LEB Dipole and Quadrupole Prototypes for SSC

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Abstract

The Institute of Nuclear Physics manufactured the LEB dipole and quadrupole (quad) magnet prototypes. The magnets were designed at the SSCL and then modified at the BINP. The modifications were mainly introduced into the profile and design of end packs. After the end field correction, based on computation and modeling, the magnets with an almost constant magnetic length and an extremely high integral field (gradient) homogeneity were fabricated.

1. INTRODUCTION

The magnetic structure of the Superconducting Super Collider (SSC) Low Energy Booster (LEB) contains 96 main bending magnets and 90 quadrupole lenses of 8 types of different length (from 555 to 756 mm) [1]. The LEB was planned to be operated between E_{inj}=1.2 GeV and E_{extr}=12.0 GeV in a sinusoidal 10 Hz cycle. The power supply system implied that the dipoles and quads would be connected in series, which incurred rigid requirements on the stability of their effective lengths. High values of the betatron tune shifts at the injection energy, resulted from the space charge, determined the high requirements to the value of the integral field homogeneity [2].

In accordance with the agreement between SSCL and BINP, BINP fabricated two dipole and two quadrupole prototypes and performed their magnetic and electrical measurements at DC and AC. The first dipole and quad prototypes were fabricated in exact correspondence with the SSCL drawings in May, 1993. However, they did not meet the primary requirements on the integral magnetic parameters. To improve the original design, meet the requirements on the magnetic parameters, and improve the rigidity of the magnets, new end packs with special shims and chamfers were developed at BINP. The second, updated dipole and quad prototypes were manufactured in October 1993 and comprehensively tested at the Magnetic and Electrical measurement Stand at BINP.

2. MAIN REQUIREMENTS

Main requirements assumed for the second dipole and quadrupole prototypes are given in Table 1.

Table 1
Requirements to the prototypes

Parameters	Dipole		Quadrupole	
	E_{inj}	E_{extr}	E_{inj}	E_{extr}
Gap / diameter (mm)	57.2		100	
Core length [mm]	1875		592	
Current range (amps)	390	3900	390	3900
Field (Gradient) [kGs / kGs/cm]	1.36	13.6	0.156	1.56
L_{eff} [mm]	1875		592	
ΔL_{eff} [mm] over the entire current range, ≤	1.2		1.5	
Field nonhomogeneity (nonlinearity), $\Delta B/B$, ≤	10^{-4}	2×10^{4}	10^{-3}	10^{-3}
in a good field aperture Δx (R_0) [mm]	±30	±15	40	40

3. DESIGN AND FABRICATION

2.1 Steel

The SSCL project supposed the use of a 0.635 mm thick M27 steel for the core fabrication. In accordance with the Russian standards, we used Russian 0.5 mm thick 2312 steel with ~2% silicon and less than 0.003% carbon contents. The comparison has shown that this steel is similar to the M27 steel as for magnetic and electrical parameters. The coercive force of the steel is within 0.8-1.0 Oe.

A special attention was paid to the electrical and radiation resistance of the insulating coating. It has not lost the insulating properties after testing for 10^9 Rad.

The laminations (lams) were die-punched at the "ZVI" plant, Moscow. The accuracy of the punching was 0.025 mm, the maximum burr size didn't exceed 0.04 mm.

2.2 Core stacking and fabrication of the coils

Dipole core consists of 38.5 mm thick packs assembled of whole size laminations. The laminations of each pack were rotated trough 180° to those of the neighboring packs in order to average their mechanical errors. The thickness of the packs for the quads was 54 mm. The laminations for each pack were selected from different steel rolls so that the most effective averaging of their magnetic properties was obtained (see s.3). Dipole cores were assembled in vertical fixtures, the quads were assembled in horizontal ones.

Each pack was placed lamination by lamination in the fixture and compressed with a force of 40 tons for the dipole and 6 tons for the quad. In the process of stacking we continuously controlled the tight contact of the reference surfaces of each lamination against those at the fixtures. The dipole lamination stack was compressed 4 times, while the quad one was compressed 5 times.

One of the most important requirement to the core, which determines the quality of the magnetic field, is a high and homogeneous packing factor all along the core. To obtain it, we weighed each pack before adding to the stack to be compressed and measured the total height of the stack after each compression. After this measurement, we added or removed one or two laminations, when it was necessary, so that the average stacking factor remained constant. Thus, we finally obtained a 98.5 % packing factor homogeneous along the core length.

