Analysis of the electron beam tests done during G14 (DRAFT 1)

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1 Introduction

This report presents the analysis of two tests done in 2012 to investigate the behavior of polarized HD under an electron beam. They consisted on sending a nA or sub-nA electron beam on the JLab Hall B polarized HD target. The first test was done on cell 21a and started on Feb. 23$^{\text{rd}}$ 2012. The second test was on cell 20b and started on March 29$^{\text{th}}$ 2012. After presenting the polarimetry and polarization lifetime results and stating what we learned from those, we tentatively interpret the data and discuss improvements for future tests.

A shortcoming of these tests was the very low target polarization: 2% to 2.5% for D and H for both cells. This is because the tests were done during a HD photon experiment (G14) when the decrease in target polarization could not warrant physics data taking. Two consequences are that:

- It was impractical to gather electrons scattering data as an alternate polarimetry because it would take too long and would interfere too much with the running of other halls.
- At low polarization, knowing the Thermal Equilibrium polarization (TE) is necessary as it should be the baseline to which the polarization decays to. If the TE value is negligible compared to the polarization, then no absolute calibration is needed. This makes the analysis more robust. Yet, in our low polarization case, an absolute calibration is in principle needed. However, as it will be explained, even knowing precisely the TE and the absolute polarization may not have been sufficient as it appears that the polarization decayed to an effective equilibrium value rather that the TE value. As we will discuss, this effective value can be either larger or smaller than TE, depending on the mechanisms at play.

Since we are possibly dealing with different relaxation mechanisms we reserve the notation T_1 for the regular spin-lattice relaxation seen in HD undamaged by radiations. Generally, the relaxation time of HD after it has been under beam will be labeled T_R. We caution that since the beam-on loss rates are generally much higher than beam-off rates, and since there were beam-off time gaps of varying duration before and after irradiations, the extraction of an overal time constant T_R can be biased.

Note on spin-spin diffusion time. We call T_2 the spin-spin diffusion characteristic time. It is the time it takes for spatial polarization inhomogeneities to disappear by spin diffusion, i.e. assuming T_1 or $T_R \to \infty$. T_2 may depend on temperature, dose (radiation damage), polarization gradient between the high and low polarization areas, location of the low and high polarization areas, HD aging, magnetic field and HD lattice quality (cracks in the lattice will increase T_2). After G14, a polarization hole (Pol.=0) was burned with high RF power on cell 19b in PD2 (cell exposed to photon beam only). The target was well aged (about 3 months) and the measurement was done at a field B=0.3T and a temperature T=4.3K. The hole healed within 7 min. for H. The test was done as well on cell 22b (again, cell exposed to photon beam only, well aged and measurement done at 0.3T and 4.3K). The hole was healed in about 1h for H. Similar test had been done once before at BNL with a 8h healing for H at 2K. However, these measurements do not provide T_2 because the hole is made in *B-field* space, while we need to know how *spatial* polarization inhomogeneities disappear. The two spaces are partly correlated because part of the NMR peak width (where the hole is made) is due to spatial field inhomogeneity. Typically in the PD, the H peak width is 4.5 Gauss while the natural width is about 3.5 Gauss. Consequently, the 7 min. or 1h measurements may significantly underestimate of the true T_2. For ex. assuming for simplicity that the H peak width is 4.5 Gauss -its natural width, then the hole made in the B-field space is spread homogeneously everywhere on the surface of the cell and the spin diffusion needs only to occur over very small distances (of the order of the HD lattice spacing, i.e. Å ?), while in the case of spatial inhomogeneities due to beam, the spin diffusion needs to occur over distances of the order of the raster radius (cm), that is 10^8 larger. Measurements were also made with cells 19b and 22b for D. But no trace of hole could be seen. This can be because the recovery for D is extremely fast (most likely) or because the size of the "hole" covered the full D peak, effectively reducing the peak size rather than altering its shape (unlikely but not ruled out).

In addition, the measurements are not done in the electron test conditions: The temperature is between 1 to 2 orders of magnitude lower when the beam is off, the cells had different aging (much longer for 21a and shorter for 20b) and had radiation

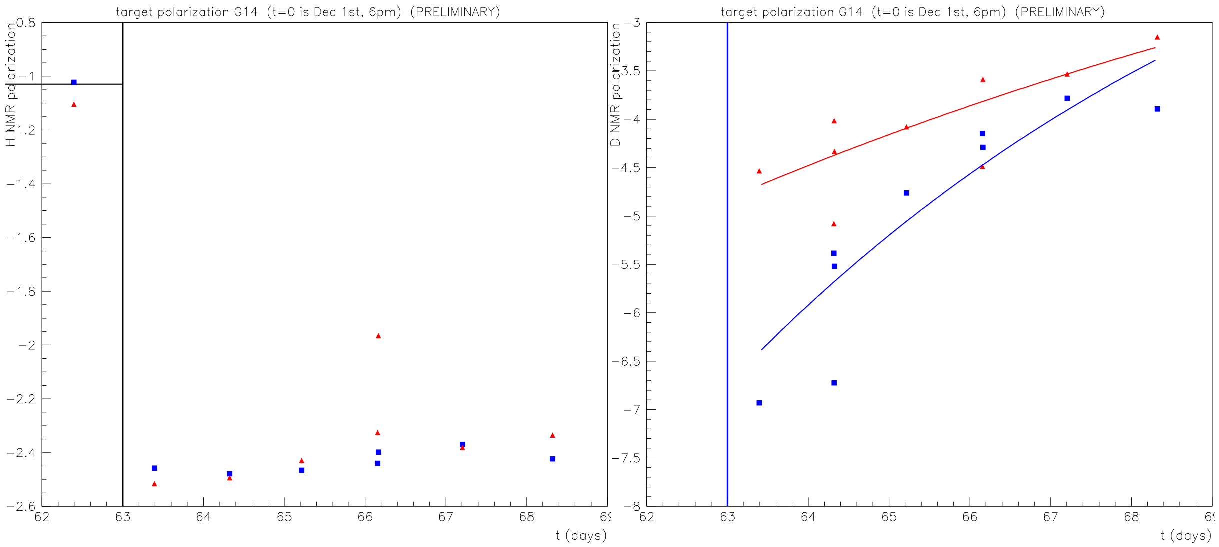


Figure 1:
Left: evolution of cell 21a H polarization after the "pseudo-quench". The vertical black line indicates the time of the "pseudo-quench". Note the lower polarization prior to the "pseudo-quench". Its average over the previous weeks is indicated by the horizontal line . Right. Same for D.

damage. Also, cell 21a displayed 2 peaks during the high polarization D NMR, indicating stress on the HD crystal, while cell 19b and 22b did not present such feature (***this statement needs to be verified. It is only my recollection***).

In conclusion, T_2 may be needed for our interpretation of the electron tests but the interpreting time of healing of a hole in the B-field space into a healing time of a hole made in the physical space by the electron beam is at best convoluted.

2 Data

2.1 Cell 21a (Magnet "pseudo quench")

Before the first electron test, the target main magnet underwent a rapid ramp down triggered by the IPS power supply. For about an hour, the cell was only under 100G from the main magnet plus the 100G from the back-up coil (total≃200G). The D polarization losses during the ramp down were high (pol. dropped from about -16% to about -6%) and consequently cell 21a was not suited anymore for nuclear data taking. It was then decided to proceed with the electron beam test. Purposely, the H polarization had been mostly erased 50 days before the "pseudo-quench" and was about -1%. During the event, the H polarization increased to about -2.5%, probably from D polarization transfer, albeit there is no clear mechanism known to explain such relatively efficient transfer. The rapid ramp down warmed up the IBC and evaporated part of the ^{3}He of the cooling mixture. The consequence was that during the several days of the IBC "pseudo-quench" recovery, the IBC temperature was hight: from 600mk to 500mk during the first 3 days. During this period, we saw the first evidence of target depolarization, see Fig. 1. Because the T_1^H and T_1^D at $\sim$ 500mK are too large to explain these decays, we assume that they are due to the relatively large IBC temperature combined with permanent radiation damage during the photon beam delivery. This damage is assumed to stem from e^-/e^+ pair creation and can be estimated, with large uncertainty, to the equivalent of 15 min of 1 nA electron beam on the HD target (M. Lowry).

Fits to the decaying polarizations during the IBC recovery yield, for the lock-in x-channel down/up signals respectively: $T_R^H = 128 \pm^{59}_{30}$ (down) $/48.5 \pm ^{9}_{6}$(up) days for H and $T_R^D = 7.6 \pm 1.4$(down)$/13.4 \pm 3.4$(up) days for D. For these estimates, we accounted for the non-negligible TE values to which the signals should decay. It should be kept in mind that the temperature was constantly decreasing during the measurements and since the T_R temperature dependence is not known, we did not attempt to correct for it. The results indicate that:

- T_R^H after pseudo-quench is larger than the initial T_1^H (about 45 days). This is due to the H aging during the 2 months of photon running (if T_1^H doubled every 2 weeks due to aging, its value would have been 4 years). However, T_R^D after pseudo-quench is smaller than the initial T_1^D (about 400 days), possibly because the radiation damage balanced the aging.

- H is more resilient to permanent radiation damage than D. This conculcates the experience with other types of target such as DNP targets. This also contradicts the results of the end of the second electron test discussed in this report. A possible explanation for this contradiction will be discussed in section 4. It could also be that the assumption that after the "pseudo-quench" we are measuring T_R due to radiation damage is incorrect.

2.2 Test on Cell 21a (First electron test)

The detailed characteristics of cell 21a and its NMR calibration are given in [1]. The evolutions of the target H and D polarizations during the first test are shown on Figs. 2 and 3. Typically, the beam was delivered after establishing it appropriately into the tagger beam dump. The raster size, integrated charge on target, and beam current varied during these tests, see [2] for a summary of the beam characteristics. The beam quality appears to be a relevant parameter since it can influence the instantaneous temperature or the amount of charge (cell partially missed or, contrarily, extra charges due to scrapping). However it is hard to quantify its effect. We performed NMR measurements before and after each beam delivery. In between beam deliveries, we varied the magnetic field and temperature conditions in order to study their influence on T_R. The goal was to verify the initial model for beam induced polarization losses [M. Lowry, ref ??] by checking the magnetic field and temperature dependence. Generally, we performed two NMR measurements for each condition in order to compute the T_R. In retrospect, this was not an appropriate procedure for several reasons:

- The unknown value of the equilibrium polarization, sometime not negligible compared to the HD polarization and different from the TE value, makes two points not enough to determine T_R. More points are necessary to determine the value of the equilibrium polarization.

- They are more than just permanent radiation damage at work: possible transient T_R (see section 4), large temperature rises during beam-on due to inappropriate raster, possible spin-spin diffusion ($T_2 \neq 0$ and $T_2 \neq \infty$) between parts of the cell exposed or not exposed to the beam.

- Given the possible transient T_R or T_2, there was not enough time for an uncontaminated T_R measurements. With more than 2 points one could have tried to disentangle the transient effects from the permanent ones.

During the first test, the NMR polarimetry system could not perform automatic monitoring because the remote control of the IPS power supply was jammed. Sweeps had to be performed manually which required access to the hall. This forbade the possibility of beam-on polarimetry monitoring and limited severely the amount of data.

T_R extracted during the beam-on and beam-off periods are given in Table 1. In addition, we list the initial T_1^H and T_1^D before the start of G14. Those are only indicative since no dedicated T_1 measurement is available. We also list the T_R measured during the magnet "pseudo quench". The fit uncertainties are obtained by scaling the signal uncertainties so that $\chi^2/ndf = 1$, unless there are only 2 usable data points (then, χ^2/ndf is not defined). In that case, the original error is used. Since each fit is based on a limited number of points (usually 4, sometimes more), the given uncertainty is not accurate. In particular, the extracted T_R depends on the equilibrium value, which may not be the TE value which in any case would not be well known due to temperature uncertainty and polarimetry calibration uncertainties (e.g, there is a 30% NMR calibration shift near day 50, presumably due to the beam hitting the copper ring). T_R becomes more uncertain as the target polarization gets closer to the polarization equilibrium. The T_R are computed from the online results (ON) or the offline results of V. Laine (OF) when available. The online results display a systematic difference between the up and down signals (the down signals are systematically smaller in absolute value). The offline results do not have such asymmetry. Unless it can be estimated from the data, the assumed equilibrium polarization is taken to be TE/2±TE/2. This covers the full range of possible equilibrium values, unless spins diffuse ($T_2 \neq 0$ and finite) from highly polarized (pol.>TE) areas of cell combined with long enough average T_R value. In that case the equilibrium value can be larger than the expected TE value. Other possibilities for the equilibrium to be larger than TE are if only part of the target sees the beam (then the equilibrium is at TE + a baseline from the still frozen HD of the highly polarized unradiated zone), or if T_R evolves with time (if T_R increases with time, as in one of our models discussed in section 4, then the HD may reach the frozen spin mode before having time to fully decay to its TE). Our TE/2±TE/2 choice ignores these cases although they are possible. However, if we do not neglect them, we cannot make any statement on the equilibrium value and T_R cannot be extracted. This emphasizes the need of making more measurements over a longer time for each condition and the unreliability of cell 21a data set. The ±TE/2 error is propagated to the T_R uncertainty (linearly added to the T_R fit uncertainty). The temperature is taken as the mixing chamber temperature, except when the beam is on. In that case, we assume that the temperature is high enough (order of a Kelvin) so that TE∼0.

