Effect of polarization lifetime T_1 on thermal equilibrium polarimetry

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1 Introduction

TE (thermal equilibrium) polarimetry is done on materials that display a wide range of polarization lifetimes T_1: CH_2 cells have small T_1 (unmeasured but estimated to be small because the CH_2 responds immediately to temperature changes, see [1] or to field changes). In another hand, newly made HD cells should have T_1 of a few minutes. HD cells made with pre-aged gas have been measured to have T_1 of about 40 minutes [2]. In this note, we investigate effects of T_1 on the TE polarimetry: If T_1 is similar or longer than the time over which the magnetic field is ramped, then the target does not have time to reach TE at the NMR condition and the value of the polarization is not the TE one.

2 Effect of long T_1 on the TE polarization measurement

We simulated the effect of non-zero T_1 on the measured TE polarization. We split a magnetic field sweep into 4 times, see Fig. 1. The typical times are t overhead=60s, t down=t up=30s, t wait=1s. For hydrogen measured using the white RF cable, we typically set B span to 300 Gauss with B_0 around 3000 Gauss. In our calculations, we assumed that the field value at the resonance condition B_{res} is at the center of the sweep (i.e. $B_0 = B_{res}$).

For the results presented in this note, we assume that the initial target polarization is 0 (B=0 at t=0). We also assume a sample temperature T=1.8K. We evolve the polarization $P(t)$ during t overhead, t down, t wait and t up. If $P(t)$ is higher than the thermal polarization, we evolve $P(t)$ using $P(t) = \triangle P \times e^{-t/T_1} + P_{TE}(B)$ with $\triangle P = P(t - \partial t) - P_{TE}(B)$ and P_{TE} the thermal polarization for a temperature T and field $B(t)$. If $P(t)$ is lower than P_{TE}, we evolve using $P(t) = -\triangle P \times (1 - e^{-t/T_1}) + P(t - \partial t)$. We divide the ramp Down and ramp Up into 100 steps for better accuracy of the calculation.

Results are shown in Figs. 2-5 for 4 different values of T_1.

On Fig. 2, the result with a very short T_1 is presented ($T_1 = 10^{-3}$ minute, much shorter than the times discussed in Fig. 1). As expected, the polarization

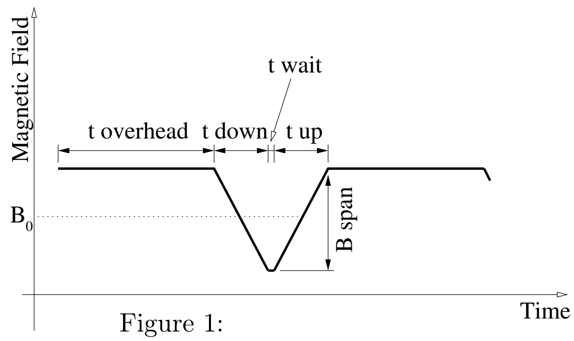

Figure 1:
Magnetic field versus time for a NMR sweep.

value rises immediately to the TE value. Here, the TE value is computed using B_{res}, the value of the field at the resonance condition.

On Fig. 3 (T_1 = 6 seconds) we see an oscillation around a value larger by 0.44% than the expected TE value computed with B_{res}, the magnetic field at the resonance. The Down sweep measurement is 4.8% larger than the Up sweep measurement and 2.8% larger than the calculated TE value. The Up measurement is 2.0% lower.

On Fig. 4 (T_1 = 3 minutes) the oscillation between Down and Up signals is smaller but the Down-Up averaged signal is further away (by 2.42%) than the expected TE value computed with B_{res}. The Down sweep measurement is 0.8% larger than the Up sweep measurement and 2.82% larger than the calculated TE value. The Up measurement is 2.02% higher than the expected TE value. As T_1 becomes comparable or larger than the times discussed in Fig. 1, then the relevant magnetic field value for the TE calculation becomes closer to the magnetic field value averaged over a cycle. This field value is larger than B_{res} because the magnetic field stays at its highest value ($B_0 + \frac{B_{span}}{2}$) during the long overhead time. The Down-Up averaged signal is 0.12% higher than the TE value computed with this time averaged magnetic field. The Down sweep measurement is 0.52% larger larger that this TE value and the Up measurement is 0.68% lower.

