EFFECTS OF ENHANCED CHROMATIC NONLINEARITY DURING THE AGS γ_t-JUMP*

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Abstract

The γ_t-jump designed to reduce the bunch self-field mismatch and intensity loss during the AGS transition crossing can cause significant orbit and lattice distortions and dramatically enhance chromatic nonlinear effects. Employing a low-intensity, small emittance proton bunch crossing transition with the γ_t-jump quadrupoles excited, we found that the nonlinear momentum-compaction factor α_1 increases from 2.2 to about 90 in the presence of the γ_t-jump. On the other hand, this enhancement can be effectively suppressed by properly exciting the chromaticity sextupoles, reducing α_1 from 90 to 16. The experimental measurement agrees well with computer simulations using MAD and TIBETAN.

I. INTRODUCTION

During recent years, the γ_t-jump method[1] has been extensively used in hadron accelerators to improve crossing efficiency at transition energy. In the Brookhaven National Laboratory AGS, a γ_t-jump has been successfully commissioned and routinely used since 1994 in both[2] proton and heavy ion operations. With the γ_t-jump, bunch-shape mismatch caused by beam self fields is significantly reduced. Acceleration of high intensity protons (up to 6×10^{13} per pulse)[3] can be achieved with relatively small beam loss.

During operation, it has been observed that the second-order γ_t-jump scheme[2] currently used in the AGS causes significant distortion in the machine lattice. The measured maximum dispersion increases from about 2.2 to 8.6 meters, and momentum aperture is significantly reduced. Even with low-intensity beam, quadrupole-mode bunch oscillations (Fig. 1) and occasional beam loss occur near transition energy when γ_t-jump is employed.

Under the hypothesis that bunch oscillations and beam loss of low-intensity beams are caused by chromatic effects,[4] which are enhanced by the lattice distortion during the γ_t-jump, we proposed an experiment to first measure the increase in the nonlinear momentum-compaction factor α_1 in the presence of the jump, and then to demonstrate the possibility of reducing α_1 by exciting the sextupole families. Section II of this paper summarizes the experimental method used to measure the α_1 factor and the momentum aperture during the jump. The results are compared with computer simulations in Section III using the programs MAD and TIBETAN. The conclusion is given in Section IV.

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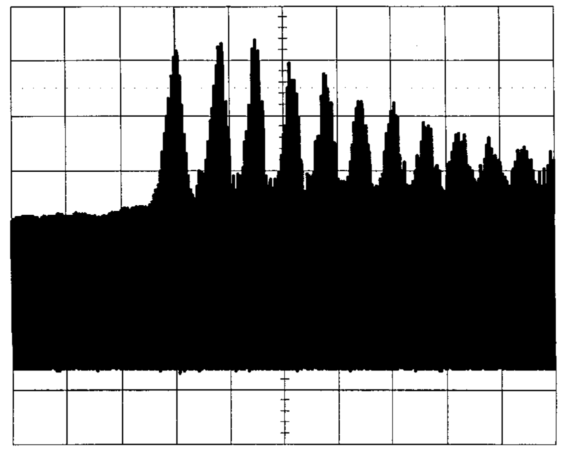

Figure. 1. The envelop of the longitudinal pick-up signal during transition showing more than 100% amplitude modulation. The abscissa is time (5 ms per division).

II. EXPERIMENTAL ANALYSIS

In the low-intensity limit when multiparticle effects are negligible, the longitudinal motion of the particle can be described in terms of its rf phase ϕ and energy deviation $W \equiv \Delta E/h\omega_s$ by[5,6] the equations

$$\begin{cases} W_{n+1} = W_n + \dfrac{qeV}{h\omega_s}(\sin\phi_n - \sin\phi_{s,n}) \\ \phi_{n+1} = \phi_n + \dfrac{2\pi h^2\omega_s\eta(W_{n+1})}{E_s\beta_s}W_{n+1} + \phi_{s,n+1} - \phi_{s,n} \end{cases} \quad (1)$$

where ϕ_s, ω_s, β_sc, E_s are the synchronous phase, revolution frequency, velocity, and energy, respectively, and h and V are the rf harmonic and voltage. The slip factor

$$\eta(\delta) \approx \alpha_0 - \frac{1}{\gamma_s^2} + \alpha_0\left(\alpha_1 + \frac{3}{2}\beta_s^2\right)\delta + \left[\alpha_0\alpha_2 + \frac{(1-5\beta_s^2)\beta_s^2}{2\gamma_s^2}\right]\delta^2 \quad (2)$$

includes the nonlinear dependence in momentum δ ($\equiv \Delta p/p = h\omega_s W/E\beta_s^2$) for both the machine lattice and the particle motion. Here, α_0 ($\equiv 1/\gamma_{t0}^2$), α_1, and α_2 are the zeroth, first, and second order momentum-compaction factors.[5]

