, which occur inside of these separatrixes, are involved in the quadrupole phase oscillations. These oscillations lead to the modulation of the beam line density, which reaches its maximum when the bunches inside of the parasitic separatrixes become vertical (Fig. 1b). The induced voltage increases correspondingly, which in its turn leads to the rise of the line density modulation and so on. Thus the positive (self-excited) feedback between the beam current perturbations and the induced voltage takes place, which is specific for instabilities.

As a result some "pseudobunches" appear in the beam centre. Their sequence frequency in this case corresponds to the 26-th harmonic of the revolution frequency. These pseudobunches give a part of their energy to the passive cavities and as a sequence displace gradually to smaller radius and even come through the edge of the beam (Fig. 1c). Fig. 2 shows the corresponding time dependence of the most dangerous harmonics of the beam, normalised to its average current. It is seen that the pseudobunches have captured more then 25% of all particles.

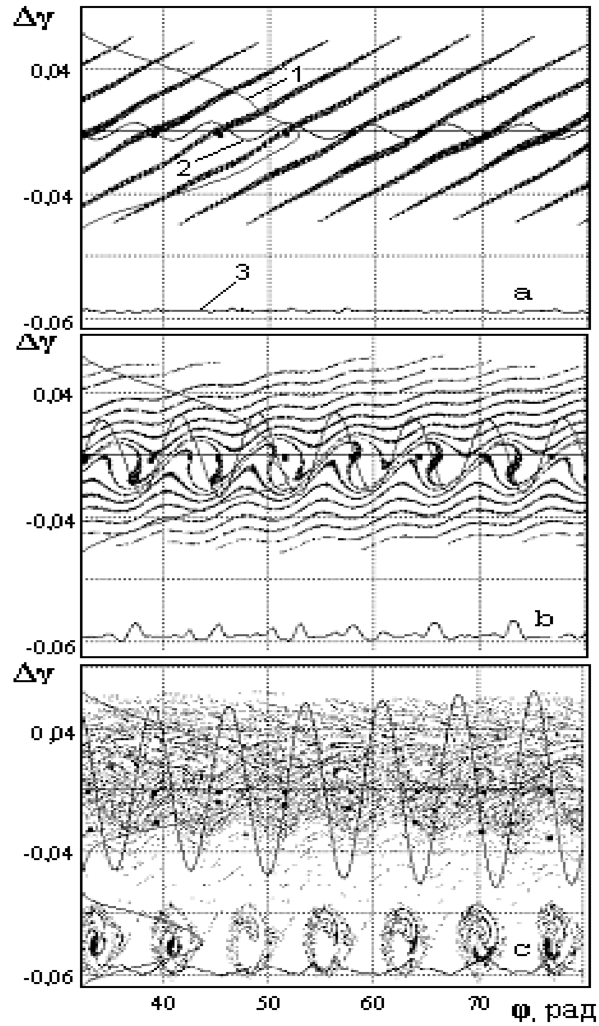

Figure 1: The beam with $N = 1\times10^{13}$ protons/pulse and initial $\Delta p/p_s = 0{,}92 \times 10^{-3}$ in 25 ms (a), 150 ms (b) and 650 ms (c) after start of the drift.
Curve 1 – energy distribution, 2 – induced voltage, 3 – line density.

All above stated have lead the authors to conclusion, that the principal factor of the considered problem was the filament structure of the beam, formed by the drifting bunches. The Keil–Shnell criterion is not valid for such kind of phase space distribution.

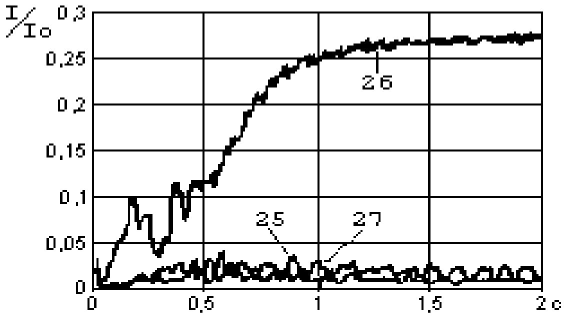

Figure 2: Harmonics of the beam current for the beam shown in Fig. 1. The slow extraction is absent.

This conclusion has prompted the authors to use an effective method for curing the selfbunching in the U–70 [3]. The main instrument for this was the existing 200 MHz RF station. The filament structure of the beam was destroyed *partially* by the *unmodulated* voltage of this station.

The 200 MHz voltage of ~200 kV was switched on after the beam structure had become well filament. Vertical dimension of the corresponding separatrixes was much greater then local momentum dispersion of the drifting bunches. The particles mixed up while performing phase oscillations. As a sequence the momentum dispersion in the central part of the beam increased. It resulted in considerable rise of the selfbunching threshold which was proportional to $(\Delta p/p)^2$. Note that the switching on and especially switching off the 200 MHz voltage should be adiabatic to keep the total momentum dispersion of the beam unchanged.

