ENERGY CALIBRATION AND TUNE JUMPS EFFICIENCY IN THE PP AGS*

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Abstract

The AGS tune jump system consists of two fast quadrupoles used to accelerate the crossing of 82 horizontal intrinsic spin resonances. The fast tune jump of $\Delta Q_x = +0.04$ within 100 µs requires excellent localization of each of the 82 resonant conditions. Imperfect timing of the tune jumps results in lower efficiency of the system and lower transmission of the polarization through the AGS acceleration cycle.

Investigations during the end of the pp AGS Run13 revealed weaknesses in the energy measurement at high energy, causing less than optimal timing of the tune jumps. A new method based on continuous polarization measurement to determine the energy during the acceleration cycle has been developed. Strong operational constraints were taken into account to provide a convenient system of energy measurement. This is also used to calibrate the usual determination of the energy based on revolution frequency of the beam or measured dipole magnetic field.

This paper shows the tools developed and the results of the first tests during the AGS Run 14. Simulations of the expected tune jumps efficiency using the AGS Zgoubi model [1,2] are also presented and compared to experimental results.

INTRODUCTION

The AGS uses a dual partial snakes configuration. While this allows overcoming vertical spin resonances it also creates horizontal intrinsic spin resonances by tilting the stable spin direction away from the vertical axis [3]. Horizontal intrinsic spin resonances occur when $Q_s \pm Q_x = I$ with Q_s the spin tune, Q_x the horizontal tune and I an integer [4]. The resonant condition is satisfied twice per unit of $G\gamma$, resulting in 82 crossings from injection at $G\gamma = 4.5$ to extraction at $G\gamma = 45.5$, with G the anomalous g factor of the proton and γ the Lorentz factor. Although the depolarization across a single resonance is very small, the loss of polarization through the entire AGS accelerating cycle is estimated to be around 15% to 20% [5].

The polarization losses are mitigated by quickly changing the horizontal tune Q_x, increasing the crossing rate of the resonances. The tune jump system is composed of two fast quadrupoles. One of the main challenge to maximize the tune jump system efficiency is to accurately position each tune jump, centering it around the resonant condition.

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Tune Jump Timing

The timing of the AGS tune jumps is critical. Errors in the timing of the tune jumps results in lower efficiency of the system. Figure 1 shows tracking results[1] for the crossing

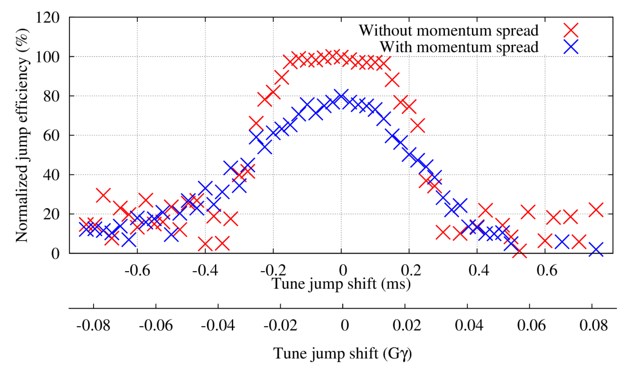

Figure 1: Normalized tune jump efficiency as a function of the tune jump shift with or without momentum spread. The second axis gives the equivalent shift in energy at the accelertion rate of $d[G\gamma]/dt = 110\,\mathrm{s}^{-1}$.

of two horizontal intrinsic resonances around $G\gamma = 41$. The multiparticle trackings were done with the Zgoubi code [1] and with realistic beam and machine conditions. Realistic longitudinal emittance of 1.0 eV.s was used, leading to a beam energy spread of $\sigma_{G\gamma} = 0.02$. Although the energy spread varies along the AGS energy ramp Figure 1 is representative for most resonances on the AGS cycle.

Without momentum spread the resonance condition is very narrow. The tune jumps efficiency is constant and maximum until the jump misses the resonance. With momentum spread the resonance condition is large compared to the tune jump amplitude, mainly due to the spin tune spread of the beam. The tune jumps timing needs to be perfect for maximum efficiency. One can see that an error of ±200µs would be unacceptable.

In the AGS the spin tune is function of beam energy and strengths of the two Siberian snakes. Measurement of the energy and horizontal tune along the ramp allows a dedicated application to automatically time each tune jump. However the measurement of the energy is complex and believed to limit the accuracy on the timing of the tune jumps [6]. Two radically different methods to measure the energy will be presented and experimental data will be compared.

