RHIC/AP/60

Experimental Study of the Momentum Effects at AGS Transition Energy

Jie Wei, BNL, March 24, 1995

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I. Introduction

\[ \frac{\Delta t}{t} = \frac{\Delta L}{L_0} - \frac{\Delta U}{U_0} \]

\[ = \left( \alpha - \frac{1}{\gamma^2} \right) \frac{\alpha p}{p} \]

\[ \eta \]

* No longitudinal focusing

* Non-adiabatic synchrotron motion

Characteristic time \( T_c \)

\[ T_c = \left( \frac{\pi \beta_s^2 Y_T^2}{8 \text{eV} |\cos\phi| \gamma \hbar \omega_s} \right)^{\frac{1}{3}} \]

\[ \sim \begin{cases} 
\pm 5 \text{ ms} & \text{w/o } Y_T \text{ jump} \\
\pm 1 \text{ ms} & \text{w/ } Y_T \text{ jump}
\end{cases} \]
Single-particle effects

* chromatic non-linearity (Johnson effect)

* timing mismatch, non-linear bucket

  $\Rightarrow$ longitudinal dipole-mode oscillation, beam loss

Multi-particle effects

* bunch-bucket mismatch due to self fields
  longitudinal quadrupole mode, beam loss

* combination of self fields and non-linearity
  high current, slow ramp, e.g. RHIC

* microwave instability
  beam microwave signal, break up
  secondary bunches

$\Rightarrow$ Use $\gamma$-jump
Use $\eta$ jump at transition

**advantage:**

* for given $\alpha$, reduce the chromatic non-linear effect
* reduce self field mismatch (e.g. space charge force $\sim 1/\sigma_z^3$)
* reduce beam momentum spread at $\eta$

**disadvantage:**

* distort the lattice, enhance $\alpha$
* increase the dispersion, reduce the momentum aperture
Johnson effect

non-adiabatic time:

\[
T_C = \left( \frac{\pi E \beta_s^2 \gamma_s^3}{q \text{eV} | \cos \phi_s | \gamma_s h \omega_s^2} \right)^{\frac{1}{3}}
\]

nonlinear time:

\[
T_{nl} = \frac{\left| (\alpha_1 + \frac{3}{2} \beta_s^2) \right| \delta(0) \gamma_{t0}}{\dot{\gamma}_s}
\]

\[
\frac{\Delta S}{S} \approx \begin{cases} 
0.38 \frac{T_{nl}}{T_c}, & \text{for } T_{nl} \ll T_c \\
\frac{2^{1/2} T_{nl}^{3/2}}{e^{3/2} \left( \frac{T_{nl}}{T_c} \right)^{3/2}} - 1, & \text{for } T_{nl} \geq T_c
\end{cases}
\]
particles of different momenta cross transition at different time
History:

* discovery of the transition energy

N. M. Blackman and E. D. Courant
Rev. Sci. Instr. 20 596 (1949)

* discussion on the chromatic nonlinear effect


* experimental study of the chromatic effect

at AGS since 1993

* to cross transition in RHIC
Experimental Study of Slow-Rate Transition Crossing in AGS

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Abstract
The nonlinear momentum-compaction factor $\sigma_1$ has been obtained in the AGS by measuring transition energies at different radial orbits using a low-intensity slow-ramped Au$^{77+}$ beam. The beam loss during the transition crossing is found to increase with increasing rf voltage, and to decrease with increasing ramping rate, which indicates that the effect of chromatic nonlinearity (Johnsen effect) dominates the transition crossing. The experimental measurement of beam loss agrees very well with TIBETAN computer simulation.

