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SECTOR DC DIPOLES DESIGN FOR THE BEAM TEST FACILITY UPGRADE

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Abstract

The Beam Test Facility (BTF) is part of the DAΦNE accelerators system of INFN Frascati National Laboratory (LNF). It is a transfer-line optimized for selection, attenuation and manipulation of electrons and positrons extracted from the DAΦNE LINAC. An upgrade of the line is scheduled by the end of 2018 in order to reach a beam energy of 920 MeV (compared to the actual 750 MeV), and adding a new branch to the present transfer line, in order to use two different beam lines. The layout of the new lines foresees seven new quadrupoles, one fast ramped dipole, two H-shape sector dipoles, and finally a C-shape sector dipole.
In this paper, the magnets requirements, all the magnetic design aspects of the two H-shape and of the C-shape sector dipoles shall be presented, including the Finite Elements Analysis (F.E.A.), the sizing of the water-cooling and an overview of the status of the manufacturing.

INTRODUCTION

The Beam Test Facility (BTF) is part of the DAΦNE accelerators system of INFN Frascati National Laboratory (LNF). It is a transfer-line optimized for selection, attenuation and manipulation of electrons and positrons extracted from the LINAC. BTF is characterized by a high versatility in terms of beam energy, intensity, dimensions and position.

The present configuration allows to split the 50 electron or positron pulses per second from the LINAC in three different lines: the first one leads to the storage rings (if the beam is not bent). The second one bends the beam by a 6 degrees angle by means a pulsed dipole, leading to a magnetic spectrometer (60 degrees bending dipole followed by a segmented detector) for an energy measurement at the end of the LINAC. The third one is dedicated to the BTF, through a pulsed 3 degrees dipole. Figure 1 shows also the transfer-line to the BTF experimental hall: the energy beam selection is carried out by a DC dipole with a bending angle of 42 degrees and by a collimator system, followed by a focusing quadrupoles doublet. Furthermore, in the present configuration, in the BTF line there is a DC dipole with a bending angle of 45 degrees that leads the beam along the main axes of the experimental hall.
The maximum energy reached in the transfer lines for the electron beam is 750 MeV, but the new project foresees a LINAC energy increase to about 920 MeV, adding four accelerating structures, fed by further RF sources. The BTF-2 project [1] [2] foresees a new branch of the actual BTF transfer line, in order to have two different beam lines, into two separate experimental halls as shown in Fig.1.

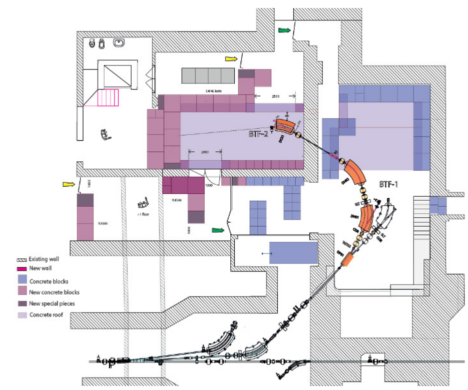

Figure 1: New Layout of BTF

For this purpose, a crucial element of this new configuration is a dipole driving the beam alternatively in one of the two lines (labeled in Fig.1 as BTF-1 and BTF-2), with a bending angle of 15 degrees, in order to have a suitable space to place all the elements of the new beam line [3]. The other magnets of the new transfer line (BTF-2) are three sector dipoles and six quadrupoles operating in DC current, so they have constructive requirements and completely different features (as shown in Fig.1). Particularly, the task of these three dipoles is to bend the beam of further 125 degrees, in addition to the 15 degrees of the DP01. So, the total 125 degrees bending angle will be performed by two identical 45 degrees sector dipoles with H-shape cross section profile (DH01-02) and one 35 degrees sector dipoles with a C-shape cross section profile. The design of the magnets has been completely performed at INFN, including electromagnetic, mechanical, thermal and hydraulic aspects. Electromechanical Enterprise partner were involved in the design phase in order to optimize the manufacturing process. This effort leads to a complete set of detailed CAD drawings that can be directly used by industrial partners to build the magnets. Magnetic measurements will be then performed at our Institute. This Paper is focused on the design of the DH01-02 and DC01 dipoles. In particular, Section II presents the magnetic design of the two dipoles; Section III presents an overview of the mechanical drawings. Then, conclusions follow in Section IV.

