Development of a detector system based on HV-CMOS for the measurement of the proton electric dipole moment

Abstract

This project will describe how monolithic detectors using High Voltage Complementary Metal Oxide Semiconductors (HV-CMOS), also known as High Voltage Active Pixel Sensors (HV-MAPS) could be used to measure the proton electric dipole moment. Research and development will be undertaken on a HV-CMOS based polarimeter to measure the left-right imbalance of polarized protons deflected from a carbon target in an all electric storage ring. HV-MAPS are very attractive in this application as they have a high position resolution and can withstand large particle densities and fluences in high energy particle experiments.

Introduction

Measurements of electric dipole moments (EDM) of fundamental particles are interesting as they can be used as powerful probes into physics beyond the standard model (BSM). The EDM is a measure of the distribution of positive and negative charges in a particle, the standard model predicts an incredibly small EDM in a proton (d ~ 10^−32 e·cm).
A discovery of a larger proton EDM then this would signal new physics specifically involving CP (Charge Parity) violation. CP violating mechanisms can be used to explain the imbalance between matter and antimatter in the universe but unfortunately, there is not enough CP violation in the standard model to have created the current universe. The unprecedented precision needed to measure this value can only be achieved with highly granular detector and a storage ring with polarized protons.
The experimental method proposed will be to confine polarized protons in an 'all electric'. By using only an electric field and no magnetic field, the polarized

Some theories such as supersymmetry (SUSY) and multi-Higgs scenarios predict proton EDM values large enough to be measured by the proposed experiment.

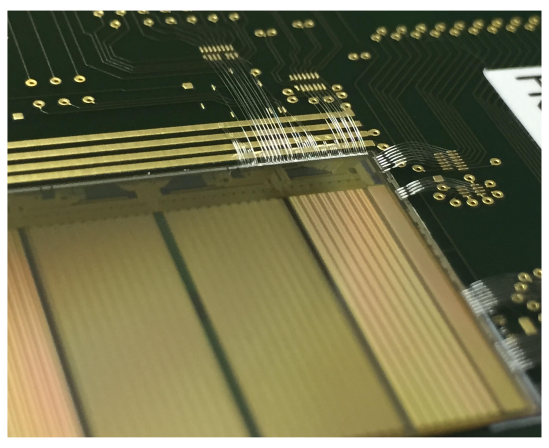
Aims
- HV-CMOS polarimeter design for storage ring experiment
- Protons Placed in all electric storage ring
- Align spin along momentum vector (Freezes horizontal spin precession)
- Measure time development of polarization

High Voltage CMOS

Monolithic CMOS detectors take the idea of P-N junction detectors and build the necessary amplifier and readout electronics into each pixel, as opposed to a separate circuit. This gives the detectors more refined output signals, improves response time and allows the sensors to be produced thinner.

By using deep N-wells (N-doped wells implanted deep into a substrate to isolate certain parts of a semiconductor device), the voltage can be raised to improve the drift effect making charge collection faster. These HV-MAPS and are very attractive in particle physics as they are monolithic and therefore remove the need for hybridization which is time consuming and expensive. These detectors collect charge caused by incoming particles via drift, by biasing to a higher voltage the drift time can be reduced significantly meaning very fast response time and potentially high radiation tolerance. Using HV biasing has the added benefit of increasing the radiation tolerance of these detectors which is useful for high energy physics experiments.

- Due to industry standard processes, they are comparatively cheap for the performance.
- Due to in-pixel amplification and processing, the signal output from each pixel is very high and well digitized.
- Low leakage current meaning high signal-to-noise ratio.
- The readout electronics can be integrated in the sensing area of the pixels which leads to a fill factor (FF) close to 100% although some components such as bias blocks, voltage regulators and High Voltage CMOSI/O pads cannot be built into the sensitive area.



CP Violation... WHAT & WHY?

This can be understood by imagining Ampere's 'Right Hand Rule'. By holding a pencil with the point facing up in a clenched fist of a right hand, the fingers show the direction of a magnetic field around a current in the direction that the pencil is facing. Now look at this hand in a mirror and see the pencil faces the same direction but the magnetic field (shown by the direction of the fingers) does not, this mirror image represents a matching symmetry in nature called parity (P symmetry).

Time reversal symmetry also exists; this can be understood by imagining a wire carrying a current, now let time run in reverse so that the charge carriers are moving in the opposite direction thereby reversing the current. A violation of this symmetry would be seen as the current changing while the associated electric field would not.
In nature a reversal of 'CPT symmetries' is said to be invariant.