In Table 1 below, "-" means that there is no meaningful fit value (usually because there is no polarization loss (or gain if pol.<equilibrium pol.) between consecutive data points).

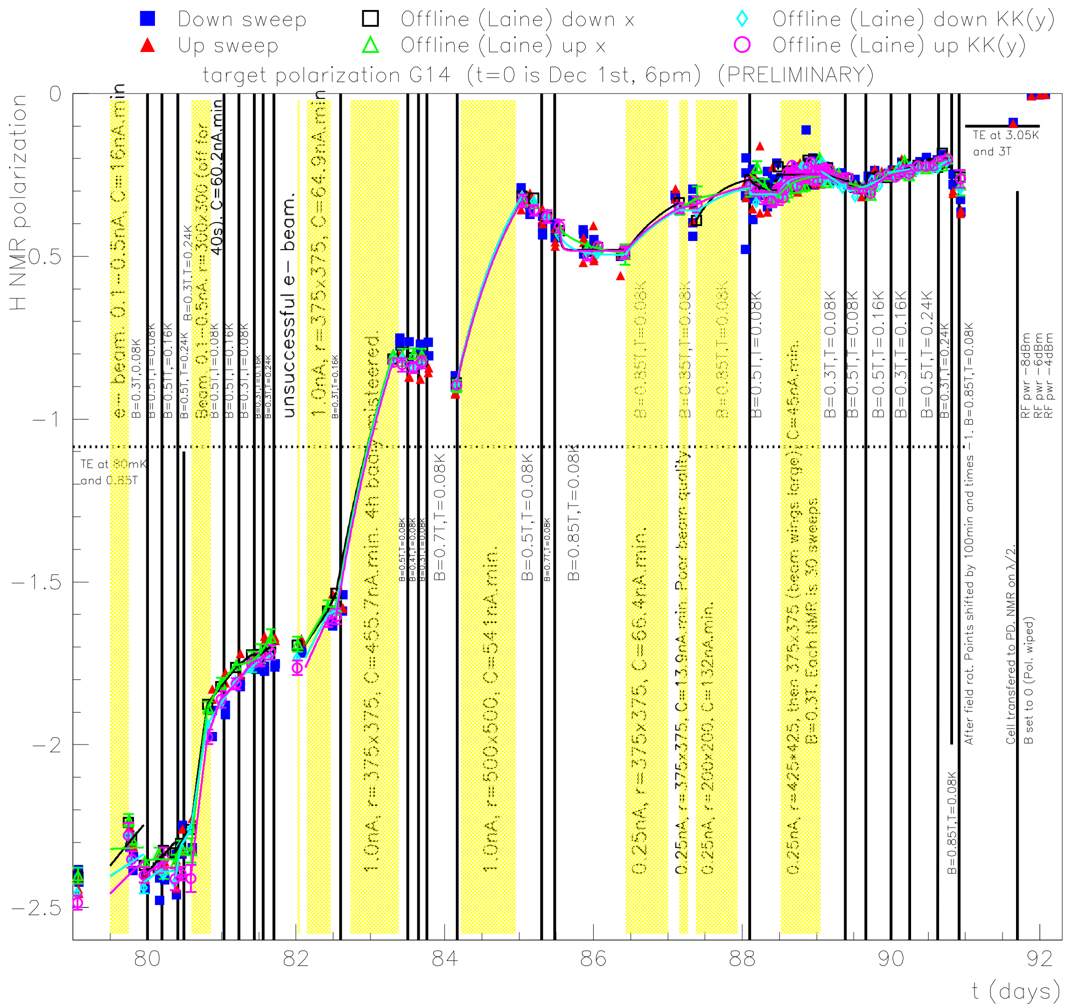


Figure 2:
Evolution of the hydrogen polarization during the first test period (cell 21a). The different symbols are for the online and offline analysis results. Online analysis was performed only for the up and down sweep signals of the lock-in x-channel. Offline analysis was performed on both x and y channels. The yellow bands indicate the approximate times when beam was on target. The horizontal dash line is a reference indicating the TE value for T=80mK and B=0.85T. The vertical plain lines separate periods during which the target was at different temperature and magnetic field conditions.

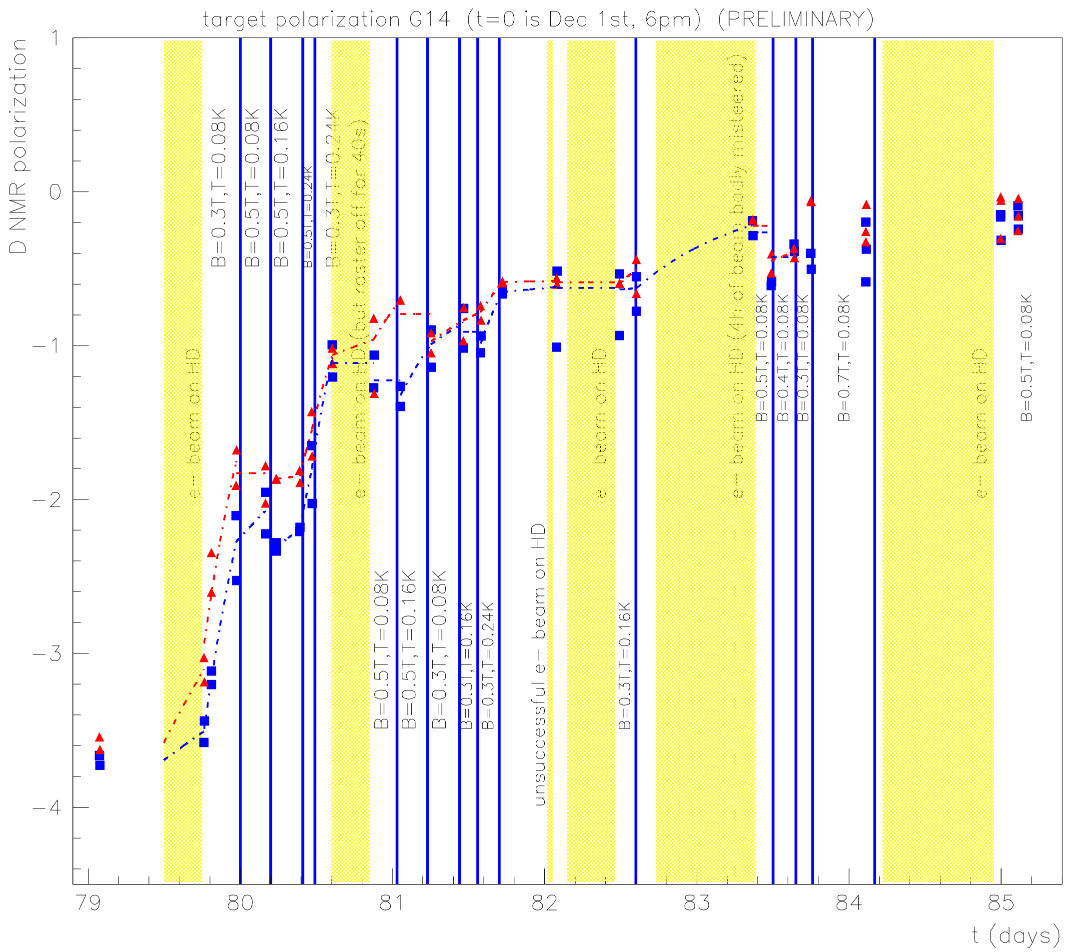


Figure 3:
Same as Fig. 2 but for Deuteron.

#	date	T_R^H (days) x down/up y down/up	T_R^D (days) x down/up y down/up	Estimated H/D Eq. Pol. in %	*IBC* T (K)	B (Tesla) H/D	Integ. charge ($nA.min$)	run comment
1	9/29/2011-11/29/2011	?45?	?400?		2	2/2	0	T_1. Inferred from transfer losses
2	2/4-7/2012	$128\pm^{59}_{30}/48.5\pm^{9}_{6}$ (ON)	$7.6\pm1.4/13.4\pm3.4$(ON)	TE=0.16 ±0.01/ 0.032 ±0.003	0.55 ±0.05	0.85/ 0.85	15 nA.min w/γ beam	Magnet "pseudo" quench.
3	2/23/2012	8±7/-±− (OF) 16±28/10±9 (OF)	5.06±1.99/1.85±0.36(ON)	*0/0*	IBC: 0.12	0.85/ 0.85	31	Irradiation 1. Contaminated by subsequent Pol increase?
4	2/23/2012	Pol growth.	0.49±0.08/0.40±0.06(ON)	0.192/±0.192/ 0.039 ±0.039	0.08	0.3	31	Possible H Pol. increase. D→H spin transfer? Spin diffusion? NMR electronic altered?
5	2/23/2012	8±7/-±-(OF) 12±17/13±3(OF)	growth/2.2 ± 2.29(ON)	0.32/±0.32/ 0.065 ±0.065	0.08	0.5	31	H Higher limit: Could be contaminated by previous Pol increase.
6	2/23/2012	8±10/-±−(OF) -±-/-±−(OF)	3.0±0.7/17.2±110(ON)	0.16/±0.16/ 0.033 ±0.033	0.16	0.5	31	
7	2/23/2012	5.9±3.6/3.7±2.6(OF) 1.5±0.4/11±24(OF)	0.40±0.20/0.45±0.24(ON)	0.11/±0.11/ 0.022 ±0.022	0.24	0.5	31	
8	2/23/2012	7±3/-±−(OF) 6±2/-±−(OF)	0.26±0.07/0.36±0.10(ON)	0.06/±0.06/ 0.013 ±0.013	0.24	0.3	31	
9	2/24/2012	1.2±0.0/1.1±0.1 (OF) 1.5±0.1/1.1±0.1 (OF)	growth/2.78±6.08(ON)	*0/0*	IBC: 0.09-0.16	0.85	91	Irradiation 2. Raster failed for 40s
10	2/24/2012	5.0±2.0/3.7±2.5(OF) 4.6±2.2/2.5±1.2(OF)	growth/0.52±0.39(ON)	0.32/±0.32/ 0.065 ±0.065	0.08	0.5	91	Can be compared to #5 if permanent rad damage negligible
11	2/24/2012	5.6±1.5/5.9±2.5(OF) 4.8±1.3/7.1±5.1(OF)	0.67±0.30/growth(ON)	0.16/±0.16/ 0.033 ±0.033	0.16	0.5	91	Can be compared to #6 if permanent rad damage negligible
12	2/24/2012	8.5±2.6/29±92(OF) 8.5±3.5/5.3±*2.6*(OF)	1.33±1.52/1.34±1.24(ON)	0.192/±0.192/ 0.039 ±0.039	0.08	0.3	91	
13	2/24/2012	-±-/8±13(OF) 6.1±3.0/17±37(OF)	growth/1.67±3.25(ON)	0.10/±0.10/ 0.020 ±0.020	0.16	0.3	91	
14	2/24/2012	10.0±4.1/4.7±3.9(OF) 38±98/11±16(OF)	0.34±0.04/0.49±0.10(ON)	0.06/±0.06/ 0.013 ±0.013	0.24	0.3	91	Can be compared to #8 if permanent rad damage negligible
15	2/25/2012	-	5±25/22±55(ON)	0/0.15	IBC: 0.06	0.85	91	Unsuccessful irradiation 3.
16	2/25/2012	4.8±0.3/4.3± 1.1(OF) 3.7±0.4/3.4±0.7 (OF)	no losses	0/0	IBC: 0.08-0.14	0.85	156	irradiation 4.
17	2/25/2012	2.5±0.9/-±-(OF) 13±18/16±58(OF)	9±120/0.66±0.82(ON)	0.10/±0.10/ 0.020 ±0.020	0.16	0.3	156	Can be compared to #13 if permanent rad damage negligible

