Chapter 10.
The Superconducting Inflector

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10.1. Introduction

The inflection of a particle beam into a storage ring is usually done with a pulsed magnetic inflector, which locally cancels the field of the main magnet, so that the beam enters the storage region as close as possible, and almost tangent to the equilibrium orbit of the ring. Further manipulation of the beam with a full aperture kicker would assure the permanent acceptance or storage of the inflected beam. A problem with a pulsed inflector is the persistence of the magnetic stray fields. In the third CERN $(g-2)$ experiment, a coaxial structure pulsed inflector was used. The skin depth of the copper determines the initial magnitude of the pulse which propagates as a wave away from the device. In the storage region, the fringe field from the pulsed inflector is several hundred gauss at 1 μs and decreases to about 20 gauss at 600 μs, the time when data collection ends.

Fig. 10.1.1 shows the cross section of the CERN device, and Fig. 10.1.2 shows the time dependent fringe field pattern.

In the present experiment (E821), the injected beam is pulsed up to 12 bunches per AGS cycle (It may be changed to 8 bunches). The AGS cycle is from 1.4 seconds to 3 seconds depending on the extraction mode used for sharing protons between E821 and the rest of the physics program. Ideally, when the experiment is ready to collect data, all 12 (or 8) bunches in the AGS would be used, with as short a cycle time as possible. The major difficulty in using a variation of a CERN pulsed design is that CERN's device was pulsed only once per CERN PS cycle (2.3 seconds); E821 would require up to 12 (or 8) times per AGS cycle. Extensive studies on a pulsed inflector for E821 were carried out, including material heating-stress, solid state switches and ignitrons [1]. The study concluded that a pulsed inflector for E821 would be very difficult to accomplish.

A direct current non-ferrous superconducting septum magnet may overcome the above problems. It will be shown that current distributions and their combinations can be used to reduce the fringe field. The integrated fringe field will be dominated by the end of the septum near the storage area, but it allows at least static shimming and precise

Figure 10.1.1: The CERN Inflector

measurement of the numerical correction to be applied. Since the cross section of the inflector is constrained by the limited space between the muon storage region and the superconducting coils of the storage ring magnet, it is impossible to make the field near zero everywhere along the injection trajectory. An optimum path has been selected to minimize the amount of inflector aperture used up by this curvature in a straight channel[2].

The requirements of the DC $(g-2)$ inflector are: (1) to produce a homogeneous dipole magnetic field 1.5 T over the length of 1.7 m, in order to essentially cancel the integrated fringe field of the storage ring; (2) to keep its own stray field low enough and acceptable for the magnetostatic shimming.

The conceptual design of the inflector was completed by Boston University; detailed design and construction have been carried out by Boston, BNL, and Japan KEK.

Figure 10.1.2: The Time Dependent Fringe Field From the CERN Inflector

10.2. Design Principle

10.2.1. Double Cosine Theta Distribution

The Magnetic configuration for the device is developed from the well known cosine theta distribution of surface current, where in cylindrical coordinates at a certain radius R, a surface current K is applied, which is modulated according to

$$K = \hat{K} \cos(N\theta) \tag{10.2.1}$$

$\hat{K}$ is the amplitude of the distribution of dimension A/m, θ is the polar angle and N is an integer. N = 1 creates a pure dipole field inside the circle of radius R, N = 2 creates a pure quadrupole, and so on. Since K does not depend on the axial coordinate, the magnetic field is two-dimensional, so that one can introduce profitably complex potentials which depend on the variable z = x + iy. For instance, the vector potential $\vec{A}$ has a single component A(x,y) pointing in the axial direction. Thus we would write for N = 1:

$$A^{int} = -\left(\mu_o \hat{K} R/2\right)(\mathrm{x}/R) = -\left(\mu_o \hat{K} R/2\right) \; R_e\,(z/R) \qquad |z| < R \quad (10.2.2)$$

$$A^{ext} = -\left(\mu_o \hat{K} R/2\right)(\mathrm{x}R) / \left(\mathrm{x}^2 + y^2\right) = -\left(\mu_o \hat{K} R/2\right) R_e\,(R/z) \qquad |z| > R \quad (10.2.3)$$

