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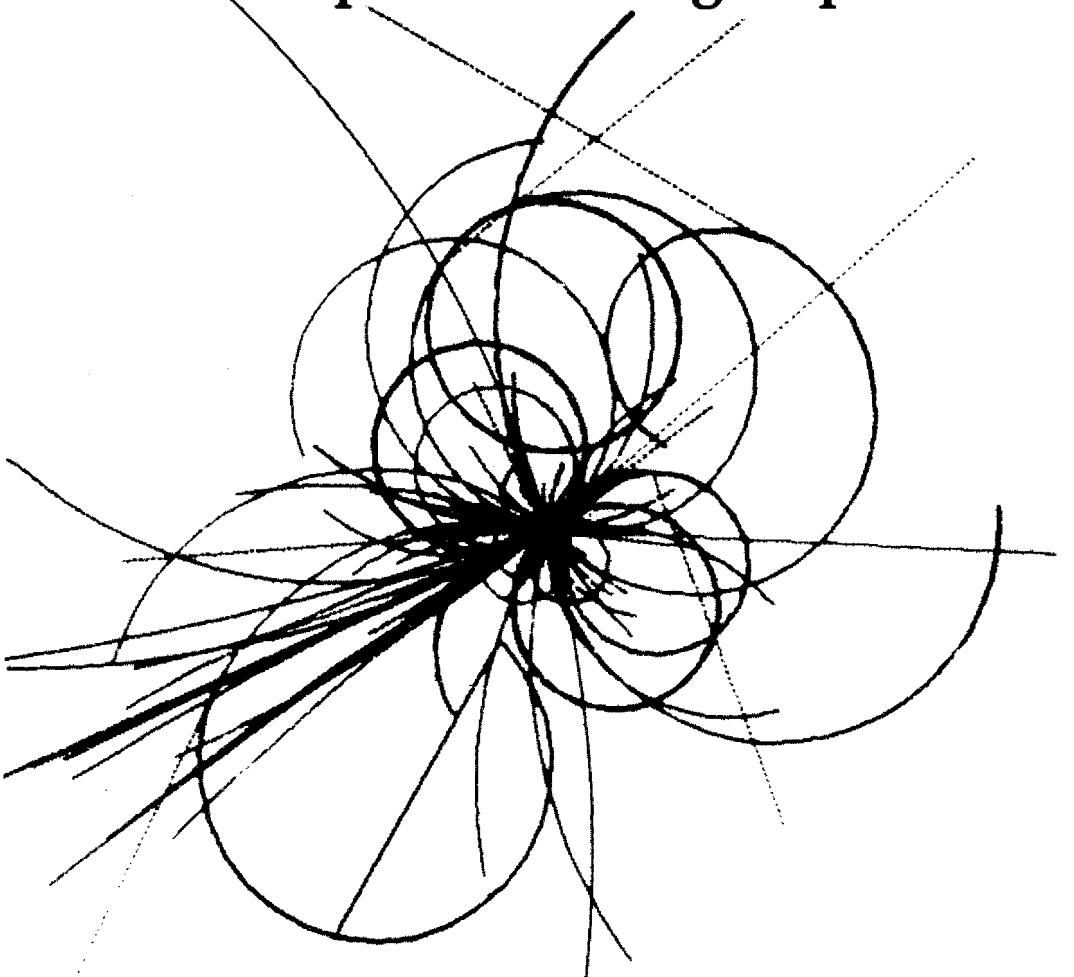
The Superconducting Super Collider



Magnet Field Quality Requirements for the SSC

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MAGNET FIELD QUALITY REQUIREMENTS FOR THE SSC*

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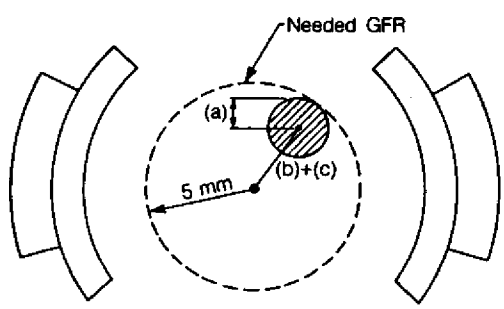
Abstract. - The question of magnet field quality can be asked in two ways. The direct way is to start with a magnet design, find out the field uniformity that is achieved by the design and then ask if the beam can take the achieved field uniformity. The question can also be asked in a reversed way. One then starts with the fact that the beam needs a "good field region" (GFR) for its stable operation. The GFR requirement translates into tolerances of field non-uniformity and one then asks if the magnets can make such tolerances. In this paper, we will address the reverse question and will use the SSC design, as presently conceived,[1] as example.

