# DESIGN STUDY OF SCALED DOWN DIPOLE MAGNET FOR PROTON SYNCHROTRON SUB-SYSTEMS PROJECT

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*Abstract*

This paper presents the design study of scaled down rapid cycling dipole magnet to be developed in few numbers and qualified in resonant exciting system. The objective is to meet the challenges and its solution associated with the full scale developments for 1 GeV Proton Synchrotron. The design features and the parameters of the full size dipole magnet are also discussed in this paper. The sizing of the scaled down version has been done keeping the pole gap field and the ratio of inductance (L) to resistance (R) equal to that of the full scale dipole magnet. The losses and the *Q* value estimated for the magnets are also presented in this paper.

## INTRODUCTION

In RRCAT Indore, rapid cycling prototype magnets are being developed for use at repetition rate of 25 Hz, for a typical 1 GeV Proton Synchrotron[1] . In the first phase of the Proton Synchrotron Sub-systems project, it is proposed to develop and test scaled down (in size and power rating) dipole magnets forming resonant network in the energizing power supply topology. This will particularly help us in taking corrections/countermeasures on meeting the various difficulties arises due to the variation of the inductances and magnetic fields among the magnets. Unlike electron synchrotron, these magnets operate at a high repetition rate and have large apertures to accommodate large beam size (to reduce space charge effect) and to keep the beam losses within the acceptable limit. This gives rise large leakage fields at the magnet ends resulting in eddy current heating of the end plates. AC excitation of 25 Hz also induces other losses e.g. core loss and eddy current losses in the coils. In this paper the design of the full scale dipole magnet is presented. Then the design study of the scaled down model is discussed. The various parameters of the full size and scaled down magnets are also compared and presented in this paper.

## MAGNET DESIGN

### Full scale magnet

A preliminary study of the beam dynamics of 1 GeV proton synchrotron (basic cell type FODO) gives the requirement of the pole gap of 218 mm for the full scale dipole magnet [2]. At the left of the fig.1, $1/4^{th}$ cross section of the H type dipole magnet has been shown. The optimization of pole shape and field calculation has been done using POISSON code [3]. The magnets will be excited with a dc biased sinusoidal current waveform at a repetition rate of 25 Hz. To have control on the deformation of the waveform under resonance condition the variation of the inductance with excitations is kept within 1 %. Silicon steel laminations of 0.5 mm thick will be used to form the magnet core. To reduce the eddy current losses in the magnet coils, twisted stranded conductor with strand diameter of 3.2 mm is chosen. The main parameters of the magnet are listed in table-1.

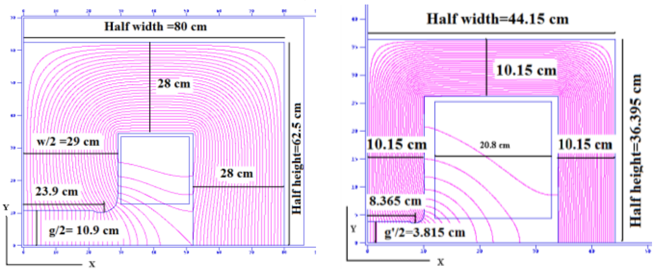


Figure 1: 1/4th cross-section of the full size (left) and scaled down dipole magnet (right) (all dimensions in cm).

Table 1: Main parameters of the dipole magnet

| Parameter | Value |
|---|---|
| Bending angle | $15^0$ |
| Bending radius | 7.161972439 m |
| Field strength | 0.2T @ 100 MeV; 0.8 T@ 1 GeV |
| Total Amp-turns (max.) | 142000 |
| Pole gap | 0.218 m |
| Good field region | ±0.125 m (horizontal); ±0.100 m (vertical) |
| Field uniformity | ±0.02 % |

### Scaled down magnet

The scaled down model of the dipole magnet is designed taking into consideration of the following requirements. The small magnet should generate equal pole gap field ($B_0$) (0.2 T -0.8 T) and should have either equal inductance (L) and resistance (R) or have equal ratio of L to R as that of the full scale magnet. The later requirement is imposed to get the *Q* (ratio of stored energy to losses) value close to that of the full scale magnet.

We have used the notations *w*, *g* and *l* as the pole width, pole gap and effective length of the actual dipole magnet respectively. Where as $w' = \beta w$ , $g' = \beta g$ and $l' = \gamma l$ are the pole width, pole gap and length of the scaled down magnet respectively ($\beta$ , $\gamma$ <1). *NI* is the ampere turn of the actual magnet and $N'I' = N'\alpha I$ is the ampere turn of the scaled down magnet ($\alpha$ <1).

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Comparison of the equal magnetic field in the pole gaps of the magnets, $B_o = \frac{\mu_o NI}{g} = \frac{\mu_o N' \alpha I}{\beta g}$ shows that

$$\frac{N'}{N} = \frac{\beta}{\alpha} \qquad (1)$$

The inductance of the small magnet can be scaled as

$$L' = \frac{B_o^{\,2}}{\mu_o} \frac{w' g' l'}{I'^2} = L \frac{\beta^2 \gamma}{\alpha^2} \qquad (2)$$

where $L = \frac{B_o^{\,2}}{\mu_o} \frac{wgl}{I^2}$ is the inductance of the full scale magnet. Here the fringing zones at the pole edges are neglected. From equation (1) and equation (2) it is seen that for $L' = L$ and $B_o' = B_o$, $N' > N$ as long as $\gamma < 1$ and if $\alpha = \beta$, then $N' = N$, $B_o' = B_o$ and $L' = \gamma L$.

