Printed ISSN 1330–0016
Online ISSN 1333–9133
CD ISSN 1333–8390
CODEN FIZBE7

# SPIN PHYSICS AT HERMES: RECENT RESULTS

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Received xx October 2007; Accepted 20 February 2008
Online 20 June 2008

The HERMES experiment at DESY has been designed to study the spin structure of the nucleon. Impressive results have been obtained not only from inclusive processes but also for semi-inclusive and exclusive processes in deep-inelastic lepton scattering, helping to clarify the spin puzzle of the nucleon.

PACS numbers: 14.20.Dh, 13.60.-r UDC 539.125
Keywords: nucleon, spin structure, deep-inelastic lepton scattering, inclusive, semi-inclusive and exclusive processes

## 1. *The spin structure of the nucleon and the spin puzzle*

The spin structure of the nucleon has been one of the most important subjects in quantum chromodynamics (QCD) since the European Muon Collaboration [1] reported that the quark spin contribution to the proton spin is small, leading to what is called the "Proton Spin Puzzle". In a formalistic way, the nucleon's total spin of 1/2 can be decomposed into the spin of its constituents

$$\langle s_N \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G + \Delta L_q + \Delta L_G \,,$$

where the three terms are the contributions from the quark and gluon spins and from their total angular momenta. The total quark helicity $\Delta\Sigma$ is defined as the sum of the helicity distributions of up, down and strange quarks and antiquarks. The HERMES experiment can probe all single pieces of the above relation. In fact, from the inclusive deep-inelastic scattering (DIS) measurements, it is possible to obtain the polarised structure function $g_1$, related to $\Delta\Sigma$; by semi-inclusive DIS (SIDIS) measurements with the observation of a produced hadron, the helicity distributions of individual quark flavours in the nucleon can be extracted; by measuring the asymmetry for SIDIS from a transversely polarised target, it is possible to access the transversity distribution, the third leading-order structure function; moreover, the possible role of quark angular momentum is addressed by studying exclusive reactions, which can be interpreted in terms of the generalized parton distributions (GPDs).

## 2. The HERMES experiment

The HERMES is located in the East Hall of the HERA *ep* collider at DESY in Hamburg, Germany and it was taking data since 1995, immediately after its installation, until the HERA shut down at the end of June 2007. HERMES scattered longitudinally polarised electron or positron beams of 27.5 GeV from longitudinally or transversely polarised targets internal to the HERA storage ring. The HERMES spectrometer is described in detail in Ref. [2]. It is a forward spectrometer in which both scattered positron and produced hadrons are detected within an angular acceptance of ± 170 mrad horizontally and ± (40 − 140) mrad vertically. The beam line separates the spectrometer in the upper and lower part with independent detector systems and trigger for the top and bottom sections. Drift chambers before and after the spectrometer magnet are used for the track reconstruction and momentum analysis. The particle identification (PID) is obtained by a transition radiation detector, an electromagnetic calorimeter with a preshower detector preceding it and a threshold Cherenkov counter, upgraded to a dual Ring Imaging System (RICH) in 1998: the use of these detectors in combination allows the identification of leptons with an efficiency of 98% or better with a hadron contamination of less than 1%. The RICH provides full separation between charged pions, kaons and protons over essentially the entire momentum range of the experiment: this is a mandatory prerequisite in *flavour tagging*, which is the technique used to relate a struck quark of a given flavour to a produced hadron of a given type.

## 3. Inclusive DIS: the spin structure function $g_1$

The structure function $g_1(x)$ contains information on the helicity-dependent parton contributions to the deep-inelastic lepton scattering cross section. Final results on $g_1(x, Q^2)$ are obtained from a refined analysis of data taken with longitudinally polarised hydrogen and deuterium targets in the kinematic range $Q^2 > 0.1$ GeV$^2$ and $W > 1.8$ GeV [3]. For both targets, $g_1$ is determined from the ratio $g_1/F_1$, which is approximately equal to the virtual photon asymmetry $A_1$ measured via the longitudinal cross section asymmetry $A_\parallel$. The neutron spin structure function is obtained from $^3$He target. The so far, most precise results have been obtained when $g_1^n$ is derived from the difference of $g_1^d$ and $g_1^p$. The measured asymmetries have been corrected for detector smearing and QED radiative effects in a rigorous model-independent unfolding procedure, in which Monte Carlo is used to compute the migration of events between kinematical bins. A compilation of the world data on the $x$-weighted structure function $g_1$ is presented in Fig. 1 (left panel) at their measured $Q^2$: all data are in excellent agreement, even though the $Q^2$ values of the measurements are different. Important informations about the spin structure of the nucleon can be obtained from the first moment of $g_1$, in particular when combining results on proton, deuteron and neutron. For $x < 0.04$, $g_1^d(x)$ becomes compatible with zero and its measured integral shows saturation. Under this assumption, and assuming the validity of the SU(3) flavour symmetry in hyperon $\beta$ decays, the value $\Delta\Sigma = 0.330 \pm 0.011$ (theor.) $\pm 0.025$ (exp.) $\pm 0.028$ (evol.) is obtained from the HERMES deuteron data, in the $\overline{MS}$ scheme at $Q^2$=5 GeV$^2$. The data, therefore, suggest that the quark helicities contribute a substantial fraction (about 30%) to the nucleon helicity, but there is still the need for a major contribution from gluons and/or orbital angular momenta.

