VACUUM CHAMBER EDDY CURRENT CORRECTION COIL FOR THE AGS BOOSTER*

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Abstract

The AGS Booster injector will perform a variety of functions.[1] Heavy ion acceleration requires a bakeable, ultra-high vacuum system (VC). Acceleration for intense proton beams requires rapid cycling ($\dot{B} \leqq 10T/sec$). If straight forward heavy walled VC are used, the field perturbations due to eddy currents are large. The state of the art lattice has highly distributed lumped sextupoles capable of substantially correcting the induced field nonlinearity.[1] Nevertheless, for the very highest space charge-intensity limits, it is desirable to have the capability to remove eddy current fields at the source. Correction coils attached to the outside of the VC cancel its current aberrations over the required good field aperture. These can be passively powered by transformer action, using two turn windings around the magnet yoke. Programmed power supplies can also be used. This inexpensive additional correction option uses a three turn per quadrant coil which follows the local contour of the VC. Transverse movements of several mms of the VC will have no beam optical effect since the large field aberrations and their corrections have the same displaced coordinates. Experimental and computer studies will be presented, as well as mechanical and electrical design of a simple method of construction.

Description of New Correction Concept for Booster

A coil system has been devised for correction of vacuum chamber (VC) eddy current field aberrations, powered by transformer action using a magnet yoke winding, or by a programmed external power supply.

The Booster vacuum system is complex. The VC must be curved to fit inside the 10° dipole magnets and must be bakeable in situ to 200°C. High vacuum capability is required for heavy ions. Very high intensity proton operation requires rapid cycling, $dB/dt \leq 10T/sec$. Standard thick wall chamber design (like the Brookhaven AGS) is rugged and economical, but eddy currents are large. Complex corrugated or externally supported thin-walled designs are expensive. They are also more delicate, which raises concern with respect to stress and corrosion for application to the multipurpose Booster. The eddy currents have two components relevant to lattice behavior and control. The average eddy current fields generated are proportional to nominal wall thickness, conductivity and chamber geometry. Here the thin walled chamber is superior. The random variation chamber-to-chamber is proportional to variations in the above: i.e., to tolerances. It is not obvious which is superior here.

The Booster is a state of the art machine, with fully distributed chromaticity sextupoles in the lattice of adequate strength to also correct, at least in first order, for the average dipole induced VC eddy current sextupole. VC eddy current fields are large: by far the dominant source of nonlinear field error for the rapid cycling proton operation. Unit-to-unit variations will also be larger than from any other sources. Vacuum chambers are "tin ware," and have much looser tolerances than iron magnet cores. The VC correction coils can remove sextupole and other aberrations at the source, thereby eliminating the need for correction by the chromaticity sextupoles. These coils also correct for VC positional errors. This will permit an additional parameter for control and optimizing Booster operation at modest cost (< 1K$ per magnet). In summation, since the plan is to push the Booster and AGS complex to the very highest limits of intensity practical for proton beams, space charge electrostatic repulsion in the Booster beam will be a very large factor. It seems reasonable to attempt to produce the largest "good field" linear aperture acceptance to avoid resonances. Starting from a base of minimum deviation from the designed lattice, controlled nonlinearity can then be introduced empirically, as part of ongoing studies and theoretical analysis, to maximize performance.

Booster Vacuum Chamber Experiments

An early VC model, 60 cm long, was measured for eddy current content. (Fig. 1). "Self-correction" was studied using insulated 1.9 mm Cu wires taped on the VC, powered by magnet yoke windings. Note that the final Booster VC design will be described later.

Proton injection (200 MeV) occurs at 0.16T, ejection (1.5 GeV) at 0.55T. For the proton rapid cycle $\dot{B} = dB/dt = 1.4T/sec$ at injection, and increases slowly to ~ 8T/sec 30 millsec. later at 0.25T. The maximum $\dot{B}/B$ is about 8T per sec/0.25T.

Experiments were carried out for constant $\dot{B} = 8T/sec$. At first impulse a VC will behave diamagnetically. The time constant of the Booster VC is $\tau = 0.35$ millisec. For the actual Booster cycle with variable $\dot{B}$ after injection, the rate of change is sufficiently slow, the behavior is "adiabatic". Thus the relative eddy current field shape is constant, all terms scale linearly with $\dot{B}$. The first difference dB/dr was measured at $\dot{B} = 8T/sec$ across the horizontal midplane (HMP). A fit to this data was expressed at full VC radius r = 7.6 cm: dipole = - 21g, sextupole = + 10.0 g, 10-pole = + 0.8g, "14-pole" = - 5.2g ("14-pole" includes any higher terms). Note that the VC sextupole alone at r = 7.6 cm is about 0.4% of the 0.25T dipole at maximum $\dot{B}/B$, larger than other sources of sextupole error.

