OVERVIEW OF GAS TARGET DEVELOPMENT

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Experimental setups utilizing polarized internal gas targets are presently used at various electron and proton machines with typical luminosities of 10^{31} cm$^{-1}s^{-1}$ and 10^{29} cm$^{-1}s^{-1}$, respectively. The paper focuses mainly on experimental aspects, the design and construction of storage cells, and different methods employed for polarimetry.

1 Introduction

Storage cells to enhance the target thickness provided by a source of polarized atoms have already been conceived some thirty years ago[1]. An application of this technique to nuclear and particle physics became possible only through the advent of storage rings. The stored beam passes through the *internal* target about a million times per second and thus compensates for the low target thickness. In order to obtain higher target thicknesses compared to a free beam of polarized atoms, the dwell time of atoms in the vicinity of the stored beam must be increased. For that purpose an open ended T-shaped storage cell is inserted into the ring through which the stored beam passes and into which the atomic beam is injected. Thereby the luminosity can be raised by about two orders of magnitude. Polarized internal targets nowadays provide densities around 10^{14} atoms/cm^2 and nuclear vector or tensor polarization close to the theoretical maximum at various storage rings.

2 Overview

The suggestion by Haeberli[1] to use a storage cell to enhance the available target thickness produced by an atomic beam source (ABS) in **1966** was motivated by the successful application of a storage container in the hydrogen maser[2]. The proof of principle, carried out by the Wisconsin Group in **1980**, used a 12 MeV beam of α-particles incident on a proton target[3]. The atomic beam entered the storage vessel through a 10 cm long tube of 10 mm diameter. The storage volume (0.26 l) was coated with Teflon to avoid depolarization. The measured polarization after background subtraction was compatible with the polarization of a free beam, thus essentially no depolarization occurred during an average of 900 wall collisions inside the vessel. An improvement in target thickness of a factor of six over that of a free beam was reported.

In **1985** the FILTEX group proposed an internal polarized hydrogen target for LEAR at CERN[4]. The objective was to polarize a stored beam of antiprotons by spin-dependent attenuation in the target (Spin-Filter-Method[5]) and to carry out $\bar{p}p$-interaction studies. Target densities of 10^{14} atoms/cm^2 in one substate were required.

Since **1988** an internal polarized deuterium target is operated at VEPP-3 in Novosibirsk for $e\vec{d}$-scattering[6,7] experiments. Substantial progress in atomic beam intensity could be achieved through superconducting magnets[8].

In **1992**, the FILTEX target was tested at TSR[a] [9,10]. A target thickness close to 10^{14} atoms/cm^2 in two substates, with a nuclear polarization of 0.8 in one substate was obtained (see also Sec. 4.2).

In **1992**, an optically pumped polarized $^3\vec{\mathrm{H}}\mathrm{e}$ target was installed at IUCF to study spin-dependent $\vec{p}\,^3\vec{\mathrm{H}}\mathrm{e}$-reactions[11]. This experiment constitutes the first measurement with a polarized beam incident on a polarized internal target in a storage ring. A target thickness of $1.5 \cdot 10^{14}$ atoms/cm^2 was reported[12]. In **1995**, the target was installed at the HERMES experiment at HERA/DESY to investigate the spin-structure of the nucleon[13].

In **1996**, the polarized source[9], initially developed for the FILTEX experiment, was installed at HERMES. The HERMES storage cell setup is discussed in Sec. 4.2.

Since **1994** the PINTEX[b] collaboration at IUCF[14] is operating a polarized hydrogen and deuterium gas target[15] (see also Sec. 4.2).

Until **1999** $e\vec{d}$-reaction studies have been carried out at NIKHEF with an electron beam incident on a tensor polarized internal deuterium gas target[16,17]. An ion-extraction system was developed to determine the target polarization (Sec. 5.1).

Among the operating polarized internal target experiments, EDDA at COSY[c] is the only one that utilizes a free atomic jet[18]. First tests with a storage cell[19] have been recently carried out (see also Sec. 4.2).

