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DESCRIPTION OF NEW VACUUM CHAMBER CORRECTION CONCEPT*

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Abstract

For rapid cycled accelerators eddy currents induced in vacuum chambers (VC) are typically the dominant source of systematic and random field aberrations. Complex thin wall VC are expensive and delicate where bakeout is required, as in the AGS Booster under construction.[1] Thick wall VC are rugged and economical but produce large eddy currents. A "Self-Correction" concept has been developed and tested which corrects automatically by transformer action, even for variable $\dot{B}$ cycles. Coils attached to the outside of the VC cancel eddy current aberrations over the entire "good field" aperture. The (inexpensive) correction coils follow the local contour of the VC, so large transverse VC movements are tolerated; both the aberrations and their corrections have the same displaced coordinates. Experimental results are presented for Booster correction coil designs demonstrating both self-correction and excitation by a separate power supply. Analytic results applicable to the Booster and other fast cycling accelerators are discussed.

The eddy current field aberrations induced in a pre-production full size vacuum chamber inserted in an AGS Booster[1] dipole have been successfully eliminated by the "self correction" coils attached to its surface. The voltage induced in a two-turns per pole "back leg" winding is sufficient to supply the necessary current through the correction winding. A nichrome wire attached in series provides adjustable resistance for current control.

Discussion

The (curved) 10° dipole magnets of the Booster require curved vacuum chamber. High intensity proton acceleration requires rapid cycling with dB/dt up to 10T/sec. Heavy ion acceleration requires high vacuum fabrication techniques for the Booster vacuum system, with <u>bakeout</u> capability. Thin walled VC are costly and complex. They are also less rugged than standard thick walled VC. Since the <u>average</u> eddy current fields are proportional to design wall thickness, the simple thick-walled, self-supporting VC have larger eddy currents. Chamber-to-chamber variations due to wall thickness, conductivity and geometrical tolerances produce random eddy current field variations. For thick walled chambers random variations can be quite well controlled.

Actually, unit-to-unit random variations can also be removed with the "self-correction" system, based on field measurements.

Thick walled inconel VC were chosen for the Booster[1] dipoles. The VC eddy currents are the largest source of nonlinear field errors for the rapid cycle proton acceleration. The VC have much larger tolerances than the iron magnet cores, so unit-to-unit variations can be larger for VC geometry and location. The curvature, combined with thermal insulation blankets and bakeout capability, result in a situation where VC movement is hard to control.

The self-correction coils follow the translations and rotations of the VC itself, so these errors are automatically corrected for. Sextupole and higher terms are removed at the source. This feature is not available when separate correction magnets are used.

The Booster has fully distributed chromaticity control sextupoles in the lattice. These are strong enough to correct in first order for the VC eddy current aberrations. However, "self-correction" provides an inherently superior <u>additional</u> parameter for optimizing Booster performance. The goal is to obtain the very highest intensity of protons from the AGS complex. Minimizing non-linear errors to give benchmark lattice optics close to its design parameters is desirable for maximum acceptance. Controlled nonlinearity can then be introduced systematically to maximize high current performance.

Computational Studies

The self-correction concept was first tested experimentally using a short section of model VC.[2] Simple empirically located current corrections quickly demonstrated large reductions in sextupole by transformer action.

This success led to a rigorous design using the computer Code "POISSON".

Figure 1 shows the AGS Booster vacuum chamber cross section. Figure 2 shows the VC approximated by a large number of current elements which were used for the POISSON calculation. For a given dB/dt in a dipole field, the voltage applied to each element of current is proportional to its horizontal position, where x=0 is the center of the chamber. The position x, the area of the elements and its conductivity define the current for a given dB/dt. The sum of the fields produced by all elements then should predict the VC eddy current field.

The second step was to look for a simple configuration, with minimum number of turns, which produced the same nonlinearity as the VC itself. A "two block" configuration with 3 turns per quadrant was found. This correction geometry is shown in Figures 1 and 2.

Each copper turn is insulated and sheathed in a stainless steel tube. This type of insulated conductor is industrially available. The outer tube is spot welded periodically to the VC (Fig. 1). The detailed construction will be described elsewhere.

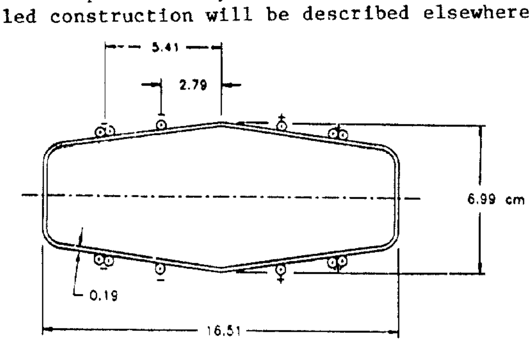

Fig. 1. Booster VC with correction coil.

