COMPUTATIONAL SIMULATION AND EXPERIMENTAL RESEARCH OF BEAM RF CAPTURE INTO IHEP BOOSTER

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Abstract

The results of the numerical and experimental investigations of the beam RF capture in the booster – fast-cycling proton synchrotron are presented in this report. The existing features of the magnetic field cycle of the accelerator are taken into account in the simulation. The time dependence of the RF voltage as well as the moment of the beam injection (during the field cycle) have been optimized to get the maximum efficiency of the capture. The experimental results giving nearly 100% beam capture in the Booster are presented.

INTRODUCTION

The booster running as an injector for the synchrotron U-70 accelerates protons from 30 MeV up to 1.32 GeV. Particles intensity of an impulse can be varied from $2 \cdot 10^{11}$ up to $1 \cdot 10^{12}$ in dependence on the needs of physical experiments. Fig. 1 shows the time dependence of the guiding magnetic field $B(t)$ and the corresponding change of the beam intensity. The detailed characteristics of the booster one can find in Ref. [1].

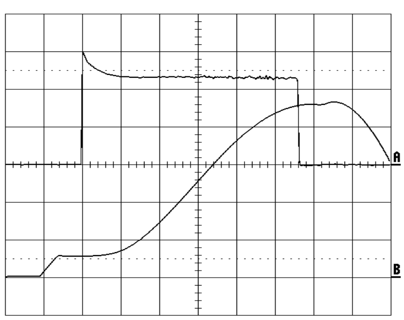

Fig. 1: line A - beam intensity, line B - a magnetic field (time scan – 5 ms/step)

The protons are injected into the booster from the linear accelerator LU-30. By now the mounting of special equipment has been completed for injection of light ion nuclei from linear accelerator I-100. A beam of deuterons has been accelerated up to the energy of 450 MeV/n, and efforts to increase its intensity are now in progress.

The standard adjustment modes of the technological systems which provide a steady operation have been determined during the accelerator running. But until recently some special features of these modes have not been studied. Therefore the results of the numerical and experimental investigations of the longitudinal proton beam motion with the real booster parameters are presented in this report.

The optimization of the particles capture into the acceleration process was studied in Ref. [2], where was proposed to realize the so-called "quasi-adiabatic capture" But such a mode has not been realized in practice. Instead the non-adiabatic capture is used. The experimentally found adjustment mode shows that the best conditions for getting the maximum intensity are the ones when beam injection occurs at the decreasing magnetic field with $B' \approx -4$ Gs/ms.

OPTIMIZATION OF BEAM CAPTURE PARAMETERS

The longitudinal motion of particles in a synchrotron is described by a system of two nonlinear differential equations of the first order for usual variables $\Delta p = p - p_s$ and φ [3]. The code for numerical integration of these equations has been written making use of the package "Mathcad 13" [4]. The measured time dependence of the magnetic field was used as the basic data. The signals of the field and its derivative for the starting stage of the magnetic cycle are shown in Fig. 2; the beam is injected into the accelerator at time $t = 0$. Some ripple of the derivative B' near $t \approx 3$ ms (see curve 1 in Fig. 2) corresponds to powering up time of feeding rectifiers which provide stabilization of the magnetic field shape [5].

In simulation of the phase motion this fast ripple was neglected and the real dependence $B'(t)$ was smoothed by polynomials in t. The time scale was displaced to provide the time counting from the moment at which the derivative $B'(t)$ equals to zero (Fig. 3).

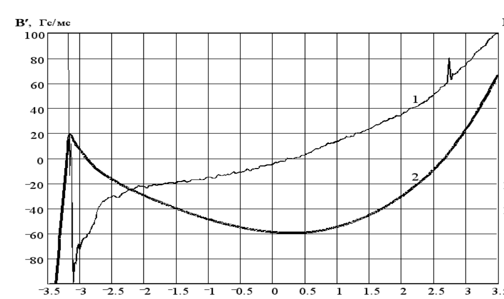

Fig. 2: 1 – field derivative $B'(t)$, 2 – field $B(t)$

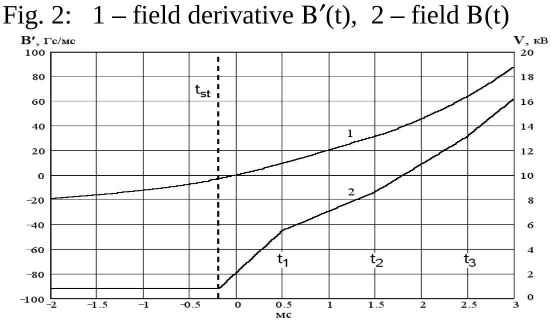

Рис. 3: 1 – the smoothed derivative $B'(t)$, 2 – voltage $V(t)$ used in simulation