A new type of polarized hydrogen and deuterium source based on spin-exchange optical pumping is currently installed at IUCF. First results in $\vec{p}\vec{d}$ elastic scattering could be obtained[20] (see also Sec. 4.2).

Two **new facilities** employing polarized internal gas targets, are presently prepared for nuclear physics experiments. At the BLAST[d] experiment[21] the polarized source previously used at NIKHEF will be utilized

[a] **T**est **S**torage **R**ing in Heidelberg, Germany.
[b] **P**olarized **IN**ternal **T**arget **EX**periments, at IUCF, Bloomington, Indiana, USA.
[c] **CO**oler **SY**nchrotron in Jülich, Germany.
[d] **B**ates **L**arge **A**cceptance **S**pectrometer **T**oroid, Cambridge, Massachusetts, USA.

for studies in polarized *ed* reactions. At COSY a polarized internal storage cell gas target[22] is being developed to study the $\vec{p}\vec{d}$-breakup reaction[23] at small scattering angles with the magnetic spectrometer ANKE[e 24].

3 Polarized Internal Targets for Storage Rings

The interaction region produced by a target source alone is typically of the order of a cm^3, given by the volume of overlap between stored and atomic beam. Target sources for this type of setup are optimized for *volume density* in the interaction zone, which increases with decreasing atomic velocity. When a storage cell is used, the *intensity* fed into the acceptance of the feed tube of the cell is optimized instead. In this case the interaction region is extended. Typical cell dimensions range from 250 to 600 mm in length, and from 10 to 30 mm in diameter.

The main advantages of polarized gas targets over solid targets are: *i)* **high isotopical purity**, *ii)* possibility of **rapid spin reversal** up to 100 Hz in $\vec{H}$ or $\vec{D}$ targets, *iii)* **low background**, since no container walls intercept the particle beam, *iv)* **no radiation damage**, because the target gas is replenished every few ms. Polarized gas targets combined with beams internal to storage rings are therefore ideally suited for high precision experiments.

4 Storage Cells for polarized internal Targets

The main objective in the development of storage cells for polarized internal targets was the identification of suitable wall coating materials that inhibit depolarization of atoms in the cell that are at the same time compatible with the ultra-high vacuum requirements of a storage ring.

4.1 Cell Coating

Studies of wall depolarization in storage cells were performed by Price and Haeberli with an apparatus described in Ref.[25]. A 50 keV beam of D^+ ions from a duoplasmatron source passes through a storage cell. Polarized $\vec{H}^0$ atoms are injected through a feed tube into the cell, over which a weak magnetic guide field of 5 mT is applied. In a weak field electrons and protons of hydrogen atoms in a state $|m_j = \frac{1}{2}, m_I = \frac{1}{2}\rangle$ carry the same polarization. The electron pickup reaction $D^+(50\,\mathrm{keV}) + \vec{H}^0 \rightarrow \vec{D}^0(50\,\mathrm{keV}) + H^+$ in the

[e] **A**pparatus for Studies of **N**ucleon and **K**aon **E**jectiles

cell transfers the initial polarization of the electrons through hyperfine interaction to the deuterium atom, which acquires a nuclear tensor polarization. The neutral $\vec{\mathrm{D}}^0$ atoms impinge on a tritiated foil located in a strong field of 30 mT. From the neutron asymmetry of the $^3\mathrm{H}(\vec{d},n)^4\mathrm{He}$ reaction the tensor polarization of the deuterons is deduced. The depolarization behaviour of various wall coating materials was investigated. Among the various materials studied, Teflon stands out for its low depolarization and good vacuum compatibility.

4.2 Design and Construction of Storage Cells

The design of a storage cell must be well adapted to the specific requirements of an experiment, taking into account properties of the stored beam, detector acceptance, possible background from the cell walls, etc. These design constraints for polarized internal targets have been reviewed by Meyer[26]. A few experiments employing storage cells are discussed in the next section.