#	date	T_R^H (days) x down/up y down/up	T_R^D (days) x down/up y down/up	Estimated H/D Eq. Pol. in %	*IBC* T (K)	B (Tesla) H/D	Integ. charge (*nA.min*)	run comment
18	2/26/2012	1.2±0.0/1.1± 0.0(OF) 1.2±0.0/1.2±0.0 (OF)	0.72±0.18/0.60±0.35(ON)	0/0	IBC: 0.15-0.3	0.85	612	irradiation 5. Bad beam for 4h
19	2/26/2012	no loss (too close to equil.pol.?)	pol. gain (unexpected: TE should be lower)	0.32/±0.32/ 0.065 ±0.065	0.08	0.5	612	Can be compared to #5 and #10 if permanent rad damage negligible
20	2/26/2012	no loss(too close to equil.pol.?)	no loss(too close to equil.pol.?)	0.26/±0.26/ 0.052 ±0.052	0.08	0.4	612	
21	2/26/2012	no loss(too close to equil.pol.?)	no loss(too close to equil.pol.?)	0.19/±0.19/ 0.039 ±0.039	0.08	0.3	612	
22	2/26/2012	Equil. pol. too uncertain compared to pol. level	no loss(too close to equil.pol.?)	0.45/±0.45	0.08	0.7	612	
23	2/27-28/201	0.86±0.01/0.88± 0.05(OF) 0.85±0.02/0.89±0.06 (OF)	-	0	IBC: 0.11-0.16	0.85	1153	irradiation 6.
24	2/27/2012	Equil. pol. too uncertain compared to pol. level	-	0.32/±0.32	0.08	0.5	1153	
25	2/27/2012	Equil. pol. too uncertain compared to pol. level	-	0.45/±0.45	0.08	0.7	1153	
26	2/27/2012	0.02±-/0.42±0.80(OF) 0.17±0.06/0.03±1.3(OF*)*	-	**0.54**/±0.54 **(meas: 0.49±0.02)**	0.08	0.85	1153	Growth to near Pol. Eq. Fits are not converging well (several χ^2 minima)
27	3/01/2012	0.71±0.20/0.88± 0.37(OF) 0.88±0.23/0.88±0.35 (OF)	-	Assume 0.25±0.03	IBC: 0.08-0.10	0.85	1219	irradiation 7. Low current (0.25nA). Assume eq.pol=0.25 as for irradiation 10
28	3/01/2012	-±-/0.63± 1.08(OF) -±-/2.1±6.1 (OF)	-	Assume 0.25±0.03	IBC: 0.08-0.10	0.85	1233	irradiation 8. Low current (0.25nA). Assume eq.pol=0.25 as for irradiation 10
29	3/01-02/2012	0.32±0.36/1.31± 2.59(OF) 0.65±0.42/0.71±0.87 (OF)	-	Assume 0.25±0.03	IBC: 0.08-0.10	0.85	1365	irradiation 9. Low current (0.25nA). Assume eq.pol=0.25 as for irradiation 10
30	3/02/2012	0.12±0.07/30±30(OF) -±-/23±72(OF*)*	-	**0.32**/±0.32 **(meas: 0.30±0.01)**	0.08	0.5	1365	Growth to near Pol. Eq. Fits converging badly (not enough level arm?)
31	3/02-03/2012	-±-/0.20± 0.24(OF) 0.13±0.20/0.11±0.27 (OF)	-	0.25±0.03	IBC: 0.08-0.10	0.28	1610	irradiation 10. Seems eq.pol=0.25±0.03 Continuous NMR monit. Used -30dBm => Ignore RF losses

#	date	T_R^H (days) x down/up y down/up	T_R^D (days) x down/up y down/up	Estimated H/D Eq. Pol. in %	*IBC* T (K)	B (Tesla) H/D	Integ. charge ($nA.min$)	run comment
32	3/03/2012	8±8/9.9±12(OF) 13±11/0.28±0.26(OF)	-	**0.19/±0.19** **(meas:** **0.28±0.02)**	0.08	0.3	1610	Growth to near Pol. Eq.Fits converging badly (not enough level arm?)
33	3/03/2012	1±8/9.9±12(OF) 13±11/20±41(OF)	-	**0.32/±0.32** **(meas:** **0.8±0.5)**	0.08	0.5	1610	Growth to near Pol. Eq.Fits converging badly (not enough level arm?)
34	3/04/2012	$0.94\pm^{1.57}_{0.92}/0.56\pm^{0.94}_{0.48}$(OF) $0.99\pm^{1.57}_{0.77}/0.75\pm^{0.39}_{0.46}$(OF)	-	0.16/±0.16	0.16	0.5	1610	Too close to (uncertain) Eq. Pol. value
35	3/04/2012	$1.6\pm^{1.9}_{1.1}/5.2\pm^{12.3}_{0.}$(OF) $3.5\pm^{5.9}_{0.}/2.9\pm^{3.5}_{2.4}$(OF)	-	0.10/±0.10	0.16	0.3	1610	
36	3/05/2012	too close to Pol. Eq. (pol is flat)	-	0.11/±0.11	0.24	0.5	1610	Too close to (uncertain) Eq. Pol. value
37	3/05/2012	1.0±2.8/2.3±5.9(OF) 1.1±1.2/2.3±1.7(OF)	-	0.06/±0.06	0.24	0.3	1610	
38	3/05/2012	-	-				1610	After B-field rotation. NMR calibration 25% greater in this direction.
39	3/06/2012	0.8±0.2	-	0.005	2	0.1	1610	From decay during IBC-PD2 transfer
40	3/06/2012	$T_1 = 0.83 \pm 0.17$	-		3.05	0.16/ 1.03	1610	IN PD TE at 3.05K and 3T. Pol.Erased with B=0. Run at -8, -6 and -4dBm

Table 1. T_R from the first electron test

2.2.1 PD2 after-test runs (before erasing the polarization)

On March 6$^{\text{th}}$, cell 21a was moved to PD2 (T=3.053K). Fast resonance scan on $\lambda/2$ yielded: f=6768.4 kHz, A=1.113mV and $\varphi = -11.6^o$. runs at -8dBm were carried on D (PD207365679, 1 cycle) and H (PD207365940, 1 cycle).

The signals are shown on Fig. 4. The runs characteristics are (we add the CH_2 run 199111047 done with PD2 for comparison):

cell:	H run	D run	CH_2
B_{center} (input)	1588	10284	1583
B_{center} (calculated)	1503	10498	1592
RF freq.	6769	8619	6742
B_{NMR}	1590	10357	1583
B_{span}	300	300	300
T_{up}	31s	31s	31s
down-up difference	$\sim -2.2\%$	-	$\sim -12\%$
T_R or T_1 in minutes	-	-	0.17
Equil. Pol. down & up	-	-	8.26×10^{-5} 7.49×10^{-5}
TE	5.31×10^{-5}	6.445×10^{-5}	8.037×10^{-5}

The signals are large compared to a PD2 TE signals (after correcting for power, frequency, temperature H, density differences and the fact that cell 21a has 20% less HD [1]):

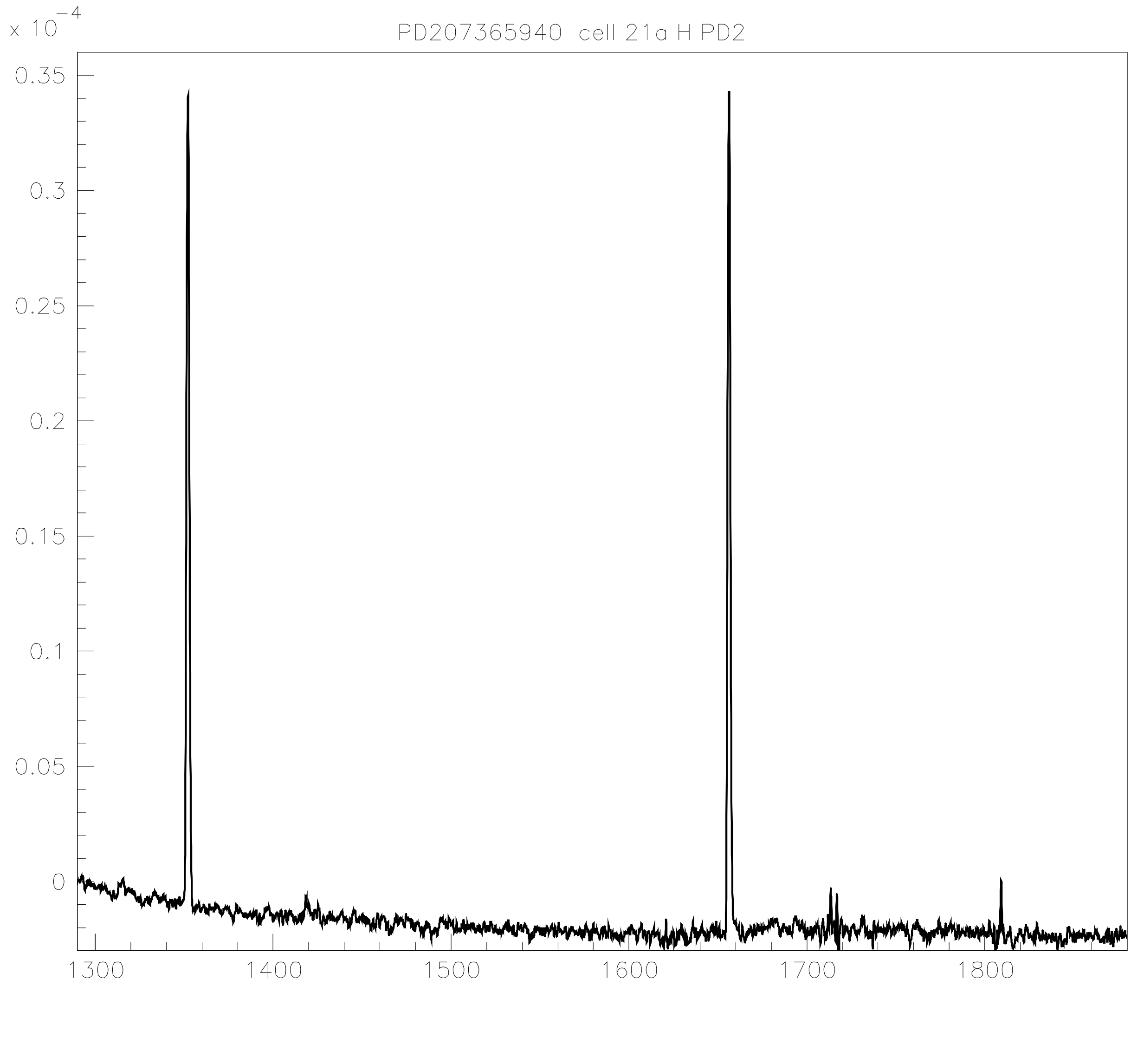


Figure 4:
Cell 21a results from PD2 runs after the electron test.

peak	area (integration range)	area (integration range) and pol.
H (CH2), down	1.038×10^{-5} (45Gauss)	0.533×10^{-5} (50Gauss)≡0.0083%
H (CH2), up	0.936×10^{-5}(45Gauss)	0.477×10^{-5}(50Gauss) ≡0.0075%
H (HD), down	6.77×10^{-5} (15 Gauss)	6.67×10^{-5} (20Gauss) ≡0.103%
H (HD), up	6.92×10^{-5} (15 Gauss)	6.81×10^{-5} (20 Gauss) ≡0.107%
D (HD), down	0.857×10^{-5} (10 Gauss)	0.874×10^{-5} (15 Gauss)
D (HD), up	0.763×10^{-5} (10 Gauss)	0.755×10^{-5} (15 Gauss)

T_R estimates

Up-down peak comparison method. The difference in peak areas between the down and up signals can be used to estimate T_R if this one is smaller than a few minutes, see [1] and if the RF losses are significant between sweeps. Since T_R is likely larger that a few minutes and since we ran only one sweep, we cannot use this method.

Signal evolution method. Since we measured only one sweep, this method cannot be used.

Absolute comparison of IBC and PD signals for H. The last IBC measurement gave a target polarization of 0.25±0.05%. The measurement in the PD2 18h later gave 0.1%. Assuming no transfer losses and a decay toward the TE in the TC (0.005% for 0.1T, 2K), the resulting T_1 is 0.8±0.2hours : This method is not very reliable since it uses absolute measurements from 2 different cryostats and assume no evolution of the signals during the transfer (e.g. growth to TE in the IBC, decay to TE in the TC and subsequently in the PD2). Although the data are available (D measurements after B-field rotation and D measurements in PD2), we do not apply this method for D because of the NMR calibration uncertainty when NMR is performed with its field anti-aligned (we could do it for H because we have the standard field-aligned NMR data as well).

2.2.2 PD2 after-test runs (after erasing the polarization)

One run (PD207366653) was done after erasing the cell 21a polarization by setting B=0. The conditions are (we set time origin t=0 when we erased the polarization):

Condition # start, stop time(hours)	PD temp.	NMR on	# cycles	power	B_o Gauss	field span	T_{up}	freq./phase	comments
1 t=0.13-2.83	3.21K	D	80	-8dBm	10284	300	31	$6769/-8^o$	Noisy (spikes). Signal visible but very small
2 t=2.87-4.57	3.07K	D	54	-6dBm	10284	300	31	$6769/-8^o$	Noisy. Small signal
3 t=4.60-5.55	3.11K	D	28	-4dBm	10284	300	31	$6769/-8^o$	Noisy. Small signal
4 t=5.65-8.35	3.041K	H	80	-8dBm	1588	300	31	$6769/-8^o$	Starts to be noisy (spikes) at cycles#13
5 t=8.38-10.18	3.036K	H	54	-6dBm	1588	300	31	$6769/-8^o$	
6 t=10.22-11.12	3.050K	H	28	-4dBm	1588	300	31	$6769/-8^o$	

The time evolution of the signal can be seen on Fig. 5. The RF losses in PD2 with purple cable were determined using the H runs at -6 and -4 dBm (conditions 4 and 5). We found 3% losses at -4dBm for the PD2/purple cable set.

Determination of T_R^H The initial polarization P_0 for condition 4 should have been the polarization reached under *deuteron* field conditions after growing for 5.65h and decaying for 4min while we transit from the conditions 3 to 4. This represents a $P_0 = TE(B = 1.03T)*0.92$. Instead, we had to take $P_0 = TE(B = 1.03T)*0.25$ for the down signal and $P_0 = TE(B = 1.03T)*0.2$ for the up signal (it is expected that up is smaller since it starts 30s later that the down). Apart fof this caveat, we can extract T_1 relatively precisely from these data. We found $T_1 = 0.83 \pm 0.17$ hours.

