Detectors for High-Flux Experiments at Jefferson Lab

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Abstract :

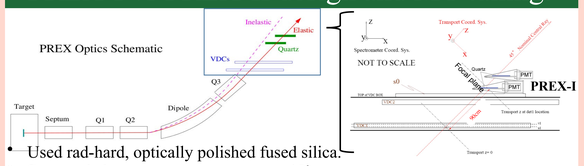
Parity-violating electron scattering experiments at Jefferson Lab use detectors that routinely intercept and "count" scattered electrons at extremely high rates:10^7 to 10^{11} Hz. This is because these experiments measure tiny asymmetries (A_{PV}), typically of order 10^{-6} to 10^{-8}, to access neutral current weak interaction amplitudes with high precision and statistics-dominated uncertainty. Two recent A_{PV} measurements at Jlab, PREX-II and CREX, required focal plane detectors to count electrons at ~2.2 GHz and 27 MHz, respectively. A future A_{PV} measurement, MOLLER, will have focal plane detectors with rates near 8 - 10 GHz. These high flux rates impose stringent rad-hard requirements on the design and material properties of the detectors. The current designs use a novel "thin-quartz" Cerenkov radiator coupled to a pmt to capture a ~uniform flash of light for each intercepted electron. This poster will detail the design and performance of the HRS focal plane package for PREX-II and CREX. Designed, constructed and operated by the ISU parity group, the PREX-II/CREX detector package includes four thin-quartz detectors and three 10 cm x 20 cm active area GEM tracking chambers for each HRS arm. The four quartz detectors consist of the main integrating "tandem-mount" and two auxiliary (background monitor) detectors. Additionally, we designed and installed multiple generations of Hall A SAMs (previously known as LUMIs)-which count primary and secondary scattered flux from the target to monitor both beam and target performance.

Background and Motivation:

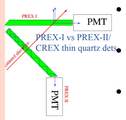
PREX-II/CREX

- High precision, statistic limited measurements of A_{pv}.
- Require extreme control over systematic errors.
- The focal plane (FP) detector package together with Hall A standard HRSs, VDCs, and scintillating trigger systems constitutes PREX-II/CREX detector system.
- R & D preparations for the FP detectors include
  - FP simulations to get elastic peak size and expected flux rates.
  - PMT gain curve measurements.
  - Several beam tests at MAMI and SLAC for benchmarking optical MC.
  - PE yields and resolution, position, and angle dependence.
  - Precision PMT non-linearity characterization.
  - Custom GEM readout design; cosmic-ray tests and SLAC test-beam.

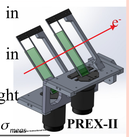
PREX-I vs PREX-II design and MC tuning:



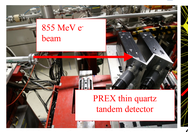
- Used rad-hard, optically polished fused silica.
- Scattered electrons traverse quartz at 45^0.
- Used aluminum air-core light guide to direct Cerenkov light to pmt.



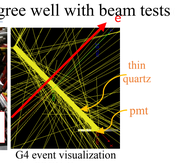
- PREX-I used 6 mm (10 mm) thick quartz in upstream (downstream).
- PREX-II and CREX used 5 mm thick quartz in all detectors.
- Quartz thickness was chosen based on light yield and resolution.
  - ➢ The resolution affects A_{pv} width by $\sigma_{A_{pv}} = \frac{\sigma_{meas}}{\sqrt{1+\left(\frac{RMS}{Mean}\right)^2}}$



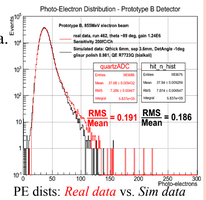
- Orientation between quartz, pmt and scattered electron changed:
  - scattered electrons traverse perpendicular to quartz plane.
  - allows capture of both sides of Cerenkov cone – instead of losing one side due to critical angle.
  - use TIR inside quartz as light guide – instead of aluminum air-core reflector to direct light to PMT.
  - less sensitivity to extra noise due to δ-ray production.
  - effectively ~doubles light yield and improves RMS by $\sqrt{2}$.
  - however, more light yield variation for electrons with different incident angles.
  - multiple beam tests at MAMI and SLAC.
  - tuned simulations agree well with beam tests data.