FILTEX: A boundary condition initially imposed by the machine group during the measurements was to allow for injection of the beam without the storage cell acting as acceptance limiter. Therefore a storage cell that could be opened and closed like a clam-shell (Fig. 1) was developed[10]. After the

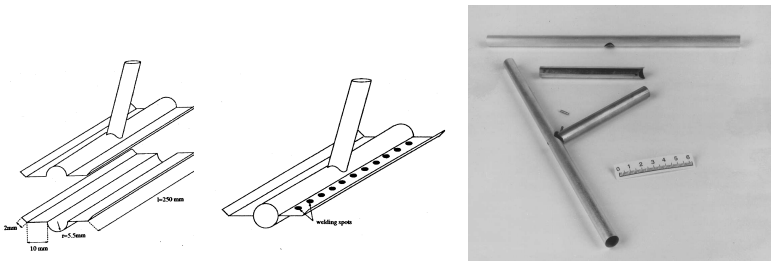

Figure 1. Storage cells used during the FILTEX test experiment at TSR[10]: Clam-shell cell (left), spot-welded clam-shell (center), and cell made from cylindrical tubing (right).

beam had been injected and cooled the cell was closed. The upstream end of the cell was attached to a cold head, thereby the cell center could be cooled to temperatures between 50-300 K. The rather low polarization observed for the clam-shell cell ($\approx 50\%$ of the theoretical maximum) was probably caused by exposure of atoms to the badly-coated fins of the cell. Spot-welding the two half cells together (Fig. 1) substantially increased the polarization. Eventually, closed cells manufactured from cylindrical aluminum tubes were used. All cells

were of the same dimensions, 250 mm length with a diameter of 11 mm and a wall thickness of 0.2 mm. The first two cell types (clam-shell, spot-welded clam-shell) were coated with Teflon FEP 120, while the final cells had Teflon TPFE 3170 coatings. All cells were equipped with small capillaries near the cell center to inject unpolarized gas for background studies. Results of the polarization measurements are presented in Sec. 5.1.

^{3}He-**Target at IUCF:** Depolarization in wall collisions in polarized ^{3}He gas targets is inhibited due to the absence of hyperfine interaction. Storage cells for experiments with ^{3}He (Fig. 2) therefore remained uncoated[11]. Aluminized mylar sheets of 1.7 μm thickness were attached to a support frame consisting of 0.2 mm thick aluminum pieces to form a 400 mm long cell of rectangular cross section (h = 16.6 mm, w = 13.1 mm). The experimental setup did not include any provision to cool the cell. A target thickness of $1.5 \cdot 10^{14}$ atoms/cm^2 was reported. Without restrictions due to deadtime, an order of magnitude higher target thickness would have been possible.

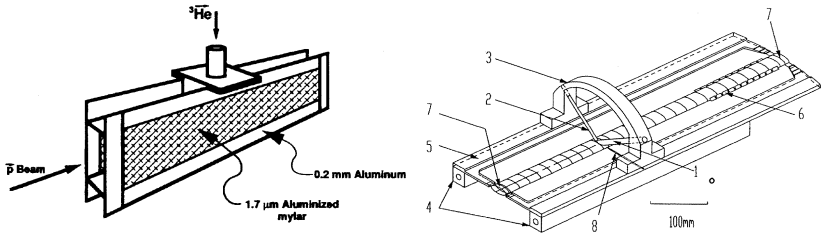

Figure 2. Storage cells used for the $\bar{p}^3\vec{He}$ studies at IUCF[11] (left) and the storage cell for HERMES[27] (right): 1) H/D feed tube, 2) sample tube, 3) support arch, 4) cooling rails, 5) support plates, 6) cell extension, 7) end support 8) unpolarized feed tube.

