Design, manufacture and measurements of permanent dipole magnets for DIRAC

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I. INTRODUCTION

THE one of the aim of the DIRAC experiment is the observation of the long-lived $\pi^+\pi^-$ atoms, using the proton beam of the CERN Proton Synchrotron [1]. Two dipole magnets are needed for the for the DIRAC experiment as high resolution spectrometers. The dipole magnet will be used to identify the long-lived atoms on the high level background of $\pi^+\pi^-$ pairs produced simultaneously with π+π- atoms.

The proposed design is a permanent magnet dipole with a mechanical aperture of 60 mm. The magnet, of a total physical length of 66 mm, is based on Sm_2Co_{17} blocks and provides an integrated field strength of $24{\cdot}10^{-3}$ T×m. The Sm_2Co_{17} was chosen as a material for the permanent magnet blocks due to its radiation hardness and weaker temperature dependence. The magnetic field quality is determined by 2 ferromagnetic poles, aligned together with the permanent magnets blocks.

The paper describes the design, manufacture and magnetic measurements of the magnets.

II. REQUIREMENTS AND CONSTRAINS

The magnet parameters, such as aperture, integrated magnetic field and required field quality are determined by the beam optics considerations. The full magnet aperture should be 60 mm. The magnet should provide the integrated field strength of $20{\cdot}10^{-3}$ T×m, defined as an integral of horizontal field component B_x at transverse position X=Y=0, where the magnet centre is taken as z=0 mm. The integrated field homogeneity $\Delta\int B_x dz/\int B_x(0,0,z)dz$ has to be better than ± 2% inside the rectangular Good Field Region (GFR) of 20 mm × 30 mm. The overall length of the magnet is restricted and has to be less than 66 mm and the overall magnet width and height should not exceed 130 mm and 170 mm respectively. Table I summarizes the magnet requirements. Fig. 1 shows the sketch of required magnet.

TABLE I REQUIREMENTS FOR THE DIPOLE MAGNETS

Parameter	Value
Overall length	< 66 mm
Overall width × height	< 170 mm × < 130 mm
Magnet full aperture height	> 60 mm
Integrated field strength	$20{\cdot}10^{-3}$ T×m
Good field region (GFR) width ×height	30 mm × 20 mm
Integrated field strength error inside the GFR	< ± 2%

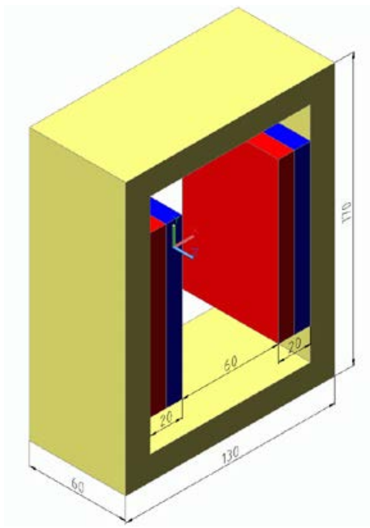

Fig. 1. The sketch of the required permanent dipole magnet for DIRAC

III. MAGNET DESIGN

A. Magnet description

The proposed design is a permanent magnet dipole with a mechanical aperture of 60 mm. The overall dimensions of the magnet are 130 mm (width) × 170 mm (height) × 66 mm (length). The total magnet mass is 8.6 kg. The support is not included in the above mentioned dimensions. The main magnet parameters are given in the Table II. The required

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integrated field is provided by two permanent magnet assemblies, as flux generators. In order to have some margin the magnet was designed to achieve the value of the integrated field of $24.6\cdot10^{-3}$ T×m. Each magnet assembly consists of three permanent magnet blocks as shown Fig. 2. The Sm_2Co_{17} was chosen as a material for the permanent magnet blocks due to its radiation hardness and weaker temperature dependence.

The field quality inside the magnet aperture is controlled by the soft ferromagnetic poles of suitable size. In addition, the soft ferromagnetic poles will smooth the effects of possible permanent magnet blocks inequalities.

The return yoke consists of four pieces made of soft ferromagnetic steel.

The correct assembly of the magnet is guaranteed by two non-magnetic blocks (central inserts) made of stainless steel. The permanent magnet assemblies, soft ferromagnetic poles and return yoke pieces will be mounted on these blocks and fixed by the bolts. Two aluminum cover plates of 3 mm thickness are fixed on each side of the magnet, preventing the possible movement of the magnet components in axial direction. Fig. 3 shows the mechanical layout of the permanent magnet dipole.