1 INTRODUCTION
During the past several decades, the crossing of transition

2 EFFECTS OF CHROMATIC NONLINEARITIES
In the low-intensity limit when the multiparticle effects are negligible, the longitudinal motion of the particle can be described in terms of its rf phase $\phi$ and energy deviation $W \equiv \Delta E/\hbar \omega_s$ by the equations

$$\begin{align*}
W_{n+1} &= W_n + \frac{qeV}{\hbar \omega_s} (\sin \phi_n - \sin \phi_{s,n}) \\
\phi_{n+1} &= \phi_n + \frac{2\pi \hbar \omega_s \eta (W_{n+1})}{E_s \beta_s} (W_{n+1} + \phi_{s,n+1} - \phi_{s,n})
\end{align*}$$

where $\phi_s$, $\omega_s$, $\beta_s$, $E_s$ are the synchronous phase, revolution frequency, velocity, and energy, respectively, and $\hbar$ and $V$ are the rf harmonic and voltage. Here the slip factor

* use low intensity Au$^{77+}$, slow ramp
* $\gamma$+ jump off, sextupoles on/off
* developed QT-ANALYZE mountain range analysis
* calibrated system bandwidth, rf voltage, radial loop, etc.
3 EXPERIMENTAL SETUP AND DATA REDUCTION

We perform the experiment in the AGS with Au$^{77+}$ beams at an intensity of about $1 \times 10^8$ ions per bunch. The beam was made to cross transition ($\gamma_0 \approx 8.3$) at various rates $B = 0.05, 0.1$, and $0.5 \text{T/s}$. The longitudinal bunch profiles measured through the wall current monitor were recorded at 5 ms time intervals on a LeCroy 7200 digital oscilloscope with 1 ns sampling resolution triggered by the gauss-clock event which corresponds to a specified $B$ field. The recorded data (Fig. 1) was then transferred into SDS (Self-Describing Structure) format along with various beam and machine parameters, including beam intensity, $V$, $B$, $\gamma_1$, and the trigger delay time.

Signal deterioration due to system bandwidth limitation and cable attenuation was determined by analyzing the signals on the LeCroy scope generated by a series of pulses of various time duration, inserted at the wall-current monitor terminal. For pulses of FWHM width ($W_r$) from 2 to 15 ns, the measured width ($W_m$) is broadened by about 1.9 ns,

$$W_m = 1.03 W_r + 1.9 \text{ (ns)}.$$

The corresponding correction is made to the measured data during the analysis.

A computer program GTANALY has been developed to analyse the SDS format beam-profile data generated either from the LeCroy scope or TIBETAN computer simulation. GTANALY first evaluates the average background level using $\chi^2$ fitting. After the background is subtracted, the beam intensity, rms bunch length, skewness, and kurtosis are subsequently evaluated by numerical integrations. The longitudinal beam emittance is calculated from the obtained bunch length using the calibrated $V$ voltage, magnetic field, and other machine parameters. The beam loss is determined by evaluating the difference in beam intensity at times (typically 100 ms) before and after the transition phase jump, which are long compared with $T_C$ (typically 10 ms).

The accuracy of the beam emittance calculation depends on the calibration of the average magnetic field, the rf voltage, and the pulse broadening. The magnetic field is obtained from the gauss-clock reading which has been calibrated by the frequency measurement. The rf voltage is calibrated at various ramping rates ($B = 0.05, 0.1$, and $0.5 \text{T/s}$) by evaluating, at various voltage settings from 20 to 270 kV, the actual rf voltage applied on the beam, which is deduced from the amount of synchronous phase jump at transition.

4 MEASUREMENT OF $\alpha_1$ FACTOR

Measurement of the nonlinear momentum-compaction factor $\alpha_1$ is performed under three sextupole current ($I_H, I_V$) settings at (190 A, 0), (0, 200 A), and (0, 0), respectively. At each sextupole setting, the beam is made to cross transition at two different radial orbits. As shown in Fig. 2, the time of synchronous-phase switch-over near transition is varied at two radial-loop settings. The times for the beam center to cross the transition energy correspond to the times of the minimum beam loss. The difference $\Delta t \approx (-72 \pm 7) \text{ ms}$ in the minimum-loss delay time between these two orbits corresponds to the difference in transition energy at these two momentum offsets.

In order to determine the factor $\alpha_1$ using Eq. 3, the momentum offset $\delta$ is calibrated against the radial-loop setting $V_R$ using the frequency measurement. The measurement is performed at energy $\gamma = 12.0$ far above the transition energy. The relation obtained is

$$\delta/\Delta V_R = (4.8 \pm 0.2) \times 10^{-3} \text{ V}^{-1}. \quad (6)$$

This result is consistent with the Ionization Position Monitor (IPM) measurement of the beam radial centroid position at different radial-loop settings using a dispersion of 3.2 meters at the IPM location.