Figure 3, obtained by computer simulation, illustrates efficiency of this method. It is seen that we came to almost uniformly debunched beam (compare to Fig. 1c).

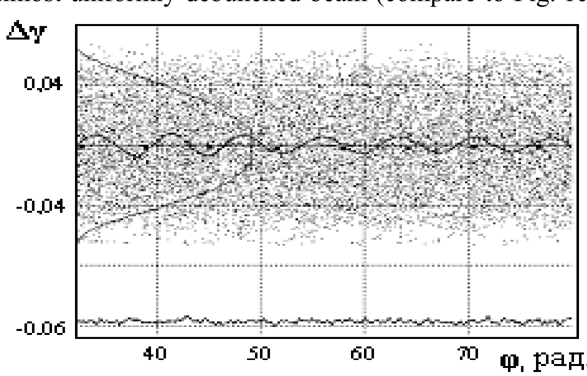

Figure 3: The beam in 2 s after start of the drift. Unmodulated voltage has destructed the filament structure at the beam center.

The initial total momentum dispersion of the beam has not changed. The price for it is that the 200 MHz voltage should be switched on only after *several* neighbouring bunches have overlapped and the beam structure has become really filament. In practice it should be done in 20 – 30 ms after start of the drift. Unfortunately this time is long enough for the selfbunching to develop at higher intensities. The typical total momentum dispersion in the U–70 is $\Delta p/p_s \approx \pm(0.8\text{–}1.0)\times10^{-3}$. Computer simulation has shown and experiments have proved, that for such $\Delta p/p_s$ the described method is effective for total intensities not more then 1×10^{13} protons.

At higher intensities the filament structure of the beam was *completely* destroyed due to the *modulated* 200 MHz voltage. This method is the improvement of previous one. It showed to be effective during the last U–70 runs at slow extraction of the beam with today's intensity $N = 1.5\times10^{13}$. This time we modulate the frequency of the 200 MHz voltage and switch it on at the same time with the drift start. Using the optimal parameters of modulation we can provide total mixing of particles in the beam and as a sequence the complete destruction of its filament structure. As an example the beam with $N = 1.5\times10^{13}$ protons is shown in Fig. 4 in 50 ms after switching off the main accelerating voltage. It is seen that i) the filament structure is actually destroyed and ii) almost uniform momentum distribution is formed which is good for the slow extraction. Maximum momentum dispersion of the beam increased by factor 1.2 compared to its value before the drift had started and did not exceed $\Delta p/p_s \approx \pm1.2\times10^{-3}$. Such growth of $\Delta p/p_s$ is not dangerous for the slow extraction, and the resulting uniform momentum distribution is quite useful from the viewpoint of the extracted beam quality.

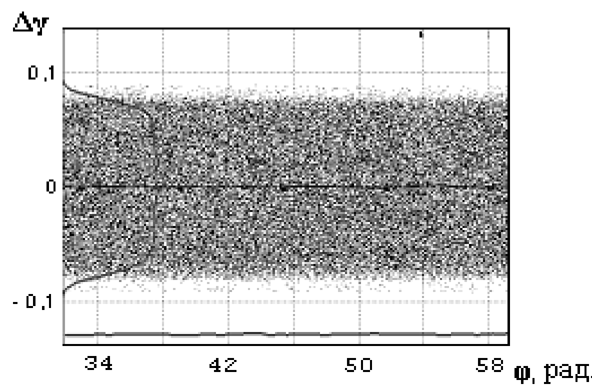

Figure 4: The beam in 50 ms after switching on the modulated 200 MHz voltage.

In the above example the frequency-modulated voltage with the central frequency of 200 MHz was used:

$$v(t) = V_{200}\sin\left[\Omega_0 t + \left(b/a\right)\sin at\right] \qquad (1)$$

Here Ω_0 is the central angular frequency, V_{200} is the voltage amplitude, a and b are the angular frequency and the amplitude of its modulation. The factor $\xi = b/a$ is the modulation index. The function (1) has the line spectrum with frequencies

$$..., \Omega_0 - na, ..., \Omega_0 - a, \Omega_0, \Omega_0 + a, ... \Omega_0 + na, ...$$

and amplitudes proportional to the Bessel functions

$$..., J_n(\xi), ..., J_1(\xi), J_0(\xi), J_1(\xi), .., J_n(\xi), ...$$

Actually this infinite spectrum can be treated as the restricted one because the Bessel functions become negligible at $n >> \xi$. Computer simulations show that for the range of intensities $N = (1 \div 3) \times 10^{13}$ the values $3 \le \xi \le 4$ are optimal.

