DIPOLE AND QUADRUPOLE MAGNETS FOR THE DUKE FEL BOOSTER*

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Abstract

The full energy booster injector for the Duke FEL storage ring is presently under installation [2]. The booster is designed to provide continuous injection into the Duke FEL storage ring in top-off mode at the energy variable from 0.27 GeV to 1.2 GeV. The magnetic elements for the booster have been fabricated and magnetically measured at Budker Institute of Nuclear Physics, Russia. The paper presents magnetic and mechanical design of the booster dipole and quadrupole magnets and results of their magnetic measurements. Results of simulation of the booster lattice taking into account residual field and non-linearity of the magnets are also presented.

INTRODUCTION

The DFELL booster synchrotron is a compact 31.9 m circumference machine with race-track shape [1,2,3,4]. It has two identical arcs separated by two 6.24 m long straight sections. Each arc consists of 6 bending magnets with parallel edges, 4 focusing quadrupoles, and 4 defocusing quadrupoles. The bending dipoles and all the quadrupoles are fed by the same power supply with maximum current of 700 A. The duration of operation is 1.2 sec in the single bunch mode and 2.5 sec in the multi-bunch mode [2,3,4]. The ramping time from the injection energy of 0.27 GeV to the maximum energy of 1.2 GeV in both modes is 0.55 sec.

DESIGN AND FABRICATION

A total of 13 bending magnets, including one spare, and 18 quadrupole magnets, including one spare of QF1 and one spare of QD, have been fabricated at BINP.

Table 1: Parameters of the booster quadrupoles.

# of dipoles in the ring	12
Bending angle [rad]	$\pi/6$
Maximum field [T]	1.76
Maximum current [A]	700
Number of turns	2×28
Gap [mm]	27.00 ± 0.02
Radius of curvature [m]	2.273
Core length L_{core} [m]	1.170
Effective length at E=1.2 GeV L_{eff} [m]	1.190
Relative strength of the trim coil [%]	2.0

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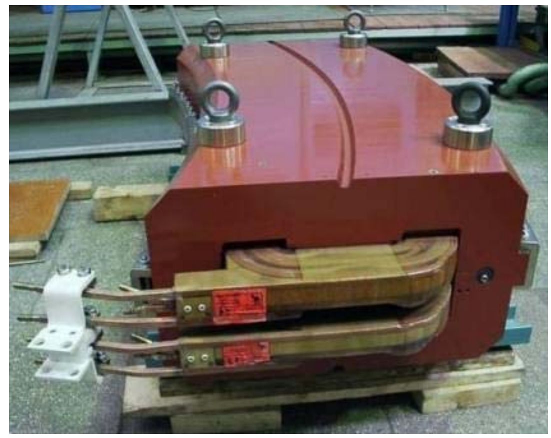

Figure 1: Booster dipole at BINP ready to ship to Duke.

Table 1 shows the key parameters of the dipoles. The parameters of the quadrupoles are listed in the Table 2. The fast ramping requires a laminated core for both bending dipoles and for quadrupoles. The dipole cores were fabricated from 1 mm thick laminations of Stabocor 1500-100SG low carbon steel. Each lamination has a layer of glue on each surface. To fabricate the parts of the core for both quads and dipoles the laminations are stacked in fixtures under a specific pressure and then baked out. This makes the core practically solid, so that its parts may be machined, drilled, etc. The stacking factor for the core is 0.980. For the fabrication of the quadrupole quadrants we used 0.5 mm thick laminations made of Stabocor 940-50A low carbon steel. Both of these type of steel have less than 0.01% of a carbon content and less then 0.2 % of silicon content.

Figure 2: Quadrupoles at BINP ready to ship to Duke.

Table 2: Parameters of the booster quadrupoles.