Using Eq. 6, the factor $\alpha_1$ has been obtained along with the transition energy $\gamma_0$ at the various sextupole settings. The results are summarized in Table 1.
5 COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

With $\gamma_{10}$ and $\alpha_1$ given in Table 1, and with the initial longitudinal emittance evaluated by GT.ANALY, computer simulation is performed to verify the experimental measurement on beam loss as functions of the phase-switch time, rf voltage $V$, and ramping rate $\dot{B}$. The simulation is performed with 2000 test particles using the computer program TIBETAN based on Eq. 1. The solid line in Fig. 3 shows the simulated beam loss versus switch-over time, which agrees well with the experimental results of both the GT.ANALY beam-profile analysis and the beam current transformer readings (see background).

Figure 3: Beam loss versus the synchronous-phase switch-over time at $\dot{B} = 0.5$ T/s.

Figure 4: Beam loss versus rf voltage at $\dot{B} = 0.5$ T/s.

Figure 5: Beam loss versus crossing rate $\dot{B}$ at $V = 114$ kV.

Table 1: AGS Transition energy and $\alpha_1$ at $V_R = 3.0$ V.

<table>
<thead>
<tr>
<th>$(I_H, I_V)$ (A)</th>
<th>(190, 0)</th>
<th>(0, 200)</th>
<th>(0, 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{10}$</td>
<td>8.28</td>
<td>8.34</td>
<td>8.31</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>2.1±0.5</td>
<td>4.5±0.9</td>
<td>5.4±1.0</td>
</tr>
</tbody>
</table>
AGS proton run, 1995

with $\gamma^*$ jump on,
even with low intensity beam,
beam loss & quadrupole oscill. occur.
($B = 2.27$ fast ramp)

with $\gamma^*$ jump off

@ Transition 1/26/95

1.3Tp no $\gamma^*$ jump

Peak detected signal in MCF
II. Results of the Experimental Study

Plan:

* measure $\chi_1$ when $Y_r$ jump is off.
* measure $\chi_1$ in the $Y_r$-jump lattice
  study the enhancement of the nonlinearity
* repeat step 2 with sextupoles excited
  observe the improvement in nonlinearity
* study the change in momentum aperture
\[ \beta^2 \frac{B}{B} \cdot \Delta t = - (\alpha_1 + \frac{1}{2}) \cdot \frac{\Delta p}{p} \]

* Vary \( \frac{\Delta p}{p} \) by displace the radial orbit measure the change in average orbit

* Measure beam loss at transition versus the delay time for phase switch-over determine the transition energy \( \text{timing} \) (at) from the minimum loss

* Extract \( \alpha_1 \)

\( \text{Ideal} \) \( \alpha_1 = - \frac{3}{2} \)
slope \sim 1

orbit II

\frac{\Delta Y_r}{Y_{T_0}} = \beta^2 \frac{\dot{B}}{B} \cdot \Delta t = - (\alpha_1 + \frac{1}{2}) \cdot \delta

slope \sim (\alpha_1 + \frac{1}{2})
AGS Transition Study (Feb. 2, 1995)

case 1: $V_{CMD}=3.3$ V; $\gamma$, jump on; sext. off

Fractional Beam Loss vs. Delay Time (ms)

TRANS_GT=67745
AGS Transition Study (Feb. 2, 1995)

case 2: $V_{CMD}=3.0$ V; $Y_{j}$ jump on; sext. off

Fractional Beam Loss

TRANS_GT=67745

Delay Time (ms)
\[ \gamma_T = 10.12 - 9.18 \times 10^2 \Delta p/p \]
\[ \alpha_i = 90 \]
\[ \gamma_T = 10.12 - 1.65 \times 10^2 \Delta p/p \]
\[ \alpha_i = 16 \]

