DIPOLE SEPTUM MAGNETS

R.L. Keizer
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DIPOLE SEPTUM MAGNETS

R.L. Keizer
SUMMARY

The two-dimensional theory of septum magnets is treated with the aim of arriving at a better understanding of how linearization of end fields may be achieved. Two practical applications -- mirror plates and extended septa -- are discussed. A method of extending the theory of linearized end fields to multturn septa is given.

Based on the above theory, the calculation of field errors arising from finite permeability effects and septum geometry is then shown to be possible by simple hand calculation. Various methods of correcting these field errors are indicated.

Several septum constructions are shown and their specific difficulties discussed.
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List of symbols used (MKS system)

A = total cross-sectional area of an ideal septum

A_{Cu} = copper cross-sectional area of an imperfect septum

A_{g} = cross-sectional area of upper and lower gaps

A_{n} = cross-sectional area of the noses or vertical extension of a septum

A_{w} = cross-sectional area of the cooling ducts

A_{X} = x-component of the vector potential

b = geometrical factor

B(x) = field density of the main field of an imperfect magnet

B_{bleg}(x) = field induced by a back-leg winding parallel to the inner conductor

B_{centr}(x) = field caused by septum geometry around the median plane

B_{comp}(x) = field induced by compensation coils

B_{corr} = field induced by vertical extensions of the septum

B_{Fe}(x) = average field density in the yoke

B_{id}(x) = z-component of the field density in an ideal magnet

B_{rel}(x) = field induced by reluctance losses

B_{rem}(x) = remanent field

B_{sleg}(x) = field induced by a back-leg winding parallel to the septum

B_{source} = source strength of the various perturbations

\bar{B}(B_x, B_y, B_z) = components of the field density caused by hysteresis effects

d = thickness of the current-sheet

d\xi = incremental length of flux path

D = magnetic dipole strength

F, dF = surface element in the x,y-plane

F(\chi) = form factor, describing the shape of the fringing field

g = thickness of gap between septum and yoke

h, h_s, dh = gap height and incremental gap height

h_{Fe}(x) = length of a flux path in iron

H_c = coercive force

I, I_{eff} = total and effective amp\ê re-turns in a coil

I_{parallel} = parallel current in a single-turn septum

j = current density in an ideal septum

j_{*} = perturbation current density in the copper cross-section due to \Delta I_{*}
\( j \) = perturbation current density in the non-conducting parts of the septum

\( j_{\text{centr}} \) = average perturbation current density around the median plane

\( J \) = current density vector

\( J(x, y, z) \) = line current density vector

\( k(x) \) = geometrical factor

\( l_{\text{coil}} \) = width of return conductor

\( l_{\text{end}} \) = thickness of the end plate

\( l_{\text{ext}} \) = length of extended septum

\( l_{\text{Fe}} \) = iron length of a magnet

\( l_{\text{m}} \) = magnetic length of a field

\( n \) = number of turns

\( \bar{n} \) = direction vector of unit surface

\( r \) = radius vector

\( t \) = septum thickness

\( t_{\ell} \) = thickness of a lamination

\( w \) = free horizontal aperture

\( x, y, z \) = Cartesian coordinates

\( \bar{x}, \bar{y}, \bar{z} \) = unit direction vectors

\( \alpha(x) \) = angle of refraction of field lines

\( \beta(x) \) = angle of refraction of current lines

\( \Delta I \) = total ampère-turns in back-leg or compensation coils

\( \Delta I_{+}, \Delta I_{-} \) = positive and negative currents caused by septum imperfections

\( \Delta J_{+}(x, z), \Delta J_{-}(x, z) \) = distributions of positive and negative perturbation current densities

\( \rho \) = resistivity of the current-sheet

\( \rho_{\text{air}} \) = resistivity of the current-sheet in the air region

\( \rho_{\text{iron}} \) = resistivity of the current-sheet in the iron region

\( \rho_{\text{Cu}} \) = vol. resistivity of copper

\( \phi \) = scalar potential

\( \phi_{z} \) = vertical component of the flux

\( \mu_{0} \) = absolute permeability, \( 4\pi \times 10^{-7} \text{ H/m} \)

\( \mu_{\text{Fe}} \) = relative permeability of iron
1. **INTRODUCTION**

A septum is a boundary that separates or combines beams by providing a different deflecting field on either side of this boundary\(^1\). Very thin septa are possible in the case of electrostatic fields. The majority of existing septum devices are, however, electromagnetic.

Beam optics often require a septum which is as thin as possible, usually the first element of a beam extraction system. The grounded e.s. septum is either a thin foil [CERN\(^7\)] or an array of tungsten wires [NAL\(^8\) and BNL\(^9\)]. The apparent thickness is in the order of 50 to 150 microns.

A thin e.m. septum magnet\(^{12-22}\) is usually placed in the shadow of the e.s. septum. The thickness varies from 0.75 to 1.50 mm. The cooling problems are severe, and the magnets are usually pulsed with a low duty factor to keep the average power dissipation acceptable.

The thin septa are followed by the extractor magnet\(^{23-35}\), which consists of a number of multiturn septum magnets with septa of 3 to 10 mm thickness. The mode of operation ranges from d.c. to fast pulsed (300 μsec, 2000 V typically).

Problems particular to these magnets are:
- low fringing fields;
- uniform dipole strength over the whole aperture;
- e.m. forces on the septum; these septa expand thermally, thereby causing friction and wear; the forces are often pulsating;
- cooling of the septum, hydraulic losses should be minimized;
- vacuum problems, since these magnets are placed inside the vacuum chamber; hence a low outgassing rate is required, even when the septa are hit by the beam;
- vacuum-tight cooling water and electrical current connections;
- electrical insulation which should be radiation resistant;
- radiolysis of the cooling water, corrosion, and deposition of thin, thermally insulating layers in the cooling ducts;
- design of radiation-resistant magnets; adaptation to remote-handling equipment.

