5 MeV Mott Polarimeter Progress

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Outline

- Mott Scattering: Cross Section and Sherman Function
- Measuring Mott Asymmetry
- Mott Detectors
- Data Acquisition
- Analysis
- Charge Asymmetry
- 1% Polarization Measurement – Error Budget

Mott Scattering

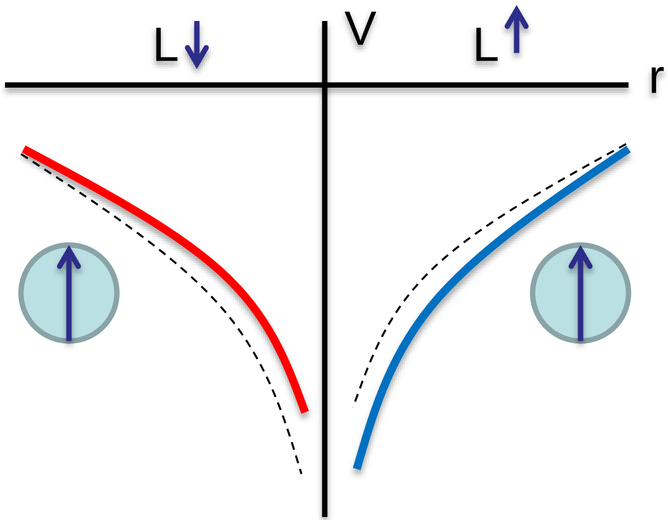
- Electron motion in the electric field of nucleus results in magnetic field in electron rest frame, $\vec{B} = -\frac{1}{c}\vec{V} \times \vec{E}$ if $\vec{r}$ is nucleus-electron separation, then $\vec{E} = \frac{Ze}{r^3}\vec{r}$ and

$$\vec{B} = \frac{Ze}{cr^3}\vec{r} \times \vec{v} = \frac{Ze}{mcr^3}\vec{L}$$

- Interaction of this magnetic field with electron (spin) magnetic moment introduces a term $V_{so} = -\vec{\mu}_s \bullet \vec{L}$ in the scattering potential,

$$V = V_c + V_{so} = \frac{Ze}{r} + \frac{Ze^2}{2m^2c^2r^3}\vec{L} \bullet \vec{S}$$

- Presence of spin-orbit term in scattering potential introduces spin dependence in scattering cross section $\sigma(\theta)$ which could be detected as a left/right count rate asymmetry



Note:

- Parity-conserving: Measure spin-momentum correlation of the type: $\vec{S}.\left(\vec{k}_1 \times \vec{k}_2\right)$

  Transverse (or Normal) Beam Asymmetry measured recently using the setup of parity-violating experiments at high energies (due to two-photon exchange) probes the same spin-momentum correlation as Mott Asymmetry at low energies (due to spin-orbit interaction of electron moving in a Coulomb field).

- Parity-violating: Measure spin-momentum correlation of the type: $\vec{S}.\vec{k}_1$

Mott Cross Section and Sherman Function

- Mott cross section:

$$\sigma(\theta) = I(\theta)[1 + S(\theta)\vec{P} \bullet \hat{n}]$$

Non-spin-flip Amplitude

Spin-flip Amplitude

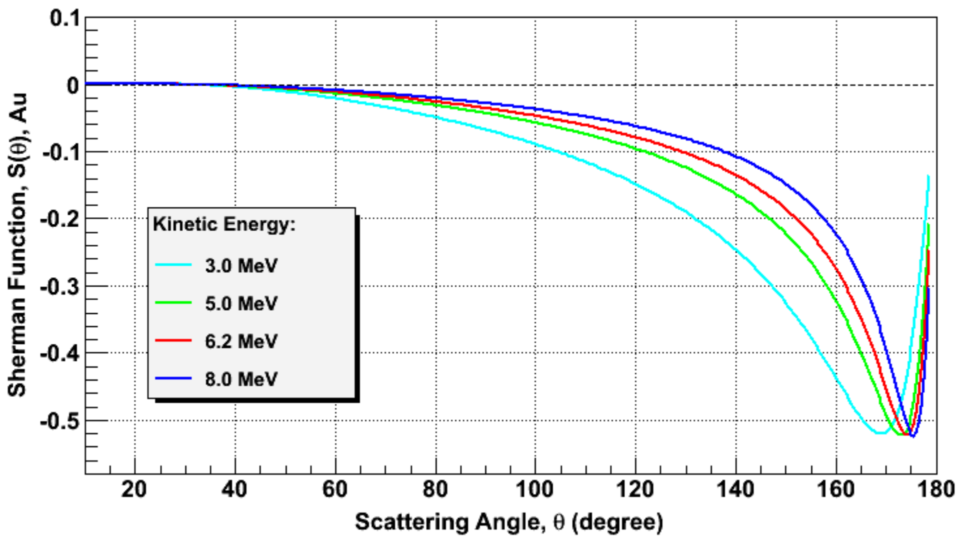
where, $I(\theta)$ is the un-polarized cross section,

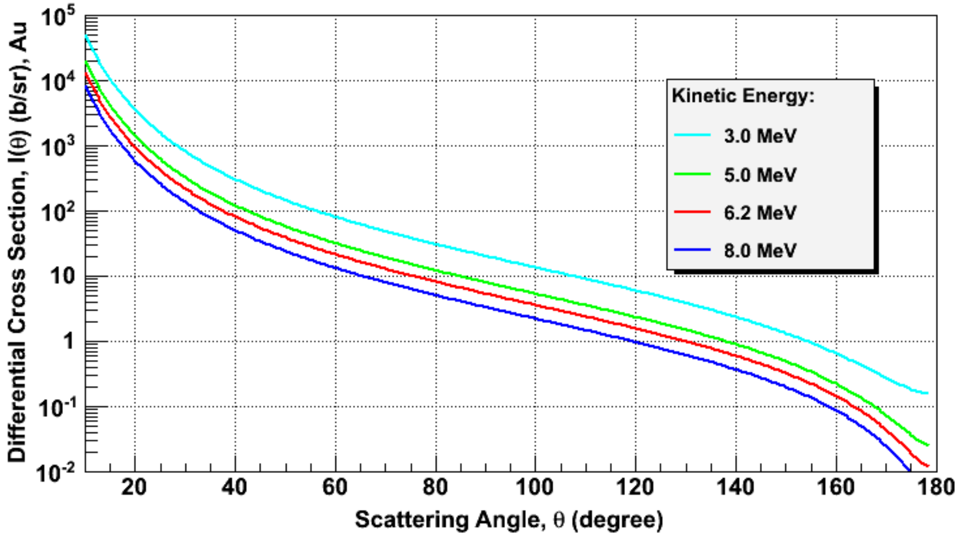
$$I(\theta) = \left(\frac{\hbar c}{p}\right)^2 \left[\left(\frac{Ze^2}{\hbar c\beta}\right)^2 \left(1 - \beta^2\right) \frac{|F(\theta)|^2}{\sin^2(\theta/2)} + \frac{|G(\theta)|^2}{\cos^2(\theta/2)}\right]$$

and $S(\theta)$ is the analyzing power (Sherman Function),

$$S(\theta) = 2 \times \left(\frac{\hbar c}{p}\right)^2 \left(\frac{Ze^2}{\hbar c\beta}\right) \frac{\sqrt{1-\beta^2}}{\sin(\theta/2) I(\theta)} \left[F(\theta)G^*(\theta) + F^*(\theta)G(\theta)\right]$$

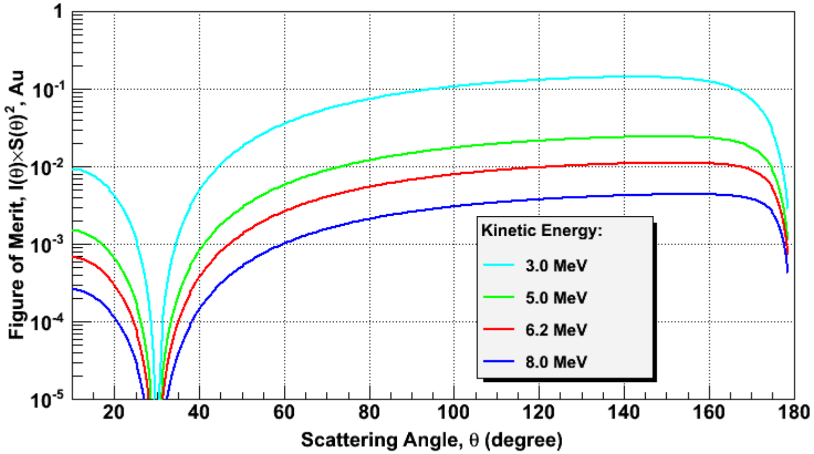
- The Sherman Function is largest for high-Z (Gold, Z=79) targets and low-energy electrons

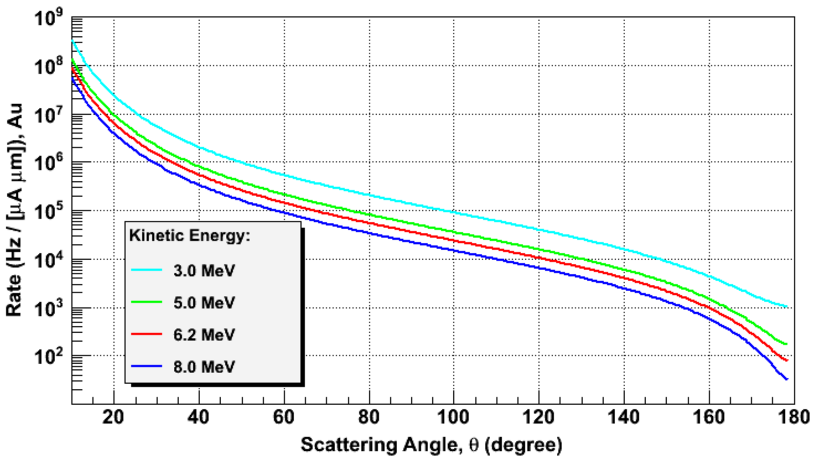




- Theoretical corrections to Sherman Function:
  I. Screening by atomic electrons which is relevant for low energy electrons
  II. Nuclear extended charge distribution which is relevant for high energy electrons

Mott Polarimeter Optimization





- Statistical error of polarization measurement is proportional to inverse of Figure of Merit (*fom*),

$$fom(\theta) = I(\theta) \times S(\theta)^2$$

The goal is to maximize *fom*

- The detector rate (*R*) is

$$R(\theta) = I(\theta)\rho_{Au} d_{foil} \frac{N_A}{M_{Au}} \frac{I_{beam}}{e^-} \Delta\Omega$$

Measuring Mott Asymmetry

- How to measure the Mott Asymmetry A_{LR}?
  - For one helicity state, measure the number of left and right E detector events, $N_L^{\uparrow}$ and $N_R^{\uparrow}$
  - Flip the electron polarization, measure the number of events again, $N_L^{\downarrow}$ and $N_R^{\downarrow}$
  - Calculate the *cross-ratio* (r),

$$r = \sqrt{\frac{N_L^{\uparrow} N_R^{\downarrow}}{N_L^{\downarrow} N_R^{\uparrow}}}$$

  - Then, the Mott Asymmetry (*A*),

$$A_{LR} = \frac{1-r}{1+r} \qquad P = \frac{A_{LR}}{S}$$

- The same for A_{UD}
- This cancels false asymmetries from detector efficiency, beam current, target thickness, and solid angle
- Dead time is caused by slow DAQ and is common to all detectors – cancels to all orders

Statistical Uncertainty

$$(\Delta A)^2 = \frac{r^2}{(1+r)^4}\left[\left(\frac{\Delta N_L^{\uparrow}}{N_L^{\uparrow}}\right)^2 + \left(\frac{\Delta N_L^{\downarrow}}{N_L^{\downarrow}}\right)^2 + \left(\frac{\Delta N_R^{\uparrow}}{N_R^{\uparrow}}\right)^2 + \left(\frac{\Delta N_R^{\downarrow}}{N_R^{\downarrow}}\right)^2\right]$$

- With the approximation,

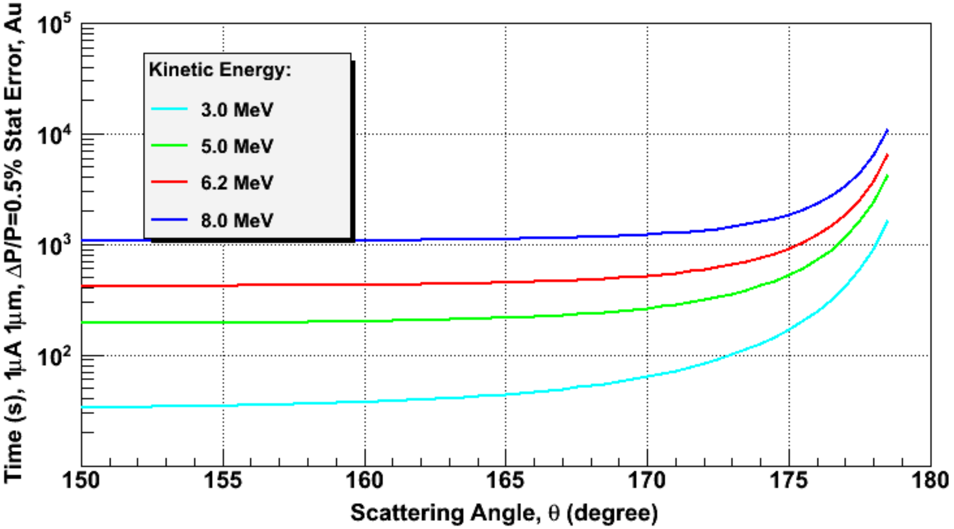
$$N = N_L^{\uparrow} = N_R^{\downarrow} = N_R^{\uparrow} = N_L^{\downarrow}$$

Error simplifies to

$$\Delta A = \sqrt{\frac{1}{4N}}$$

or,

$$N = \frac{1}{4(\Delta A)^2}$$

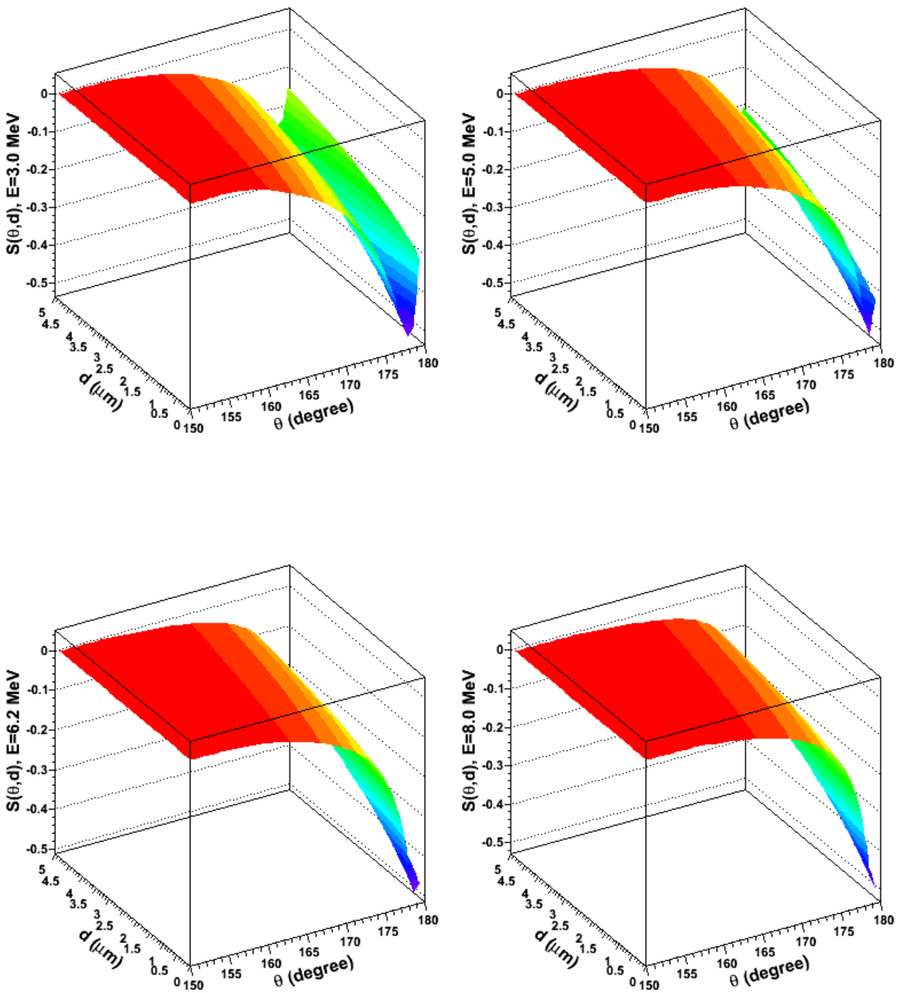


- Time needed to measure beam polarization of P to statistical error of $\Delta P / P$ is

$$T = \frac{2N}{R} = \frac{1}{2R(\Delta A)^2} = \frac{1}{2R(\Delta P \cdot S(\theta))^2} = \frac{1}{2\Delta P^2 \cdot fom}$$

Sherman Function and Target Thickness

$$P = \frac{A}{S_{eff}(\theta)}$$



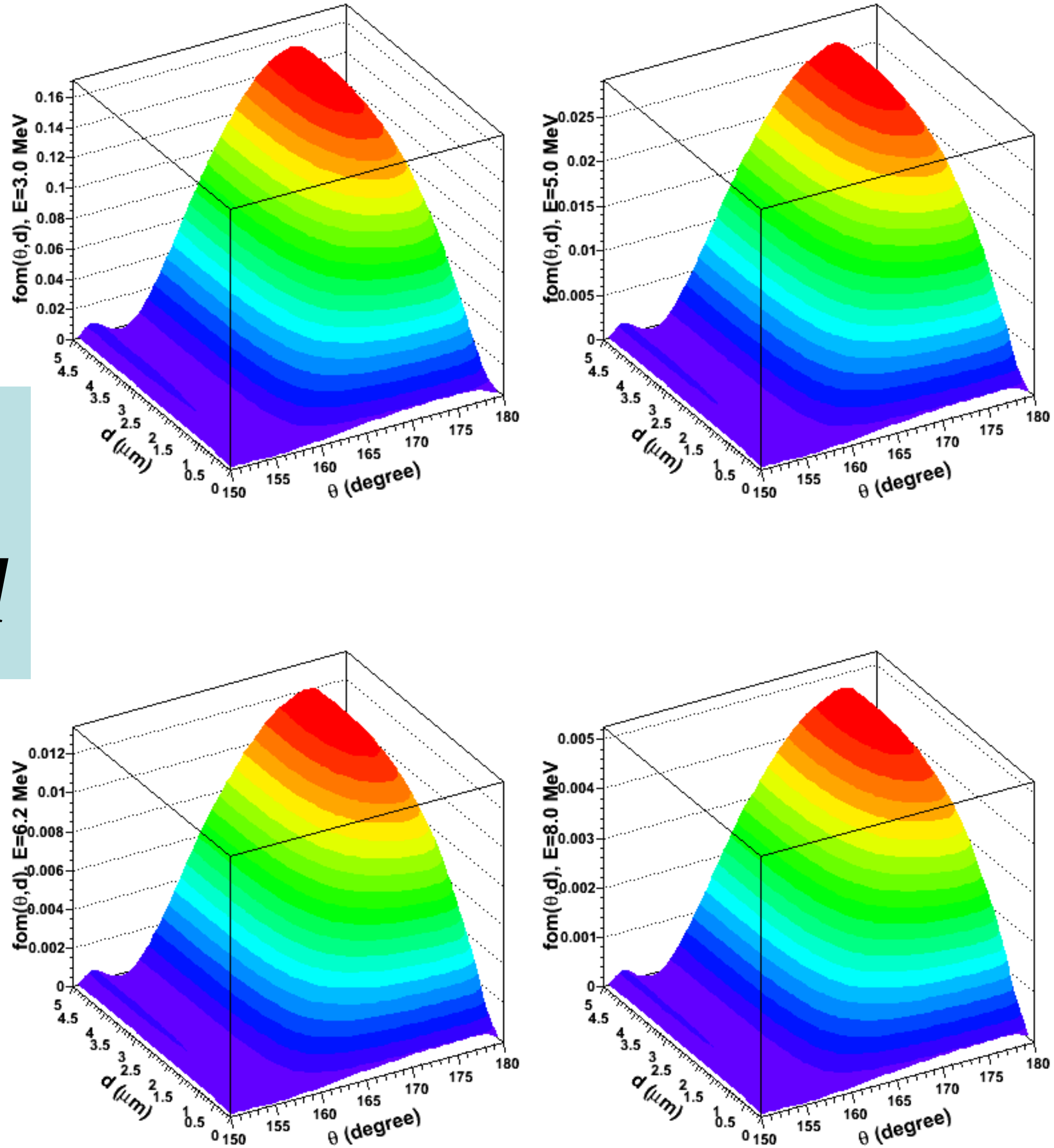
- Single-Atom Sherman Function $S_{SA}(\theta)$ must be corrected for plural scattering (a few large angle scattering) in the target:

$$S_{eff}(\theta, d) = \frac{S_{SA}(\theta)}{1 + \alpha(\theta) \cdot d}$$

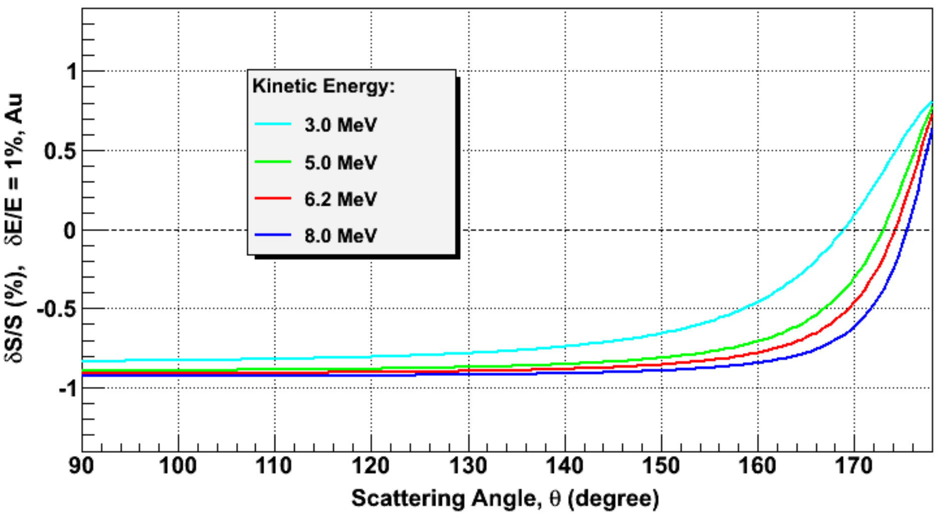
- alpha = 0.3/um for 5 MeV electrons. Depends on electron energy and may depend on scattering angle