Quadrupole family	QF1	QF2	QD
# of quads in the ring	4	4	8
Inscribed radius [mm]	50.00 ± 0.02		
Maximum current [A]	700		
Maximum gradient [T/m]	27.62	19.54	8.37
Turns per coil	10	7	3
Core length L_{core} [m]	0.146		0.125
Effective length L_{eff} [m]	0.151		0.131
Maximum strength of individual trims at E=1.2 GeV:			
Y-trim Y' [mrad]	1.0		
Q-trim $\Delta G/G$ [%]	3.3	4.7	11.0

For the installation of the vacuum chamber in the booster arcs the bending dipoles and the quadrupoles are split in halves. Special attention has been paid to provide for the mechanical reproducibility of their re-assembly. Each quadrupole magnet is assembled of 4 identical quadrants which are bolted together. The bottom pair of quadrants is mounted on a stainless steel base frame, rigid and machined into very high tolerances. This base frame provides for the reproducibility of the re-assembly of the quads within 0.02-0.03 mm.

There are three quadrupole families, two focusing (QF1 and QF2) and one defocusing (QD). The required variety of the quad strengths is provided by combination of three types of coils and two types of cores. The coils have the same shape but different number of turns (10, 7 and 3 for QF1, QF2 and QD respectively). The cores are the same in cross section and different in length (Table 2).

The pole profile of the quads is shimmed to minimize 2D harmonic contents to be within $|b_n/b_2|<\pm5\times10^{-5}$ for n=6, 10, 14, and 18 at R_n=2.4 cm for any current up to I=700 A. A comprehensive end chamfer, optimized for the minimum integral harmonic content ($|\int b_n ds/\int b_2 ds|<\pm3.6\times10^{-4}$, n=6, 10, 14, and 18, at R_n=2.4 cm, for the quads of all types at any current up to I=700 A), also provides against 3D edge saturation during the fast ramp of current. For the dipoles we used end chamfer design optimized for the fast ramp and originally developed for 10 Hz operation cycle [5]. Simulations and optimization for all the magnetic elements of the Booster have been done with the use of MERMAID 3D code [6].

MAGNETIC MEASUREMENTS

Each bending dipole and quadrupole passed through a comprehensive set of magnetic measurements at BINP Magnetic Measurement Stand. The dipoles and the quads were mapped using a Hall probe array calibrated against NMR probe. The accuracy of the field measurements was better then $2\cdot10^{-4}$ for the field range of 0.5-1.8 T, and not worse then 0.05 mT for the filed below 0.5 T. To measure the current and to set it accurately we used CERN DCCT 1500/1.5kA with better then 10^{-4} accuracy at 1.5 kA. 11 dipoles were mapped at currents correspondent to the booster energies E=0.27, 0.75, 1.05, and 1.2 GeV. Two of them were mapped at 10 energy checkpoints. All 18 quadrupoles were mapped at 13 energy settings.

Figure 3: Magnetic measurement set-up for the dipoles.

COMPARISON OF THE MAGNETIC SIMULATIONS AND MEASUREMENTS

The variation of the integral between the dipoles was measured within ±0.6–1.0·10-3 peak-to-peak. This is roughly correspondent to the variation of their length within the thickness of a single lamination of ±1 mm. The variation of the integral strength of the quads was within ±0.5·10-3. Fig.4 shows the difference between magnetic measurement and magnetic simulation by the MERMAID 3D interpreted in terms of booster energy.

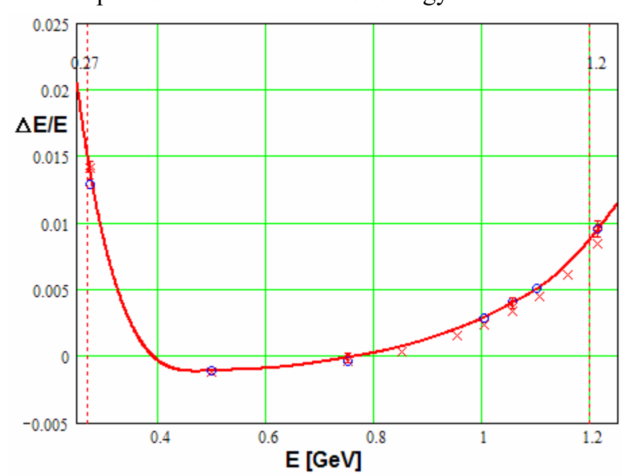

Figure 4: Difference in the strength of dipoles between the magnetic measurement data and magnetic simulations.

