PRECISION MAGNETIC ELEMENTS FOR THE SNS STORAGE RING*

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Introduction

Magnetic elements for an accumulator storage ring for a 1 GeV Spallation Neutron Source (SNS) have been under design. The accumulation of very high intensity protons in a storage ring requires beam optical elements of very high purity to minimize higher order resonances in the presence of space charge. The parameters of the elements required by the accumulator lattice design[1] have been reported. The dipoles have a 17cm gap and are 124cm long. The quadrupoles have a physical length to aperture diameter ratio of 40cm/21cm and of 45cm/31cm. Since the elements have a large aperture and short length, optimizing the optical effects of magnet ends is the major design challenge. Two dimensional (2D) computer computations [2] can, at least on paper, produce the desired accuracy internal to magnets, i.e. constant dipole fields and linear quadrupole gradients over the desired aperture to $1x10^{-4}$. To minimize undesirable end effects three dimensional (3D) computations can be used to design magnet ends.[3] However, limitations on computations can occur, such as necessary finite boundary conditions, actual properties of the iron employed, hystersis effects, etc., which are slightly at variance with the assumed properties. Experimental refinement is employed to obtain the desired precision.

1 SNS DIPOLE MAGNETIC DESIGN

Edge shims are employed inside the dipole in order to give a uniform field over the desired aperture (Fig. 1).
The computed (2D) field is everywhere more uniform than $\Delta B/B=1x10^{-4}$ inside the "isofield" of $1x10^{-4}$. The computed field in terms of the multipoles expressed at a design radius of r=7cm are all small compared to $1x10^{-4}$.

An actual magnet design must minimize construction errors. For reference, the dipoles constructed for the high intensity Booster [4] upgrade of the Brookhaven AGS proton synchrotron were assembled from one piece lamination stampings. By left-right, up-down inversion in assembly, the small residual errors due to die dimensions, steel rolling direction, etc were rendered symmetric. As a result actual measurements showed essentially agreement with predictions. The SNS dipole cross-section is too large for a one piece stamping. Joining of two nominally identical pieces at a mid-plane is required. Careful control must be designed in for precision relative alignment of the two pole surfaces.

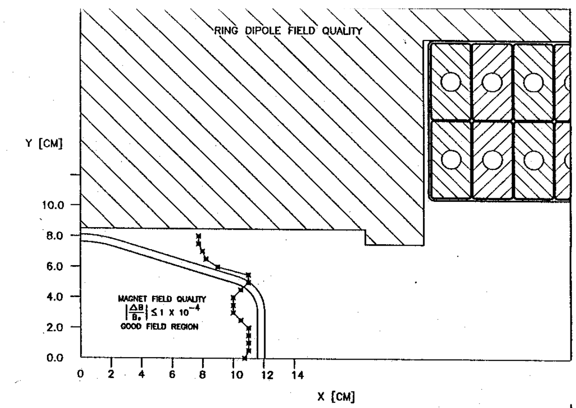

Fig. 1
Dipole Pole Profile and Isofield

For the SNS accumulator, a design option is to make the magnet a mechanical assembly out of solid steel plate. A prototype is under construction. The yoke is composed of 4 pieces. Precision machining of the two mid-plane pieces simultaneously should ensure parallel top and bottom yoke surfaces, to which each pole piece is attached. If required, a thin shim placed on either side could eliminate gradient fields to high order of accuracy. The magnetic field is iron dominated. The coil is located sufficiently remote from the pole surface so that even with the inevitably much cruder tolerances on location in coil construction, the influence on the field can be expected to be at the $1x10^{-4}$ level, interior to the magnet.

2 DIPOLE END EFFECTS

The SNS dipoles are straight. The ends are wedge shaped, where the angle of each wedge end equals half the total beam angle of deflection. The proton beam central axis enters and exits the magnet normal to the plane of the pole ends. In the simplest, first order form, the pole cross-section ends abruptly with each end a plane vertical surface. This geometry has been computed. The integral of the magnetic field through the magnet was calculated. Because of the wedge ends,

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the magnetic length varies linearly across the HMP, as required optically.