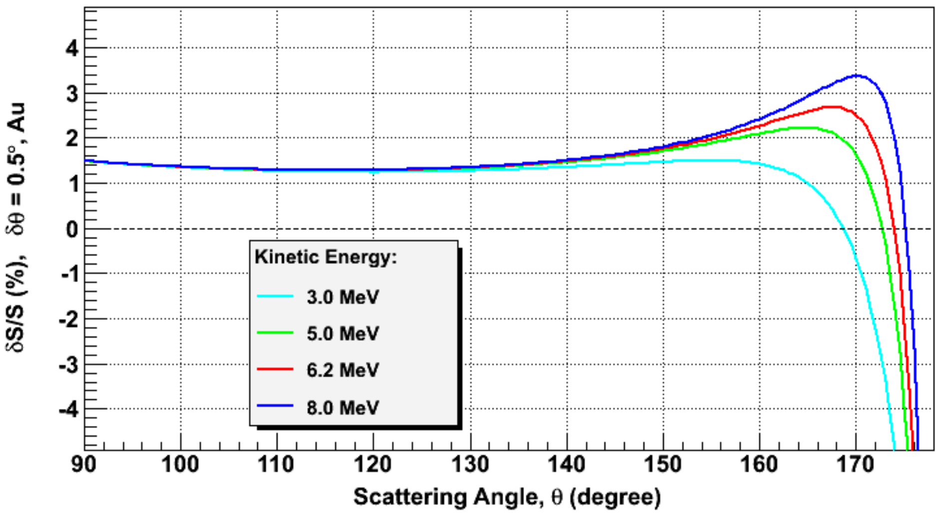
- Run with the thinnest target

$$fom(\theta, d) = I(\theta) \cdot S_{eff}(\theta, d)^2 \cdot d$$

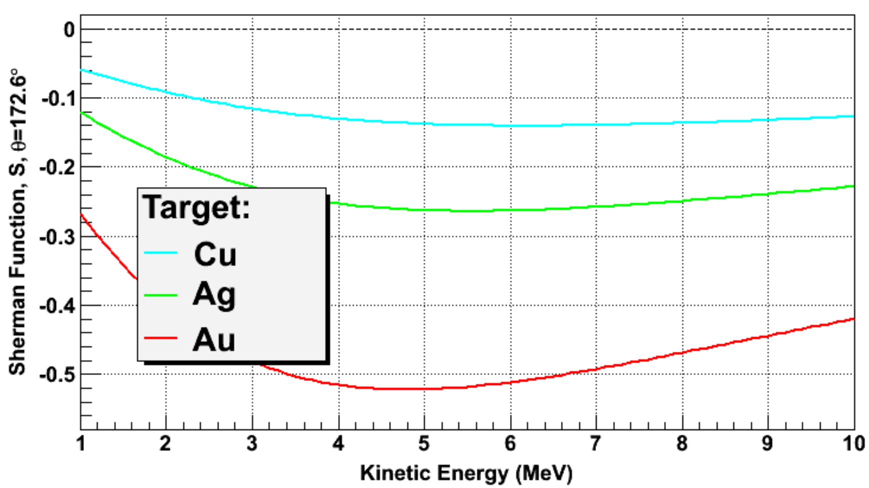


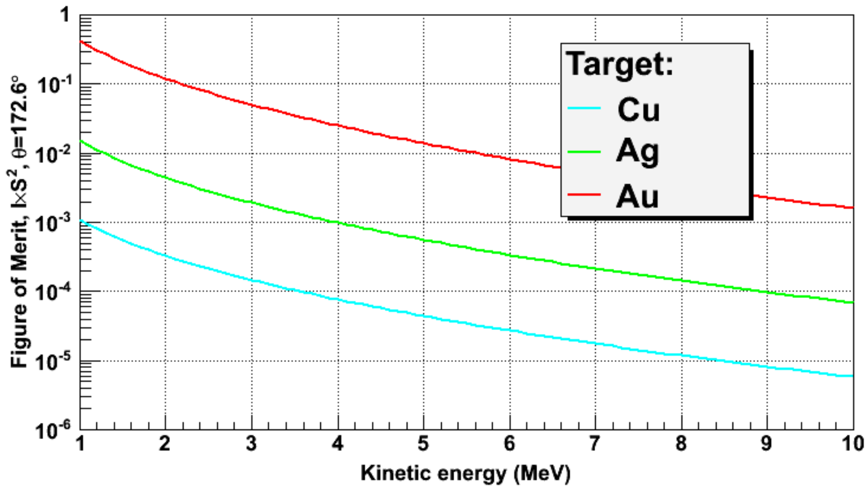
Sherman Function Sensitivity to Energy and Angle

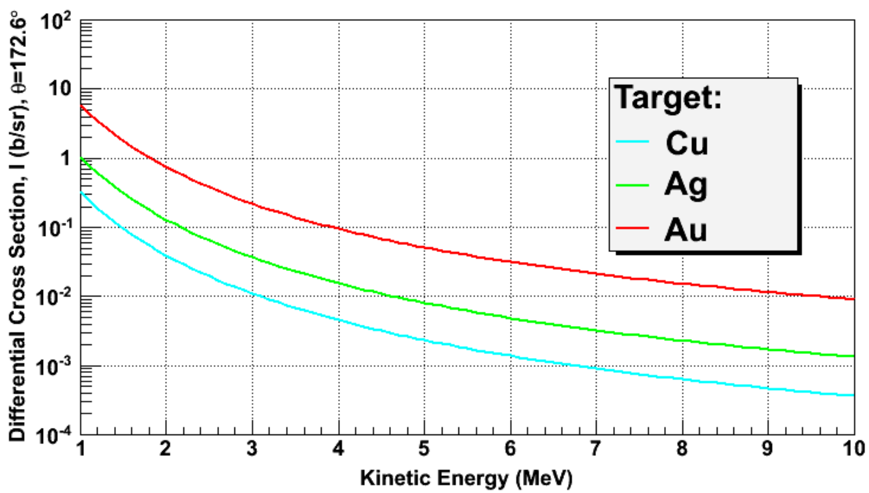


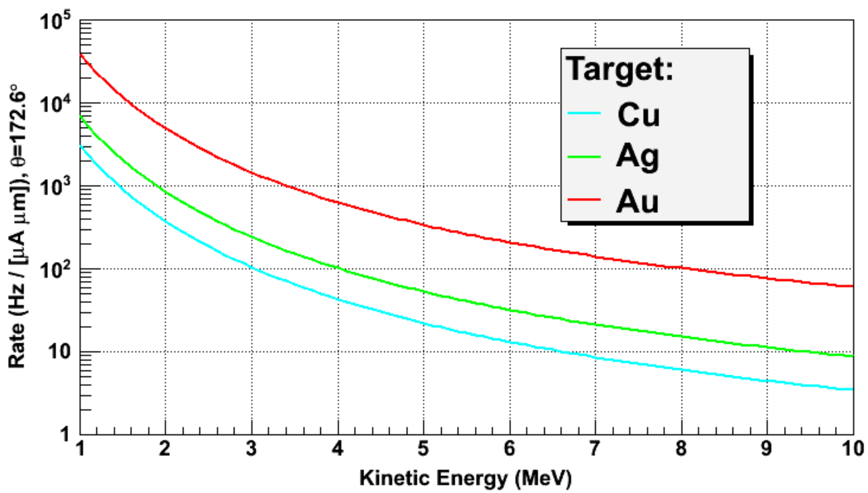


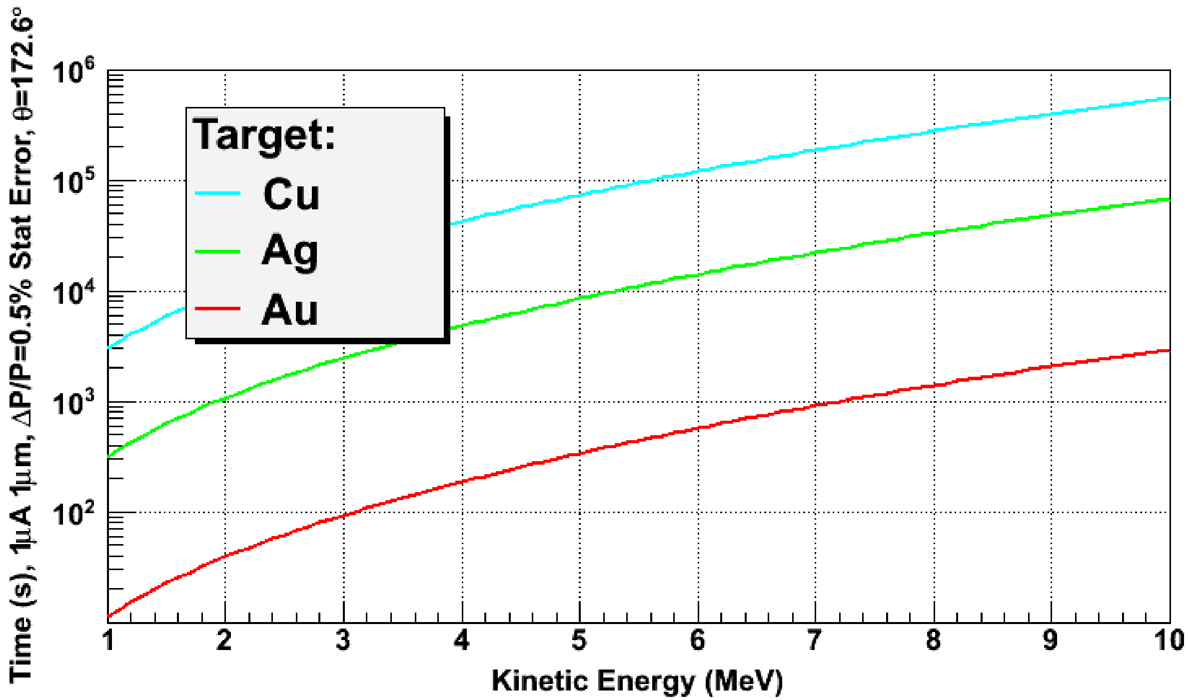
Three Targets (Z=29, 47,79)

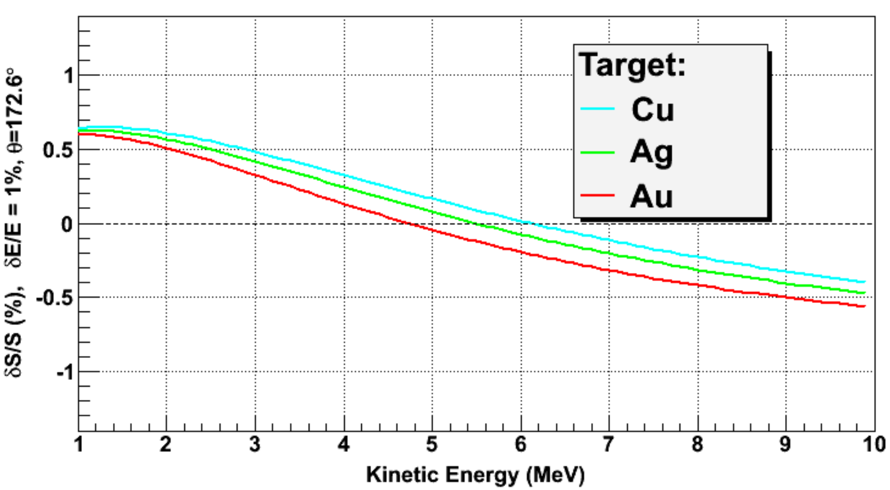


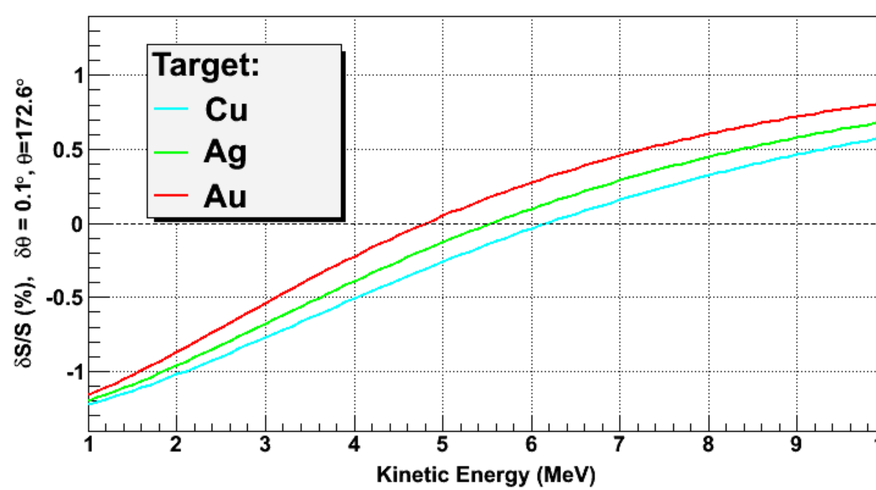







Time (s), 1μA 1μm, ΔP/P=0.5% Stat Error, θ=172.6°
Kinetic Energy (MeV)
Target:
Cu
Ag
Au


δS/S (%), δE/E = 1%, θ=172.6°
Kinetic Energy (MeV)
Target:
Cu
Ag
Au


δS/S (%), δθ = 0.1°, θ=172.6°
Kinetic Energy (MeV)
Target:
Cu
Ag
Au

Corrections to Measured Asymmetry

I. Background

   I. Shielding and Collimation

   II. Coincidence, Time-of-flight

   Or … Subtract background: $N_L^{\uparrow} = \left(N_L^{\uparrow}\right)_{raw} - br_L^{\uparrow}$

$$\left(\frac{\Delta N_L^{\uparrow}}{N_L^{\uparrow}}\right)^2 = \frac{\left(N_L^{\uparrow}\right)_{raw} + br_L^{\uparrow}}{(N_L^{\uparrow})^2}$$

II. Target Thickness:

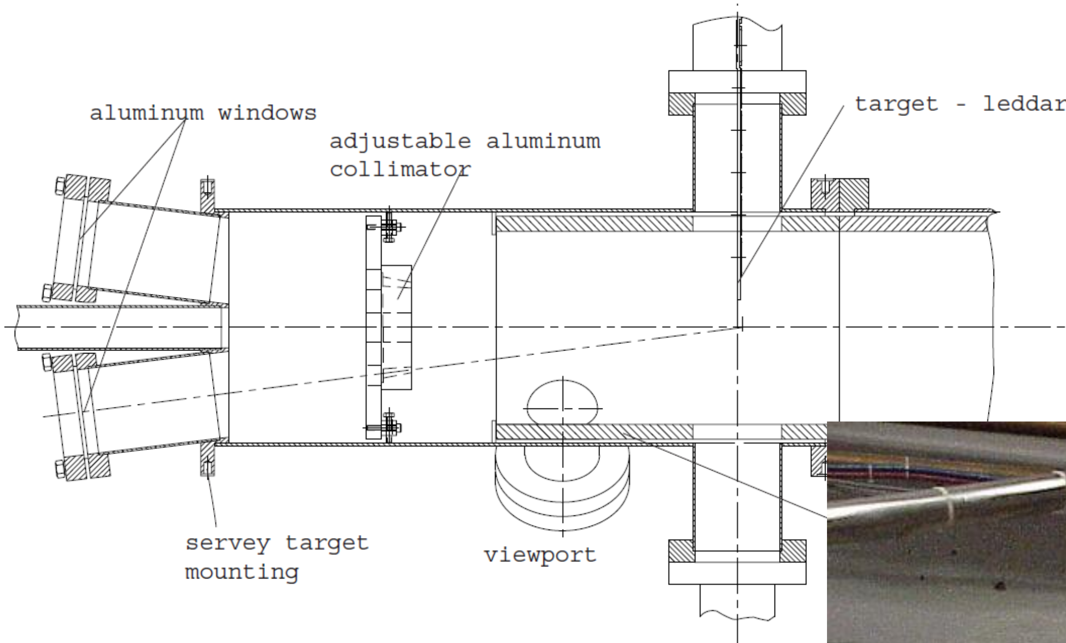
- Single-Atom Sherman Function must be corrected for plural scattering (a few large angle scattering) in target:

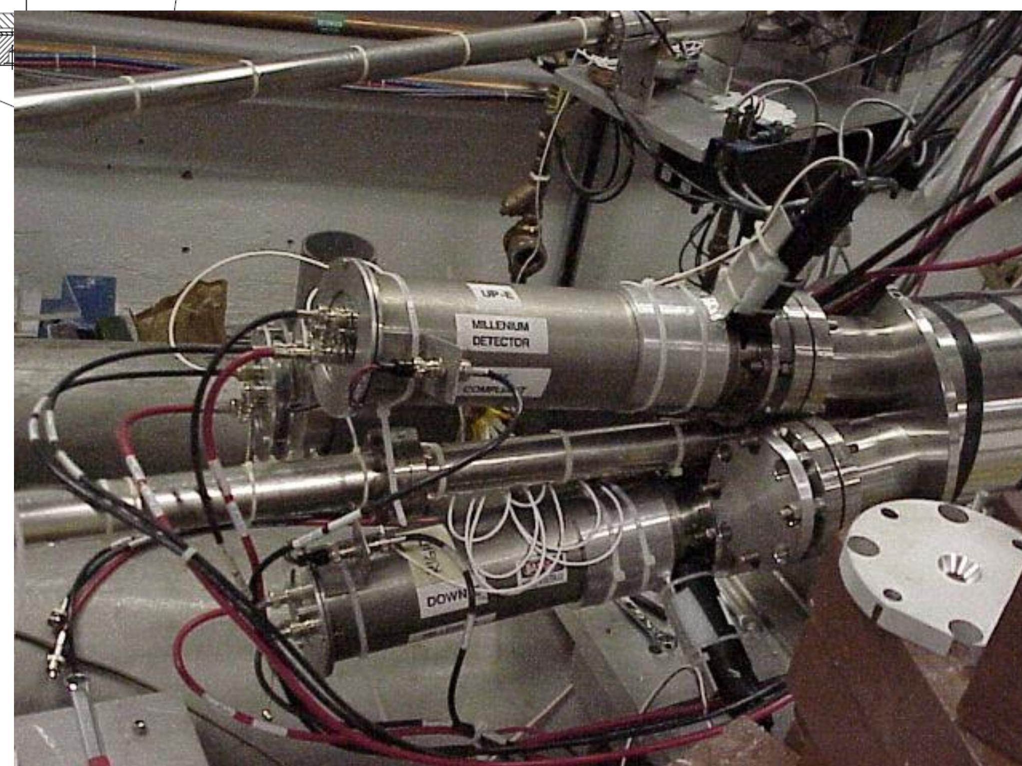
$$S(d) \cong \frac{S_{SA}(0)}{1+\alpha \cdot d}$$