2. **THEORY OF TWO-DIMENSIONAL CURRENT-SHEETS OF FINITE THICKNESS**

2.1 **Plane current-sheets**

The problem will be treated in a general way which makes it easier to understand end-field linearization through the use of extended septa or mirror plates.

Imagine a two-dimensional cavity of arbitrary shape in the \(x,y\)-plane, the walls of which run parallel to the \(x\)-axis as shown in Fig. 1. The walls consist of ferromagnetic material, and a number of arbitrarily positioned current conductors run also parallel to the \(x\)-axis and magnetize the cavity.
Fig. 1 A two-dimensional magnetized cavity terminated by a plane current-sheet

Suppose the block is cut parallel to the $y,z$-plane, at a position $x = d$, and the cavity is terminated by a current-sheet of thickness $d$. The current-sheet is mounted inside the cavity, as shown in Fig. 2.

a) Actual construction of a single-turn septum dipole

b) C-type septum dipole with thick end plates

Fig. 2
The field density $B$ will be two-dimensional and thus independent of $x$-position. It is then easy to show (see Appendix 1) that at every point in the current-sheet the field density satisfies the relation:

$$\text{Curl } B = \mu_0 J,$$

where $J$ is the line current density. This means that $B \equiv 0$ everywhere in front of the current-sheet, i.e. for $x \geq d$.

2.2 Cavity with two plane current-sheets and coaxial feeding

In this case the magnetized cavity, as shown in Fig. 1, does not extend to $x = \infty$ but has a certain depth and is also terminated at the rear-end by a current-sheet, which could have a different thickness.

The current connections could then be made somewhere through a hole in the iron, and the device could be fed coaxially.

The field inside the cavity then has the property of being truly two-dimensional. Using this principle, several kinds of septum magnets can now be envisaged.

Since the field is two-dimensional, it is easy to show that for any septum magnet which is symmetrical with respect to the $x,y$-plane the dipole strength is independent of the $z$-position.

3. APPLICATION TO SEPTUM DIPOLES

3.1 The single-turn septum dipole with extended septum

The basic cavity is of rectangular shape (Fig. 2a), and the septum extends theoretically from $-\infty < y < \infty$. For practical purposes, however, it is necessary to reduce the length of the septa, and the length of the extended septa $l_{\text{ext}}$ should be such that the end field at cut-off is almost zero. In general, it suffices to take

$$l_{\text{ext}} \approx h.$$  

The inner conductor (see Fig. 2a) should theoretically also be provided with extension pieces. In practice, however, this is not necessary since the quality of the main field near the inner conductor is of lesser importance.

In most cases $l_{\text{ext}} = 0$, and a strong fringing field exists which is caused by the return conductors of the coil.

The current leads to the magnet coil should preferably be coaxial. A solution which is easier to realize is shown in Fig. 2a, where flat strips are used with a thin electrical insulation in between. Hence, a septum magnet constructed following the above principles has the property that the end fields are perfectly two-dimensional. The end fields are said to be linearized. The magnetic kick is therefore constant over the whole aperture.

3.2 The single-turn septum dipole with thick end plates

The basic magnetized cavity is again of rectangular shape (Fig. 2b) but is surrounded by iron on all sides. The end plates create this way have thickness $l_{\text{end}}$. Since the flux in these plates is small, it is possible to drill holes through which the beam can pass.
An approximation of this ideal construction is often used in the form of a linearization end plate of thickness \( \delta_{\text{end}} \) mounted at a short distance \( \delta_{\text{coil}} \) from the core. This construction is often used when the number of septum conductors is large.

### 3.3 Multiturn septum dipoles

In case of a vertically split septum (see Fig. 3a) the linearization of the end field poses no particular problems theoretically. All septum conductors have the same shape and differ in the position of the current leads.

![a) A vertically split three-turn septum dipole](image)

![b) A horizontally split six-turn septum dipole](image)

Fig. 3

For horizontally split magnets, there exists also a theoretical solution which is, however, more difficult to realize in practice. For a multiturn magnet (n turns) the position of (n-1) current flow lines in an ideal septum is calculated. This could be done with a magnetic field computing program which calculates the position of n-1 isoscalar potential lines. The septum may then be cut along these lines without affecting the current distribution. The example of a six-turn magnet is shown in Fig. 3b.

### 3.4 Iron septum dipoles

In some cases **it is advantageous to use an iron septum dipole. This is an ordinary window-frame magnet** with or without linearization plates. At one particular place, however, a deep groove is made in the core, which divides the flux into two separate systems (see Fig. 4a). The core shape is such that the reluctance of the two systems is more or less equal (for a particular field value). With a correction coil and a stray-field sensing device in the groove, the magnetic reluctance of the two systems may then be balanced.

The end field of an iron septum can also be linearized using extended septa or thick end plates, as shown schematically in Fig. 4b.

---

*) First proposed by G. Lambertson (LRL) and B. de Raad (CERN).

**) In case the beam is displaced out of the median plane which, for circular accelerators, means a vertical deflection.
4. CALCULATION OF DIPOLE MAGNETS

4.1 General conditions

The septum magnet forms part of the beam transport system which imposes its requirements on the choice of

- septum thickness, gap height, gap width, and total available length;
- the dipole strength $\int B_z \, dy$, its homogeneity, and the maximum permissible integrated fringing field.

The power supply, the distance between supply and magnet, and the available water pressure, influence

- the number of turns;
- the current.

