Design, Manufacture and Test of a 1.3 T / 10 Hz dipole model for Rapid Cycling Synchrotrons.

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Abstract— *The construction of a compact rapid cycling synchrotron has recently been studied at CERN to replace the first stage of its accelerator complex, the proton synchrotron booster. Although currently there are no plans to build this machine, fast cycled accelerator magnets are of general interest for numerous reasons. This has led to the design, manufacture and testing of a scaled model dipole as detailed in this paper to show the capability of producing and characterising a magnet design based on high-silicon content grain-oriented steel able to operate up to 1.3 T at 10 Hz.*

Index Terms—Accelerator normal conducting magnets.

I. INTRODUCTION

FOLLOWING the feasibility study and cost estimate for an upgrade of the CERN Proton-Synchrotron Booster (PSB) to a beam energy of 2 GeV [1], the question was raised whether a new machine to replace the PSB would be a viable option. An advantage of such a scenario over an upgrade of the existing machine would be not only to replace a 40 year old accelerator by a new one, but also to commission the machine off-line before connecting it to the downstream Proton-Synchrotron (PS) and Super-Proton-Synchrotron (SPS), thus minimizing risk and down time. A preliminary Rapid Cycled Synchrotron (RCS) layout was parameterized requiring 30 dipole magnets capable of providing a field of 1.3 T at 10 Hz [2]. Although currently there are no plans to build this machine, fast cycled accelerator magnets are of a general interest for numerous reasons. This has led to the design, manufacture and testing of a scaled model dipole as detailed in this paper to show the capability of producing and characterizing a magnet based on high silicon content grain-oriented steel able to operate at field levels beyond that achieved for other RCS machines [3].

II. TECHNICAL REQUIREMENTS FOR THE MODEL DIPOLE

The model magnet shown in Fig. 1. is a demonstrator dipole accelerator magnet designed for operation at 10 Hz with a peak field of at least 1.3 T overcoming the problems of current-magnetic field response typically observed in accelerator cycled magnets. In these magnets, the combination of saturation, hysteresis and most of all eddy currents produce

a nonlinear, in both amplitude and time, relation between supply current and magnetic field [4], often requiring the use of on-line field feedback, the so-called B-train [5]. The RCS dipole design intends to tackle these aspects by acting on the materials and techniques used for the yoke construction.

The requirements of the model dipole were determined by the availability of the power supply to perform the magnetic measurements, the available current and voltage being 700 A and 450 V respectively. As the magnet was not to be used in a machine and the main interest being the performance of the magnetic circuit it was decided to use existing coils from another magnet type to speed up the construction.

Fig.1. The RCS model dipole.

III. MAGNETIC DESIGN

A pair of existing spare coils was selected meeting the requirement of the power supply, and at the same time to allow for the construction of a reasonably long magnet with a workable aperture height and pole width. The parameters of the coils are listed in Table I.

TABLE I

COIL PARAMETERS

Parameter	Units	Value
Dimensions		
Overall length	(mm)	481
Overall width	(mm)	242
Allowable pole length	(mm)	330
Allowable pole width	(mm)	150
Electrical Parameters		
Number of turns	(#)	27
Resistance @ 20°C	(mΩ)	11.5
Cooling Parameters		
Pressure drop	(bar)	10
Cooling flow	(l/min)	2.0

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Using the coil parameters listed in Table I and the magnetic cycle from the machine study as shown in Fig. 2, the model design allows an adequate margin for the power supply. The relevant main parameters of the dipole model are listed in Table II.

Fig.2. Proposed RCS magnetic cycle.

TABLE II

RCS MODEL DIPOLE MAGNET PARAMETERS

Parameter	Units	Value
Dimensions		
Iron length	(mm)	270
Overall length	(mm)	480
Iron width	(mm)	390
Iron height	(mm)	300
Aperture height	(mm)	20
Aperture width	(mm)	90
Weight	(kg)	300
Magnetic Parameters		
Nominal Field	(T)	1.4
Magnetic length	(m)	0.29
Integrated field	(T.m)	0.405
# turns per pole	(#)	27
# turns total	(#)	54
Iron losses	(W)	100
Electrical Parameters		
Current at nominal field	(A)	427
Current at injection	(A)	79
Current r.m.s.	(A)	280
Resistance @ 20°C	(mΩ)	23
Inductance	(mH)	10
Max. volt-drop	(V)	100
Dissipated Power	(kW)	1.8

The steel selected for the construction of the stamped laminations is a 0.35-mm-thick grain-oriented inorganic coated steel; designation M111-35N. This steel offers high permeability, low hysteresis losses and a high electrical resistance. Typical test data and physical properties can be found in Table III [6]. The 2D profile of the dipole magnet has been designed so that the steel is far from saturation with field levels below 1.5 T in the rolling direction and 1.3 T perpendicular to it. The estimations of losses in the iron yoke [7] are listed in Table II. Magnetic flux distribution in the dipole cross-section simulated using Finite Element Method Magnetics (FEMM) [8] is shown in Fig. 3 also indicating the rolling direction.

TABLE III

TEST DATA AND PHYSICAL PROPERTIES FOR M111-35N
GRAIN ORIENTED STEEL

Parameter	Units	Value
Physical		
Thickness	(mm)	0.35
Silicon content	(%)	3.1
Resistivity	(μΩ.cm)	48
Test data		
Specific total loss at frequency of 50 Hz		
B = 1.5 T	(W/kg)	1.06
B = 1.7 T	(W/kg)	1.52
B at H = 800 A/m, 50 Hz	(T)	1.83

Fig.3. FEMM 2D simulation of the dipole scaled model.