Because of the finite width of the poles and of the coil ends, the field end effects also show a relatively large nonlinearity. Fig. 2 shows the residual integral of field through the magnet on the HMP, normalized to the central field integral, after the wedge induced gradient is subtracted out. This calculation was done with pole edge shims running the entire length of the poles as shown in Fig. 1. As a result the Fig. 2 field aberration computed is entirely located in the magnet ends.

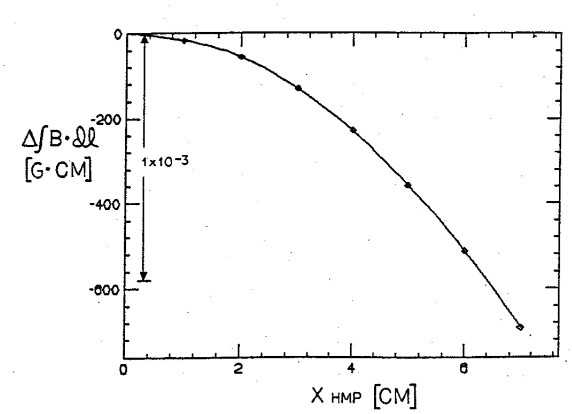

Fig. 2
Residual Nonlinear Field Integral

Detailed shaping of the end regions will be employed. Field and orbitral calculations are being used to minimize optical aberrations. This will be refined on the soon to be available prototype dipole. The magnet pole ends contain removable short sections which will facilitate shaping in 3 dimensions. Integral and point by point precision measurements will be made, using techniques and apparatus largely available from the development of the AGS Booster dipole.

3 SNS QUADRUPOLE MAGNETIC DESIGN

The SNS quadrupoles are particularly sensitive to end effects because of the very small ratio of length to aperture diameter. Fortunately, precision 16.5cm quadrupoles were developed for the AGS Booster which were also relatively short with a ratio of length to aperture diameter of 3/1. The SNS quadrupoles can be directly scaled from the precision Booster design. However, the ends will have to be modified to compensate for the even smaller ratio of length to diameter.

A model quadrupole of 21 cm diameter has been designed. This will be studied and ends optimized. Fig. 3 shows the computed cross-section.

Eq. 1 presents in cylindrical coordinates the axially symmetric 3D radial field for quadrupole symmetry. This is for the case where symmetry breaking imperfections are zero. In the case of the AGS Booster 4 piece laminations were mounted on 4 corner precision located pins. In fact, this did maintain 4-fold symmetry

$$\begin{aligned} B_r = & \sin 2\theta\, [\{(2r\, f_{2,2}(z)\} + 4r^3 (-1/12) f_{2,2}^{ii}(z) + \ldots] \\ & + \sin 6\theta\, [\{6r^5 f_{6,6}(z)\} + 8r^7(-1/28) f_{6,6}^{ii}(z) + \ldots] \\ & + \sin 10\theta [\{10r^9 f_{10,10}(z)\} + 12r^{11}(-1/44) f_{10,10}^{ii}(z) + \ldots] \\ & + \ldots \end{aligned} \qquad (1)$$

to a high degree. Azimuthal and longitudinal field equations are also listed in a reference.[5]

