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# Development of a silicon based polarimeter for the low energy prototype proton EDM ring

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ABSTRACT: This article details the design of a silicon based polarimeter for use in a prototype storage ring for proton EDM (Electric Dipole Moment) studies. The polarimeter consists of layers of LGAD (Low Gain Avalanche Diode) sensors for a low material budget, time-of-flight measurement and complemented with HV-CMOS (High Voltage CMOS) sensors for accurate scattering angle measurement and tracking. This design has the objective to optimize the polarization measurement of protons with energy 30–45 MeV. Simulations show that the excellent time resolution of LGAD sensors provides a sufficient energy resolution to meet the experiment specifications. HV-CMOS sensors are included to provide complementary spatial resolution with minimal additional material budget. The simulations show that the detector configuration is capable of measuring the scattering angle of a proton scattered off a carbon target to just a few hundredths of a degree. The time-of-flight measurement performance is demonstrated with lab experiments using electrons from a Sr90 source.

KEYWORDS: Radiation-hard detectors; Si microstrip and pad detectors; Solid state detectors; Timing detectors

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# Contents

## 1 Introduction

This article describes a silicon-based polarimeter for low energy proton beams in a prototype storage ring proposed by the JEDI collaboration, which is a stepping stone towards a proton electron-dipole moment (EDM) measurement experiment [1]. If a non-zero EDM is observed in the sensitivity range of this experiment ($>10^{-29}$ e cm), it would signify new physics beyond the standard model.

The interaction between a strong electric field and any permanent proton EDM induces a torque that leads to proton spin precession. This can be deduced from the asymmetry in the scattering of the proton off a carbon target. The proton energy depends on the two operation modes of the prototype storage ring. First, there is an all-electric mode where the protons are accelerated using electric fields up to 30 MeV. Second, there is a "frozen spin" mode where a combination of electric and magnetic fields freezes the spin orientation of a 45 MeV proton. This method entails balancing fields so that the spin is "frozen" within the particles reference frame, leading, in principle, to a cleaner measurement.

The experiment monitors the left/right asymmetry of proton-carbon scattering over the beams storage time (1000 s). A non-zero permanent EDM will induce a more pronounced asymmetry. Additionally, an energy measurement needed to reject inelastically scattered events needs to be performed as which are less likely to contribute to the spin measurement. A common type of inelastic scattering is where a nucleus in the carbon target is left in an excited state. To distinguish an elastic event from this type of inelastic scattering, an energy resolution of less than 3% is required. Multiply scattered events also lose spin information and can be also distinguished with this energy resolution. This article reports on work to develop an in-beam, silicon-based ToF (Time-of-Flight) polarimeter and a proof of concept telescope being developed. The end goal of this telescope will be to demonstrate a high enough timing accuracy to measure particle energy to the degree needed to distinguish between inelastic and elastic scattering in the final polarimetry measurement.

## 2 Polarimetry

The polarimetry technique will use an "analyzing power", an established value found in early double scattering experiments in which an unpolarized beam was scattered from an unpolarized target nucleus. The resulting beam in a single angle was found to scatter with a small left/right asymmetry in the same plane. This asymmetry is accounted for by adding a spin-dependent term to the elastic scattering cross section. The analyzing power addition to the polarized cross section is as follows:

$$\sigma_{\text{pol}}(\theta) \approx \sigma_0(\theta)(1 \pm PA(\theta)). \tag{2.1}$$