IV. MECHANICAL DESIGN AND TECHNOLOGY

The yoke has been produced in two halves. Each half consists of 270 mm of laminations compressed between 20 mm stainless steel end plates; while under compression similar stainless steel tie bars have been positioned on each side and top of the yoke half, which are then carefully welded to avoid deformation as shown in Fig. 4. The exclusive use of the solid stainless steel endplates and tie bars aims to minimize eddy current build ups during cycling. The two yoke halves are then bolted together, with the coils held in position by means of compressing elastic shimming material between the inner yoke and coil surface.

Fig.4. Welded half yoke assembly.

V. MAGNETIC MEASUREMENTS

Magnetic measurements have been performed by means of a short and of a long fixed coil positioned in the aperture of the magnet. The short coil measuring a few centimeters in length has been positioned in the longitudinal center of the magnet to measure the central dipole field, while the 0.8-m-long coil measures the integrated dipole field including end effects. The voltage induced in these coils as well as the current during the cycle has been measured as a function of time and used to evaluate the performance of the magnet.

The excitation curve for the magnet showing the evolution of the dipole field and magnetic length against the current is plotted in Fig. 5: the dipole field is calculated from the short coil, while the magnetic length is determined from the integrated dipole measurement from the long divided by the dipole field of the short coil. As expected, after an initial slight increase due to the increase in iron permeability, the magnetic length decreases by up to 10 mm at a current of 600 A, corresponding to 1.7 T in the magnet aperture and about 1.9 T in the yoke due to the saturated pole ends. It can be seen that the level of saturation is approximately 15%. In the case of the demonstrator dipole the pole ends have not been chamfered; including chamfers would reduce the amount of saturation, reducing this effect.

Fig.5. Central field and Magnetic Length vs. Magnet Current.

Dynamic field measurements have been made at ramp rates of ~ 30 kA/s which corresponds to the required ramp rate for 10 Hz operation. The evolution of the dipole transfer function, intended as the ratio between magnetic field amplitude and supply current, with respect to the magnetic cycle measured with the short coil is shown in Fig. 6. The transfer function decreases when the magnet starts to enter into saturation; however, no eddy currents field contribution is visible at the end of the ramp and during the flat top.

Fig.6. Central field and transfer function vs. time near the current plateau as measured at 30 kA/s ramp rate.

A corresponding integrated dipole measurement including any end effects is shown in Fig. 7. Here again, the plot shows that the integrated dipole transfer function (T_m/A) decreases due to saturation; again there are no measureable field contributions that could be expected with the presence of eddy currents decaying at the end of the ramp and start of the flat top.

Fig.7. Integrated field and transfer function vs. time near the current plateau measured at 30 kA/s ramp rate.

For comparison a similar plot for the CERN PSB main dipole magnet [9] is shown in Fig. 8. The integrated transfer function of this magnet still decreases with saturation, but in this case the effects of the thick solid magnetic end plates and tie bars can be seen at the end of the rising ramp. The effects are small, though, the ramp rate is around 20 times slower (4.3 T/s compared to 85 T/s) and the magnet longer (1.6 m). In total the field contribution after the ramp as the eddy currents decay equates to 0.3% of the integral dipole field which has to be corrected during operation.

Fig.8 Integrated field and transfer function vs. time near the current plateau for the CERN Proton Synchrotron Booster main dipole magnet at 20 kA/s ramp rate.

VI. CONCLUSION

The demonstrator RCS dipole magnet described in this paper has been designed and constructed to minimize dynamic effects seen in traditional cycled accelerator magnets leading to delays between current and field, such as high levels of saturation, hysteresis losses and most importantly eddy currents. To achieve this, the magnet has been constructed from a relatively thin grain oriented silicon steel offering high permeability, low hysteresis and high electrical resistance; the final assembly uses exclusively non-magnetic end plates and tie bars. The magnetic measurements performed so far indicate no measureable eddy current or hysteresis losses at field levels of 1.4 T and greater proving the ability to construct a high field normally conducting dipole magnet for rapid cycled machines.

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REFERENCES

- [1] K. Hanke et al., "PS Booster Energy Upgrade, Feasibility Study, First Report", November 2010, <https://edms.cern.ch/document/1082646/3>.
- [2] K. Hanke et al., "Feasibility Study of a Rapid Cycling Synchrotron to replace the PS Booster", <https://edms.cern.ch/document/1154705/1.0>.
- [3] N. Tani et al., "Design of RCS Magnets for J-PARC 3-GeV Synchrotron", IEEE Trans. Appl. Supercond. Vol. 14, 2004.
- [4] M. Buzio et al., "Magnetic Measurements for Medical Accelerators", February 2010, <https://edms.cern.ch/document/1060995/1>.
- [5] M. Buzio et al., "Development of upgraded magnetic instrumentation for real-time reference field measurement systems", November 2009, <https://edms.cern.ch/document/1053793/1>.
- [6] P. Beckley, "Electrical steels for rotating machines". London: The Institute of Electrical Engineers, 2002, pp. 272-286.
- [7] D. Tommasini, "Practical definitions & formulae for normal conducting magnets", September 2011, CERN Internal Note, <https://edms.cern.ch/document/1162401/3>.

- [8] D. C. Meeker, "Finite Element Method Magnetics", Version 4.2 (11Apr2012 Build), <http://www.femm.info>.
- [9] A. Newborough, M. Buzio, R. Chritin, "Upgrade of the CERN Proton Synchrotron Booster bending magnets for the 2 GeV Energy Upgrade", IEEE Trans. Appl. Supercond. **23** submitted for publication.