Corrections were taped on the VC, with two or three turns located above and below the HMP. "Self correction" by transformer action from loops around the magnet "back leg" was applied. A variable resistor in series with the VC turns and the "back leg" loops adjusted the correct current. The correction automatically adjusts to variable $\dot{B}$. (Excitation by a small power supply was also demonstrated.) Figure 2 shows results of transformer induced correction with the simple coil arrangement of Fig. 1. Since dB/dr is measured, sextupole appears as a linear gradient. The solid line with the small slope is the sum of VC eddy currents plus both correction loops. The residual sextupole could be adjusted to zero by increasing I to 20.2A. This results in good correction to about ± 5 cm, with this rough empirical model. (The dotted curves show the effect of each correction turn alone). Other correction geometries were also successfully tested.

Analytical Solutions Using "Poisson"

These simple experiments encouraged application. An analytical study was carried out. The VC model was approximated by a large number of current elements (Fig. 3). In a dipole field with constant $\dot{B}$, a voltage proportional to radius r is imposed on each element (r = 0 is the VC center). Agreement of the computed eddy current field with experiment was excellent. Based on the multipoles computed for each VC element, analysis was used to arrive at the simplest two-location per quadrant solution shown in Fig. 3. For $\dot{B} = 8T/sec$, 10 amperes in the three turns per quadrant coil reduces the sextupole to zero. Two "back leg" turns around each pole, plus a series resistance, are the current source.

The top and bottom surfaces of the VC produce mainly sextupole (and dipole). The correction addresses this, plus suppression of higher moments. Figure 4 shows the computed model VC eddy current variation with radius on the HMP (y = 0). Curve (c), the computed but corrected chamber, is better than curve (b) which

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is a pure mathematical subtraction of the sextupole term only: the correction is compensating for higher terms as well.

Figure 5 shows what happens off the HMP. Clearly this two location correction produces field bumps immediately adjacent to the conductors. Assuming an injection vertical beam size of ±2.54 cm, which is larger than expected for the A.G.S. Booster, the maximum perturbation (at 0.25T) for extreme particles would be $\leq 2 \times 10^{-4}$ of the dipole. Full radial aperture of 7.6 cm at injection, becomes 6.1 cm by phase space shrinkage. The horizontal bump injection scheme[1] further reduces beam width well below ± 6.1 cm.

Consider a full length application. The entire circuit, i.e., the four back leg turns in series with the six VC correction turns, would generate 15 volts open loop. If the circuit resistance was 1.5 ohms, 10 amps of correction current would flow. The back leg turns are flat Cu ribbons at the base of the coils, with negligible resistance. Using Cu conductor 1.6 mm in diameter the entire correction coil resistance equals 0.3 Ω. Series resistance of 1.2 Ω is required. The correction winding peak power dissipation is 30 watts: this corresponds to a thermal load of 1 watt per linear meter of correction wire. "Poisson" calculations show the circuit inductance = 0.24×10^{-3}h. The circuit time constant would be short, ~ 0.2×10^{-3} sec.

Booster VC Correcting Coil Design

Figure 6 shows the Booster VC design. "Poisson" results for uncorrected VC eddy current fields at $\dot{B}$ = 8T/sec, are dipole = 31g and sextupole = 10.5g at r = 6.35 cm. A preliminary design for a correction coil is shown on Fig. 6, which removes sextupole, etc., with a current of 14.4 amps. The residual field errors are very small, essentially the same as shown in Fig.5, over the entire acceptance area.

A full length model has been constructed. Windings use a standard industrial product: 4.8 mm O.D. thin walled stainless steel tube containing non-organic insulator and 1.6 mm Cu wire. Small stainless tabs are used to tack weld the windings to the VC. Templates used during welding ensure the location of the windings relative to each other; they follow the local VC contour. Sharp bends are permitted for coil ends.