HOW MUCH GOOD FIELD REGION DOES THE BEAM NEED?

Good field region is the region occupied by the beam during routine operations. For the SSC, its requirement comes from three sources: (a) the beam has a finite size, (b) the beam is allowed to have a closed-orbit deviation from magnet center, and (c) the beam might be injected with errors. The needed GFR is estimated to be 5 mm radius, i.e. the dipole magnet must provide uniform field in a region within 5 mm from the magnet center. It turns out that each of the three sources contributes about 1/3 to the GFR requirement for the SSC. The situation is illustrated in Fig. 1.



(a) Beam size
(b) Orbit deviation
(c) Injection error

Figure 1. Good field region requirements for the SSC dipole magnet.

HOW UNIFORM THE FIELD HAS TO BE IN THE GFR? (RANDOM ERRORS)

This question will be asked twice in this paper, first concerning random field multipole errors in this section, and then again later concerning the systematic field errors. As we will see, random and systematic field errors have qualitatively different effects on particle motion and the field quality tolerance depends on whether the errors are random or systematic from magnet to magnet.

Magnet errors can be described by the multipole error coefficients a_n and b_n by

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n \qquad (1)$$

where x and y are the horizontal and vertical deviation from magnet center. Ideally, all coefficients vanish except for $b_0 = 1$. In reality, GFR is limited by the non-vanishing coefficients a_n and b_n.

In perfectly uniform field, particle motions in x and y are purely sinusoidal, as sketched in Fig. 2(a). The number of x and y-oscillations made by a particle as it makes one revolution around the accelerator are called the horizontal and vertical tunes ν_x and ν_y.

When random a_n and b_n are included, particle motion deviates from being purely sinusoidal in a manner illustrated (exaggerated) in Fig. 2(b). The deviation can be quantified in several ways. In particle tracking studies, it is most conveniently quantified by the "smear" parameter.[1] In perturbation theory, one uses "distortion functions".[2] In the Lie algebraic approach, one can use the polynomials that describe the nonlinear mapping.[3] All these approaches give similar numerical results. In the following, we will use the "smear" language. For the SSC, the GFR due to random a_n and b_n is specified by the condition

$$\text{smear} < 10\% \qquad (2)$$

Close to the magnet center, the field is dominated by the uniform field; smear is approximately zero. As one deviates from the magnet center, the smear increases. GFR is determined as 10% smear, calculated by tracking studies, is reached. Outside the GFR, the smear > 10%. This is illustrated in Fig. 3.

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* SSC-75

† Operated by Universities Research Association for the Department of Energy

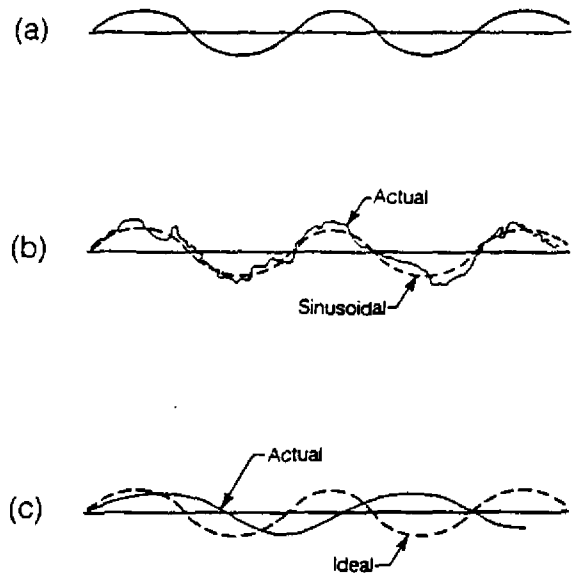

Figure 2. Qualitative differences among particle motions in
(a) perfectly uniform field,
(b) field with random field multipoles errors, and
(c) field with systematic multipole field errors.

