Off-Axis Magnetic Flux Density of a PPM Focusing System

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Abstract: *This paper describes a series solution to determine the magnetic flux density off-axis for ring-shaped permanent magnets axially magnetized used in periodic-permanent magnet (PPM) focusing systems of power linear microwave tubes such as traveling-wave tubes (TWT) and klystrons.*

Keywords: Magnetic electron beam focusing; off-axis magnetic field, power microwave devices, periodic-permanent magnet.

The developed method

The solution found uses the equivalent magnetic charge concept [1]. Either the radial or the axial magnetic field component can be written as a function of the inner radius, outer radius, thickness and remanence of the ring-shaped permanent magnet. The resultant field of a PPM stack is obtained by means of superposition principle, since do not exist ferromagnetic pole pieces between the rings, so that it would be possible to evaluate the magnetic force on any electron of a beam and improving simulators accuracy. The development begins with the expression of the scalar magnetic potential

$$\psi(\vec{r}) = \frac{1}{4\pi}\int \frac{\vec{M}(\vec{r}\,')\cdot\hat{n}}{|\vec{r}-\vec{r}\,'|}dS' \qquad (1)$$

where $\vec{M}$ is the magnetization vector, $\vec{r}$ the field point, $\vec{r}\,'$ the source point and $|\vec{r}-\vec{r}\,'|$ is the modulus of $(\vec{r}-\vec{r}\,')$.

After a vector analysis in the geometry shown in Fig. 1, the magnetic scalar potential originating from the magnet frontal surface will be given by

$$\psi_{\sup}(\vec{r}) = \frac{M_0}{4\pi}\int_{R_1}^{R_2} \frac{4\rho' d\rho'}{\left[(\rho+\rho')^2+(z-L)^2\right]^{1/2}}K(\kappa) \qquad (2)$$

where M_0 is the magnetization, ρ and z are the radial and the axial coordinates where the field is evaluated, ρ' is the integration variable, L is the half-length of one magnet and $K(\kappa)$ is the complete elliptic integral of first order , which was expanded by means of a series summation, expressed in (3), and each term of the series was integrated.

$$\psi_{\sup}(\vec{r}) = \frac{M_0}{2}\int_{R_1}^{R_2} \frac{\rho' d\rho'}{\left[(\rho+\rho')^2+(z-L)^2\right]^{1/2}}\left\{1+\left(\frac{1}{2}\right)^2\kappa^2+\left(\frac{3}{8}\right)^2\kappa^4+\ldots\right\} \qquad (3)$$

The fundamental integrals to be evaluated, obtained from (3), follow the general expression

$$\psi_n(\rho,z) = \rho^{n-1}\int_{R_1}^{R_2} \frac{\rho'^n d\rho'}{\left[(\rho+\rho')^2+(z-L)^2\right]^{n-(1/2)}} \qquad (4)$$

where $n \geq 1$and the term $(z-L)$ must be changed by $(z+L)$ in (4) to consider the effect from the second "magnetically charged" surface. Finally, the total scalar magnetic potential can be written as terms summation of (4) indicated by the folowwing expression

$$\psi_{total}(\rho,z) = \sum_{n=1}^{N}\psi_n(\rho,z) \qquad (5)$$

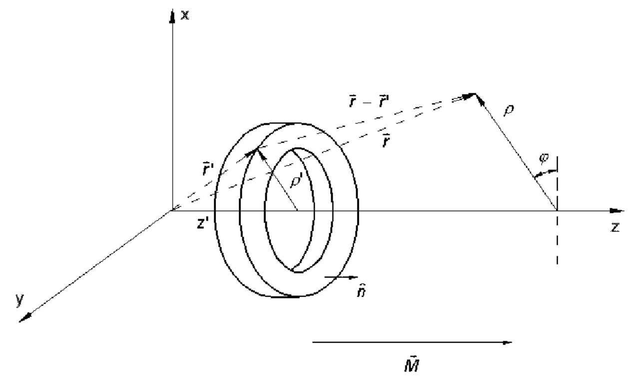

Figure 1. Geometry used to determine the magnetic flux density off-axis for ring-shaped permanent magnets axially magnetized.

Results and discussion

A comparison between theoretical and experimental axial field profiles to verify the accuracy developed method is presented in Fig. 2 (a-d) for the ferrite magnets characterized in Tab. 1. It is possible to notice that there is a good agreement of the results for every case, using $n = 5$. Increasing the distance between the axis of symmetry and the field point, the axial component of the magnetic flux density $B_z(\rho)$ also increases, that is also indicated by the proposed method.