Having established the main parameters, attention should be paid to the following points:

- the choice of the soft magnetic core material, which is influenced by the maximum field density, fringing field requirements, homogeneity of the main field, remanent magnetism, and eddy-current heating;
- the construction of the core, which is influenced by factors such as the outgassing properties in vacuum, radiation damage, etc.,
- cooling of the coil, joule losses, heating of the coolant by turbulence, and possible radiation heating when the full beam hits the septum;
- the septum construction, which is determined by factors such as mechanical stresses due to non-uniform temperature distributions, magnetic pressure in the gap and, for instance, shock waves generated in fast pulsed magnets;
- the choice of coil material, which is influenced by radiation effects, radiolytic corrosion, and resistivity;
- the choice of the electrical insulation, which is very strongly influenced by the wear-resistant, radiation-resistant, hygroscopic, and outgassing properties;
- finally, the over-all design should also be approached from the maintenance point of view and the remote handling of highly radioactive components.

In the next sections, only the problems associated with the magnetic requirements will be treated. Most of the above-mentioned problems are treated in the references under the heading "General".

4.2 Septum constructions

The septum may be integrally cooled (Fig. 5a) or edge-cooled (Fig. 5b). It is not necessary to insulate a single-turn septum electrically, as explained in Appendix 3 if the core is laminated\textsuperscript{27,30}). In order to have a homogeneous line current distribution, the edge-cooled septums should be profiled (Fig. 5b), since the temperature gradient is very high. The stability of a multiturn horizontally split septum\textsuperscript{9}) (Fig. 5c) depends on the rigidity of the supporting plate and the pressure exerted on the conductors in the vertical direction by the pole faces.

In the case of d.c. magnets, very little support is needed to prevent inward displacement of the coils. For pulsed magnets, however, strong springs have to be provided which push the coils outwards since even small movements cause considerable wear on the insulation.

![Fig. 5](image-url)

a) Single-turn septum dipole, integral cooling

b) Single-turn septum dipole, edge cooling

**c) A six-turn horizontally split septum dipole**
The insulation can be epoxy resin or a polyimide such as Kapton, both of which are organic materials producing strong outgassing when hit by the beam. More stable insulations are boron-mica, glass-mica or alumina. Each of these materials has its own difficulties, being either brittle, difficult to apply, or hygroscopic, causing heavy initial outgassing.

The three examples shown are by no means exhaustive, but are intended as a general guide.

4.3 Transversal field calculations

4.3.1 Introduction

Only septum magnets with perfect linear end fields are considered, since in this case the dipole strength \( \int B_2 \, dy \) is very homogeneous and the fringe fields are calculable.

The assumption is made that non-linear effects due to saturation are small. The field of the magnet may then be treated as a linear superposition of three kinds\(^1\) of fields, namely:

a) the field in an ideal septum magnet, with infinite permeability and ideal (i.e. solid) conductors of finite thickness;

b) the field caused by either the reluctance losses in a yoke having finite permeability or by hysteresis effects;

c) the field caused by the departure from the ideal septum geometry; a distribution of negative currents represents the cooling ducts, insulation and gaps, and a positive current in the copper section makes the net current zero.

This method of separating the various effects at a given main field has certain advantages.

For instance, for calculations using a high permeability, the main field may be hand-calculated and the perturbations (point c) can then be programmed independently.

For finite permeability calculations, the main field and the average permeability of the yoke are computed first. Thereafter, the perturbations (point c) are programmed separately using a constant average permeability.

The perturbations may therefore be investigated and optimized individually.

4.3.2 The ideal magnet with finite permeability

Consider an ideal septum magnet with the vertical component of the field density \( B_{id}(x) \) pointing in the positive \( z \)-direction and infinite permeability, see Fig. 6b. With the law of Ampère follows

\[
B_{id}(x) = \frac{\mu_0}{h} I, \quad -0.5w < x < 0.5w
\]

\[
\neq 0 \quad 0.5w + t < x.
\]

With a finite relative permeability \( \mu_{Fe} \), the actual field density in the gap \( B(x) \) is somewhat less if the total current \( I \) is kept constant:

\[
B(x) = B_{id} + B_{rel}(x)
\]

and

\[
B_{rel}(x) = -\frac{h_{rel}(x)}{h \mu_{Fe}(x)} B_{Fe}.
\]
The flux path in iron \( h_{Fe} \) is \( x \)-dependent, and the average field density in the iron is dependent on the shape of the core. The reluctance losses in the yoke are represented by the function \( B_{rel}(x) \) which is shown in Fig. 6c. The main field inside the coil is inhomogeneous (Fig. 6a), and the fringing field in front of the septum is negative. For a quick evaluation of the reluctance effects, the following procedure could be used\(^1\). The assumption is made that

\[
B_{Fe}(x) = k(x)|B_{id}(0)|,
\]

where \( k \) is a geometrical factor which depends on the shape of the core and the flux path under consideration. At \( x = 0.5 \) the reluctance losses attain a maximum, and this value could be taken as the source strength

\[
B_{source} = B_{rel}(0.5w) = -k \frac{h_{Fe} \mu_0}{h} \frac{B_{id}}{\mu_{Fe}} I .
\]

The value of the fringing field may then be calculated at any point around the septum by multiplying \( B_{source} \) by the form factor \( F(x/h) \) (see Fig. 16, curve \( A \)).

4.3.3 Hysteresis effects

The same procedure may be adopted to estimate hysteresis effects where the remanent field \( B_{rem}(x) \) has the same shape as \( B_{rel}(x) \) but with a positive sign as shown in Fig. 6c. The source strength at \( x = 0.5 \) then becomes

\[
B_{source} = B_{rem}(0.5w) = \frac{h_{Fe} \mu_0}{h} |H_c(B)| .
\]

The (negative) coercive force is a function of the saturation field density of preceding current cycle. The fringing field may now be calculated by reading Fig. 16, curve \( A \).
4.3.4 Back-leg windings

Fringing fields or inhomogeneous main fields caused by finite permeability of the yoke may be compensated by so-called back-leg windings which are connected parallel to the coil conductors. In this case the corrective current is always linked to the main current (see Fig. 7). In other cases, separate compensation coils are provided for this purpose in the way shown in Fig. 7a on the extreme right. The current $\Delta I$ may then have either sign.