On Fig. 5 (T_1 = 40 minutes) the oscillation between Down and Up signals is very small and the Down-Up averaged signal remains away from the expected TE value computed with B_{res} by 2.42% (same as for the T_1=3min case). The Down sweep measurement is 0.06% larger than the Up sweep measurement and 2.45% larger than the calculated TE value. The Up measurement is 2.39% higher than the expected TE value. The Down-Up averaged signal is 0.12% higher than the TE value computed with the time average B. The Down sweep measurement is 0.15% larger larger that this TE value and the Up measurement is 0.09% lower.

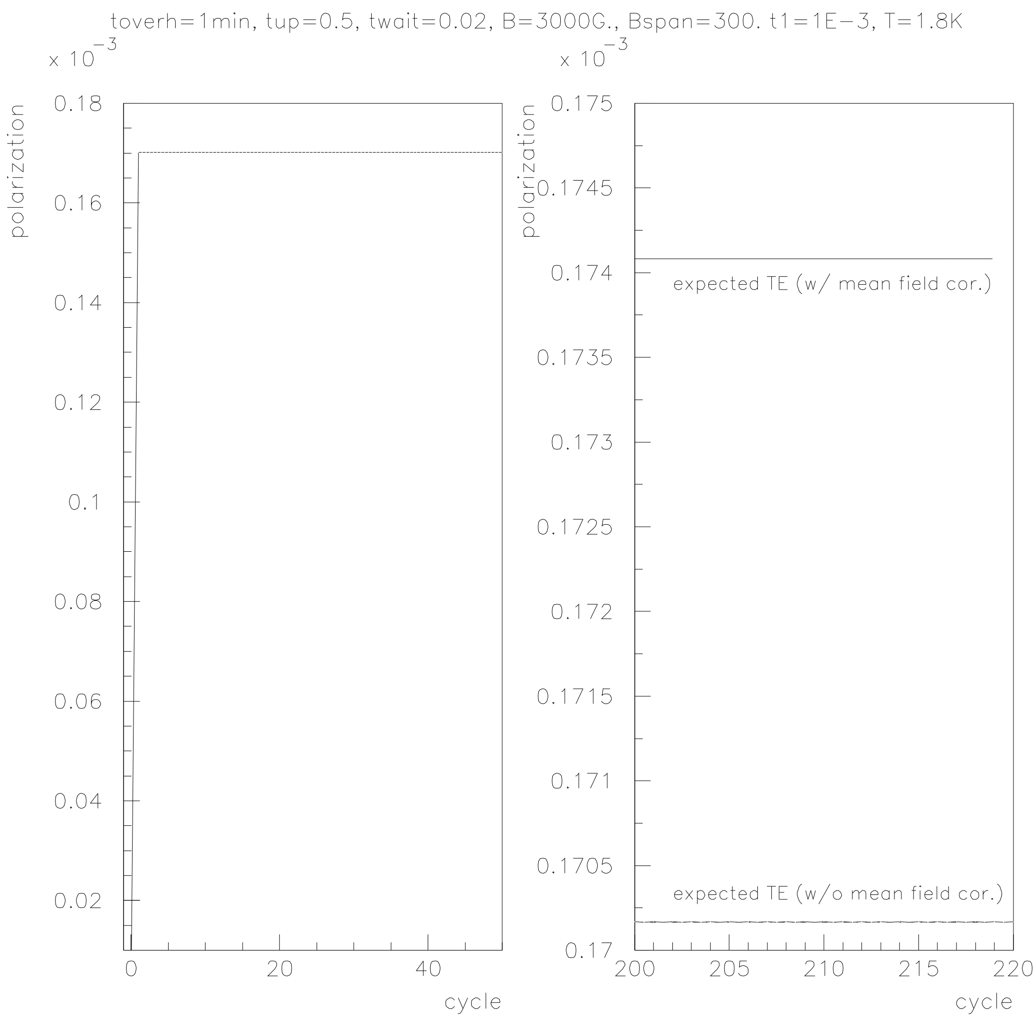

Figure 2:
Polarization values for $T_1 = 10^{-3}$ minute versus cycle (i.e. time). The other parameters used in the polarization calculation are writen above the plots. The left plot shows the first 50 cycles and the rise to the TE value. The right panel is a zoom after reaching TE. The expected value for TE (using B_{res}) and the measured polarization lie on each other (lower lines), as expected. The higher line is a calculation of the expected TE using the magnetic field value averaged over a cycle. It is relevant only for measurements of materials with longer T_1.

