Statistical Suppression of Sign-Symmetric Noise in Spectroscopic Measurements

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Foreword: Low-Level Radiation at JLab

- Problem at hand at JLab: Administrative requirement to limit operational radiation dose accumulation at CEBAF boundary to no more than 10% of the natural background level, which is about 2 mSv/year (200 nSv/h) in Virgina Peninsula, mostly gammas and cosmic muons, and varying by 5-10%, function of barometric pressure and wind
  - Needed practical solution with sensitivity and stability of the detectors at levels below or about 2-5 nSv/h, in challenging environmental conditions
- Naturally, problems of noise evaluation and suppression were central in our work; details of our approach will be illustrated below

Introduction

- The necessity to assess, minimize, and correct for the signal noise is a typical problem in spectroscopy, specifically in studies of:
  - Low amplitude signals close to the threshold
  - Spectra with significant noise contributions
  - Spectra requiring high stability and precision
- A new method of evaluation and suppression of sign-symmetric noise in spectroscopic measurements has been developed, tested, and implemented at Jefferson Lab
- Demonstrated outstanding long-term stability and precision in environmental radiation measurements around the CEBAF accelerator site

Sign-Symmetric Noise

- Sources of noise in spectroscopic setups:
  - Temperature-related fluctuations in the number N of charge carriers during measurement, “white” noise:
    - Fluctuations are statistically symmetric around average at large N
  - Radio frequency noises in the environment, or acoustic noises:
    - Random-phase fluctuations are statistically symmetric around average
- “Sign-Symmetric”: the sign of the disturbances along the signal line could be random and accidental, and the shapes of the disturbances are independent of their sign
- Sign-Symmetric noises are often major contributing

Sign-Asymmetric Signals

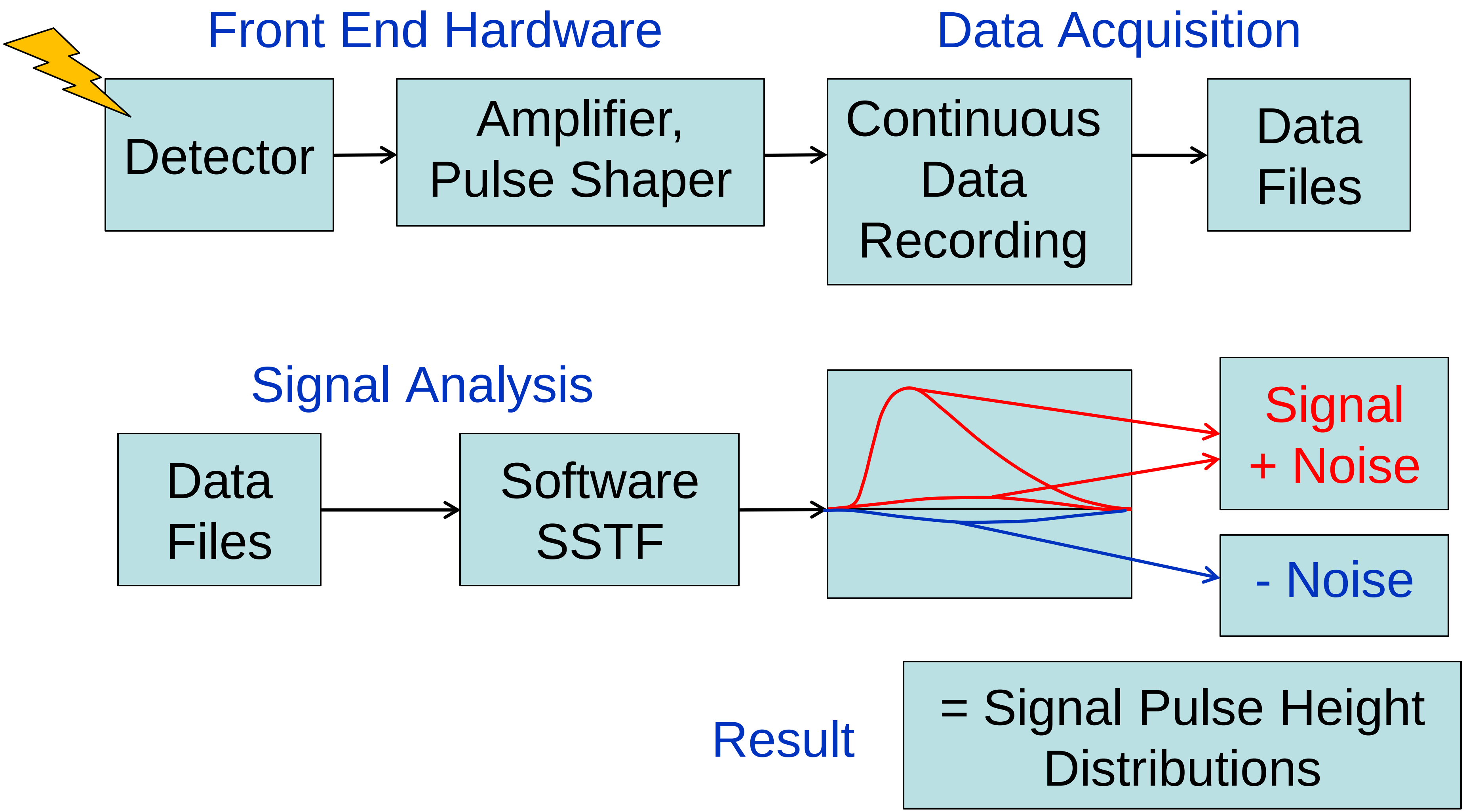
- Real signals from most of the spectroscopic devices are sign-asymmetric (unipolar): PMT, semiconductor detectors, proportional counters, etc.
- Separating sign-symmetric component in the signal spectrum from the sign-asymmetric would allow us to evaluate the noise contributions to the measured spectra, assuming all noise is sign-symmetric
- Validity of such assumption should be verified for each particular implementation of the method
- Sources of Sign-Asymmetric noise may include sharp RF or acoustics wave fronts (say, from explosions or knocks), which cannot be separated from real signals by such technique alone

Sign-Symmetric Trigger Function

- Separating sign-symmetric noise from the unipolar signal spectra in spectroscopic measurements is achieved by using a zero-average-level signal line (a proper AC connection, for example), and by replacing the standard signal triggering schematics
- The Sign-Symmetric Trigger Function (SSTF) block works as a function of the absolute value of the input signal level, providing identical response both for negative and for positive level variations in the signal line. Real and noise signals of the same sign are triggered similar to the traditional trigger scheme. But noise signals of opposite sign are also symmetrically detected by the SSTF, and may be recorded for subsequent analysis and subtraction.

Implementation Block-Scheme

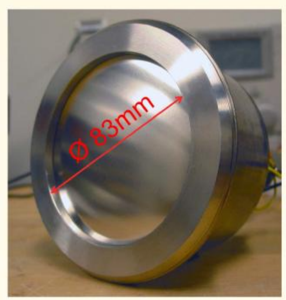
Continuous Data Recording



Detectors Used: Ar and Xe HPICs

Ion Chamber model	Reuter-Stokes (GE) HPIC	VacuTec model 70 181 HPIC
Filling gas	Argon, 25 atm. 8-liter, 357 g	Xenon, 5 atm. ~0.27-liter, ~8 g
Shell or window thickness	Stainless steel, 2.37 g/cm^2, 3.39 mm	Stainless steel, 0.04g/cm^2, 0.05 mm
Dimensions	25 cm in diameter sphere	Cylinder Ø100 mm×62 mm
Total mass	15 kg	0.86 kg
e$^-$/ion pair production energy	Ar→24 eV/pair,	Xe→22 eV/pair

(GE) Reuter-Stokes HPIC in aluminum enclosure with open top.