Determination of T_R^D The D data are not precise enough to apply the above method.

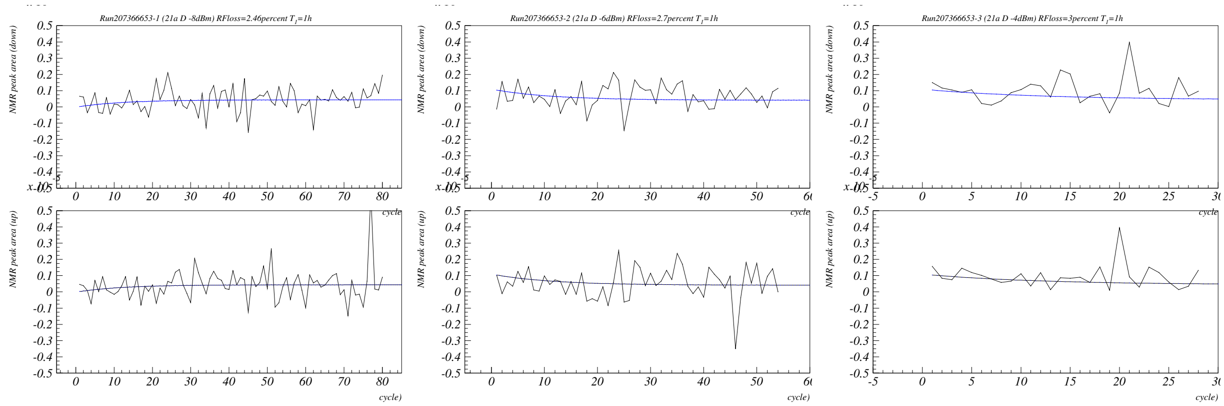
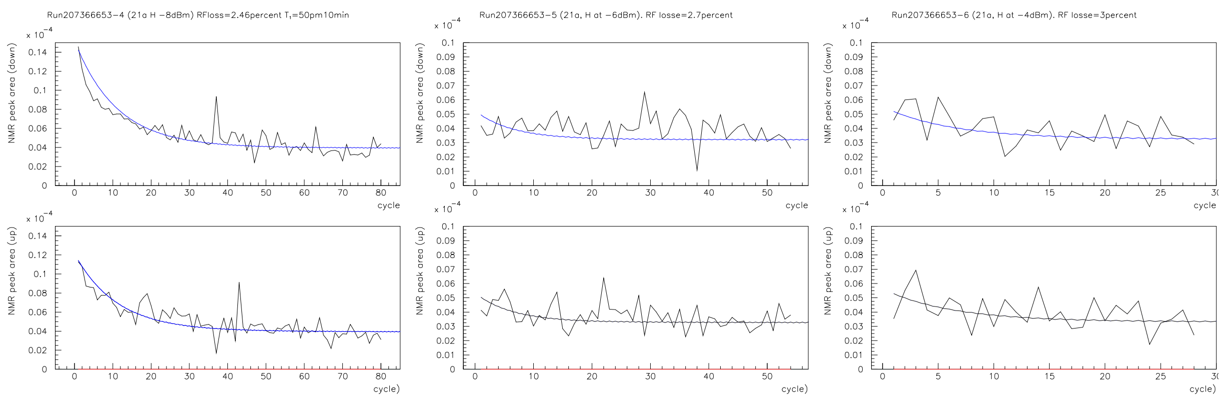


Figure 5:



Time evolution of the cell 21a signal after erasing the polarization. Top rows: deuteron. Bottom rows: hydrogen.

2.3 Cell 20b

The detailed characteristics and the NMR calibration for cell 20b are given in [3]. This cell was used because its low polarization was unsuitable for the nuclear physics run (G14) and no other cell was available for G14 at the moment. This situation allowed us to perform a second electron test. It was done in better conditions than the first test: Since the remote control of the IPS was repaired, we performed NMR measurements continuously before, during and after beam deliveries. The sweeps were performed every 15 min in the following pattern: 1 D sweep, 5 H sweeps, 1 D sweep, etc... We also did not vary the IBC field and temperature conditions once the beam was terminated, focusing on precise measurements for increasing integrated charges but same field and temperature. During the first exposure the beam current was 100pA and then a few pA. The beam delivery condition was unusual because we purposely used a small raster but with a defocused beam, see [2]. The evolutions of the target polarizations during the second test are shown on Figs. 6 and 7.

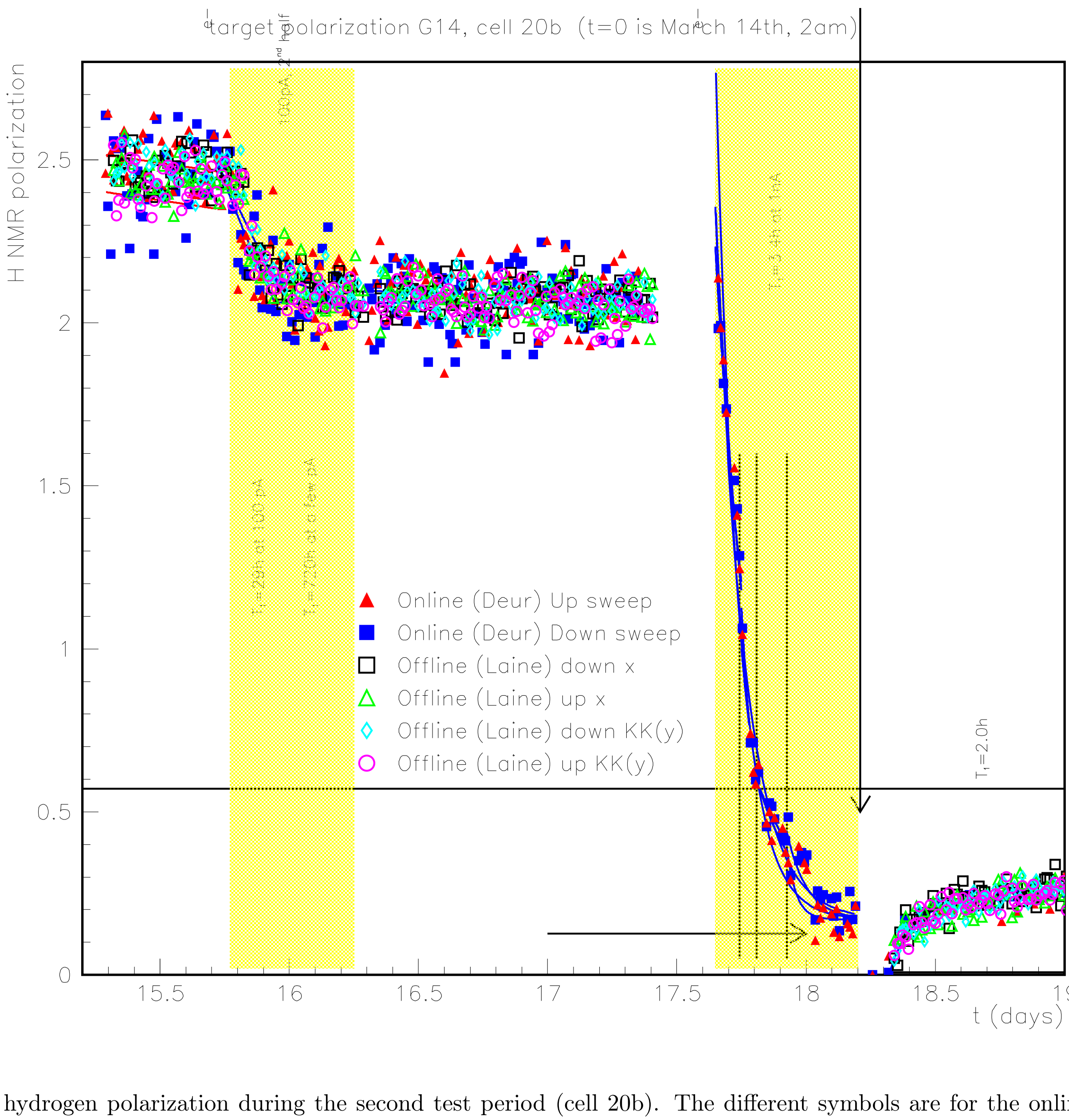


Figure 6:
Evolution of the hydrogen polarization during the second test period (cell 20b). The different symbols are for the online and offline analysis results. Online analysis was performed only for the up and down sweeps signals of the lock-in x-channel. Offline analysis was performed on both x and y channels. The yellow bands indicate the approximate times when beam was on target. The horizontal line is a reference indicating the TE value for T=50mK and B=0.27T.

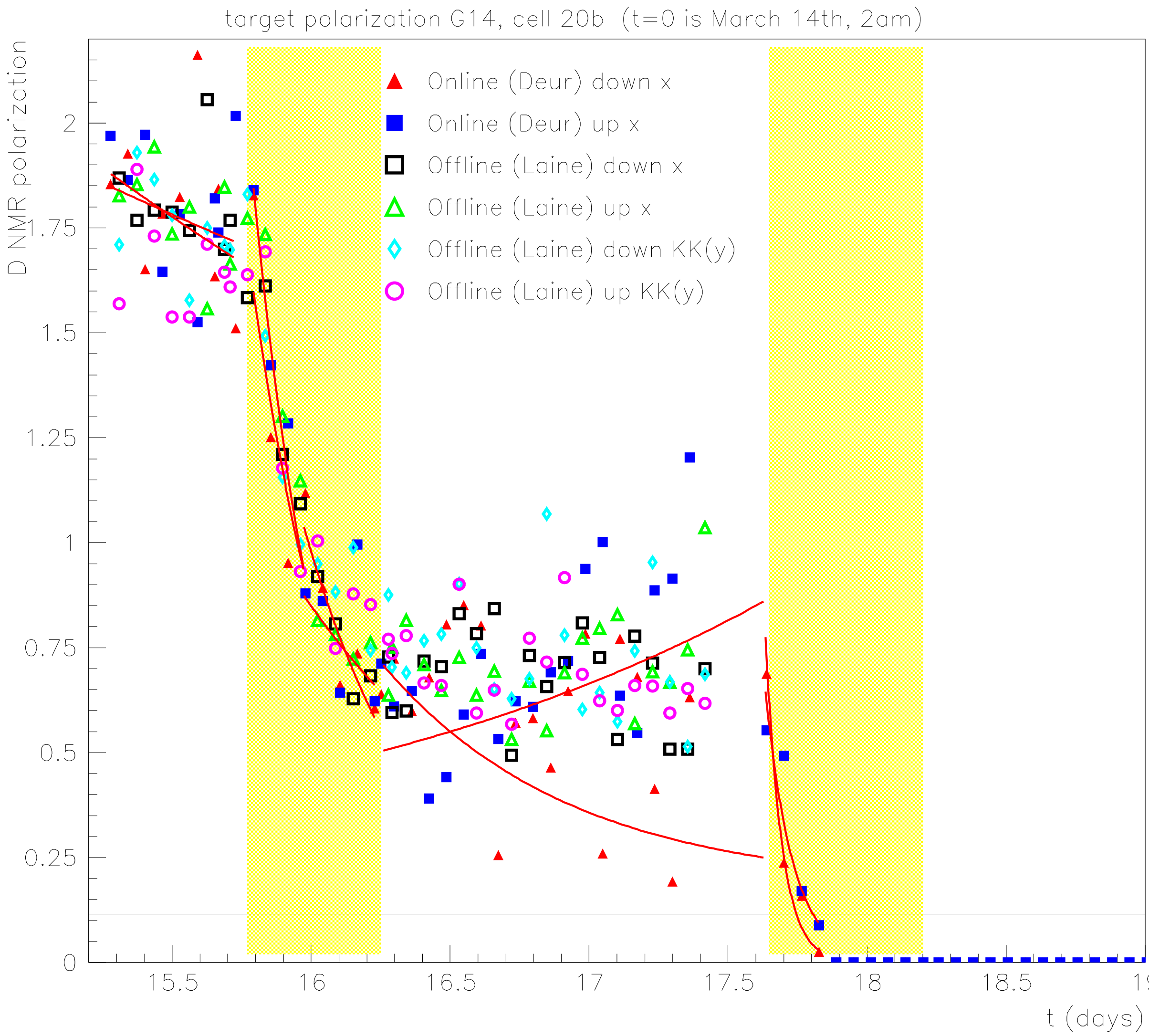


Figure 7:
Same as Fig. 6 but for Deuteron. Note: we do not plot any signal after zeroing the HD polarizations (at t=18.2 days, by setting B=0) because the analysis program cannot identify the small NMR peaks among the background. However, there is a clear regrowth of the D signal, see text.