Verifying the last situation presented (see Fig. 2 (d)), B_z profile measured is larger than that theoretically found, indicating the need to obtain more terms of the expansion in order to improve the agreement.

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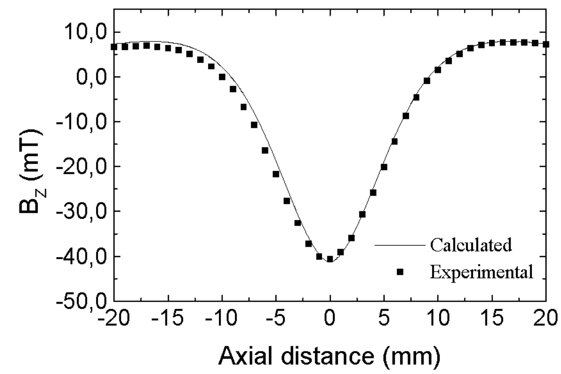
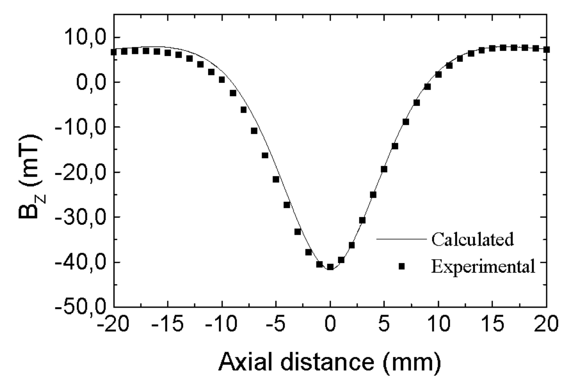
Table 1. Physical and magnetic properties of the ferrite samples analyzed (R_1 refers to inner radius, R_2 to outer radius, 2L to magnet thickness and B_r to remanence).

Material	R_1 (mm) (± 2%)	R_2 (mm) (± 2%)	2L (mm) (± 2%)	B_r (T) (± 2%)
Ferrite	8.9	19.9	6.0	0.25



(a)



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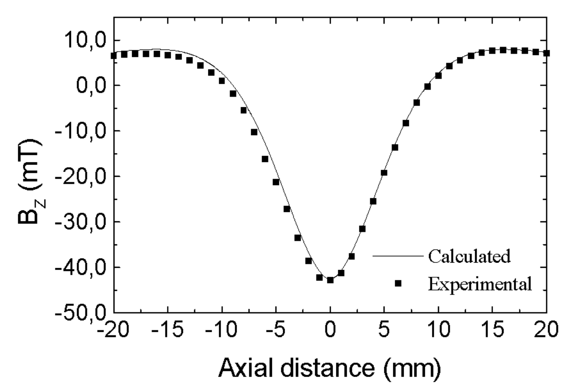

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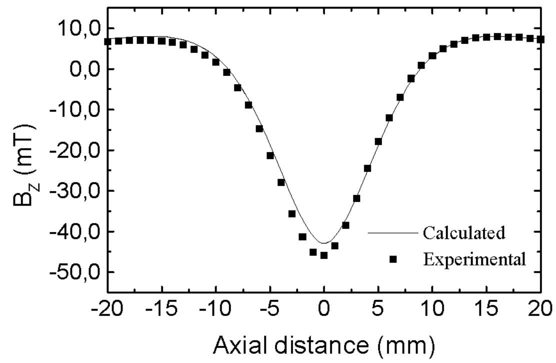

(d)

Figure 2. The axial magnetic flux density profile for the ferrite samples characterized in Table 1. Measurements carried out for (a) $\rho = 0$, (b) $\rho = 1$mm, (c) $\rho = 2$mm and (d) $\rho = 3$mm.

Conclusions

It is presented an expression which determines the magnetic flux density of one permanent magnet either on-axis as well as off-axis. This method depends on the remanence and the sample dimensions. A PPM field profile can be found using the superposition principle. Comparison between calculated and measured data is satisfactory. It was found theoretically, up to $\rho = 3$mm, the B_z profile with acceptable agreement compared to experimental data. This radial distance is suitable for a typical electron beam radius used in microwave vacuum devices and the method could be adapted to a simulator to determine precisely the magnetic force on any electron of the beam.

References

1. Jackson, J. D., *Classical Electrodynamics*. 2° ed. New York, NY: John Wiley, 1975.