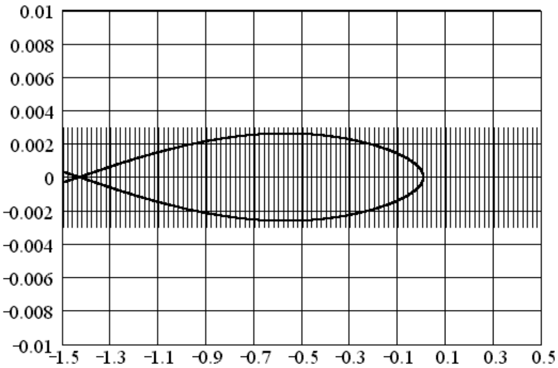

Fig. 4a: t_{st} = - 0.1853 ms, $B'(t_{st})$ = -3 Gs/ms

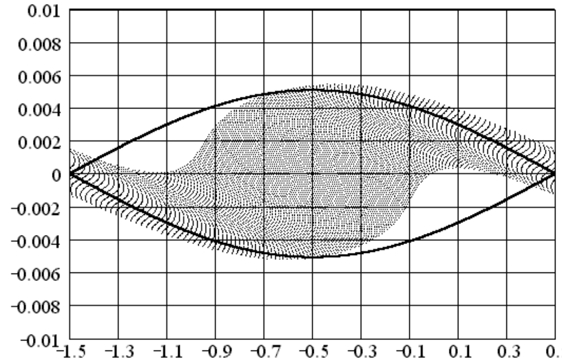

Fig. 4b: t = 0 ms, $B'(t)$ = 0 Gs/ms

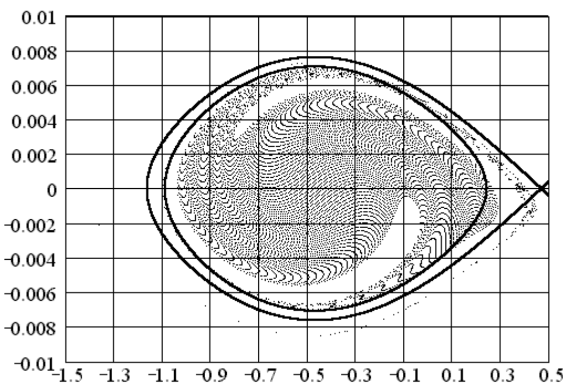

Fig. 4c: t_1 = 0.5 ms

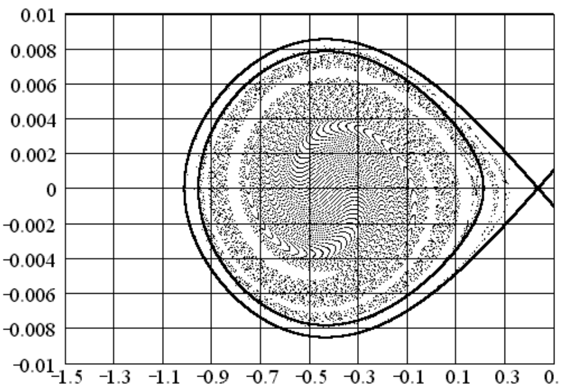

Fig. 4d: t_2 = 1.5 ms

The amplitude of the accelerating voltage $V(t)$ is composed of linear segments between the time points selected as nodes. The spacing of these nodes takes into account that the real amplitude is created via 31 vectors of the functions generator. The optimization result of $V(t)$ in the starting interval is shown in Fig. 3. Nodes are fixed at the moments $t_1 = -0.5$ ms, $t_2 = 1.5$ ms but the starting moment t_{st} (beam injection) varies to optimize beam capture. The particles motion during the capture is shown in the phase space in Figs. 4 ($\Delta p/p$ – ordinate, φ/π – abscissa).

At t_{st} particles are distributed uniformly in the rectangular area with $\Delta p/p = \pm 0.003$ and phase interval 2π. Figs. 4 show also an instantaneous separatrix and the “instant phase trajectory” which contains 95% of all the particles inside the separatrix. It is evident that by $t_1 = 0.5$ ms the beam is already bunched. Calculations have shown that if the separatrix area does not decrease during the interval from t_1 to t_2 the particles trapped by such a separatrix will not be lost later. Thus the capture is actually completed by the moment t_1. The capture efficiency factor η defined as the ratio of the particles number within the separatrix at t_1 to the initial number of particles (usually $\geq 10^4$).

The following parameters were varied in the capture optimization: t_{st}, V_0 and V_1 – the amplitudes at t_{st} and t_1 respectively. The variation of t_{st} was coupled to integer values of B', for example $t_{st} = -0.1853$ ms while $B'(t_{st}) = -3$ Gs/ms. It was done with the purpose of the further testing of the simulation results using the measured characteristics of the magnetic field. It was also taken into account that the accelerating stations can provide the minimally acceptable stable value of the voltage amplitude 0.8 kV.

The simulations show that η increases with the amplitude V_1. So it is optimal to select $V_1 = 5.5$ kV and $B'(t_{st}) = -3$ Gs/ms. At the next stage of calculations the effect of the amplitude V_0 on η was defined. The results show that the increasing of V_0 worsens the capture factor. As a consequence the minimum acceptable value of 0.8 kV is at the same time the optimal one.

The behavior of η versus t_{st} was studied with different values of total momentum spread of particles in the injected beam. It follows from the simulations the interval $B'(t_{st}) = -(3 \div 4)$ Gs/ms is the best for injection in all cases. This explains the well-established modes of the practical accelerator adjustment. The phase portraits of the injected beam shown in Figs. 4 was received for the optimal parameters. After the optimization we have got at the moment t_1 the capture factor $\eta = 0.991$.