After each compression, intermediate welding seams were applied to the newly compressed part. The fully stacked and compressed core, together with the end packs, was finally welded to four angular bars applied over the corners. We used MIG welding without a flux. A special sequence of applying the welding seams was developed to minimize the mechanical deformations of the core.

We achieved a flatness of the reference surfaces for the dipole cores better than 0.05 mm in the vertical position, and ~ 0.10 mm in the horizontal position. The pole tip-to-tip and shim-to-shim gaps were controlled after the assembly. The deviation of those gaps along the core were ~ 0.01 mm (tip-to-tip) and ~ 0.02 mm (shim-to-shim).

The coils were wound with an oxygen-free high conductivity hollow copper conductor of rectangular cross-section (18×21 mm for dipoles and 21.9×23 for quads), bore size 9 mm and 6.5 mm, respectively, produced by Outokumpu company, Finland. A half-lapped thick mylar tape followed by annealed fiberglass was wrapped around the conductor. The wrapped coils were vacuum impregnated with an epoxy compound tested for 10^9 Rad radiation resistance.

2.3 End packs

Figures 1 and 2 show the design of the new end packs for the dipole and quad prototypes #2.

The new end packs had a much better mechanical rigidity. New chamfers and shims correcting the integral field (gradient) homogeneity were developed for them. They were shaped with the use of special correcting laminations (see Fig. 1, 2). The chamfers turned out much longer than those initially designed at the SSCL.

The study of the end field correction was carried out on the dipole and quad models. Magnetic measurements of the second prototypes showed an excellent result.

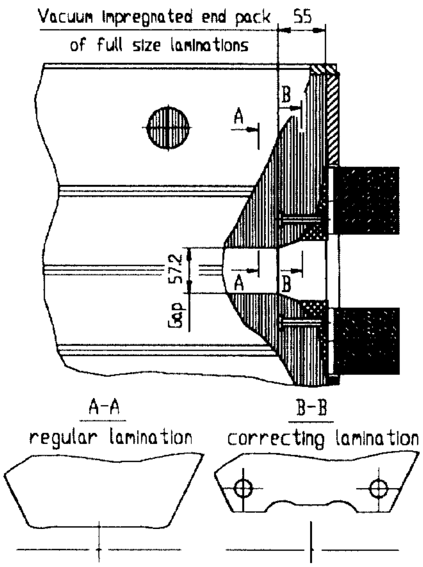

Figure 1. End pack of dipole prototype #2.

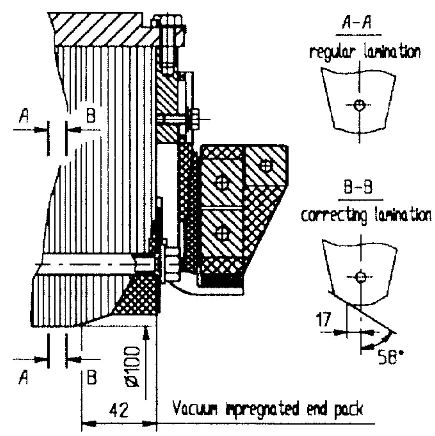

Figure 2. End pack of quad prototype #2.

4. MAGNETIC FIELD MEASUREMENTS

For a preliminary study of specific effects resulted from laminated structure of the magnets, for the development of the end field correction, and for the magnetic measurements of the prototypes the following techniques were used:

1. Hall probe array of 11 probes, calibrated against NMR, used for complete field mapping of dipoles and quads at DC;
2. a set of vertical and horizontal flat coils ("airplane coils") moving across the magnetic axis, used for precise DC measurements of field harmonics in the dipole;
3. strip flat horizontal coils, used for the measurements of total and body integral field distribution in the dipole at AC, with and without the vacuum pipe inside;
4. a set of rotating coils, used for the harmonic analysis of magnetic field in the quads at DC and AC.

In order to efficiently average the difference in the magnetic properties of the laminations, we tried to minimize the characteristic period of the field irregularities along the axis and, therefore, their magnitude (within ± 1.5 Gs for dipole prototype #2). We observed 8-9 Gs remnant field in the dipole uniformed within ± 0.5 Gs, which witnessed a good quality of the steel. We also observed about 30 μm nonparallelity in the dipole gap along the axis.

