THE MAGNETS OF bERLinPro: SPECIFICATION, DESIGN, MEASUREMENT AND QUALITY ANALYSIS*

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Abstract

A total of 77 magnets form the magnetic lattice of the bERLinPro energy recovery linac prototype: 1+8+8 dipole magnets of three different types, 12+40 quadrupole magnets of two different types and 8 sextupole magnets have been produced by BINP.

After the design phase, magnets production started in 2015, measurements and delivery took place in 2016, first assembly stage was finished in 03/2017.

The motivation for the magnet specification and a summary of the basic design is given in this paper. Selected measurement data from the final acceptance tests are presented and analysed to ensure the magnet quality.

INTRODUCTION

The Helmholtz Zentrum Berlin is constructing the Energy Recovery Linac Prototype bERLinPro on its site in Berlin Adlershof [1, 2]. The project goal is the acceleration of a high current (100 mA, 50 MeV), high brilliance (normalised emittance $\varepsilon_n < 1$ mm·mrad) cw electron beam and the demonstration of successful and efficient recovery of the beam energy.

MAGNET SPECIFICATION

The magnetic system of the accelerator (see Fig. 1) consists of an injection and beam dump parts with the design beam energy of up to 10 MeV, whereas normal high current operation with 6.5 MeV beam is foreseen. The recirculation part of the accelerator is designed for the maximal beam energy of 50 MeV. Therefore, the nominal energies for the magnets were defined as 10 and 50 MeV, and two types of dipoles (BM1 and BM3) and quadrupoles (QM1 and QM2) were specified. Additionally, one dipole with an increased aperture for the dump line (BM2) with the nominal energy of 10 MeV was necessary. Sextupole magnets to correct second order nonlinearities are installed in the 50 MeV arcs. A summary of magnet parameters is given in Table 1.

The geometry of two high energy chicanes (see Fig. 1) with 3 dipoles implies that the middle dipole bends by twice the angle of the two other dipoles. These middle dipoles define the necessary strength of the BM1 magnets. Additional efforts to design one more type of dipoles have been considered unnecessary, though a bit more compact merger region would be possible.

Specification of the field quality for the magnets was done on the basis of numerical calculation of the non-linear beam optics with the tracking code Elegant [3]. Normal operation mode of the bERLinPro was considered as a basis. Reduction of the beam line acceptance compared to purely linear optics was investigated. Integrated multipole components for each individual multipole in each type of magnets causing 10% acceptance reduction were found. First, systematic (same for all magnets of the type) and random (Gauss-distributed) multipoles were studied separately. Afterwards, all errors were included in the model simultaneously and were scaled to achieve again 10% acceptance reduction. These values for multipole components were included in the specification (Table 1).

The only one BM2 magnet is the last dipole in the beam line before the beam dump. Its effect on the beam quality is less important; therefore, no requirements on the multipole content of BM2 were specified. Rather, the design of the BM1 magnet was taken over with the only change of the height of the side walls. Since the BM1 magnets were designed for twice the field necessary for BM2, increasing the aperture from 52 to 82 mm resulted in nominal current of less than the nominal current of BM1.

The nominal integrated strength of the sextupole magnets is 8 T/m. The multipoles up to K_7 in the sextupoles are suppressed due to the magnet symmetry.

DESIGN

High quality, magnetically soft iron is used as the yoke material to minimise residual fields. Though all magnets should operate in DC mode, for 40 MQ2 magnets laminated design is chosen as more cost-efficient. All other magnets' yokes are made of solid iron.

All magnet types except for BM3 were designed air cooled and to be used with 8 A 40 V power supplies. BM3 dipoles are water cooled with the rated current of up to 100 A. All magnets include correction coils with about 5% strength of the main coils. Correction coils will be powered with 3 A power supplies.

The magnets can be disassembled into two parts for installation and bake out of the accelerator vacuum system. Tapered pins are used to ensure the accurate assembly of the yokes and reproducibility of the field.

Magnetic design was analysed first with the MERMAID software [4] and refined further with the CST STUDIO.