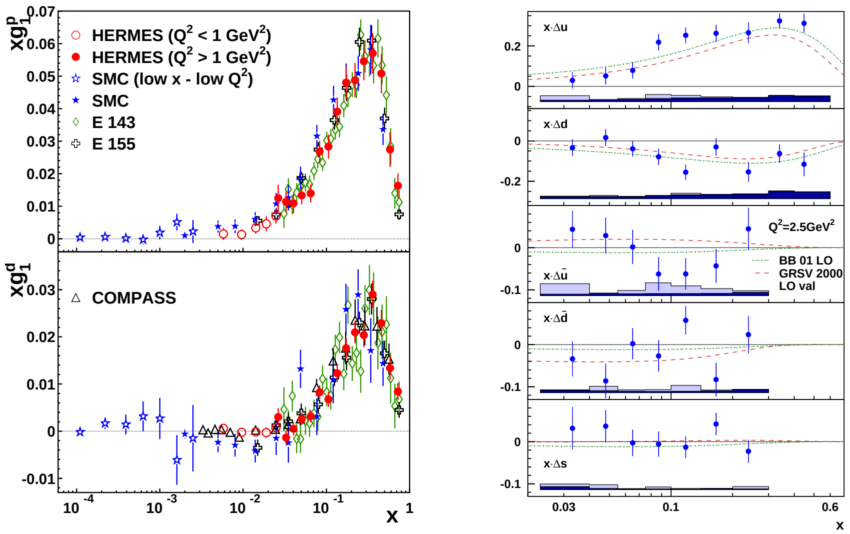


*Fig. 1. Left: World data on the $x$ weighted spin structure function $g_1$ for the proton (top) and deuteron (bottom). Right: The quark helicity distributions $x\Delta q(x, Q_0^2)$ evaluated at a common value of $Q_0^2 = 2.5$ GeV$^2$ as a function of $x$. The curves show LO QCD analyses of inclusive polarised data.*

## 4. *Semi-inclusive DIS: the flavour decomposition*

Semi-inclusive DIS (SIDIS) is a powerful tool to determine the separate contributions $\Delta q_f(x)$ of the quarks and antiquarks of flavour $f$ to the total spin of the nucleon. The hadron asymmetries $A_1^h(x)$ are related to the quark distributions $\Delta q_f(x)$ through the so-called purity matrix $P_f^h$, which describes the probability that a hadron $h$ originates from a quark of flavour $f$. The purities were generated form a Monte Carlo simulation using LEPTO to produce the hard scattering event and JETSET, which is based on the LUND string model, to simulate the fragmentation process. The quark helicity distributions $\Delta q(x)$ can be derived by multiplying each of the quark polarisations with the corresponding unpolarised parton distribution function at fixed $Q^2$=2.5 GeV$^2$. For the first time, a global analysis of the smearing unfolded inclusive and semi-inclusive spin asymmetries for $\pi^+$, $\pi^-$, $K^+$ and $K^-$ has been carried out for longitudinally-polarised targets of hydrogen and deuterium [4]. The results of the decomposition are presented in Fig. 1 (right panel) and compared to LO QCD analyses of inclusive data. No assumptions have been made on the symmetry of the sea flavours, except that $\Delta\bar{s}/\bar{s}$ is assumed to be zero. For $x > 0.3$, the polarisation of the sea flavours was fixed to zero and the small variations from this value have been included in the systematic errors. As expected, the helicity density of the $u$ quark is found to be positive and large at $x > 0.1$, and that of the $d$ quark is negative, while the helicity densities of the light sea quarks are found to be compatible with zero. For sea quarks, there is no disagreement with the QCD fits within the experimental uncertainties.