The method of linear superposition of known fields, as explained in Section 4.3.1, is also applicable in these cases.

![Diagram showing back-leg windings](image)

a) Back-leg winding parallel to the inner conductor

b) Back-leg winding parallel to the septum conductor

Fig. 7

Compensation of hysteresis effects

A back-leg winding parallel to the inner conductor, with current $\Delta I$ (see Fig. 7a), may be considered as a linear superposition of

- an ideal magnet with finite permeability, equation (3), field density $B(x)$;

- a C-type magnet with $\Delta I$ ampere-turns, infinite permeability, and field $B_{b\text{leg}}$ with polarity opposed to that of $B(x)$ and $B_{\text{rem}}$. The fringing fields are identical in both cases, but the gradients of the main fields differ (cf. Figs. 6c and 7a).

Here again, with the graph shown in Fig. 16, curve A, the shape of the field $B_{b\text{leg}}(x)$ around the septum may be determined using the expression

$$ B_{\text{source}} = B_{b\text{leg}} = -\frac{B_s}{h} \Delta I. $$

(8)
If at non-zero excitation the remanent field has to be cancelled, it is necessary that the two source strengths are equal

\[ B_{\text{source}} = B_{\text{sleg}} = B_{\text{rem}} \]  \hspace{1cm} (9)

\[ \Delta I = h_{Fe} |H_c| \]  \hspace{1cm} (10)

Compensation of finite permeability effects

The back-leg winding is now connected parallel to the septum conductor (Fig. 7b), and the resulting field is a linear combination of:

- an ideal magnet with finite permeability and an effective current \( I_{\text{eff}} = I - \Delta I \);
- a C-type magnet with \( \Delta I \) am\'ere-turns, infinite permeability, and field \( B_{\text{sleg}} \) of polarity opposed to that of the reluctance field \( B_{\text{rel}} \). The fringing fields are identical in shape, but the gradients of the main fields differ (cf. Figs. 6c and 7b).

Hence with Eqs. (3) and (6)

\[ B(x) = \frac{\mu_0}{h} (I - \Delta I) - k \frac{h_{Fe} \mu_0}{h^2} (I - \Delta I) \]  \hspace{1cm} (11)

The source strength of \( B_{\text{sleg}} \) is then

\[ B_{\text{source}} = B_{\text{sleg}} = \frac{\mu_0}{h} \Delta I \]  \hspace{1cm} (12)

The fringing field may be evaluated with Fig. 16, curve A. If at a certain field the two fringing fields should cancel, one finds

\[ B_{\text{source}} = B_{\text{sleg}} = B_{\text{rel}} \]  \hspace{1cm} (13)

Hence, with Eqs. (6) and (12),

\[ \Delta I = \frac{k h_{Fe}}{h h_{Fe} + k h_{Fe}} I = k \frac{h_{Fe}}{h h_{Fe}} I \]  \hspace{1cm} (14)

Equation (14) shows that the ratio \( \Delta I/I \) increases with the field in the iron.

4.3.6 Compensation coils

Compensation coils are used to reduce the fringing field. An example is shown in Fig. 8. The difference with back-leg windings is that the excitation is independent of the main current and therefore may be programmed differently.

Compensation of hysteresis effects

The analysis is identical to that of Fig. 7a with the difference that the representation has to be taken literally. The current in the coil (Fig. 8a) is determined by

\[ B_{\text{source}} = B_{\text{comp}} = - \frac{\mu_0}{h} \Delta I \]  \hspace{1cm} (15)

where the field shape is that of Fig. 16, curve A. To compensate the remanent field \( B_{\text{rem}} \) it is necessary that

\[ \Delta I = h_{Fe} |H_c| \]  \hspace{1cm} (16)

The difference with Eq. (10) is that it is now possible to compensate at zero excitation of the main coil.
Compensation of finite permeability effects

In this case the current in the compensation coil $\Delta I$ must have a negative sign (Fig. 8b):

$$B_{\text{source}} = B_{\text{comp}} = \frac{u_2}{h} \Delta I.$$

The compensation current is then calculated with Eq. (14).

4.3.6 Septum geometry

Positive and negative currents

An imperfect septum (see Fig. 9) may be considered as the linear superposition of:

- an ideal septum with current $I$;
- a grid of negative currents representing the gaps and cooling ducts with total current $\Delta I_-$;
- a matrix of positive currents with total current $\Delta I_+$.

The last correction is indispensable since in general $\Delta I_-$ is not negligible and should be compensated by $\Delta I_+$ to keep the total current $I$ constant.

The negative and positive currents cancel each other, therefore

$$\Delta I = |\Delta I_+| = |\Delta I_-|.$$
Fig. 9 Analysis of septum imperfections

The current densities $j$, $j_-$, and $j_+$, which flow in the $y$-direction, are defined as follows:

$$j = \frac{I}{A}, \quad j_- = \frac{\Delta I}{A_w + 2A_g}, \quad j_+ = \frac{\Delta I_+}{A_{Cu}}. \quad (19)$$

Since the effective current density in the cooling ducts is zero,

$$j + j_- = 0. \quad (20)$$

Therefore with Eqs. (10), (19), and (20):

$$j_- = -\frac{I}{A}, \quad (21)$$

and

$$j_+ = \frac{A_w + 2A_g}{A_{Cu}I}. \quad (22)$$

The problem of how these currents will influence the main and the fringing fields can now be resolved.

