Magnetic Performance of the EUTERPE Ring Dipole

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Abstract

The magnetic performance of the 30^0 bending magnet of the proposed EUTERPE storage ring has been determined with two different types of equipment. One is a Hall probe system for measurements in the median plane of the dipole. Another is an integral measuring device applying a "banana shape" coil corresponding to the particle orbit. With the second method, a relative reproducibility of 5×10^{-5} has been obtained. Apart from the bending strength of the magnet, integral quadrupole and sextupole components have been determined. Formulae applied for this are presented. The coil setup is described in this paper. Magnetic field measurements for the prototype dipole magnet of the EUTERPE ring are given.

1 INTRODUCTION

The EUTERPE ring is an electron storage ring with a nominal beam energy of 400 MeV and with an injection energy 75 MeV [1]. It has been designed with a highly flexible lattice structure for the investigation of beam dynamics and synchrotron radiation applications. For bending the particles and use as synchrotron radiation sources, twelve dipole magnets are needed. The requirement for the magnetic induction is 0.25 T for low energy and 1.35 T for high energy. The construction of these dipoles is unconventional [2]. Laminated rectangular blocks of transformer steel are fixed together and comprise the C-shaped magnet. Its dimensions are $48 \times 39 \times 35$ cm^3. The poles are completely flat. The real magnet shape has been determined on the basis of Poisson-calculations. The prototype magnet has been made by the workshops in Eindhoven University of Technology, see fig.1. Its magnetic performance has been determined with NMR equipment and a Hall probe system. Particularly the integral fields have been determined with a "banana shape" coil measuring device.

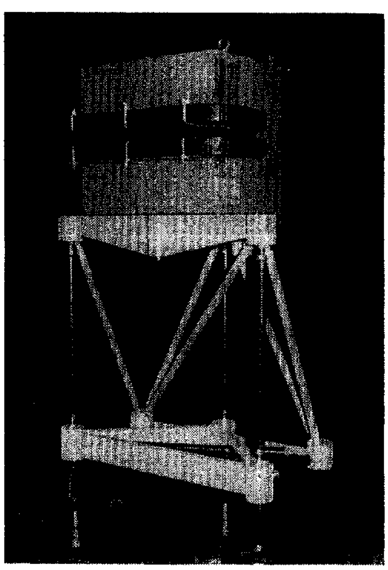

Figure 1: *Dipole magnet and support system of EUTERPE ring.*

2 MEASURING DEVICES

2.1 Integral coil setup

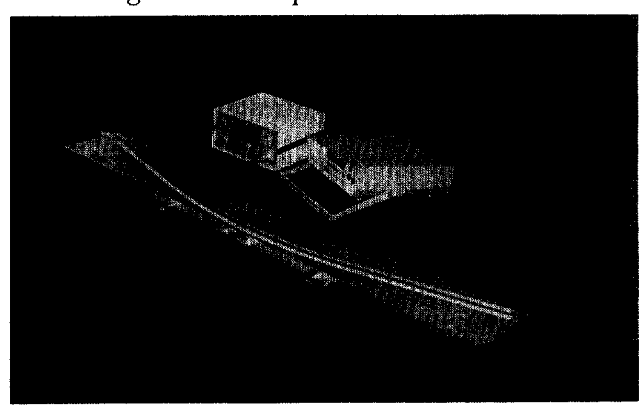

Figure 2: *Integral field measuring coil device.*

In order to measure the integral field of the bending magnets we developed a device with a "banana shape" measuring coil. The setup is shown in fig.2. The shape of the middle axis of the measuring coil is just the same as the designed reference closed orbit. The coil has a width of 15 mm and a height of 5 mm with 29 turns. During measurements, the "banana shape" coil is put in the median plane of the dipole. The sides of the coil stick out of the dipole magnet for more than ten times the gap space. The induced voltage V in the measuring coil is integrated with a RC integrating circuit, following Faraday's Law:

$$\int V dt = \Phi = \oint \vec{B}_z \cdot \vec{n} da, \qquad (1)$$

where Φ is the total magnetic flux enclosed by the measuring coil, B_z the magnetic field perpendicular to the middle plane of the dipole. When the dipole is excited, B_z has a large value at the middle part of the coil and has zero value at both end parts of the coil. For a certain excitation current, one gets a distribution of the integral magnetic field $F(x,0)$ in the median plane (z=0) if the measuring coil is moved along the radial direction. [1]