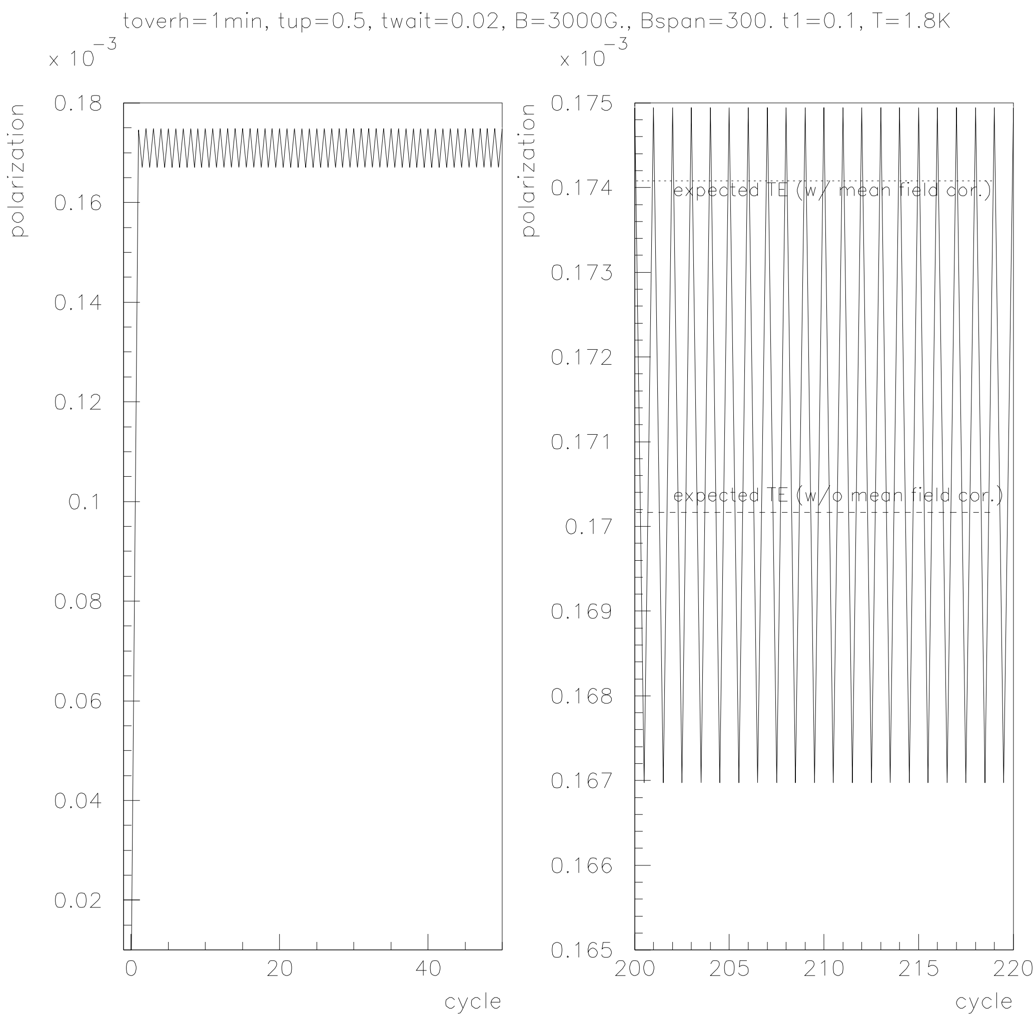

Figure 3:
Same as Fig. 2 but for $T_1 = 6$ seconds.