- $S_{SA}(0) = -0.5215$, $S(1.0\ \mu m) = -0.4006$

- If possible, run with the thinnest target

5 MeV Mott Beamline

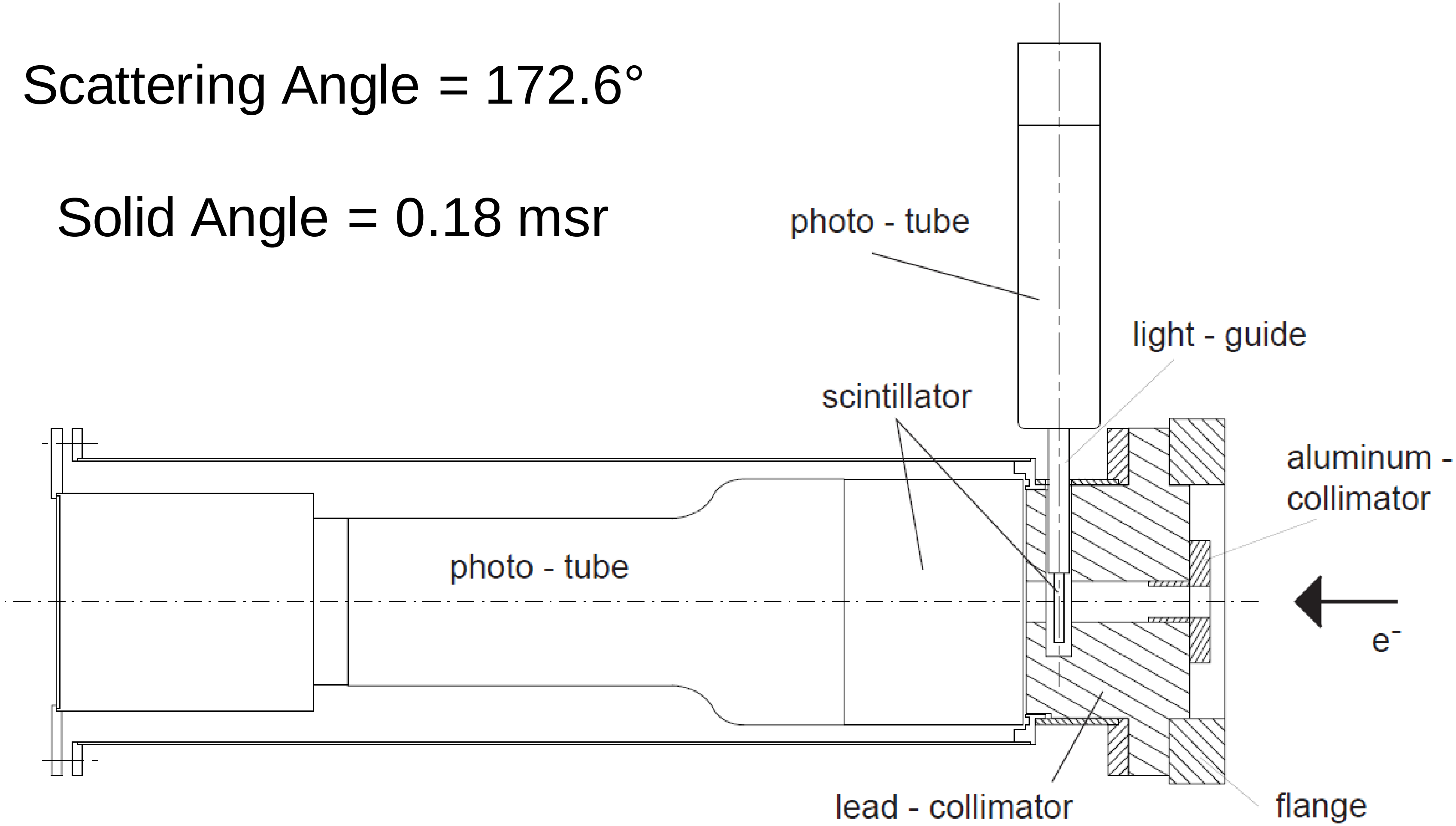




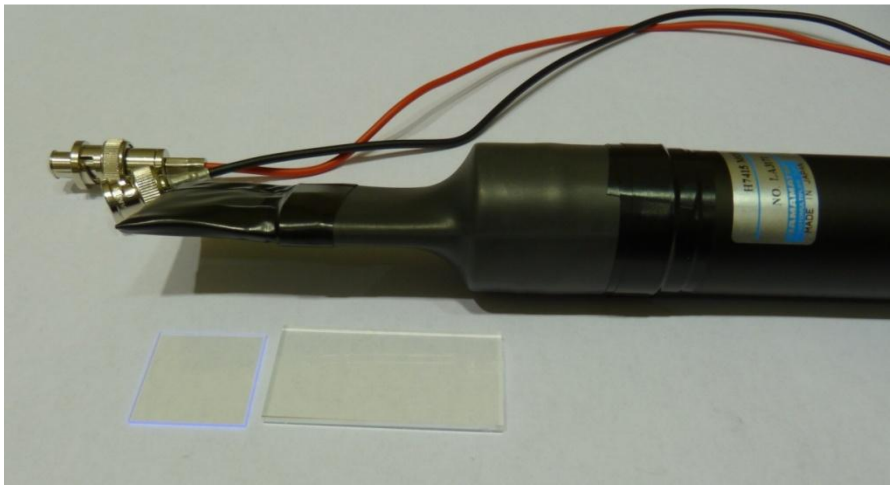
Detector Assembly

I. Scattering Angle = 172.6°

II. Solid Angle = 0.18 msr



New ΔE and E Detectors Installed



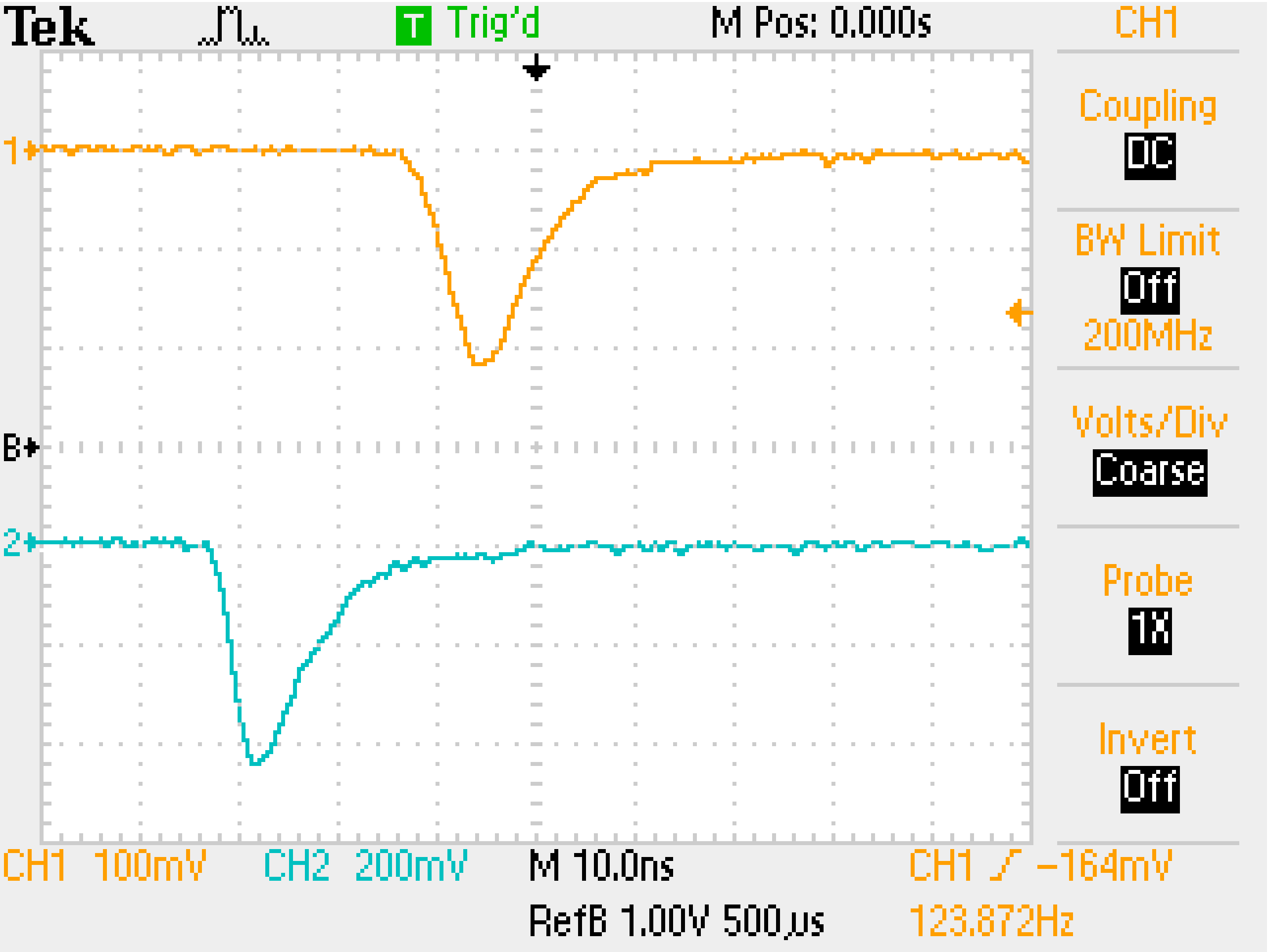
- H7415 (R6427) 1" PMT
- 1 mm x 1" x 1" EJ-212 Plastic Scintillator
- 0.125" x 1" x 2" Acrylic Light Guide

- H6559 (R6091) 3" PMT
- 3" diameter x 2.5" long EJ-200 Plastic Scintillator painted with EJ-510

ΔE and E Signals

ΔE Detector

E Detector

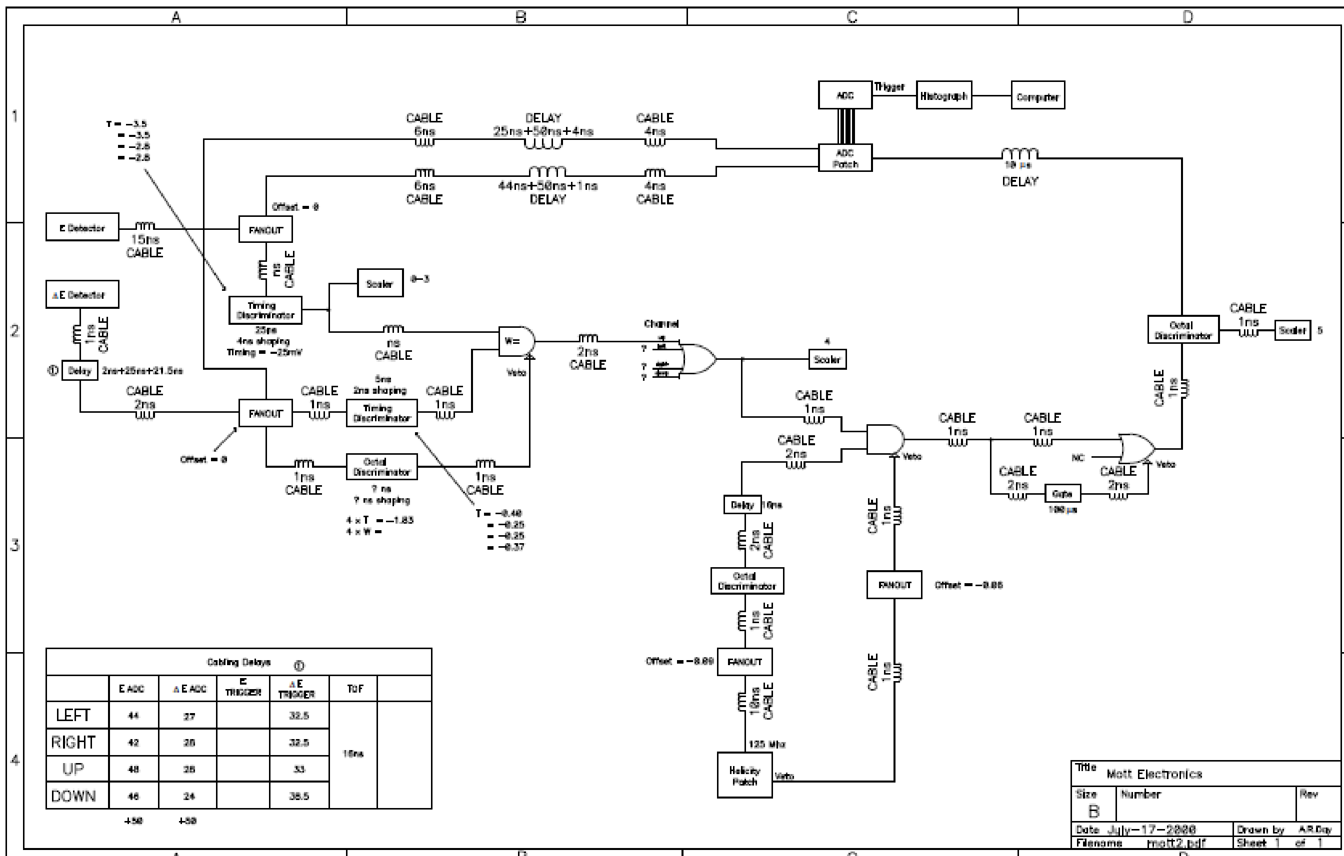


Old 5 MeV Mott DAQ

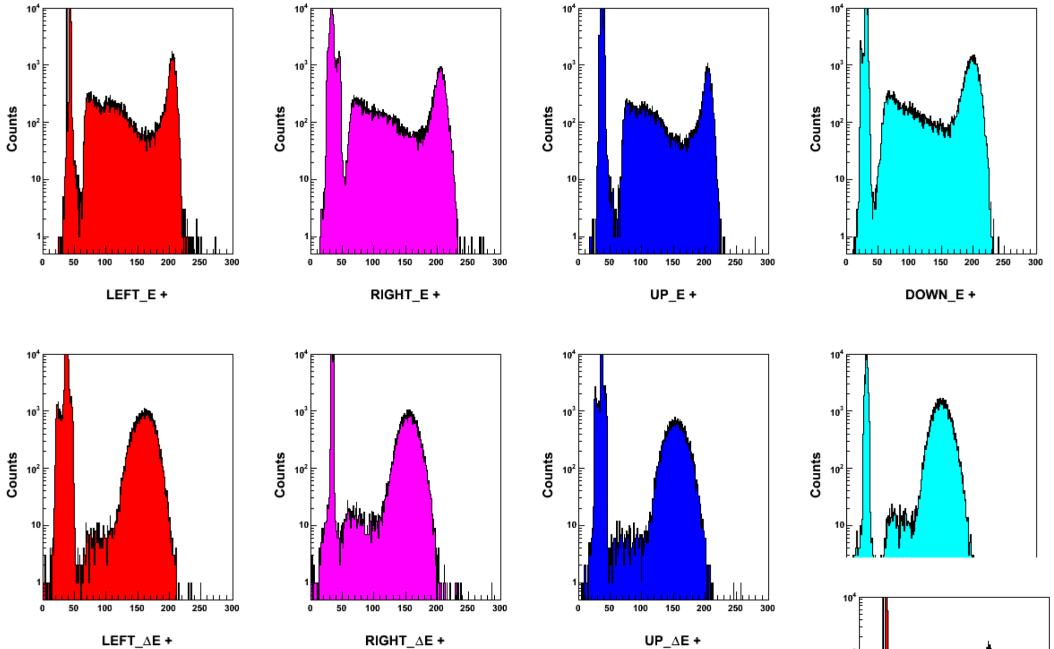
- LeCroy CAMAC 4303 Time-to-FERA Converter (TFC)

- LeCroy CAMAC 4300B Fast Encoding and Readout ADC (FERA), 10 Bit

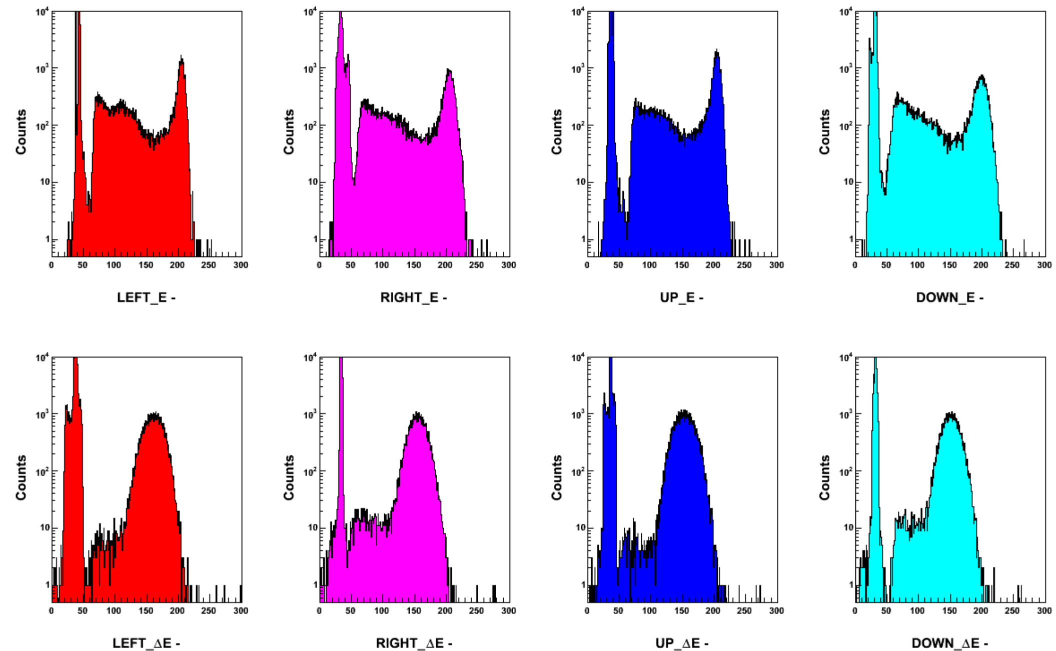
- ORTEC CAMAC HM 413 HISTO-MEMORY



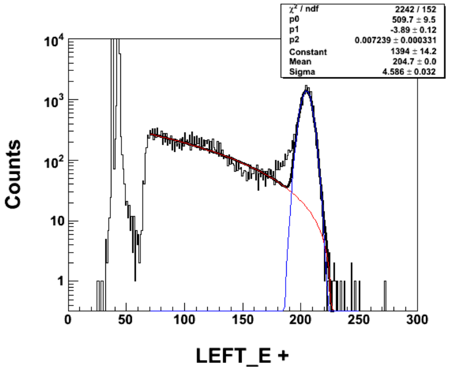
Detectors Spectra

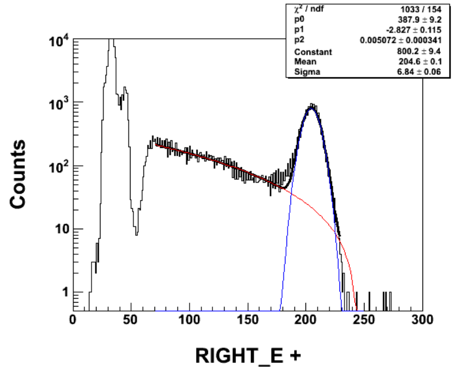


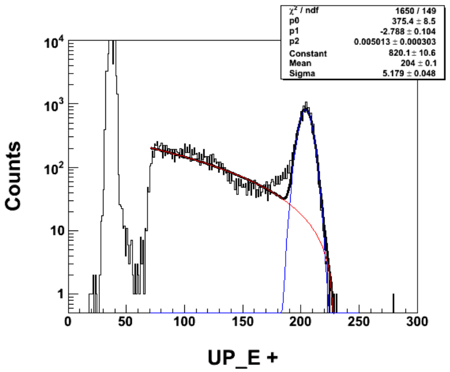
- Beam Current = 0.5 μA
- Gold Target 1.0 μm
- Trigger Rate 1 kHz
- 5 minutes of data