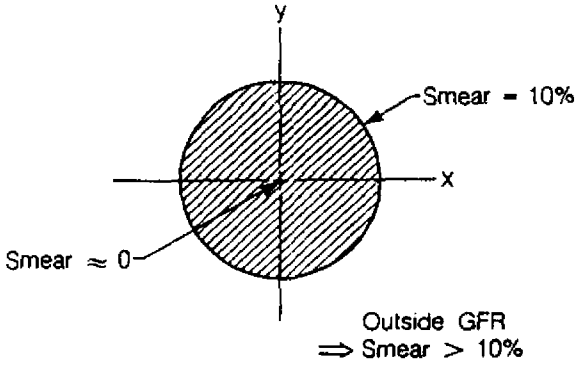

Figure 3. Smear as function of deviation from magnet center. Boundary of the GFR is determined by the condition that smear = 10%.

ESTIMATE OF GFR, GIVEN RANDOM FIELD ERROR SPECIFICATIONS

Given specifications on the random a_n and b_n, extensive studies generally are needed to obtain the GFR. Quick estimate of the GFR, however, is possible if only a rough answer is asked for.

If the higher multipole errors are sufficiently small, smear is dominated by the skew sextupole and sextupole errors a_2^2 and b_2^2 in the region of interest. In fact, the quick estimate to be given below relates smear with magnet errors only through the quantity $a_2^2 + b_2^2$.

In addition to the magnet multipoles, smear also depends on the accelerator lattice design, especially on the design of the unit cell that makes up the bulk of the lattice. For a given phase advance per cell (taken to be 60° below), the parameter that specifies the unit cell is its length L. So smear depends on L.

Guided by the perturbation theory, a semi-empirical fit of smear for the SSC, in the neighborhood of the parameter space of interest, is[4]

$$\text{smear} = 0.09\ L(a_2^2 + b_2^2)^{1/2}\ N_b^{-1/2}\ A^{1.35} \qquad (3)$$

where L is in meters, a_2 and b_2 are in 10^{-4}cm^{-2}, A is the deviation from magnet center in mm, N_b is the total number of dipole magnets in the accelerator. Take L = 192 m, $(a_2 + b_2)^{1/2} = 2.3\times10^{-4}\text{cm}^{-2}$ [corresponding to a design with inner coil diameter of d_c = 4 cm] and N_b = 4000 for the SSC,[1] the smear = 10% condition is reached at A = 5.5 mm.

This GFR of 5.5 mm, achieved by a d_c = 4 cm magnet design, is more than the needed 5 mm. It seems one can conclude that the magnet design has provided the needed GFR and is thus acceptable. However, although this turns out to be true, there is a complication to be discussed next.

MAGNET SORTING

Even when the rms specifications of all a_n and b_n are given, smear still depends on their exact arrangement in the accelerator lattice. A given set of 4000 magnets arranged in different sequence will give a different smear. Equation (3) gives only the average smear; the actual smear for a specific arrangement has a spread around the average. Taking this into consideration, the achieved GFR for the SSC is actually[1]

$$A = (5.5 \pm 1.3)\ \text{mm} \qquad (4)$$

which is not acceptable because there is now a finite chance that the actual GFR is less than the needed 5 mm.

The dependence of GFR on magnet arrangement can be used to our favor. By measuring magnets in batches of 60 and by artificially arranging the order of the magnets in each batch in a favorable way, one always samples the upper end of the spread in equation (4). This process is called magnet sorting. The sorting method is not unique but a simple method has been used to give[1]

$$A = (8.9 \pm 2.0)\ \text{mm} \qquad (5)$$

This GFR is about 2 x sigma above the needed 5 mm and is believed to give the needed GFR with sufficient confidence level. Sorting is extremely helpful in reducing the effect of random field errors.

THE DYNAMIC APERTURE

So far, the GFR defined has been called the "linear aperture" technically. It represents a prime region for routine beam operations. In addition to the linear aperture, it is also important to consider a region of lesser quality for non-routine operations such as beam diagnosis, abort, beam injection tuning, etc. This lesser region is called the "dynamic aperture".

Although the linear aperture requirement restricts mainly the lower multipoles, the dynamic aperture does depend on the higher multipoles and is more relevant in setting their tolerances. Table I shows the specifications of the rms of the random multipoles for the SSC dipoles.[5]

Table I

Specifications of multipole field error tolerances for the SSC dipole magnet. The rms specifications are given for the random field errors. The units are $[a_n] = [b_n] = 10^{-4} cm^{-n}$.

