

END EFFECT CORRECTIONS IN A SHORT LAMBERTSON SEPTUM MAGNET*

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Abstract

A short magnet of the Lambertson type, to be used to add a forty milliradian angular separation to beam paths differing by a few millimeters as part of a beam splitting system at IUCF, is described. Magnetic measurements made on a prototype of this magnet showed that a significant beam deflection would occur on the nominally field-free path because of fields wrapping over the end of the split pole tip. This effect is not important in the longer magnets used to separate high energy beams. A cure for the difficulty, involving a combination of a projecting step on the tip and a field clamp, is described. The corrected ends produce a path-integrated field ratio greater than 300. Magnets of this type will be used for beam splitting at IUCF and for injection into the IUCF Cooler.

Introduction

Electric deflectors, in which a high electric field is applied normal to one face of a thin conducting septum, have been used since beams were first extracted from circular accelerators¹. A current-carrying magnetic septum, with a high current density parallel to the beam direction, is a second common device for increasing the physical separation of closely-spaced particle beams. Both of these devices produce a force which differs for two beams passing on either side of the septum. The direction of the force is normal to the septum. The two beams experience a relative deflection in the plane of their initial separation which can be used to increase (or decrease) their spatial separation. In application to injection or extraction of beams in circular accelerators, one of the beam paths would correspond to an internal (stably-confined) orbit and the other to an external beam, entering or leaving the machine.

An alternative device which requires neither high electric field strength nor high current density in order to effect an increase of spatial separation of two closely-spaced particle beams is the Lambertson septum magnet. This device was apparently first proposed as part of the Berkeley 200 BeV design study² and has been used, for example³, in extraction from the FNAL main ring synchrotron. The basic concept is illustrated in Figure 1. A magnetic field perpendicular to the direction of separation of the two beams passes through one beam, giving a force perpendicular to the direction of separation. The field then enters a split steel pole tip where it is guided by the steel to pass on either side of the second beam path. The second beam thus experiences little or no force during its passage through the magnet.

The strength of the deflecting field is lower than the field at which the tip material would experience appreciable saturation by the sine of the bevel angle. A field in the gap of 1 Tesla, with an angle of 45°, gives a field in the split tip of $\sqrt{2}$ Tesla, low enough, for ordinary magnet steel, that the H field in the tip results in a leakage field in the nominally field-free region of the order of a milliTesla or less.

A force acting perpendicular to the initial separation appears awkward at first glance, making all applications three-dimensional. The great advantage in terms of strength of the applied force, and in the simplicity and compactness of the Lambertson septum magnet make it attractive for many uses. Combinations of two or more such devices can be used to cancel the out-of-plane deflection. Often a small displacement of one beam plane relative to the plane of the other causes no serious problem in comparison to the design difficulties of high electric field or high current devices.

The septum is vanishingly thin at a single point. The questions of the effective thickness, and of the leakage field in a typical application, are addressed below.

