Beam-Induced Depolarization and Application to a Polarized Gas Target in the LHC Beam

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Abstract
This note summarizes the results achieved at HERMES (DESY, Germany) on Beam-Induced Depolarization (BID) of a polarized hydrogen gas target in a bunched High-Energy electron beam, and gives a first extrapolation to the conditions at the LHC.

Keywords
beam-induced depolarization; polarized; hydrogen gas target; LHC fixed target

1 Introduction

Depolarization by the bunch fields of the stored beam has been observed and studied at the HERA Electron Ring by the HERMES experiment in cooperation with the HERA machine group. A detailed study of the results [1] has been performed by P. Tait in his dissertation [2], in which he could trace back the observed effects to the properties of the bunch fields. Based on these results, a preliminary estimate has been performed of the effects of the LHC beam on a polarized hydrogen gas target which is presented in this note.

The polarization direction of the polarized (hydrogen) gas stored in the cell is defined by a homogenous magnet holding field B_0, which is longitudinal for helicity effects (here a double-polarized measurement is required, i.e. polarized target and beam), or transverse for transverse spin effects. As the LHC beams cannot be polarized, measurements of the 2nd kind can be performed, only. A transverse spin effect is observed in the azimuthal distribution of ejectiles if the transverse target polarization is switched between opposite signs (single-spin azimuthal asymmetry).

The holding field must be strong enough in order to decouple the nuclear and electron spins in the H-atom. This has two beneficial effects: (i) Nuclear polarization Pp of the protons inside the H atoms approaches the maximum value, and (ii) the spin-flip probability of the protons induced by the bunch field is suppressed. At HERMES, a holding field of about $B_0 = 6B_c = 300mT$ has been used, with $B_c = 50.5mT$ being the critical field of the H-atom. The exact value of B_0 must be chosen such that resonant depolarization is minimized, e.g. by placing the B_0 Working Point (WP) in between resonances between hyperfine states. This requires a high homogeneity, depending on the type of resonance.

The magnetic component of the bunch field B_1 in the laboratory frame has (approx.) cylindrical symmetry around the beam axis and is tangential to the coaxial circular field lines. There are two classes of resonances, i.e. resonant depolarization, induced by the periodic nature of the bunch fields, with F = total spin of the hyperfine state of atomic hydrogen H (F = 0, 1):

π resonances with $B_1 \perp B_0 : \Delta F = 0, 1, \Delta m_F = \pm 1$. Transitions: $\mathbf{1-2}, 2-3, 1-4, \mathbf{3-4}$.

σ resonances with $B_1 \parallel B_0$: $\Delta F = \pm 1, \Delta m_F = 0$. Transition: $\mathbf{2-4}$.

Here the hyperfine states of H are numbered from 1 to 4 with decreasing energy in a magnetic field. The transitions in bold-face do change nuclear polarization P_p of the proton. They are particularly important in our context. For longitudinal B_0 as it was the case for the HERMES helicity measurements, only π resonances are induced. Those with nuclear spin flip are $\pi(1-2)$ and $\pi(3-4)$. They have low

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transition energy E, which can be induced with low harmonics k of the bunch frequency f_b (= 40.08 MHz for LHC; for comparison: 10.41 MHz for HERA). E can be expressed in terms of a transition frequency $f = E/h$ (h = Planck constant). The harmonics k are then given by $k = E/(hf_B)$.

At $B_0 = 300mT$, f is about 0.7 GHz for the $\pi(1-2)$ and $\pi(3-4)$ transitions. The corresponding harmonics at the LHC for these transitions are of the order k = 17, about 4x smaller than for the HERA case which implies a 4x wider spacing of the nuclear depolarizing resonances in B_0 i.e. about 1.4 mT. For transverse B_0, both π and σ transitions can be induced. This adds another class of depolarizing resonances, (2-4) , with f = 8.54 GHz and a harmonic number about 213 for the LHC and 820 for HERA. Due to the higher slope of the energy curve (see Fig.1 left), a more narrow spacing of resonances as function of the guide field B_0 is expected. Due to its higher k it will experience a much lower Fourier component of the bunch field.

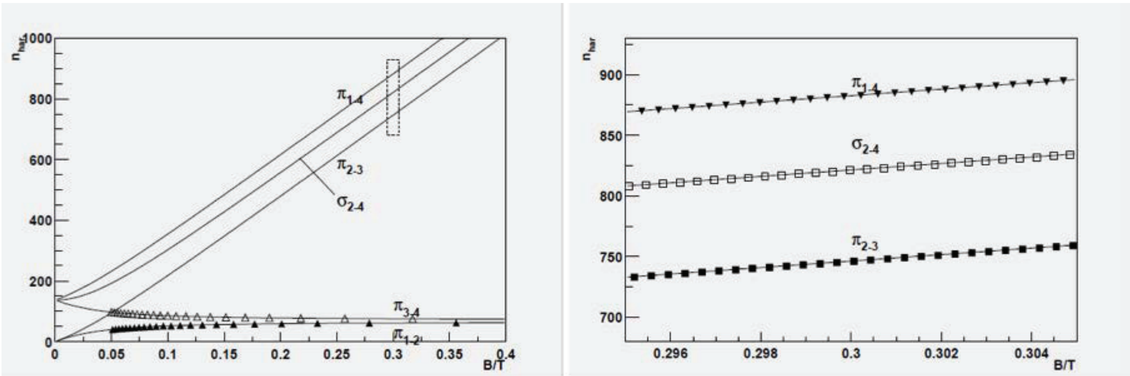


Figure 1: Taken from Ref.[2]. Left: Harmonics of energies of the hyperfine states for the full B range; right: zoom into box around working point B_0. The harmonics, here denoted as n, are given for HERA-e, the HERA electron ring. For the LHC, the n=k values are a factor f_B^{HERA}/f_B^{LHC} = 0.26 smaller.