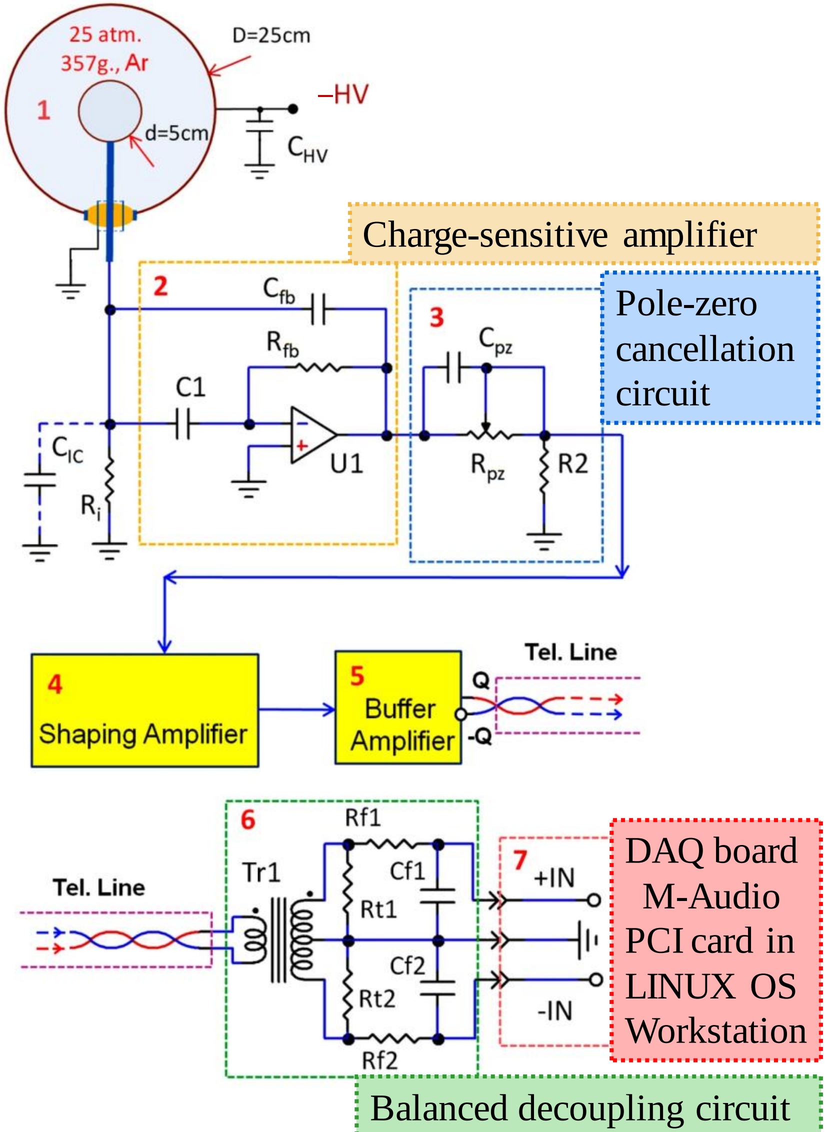
Xe-filled 70 181 by VacuTec ion chamber. View from the side of 50 μ stainless steel window.

High Pressure Non-Gridded Ionization Chambers (HPIC) used: commercial devices by GE Reutter-Stokes, USA, and by VacuTec, Germany. Pulse mode readout designed at JLab.

Ar ICs are operating continuously at JLab site measuring radiation produced by the CEBAF Accelerator in the environment

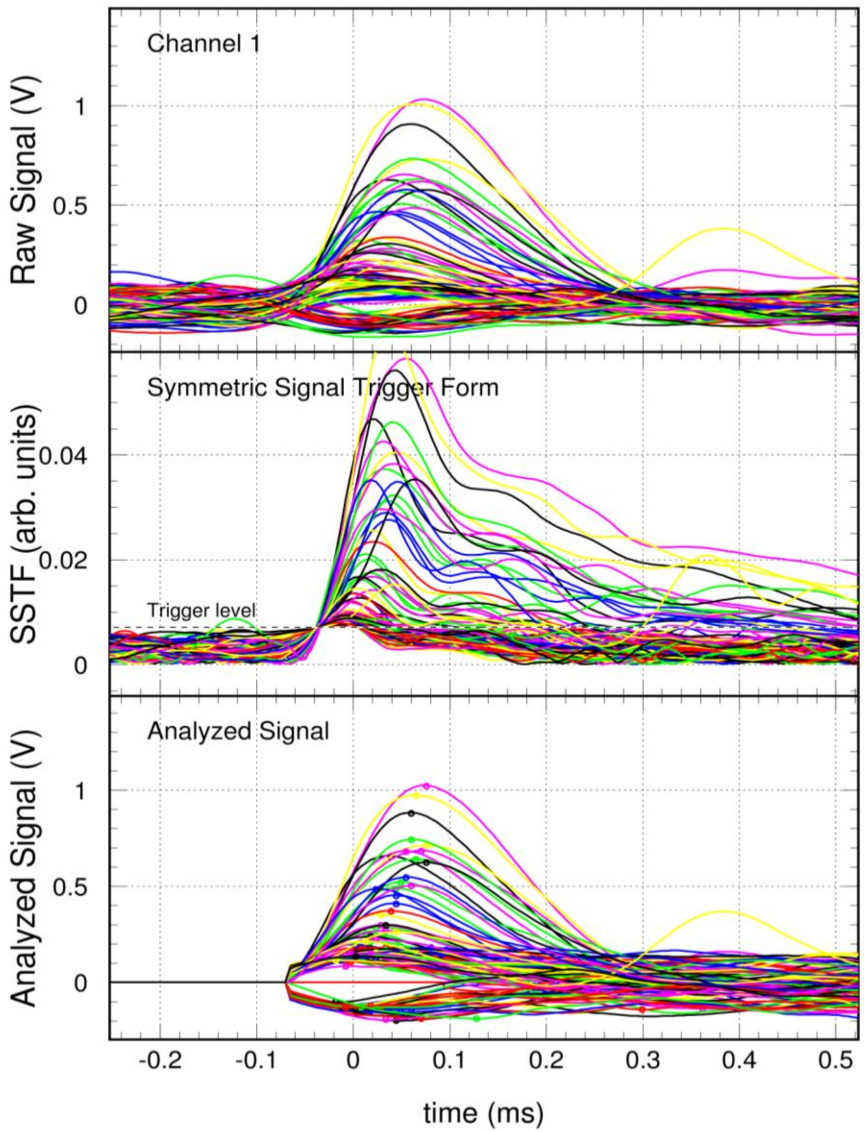
Xe IC: low energy extension

SHPIC Electronics Front-End



- Electrons produced in an ionization event in the gas are collected at the anode in about 0.1 msec
- The pulse is amplified, formed, shaped and transferred through ~200 m long twisted telephone line to the DAQ workstation