Take an electron traveling in a wire:
Reverse charge of electron by replacing with a positron.
Reverse time so that the current and therefore the electric field is reversed.
Reverse parity by looking at this system in a mirror and the same electric field as the original is observed.

The system is invariant after all three symmetries have been flipped.

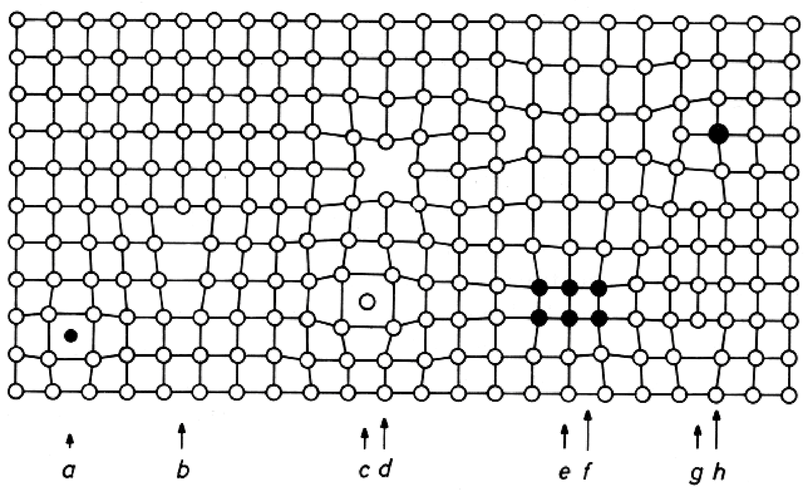
Protons polarized in an electric storage ring with a constant electric field will experience a torque of E X d which causes it to precess over time if there is a non zero EDM, this breaks time reversal symmetry and subsequently CP is also violated!
Any experimentation on new potential areas of CP violation are therefore very important to our understanding of the universe. Some BSM (beyond standard model) theories such as supersymmetry, Left-Right symmetric (LR) models and multi-Higgs scenarios can be explored at the level of sensitivity expected from a future storage ring experiment.

To achieve high levels of sensitivity, a highly granular polarimeter must be designed, the time dependent changing distribution of incident particles will be measured so a very fast response time is imperative.

Radiation Damage

Radiation damage is a problem when very high energy particles are incident with a detector. With high energy nucleons such as protons there is a chance of bulk damage where the atoms from the semiconductor lattice can be dislodged altering the band gap in the detector and potentially create energy levels between the gap. This will modify the doping, altering the depletion voltage, potentially trapping the charge carriers and make it easier for them to be thermally excited across the band gap causing higher leakage currents. Reducing the effects of this radiation damage is imperative.

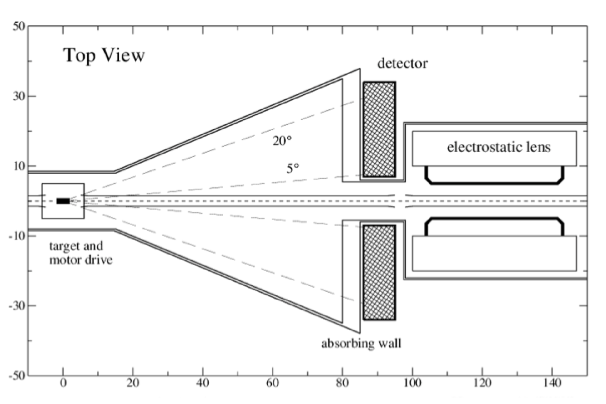
a) Interstitial impurity atom
b) edge dislocation
c) Self interstitial atom
d) Vacancy
e) Precipitate of impurity atoms
f) Vacancy type dislocation loop
g) Interstitial type dislocation loop
h) Substitutional impurity atom



