Polarized Protons Studies in AGS

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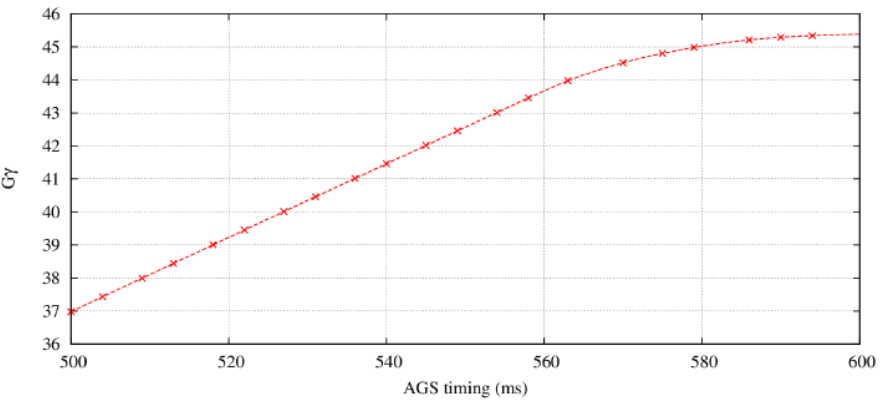
AGS Main Magnets roll over onto the flat-top : Zgoubi Simulations

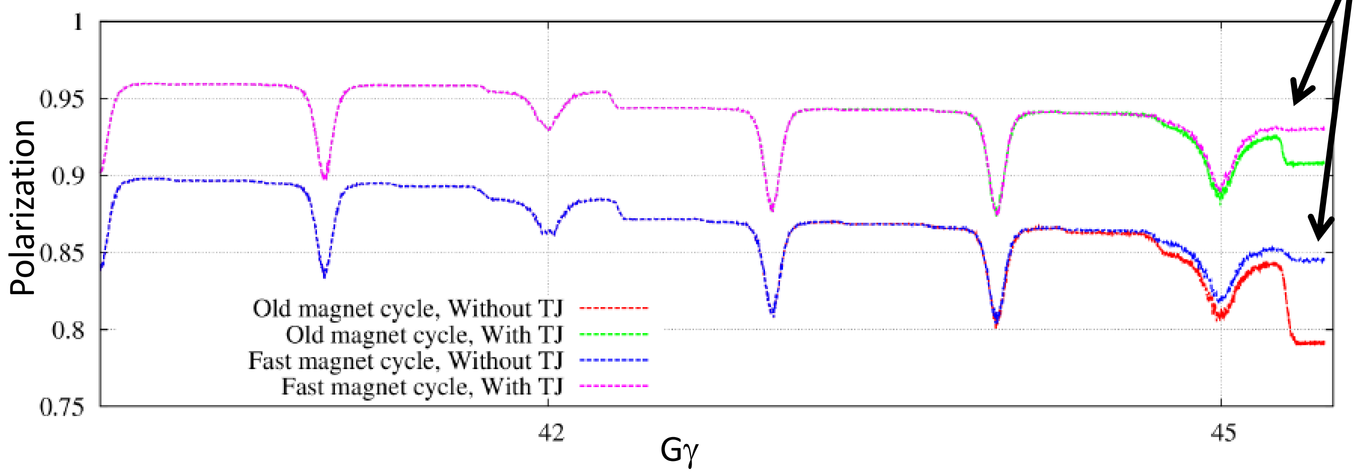


The acceleration rate was slowly reduced over 50 ms. Depolarizing resonances crossed slowly lead to higher depolarization.

Important depolarization across the last horizontal intrinsic resonance can be avoided by removing the roll over onto the flat-top, i.e. constant acceleration rate up to Gg=45.5

Spin tracking using a realistic optics set-up by the AGS Zgoubi online model.

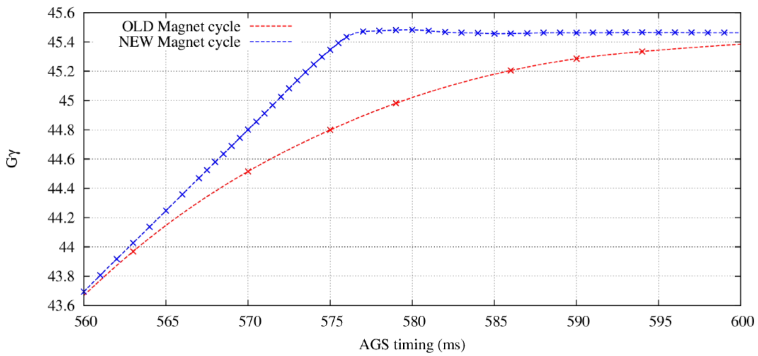
2000 particles in a 6D Gaussian distribution were tracked from Gg=19.5 to Gg=45.5 with the Zgoubi code on NERSC systems.



Simulation	Relative polarization gain
Without tune jumps	+6.38% (≡ 4 points / 65%)
With tune jump	+2.37% (≡ 1.5 points / 65%)

Important polarization gain is expected from a constant acceleration rate.

AGS Main Magnets roll over onto the flat-top : Experimental results



Different solutions were explored to achieve a faster acceleration rate a the end of the cycle.
A new Main Magnets cycle providing a much shorter roll-over was found to be reliable for operations. This new magnet cycle holds the maximum acceleration rate up to around Gg=45.4, i.e. after the last spin resonance.

The new magnet cycle was tested against the old one on April 6th 2013.

	Measurement			Simulation
Tune jump	Slow roll over	Fast roll over	Relative gain	Relative gain
OFF	62.8 ± 1.1 %	67.3 ± 1.1 %	+ 7.2 %	+ 6.38 %
ON	70.1 ± 1.1 %	70.5 ± 1.1 %	+ 0.6 %	+ 2.37 %

The agreement without tune jump gives strong confidence in the model.