HERMES The storage cell for HERMES (Fig. 2) is adapted to the beam distribution by an elliptical cross section (w = 30 mm, h = 10 mm). The cell walls consist of 75 μm thick aluminum, coated by drifilm to prevent depolarization[28]. The cell can be cooled to temperatures between 35-260 K by cold helium gas that passes through cooling rails alongside of the target cell. A thin layer of ice formed inside the cell was found to effectively suppress both depolarization and recombination. This effect was first observed at Heidelberg during the development of the target polarimeter[29]. The strong magnetic holding field must be rather uniform to prevent depolarization of target atoms by hyperfine transitions, induced by the periodic time structure of the HERA positron beam[30]. The HERMES target[31] is further discussed in Sec. 5.1.

PINTEX: For detection of low-energetic recoil particles, e.g. spectator protons from a deuteron target, thin cell walls are required. The PINTEX cell complies with this requirement (Fig. 3). Cells of this type were used for measurements of polarization observables in *pp*-elastic scattering at IUCF[32]. Teflon foil of ≈ 450 μg/cm^2 thickness, stretched over fins, form a quadratic channel of about 1 cm^2 cross section[33,34].

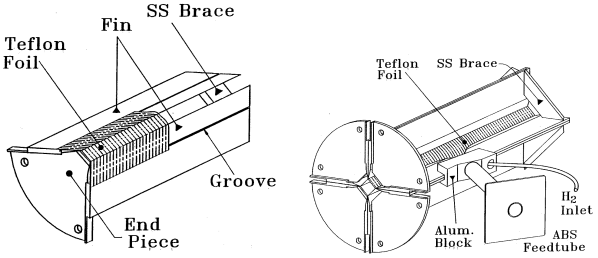

Figure 3. Storage cell for measurements of polarization observables in *pp*-elastic scattering[32]. One quadrant is depicted on the left, the fully assembled cell is shown on the right. (Figures from ref.[33].)

The cells for the pion production experiments[35] were made from 25 μm aluminum foil, coated by Teflon TPFE 3170. For the measurements of the nuclear polarization of molecular hydrogen formed by recombination, the cells had a teflon coated valve and a Cu-recombiner box attached at the center, whereby the atomic-to-molecular fraction inside the cell could be varied[36].

EDDA: Tests with a storage cell at COSY have been performed by the EDDA collaboration[19] Although the EDDA detector [18] was not designed to accomodate an extended target, employing a storage cell would lead to an enhancement in target thickness of about a factor ten[19], not taking into account the significant reduction in beam intensity because of acceptance limitations due to the cell during injection. For the time-reversal-invariance experiment[37] the full target thickness contributes and an enhancement factor of about 60 applies. The EDDA cell (Fig. 4) consists of a 300 mm long cell corpus ($h = 12$ mm, $w = 29$ mm) of 0.2 mm thick aluminum, coated by Teflon PTFE 3170, that can be cooled to 80-100 K. Polarized atoms are injected into the cell through a conical 10 cm long feed tube (entrance/exit diameter 20/12 mm, Fig. 4), not rigidly attached to the cell, in order to remove the cell from the beam position without breaking of vacuum.

Laser-driven Spin-Exchange Target: The storage cell of the first internal target experiment utilizing a laser driven spin-exchange source,

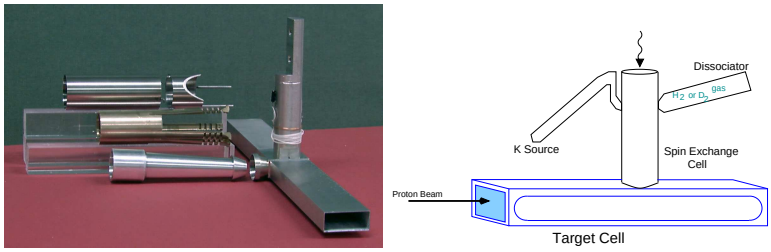

Figure 4. Storage cell used by EDDA at COSY (left) with cell body and mechanical fixture to hold the conical entrance tube in place[19]. Storage cell for the optically pumped spin-exchange target at IUCF[38] (right).