Ar, 25 atm SHPIC Signal Processing

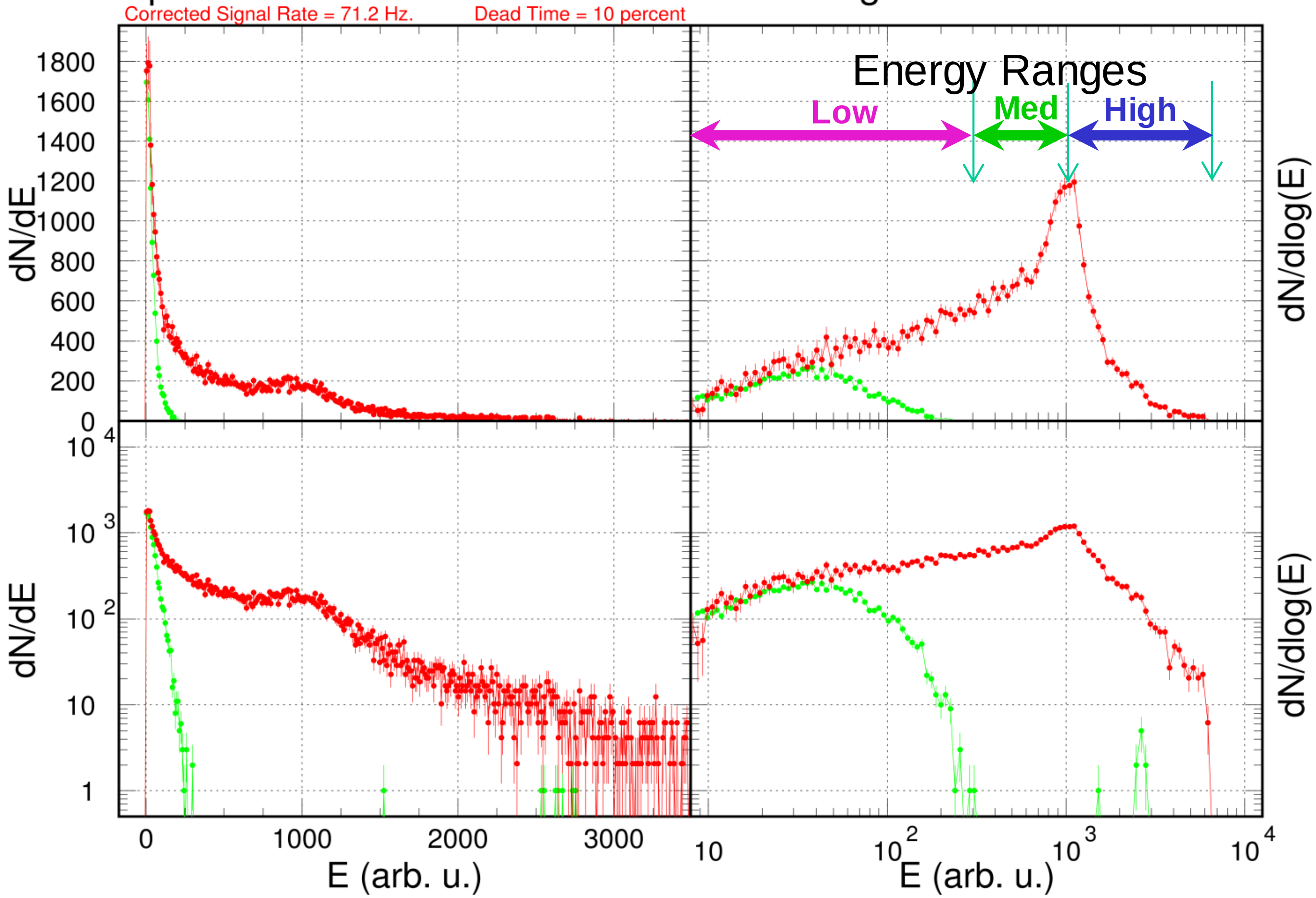


- Typical raw signals (top panel) as recorded in the Wave file data stream synchronized with the sign-symmetric trigger functions (middle panel)

- Corresponding analyzed signals with pedestal subtracted and positive or negative amplitude values found (dots at the top of each signal)

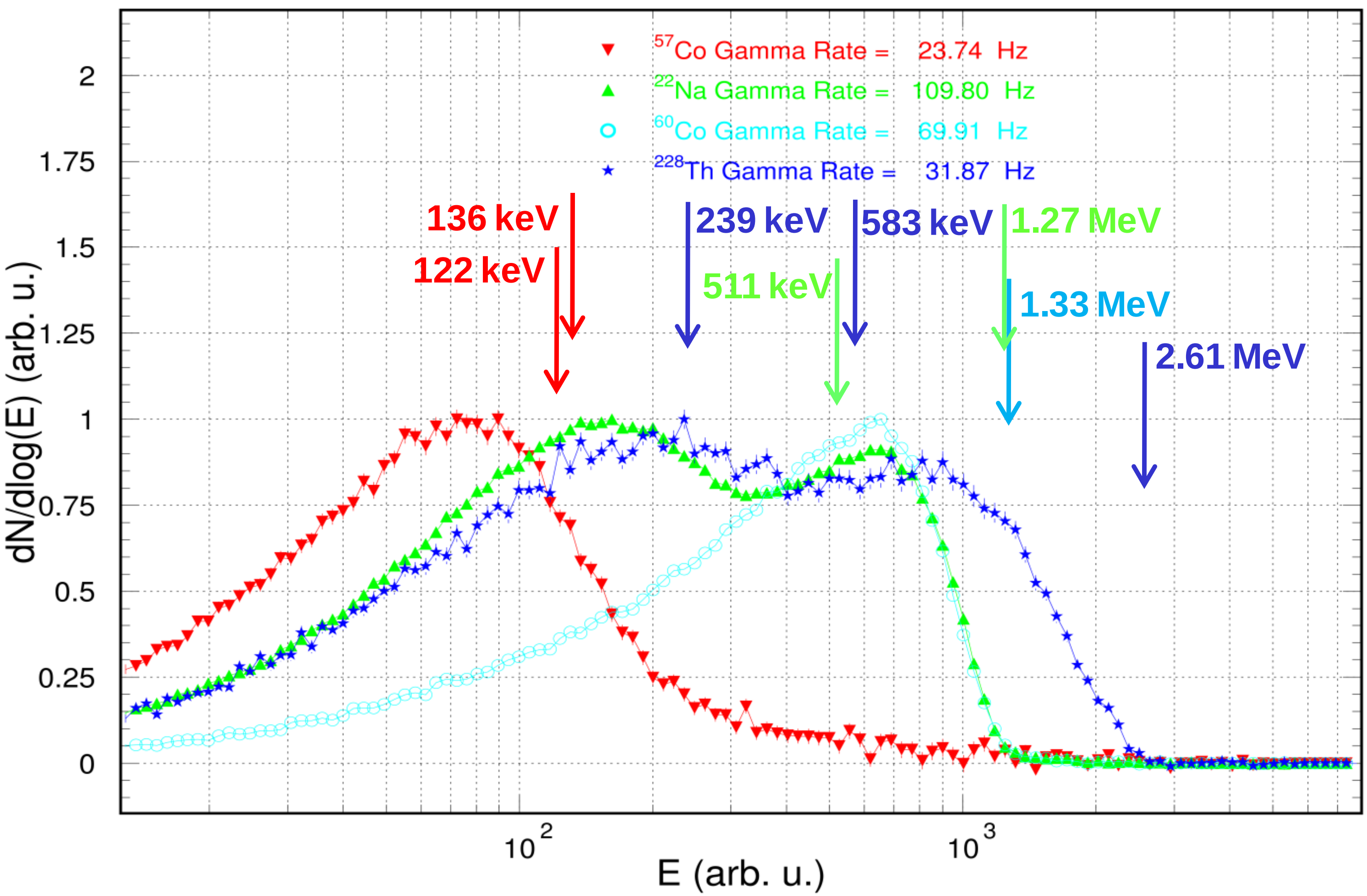
Ar SHPIC Environmental Spectra

Sample 10-minute run. Green: Noise. Red: Signal with noise subtracted



Typical example of a signal spectrum from the HPIC, accumulated in a 10 min time interval, and shown in all combinations of linear and log scales.