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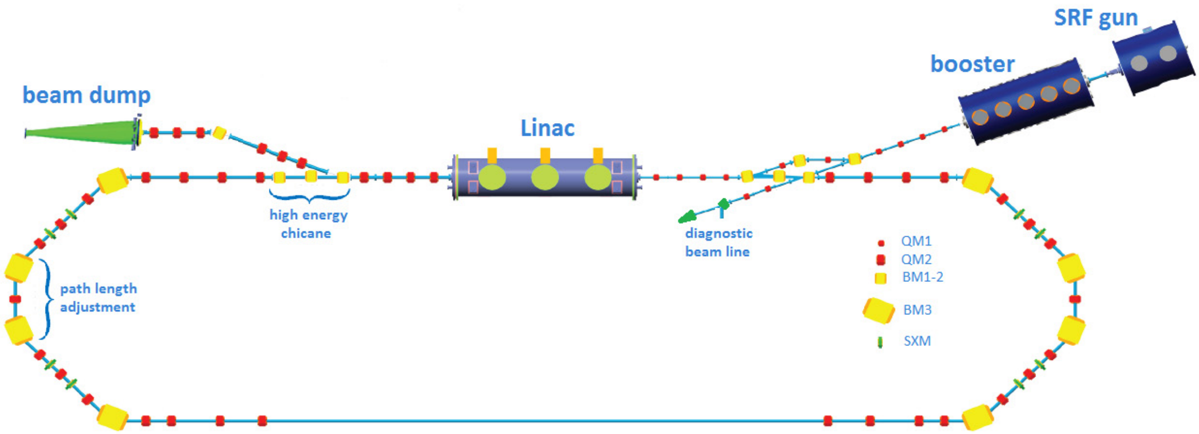

Figure 1: Layout of the bERLinPro magnetic system.

Mechanical tolerances for the iron yoke were set to ensure the specified multipole components are achieved. After assembling of the magnets, critical mechanical dimensions were controlled with a coordinate-measuring machine.

Thermal switches have been impregnated into coils to protect magnets from overheating in the bERLinPro machine protection system.

Table 1: bERLinPro Magnets Parameters and Maximal Tolerable Multipole Components (K_n, in Elegant [3] definition).

Magnet	BM1	BM3	QM1	QM2
Nominal field *	0.09 T	0.22 T	0.075 T	0.34 T
Iron yoke length, m	0.2	0.53	0.1	0.15
Aperture, mm	52	52	52	82
K_1, m^{-2}	0.1	0.025	-	-
K_2, m^{-3}	25	2	5	1
K_3, m^{-4}	6e3	150	1e3	300
K_4, m^{-5}	1.5e6	6e4	2e5	6e4
K_5, m^{-6}	4e8	1.5e7	7e7	1e7

* for QM1, QM2 and SXM integrated gradients are given

MAGNETIC MEASUREMENTS

Hall Probe Measurements

The measurement methodology is described in [5]. A series of measurements was made for one magnet of each type:

- field map for the nominal current (main coils)
- residual field after switching off the power supply
- field map after a magnet disassembling/assembling for the nominal current (main coils, reproducibility check)
- field map for the nominal current (correction coils)
- hysteresis curve (increasing and decreasing the current)

Some typical results of the measurements are shown in Figs. 2-5 and Fig. 7.

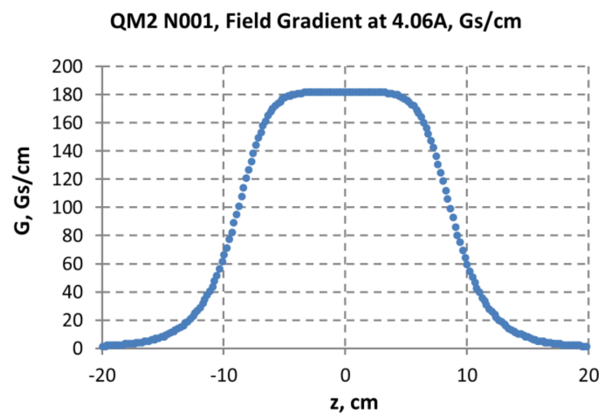

Figure 2: Gradient profile of a QM2 magnet derived from the Hall probe measurement. z is the coordinate along the beam axis.

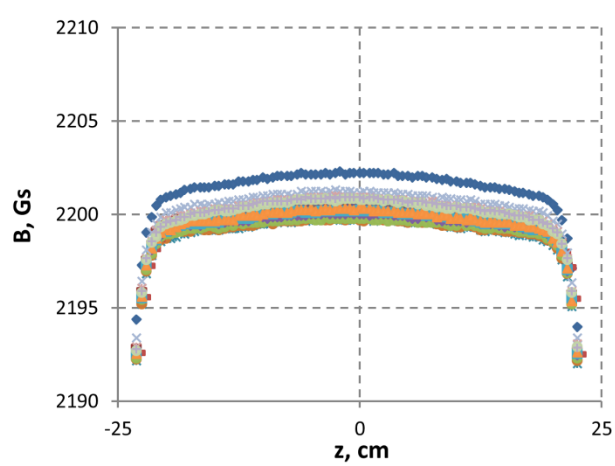

Figure 3: Field profile of a BM3 magnet near the magnet centre. Data from 16 Hall probes at different horizontal (x) positions (-7.5 cm < x < 7.5 cm with Δx = 1 cm) are shown.