Where $\sigma_0(\theta)$ is the scattering cross section of the interaction, $P$ is the polarization of the beam and $A(\theta)$ is the analyzing power of the interaction. The polarimeter objective is to measure this left/right asymmetry with a small statistical error using as many particles as possible sampled from the beam within the allotted storage time. To enable this, the detector needs a high geometric acceptance and a high detection efficiency. In addition, multiple scattering degrades the performance of the measurement and therefore low material budget is needed. Simulations show that this requirement is satisfied if the thickness of silicon layers is up to 250 μm. The proposed polarimeter is a cylindrical, three-layer, ToF device surrounding multiple, thin, carbon-ribbon targets, see figure 1(a). The innermost layer is a thin (<100 μm) HV-CMOS pixel layer and the two outer layers are each comprised of two perpendicular LGAD strip sub-layers. These LGAD layers are used for the ToF measurement. The silicon detector types are described in section 3. In order to optimize the detector acceptance, a figure of merit is used that combines the angular cross section dependence and the analysing power of the proton-carbon interaction [2]. For 30–45 MeV protons, the optimal regions are at 22–40° and 48–65°, see figure 1(b). These regions signify areas where a high asymmetry can be seen due to differences in polarization of the beam combined with enough scattering events due to a high cross section at these angles. Low angles were chosen not to be included because of the challenges associated with instrumenting areas of relatively high rates efficiently.
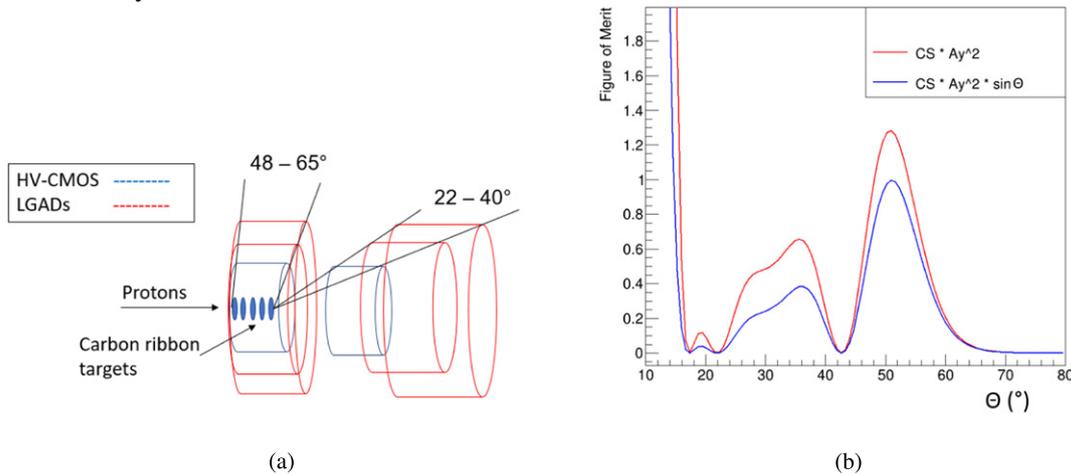


<div align="center">(a)              (b)</div>

**Figure 1.** The geometry of the proposed polarimeter in (a). A diagram showing the angular dependence upon the figure of merit in (b); areas between 22–40° and 48–65° are chosen as optimal regions.

## 3 Detector technologies and simulation

Monolithic HV-CMOS sensors [3] use industry standard processes to combine a high voltage p-n junction into the same silicon substrate as low voltage electronics used for the readout.

A large depletion region is formed as a result of the high biasing voltage and a high field for a fast charge collection time and good radiation tolerance with levels above $10^{15} n_{eq} \, cm^{-2}$ [4]. A Deep N-Well[1] shields the readout electronics from the silicon substrate and therefore very large voltages (e.g. >80 V) can be used to bias the substrate and create depletion zones of a few tens of μm. The built-in readout electronics remove the need for hybridization (a combination of separate sensor and readout chips) and significantly reduce the detector system cost and turnaround time. Without the need for an attached readout chip these sensors can be very thin. A practical example of such a device is MuPix [5] at the Mu3e experiment [6], which is composed HV-CMOS sensors thinned to just 50 μm.

LGADs (Low Gain avalanche Diodes) [7] are CMOS detector devices with a heavily doped p-type avalanche region implanted into this substrate and used to multiply the signal induced by an incoming particle. The incoming radiation causes impact ionization in a region with a high electric field, which results in avalanche breakdown multiplying even a very small signal to a measurable amount. The gain is kept around 5–10 to avoid noise and leakage currents. LGAD sensor thickness is typically 300 μm, although the active area is just 50 μm. This study uses UFSD2 LGAD sensors produced by FBK (Fondazione Bruno Kessler) [8]. A 50 ps timing resolution has been demonstrated with LGADs in the HADES time-zero and beam tracking systems [9]. With current advancements, an overall time of flight time resolution is expected to lie between 30 and 50 ps. A simulation with four LGAD layers (two pairs of perpendicular strip sub-layers) have been defined as silicon disks with a 40 ps time resolution. These sensors have user defined thicknesses and are in the range 100–600 μm.

The difference between the truth value of the initial proton energy and the energy recovered from the LGAD time of flight system (with 100 μm thick LGAD sub-layers) recorded in the simulation is shown in figure 2(a). When position and timing resolutions are included, the energy loss uncertainty increases as the effects from these outweigh the effects from this thickness of silicon. This is shown in figure 2(b).

With these uncertainties on the LGAD measurements, a standard deviation on the energy loss is found to be 0.68 MeV, corresponding to a relative energy resolution of about 1.5%.

As particles pass through silicon and lose energy, their trajectories are likely to change slightly and with low energy protons as proposed for the prototype ring this trajectory change can be large. The energy measurement from time of flight relies on a well defined distance between the hits where the time is recorded.