AGS proton run, Feb. 2, 1995
- \( \gamma_T \) jump on, sext. off
- \( \times \gamma_T \) jump on, sext. on
- \( \square \gamma_T \) jump off, sext. off

using actual orbits
\[ \gamma_T = 8.45 - 25.4 \Delta p/p \]
\[ \alpha_i = 2.5 \]

\[ \Delta p/p \]

center of sextupoles

"normal" AGS operation with high intensity protons:
\[ \frac{\Delta p}{p} \sim \pm 0.005 \]

\[ \Rightarrow \] partial beam not "jumped" across \( \gamma_T \)
reduction in momentum aperture due to $\gamma_T$ jump

* $\gamma_T$ jump off
  sext. off

* $\gamma_T$ jump on
  sext. off

* $\gamma_T$ jump on
  sext. on
  $I_n = 100 A$

\[
\frac{\Delta P}{P} \mid_{lap} \approx \pm 7.9 \times 10^{-3}
\]

\[
\frac{\Delta P}{P} \mid_{lap} \approx \pm 4.7 \times 10^{-3}
\]

\[
\frac{\Delta P}{P} \mid_{lap} \approx \pm 4.3 \times 10^{-3}
\]

Note:

* size of the "pencil" beam: $s = 0.3 \text{ aV } s$

\[
\frac{\Delta P}{P} \approx \pm 2.8 \times 10^{-3} \quad \text{at } \gamma_T \text{, without the jump across \ (both jump on/off)}
\]

* measured only in negative $\alpha P/p$ side
every program (MAD, SYNCH, ...) does not give identical result, especially when off momentum
\( \gamma_T \) jump on: \( \gamma_T \) quads. at 1700 Amps.

\[ \Rightarrow \frac{\partial \gamma_T}{\partial p} = 1.6 \quad \text{for} \quad \frac{\partial p}{p} = 0 \]

sextupole on: \( I_{\text{sext, } H} = 100 \, \text{A} \),
\[ I_{\text{sext, } V} = 0 \]
MAD output for AGS study

- $\gamma_T$ jump on, sext. off
- $\gamma_T$ jump on, $I_{\text{sex}}(H) = 100$ A
- $\gamma_T$ jump off, sext. off

Maximum Horizontal Dispersion (m)

8.6 m

2.2 m

$\Delta p/p$

0 0.005 0.007 0.009 0.011 0.013 0.015 0.017 0.019 0.021 0.023 0.025 0.027 0.029 0.031 0.033 0.035 0.037 0.039 0.041 0.043 0.045 0.047 0.049 0.051 0.053 0.055 0.057 0.059 0.061 0.063 0.065 0.067 0.069 0.071 0.073 0.075 0.077 0.079 0.081 0.083 0.085 0.087 0.089
$\gamma$ jump off, $\alpha_1 = 2.5, S_\theta = 4\text{ eV s, } \gamma = 7$

$\gamma = 7$

$\gamma$ jump off, $\alpha_1 = 2.5, S_\theta = 4\text{ eV s, } \gamma = 8$

$\gamma = 8$

$\gamma$ jump off, $\alpha_1 = 2.5, S_\theta = 4\text{ eV s, } \gamma = 9$

$\gamma = 9$

$\gamma$ jump off, $\alpha_1 = 2.5, S_\theta = 4\text{ eV s, } \gamma = 14$

$\gamma = 14$
Y jump off
Sex. off.
extreme case: $\alpha_i = 90°$ constant
(actual: $\alpha_i = 2.5 \rightarrow 90 \rightarrow 2.5$)
extreme case
Future improvements on simulation:
* $\alpha$, ramp along with the jump
* program $V_{rf}$
* add radial loop tracking
* momentum aperture
* $\alpha_2$ effect as per MAD
IV. Conclusions and Discussion

* The current $Y\gamma$ jump scheme strongly distort the lattice and enhances non-linearity $\alpha_1$:
  $\alpha_1 : 2.5 \rightarrow 90$ momentarily
  $x_p : 2.2 \rightarrow 8.6$ m, on momentum 14 m, at $\frac{\alpha_p}{\rho} = -0.005$

* The current sextupole setup can greatly improve the longitudinal behavior $\alpha_1 : 90 \rightarrow 16$
  but further limits the momentum aperture

* Improvements on $Y\gamma$ jump / sextupole setup can improve the AGS operation