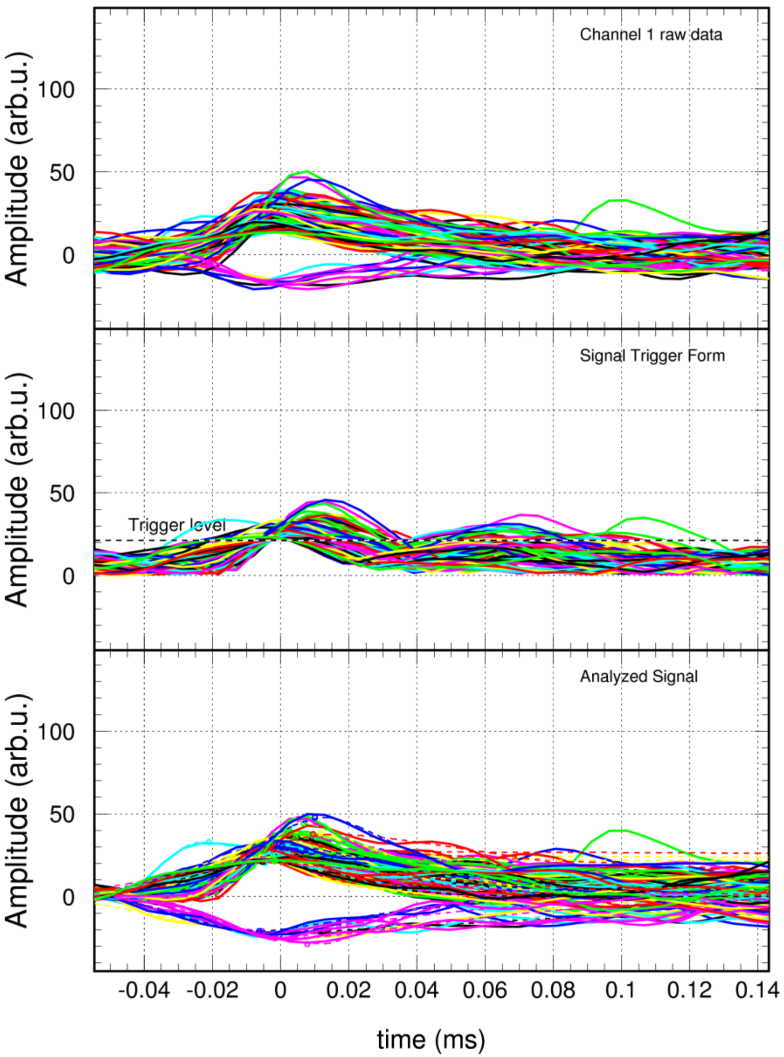
Ar SHPIC Pulseheight Distributions



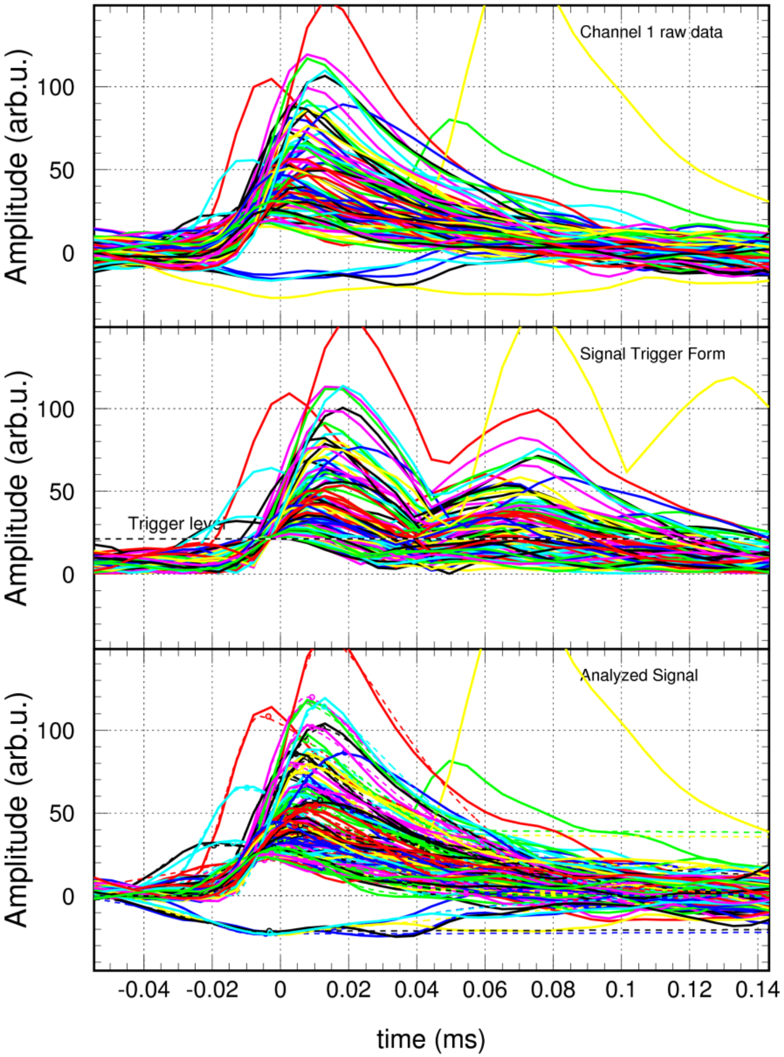
Irradiation of the Agron-filled SHPIC in the lab using different low intensity radioactive isotopes with range of energies 122 keV – 2.61 MeV