The complex potential of this system would be:

$$\zeta^{int} = A^{int} - iG^{int} = -\left(\mu_o \hat{K} R/2\right)(z/R) \qquad |z| < R \qquad (10.2.4)$$

$$\zeta^{ext} = A^{ext} - iG^{ext} = -\left(\mu_o \hat{K} R/2\right)(R/z) \qquad |z| > R \qquad (10.2.5)$$

where the imaginary part of ζ, G, is the current related potential. Magnetic flux lines follow lines of constant A, which close upon themselves, whereas lines of constant G, which are orthogonal to those of A, provide the direction of the force on axial current elements. Lines of constant G are discontinuous on current boundaries in magnitude and direction and are most useful to lump in optimal fashion a distribution of surface currents into a distribution of line currents, making thereby the device physically realizable.

10.2.2. Truncation

One may modify the shape of the useful volume if a circle (or ellipse) on which the surface current is projected, does not satisfy the geometrical requirements. Charged particle beams may require a channel which is narrow but quite high. In this case one uses only part of the field plot associated with the $\cos\theta$ distribution, i.e., the field is truncated. The truncation is invariably along a line of constant A. On this line can be projected a surface distribution of current, which nullifies the field on the outside but leaves unaltered the field on the inside. The boundary condition in this case would be:

$$\vec{n} \times \vec{B}^{int} = -\mu_o \vec{K} \qquad (10.2.6)$$

$\vec{n}$ is the outward unit vector normal to the truncation, $\vec{B}^{int}$ is the flux density on the inside of the truncation and $\vec{K}$ is the surface current density on the truncation.

Fig. 10.2.1(a) shows the principle for a dipole septum (upper half). The cosine theta distribution is now limited to the circle segment 1. The truncation consists of a straight line segment 2, the septum, on which the current density is K/2, or half the amplitude of the cosine distribution on segment 1. The septum boundary is closed by the circle segment 3, on which the surface current density equals $|B|/\mu_o$. The useful dipole field is contained in the area between 1 and 2, the dead space (for return flux) is between 1 and 3, and the

Figure 10.2.1: The Principle of the Truncated Double Cosine Theta Septum Magnet

area outside 2 and 3 is field free. The total current in 1 is opposite and equal to the sum of the currents on 2 and 3.

The truncated DOUBLE cosine theta septum has the purpose to reduce drastically the dead space encountered in a single cosine theta distribution. To this end we consider the magnetic field produced by two concentric cosine theta distributions, $(\hat{K}, R)$ and $(\hat{K}', R')$, creating three regions where the potential differs:

$$\zeta_1 = -\left(\mu_o \hat{K} R/2\right)(z/R) - \left(\mu_o \hat{K}' R'/2\right)(z/R') \qquad |z| < R \tag{10.2.7}$$

$$\zeta_2 = -\left(\mu_o \hat{K} R/2\right)(R/z) - \left(\mu_o \hat{K}' R'/2\right)(z/R') \qquad R < |z| < R' \tag{10.2.8}$$

$$\zeta_3 = -\left(\mu_o \hat{K} R/2\right)(R/z) - \left(\mu_o \hat{K}' R'/2\right)(R'/z) \qquad |z| > R' \tag{10.2.9}$$

It is noticed that under circumstances ζ_1 may be made zero, creating a field free region inside R. Likewise one may find the condition for which ζ_3 is zero, creating a field free region outside R'. Useful as this may be for certain applications, the objective here is to reduce the overall size of the dipole septum. In the case of Fig. 10.2.1(a), we have the relation $pq - R^2 = 0$, in which p is the distance from origin to septum, measured on the x-axis, and q is the distance from origin to boundary 3, also measured on the x-axis. Clearly, q can be quite large, dependent on the aspect ratio of the useful dipole region. But the double cosine theta distribution allows one to squeeze the return flux at will, albeit at the expense of more ampere turns for the same useful dipole strength. Fig. 10.2.1(b) shows an example, scaled to give the same useful dipole region as shown in Fig. 10.2.1(a), but a second virtual cosine theta distribution $K' = \hat{K}' \cos\theta$ is applied on circle 4 of radius $R' > R$. The dipole area has the boundary 5 and 6 and the area outside 6 and 7 is field free. The generating currents on 4 are virtual, since they are not physically present in the device. However 7 is uniquely determined by specifying K' in addition to K, R and p. Since boundary 7 follows a line of constant A, its value equals the potential of septum 6: $A_6 = A_7$, or:

