ENERGY CALIBRATION IN THE AGS USING DEPOLARIZATION THROUGH VERTICAL INTRINSIC SPIN RESONANCES*

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Abstract

The AGS tune jump system consists of two fast pulsed quadrupoles used to accelerate the crossing of 82 horizontal intrinsic resonances. Timing of the tune jumps requires accurate tune and energy measurements. Although cross calibration using measurements of the beam revolution frequency shows good accuracy for most of the AGS energy range it is not adequately sensitive as the beam becomes highly relativistic. This drives a strong interest for a new independent energy measurement method.

Reduction in the vertical tune across vertical intrinsic spin resonances can induce significant depolarization of the beam. Therefore it was proposed to use the negative vertical tune shift created by this tune jump system to calibrate the energy measurement at few locations along the AGS acceleration cycle. The fast tune jump, of $\Delta Q \approx -0.02$ within $100\,\mu$s in the vertical plane, allows to accurately locate the spin resonant condition, independently from orbit or field conditions. Simulations using the AGS Zgoubi online model facilitate the interpretation of the experimental results. This paper introduces the experimental procedure and shows some of the latest results.

INTRODUCTION

The partial snakes configuration of the AGS creates horizontal intrinsic spin resonances by tilting the stable spin direction away from the vertical direction [1]. The resonant condition $Q_s \pm Q_x = n$ is satisfied twice per unit of $G\gamma$ during the ramp, inducing every time a small depolarization of the beam. The polarization losses are reduced by quickly changing the horizontal tune Q_x, increasing the crossing rate of the resonance [2].

The system is composed of two fast quadrupoles allowing a change in the horizontal tune of $\Delta Q_x = +0.04$ in $100\,\mu$s. One of the main challenge is the accurate timing required for each jump, such that the tune jump is centered around the resonance.

Tune Jump Timing

While the spin tune Q_s is a function of the energy, tune and energy measurements along the ramp allow precise timing of each jump. During the polarized protons operations these measurements are regularly used to generate new timings for the tune jumps. This is supposed to compensate for any drift in the location of the resonant condition, for instance due to a drift of the tune over time. During the AGS Polarized Proton Run 13, these measurements were regularly conducted to provide the highest polarization to the RHIC.

Table 1: Polarization Measurements During Run 13

Measurement date	Timings	Polarization
May 5th	from April 6th	$66.0 \pm 0.9\,\%$
May 5th	from April 29th	$59.7 \pm 1.1\,\%$
May 5th	from May 5th	$62.8 \pm 1.1\,\%$
June 6th	Uncalibrated	$64.4 \pm 3.9\,\%$
June 6th	Calibrated	$70.9 \pm 1.6\,\%$

In late April 2013, after a few weeks of running with the same tune jumps timings, new timings were generated but the polarization decreased. Table 1 shows that on May 5th the measured polarization was higher for the older timings. The two sets of timings more recently generated led to a consistently lower polarization.

To explain this deterioration the entire process from the computation of the jumps timing to the trigger of the pulsed power supply was verified, without finding any error. We decided to investigate on the measurements used to compute the jump timings : tune and energy measurements.

The tune measurement is based on the free oscillation of the beam, it is therefore an absolute measurement and is unlikely a source of significant error. The energy measurement is more complex and needs to be calibrated, making a possible suspect for our problems.

ENERGY MEASUREMENT IN THE AGS

The AGS uses a dedicated device called the *GgammaMeter* to measure the energy along the ramp. The energy is determined using the measured RF frequency f and average radius of the beam dR (Eq. 1) or the measured field $(B_{\text{inj}} + B_{\text{clock}}/C_{\text{scal}})$ and the average radius (Eq. 2) :

$$G\gamma = G\frac{1}{\sqrt{1-\frac{1}{c^2}\left(\frac{f}{h}\right)^2(2\pi)^2(R_0+dR)^2}} \qquad (1)$$

$$G\gamma = G\sqrt{\left[\frac{(1+\gamma_{tr}^2 dR/R_0)\rho_0 c(B_{\text{inj}}+B_{\text{clock}}/C_{\text{scal}})}{M_0}\right]^2+1} \qquad (2)$$

With γ_{tr} the transition energy, R_0 the radius and ρ_0 the radius of curvature of the AGS. The parameters in red (f, dR and B_{clock}) are measured quantities while the blue ones are machine parameters(R_0, γ_{tr}^2, ρ_0, B_{inj} and C_{scal}) that can be adjusted and the black are fixed physical constants.

The *GgammaMeter* is cross calibrated : at low energy the machine parameters in equations 2 and 1 are adjusted manually until the two methods report the same energy along

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* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

the ramp. But at high energy the measurement based on the RF frequency (Eq. 1) is too sensitive, due to the highly relativistic beam.