Xe, 5 atm SHPIC Signal Processing

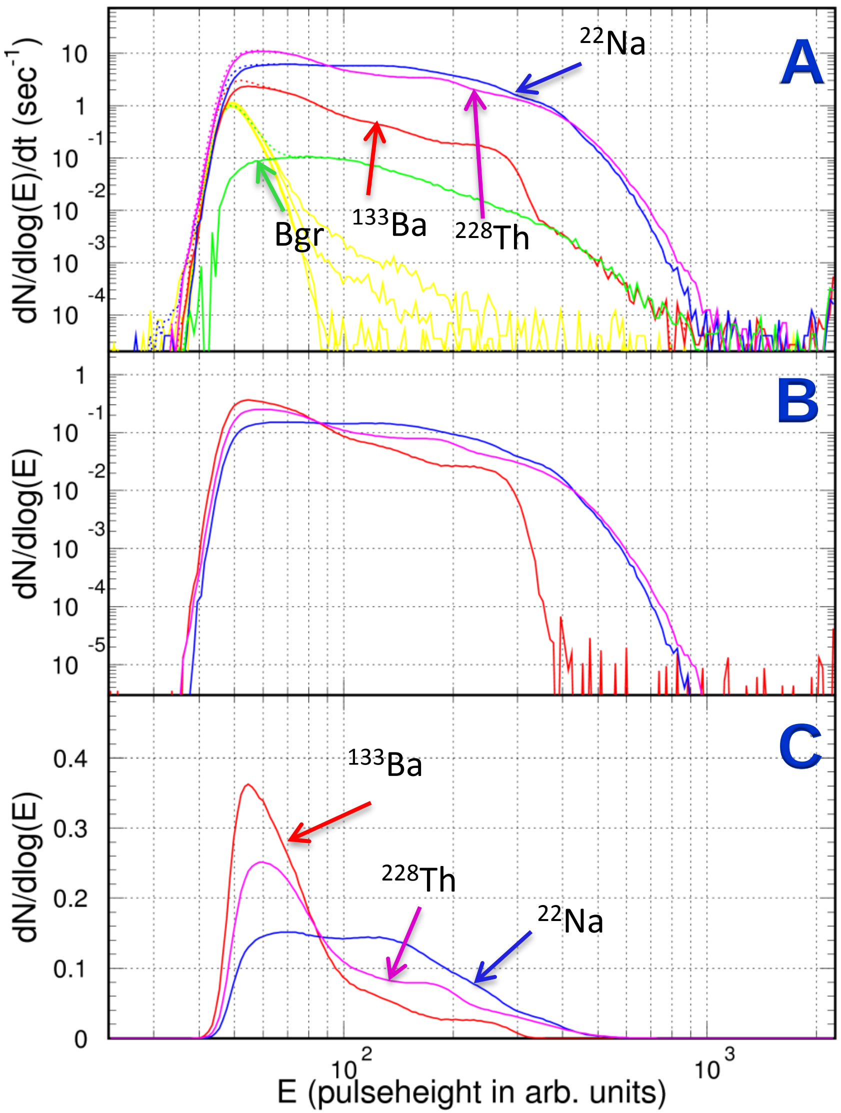
^{109}Cd, 88 keV gamma



^{22}Na, 0.5-1.3 MeV gamma



Xe SHPIC Pulseheight Distributions

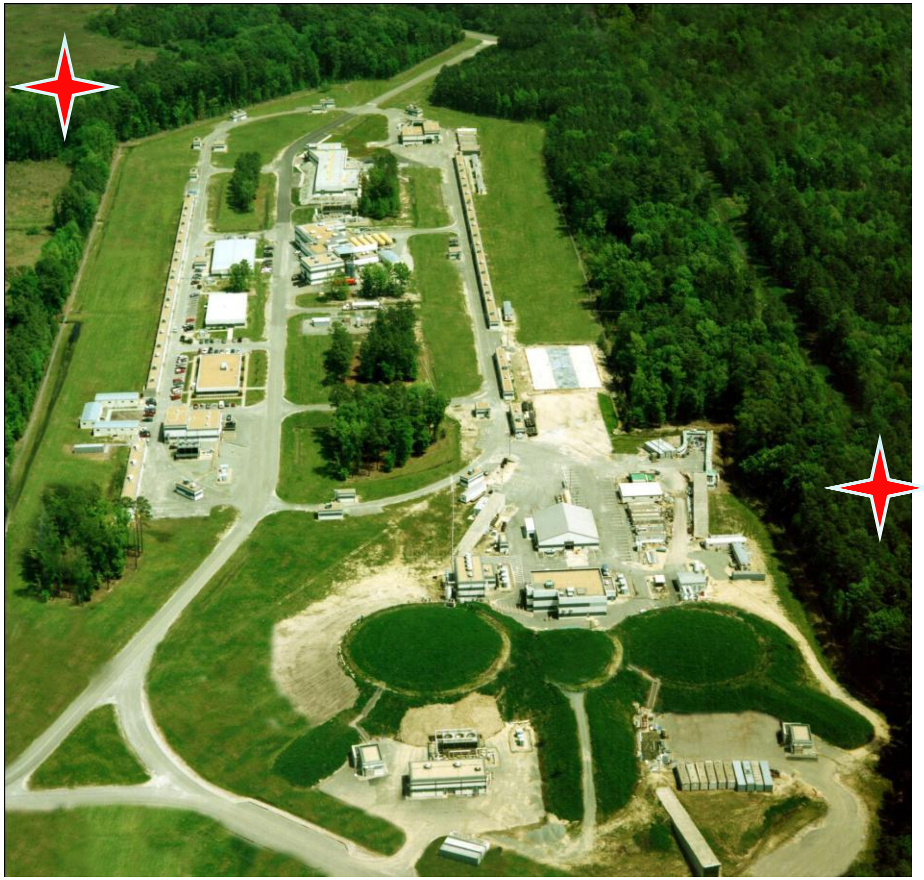


A - Irradiation of the Xe SHPIC in the lab using different low intensity radioactive isotopes with range of energies from 0.081 to 2.61 MeV. Green distribution shows natural background including cosmic radiation in the room. Yellow distributions illustrate the noise contributions measured using our SSTF method.

B,C - Resulting PHDs obtained by first subtracting noise from all distributions, and then subtracting the natural background spectrum from the spectra of the radiation sources.

Noise subtraction allows lower detection threshold and increases sensitivity and stability of the system

SHPIC Detectors at JLab



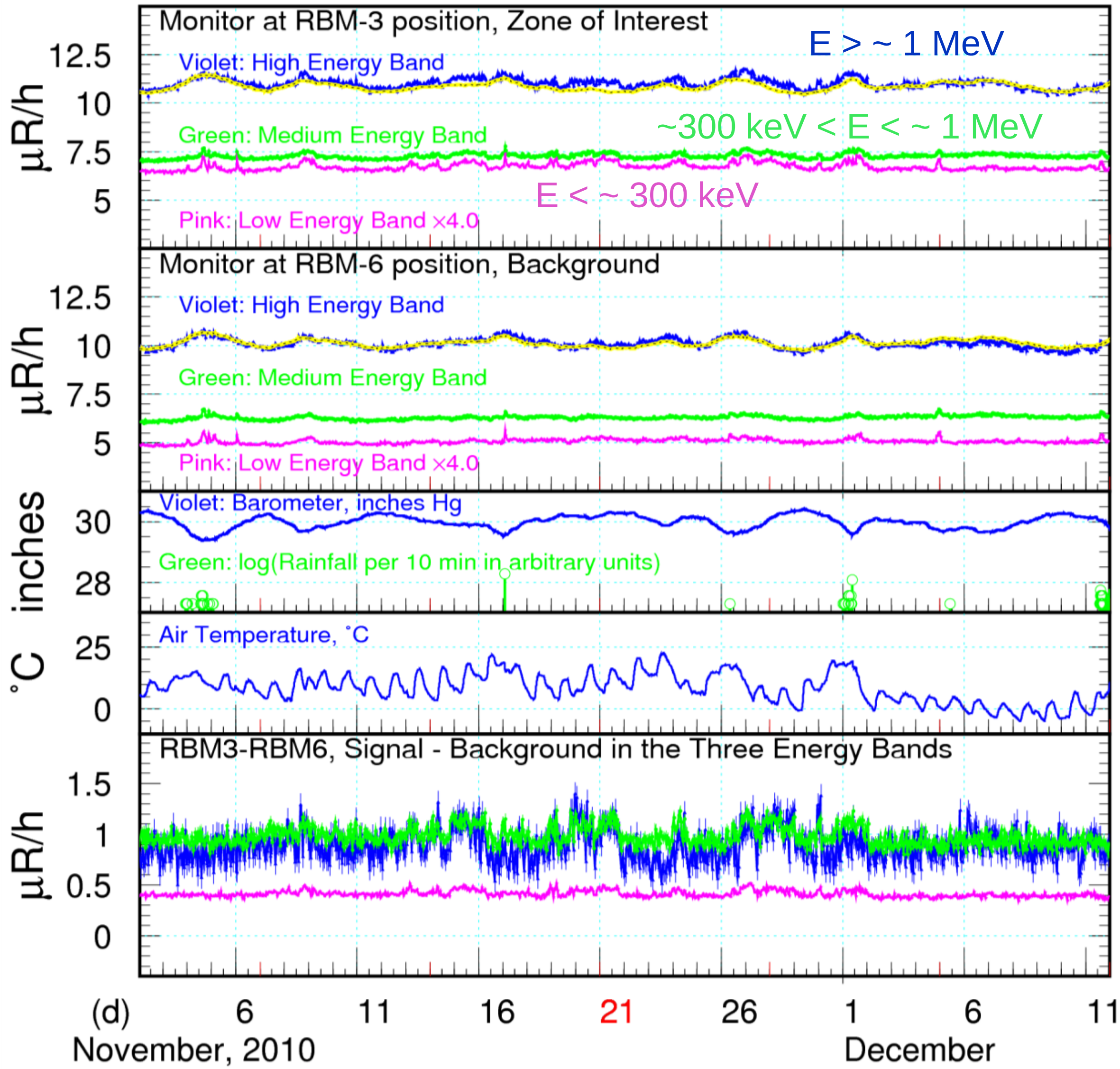
First two detectors on the site boundary: January 2009