Even particles that do not deviate in direction will have some inherent uncertainty due to detector position resolution. The geometry used to study these effects is a standard cylindrical as previously shown in figure 1(a) with layer radii of (60, 65 and 200 mm). A uniform distribution of the position resolution of the detectors is used to smear each hit. A straight line is fitted and then compared to the initial values (truth) of $\theta$ and $\phi$. The angular resolution of the polarimeter

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[1] A "Deep N-Well" is an N-doped well implanted deep into a substrate to isolate certain parts of a semiconductor device.
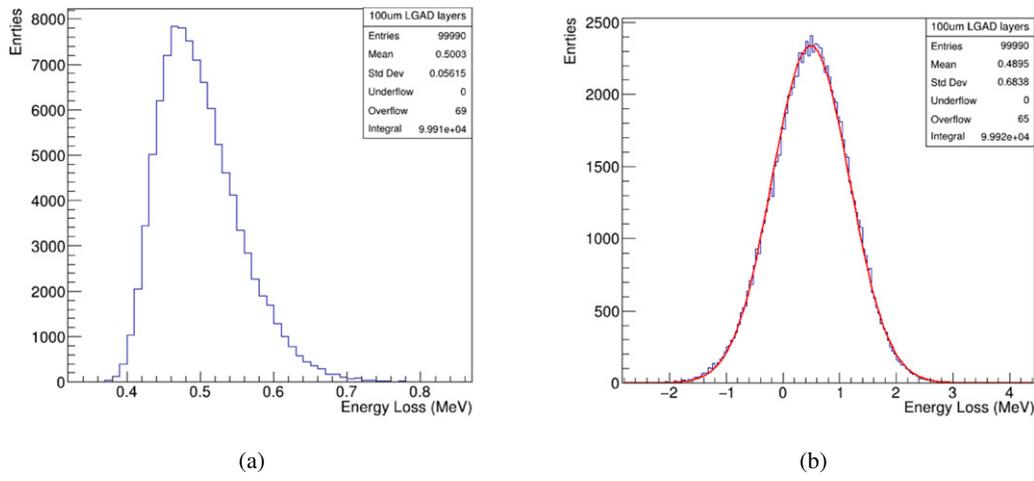
(a)



(b)

**Figure 2.** Energy loss of 45 MeV protons formed in a distribution from a single center point with only interference from the layers of silicon detector (HV-CMOS 100 μm, LGAD $4 \times 100$ μm with 500 mm separation) (a) assuming infinite timing and spacial resolutions, (b) the energy resolution as it is affected by a 40 ps time resolution and 60 μm position resolution within the LGAD layers.

in the azimuthal and polar angles, $\phi$ and $\theta$, respectively is shown in figures 3(a) and (b). These figures show the difference between the generated and reconstructed track angle per proton event. The distribution shows a Gaussian core with non-Gaussian tails likely due to the combination of the sensor uncertainties and the uncertainties of energy lost in the silicon. The Gaussian cores are fitted and give a resolution of approximately $(2.5 \times 10^{-3})°$ for $\theta$ and $(9 \times 10^{-3})°$ for $\phi$.
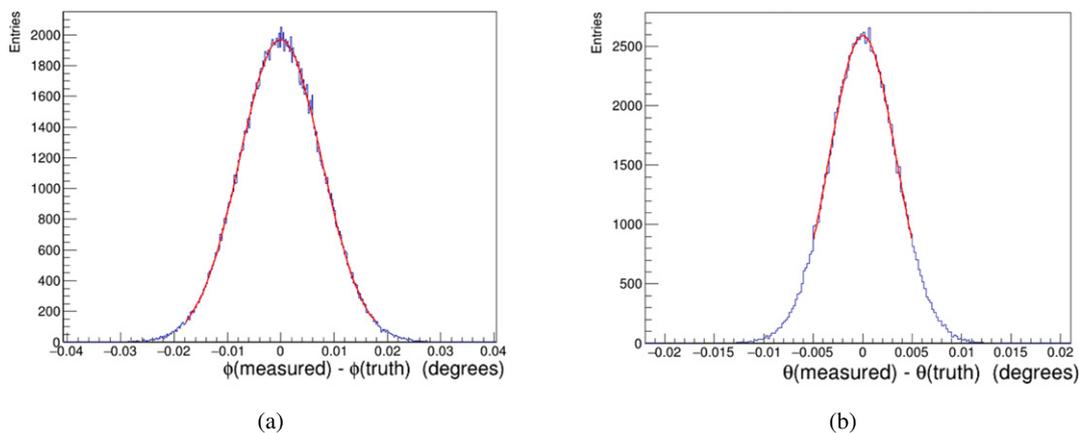


(a)



(b)

**Figure 3.** The angular resolutions of the detector system in the azimuthal angle (a), and the polar angle (b). The Gaussian cores are fitted and give a resolution of approximately $(2.5 \times 10^{-3})°$ for $\theta$ and $(9 \times 10^{-3})°$ for $\phi$.