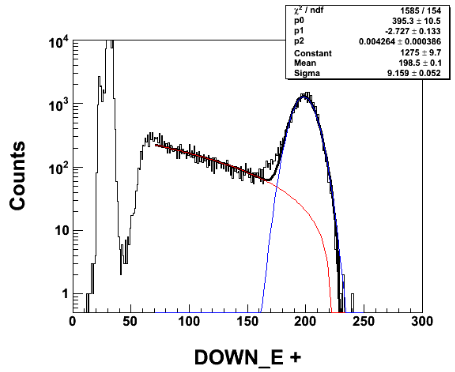


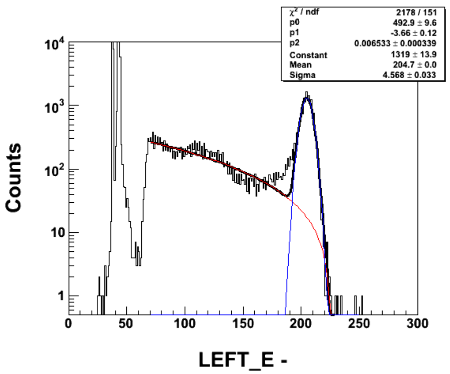
E Detectors Spectra

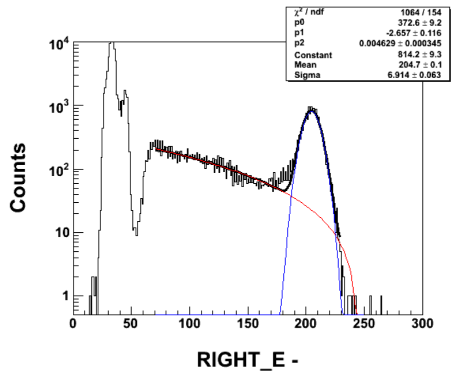


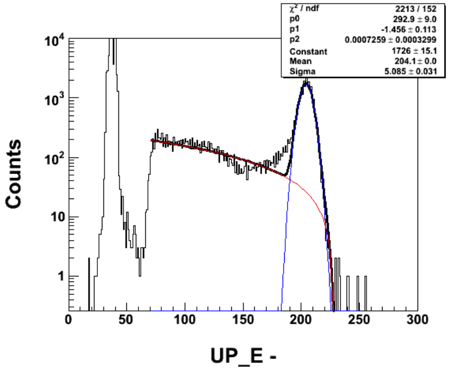


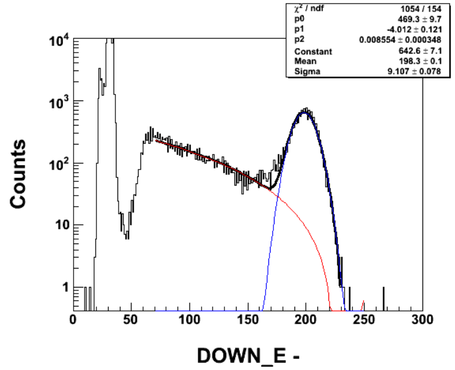




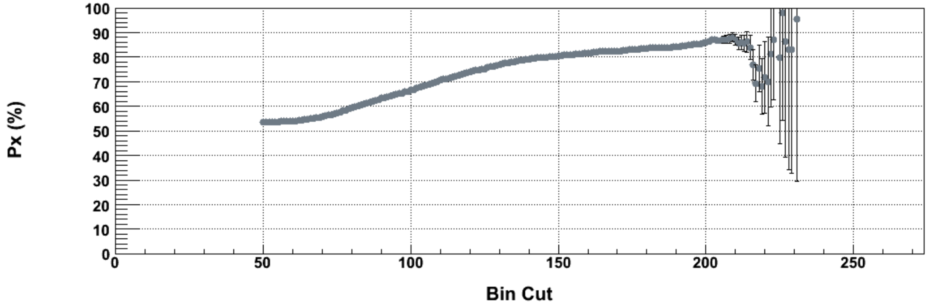






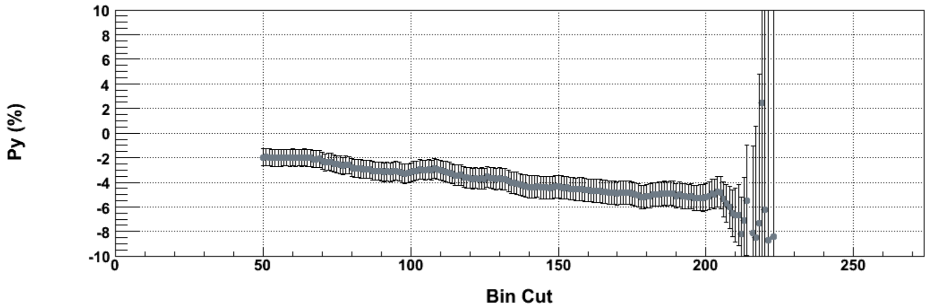


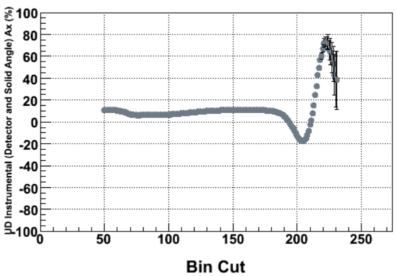
Mott Asymmetries

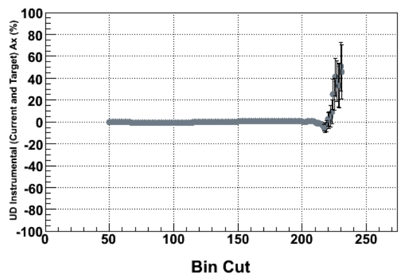


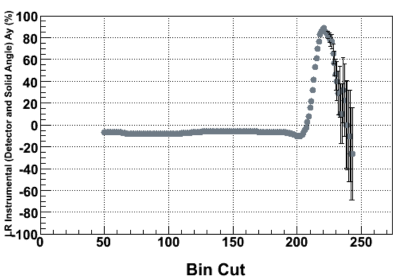
- A_{UD} = 33.98 ± 0.36 %

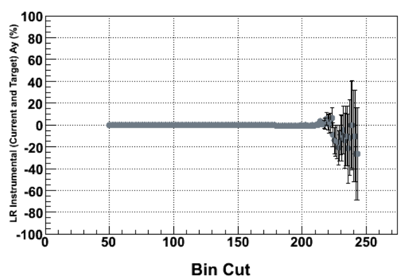
- A_{LR} = -2.11 ± 0.44 %











- UD Instrumental (Detector Efficiency and Solid Angle)
A1 = 12.91 ± 0.40 %

- LR Instrumental (Detector Efficiency and Solid Angle)
A1 = -3.78 ± 0.44 %

- UD Instrumental (Beam Current and Target Thickness)
A2 = 0.75 ± 0.41 %

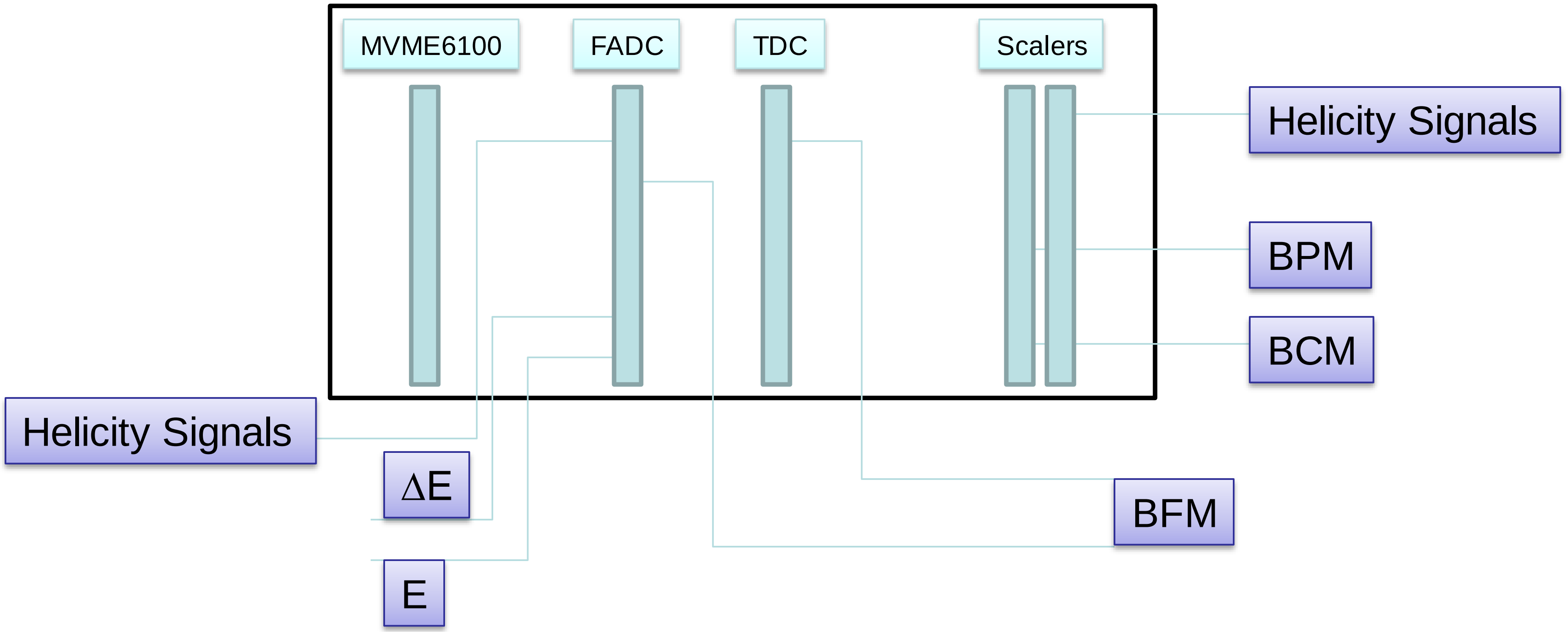
- LR Instrumental (Beam Current and Target Thickness)
A2 = -0.75 ± 0.44 %

New DAQ for Mott Polarimeter

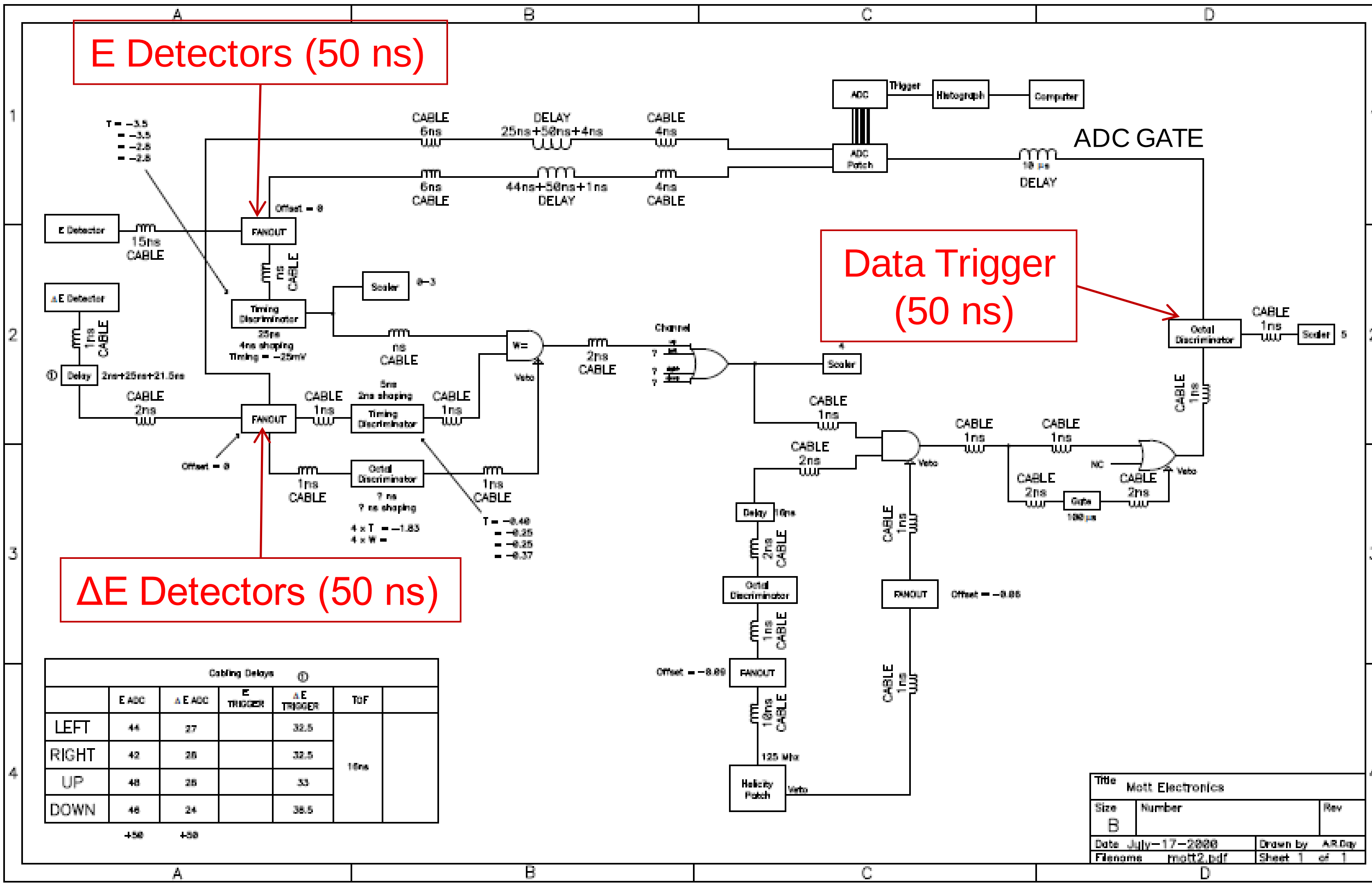
- Will record the pulse shape and timing of detected electrons
- No dead time at rates <5 kHz, will be able to run at higher currents
- Can process delayed helicity reporting and measure time-of-flight of detected electrons

- Consists of:
  - CODA (CEBAF Online Data Acquisition)
  - Hardware:
    - VME64x Backplane 6U Crate
    - Motorola MVME6100
    - JLab Flash ADC: 16 channel, 12 bit, 250 MS/s
    - SIS 3801 Scalers: Beam current and position
    - CAEN V775 TDC: BFM

DAQ Schematic Diagram

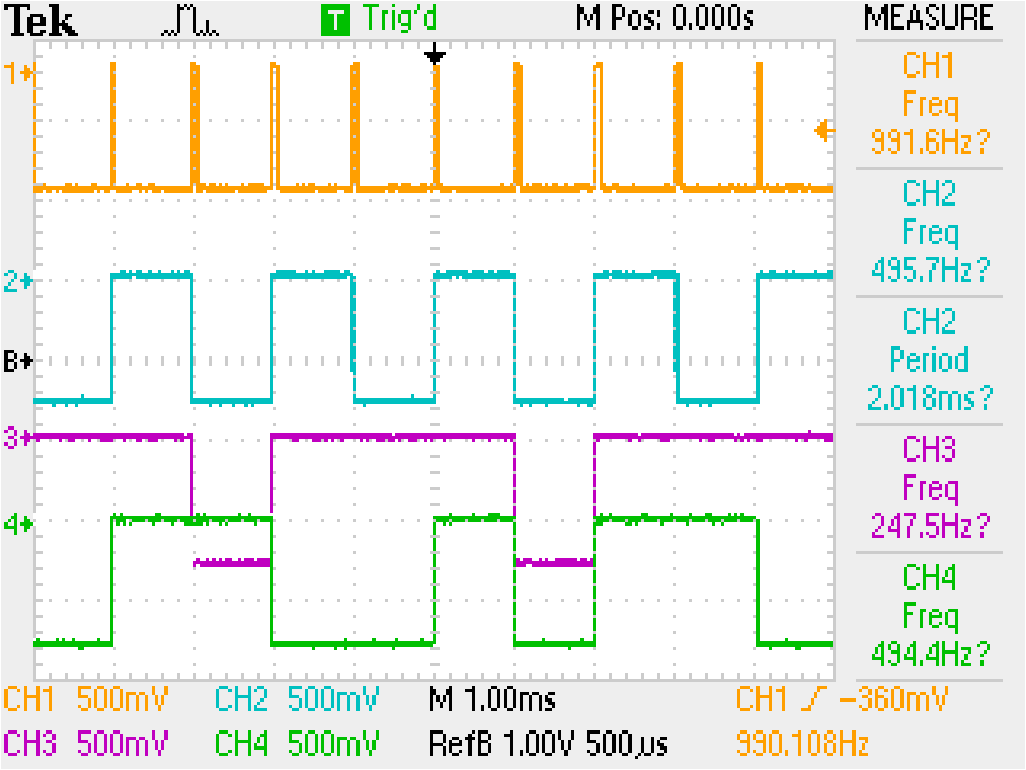


Detector Signals to fADC
(Parasitic to old DAQ)



Cabling Delays ①						
	E ADC	ΔE ADC	E TRIGGER	ΔE TRIGGER	TOF	
LEFT	44	27		32.5	16ns	
RIGHT	42	28		32.5		
UP	48	28		33		
DOWN	46	24		38.5		
	+50	+50				

Helicity Signals



T- Settle

Pair Sync

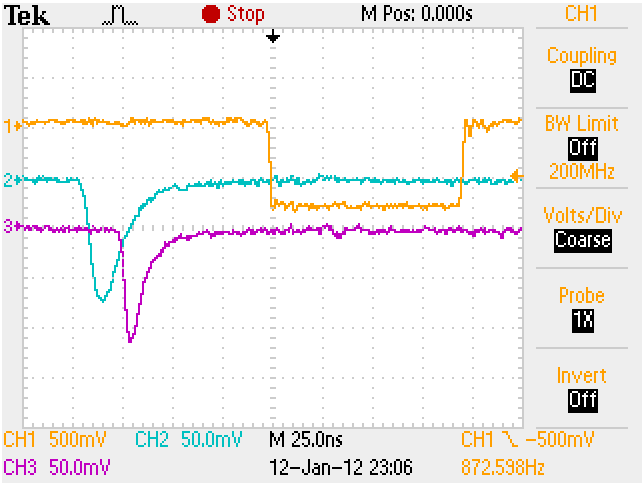
Pattern Sync

Delayed Helicity

FADC Signals

FADC Chan	Signal
0	E LEFT
1	E RIGHT
2	E UP
3	E DOWN
4	ΔE LEFT
5	ΔE RIGHT
6	ΔE UP
7	ΔE DOWN
8	BFM
9	
10	Mott Trigger
11	
12	Delayed Helicity
13	T_Settle
14	Pattern-Sync
15	Pair-Sync