presently installed at IUCF[20], is shown in Fig. 4. The spin exchange cell is directly attached to the storage cell. Depolarization is inhibited by drifilm coating. Condensation of potassium vapour on the cell walls is prevented by operating the cell at 180 °C. The 400 mm long cell (wall thickness 3.2 mm ($h = 19.1$ mm, $w = 38.1$ mm) has thin windows of 0.3 mm thickness to the left and right to reduce multiple scattering of ejectiles. A flux of about 10^{18} polarized atoms/s generates a target thickness of $4 \cdot 10^{14}$ cm^{-2}, with vector polarization $P_z = 0.25$ for both hydrogen and deuterium targets[38].

5 Polarimetry of Internal Gas Targets

Various methods have been applied to measure the nuclear polarization of an internal gas target: *i)* Polarimetry through a **known reaction**, *ii)* **extraction of ions** formed inside the storage cell and subsequent polarization analysis, and *iii)* polarization analysis of an **extracted sample of neutral atoms** from the cell. These methods are discussed in more detail below.

Two **optical methods** were applied to determine the polarization of an internal gas target. At this stage both are suitable as a monitor only, and not for an absolute determination of the target polarization. The Balmer polarimeter measures the circular polarization of light from hydrogen atoms excited to $n = 3$ states by electron impact[39]. The initial electron polarization of the ground state atoms is partially transfered into angular momentum of the excited state. The emitted Balmer light is therefore circularly polarized and a measurement of the initial electron polarization is possible. The method is restricted to polarized targets operated in a weak guide field, where to a good approximation electron and nuclear polarization of hydrogen atoms are

the same. At the ^{3}He target of HERMES an optical monitor measured the circular polarization of photons emitted in the $4^1D \rightarrow 2^1P$ transition[40].

It should be noted that a known (calibrated) reaction does not distinguish atoms from molecules, nor from any other contaminant in the cell. This method is therefore the first choice wherever feasible, because the target is sampled in the same way as in the experiment under consideration. Other methods determine the nuclear polarization of atoms, and, with additional instrumentation also the atomic-to-molecular fraction in the cell. Recently, the nuclear polarization of molecules was studied. A first measurement at NIKHEF[41] suggested a non-vanishing nuclear polarization of recombined deuterium molecules inside a storage cell $P_{\rm molecule}({\rm D}_2^{\rm rec})/P_{\rm atom}({\rm D}) = 0.81 \pm 0.32$. A more precise experiment with hydrogen molecules, reports $P_{\rm molecule}({\rm H}_2^{\rm rec})/P_{\rm atom}({\rm H}) = 0.42 \pm 0.02$ in a 0.66 T magnetic field[36].

5.1 Known Reactions

Suitable for the determination of the nuclear polarization is any *calibrated* reaction. Two examples are discussed below.

Example 1: 27 MeV αp scattering:

Analyzing power and cross section for 27 MeV α particles incident on a proton target are well known[42]. During the FILTEX test experiment at TSR (Fig. 5), polarization and density of the FILTEX polarized hydrogen target could be measured[10]. The target was operated in a weak vertical magnetic guide field. Two measurements, separated in time by about four weeks during which high proton currents were stored, revealed that the polarization of the target is very stable (Fig. 5). It was concluded that no damage to the wall coating occurred. The target was operated at a temperature of 125 K where the figure of merit is highest.