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CONVENTIONAL ENERGY MEASUREMENT

The conventional energy measurement uses the *GgammaMeter* to measure the energy along the ramp. The energy is determined using the measured RF frequency f and average radial shift 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) :

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

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

With γ_{tr} the transition energy, h the harmonic number, R_0 the radius and ρ_0 the bending radius 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: the machine parameters in equations 2 and 1 are adjusted manually until the two methods report the same energy along the ramp. But at high energy the measurement based on the RF frequency (Eq. 1) is very sensitive to f and dR, due to the highly relativistic beam.

To overcome this problem an application named *AgsGgammaCal* was developed to collect and average the data from consecutive cycles. By assuming that machine conditions do not vary over few tens of minutes, the data from hundreds of consecutive cycles can be averaged to considerably reduce the statistical uncertainty on the measured quantities. The application also features an automatic fitting algorithm to minimize the difference between equations 2 and 1 along the AGS acceleration cycle by adjusting R_0, C_{scal} and a special empirical parameter, not detailed here, that compensates for the response of the field measurement apparatus to the main dipole ramping rate.

ENERGY MEASUREMENT FROM ASYMMETRY

While the polarization in the AGS is only measured at extraction energy, a new method was developed to continuously measure the asymmetry during acceleration. The

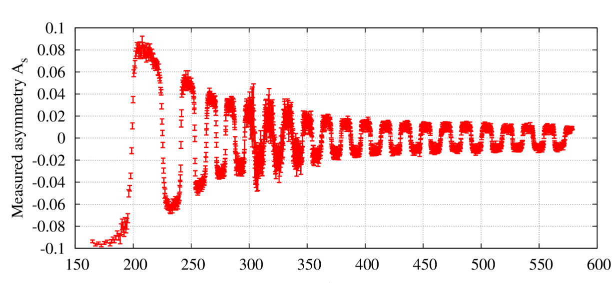

Figure 2: Measured asymmetry in the AGS as a function of the AGS timing [7].

analyzing power A_p connects the averaged polarization on the vertical component S_z of the spin to the raw asymmetry A_s in Figure 2 by $A_s = S_z \times A_p$. The analyzing power is only known at $G\gamma = 45.5$ so the measured asymmetry cannot give absolute beam polarization along the ramp but only relative numbers.

Spin Flip Timing

Figure 2 highlights a particular effect of the AGS partial snakes configuration. The stable spin direction flips across every integer in $G\gamma$. This create a full spin flip of the beam seen in Figure 2 when the measured asymmetry changes sign.

It was proposed to use the spin flip measured by the polarimeter to accurately determine the crossing time of every integer $G\gamma$ during the ramp. This method is completely independent from other measured quantities involved in the conventional energy measurement and could be used to calibrate the conventional energy measurement system.

The stable spin direction at a particular position of the AGS only depends on the beam energy. The expression of the vertical component of the stable spin direction as a function of the energy at the C15 polarimeter is showed in equation 3.

$$n_{0,z}(G\gamma) = \frac{1}{\sin(\pi Q_s)}\left[\cos\left(\frac{A_w}{2}\right)\cos\left(\frac{A_c}{2}\right)\sin(G\gamma\pi) + \sin\left(\frac{A_w}{2}\right)\sin\left(\frac{A_c}{2}\right)\sin\left(G\gamma\frac{\pi}{3}\right)\right] \quad (3)$$

The spin tune Q_s and the spin rotation angles of the two AGS snakes A_c and A_w are also used to compute the stable spin direction. Their dependences on beam energy are known. Finally the beam polarization P is linked to the measured asymmetry by:

$$A_s = P \times A_p \times n_{0,z}(G\gamma) \quad (4)$$

Using equation 4 one can determine the energy at a given timing assuming that:

- the analyzing power A_p is constant over the interested range. This only generates a small error if the range is small or in the later part of the cycle where the analyzing power varies slowly.
- the beam polarization is constant over the interested range. The polarization losses are likely spread along the acceleration cycle, hence this assumption would only introduce very small errors if the fitted range is small enough.
- the acceleration rate is constant. While the acceleration rate varies strongly at low and high energy, it remains almost constant elsewhere.

The assumption that $P \times A_p$ is constant certainly have an effect on the final energy measurement. However the statistical uncertainties from the measured asymmetry is believed to be the main source of error in the energy measurement. Therefore systematic uncertainty associated to the above mentioned assumptions were not investigated and from now on we will only refer to statistical uncertainties.

Method

A fitting algorithm was developed to handle the different steps involved and the associated statistical uncertainty study. The method follows the steps below:

1. The energy measured using the conventional method is used to determine the acceleration rate around $G\gamma = I$ with I an integer. The range of energy giving the best results appears to be for a range of 1.25 units on either side of $G\gamma = I$. The energy can then be expressed as a function of time by

$$G\gamma(t) = A_r \times t + b \quad (5)$$

   where t is the time and A_r is the acceleration rate.

