Compton Polarimeter: opportunity, challenges and adaptations in the context of medium energy Physics

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Outline

1. **Why do you care !**
2. The measurement method : The challenge
3. The measuring tool : The detector
    a. detector concept and implementation
4. Data analysis : extraction technique, systematics results
5. More about the detector
    a. Fabrication
    b. Evaluation and testing
    c. What is challenging
    d. What is awesome !

What is everything made of ?

Ancient approach

Since antiquity reductionist approach has concluded that all matter is made up of some fundamental constituents

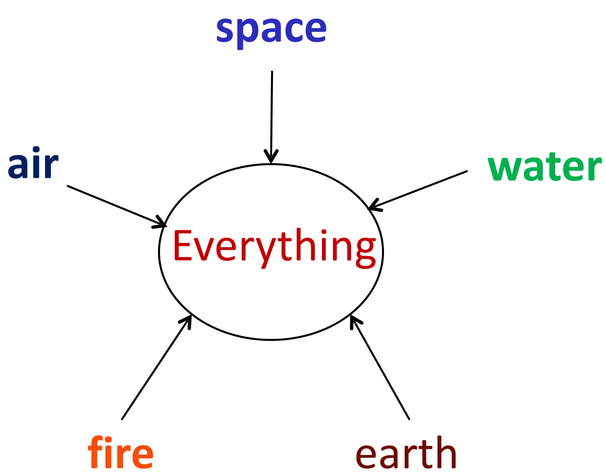
The Greek/Aristotelian view

+ Space (the Indian view)[1]

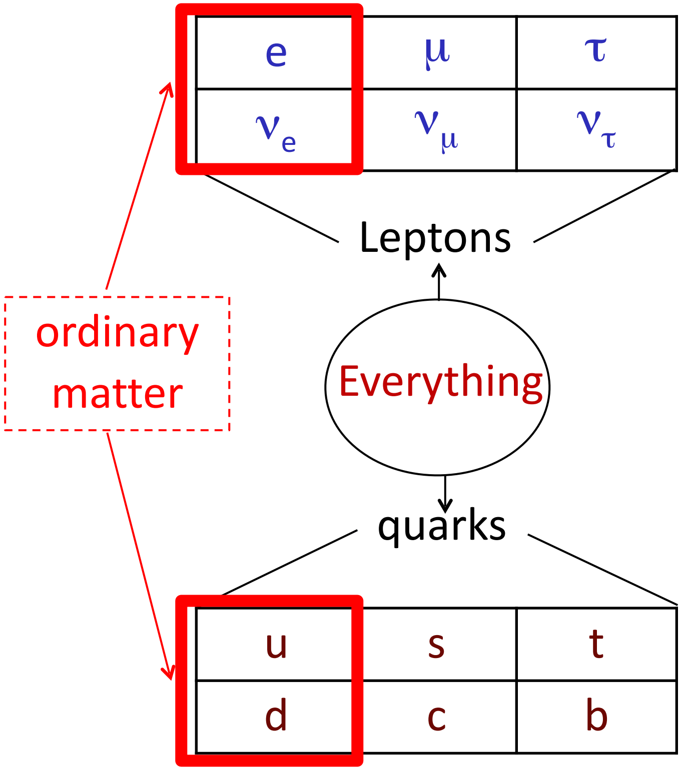
[1]Samkhya-Karikas by Ishvarakrsna (circa 5th century AD)

What is everything made of ?

Ancient approach	Modern approach



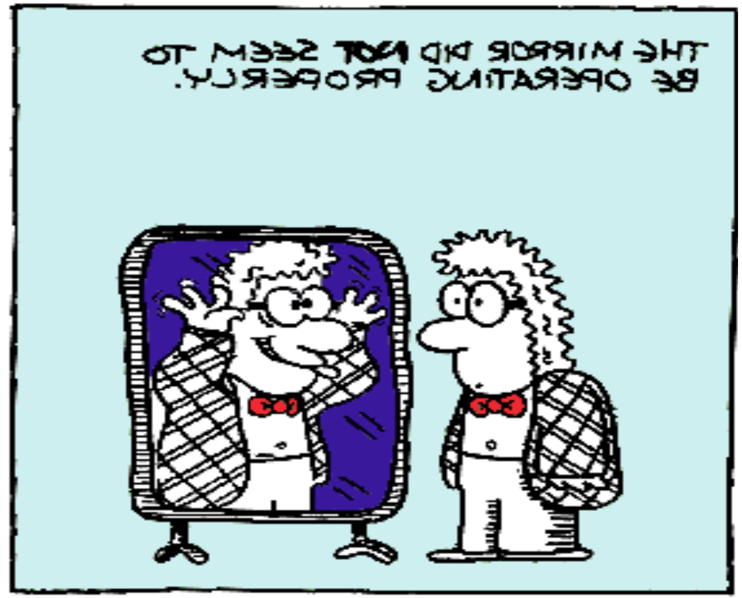
Panch tatwa



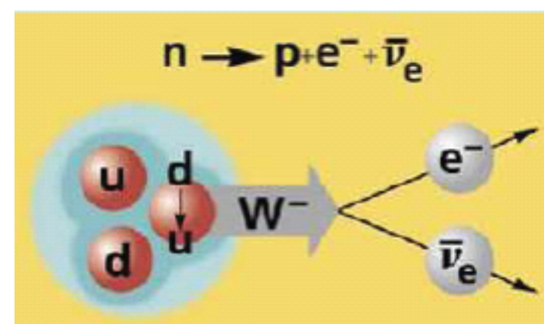
Standard Model

Interactions

1. Gravitation
2. Electromagnetic
3. Weak Interactions
4. Strong Interactions



The Weak force responsible for nuclear decays



The Electro-Weak theory is the most precisely verified theory (i.e. the most well understood)

It is also the weirdest: violates parity (mirror symmetry)

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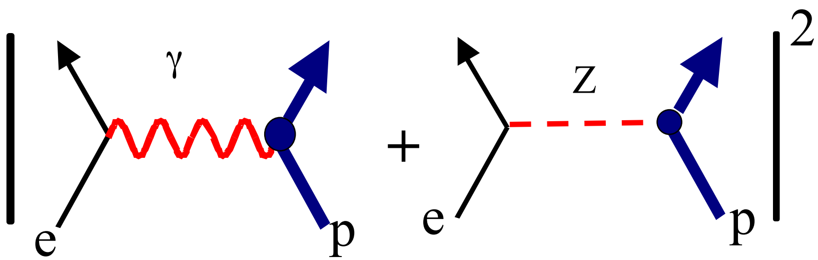
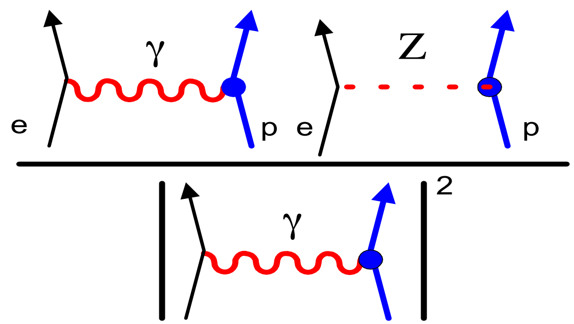
The measurement technique

To access the weak interaction : $e^- + p \rightarrow e^- + p$

$\sigma =$



$A_{PV} = \frac{N^+ - N^-}{N^+ + N^-}$ ~



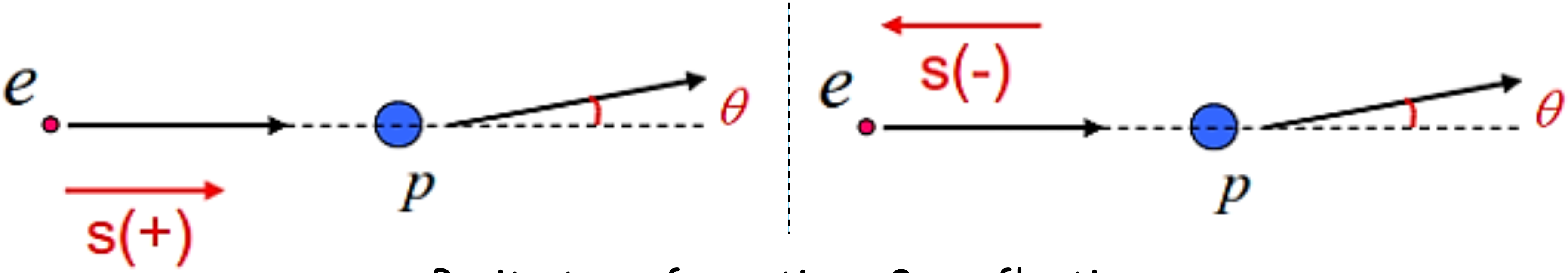
- hundred ppb

$A_{PV} = P_e A_{e-p}$

measured asymmetry in elastic e-p scattering

beam polarization

PV via elastic e-p scattering



Parity transformation : 2x reflection

Parity violation ⇒ difference in scattering rates for the two helicity states

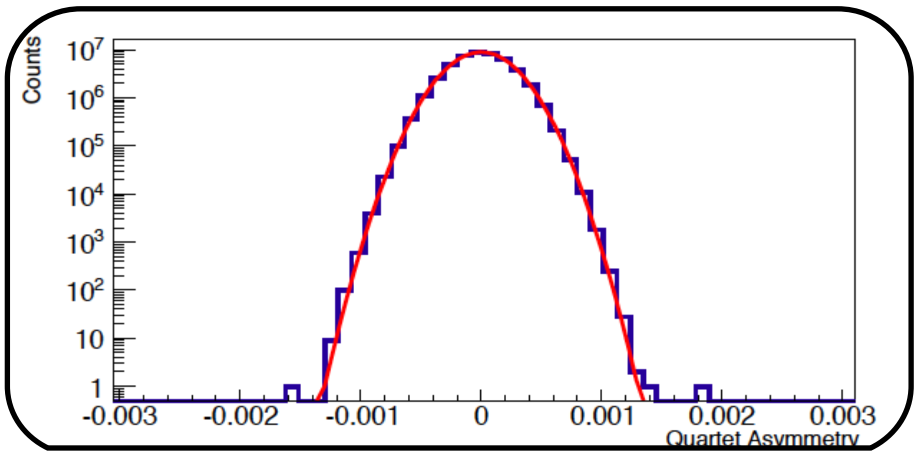
The MOLLER experiment aims to measure Q_w^e with an accuracy of 2.3%, by measuring the parity violating asymmetry in polarised e-p elastic scattering with a precision of 2.1%

How Small is the few ppb PV Signal?

.. and we have to measure it to ~ 2% precision!

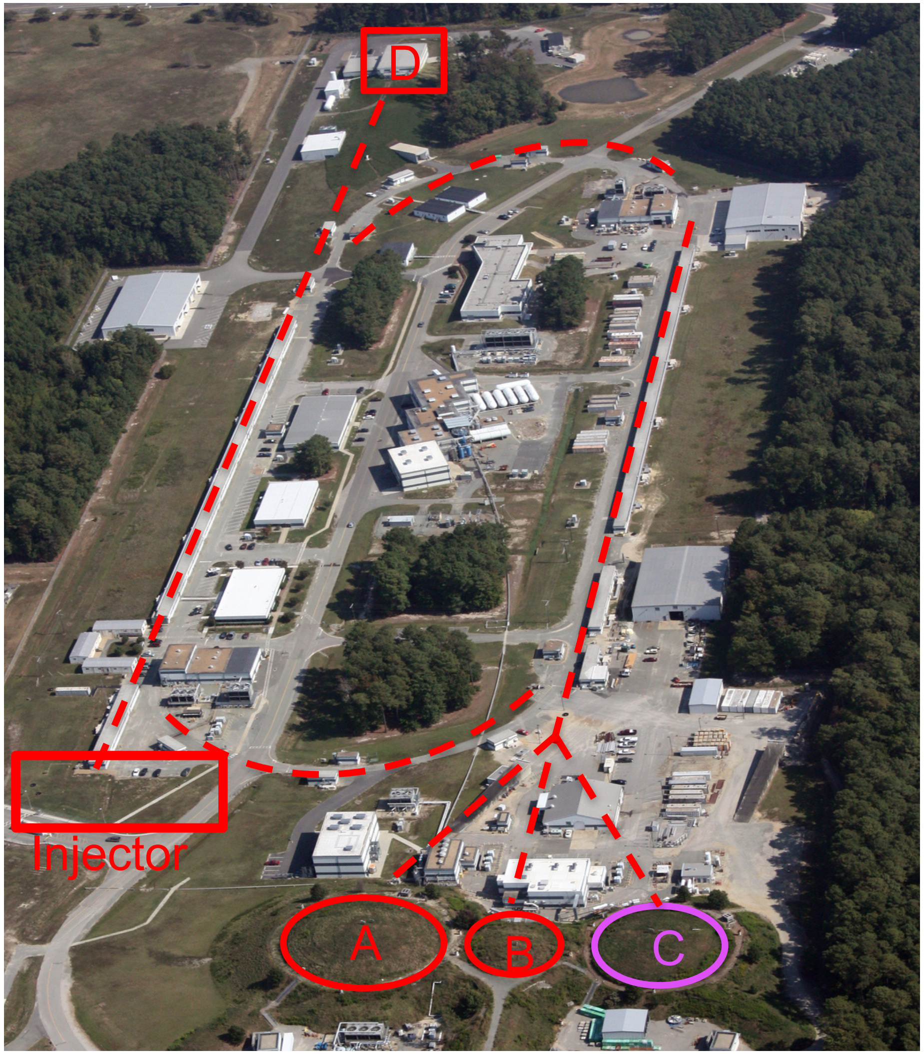
Experiment strategy:

