MEB RESISTIVE MAGNETS PROTOTYPES MANUFACTURING

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This report presents the work, that was done under the agreement between the Moscow Radiotechnical Institute of Russian Academy of Science (MRTI RAS) and Superconducting Super Collider Laboratory of USA (SSCL), signed in May, 1992. According this agreement, 245 quadrupoles and 406 dipoleshad to be done in Russia for Middle Energy Booster (MEB). The whole program was to be completed till 1996. Because of SSCL elimination in 1993 only two magnets (one dipole and one quadrupole prototypes) were done in 1994.

COOPERATION FOR MAGNET PRODUCTION

To fulfill the work properly and in time the following cooperation was organized in Russia:

Moscow Radiotechnical Institute (MRTI RAS),

The Central Research Institute for Ferrous Metallurgy (CRIFM),

Novolipetsky Integrated Iron and Steel Works (NIISW),

Joint Stock Company "SILA” (the former St. Petersburg’s Electrical Engineering Pilot Production Works (SPEEPPW)),

Electrophysical Apparatus Pilot Production Works (EAPPW),

Research and Technology Center "TEMP" (RTC "TEMP"),

Institute for High Energy Physics (IHEP).

This cooperation was build to utilize the equipment and experience of participants which they had in a field of resistive magnets building for Accelerating-Storage Complex (UNK) that was being created in Russia (Protvino, IHEP).

MAIN REQUAREMENTS

The main requirements to magnets were quality, reliability, interchangeability and accuracy. That's why very stringent requirements were imposed on geometrical, mechanical, electrical and magnetic parameters. This requirement has resulted from a very high degree of accuracy of different parameters. For example:

a) tolerance on working and base surfaces of magnets laminations - 25 μm;

b) tolerance on unflatness of base magnets surfaces - 50 μm.

c) tolerance on effective magnetic length, according to SSCL specification - 0.1 %.

Such a rigid tolerances can ensure the opportunity of interchangeability of main ring elements. However the cost of such a convenience may be rather hard.

There were several types of dipoles and quadrupoles to be done for using in MEB. Tables below presents main parameters of typical quadrupole and dipole which were put in the foundation of design work.

NOMINAL CHARACTERISTIC OF MEB DIPOLE

Effective length (m)	6.441
Injection current (A)	273
Extraction current (A)	4983
Max. mag. field (T)	1.7
Max. integrated field (T-m)	11.60
High field error at 25 mm	$3.0\text{x}10^{-4}$
Low field error at 25 mm	$1.0\text{x}10^{-4}$
Weight of magnet (kG)	21136
Power consumption (kW)	44
Core length (m)	6.450
Lamination height (mm)	600.0
Lamination width (mm)	15.4
Lamination thickness (mm)	1.5
Minimum pacing factor (%)	97
Minimum air gap (mm)	50.8 x 101.6
Sagitta (mm)	14.01
Copper weight/mag (kg)	2200
Number of turns / mag.	2x8
Conductor:	
Width (mm)	22
Height (mm)	55
Hole diameter (mm)	9
Number of water circuits/mag	2

NOMINAL CHARACTERISTICS OF MEB QUADRUPOLE

Effective length (m)	2.441
Injection current (A)	252
Extraction current (A)	4210
Extract. current dens. (A/mm^2)	6.8
Max. mag. field in core (T)	1.5
Max. gradient (T/m)	21.5

Max. integrated field (T)	52.237
High field error at 25 mm	3.4×10^{-4}
Low field error at 25 mm	4.8×10^{-4}
Weight of magnet (kg)	5500
Power consumption (kW)	49
RMS power consumption (kW)	20
Core length (m)	2.400
Lamination height (mm)	666
Lamination width (mm)	662
Minimum packing factor (%)	98
Core weight/mag (kg)	4932
Copper weight/mag (kg)	486
Number of turns / mag.	4x4
Conductor	
Width (mm)	26
Height (mm)	26
Hole diameter (mm)	8
Number of water circuits / mag	2