The resistance ($R'$) of the scaled down magnet is related with that of the full scale magnet ($R$) as

$$\frac{R'}{R} = \frac{N'(\beta w + \gamma l)}{N(w + l)} \frac{A_c}{A_c'} \qquad (3)$$

where $A_c$ and $A_c'$ are the conductor cross- sections of the scaled down and the actual magnets respectively. Here the contribution due to the bending radius of the conductor has been ignored for the time being. While estimating the resistance of the coils for the scaled down magnet, limitation in reducing the size of the coil window has been observed. The size of the coil window for the scaled down magnet can be related with that of the full scale magnet as $N' A_c' = \beta^2 N A_c$. Using equation (1) and equation (3) one can write $N' A_c' = \frac{\beta^2 (\beta w + \gamma l)}{\alpha^2 (w + l)} \frac{R}{R'} N A_c = f N A_c$

where $f = \frac{\beta^2 (\beta w + \gamma l)}{\alpha^2 (w + l)} \frac{R}{R'}$. For either of the two cases – equal resistance & inductance ($R' = R$, $L' = L$, $\alpha = \beta \sqrt{\gamma}$) or equal ratio of inductance to resistance ($R' = \gamma R$ as $L' = \gamma L$), $f$ is found far away from $\beta^2$, rather it is close to 1 (for typical values of $w$~0.6 m and $l$~2 m). This prompted us to choose the same stranded conductor (overall dimension 30 mm x 30 mm) with the same number of turns (36 turns per pole) for the scaled down magnet, as that of the actual magnet. This also avoids the development of conductor of different size for the scaled down version.

The requirement of minimum bending radius of 120 mm (to be kept for this conductor), led to the maximum shrinking of the pole width of the scaled down magnet to ~35 % of that of the full scale magnet. Adjusting the length of the scaled down magnet (γ=0.41) we have found that the ratio of the inductance to resistance value of the scaled down magnet is very close to that of the actual magnet (variation within 3 % ).Fig.1 (right) shows the 1/4$^{th}$ cross section of the scaled down magnet.

The field profiles of the scaled down magnet within the (scaled down) good field zone are compared and found in good agreement with that of the full scale magnet (see fig.2). The magnets are designed for the field uniformity of 2 x $10^{-4}$. The final parameters along with the various losses of both the magnets are listed in table-2.

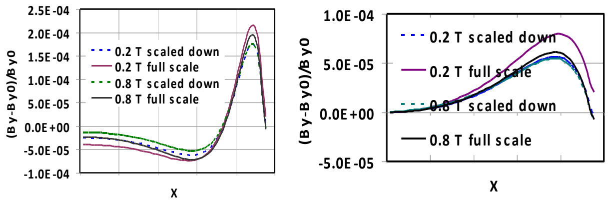


Figure 2: Comparison of magnetic field uniformities at the 1$^{st}$ quadrant of the upper boundary of the good field zone (left) and at the mid plane (y=0) (right).

Table 2: Comparison of the parameters of the full size and scaled down dipole magnets.

| **Parameter** | Full scale magnet | Scaled down magnet |
|---|---|---|
| Total width ($w$) in mm | 1600 | 883 |
| Total height ($h$) (mm) | 1250 | 727.9 |
| Effective length ($l$) ( mm) | 1875 | 768.75 |
| Coil window (mm x mm) | 230 x 230 | 247 x 230 |
| Pole gap (mm) | 218 | 76.3 |
| $I_{dc}$ (A) | 1232.64 | 431.42 |
| $I_{ac}$ (A) | 739.58 | 258.85 |
| DC Joule heating (kW) | 33.58 | 1.904 |
| Inductance (mH) (using POISSON) | 44.548@0.2 T 44.485@0.8T (0.14 %) | 20.143@0.2 T 20.04 @0.8 T (0.5 %) |
| AC Joule heating (kW) | 6.05 | 0.343 |
| Core loss (kW) | 3.2 | 0.42 |
| Conductor (eddy loss, kW) | 0.535 | 0.04 |
| End plate (eddy loss, kW) | 1.5 | 0.2 |
| $R_{dc}$ (mΩ) | 22.10 | 10.23 |
| $R_{eff}$ (mΩ) | 22.42 | 10.42 |
| Q | 316 | 308 |
| $Q_{eff}$ | 169 | 105 |

# CONCLUSIONS

The restriction on downsizing the coil window of the scaled down magnet prevents the reduction of the core loss and eddy current losses at the end plates (calculated using [4]) at the same proportion as that of the full size magnet. This led to a significant variation of the effective $Q$ ($Q_{eff}$) between the two magnets. However, the development and testing of the scaled down dipole magnets in resonant exciting system would help immensely in predicting the various parameters of the full scale magnet with confidence.

# REFERENCES


[1] D.D. Bhawalkar and A.S. Rajarao, "Recent and Future Accelerator Activities in India", APAC 2001, Beijing 2001,p.16;http://accelconf.web.cern.ch/Acclconf/a01/PDF/MOA04.pdf

[2] Amalendu Sharma, Private Communication.

[3] POISSON Group of Codes, Los Alamos National Laboratory, Los Alamos, New Mexico 86545.

[4] Opera-3D version 12, Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England.