#	date	T_R^H (days) x down/up y down/up	T_R^D (days) x down/up y down/up	T (K) cryostat	B (Tesla) H/D	Integ. charge ($nA.min$)	run comment
1	3/13/2012	0.92	0.59	3	2.2-2.9/ 2.2-2.9	0	PD measurements
2	3/14/2012- 3/28/2012	$189\pm^{30}_{22}$/ $176\pm^{30}_{22}$	$95\pm^{15}_{12}$/ $142\pm^{24}_{17}$	0.05	0.9	0.	IBC meas. No beam. Before SFP
3	3/28/2012	$12.9\pm^{10.3}_{4.0}$/ 19.8 ± 5.6	$3.54\pm^{2.79}_{1.05}$/ $5.45\pm^{16.1}_{2.31}$	0.05	0.265/ 0.273	0.	IBC meas. No beam. After SFP
4	3/29/2012	$1.09\pm^{0.11}_{0.09}$/ $1.32\pm^{0.20}_{0.15}$	$0.34\pm^{0.14}_{0.09}$/ $0.27\pm^{0.02}_{0.02}$	0.11	0.265/ 0.273	24	1^{st} part of 1^{st} irradiation. I=0.1nA
5	3/29/2012	$25.8\pm^{\infty}_{16.1}$/ $7.52\pm^{\infty}_{3.76}$	$0.44\pm^{0.08}_{0.06}$/ $0.91\pm^{0.75}_{0.28}$	0.11	0.265/ 0.273	26.1	2^{nd} part of 1^{st} irr. I=a few pA
6	3/30/2012	no decay/ $69.0\pm^{\infty}_{37}$	no decay no decay	0.05	0.265/ 0.273	26.1	No beam
7	3/31/2012	$0.11\pm^{0.01}_{0.01}$/ $0.09\pm^{0.01}_{0.01}$	$0.058\pm^{0.004}_{0.004}$/ $0.099\pm^{0.008}_{0.008}$	0.17	0.265/ 0.273	851.1	2^{nd} irradiation. I=1nA
8	3/31/2012	$0.15\pm^{0.03}_{0.03}$/ $0.13\pm^{0.02}_{0.02}$	-	0.17	0.265/ 0.273	165.6	1^{st} part of 2^{nd} irr. I=1nA
9	3/31/2012	$0.089\pm^{0.03}_{0.02}$/ $0.064\pm^{0.01}_{0.01}$	-	0.17	0.265/ 0.273	263.1	2^{nd} part of 2^{nd} irr. I=1nA
10	3/31/2012	$0.20\pm^{0.03}_{0.03}$/ $0.16\pm^{0.02}_{0.02}$	-	0.17	0.265/ 0.273	438.6	3^{rd} part of 2^{nd} irr. I=1nA
11	3/31/2012	$0.077\pm^{0.00}_{0.00}$/ -	-	0.17	0.265/ 0.273	850	4^{th} part of 2^{nd} irr. I=1nA. Poor fit.
12	4/1-2/2012	0.08 ± 0.01/ 0.08 ± 0.01	0.36 (see discussion below table)	0.05	0.265/ 0.273	851.1	After polarization is erased

The NMR D peaks after polarization was erased (run 209635528) are barely visible above the noise. The D parts of run 209635528 were done at -21dBm, $B_0 = 2829$G and $f = 1757$ kHz. Compared to previous D runs, B_0 was increased by 100G to compensate for turning off the back-up coil. We took 16 D sweeps. The results for each D sweeps are shown on Figs. 8 and 9. NMR peaks are hardly visible. We averaged 3 consecutive sweeps together to identify the NMR peaks better (we combined the 4 last sweeps together). (The file containing the D sweeps and their average has been assigned run number PD209635529). The combined sweeps are shown on Fig. 10. Growing peaks can be seen with a signal for condition 32 of about $2\mu V$, corresponding to 0.12% polarization. However, it is hard to deduce a T_R from it. The TE value at 0.27T and 0.05K is 0.113%, so D already reached its full TE value at cycle 32 (contrary to H for which the equilibrium is ∼TE/2.5). It seems that by sweep ∼ 20, we already reached a signal close to TE. Assuming that we have reached 80% of the equilibrium value by sweep #20 (14h after erasing the polarization), then $T_1^D \sim 8.7$ hours. Assuming it reached 90% would yield 6 hours.

3 Analysis

3.1 Beam-on depolarization for Hydrogen

There is a clear drop of polarization when the beam is on target. This depolarization rate is greatly reduced as soon as the beam stops, as can be best seen from Figs. 6 and 7. Deuteron polarization is more vulnerable to it than Hydrogen. This depolarization can be caused by the increase of the HD temperature: Such increase is expected (in retrospect) because it was realized that the Hall B raster was not fast enough to homogenized the beam heat load on the cell surface. A head/raster model indicates that temperatures as high as 1.5K lasted for 0.5s at a given cell location [??M. Lowry/C. Bass. reference??]. The temperature increase is a function of the beam current and raster size. Beam quality may also influence it. The measured depolarizations rates with beam-on are compatible with the hypothesis that the increase of temperature causes a decrease of T_1 which in turn causes the polarization to drop. Effects pointing toward heat being a major cause of the beam-on depolarization are:

- Cell 20b: The best data are from this cell. Prior and after the first irradiation, $T_1^H \sim T_R^H \sim 20$ days (same magnetic field as the NMR) with a cell temperature of 0.05K. Under 0.1nA, $T_R^H \sim 1$ day and the averaged temperature is modeled to be about 0.5K. Under 1nA, $T_R^H \sim 0.1$h and the averaged temperature is modeled to be 1.0K, peaking at about 1.5K.

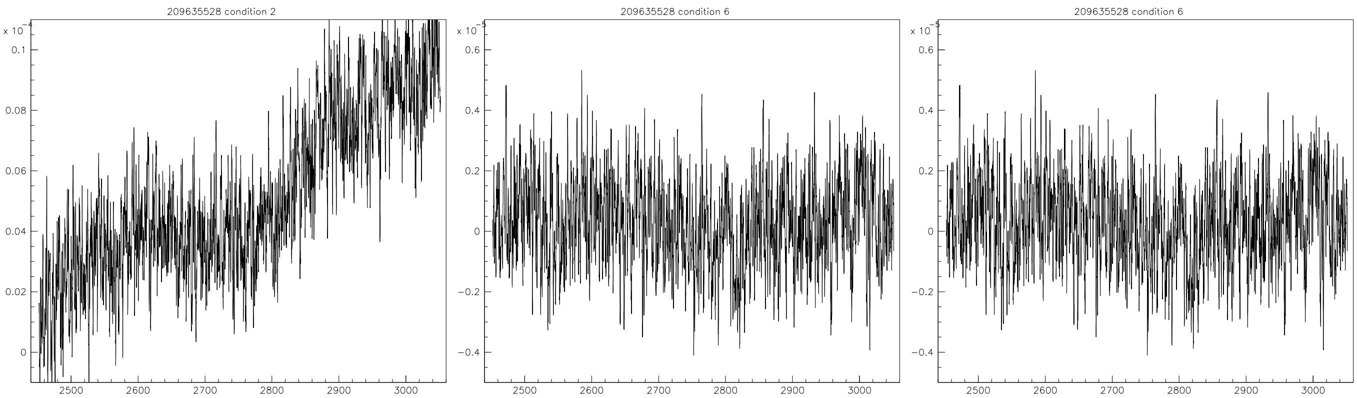
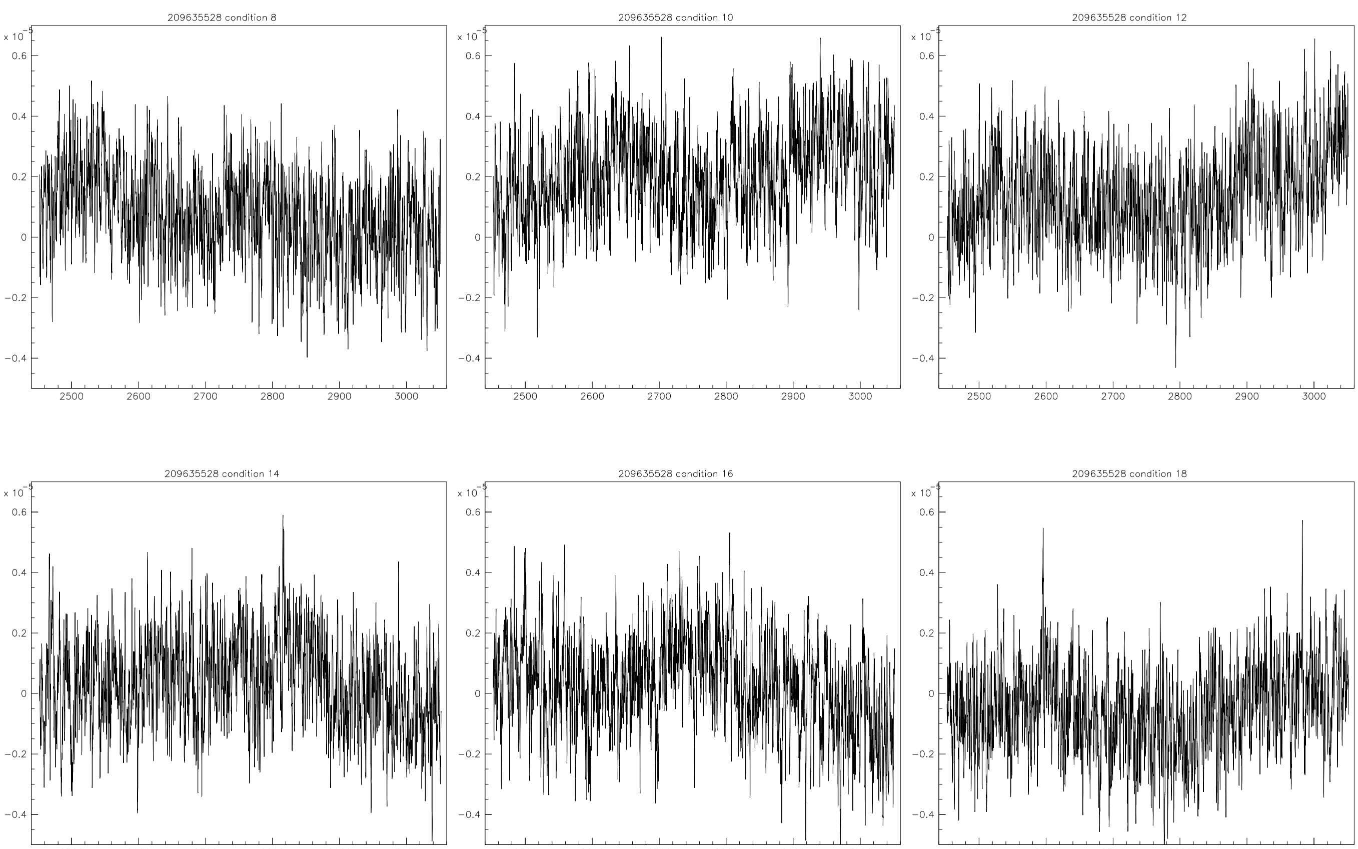
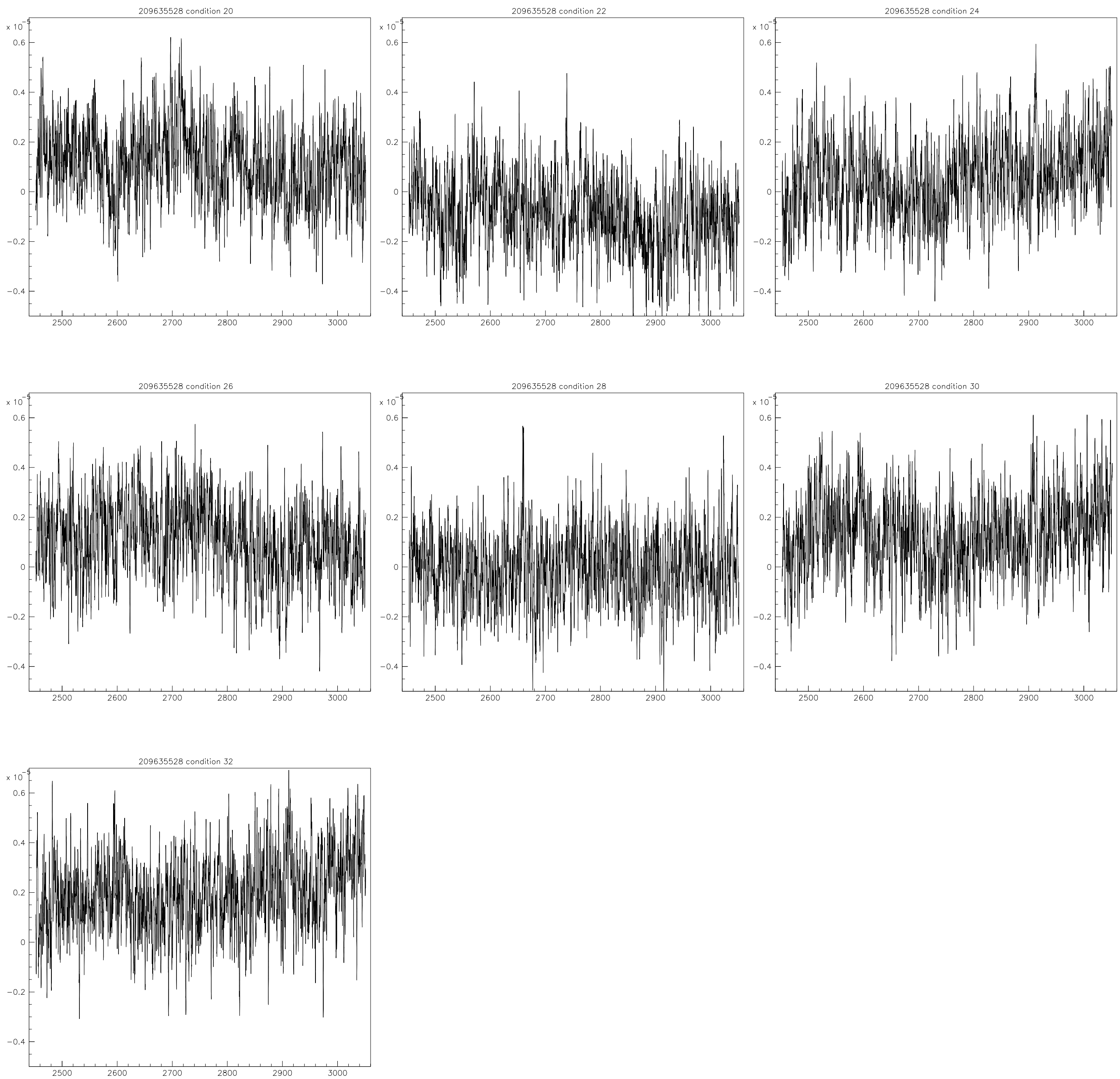


Figure 8:



First 12 D sweeps of run PD209635528. Due to the code processing the data, the sign of the peak is arbitrary (some NMR peaks may be positive, e.g. sweep 9 and others negative. e.g. sweep10)

Figure 9:



Continuation of Fig. 8.