MAGNET DESIGN

Several F.E.A. simulations have been performed in order to reach performances that fulfill the requirements of Table

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Table 1: DH01-02 Field Quality Analysis

Parameter		DH01-02	DC01
Beam Energy	[MeV]	920	920
Gap	[mm]	35	35
Curvature Radius	[m]	1.8	1.8
Deflection angle	[°]	45	35
Nominal Flux Density	[T]	1.7	1.7
Good Field Region	[mm]	±15	±15
Field quality		1E-3	1E-3

1. The first step was the quantification of the Ampère-Turns necessary to reach the required flux density (31440 Ampère-Turns and 26500 Ampère-Turns respectively for DH01-02 and DC01) and the selection of an iron yoke material with an high relative magnetic permeability. The AME pure iron has been individuated as the ideal material for the iron yoke manufacturing. It is a low carbon steel equivalent to ARMCO® Pure Iron Grade4 with a particular homogeneity of magnetic and mechanical properties and an high relative permeability ($\mu_r = 4590$).
Then the magnet cross section has been defined and implemented in the 2D F.E.A.software Poisson Superfish, in order to optimize the field quality in the aperture gap and to have a uniformity of the flux density in all the iron yoke. Aiming to reach the 1.7 T in the gap aperture for both magnets, the poles has been designed with a trapezoidal cross section, in order to increase the flux density along the pole length reaching the maximum at the magnet aperture.
The next phase was the coil sizing. First of all, the number of turns has been estimated in order to limit the operating voltage of the coils, therefore the thickness of the insulation tape and the output voltage of the power supply. Considering a current density of about 4A/mm^2 for both magnets, a water cooled coils, composed by OFHC hollows conductor, has been chosen. So the cross section of the copper has been sized together with the hole diameter for the water cooling, taking into account the parameters of the actual BTF cooling system. Thus the water pressure drop has been limited under 4 bar and the nominal water velocity was set in a range between 0.8-1.3 m/s in order to avoid any deposit or erosion of the copper conductor.

The last step of the design was the 3D simulations with the Opera 3D software, where the mechanical length of the dipoles has been evaluated in order to fulfill the requirements.
The flux density in the iron yoke of DH01-02 and the vertical component of flux density B_Y along the transverse direction x for several heights (y=0, y=20 mm , y=100 mm and y=200 mm) are shown respectively in Fig.2 and Fig.3.

Figure 2 and Figure 3 show that the flux density in the poles reaches a value of about 2 T, while the in both the "legs" the flux is balanced at a 1.5 T value. The behavior of the magnetic field in the gap aperture is shown by the curve "y=0" in the interval of x=±110mm (see also "pole width"

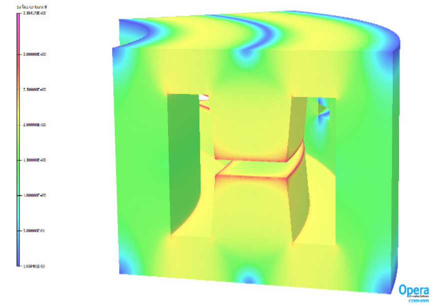

Figure 2: Flux Density in DH01-02 Iron Yoke

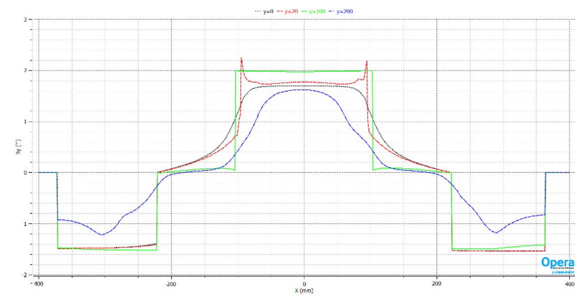

Figure 3: Vertical Component of Flux Density B_Y along the Transverse Direction x for several heights y in the middle plane of the dipole in DH01-02

parameter in Table 4) where the maximum value is 1.6952 T.

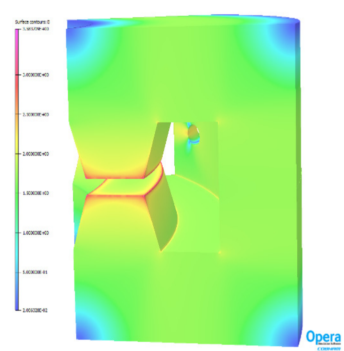

Figure 4: Flux Density in DC01 Iron Yoke

The flux density in the iron yoke of DC01 and the vertical component of flux density B_Y along the transverse direction x for several heights (y=0, y=20 mm , y=100 mm, y=200 mm) are shown respectively in Fig.4 and Fig.5.

Figure 4 shows that the flux density in the iron yoke is almost uniform at 1.5 T, excluding the poles where it rises to almost 1.8 T as shown in Fig.5. The behavior of the magnetic field in the gap aperture is shown in Fig.5 by the curve "y=0" in the interval from x=±107.5mm (see also "pole width" parameter in Table 4) where the maximum value is 1.6878 T.
For the field quality estimation, two parameters have been taken into account: the maximum flux density (B_{MAX}) and the field integral over six different paths parallel to the nominal one on axis. These trajectories are composed by three

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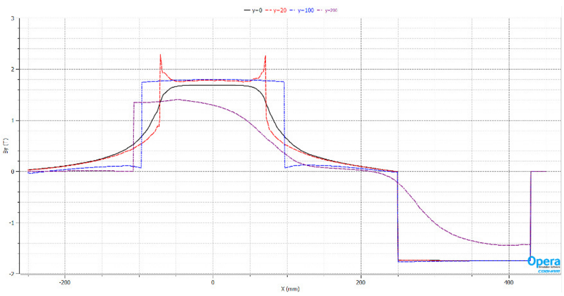

Figure 5: Vertical Component of Flux Density B_Y along the Transverse Direction x for several heights y in the middle plane of the dipole in DC01

branches: an arc in the poles region and two straight branches outside the magnets, each one 200 mm long. These paths are spaced 5 mm apart in the good field region corresponding to a distance from the axis of ±15mm.

