THE TRANSITION JUMP SYSTEM FOR THE AGS*

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Abstract

In an attempt to generate a lossless crossing of an accelerator's transition energy, one procedure is to alter the transition energy of the accelerator quickly as the beam passes through this energy region by changing the optics of the lattice – a so-called "transition jump," or "γ_t-jump" scheme. Such a system was first implemented at CERN[1] and later adopted at other accelerator laboratories. A scheme for the AGS was developed in 1986. The system has become operational during the 1994 high intensity proton run. It consists of three quadrupole doublets, each magnet having an individual power supply and crowbar circuit. After a brief theoretical description of the jump system for the AGS, we describe the engineering aspects of the hardware and our experience with the system during its commissioning.

I. FIRST PRINCIPLES

Changing the transition energy in the AGS amounts to changing the average value of the dispersion function, D_x, in the bending magnets of the accelerator. The value of γ_t for a synchrotron with sector bending magnets is given by

$$\frac{1}{\gamma_t^2} \equiv \frac{\Delta C/C}{\Delta p/p} = \left\langle \frac{D_x}{\rho} \right\rangle, \qquad (1)$$

where the average is taken over the circumference of the accelerator. The value of ρ is path length dependent, and has infinite value in straight sections. Hence, it is the value of the dispersion function in the bending magnets which one is after in this exercise of altering γ_t.

A. Lattice Perturbations

By introducing quadrupoles in the normal AGS lattice, one can perturb the dispersion function and hence, hopefully, alter γ_t in a constructive way. The choice of quadrupole locations for this purpose in the AGS resulted from a study in 1986[2],[3]. The AGS system alters the dispersion function as shown in Fig. 1.

By varying the strength of the six quadrupoles, one can tune the accelerator to various values of γ_t. Perturbations to the lattice functions of the AGS will have approximate values given by[4]:

$$\Delta\hat{D} \approx \frac{D_0(\beta_0 q)}{2}\sqrt{1+\tan^2(\frac{\pi\mu}{2})}, \qquad (2)$$

$$\left|\frac{\Delta\beta}{\beta}\right|_{max} \approx \left|\frac{\beta_0 q}{2}\right| \qquad (3)$$

where $q \equiv \Delta B'\ell/(B\rho)$, $\mu = \nu/3$ is the tune across one-third of the ring (the new superperiod), and D_0 and β_0 are the unperturbed lattice functions at the quadrupole locations. As an example, taking $\beta_0 q = 1$ (approximate value of the AGS γ_t quads running at 1500 A near the AGS transition energy), we get $\Delta\hat{D} \approx$ 7.5 m, and $\Delta\beta/\beta \approx 0.5$. Detailed calculations of the jump system using the code SYNCH[5] are in agreement with these predictions.

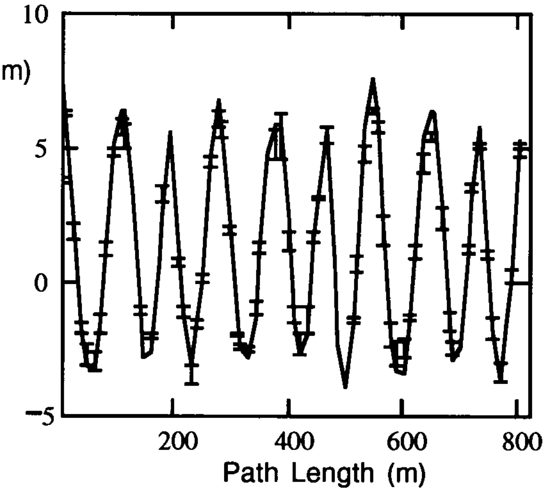

Figure. 1. Measured AGS dispersion function during the γ_t-jump. The solid curve is the dispersion function predicted using SYNCH.

B. Estimation of Tune Shift

According to the well-known tune shift formula, $\Delta\nu = \beta q/4\pi$, there should be no tune shift from six regularly spaced, alternating gradient quadrupoles in the AGS. However, the strength of these quadrupoles can be large enough that second order effects come into play, and results in

$$\Delta\nu_{x,y} \approx \frac{3\tan\pi\mu}{8\pi}(\beta_{0(x,y)}q)^2. \qquad (4)$$

As an example, for the AGS with a tune of 8.75, and for q = 1/20m, we get $\Delta\nu_x = -0.03$, and $\Delta\nu_y = -0.007$. Notice that both tune shifts are of the same sign, since they depend upon the square of the quadrupole strength.

C. Estimation of Shift in Transition Energy

To obtain an estimate of how much one can change γ_t with the AGS system, we can use Eq. 1 to see that

$$\Delta\gamma_t \approx \frac{-\gamma_{t0}^3}{2\rho}\,\Delta\langle D\rangle \qquad (5)$$

for small variations in the lattice parameters. For the AGS system, consider the change in the dispersion function, ΔD, across one new superperiod (one third of the ring). By computing the change in the dispersion function at a "positive" quad, and propagating this change through two standard superperiods of the

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*Work performed under the auspices of the U.S. Department of Energy.