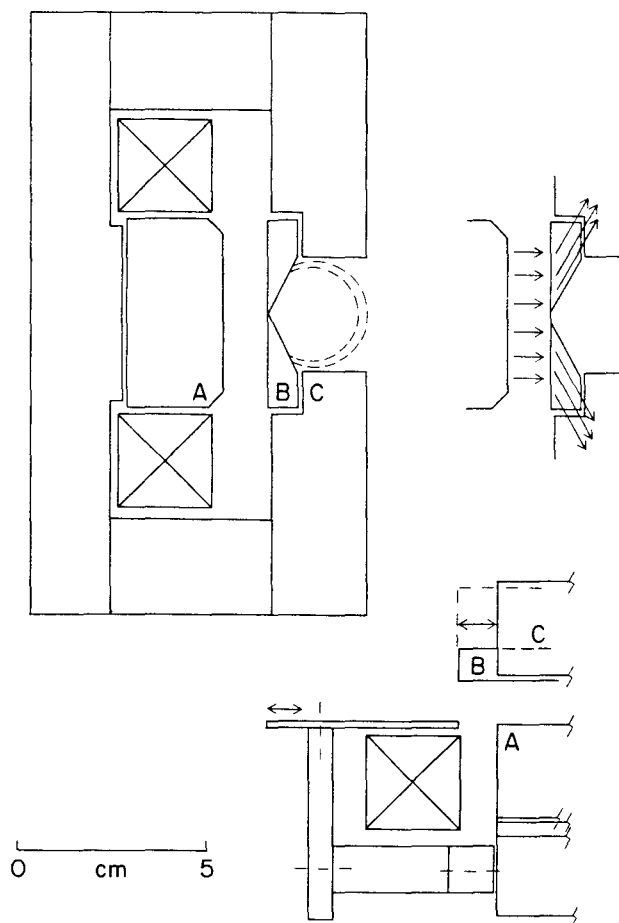


Figure 1. Sketch showing an example of a Lambertson septum magnet. The high field in the 1 cm gap to the left of the septum is about 0.4 Tesla. The length is 0.21 m. The cylindrical shield was added after mapping to reduce the field along the low field path (see text). The end detail shows the field clamp and projection of the septum pieces to reduce the end field as discussed below.

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Effective Septum Thickness

We can characterize a beam envelope by two transverse emittances ϵ_x and ϵ_y , by a momentum half-width $\delta = \Delta p/p$, by the dispersions η_x and η_y , and by the aperture functions β_x and β_y . We assume for simplicity two parallel beams, labelled 1 and 2, matched by having identical dispersions and aperture functions, but not necessarily equal emittances or momentum spreads. The beam centers are separated by a distance s_x at a double waist (a region of minimum β_x and β_y), where the septum magnet is to be placed.

The condition that the two beams not overlap at the waist position is:

$$s_x \geq (\beta_{x1}\epsilon_x/\pi)^{1/2} + (\beta_{x2}\epsilon_x/\pi)^{1/2} + \eta_x(\delta_{x1} + \delta_{x2})$$

This is a minimum value. A larger separation would be required to permit the insertion of a physical septum of finite thickness, or to allow for an alignment tolerance or a departure of the septum shape from the shape of the particle path.

Because the aperture function β increases as one moves along the beam path a distance z away from a waist according to:

$$\beta = \beta_w + z^2/\beta_w, \text{ where } \beta_w \text{ is the value at the waist,}$$

the beam separation must be increased to make room for a septum of finite length. This means that the necessary separation at the waist may have to be larger than would be expected from the physical dimensions of the septum, and that a short, strong field septum magnet with a septum of non-vanishing thickness may require a smaller initial beam separation than a longer, weaker-field device.

We can define an effective septum thickness as the minimum increase in beam separation necessary to allow the insertion of a septum of finite length.

Because of the characteristic double wedge-shape of the Lambertson septum, the beam dimension perpendicular to the separation affects the minimum spacing. The wedge angle also determines the ratio of tip field to gap field and hence the saturation limit to the strength of the separating force.

A sample geometry is illustrated in Figure 2. The only dispersion in this example lies in the plane of initial separation x . The separating force has only a y component.

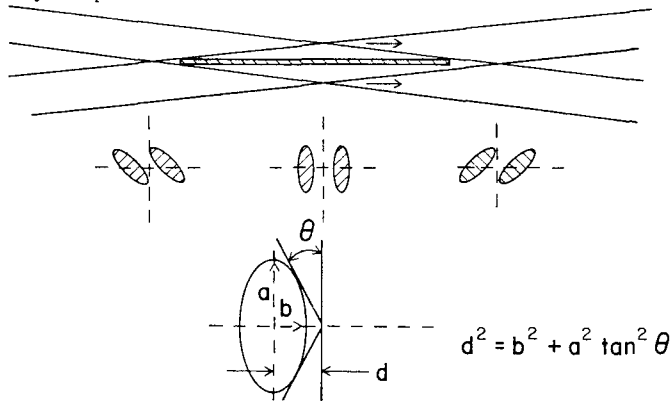


Figure 2a. The effective septum thickness for a long septum depends on the divergence at the beam waist.