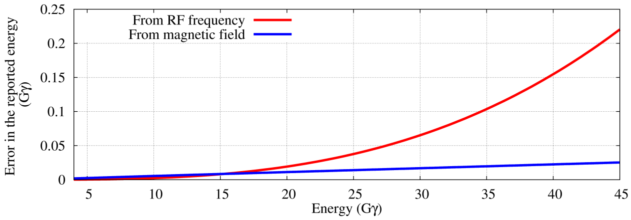

Figure 1: Error on the reported energy caused by an error of 1 mm in the measured average beam radius.

Figure 1 shows the derivative of equations 2 and 1 with respect to the measured average radius: $\partial G\gamma/\partial(dR)$. As the energy increases, we can see that the sensitivity of the energy measurement based on the revolution frequency becomes very large. While we consider that the measured average radius is known within a fraction of millimeter we also need an accuracy of around $0.01\,G\gamma$. It becomes apparent that the actual method of cross calibration is very hard at high energy.

This drives a strong interest to develop an independent method on energy measurement, possibly to calibrate the *GgammaMeter*.

Since the AGS accelerates polarized protons, methods based on the depolarization of the beam can be explored. A promising method using the current hardware of the AGS uses the tune jump system to accurately locate a strong vertical intrinsic resonance.

Tune Jump and Depolarization

While the tune jump system is used for its effect on the horizontal tune, it also induces a tune shift of $\Delta Q_y \sim -0.02$ in the vertical plane, within $100\,\mu$s. In addition, the partial snake configuration of the AGS modifies the spin tune, opening a forbidden band or "spin gap" in which the vertical tune is placed to avoid the vertical intrinsic resonances $Q_s \pm Q_y = n$. It is then possible to use a single tune jump to lower the vertical tune below the maximum value of the spin tune $Q_s^{\max}$, leading to a depolarization of the beam.

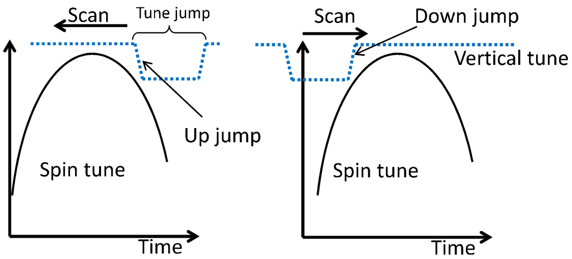

Figure 2: Illustration of the method used to locate the vertical intrinsic resonance.

Figure 2 shows the principle of the measurement. First the vertical tune is lowered to just above $Q_s^{\max}$, such that the tune jump is able to lower the vertical tune out of the spin gap. Then the timing of the tune jump is scanned across the spin resonance and the polarization at the end of the ramp is measured for each timing of the tune jump. If the spin tune crosses the vertical tune, a lower polarization is measured due to the depolarization across the resonance. The up-jump determines the location of the right side of the resonance and the down-jump allows to locate the left side.

The single crossing of the resonance, at the regular acceleration rate, has to strongly depolarize the beam in order for the difference in polarization to be clearly measured. Therefore the measurement is only carried at the two very strong vertical intrinsic resonances: $0+$ and $36+$.

While the method shown in figure 2 is very simple, several factors complicate the expected behavior :

- The vertical and spin tunes possess some spread due to energy spread of the beam and chromaticity of the machine, potentially blurring the transition between no depolarization and depolarization.
- The two resonances in each sides of $Q_s^{\max}$ can have different strengths, depending on the distance between them.

The experimental results are expected to be complex and no simple theoretical model can predict the observed polarization, the only solution to take everything into account would be to completely simulate the experiment. Thankfully the Zgoubi code[3] and the AGS Zgoubi online model[4] provide the perfect tools to simulate this experiment.

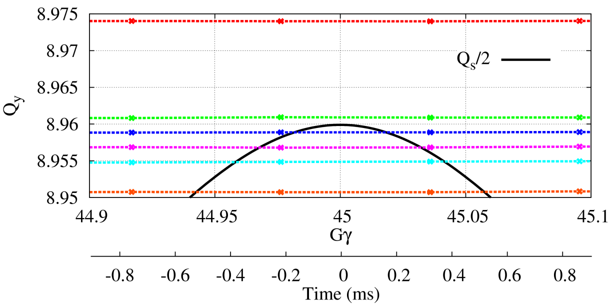

Figure 3: Vertical tune for the 5 different simulations and resonant condition for the second order snake resonance ($Q_s/2$) as a function of the energy or the time from $G\gamma = 45$.

Simulation at 36+

At $G\gamma = 45$, where the resonance $Q_y + 36 = Q_s$ is located, strong enough that the crossing of the second order snake resonance ($Q_s + 2Q_y = n$) induces a significant depolarization of the beam.