$$A_6 = R_e\left(\zeta_1\right)_{\mathrm{x}=p} = -\frac{1}{2}\mu_o p\left(\hat{K} + \hat{K}'\right) \tag{10.2.10}$$

$$A_7 = R_e\left(\zeta_2\right) = -\left(\frac{1}{2}\mu_o \hat{K} R^2\right) \mathrm{x}/\left(\mathrm{x}^2 + y^2\right) - \left(\frac{1}{2}\mu_o \hat{K}'\right)\mathrm{x} \tag{10.2.11}$$

$$\hat{K} R^2 \mathrm{x}/\left(\mathrm{x}^2 + y^2\right) + \hat{K}'\mathrm{x} = \left(\hat{K} + \hat{K}'\right) p \tag{10.2.12}$$

$$\hat{K} R^2/q + \hat{K}' q = \left(\hat{K} + \hat{K}'\right) p \tag{10.2.13}$$

Eq. (10.2.12) is the equation for boundary 7 and Eq. (10.2.13) is the equation for the end point q. The parameters leading to the construction of Fig. 10.2.1(a) and Fig. 10.2.1(b) are shown in Table 10.3.1, in relative units.

It is noticed that the squeezing of the return flux by a factor of 2 in Fig. 10.2.1(b), reduced the dipole field by 10%. The equation for boundary 7 reads:

$$y^2 = 10\mathrm{x}/\left(\mathrm{x}+3\right) - \mathrm{x}^2 \tag{10.2.14}$$

Fig.	$\hat{K}$	$\hat{K}'$	R	p	q	B(dipole)
1	1	0	1	1/3	3	1
2	1	-0.1	1	1/3	2	0.9

Table 10.2.1: Relative Parameters of Fig. 10.2.1(a) and (b)

10.2.3. Line Currents

Assuming that the superconductors have a relatively small superconducting core, embedded in a much larger stabilizing matrix, the continuous surface current must be concentrated in what one could call a distribution of line currents. It will be shown how to determine the optimum location of each line current, and how to study the effect of the granularity on the quality of the dipole field, i.e., the amount of stray field adjacent to the septum.

The method consists of constructing an arithmetical series of the complex potential. The real part is constant and equals the value of A on the current boundary. The imaginary part of the series has a progression proportional to the current in the wire: $G_{j+1} - G_j = \pm\mu_o I$. Since $G = 0$ in the median plane, $y = 0$, the first G in the series would be $G_1 = 0$ for an odd number of turns and $G_1 = \mu I/2$ if the number of turns is even. Having established the series of ζ, one may solve for z. Fig. 10.2.1(c) shows an example. The cosine theta distribution segment 8 can be made discrete if the conductor density vs. y is constant, by virtue of the cosine law. One should preferably select an even number of layers, since the number of conductors on the septum 9 is somewhat less than half the number on 8. This ensures a reasonable and uniform packing density on the septum, where the conductors must be evenly spaced according to the relation

$$\zeta_1 = -\mu_o\left(\hat{K} + \hat{K}'\right)z/2 \tag{10.2.15}$$

The equation for ζ_2 applies to boundary 10. As this equation can be solved for z, and the discrete series of ζ_2 is known, the position of the conductors is:

$$z = \{-\zeta_2 \pm \left(\zeta_2^2 - \mu_o^2\hat{K}\hat{K}'R^2\right)^{\frac{1}{2}}\}/\left(\mu_o\hat{K}\right) \tag{10.2.16}$$

Figure 10.2.2: The Conductor Arrangement

The second root in the solution is due to the analytical continuation of G_2 and A_2.

Fig. 10.2.1(c) shows that near the intersect of boundary 8, 9 and 10, physical interference of some conductors could occur. These conductors must be deleted in a pairwise fashion as shown in Fig. 10.2.2. In the present example the cosine theta distribution lost one turn, so that the return conductors on the septum and the closing boundary should be reduced by one turn. In this case an enhancement of the stray field and impurity of the harmonic content of the dipole field may occur. Small perturbations of the position of adjacent conductors will reduce either enhancement.

Fig. 10.2.2 is the first version of the inflector. The parameters for this version are shown in Table 10.3.2, and the harmonic contents are shown in Table 10.3.3, which were calculated using an algorithm developed at Boston University[3].