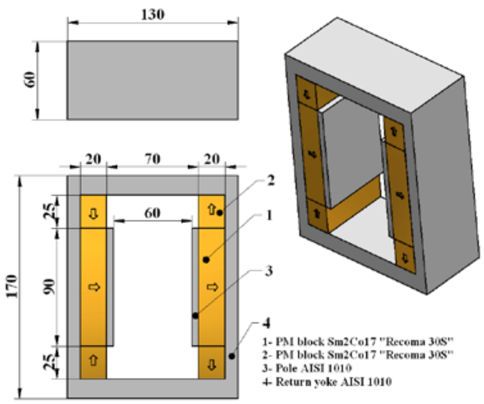

Fig. 2. Schematic features of the permanent dipole magnet (only magnetic components are shown), arrows indicate the direction of magnetization of the permanent blocks.

TABLE II MAIN DESIGN PARAMETERS OF PERMANENT DIPOLE MAGNETS

Description	Value	Unit
Magnet height × width × length	170 × 130 × 66	mm
Full aperture height	60	mm
Integrated field strength	$26.4\cdot10^{-3}$	T×m
Magnetic length	96.5	mm
Good field region (GFR) width ×height	30 ×20	mm×mm
Integrated field errors inside the GFR	< ±2	%
Material of permanent magnet blocks	Sm_2Co_{17}	
Material of soft ferromagnetic parts	AISI 1010	
Material of central inserts	316L+N	
Material of cover plates	EN-AW-6082	

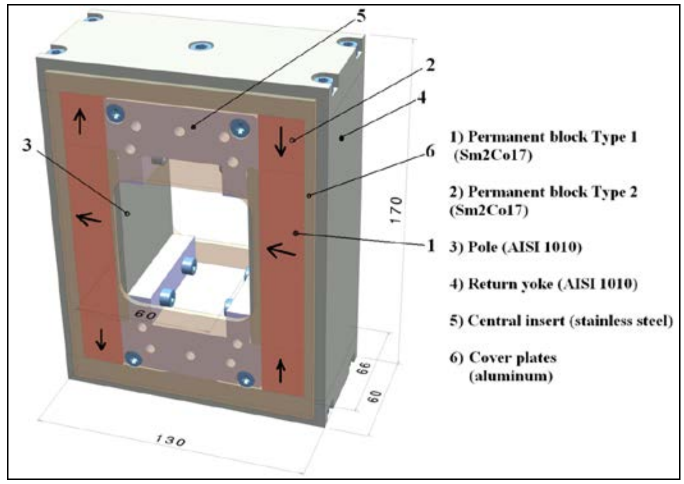

Fig. 3. Assembly drawing of the magnet

B. *Magnetic field computation*

Since the magnets are short and have a large aperture, the fringe field in the direction of the beam axis (z-axis) is significant. In this case, the 2D field calculations give only the preliminary results and need to be verified by the 3D modelling. Thus, 3D model of the magnet was constructed and used for analysis of the integrated field characteristics.

The calculation was done by Opera-3D/TOSCA program [2]. Due to symmetry only 1/4 of the magnet geometry was modeled. The boundary conditions were chosen in a way that the flux lines were perpendicular to the vertical middle plane and parallel to the symmetry axis and the limiting edge of the model.

The pole width, return yoke cross-section, permanent blocks sizes and position were optimized in order to satisfy the requirements on the integrated field strength and integrated field homogeneity, taking into account the limitations of the magnet overall dimensions.

Fig. 4 shows the OPERA-3D model with the field distribution on the magnet surface. For the selected magnet structure the integrated horizontal field of 24.6×10^{-3} T×m was achieved see Fig. 5.

The integrated horizontal field error stays below ± 2% inside the GFR defined above as a rectangular region with X= ± 10 mm and Y= ± 15 mm, see Fig. 6.

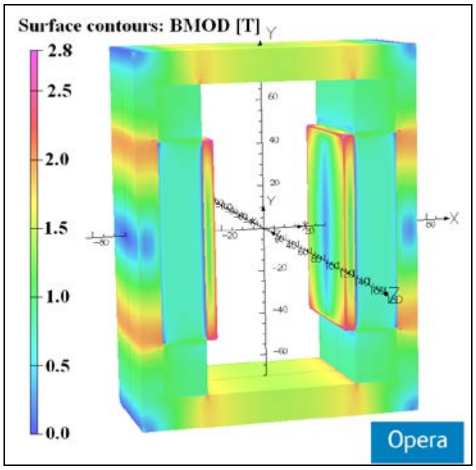

Fig. 4. Opera 3D model with surface field distribution.