Example 2: *pp* elastic scattering: The PINTEX detector system at IUCF[14], is designed specifically for experiments involving both polarized beams and polarized targets. It enables a determination of target and beam polarization through the detection of *pp* elastic scattering. A precise analyzing power measurement in *pp* elastic scattering[43] provides the basis of a polarization calibration. It is of great importance that the polarization can be exported to serve as a standard at other energies[44]. Through the analysis of elastic *pp* events, it was possible to measure the target polarization along the cell axis, as shown in Fig. 6. It was also possible to deduce the effective reversal time (7 ± 1 ms), e.g. the time it takes to completely reverse or reorient the target polarization. High stability and high polarization characterize the longterm behaviour of the target, as illustrated in Fig. 6. Typical target

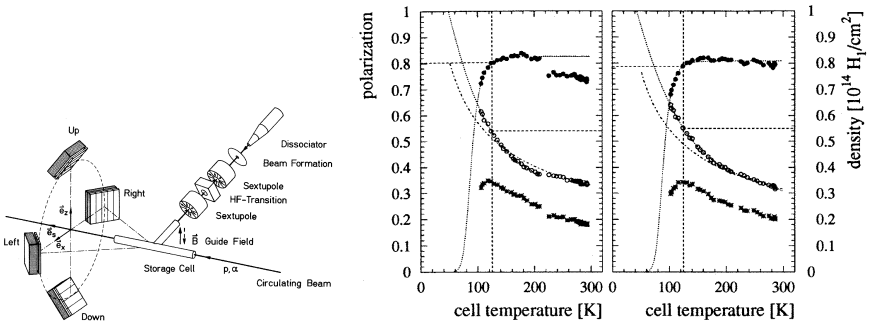

Figure 5. Polarized internal target setup of the FILTEX test experiment[10] (left). Four sets of scintillation counters are used to detect scattered α-particles. Polarization P ($\bullet$), density d_t ($\circ$), and figure of merit $P^2 \cdot d_t$ ($\star$) of the target as a function of the central cell temperature (right) for two measurements separated by four weeks.

thicknesses of $2 \cdot 10^{13}$ atoms/cm^2 with atomic beam intensities injected into the feed tube of the storage cell of about $3.6 \cdot 10^{16}$ atoms/s were obtained, with luminosities of about $5 \cdot 10^{28}$ cm^{-2}s^{-1} [32].

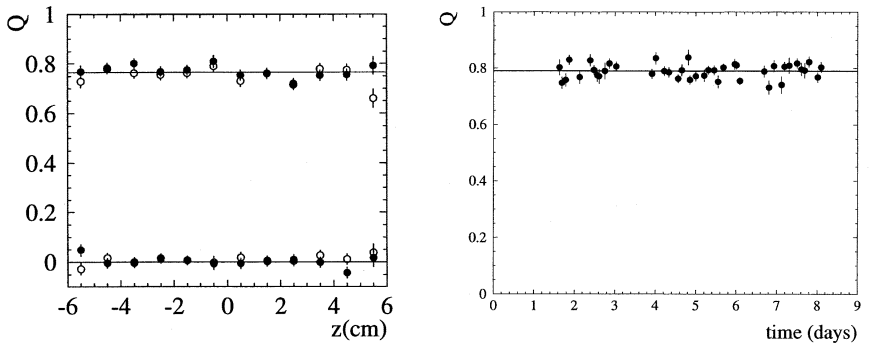

Figure 6. Target polarization as a function of the longitudinal position in the storage cell (left) and as a function of time during a run (right). (Figures from ref.[45].)

Ion-Extraction: A first experiment of this type used a low-energetic electron beam to ionize the target atoms, which were extracted, accelerated to 70 keV, and directed on a tritiated foil for polarization determination by the $^3\mathrm{H}(\vec{d}, n)^4\mathrm{He}$ reaction[46] (Sec. 4.1). The method can be directly applied to cell

targets internal to storage rings, because enough atoms are ionized by orbiting particles. The method is particularly useful in applications, where a strong longitudinal holding field is applied over the target which focuses the ions. The ion-extraction system of the internal target at NIKHEF [47,16] employed a spherical deflector (Fig. 7). Unfortunatley, this configuration is not directly