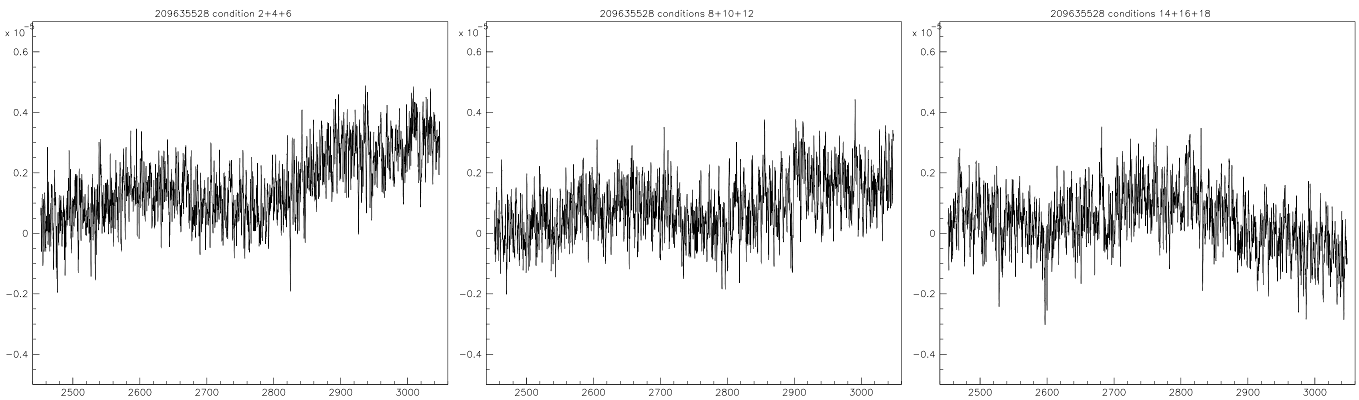
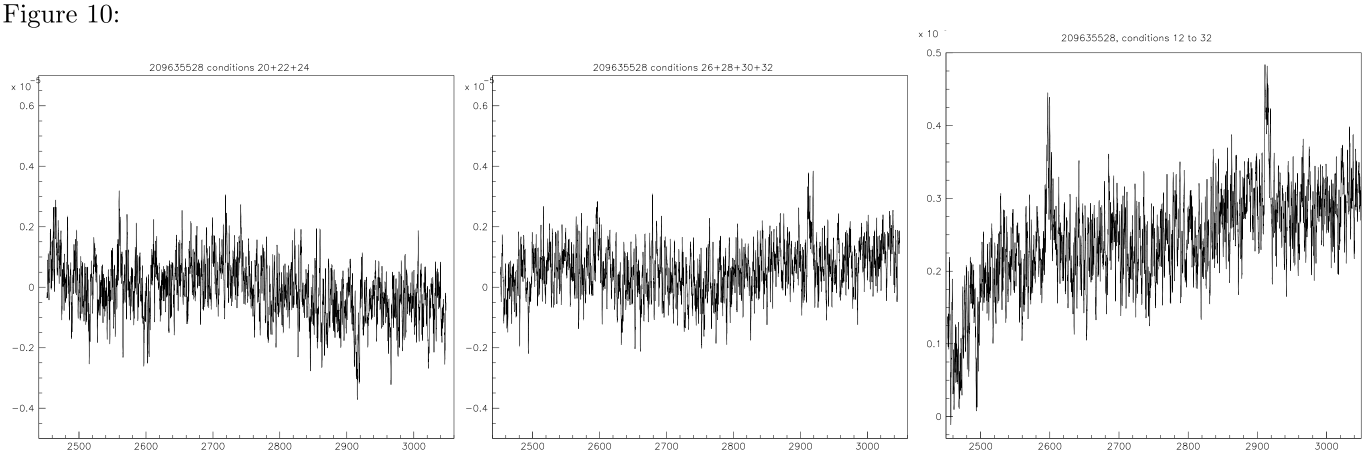


Figure 10:



same as Figs. 8 and 9 but with 3 sweeps averaging except for the next to last plot for which we averaged 4 sweeps. The last plot shows the average over the last 20 sweeps. The D signal is clearly visible. (Note that the sign of the peak is arbitrary. The plotting program automatically assigns a positive sign to the data point with largest absolute value. When the signal is dominated by noise, this assignment is random. For example, the averaged peaks for sweeps 20, 22 and 24 are negative while the peaks for the average for sweeps 26, 28, 30 and 32 are positive. This is a coding artifact: in all case the peaks should be positive).

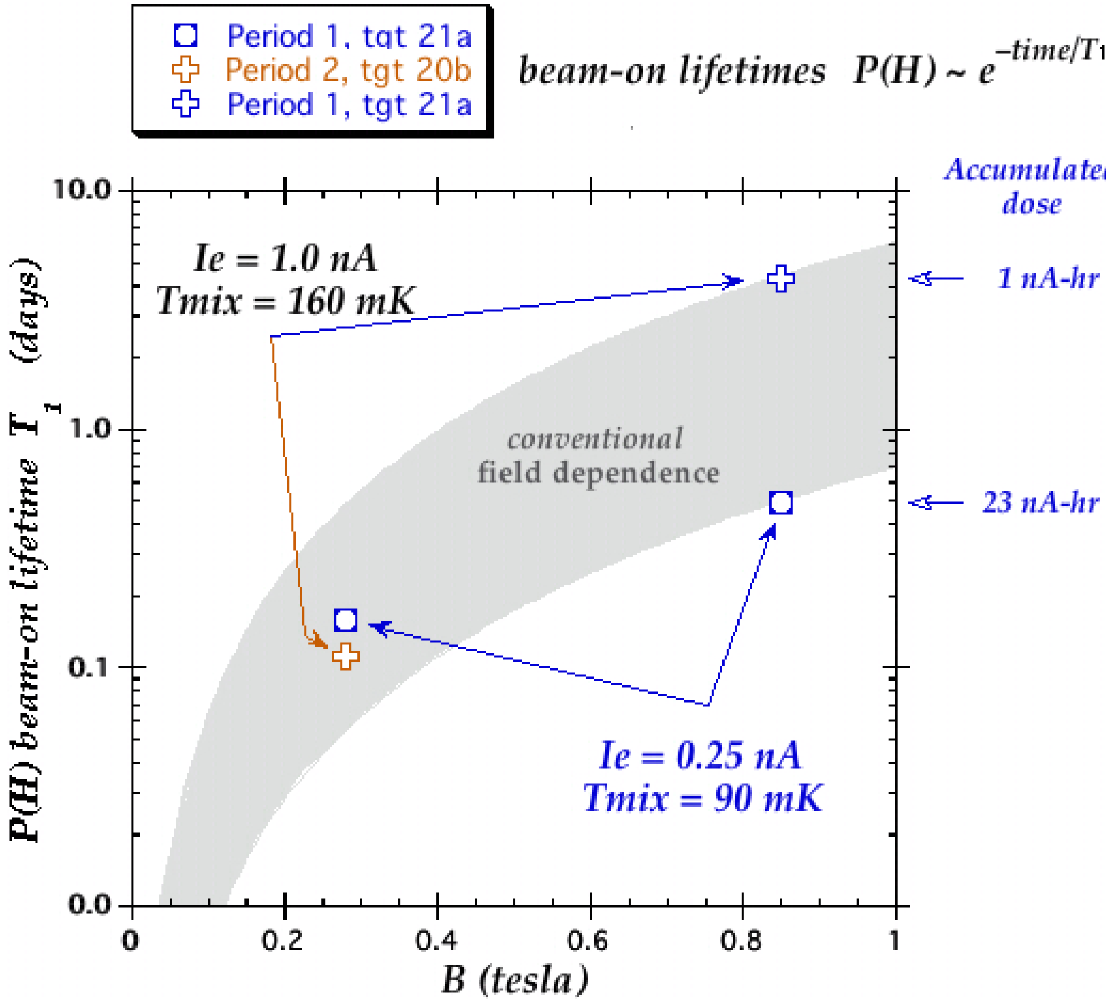


Figure 11:
Beam-on T_R for cell 21a and 20b (the vertical scale label should read T_R). The "conventional" field dependence is quadratic and expected if the depolarization is dominated by T_1. (Figure, courtesy of A. Sandorfi).

Assuming a temperature dependence of T_1 between linear and quadratic accounts for the data trend. However, once permanent radiation damage sets in (after the 1nA irradiation), such relation is broken ($T_R \sim 3$h with beam off).

- Comparison between H and D: The beam-on depolarization process is significantly more important for D than H. This compatible with a temperature driven depolarization together with the steeper temperature dependence of T_1^D compared to T_1^H (ref.: [X. Jiang]). On the other hand the alternate possibility -depolarization via ionization- occurs through magnetic moment coupling and since $\mu_P \sim 3\mu_D$, the D should be more resilient, contrary to what is observed. (We note that for both cells 21a and 20b just prior the tests, $T_1^H > T_1^D$ already but this does not affect the $\mu_P \sim 3\mu_D$ argument since depolarization via ionization is *a priori* not coupled with T_1 relaxation, i.e. we assume that if T_R is dominated by ionization or any other non-T_1relaxation mechanism, then T_R is not a function of T_1).
- Comparing T_R in same condition except for magnetic fields (e.g. cell 21a under 1nA with B=0.85T and cell 20b under 1nA and B=0.27T) supports a linear to quadratic dependence of the T_R, see Fig. 11, in agreement with the expected quadratic dependence of T_1 with B. It is unclear what should be the T_R field dependence if T_R is dominated by ionization.

Other depolarization processes may be at work. Another possible process is ionization of HD, mostly via the large Moller cross section, see [Note A. Sandorfi]. The lone electron of the HD$^+$ centers and the polarized H or D nucleus can spin flip via hyperfine interaction. During beam-on, the temperature of the HD is high and unpaired electrons are less polarized. The unpolarized fraction of unpaired electrons acts as spin sink for the H and D. The HD$^+$ centers should be neutralized by electrons from the Aluminum cooling wires. However, if this neutralization rate is smaller than the ionization and depolarization rates, it cannot compensate for the beam effect.

T_R^H during beam-on are shown on Fig. 12 top left plot. Both cell 21a and 20b results are shown. The cell 20b results are scaled by a factor 8 to match the initial T_1 of cell 21a (cell 20b was less aged so its T_1 was smaller. Also, it was measured at

B=0.27T, while the cell 21a was measured at B=0.85T). We see a decay of T_R (measured during beam) with dose. The plot resembles the right top plot of Fig. 12 showing the decay of T_R (measured after beam) with dose. Hence part of the decay with dose seen during beam-on can be attributed to permanent radiation damage. The T_1 contribution during beam-on can be established by the difference between the top right and top left plots. Permanent radiation damage is also clearly established after high beam currents were put on cells 21a and 20b. This is discussed next.

3.2 Lifetime after photon beam exposure

Figure 12 also provides the T_R^H measured once the beam has been turned off. On the top right panel, the results are plotted vs the accumulated dose. One can see overall the decay of the polarization with accumulated dose, indicating the presence of permanent beam damages. This decay cannot be due solely to transient effects (decrease of T_R over hours only or days) of the type discussed in section 4 since T_R drops regularly with dose during the week. However a contribution from transient effects, which would steepen the actual T_R slope, thus cannot be ruled out. On the bottom left panel, the results are plotted vs temperature. On the bottom right panel, T_R are plotted vs magnetic field.

3.2.1 Dependence with accumulated dose

The dependence with accumulated dose is clear. It was already apparent on the top left panel of Fig. 12. The higher values for dose=1600 nA.min may be due to inaccurate measurements: the measurements done after the 4^{th} beam delivery (160 nA.min of accumulated dose) becomes less reliable because the polarization is close to its equilibrium value.