## 4 LGAD telescope

A telescope has been constructed for demonstrating the ToF technique for protons with a similar energy to the prototype ring experiment. This telescope consists of 4 layers of LGAD sensors (each with 2 perpendicular sub-layers). The LGAD sensors are read out using a 264 channel FPGA based TDC (Time-to-Digital Converter) called TRB3 [10]. The apparatus is shown in figures 4 and 5.
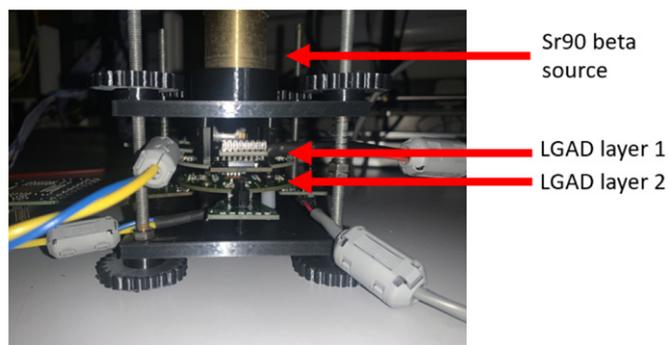


**Figure 4.** A small-scale setup for measuring the response from a Sr90 $\beta$ source with ToF distances of less than 10 mm.
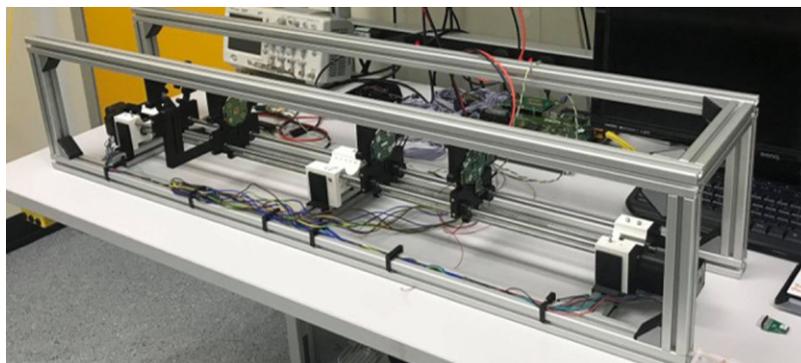


**Figure 5.** A larger telescope with 8 remotely adjustable layers used to measure responses of proton beams with a ToF region up to 1 m.

ToF measurements of Sr90 $\beta$ source were undertaken for two sub-layers placed at a distance of 5 mm and a ToF of 460 ± 1200 ps was recorded (see figure 6). Strontium-90 has two decays the first of which is a $\beta$ decay into Yttrium-90 and then a subsequent $\beta$ decay into a stable Zirconium-90. This decay spectrum has an average energy of 0.3 MeV and a maximum energy of 2.2 MeV. The ToF measured corresponds to a $\beta$ particle kinetic energy of 0.66 keV, suggesting that most of the particle energy is lost within the first 300 μm layer of silicon. Whilst this energy lies within
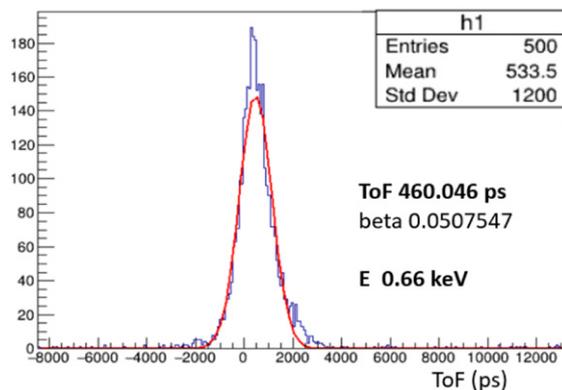
**Figure 6.** ToF measurement results from Sr90 $\beta$ source over 5 mm through 300 μm of silicon and air at normal atmospheric pressure.

the spectrum, the uncertainty was large caused by fitting of data with low statistics. Most triggers of the first layer did not result in a measurement meaning there was large deflections and energy losses before the second layer.

The larger telescope was also tested at two proton beam facilities. First, the telescope used a single LGAD layer, a scintillator and a Hamamatsu photo-multiplier tube layer at the Rutherford Cancer Centre in Northumberland, U.K. Once the telescope had all 8 layers operational, it was then tested with 28 MeV protons at the MC40 Cyclotron Facility at the University of Birmingham, U.K. ToF measurements at several different lengths were performed and the analysis of the results is ongoing.

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