Figure 2b. A typical geometry illustrating the relation between beam envelope, the initial beam separation, and the effective septum thickness for a Lambertson septum.

Strength Comparison

The initial separation of beams at the location of the septum is often difficult to arrange, so that small changes in effective septum thickness can have appreciable economic consequences. For example in a cyclotron the turn spacing for clean single turn extraction often determines the rf power level. It is therefore of interest to try to establish the energy regime in which the Lambertson geometry has a distinct advantage over electrostatic or current-carrying septa.

As an example, consider the internal beam in the IUCF main cyclotron. The minimum bend θ_{min} is fixed by the distance to, and properties of, the next extraction element. The approximate values of the beam parameters are:

$\epsilon_x = 2\pi$ mm mrad	$\epsilon_y = 2\pi$ mm mrad
$\beta_x = 2$ m	$\beta_y = 3$ m
$\eta_x = 2$ m	$\eta_y = 0$
$\delta = 0.03\%$	$B\rho_B = 2.2$ T-m
$\theta_{min} = 20$ mrad	$E_{pE} = 350$ MV

An electrostatic deflector is seen to require a gap of about 6 mm and a length of about 1.2 m to keep the electric field below 10 MV/m. The effective septum thickness in this case is about 0.2 mm which is a small contribution to the minimum turn separation required.

Now we repeat the argument at a beam splitter⁴ location. There is no change in beam rigidity, momentum spread or emittance. The changed values are:

$$\beta_x = 0.01 \text{ m, } \beta_y = 10 \text{ m, } \eta_x = 4 \text{ m, } \theta_{min} = 40 \text{ mrad.}$$

The split point is at the output of a beam energy analysis system and therefore has a large value of the resolving power parameter η_x/β_x . An electric deflector is impractically strong for the necessary deflection at this point, as can be seen from the following table. An E.V product larger than 1-2 MV²/m is apt to cause voltage holding difficulties in vacuum. The effective septum thickness is not small compared to the minimum beam separation.

Table 1. Electrostatic deflector at low β point.

Septum Length (m)	Electric Field (MV/m)	Gap (mm)	Voltage (MV)	E.V Product (MV) ² /m	Effective Septum Thickness
.2	70	5	.35	20	2.8 mm
.6	23	11	.25	6	8.4
1.0	14	17	.24	4	14.

A current-carrying septum magnet of length 0.2 m at the same split point would require a field of about 0.5 Tesla and for a current sheet made of 5 x 5 mm conductor, the current required would be 2000 Amp (8000 Amp/cm²). The effective septum thickness would be about 8 mm. Doubling the magnet length does not help reduce either the current density or the effective septum thickness.

The Lambertson magnet shown in Figure 1 is designed to operate at this split point, and has no difficulty providing the necessary bend. Power consumption and current are both quite low. The effective septum thickness is about 3 mm, a value small enough to make possible a radiofrequency time-sharing of the IUCF beam by means of a resonant ferrite deflector located upstream of the split point.

End Effects in the Lambertson Septum Magnet

For a very long magnet, it is only necessary to arrange that the magnetic fields in the interior have the desired properties. The end effects become increasingly important if the gap is not negligible in relation to the length. For the application discussed above, we find a regime at intermediate energies where an electrostatic septum device becomes uncomfortably long or unrealistically strong, while a Lambertson septum magnet can be quite short and simple.

A prototype of the magnet shown in Figure 1 was built and its magnetic field was measured. The field in the high field gap region was unremarkable in its properties and will not be further discussed. The field in the supposedly field-free region was far from zero when the mapping began. It is the purpose of this section to discuss the properties of the design which led to an imperfect screening and the steps taken to improve the design, and to show the best ratio between high and low field deflection which was achieved.

The first design difficulty arose from the small gap introduced between the septum and the adjacent return piece. The gap was added to make it possible to insert a stainless steel vacuum foil at this location. The result was an appreciable magnetic potential difference between the side wall and the V-shaped bottom of the low field region. The potential led to an appreciable field strength everywhere in the low field region. The field is much smaller without the foil gap.

