PRELIMINARY ANALYSIS OF THE NUCLOTRON MAGNETIC FIELD

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Abstract

The superconducting heavy ion synchrotron Nuclotron is under operation since March 1993. The Nuclotron ring includes 96 dipoles and 64 quadrupoles. The dipole and quadrupole magnets have iron yokes and coils made of a hollow superconductor and cooled with a two-phase helium flow.

This paper describes the apparatus for ”warm” and ”cold” magnetic field measurements, results of these measurements and criteria of the field quality control. The adjustment of the midplane in the magnet gaps and the magnetic field correction in the Nuclotron ring are also discussed.

1 INTRODUCTION

The Nuclotron concept, choise of its lattice, the magnet parameters as well as the first results of the operation are presented in [1]–[4]. The existing linac is used to inject a single turn of 20 MeV protons or 5 MeV/u ions with the charge to mass ratio over a range of $0.33 < q/A < 0.5$. A slow extraction will be performed at energy range from 0.2 to 6 GeV/u.

The chosen lattice contains 8 superperiods. Each superperiod consists of 3 regular FODO cells with dipole magnets and one cell without them. One regular cell includes focusing and defocusing quadrupole lenses, 4 dipole magnets and two small drift spaces used to install correcting magnets, beam monitors and so on.

The magnetic system is based on the pulsed magnet with a ”cold” iron yoke in the magnetic gap of which a saddle-shaped hollow superconductor winding is placed. A high electrical strength, a low inductance and good conditions of their cooling make it possible to provide a high (up to 1 Hz) repetition of accelerating cycles with a maximum magnetic field of about 2 T. The dipole and quadrupole main parameters are presented in the Table 1.

2 MEASUREMENT PROCEDURE

The magnetic measurements of the main harmonics, effective lengths and field imperfections were carried out by three rotating harmonic coils measuring the central and edge fields using the standard devices including an integrator, an amplifier, an AD convertor and a computer. The lengths of the each are 458 mm for the dipoles and 248 mm for the quadrupoles, the radius 19.8 mm. The coils were installated relative to base points on the yoke with a high accuracy . The coils were rotated by means of a step motor with computer control. For serial tests, the step was 9 degrees.

Table 1: The parameters of the lattice dipole and quadrupole magnets

Parameter	Dipole	Quad.
Yoke length (mm)	1370	430
Number of winding turns	16	5
Aperture (mm×mm)	110×55	120×63
Critical current (A)	6600	6600
Induction(T), gradient(T/m)		
at injection	0.0294	0.5
maximum	2.08	35.1

The results of the measurements were recorded on computer memory, and after one turn of coil rotation, the field harmonics were calculated including a dipole component as a function of displacement between the coil and magnet axes.

The field measurements at the room temperature were made after their assembling. The purpose of this procedure at a current of 50 A was to check the quality of the work and to obtain data near the injection point (I = 80 A). At this stage, it was needed to correct the median planes of a few dipoles only. The thin textolite layers were put under or above magnet coils.

The cold measurements were carried out at an iron yoke temperature of T=(6–9) K. The range of coil current was I=(640–6400) A with a speed dI/dt of 6400 A/s. All 96 dipoles were subjected by this procedure. The good correlation of the warm and cold tests allowed us to limit ourselves to cold measurements of 16 quadrupoles only and to spread these results over all the lattice lenses. The resolution of the measurements was no more than 5×10^{-5} relative to the main amplitude.

3 RESULTS

The field components of the magnetic elements in the rectangular (x,y) and polar (r,θ) coordinate systems are connected by the formula

$$B_{\mathrm{x}} + iB_{\mathrm{y}} = B_{\mathrm{r_0}} \sum_{n=0}^{\infty} (b_{\mathrm{n}} + ia_{\mathrm{n}}) e^{\mathrm{i}n\theta} \left(\frac{r}{r_0}\right)^{\mathrm{n}}$$

where $B_{\mathrm{r_0}}$ is the guide magnetic field in dipoles, $\mathrm{r_0}$ is reference radius at which distortions are compared ($\mathrm{r_0}$ =

$40\mathrm{mm})$, b_n and a_n are the amplitudes of the normal and skew n–th order harmonics.

