

## SLOW EXTRACTION SYSTEM FROM IHEP ACCELERATOR U-70 STATUS AND DEVELOPMENT

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### Abstract

Slow extraction system of the accelerated proton beam from U-70 is used for physical experiments with the counting principles with the spill duration of 1-2 seconds on the flat-top magnetic field at energy 50-70 GeV. The slow extraction system commissioning took place in 1979. Initial efficiency of an extraction did not exceed 83-85%. Inclusion in extraction system an electrostatic deflector with the wire septum of 0.1 mm thickness has allowed to simplify the scheme of an extraction which began to contain only two septum-magnets in 24-th and 26-th straight sections. Extraction efficiency was 85-87% that was insufficiently for an extraction of intensity more  $1 \cdot 10^{13}$  ppp. Modernization of the system of the resonant extraction with inclusion in structure of the accelerator two additional quadrupole lenses has allowed to increase structural  $\beta$ -function in the location of electrostatic septum to reduce losses on it and on the first septum-magnet three times and reach extraction efficiency  $95 \pm 2\%$ . For suppression of modulations of intensity of an extracted beam the method of phase displacement on RF-separatrices of 200 MHz is used. Effective time (duty factor) of an extraction reaches thus 95%.

### HISTORY

Historically the slow extraction system was created after the fast extraction system start. The direction of the extracted beam was set in view of a direction of channels of fast extracted protons and secondary particles in an experimental hall [1]. The slow extraction system is based on the resonant growth of radial betatron amplitudes with the help of a nonlinear third order resonance  $3Q_r = 29$ . This resonance possesses a number of advantages in comparison with other resonances and the working point on a diagram of betatron frequencies lays near  $Q_{res} = 9\frac{2}{3}$ . The resonant harmonic of square-law nonlinearity is created by two pairs of sextupole lenses. In each pair lenses have a different sign and located oppositely on a ring of the accelerator so they raise all odd harmonics of square-law nonlinearity and do not create the constant component (that influence on chromaticity). Two pairs are located from each other under a corner  $90^\circ$ , and with their help it is possible to adjust of resonant harmonic phase on  $360^\circ$ . Sextupole lenses located in straight sections (SS): 12; 42; 72; 102 (see Fig. 1).

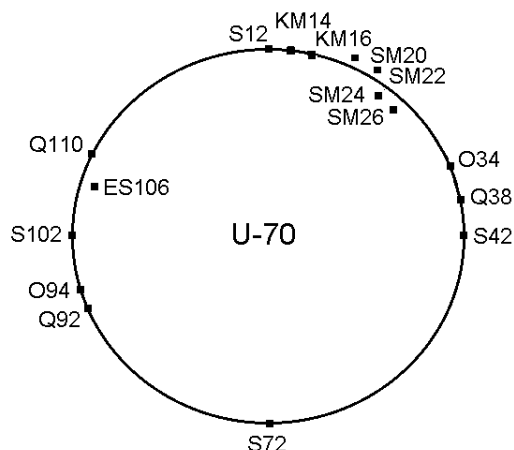


Figure 1: The arrangement of extraction system elements on the ring of accelerator U-70: S – sextupole lens, Q – quadrupole lens, O – octupole lens, KM – fast kicker-magnet, SM – septum-magnet, ES – electrostatic septum

In order to change the radial betatron tune at approaching on a working resonance at extraction the quadrupole lens located in 38-th straight section used. Perturbed by the radial resonance the beam firstly got to the bend-magnet SM18 (see Fig. 2) having septum with effective thickness of 0.7 mm.