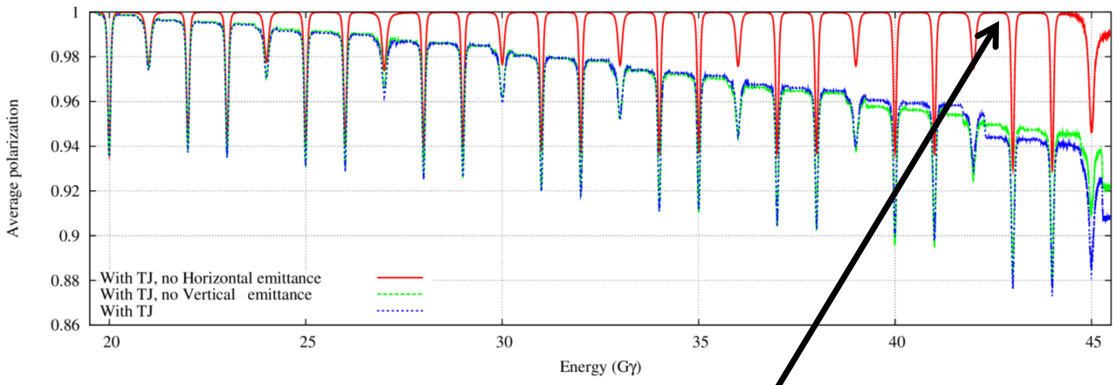
Discrepancies between simulations end measurements could be explained by :

- The uncertainty on the measured polarization.
- The limited range of the simulation (from Gg=19.5 to Gg=45.5).
- The simulations show the polarization averaged over all the particles but the measurements are done with a vertical at the center of the beam.
- The acceleration rate used on the simulations, very small across the last horizontal intrinsic resonance .
- The different tune jumps timings are less than perfect.

The new magnet cycle was quickly implemented and has been used for operation since March 2013.

The delay between the simulations and the implementation of a solution in the machine has been very short.

Snake strength : depolarization sources in the Zgoubi simulations



Spin tracking using a realistic optics set-up by the AGS Zgoubi online model.
2000 particles in a 6D Gaussian distribution were tracked from Gg=19.5 to Gg=45.5 with the Zgoubi code on NERSC systems.

Without horizontal emittance the polarization losses are almost removed. In this simulation the polarization losses are dominated by the horizontal intrinsic resonances.

The polarization losses through horizontal intrinsic resonances are due to the snakes but the snakes allow to reduce or remove the polarization losses through the vertical intrinsic resonances. The snake strength is then a trade-off between stronger snakes with important depolarization through the horizontal intrinsic resonances and lower snake strength leading to a depolarization through the vertical intrinsic resonances.

Unlike the warm snake, the cold snake field can be adjusted to our needs.
From the simulations above we expect that a lower cold snake would give higher polarization.

Snake strength : experimental results

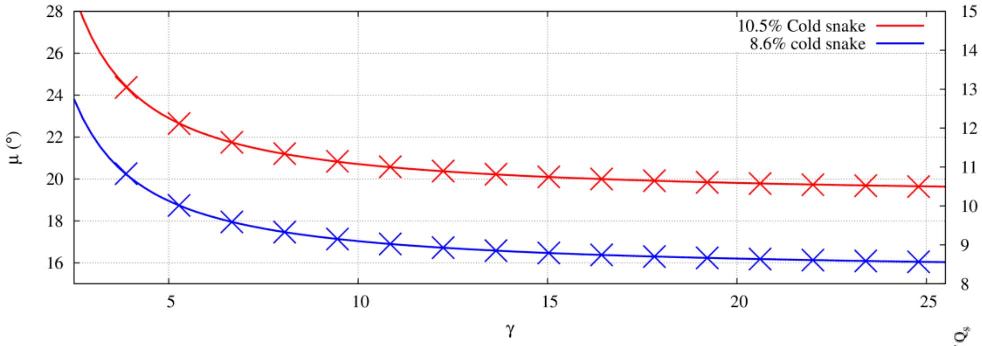
It was decided to compare the polarization profiles with the regular cold snake strength, with a lower cold snake (field lowered by 10%) and with a higher cold snake (field increased by 10%).

For each case the measurements were done after changing the cold snake settings and retuning the machine for the conditions to be as close to the usual machine as possible.

Tune jumps	Plane	Quantity	Lower cold snake (B-10%)	Regular cold snake	Higher cold snake (B+10%)	Expected behavior
ON	H	P_{max}	63.7 ± 1.3 %	70.96 ± 0.36 %	74.1 ± 1.6 %	↗
		R	0.134 ± 0.038	0.092 ± 0.007	0.304 ± 0.041	↗
	V	P_{max}	70.6 ± 1.7 %	67.84 ± 0.41 %	65.0 ± 1.5 %	↘
		R	0.261 ± 0.043	0.086 ± 0.010	0.130 ± 0.035	↘
	$\frac{P_0}{(R_x+1)(R_y+1)}$		61.3 ± 2.4 %	66.5 ± 0.6 %	63.0 ± 2.4 %	
	Zgoubi model prediction					
OFF	H	P_{max}	64.4 ± 0.8 %	64.7 ± 0.9 %	65.4 ± 0.8 %	↗
		R	0.225 ± 0.023	0.252 ± 0.025	0.256 ± 0.021	↗
	V	P_{max}	66.5 ± 0.8 %	63.2 ± 0.8 %	63.5 ± 0.8 %	↘
		R	0.224 ± 0.021	0.190 ± 0.022	0.112 ± 0.020	↘
	$\frac{P_0}{(R_x+1)(R_y+1)}$		59.1 ± 1.3 %	57.9 ± 1.3 %	59.3 ± 1.3 %	
	Zgoubi model prediction					

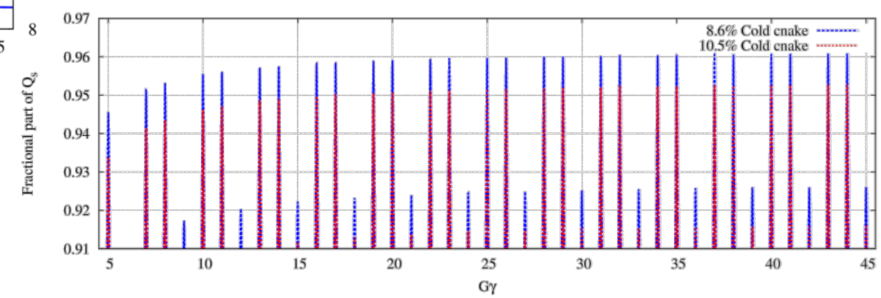
With tune jumps it would seem that the actual cold snake strength is already optimized. Without tune jump the 3 cases are equivalent, within the uncertainties. More tuning time might be required.