MAMI testbeam with PREX det



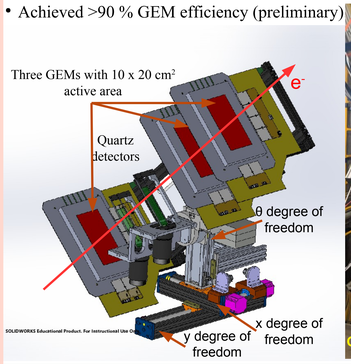
G4 event visualization for PREX-II detector



PE dists: *Real data* vs. *Sim data*

FP det. CAD drawing and installed in HRS:

- Tandem design provides independent redundant A_{pv} measurement (in case one detector has problem)
- Yield: 28 photo-electrons (in peak).
- PREX-II rate: ~2.2 GHz and CREX rate: ~27 MHz.
- Achieved >90 % GEM efficiency (preliminary)



PMT linearity and gain curve characterization:

- Detector non-linearity is one of the most important systematic errors.
- Each PMT was tested for linearity at various high voltages (HV) and several light levels.
- Multiple tests were performed to check repeatability.
- HV for a PMT was chosen based on it's best linear performance.
- We also performed the linearity test after PREX-II at the exact running HVs. Non-linearity should contribute ~0.3 % systematic as proposed.
- The following Fig. shows non-linearity of PREX-II Main detector PMTs as a function of HV. The data points within oval were taken after PREX-II running and the rest were taken before running and installation in the HRS detector huts.
- A gain curve was measured for each PMT before installing them in the detector hut. Up to 1800 V, the curve follows $G = g(V/n)^n$, V is HV, g and n are the fitting parameters, then goes linearly with HV.

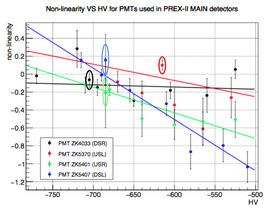


Fig. Non-linearity of PREX-II MAIN detector's PMTs. They ran at the marked HVs.

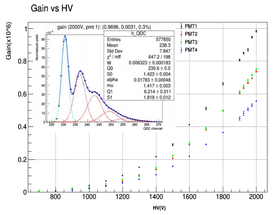


Fig. Gain curves for PREX-II MAIN detector's PMTs (taken from B. Lowe).

Small Angle Monitors (SAMs):

- SAMs are a modified design of Hall A luminosity monitors (LUMIs).
- Eight SAMs symmetric around beamline, ~7 m downstream of the target.
- Three of the four pairs have unity gain to handle high rates (~100 GHz).
- They each use 3.3 x 2.0 x 1.3 cm³ fused-silica as Cerenkov radiator.
- Cerenkov photons are directed to the Hamamatsu R375 (2") PMT window using air-core mirrored-aluminum light-guide.
- Monitor null asymmetry (theoretical) at extremely small Q^2 and small-angle (~0.5^0).
- Thee extreme rates allow a measure of electronic noise-floor in the hall.
- They could also monitor and help correct potential false asymmetry.
- They could serve as diagnostic tools for target density fluctuations.

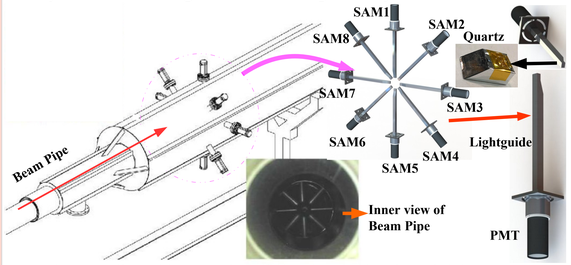
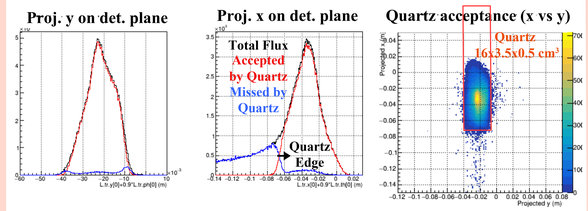


Fig. Beamline with SAMs installed and CAD drawing of eight SAMs.

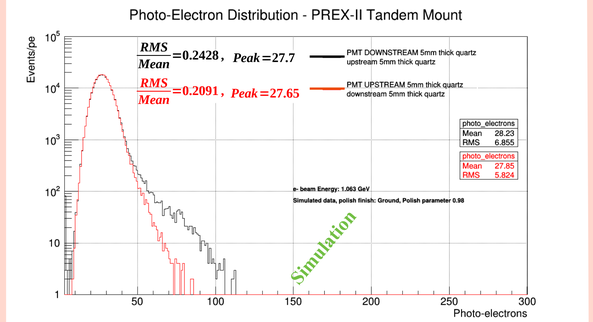
FP Detector Alignment:

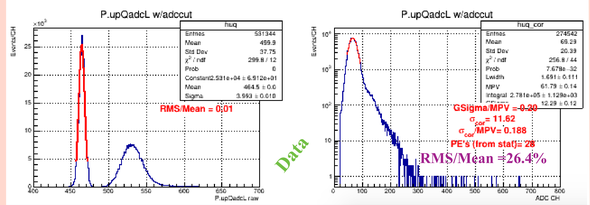
- Each FP detector was aligned, ensuring that inelastic events were well excluded from the quartz acceptance, and checked regularly for any potential shift in elastic peak due to tiny beam energy drifts.