A. *Measurement of the α_1 factor*

The factor α_1 has been evaluated by measuring at various radial orbits (momenta) the change in time Δt when transition energy is crossed, i.e., when the minimum beam loss is measured as we vary the time to switch over the synchronous phase, as shown in Fig. 2. For small δ, we can neglect higher order nonlinear terms,

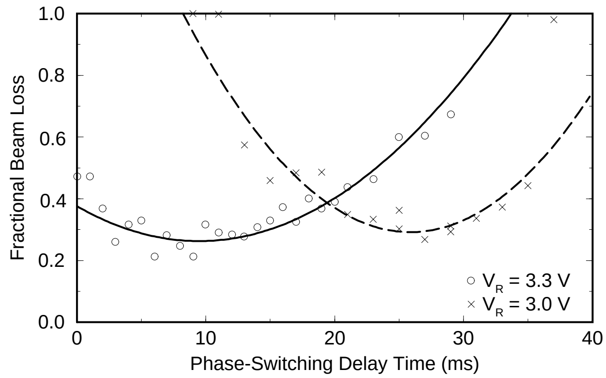

Figure. 2.   Beam loss versus the phase-switch delay time at radial positions V_R =3.3 V (left) and 3.0 V (right), respectively, at $\dot{B}$ =2.2 T/s with γ_t-jump quadrupoles at $I_Q = 1.7$ kA. The solid and dashed lines are the fitted data.

$$\beta_s^2 \dot{B} \Delta t = -\left(\alpha_1 + \frac{1}{2}\beta_s^2\right) B\delta. \qquad (3)$$

The magnetic field B and the ramping rate $\dot{B}$ were measured with the Gauss clock. The momentum δ was calibrated against the radial-loop voltage setting V_R by measuring the average orbit position using the beam position monitors.

As a reference, we first measure the change in γ_t without exciting the γ_t-jump quadrupoles and chromaticity sextupoles, as shown by the squares in Fig. 3. γ_{t0} is equal to 8.45, and α_1

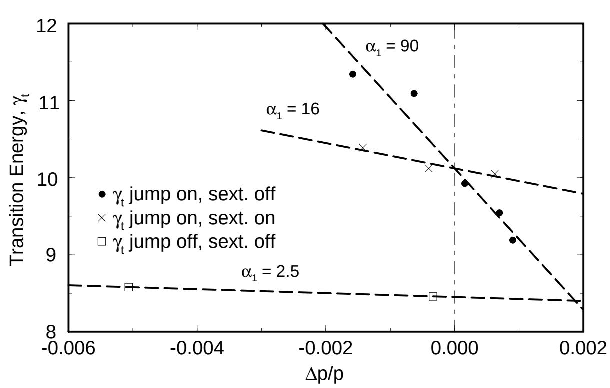

Figure. 3.   Measured transition energy as a function of the momentum deviation.

obtained from Eq. 3 is equal to 2.5. This result is consistent with the previous findings.[6]

To study the enhancement of α_1 during the γ_t-jump, we excited the γ_t-jump quadrupoles with a peak current of $I_Q = 1.7$ kA for about 60 ms. As shown by the solid lines in Fig. 4, the beam is made to cross transition during this period when γ_{t0} is at the maximum value of about 10.1. The measurement is performed at five different radial orbits, as shown by the dots in Fig. 3. The nonlinearity is greatly enhanced by the γ_t-jump, and α_1 is equal to 90.