Multiparticle trackings using the Zgoubi code were done for a short simulation from $G\gamma = 44.5$ to $G\gamma = 45.5$. Realistic lattice conditions and acceleration rate were set up using the AGS Online model[4]. Each simulation consists in a tracking of 408 particles picked in a realistic 6-D Gaussian distribution for 3800 turns. The simulations total up around 20 000 CPU·hours[1].

Figure 3 shows the vertical tune without tune jump at $Q_y \sim 8.975$, lower than the operational tune across this resonance in order to cross the spin resonance when the jump quads are fired. Below, the different tunes on the jump were chosen across a wide range to determine the best configuration for the measurement.

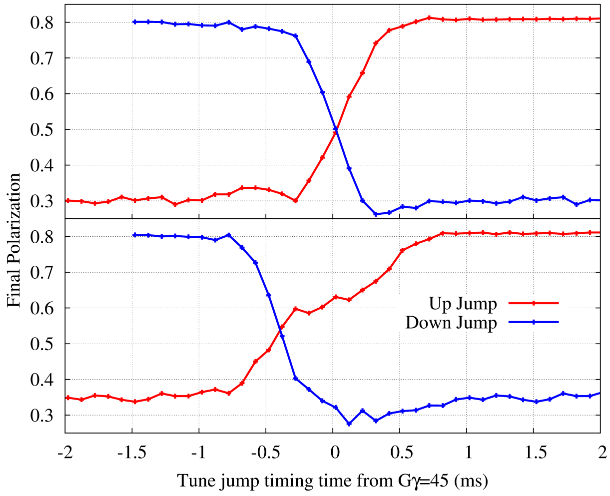

Figure 4: Final polarization for the up and down jump locations as a function of the time from $G\gamma = 45$ for the vertical tune on the jump just below the resonant condition (top plot) and for $Q_y = 8.951$ (bottom plot).

Figure 4 shows the experiment simulated for 2 different vertical tune on the jump. On the top plot the vertical tune on the jump is very close to the maximum value of the spin tune and the two vertical intrinsic resonances on either side of $G\gamma = 45$ are so close that they have the same effect on the beam and the figure is very symmetric, centered around $G\gamma = 45$. For a lower vertical tune the result is distorted due to the two resonances having different strengths when the distance separating them increases. These simulations show that the vertical tune on the jump should be positioned as close as possible from the maximum value of the spin tune.

Experiment at 36+

To correctly place the vertical tune we determined the maximum value reached by the spin tune across the resonance. By measuring the final polarization as a function of the vertical tune across $G\gamma = 45$ we determined that $Q_s^{\mathbf{max}}/2 = 0.956$. The vertical tune on the jump was placed at $Q_y = 8.954$ just below the resonant condition.

The polarization on the flat-top was measured as a function of the up and down jumps locations, by step of 200 μs. Figure 5 shows the measured data along with the simulation closest to the experimental conditions. The simulation results were numerically matched : vertically to account for the polarization lost outside the simulated range and horizontally shifted.

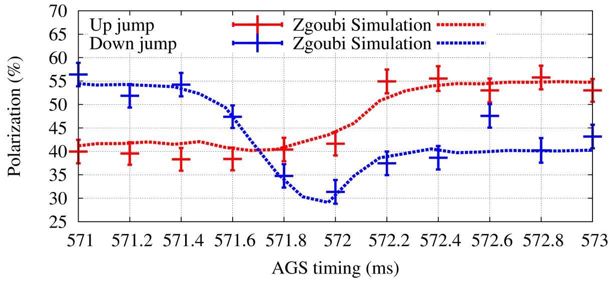

Figure 5: Final polarization for the up and down jump locations as a function of the time AGS time.

The matched horizontal shift of the simulation allows to determine that $G\gamma = 45$ is crossed at $T = 571.85$ ms. From the *GgammaMeter* data, we expected to see $G\gamma = 45$ at T = 572.7 ms. This difference is equivalent to $\sim 0.1\,G\gamma$.

RESULTS

The energy measurement at 36+ led to surprising results but the magnitude would suffice to explain an important loss of efficiency for the tune jumps. The same method was applied at $G\gamma = 9$ where a strong vertical intrinsic resonance is located, reporting a smaller disagreement with the energy measured by the *GgammaMeter* of $\Delta T = 0.1$ ms. Therefore it would appear that the energy reported by the *GgammaMeter* drifts along the ramp.

These results were used to recalibrate the the *GgammaMeter* and generate new tune jumps timings. Higher polarization was measured with the new timings on June 6th(Table 1), giving strong confidence into the energy measurement.

CONCLUSION

The energy measurement based on depolarization provided interesting results but the procedure is complex and the data taking is very long. But a faster method based on a continuous polarization measurement along the ramp is being developed and could be used for operation while the method described in this paper would be an important tool for experts to cross-check the results.

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[1] This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.