We developed a second order correction of integral field homogeneity for the dipole with the help of the correcting laminations. As for the quad, some quantity of correcting lams was also added to the ends of the body core so that the laminations added to the end packs corrected only the contribution of the end fields to the integral nonlinearity, while the laminations added to the central body corrected only the whole body nonlinearity. It allows us to use the same end packs in any quadrupoles independent of their length, which is necessary taking into account the difference in length of the serial quads.

The measurements of the prototypes were performed at 9 current levels at DC and all over the rising half of the current period at AC. Figures 3, 4, and 5 show some of the most significant results obtained for the dipole prototypes:

1. We obtained the total integral homogeneity within $\Delta B/B \leq \pm 3\text{-}4\times 10^{-5}$ in 60 mm aperture at the currents up to 2-2.5 kA, while for the whole body integral this homogeneity was $\Delta B/B \leq \pm 8\text{-}9\times 10^{-5}$ (see Fig. 3).

Thus, we corrected the inhomogeneity of the body field resulted from some overshimming of the poles. The bumps in the $\Delta\int Bdl/\int Bdl$ curve can be easily associated with those of the correcting shims (see correcting lamination in Fig. 1).

The quality of the field in the quads was basically determined by the accuracy of the assembling, though we considerably decreased the integral contribution of quadrupole harmonics.

2. We achieved stability of the effective length (L_{eff}=1877 mm) at DC over the entire current range $\Delta L_{eff}\approx 0.6\text{-}0.8$ mm, while it was about 7.1 mm for prototype #1 (see Fig. 4). At AC this stability was $\Delta L_{eff} \approx 2.2$ mm due to the earlier saturation of the core ends in comparison with DC.

As for the quads, L_{eff} =596 mm; $\Delta L_{eff} \approx 1.8$ mm for prototype #2, and 5.1 mm for prototype #1.

3. We observed considerable difference in behavior of the magnetic length of dipole prototype #2 (see p.2 above), and quite noticeable difference in the total integral distribution, at AC in comparison with DC. These distinctions seem to be a great deal higher for the prototype #1.

As for the quadrupole, we observed practically no difference between AC and DC harmonics.

Resuming, we can conclude that we practically met the requirements to the specified parameters of the prototypes.

5. ACKNOWLEDGMENTS

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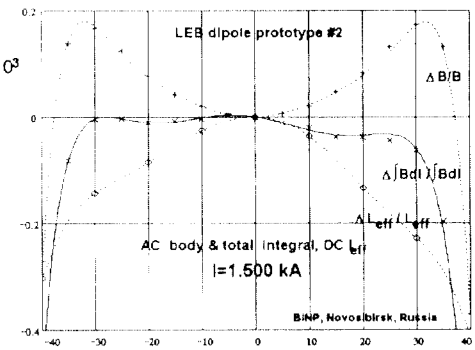

Figure 3. End field correction on dipole prototype #2.

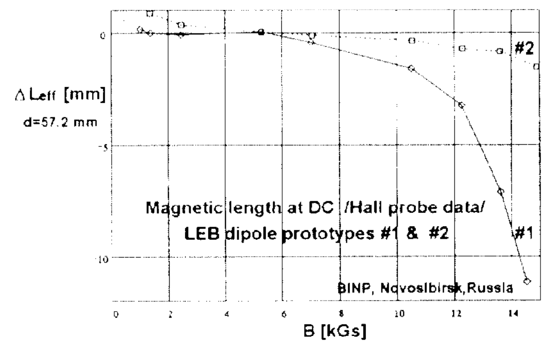

Figure 4. $\Delta L_{eff}(I)$ in dipole prototypes #1 and #2.

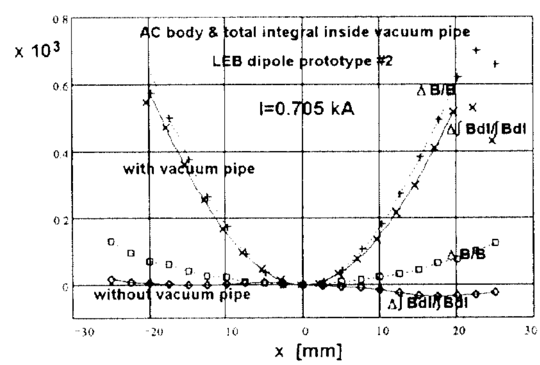

Figure 5. Maximum distortion of the field in dipole #2 by vacuum pipe (stainless steel, 1 mm thick, d≈60 mm) at AC.

6. REFERENCES

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