BEAM ENERGY RAMPING AT SIBERIA-2

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1 INTRODUCTION

Electron storage ring SIBERIA-2 [1] is a dedicated synchrotron radiation (SR) source for wide range of experiments in many fields of science. Its commissioning started in 1995. One of the main commissioning goals — working energy 2.5 GeV — was achieved on 23 March 1996. This paper describes ramping energy process organization and main phenomena that defined its character. First, it is iron saturation in the yokes of magnetic elements, second, short beam lifetime at the initial stage of commissioning and, finally, different temporal characteristics of power supplies. Experimental data for time and efficiency of ramping are given.

2 STORAGE RING

Storage ring consists of 6 mirror-symmetry cells. Each of them contains achromatic bend and two 3-meter long straight sections for injection, RF-cavities and insertion devices. Magnet lattice was optimized to get bright SR beams from all radiation points. All bending magnets are connected in series. Six quadrupole families provide strong focusing, two sextupole families compensate natural chromaticity. General parameters of storage ring are given in Table 1.

Table 1. General parameters of SIBERIA-2 storage ring.

Circumference, m	124.13
Injection energy, GeV	0.45
Working energy, GeV	2.5
Betatron tunes Q_x, Q_z	7.77, 6.70
Natural chromaticity C_x, C_z	-17, -13
Field in bending magnets at 2.5 GeV, T	1.7
Field gradient in quadrupoles at 2.5 GeV, T/m	up to 35

Control system [2] is based on CAMAC-oriented computers “Odrenok“ designed in BINP. System operates with 5 Hz frequency and provides real-time controlling both one selected element and group of elements. All storage ring is controlled by means of special tables of settings — so called regimes. Regimes can be saved to file, edited, set to hardware for given number of steps, organized into series (processes) and so on.

Several diagnostic tools are worth to be mentioned. Magnetic field in bending magnets is measured by nuclear magnetic resonance method (NMR) so we know an electron energy under the stable conditions. Betatron tunes are determined by resonance excitation with period of 1 second, closed orbit is measured every 5 seconds by set of 24 pickup stations.

3 RAMPING PROCEDURE

3.1 Iron saturation

Because of relatively small circumference of the ring magnetic elements are short and have high level of magnetic field. From the other hand, working energy exceeds injection one by multiple of 5.5. It leads to strong saturation of magnet yokes at 2.5 GeV. Fig. 1 illustrates dependence of the field in bending magnets measured by NMR method on power supply current.

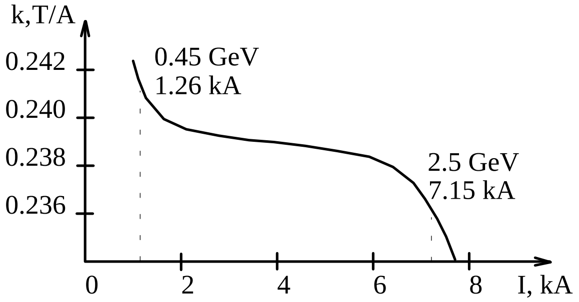

Figure 1 Dependence of normalized magnetic field *k*=*B*/*I* in bending magnets on supply current *I*.

Field gradients in quadrupoles demonstrate the same behavior. Strong saturation starts after 550 A while working currents are 600-750 A at 2.5 GeV. All elements have residual magnetic field at small current levels because of unipolar power supply.

For ramping experiments we must every time return to the same working point at the injection energy. For this purpose a cycle of overmagnetization was organized for main magnetic elements (see Fig. 2). I_{max} is near to possible maximum value for power supplies. I_{min} is near to the lowest stabilized current. I_{inj} corresponds to injection energy.

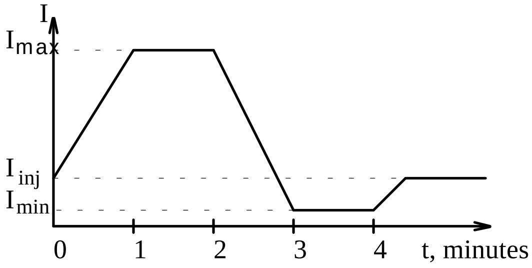

Figure 2. Cycle of overmagnetization for magnetic elements of SIBERIA-2.

Usually only one such cycle is sufficient to get initial betatron tunes with accuracy of 0.002. Current levels for main magnetic elements are given in Table 2.

Table 2. Currents in magnetic elements during overmagnetization cycle.

Elements	**I_{min}, A**	**I_{inj}, A**	**I_{max}, A**
Bending magnets	500	1260	7900
Quadrupoles	30	90-130	800
Sextupoles	0	0.5-1.2	15

Due to saturation effect we cannot set working energy regime just after injection energy one even for great number of steps. In this case field in bending magnets and gradients in different quadrupole families will change unproportionally and beam will be lost on resonances because of large betatron tune shifts. So intermediate regimes were introduced into ramping process. At low energies difference between neighboring regimes reaches 30% in energy, but after 2 GeV this difference is not more than 0.1 GeV. Now we use 10 intermediate regimes. They were constructed by slow increasing of energy step by step. Current in quadrupoles and sextupoles was changed according to magnetic measurement results. Additional weak correction was introduced into lenses of dispersion-free straight sections in order to keep initial values of the betatron tunes. Chromaticity compensation was proved in every regime. Dipole correction currents increased proportionally with energy to keep the same form of closed orbit, but above 2 GeV additional orbit correction was made. Closed orbit distortions during ramping do not exceed 2 mm at pickup azimuths. When experiments at 2.5 GeV are finished injection regime is set after cycle of overmagnetization mentioned above.