## 5. *Gluon helicity distribution*

A direct leading-order (LO), model-dependent extraction of $\Delta g/g$ has been performed studying charged hadron production at large transverse momenta, $p_T$, relative to the direction of the virtual photon. A refined extraction method has been used compared to previous results [5], by using the high statistic data sample of antitagged (vetoed by the beam particle) single inclusive charged hadrons from deuterium. To relate the measured longitudinal double-spin asymmetry to the gluon polarisation $\Delta g/g$, information on the relative contributions of the various subprocesses to the inclusive hadron production cross section, their asymmetries and variation with $p_T$, has been obtained from detailed Monte Carlo simulation using Pythia 6.2 and parameterisations of the spin-dependent parton distributions of the nucleon and the photon. This information is used to obtain the signal asymmetry which still contains a convolution of $\Delta g(x)/g(x)$ with the hard-subprocess cross section. The average $\langle\Delta g/g\rangle(p_T)$ has been extracted using two different methods, corresponding to two different assumptions on the shape of $\Delta g/g$: in the first one, $\Delta g/g$ is assumed to be constant in the measured $x$ range, while in the second one, it is following a functional form. With the latter, by integrating over $1.05 < p_T < 2.5$ GeV, a value of $\Delta g/g = 0.071 \pm 0.034$ (stat) $\pm 0.010^{+0.127}_{-0.105}$ (sys-models) has been obtained at $\langle x\rangle$=0.22 and $\mu$=1.35 GeV$^2$.

## 6. *Transverse spin asymmetries*

In addition to the structure functions $F_1(x)$ and $g_1(x)$, a third-leading order structure function, $h_1(x)$, known as transversity distribution, is required to provide a complete description of the quark structure of the nucleon. It is related to a forward scattering amplitude involving helicity flip of both quark and target nucleon. Since hard interactions conserve chirality, transversity has so far remained unmeasured in inclusive processes due to its chiral-odd nature. Contrary to $F_1$ and $g_1$, this distribution can only be accessed in SIDIS processes as both the quark and nucleon need to flip their spin. Hence, additional angular momentum needs to be absorbed by a hadron produced in the reaction. The transverse polarisation of the struck quark can influence the transverse momentum component of the produced hadron orthogonal to the virtual photon, thereby leading to an azimuthal dependence of the cross section on the angle $\phi$ about the virtual photon direction in the lepton scattering plane. A fragmentation function describing this spin-momentum correlation is known as the Collins fragmentation function $H_1^{\perp}$, it represents the interference of the two scattering amplitudes with different imaginary parts giving rise to single-spin asymmetries. Azimuthal spin asymmetries can also be generated by the $T$-odd Sivers distribution function $f_{1T}^{\perp}(x, k_T)$ that appears in the cross section together with the unpolarised fragmentation function $D_q^h$. The $f_{1T}^{\perp}(x, k_T)$ describes a correlation between the transverse polarisation of the target nucleon and the intrinsic transverse momentum of the struck quark. The Collins and Sivers mechanisms can be separated using a transversely polarised target since they have different azimuthal dependences with respect to the axis of transverse polarisation. While the Sivers mechanism gives rise to a $\sin(\phi - \phi_S)$ behaviour, the Collins mechanism exhibits a $\sin(\phi + \phi_S)$ behaviour in the azimuthal angle, with $\phi_S$ being the angle between the lepton scattering plane and the transverse spin component of the target nucleon. The extracted Collins and Sivers moments for charged pions and kaons are shown in Fig. 2 as a function of $x$, $z$ and transverse hadron momentum $P_{h\perp}$. The Collins amplitude, shown in the left panel, is positive for $\pi^+$ and negative for $\pi^-$ with a magnitude for $\pi^-$ comparable or larger than the one for $\pi^+$. One