The region around the median plane

The average perturbation current density around the median plane $j_{\text{centr}}$ may be defined as follows (see Fig. 9):

$$j_{\text{centr}} = \frac{j_- A_{Cu} + j_+ A_w}{A_{Cu} + A_w}. \quad (23)$$

Hence with Eqs. (21) and (22):

$$j_{\text{centr}} = \frac{2g}{h} \frac{I}{A_{Cu}}. \quad (24)$$

This perturbation current density is slightly positive so that the main field near the conductors will be somewhat higher and the fringing field will be more negative than in the case of an ideal magnet with finite permeability. This is illustrated in Fig. 9.
Assume that the region of positive perturbation current density extends over the incremental conductor height \(dh\). With the law of Ampère

\[
\oint \mathbf{B} \cdot d\mathbf{l} = j_{\text{centr}} \, dh.
\]  
(25)

Hence with Eqs. (1) and (24) the source strength of the perturbation field density near the inner and outer septum wall \(B_{\text{centr}}(x)\) will be

\[
B_{\text{source}} = B_{\text{centr}}(\text{septum}) \approx \pm \frac{g}{h} B(0).
\]  
(26)

For the inner conductor it follows likewise that

\[
B_{\text{source}} = B_{\text{centr}}(\text{inner}) \approx 2 \frac{g}{h} B(0).
\]  
(27)

The presence of the iron boundary in the latter case doubles the value of the field. The shape of the function is shown in Fig. 16, curve B. Because the shape is different from that caused by a back-leg winding or compensation coil (A), it is not possible to compensate geometrical effects completely. Partial compensation may be obtained with a back-leg winding parallel to the septum conductor (Fig. 7b) or a compensation coil (Fig. 8b).

A more detailed treatment of septum imperfections is given in Ref. 28.

4.3.7 Septa with noses and vertical extensions

The idea of a superposition of positive and negative currents may also be applied to septa with noses (Fig. 10a) and vertically extended septa (Fig. 10b).

![Fig. 10](image-url)
The analysis is identical to that of the back-leg winding parallel to the septum conductor, Section 4.3.4 and Fig. 7b:

\[ B_{\text{source}} = B_{\text{corr}} = \frac{\mu_0}{h} \Delta I. \]  
(28)

\( \Delta I \) is a fixed fraction of the main current \( I \). The shape is that of curve A, Fig. 16. Since the field is positive, it is possible to correct finite permeability effects.

Let \( 2A_n \) be the cross-sectional area of the noses and \( A_{Cu} \) the copper cross-section of the septum without noses; it then follows that

\[ \Delta I = \frac{2A_n}{A_{Cu}} I. \]  
(29)

\[ B_{\text{corr}} = 2 \frac{A_n}{A_{Cu}} \frac{\mu_0}{h} I. \]  
(30)

If the fringing field due to reluctance has to be cancelled,

\[ B_{\text{source}} = B_{\text{corr}} = B_{rel}(0.5 w). \]

With Eqs. (6) and (30)

\[ A_n = k \frac{A_{Cu}}{2h} \frac{h_{Fe}}{\mu_{Fe}}. \]  
(31)

Hence cancellation is possible only at one field density.

4.4 **Longitudinal field calculations**

4.4.1 **The end field**

Consider the variation of \( B \) with the azimuthal coordinate or \( y \)-axis (Fig. 2a). The shape is roughly that of curve A, Fig. 16, which represents the case where the return conductors are far away from the median plane. The nearer the conductors are to the magnet gap, the steeper the curve drops. In the other extreme case, with the conductors in the median plane (hence a septum) the field is represented by curve B.

If the angle of deflection is small, the effective magnetic length \( \xi_n \) of a magnet with iron length \( h_{Fe} \) may be defined as

\[ \xi_n = \frac{1}{B(0)} \int_{-\infty}^{\infty} B(y) \, dy \]  
(32)

\[ = \xi_{Fe} + 2b h \quad 0.2 < b < 0.5. \]  
(33)

The factor \( b \) depends on the position of the return conductors as explained above. Quite generally one finds

\[ b \approx 0.5 \quad \text{for normal end fields} \]
\[ b \approx 0.25 \quad \text{for end fields with end plates, extended septa, etc.} \]

4.4.2 **Dipole strength**

The dipole strength \( D \) of a bending magnet may be defined as

\[ D = \int_{-\infty}^{\infty} (B \cdot z_0) \, dy. \]  
(34)
In the case of linearized end fields, D is independent of the transversal position x or vertical position z.

This property is easy to understand by remembering that the vertical flux $\phi_z$ in the magnet has the same value in any horizontal x,y-plane:

$$\phi_z = \int \mathbf{B} \cdot d\mathbf{F} = \int_{-w/2}^{w/2} dx \int_{-\infty}^{\infty} (\mathbf{B} \cdot \mathbf{z_0}) dy.$$  \hspace{1cm} (35)

From Eqs. (34) and (35) it then follows that

$$D = \frac{\phi_z}{w} = \text{constant}.$$  \hspace{1cm} (36)

4.4.3 The fringing field

The fringing field near to the septum may be qualitatively understood by applying the idea of positive and negative currents to current sheets.

The end field of an existing magnet is then represented as the linear superposition of

- an ideal two-dimensional end field terminated by a surface current distribution $\mathbf{J}(y,z)$ ideal;
- the field caused by a positive perturbation surface current which is principally present in the non-ideal and existing current sheet (or conductor system) $\mathbf{J}_p(y,z)$;
- the field caused by a negative perturbation current in the complementary current sheet which reduces the effective current to 0: $\mathbf{J}_n(y,z)$.

An example is shown in Fig. 11, where a normal end field is analysed. The gaps between septum and yoke have been neglected.

The positive current $\Delta J_p(y,z)$ will in effect

- increase the positive main field inside the magnet, and
- render the negative fringe field in front of the septum even more negative.

![Fig. 11 Analytical break-up of the end field](image-url)
The negative current $\Delta J(y,z)$ will do the opposite and thus
- decrease the end field, and
- increase the fringe field to large positive values.