	Random	Systematic
a_1	0.7	0.2
a_2	0.6	0.1
a_3	0.7	0.2
a_4	0.2	0.2
a_5	0.2	-
a_6	0.1	-
a_7	0.2	-
a_8	0.1	-
b_1	0.7	0.2
b_2	2.0	1.0
b_3	0.3	0.1
b_4	0.7	0.2
b_5	0.1	0.02
b_6	0.2	0.04
b_7	0.2	0.06
b_8	0.1	0.1

Table I is consistent with the field errors presently expected of a d_c = 4 cm design.[6] The table is not rigid in the sense that trade-offs are still possible between higher multipoles and between a_2 and b_2. One can also trade off tolerance specifications with the various correction schemes outside the dipole magnets. One should note however that trade-off between random and systematic errors is not allowed.

With the random multipoles given in Table I, both the GFR and the dynamic aperture are acceptable. The geometry of the aperture situation is illustrated in Fig. 4.

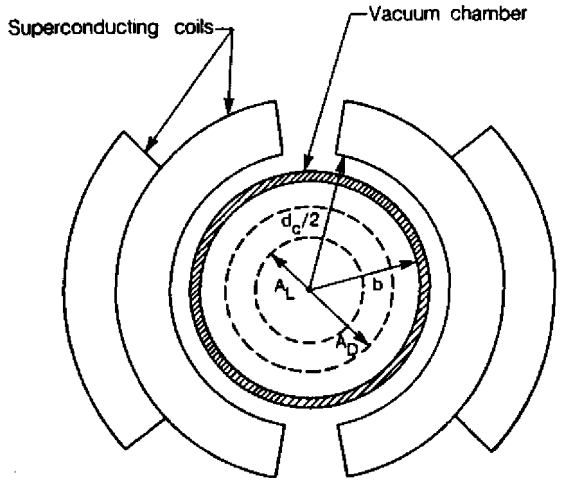

Figure 4. The relative positions and sizes of the superconducting coil packages, the vacuum chamber, and the linear and dynamic apertures. The SSC design has $d_c/2$ = 2 cm, b = 1.65 cm, A_D = (1.2 ± 0.15) cm and A_L = (0.89 ± 0.2) cm.

HOW UNIFORM THE FIELD HAS TO BE IN THE GFR? (SYSTEMATIC ERRORS)

As mentioned, the effect of systematic field errors on particle motion is qualitatively different from that of random field errors. The systematic a_n and b_n errors give negligible "smear" but does produce sizable "tune shift". The effect (exaggerated) is sketched in Fig. 2(c). The particle motion is still basically sinusoidal but the oscillation wavelength has changed.

For the SSC, the GFR requires that the tune shift $\Delta\nu$ satisfies the condition

$$|\Delta\nu| < 0.005 \qquad (6)$$

or equivalently, ν has to be controlled to the level $\Delta\nu/\nu < 0.6\times10^{-5}$ since ν is about 80.

The tune shift due to systematic multipoles can be calculated analytically or numerically.[1] The tolerances obtained by imposing the condition (6) are given in Table I. The tolerances on a_1 and b_1 assumes the use of skew quadrupole and quadrupole windings in the secondary and primary correction packages outside the magnets. The tolerances on a_2, a_3 and a_4 assume the horizontal and vertical tunes are separated by an integer.[7] The tolerances on b_2, b_3 and b_4 assume the use of beam tube corrector windings, which are discussed next.

BEAM TUBE WINDINGS (BTW)

The BTWs are actually capable of removing systematic b_2, b_3 and b_4 errors that are larger than those listed in Table I. For example, assuming 5 μm superconducting filaments, it is estimated[6] that the persistent current at injection field gives systematic $b_2 = -4.7\times10^{-4}cm^{-2}$ and $b_4 = 0.3\times10^{-4}cm^{-4}$. The BTWs are capable of correcting for those errors, plus those listed as tolerances in Table I.

The magnet design needs to be such that the systematic errors are known sufficiently accurately on absolute scales so that the BTWs can be pre-set to desired values before the beam operation starts. The accuracy needed is somewhat flexible but at present is set to be $\pm0.5\times10^{-4}cm^{-2}$ for b_2 and $\pm0.1\times10^{-4}cm^{-4}$ for b_4.