The sextupoles in the machine can change the chromatic properties of the lattice and thus the α_1 factor. To study their effects, during the transition period we excited the horizontal chromatic sextupole families with a current of $I_S = 100$ A, in addition to

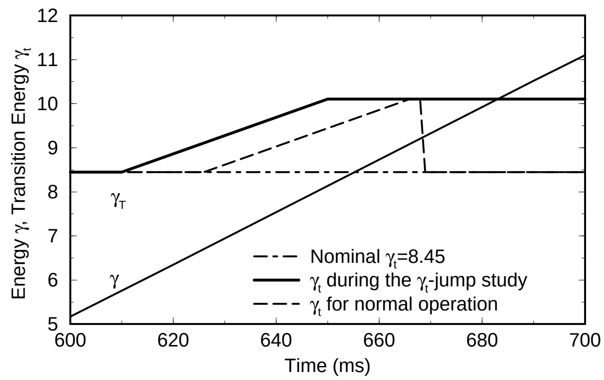

Figure. 4.   The excited transition energy γ_t (solid line) during the study, compared with the nominal (dot-dashed line) and the one for normal γ_t-jump operation (dashed line).

exciting the γ_t-jump quadrupoles. As shown by the crosses in Fig. 3, the nonlinearity is significantly reduced, and α_1 is equal to 16.

B. *Measurement of the momentum aperture*

The momentum aperture of the machine under various γ_t-jump quadrupole and chromaticity sextupole settings was explored by displacing the beam at various radial orbits while measuring the beam survival. Since the momentum spread of the beam becomes very large at transition, especially in the absence of the proper γ_t-jump (dashed line in Fig. 4), the study was performed by measuring the beam loss at transition. Taking into account the beam size of about $\Delta p/p = \pm 2.8\times 10^{-3}$ at transition (bunch area 0.3 eV·s), the measured results are summarized in Table I. Obviously, the

Table I
Measured AGS γ_t, α_1, and momentum aperture at various γ_t-jump quadrupole (I_Q) and sextupole (I_S) settings.

(I_Q, I_S) (A)	(0, 0)	(1700, 0)	(1700, 100)
γ_{t0}	8.45	10.12	10.12
α_1	2.5	90	16
$\Delta p/p\|_{ap}$ ($\times 10^{-3}$)	±7.9	±4.7	±4.3

γ_t-jump significantly reduces the momentum aperture $\Delta p/p|_{ap}$. The further reduction caused by the excitation of the sextupoles is secondary.

C. *Discussion*

During normal high-intensity proton operation, the beam is made to occupy the entire momentum aperture to minimize the beam self fields.[3] Near transition, when the γ_t-jump is excited, particles of different momenta experience dramatically different slip factors η in longitudinal motion. Consequently, emittance growth and beam loss occur in the longitudinal dimension, along with the beam loss caused by the momentum aperture reduction in the transverse dimension. With the proper excitation of the sextupole families, the nonlinearity in the longitudinal dimension can be greatly reduced. However, the limitation in the transverse dimension can only be removed by improving the γ_t-jump scheme.

III. COMPARISON WITH SIMULATIONS

A. Comparison with MAD

We have compared the measurement results (Fig. 3) with computer simulation using MAD[7,8] (Fig. 5). Considering the simple

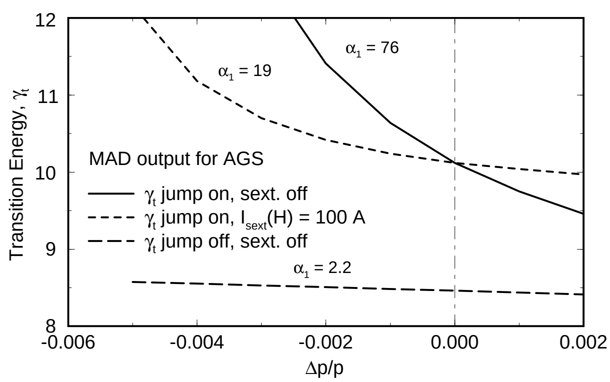

Figure. 5. Transition energy as a function of the momentum deviation evaluated from the program MAD.

modeling of the AGS lattice, the agreement on the first-order nonlinear factor α_1 is excellent. On the other hand, MAD calculation also indicates significant amount of second-order nonlinearity (α_2 in Eq. 2) when γ_t-jump is used. Therefore, we extract both α_1 and α_2 from Fig. 5 using the relations

Table II
MAD calculation of AGS γ_{t0}, α_1, α_2 and maximum dispersion $\eta_x|_{max}$ at the γ_t-jump quadrupole and sextupole settings corresponding to Table 1.