The actual fringe field is shown in Fig. 12.

Fig. 12  The fringing field, shown qualitatively

Theoretically it is quite possible to calculate the current distributions $J(y,z)$, $J(y,z)_{\text{ideal}}$, $\Delta J(y,z)$, and $\Delta J(y,z)$, and to calculate a first-order three-dimensional magnetic field near the septum using the law of Biot and Savart.

4.5 Recapitulation and field perturbations in general

All formulae hitherto derived are listed in the table of Fig. 13. The main field in the septum magnet is thus given by

$$B(x) = B_{\text{id}} + \sum B_{\text{source}} F \left( \frac{x}{h} \right) ,$$

(37)

where the field in the ideal magnet $B_{\text{id}}$ is given by

$$B_{\text{id}} = \frac{I_e}{h} I_{\text{eff}} ,$$

(38)

and the perturbations are represented by the summation. The effective current $I_{\text{eff}}$ is equal to $I$ or $I-\Delta I$ depending on the kind of perturbation under consideration.

This method of rapid calculation, using source functions and form factors which allow algebraic summation of the various effects, may also be applied to the main field of a window-frame magnet.
The basic assumption is that the perturbations are small and the method fails in case of strong saturation. The main purpose of this theory is to enable the magnet constructor or magnet designer to form a mental picture of the various effects by applying the idea of positive and negative perturbation currents.

![Diagram](image)

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Main field $B(x)$</th>
<th>Perturbation $B_{source}$</th>
<th>$E(x)$ ( \frac{\text{N}}{\text{m}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal magnet</td>
<td>$B(x) = B_{id} + \frac{\mu_s}{\mu_r} I$</td>
<td>$B_{rel} = -k(x) \frac{\mu_s}{\mu_r} I$</td>
<td>0</td>
</tr>
<tr>
<td>Ideal magnet</td>
<td>$B(x) = B_{id} + \left( B_{rem} \text{ or } B_{rel} \right)$ ( and \ I_{eff} = I )</td>
<td>$B_{rem} = \frac{\mu_s}{\mu_r}</td>
<td>H_c</td>
</tr>
<tr>
<td>Id. magn. back-leg parallel to inner</td>
<td>$B(x) = B_{id} + B_{rel} + B_{bleg}$ ( and \ I_{eff} = I )</td>
<td>$B_{bleg} = \frac{\mu_s}{\mu_r} \Delta I$, compensation</td>
<td>A</td>
</tr>
<tr>
<td>Id. magn. back-leg parallel to septum</td>
<td>$B(x) = B_{id} + B_{rel} + B_{sleg}$ ( and \ I_{eff} = I - \Delta I )</td>
<td>if $\Delta I = \frac{\mu_s}{\mu_r}</td>
<td>H_c</td>
</tr>
<tr>
<td>Id. magn. comp. coil for $B_{rem}$</td>
<td>$B(x) = B_{id} + B_{rel} + B_{comp}$ ( and \ I_{eff} = I )</td>
<td>$B_{comp} = -\frac{\mu_s}{\mu_r} \Delta I$, compensation</td>
<td>A</td>
</tr>
<tr>
<td>Id. magn. comp. coil for $B_{rel}$</td>
<td>$B(x) = B_{id} + B_{rel} + B_{comp}$ ( and \ I_{eff} = I )</td>
<td>if $\Delta I = \frac{\mu_s}{\mu_r}</td>
<td>H_c</td>
</tr>
<tr>
<td>Imperfect magnet</td>
<td>$B(x) = B_{id} + B_{rel} \left( B_{-centr}(\text{sept}) \text{ or } B_{-centr}(\text{inner}) \right)$</td>
<td>$B_{centr}(\text{sept}) = \frac{\mu_s}{\mu_r} B(0)$</td>
<td>B</td>
</tr>
<tr>
<td>Id. magn. sept. with noses or vert. ext.</td>
<td>$B(x) = B_{id} + B_{rel} + B_{corr}$ ( and \ I_{eff} = I - \Delta I )</td>
<td>$B_{centr}(\text{inner}) = 2 \frac{\mu_s}{\mu_r} B(0)$, exact compensation not possible</td>
<td>0</td>
</tr>
</tbody>
</table>

---

Fig. 13  Listing of the derived formulae
APPENDIX I

PLANE TWO-DIMENSIONAL CURRENT-SHEETS OF FINITE THICKNESS

Consider the magnetized cavity, as shown in Figs. 1 and 14a, which is terminated by a current-sheet of thickness d. The magnetic field cut-off is thus obtained by using the electrical analogue of the cavity, scale one-to-one.

In any y,z-plane, \( x \leq 0 \), the magnetic field density \( \mathbf{B}(y,z) \) is given by

\[
B_y = \frac{\partial A_x}{\partial z}, \quad B_z = -\frac{\partial A_x}{\partial y}, \quad B_x = 0, \quad \frac{\partial \mathbf{B}}{\partial x} = 0. \tag{Al.1}
\]

The x-component of the vector potential \( A_x \) is calculated by integrating the Poisson equation

\[
\frac{\partial^2 A_x}{\partial y^2} + \frac{\partial^2 A_x}{\partial z^2} = -\frac{\rho j_x}{4\pi}, \tag{Al.2}
\]

where \( j_x \) is the current density in the current source and drain. Hence it follows that

\[
A_x = \frac{\mu_0}{4\pi} \oint_F \frac{j_x \, d\mathbf{F}}{r}, \tag{Al.3}
\]

where the vector potential of point \((y,z)\) is obtained by integrating over the whole surface \(F\) which lies in the y,z-plane. The distance between \((y,z)\) and surface element \(d\mathbf{F}\) is denoted by \(r\). In a similar way, the components of the current density \( \mathbf{j} \) in the region \( 0 \leq x \leq d \) are given by

\[
j_y = -\frac{1}{\rho} \frac{\partial \phi}{\partial y}, \quad j_z = -\frac{1}{\rho} \frac{\partial \phi}{\partial z}, \quad \text{div} \mathbf{j} = 0, \tag{Al.4}
\]

where \( \rho \) is the resistivity of the current sheet and \( \phi \) is the scalar potential.