AGS, summing up the changes ΔD in the bending magnets between two consecutive "positive" quads, say, and taking their average, one can employ Eq. 5 above to estimate $\Delta\gamma_t$. Doing so, we obtain:

$$\Delta\gamma_t \approx \frac{\gamma_{t0}^3 D_0}{32\rho}\left(\frac{\tan\pi\mu}{\cos^3\frac{\pi\mu}{2}}\right)\langle\mathcal{A}\rangle_{\mathrm{bends}/6}\;(\beta_0 q)^2. \tag{6}$$

where $\mathcal{A}_i \equiv$

$$\sqrt{\frac{\beta_i}{\beta_0}}\left[\sin(\psi_i - \frac{3\pi\mu}{2}) + \left(\cos\frac{\pi\mu}{2} - \alpha_0\sin\frac{3\pi\mu}{2}\right)\sin\psi_i\right]. \tag{7}$$

Here, β, β_0, α_0, and D_0 are unperturbed values of the lattice functions (β_0, α_0 and D_0 are at a γ_t-quad), $\Delta\psi$ is the phase advance from the nearest upstream γ_t-quad, $\mu = \nu/3$, and the average taken in the above expression is over the bending magnets in one sixth of the AGS circumference.

For the AGS, with ν = 8.75,

$$\langle\mathcal{A}\rangle_{\mathrm{bends}/6} \approx 0.025 \tag{8}$$

and taking $\nu = 8.75$, $\gamma_{t0} = 8.5$, $\rho = 85.38$ m, and D_0 = 2.1 m, we get

$$\Delta\gamma_t \approx 1.7\;(\beta_0 q)^2. \tag{9}$$

Quick estimates of system parameters for a nominal AGS horizontal tune of 8.75 can be made using the following summary:

$$\Delta\gamma_t = 1.7\;(\beta_0 q)^2 \tag{10}$$

$$\hat{D} = \hat{D}_0(1 + 3.2\sqrt{\Delta\gamma_t}) \tag{11}$$

$$\hat{\beta} = \hat{\beta}_0(1 + 0.4\sqrt{\Delta\gamma_t}) \tag{12}$$

$$\Delta\nu_x = -0.02\Delta\gamma_t \quad , \quad \Delta\nu_y = -0.005\Delta\gamma_t \tag{13}$$

II. ENGINEERING ASPECTS OF THE JUMP SYSTEM

The design of the transition jump system called for 3 quadrupole doublets, with one magnet in every other superperiod at a horizontal β_{max} location. This geometry was achieved by redesigning the tune correcting quadrupoles in a more compact way such that two quadrupole magnets could be installed in the #17 straight sections of each superperiod in the AGS. Total tune shifting quad strength has not been sacrificed by acquiring higher rated power supplies.

The power supply for each magnet is comprised of a remotely programmed charging supply connected to the magnet through a triggerable switch (see Fig. 2). The power supply is ramped to the desired current, at which time the switch is opened and the current is crowbarred through a power resistor. The time constant of this current has been a central design issue and a value of 600 μsec has been achieved.

To handle the switching requirement of 3 kA a solid state Gate Turn-off Thyristor (GTO) was selected. GTO's possess the current and voltage handling capabilities needed and can be rapidly triggered on and off. The Marconi DG758BX45 was selected for at the time of the design it had the highest on-state current of any GTO on the market. Two GTO's in parallel are used in the switch (GT01 and GT02). These GTO's were purchased in matched pairs to optimize current sharing. Delay and storage times as well as on-state voltage were the matching parameters.

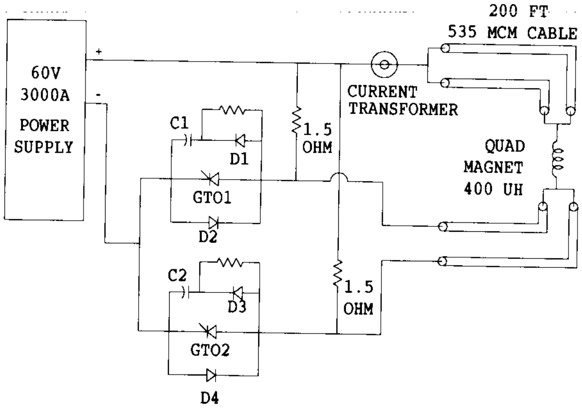

Figure. 2. Schematic diagram of the main components of the transition jump system.