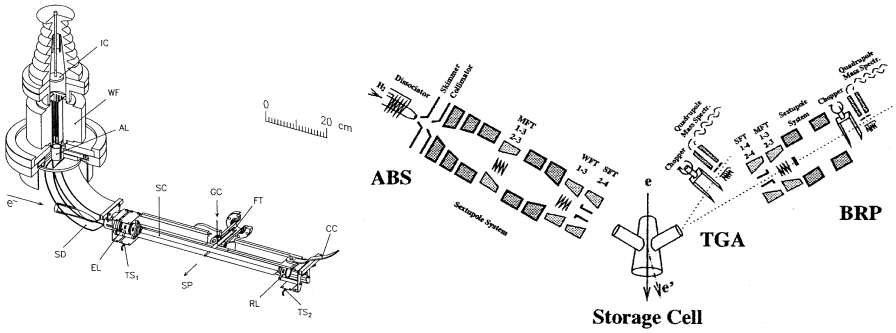

Figure 7. Left: Storage cell and ion-extraction system used by the NIKEF group[47]. SC: storage cell, FT: feed tube, SP: sample port, RL: repeller lens, EL: extraction lens, SD: spherical deflector, WF: Wien-filter. Right: The HERMES target[48]. The storage cell is fed by an atomic beam source (left). The composition of the target gas is measured via a target gas analyzer (TGA). The polarization of the target gas is measured by the Breit-Rabi Polarimeter (BRP).

applicable to polarized hydrogen targets, because of a lack of suitable low energetic reactions to analyze the polarization of protons. The ^{6}Li($\vec{\mathrm{p}}$,^{3}He)^{4}He reaction, mentioned in ref.[46], requires energies of at least 260 keV, where the analyzing power becomes sufficiently large. A more promising method for both hydrogen and deuterium gas targets might be the combination of an ion-extraction system and a Lamb-shift polarimeter[49]. Such a polarimeter system is presently being developed at the University of Cologne for first use at the polarized internal gas target of ANKE at COSY[50].

Extraction of a Sample of Polarized Atoms: The HERMES target polarimeter determines the nuclear polarization of a small fraction of the target gas ($\approx 3\%$) extracted through a sample tube (Fig. 2). A polarization analysis is performed through a measurement of hyperfine state occupation numbers in a Breit-Rabi Polarimeter[29]. The polarimeter (Fig. 7) consists of a set of strong and weak-field transition units and a sextupole magnet system. A chopper is used to suppress background. A separate target gas analyzer measures the atomic-to-molecular fraction of the gas. Systematic errors of 0.01 for the nuclear polarization of the extracted sample of atoms are reported[48].

6 Conclusions and Outlook

Much experience has been gained in operating polarized internal targets in the environment of electron and ion storage rings. An impressive body of information on systematic effects arising from interactions of beam and target, such as unwanted reactions with the walls of the storage cell, radiation damage of the wall coating, longterm behaviour etc. has been obtained. The physics results cover a wide range from deep inelastic polarized lepton-nucleon scattering to measurements of spin correlation parameters and analyzing powers in elastic and inelastic *pp* collisions. Atomic physics experiments are carried out to investigate the nuclear polarization of recombined hydrogen and deuterium molecules. The experiments benefit from the high purity of the target material and the high degree of polarization. Fast polarization reversal and the alignment along different axes eliminates systematic asymmetries to a high degree. Furthermore, the low target thickness turns out to be actually a benefit, because lifetime and high momentum resolution of the stored beam are hardly altered by the thin target. Polarized targets internal to a storage ring can thus be regarded as an ideal tool for high precision experiments. They have just begun to open a new door to hadronic interaction studies and they will continue to play a major role in years to come.

The need for higher target thickness prevails, particularly for electronuclear experiments. Most experiments could digest a factor ten higher intensity from sources of polarized H and D atoms to feed storage cell targets. New developments in this field address a new dissociator based on a surface wave plasma discharge[51] and studies of a carrier jet system[52]. Higher fluxes of polarized atoms may be achieved through the application of new high field sextupole magnets. Considering the achievable fluxes from modern sources, a substantial increase inluminosity may also come from reduced transverse dimensions of the employed storage cells.

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