Snake strength : simulations with a lower cold snake using the Zgoubi online model

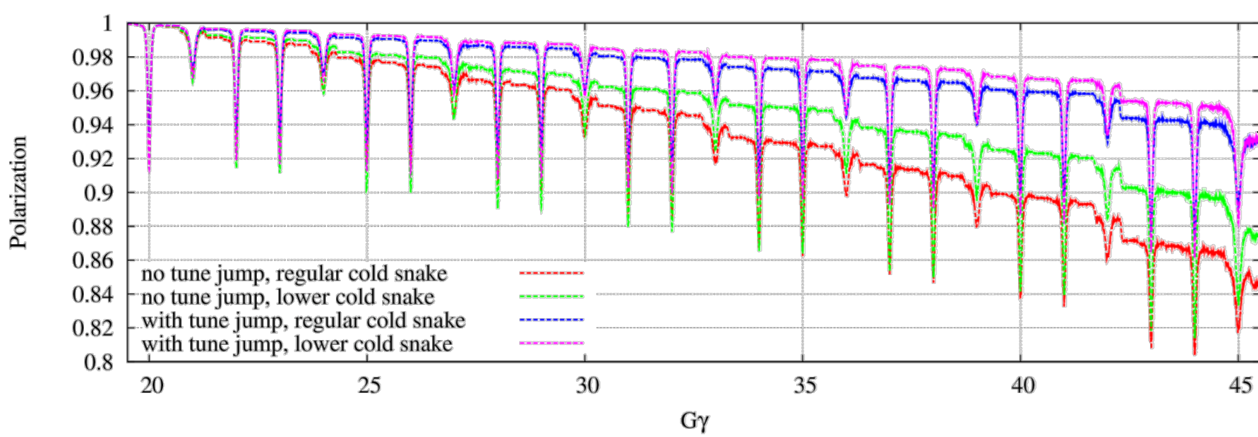


Snake angle for the regular cold snake strength and for a lower cold snake, which field has been reduced by 10%.

The effect of the lower cold snake strength on the spin tune is small. In particular the locations of the higher order snake resonances stays almost the same.



With the tune jumps, only a very small gain can be expected from reducing the cold snake strength by 10%.



Simulation do not fully agree with experiments.

- On going developments to track from injection.
- Comparison requires the same observables, i.e. R profile values and center polarization P_0.

Energy calibration by depolarization : Tune jumps timings

The AGS tune jumps are meant to accelerate the crossing of the horizontal intrinsic resonances. These resonances occur when : $Q_s \pm Q_x = I$

With Q_x the horizontal tune, I an integer and Q_s the spin tune, which is close to Gγ in the AGS, when a horizontal intrinsic resonance is crossed.

The tune jumps create a horizontal tune shift of +0.04 within 100 μs.

Timing of the tune jumps requires accurate tune and energy measurements to locate the resonant condition and trigger the tune jumps pulses at the correct time.

Problematic

Tune jumps timings	April 6th	April 29th	May 5th
Polarization (%)	66.0	59.7	62.8
Number of measurement	8	4	4
Statistical error	0.9	1.1	1.1
Standard deviation	2.5	0.4	2.4

New timings are generated regularly to compensate for drifting of the machine parameters.
Polarization measurement taken on May 5^{th}.

Newly generated timings led to smaller polarization gain than “old” ones.
Since the difference in tune jumps time is always very small (<<ms) it is unlikely that the beam dynamics differs with different tune jumps timings.
The computation of the tune jumps timings from tune and energy data were checked and found exact.

Timings were generated by hand to verify the application and directly verified using dedicated monitoring hardware and scopes.

The problem is more likely due to the measured data, used to time the jumps. The tune measurement being both accurate and reliable it is probably not the source of error.
The energy measurement is a complex system and investigation on its operation might be worthwhile.

Energy calibration by depolarization : The GgammaMeter

In the AGS a dedicated device using RF frequency and field measurement is used to measure the energy.

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

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

The device is **cross calibrated, at low energy**, by adjusting the available variables (in blue) to reach the agreement between the two methods. But at high energy the energy measurement based on the RF frequency is not accurate enough.

$$\frac{\partial G\gamma(f)}{\partial f} = \frac{G(2\pi)^2 f(dR+R_0)^2}{c^2h^2\left(1-\frac{(2\pi)^2f^2(dR+R_0)^2}{c^2h^2}\right)^{3/2}}$$

$$\frac{\partial G\gamma(f)}{\partial R_0} = \frac{G(2\pi)^2 f^2(dR+R_0)}{c^2h^2\left(1-\frac{(2\pi)^2f^2(dR+R_0)^2}{c^2h^2}\right)^{3/2}}$$

The energy needs to be known at the 100μs level, equivalent to 0.01 Gγ during the ramp.
This is very hard to achieve such accuracy at extraction, from the measured frequency and radius.

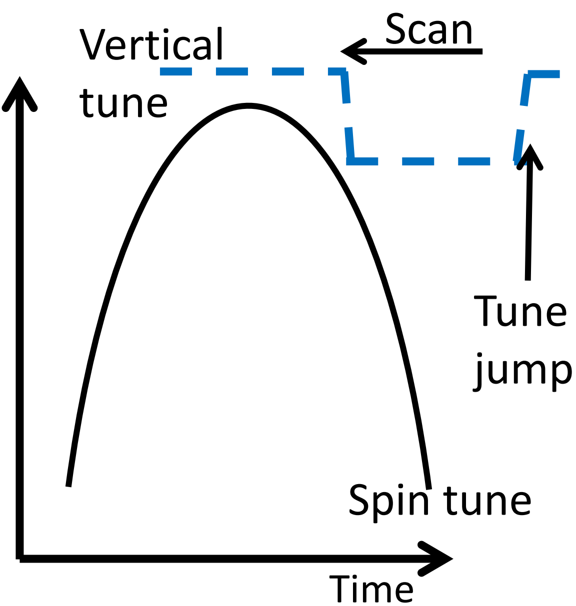
$$\frac{\partial(G\gamma(f)=45.5)}{\partial f} = 9.8\,10^{-3}\,G\gamma.\mathrm{Hz}^{-1}$$

$$\frac{\partial(G\gamma(f)=45.5)}{\partial R_0} = 3.9\,10^{-1}\,G\gamma.\mathrm{mm}^{-1}$$

An **independent method** of energy measurement would give strong confidence in the reported energy from the *GgammaMeter*.