Table 10.2.2: Preliminary Parameters of $(g-2)$ Inflector.

R = 50 mm	Number Turns = 50	B Dipole = 1.5 T
p = 15 mm	Number Cosine Wires I = 50	I/Wire = 5200A
q = 93 mm	Number Septum Wires II = 22	J= 550 A/mm^2
h = 61 mm	Number Rear Wires III = 28	Channel = 18x 45 mm
	K_1=2400 A/mm	$K_1{}' = -360$ A/mm

Table 10.2.3: Harmonic Expansion of the Inflector Field.

Order of Multipole	(a) Center of Pion Channel x = 30 mm, y = 0 R=12.5 mm	(b) Center of Muon Channel x = -45 mm, y = 0 R=50 mm	(c) Center of Pion Channel x = 30 mm, y = 0 R=80 mm
N	Na$_N$/R(gauss)	Na$_N$/R(gauss)	$\bar{\kappa}_N(A/m)$
1	-15064	1.1	0.5657E-02
2	-7.6	5.1	0.1092E-02
3	-0.5	6.7	-0.8858E-03
4	1.2	5.2	0.5153E-03
5	-0.1	2.2	0.5031E-02
6	-0.3	-0.6	-0.1320E-02
7	0.6	-2.1	-0.2269E-02
8	-1.3	-2.3	0.1154E-02

10.3. Physical Realization

After August 1989, a new $(g-2)$ inflector was designed in order to accommodate an existing superconductor, to be supplied by Japan KEK. This conductor has been fully developed for the ASTROMAG (Particle Astrophysics Magnet Facility) project and therefore has no development cost.

10.3.1. The Conductor

The KEK aluminum stabilized superconductor consists of multi-filament; there are 3050 NbTi/Cu filaments in the core. The basic parameters are listed in Table 4.

To investigate the detailed electric and magnetic properties of the conductor, short sample measurements were taken at the BNL Accelerator Development Department. We thank Bill Sampson for that. Fig. 10.3.1 shows the test result. In the upper right corner, B_a stands for the applied magnetic field in the test dipole magnet; B_p stands for the peak field, in which the self field is taken into account; and I_c is the critical current at the peak field. The result is scaled to the temperature of 4.224 K.

10.3.2. Field Calculation

Together with the insulation and the fiber glass tape, the apparent sectional area will be $2.3 \times 3.3mm^2$. Due to the improved granularity, the field quality inside the channel will be almost perfect and the stray field almost absent. This allows one to delete two pairs of conductors, and to relocate some conductors so that the bending radius around the ends of the inflector would be increased. The revised distribution is shown in Fig. 10.3.2. There are 88 turns; the operating current is 2850 A. The channel width is 1.8 cm and the height is 5.6 cm. The flux plot and the harmonic components are shown in Fig. 10.3.3.

If the storage ring magnetic field is superimposed, fields are eliminated inside of the device channel, and enhanced in the return flux region. By considering the self-field effect (2.5 gauss per ampere), some particular portions of the superconductor windings have to stand peak fields up to 3.5 tesla.

Figure 10.3.1: Short Sample Tests of the Conductor

Figure 10.3.2: The Revised Conductor Distribution

Figure 10.3.3: Flux Plot and Harmonic Content

10.3.3. Magnetic Force

According to the 2D calculations, the components of the force per unit length, $\vec{F}_{jk}$, on wire k due to the field produced by wire j, may be shown[4]:

$$(F_k)^i_x = \sum_j (F_{jk})_x \qquad j \neq k \tag{10.3.1}$$

and

$$(F_k)^i_y = \sum_j (F_{jk})_y \qquad j \neq k \tag{10.3.2}$$

where the superscript i stands for "internal", and later on, e for "external".

If the wire system is immersed in an external magnetic field, the forces on the wires contain the additional terms:

$$(F_k)^e_x = -I_k B^e_y, \quad (F_k)^e_y = I_k B^e_x \tag{10.3.3}$$

where the components of B^e are to be evaluated at the location x_k, y_k.

Either $(F_k)^i$ or $(F_k)^e$ are transmitted to the supporting body on which the conductors are positioned, but whereas $\sum(F_k)^i = 0$, there can be a residual $\sum(F_k)^e$ and a torque M, if the external field is not uniform.