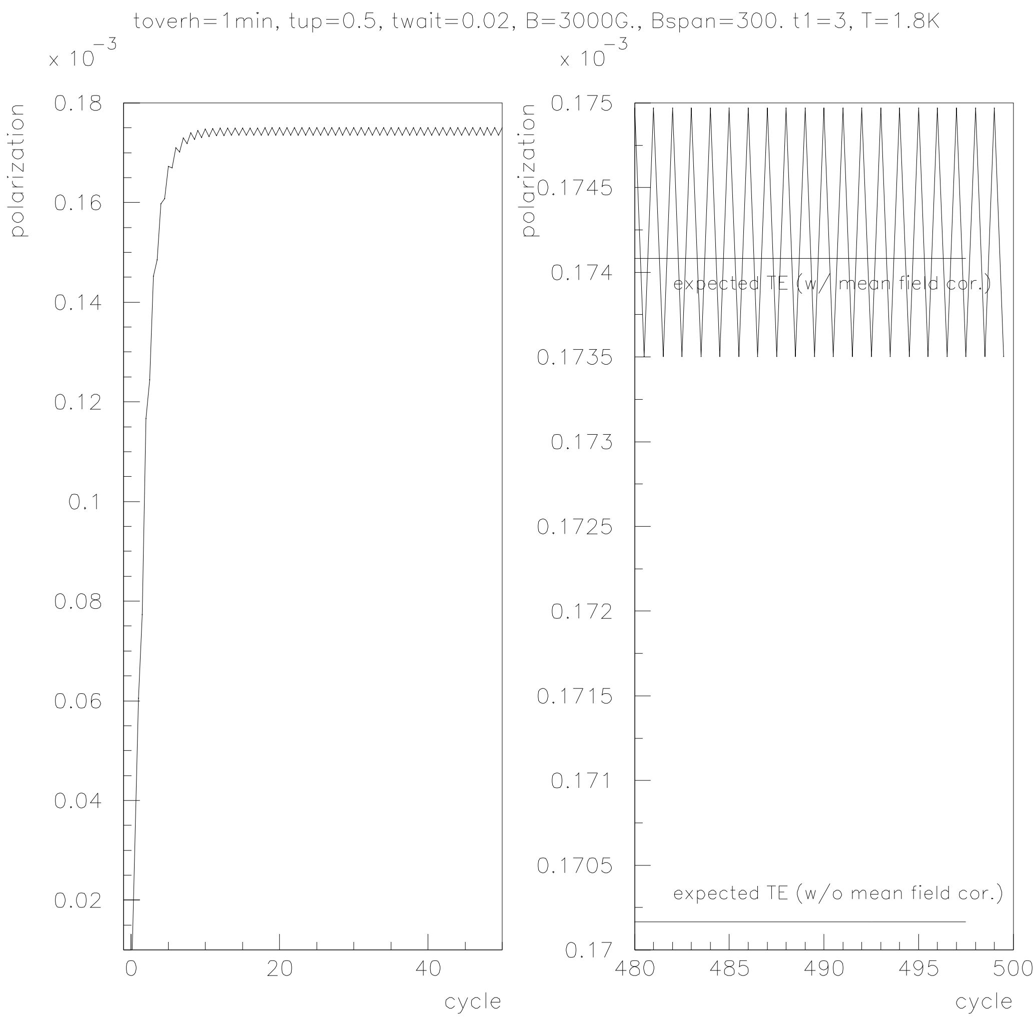

Figure 4:
Same as Fig. 2 but for $T_1 = 3$ minutes.