Although, the overall decay trend is obvious, the dependence of T_R with accumulated dose should be checked for measurements under same conditions of temperature and magnetic field if the T_R dependence on these parameters is significant. (Alternatively, the dependence could be corrected for if it is know, which is not the case.) We list below the cases for which there is more than one T_R measurement in a given condition. In all cases, a decay of T_R with dose is observed.

1. T=0.05K, B=0.27T (cell 20b)
2. T=0.16K, B=0.5T (cell 21a)
3. T=0.16K, B=0.3T (cell 21a)
4. T=0.24K, B=0.3T (cell 21a)
5. T=0.08K, B=0.5T (cell 21a)
6. T=0.08K, B=0.3T (cell 21a)

The dependence with dose does not seem to be linear (even on the semi-log plot) but this may be due to the fact that measurements at large accumulated dose are less precise. Otherwise, it would reveal a T_R dependence with dose steeper than exponential.

3.2.2 Dependence with temperature

We list below the cases for which there is more than one T_R measurement at fixed accumulated dose and field conditions:

1. Dose=31nA.min, B=0.5T (cell 21a): A drop of T_R with temperature is seen.
2. Dose=1610nA.min, B=0.5T (cell 21a): A possible drop of T_R with temperature is seen, but compatible with no dependence.
3. Dose=91nA.min, B=0.5T (cell 21a): no dependence of T_R with temperature is seen in spite of 3 data points.
4. Dose=91nA.min, B=0.3T (cell 21a): no dependence of T_R with temperature is seen in spite of 3 data points.
5. Dose=1610nA.min, B=0.3T (cell 21a): no dependence of T_R with temperature is seen in spite of 3 data points.

Overall, no dependence with temperature is seen. We expect a strong temperature dependence if T_R is dominated by T_1.

3.2.3 Dependence with magnetic field

We list below the cases for which there is more than one T_R measurement at fixed accumulated dose and temperature conditions:

1. Dose=1610nA.min, T=0.08 (cell 21a): A possible rise of T_R with magnetic field is seen.
2. Dose=31nA.min, T=0.24 (cell 21a): A drop of T_R with magnetic field is seen.
3. Dose=91nA.min, T=0.08 (cell 21a): A drop of T_R with magnetic field is seen.

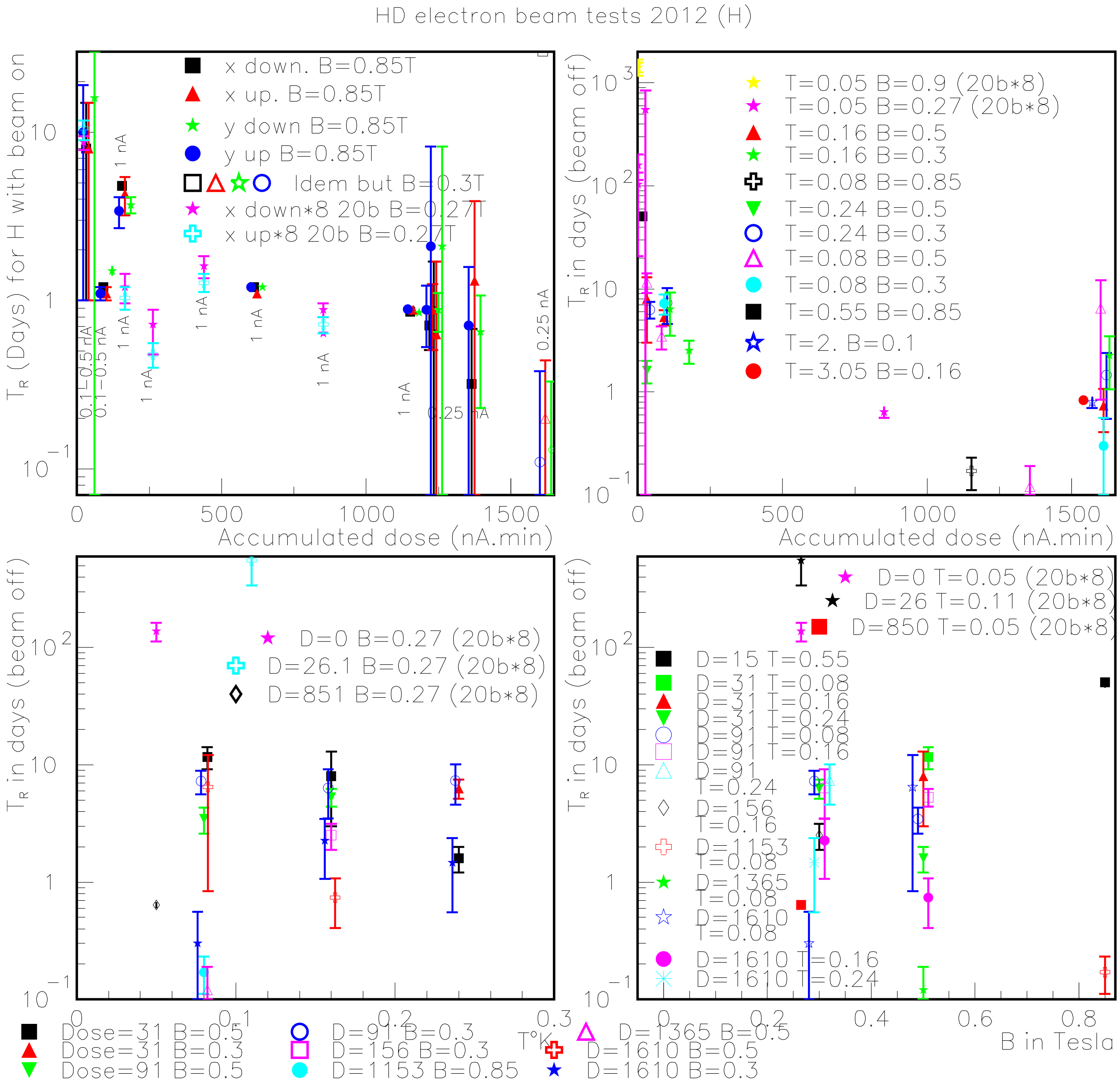


Figure 12:
T_R^H for cells 21a and 20b for the data with and without beam. Hydrogen lifetimes T_R^H during beam-on are shown by the top left plot. The beam currents used are indicated on the figure near the data points. The three other panels are for T_R^H measured during beam-off. On the top right panel, the same data are plotted vs the accumulated dose. On the bottom left panel, the results are plotted vs temperature. On the bottom right panel, T_R are plotted vs magnetic field. The cell 20b results are scaled by a factor 8 to match the initial T_1 of cell 21a. Points at similar values of accumulated dose (e.g. near 1600 nA.min) or temperature (e.g. near 0.16K) or field (e.g. near 0.5T) actually have same value but were slightly offset for visual clarity.

4. Dose=1610nA.min, T=0.16 (cell 21a): A possible drop of T_R with magnetic field is seen.

Overall, no dependence with magnetic is seen, although there are indications of a decrease of T_R with magnetic field. We expect the opposite dependence if T_R is dominated by T_1. Most models would predict a quadratic dependence (M. Lowry) because in those, the nuclear spin flip is done via a magnetic moment at some frequency and magnetic field B that are not at central NMR condition. The flip occurs anyway because of the non-zero width of the NMR peak. The natural profile is Lorentzian and its wings decrease as $1/B^2$, leading to an expected B^2 dependence of the spin flips causing the depolarization.

3.3 Beam on depolarization for Deuteron data

There are less data for D than for H because its polarization quickly dropped to levels where measurements are unreliable. As for H, there is a clear D polarization drop when the beam is on target. This depolarization is more dramatic than for H, which, cf. section 3.1 is expected if it is due to T_1 rather than radiation damage. As for H, the depolarization is largely reduced as soon as the beam stops, see Figs. 3 and 7. T_R^D with beam-on are shown on Fig. 13 top left plot. As for H we see a decay of T_R (measured during beam) with accumulated dose to which permanent radiation damage must be contributing partly (compare the left and right top plots of Fig. 13.

3.4 Lifetime after beam exposure

The T_R^D measured under beam-off are also shown on Figure 13.

3.4.1 Dependence with accumulated dose

The dependence with accumulated dose is clear and much more marked than for H (see top right panel of Fig. 12), although, contrary to H, there are some cases for which the drop of T_R with dose is not clearly observed. This reveals that the D data are less precise. We list the cases for which there is more than one T_R measurement at fixed temperature and field condition and what is observed.

1. T=0.05K, B=0.27T or B=0.9 (cell 20b). A strong decay is observed. It can be attributed to either the larger dose or the lower magnetic field but this later is unlikely given the size of the drop and the little dependence of T_R with B seen in the bottom right panel of Fig. 13.
2. T=0.16K, B=0.5T (cell 21a). A clear decrease of T_R with dose is observed.
3. T=0.16K, B=0.3T (cell 21a). A possible decrease of T_R with dose is observed but the data are also compatible with no dependence.
4. T=0.24K, B=0.3T (cell 21a). A possible *increase* of T_R with dose is observed but the data are also compatible with no dependence.
5. T=0.08K, B=0.5T (cell 21a). A clear decrease of T_R with dose is observed.
6. T=0.08K, B=0.3T (cell 21a). A clear *increase* of T_R with dose is observed.

3.4.2 Dependence with temperature

We list below the cases for which there is more than one T_R measurement at fixed accumulated dose and field conditions. In all cases, a drop of T_R with temperature is seen.

1. Dose=31nA.min, B=0.5T (cell 21a)
2. Dose=31nA.min, B=0.3T (cell 21a)
3. Dose=91nA.min, B=0.3T (cell 21a)

Overall, it seems that a decrease of T_R with temperature is present. For H no such trend could be seen.

3.4.3 Dependence with magnetic field

We list below the cases for which there is more than one T_R measurement at fixed accumulated dose and temperature conditions:

1. Dose=31nA.min, T=0.24 (cell 21a): A possible rise of T_R with magnetic field is seen but the data are also compatible with no dependence.

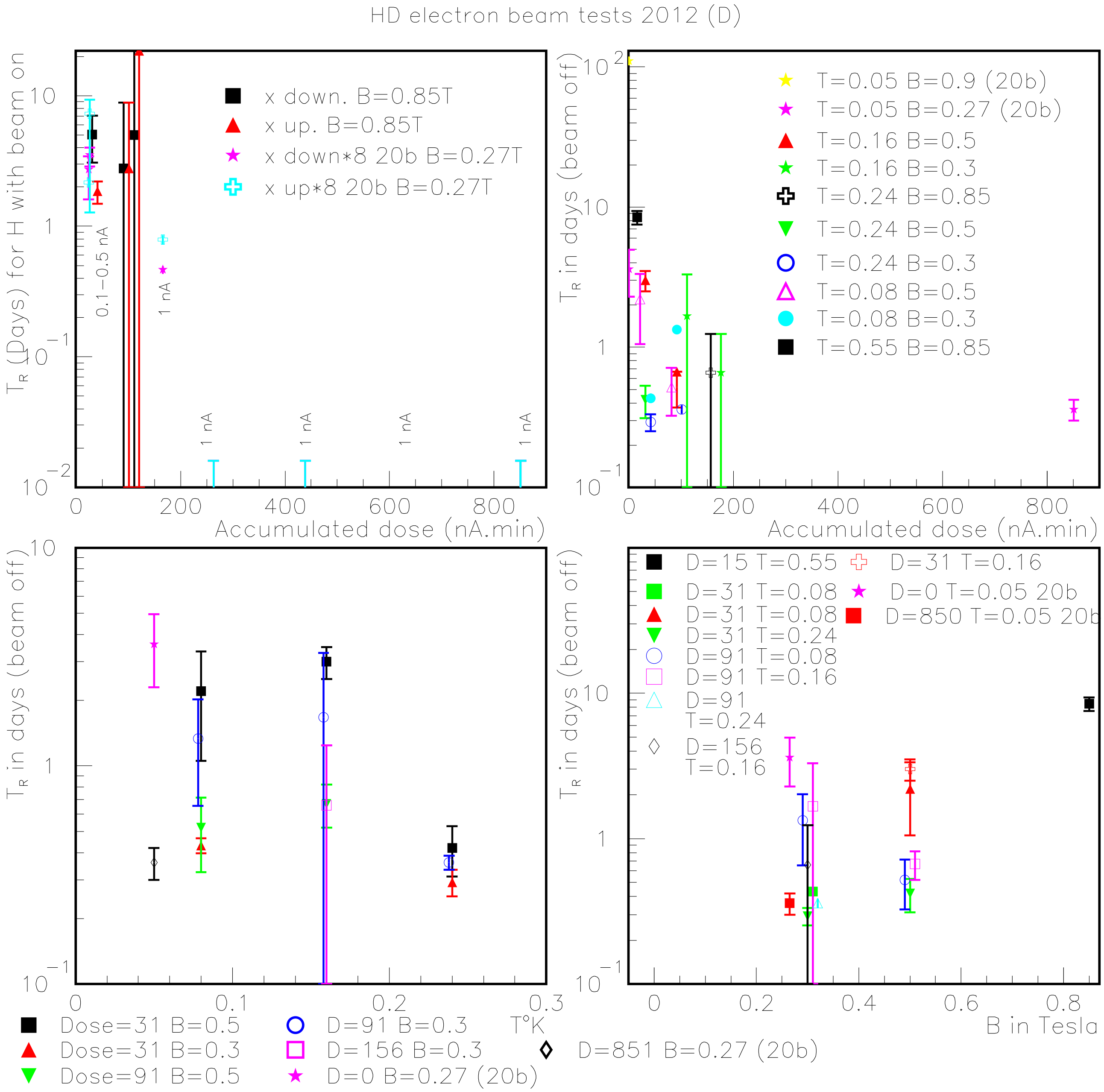


Figure 13:
Same as Fig. 12 but for D. The cell 20b data are rescaled by 8 only for the top left plot.