(I_Q, I_S) (A)	(0, 0)	(1700, 0)	(1700, 100)
γ_{t0}	8.45	10.12	10.12
α_1	2.2	76	19
α_2	8.9	-2.7×10^3	-1.6×10^3
$\eta_x|_{max}$ (m)	2.2	8.6	8.6

$$\alpha_1 \approx -\gamma_t'\sqrt{\alpha_0} - \frac{1}{2}, \quad \alpha_2 \approx -\frac{2}{3}\gamma_t''\sqrt{\alpha_0} + \gamma_t'^2\alpha_0 - \frac{2}{3}\alpha_1, \quad (4)$$

where γ_t' and γ_t'' are the first and second derivatives with respect to δ. Table II summarizes $\alpha_0, \alpha_1, \alpha_2$, and the maximum dispersion $\eta_x|_{max}$ for the on-momentum particle. Due to the γ_t-jump, $\eta_x|_{max}$ increases from 2.2 to 8.6 m, significantly reducing the momentum aperture.

B. Comparison with TIBETAN

We have performed computer simulations of the longitudinal motion using TIBETAN.[5] In the absence of the γ_t-jump, quantitative agreement has previously been achieved[6] on the beam loss at transition caused by chromatic nonlinearity as functions of rf voltage, ramp rate, and synchronous-phase switch-over time. With the γ_t-jump and the enhanced α_1, the simulation shows that emittance growth and beam loss may occur. On the other hand, the reduction in nonlinearity given by the proper excitation of the sextupoles is adequate to eliminate beam loss in the longitudinal dimension. The contribution from the second-order α_2, however, is not significant within the currently available momentum aperture.

IV. CONCLUSION

The γ_t-jump intended to reduce the bunch mismatch and intensity loss during the AGS transition causes significant lattice distortions. Consequently, the α_1 factor is significantly increased, enhancing the chromatic nonlinear effects. Employing a low-intensity, small emittance proton bunch, crossing transition with the γ_t-jump quadrupoles excited, we measured the transition energies at different radial orbits and found that α_1 increases from 2.2 to about 90 in the presence of the γ_t-jump. The excitation of the chromaticity sextupoles significantly changes the chromatic properties of the lattice and, if performed properly, minimizes the nonlinearity. The experimental measurement of the α_1 factor agrees well with computer simulations using MAD under various circumstances.

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V. REFERENCES

1. W. Hardt, et al., Proc. 7th Int. Conf. on High-Energy Accel., Yereran, 329 (1969); L.C. Teng, FN-207/400 (FNAL, Batavia, 1970); L. Thorndahl, ISR-300/LI/69-38 (CERN, Geneva, 1969); A. Sørenssen, Part. Accel. 6, 141 (1975); L. Ahrens, et al., AD/No.265 (BNL, 1986); S.Y. Lee and K.Y. Ng, Proc. Fermilab III Instab. Workshop, 170 (1990).
2. P. Yamin, et al., AGS Note 265 (1986); Proc. 1987 IEEE Part. Accel. Conf., 87CH2387-9, p.194; W.K. van Asselt, these proceedings.
3. M. Brennan; M. Blaskiewicz, et al., these proceedings.
4. K. Jøhnsen, Proc. CERN Symp. High-Energy Accel. and Pion Physics (Geneva, 1956), Vol.1, p.106; K. Takayama, Part. Accel. **14**, 201 (1984); E. Ciapala, et al., IEEE Trans. Nucl. Sci. **NS-26**, 3571 (1979); P. Faugeras, et al., IEEE Trans. Nucl. Sci. **NS-26**, 3577 (1979); S.Y. Lee and J. Wei, EPAC Proc. (Rome, 1988), p.764.
5. J. Wei, Ph.D thesis (1990), revised Nov. 1994; J. Wei, Proc. 3rd EPAC, Berlin, 643 (1992).
6. J. Wei, et al., EPAC 1994, London, p.976 (1994); J. Wei, et al., EPAC 1994, London, p.973 (1994).
7. H. Grote et al., MAD 8.13, CERN/SL/90-13 (1990).
8. J.P. Shan, et al., Particle Accelerators **45** 1 (1994).