Based on the two dimensional calculation, Fig. 10.3.4(a) and Fig. 10.3.5(b) show the magnitude and the direction of forces on each conductor, in the cases of without and with the storage ring field, respectively. The magnitude of the forces is of the order of several thousand newton per linear meter.

In reality, the inflector is a three dimensional device. One end is located in the homogeneous storage ring magnetic field and the other end is located in the storage ring fringe field; therefore the external field is not uniform. Three dimensional forces have been calculated, and the total residual forces are shown in Fig. 10.3.6.

Figure 10.3.4: (a) Forces on the Conductors - No Storage Ring Field

Figure 10.3.5: (b) Forces on the Conductor - With Storage Ring Field

Figure 10.3.6: Residual Forces

10.3.4. The Critical Surface

The critical current density, critical temperature and critical field are related to each other by the critical surface in $BJ\theta$ space, which is characteristic of the material in use. Superconductivity prevails everywhere below this surface with normal resistivity everywhere above it. Fig. 10.3.1 actually shows the profile of the critical surface at the temperature of 4.224 K. The critical current at this temperature is 4350 A.

Two phase helium cooling option has been chosen for the superconducting inflector. The operating temperature is 4.6 K. Critical currents at different temperatures are calculated [5] as following:

$I_c = 3890A \ at \ \theta = 4.6K \ and \ B = 3.5T$

$I_c = 3000A \ at \ \theta = 5.5K \ and \ B = 3.5T$

The inflector will be operating around 73% of the full load.

10.3.5. The Configuration of the Inflector Ends

The fringe field of the inflector is dominated by two ends. By measuring the fringe field of a room temperature wire model, it became clear that to close the downstream end would reduce the fringe field by a factor of 6 (integrated dipole component). From an engineering point of view, if both ends are closed, it will be much securer for force support and quench prevention (Table 10.3.1). In this case, incoming particles (pions or muons) must penetrate superconductor layers. Table 10.3.2 lists the calculation results of muon storage ratio for all three options. It shows that if one leaves the upstream end open, the experiment running time would not have a significant reduction; therefore, closing both ends is the best choice.

10.3.6. Engineering Design and Construction

The detail engineering design was completed by KEK. The inflector body consists of three parts (Fig. 10.3.7):

a)inner coil (one winding on the aluminum mandrel);

b)outer coil (two windings on the aluminum mandrel);

c)housing jacket (aluminum) with two liquid helium tubes.

The inner and outer coil will be wound separately; the housing jacket will be shrink-fitted and constrain the two mandrels firmly. The end loops will be confined by end caps (Fig. 10.3.8). The whole assembly will be epoxy impregnated and cured, becoming one integrated solid.

Table 10.3.1: Summary of the meeting with A. Yamamoto on July 29, 1991 to discuss the inflector design and development.

A liquid nitrogen heat shielding is proposed by KEK. Fig. 10.3.9 shows the upstream case: two squared nitrogen tubes are attached on the shield plate, which surround the inflector assembly.

Several test windings have been done at KEK. A superconducting prototype with shortened length (0.5 meter long) has been constructed and tested in KEK (March 1993) and

Table 10.3.2: Muon Storage Comparison for Open and Closed Inflector Ends

Figure 10.3.7: The KEK Inflector Body

Figure 10.3.8: The Inflector End Loops

Figure 10.3.9: KEK Design with Heat Shield

in BNL (March 1994), with and without the external field, respectively. The construction of the full length superconducting inflector will be completed by the end of 1994.

10.3.7. Cryostat and Beam Chamber Complex

10.3.7.1. The Location of the Inflector in the Storage Ring

Fig. 10.3.10 shows the location and the orientation of the inflector in the storage ring magnet. The injection beam line is 1.25 degree from the tangential reference line. The inflector is aligned along this tangential reference line and its downstream end is positioned at the injection point which is 12.35 degree west from of southerly axis of the building.

10.3.7.2. Integrated Inflector Cryostat and Beam Chamber

Due to the limited space, the inflector cryostat is being designed together with one of the beam vacuum chamber section of the storage ring to form an integral structure but with two different vacuum zones. It is an aluminum structure sealed with aluminum welding for vacuum integrity. Viton O-rings will be used in the flange area. Vacuum quality better than 10^{-5} torr will be achieved for cryogenic insulation.