1. Maximise counts
2. Minimise noise
3. Minimise systematics



(Quartet Asymmetries over several days)

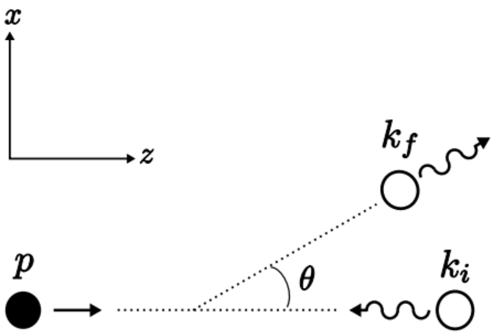
Jefferson Lab – Hall C



Qweak Error Budget		
Uncertainty	$\delta A_{PV}/A_{PV}$	$\delta Q_W/Q_W$
Statistical (~2500 hours at 150 μA)	2.1%	3.2%
Systematic:		2.6%
Hadronic structure uncertainties		1.5%
Beam polarimetry	**1.0%**	**1.5%**
Effective Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated beam properties	0.5%	0.7%
Total:	**2.5%**	**4.2%**

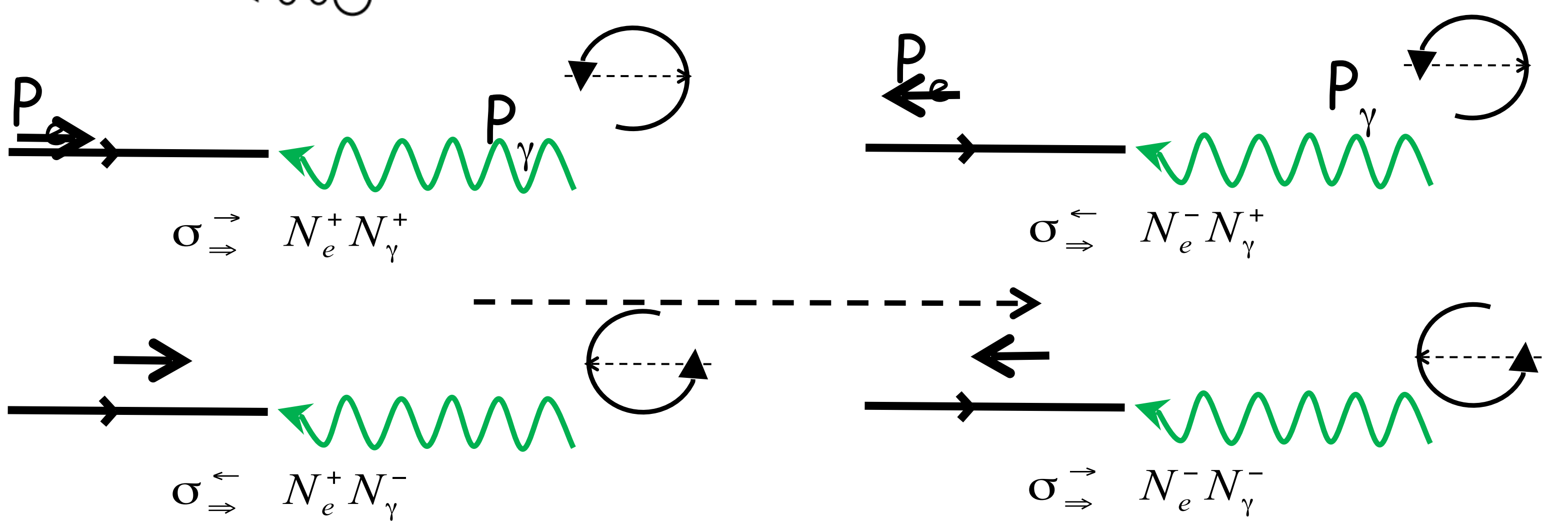
The largest experimental contribution to error budget and hence the biggest constraint was the beam polarimetry

Compton interactions



A. H. Compton

$$A_{theory} = \frac{\sigma^{\rightarrow}_{\Rightarrow} - \sigma^{\leftarrow}_{\Rightarrow}}{\sigma^{\rightarrow}_{\Rightarrow} + \sigma^{\leftarrow}_{\Rightarrow}}$$



$$A_{\exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_e P_\gamma A_{theory}$$

precisely known in QED

measurable in-situ

Compton polarimeter overview

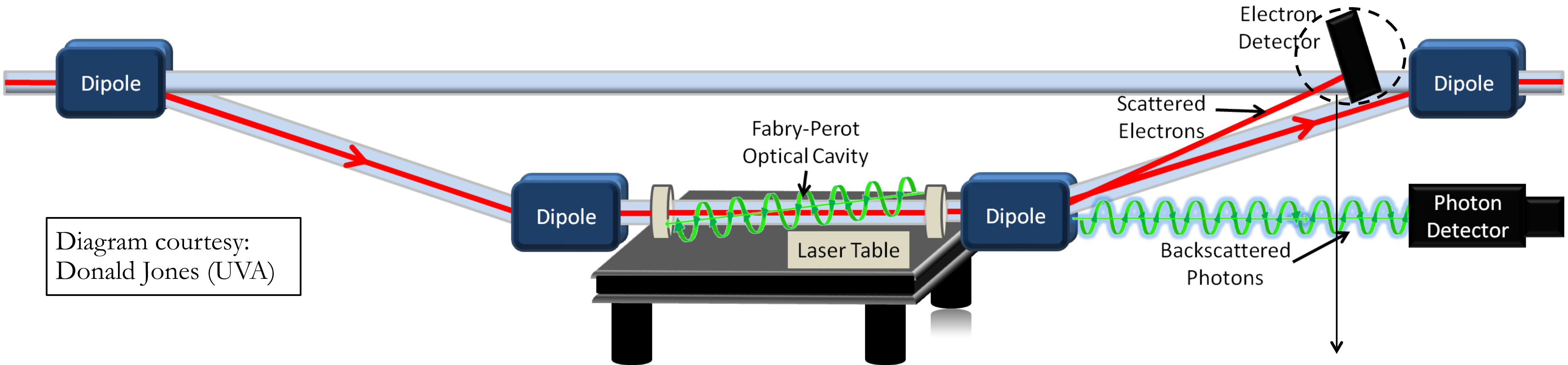
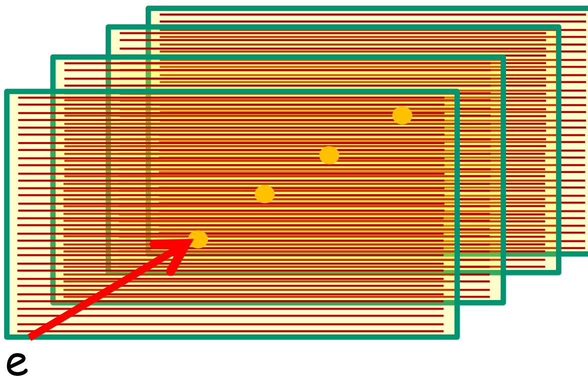


Diagram courtesy:
Donald Jones (UVA)

Parameter	Value
Beam Energy	1.16 GeV
Laser Wavelength	532 nm
Cavity Power	~ 1.0 - 1.8 kW
Chicane bend angle	10.1 deg
Electron free drift distance	1.6 m
Max. Electron Displacement	17 mm
Compton edge energy	46 MeV



=> **Radiation hard detector**

The Compton polarimeter : **continuous, non invasive** and operates at **high currents**

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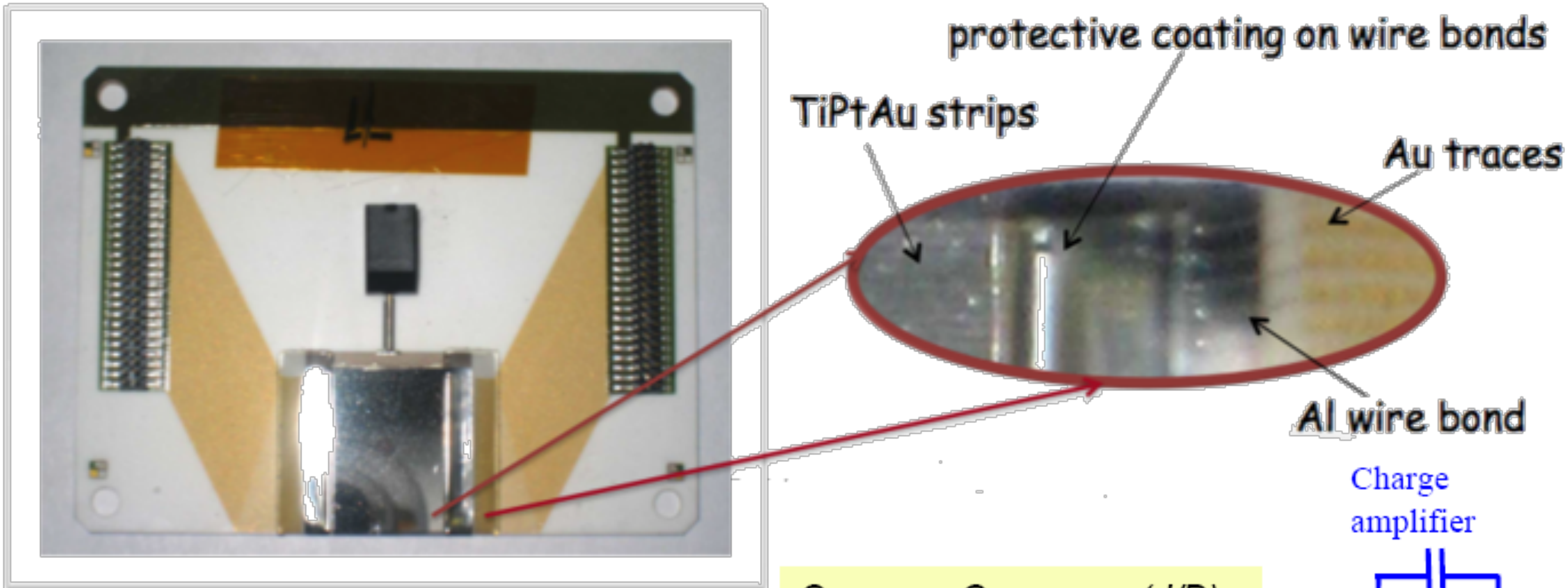
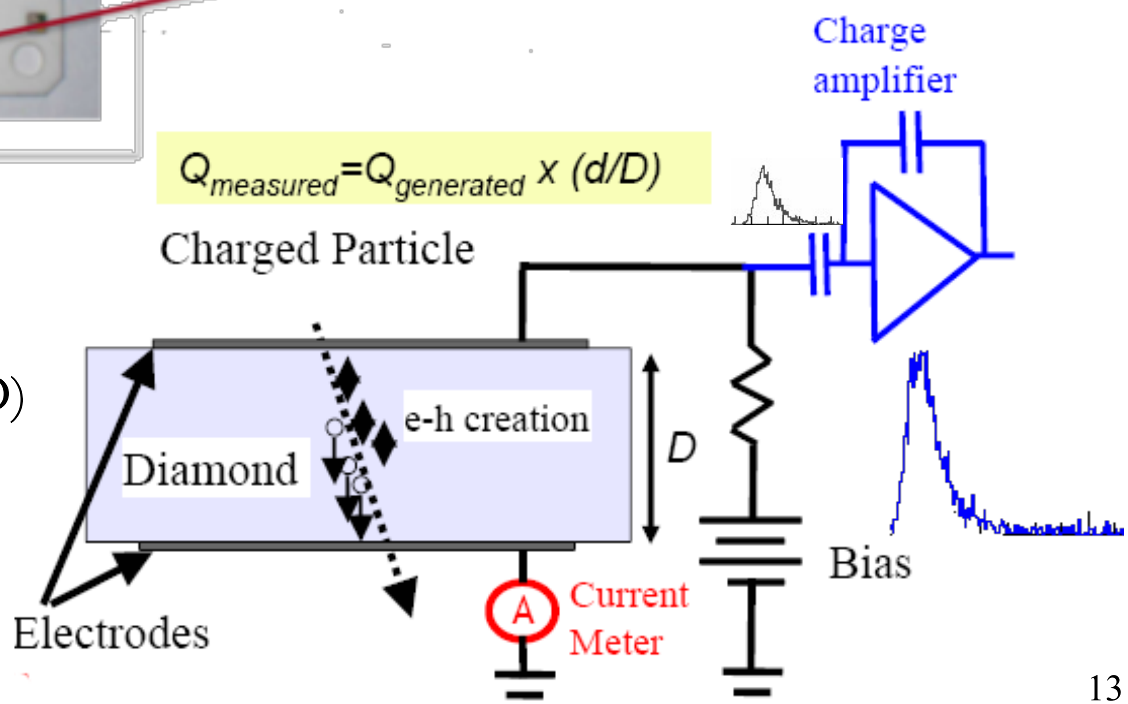
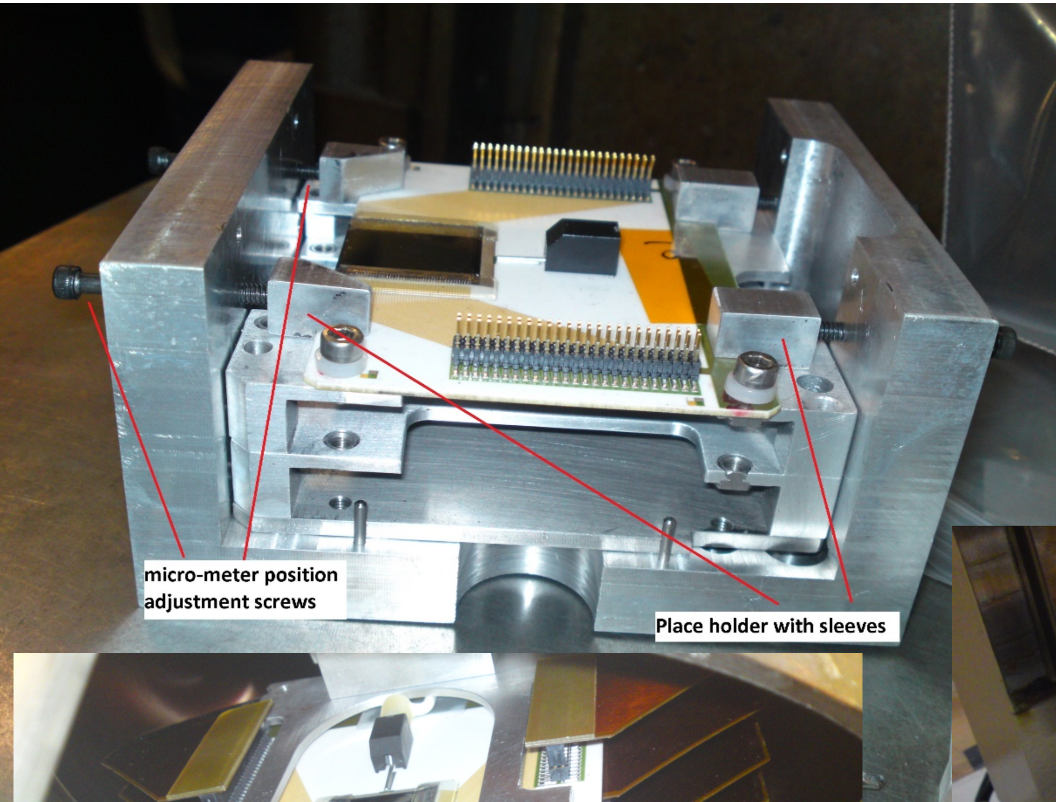
Diamond μ-strip electron detector