With the current hardware in the AGS, **methods based on the depolarization of the beam can be explored**. The most promising method would be based on the tune jump to reduce the vertical tune across a vertical intrinsic resonance, inducing depolarization.

Energy calibration by depolarization : method

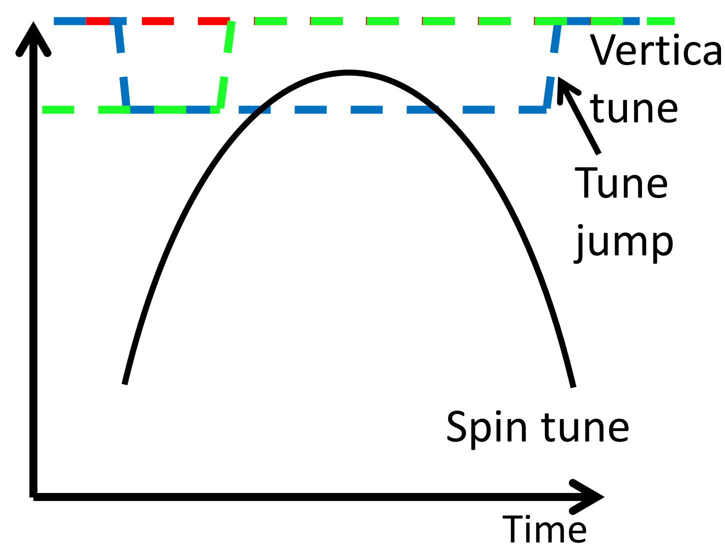


The tune jump system creates a vertical tune shift of $\Delta Q_y \sim -0.02$ within 100μs.

By positioning the vertical tune just above the spin gap we can use the tune jump to cross the vertical intrinsic resonance.

By **scanning the timing of a single tune jump** we can expect to loose polarization when the vertical tune crosses the spin tune. **The polarization is measured as a function of the timing of each edges of the tune jump.**

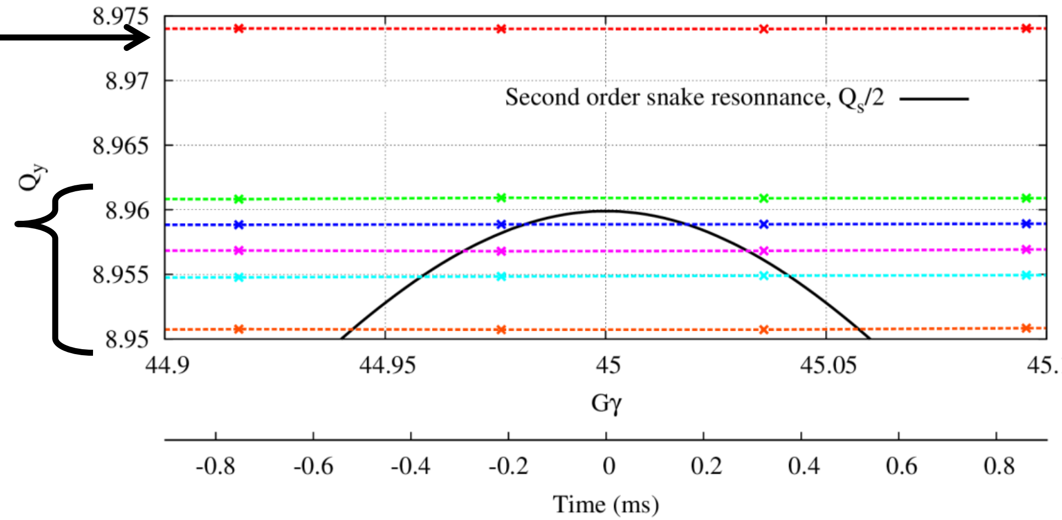
Simulations are required to understand the measurement, particularly as a function of the vertical tune across the resonance.



Energy calibration by depolarization : Simulation at 36+

At Gγ=45 the resonance $Q_s=36+Q_y$ is so strong that we do not need to cross the intrinsic resonance. In this case we will only cross the second order snake resonance $Q_s=2*Q_y+[I]$.

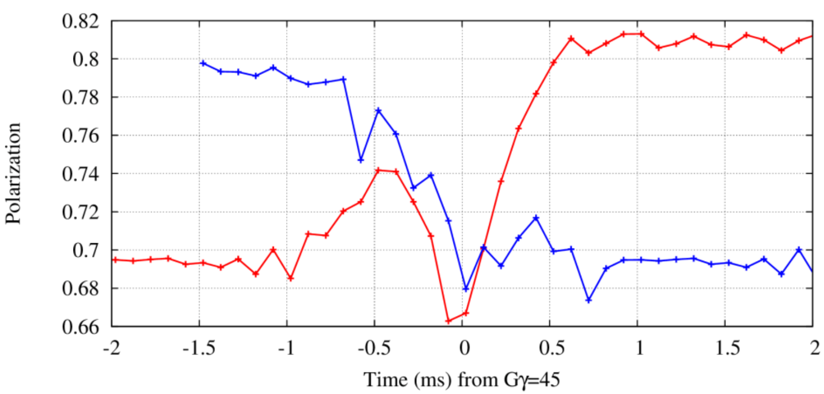
Tune off the jump
Qy = 8.974



Tune jump scan was simulated for 5 different vertical tune across the intrinsic resonance : 8.961, 8.959, 8.957, 8.955 and 8.951