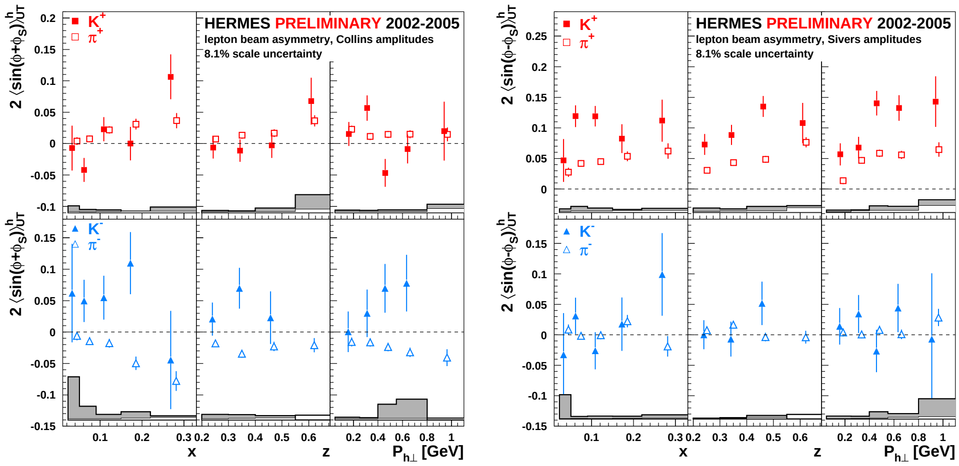


*Fig. 2. Collins (left) and Sivers (right) moments for charged pions and kaons as a function of $x$, $z$ and transverse hadron momentum $P_{h\perp}$. The error bars represent the statistical uncertainties, while the lower band represents the maximal systematic uncertainty due to acceptance and detector smearing as well as possible contributions from $\cos\phi$ moments of the unpolarised cross section. Plots available in http://www-hermes.desy.de/notes/pub/TRANS.*

explanation could be a substantial magnitude for the disfavoured Collins fragmentation function with an opposite sign than the favoured one. These non-zero Collins asymmetries provide a clear evidence for the existence of both the transversity distribution and the Collins fragmentation function. The Sivers amplitude, shown in the right panel, is significantly positive for $\pi^+$ $(0.017 \pm 0.004)$, providing an indication for the non–zero orbital angular momentum of quarks in the nucleon and the first evidence of a $T$-odd distribution function, while it is consistent with zero for $\pi^-$. Since there is no reason to expect a similar Collins amplitude for $K^-$ and $\pi^-$, $K^-$ being a fully sea object, the $u$–quark dominance in DIS would suggest a similar amplitude for $K^+$ and $\pi^+$. However a smaller amplitude is observed for $K^+$ than for $\pi^+$. As in the case of unpolarised structure funtions, the Collins function may thus differ for fragmentation of $u$ into $K^+$ and $u$ into $\pi^+$. On the other hand, the amplitude of the Sivers moment for $K^+$ is roughly twice that of $\pi^+$ in the region of $x \approx 0.1$, suggesting that the sea quarks may provide an important contribution to the Sivers function and may carry significant orbital angular momentum in the nucleon. It will be usefull to compare this function in the Drell-Yan processes, where it is predicted to have opposite signs due to its fundamental time reversal invariance in QCD.

## 7. *Exclusive processes*

The measurement of hard exclusive reactions provides a new tool in understanding the structure of the nucleons in terms of the so called generalised parton distributions (GPDs). They represent a new theoretical development, which encompasses both the well known parton distribution functions and the nucleon form factors as limiting cases and they are sensitive to partonic correlations. By making use of different polarisation states, targets and final states of hadrons, the experiments are sensitive to different combinations of GPDs. For the presented data set, the recoiling target nucleon is not detected, the esclusivity of the processes has been ensured by the missing mass technique or missing energy technique.

### 7.1. *Deeply virtual photon scattering*

The cleanest process to measure GPDs is the deeply virtual Compton scattering (DVCS), the hard electroproduction of a real photon. DVCS amplitudes can be determined through a measurement of the interference between the DVCS and the Bethe-Heitler (BH) processes, in which the photon is radiated from a parton and from a lepton, respectively. As the interference term in the cross section depends on the polarisation and charge of the beam and the azimuthal angle $\phi$ of the emitted photon, measurements of the $\phi$ dependence of the beam spin and beam charge asymmetry make it possible to obtain data that are proportional to the real and imaginary parts, respectively, of the DVCS amplitudes. A measurement of the beam-charge asymmetry requires the availability of both electron and positron beams at the same experimental setup: both beams are available at HERA.

#### *7.1.1.* Beam spin and beam charge asymmetry

Results on azimuthal asymmetries with respect to the beam helicity have been already published by HERMES [7]. In Fig. 3, the first measurement of the beam-charge asymmetry $A_C$ from a hydrogen and deuterium target is reported [8]. On the left panel, the $A_C$ for the proton as a function of the azimuthal angle $\phi$ is shown. On the right panel, the $\cos\phi$ amplitude derived from the four-parameter fit and corrected for background is shown as a function of the four-momentum transfer to the target $-t$ for the proton and deuteron. The comparison with GPD-based model calculations, assuming a factorised or Regge inspired $t$ dependence with and without the $D$ term contribution, shows that the beam charge asymmetry has high sensitivity to different GPD parameterizations. Ten times larger set of data is under analysis.