Signals on Scope

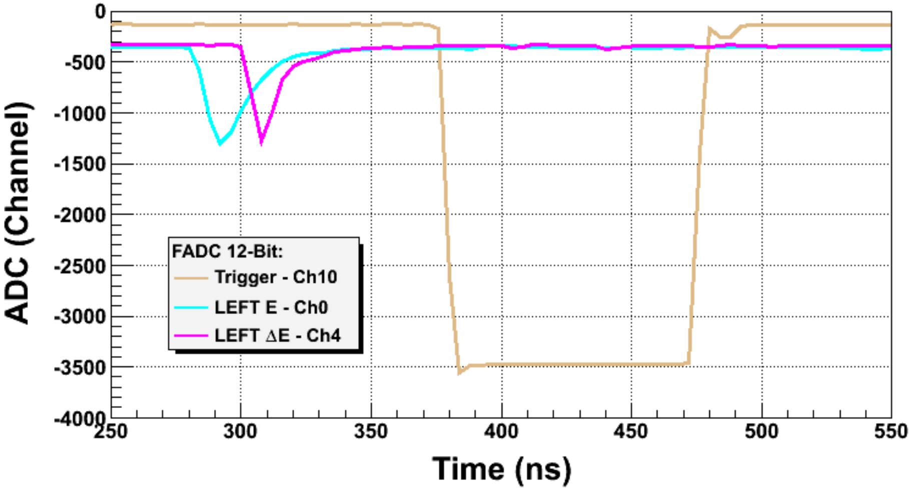


Mott Trigger

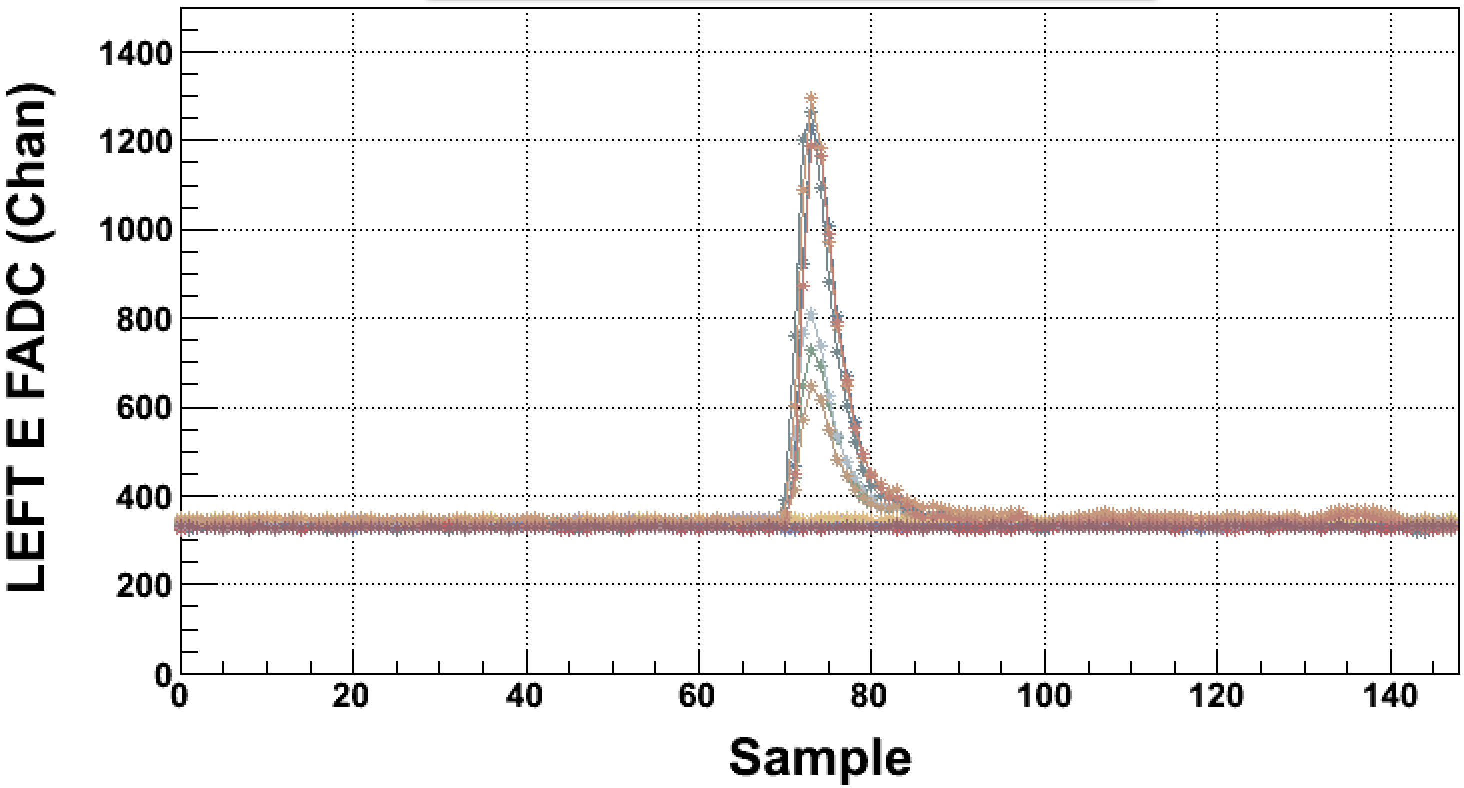
Left E

Left ΔE

Signals in FADC Data



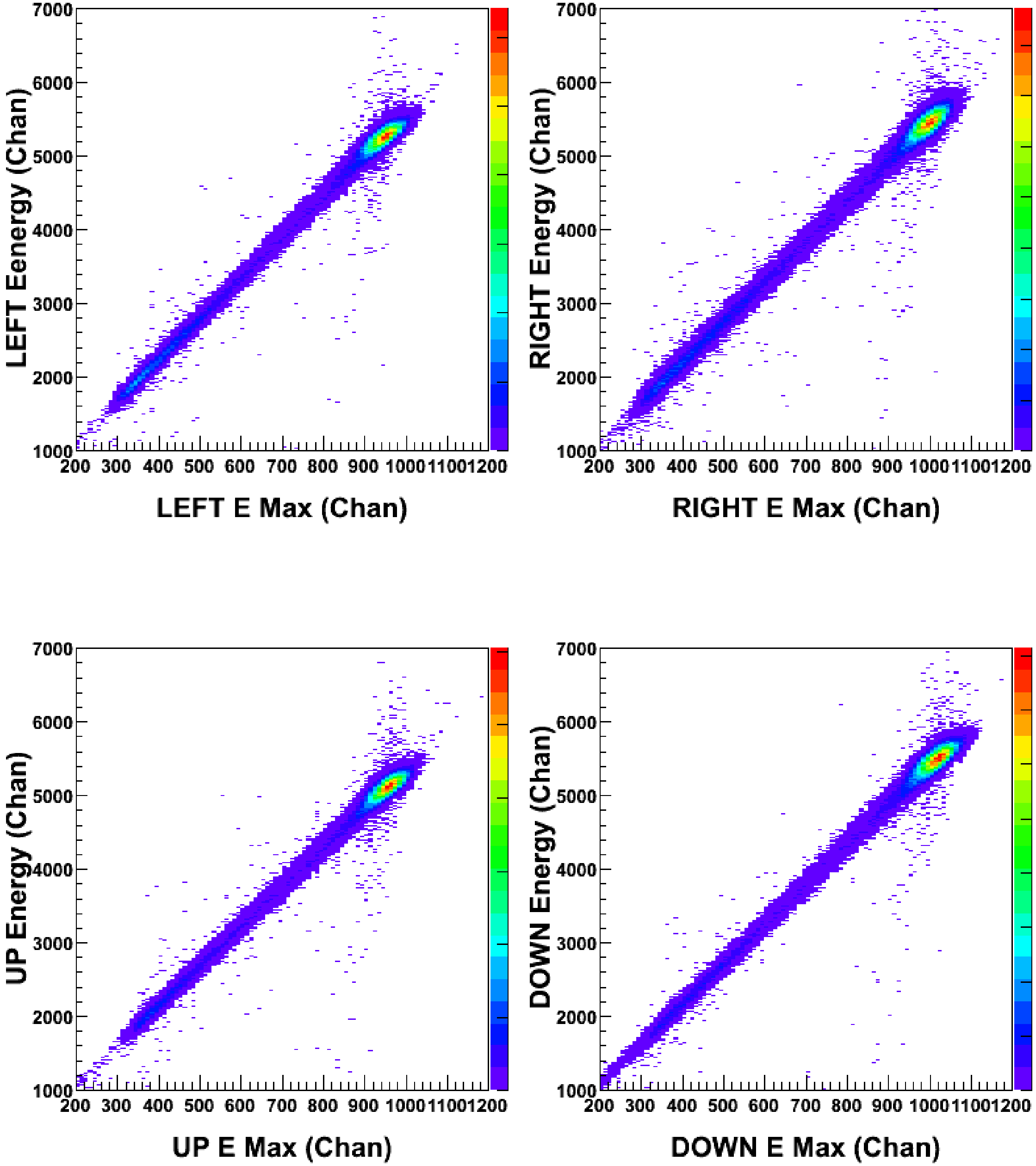
Few FADC Events in LEFT Detector

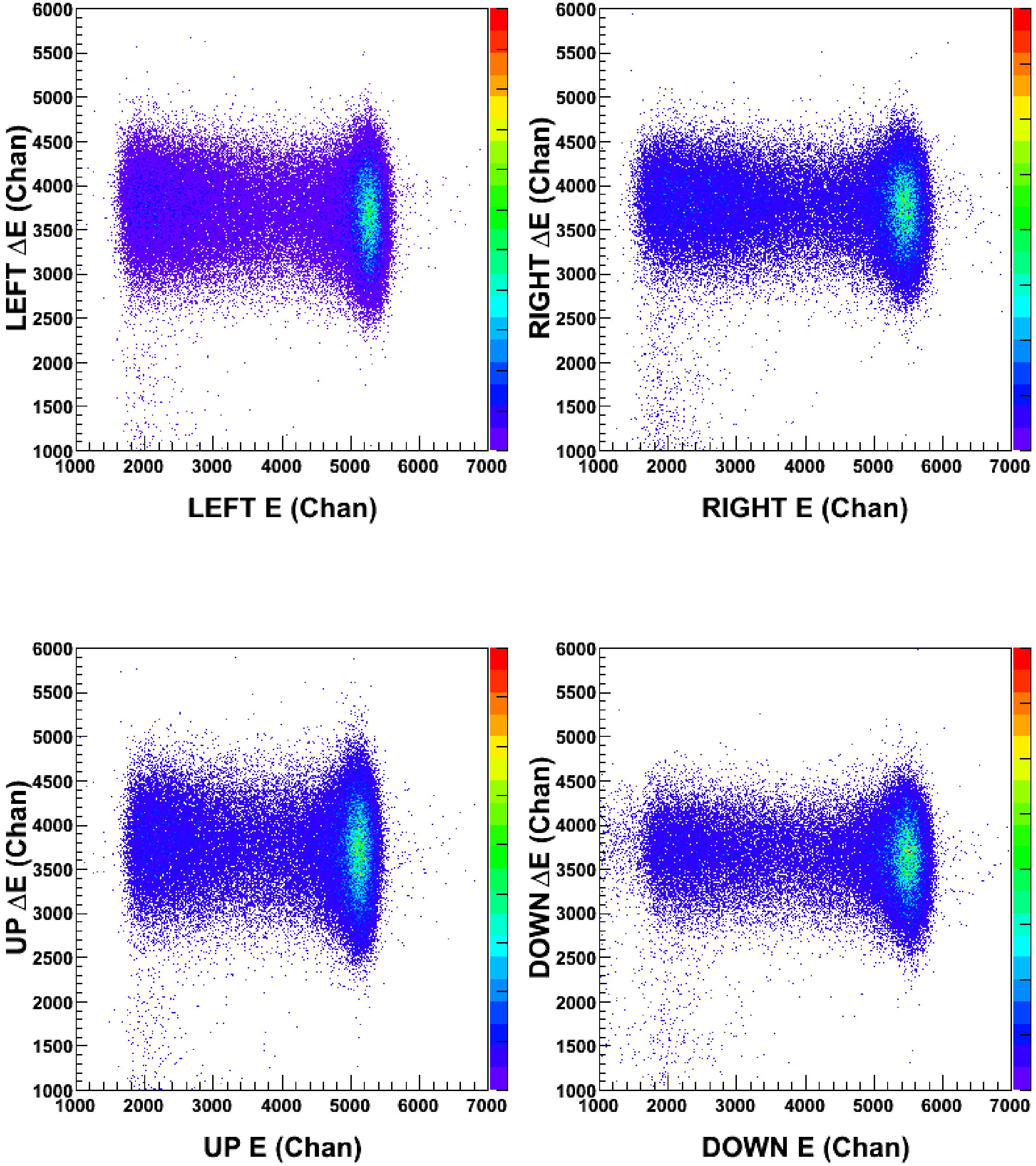


Calculate pedestal and Energy:

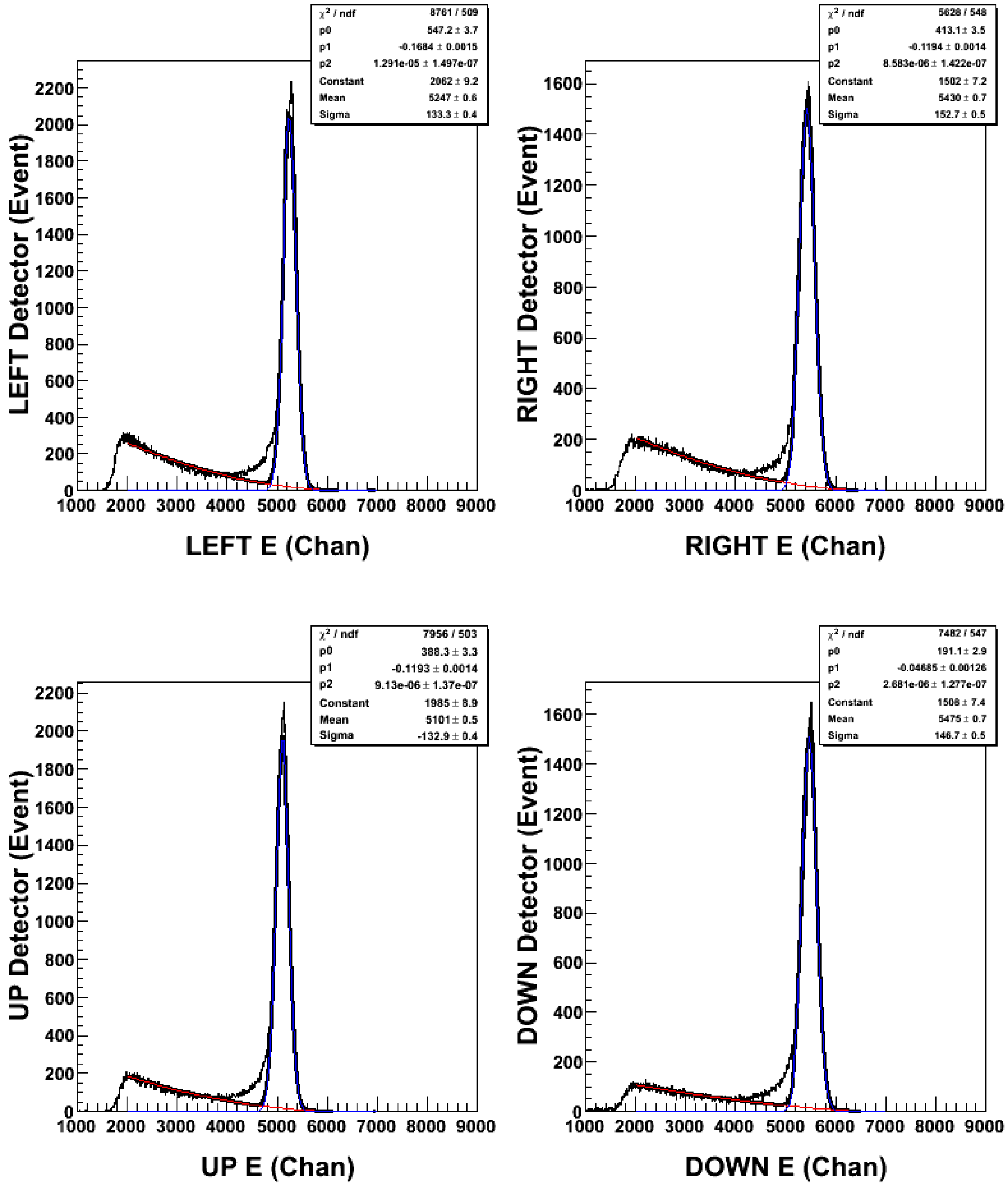
$$Pedestal = \frac{1}{5}\sum_{sample=60}^{64} ADC$$

$$E = \sum_{sample=60}^{97} ADC - 38 \times Pedestal$$


LEFT Eenergy (Chan)
LEFT E Max (Chan)
RIGHT Energy (Chan)
RIGHT E Max (Chan)
UP Energy (Chan)
UP E Max (Chan)
DOWN Energy (Chan)
DOWN E Max (Chan)
1000
2000
3000
4000
5000
6000
7000
200 300 400 500 600 700 800 900 1000 1100 1200

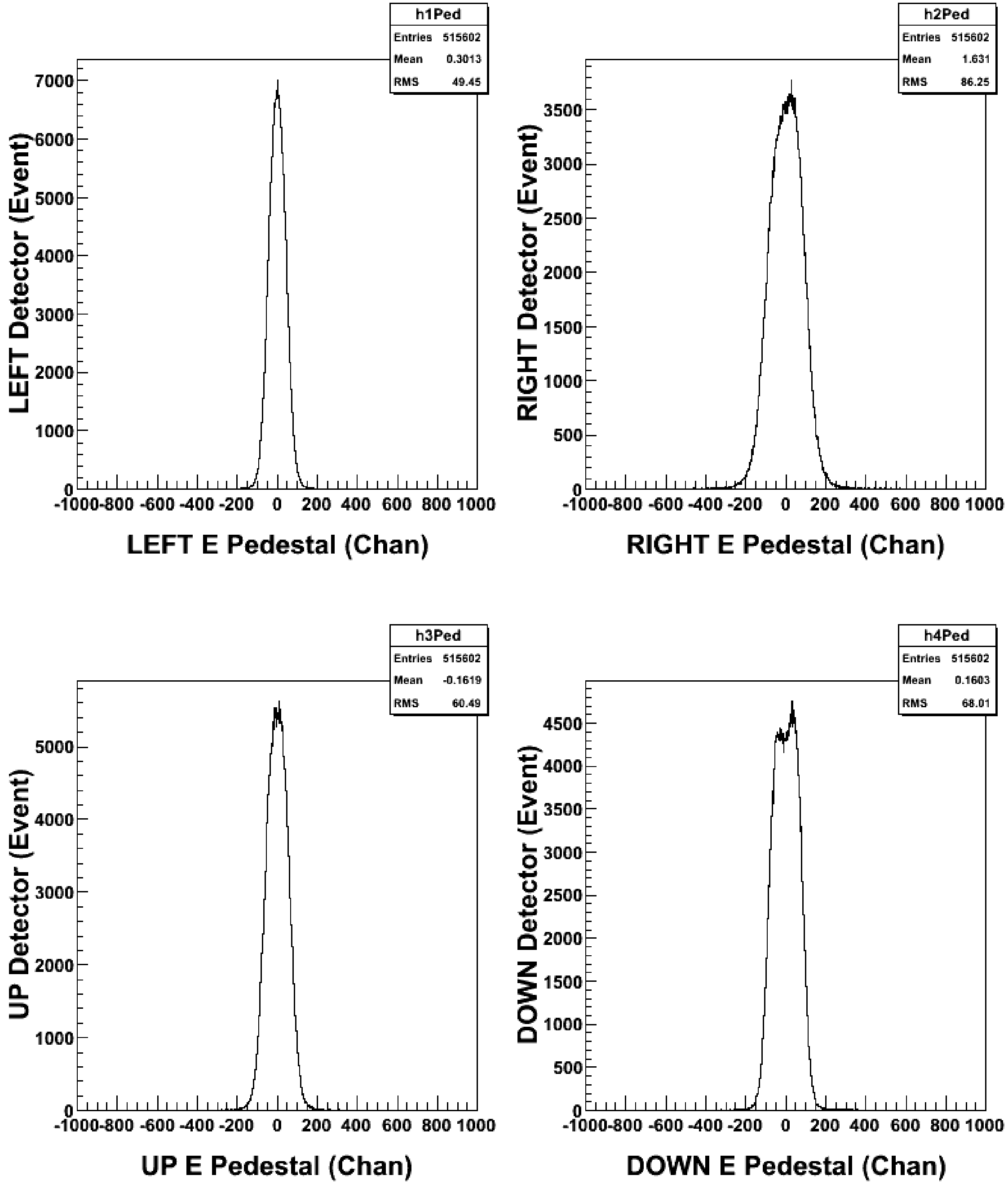

LEFT ΔE (Chan)
LEFT E (Chan)
RIGHT ΔE (Chan)
RIGHT E (Chan)
UP ΔE (Chan)
UP E (Chan)
DOWN ΔE (Chan)
DOWN E (Chan)

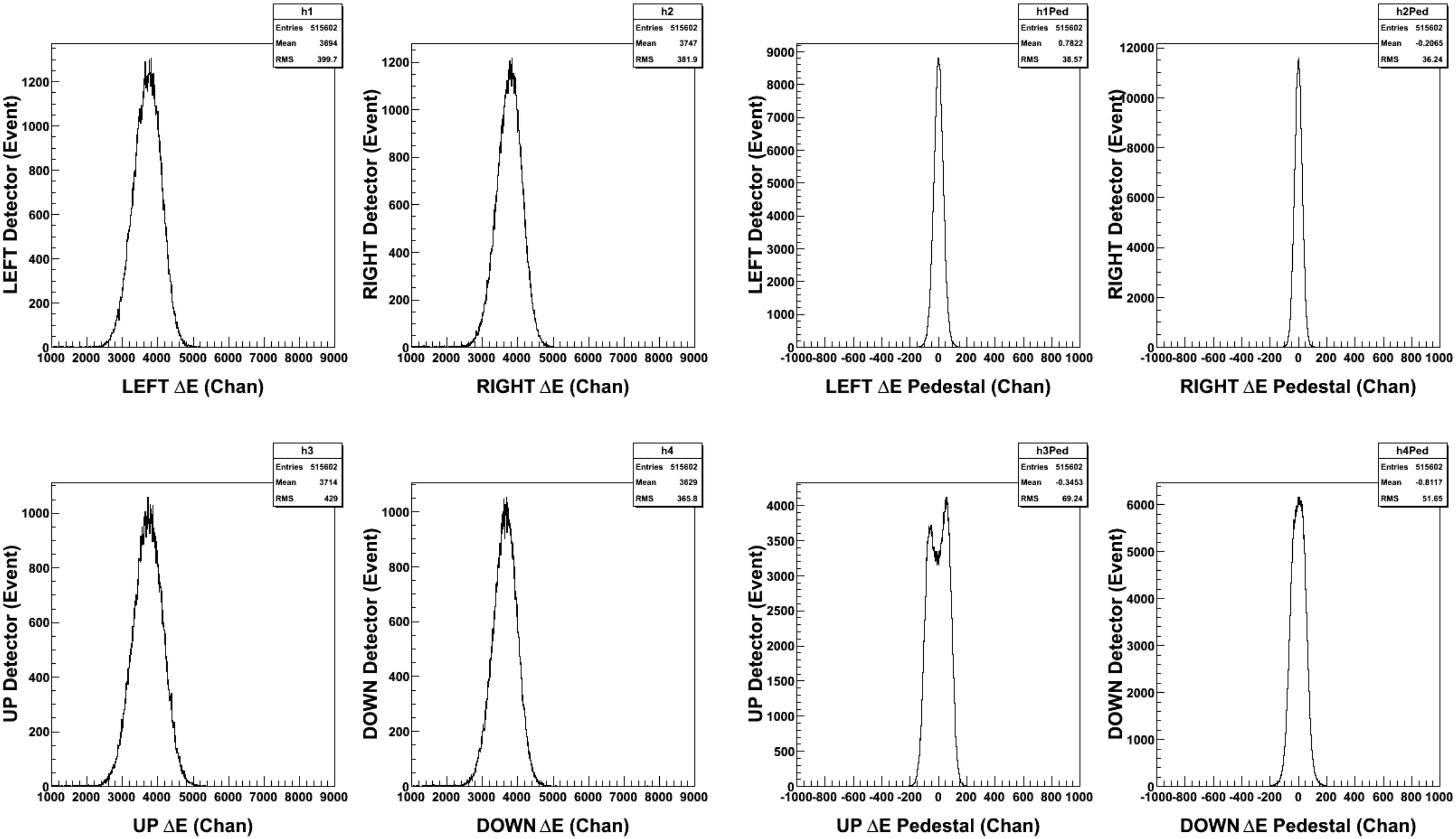
Energy Resolution=2.7% (same as old DAQ)



Pedestal Resolution

Energy Resolution=2.4% (after Pedestal Correction)




h1
Entries 515602
Mean 3694
RMS 399.7
LEFT Detector (Event)
LEFT ΔE (Chan)
h2
Entries 515602
Mean 3747
RMS 381.9
RIGHT Detector (Event)
RIGHT ΔE (Chan)
h1Ped
Entries 515602
Mean 0.7822
RMS 38.57
LEFT Detector (Event)
LEFT ΔE Pedestal (Chan)
h2Ped
Entries 515602
Mean -0.2065
RMS 36.24
RIGHT Detector (Event)
RIGHT ΔE Pedestal (Chan)
h3
Entries 515602
Mean 3714
RMS 429
UP Detector (Event)
UP ΔE (Chan)
h4
Entries 515602
Mean 3629
RMS 365.8
DOWN Detector (Event)
DOWN ΔE (Chan)
h3Ped
Entries 515602
Mean -0.3453
RMS 69.24
UP Detector (Event)
UP ΔE Pedestal (Chan)
h4Ped
Entries 515602
Mean -0.8117
RMS 51.65
DOWN Detector (Event)
DOWN ΔE Pedestal (Chan)

Mott Asymmetry

Data with Old DAQ

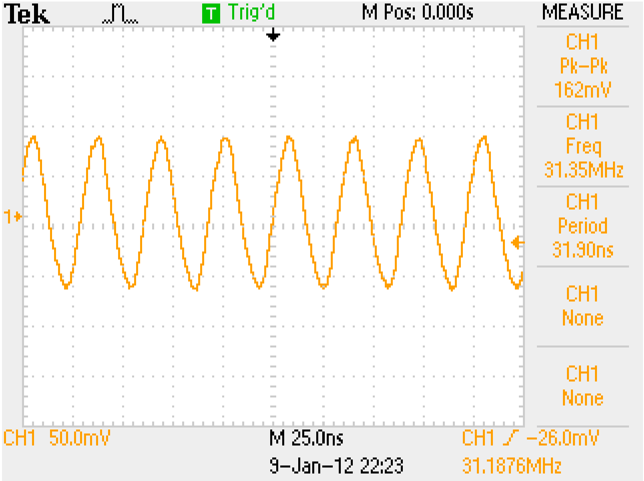
IHWP	FILE	P_V	P_X
OUT	16Feb12 08:30:41	86.9 +/- 1.1 (stat)	1.6 +/- 1.2 (stat)
IN	16Feb12 08:36:18	-87.3 +/- 1.1 (stat)	-2.7 +/- 1.1 (stat)
OUT	16Feb12 08:54:56	86.3 +/- 1.1 (stat)	2.7 +/- 1.2 (stat)
IN	16Feb12 08:54:56	-85.7 +/- 1.1 (stat)	-4.1 +/- 1.1 (stat)
AVERAGE		86.6 +/- 0.6 (stat)	2.8 +/- 0.6 (stat)

Difference due to different energy cuts in analysis

Simultaneous Data with New DAQ

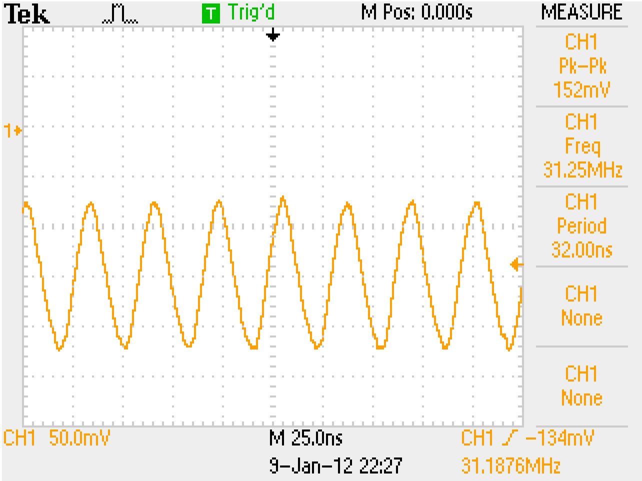
IHWP	Run #	P_V	P_X
OUT	2652	86.4 +/- 1.1 (stat)	0.6 +/- 1.2 (stat)
IN	2653	-85.6 +/- 1.0 (stat)	-3.4 +/- 1.1 (stat)
OUT	2654	85.2 +/- 1.1 (stat)	2.4 +/- 1.2 (stat)
IN	2655	-85.6 +/- 1.0 (stat)	-3.0 +/- 1.0 (stat)
AVERAGE		85.7 +/- 0.5 (stat)	2.4 +/- 0.6 (stat)