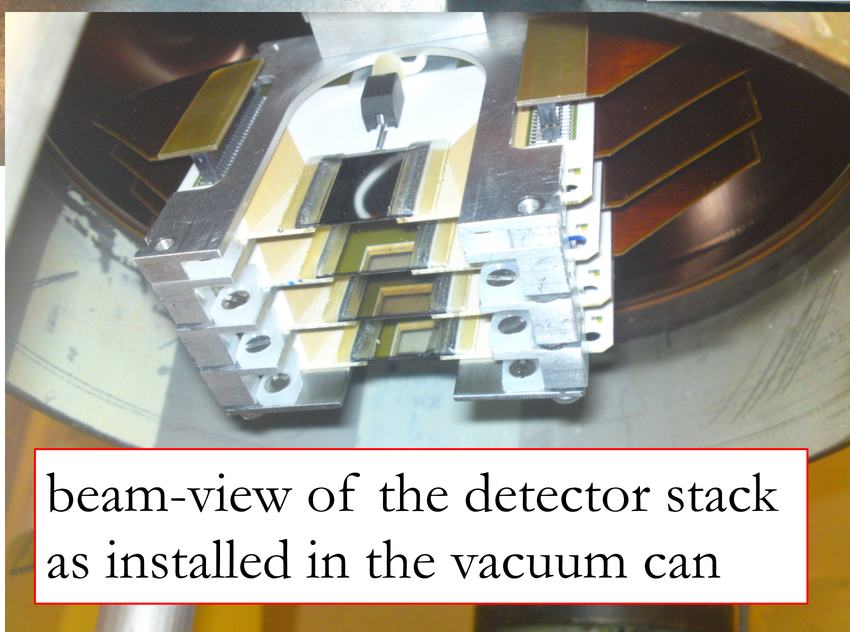
The detector uses poly-crystalline diamond, artificially grown using Chemical Vapour Deposition (CVD)



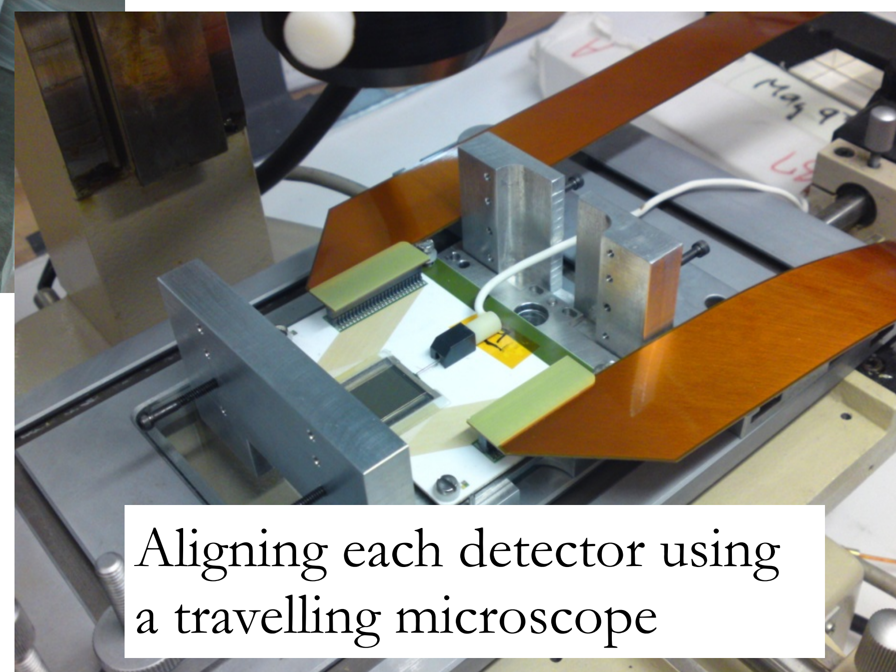
Detector Installation



This is the **first** Diamond micro-strip detector to be used as a tracking device in an experiment



beam-view of the detector stack as installed in the vacuum can



Aligning each detector using a travelling microscope

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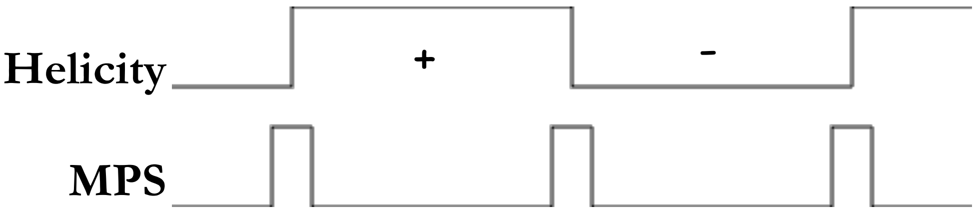
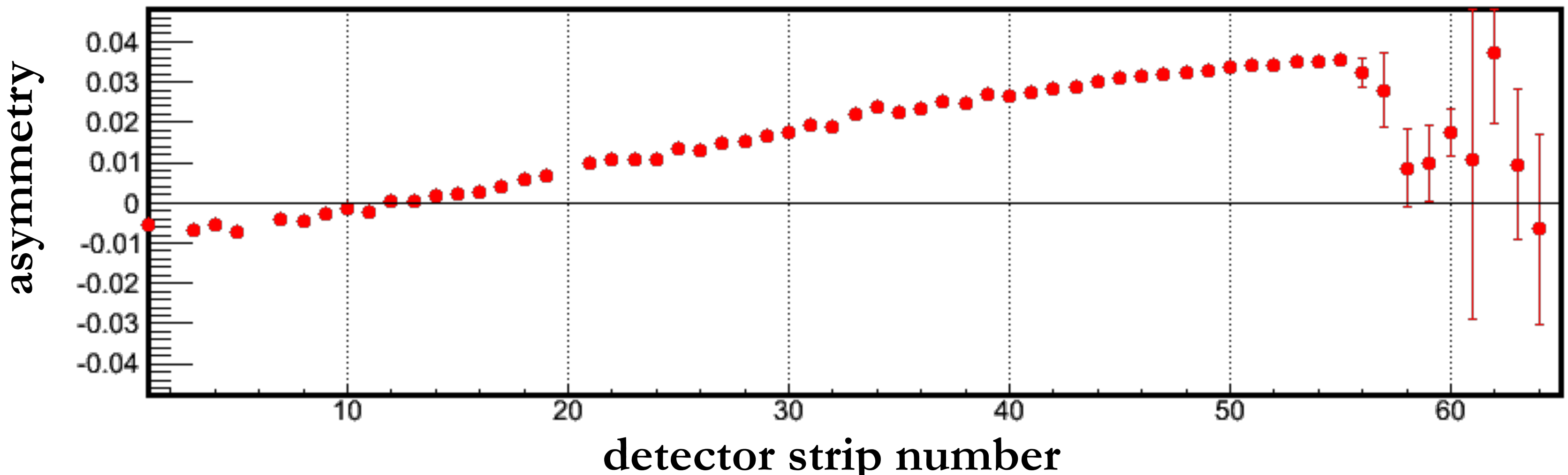
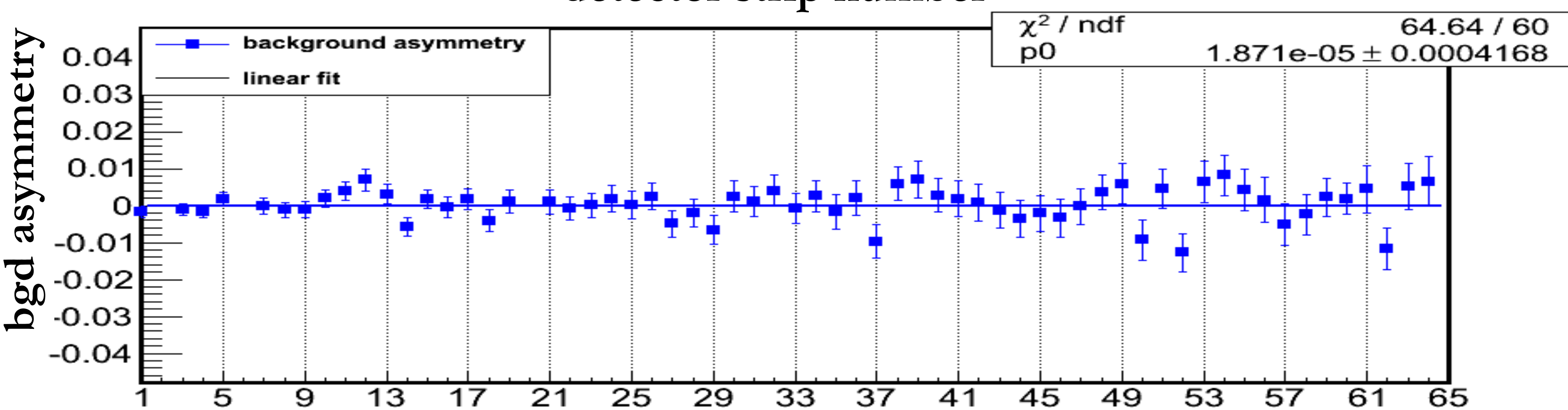
Compton Asymmetry