Integral to the switch design was the snubber design. For reliable GTO turn-off, the rate of rise of the off-state voltage (dV/dt=500 V/μsec) can not be exceeded. The capacitor selected for the circuit was a Maxwell mini double ended 37600. Four of these 2 μF, 5 kV capacitors are connected in parallel using copper bus (C1,C2). Each capacitor has an inductance of less than 20 nH and a shot life of greater than 10^8. This inductance is important because the rapidly falling GTO anode current at turn-off is transfered to the snubber circuit until the capacitor is fully charged. The overall circuit inductance dictates the magnitude of the voltage spike across the GTO at this time. This spike must be minimized to protect the GTO from excessive turn-off power dissipation. The component interconnections also contribute to the circuit inductance. Care was taken to mount all snubber components as close as possible to each other. Large buswork and component heatsinks were used as connections to eliminate wire connections. Buswork inductance is estimated to be 100 nH, well below the manufacturer's recommended value of 200 nH. Also adding to the GTO turn-off voltage spike is the forward recovery voltage of the snubber diode (D1,D3). This transient voltage is developed after forward voltage is applied to the diode and before it fully conducts. The International Rectifier R52KF45 was selected for its low forward recovery voltage of approximately 100 V. This fast recovery diode is rated for 990 A, 4500 V and has a recovery time of 5 μsec. Using this design, GTO turn-off voltage spikes of less than 300 V were obtained when switching 3 kA.

The crowbar resistor proved to be another design challenge. Two 1.5 Ω, 2 kW resistors were needed. High voltage, high energy dissipation ceramic disc resistors of 0.125 Ω each were selected. When purchased they were mounted as stacks of 12 on an insulating non-reinforced polyimide rod. During testing resistors failed due to arcing. This was caused by the fact that the torque keeping the discs in place could not be maintained due to the inherent creeping properties of the polyimide material. A brass rod was used as replacement and G-10 was used to insulate the rod from the discs. Belville washers were used to keep

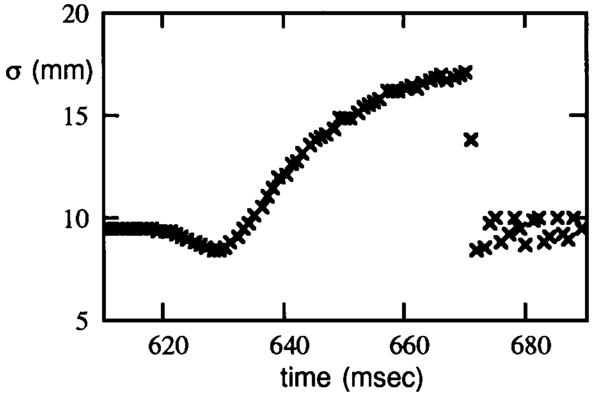

Figure. 3. The beam size measured by the IPM, during the ramp and discharge time of the transition quadrupoles.

the torque constant on the discs by compensating for any thermal cycling during operation. As an added measure, fans were installed to cool the length of the resistors.

The power supplies are located in the service buildings closest to each magnet. A quadruplex 535 MCM cable run with an average length of 200 ft connects the supplies to the magnets. The cable resistance (5 mΩ) and inductance (20 μH) only marginally contribute to the time constant of the current decay.

III. COMMISSIONING OF THE JUMP SYSTEM

The power supplies became available in early 1994 and the commisioning of the system began in March during the startup period of the FY94 high energy physics run. After verifying polarities and timing of the individual quad systems, it was found that beam loss occured while the entire system was pulsed at currents well below the design value. The BPM system showed orbit excursions well over 10 mm during the ramp of the quadrupoles, which were found to be caused by rather large excursions of the orbit with respect to the quadrupole magnets. To reduce this effect the AGS main dipole magnets have been realigned. To minimize this steering effect even further, the quadrupole magnets themselves have been moved to center the orbit as well as possible in the magnets.

As illustrated in Fig. 1 there are large excursions of the dispersion function during the time when the transition energy is modified. At the Ionization Profile Monitor (IPM) location, the dispersion changes from the nominal 2 m to about -5 m, when the magnets are ramped to 1500 A, corresponding to a change in the transition energy of 1.5 units. In Fig. 3 the measured beam size is plotted during the ramping of the currents in the quadrupoles. At first the beam size decreases with the dispersion, but increases significantly later when the absolute value of the dispersion becomes larger than for the nominal machine. For a given momentum spread, this effect limits the maximum size of the transition jump, because it leads to beam scraping.

By the same token, for a given jump size the maximum acceptable momentum spread is set by the beam losses at transition. To reduce this increase, part of the longitudinal beam dilution process using the Very High Frequency (VHF) cavity, which is required for stability later in the acceleration cycle, is exercized after transition. In addition, the voltage of the main RF system is decreased during the time before the jump.

IV. STATUS AND OUTLOOK

The intensity in the AGS has reached the design goal of 6×10^{13} and the transition jump system has been one of several systems which have been essential in achieving this. Because the beam size increases with intensity the beam blowup due to the jump also increases, causing beam losses in the vicinity of transition. During the present FY95 high energy physics proton run transition losses of 2 to 3% at intensities above 5×10^{13} are typical.

Under typical operating conditions the quadrupoles are ramped to approximately 1500 A, which is far below the capacity of the jump system. The system has been used at full capacity during acceleration of gold ions when the field at which transition occurs is much higher.

Experimental studies and modeling of non-linear chromatic effects associated with the present jump system are described in a separate paper.[6]

With the outlook of even higher intensities in the future and the demand for the lowest possible beam losses, the consequences of the large excursions of the dispersion function with the present system are imminent. For that reason an investigation towards the possibility of implementing a linear jump system [7] for the AGS has started.

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