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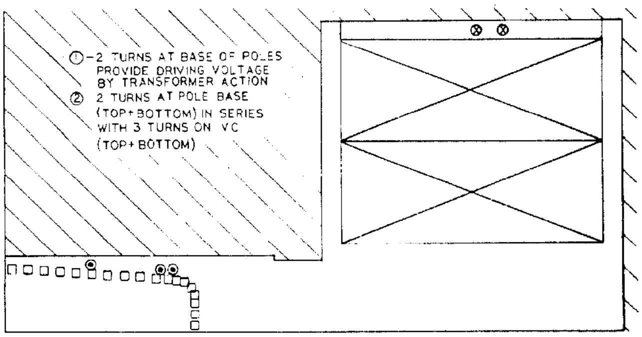

Fig. 2. Computer simulated VC with correction coil.

The agreement of computed VC eddy current field and experiment is excellent. The top and bottom surfaces of the VC produce mainly sextupole (plus dipole). The correction removed the sextupole as well as suppressing higher moments. It only partially cancels the dipole.

The computed VC eddy current field variation on the horizontal midplane (HMP) is shown in Fig. 3 in curve (a). The corrected field nonlinearity shown in curve (c) is better than a purely sextupolar correction would be (curve (b)).

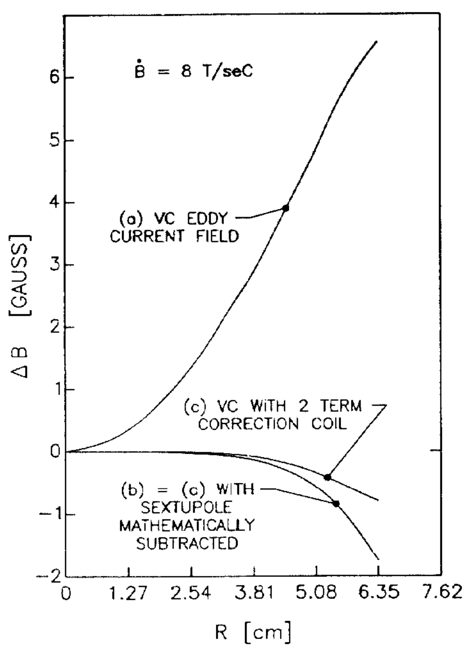

Fig. 3. POISSON computations of VC and correction on HMP.

The two location correction coil will produce field bumps immediately adjacent to the current elements. Figure 4 shows that these have a very small impact. Consider an injection beam size vertically of ± 2.54 cm. This would shrink to ± 2 cm by 0.25T, where $\dot{B}/B$ is maximum. Note that the injected beam vertical size is expected to be smaller than this aperture limit assumption. Similarly the full radial aperture of ± 7.6 cm at injection would have shrunk to ± 6.1 cm by 0.25T. In fact, the horizontal bump injection mechanism considerably limits beam width below the full aperture width.

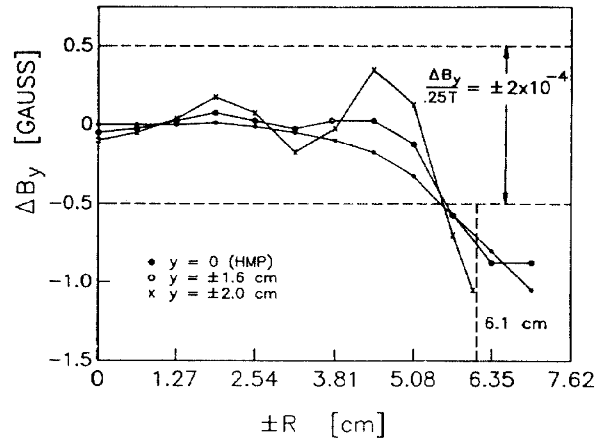

Fig. 4. POISSON computation of VC with correction off the HMP.

Experimental Results

A long curved search coil penetrated the prototype VC in the Booster dipole magnet.

The magnet was fast pulsed with a current excitation approximately that required for proton acceleration. Figure 5 shows (curve 1) the variation in field with radius on the HMP. The (circled) point at r = 0 is arbitrary or normalized (dipole). Measurements made previously without a VC show a very much smaller radial variation. Thus the large nonlinearity which is predominantly sextupolar is due to the VC. This uncorrected result was obtained at $\dot{B}$ = 11T/sec.

The VC correction coil was first powered with a small auxiliary power supply. The field produced as a function of radius was measured with the long coil. It was observed that a current of about 20 amps was required to produce a field variation equal and opposite to that produced by the VC alone.

Figure 5 (curve 2) shows the effect of connecting the self-correction circuit. A variable series resistor is set to the proper value. Since $\dot{B}/B$ max occurs at 2500 gauss, the field is everywhere flat to 1 x 10^{-4} by transformer action throughout this fast proton cycle.