Up Jump
Down Jump

Tune jump is 3ms long

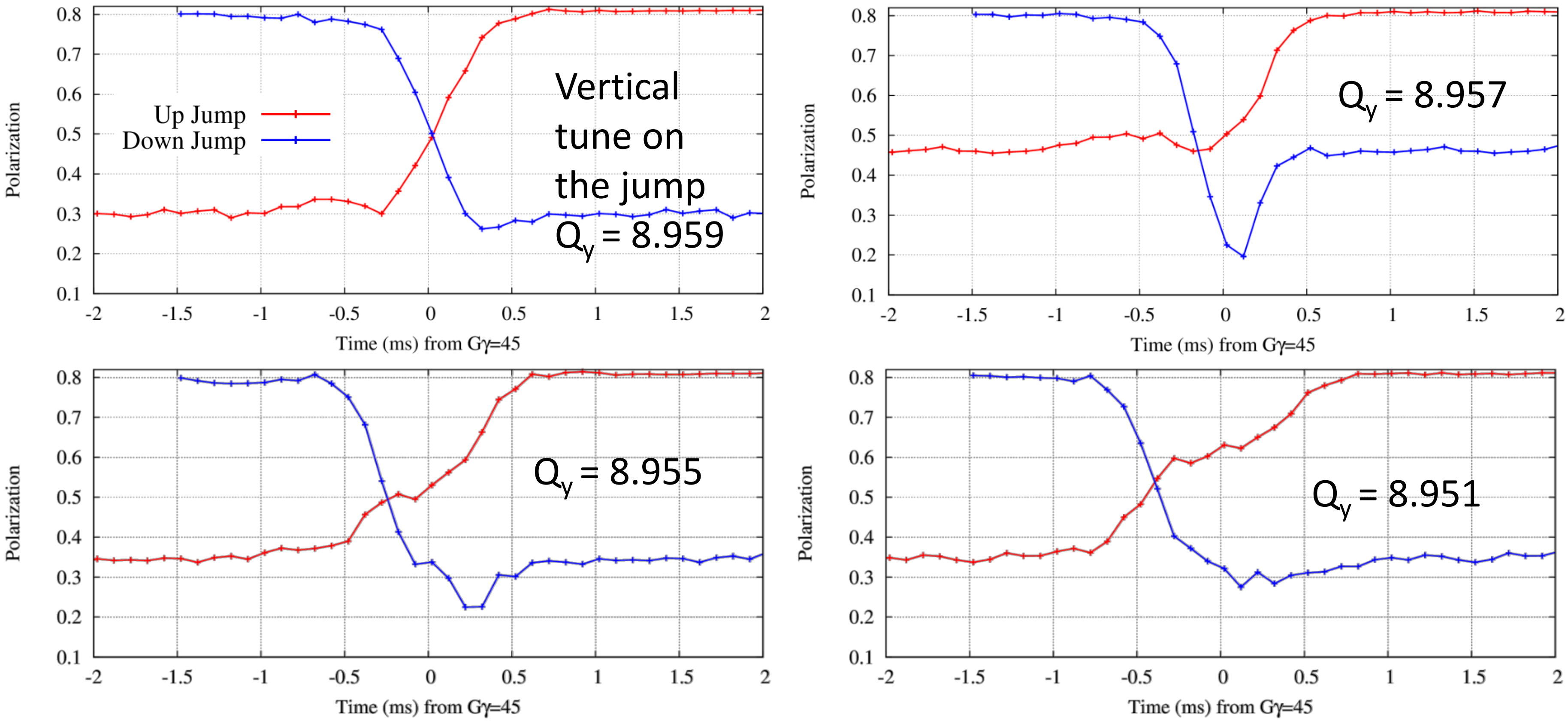


Each simulation consists in a tracking of 400 particles in a realistic 6D Gaussian distribution, using the Zgoubi code. The versatility of the Zgoubi code allows to generate different tune jump strengths to vary the vertical tune on the jump.

In this case the vertical tune on the jump (Q_y=8.961) is above the second order snake resonance, therefore the depolarization induced by the lower vertical tune on the jump is too small.

Every point is the final polarization of a multiparticle tracking with a particular tune jump timing function. The plot on the left requires approximately 1000 CPU hours.

Energy calibration by depolarization : Simulation at 36+



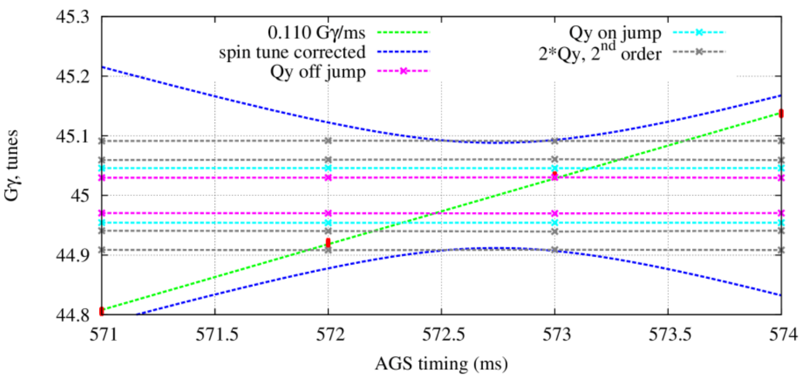
The energy is most accurately determined if the vertical tune on the jump is just below the maximum value of the spin tune (or half the spin tune in this case), here when $Q_y = 8.959$. We can see that the location where the polarizations crosses shifts as the vertical tune gets lower across the resonances.

The best way is to lower the vertical tune with the jump quads just below the maximum value of the spin tune but we can also see when the beam starts to depolarize.

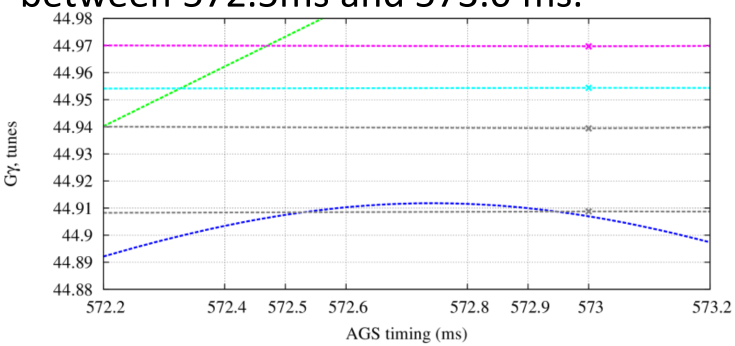
Energy calibration by depolarization : Experiment at 36+

On June 1st the measurement was carried on across the strong vertical intrinsic resonance 36+, at $G\gamma=45$.

