The excitation of a novel backleg winding system has significantly contributed to increasing the intensity of the AGS. The benefits of the improved magnetic lattice properties at fields in the vicinity of injection were demonstrated, both for future operations and for quantitative study of high intensity phenomena.

A record intensity of $3.2 \times 10^{12}$ protons per pulse was attained when some portions of these windings were activated. This occurred approximately two years ago, too late for the previous Conference. The underlying ideas and computations preceded this date by about two years. While many turn backleg windings already existed on the AGS magnets, the appropriate systems connections had to be constructed and installed during a shutdown. It was hoped by now to have experimental studies using all the systems, but time commitments have prevented further work to date. However the ideas used and the particularly simple approach to orbit analysis developed warrants being described.

I. Introduction

The lattice design of the AGS is based on the dynamic magnetic field characteristics. However, at low dynamic field values (near injection) the eddy currents and remanent fields have a major perturbing effect on synchrotron properties, just when the beam is most vulnerable. Eddy currents in the vacuum chambers and end plates depress $k$ values and also introduce some higher multipole nonlinearity. The $y$ values of the machine are affected by eddy currents, but the lattice symmetries are substantially maintained. Remanence, on the other hand, also introduces effects which depend on whether the hyperbolic poles open or close with respect to the backleg magnet yokes. The open or closed configuration does not vary in step with the cell structure.

The AGS has always had one pair of tuning quadrupoles per superperiod. In the course of tuning up the machine these quantized quadrupoles themselves produce large $\beta$ distortions. A considerably greater number is necessary to give high enough multiplicity so that tuning itself is not a major source of distortion. The two problems of $\beta$ distortion and tuning of the rapidly changing $y$ values near injection lead to the formidable requirement of introducing very large numbers of $\epsilon$-correction and tuning quadrupoles into the existing machine. Indeed such magnets have been planned as part of the Conversion.

II. Lattice Correction

The present idea was simply that the excitation of the 240 main magnets could be varied to give the desired focusing strengths while the resulting dipole perturbations could be easily handled. With combined function magnets any variation in gradients leads, of course, to a proportional variation in the dipole fields. Although AG machines are very sensitive to dipole field perturbations, in this case the orbit distortion is quite small. This comes about because one is varying the fields with very high multiplicity compared to the $y$ values of the machine (i.e. $N=60$, the number of cells versus $y<9$). As a result the forcing function has this relatively high frequency.

A study of such systems was carried out and extensive computations were made using the SYNCH Program and Fourier analysis.

The phase-amplitude solutions elegantly and accurately describe synchrotron behavior. The azimuthal modulation of the phase and of the amplitude coordinates is commonly incorporated into a new set of coordinates which are variable in real space so that the behavior in the new coordinate system can be described by harmonic functions rather than being governed by Hill's Equation. In the present work a particularly simple approach was used. The azimuthal modulation of phase angle at a frequency which is both compatible to the harmonic terms necessary to describe orbit errors and their corrections. Deviations from the ideal machine were described by harmonic series, with the $\beta$ amplitude correction applied, but the phase modulation ignored. Any resulting small systematic changes in the harmonic components describing an orbit error applies equally to its $180^\circ$ phase shifted corrected and nothing is lost. In all cases the actual orbit calculation is unchanged by this simplification.

The computational study led to three types of windings being designed: (1) $\epsilon$-correction windings to equalize all gradients. (2) new and simplified harmonic correction windings based on the above ideas and (3) $\gamma$ tuning windings capable of dynamic tuning of the machine without $\beta$ distortion. (1) $\epsilon$-correction. The results showed that 12 ampere turns in a circuit around all the backlegs equalize the gradients to completely remove the backleg $\beta$ distortion. Because of the structure of the lattice, this in turn leads to some equilibrium orbit distortion. Therefore, with the gradients corrected, the orbit distortion was Fourier-analyzed. Imposing a sin 12$\beta$ correction of 5 ampere turns in a circuit around 24 equally spaced magnets reduces the maximum orbit displacement below 100 mils. This modest residue is predominantly 24$\beta$ and in fact could be removed if desired. The $\beta$ distortion reintroduced when the 12$\beta$ orbit correction is imposed is negligible, only 15.