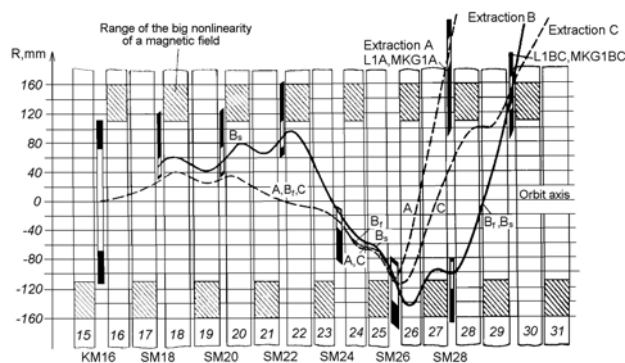


Figure 2: The initial scheme of beam trajectories of fast and slow extraction

Further the beam was transferred on the chain through magnets SM20, SM22 and SM28. Last magnet directed proton beam to 30-th straight section. Slow extraction efficiency did not exceed 83–85% in so complex multistage scheme. In order to increase extraction efficiency electrostatic septum (ES106) with thickness of 0.1 mm (about 0.15 mm effective thickness at 3 m long)

and working strength of the electric field 70 kV/sm have been established in SS106. At such parameters of the septum deflection of the beam did not exceed 0.3 mrad. The angular width of a beam on input of the deflector at extraction of the beam with emittance 2 mm-mrad makes also 0.3 mrad. Therefore clear split of extracted and circulating beam at input in SM18 practically was not. Extraction efficiency with electrostatic septum has reached 85—87% that was insufficiently for an extraction of the high intensity. In connection with change of the program of physical experiments configuration of the experimental hall and channels of transportation of particles [3] has been changed. The scheme of a fast extraction of a proton beam has been changed and essentially simplified (see Fig. 3). It became three-stage.

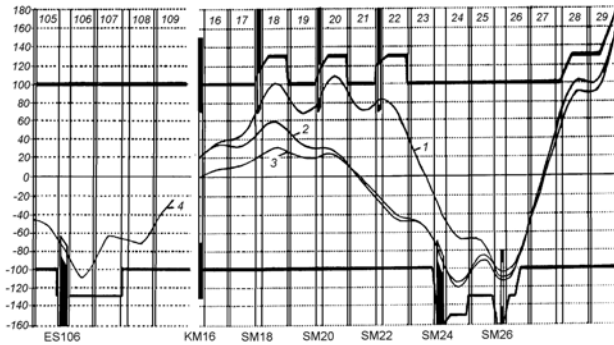


Figure 3: The modern scheme of fast and slow extraction

At modernization of the fast extraction scheme has undergone changes and configuration of the scheme of a slow extraction. The arrangement of the first deflecting septum-magnet after electrostatic septum coincides with an arrangement of septum-magnet SM24 of the fast extraction system. Thus, there came to uniform configuration the extraction systems including three elements of the slow extraction (ES106; SM24; SM26) and three elements of the fast extraction (KM16; SM24; SM26). The full quantity of elements in the extraction scheme began to be only four, and two of them are the common for fast and slow extraction. Increase of the efficiency of the slow extraction have not taken place, as parameters of the beam thus have not changed. In accordance with requirements of experimental complex using slowly extracted beam, extraction of the intensity more than  $1 \cdot 10^{13}$  ppp demand the essential increase of the extraction efficiency. Efficiency of the slow extraction in our scheme is defined by losses of the extracted beam on the first two elements: electrostatic septum ES106 and septum-magnet SM24. Additional losses can arise due to limitation of the extraction devices apertures, especially vertical. At excitation of the working resonance of slow extraction  $3Q_r = 29$  the parasitic coupling resonance of the third order  $2Q_z + Q_r = 29$  is simultaneously raised. At growth of radial amplitude in the working resonance vertical amplitude grows due to a coupling resonance. Losses on first septum are defined by effective thickness of wires of 0.15 mm and increase of the effective

thickness seen by the beam along the length  $l_{ES} = 3$  m due to angular width  $\Delta r'_{106} = 0.3$  mrad in the extracted beam near ES106  $\Delta r = \Delta r' \cdot l_{ES}$ . Losses on the septum-magnet are defined by size of clearance between the extracted and circulating beams, arising due to deflection of the extracted beam in ES106. The angular beam width in outgoing separatrices on the first extracted device is defined by emittance and volume of the structural  $\beta$ -function  $\Delta r'_{106} = \frac{\pi}{\sqrt{3\pi\sqrt{3}}} \frac{\sqrt{\epsilon_r}}{\sqrt{\beta_{r106}}}$ . From here one can see in order to reduce of the angular beam width on first septum it is necessary to increase  $\beta$ -function.