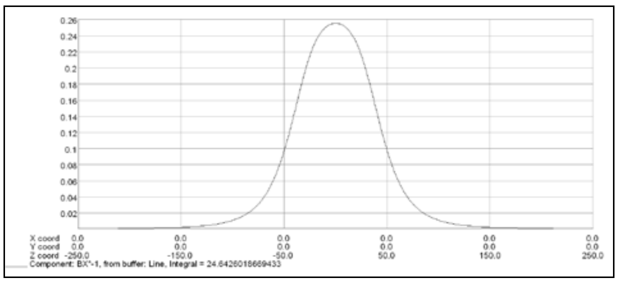

Fig. 5. Horizontal field distribution along z-axis.

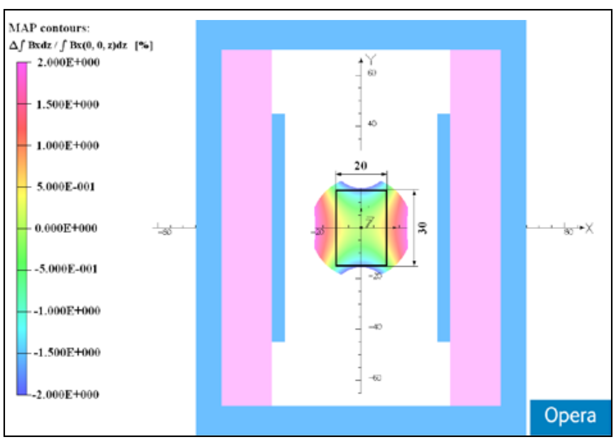

Fig. 6. Integrated horizontal field homogeneity [%].

IV. Manufacture and Magnetic Field Measurements

The assembly of the magnets was performed at CERN premises.

The dipole magnet needs two permanent magnet assemblies of 60 mm length; each consists of three permanent blocks of different width. The permanent magnets blocks made of Sm_2Co_{17} were supplied by China Rare Earth Magnet Ltd. [3]. The dimensional tolerances of the permanent magnet blocks are within ± 50 µm.

The soft ferromagnetic parts and non-magnetic central inserts were machined to a tolerance of ± 10 µm.

The permanent magnet blocks were inserted between the pre-assembled iron poles and return yoke. A specific assembly device to guide the permanent blocks into their positions was designed and built (see Fig. 7). The assembled permanent dipole magnet is shown in Fig. 8.

The magnetic properties of the permanent magnets blocks were measured by the supplier and found consistent with the properties as listed in the technical documentation.

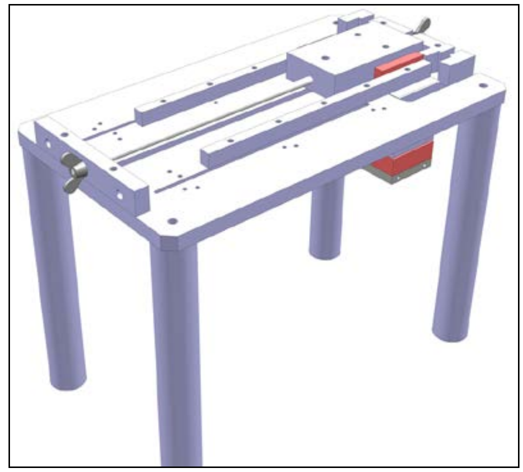

Fig. 7. Assembling device.

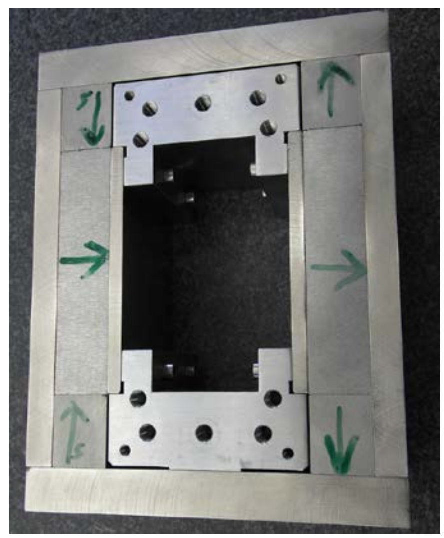

Fig. 8. Assembled permanent dipole magnet

The magnetic field measurements [4] carried out at CERN using a 3D scanning machine equipped with a Hall probe head. The magnetic field was measured along z-axis at several points as shown on Fig. 9.

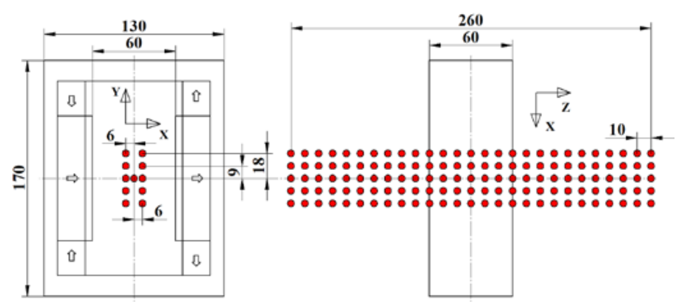

Fig. 9. Scheme of magnetic field measurements

The distributions of measured horizontal field along the z-axis with compare to computed values are shown in Fig. 10.