The effective length of the dipole or quadrupole magnet is defined as

$$L = \frac{1}{h}\int_{-\infty}^{+\infty} h(s)ds,$$

where $h = B_0, G_0$ – the field or gradient in the center of dipole or quadrupole. The measured effective lengths of the lattice magnets are shown in Figure 1. The measured dipole and quadrupole field imperfections are shown in Figs. 2, 3 (regular) and in the Table 2 (random).

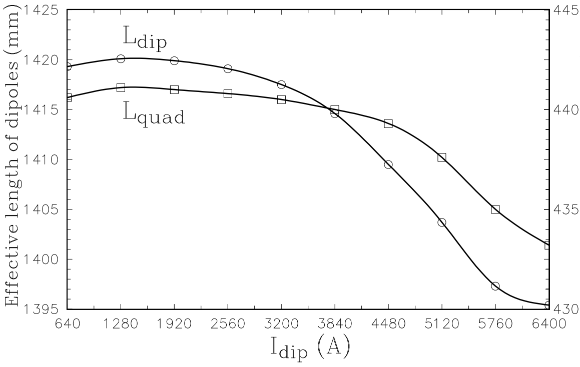

Figure 1: The effective length of dipoles and quadrupoles as a function of drive current

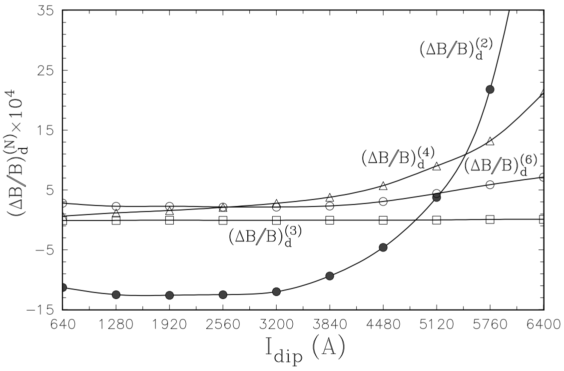

Figure 2: The regular dipole errors at the radius 4 cm (N – order of field derivative)

These data show, that the regular components (odd harmonics for the dipoles and 6–th, 10–th and so on for the quadrupoles) make a the main contribution to the field errors. These values increase when moving to the saturation state.

The dipoles, focusing and defocusing quadrupoles have independent power supplies. To keep the position of the operating point near $Q_x = 6.8, Q_z = 6.85$, the ratios of currents in these elements $I_{f,d}/I_{dip}$ must change so that the ratios $(GL)_{f,d}/(BL)_{dip}$ should be constant during all the acceleration time. The ratios $I_{f,d}/I_{dip}$ are presented in Fig. 4. Decreasing the values of $I_{f,d}/I_{dip}$ at large currents is explained by the defference of saturation in the dipoles and quadrupoles. These dependences are used as base guide functions for computer control programs.

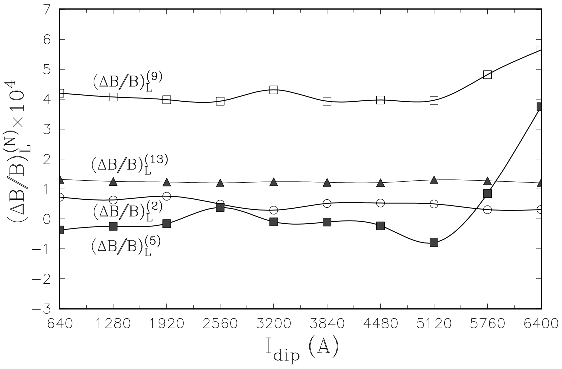

Figure 3: The regular quadrupole errors at the radius 4 cm as a function of drive current (N – order of field derivative)