## MODERNIZATION OF THE SLOW EXTRACTION SYSTEM

To change volume of the structural  $\beta$ -function it is possible by introduction quadrupole lenses into magnetic structure of the accelerator with the force  $k = \frac{G_q l_q}{B_0 R_0}$ , where  $G_q$  – gradient of the magnetic field,  $l_q$  – his length,  $B_0 R_0$  – beam rigidity:

$$\beta = \beta_0 - \beta_0^2 \sin^2(2\Delta\psi) \frac{k}{2} + \beta_0^3 \sin^2(\Delta\psi) \frac{k^2}{4},$$

$\Delta\psi$  - phase advance from quadrupole up to the point of supervision. For localization of the disturbance it is necessary to use at least two quadrupole lenses with the phase advance between them equal to odd number  $\pi$ . Additional quadrupole lenses on the accelerator U-70 ring have been established in SS92 and SS110. Force of lenses is chosen so that it was possible to increase  $\sqrt{\beta_{r106}}$  up to 1.5 times. Thus the angular width in the beam decreases up to 0.2 mrad, and we have visible spatial clearance between extracted and circulating beams on the septum-magnet SM24. Deflected in ES106 beam passed through quadrupole lens in SS110 receives additional spatial displacement of

$$\Delta r_{24} = -m_{12(106-110)} m_{12(110-24)} k_{110} \Delta r'_{ES} = -4.3 \text{ mm},$$

where  $m_{12(106-110)} = 23$  m,  $m_{12(110-24)} = 25$  m – transfer matrix element from SS106 up to SS110 and from SS110 up to SS24 accordingly. The common deflection of the beam in SS24 makes about 6 mm.

On Fig. 4-5 results of the numerical simulation of the resonant process in the old and modernized slow extraction system are shown.

On Fig. 5 the angular clearance between the circulating beam (to the right of coordinate of -65 mm) and the beam deflected in ES106 is seen. On Fig. 6-7 the radial movement phase plane in SS24 is shown.

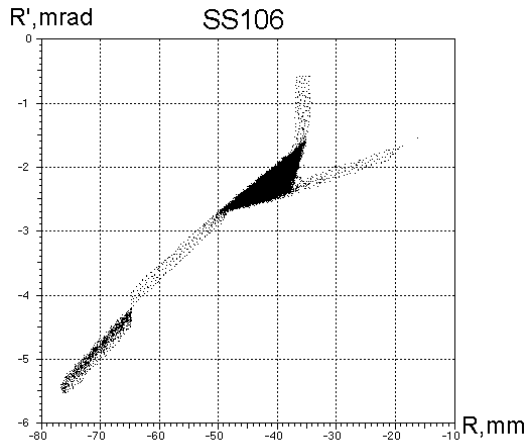


Figure 4: The phase plane of radial movement in SS106 in not modernized slow extraction system

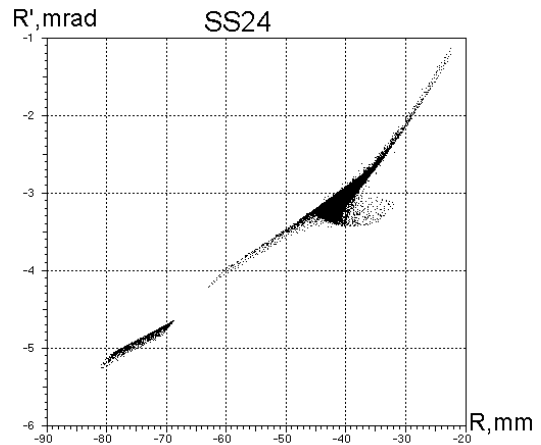


Figure 7: The phase plane of radial movement in SS24 in the modernized slow extraction system