Momentum dispersion $\Delta p/p_s$ of the beam steadily decreases in process of the slow extraction. The instability threshold is well known to be proportional to $(\Delta p/p_s)^2$. It means that the selfbunching inevitably appears during the slow extraction independently of initial particles distribution. It was said above that we obtained almost uniform momentum distribution of particles after acting on the beam with the modulated voltage. Selfbunching cannot appear *inside* of such a beam. In fact it appears at its lower edge. But in this case the selfbunching increment and number of involved particles are less then in case when it develops in much more dense central part of the beam with a typical bell-shaped distribution. Computer simulations with real parameters of the slow extraction have proved this statement. For reality the duration of the extraction corresponded to its real value (2s) and the particles, which found themselves in the resonant conditions, were deleted from the code.

The results for the slow extraction at future intensity of $N = 3{,}0 \bullet 10^{13}$ are considered below. To decrease the parasitic impedance the accelerating cavities were divided into two groups. From 40 cavities 25 were tuned out of the acceleration frequency by $\Delta f = -4{,}65\ f_{rev}$ and 15 by $\Delta f = -3{,}75\ f_{rev}$. Such dividing minimizes the imaginary part of the impedance at most dangerous 26-th harmonic of the revolution frequency. The simulation showed that after the modulated 200 MHz voltage had been switched on the initial momentum spread of the beam has increased slightly (by ~7%) and became $\Delta p/p_s \approx \pm 1.4 \bullet 10^{-3}$. It is important that the beam was circulating undisturbed for a long time (0.7 s) and only after this a weak selfbunching showed at its lower border.

Figure 5 shows the corresponding time dependence of the beam current harmonics. As it was expected the maximum value of these harmonics is not high in view of low particles population at the edge of the beam. In this case it did not exceed 3% of the average current, which is quite acceptable for the slow extraction. It differs drastically from the case shown in Fig. 2 where the instability appeared in the densest central part of the beam.

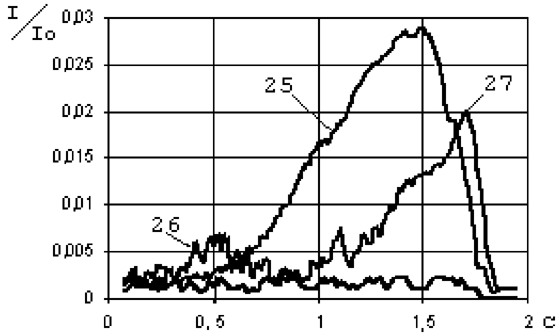

Figure 5: Harmonics of the beam current during slow extraction of beam with $N = 3 \cdot 10^{13}$ ppp.

Thus, acting of the modulated 200 MHz voltage on a beam leads to the following important results: a) total destruction of the filament structure of the beam; b) almost uniform momentum distribution of particles is formed, which is useful for the slow extraction; c) particles density is reduced both inside the beam and at its edges; d) beam displacement towards the accelerator's centre is eliminated.

It is natural to try to minimize both the momentum dispersion and the number of self-bunched particles. But decreasing of the first causes growth of the second. Figure 6 shows the calculated optimal values $(\Delta p/p_s)_{opt}$ (after acting of the modulated voltage on the beam) versus intensity *N*. The term "optimal" in our case means the value of momentum dispersion, at which the amplitudes of unstable harmonics during the slow extraction would be about 2 – 3 % of the average current.

Having found from Fig. 6 the optimal $(\Delta p/p_s)_{opt}$ for a given *N*, one should determine the appropriate modulation parameters to provide such a value of momentum dispersion. The choice of these parameters is scrupulous but not too difficult routine. Note that this choice depends on $\Delta p/p_s$ of bunches before the drift.

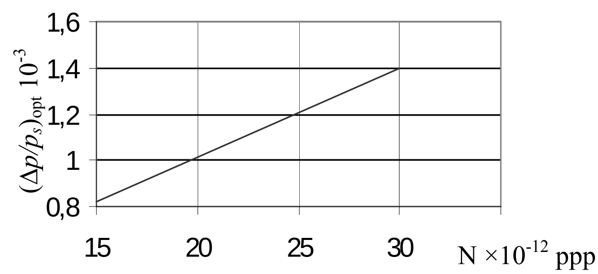

Figure 6: $(\Delta p/p_s)_{opt}$ after acting of the modulated voltage on the beam.

Thus, acting on a beam with the modulated voltage has proved to be a very effective method for curing the selfbunching up to intensity of 3.0×10^{13} ppp. The price for it is some increase of the initial $\Delta p/p_s$.

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