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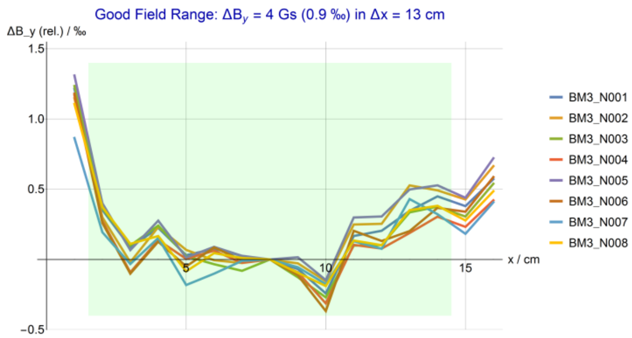

Figure 4: Homogeneity of magnetic field in the centre (z) of 8 BM3 magnets, measured with 16 Hall probes. The field is normalised to the central (x = 8 cm) Hall probe. Good field region (ΔB = 4 Gs, Δx = 13 cm, shown as green rectangle) is within specification. Probe to probe systematic error of ~ 0.3‰ can be seen.

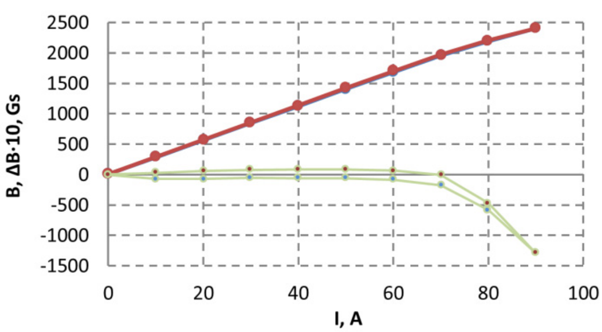

Figure 5: Hysteresis curve of a BM3 magnet. Field in the magnet centre for increasing current from 0 A to 90 A in 10 A steps is shown with red markers, for decreasing current – with blue. Green line shows the difference between the measured field and a straight line (multiplied with 10 for visualisation). Slight saturation is seen and can be accounted for during operation.

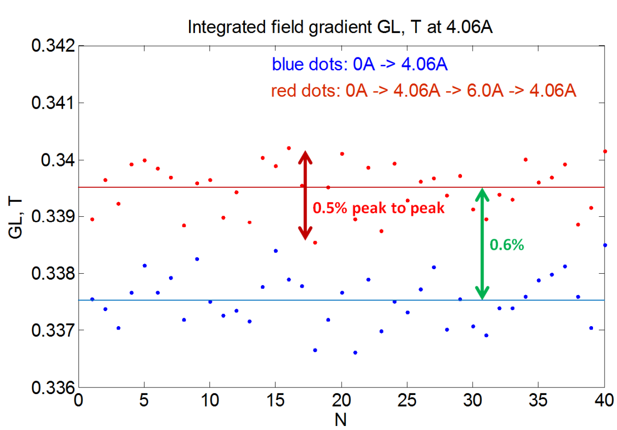

Figure 6: Integrated gradient of 40 QM2 quadrupoles measured with the rotating coil. The measurement allows estimating the spread of the quads strength and importance of the special turn-on procedure, which is chosen as increasing the current to 6.0 A and reaching the set value afterwards from above.

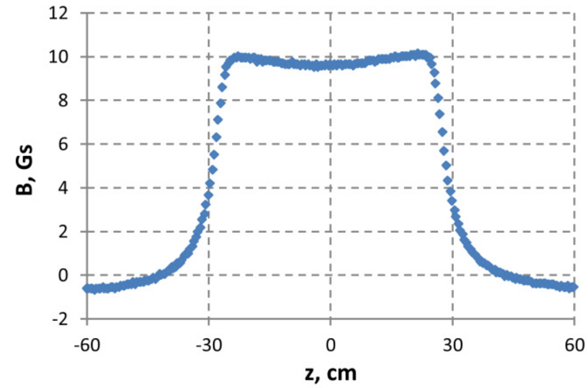

Figure 7: Residual field profile of a BM3 magnet. The central Hall probe is used.

Rotating Coil Measurements

The measurement methodology is described in [6, 7]. Each magnet (except for BM3 type) was measured with this method. As an example the summary of the measurement results for MQ2 quadrupoles is shown in Fig. 6.

CONCLUSION

The magnetic system for bERLinPro was designed in 2015, manufactured in 2016 and installed in the accelerator hall this year. The results of quality control and magnetic measurements are of a high standard and show very good field quality matching the specifications.

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