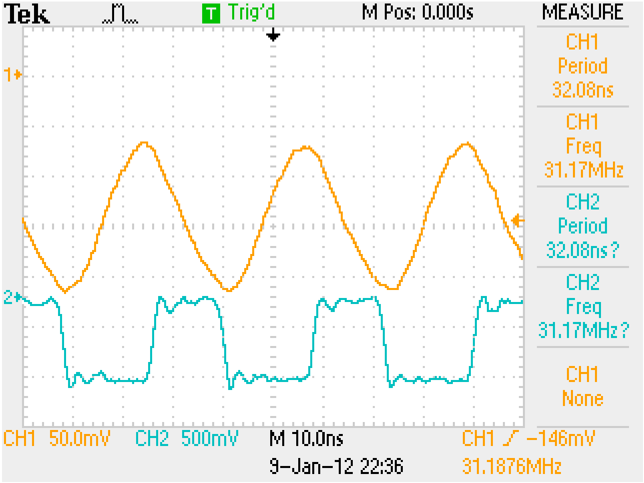
BFM Signal



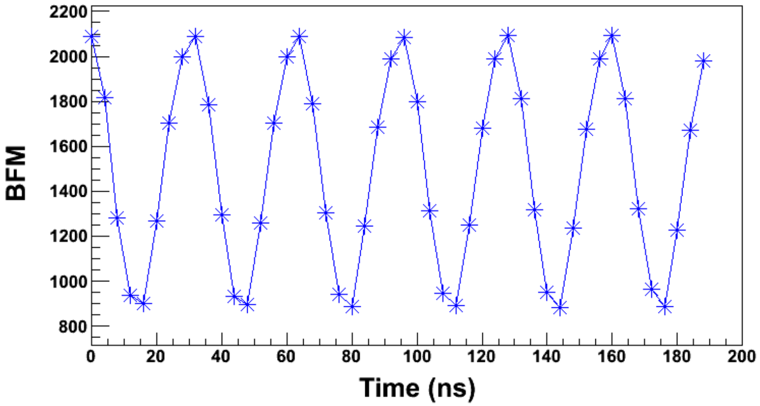
BFM

BFM after
-140 mV offset



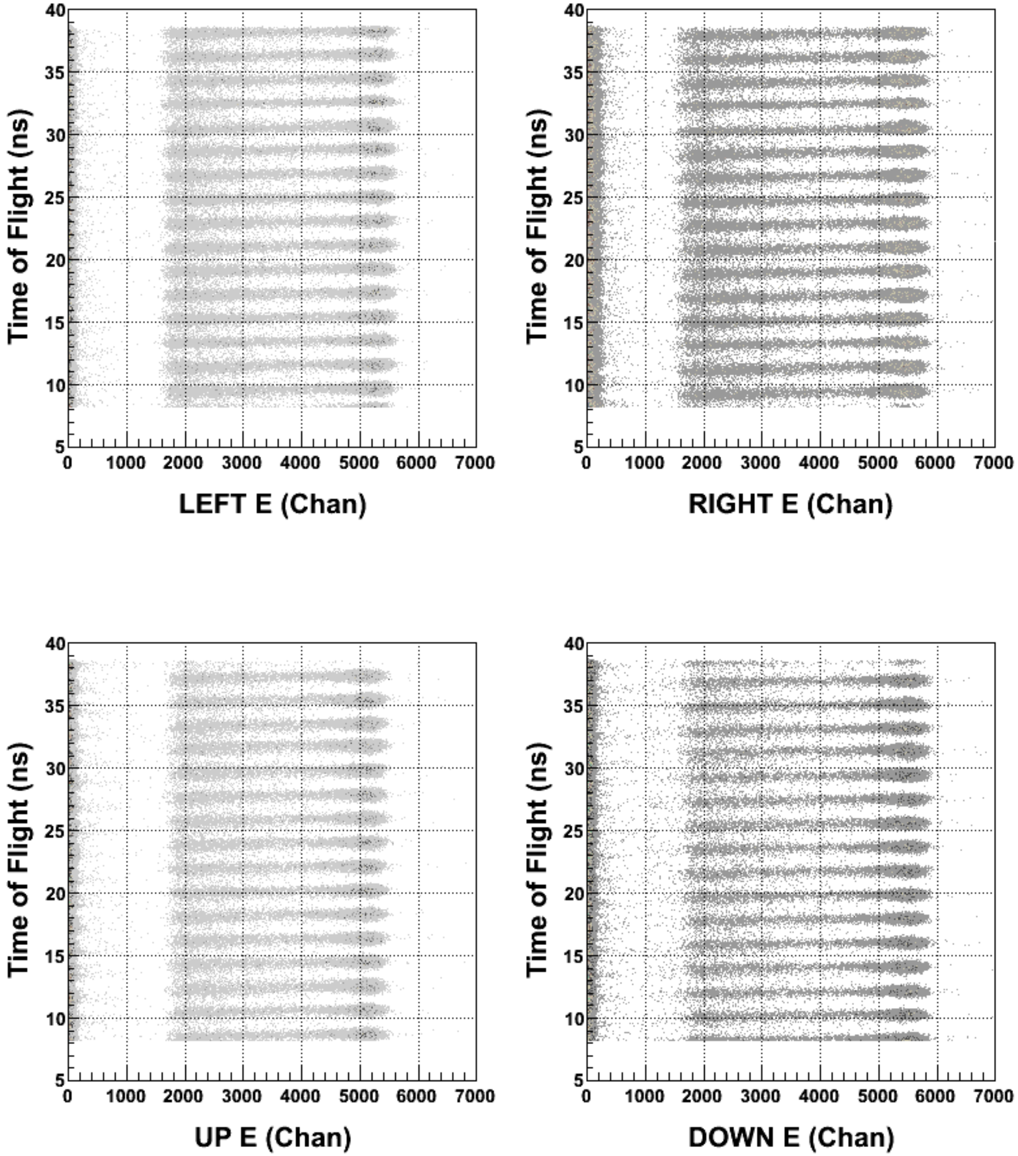


BFM after
-145 mV discrimination (TDC)