To permit the foil gap to be used, a cylindrical shield was added surrounding the low field path and mated to the septum pieces. This cylinder did not touch the side walls, and formed a nearly equipotential screen to isolate the low field region from the different potential of the side walls. The effect was a decrease in the field strength in the interior from 6% of the gap field to below 1%, as shown in Figure 3b.

The second, more fundamental difficulty with the short Lambertson design is illustrated in Figure 3a which is a field scan of the transverse field measured as a function of length along the magnet axis. It is clear that there is a large field in the end region, reaching a maximum value of about 15% of the gap field. The integrated effect over the two ends gives a beam deflection which is about 2% of the gap field deflection.

An improvement was obtained by adding the adjustable field clamp shown in Figure 1b, which covered much of the coil and extended to within about one gap of the solid tip. This distance must be great enough that the clamp does not saturate. The end field width and magnitude are reduced as seen in Figure 3b.

The original design had the septum pieces and the facing pole tip of equal length. The explanation of the end field remaining is that the screening of the low field region by the septum stops abruptly at the physical end of the septum, whereas the gap field continues to be strong for about half a gap beyond the end of the tip. The flux through the end region must return to the septum in some manner, and chooses to do so by looping over the end and entering the septum from the back side. This explanation also accounts for the reversal seen on the interior side of the field excursion in Figure 3a.

The explanation was tested by shifting the location of the cylindrical shield discussed above and the septum pieces so that they all extended beyond the solid tip by about 1/2 gap. The improvement to the end effect is shown in Figure 3c. The shield removes the

undershoot by providing an alternate path for the flux looping over the end, while extending the septum and shield together reduces both the magnitude of the field excursion and its width.

The best compromise is shown in Figure 3c. The magnitude of the end field is reduced to less than $\pm 2\%$ of the gap field, while the positive and negative excursions cancel to an integrated level of about 0.15%. The position of the clamp and protruding septum has been adjusted so that the flux lines divide between the extended septum and the clamp, leaving very little flux to find its way into the low field region.

Summary

A Lambertson magnet offers an attractive alternative to electric field or current-carrying septa, especially at energies where the electric devices become too long. The short Lambertson magnet has some significant end field errors. These can be corrected by extending the septum and adding an appropriate field clamp. The corrected magnet can have a ratio between deflection angles for beams passing through the high and low field regions of at least 600 for a magnet of 20 gaps length.

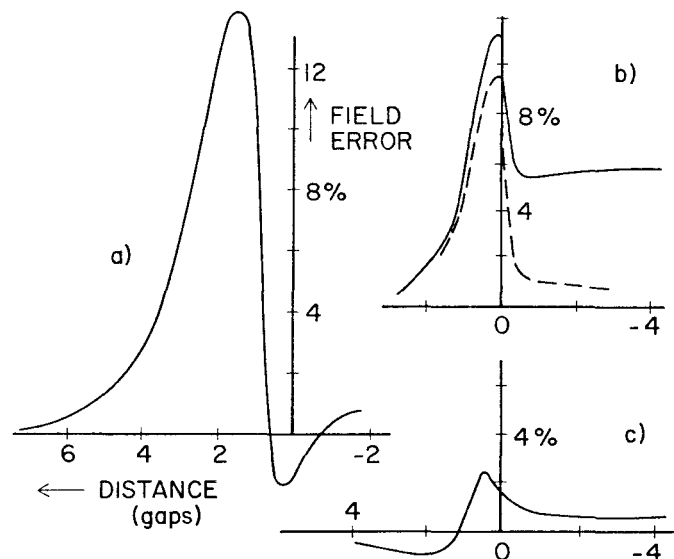


Figure 3a. Field measured along a path through the low field region for the uncorrected magnet. Field strength is given as a percentage of the field in the main gap.

Figure 3b. The field clamp has reduced the width and magnitude of the end field excursion. The effect of the cylindrical shield in reducing the interior error field caused by the vacuum foil gap is also shown.

Figure 3c. The final design with protruding septum, shield and field clamp positions adjusted to minimize deflection along the path to 0.15% of gap deflection.

References

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