$$A_{\exp} = \frac{n^{+} - n^{-}}{n^{+} + n^{-}}, \quad n = \frac{N}{Q}$$

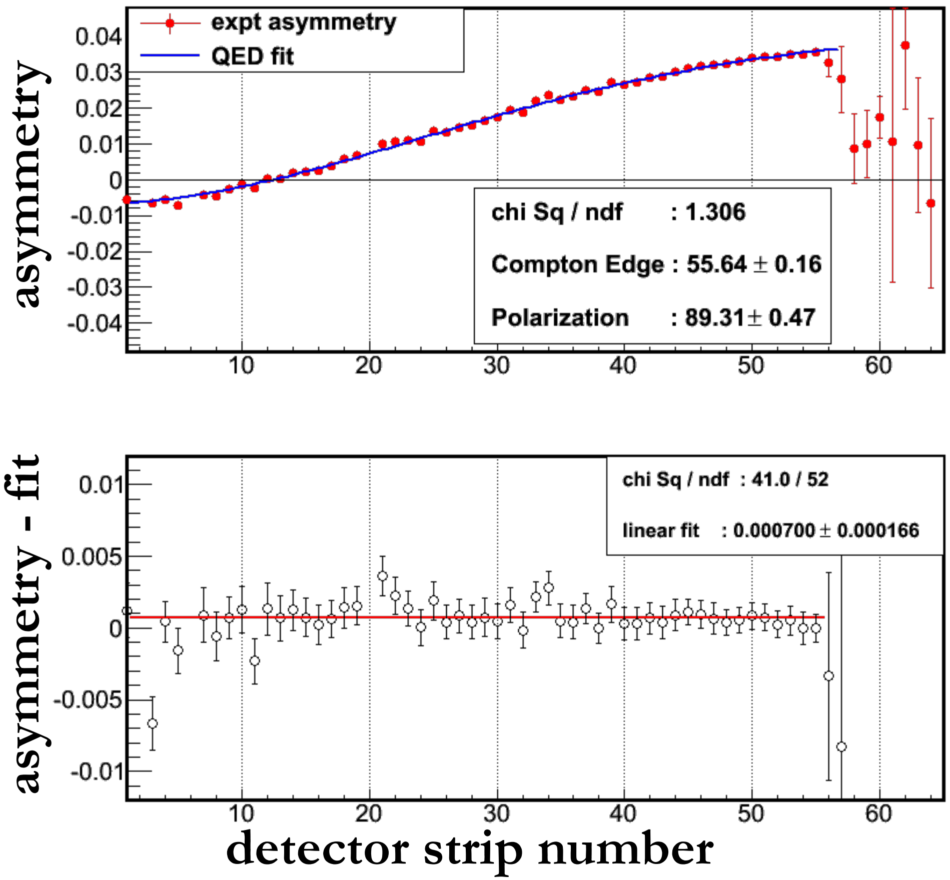




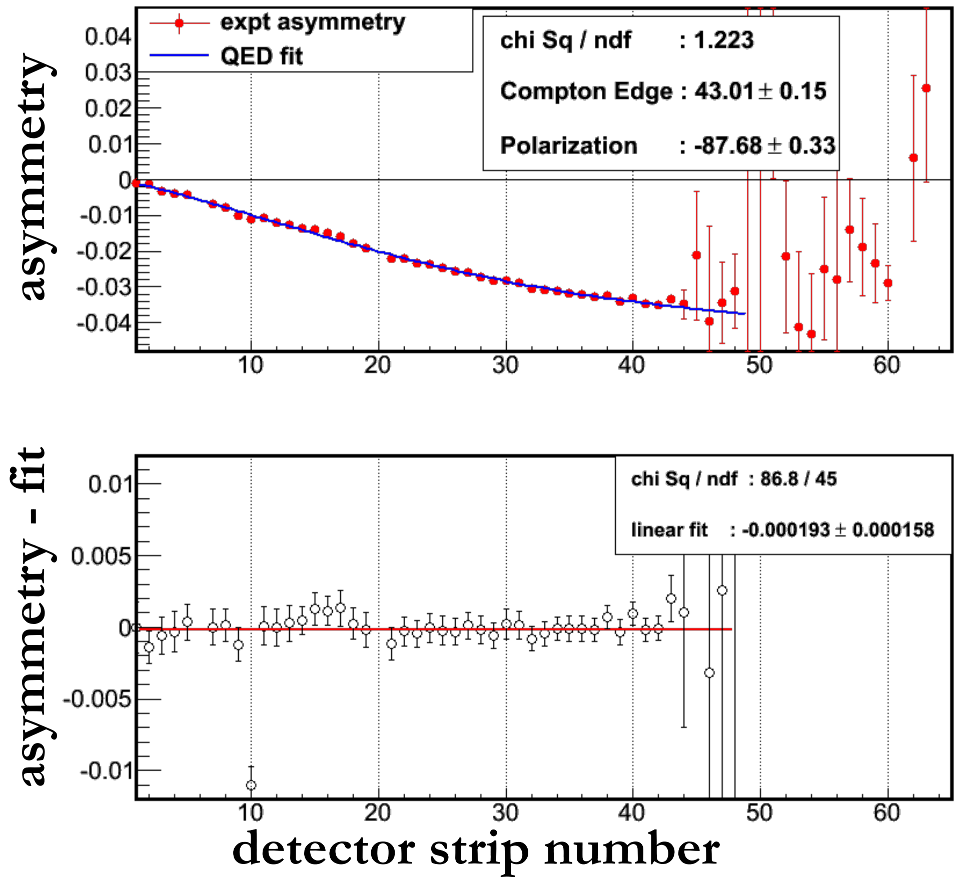
Polarization Fit

We use an Insertable Half Wave Plate (IHWP) to reverse the beam polarisation every few hours of data as a check of any systematic deviation in beam polarisation

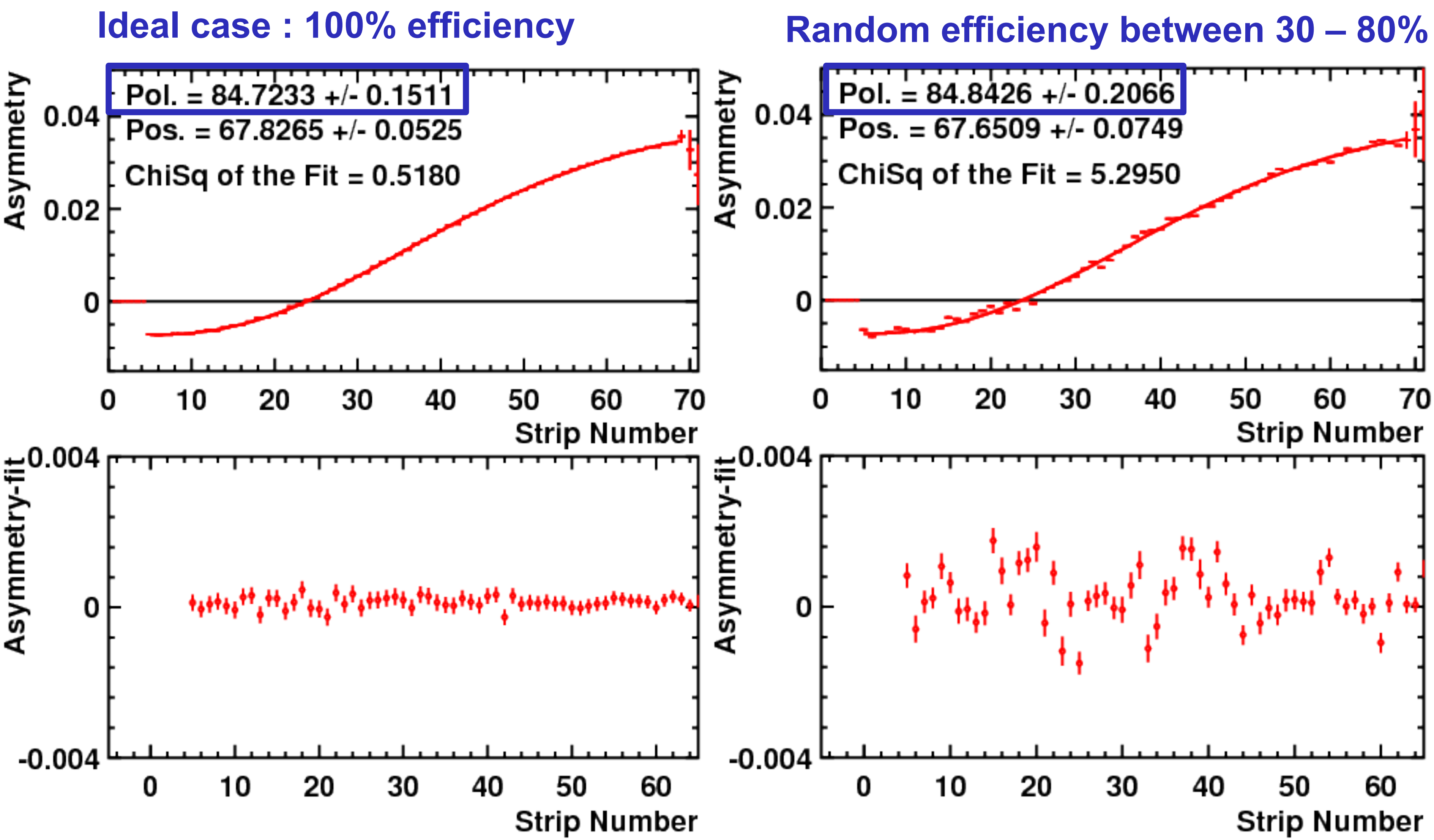
IHWP Out



IHWP In



Detector Efficiency

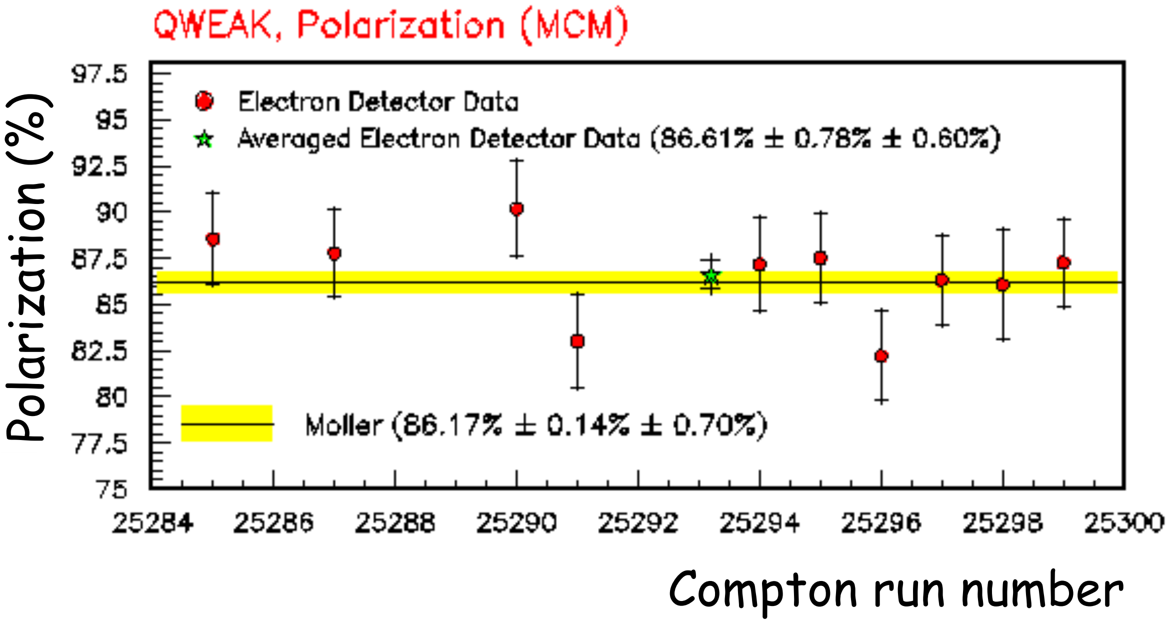


The change in polarization due to inefficiency is within statistical uncertainty

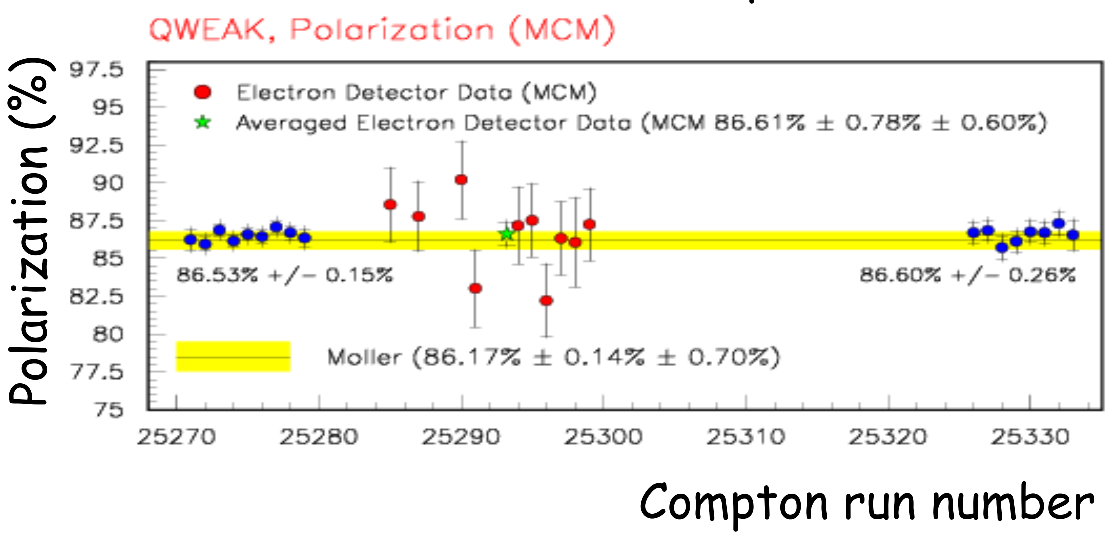
Systematic Uncertainty

Systematic Uncertainty	Uncertainty	ΔP/P (%) Plane-1
Laser polarization	0.1%	0.10
Plane-to-plane	Secondary electrons	0.00
Dipole field strength	(0.0011 T)	0.01
Beam energy	1 MeV	0.08
Detector longitudinal position	1 mm	0.03
Detector rotation (pitch)	1 degree	0.03
Detector rotation (roll)	1 degree	0.02
Detector rotation (yaw)	1 degree	0.04
Detector trigger	1/3 – 3/3	< 0.19
Detector efficiency	0-100%	< 0.10
DAQ dead time	100 %	0.70
Detector noise	Up to 0.2% events	< 0.10
Fringe field	(100%)	0.05
Radiative correction	20%	0.05
Total		**0.70**

Moller – Compton - Moller



Polarization recorded in the two polarimeters in chronological order.