Table 2: Dipole and quadrupole rms harmonics $(\times 10^5)$

Current	Dipoles/Quadrupoles					
I(kA)	b2	a2	b3	a3	b4	a4
0.64	6.8	17.2	17.0	10.3	7.9	15.2
			16.0	13.9	4.1	11.5
1.28	6.6	17.4	24.0	9.8	7.8	15.6
			15.2	15.2	4.4	11.8
1.92	6.2	17.7	28.0	10.1	8.1	15.3
			14.2	14.5	4.1	12.1
2.56	6.1	17.1	28.0	10.3	8.1	15.0
			14.5	14.9	4.0	12.5
3.20	5.8	17.5	8.5	10.0	8.0	15.0
			14.6	15.0	4.0	12.9
3.84	5.4	17.0	16.0	9.8	8.3	14.8
			15.3	15.8	3.9	13.5
4.48	5.2	15.7	20.0	9.8	8.8	14.5
			15.4	17.0	3.9	13.8
5.12	5.9	16.2	12.0	10.3	10.0	12.9
			16.2	18.2	3.7	14.4
5.76	10.5	33.7	25.2	13.4	11.5	14.4
			17.9	21.1	3.6	14.4
6.40	25.7	53.1	38.1	25.3	16.6	23.9
			17.5	22.2	3.5	13.7

4 FIELD CORRECTION

The chosen operating point $(Q_{x,z} = 6.75)$ is placed far from the lattice betatron resonances. That's why we considered regular distortions of the field only as a source of the tune shift and tune spread and random errors as the cause of the closed orbit distortions and the excitation of nonlinear betatron resonanses. The bandwidths of the sum and difference

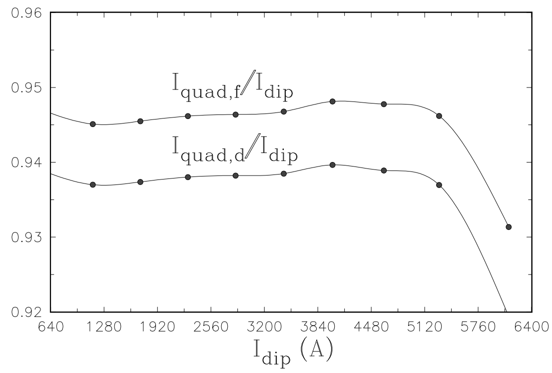

Figure 4: The ratios of lense and dipole current during acceleration

resonances are shown in Fig. 5

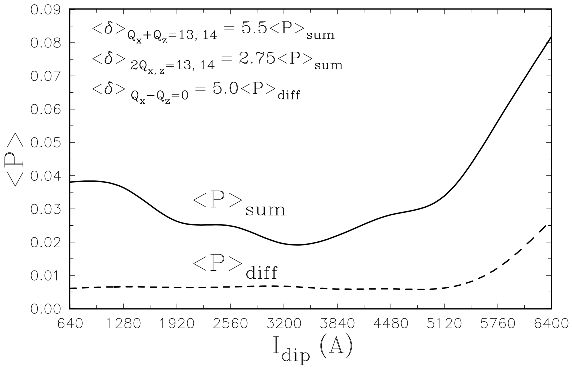

Figure 5: The rms of the sum and difference resonances bandwidths as a function of drive current

To decrease the closed orbit distortion, the neighbouring dipoles in the each cell were combined to pairs (”long” + ”short”) from 5–6 magnets that had been prepared to be installed in the accelerator tunnel. After this procedure, the closed orbit distortions are mainly determined by the magnet misalignments.

The main problem introduces the third regular harmonic (sextupole component) into dipoles causing the momentum tune spread in a first approximation and the amplitude tune shift in a second one. The numerical evaluation [5] shows that tune spread is smaller than 0.01 and it is possible to correct these both effects by means of the present correcting system.

The correcting system is composed of 32 superconducting multipole magnets. It performs the corrections of closed orbit distortion, chromaticity, octupole tune spread and the most important resonances up to the 4-th order, inclusive. Each correcting magnet contains the windings, forming independently normal and skew dipoles, and 2 different types of magnetic fields out of 6 available ones: normal or skew quadrupole, sextupole and octupole.

All the windings are placed on a cylindrical framework wrapped with a hollow tube [6]. The liquid helium flow inside the tube cools the winding due to a thermal contact. The iron cylindrical screen around the windings allows one to increase the maximum field in the corrector by a factor of 1.7–1.8. The screen and windings are placed in the cryostat cooled with liquid nitrogen.

5 CONCLUSION

There were nine runs of the Nuclotron operation of total duration about 2200 hours. The data on beam dynamics confirmed that the parameters of the magnets correspond to the design one. The imperfections can be improved by the multipole correctors. The stable circulation of the accelerated beam during 10 s to be carried out in the last run makes us believe a high efficiency slow extraction will be realized.

6 ACKNOWLEDGEMENTS

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