EFFECT OF EDDY CURRENT IN MAGNETIC LAMINATIONS ON PULSED SEPTUM MAGNET RESPONSE

R.S. Shinde#, R.K. Mishra, P. Pareek, M.M. Pandey, Vinod Gaud, S. Senthil Kumar, S. Kotaiah
Raja Ramanna Centre for Advanced Technology, Indore, Madhya Pradesh, India

Abstract

Pulsed Septum magnets have been developed for injection of 500 – 600 MeV, e beam into 2.5 GeV Storage ring (Indus-2). A Pulsed magnet system consists of a thin & thick passive type Septum magnets kept inside Vacuum Chamber & Kicker Magnets. Thin & thick septum magnets were excited using 50 μs & 100 μs half sine wave pulse respectively. A magnetic field homogeneity ($\Delta B/B$) of the order of 10^{-3} & integrated stray fields ($\int B_{stray}.\ dl$) of nearly 0.7 Gm has been achieved.

This paper focuses on Pulse magnetization of Ni-Fe laminations; engineering challenges for septum magnets, Eddy current in lamination & their effects on pulse response of magnets.

INTRODUCTION

Injection of e beam into the Storage ring in the horizontal plane is carried out by combination of Thin & Thick Septum magnets & four kicker magnets. The Septa are used to deflect a beam coming from the transfer line-2 (TL-2) into a direction, which is parallel to that of the beam circulating in the Storage ring [1].

This method provides a smooth & continuous injection. Injection efficiency is the main requirements of the Pulsed Septum magnets. To this end we rely on the field produced by the magnet to have a maximum relative error ($\Delta B/B$), below 10^{-3} in the useful aperture & time interval. There are several constraints on the development of these Septum magnets (Table-1). These are due to the accelerator geometry, the injection scheme and the materials used.

Table 1: Constraints on parameters of the Septum magnet

Parameters	Thin	Thick
Max. Septum Thickness (mm)	3.0	3.5
Deflection angle, degree	2	19
Magnet aperture (W X H), mm	28.5 x 10	26.5 x 10
Max. Stray magnetic field	< 2 G-m	--

In addition to the objectives & constraints, technology for development of the magnets taken into account the needs of low cost, HV insulations, Out gassing rates & easy maintenance.

MAGNET SYSTEM

Injection system of Indus-2 consisting of two Pulsed Septum magnets – thin & thick and Four Kicker magnets. In the injection scheme, a compensated bump (16 mm) produced by four Kicker magnets & the e beam is injected through two septum magnets. In order to minimize the thickness of septum magnets launching the e beam, thin & thick septum magnet combination has been adapted. Septum magnets are required to provide necessary deflection to the incoming beam to match the angle of the beam transfer line to the accelerator orbit. The design of such a system has to meet many requirements in order to achieve a high reliability injection operation, some of them are [2]:

(i) Septum sheet as thin as possible in order to enhance injection efficiency as septa isolates injected beam & circulating beam
(ii) High magnetic field (due to geometrical limitation)
(iii) Pulse magnetization of Ni-Fe lamination – high Pulse Permeability for stability & homogeneity of field greater than 100 ppm, high frequency response upto 100 KHz
(iv) Low out gassing rate, as magnets are to be placed in UHV environment
(v) Very low Stray fields (due to beam optics)

The magnet configuration, high pulse permeability & high Bknee on first magnetization curve of laminated yoke and Pulse power supply combinely determine the high performance of Septum magnet system

The main design criteria for the Pulsed Septum magnet are to produce Pulse magnetic field waveform with amplitude of ~ 1 T & pulse length ~ 50 μs & 100 μs. The requirement of magnetic field pulse shape for injection is half sine wave with field stability on top is of the order of ($\Delta B/B$) ~ 1 X 10-3. As magnets have to keep inside vacuum, there are severe engineering challenges both in space & fabrications are involved [2].

PULSE MAGNETIZATION

Pulsed Septum magnets are to be operated at high field strengths, the magnetization rates (dB/dt) are involved are up to about ~ 1 T / μs & magnetization reverses in the order of μs. Also magnet performance greatly depending on magnetization of laminations. Therefore, it is necessary to know the behaviour of soft magnetic materials when its magnetization reverses in the order of μs.

The response of the magnetic field due to the time varying current in the septum coil is influenced by the

---

#shinde@cat.ernet.in

eddy current effects. The time delay and attenuation caused by eddy currents in the lamination of the yoke. This lead to inhomogenities in the field distribution.

The eddy current losses in the laminations were analytically computed [2]. Taking into account the skin effect in the thickness of the laminations has been choosen in such a way that to operate in linear region of B (H) curve & to avoid the magnetic saturation.