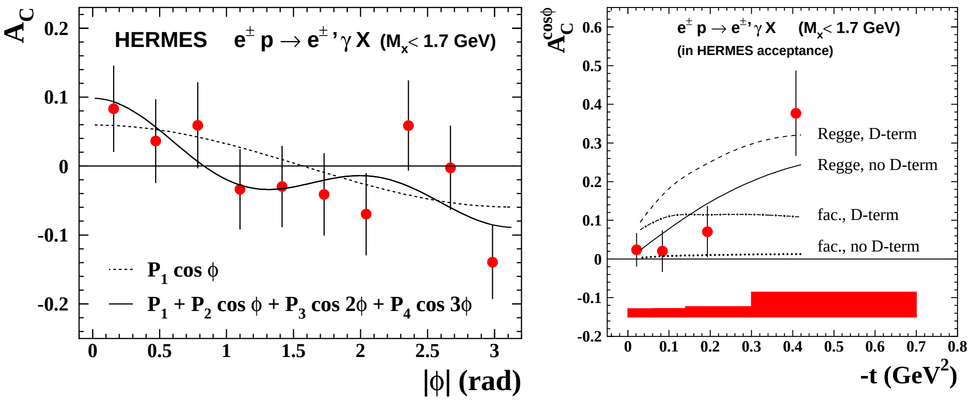


*Fig. 3. Left: Beam charge asymmetry (BCA) for the hard electroproduction of photon off the proton as a function of the azimuthal angle $\phi$; curves show the result of the indicated fits. Right: The $\cos\phi$ amplitude of the BCA for proton and deuterium as a function of $-t$. The curves represent the model calculations based on different GPD parameterizations.*

#### *7.1.2.* Target Spin Asymmetry

The access to the GPD $E$ can be gained by measuring the transverse target spin asymmetry in hard exclusive meson production, where the asymmetry depends linearly on $E$. This observable also provides sensitivity to the total angular momentum carried by the $u$-quarks. A parameterization for GPDs has been proposed [9], where the GPD $E$ is modelled using the quark total angular momenta $J_u$ and $J_d$ as free parameters. In Fig. 4 (left panel), the first results obtained at HERMES [10] on the transverse target spin asymmetry associated with DVCS on the proton are shown: they are based on a model-dependent constraint on $J_u$ vs $J_d$ obtained by comparing the HERMES results and theoretical predictions based on the above mentioned GPD model. The analysed data are only 50% of the full data set.

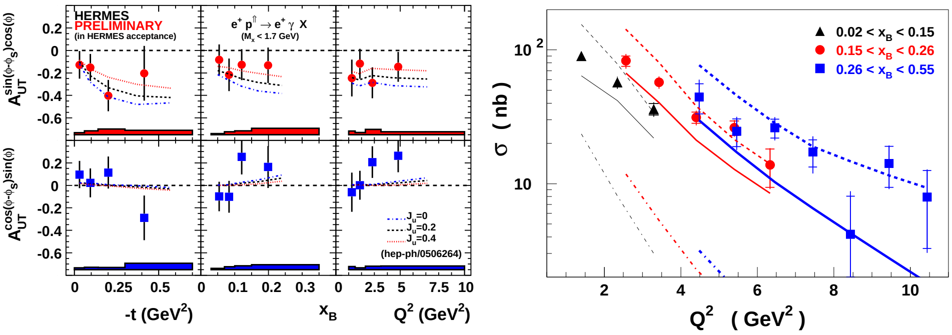


*Fig. 4. Left: The $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ and $A_{UT}^{\cos(\phi-\phi_S)\sin\phi}$ moments as a function of $-t$, $x$ and $Q^2$, compared to the predictions based on a GPD model [12]. The symbol UT is related to the unpolarised beam and to the transverse target polarisation. Right: Cross section for exclusive $\pi^+$ production by virtual photons as a function of $Q^2$ for three different $x_B$ bins and integrated over $t'$. The curves represent calculations based on a GPD model [12] for $\sigma_L$ (dashed-dotted lines: LO calculations; solid lines: with power corrections) and a Regge model [13] for $\sigma$ (dashed lines).*