Discussion

Note that with this simple geometry the correction of the VC dipole term is only partial. In the Booster, a dipole and two quadrupoles, all containing VC's, operate in series with the magnet strings. Transducers measure the dipole, QF and QD, respectively. This includes contributions from eddy currents and also magnetization. With higher moment aberrations canceled, servoing can be used to completely control systematic dipole and quadrupole fields and thus the tune.

For the Booster proton cycle, the eddy currents will change adiabatically: $\tau_{VC} \sim 1/3 \times 10^{-3}$ sec, τ correction ~ $1/4 \times 10^{-3}$ sec. More generally, by adding series inductance as well as resistance, the correction time constant could be matched to the VC which could be useful for very rapidly cycled accelerators. The simple correction was chosen because of the desire for a high temperature design. For rapid cycling machines where bakeout is not required, printed circuits permit many turn corrections at low cost. The density of corrector wires would increase ~ radially and more closely match the VC eddy current.

In conclusion, the Booster design calls for very accurate magnets, located to the best surveying accuracy. The curved VC are surrounded by thermal insulation. They cannot be strongly mechanically coupled to the magnet poles. Subject to bakeout, they may move around considerably, resulting in large displacements of the centers of the strong eddy current "magnets". The correction moves with the chamber. Thus, with this scheme, the tolerances on chamber location can be very loose as far as beam optical errors are concerned. This may prove to be very important: external corrections or even pole face windings cannot do this. The vacuum chamber correction coils can do an excellent job of correcting the eddy currents in the chambers. Otherwise these are the dominant source of errors in the Booster magnets.

Acknowledgements

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References

1. Booster Design Manual, BNL, October, 1986.

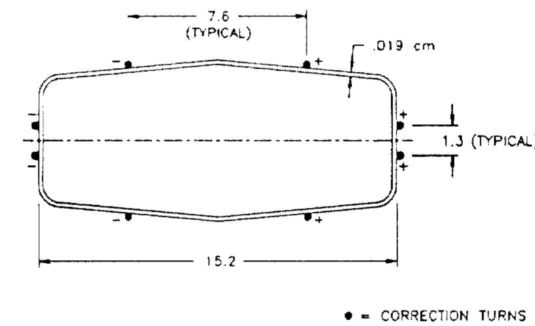


FIG. 1 BOOSTER VC: EARLY MODEL

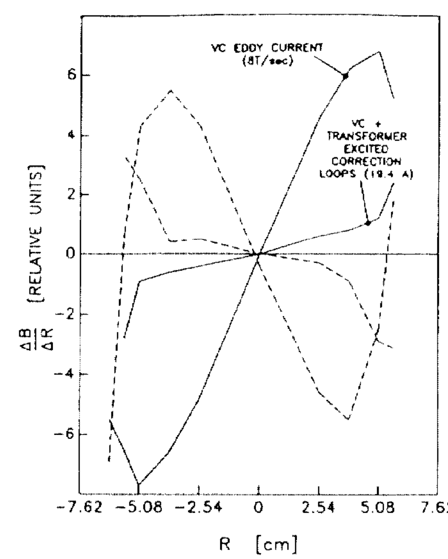


FIG. 2 EARLY VC MODEL MEASUREMENTS

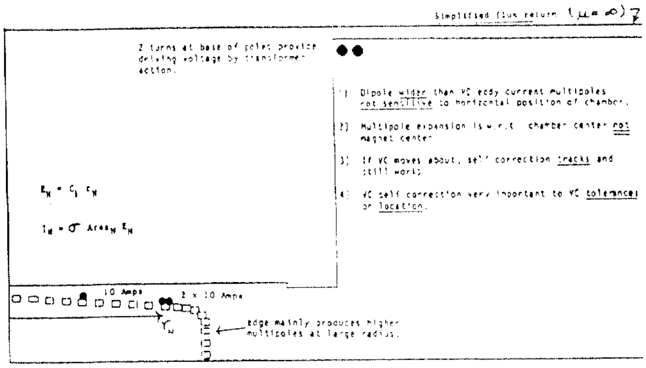
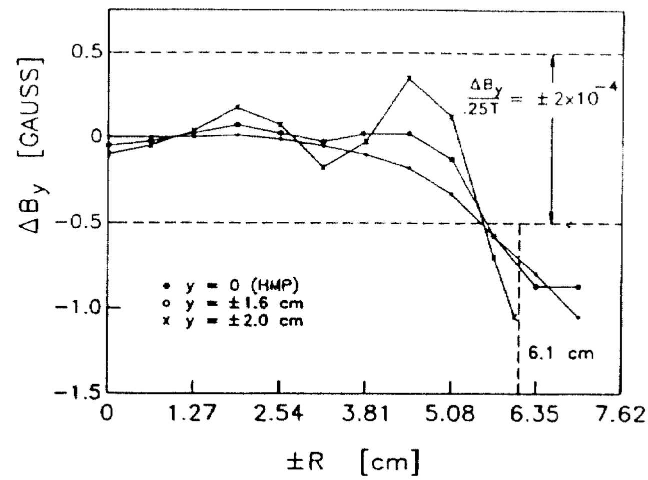