The assumption is made that in the current source and drain the current density falls-off linearly as shown in Fig. 14a, or mathematically

\[
\frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = -\frac{\rho j_x}{4\pi d}. \tag{Al.5}
\]

From Eqs. (Al.4) and (Al.5) it then follows that

\[
\frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = -\frac{\rho j_x}{d}. \tag{Al.6}
\]

Integrating Eq. (Al.6) yields

\[
\phi = -\frac{\rho}{4\pi d} \oint_F \frac{j_x \, d\mathbf{F}}{r}. \tag{Al.7}
\]

Under suitable boundary conditions, Eqs. (Al.3) and (Al.7) lead to the condition

\[
\frac{A_x}{\mu_0} = \frac{\rho d}{\mu_0}, \tag{Al.8}
\]

and Eq. (Al.4) may be written as

\[
j_y = -\frac{1}{\mu_0 d} \frac{\partial A_x}{\partial y}, \quad j_z = -\frac{1}{\mu_0 d} \frac{\partial A_x}{\partial z}. \tag{Al.9}
\]
a) Magnetized cavity terminated by a current-sheet  
b) Elementary surface in a thick current-sheet

Fig. 14

With Eq. (A1.1) and using $B_x(0)$ instead of $B_x$ to distinguish between the regions $x < 0$ and $x > 0$,

$$\begin{align*}
    j_y &= + \frac{B_x(0)}{\mu_0 d}, \quad j_z = - \frac{B_x(0)}{\mu_0 d} \\
    \text{(A1.10)}
\end{align*}$$

Thin current-sheets

For thin current-sheets it is easy to demonstrate that $B \equiv 0$ at $x \geq d$.

For a thin current-sheet the line current $J$ is equal to thickness times the current density, or

$$J = d \bar{j}. \quad \text{(A1.11)}$$

Since

$$\text{Curl } \bar{B} = \mu_0 J \quad \text{(A1.12)}$$

which, using Eqs. (A1.10) and (A1.11), may be written explicitly as (see Fig. 10a),

$$\begin{align*}
    \text{Curl } \bar{B} &= \bar{\eta} \times (\bar{y}_B J_y + \bar{z}_B J_z) \\
    &= \mu_0 \bar{\eta} \times (- \bar{y}_2 J_z + \bar{z}_2 J_y) \\
    &= \mu_0 (\bar{z}_2 J_z + \bar{y}_2 J_y) \\
    &= \mu_0 J, \quad \text{(A1.13)}
\end{align*}$$

where $\bar{y}_2$ and $\bar{z}_2$ are the unit vectors in the $y$- and $z$-direction.

The magnetic field at $x \leq 0$ satisfies condition (A1.12) everywhere; this implies that the field density at $x > d$ vanishes.
Thick current-sheets

For thick current-sheets the same property, namely that \( B = 0 \) at \( x \geq d \), holds, and may be shown in the following way.

Consider the thick current-sheet as consisting of a superposition of elementary current-sheets each of thickness \( dx \) (see Fig. 14b), and that in each current-sheet there is a line current density \( J \) where

\[
J = dx \left( \bar{y}_{oJ} + \bar{z}_{oJ} \right).
\]

(Al.14)

Consider now a surface element \( dy \, dz \) of an elementary current-sheet for which the following formulae are valid:

\[
\text{Curl} \, \mathbf{B} = \mu_e \, J
\]

(Al.15)

\[
\mathbf{B} = \left[ \bar{y}_{oB} B_{yo} + \bar{z}_{oB} B_{z0} \right] \times
\]

from which it follows that, using (Al.10),

\[
\frac{3B_x}{3x} = - \mu_0 J_y = - \frac{B_z(0)}{d}, \quad \frac{3B_y}{3x} = \mu_0 J_z = - \frac{3B_x(0)}{d}.
\]

(Al.16)

Thus

\[
B_x(d) = B_x(0) + \int_0^d \frac{3B_y}{3x} \, dx = 0 \quad \text{and} \quad B_z(d) = 0.
\]

(Al.17)

(Al.18)

Hence in the current-sheet \( \mathbf{B} \) has a negative gradient in the \( x \)-direction and vanishes at \( x = d \).

**Boundary conditions**

For static magnetic fields and assuming a boundary parallel to the \( y \)-axis without loss of validity (Fig. 15a):

\[
B_x(\text{air}) = B_x(\text{iron}).
\]

(Al.19)

\[
B_y(\text{air}) = \frac{1}{\mu_F} B_y(\text{iron}).
\]

(Al.20)

![Fig. 15](image_url)

a) Boundary between two magnetic media  \quad b) Boundary between two electrical media
where \( B_z \) and \( B_y \) are the normal and tangential components, respectively. If \( \alpha \) is the angle of refraction,

\[
\frac{\tan \alpha_{\text{air}}}{\tan \alpha_{\text{iron}}} = \frac{1}{\mu_{\text{Fe}}},
\]

where for \( \mu = \infty \) the angle of refraction \( \alpha_{\text{air}} = \pi/2 \).