The TBW settings are adjustable during operation from the control room. The accelerator operators will empirically adjust these settings to reach a final level of systematic field errors of $\pm0.008\times10^{-4}cm^{-2}$ for b_2 and $\pm0.02\times10^{-4}cm^{-4}$ for b_4, which means the final magnet field accuracy is of the order 10^{-6}. Although this level of absolute accuracy is not required of the magnet design, it is required that the magnet field be held steady at the 10^{-6} level during hours of operation.

The tolerance on the systematic field errors can be relaxed by finer filaments or tighter lattice cell design. Trade-offs in these directions are possible subjects to study. One may also consider raising the injection energy to relax the effect, or to take advantage of having the BTWs and consider lowering the injection energy.

Several alternatives of BTW designs are possible. In particular, windings of the different multipoles may or may not overlap. The windings are thus either multi-layered or single-layered. The presently conceived design has single-layered windings, with b_2, b_3 and b_4 windings occupying different parts of the tube in each magnet.[5] Since b_2 is the strongest corrector, its winding is preferably located from the end to the center of the magnet, taking advantage of the symmetry of lattice functions. It seems that the similar preference on the b_3 and b_4 windings is not severe since these are weaker windings. Their lengths and relative positions in a magnet can be determined by convenience. The possibility that one can also provide the functions of the cell quadrupoles and chromaticity sextupoles in the BTW package has not been included at present.

SUMMARY

(a) An aperture evaluation algorithm exists for the SSC. More studies, both theoretical and experimental, are under way to sharpen up the algorithm.

(b) Application of the algorithm has generated a self-consistent set of magnet parameters for the SSC. Evolution of these results in terms of making various trade-offs is expected to continue.

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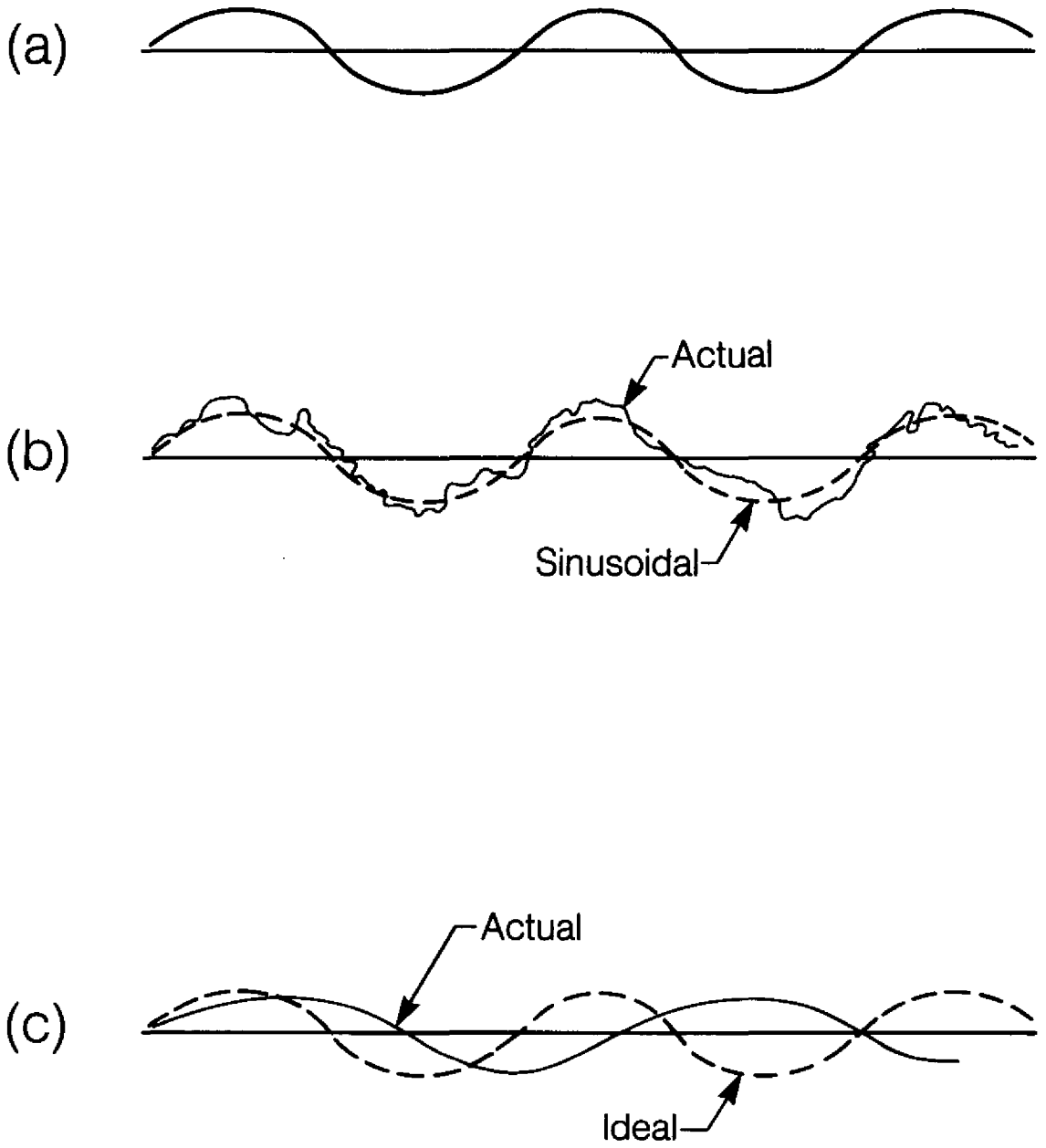