The adiabatic approach to the generation of $V(t)$ after the capture completion gives good results. It was proved by tracking the longitudinal particles motion all over the acceleration cycle. The nonadiabatic effects occur also before the beam extraction when the synchrotron oscillation frequency appreciably decreases. The dependence $B'(t)$ and the optimal amplitude $V_{opt}(t)$ during the given magnetic cycle is shown in Fig. 5. The amplitude dependence takes into account the evolution of the particles momentum spread (see Fig. 6).

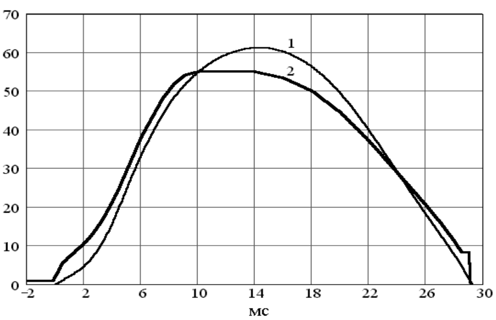

Fig. 5: 1 – derivative $B'(t)/10$ (in units Gs/ms), 2 – result of optimization $V_{opt}(t)$ (in units kV)

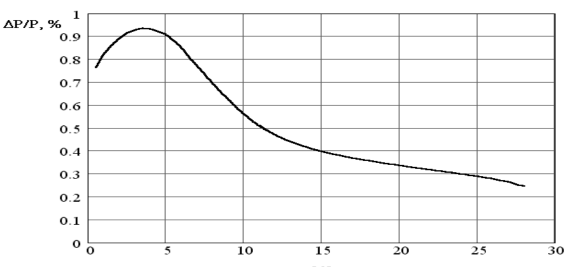

Fig. 6: Dependence $\Delta P/P$ for the beam

EXPERIMENTAL VERIFICATION OF SIMULATION RESULTS

Measurement of η was of main interest during the experimental researches. The beam losses always take place at the initial stage of acceleration approximately up to 5 ms (line A in Fig. 1). These losses can be caused both longitudinal and transverse (betatron) motions of particles. Direct method that could select of all possible losses only those related to the capture is the fast cutting of the large betatron amplitudes. This can be done by creating a fast orbit bump which moves the beam up to a scraper (mechanical shutters) and then reverts during the time noticeably shorter than the phase oscillation period. The mechanical shutters can be moved into the chamber aperture in horizontal (**x**) and vertical (**z**) directions. These shutters were moved up to a contact with a beam so that particle losses to be equal to ~5%. Then during 2.6 ms the independent bumps were formed in **x** and **z** directions. Maximum orbit deflection in a bump was at the scraper azimuth. Power supplies of the bumps correctors provided a current cutoff during ~0.8 ms. At such cutoff speed the beam moves aside from a cutting shutters faster than its radial size increases due to the phase oscillations. Then the created bumps were shifted in time to the moment t_{st} so that the beam "saw" only their recessions.

The intensity signals versus a cutting degree are shown in Fig. 7 where: the lower signal corresponds to bumps values of ~12.5 mm and ~4.2 mm for **x** and **z** directions; the upper signal corresponds to the switched off bumps. One can see that the cutting of a beam enables to remove the slow particles losses.

The beam injection was performed at $B'(t_{st}) = -(3 \div 4)$ Gs/ms. Momentum distribution as a signal from spectrum analyzer detector looks like close to the parabolic with full spread $\Delta p/p \approx \pm 0.003$. So the real momentum distribution is more preferable for the capture than the uniform distribution used in the simulation. The fact that after the beam cutting (the lower line in Fig. 7) the slow losses of particles were removed was the evidence of practically 100% capture.

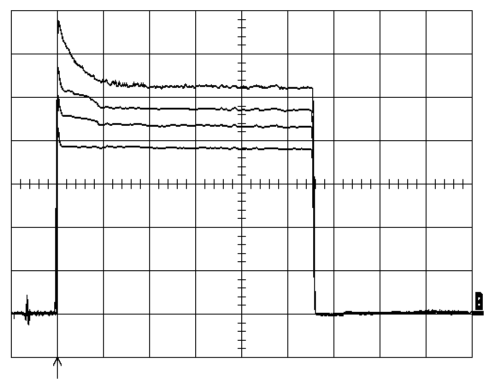

Fig. 7: Change of intensity signal form versus cutting depth (time scan - 5ms/step)

CONCLUSION

The purpose of this paper basing mainly on numerical calculations was to interpret the existing modes of the booster adjustment and to prepare it for acceleration of light nuclei. The numerical calculations were performed taking use of the real parameters of the magnetic cycle and of the operational features of stations. The simulation allowed to optimize the law of the voltage amplitude change throughout the acceleration cycle. The comparison of the calculated and experimental results is the evidence of the correct approach to the problem solution, which in turn gives a certainty of possible using the simulation program for various operating modes of the booster including ion acceleration.

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