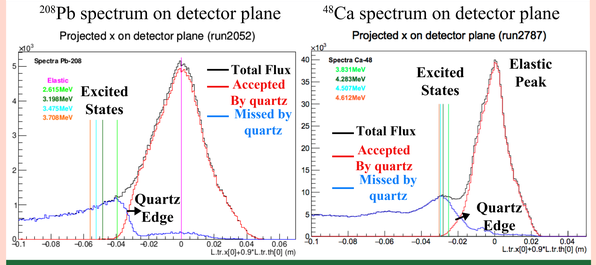
PREX-II detector alignment



- The Upstream Tandem-mount quartz was ~0.9 m above VDC.
- Fraction of events accepted along transport y = ~97%.

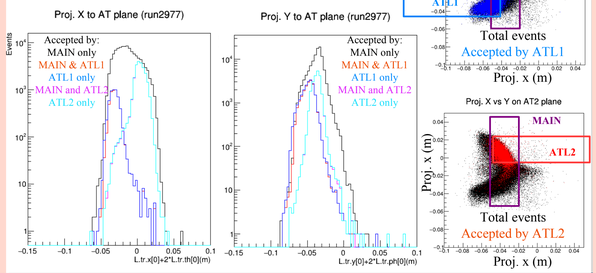






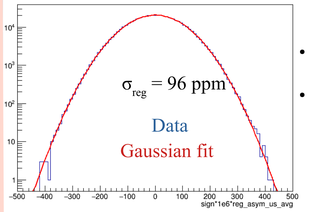
Auxiliary (AT) Detectors: background monitors

- A pair of AT detectors in each HRS.
- Sensitive to up-down dependent asymmetry due to horizontal component of transverse polarization of electron beam.



FP detector performance:

- Data was divided into ~equal statistical chunks called "slugs".
- PREX-II and CREX collected 94 and 86 slugs respectively.
- Asym. distribution of slug40 of PREX-II is given in the following figure
- No Gaussian tail over 4 orders of magnitude.
- Regressed width L/R average asymmetry is ~96 ppm (parts per million).



$$\sigma_{meas} = \sqrt{\sigma_{reg}^2 - BCM_{res}^2 - BPM_{res}^2}$$

- BPM includes position and energy monitors.
- Width on measured A_{pv} gets broadened by detector resolution.

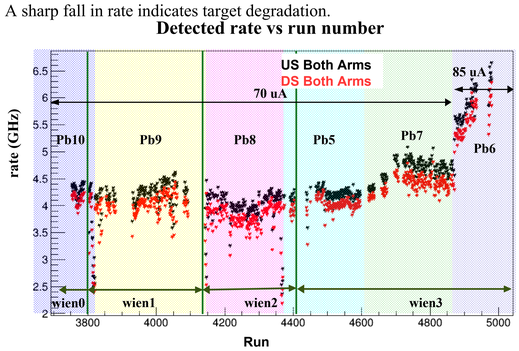
$$Det_{res} = \frac{RMS}{Mean}$$

$$\sigma_{A_{pv}} = \frac{\sigma_{meas}}{\sqrt{1+(RMS/Mean)^2}}$$

Fig: PREX-II asymmetry distribution for slug40.

- We achieved a few ppm of BCM and BPM resolution and a few tens of ppm of energy resolution.
- After correcting for BCM, BPM, energy, and detector resolutions we get pure statistical width in measured A_{pv}.
- The following plot shows the sum of the detected rate in two HRSs vs run from slug21 to slug94 during PREX-II.
- A sharp fall in rate indicates target degradation.

Detected rate vs run number



Summary:

- A new thin-quartz Cerenkov detector concept has been developed and successfully deployed for the recent high-flux parity experiments at JLab: PREX-II and CREX.
- These detectors require radiation-hard components and are constructed of high-purity, optically-polished fused silica (Spectrosil 2000) radiators.
- The PREX-II/CREX main focal-plane detectors use total internal reflection inside the radiator, and no air-core lightguide, to direct Cerenkov light to pmt.
- The new design doubles light yield and improves resolution by $\sqrt{2}$ compared to previous designs.
- PMT/base/HV settings determined to give non-linearity of focal plane detector pmt responses below 0.5% for PREX-II and CREX.
- SAMs worked well during CREX – provided valuable diagnostics and gave an understanding and plan to develop future MOLLER SAM.
- The same approach used to design the PREX-II/CREX detectors will be used to develop next generation high-flux detectors for MOLLER: ShowerMax ring calorimeter and SAMs.
- These new detector concepts will benefit MOLLER, as well as provide potential detector technology for future EIC applications.

Acknowledgements:

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