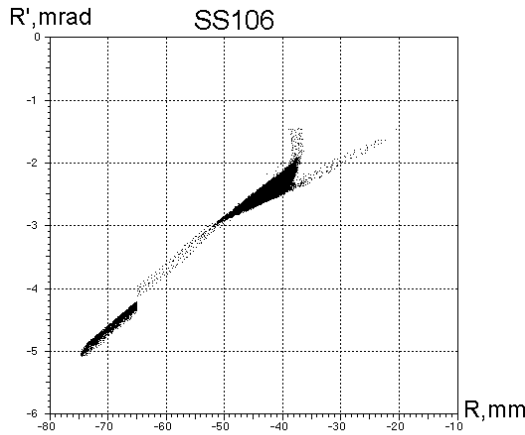


Figure 5: The phase plane of radial movement in SS106 in the modernized slow extraction system

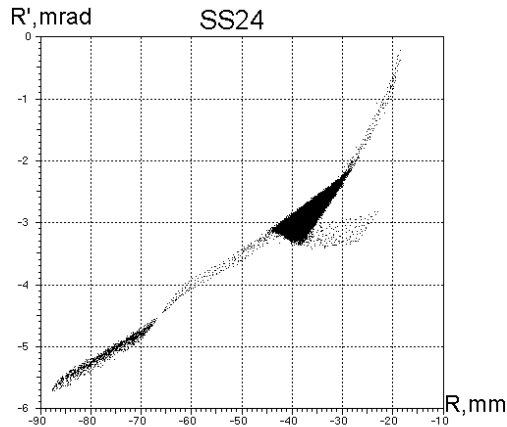


Figure 6: The phase plane of radial movement in SS24 in not modernized slow extraction system

On Fig.7 the clearance about 6 mm between circulating and extracted beams is seen that coincide with an analytical estimation. It's enough for locating of current strip of the bend-magnet SM24 having effective thickness of 2.4 mm. The numerical estimation of losses on both magnets makes about 5%. Therefore the expected efficiency estimation of the extraction should be not less than 95%.

### EXPERIMENTAL RESULTS AFTER MODERNIZATION

The increase of the structural  $\beta$ -function demands the increase of the resonant harmonic force of parabolic nonlinearity of a working resonance. It leads to growth of the coupling resonance harmonic and its stronger influence on vertical movement. For reduction of the coupling resonance influence it is necessary to move from a line  $2Q_z + Q_r = 29$  as it is possible further. The working diagram of betatron frequencies of U-70 is shown on Fig. 8.

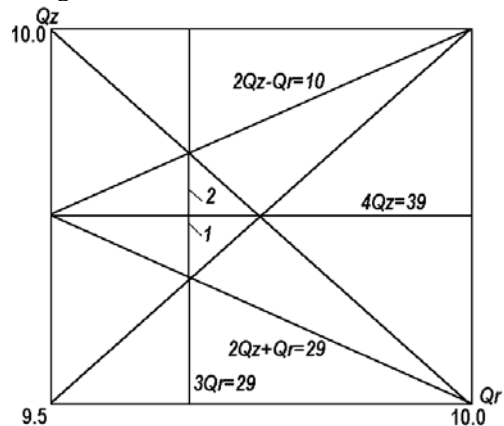


Figure 8: Working diagram of betatron frequencies and course of a working point at moving on the resonance in old (1) and the modified (2) system