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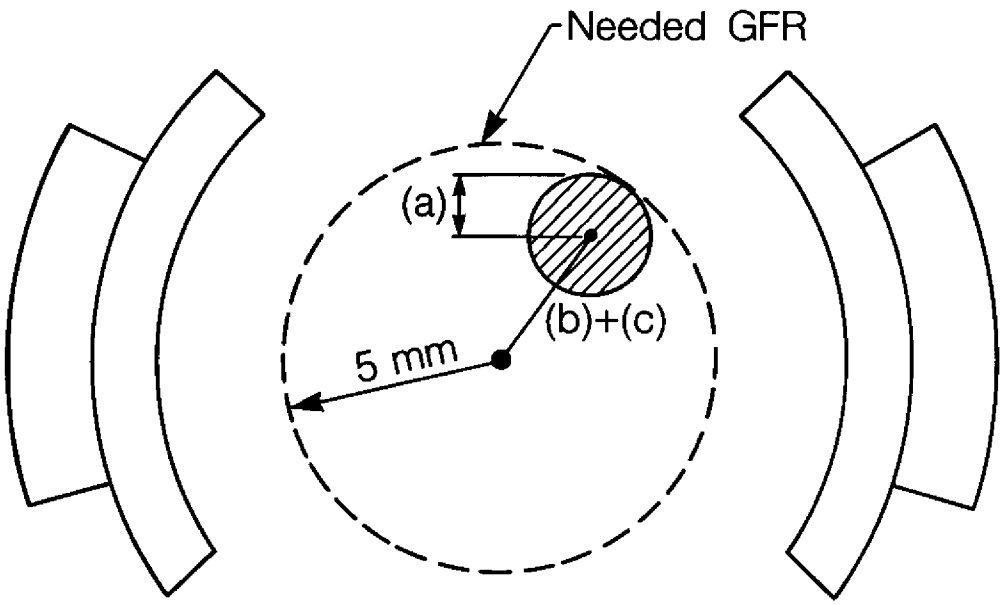