Fig. 10.3.11 shows the integrated structure of the inflector cryostat and beam chamber. The shaded area is the 1.7 meter long inflector body. The injection point is 76 mm outside the tangent point of the muon orbit and tangential reference line.

A beam window in the upstream end is designed for injection beam to come in. Another beam window in the downstream end is designed for the inflected beam to enter into the storage region. These windows will be made of 1 mm aluminum plate to let most of the muons pass through. The inflector is supported in the two ends with accessing flanges for installation and adjustment. A penetration hole in the upstream end through the outer coil and the yoke, is designed for the beam pipe to bring the beam in. Another penetration hole in the downstream end is designed for the connection of power leads and cryogenic tubes.

Figure 10.3.10: Inflector Location

Figure 10.3.11: Inflector/Beam Vacuum Chamber

10.3.7.3. Cryostat in the Downstream (Injection Point)

Fig. 10.3.12 shows the cross section view of the inflector in the downstream end where the inflector is very close to the storage region. To overcome the space limitation, the partition wall (shown in Fig. 10.3.13) which is 0.5 inch thick at the top and the bottom, is designed with a thin wall near the mid-plane, to serve following functions:

a) to separate vacuum zones between the inflector and the beam chamber;

b) to keep structure integrity under vacuum condition even when only one side is in vacuum; c) to provide at least 7 mm space between the inflector and the partition wall, because the inflector will be operated in 4.6 K, space is needed for thermal insulation;

d) to keep a minimum clear space of 48 mm radius for muon storage region in the injection point area.

The top or bottom plate (0.5 inch thick) has a 5 mm undercut to make enough room for thermal insulation. The thickness of the two outside vertical plates is 0.75 inch. Under vacuum condition the deflection of the top or bottom plate is about 0.5 mm, which is acceptable.

10.3.7.4. Cryostat in the Upstream

Fig. 10.3.14 shows the cross section view of the inflector in the upstream where the end of the inflector cut into the outer cryostat. In order to make room for inflector steering and thermal insulation, a concave wall has been designed in the outer cryostat and a 45 degree chamfer was cut in the coil cover.

10.3.7.5. Inflector Support and Steering Adjustment

The two supports of the inflector have been designed to provide steering and shifting capability for injection beam adjustment. The downstream end support (shown in Fig. 10.3.15) is designed as a pivot to keep the end of inflector in the injection point. The upstream end support (shown in Fig. 10.3.16) is designed as a slide with a motion feed through. The slide is to compensate the shrinkage of the inflector when it is cooled down. The motion feed through is to provide $+/-\ 4\ mrd$ steering adjustment for the injection beam without losing vacuum. The two supports can shift the inflector toward upstream end, up to 1.5 inch.

Figure 10.3.12: The Downstream End of the Inflector

Figure 10.3.13: Inflector Partition Wall

Figure 10.3.14: Upstream End of the Inflector

Figure 10.3.15: Downstream End Support

Figure 10.3.16: Upstream End Support

10.3.7.6. Beam Divergence and Downstream End Window

Fig. 10.3.17 shows the gradually increased width of the exit beam from the inflector. Due to the beam divergence and the range of the steering angle, a beam window will be designed to fit into a tapered partition wall without interfering with the beam.

10.3.7.7. Penetration through the Outer Coil and the Yoke

Fig. 10.3.18 shows the beam line penetration through the outer coil and the yoke. A slot will be cut in the back leg of the yoke. A beam tube will slide through the yoke and the outer coil to bring the beam into the inflector. In the downstream end, another penetration tube will be designed to support and guide the lead conductors and cryogenic tubes to a lead pot in the back of the yoke. The locations of these two penetration holes have been carefully positioned to pass through the space between tension bolts.

10.4. References

1. V.Badea et al. "Pulsed Inflector Study", Muon $(g-2)$ Note No.32, October 16, 1989.
2. H.Brown "Inflector Path into the $(g-2)$ Storage Ring", Muon $(g-2)$ Note No.29, 58, 76.
3. F.Krienen et al. "The truncated double cosine theta superconducting magnet", NIM A283(1989)5-12.
4. F.Krienen et al. "Development of Non-ferrous Superconducting Magnets", Muon $(g-2)$ Note No.63.
5. Provided by W.B. Sampson, Brookhaven National Laboratory, March 1992.

Figure 10.3.17: Beam Divergence and Window

Figure 10.3.18: The Penetration Through the Coil and Yoke