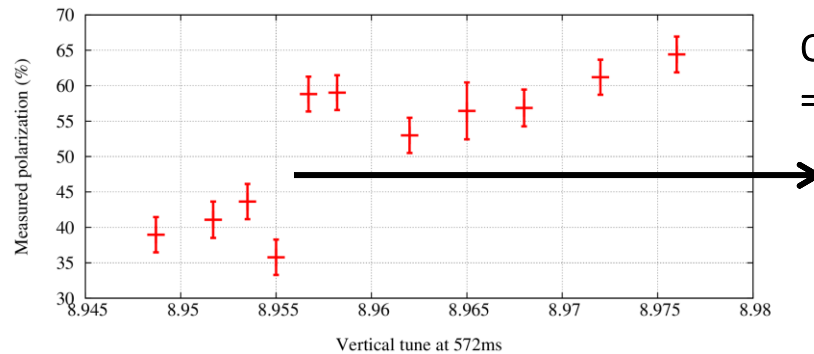
In this case we choose a vertical tune on the jump of $Q_y=8.954$, just below the maximum value of the spin tune.



Spin tune determined using the theoretical formula and energy determined by the **GgammaMeter shows that we expect Gg=45 at 572.75ms** and we expect some depolarization between 572.5ms and 573.0 ms.

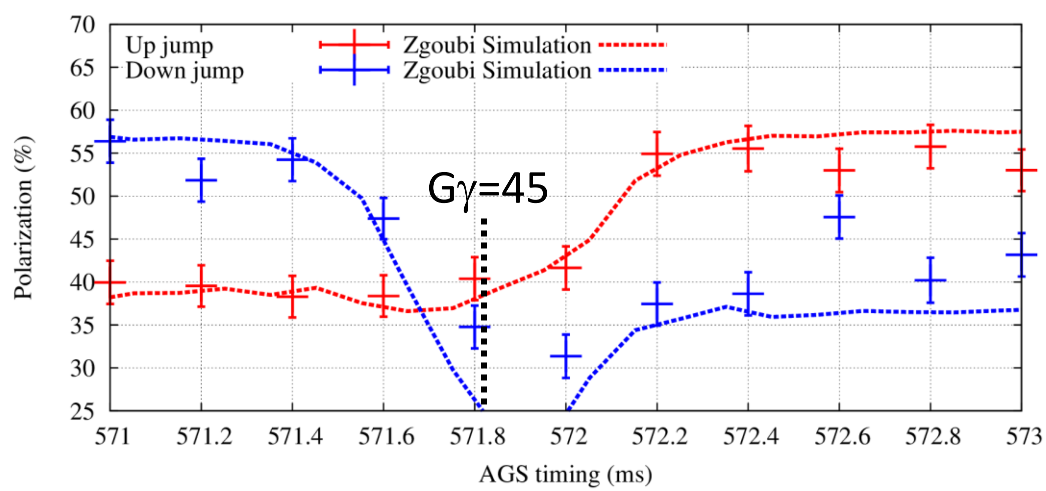


First step : locate the maximum value of the spin tune by measuring the polarization as a function of the vertical tune across the resonance.



Qs/2 (max) = 8.956

From the measured data below we see a depolarization between 571.4ms and 572.2ms, so we can estimate the **Gg=45 at 571.8ms**.



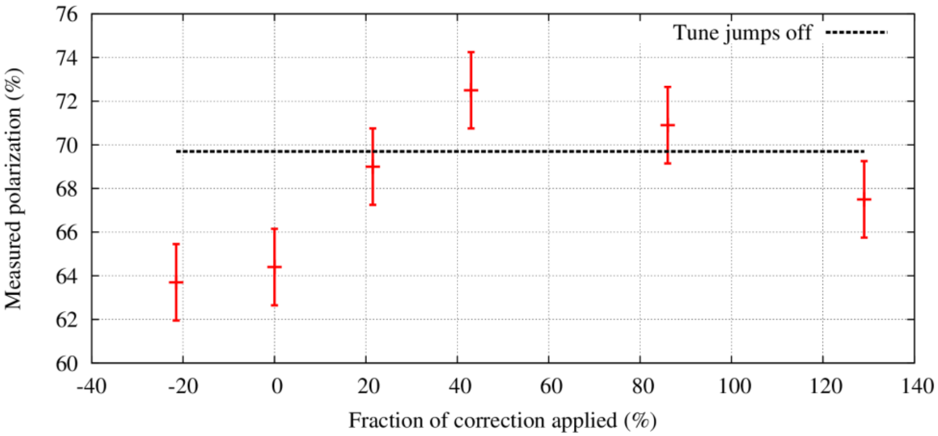
Energy calibration by depolarization : Results

- The measurement at 36+ located Gγ = 45 at 571.8ms whereas the GgammaMeterfromB located it at 572.75ms. The GgammaMeter overestimates the energy by around 0.1Gγ.
- The same measurement a 0+ measured Gg=9 at 262.8ms while the GgammaMeterfromB located it at 262.9ms. The energy measurement overestimates there the energy by around 0.01Gγ.

These measurements indicate a difference between the beam energy and the energy reported by the GgammaMeterfromB building along the cycle.

Also the GgammaMeterfromB is based on a field measurement that integrates the eddy current through a coil in a spare main magnet. The most likely source of error seems to be the calibration factor used to convert the integrated current into variation of the field.