Low current cross calibration runs shown with adjacent regular high current runs

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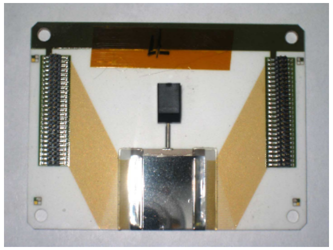
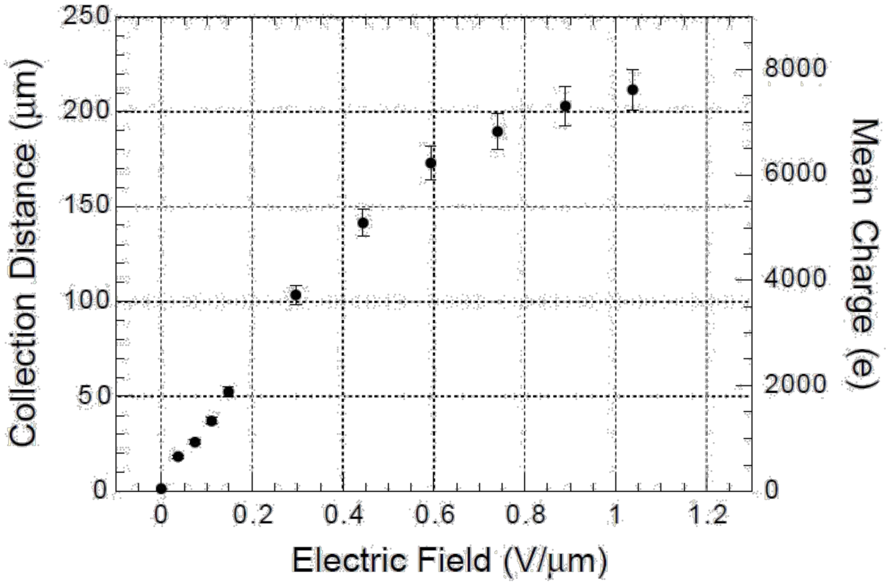
Diamond .. possibilities

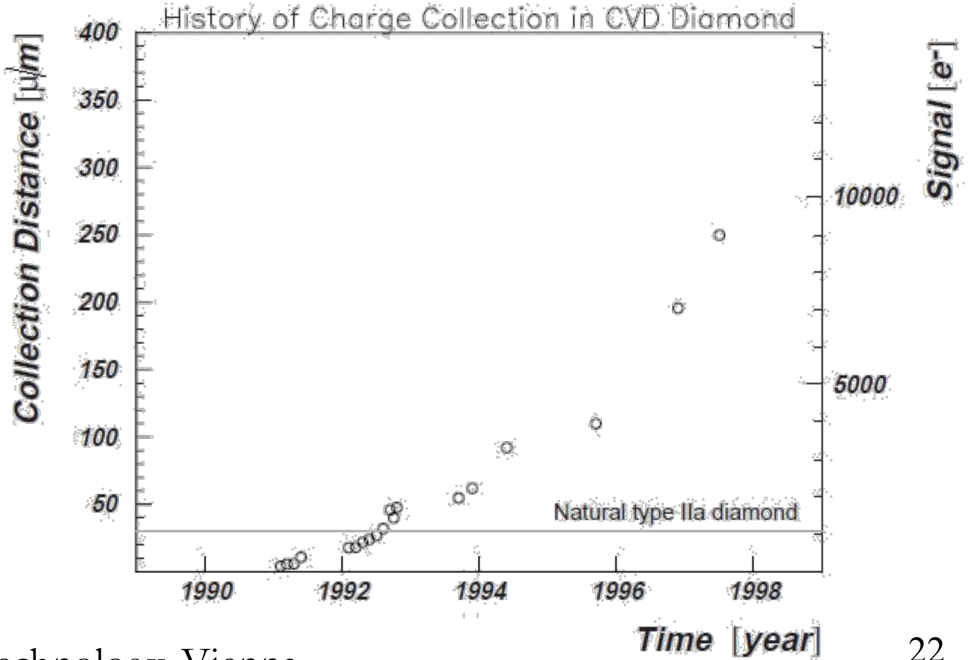
The detector that I used was made of poly-crystalline diamond (acquired from Element-6) but still costs 12,000 USD (~7.2 lakh INR)



There are several encouraging possibilities:

1. Increased crystallinity
2. Increased mobility (making diamond outstanding)
3. Improved charge collection distance (currently saturates ~ 250 um)





Courtesy (plots) : Markus Friedl, Thesis, University of Technology, Vienna

Diamond .. the making

Several methods to artificially grow diamond were already being explored (reasons: sparkle and stability)

Our answer to the growing need for detector grade diamond :

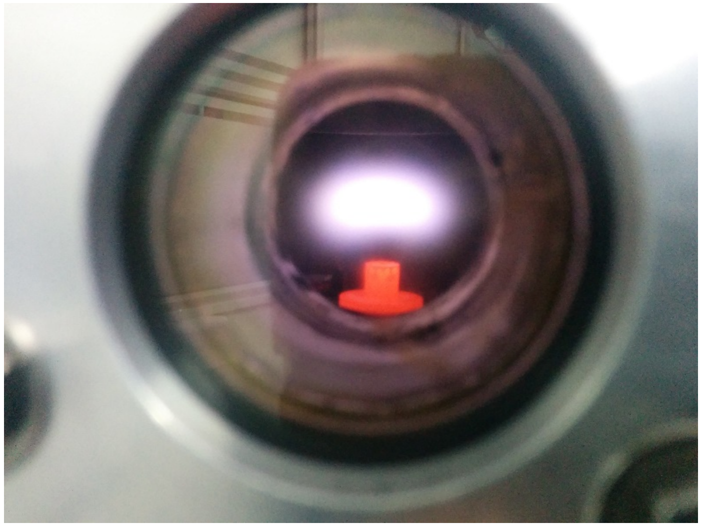
Microwave plasma assisted Chemical vapour deposition

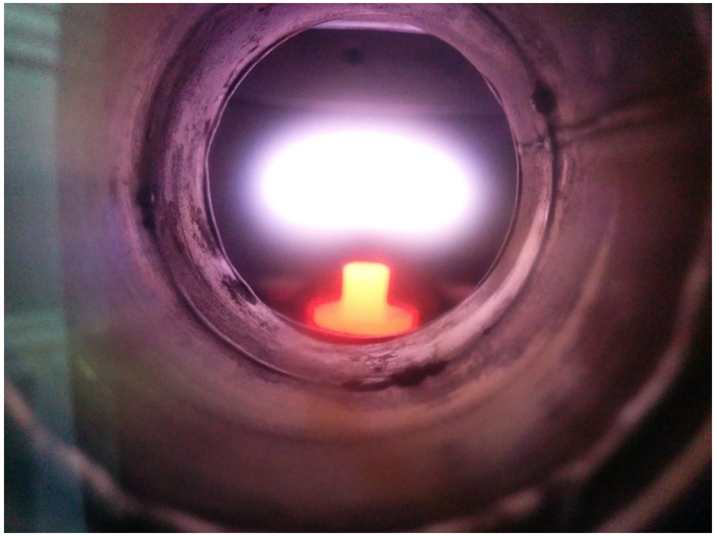
- **Specific Gas mixture**
- **Mass flow controllers**
- **Vacuum chamber**
- **Microwave power**
- **Plasma formation**

Essential care:

- **Cleanliness and substrate preparation**
- **Precise temperature and pressure control**

Diamond .. making

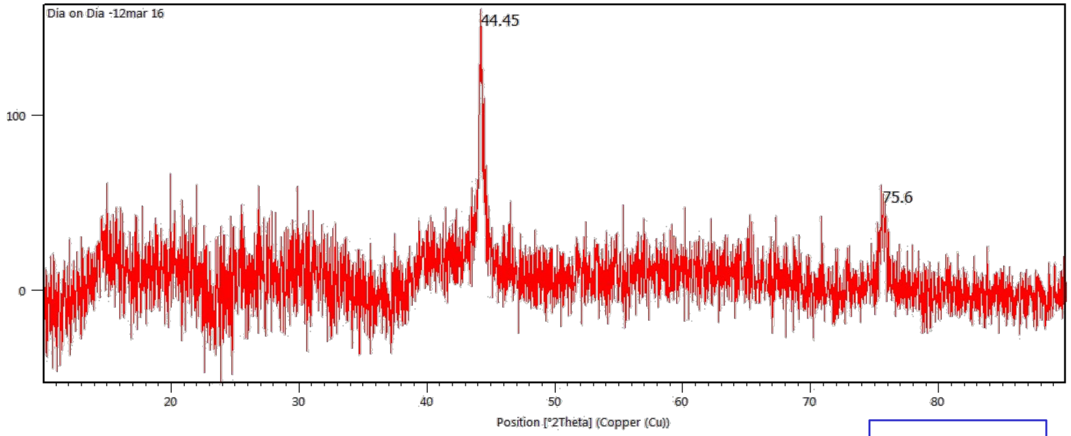


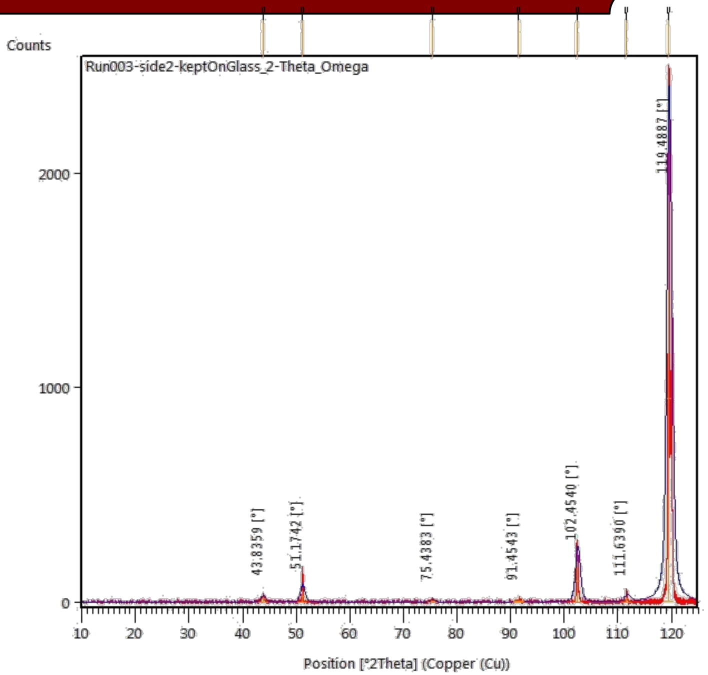


We play with several parameters to stay in the desired phase space:

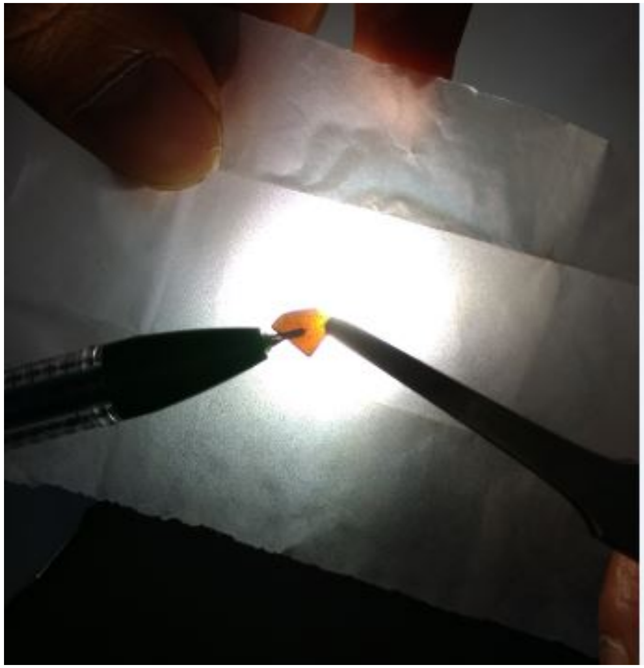
- Gas flow ratio
- Chamber pressure
- Substrate temperature
- Microwave density
- Substrate position in plasma
- Substrate preparation

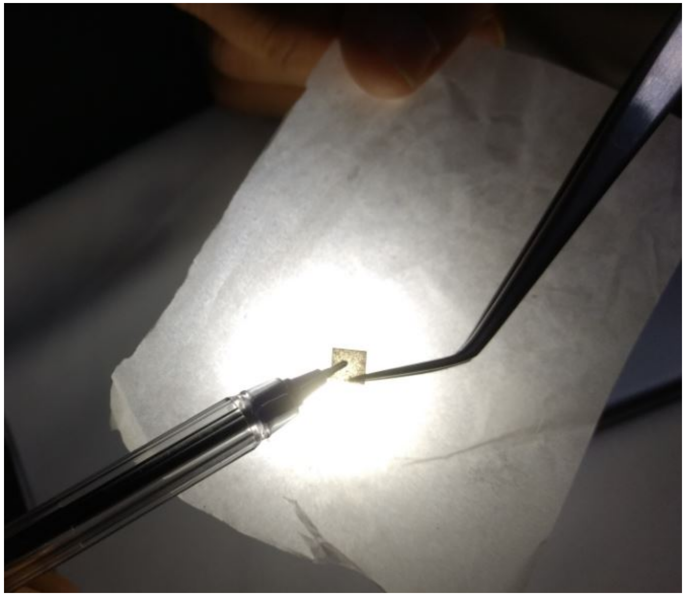
How good is our diamond !