For each trajectory, an ideal field integral (IB^*) has been defined following the equation below, where θ is the dipole deflection angle (see also Table 1), ρ_i is the curvature radius of the general trajectory and ρ_0 is the curvature radius on the axis trajectory (see also Table 1).

$$IB^* = \frac{E[MeV]}{300} \cdot \theta \cdot \frac{\rho_i}{\rho_0}$$

This field integral is required in order to have a 45 degrees deflection of a beam with an energy of 920MeV for several trajectories with different curvature radius. The relative deviation of the integral calculated through the simulations from IB^* has been considered as the integral field quality (ΔIB). Table 2 and Table 3 show, respectively for DH01-02 and DC01, the B_{MAX}, the simulated field integral (IB), the ideal field integral (IB*) and the ΔIB for each trajectory in the good field region.

Table 2: DH01-02 Field Quality Analysis results

Path [mm]	IB* [Tmm]	IB[Tmm]	ΔIB/IB*	BMAX[T]
-15	2388.48	2387.57	3.83E-04	1.6949
-10	2395.17	2394.53	2.68E-04	1.6951
-5	2401.86	2401.26	2.52E-04	1.6953
0	2408.55	2407.62	3.88E-04	1.6953
+5	2415.24	2413.85	5.78E-04	1.6952
+10	2421.94	2419.93	8.28E-04	1.6949
+15	2428.63	2426.43	9.04E-04	1.6945

The Tables 2 and 3 show that the field quality fulfills the requirements, excluding the field integral of +15mm trajectory. This error have been evaluated by the Beam Dynamics team and it was classified as negligible on the performance of the BTF2. In Table 4 all the magnets specifications are summarized.

Table 3: DC01 Field Quality Analysis results

Path [mm]	IB* [Tmm]	IB[Tmm]	ΔIB/IB*	BMAX[T]
-15	1857.71	1854.50	4.07E-04	1.6872
-10	1862.91	1860.18	1.49E-04	1.6876
-5	1868.12	1865.54	6.09E-05	1.6878
0	1873.32	1870.85	0.00E+00	1.6878
+5	1878.52	1875.25	4.23E-04	1.6877
+10	1883.73	1879.76	7.87E-04	1.6875
+15	1888.93	1883.92	1.34E-03	1.6870

Table 4: DH01-02 and DC01 specifications

Parameter	DH01-02	DC01
Curvature Radius [m]	1.8	1.8
Nominal Flux Density[T]	1.6953	1.6878
Good Field Region [mm]	±15	±15
Integrated Field quality	9.04E-4	1.34E-3
Magnetic Length [mm]	1420	1108
Pole Width [mm]	220	215
Number of Turns (per pole)	120	104
Hollow Conductor Dim.[mm]	9.5x9.5	9.5x9.5
Hole diameter [mm]	5.5	5.5
Nominal Current [A]	262	255
Nominal Voltage [V]	84	60
Total Magnet Resistance [mΩ]	276	195
Magnet Inductance [mH]	423	348
Nominal Water ΔT [°C]	15	15
Nominal Water Velocity [m/s]	1.07	1.06
Nominal Water Flow [l/min]	18	12
Nominal Water ΔP [bar]	3.17	3.15

MECHANICAL DRAWINGS

The result of the full design of the magnets is a complete set of CAD drawings. They describe in detail all the features of the magnets, including the yoke, the coils, the electrical and hydraulic connections. All the materials and tolerances have been defined. This work also aims to transfer our specific knowledge in magnet technology to the small and medium companies participating to the bid for the construction.

CONCLUSIONS

The magnets specifications defined through the F.E.A. fulfill the requirements and, for the DH01-02 dipoles, all the detailed mechanical drawings has been completed for the call for tender.

The production of the DH01-02 is starting after some design review by the manufacturer, and the delivery is scheduled by the first half of November 2018.

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REFERENCES

[1] P. Valente et al.,"Linear Accelerator Test Facility at LNF: Conceptual Design Report", *INFN-16-04-LNF, arXiv:1603.05651*

[2] P. Valente et al.,"The Frascati LINAC Beam Facility Performance and Upgrades", in *Proc. 38 th International Conference on High Energy Physics (ICHEP2016)*,Chicago, USA, Aug.2016

[3] L. Sabbatini et al., "Fast Ramped Dipole AND DC Quadrupoles Design for the Beam Test Facility Upgrade", presented at *9th International Particle Accelerator Conference (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, paper THPAL011, this conference.