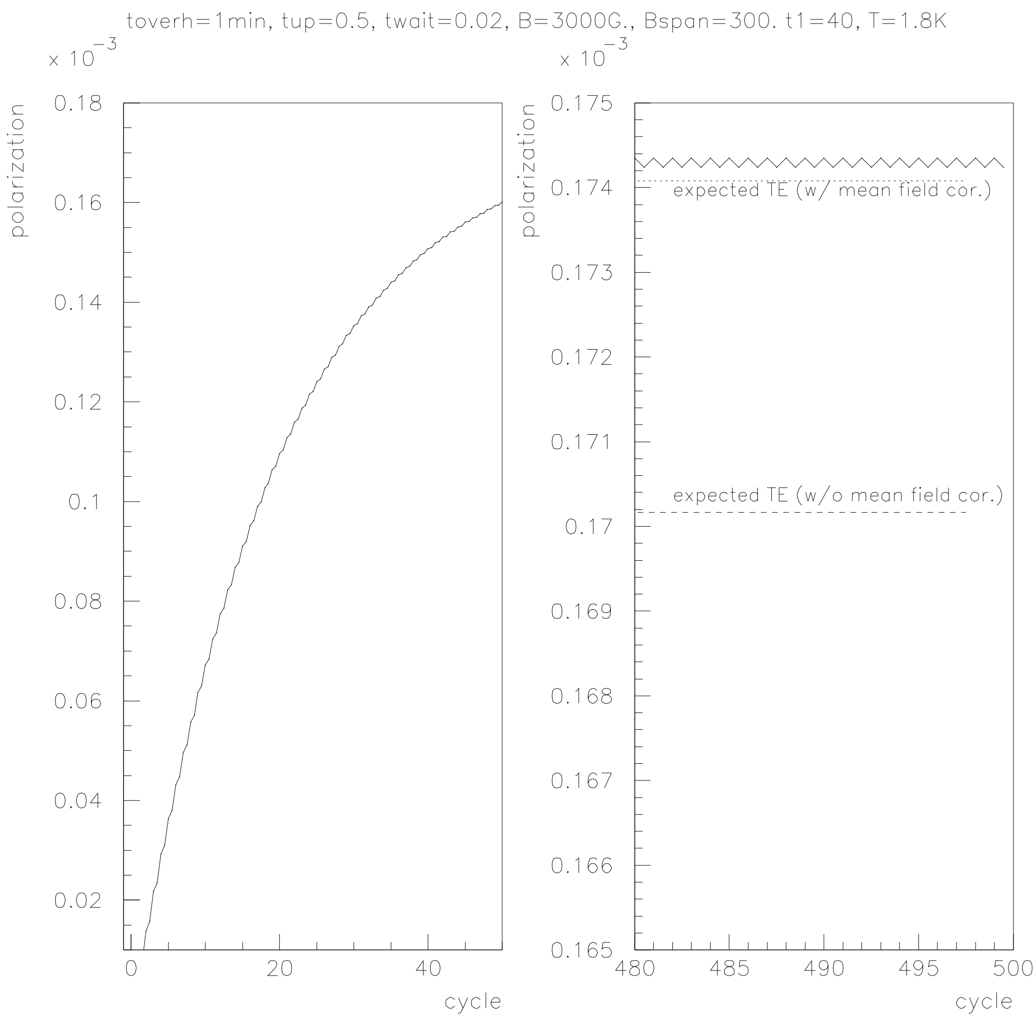

Figure 5:
Same as Fig. 2 but for $T_1 = 40$ minutes.

3 Effect of fast passage losses

During NMR Fast Passage, a small amount of the spins direction are flipped (randomized). This induces the NMR signal but also reduces the polarization. We call these losses Fast Passage losses. They are proportional to the signal, that is to the RF power. For short T_1 cells, these losses are recovered quickly and are of no concern. But for large T_1 cells, the losses are not fully recovered before a new sweep is performed and the measured equilibrium polarization signal will be lower than the TE value. This is shown on Fig. 6 for 1% Fast Passage losses. From fits to target #19 [2] and CH_2 cell #3 (8.1 min lifetime) [3] data, 1% RF losses correspond to about -5dBm of RF power.

The other effect of the losses is to distort T_1 measurements by a factor similar to the reduction of the equilibrium signal. On Fig. 6, the equilibrium value has been reduced by a factor 1.75 compared to the TE expectation. A fit to the black data yields a lifetime of 47min, while the input (true) value to produce the black data is 80min. We have $47 \times 1.75 \sim 80$. The reason for this is that the polarization grows exponentially with the speed necessary to reach the *true TE value*, but the losses from Fast Passage that lead to a lower equilibrium value are instantaneous. So the apparent (wrong) T_1 is smaller. It is important to note that the Fast Passage losses does not simply resale a growing polarization curve to a lower equilibrium value, since in that case, the growth rate would not change between the cases with no loss and with loss.

4 Effect of T_1 dependence with time.

As the H_2 and D_2 impurities decay, T_1 increases in time. For low magnetic field, as used in the PD, $T_1 = T_1(0)e^{t/t_g}$ with t_g =3.15 days. This effects, associated with large losses of polarization during a Fast Passage, creates a slow decrease of the polarization equilibrium value with time. The TE data taken on cells 14a and 19 [2] display such negative slope for the size of the equilibrium signal with time. Figure

5 Conclusion

With the sweep times discussed on Fig. 1, corrections to precise polarimetry are necessary as soon as T_1 is of the order of a minute. Even with T_1 of a few seconds, up to 5% corrections are necessary on the Down and Up signals, albeit their average value is close to the expected TE value calculated with B_{res}. When T_1 is of the order of minutes or larger, B_{res} is not relevant anymore for calculating the TE value, while the magnetic field value averaged over a cycle becomes the relevant one. **It is important, with the typical sweep times discussed on Fig. 1, to measure the T_1 of the sample in order to apply the corrections.** Such corrections can be minimized by setting (t wait=t overhead) and setting the resonance condition in the middle of the field ramp (i.e. $B_0 = B_{res}$), or by reducing the overhead time. The following value