(BETA VERSION)

First results published:

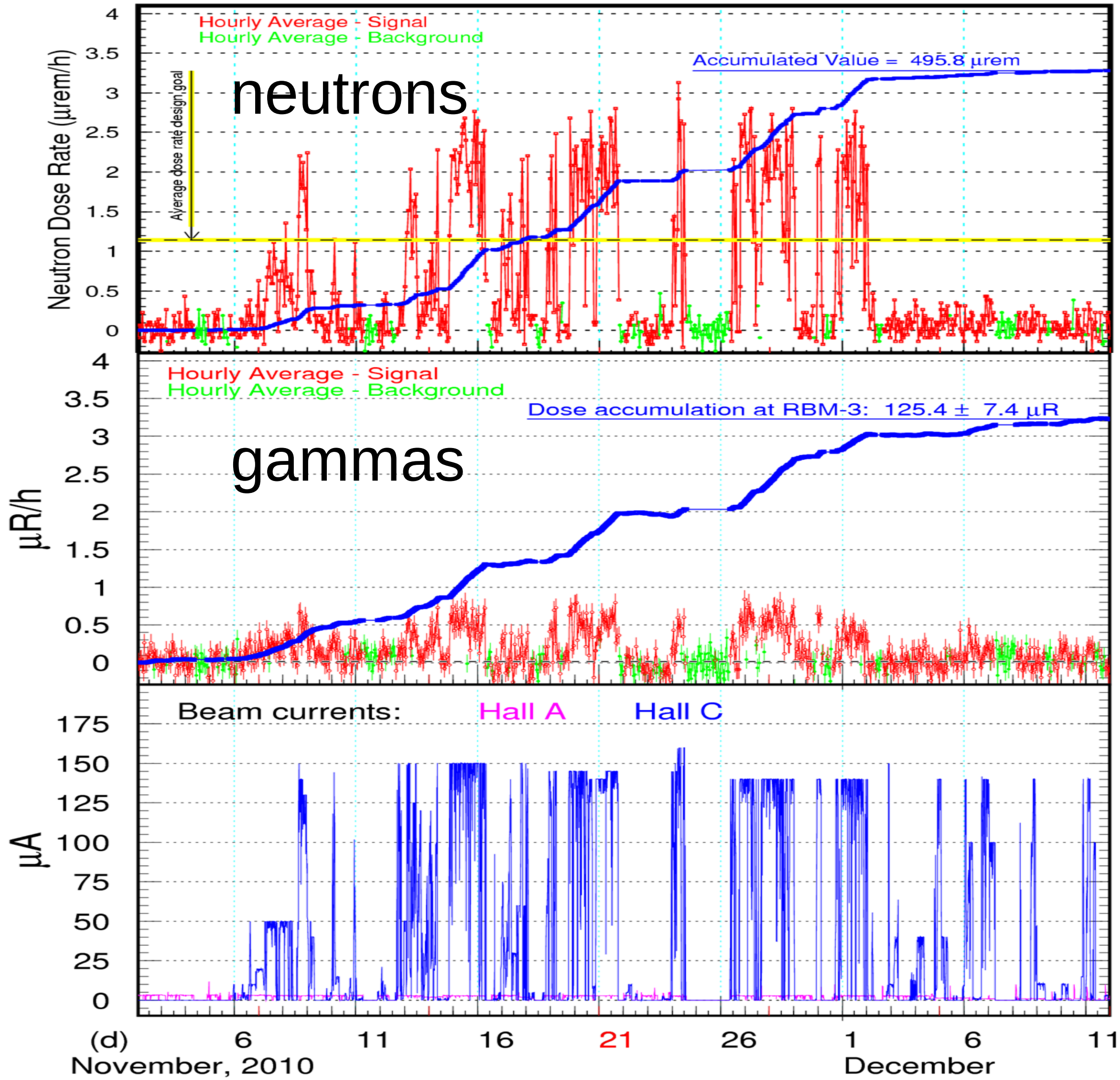
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 5, OCTOBER 2010

SHPIC Operations Example



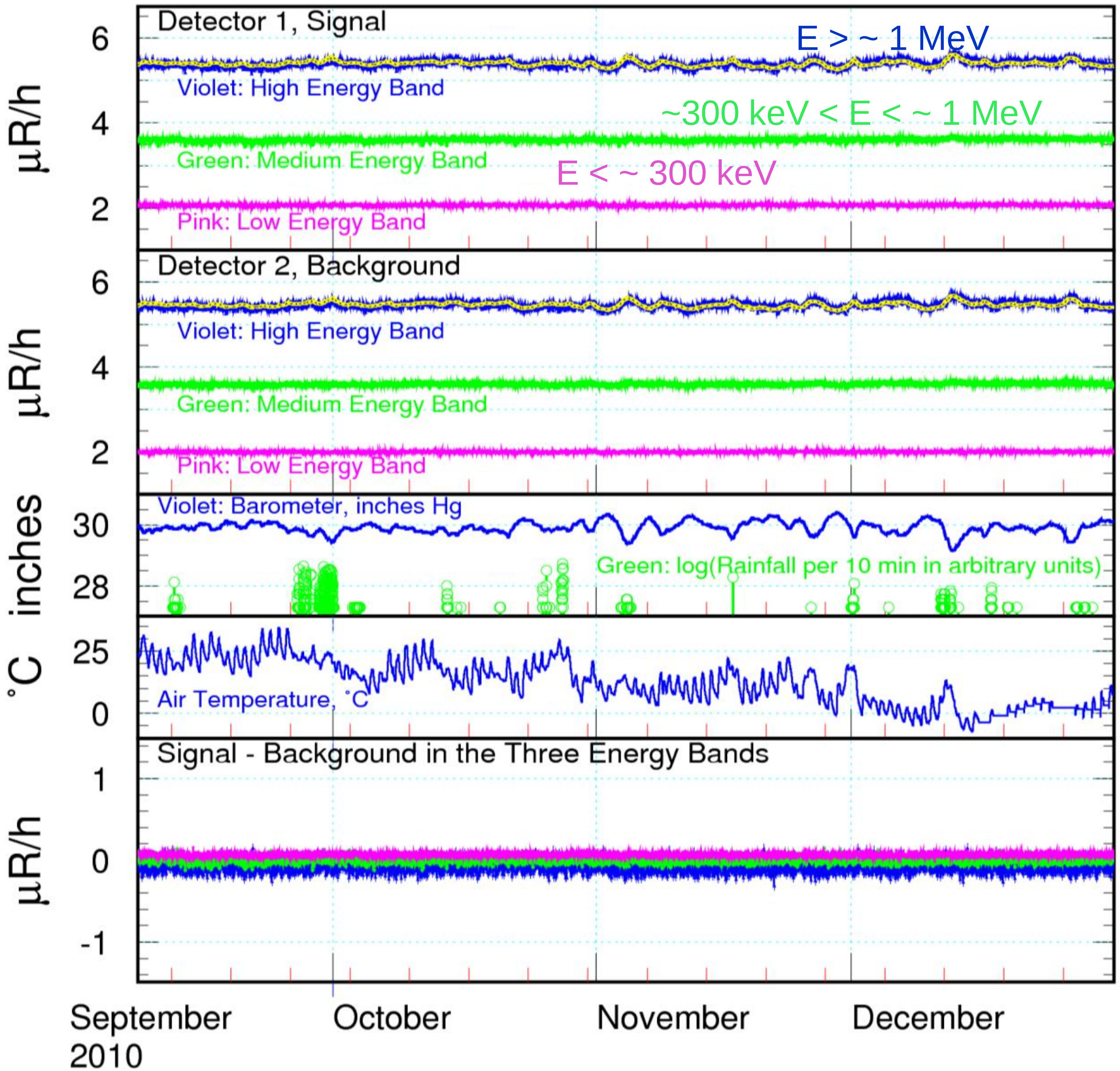
- Typical run period in 2010, including machine operations and quiet periods
- Three energy bands show different behavior depending on atmospheric pressure, rainfalls, and accelerator beam delivered to the experimental Halls