Pulse magnetization of Ni-Fe laminations has been measured by damping Sine B_{pulse} of first half peak of 100 µs [3,6]. Due to damped Sine wave, magnet comes into demagnetized state after every pulse. Measured pulse magnetization of Ni-Fe lamination is shown in fig1.

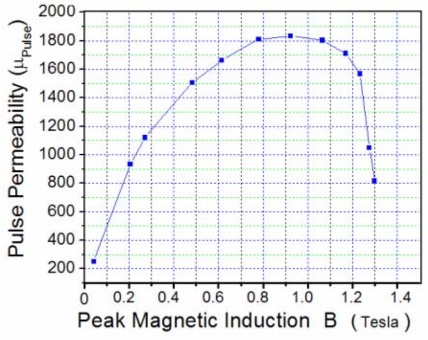


Figure 1: Pulse Magnetization Curve of Ni-Fe lamination

SEPTUM MAGNET

The magnet should produce a half sine wave field with a peak amplitude of ~ 8 KG and duration of t_d = 100 µs from zero field to zero field in the "inside" region. The stray field outside the septum edge should be < 2 G-m. At present time, the total septum thickness is 3 mm (Cu+Fe). The thickness of the lamination in the yoke is 0.1 mm. The stray field on the outside surface of the septum is calculated from [4],

$$B_{stray} = (2\sqrt{2\tau} / \sqrt{\pi e}\, \lambda_c d \sigma \mu_o)\, Bo \qquad (1)$$

Where, Bo is the amplitude of main field, τ is the pulse width of excited current, λ_c is the characteristics length of stray field decay outside the septum, d is the average thickness of septum, σ & μ_o are electric conductivity & magnetic permeability of the septum material respectively.

The time change curve of the stray field is analyzed using Flux-2D. In order to reduce the stray field further, a mu-metal shield of 1 mm thickness is placed along septum conductor. The mu metal has high magnetic permeability, which shield the stray field greatly.

The simulation results show that the stray field in front of the septum is much less than 0.1% at any position & at any time.

CONSTRUCTION

Thin & Thick septum magnets, being of Pulsed type, are constructed with laminated yoke. There are two issues considered carefully:

(i) Eddy current losses in Ni-Fe lamination. In order to reduce these losses, the core is made of 0.1 mm thick Ni-Fe lamination (36 % Ni). These laminations are annealed & then oxidized to get 10 µm oxidation thickness on both sides, which leads improvement in field quality.

(ii) The out gassing properties & the radiation resistance of the insulation material of the core and coil are crucial to the construction of the septum magnets.

The septum coil is made of Oxygen Free Copper Conductor & is insulated with Alumina by detonation process [1,6].

The cross section of the septum magnet is shown in fig 2.

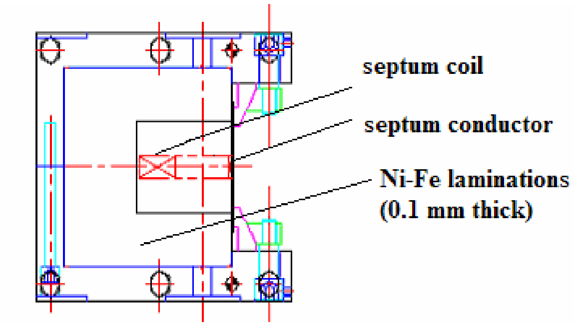


Figure 2: Cross sectional view of septum magnet

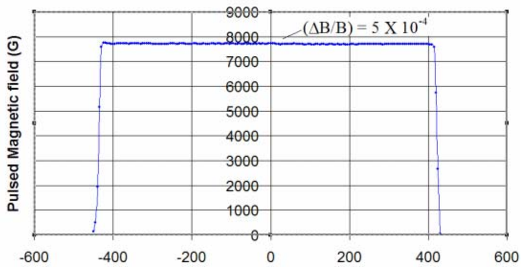
Table 2: Main Parameters of Septum magnet (600 MeV)

Parameters	Thin Septum	Thick Septum
1. Maximum Pulse magnetic field	4.190 KG	7.720 KG
2. Radius of Curvature	7162 mm	2594 mm
3. Deflection angle	2 °	19 °
4. Effective magnet length	250 mm	860 mm
5. Magnetic field Pulse shape	Half sine wave (50 µs)	Half sine wave (100 µs)
6. Effective Septum thickness	3 mm	3.50 mm
7. Maximum Exciting Current (Amp.)	3330	6140
8. Magnetic field homogeneity, ($\Delta B/B$)	~ 5 x 10^{-4}	~ 5 x 10^{-4}

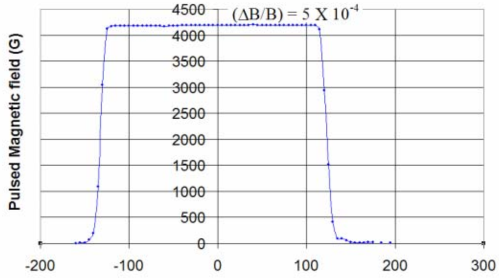
MAGNETIC PERFORMANCE

The main and stray magnetic fields are measured with integrated coil was realized with a strip of double sided PCBs & point coils. A 3-axis magnet measuring system was developed for pulsed field mapping. Magnetic field homogeneity with 100 ppm accuracy was measured using 16-bit digitizer system [5].