(a) Beam size
(b) Orbit deviation
(c) Injection error

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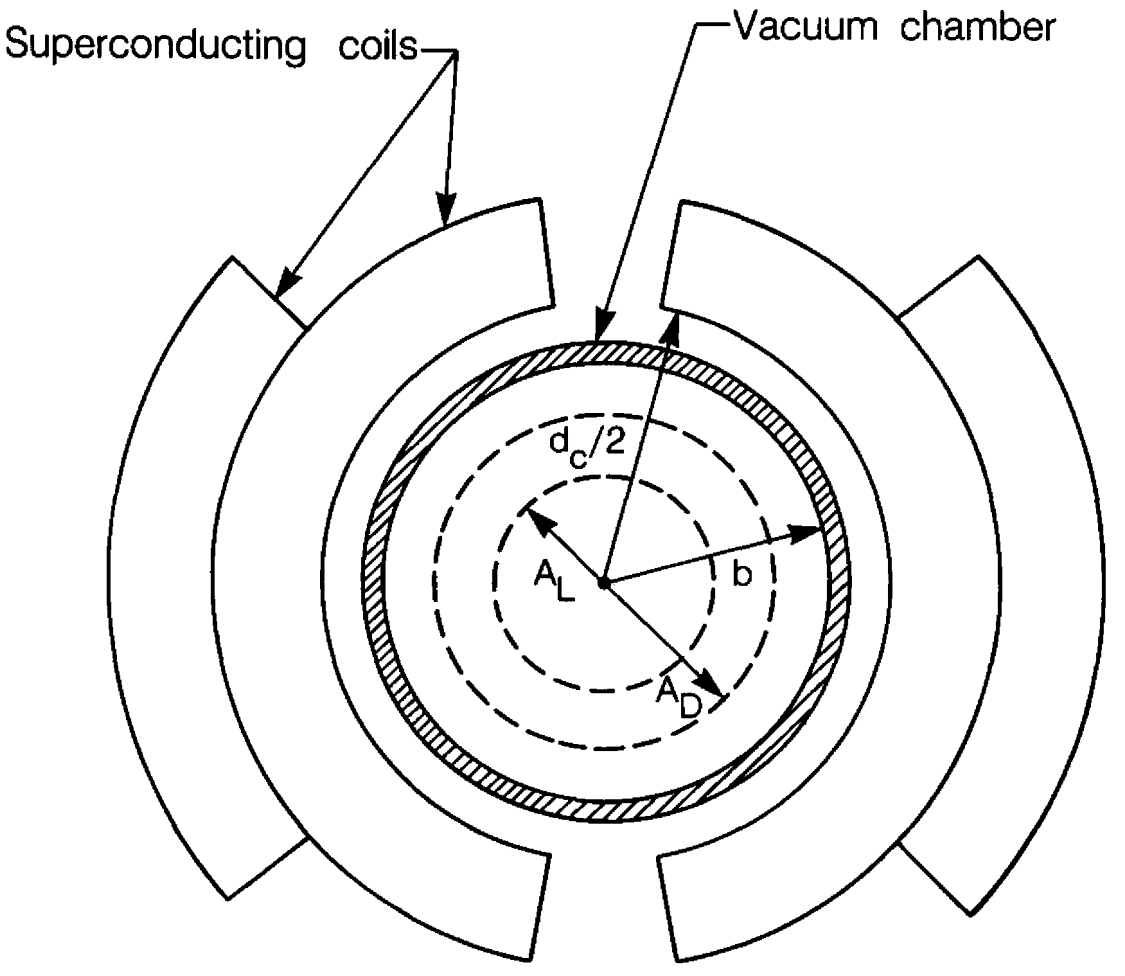

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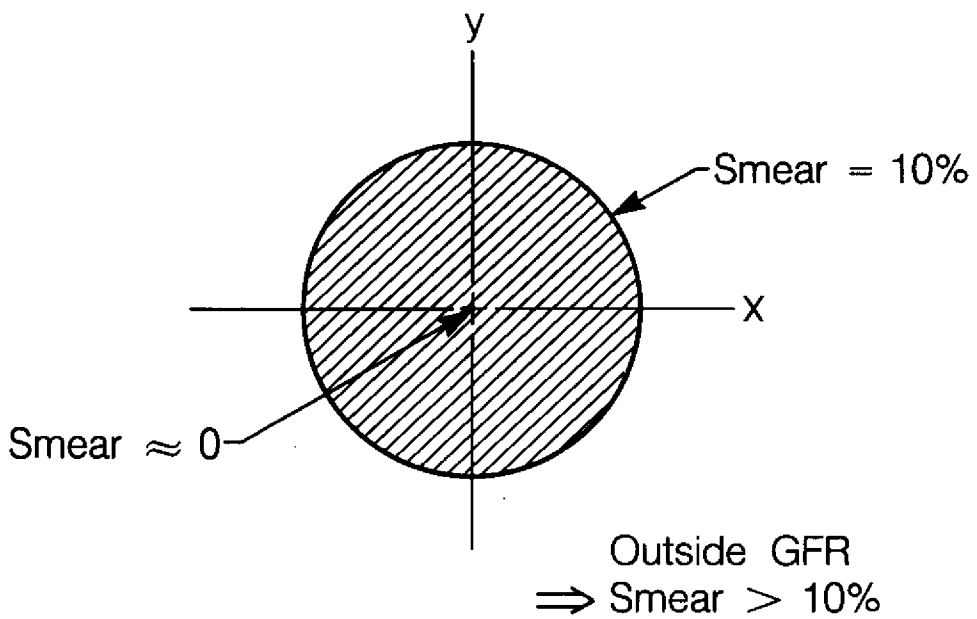

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