MAGNETS PRODUCTION

2082 and 2083 steel sorts for magnets production were developed by Novolipetsky Integrated Iron and Steel Works (NIISW). The technology of steel manufacturing included the following stages: continuous casting, decarburizing, hot reduction of 20 mm thickness steel sheets, pickling, cold reduction till 0.75 mm (for quadrupoles) or 1.5 mm (for dipoles) thickness, annealing, insulating coating formation, and sheet cutting into bands of needed width. Steel had the saturation induction 2.12 Tl, coertive force was less than 1.9 Oe for quadrupoles (2082 steel) and less than 1.0 Oe for dipoles (2083 steel). Carbon consumption was less than 0.01%. The resistance of insulation coating was tested after steel production using Franclin testing machine.

Laminations stamping was made by stamping line using 300 tons Japan press AIDA. Stamping die for quadrupole production was made with the use of Swiss-made electrical erosion machine AGIECUT-300. The die for dipole production was manufactured in USA. Stamped laminations were measured after experimental stamping with the use of three-directional measurement machine "OPTON UMESS". Measurement accuracy was detected to be not more then 5 μm. The profile of working part of magnets pole corresponds to tolerance limits.

Quadrupole quadrants and dipole half-cores were manufactured by stacking of 50 laminations packs. Mixing procedure was developed to ensure identical magnetic properties of the packs, to ensure the quadrupole and dipole magnetic properties reproduction and to maximize the filling factor . Preliminary experiments showed us that it was necessary to enlarge the press pressure to achieve 97% core stacking factor up to 25 kg/cm^2. Needed press force for dipole appeared to be 40 T instead of former 25 T. Lateral force was increased up to 2 tons per meter.

Magnets cores assembling was conducted using 50 tons hydraulic press.

After the assembling was finished, the straightness of assembly were checked, and semiautomatic welding in neutral gas in accordance with welding process card was produced.

The control has shown the practical conformity of quadrupole core parameters to drawing requirements: the deviation from flatness when resting on flat surface, taking twist into account - not more than 1,4 mm (1 mm without taking twist into account). When loaded - less than 0,05 mm. The stacking factor for four quadrants was obtained to be inside (97.02% - 97.4%) interval.

The quality of dipole core was in turn good enough to satisfy the preliminary requarements.

The coils were produced using hollow conductor. The conductor was made from an oxygen-free copper. Bus splices were executed by silver brazing of copper sleeves.

After coil winding and before insulation, hydrostatic test was conducted with the use of water under pressure 17 kg/cm.

Insulation curing process was performed with the use of termo-pressing in a mould. We used b-stage insulation technology. Polyimid tape, fiberglass tape and mica paper were used as a main components of an insulation. They were glued and saturated with epoxy compaund with latent hadener

Coils were electrically tested before and after turn insulation curing and after ground wall insulation curing. Induced voltage test used 12 V/turn voltage to detect turn-to-turn insulation quality. Impulse test used standard voltage pulse to examine the ground wall insulation. High-voltage insulation tests were conducted by application of DC 5 kV voltage between the coil conductor and the grounded foil with gradient rings during one minute period.

The assembling of coil and magnet cores to get a quadrant or half dipole was made with the use of special fixture with individual coil adjustment with the use of screw press.

The quadrupole and dipole geometry was supervised by linear measuring rods and feelers gauges (interpole distance). This testing showed us that the quality of dipole mounting could be better, if the technology of mounting was more stringent.

MAGNET TESTING

To check the quadrupole and dipole quality, prototypes magnetic measurements program was developed. According to this program, prototypes magnetic measurements were done at the Institute for High Energy Physics (IHEP). Test stands were developed for dipole and quadrupole prototypes integrated strength, body and end field and gradient, magnetic axis position, and higher multipoles measurements.