A Pulsed field homogeneity for thin & thick septum magnet is shown in figure 3 [6].

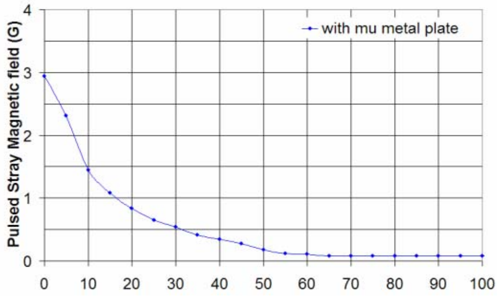


X (mm) - Along Beam direction (Thick Septum Magnet)



X (mm) - Along Beam direction (Thin Septum Magnet)

Figure 3: Pulsed field homogeneity for thin & thick septum magnet



Distance from the Septum (in mm)

Figure 4: Distribution of stray field outside of the septum

The stray field at the edge of the septum to the outside region where circulating beam travels is shown in fig 4.

The distribution of stray field outside the septum, after adopting the measures of the magnetic screen, the maximum of the stray field is reduced down to 0.05% of the peak main field. The measured waveforms of stray field agree with the simulation results.

RESULTS & CONCLUSIONS

FEA, Flux-2D has successfully used to stimulate the Pulsed field of septum with & without magnetic screens. The simulated waveform of the stray field is similar to that of practically observed. The maximum stray field on the bump orbit is about 0.3 % of the peak of its main field. In order to reduce stray field further, a mu metal – magnetic screen was used. The effective thickness of the septum at the exist of the magnet controlled within 3.5 mm. The maximum stray field of 0.7 G-m was observed, which is less than the allowed 2 G-m value. The measured waveform of main & stray fields after magnetic screen is shown in figure 5 [2, 6].

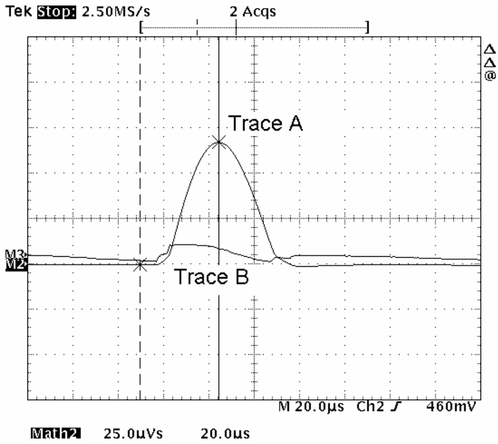


Figure 5: Integrated magnetic field along the e beam direction

Trace A: Main Pulsed Magnetic Field waveform
Trace B: Stray Magnetic Field waveform

ACKNOWLEDGEMENTS

The authors would like to thank Shri. S. Kotaiah, PM (Indus-2) & Shri. A.K. Jain, Head, ACEFD for their kind guidance, Scientific & Technical discussion during development of magnets. We indebted to thank Shri.Gurnam Singh, Head IOAPDD for Scientific discussion & encouragement. We are also greatful to Shri. Kelkar, Barothiya & Raikwar for Power Supply development. We express great thanks to Shri. R.R. Yadav & Karan Singh for Pulsed magnetic measurements of laminations & magnets. It is great pleasure to thank Shri. Shiv bachan & Lalchand Ghongde for magnet assemblies & installation into Indus-2 ring. A special thanks goes to Shri. L.V. Thorat, who made the 3-D drawings of Septum magnets.

REFERENCES

[1] R.K. Mishra, etal., "Proposed design report of Pulsed Septum Magnets for Indus-2 Ring", CAT Internal Report, May 2000.
[2] K.D. Metzmecher, "Technical discussion on Pulsed Magnets", at CERN, November 2001.
[3] R.S. Shinde, P. Pareek, V. Gaud, etal., "Pulsed Magnetization in Ni-Fe lamination – Measurements & Analysis", CAT Internal Report, October 2003.
[4] W.Kang, etal., "Development of eddy current Septum for the SSRF Storage ring", APAC 2001, Beijing, China.
[5] S.Kotaiah, etal., "Present Status of Synchrotron Radiation Source Indus-2", InPAC 2005, Kolkatta.
[6] R.S. Shinde, V.Gaud, etal., "Technical report on Pulsed Magnetic Measurements of Septum magnets" of Indus-2", CAT Report – FL, October 2005.