At the low energy the measured strength of the dipole is up to 2 % larger then that calculated by MERMAID because the residual field was not taken into account in magnetic simulations. At the high energy it is also larger by about 1 % as the magnetic quality of the iron appeared to be better than that used in the simulations. Fig.5 shows dependency of the normalized integrated body sextupole and the edge sextupole of the booster dipole, simulated and measured. In the magnet design the pole profile of the dipole was pre-shimmed so that at low energy the integrated body sextupole compensates the edge sextupole [3]. As one can see, the measured compensation is close to the designed one. The relative contribution of the

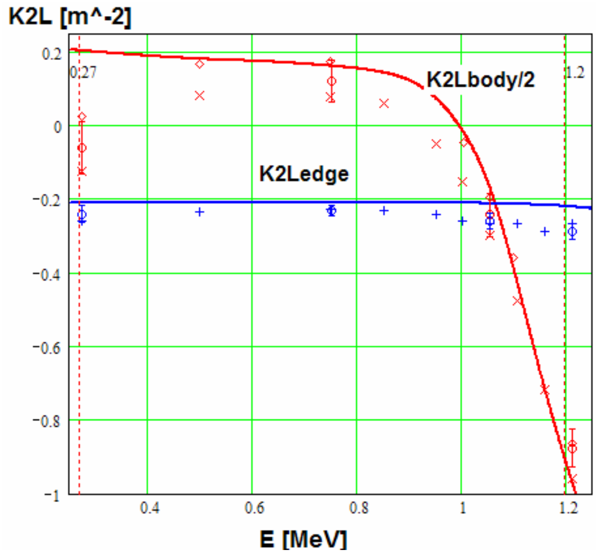

Figure 5: Integrated normalized sextupole in the bending dipole $K2L=\int B''dl/B\rho$, body and edge, simulations (solid lines) and measurements (symbols).

residual field into the strength of the quadrupoles is even larger then that in the dipoles. Thus, the difference between the measurements and the simulations for the quads of different families reaches 3-8% at the injection energy E=0.27 GeV.

LATTICE SIMULATIONS

The dipole and quadrupole magnets of the booster were magnetically designed so that betatron tunes do not cross any significant resonances on the ramp without any correction [3]. The lattice simulations have been repeated based upon the magnetic measurement data analysis (see fig.6).

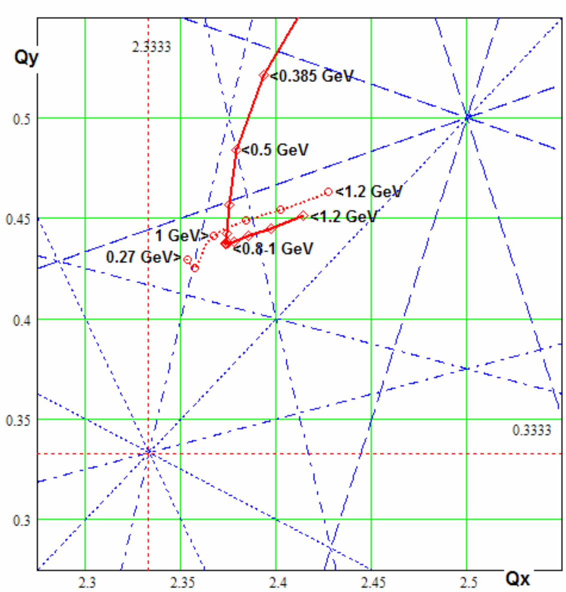

Figure 6: Drift of the betatron tunes during energy ramp 0.27-1.2 GeV with all the quads and bending magnets fed by the same current without correction. Dotted line - from magnetic simulations, solid line - from the measurements.

The contribution of the residual fields into the integrated strength of the dipoles and quadrupoles not taken into account in the magnetic simulations results in a very significant change of lattice. Apparently, this effect has to be compensated by the quadrupole trims. However, starting with energy of about 0.5 GeV and higher, the pattern of the betatron tune drift becomes very similar to the model based upon magnetic simulations. This significantly reduces the settings of the currents required for the correction of the lattice on the ramp.

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