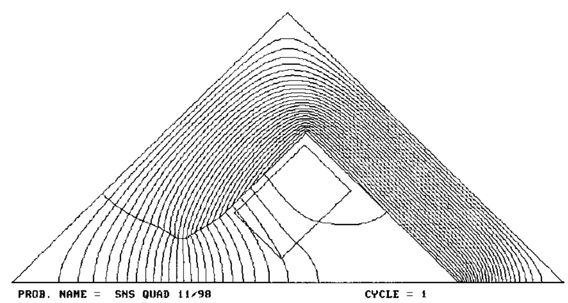

Fig. 3
Quadrupole Flux pattern

Shaping of the pole ends is used so that the 6θ, 10θ, 14θ, etc., allowed aberration terms in Eq.1 are very small both internal to the magnet and integrated through the ends. The shaping is used so that the even derivatives of these multipoles, plus the even derivatives of the quadrupole term f 2,2 (z) also present in Br and Bθ integrate to small values over each quadrupole end. Because the Booster 16.5 cm quadrupoles [4] were highly developed, the SNS quadrupoles are directly scaled to the larger diameter required. The shaped ends will be approximately the same as for the Booster, but because both the 21cm and 31cm diameter SNS quadrupoles are very short, some further interpolation will be required. This is because there is essentially no "internal" 2D region (magnets are essentially mostly ends) and also because the excitation coil is quite different in shape, and coil ends make a significant contribution to end fields. For the Booster quadrupoles, the integral allowed multipoles were at the 1×10^{-4} level at 92% of radius to the pole tip.[6]

The purpose of end shaping of the quadrupole is to arrange that positive and negative lobes are of equal magnitude. Fig. 4 shows the experimental result for the Booster quadrupole of shaping the dominant 12-pole, 6θ term in the vicinity of the pole end. The second derivative of the 6θ term (see Eq. 1) is very small, normalized to ∫f 2,2 (z) dz, ie., to the quadrupole strength. The integral, ∫f 6,6 (z) dz of 6θ though the ends is very small $<1x10^{-4}$. The same technique is used to minimize the effect of the much smaller 20 pole (10θ) symmetric aberration. These techniques will be directly applied to the SNS quadrupole designs. Prototypes are in the process of being ordered.

The same measurement techniques, and in fact much of the same apparatus that was used in the Booster development will be directly applied to the SNS prototypes. Note that there can be an extremely small optical error not present in the integral magnetic measurement, which corresponds to a proton having the same transverse coordinates as it traverses each lobe in Fig. 4. In practice, the proton will vary very slightly in radius passing through each lobe. For a 10 milliradian angle at r=5cm, the error is ~ $2x10^{-4}$.

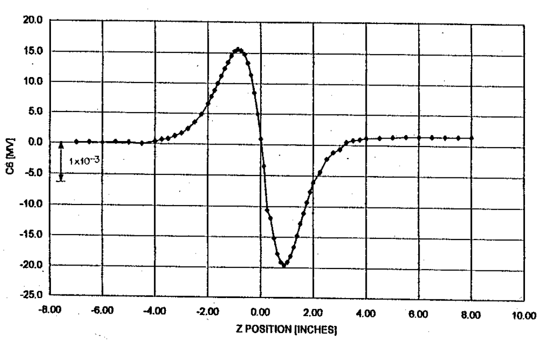

Fig. 4
Booster Quadrupole 6θ Term After End Shaping

4 CORRECTION ELEMENTS

Because of the high intensity, low loss proton beam requirements, corrections elements are required to compensate for small residual errors and also to deliberately introduce small controlled nonlinearities.

Correction elements used in the high intensity AGS and AGS Booster can be directly scaled to the somewhat larger aperture. These have not been developed yet in detail for the SNS accumulator ring, other than the rectangular box magnet which can provide various normal and skew terms.[7] Such a multifunction box magnet was previously designed and installed in the Booster, providing the necessary corrections and although very short azimuthally, with the necessary optical precision.[8]

5 REFERENCES

[1] SNS Design Manual (1998).
[2] POISSON Users Guide, LA-UR-87-115.
[3] OPERA-3D Reference Manual, VF-03-98-04.
[4] G. Danby, et al. PAC87 (1987).
[5] G. Danby, S. Lin, J. Jackson, PAC67 (1967).
[6] G. Danby, J. Jackson, PAC 91 (1991).
[7] N. Tsoupas, private communication.
[8] G. Danby, J. Jackson, MT-13 (1993).