For MEB dipole prototype investigation the next methods and apparatus were used:

1. NMR magnetometer was used for the calibration of Hall probes, and measuring of body fields (B vs I scan, longitudinal scan). Measuring range (0.1-1.9) Tl, number of probes - 5, absolute accuracy - 10^{-5}. The relative accuracy of magnetometer ($5*10^{-6}$) was checked at 0.15 Tl in a C-type permanent magnet. The absolute accuracy is defined by hyromagnetic ratio of protons in a rubber sample.

2. Hall probes were used for the measuring of nonuniformity of body field and the end field mapping. Sizes of sensitive zone was (1.5 x 0.5) mm^2, nominal current-100 mA, offset voltage -(1-4) uV, sensitivity (70 -75) mV/Tl.

Temperature coefficients for Hall voltage - 10^{-3} %/K, for offset voltage - 30.0 nV/K , for nonlinearity - 0.6 % at 2 Tl.

3. Integrated field BL were measured by stretched wire moving in a magnet median plane. To achieve a good resolution the signal from a wind was gained by preamplifier and then was integrated by V - integrator. Both amplifier and integrator were carefully calibrated.The maximum integrated voltage measurement error is equal to $1.2x10^{-4}$.

The difference between a stretched wire length and length of a magnet along centerline due a sagitta was took into account during the measurements. Summing all contributions the field integral is determined with an accuracy of $2.0x10^{-4}$.

4. Integrated field harmonics were measured by a short pick-up rotating coil. To obtain the integrated field harmonics ten measurements of body field at various distances from magnet ends (5 from both ends of magnet) and two of fringe fields were produced. The integrated field harmonics were received as an average value of these measurements. The dispersion of measured harmonics amplitudes does not exceed $1x10^{-5}$ for k=1..6 at radius 25.4 mm.

5. The magnet current was measured by Constant Current Transformer (CCT), calibrated by HOLEC. Measuring range of CCT - 10 kA, absolute accuracy 10^{-4}, linearity - 10^{-5}.

Methods and apparatus, used during quadrupole testing were similar to dipole.

Movable platform table with adjusted magnet support for quadrupole prototype measurements enable the lens's geometric axis to be aligned with the mechanical axis of the measurement system. Supports with air bearing brackets, stepping motor drive and angle-to-code transducer ensure precise rotation of measuring coils. The air bearing axis is adjusted with regard to the mechanical axis of the measuring system. Optical system was developed to provide necessary adjustment of the len's geometrical axis with the use of the Taylor-Hobson telescope. Adjustment accuracy is better than 2O microns.

Measurement tube with induction coils and stretched wires were used to provide axis position adjustment and harmonics content measurements. There were two types of pipes: 2 meter long and 0.8 meter long. Each pipe had carbon-plastic body. Precise pipe manufacturing enable us to ensure precise coil position inside a pipes.

Main results of the quadrupole prototype magnetic measurements meet all the requirements of preliminary design and confirm high quality of prototype manufacturing. Magnetic axis position is as can be seen from the table below stable sufficiently within full current operation interval.

I (kA)	0.252	0.425	2.0	4.146
Δx (μm)	-8	-12	-37	-36
Δy (μm)	90	80	52	86

Focal strength and effective length measured by means of 2.0 m rotating coil, coincide practically with design values. Current dependence of integrated efficiency GL/I is presented by the next table:

I (kA)	0.24	0.4	2.0	4.15
GL/I (T/kA)	13.045	12.932	12.92	12.608

MEB quadrupole prototype main integrated gradient normal and skew harmonics are inside the design goal.

Dipole magnetic measurements results show good results too. The production process for quadrupole prototype was very close to one for serial units. In turn this demanded less shop personal qualification factor and simplified the control and tests. As for dipole prototype, the time interval to organize dipole production was very narrow, and its quality was dependent on the personal qualification. Nevertheless it was sufficient to make the work properly. It must be said, that technology was prepared for dipole serial production too, but it was no sufficient time to make the tooling in needed grade to check it.

The experience of such kind of work gave us the confidence that cooperation of Russian works and institutes can be a reliable partner for various projects managers.

CONCLUSION

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