2.2 Basic integral formulae

Along the central orbit, B_z can be expressed as an expansion:

$$B_z(x,z,s)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}B_{n,2m}(s)\frac{x^n}{n!}\frac{z^{2m}}{(2m)!}. \quad (2)$$

And in the magnetic midplane,

$$B_z(x,0,s)=\sum_{n=0}^{\infty}B_{n,0}(s)\frac{x^n}{n!}=\sum_{n=0}^{\infty}\frac{\partial^n B_z(0,0,s)}{\partial x^n}\frac{x^n}{n!}, \quad (3)$$

where the successive derivates identify the terms as being dipole, quadrupole, sextupole, etc., in the expansion of the field.

When a real "banana shape" coil with a width $\Delta x=d$, a length L, a number of turns of N and a height $\Delta z=h$ is put in the magnetic midplane, where the middle axis of the coil is at position x_0, the total flux passing though it will be

$$\begin{aligned}\Phi(x_0) &= \sum_{l=1}^{N}\int_{x_0-d/2}^{x_0+d/2}\int_{-L/2}^{L/2}B_z(x,z,s)dsdx \\ &= \sum_{l=1}^{N}\int_{x_0-d/2}^{x_0+d/2}F(x,z)dx. \quad (4)\end{aligned}$$

It is evident that

$$F(x,z)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}F_{n,2m}\frac{x^n}{n!}\frac{z^{2m}}{(2m)!}. \quad (5)$$

For the midplane, we have

$$F(x,0)=\sum_{n=0}^{\infty}F_{n,0}\frac{x^n}{n!}=\sum_{n=0}^{\infty}\frac{x^n}{n!}\int_{-L/2}^{L/2}B_{n,0}(s)ds, \quad (6)$$

where $F_{n,0}$ are the integrals of dipole, quadrupole, sextupole, etc., in the expansion of the field. Especially, $F_{0,0}$ is the so-called integral bending strength of the dipole bending magnet. When a particle with a momentum P passes through the whole bending magnet, $F_{0,0}$ determines the total bending angle θ_0 of the trajectory by

$$\theta_0=\int d\theta=\frac{F_{0,0}}{P}. \quad (7)$$

[1] Strictly speaking, this is correct only for the central part of the "banana shape" coil. During real measurements, we move the whole coil forward and backward in the gap space of the magnet perpendicularly to the pole boundary in the magnetic midplane. In that case, the ends of the coil are moved horizontally rather than radially. However, this still gives a sufficiently accurate result because the maximum angle between them is 15^0 and the magnetic fields drop very quickly towards the end parts of the coil.

Equation (4) can be approximately expressed as,

$$\begin{aligned}\Phi(x_0) &\approx \frac{1}{h/N}\int_{-h/2}^{h/2}\int_{x_0-d/2}^{x_0+d/2}F(x,z)dxdz \\ &= N\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{(h/2)^{2m}}{(2m+1)!}\frac{F_{n,2m}}{(n+1)!}\times \\ &\sum_{l=0}^{n}\frac{(n+1)![1-(-1)^{n+1-l}]}{l!(n+1-l)!}\left(\frac{d}{2}\right)^{n+1-l}x_0^l. \quad (8)\end{aligned}$$

Let

$$\Phi(x_0)=\sum_{n=0}^{\infty}\frac{\phi_n}{n!}x_0^n, \quad (9)$$

then

$$\phi_n=\sum_{m=0}^{\infty}\frac{2N}{(2m+1)!}\left(\frac{h}{2}\right)^{2m}\sum_{l=0}^{\infty}\frac{F_{n+2l,2m}}{(2l+1)!}\left(\frac{d}{2}\right)^{2l+1}. \quad (10)$$