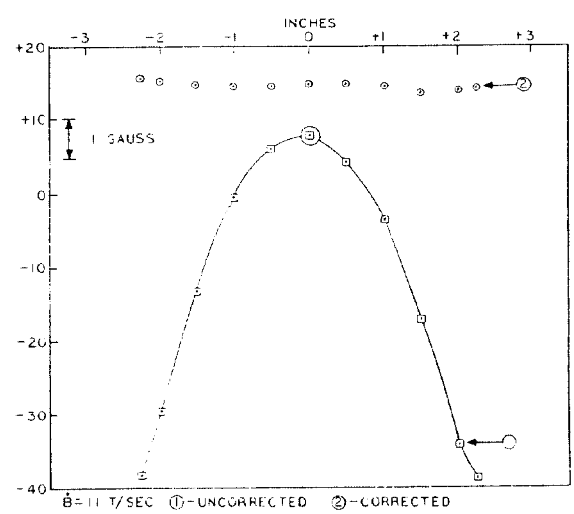

Fig. 5. Uncorrected and "Self-Corrected" field at $\dot{B}$ = 11 T/sec.

Figure 6 contains the same information but for a ten times lower rise rate. The ten times smaller VC eddy currents produced are still corrected, because the correction is independent of rise rate. The series resistance is not changed. This provides a great simplification to field control during proton acceleration since the Booster will have a complex excitation cycle, with large changes of $\dot{B}$.

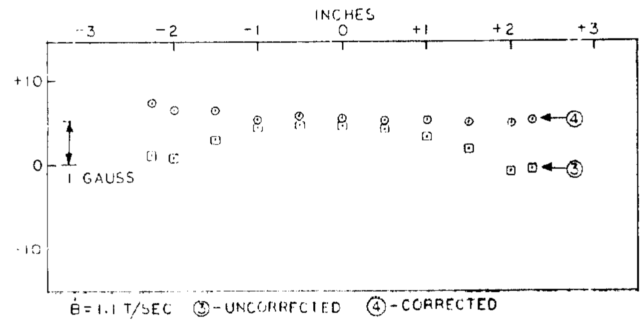

Fig. 6. Uncorrected and "Self-Corrected" field at $\dot{B}$ = 1.1 T/sec

Figure 7 shows the "self-corrected" field shape, run at three different rise rates. It is clear that this system easily removes VC eddy current field non-linearities.

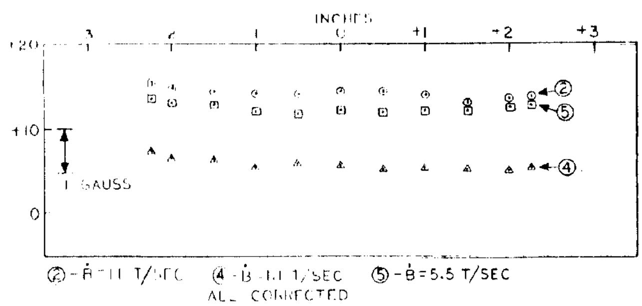

Fig. 7. "Self-Corrected" field at $\dot{B}$ = 1.1 T/sec.

For Booster proton fast cycling, injection occurs at 0.16T and ejection at 0.56T. dB/dt is only 1.4T/sec at injection, rising to 8T/sec by 0.25T, which occurs about 30 millisec later. Since the VC time constant is short, τ = 0.35 millisec, the rate of change of dB/dt is adiabatic. The time constant of the VC correction circuit is somewhat shorter than that of the VC itself. Still the combined response is faster than that of the chamber alone. While not important here, for faster cycled accelerators this could be helpful. Indeed, by adding some series inductance the two time constants could be matched, providing yet another advantage to "self-correction" by transformer action.

With the simple correction used, the dipolar term of the VC eddy current is only partially corrected. The dipoles and both quadrupole strings will all contain VC. Transducers measure the fundamental components in all three. Eddy currents in the magnets and VC, as well as magnetization in the magnets contribute to these fundamental fields: i.e to dipolar in the dipoles and quadrupolar in the quadrupoles. Servoing of power supplies controls the tracking or tune of the machine. The purpose of the "self-correction" is to suppress sextupole and higher moment aberrations.

This method can be extended to more elaborate corrector designs. In some cases printed circuit technology could be employed. Fast cycling machines can benefit. For some intermediate frequency machines the method might extend the frequency range of aluminum VC, for example.

Acknowedgments

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2. G.T. Danby and J.W. Jackson, "Vacuum Chamber Eddy Current Correction Coil for the AGS Booster," (BNL 41464), in Proceedings of the European Particle Accelerator Conference, June 1988.