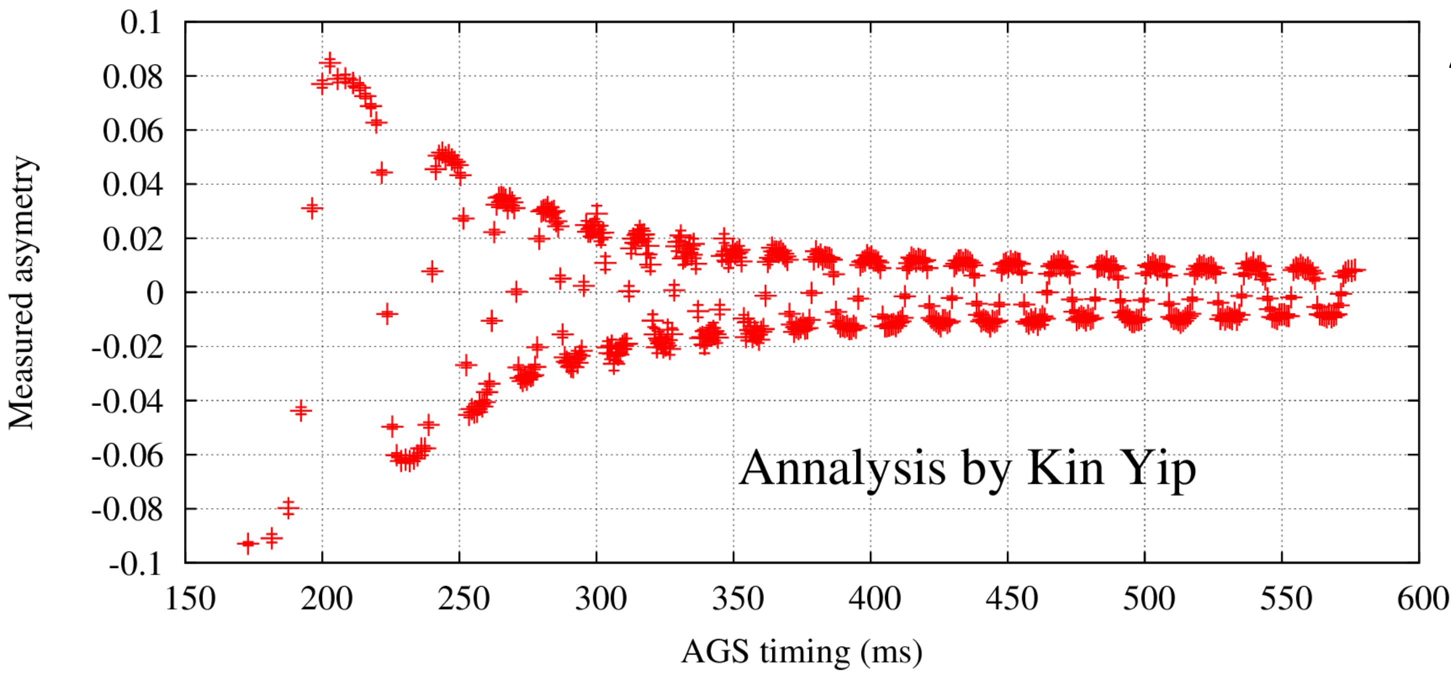
On June 9th the polarization was measured (fixed vertical target) against the fraction of correction applied to the energy measurement to generate the tune jumps timings. Results show higher polarization when the correction is applied but the highest polarization is reached for before the full correction is applied. This along with the measured polarization without tune jumps is surprising Nevertheless, it seems that the correction increases the polarization transmission.



The measurement is rather complicated and the results are surprising, even if confirmed by polarization measurements. Also the method is **very tedious**, it might not be a good choice for the operation.

-> An other method should be developed to corroborate this results. This other method should also be easy and reliable.

Energy calibration based on polarization measurement on the Ramp : Method



The asymmetry oscillates between positive and negative values due to the partial snakes configuration which flips the stable spin direction across every Gγ integer.

The polarimeter measures the vertical component of the spin. Also the vertical component of the stable spin direction depends only on the snake strengths and beam energy. Therefore the theoretical formula of the vertical component of the spin could be fitted to the measured asymmetry to determine the energy as a function of time.

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

The spin tune Qs and the snake angles Aw and Ac are also dependent on the energy and their evolution is known.

The figure above shows the maximum values of the asymmetry decreasing as energy increases. This is due to the dependence of the analyzing power with the energy, that links the measured asymmetry to the beam polarization.

Energy calibration based on polarization measurement on the Ramp : Example at Gγ=43

Also we can fit the function n0,z (Gγ) ∗ SCAL with SCAL a scaling factor that will be fitted and should take into account the analyzing power. Since each fit is realized over a small energy range the analyzing power is considered constant and the factor SCAL is independent of the energy. We also consider the evolution of the energy as a function of time to be linear and express the function to fit as a function of time :

$n_{0,z}(c * t + d) * SCAL$

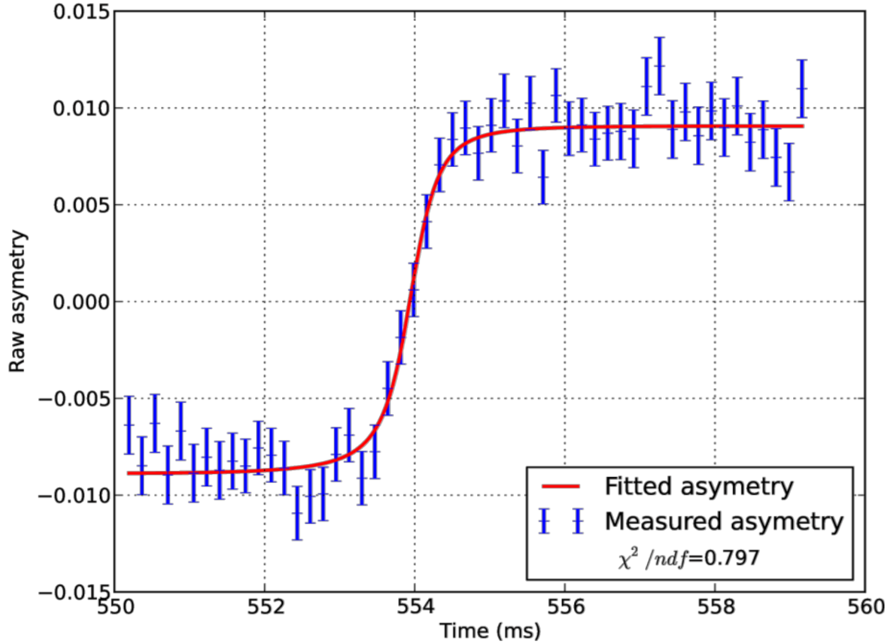
If we consider that the acceleration rate deduced from the GgammaMeterFromB is accurate enough then c is kept constant with c = A. The fit only need to determine the two terms d and SCAL.