3.2 *Beam lifetime*

Vacuum conditions determine beam lifetime at first stage of commissioning. Now lifetime is equal approximately 900 seconds for 1 mA bunch. Calculations show that lifetime also depends on Toushek effect and its value has minimum near 0.8 GeV. In order to keep more electrons for effective outgassing of vacuum chamber by SR at high energies we must pass this region with maximum speed. If we want to keep half of beam current we have to spend not more than 5 minutes to reach 1 GeV. Then beam lifetime increases and is equal 1 hour at 2.5 GeV for 1 mA bunch. An effect limiting ramping speed will be discussed in the next section.

3.3 *Power supplies temporal characteristics*

As one can see from Table 2 bending magnets and quadrupole lenses use very different power supply. Except of different current and power they have also different time-dependence characteristics. Fig. 3 shows response of these power supplies to linear energy changing and behavior of betatron tunes.

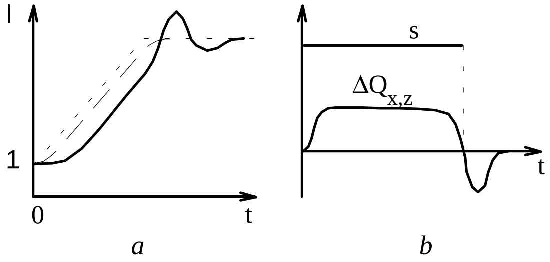

Figure 3. Transition process for different types of power supplies. *a* -- normalized current versus time (schematically), dotted line -- drive signal, dashed line -- current in quadrupoles, solid line -- in bending magnets; *b* -- normalized speed of current growing *s* and betatron tune shifts $\Delta Q_{x,z}$ in arbitrary inits versus time.

Bending magnet power supply has overregulation. This allows to increase its speed, but even in this case difference in time between two power supplies is equal approximately 0.6 of control system step T=0.2 sec or 0.12 sec. Betatron tune shifts during probe energy increasing show that field in bending magnets is behind quadrupole gradients for even longer time -- approximately 0.9T. These tune shifts can be calculated from expression:

$$\Delta Q = C \cdot \Delta I / I \cdot k \qquad (1)$$

where C is natural chromaticity, $\Delta I/I$ is normalized difference between currents in bending magnets and quadrupoles at particular moment, k=1.5 is coefficient that shows how field is behind current. At low energies two nearest resonances are dangerous for the beam, these are $4Q_x = 31$ and $5Q_x = 39$, that is shift of Q_x must not exceed -0.02 or 0.03. At high energies second resonance is not so dangerous. Now one can calculate maximum possible ramping speed. Near injection energy it is equal only 5 A/sec for bending magnets. So energy will reach 1 GeV after 5 minutes or more. It is obvious that we had to change a rule of current growing in order to increase ramping speed. The rule that we have designed (see Fig. 4) has several important features.

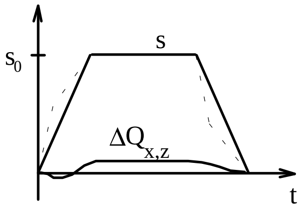

Figure 4. New rule for the normalized speed of current growing *s*. Solid trapecia-like graph -- for quadrupoles, dotted line -- for bending magnets. Square of triangles is equal to $0.9 s_0 T$. Betatron tune shifts are also shown in the same scale as in Fig. 3.

Firstly, speed of current growing at the beginning and at the end of the process changes linearly. Time of the changing is equal to one third of the whole process time but not more than $50T$. This fact eliminates strong betatron tune shifts at the end of the process. Secondly, on the first stage of the process current in bending magnets changes faster than currents in quadrupole lenses so on the second stage difference between them is permanent and equal to $0.9\Delta I$ at particular moment, where ΔI is normalized step of current. Steps for all currents are calculated before starting the ramping. On the last stage current in magnets increases more slowly than in lenses and difference between them vanishes. Fig. 4 also shows that betatron tune shifts are strongly decreased by this new rule of current growing. In order to minimize of amount of calculations during ramping all weak-current elements that are sextupoles and dipole correctors use old linear rule of current growing. Described modification of ramping process allowed to decrease ramping time down to 7 minutes and to reach 75% efficiency. Betatron tune shifts were between -0.01 and 0.03. To make all process faster we need to use more complicated rule of current growing for bending magnets.

3.4 Process modification

As one can see we spend a lot of time when stopping at intermediate regimes and preparing next part of ramping. But we can make all possible calculation before the start of the ramping and keep this information in a special file. Control program will read this file during ramping. So we have not to decrease speed of current growing down to zero at every intermediate energy. New process keep a relation between currents in magnets and quadrupoles during whole process though regimes are set for different time intervals. Speed of current growing changes during $50T$ at every regime. This modification of ramping process decreases its average speed so we can change all currents faster. Using this method we achieved whole ramping time 5.5 minutes and 80% efficiency with betatron tune shifts mentioned above.

3.5 Latest results

The process described above worked well for beam current less than 4 - 5 mA. Above this level we observed dependence of the betatron tunes on stored current, so we had to increase ramping time in order do not loose more electrons. The best result until now is 7 mA current at 2.5 GeV with ramping time of 12 minutes and efficiency of 50%.

4 CONCLUSION

Starting of operation at 2.5 GeV is a very important commissioning result for SIBERIA-2. It allows to begin effective outgassing of vacuum chamber by SR in order to increase lifetime and maximum stored current. First experiments on micromechanics were made at 2.5 GeV in April 1996.

5 REFERENCES

[1] “Magnetic lattice of SIBERIA-2 -- dedicated SR source”. G.Erg, N.Gavrilov, V.Korchuganov et al. Preprint BINP 89-174, Novosibirsk.

[2] “Control system of the synchrotron radiation source SIBERIA”. S.Kuznetsov, A.Kadnikov, Yu.Krylov et al. NIM A 352(1994), pp. 161-165.