The corresponding electrical problem is a boundary between two current-sheets of different electrical conductivity, \( \rho(\text{air}) \) and \( \rho(\text{iron}) \) (Fig. 15b):

\[
j_\parallel(\text{air}) = j_\parallel(\text{iron}),
\]

\[
\rho(\text{air}) j_\parallel(\text{air}) = \rho(\text{iron}) j_\parallel(\text{iron})
\]

\[
\frac{\tan \beta(\text{air})}{\tan \beta(\text{iron})} = \frac{\rho(\text{iron})}{\rho(\text{air})}.
\]

In order to match boundary conditions and keeping in mind that \( \mathbf{B} \) and \( \mathbf{J} \) are orthogonal,

\[
\alpha + \beta = \frac{\pi}{2},
\]

\[
\frac{\tan \alpha_{\text{air}}}{\tan \alpha_{\text{iron}}} = \frac{1}{\mu_{\text{Fe}}} = \frac{\rho(\text{air})}{\rho(\text{iron})}.
\]

If the current-sheet is insulated and is made of copper,

\[
\rho(\text{air}) = \rho_{\text{Cu}} = 1.8 \times 10^{-2} \, \Omega \text{m}.
\]

\[
\rho(\text{iron}) = \infty.
\]

Following Eq. (A1.26) this corresponds to the case where \( \mu_{\text{Fe}} = \infty \).

In the case of unsaturated yokes, \( \mu_{\text{Fe}} \geq 10^5 \), and to a good approximation Eq. (A1.25) holds. In order to avoid saturation, the boundary should be as smooth as possible, and large radii should be provided where the current connections are made, as shown in Fig. 3b.

In the case of strong saturation, the current-sheet should be constructed of two different materials, or of the same material but with two different thicknesses.
APPENDIX 2

DERIVATION OF THE FORM FACTORS OF FIG. 16

Curve A

The form factor $F(x/h)$ represented by curve A, Fig. 16, has been obtained by applying the Schwartz-Christoffel transformation to a magnet gap with rectangular corners, as shown in Fig. 13, and unit potential jump between the upper pole face and the median plane. The field density $B(x)$ is then implicitly given by

$$
\frac{x}{h} = \frac{1}{\pi} \left( \frac{B(x)}{B_{\text{source}}} - \frac{1}{2} \ln \left\{ 1 + \left[ \frac{B(x)}{B_{\text{source}}} \right] \right\} \right) .
$$

(A2.1)

In the asymptotic case where

$$
\frac{B(x)}{B_{\text{source}}} \ll 1 ,
$$

Eq. (A2.1) reduces to

$$
F \left( \frac{x}{h} \right) = \frac{B(x)}{B_{\text{source}}} = \frac{h}{\pi x} .
$$

(A2.2)

The accuracy of the latter equation is better than 4\% for $x/h > 2.0$ and better than 1\% for $x/h > 3.0$.

Fig. 16 Form factors $F(x/h)$
Curve B

The field density has been calculated in front of a thin, current-carrying strip of thickness $t$ and total height $h_s$ (Fig. 17a). The field density in the median plane is then given by

$$B(x) = \frac{\mu_0 I}{\pi} \tan^{-1} \frac{h_s}{2x},$$

(A2.3)

from which it follows that

$$F\left(\frac{x}{h}\right) = \frac{B(x)}{B_{source}} = \frac{2}{\pi} \tan^{-1} \frac{h_s}{2x}.$$  

(A2.4)

Calculations show that a reasonable value for $h_s$ is

$$h_s = 0.2h \quad 0 < x < h,$$

(A2.5)

hence

$$F\left(\frac{x}{h}\right) = \frac{2}{\pi} \tan^{-1} \frac{h}{10x}.$$  

(A2.6)

This function is shown in Fig. 16, curve B. The strength is given by Eq. (24) and Eq. (A2.3) at $x = 0$:

$$B_{source} = \frac{\mu_0 I}{h} \cdot \frac{gt}{A_{Cu}}.$$  

(A2.7)

---

(a) Calculation of magnetic field in front of a thin current-sheet

(b) Calculation of magnetic field in front of a thick current-sheet

Fig. 17
If the cooling ducts are arranged vertically, the septum may be considered as consisting of two current-sheets, placed a distance $t$ apart from each other, carrying half the surface current. The form factor then becomes

$$ F\left(\frac{x}{h}\right) = \frac{2}{\pi} \left[ \tan^{-1} \frac{h}{10x} + \tan^{-1} \frac{h}{10(x+t)} \right]. \quad (A2.8) $$

This function can be evaluated, using curve B. The source strength follows from Eqs. (A2.7) and (A2.8):

$$ B_{\text{source}} = \frac{\mu_0 I}{2h} \cdot \frac{gt}{A_{Cu}} \left[ 1 + \frac{2}{\pi} \tan^{-1} \frac{h}{10t} \right]. \quad (A2.9) $$

In the case where the septum is thick and $t \approx h$, the thick current-sheet formula should be applied (see Fig. 17b):

$$ B = \frac{\mu_0 I}{h} \cdot \frac{g}{A_{Cu}} \frac{2}{\pi} \left\{ (x+t) \tan^{-1} \left[ \frac{h_s}{2(x+t)} \right] - x \tan^{-1} \left[ \frac{h_s}{2x} \right] + \frac{1}{4h_s} \ln \left[ 1 + 4t \frac{8x + t}{4x^2 + h_s^2} \right] \right\}. \quad (A2.10) $$
THEORETICAL CALCULATION OF THE PARALLEL CURRENT
IN A LAMINATED YOKE

Holmes\textsuperscript{38} has calculated the parallel current in the yoke for the ideal case where the
laminations are perfectly electrically insulated from each other and the septum is in uni-
form contact with the laminations which are assumed to touch the septum on two sides:

\[ I_{\text{parallel}} = \frac{\tau p l_2 A_{\text{col}}}{\delta^{(\text{iron})}} I. \]  \hspace{2cm} (A3.1)

Quite generally it is found that

\[ I_{\text{parallel}} \approx 0.01 I. \]  \hspace{2cm} (A3.2)

In most cases this current is sufficiently weak to have negligible effects on the fringing
field.
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Electrostatic septa


Thin septum magnets *


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