The line 1 shows a course of a working point at moving on the resonance at slow extraction before modernization. The working point of betatron frequencies on the diagram is established by gradient correction system. The current limit in this system does not exceed 100 A. With such current at energy 70 GeV a working point approaches close to a line of the resonance  $4Q_z = 39$ . At start of the modified system of the slow extraction the high particles losses took place and efficiency of an extraction have been found out did not exceed 50% instead of expected 95%. Researches of behavior of the beam near to a working point have shown, that losses of the beam are caused by a resonance  $4Q_z = 39$ , normally excited by cubic nonlinearity of accelerator magnetic field. With sextupole lenses only, far from a line of working resonance  $3Q_x = 29$ , it is lost about 80% intensity on a line  $4Q_z = 39$ . Frequency shift from this line approximately on 0.02 provided beam conservation with sextupole lenses switching on. Explanation of such beam behavior it is possible only by resonance  $4Q_z = 39$  influence with parabolic nonlinearity in the second approximation of the theory of averaging. The system of the working resonance excitation of the parabolic nonlinearity with the help of four powerful sextupole lenses is the strong source of some resonances if to take into account the second approximation. It excites all odd harmonics of parabolic nonlinearity, therefore a resonance  $4Q_z = 39$  is a reason of the beam losses. Numerical simulations of the amplitude growth in our system near to a line  $4Q_z = 39$  have shown correctness of this point of view. On Fig. 9 the phase plane of vertical motion is shown at initial frequency  $Q_z = 9.745$ . Obvious display of the fourth order resonance is visible.

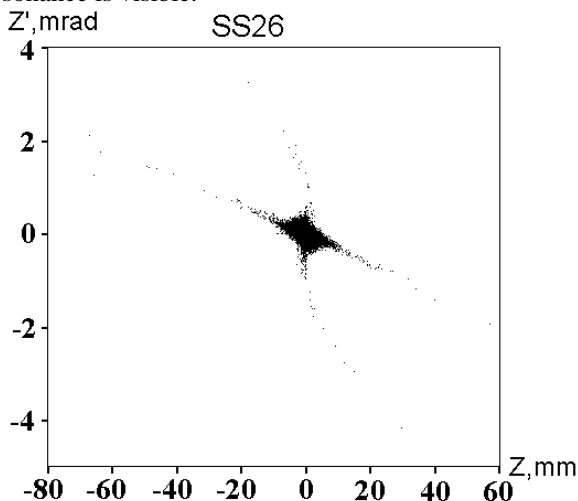


Figure 9: Phase plane of the vertical motion near resonance  $4Q_z = 39$

To set a working point at the slow extraction above line  $4Q_z = 39$  one have reduced energy of the accelerator

up to 64 GeV (field  $B_0$  from 12 up to 11 kGs). It has enabled to reach initial position of a working point of the slow extraction at  $Q_z = 9.78$  (a line 2 on Fig. 8). On Fig. 10 the phase plane of the vertical motion in SS26 is shown. One can see the absence of the fourth order resonance. In SS26 the vertical size of the ejected beam has the maximum volume. Because of the influence of the coupling resonance the vertical size makes  $\pm 10$  mm at initial  $\pm 7$  mm. The vertical magnet aperture is equal 25 mm and sufficient freedom for accommodation of a beam is not present. The vertical closed orbit distortions can reach volume of 7-10 mm. Therefore at slow extraction it is necessary to adjust ejected beam position in the bend-magnet SM26 aperture with the high accuracy by the vertical correction system. At performance of all requirements on adjustment of the slow extraction system and careful setting of ejected beam on the extraction trajectory the extraction efficiency  $95\% \pm 2$  is reached with the intensity  $1.5 \cdot 10^{13}$  ppp.