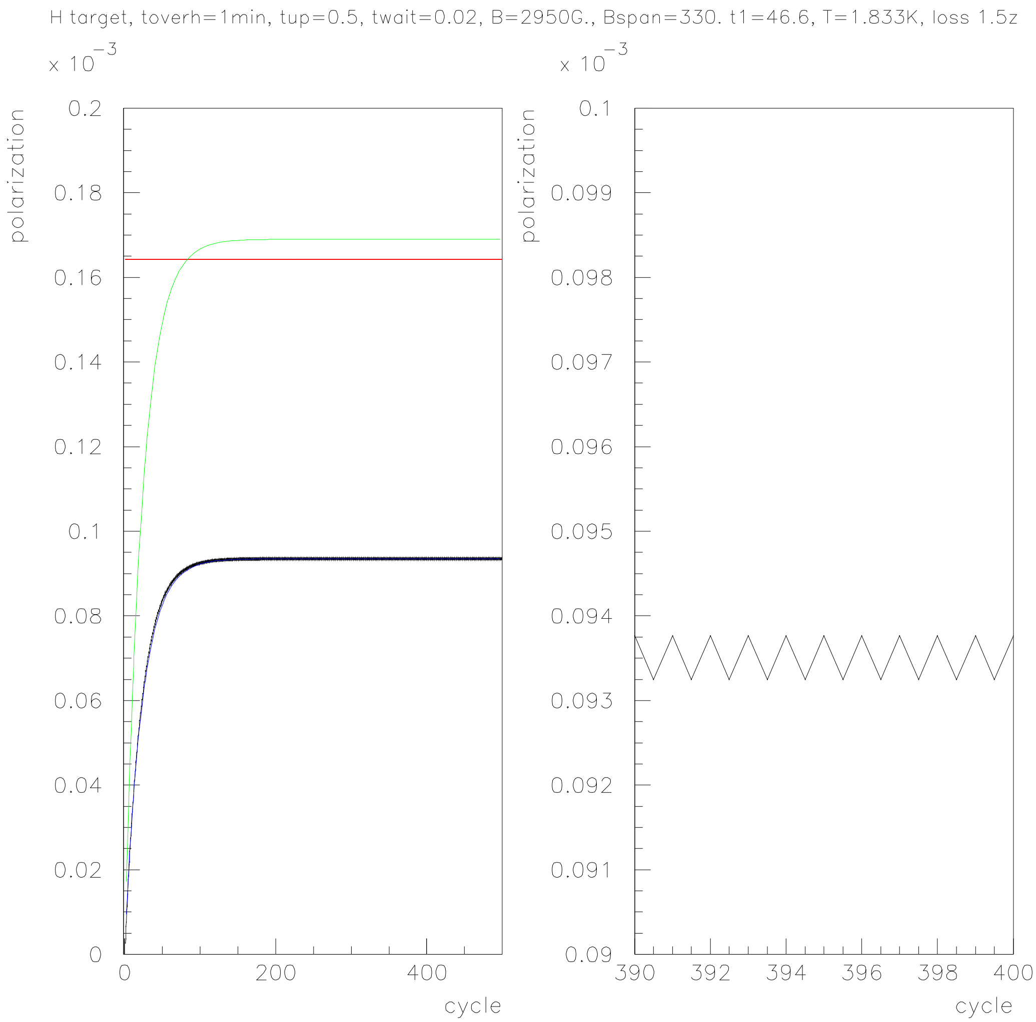

Figure 6:
Effects of important Fast Passages losses on TE measurements. The red line is the expected TE equilibrium value. The green line is the expectation without Fast Passage losses, for a T_1 =46.6min cell (the overshoot above the red line has been discussed before: the cell spends most of its time at a magnetic field higher than the NMR condition field.) The black line is when 1% of Fast passage losses are added for a T_1 =80min cell. The blue line is the fit of the black results, yielding an incorrect T_1 =46.6min.