SHPIC Operations Results



- Same run period showing dose rate at CEBAF boundary as measured by the neutron detector at the RBM-3 location (top panel), and by the difference between the SHPIC detectors at RBM-3 and RBM-6 (backgr)
- Bottom panel: beam currents delivered to the Halls at the time

SHPIC Operations Indoors



- Same run period measured indoors using the new "Alpha Version" electronics design
  - Optimized components
  - Optimized signal processing
  - Less noise
  - Dead time improved

Conclusions

- The sign-symmetric noise subtraction procedure helps to provide extremely stable long term operation of the Spectroscopic High Pressure Ionization Chambers, eliminating the temperature and external noise dependence of the detectors' outputs.
- Other implementations of the new method may include new spectroscopic devices designed for measurements of:
  - Low amplitude signals close to the threshold
  - Spectra with significant noise contributions
  - Spectra requiring high stability and precision
- Hardware implementations for the SSTF block are under consideration

References

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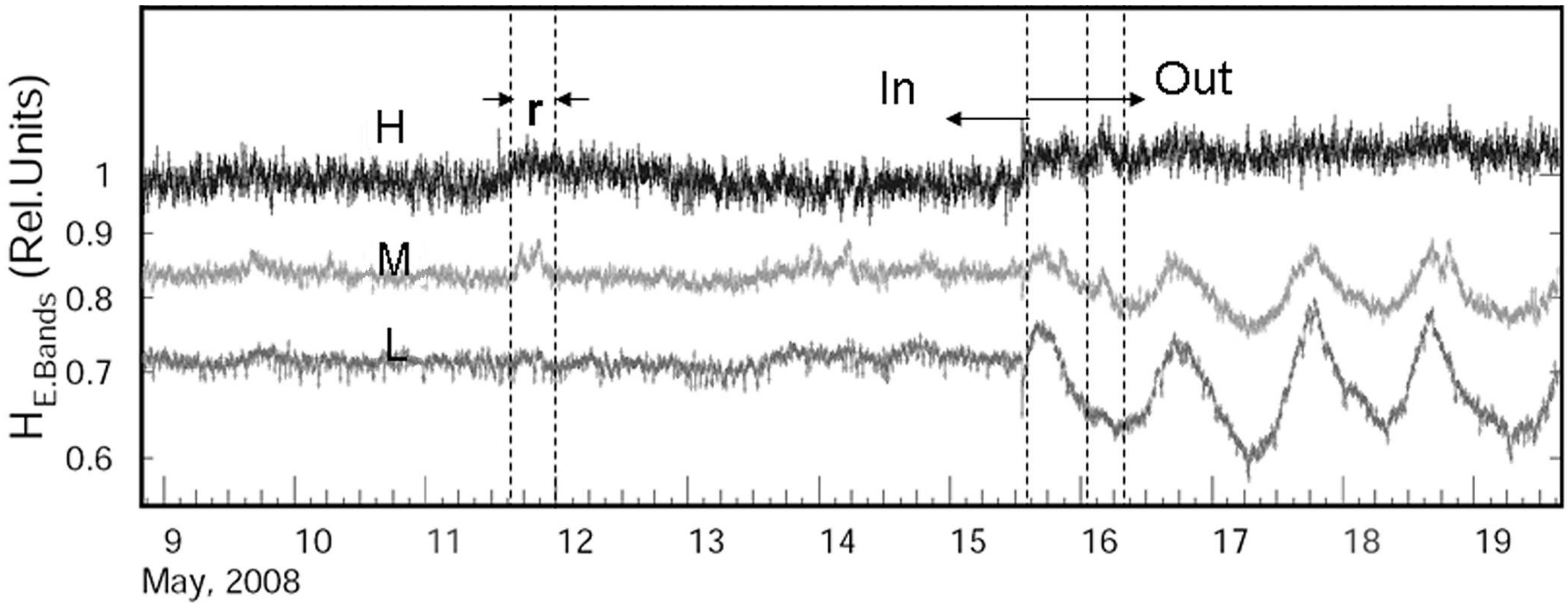
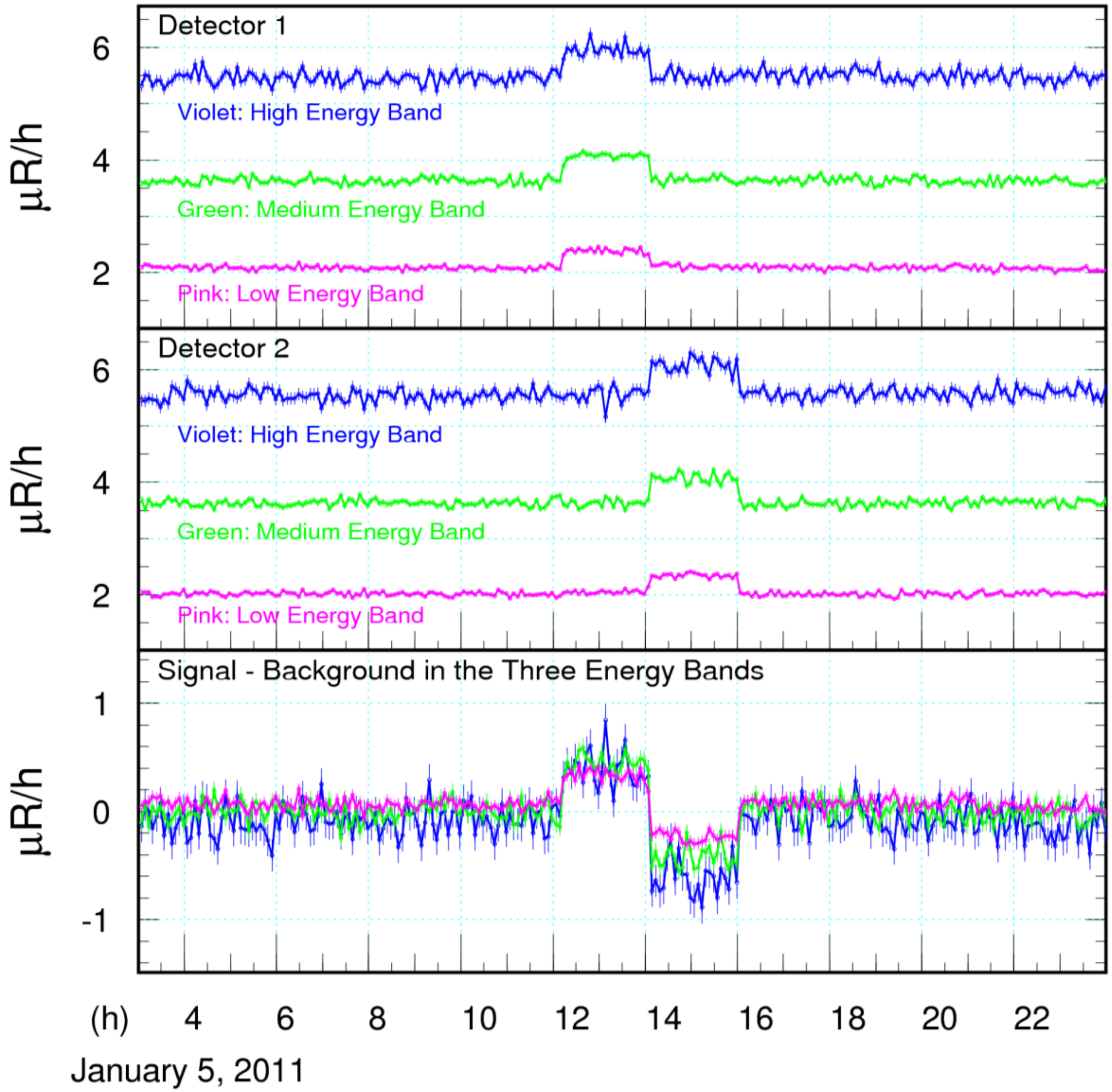
Extra Slides