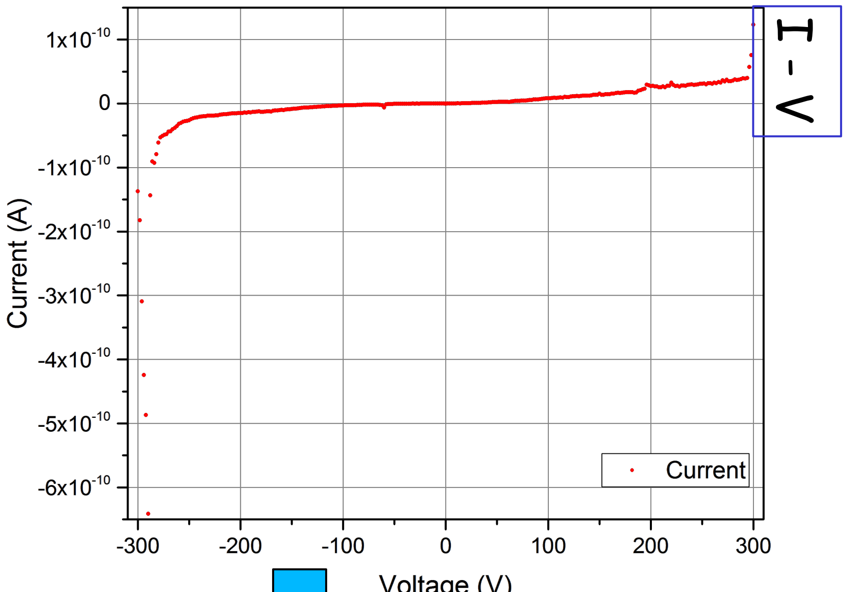


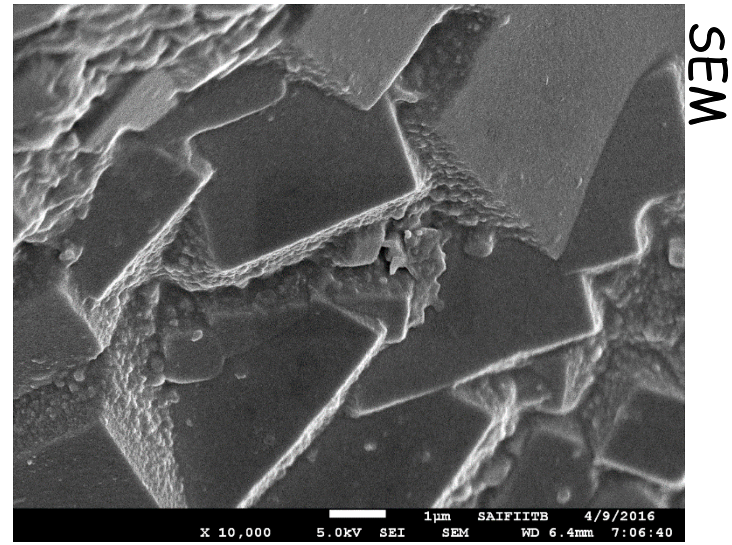
XRD

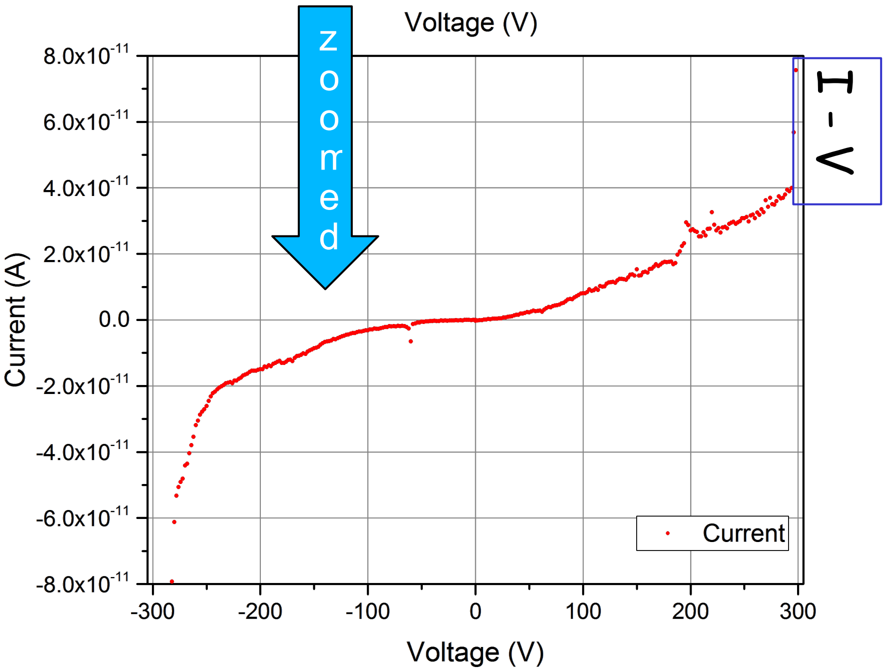


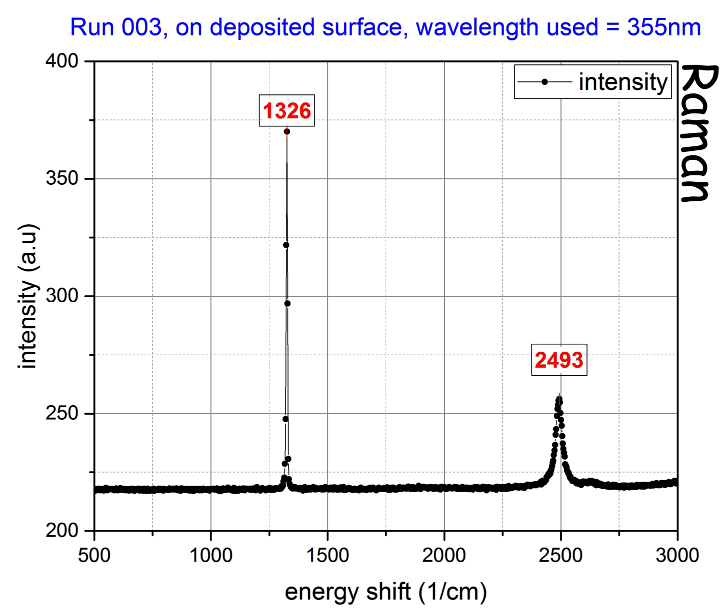


Diamond detector: status









Summary

- Used diamond micro-strip detector in a high radiation without measurable fall in efficiency to yield standalone polarization.
- Systematic uncertainty contained to < 1 % for the independent polarisation
- Moller and Compton polarimeters were found to be consistent with each other at 4.5 uA
- Growth of single crystal Diamond (>70% quality factor) using indigenous setup of CVD is possible

Thanks to the Contributors

This presentation was made possible due to contribution from:

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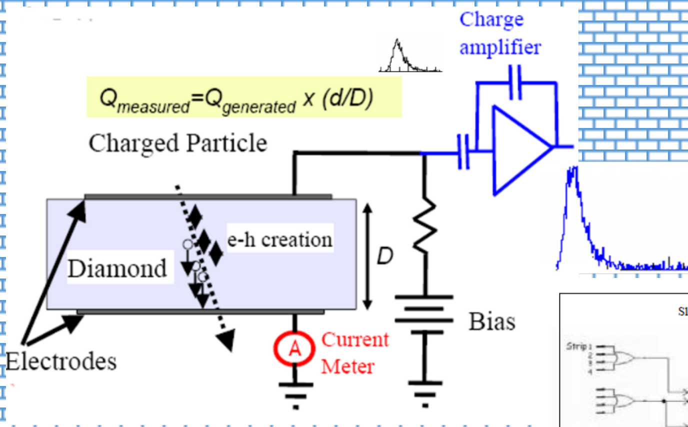
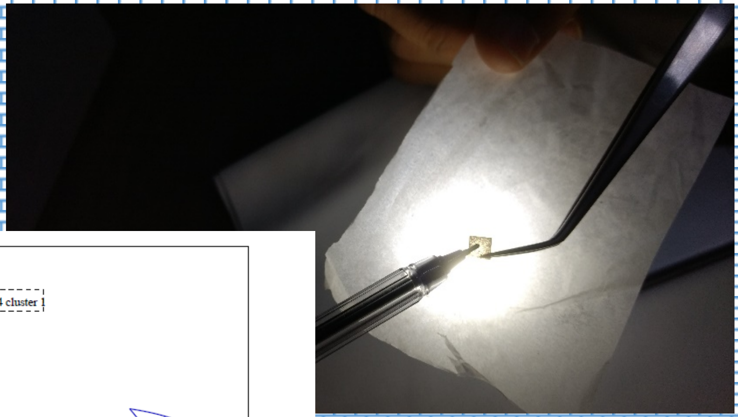
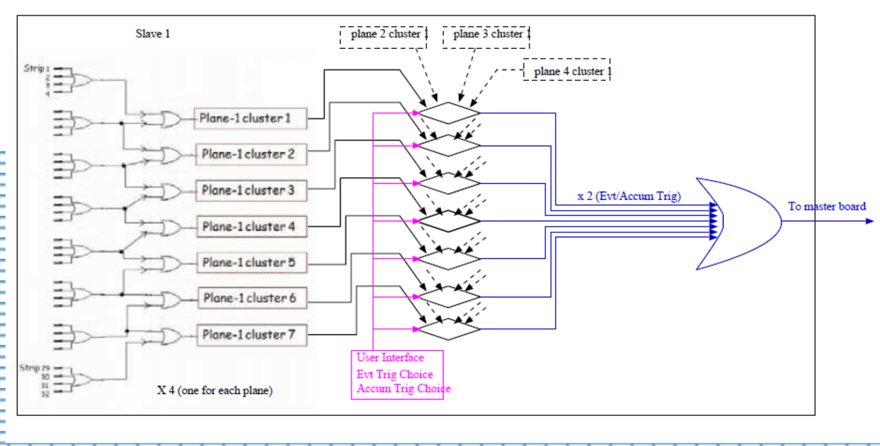
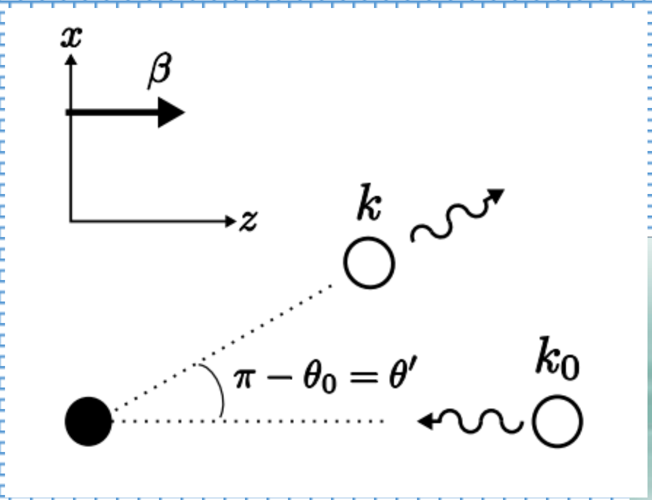
Dipangkar Dutta, Mississippi State University
Vladas Tvaskis, University of Winnipeg
Donald Jones, University of Virginia
Shyam Kumar, IIT Bombay
Raghava Varma, IIT Bombay

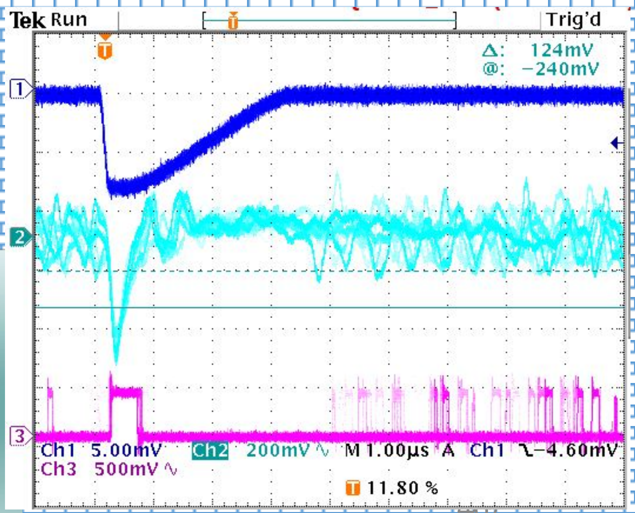

Charge amplifier
$Q_{measured}=Q_{generated}$ x (d/D)
Charged Particle
e-h creation
Diamond
D
Bias
Current Meter
Electrodes