2. Dose=91nA.min, T=0.08 (cell 21a): A possible drop of T_R with magnetic field is seen but the data are also compatible with no dependence.

3. Dose=91nA.min, T=0.16 (cell 21a): A possible drop of T_R with magnetic field is seen but the data are also compatible with no dependence.

Overall, no dependence with magnetic is seen, as for H.

4 Discussion

The two most solid facts that can be established from the data are:

- There is an instantaneous depolarization of H and D when the beam is on which disappears when the beam is turned off. It is more important for D than H. This is compatible with T_1 polarization decay (Data and raster simulation indicates large temperature enhancement from the beam heat load.)
- There are important permanent (permanent on the time scale of the electron test for cell 21a and at least of the T_R measurement procedure for 20b) radiation damages for both H and D ($T_1 < T_R$)

However, there are features in the data that cannot be accounted for with a simple T_1 effect together with permanent radiation damages. We list them in the next section.

4.1 Puzzles

1. The level of H polarization regrowth for cell 20b after the polarization was erased (see Fig. 6) is too low (about half of the expected TE polarization). There are other such instances for cell 21a when the polarization equilibrium could be measured: measurements # 26, 30 and possibly 32. However, measurement #33 is close to the TE expectation.

2. For cell 20b, the D polarization regrowth seems to reach TE, although it is uncertain given the noise level. If true, this behavior is different from the H one.

3. The value of equilibrium inferred during the last irradiation of cell 20b is too high: It implies a HD temperature of 0.162K, about an order of magnitude lower than the raster model indicates. It is similar to the equilibrium value after beam was turned off but should have been much smaller.

4. The cell 20b H data after erasing the polarization may be incompatible with the data taken during the 1nA beam: The T_R are similar: $\sim$ 3 hours (and, as already noted so is the equilibrium level). However, we expect the temperature to be much higher when beam is on, leading to larger T_R. The similar T_Rs could have been explained if $T_1 \gg T_R$. However, we know that $T_R \sim 3$h when the beam is off and the *beam-on* T_1 is expected to be about the same value, extrapolating from measurements before the beam is turned on and from measurements at 0.1nA. So the condition $T_1 \gg T_R$ is not expected to be true. For D the T_R under beam-on ($\sim$ 2 hours) is smaller than the measured T_R after erasing the polarization ($\sim$ 9 hours), as initially expected.

5. After dose #1 there is an apparent polarization increase once the beam is turned off, even if the target polarization is above thermal equilibrium (so there is no direct source to repolarize the target). Alteration of the NMR apparatus that would shift the calibration has been looked at but seems unlikely (D shows no shift. But it is measured on a different NMR circuit resonance). There is no known mechanism for a H to D transfer (but such transfer has occurred when it was not expected: during the "pseudo-quench"). Another highly polarized source could be the highly polarized electrons.

6. Permanent radiation damage seems to be larger for D than H according to Figures 2 and 3: T_R^D drops more steeply with dose than T_R^H. This is consistent with the "pseudo-quench" data. However, the opposite conclusion is reached from the clean measurements done after cell 20b polarization is erased: $T_R^D > T_R^H$ while before the test, $T_R^D < T_R^H$ indicating this time a shallower slope for D. To reconcile these facts, we can assume that 3 mechanisms are at play: Instantaneous damage (from small T_1 due to heat load), transient radiation damage (as in the ionization-neutralization model discussed next) and permanent radiation damage. As already noted, if the permanent radiation damage is from ionization, depolarization occurs through magnetic moment coupling with $\mu_P \sim 3\mu_D$ and D should be more resilient, contrary to what is observed for cell 21a.

It is doubtless that some of the puzzle below may simply be due to the low precision of the measurements. We recall that all the T_R extractions for cell 21a are based on the assumption that equilibrium value is TE/2$\pm$TE/2 and neglect the real possibility that it could be larger than TE. If it is, many of the T_R from cell 21a are overestimated. To explain the above troublesome puzzles, several models have been put forward:

4.2 The Dead Core(s) model

4.2.1 Model

The beam may have damaged the volume of the target where it passes through but not the ring near the wall where the beam does not pass. The ring will then contribute a more or less constant signal to the NMR when the beam is on, while the contribution from the core drops quickly to lower contribution. At the end of the beam delivery, the polarization corresponds to mostly the ring contribution (higher polarization, closer to the pick-up coil). If several raster sizes are used, then the NMR signals would consist of contributions from several more or less dead cores with different diameters.

4.2.2 Advantages

- It explains puzzle 1 (the observation that often the equilibrium polarization is $\sim$ TE/2): if the contribution of the ring (closer to the pick-up coil) represents half of the NMR signal from an undamaged cell and if the cell polarization reaches 0 (either on purpose because we set B=0 or because of the heat load that had reduced T_1 dramatically), then the damaged core with small T_1 quickly grows to its TE value while the ring, with its long T_1, remains almost unpolarized, leading to equilibrium polarization $\sim$ TE/2.
- It explains puzzle 2 (the possible fact that at the end of the 2$^{\text{nd}}$ electron test, Cell 20b H polarization reached TE/2 while D reached TE) if we assume that the spin diffusion is quicker for D than H: $T_2^D \ll T_2^H$.
- It explains puzzle 3 (the too high equilibrium signal during the last beam delivery of 20b): the ring contributes to a higher NMR signal because it is either still in HD frozen mode or if not, its temperature is somewhat lower than the part seeing the beam.
- A consequence of the model is that we should have (signal size right after beam exposure) + (saturated signal value after setting $B = 0$) $\simeq$ expected TE value. This is approximately true.

4.2.3 caveats

- A low T_2 value would tend to equilibrate the core and ring polarizations, merging the core and ring. As discussed in the introduction, T_2^H is unknown and cannot be inferred from the post-G14 measurements. A. Sandorfi modeled the 21a cell T_R using dead cores, first assuming no spin diffusion, but could not explain the data within this assumption [4].
- It does not explain puzzle 4 (T_R(beam-off)$\sim$ T_R(beam-off) for cell 20b during the 1nA exposure)
- It does not explain puzzle 5 (Cell 21a H polarization growth after dose 1).

4.3 The frozen Core(s) model

4.3.1 Model

This model is the same as the dead core model but with opposite regions: we assume that the ring is now less polarized than the core. This could happen e.g. if the beam wings went through the denser cell walls and heated up and sprayed particles on a ring of HD near the wall. Once the beam is off, the higher polarized core diffuses its polarization to the ring. The increase in NMR signal results from the fact that the HD ring is closer to the pick-up coils and thus contributes more to the signal than an equal amount from the core.

4.3.2 Advantages

- It explains puzzles 1 and 2 (Equilibrium polarization $\sim$ TE/2 observation for H and $\sim$TE for D) by the same reasoning as for the dead core model.
- It explains puzzles 3 : the core is still in HD frozen mode but not the ring.
- As for the dead core model, we should have (signal size right after beam exposure) + (saturated signal value after setting $B = 0$) $\simeq$ expected TE value, as seen.
- It explains puzzle 5 (cell 21a H polarization growth after dose 1) Once the beam is off, the higher polarized core diffuses spins to the ring. The increase in NMR signal is because the ring is closer to the pick-up coil and thus contributes more to the signal than an equal HD amount from the core.

4.3.3 caveats

- As for the dead core model, it does not explain puzzle 4.
- As for the dead core model, a low T_2 value should merge core and ring.

4.4 Ionization and neutralization model

4.4.1 Model

Moller scattering between the beam and molecular electrons ionizes the HD. Moller rates in the momentum range relevant to HD ionization are large (given in [5]). Once the HD is ionized, the unpaired electron of an HD^+ ion can spin flip with the H or D nuclear spin by hyperfine interaction. Because of the high temperature during beam delivery due to the inadequate raster, the unpaired electrons are not fully polarized and act as spin sinks. HD^+ ions are neutralized by recombining with electrons, presumably from the Aluminum cooling wires. If the recombination rate is slower than the ionization one, radiation damage accumulates. When the beam is turned off the depolarization continues until all HD^+ are neutralized and thereafter, the HD returns to frozen mode (long T_1), with a low polarization. Since the electron mobility slows down at low temperatures, the neutralization recovery should take longer time at lower temperatures. Also the Aluminum properties change with temperature (e.g. its critical temperature is 1.2K at 100 Gauss).

4.4.2 Advantages

- It explains puzzle 1 (the regrowth of the polarization after it is erased for cell 20b. The characteristic time of the regrowth is not the HD T_1 but the HD^+ recombination time. The HD does not reach its TE value after the regrowth because it returns to frozen mode before being able to reach it.

4.4.3 caveats

- In this context, the radiation damage is only semi-permanent with a lifetime typically given by the T_R measured after polarization is erased for cell 20b (accounting for the fact that the measurement was not done starting right after the beam is turned off). This represents a time of about 5h. In that case it does not explain the permanent radiation damage clearly seen on, e.g. top right plot of Figs. 12 and 13 which accumulated over a week. A permanent (at least at the week scale) depolarization mechanism is necessary.
- It does not explain the "pseudo-quench" data: the little radiation damage occurring during the photon beam should have been neutralized by the time the T_R measurements were done.

The heat load of the beam together with these models or possibly a combination of some of them may explain the data but need to be validated since they were designed to match our observations.

5 Conclusion and plans for further tests

The two electron tests cannot validate or invalidate the use of HD targets with electron beams. The tests were done in conditions too compromised (too low target polarization, not enough time), without an adequate raster, with difficulties for the beam control and with a too naive view of the processes at play: Only permanent radiation damage was expected to be relevant and there were arguments that this effect should be suppressed providing that the temperature was low enough and the field high enough. From the test, we conclude that:

1. Depolarization induced by permanent radiation damage is important.
2. Additional instantaneous depolarization occurs when the beam is on. Evidences point toward a T_1 increase due to the beam heat load.
3. There is probably a 3^{rd} depolarization process that is transient (see the ionization-recombination model).
4. The data are not precise enough to reveal a dependence of T_R with magnetic field. T_R^D seems to decrease with temperature and we have hints that T_R^D does as well. Dramatic dependence over the temperature and the field appears to be ruled out.
5. The parameter space is much more complicated than expected: Instead of just charge, temperature and field dependence, there might be a time dependence of part of the "permanent" damages (transient effects with ion neutralization, spin diffusion with an unknown time constant T_2), space dependence (part of the target can be undamaged or more damaged and acts as polarization reservoir or polarization sink). Beam characteristics (such as beam intrinsic size and current) and quality also play a role.

Other tests are needed for an adequate understanding of HD under electron beams. Such tests must be done in more adequate conditions:

- Higher HD polarization (Pol.$\gg P_{TE}$) so that the usually unknown equilibrium value can be neglected. It would also enhance the signal/noise ratio, yielding more precise T_R measurements. This would also help with minimizing the possible RF polarization losses, which are neglected in the present note.
- The raster must be redesigned so that the beam heat load is adequately spread over the cell cross section. The cell design can be also modified to minimize the temperature increase and speed-up the heat removal (shorter cells, larger cell diameter).
- Dedicated time for the test with enough time to perform adequate T_R measurements: The hall should stay closed to prevent noise from work in the hall. After each beam delivery, the possible transient effects (spin diffusion, ionization neutralization) must be waited out. Then each T_R must be measured with at least 3 points but should include more. Ideally, the polarization should be monitored by NMR under the condition that RF polarization losses remain negligible (low enough RF power and spaced enough NMR measurements. -25 dBm RF power and measurements every 15min seems to be adequate. B-field changes should be minimized as they warm the target via eddy-currents).
- Good control of sub-nA beams. Good operations of the NMR apparatus.
- Independent polarimetry. Measurement of elastic ep scattering seems most adequate for H. It would help to disentangle effects from spatial polarization inhomogeneities in the cell by providing the polarization of the cell portion subjected to the beam.

To check the Ionization & Neutralization Model one can erase the cell polarization (B=0) then measure T_R and the equilibrium value. Then erase again the polarization (B=0) and remeasure T_R and the equilibrium value. The first T_R measured should be a few hours (if conditions are similar as in the test done with cell 20b). The second T_R measured should be much longer (no polarization growth) because the HD is back to frozen mode. We can complement this test by resubmitting the (now unpolarized) HD to a few hours of nA beam and check again that the first T_R measured is much sorter than the second one.

It might also be useful to measure T_R when nuclear spins are anti-parallel to the holding field. This can be done by rotating the H or D nuclear spins using RF.

In addition, we may need to have a better understanding of T_2: its value and dependence with temperature, dose (radiation damage), polarization gradient between the high and low polarization areas, location of the low and high polarization areas, cell aging, lattice quality and magnetic field. There is presently no equipment for experimental investigation of T_2.

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