2. Replacing the dependence in $G\gamma$ in equation 3 and using the approximations mentioned earlier we can express the measured asymmetry as a function of time:

$$A_s(t) = \alpha \times n_{0,z}(A_r \times t + b) \quad (6)$$

   where $\alpha = P \times A_p$. Equation 6 can now be fitted to the data showed Figure 2 by varying the parameters b and α while the acceleration rate is taken from the conventional energy measurement method. Figure 3 shows the results around $G\gamma = 39$.

3. The fitted parameter b is used together with the acceleration rate A_r to determine the timing $T_{G\gamma=I}$ at which $G\gamma = I$ is crossed. We now have a pair ($T_{G\gamma=I}$, ($G\gamma = I$) $\pm \Delta b$) where Δb is the uncertainty on the parameter b.

4. The iteration of the previous steps over each integer I between injection and extraction generates a set of data points along the full AGS cycle.

Due to the approximations made earlier the results are clearly unreliable below $G\gamma = 11$. While the χ^2/ndf is very close to 1 for most of the ramp it gets very large below $G\gamma = 11$, likely due to the assumption that the acceleration rate is constant over the fitted range. Elsewhere the χ^2/ndf very close to 1 and the small uncertainty in the fitted b parameter (see Figure 3) gives strong confidence in the quality of the measured data and confirms the validity of the approximations made earlier.

EXPERIMENTAL RESULTS

Energy measurement was derived from polarization ramp measurements taken in May 2014. Results showed an uncertainty in the estimated energy of $\Delta(G\gamma) \sim 3 \cdot 10^{-3}$ equivalent

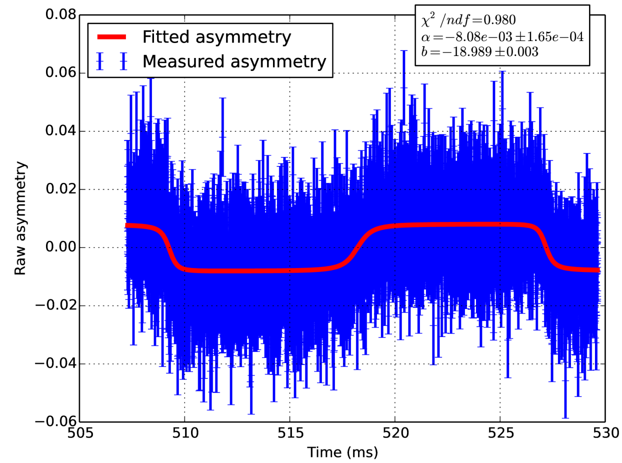

Figure 3: Measured and fitted asymmetry around $G\gamma = 39$ as a function of time.

in timing uncertainty to 30 µs. In addition results showed consistent values between measurements taken few days apart.

Differences between energy measured using the usual method based on the measured dipole field and using the polarization ramp measurement were on the order of 100 µs to 200 µs. As seen Figure 1, such error on the tune jump timing leads to non optimal efficiency of the tune jump system.

No clear evidence from polarization measurements showed improved polarization transmission in the AGS, after the tune jump timings were corrected using the energy measured from polarization ramp measurements. However the expected differences are small and more measurements should be compiled to clearly highlight the benefit of this energy measurement method.

REFERENCES

[1] F. Méot, Zgoubi code, 2014, `http://sourceforge.net/projects/zgoubi/`

[2] F. Méot et al., "Modelling of the AGS using Zgoubi-Status", IPAC'12, New Orleans, May 2014, `http://www.JACoW.org`

[3] F. Lin et al., Phys. Rev. ST Accel. Beams 10, 044001 (2007).

[4] V. Schoefer et al., "Increasing the AGS Beam Polarization with 80 Tune Jumps", IPAC'12, New Orleans, LA USA, TUXA03 (2012), `http://www.JACoW.org`

[5] Y. Dutheil et al., "Strength of Horizontal Intrinsic Spin Resonances in the AGS," IPAC'14, Dresden, Germany, June 2014, MOXAP07, These Proceedings.

[6] Y. Dutheil et al, "Energy Calibration in the AGS Using Depolarization Through Vertical Intrinsic Spin Resonances", PAC'13, Pasadena, CA USA, TUPAC10 (2013), `http://www.JACoW.org`

[7] T. Roser et al, AIP Conf. Proc. 1149 (2009).

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