Slave 1
plane 2 cluster
plane 3 cluster
plane 4 cluster
Plane-1 cluster 1
Plane-1 cluster 2
Plane-1 cluster 3
Plane-1 cluster 4
Plane-1 cluster 5
Plane-1 cluster 6
Plane-1 cluster 7
x 2 (Evt/Accum Trig)
To master board
User Interface
Evt Trig Choice
Accum Trig Choice
X 4 (one for each plane)

Thanks


x
β
z
k
$\pi - \theta_0 = \theta'$
k_0


Tek Run
Trig'd
Δ: 124mV
@: −240mV
Ch1 5.00mV
Ch2 200mV
M 1.00µs A Ch1 −4.60mV
Ch3 500mV
11.80 %

Extra Slides

Data Analysis

we know:

✓e-beam energy,

✓magnet field map,

✓detector location & geometry

⇓

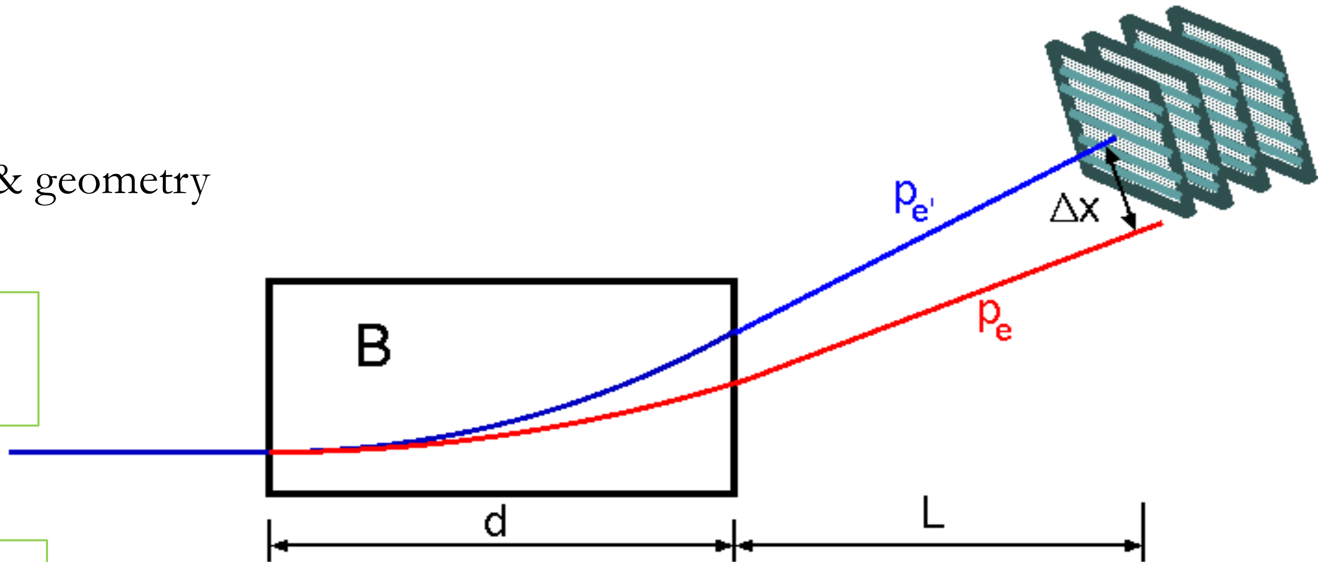
deviation from nominal e-beam

↓

momentum of Compton recoil e-

↓

Compton asymmetry is precisely known from QED as a function of momentum



$$\Delta x_{measured} \xrightarrow{(p_e,\, B_{map},\, L)} p_{e'} \longrightarrow \rho = k'/k$$

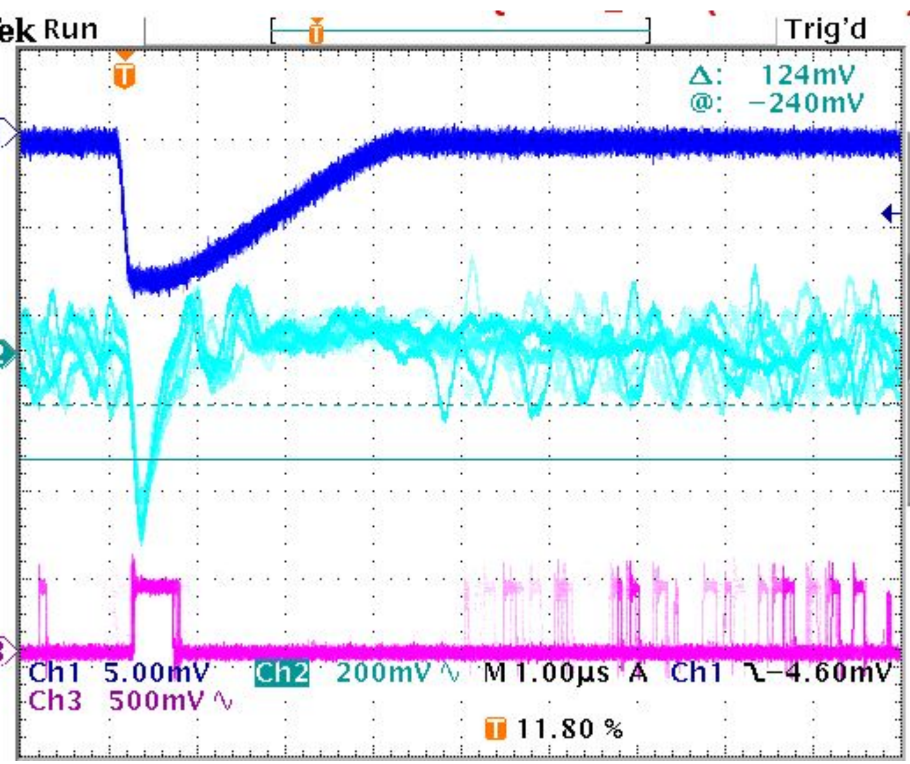
$$A(\rho)_{Theory} \longrightarrow A(\Delta x)_{Theory}$$

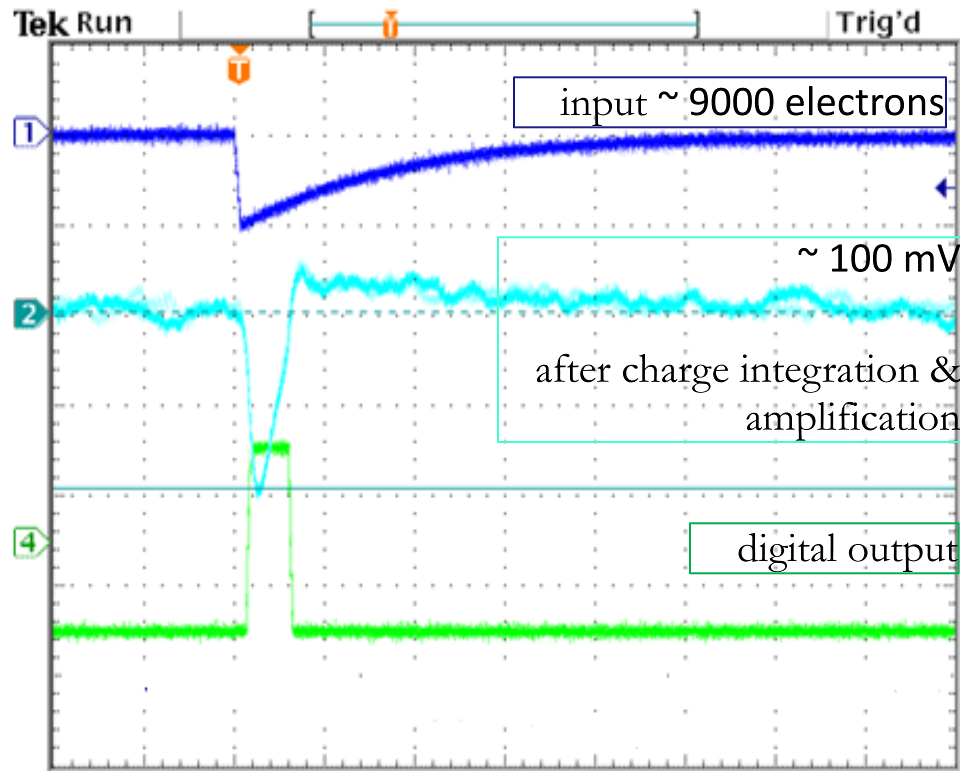
$$A_{exp} = P_e \, P_\gamma \, A_{QED}$$

Fitting the calculated asymmetry to the measured asymmetry gives us the beam polarisation

Amplifier Discriminator Card

Scope-shot of typical response





Typical Amplifier Gain : ~ 60 – 80 mV/fC

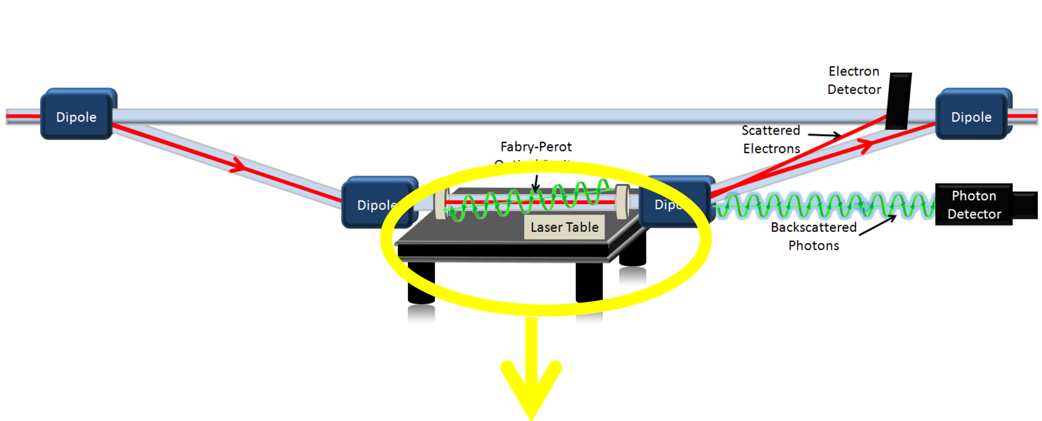
Data Acquisition

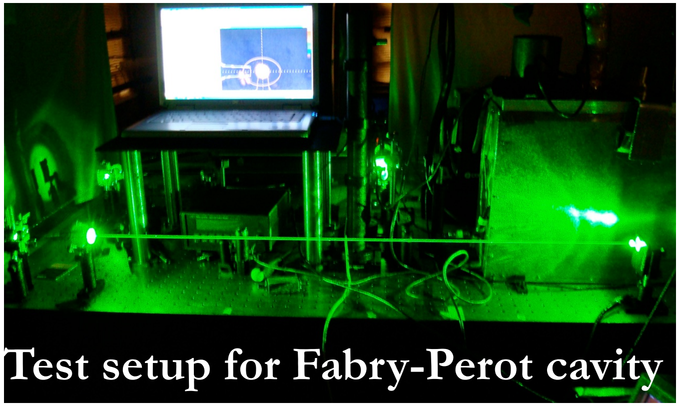
- Collected data with two different coincidence width to identify any deadtime related loss.
- Created two different triggers which were set independently and used as event mode trigger and accumulation mode trigger respectively
- Three data collection modes:
  - ✓ Event mode : **snapshot of all detector strips is recorded for every event trigger**
  - ✓ Scaler mode : **every hit on each detector strip is counted without requiring trigger**
  - ✓ Accumulation mode : **only the hits which fulfil the accumulation trigger condition are counted and histogrammed internally**
- Each programmed FPGA module handled a typical signal rate of ~ 200 kHz across different channels

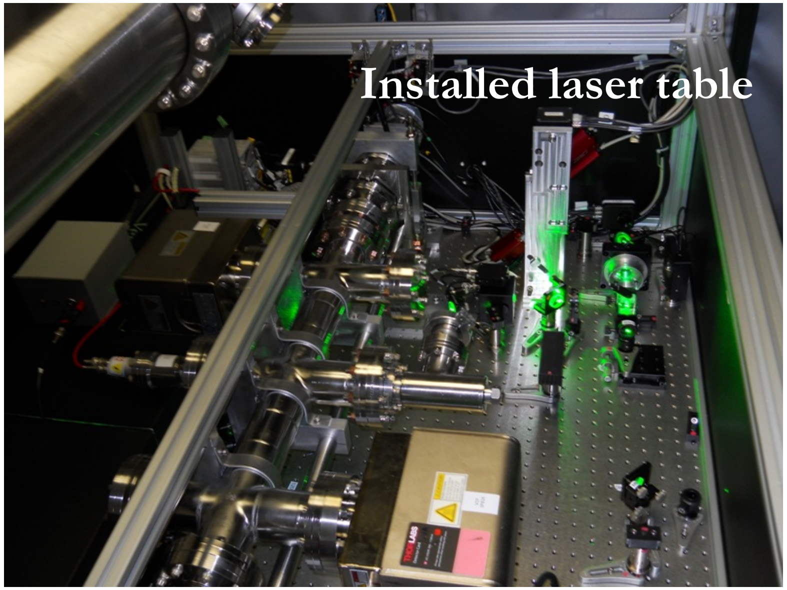
Simulating Compton Scattering

- GEANT3 based model used to simulate Compton scattering along with
  1. background due to the electron beam halo
  2. bremsstrahlung
  3. synchrotron radiation
- e and γ beams - by product of normalized Gaussian in transverse direction
- The e-beam halo - as a diffuse distribution with flat radial dependence
- FPGA modelling toolkit - MODELSIM used to simulate DAQ (shown earlier)
- Some relevant parameters:
  - beam energy: 1.159 GeV
  - beam energy sigma (%): 10^{-6}
  - beam current : 180. μA
  - electron beam polarization: 85.00 %
  - waist of laser beam: 148 μm
  - dipole current: 104.5 A