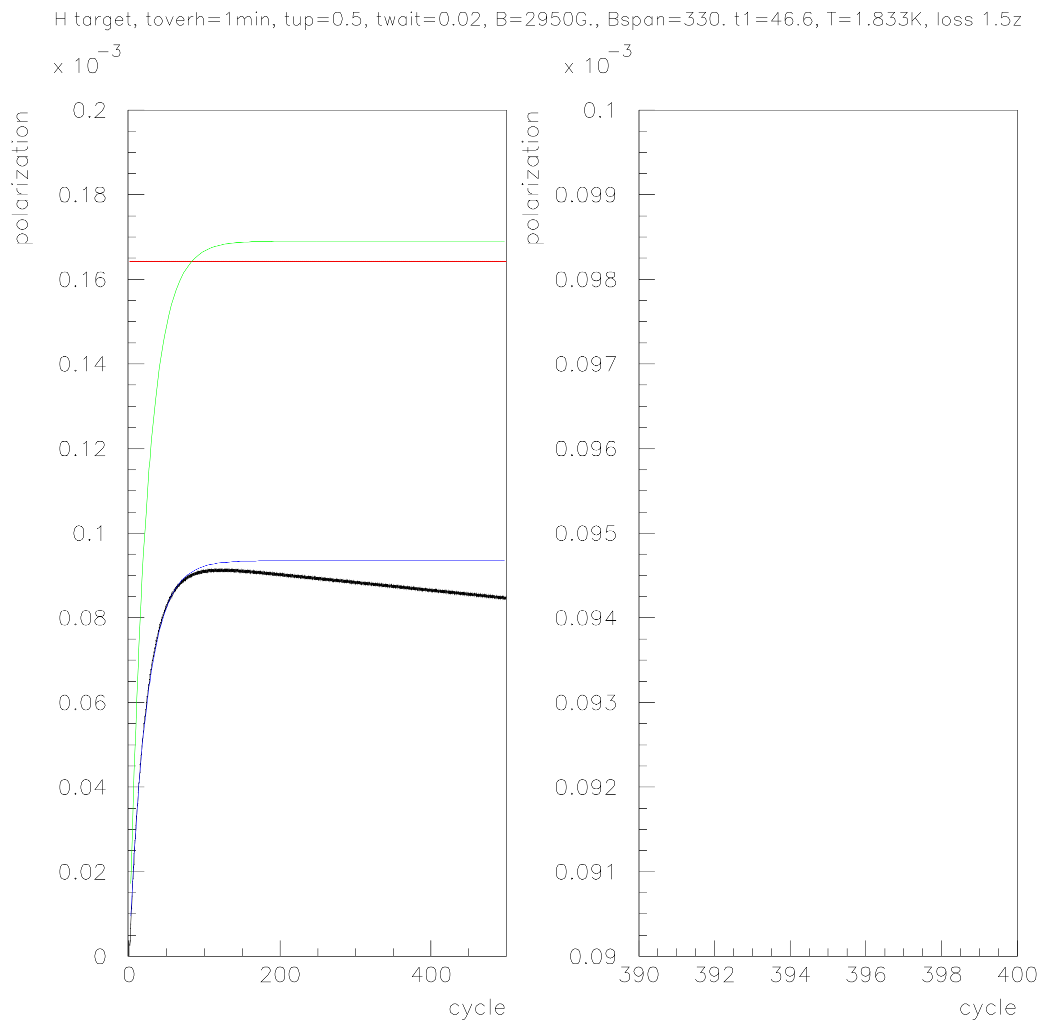

Figure 7:
Same as Fig. 6 but now including the time dependence of T_1 in the simulation (black line).

gives an example of the reduction of the correction with the shortening of the overhead time: In our previous case (t overhead=1min), for T_1 larger than a few minutes, the correction is 2.42%. For t overhead=0.5 minute the correction becomes 1.5%. For t overhead=0.2 minute the correction becomes 0.7%. For t overhead=0.1 minute the correction becomes 0.35%.

Another important effect of T_1 is that, when it is long and associated with important Fast Passage losses, it can reduce the equilibrium value by a large amount (e.g. a factor 1.75 for T_1=80min and RF power of -5dBm) and produce a time constant for the polarization exponential growth rate much shorter than the actual T_1.

References

[1] HDice_TN6: A. Deur, report on CH2 calibration target and polarimetry tests. www.jlab.org/Hall-B/HDIce/technotes/icelab_NMR.pdf

[2] HDice TN9: A. Deur, HD target polarimetry calibrations. www.jlab.org/Hall-B/HDIce/technotes/HD_nmr_2011.pdf

[3] HDice TN11: A. Deur, Systematic study of the NMR sweep parameters. www.jlab.org/Hall-B/HDIce/technotes/nmr_param_study.pdf