Prof. Dr. Helmut Föll, Defects in crystals - 2019

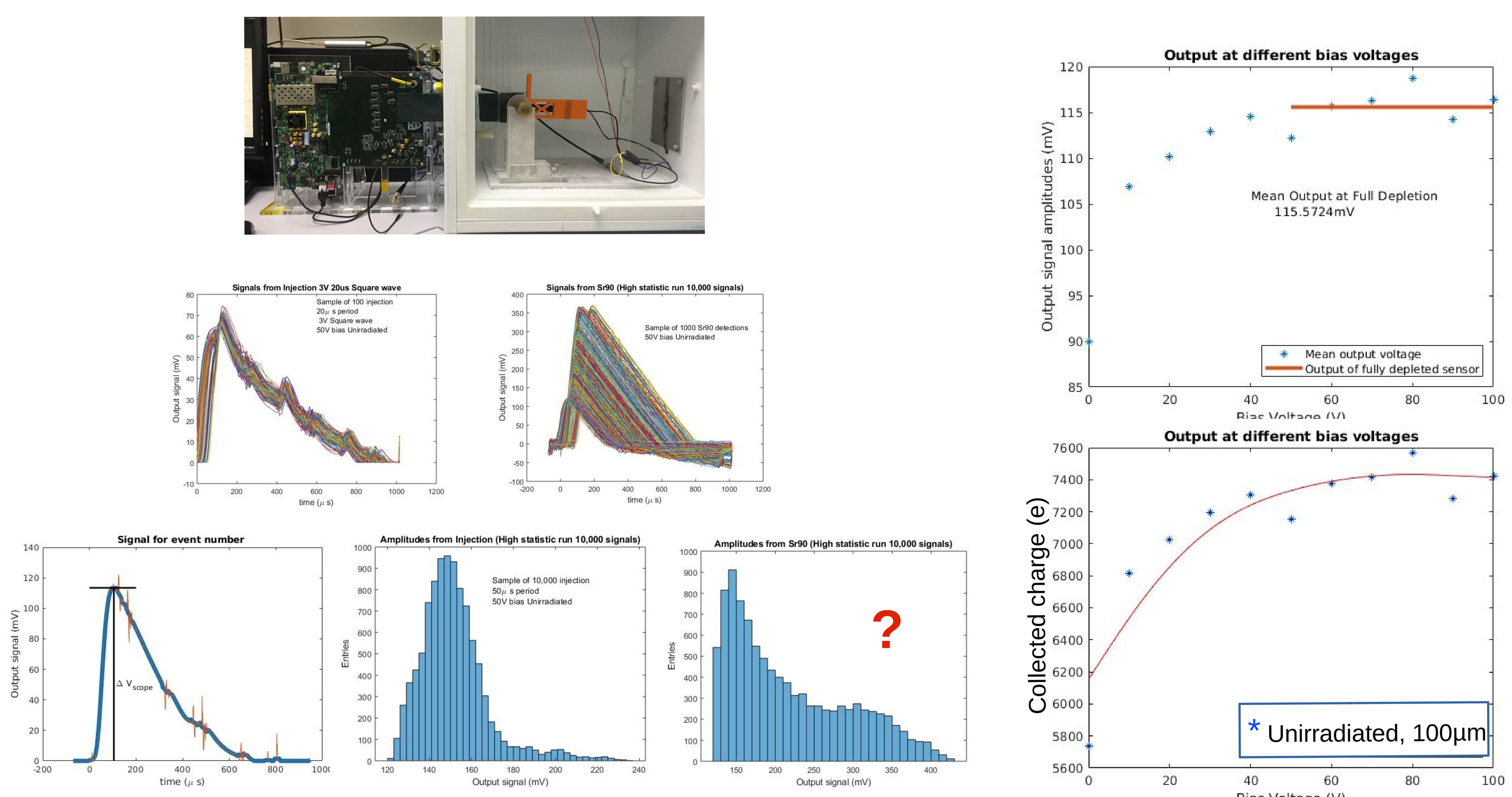
Polarimeter Design

The best way to detect small changes in beam polarisation caused by EDM at an energy of 200-250MeV is to deflect off a carbon target (forward-angle elastic scattering). A carbon target of 5-8cm thick will cause the particles to lose tens of MeVs whilst passing through, this causes the spin-orbit force to change slowly. 99\% of the time the particles incident with the carbon target undergo coulomb scattering losing enough energy to leave the ring. Around 1\% of the time they undergo spin-dependent nuclear elastic scattering and are redirected into the HV-CMOS detectors around 1m away from the target. The detectors used will be circular and surround the beam line a short distance from the carbon target in both directions (in all electric rings it is possible to have beams traveling in opposite directions at the same time). One half of the proposed polarimeter design is shown here.



Anastassopoulos, V. et.al. A Proposal to Measure the Proton Electric Dipole Moment with 10-29e.cm Sensitivity - 2011

Some Figures So Far...



Many thanks to the Huazhong University of Science & Technology for the support and funding to participate in the 5th INFIERI summer school in Wuhan, China.

James Gooding
University of Liverpool
Supervisors: Dr Eva Vilella-Figueras & Dr Gianluigi Casse