Laser Table



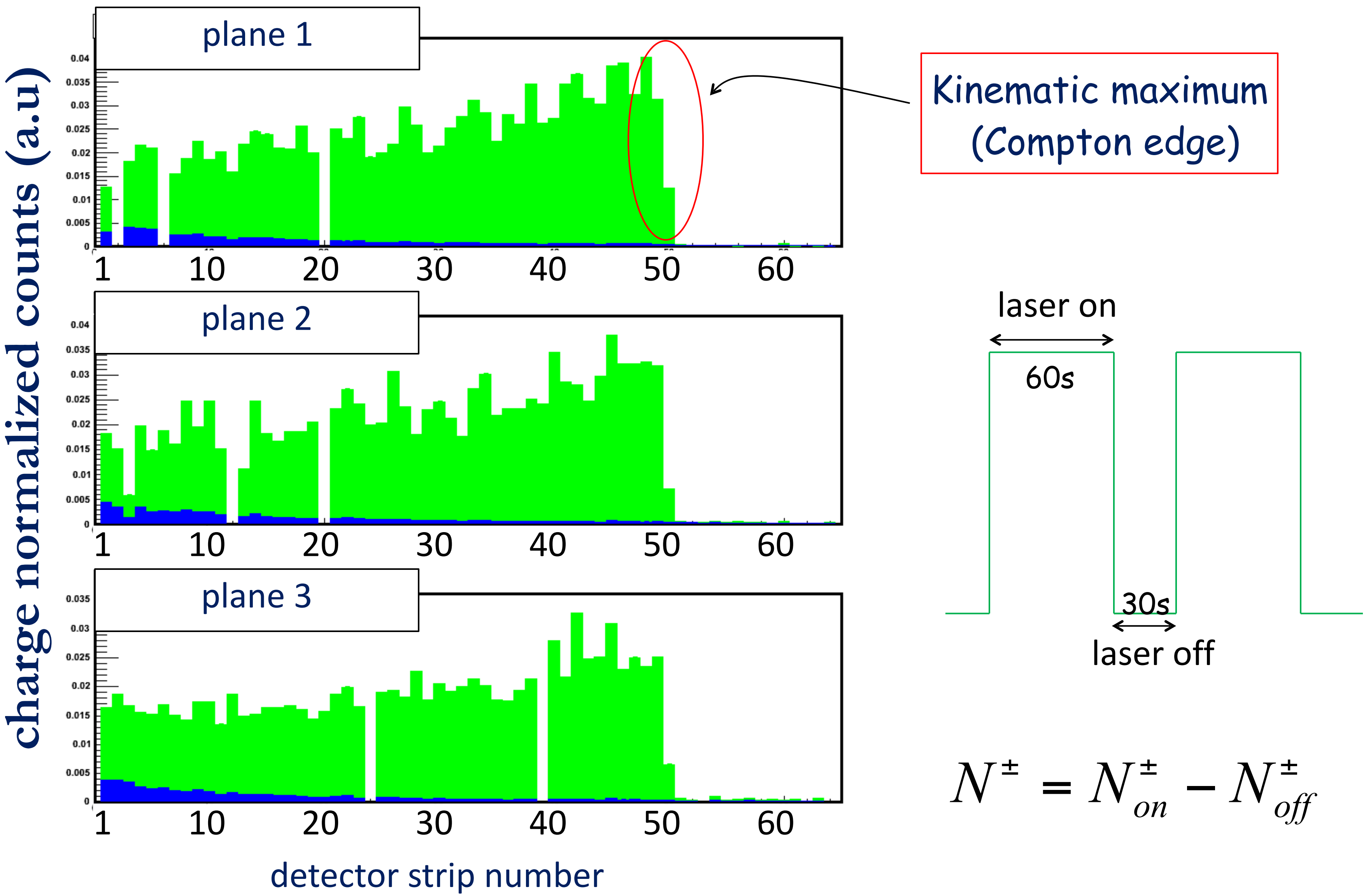

Test setup for Fabry-Perot cavity


Installed laser table

- Photon target at center of chicane is Coherent Verdi 10W laser locked to low gain Fabry-Perot cavity
- Power in the cavity is ~ 1kW
- laser polarization > 99%
- low reflectivity mirror in Fabry-Perot cavity allows robust measurement of laser polarization

courtesy: Donald Jones, University of Virginia

Detector Yield



$$N^{\pm} = N^{\pm}_{on} - N^{\pm}_{off}$$

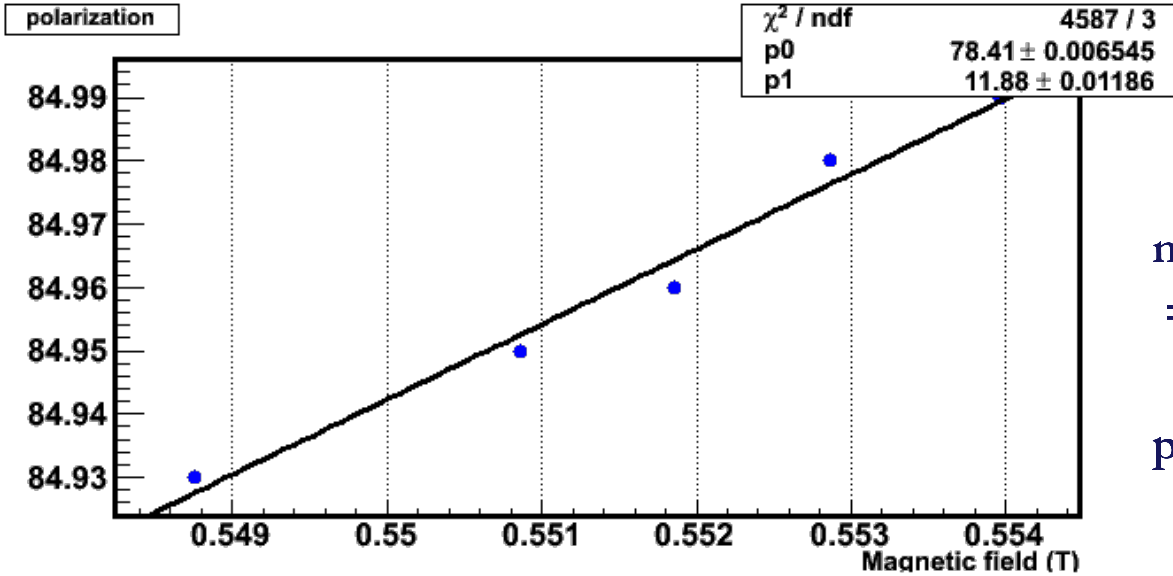
Rigorous Determination of Syst. Uncertainties

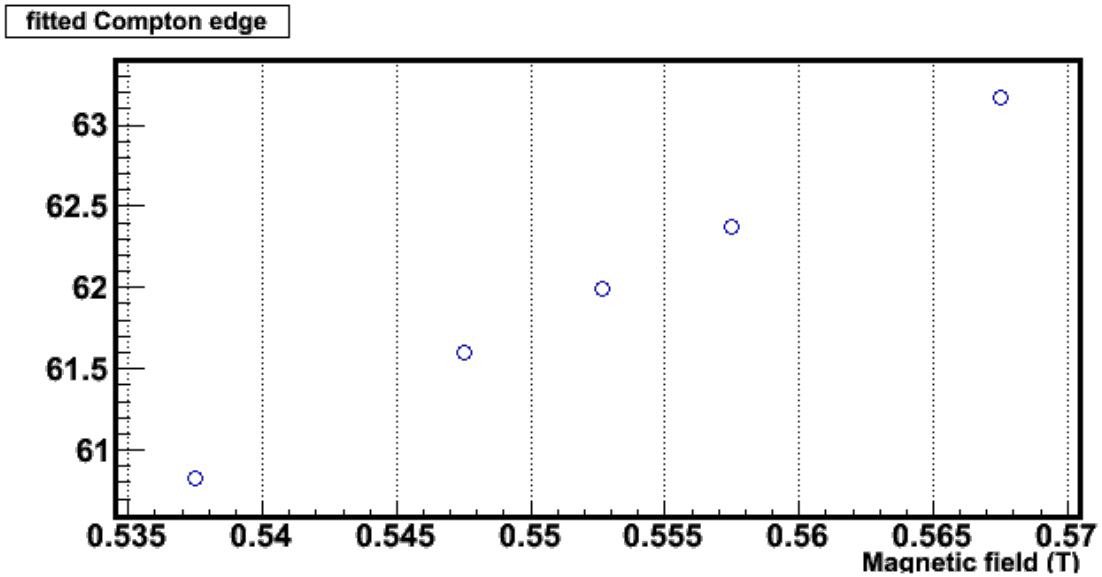
- **The MC generated Compton events are analyzed by the same method as used to analyze experimental data. This analysis yields the polarization within 0.01% of the input polarization**

- **Systematic uncertainty contribution from a parameter is estimated based on dependence of the resultant asymmetry w.r.t changes in the parameter**

- **Studying the variation in polarization in the relevant range of the experimental parameter, the resulting contribution to systematic error is estimated**

eg.: M. Field Contribution





nominal Magnetic field:

= 0.55186 T

possible range of variation:

0.2 % of nominal (=0.0011 T)

contribution to systematic error:

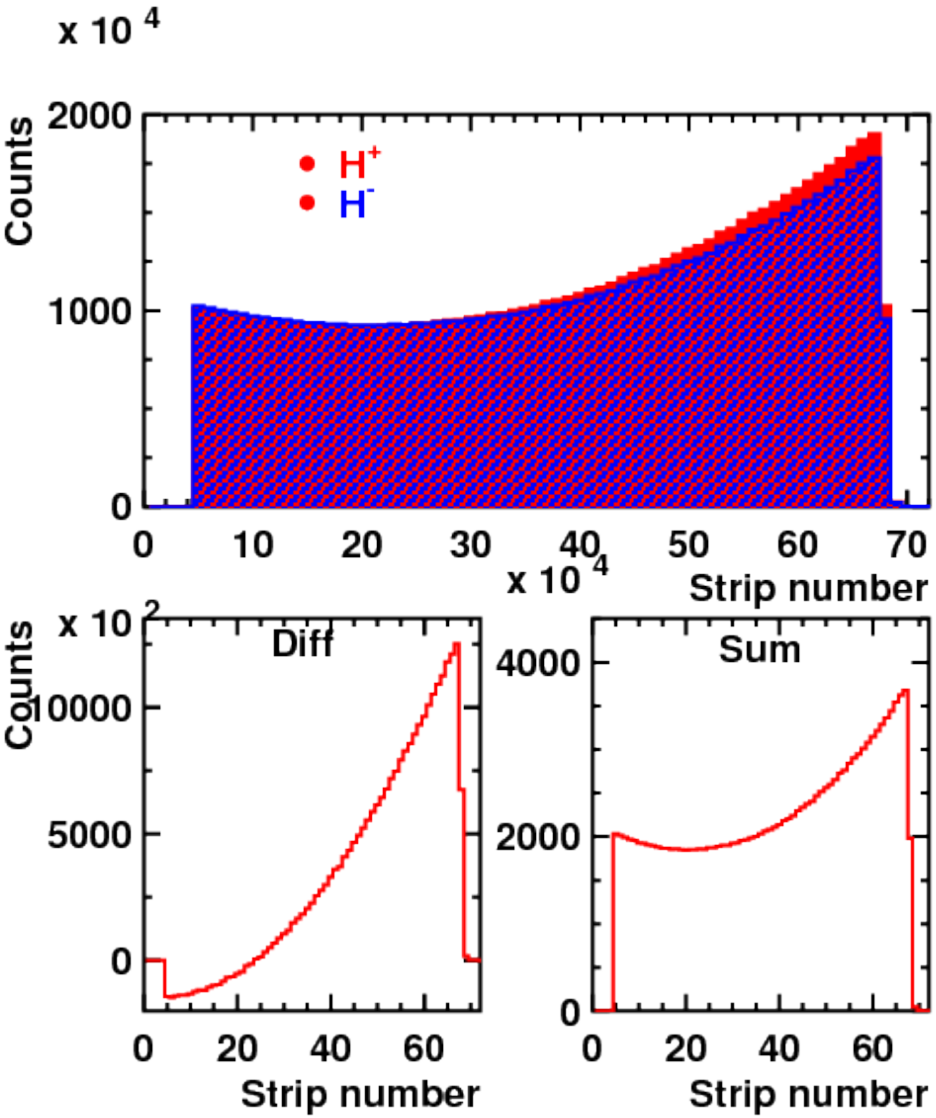
ΔP = slope x M.field variation

= 11.88 x 0.0011

ΔP = 0.0131

Detector Efficiency

Ideal case : 100% efficiency



Random efficiency between 30 – 80%