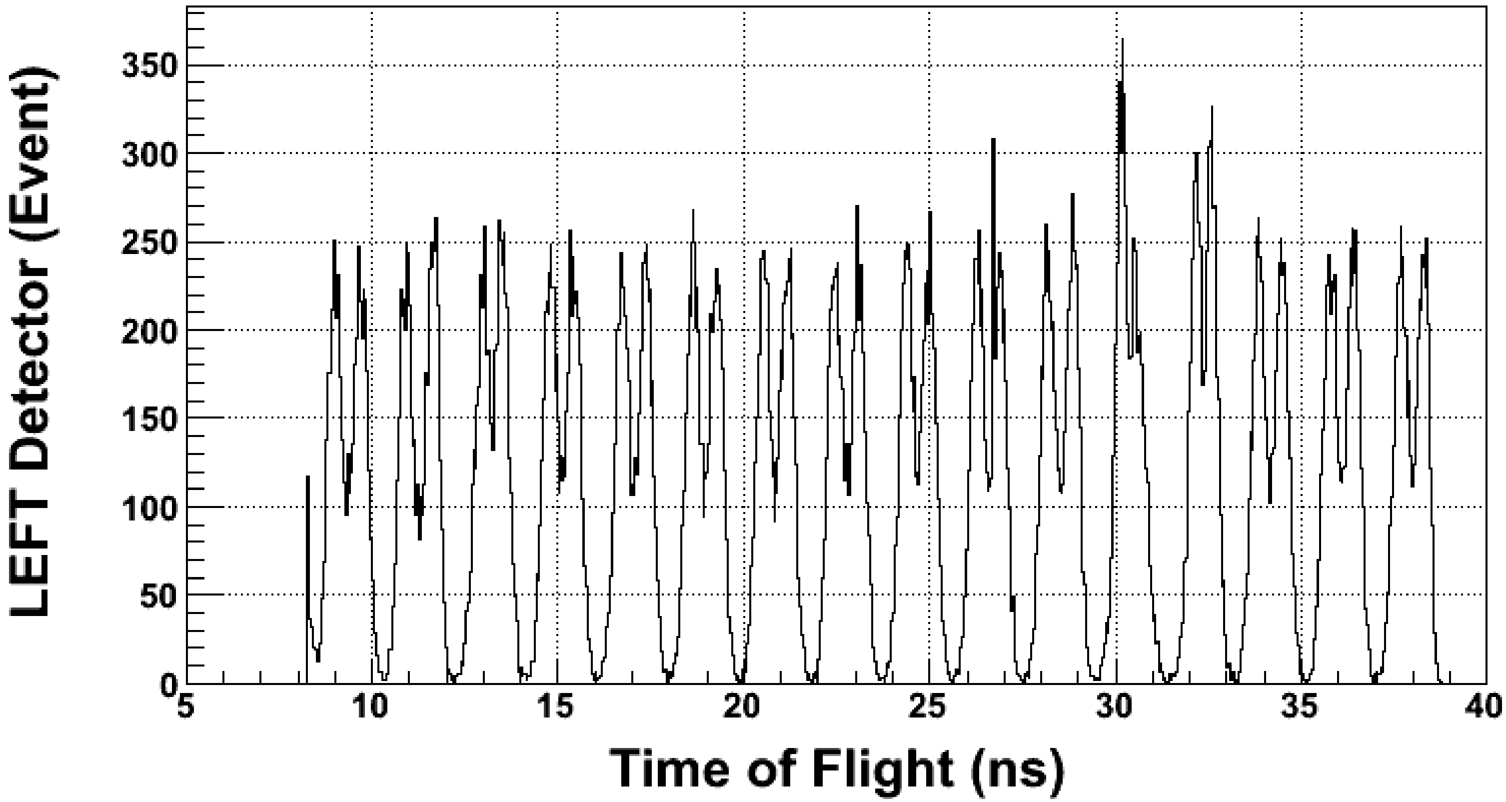
BFM in FADC

Hall C 499 MHz Beam

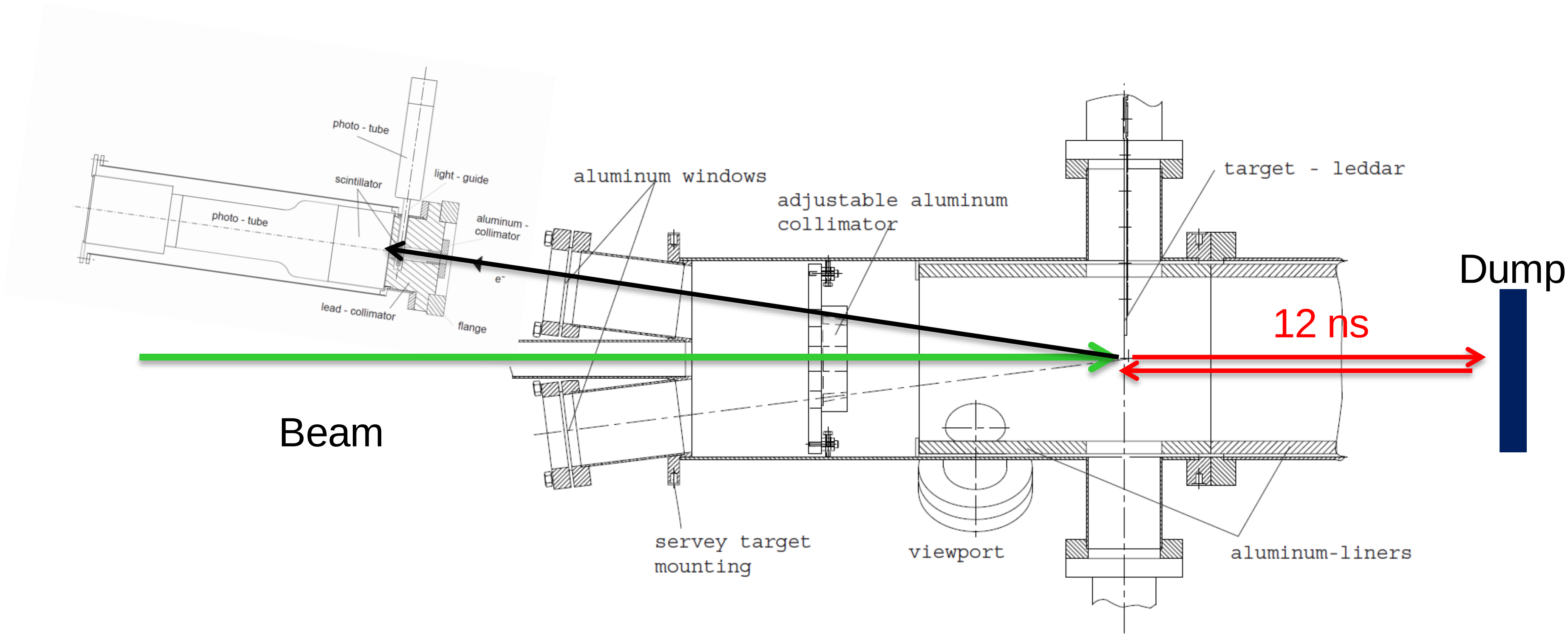


499 MHz Beam

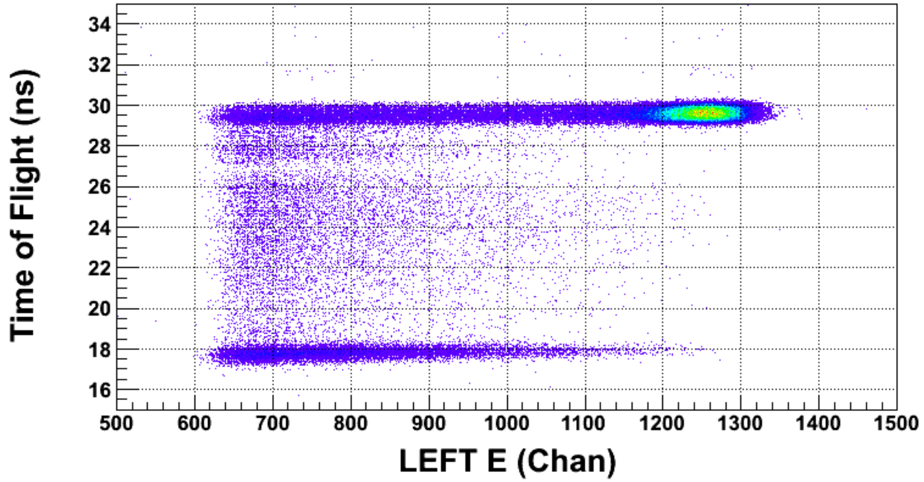
Hall B and Hall C beams at 499 MHz

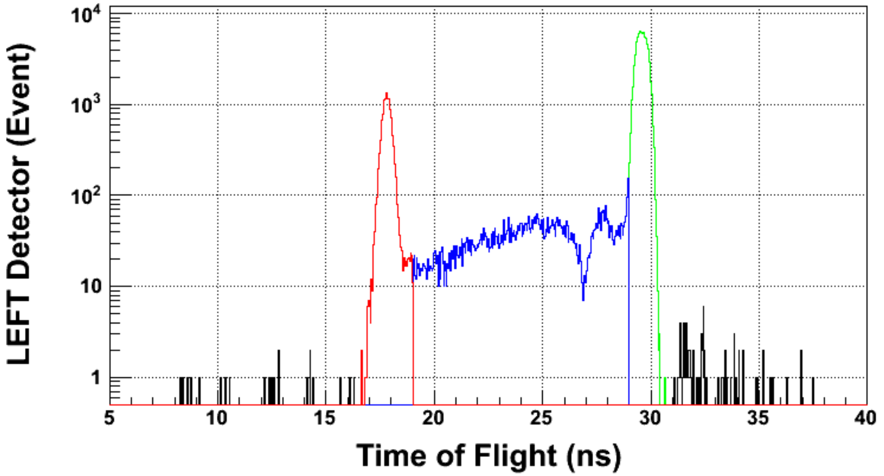


5 MeV Mott Beam-line

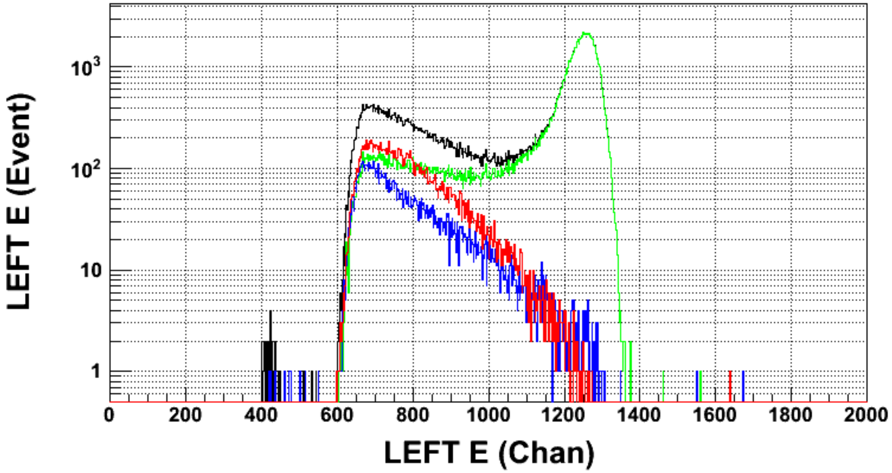


31 MHz Beam

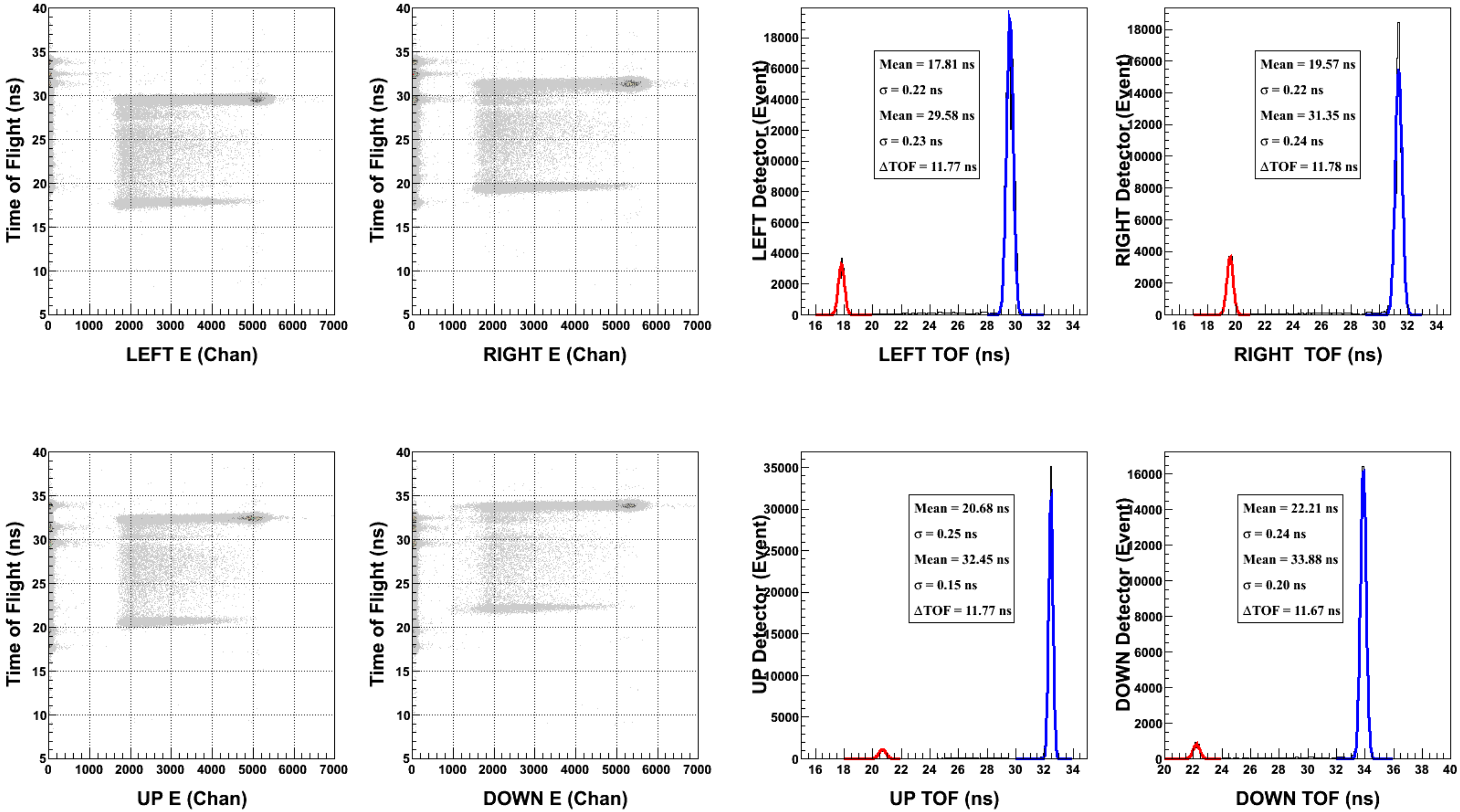


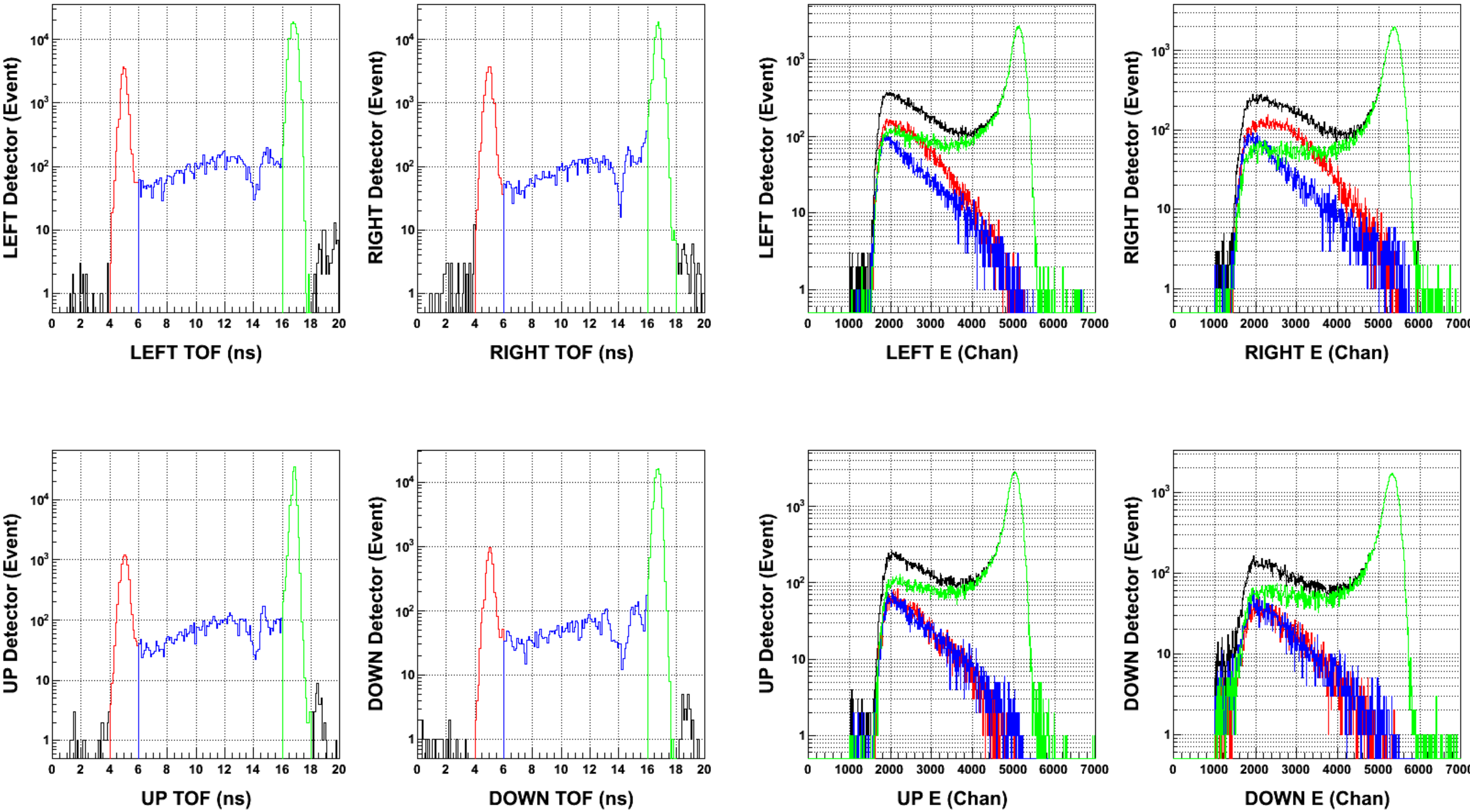


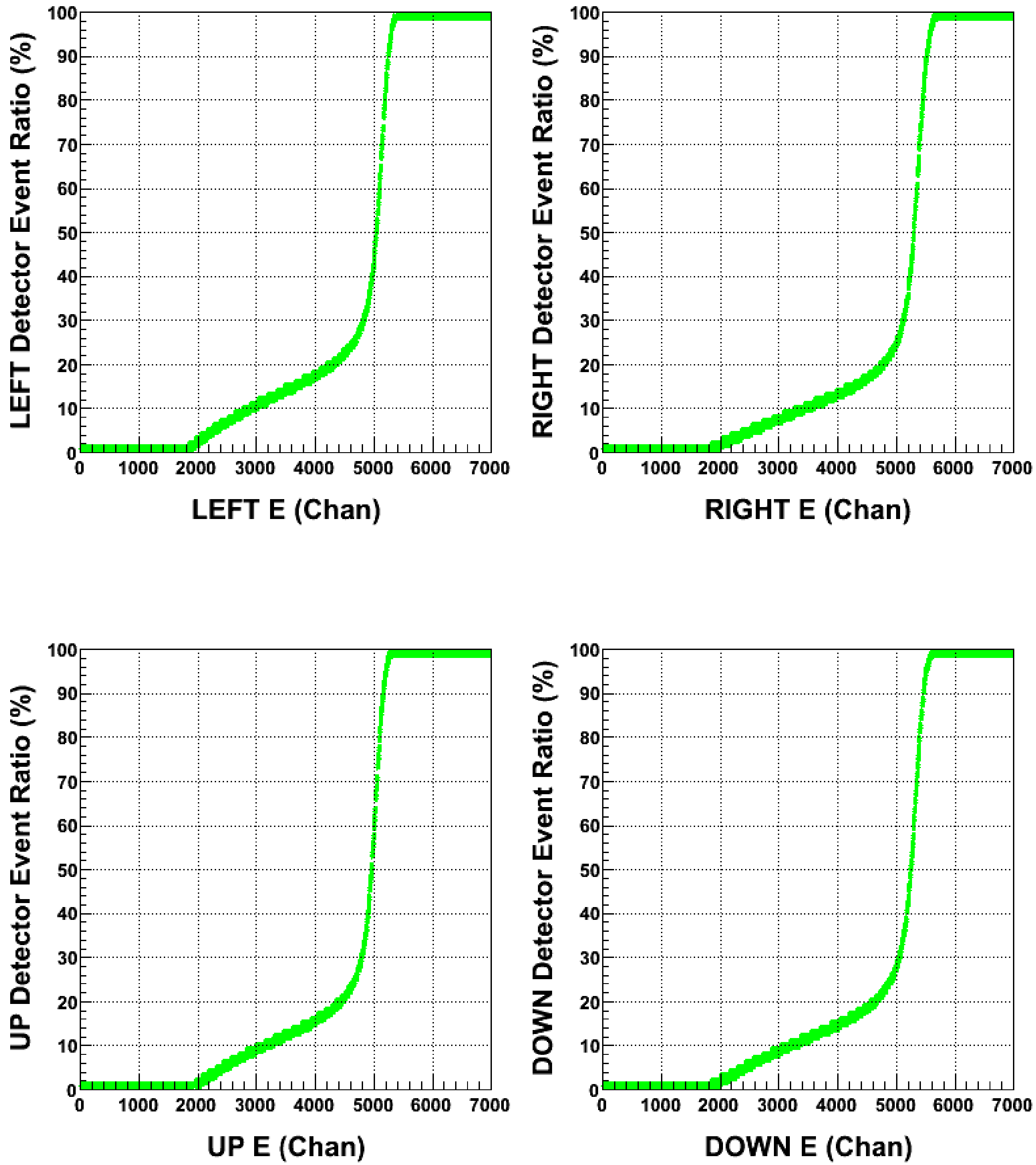
Here, “E” is the peak of Energy signal (sample=74)



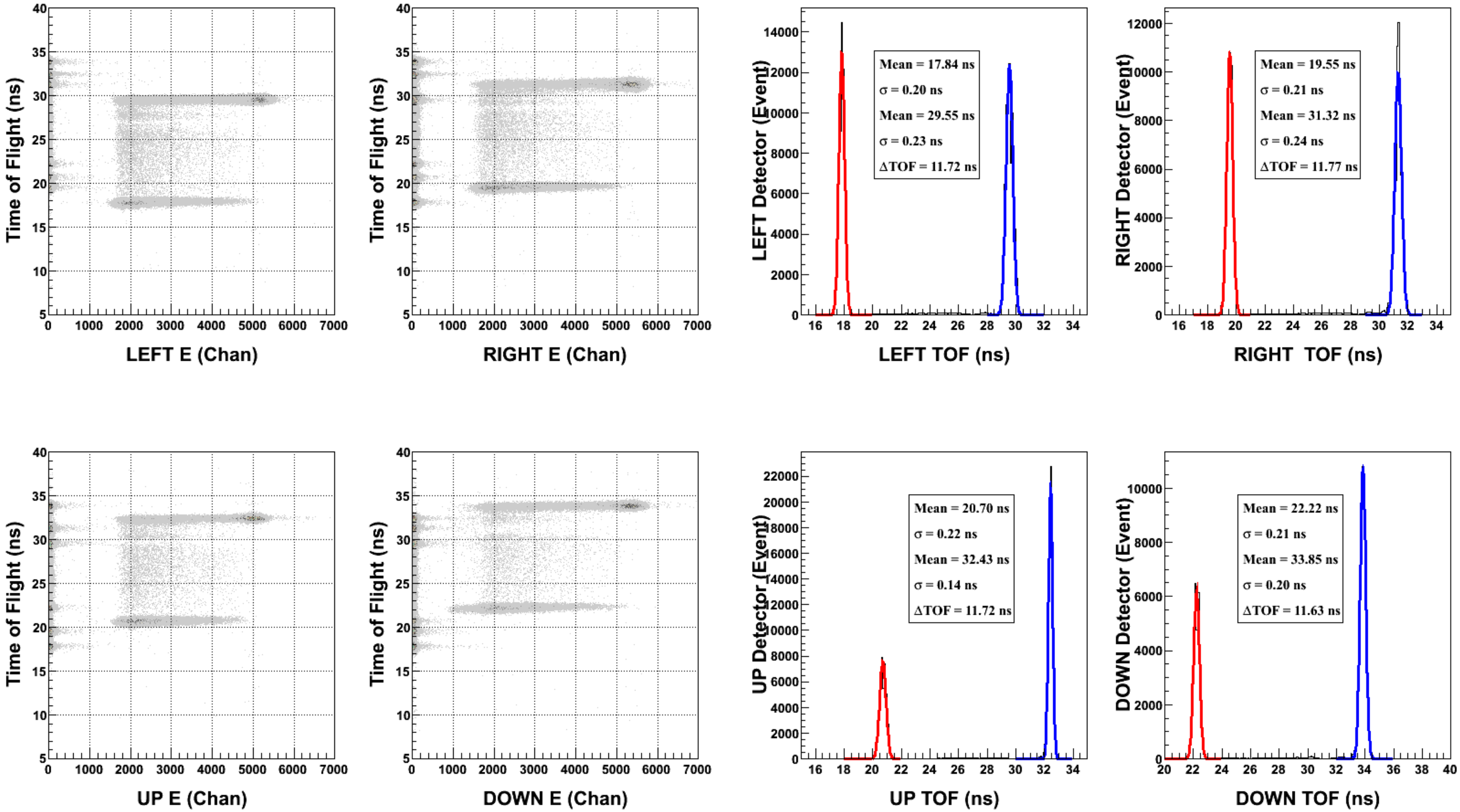
Mott Sweep Magnet at -5A

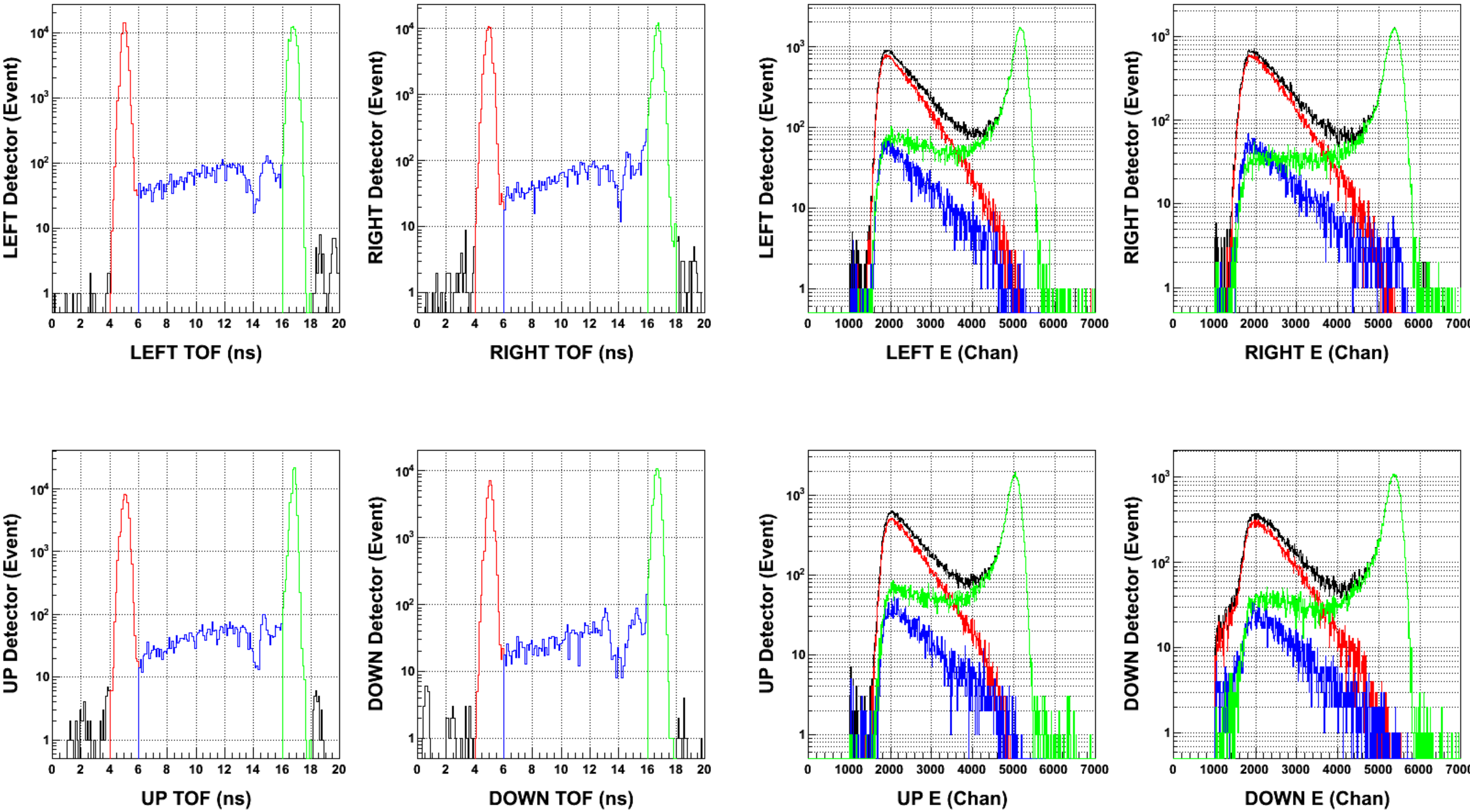


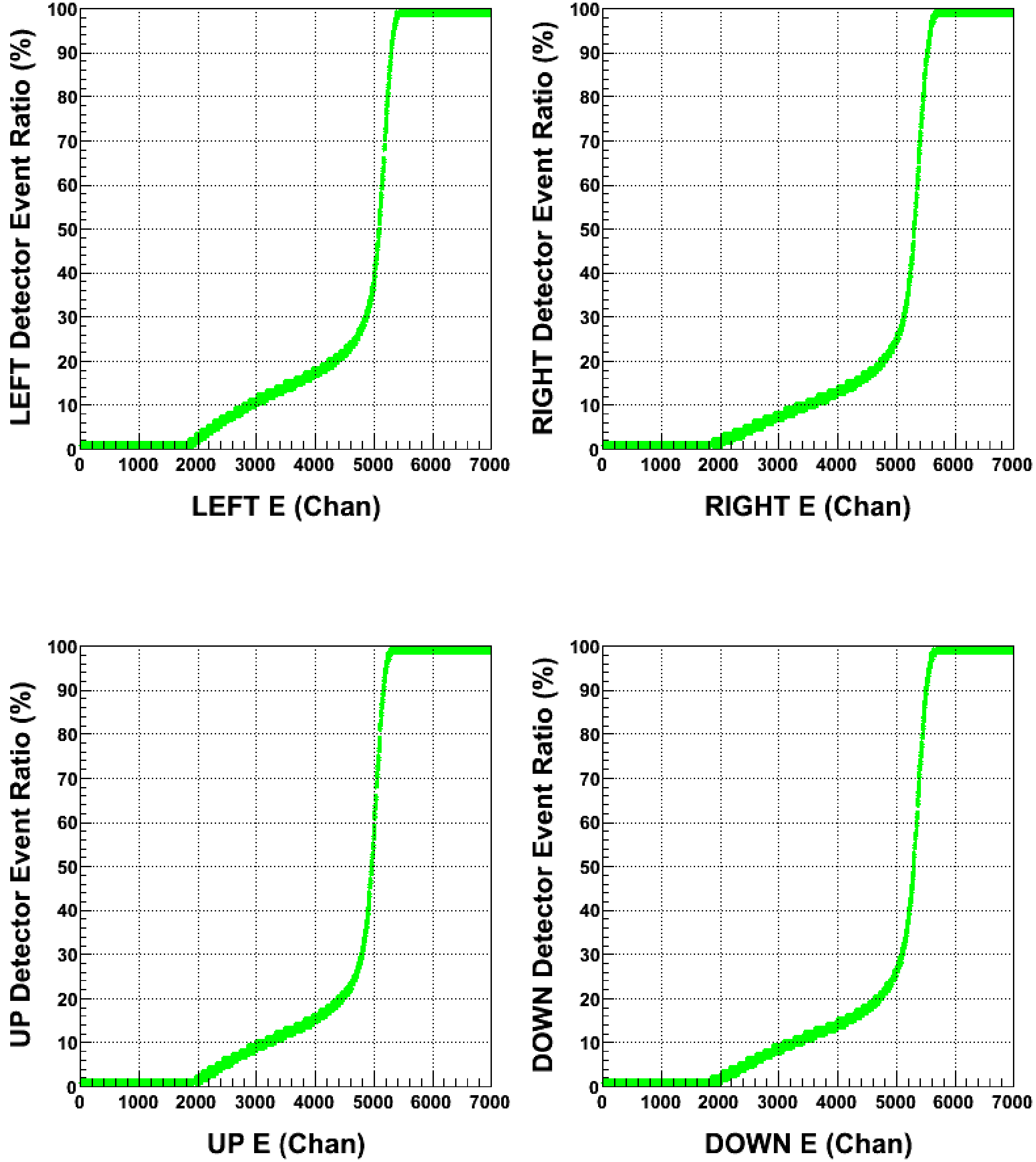

LEFT Detector (Event)
LEFT TOF (ns)
RIGHT Detector (Event)
RIGHT TOF (ns)
LEFT Detector (Event)
LEFT E (Chan)
RIGHT Detector (Event)
RIGHT E (Chan)
UP Detector (Event)
UP TOF (ns)
DOWN Detector (Event)
DOWN TOF (ns)
UP Detector (Event)
UP E (Chan)
DOWN Detector (Event)
DOWN E (Chan)


LEFT Detector Event Ratio (%)
LEFT E (Chan)
RIGHT Detector Event Ratio (%)
RIGHT E (Chan)
UP Detector Event Ratio (%)
UP E (Chan)
DOWN Detector Event Ratio (%)
DOWN E (Chan)
0
10
20
30
40
50
60
70
80
90
100
0
1000
2000
3000
4000
5000
6000
7000