Note that

$$f_n=\frac{\phi_n}{Nd}, \quad (11)$$

then

$$\begin{aligned}F_{n,0} &= f_n-\frac{f_{n+2}}{3!}\left(\frac{d}{2}\right)^2+\left[\frac{1}{(3!)^2}-\frac{1}{5!}\right]f_{n+4}\left(\frac{d}{2}\right)^4 \\ &-\left[\frac{1}{(3!)^3}-\frac{2}{3!5!}+\frac{1}{7!}\right]f_{n+6}\left(\frac{d}{2}\right)^6+\cdots \\ &-\frac{F_{n,2}}{3!}\left(\frac{h}{2}\right)^2-\frac{F_{n,4}}{5!}\left(\frac{h}{2}\right)^4-\frac{F_{n,6}}{7!}\left(\frac{h}{2}\right)^6-\cdots, \quad (12)\end{aligned}$$

where ϕ_n or f_n can be directly determined by the measurements of the "banana shape" coil. In principle, the integral value of $F_{n,0}$ can be known by this.

For bending magnets used in a storage ring, the high order components of F generally are very small. If we take $h^2 \ll d^2$, the influence of $F_{0,2}$ or $F_{1,2}$ on the determination of $F_{0,0}$ or $F_{1,0}$ can be neglected. Then $F_{0,0}$, $F_{1,0}$ and $F_{2,0}$ etc. can be easily determined with the above fomulae via the measurments.

From the above formulae, the relative difference of the bending strength between dipoles (where normally more attention needs to be paid in order to control the tolerance) can be known by

$$\frac{F_{0,0}-F^*_{0,0}}{F^*_{0,0}}\approx -1+\frac{\phi_0}{\phi^*_0}-\left(\frac{\phi_3}{\phi^*_0}-\frac{\phi^*_3}{\phi^*_0}\right)\frac{1}{3!}\left(\frac{d}{2}\right)^2 \quad (13)$$

where the parameter with the superscript "*" refers to the value of a reference dipole.

3 MAGNETIC PERFORMANCE

The dipole magnet shown in fig.1 consists of modules cemented together with an epoxy adhesive. Its excitation curve has been measured with NMR equipment and is shown in fig.3 as measured curve 2. The result indicates that this magnet has less loss of flux, especially for higher

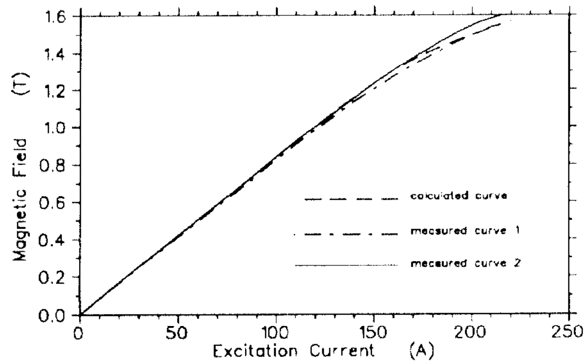

Figure 3: *Excitation curve of dipole magnet.*

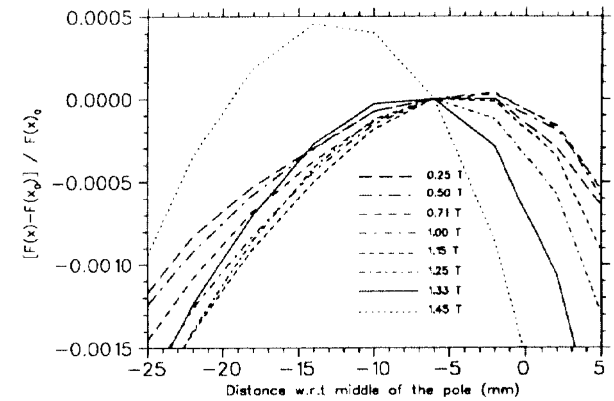

Figure 5: *Integral field distribution along radial direction on midplane of dipole*

magnetic induction, as compared with the ealier prototype magnet consisting of welded modules [2] whose excitation property is shown as measured curve 1 in fig.3.