(2) Orbit correction. The previously existing AGS 89 and 98 correction windings were complex and required many turns on the magnets. This was because of the desire to match ampere turns to the amplitude and phase modulation of each harmonic. In the present work the simplified 89, 98, and 12$\beta$ corrections were installed. For NB a circuit around 2N equally spaced magnets is used with the sign alternating, i.e. 180$^\circ$ apart.

Table 1 shows in column II the amplitudes of the harmonic components of the 12-fold orbit distortion resulting from the $\beta$-correction. Column III gives the harmonic components for a 12$\beta$ correction of arbitrary amplitude. The higher mode amplitudes are only a few percent of the 12$\beta$. Comparison of the sum of the harmonic components in columns II and IV with the analysis of the orbit with the predicted correction applied (i.e. Column V) shows the
satisfactory accuracy of both the simplified corrections and the method of analysis.

A much more severe test of the analysis is provided by imposing only the positive and negative half of the 128 excitation separately. This creates distorted 128 orbit deviations. However the sum of the harmonic description of these orbits (Column VIII) agrees very closely with Column III.

The sin 128 and cos 128 windings installed are very useful for other purposes besides the β-corrected orbit distortion, since the machine has 12 fold periodicity. (3) Tuning windings. Another winding circuit which alternates with the cell structure can be used for y tuning. Since this has the full N=60 multiplicity of the machine, there is negligible orbit or β distortion. This arrangement can be used for an extended class of y variations and the circuit is completely non-inductively coupled to the primary magnet current. This makes precise programming of a power supply for dynamic tuning very easy. For a large Δv of 0.3, the equilibrium orbit is only distorted by ~ 20 mils. This dynamic y correction is restricted to moving along the principal diagonal. In practice this combined with possible small excursions in this direction, or the minor diagonal using quantized quadrupoles, gives sufficient degree of freedom for avoiding coupling resonances etc. In practice a combined function machine is usually tuned close to the principal diagonal in any event since it requires considerably less quadrupole strength to "split" the focusing than to bootstrap all the focusing in the same direction.

Experimental Results

The β-correction winding requires 6 amperes in a circuit of two turns threading all the magnets. Because of the lattice structure there is a back emf of ~ 20 volts at injection and ~ 100 volts at maximum B. The circuit resistance is 4Ω, requiring 250 volts. For the tests a 500 volt supply was improvised with 32 1ξ of added series resistance. With 6 amperes at injection, this β corrected current dropped ~ 18% at maximum B. However by this time the dynamic field is larger and it is unlikely that this compromise effects performance significantly. With this winding switched on as per design, the early losses were greatly reduced, corresponding to 25% to 30% increase in beam held. Very stable parameter operation was obtained. Even at intensities of 3 x 10^12 a factor of two reduction in brightness gave a factor of two less beam with no retuning of the machine. Although this result must be somewhat qualified in detail, its implications for the future are clearly very great.

Discussion

The β correction and orbit correction windings are routinely used in operation of the AGS. Provision was made in the wiring system for additional sine and cosine orbit corrections for correction of non-systematic errors in the machine. Finally, the y tuning winding is used for dc tuning only at injection. No dynamic tuning experiments have as yet been performed.

References


Table I Fourier Analysis of Synch Computations

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Explanation of column headings

I. Terms in Fourier analysis
II. Results for equal gradients in all magnets at injection field.
III. Results for a 126 correction of arbitrary amplitude.
IV. Theoretical predictions of correction needed to exactly compensate the 126 term of column II, that is, III scaled by (-0.600/2.481).
V. Results for equal gradient magnets with the predicted theoretical 126 compensation superimposed.
VI. Results for a distorted partial sin 126 correction using the (0°) excitation of 12 equally spaced magnets.
VII. Similar to column VI but for negative 180° phase shifted set of 12 equally spaced magnets.
VIII. Sum of VI and VII, which should be compared to the actual 126 correction (column II).

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