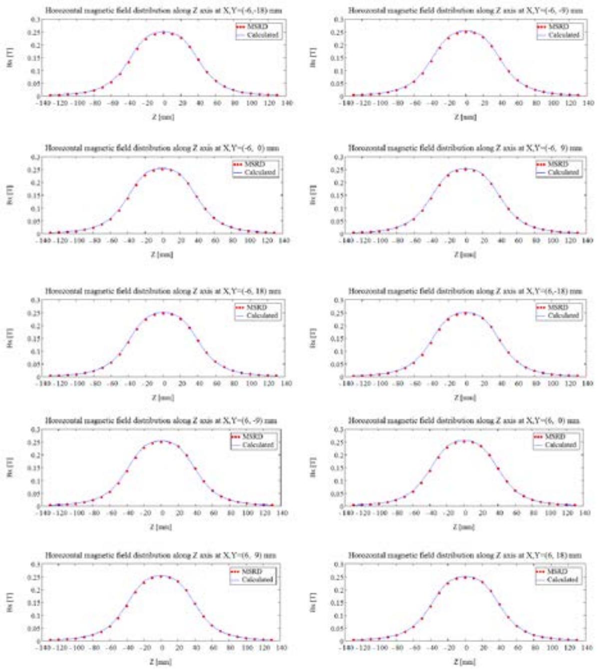

Fig. 10. Measured and calculated horizontal field distribution along z-axis at several transversal position.

The values of integrated field and integrated field errors obtained from the measured data to compare with the calculated values are presented on Fig. 11 and TABLE III. It is shown, that the measured integrated field values are close to the calculated and the required integrated field of $20\cdot10^{-3}$ T×m is achieved.

The measured integrated field errors meet the requirements on a field quality for the points inside the GFR and are close to calculated values.

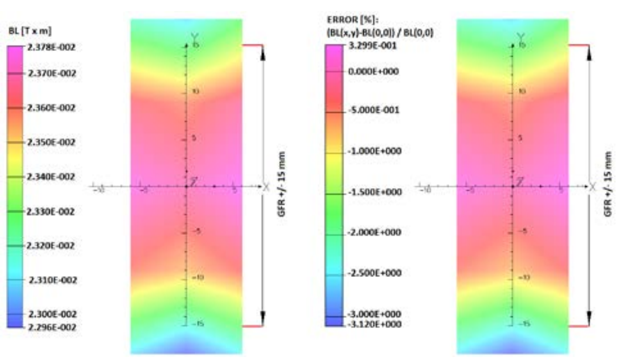

Fig. 11. Measured integrated field [T×m] and integrated field errors [%].

TABLE III Integrated Field and Integrated Field Errors

	Position		Calculated		Measured	
	X [mm]	Y [mm]	∫Bdz [T×m]	Error [%]	∫Bdz [T×m]	Error [%]
	-6	-18	0.023683	-2.1	0.023100	-2.5
	0	-18	0.023508	-2.8	0.022962	-3.1
	6	-18	0.023683	-2.1	0.023120	-2.5
Points inside GFR	-6	-9	0.024152	-0.1	0.023600	-0.4
	0	-9	0.024032	-0.6	0.023527	-0.7
	6	-9	0.024152	-0.1	0.023620	-0.3
	-6	0	0.024284	0.4	0.023760	0.2
	0	0	0.024181	0.0	0.023702	0.0
	6	0	0.024283	0.4	0.023780	0.3
	-6	9	0.024152	-0.1	0.023640	-0.3
	0	9	0.024032	-0.6	0.023580	-0.5
	6	9	0.024152	-0.1	0.023680	-0.1
	-6	18	0.023683	-2.1	0.023180	-2.2
	0	18	0.023508	-2.8	0.023096	-2.6
	6	18	0.023683	-2.1	0.023270	-1.8

V. Conclusion

The design of the permanent dipole magnet magnet for DIRAC and the results of the magnetic field measurements were presented. Two dipole magnets were fabricated and magnetically measured. The measured results confirm all aspects of the magnet design. The requirements on the integrated field strength and on the integrated field quality were achieved.

References

[1] http://dirac.web.cern.ch/DIRAC
[2] OPERA-3D/TOSCA, Vector Fields Limited, Oxford, England.
[3] www.permanentmagnet.com
[4] M. Buzio, R. Chritin, S. Kasaei, Magnetic measurements of DIRAC spare dipole permanent. Technical Note, 2012