In this case :

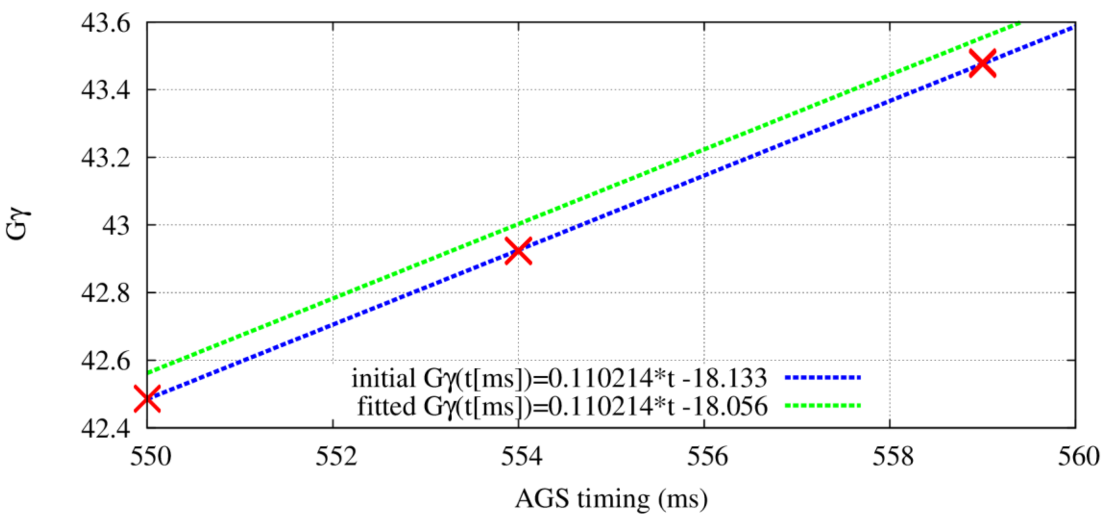
d = -18.056 ± 0.004

SCAL = $-9.1\ 10^{-3} \pm 0.2\ 10^{-3}$

The asymptotic standard deviation on the fitted parameters is very small, despite of the low number of data points.



n0,z(A ∗ t + d) ∗ SCAL

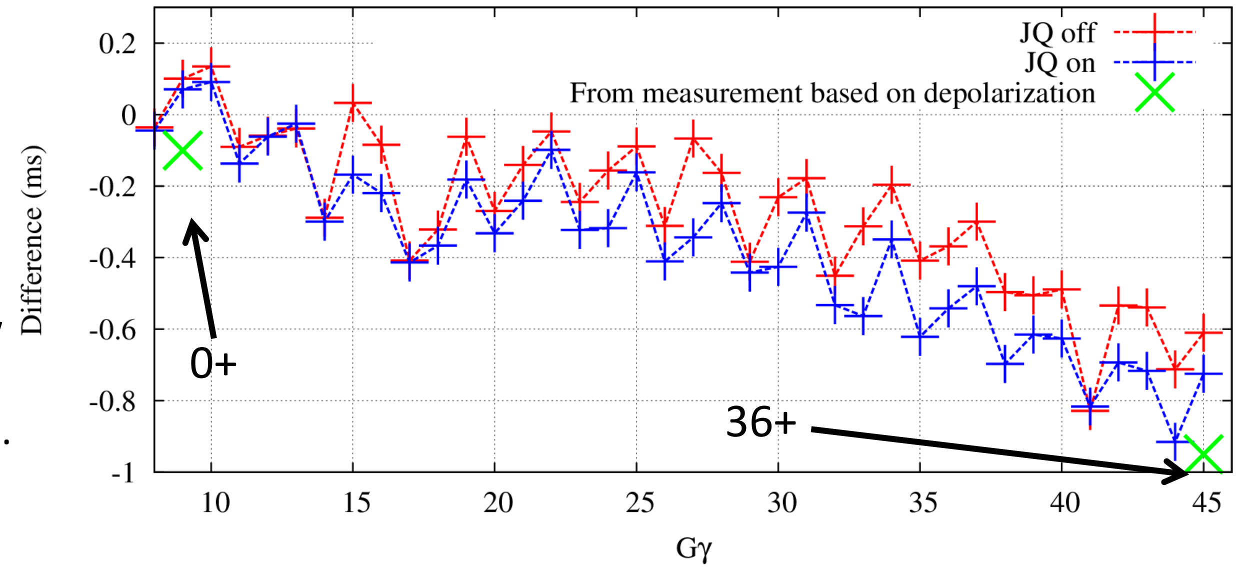


Using the determined parameter d we can draw the evolution of the energy using Gg(t) = A ∗ t + d

Energy measured by the *GgammaMeterFromB* and adjusted using the fitted d parameter. We can also deduce that for the *GgammaMeterFromB*, Gγ = 43 is reached at T = 554.7 ms but using the fitted d parameter T = 554.0 ms.

Energy calibration based on polarization measurement on the Ramp : Results

- The measurement is done along the ramp with two sets of polarization data taken with and without tune jumps.
- Since we assume a linear acceleration rate, the points below Gg=8 are ignored.
- The statistical errors are very small. We can suppose that systematics errors dominate.



- The agreement with the method based on depolarization through the strong intrinsic resonances at Gg=9 and Gg=45 is fairly good.
- The method assumes that the analyzing power and the polarization do not change over one unit in Gg but it seems that the influence on the fitted timing of the flip is limited.

Practical considerations :

- The analysis is done by a simple *Python* code, which could be run on the system if a more recent version of the library *Scipy* was installed (current is V0.7 from 2009 and at least V0.9 from 2011 would be required).
- A **new trigger based on real AGS time** should be used to bin the data from the polarimeter. The current system uses the field measurement and transforming the data to asymmetry as a function of time contains can be a source of systematic error.
- This method could be used for regular calibration of the energy measurement device. Operation by non-expert seems possible.

Conclusion

- Roll-Over : The time it took between the simulation results and an implementation of a solution for operation was very short. **The polarization gain with tune jumps is not obvious.**
- Snake strength : The polarization measurements were very long and their comparison is tedious. **The interest of changing the snake strength is not proved, yet**. More accurate measurement are required.
  Developments of the Zgoubi model are ongoing to achieve full 6D tracking from injection and extract quantities like the polarization profile.

Energy measurement is critical for the tune jumps operation. An **independent energy measurement** method is the best way to calibrate the energy measurement device based on the field measurement for a daily use.

- Depolarization method : This method is very tedious and might require an expert. **The Zgoubi model is a key for the interpretation of the results.** This is also the subject of a poster for the NAPAC13.
- Polarization on the ramp method : This method proved its accuracy and can be automatized for operation.

- Suggestions for future pp runs :
  - We have seen that the calibration of the energy measurement is critical for the tune jumps operation. **Somebody should be put in charge of the energy measurement system and its calibration along with the tune jumps timing.**