FIG. 3 POISSON COMPUTATION OF VC WITH CORRECTION COIL

FIG. 5 EDDY CURRENT ΔB_y VERSUS RADIUS OFF THE HMP, $\dot{B}$ = 8 T/sec.

ΔB_y FOR THE VC PLUS FIG. 3 CORRECTION OPERATING AT 10 AMPS/TURN.



1. y = ±2.0 cm AT 0.25 T CORRESPONDS TO y = ±2.5 cm AT 0.16 T INJECTION. WHERE $\dot{B}$/B IS SMALL. THIS IS LARGER THAN THE EXPECTED INJECTION BEAM HEIGHT.
2. FULL HORIZONTAL APERTURE, R = ±7.62 cm, WILL SHRINK TO ±6.1 cm BY 0.25 T. THE HORIZONTAL KICK INJECTION SYSTEM FURTHER REDUCES BEAM WIDTH.

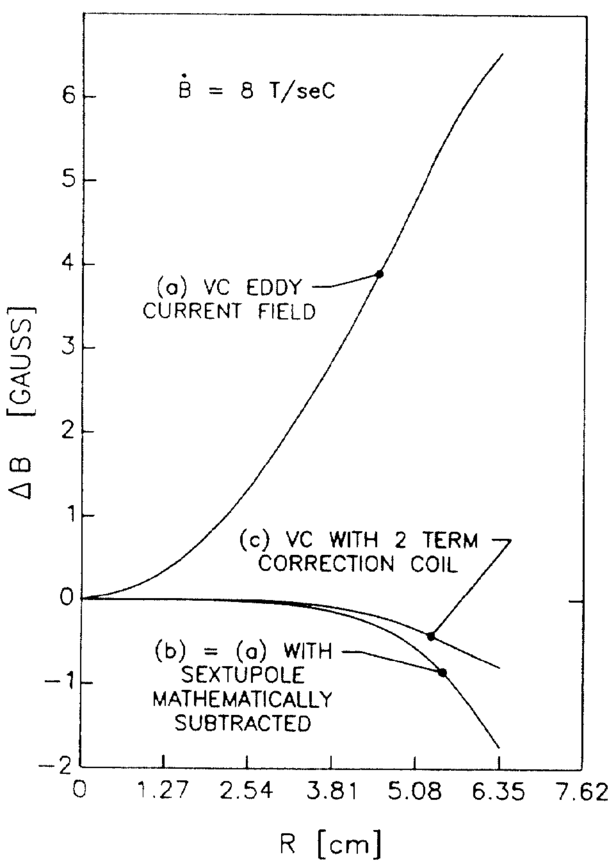


FIG. 4 POISSON COMPUTATIONS OF VC AND CORRECTIONS ON HMP

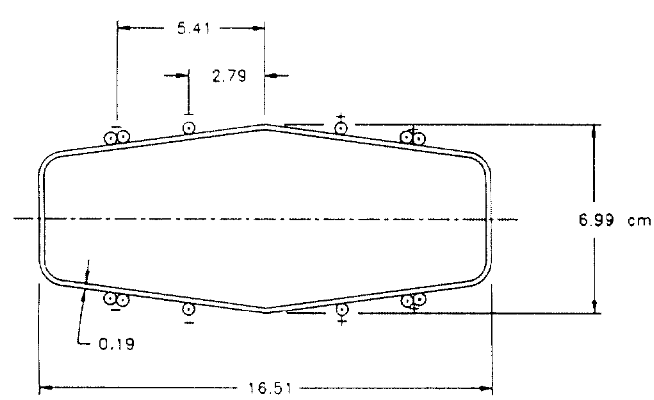


FIG. 6 BOOSTER VC WITH PRELIMINARY CORRECTION COILS