The homogeneity in the middle plane of the dipole has been measured with the Hall probe system. Fig.4 shows the result in the middle part of the dipole.

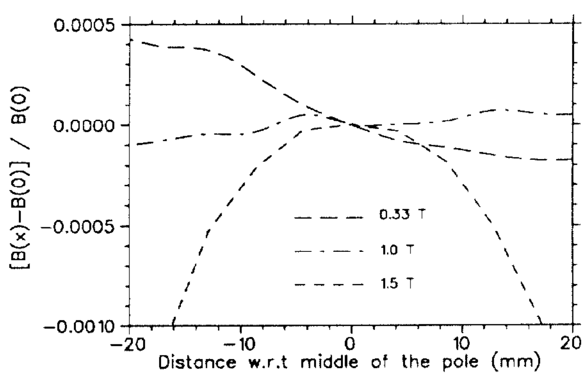

Figure 4: *Radial field profile in the middle part of dipole*

The measurements on the integral fields of this magnet have been done with the "banana shape" coil device. The relative accuracy of integral field measurements has been investigated. The reproducibility of the coil measurements is about 5×10^{-5} [3]. The integral field distribution measurement is shown in fig.5. There, the reference position x refers the entrance (and the exit) of the designed closed orbit in the midplane of the dipole, with the reference position $x = 0$ corresponding to the position of the horizontal symmetry axis of the mechanical pole surface. The measurement results tell us that the ideal reference closed orbit can be selected at a position around $x_0 = 0.6$ cm within about 1 cm where the relative difference of the bending strength is smaller than 2×10^{-4} when the magnetic field is changed from 0.25 T (injection energy) to 1.33 T (nominal energy of the machine). If all dipoles have a similar magnetic distribution the shift of the closed orbit will be very small. When the magnetic field is increased above 1.33 T, the good field region becomes narrow, caused by serious saturation of the dipole magnet (which can be seen clearly from fig.4). However, this presents no problem as the working energy of the EUTERPE is not above 400 MeV. The measured integral magnetic field performance is shown in Table 1 with $x_0 = -0.6$.

Table 1: *Integral fields v.s. magnetic intensity*

B	F_0	F_1	F_2	F_1/F_0	F_2/F_0
T	T.m	T	T/m	m^{-1}	m^{-2}
0.25	0.13267	0.0007	-1.05	0.005	-7.9
0.50	0.26029	0.0041	-2.02	0.016	-7.8
0.70	0.36919	0.0079	-3.24	0.021	-8.8
1.01	0.52277	0.0140	-5.11	0.027	-9.8
1.15	0.59832	0.0141	-7.58	0.024	-13.
1.25	0.64686	0.0035	-9.85	0.005	-15.
1.33	0.68625	-0.019	-13.9	-0.028	-20.
1.46	0.74208	-0.113	-20.3	-0.152	-27.

4 CONCLUSION

A "banana shape" coil measuring device with a relative reproducibility of 5×10^{-5} has been used to measure the EUTERPE ring dipole. The basic integral formulae with this device have been given. The measurement results indicate that the dipole magnet consisting of modules cemented together has a good magnetic performance with a broad range from 0.25 T to 1.35 T.

5 ACKNOWLEDGEMENT

We acknowledge the members of the Central University Workshop for constructing the dipoles.

6 REFERENCES

[1] Boling Xi, J.I.M. Botman, C.J. Timmermans and H.L. Hagedoorn, Nucl. Inst. and Meth. B68 (1992) 101.

[2] J.I.M. Botman, C.J. Timmermans, Boling Xi, H. Heller, H.L. Hagedoorn, P. Brinkgreve, E. Dekkers, J. Moerel, IEEE 1993 Part. Conf. Proc. (1993) 2892.

[3] A.T.A.M. Derksen, internal report VDF/NK 93/33, 1993.