SHPIC without SSTF noise subtraction



Initial operation of a SHPIC unit before introducing the SSTF-based noise subtraction. Left side (In) shows the detector behavior inside of an air-conditioned building and right side (Out) shows the records when detector was moved outside of the building

Sensitivity to Low Level Radiation



- The example here shows the series of measurements by the two indoor detectors during one day, with irradiation by a low level ^{228}Th source for an hour first one detector and then the other
- Small dose rate increases, less than 1 microrem/h can be reliably detected

Low-Level Radiation Measurements

- Problem at hand at JLab: Administrative requirement to limit operational radiation dose accumulation at CEBAF boundary to no more than 10% of the natural background level, which is about 100 mrem/year in Virgina Peninsula, mostly gammas and cosmic muons
  - Operational neutrons and gamma contribute in proportion of about 4-to-1
  - Neutron detection is relatively straightforward using ^{3}He Anderson-Braun probes, background levels at ~0.2 microrem/hour, signals up to ~3 microrem/hour
  - Gamma signals up to ~1 microrem/hour above the equivalent background of about 17 microrem/hour
  - Need sensitivity and stability of the detectors at levels below or about 0.1 microrem/hour

SHPIC Environmental Detectors

- Standard environmental gamma detectors:
  High Pressure Ionization Chambers (HPIC) with current-integrating mode of operation
  - Perfect hardware
  - Good dynamic range
  - Integrating electronics
    - Temperature-dependent biases
    - Need in frequent calibrations

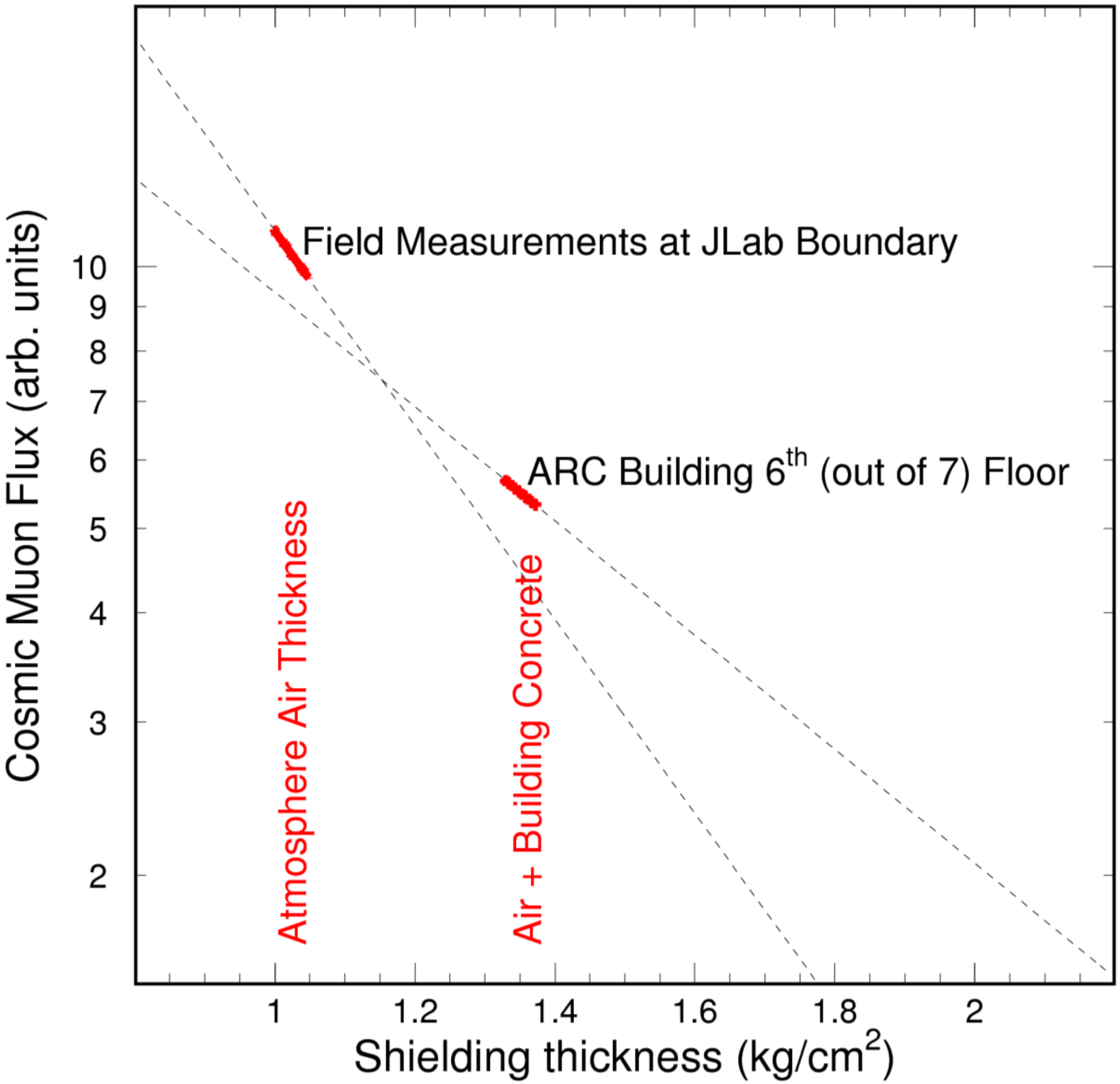
GE Reuter-Stokes RSS-1013

- Novel pulse-mode readout front-end to detect individual events of gas ionization in the HPIC
  - Count rate limited to 1-2 kHz – OK for environmental
  - Ultimate reliability and stability, no thermal drifts
  - Spectroscopic capabilities (~30% energy resolution)

Radiation Waste Monitoring with SHPICs

- Plans are under way to implement a new type of radiation waste monitoring system at JLab using SHPIC detectors
- Stability and reliability of the detectors allow to use them in an automated system that would monitor material waste and recycling site at JLab
- As an alternative solution to installing of the gate radiation monitors at JLab to protect against accidental release of the activated materials from the site, we plan to install several detectors at the central location at JLab that serves as a dedicated place for the trash removal and recycling
- All materials will be stored there at least overnight which would allow detection of a very low intensity sources that would be missed by any gate monitoring system

Environmental Radiation Variations



- Low energy band measurements outside show good signals correlated with rainfalls collecting Radon daughters in the rain
- High energy band measurements are visibly correlated with the atmospheric pressure as reported by a local weather station, consistent with the atmosphere air acting as a ~1 kg/cm2 shield