### 7.2. Exclusive pion production

While exclusive vector-meson production is only sensitive to unpolarised GPDs, pseudoscalar meson production is sensitive to polarised GPDs without the need for a polarised target or beam. The factorisation theorem for hard exclusive production of meson has been proven for longitudinal photons only. However, the transverse contribution to the cross section is predicted to be suppressed by a power of $1/Q^2$. The cross section for exclusive $\pi^+$ production [11] is shown on the right panel of Fig. 4 as a function of $Q^2$ for three different $x$ ranges. The $Q^2$ dependence of the data is in general well described by the calculations from a GPD model [12] with the inclusion of the power corrections, although the magnitude of the cross section is underestimated. The data support the order of magnitude of the power corrections for the calculations by the GPD model at low $-t$, a region where the longitudinal part of the cross section is expected to dominate, and for the available $Q^2$ range. A model calculation [13] based on the Regge formalism for both the longitudinal and the transverse part of the cross section provides a good description of the magnitude, and the $t'$ and the $Q^2$ dependence of the data.

### 7.3. The Recoil Detector

The Recoil Detector has been designed to upgrade the HERMES spectrometer to enhance the capabilities to identify exclusive processes "background free". It consists of three main components: a silicon strip detector surrounding the target cell inside the beam vacuum, a scintillating fibre tracker and a photon detector consisting of three layers of tungsten and scintillator bars. It is shown in Fig. 5.

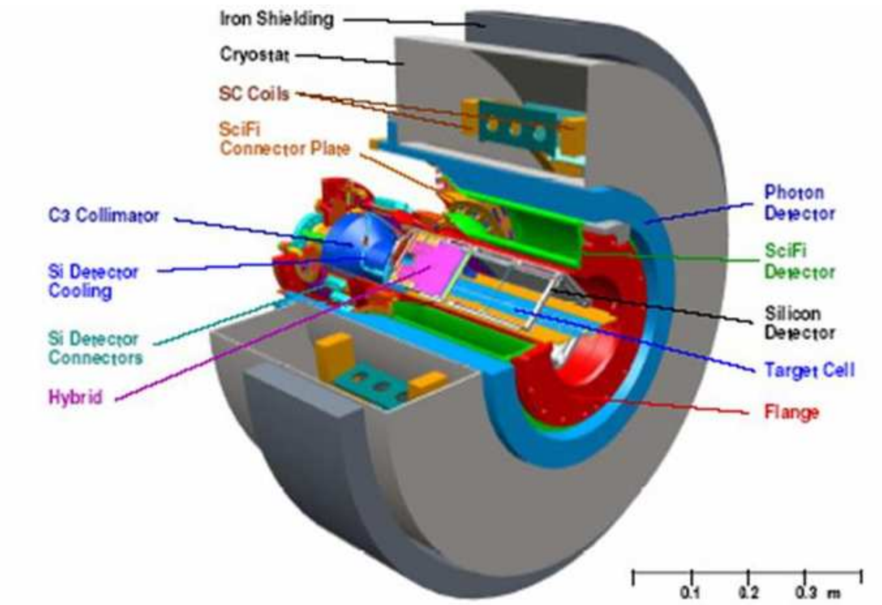


*Fig. 5. Schematic view of the HERMES Recoil Detector.*

All three detectors are placed in a longitudinal magnetic field of 1 T, generated by a solenoidal magnet. They provide a measurement of the deposited energy of the traversing particles. Momentum determination for low-momentum particles stopping inside the the silicon detector is performed using the total-energy deposition in both layers of silicon in combination with the reconstructed track direction. The momentum of fast particles is determined by their bending in the longitudinal magnetic field. The non-exclusive background for DVCS is expected to be less than 1%. The Recoil Detector has been installed in January 2006, it has been commissioned and is in full operation since September 2006. New results are expected soon with the collected data in 2006 and 2007.

## 8. *Outlook*

In spite of many years of experiments, a detailed decomposition of the spin of the nucleon remains elusive. With the recent HERMES results, some new informations have been obtained. New precision data on hard exclusive reactions will be provided soon, after the analysis of data with the Recoil Detector, installed at the beginning of 2006.

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## SPINSKA FIZIKA NA HERMESU: NEDAVNI REZULTATI

Eksperiment HERMES u DESY bio je postavljen radi proučavanja spinske strukture nukleona. Dojmljivi rezultati postignuti su ne samo inkluzivnim procesima, već i polu-inkluzivnima i ekskluzivnima u duboko-neelastičnom raspršenju leptona, što pomaže rasvjetljavanju spinske zagonetke nukleona.