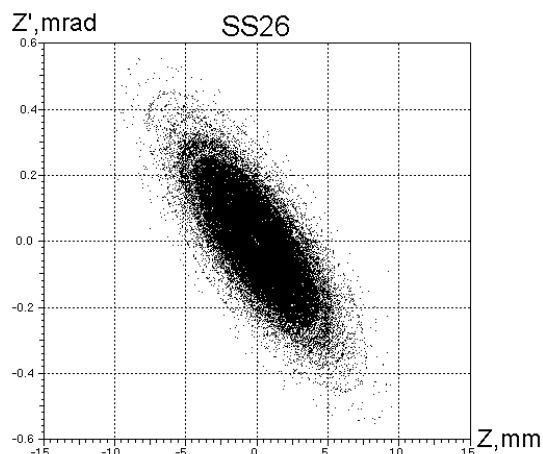


Figure 10: Phase plane of vertical motion of ejected beam in SS26 with initial  $Q_z = 9.78$

At extraction intensity more than  $5 \cdot 10^{12}$  ppp due to beam coupling with RF stations and other elements of the vacuum chamber of the accelerator the beam instabilities arise in longitudinal motion with the frequencies of the  $\sim 5$  MHz, witch leads to modulations of ejected intensity. It decreases efficiency of experimental physical set on 30-40%. For suppression of these effects after switching off 6 MHz RF system the 200 MHz RF station is switched on. The frequency modulation of 200 MHz with frequency deviation of  $\pm 500$  Hz in a range of 1000-1500 Hz changes the beam density distribution in a phase plane of longitudinal motion, doing it more flat. This procedure eliminates instability rising on high frequencies and improves quality of slow ejected beam [3].

For suppression of the ejected beam intensity modulation on low frequencies the method of phase displacement with use of accelerating station on the frequency of 200 MHz is also used. For additional suppression of modulations the low-inductance quadrupole lens included in a beam intensity feedback

system [4]. It allows to receive a quality of a slow extracted beam with duration more than 1 sec with duty-factor of the extraction ~95% (see Fig. 11).

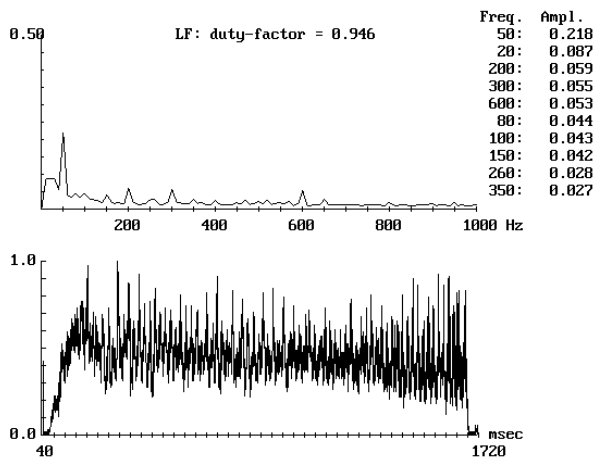


Figure 11: Spectrum and spill of slow ejected beam in last runs

Difficulties of adjustment of system of the slow extraction, defined by lacks of the vertical correction systems of the beam orbit demand the increase of the

vertical aperture of SM26 up to 30-35 mm. Thus the efficiency of the extraction up to 97% can be achieved.

## REFERENCES

- [1] K.P.Myznikov, V.M.Tatarenko, J.S.Fedotov, "Performance of systems of a slow and fast extraction of protons of accelerator IHEP on energy 70 GeV", IHEP RAS 70-79, Serpukhov, 1970, 34 pages, (in Russian).
- [2] A.G. Afonin, V.I. Dianov, A.V. Maximov, "Optimization of the scheme of a slow extraction of a proton beam from U-70", IHEP 92-121, Protvino, 1992, (in Russian).
- [3] B.A. Kalinin, V.G. Kudryavtsev, A.J. Malovitsky, K.P. Myznikov, I.I. Sulygin, "Research and suppression of a self-grouping of a beam at a slow extraction of particles from U-70", The report at the given conference.
- [4] V.V. Lapin, D.V. Korobov, O.V. Zjatkov, V.A. Jaichkov, "The first stage of modernization of a feedback on intensity of the extracted beam in slow resonance extraction from proton synchrotron IHEP on 70 GeV", The report at the given conference.