2 Comparison with LHC

The question, how the LHC case compares with the favorable conditions at the HERMES target, has to be studied in detail, taking the different beam parameters into account. An overview of the relevant parameters is given in the table below ($\alpha = 1/2\sigma_t^2$).

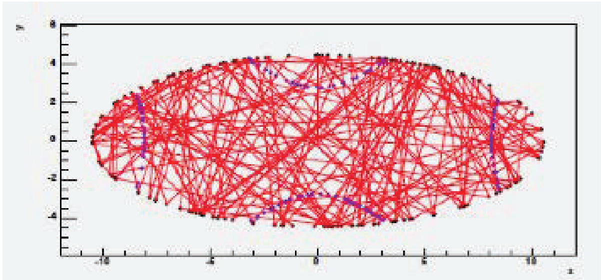
Machine	N_{Bunch} $x10^{10}$	f_{Bunch} MHz	I_{beam} A	σ_z cm	σ_t ps	α ps^{-2}	$1/e\ width$ $Fourier\ Sp.$	$I_0\ peak$ current(A)
HERA-e	2.4	10.41	0.04	0.93	31	$5.203 \cdot 10^{-4}$	5.1 GHz	36.4
LHC	15.5	40.08	1.0	7.55	253	$7.81 \cdot 10^{-6}$	0.63 GHz	55.7

Table 1: This table shows a comparison of parameters for HERA-e and LHC relevant for the beam fields.

Assumptions for a comparison HERA-e with LHC:

1. The trajectories of the MolFlow simulation are equivalent (see Fig.2);
2. Inhomogeneity equivalent, i.e. the shape of the resonant surfaces are similar, i.e. the duration of resonance crossings have the same statistical distribution;
3. Beam size very small compared to cell radius;
4. The main differences come from the bunch frequency, and the longitudinal width in z or in t ($\sigma_{z/t}$, see Table 1).

Figure 2: The trajectories of a MolFlow simulation, projected onto the transverse plane, are shown in red. Blue dots at the cell wall mark wall bounces, blue dots within the cell mark crossings of a resonance



Spin – flip Probability The probability P_n^σ for crossing a σ_{2-4} resonance can be written as (θ = mixing angle = $tan^{-1}B_c/B_0$, B_c = 50.7 mT for hydrogen; τ = crossing time, dependent on cell temperature and homogeneity, n = index of passage; Tait [2] Equ. 4.11):

$$P_n^\sigma = sin^2(2\theta)\left(\frac{\mu_B}{2\hbar}\right)^2 B_\|^2\tau^2 \tag{1}$$

$B_\|$ is the RF field parallel to B_0 (guide field $B_0 \approx$ 300 mT). For the assumptions stated above, all parameters of the right hand side of equ. (1) do not depend on the machine, but solely - at the same guide field - on the properties of the H -atom and the target. Therefore, we estimate the relative strength of BID by calculating the ratio of the square of the components of the RF field $B_\|$ parallel to the guide field for both beams. We consider periodic Gaussian bunches $I(t) = I_0 \cdot exp\left[-\alpha t^2\right]$. The k-th harmonic of the Fourier spectrum of I(t) is

$$F_k = 2I_0/T \cdot \sqrt{\pi/\alpha} \cdot \exp[-\pi^2k^2/T^2\alpha] \tag{2}$$

$$F_0 = 1/2 \cdot 2I_0/T = I_0/T = \sqrt{\pi/\alpha} I_b \tag{3}$$

with $T = 1/f_B$, $I_0 = \sqrt{\pi/\alpha} \cdot Q_B$ and Q_B = bunch charge, resulting in

$$F_k = 2Q_B \cdot f_B \cdot exp[-\pi^2k^2f_B^2/\alpha] \tag{4}$$

We obtain at the σ_{2-4} transition frequency of 8.54 GHz

- for the LHC: $F_{213} = 2 \cdot 1A \cdot 1.53 \cdot 10^{-20}$ = $3.06 \cdot 10^{-20}$A
- and for HERA: $F_{820} = 2 \cdot 0.04A \cdot 7.53 \cdot 10^{-2}$ = $6.02 \cdot 10^{-3}$A

We conclude from these first results that resonant depolarization at the LHC via the σ_{2-4} transition seems to be negligible, compared with HERA, despite the 25x higher beam current. The other transitions affecting the target polarization (π_{1-2} and π_{3-4}) have a much wider spacing in B_0 and can be avoided by a proper setting of the guide field. - It should be noted that these results have to be confirmed by a systematic study of BID at the LHC.

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References

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[2] Diss. Phil Tait, Univ. of Erlangen (2006) see http://www-hermes.desy.de/notes/pub/06-LIB/pntait.06-060.thesis.ps.gz