Mott Sweep Magnet at 0A

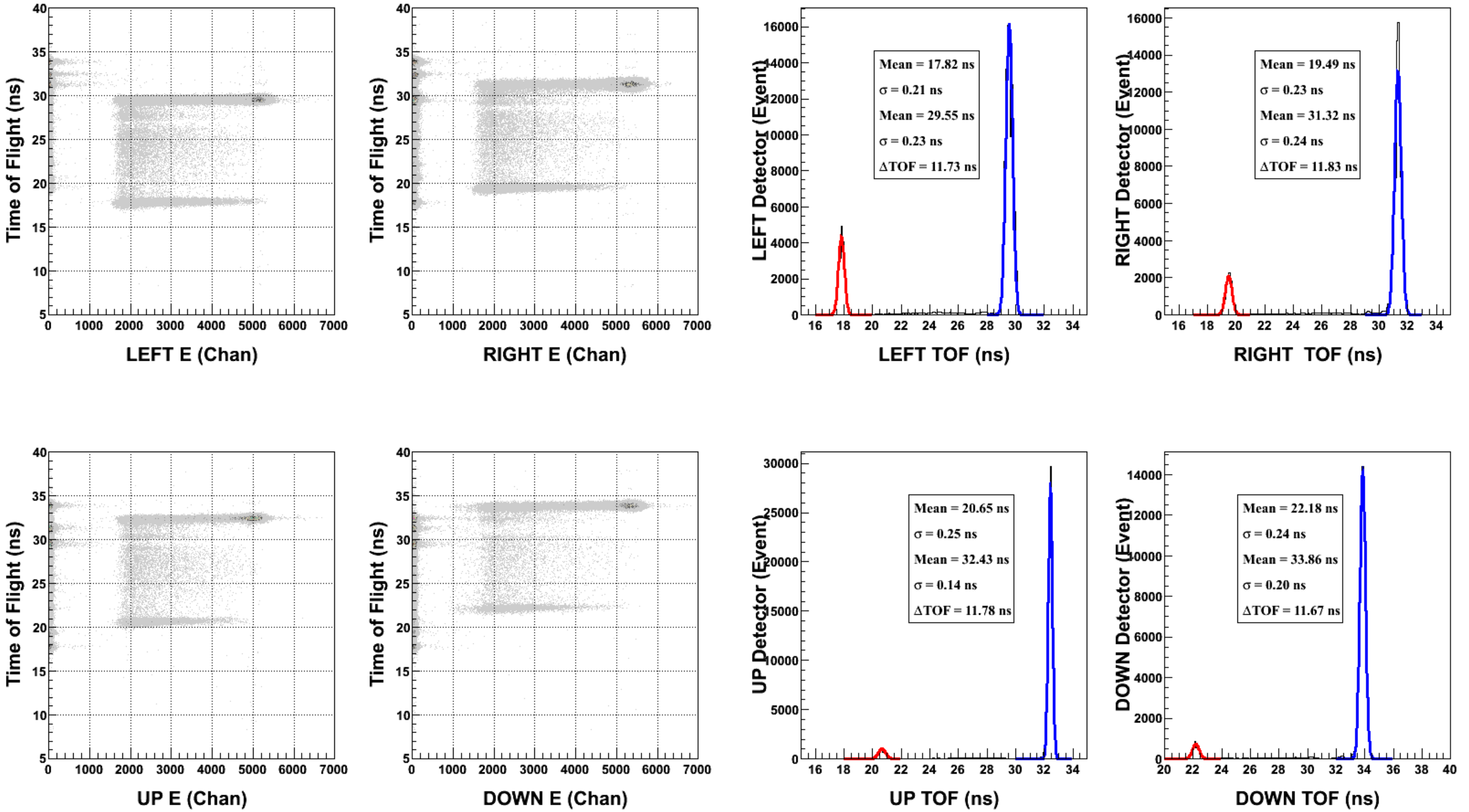


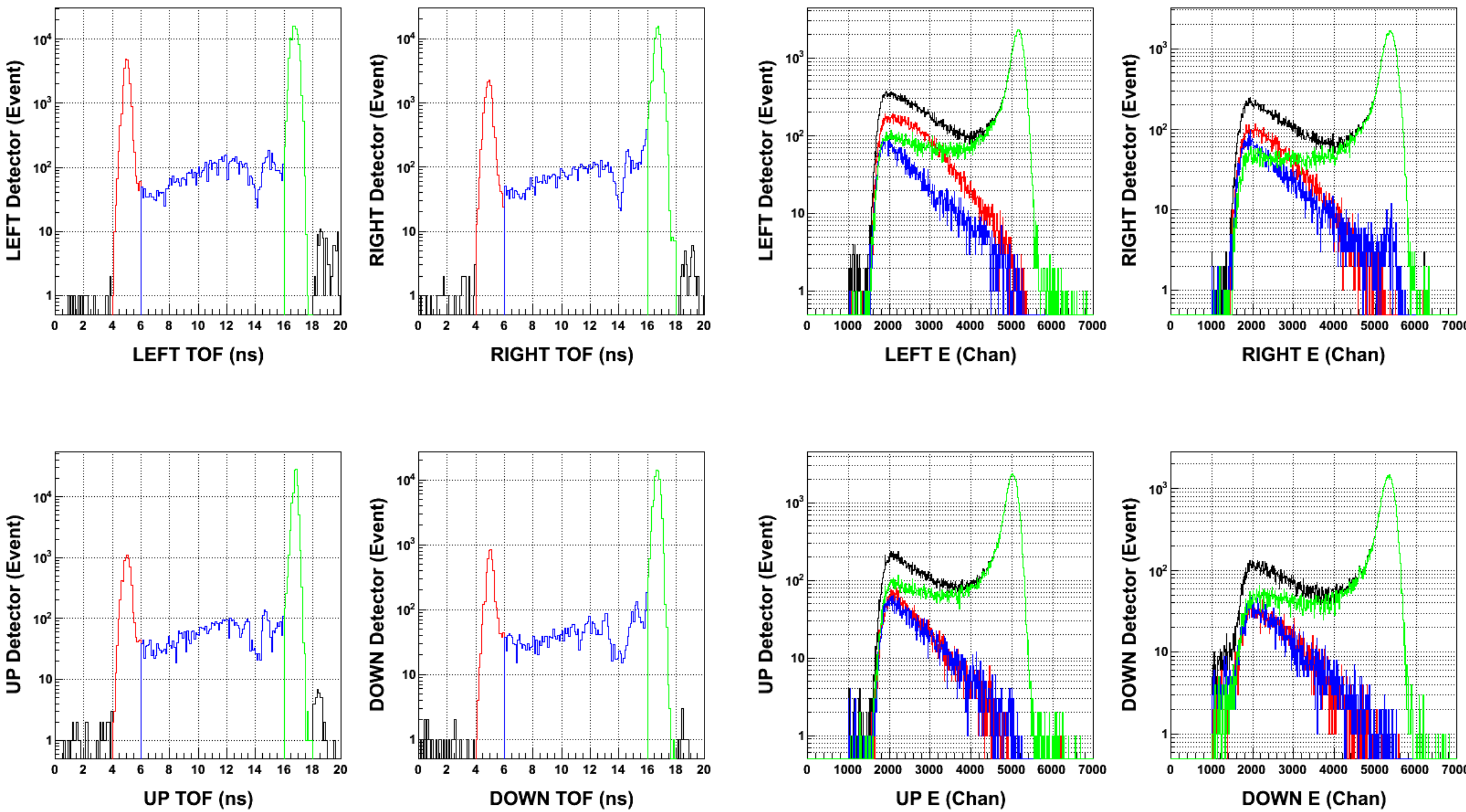

LEFT Detector (Event)
LEFT TOF (ns)
RIGHT Detector (Event)
RIGHT TOF (ns)
LEFT Detector (Event)
LEFT E (Chan)
RIGHT Detector (Event)
RIGHT E (Chan)
UP Detector (Event)
UP TOF (ns)
DOWN Detector (Event)
DOWN TOF (ns)
UP Detector (Event)
UP E (Chan)
DOWN Detector (Event)
DOWN E (Chan)

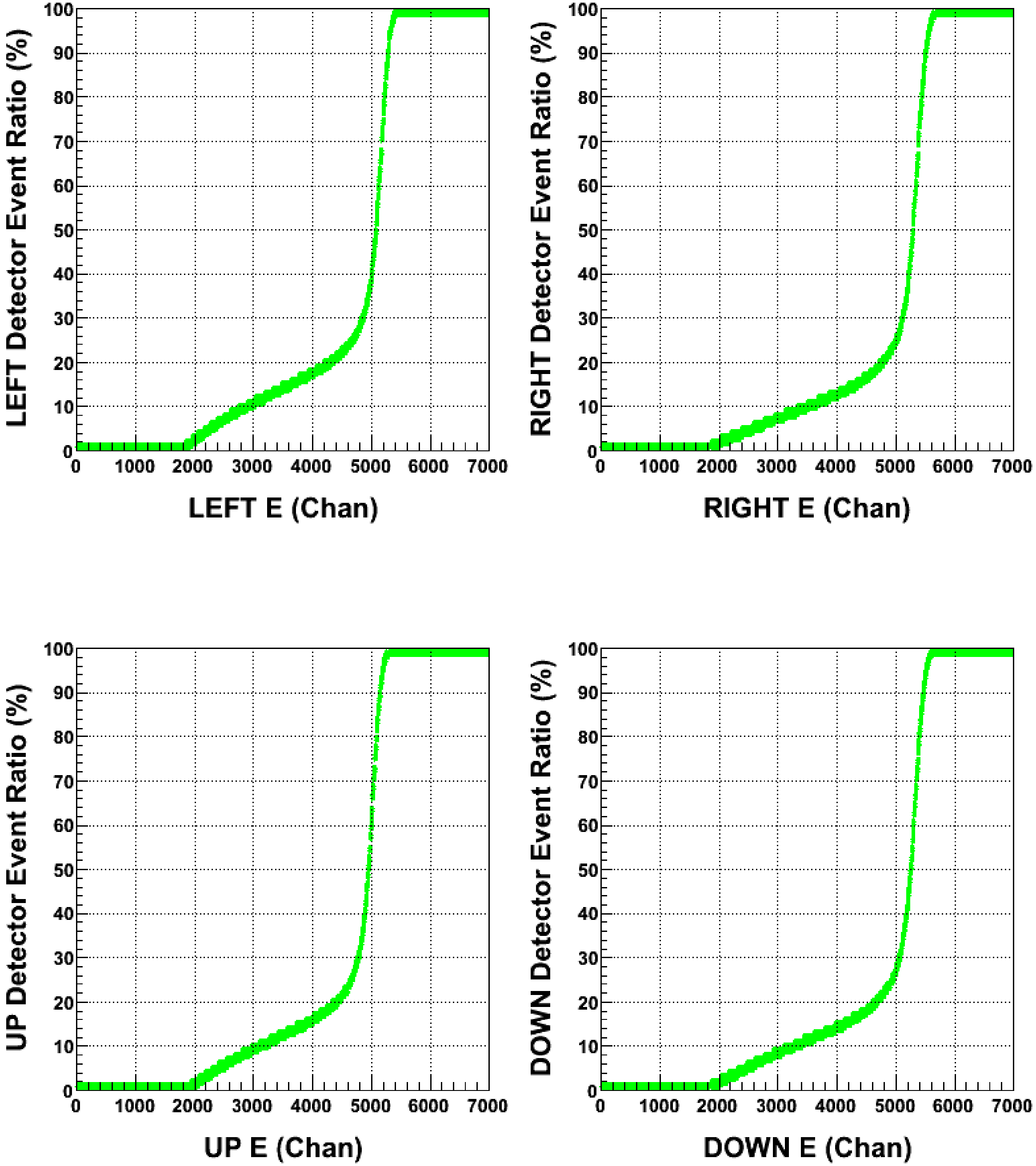


LEFT Detector Event Ratio (%)
LEFT E (Chan)
RIGHT Detector Event Ratio (%)
RIGHT E (Chan)
UP Detector Event Ratio (%)
UP E (Chan)
DOWN Detector Event Ratio (%)
DOWN E (Chan)
0 10 20 30 40 50 60 70 80 90 100
0 1000 2000 3000 4000 5000 6000 7000

Mott Sweep Magnet at +5A

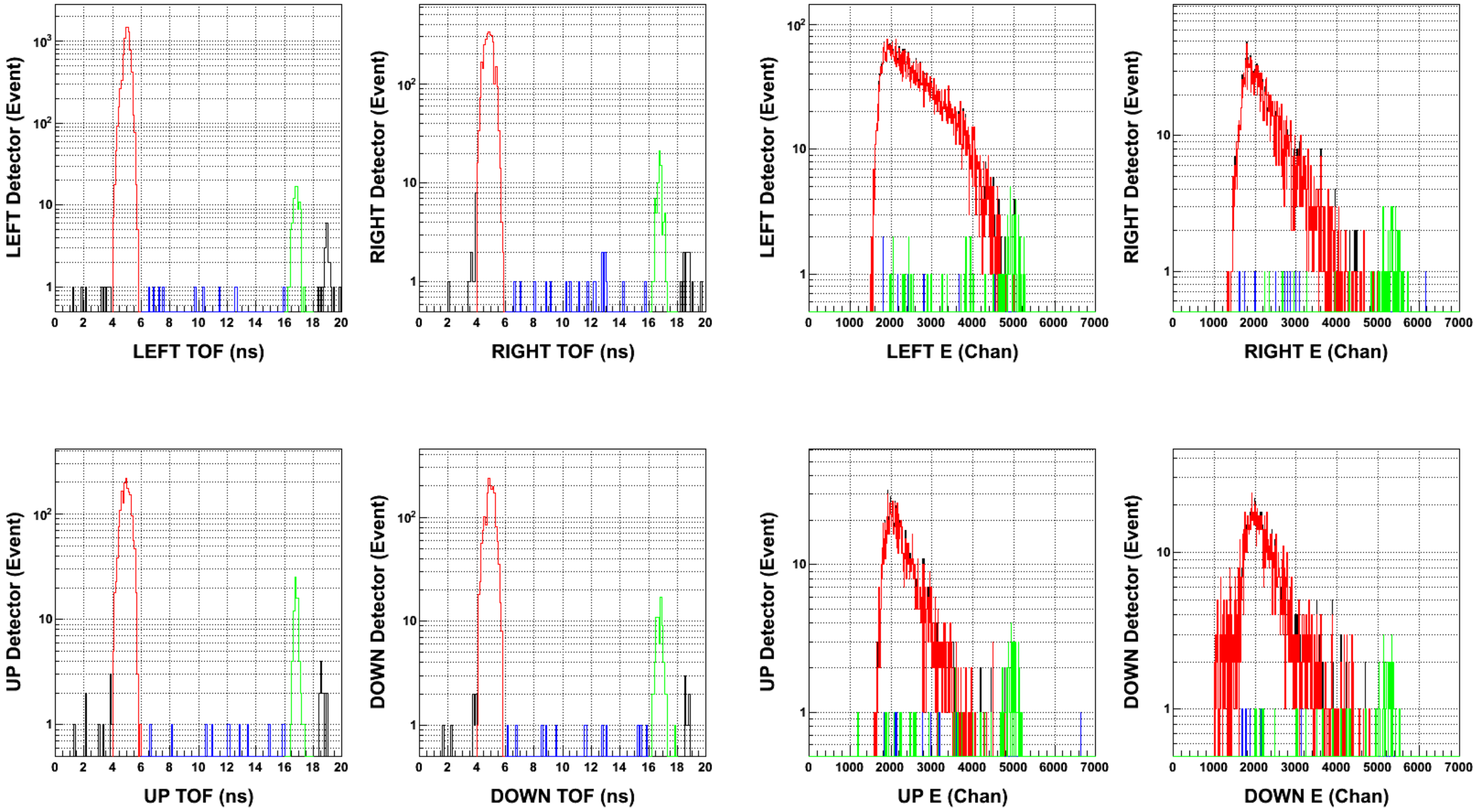



LEFT Detector (Event)
LEFT TOF (ns)
RIGHT Detector (Event)
RIGHT TOF (ns)
LEFT Detector (Event)
LEFT E (Chan)
RIGHT Detector (Event)
RIGHT E (Chan)
UP Detector (Event)
UP TOF (ns)
DOWN Detector (Event)
DOWN TOF (ns)
UP Detector (Event)
UP E (Chan)
DOWN Detector (Event)
DOWN E (Chan)


LEFT Detector Event Ratio (%)
LEFT E (Chan)
RIGHT Detector Event Ratio (%)
RIGHT E (Chan)
UP Detector Event Ratio (%)
UP E (Chan)
DOWN Detector Event Ratio (%)
DOWN E (Chan)

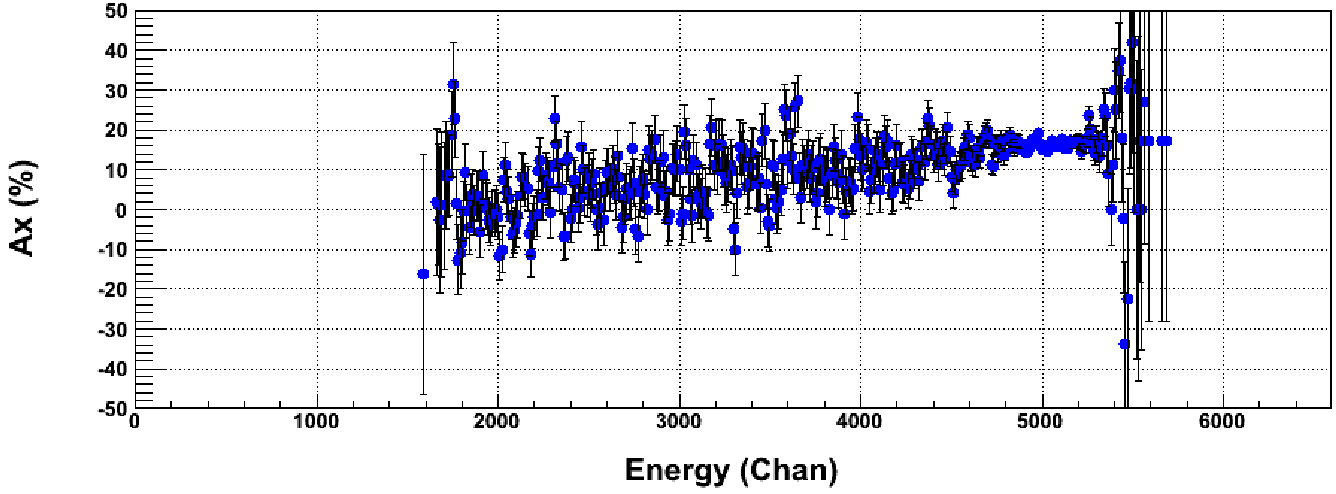
Spectra from Broken Gold Mott Target

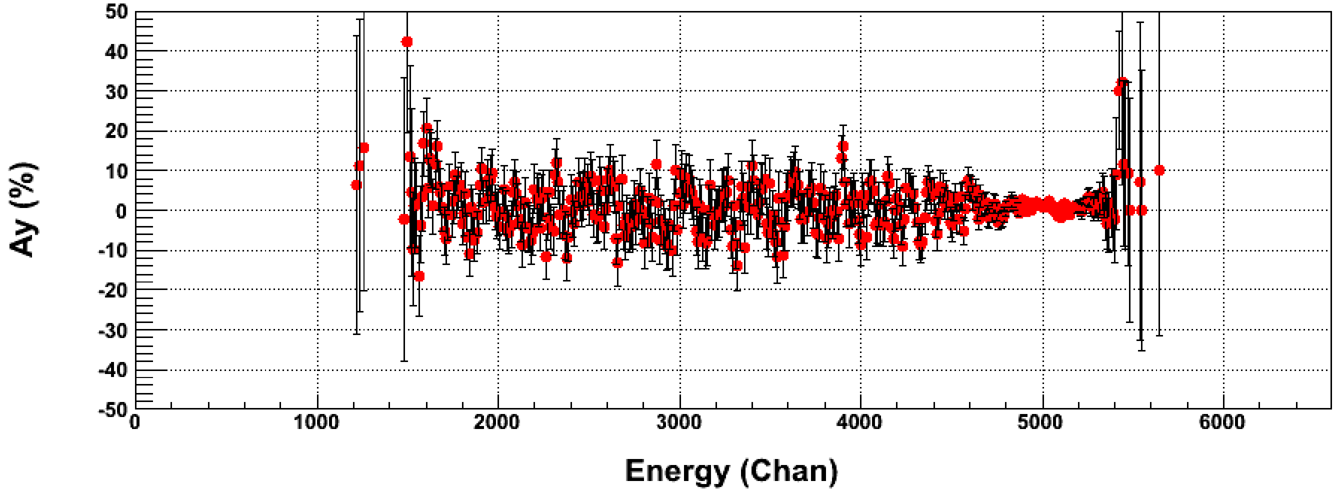
Mainly Dump Events



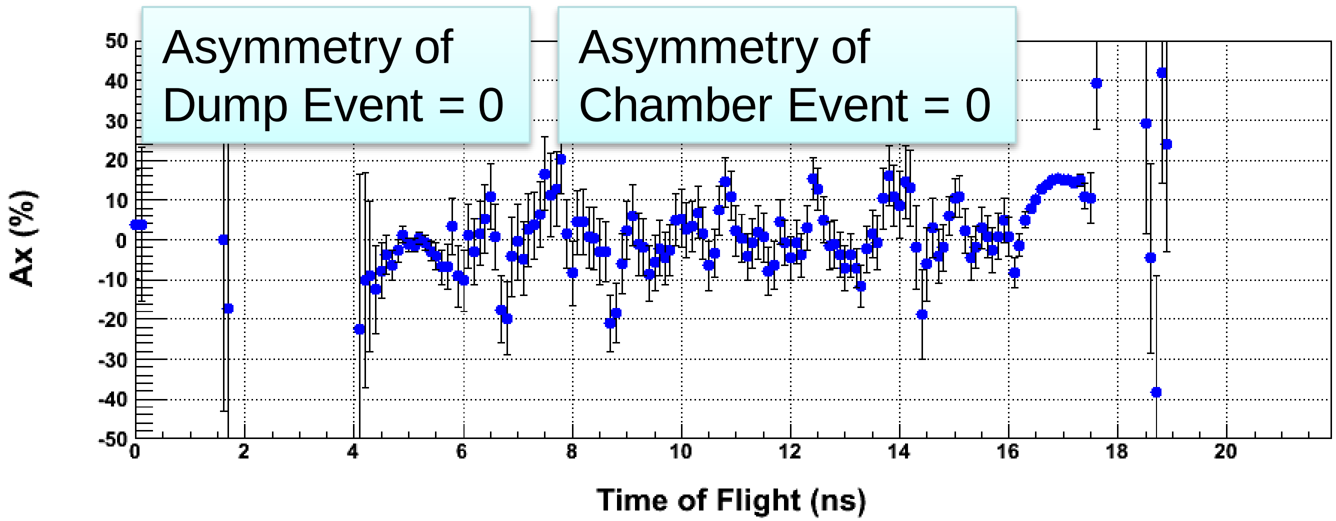
Mott Asymmetry vs. Energy

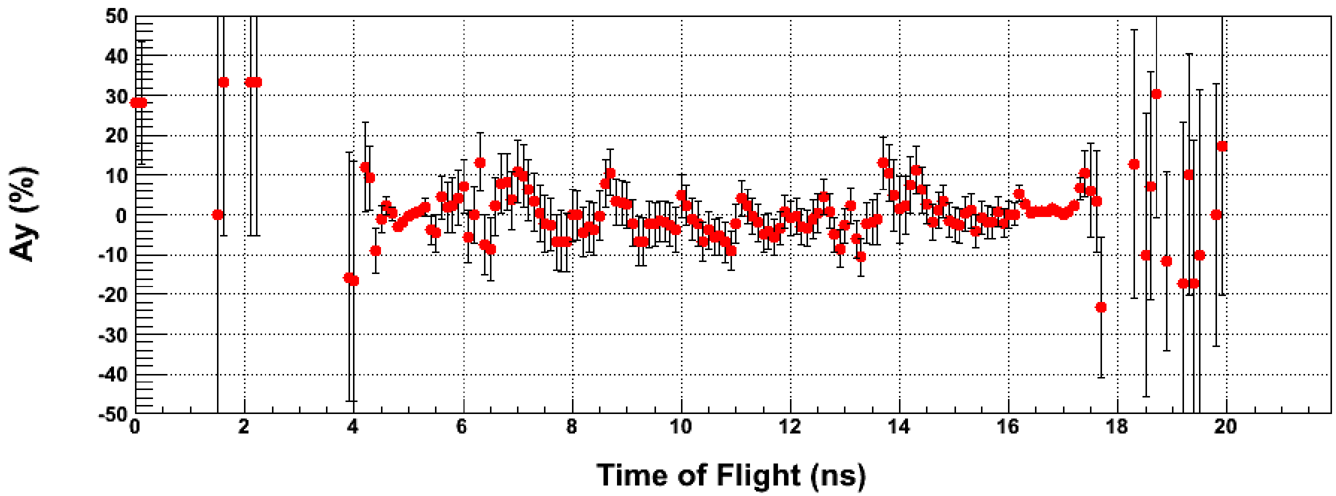
Select events coming from target with a cut on TOF





Mott Asymmetry vs. TOF





Scaler Readout

S1 Chan	Signal
0	BCM0L02 OUTPUT 2
1	40 MHz Clock
2	Mott Trigger
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	BCM0L02 OUTPUT 3
13	Delayed Helicity
14	Battery
15	

S1 Chan	BPM Signal	
16	0L01 X+	BPM 0L01
17	0L01 X-	BPM 0L01
18	0L01 Y+	BPM 0L01
19	0L01 Y-	BPM 0L01
20	0L02 X+	BPM 0L02
21	0L02 X-	BPM 0L02
22	0L02 Y+	BPM 0L02
23	0L02 Y-	BPM 0L02
24	5D00 X+	BPM 5D00
25	5D00 X-	BPM 5D00
26	5D00 Y+	BPM 5D00
27	5D00 Y-	BPM 5D00
28	5D01 X+	BPM 5D01
29	5D01 X-	BPM 5D01
30	5D01 Y+	BPM 5D01
31	5D01 Y-	BPM 5D01

BCM0L02 Readout

I. BCM0L02 Receiver output:

   1. OUTPUT 2: 0.0 – 1.0 μA → 0 – 10 V

II. Connected to VtoF (1 MHz, 10 V)

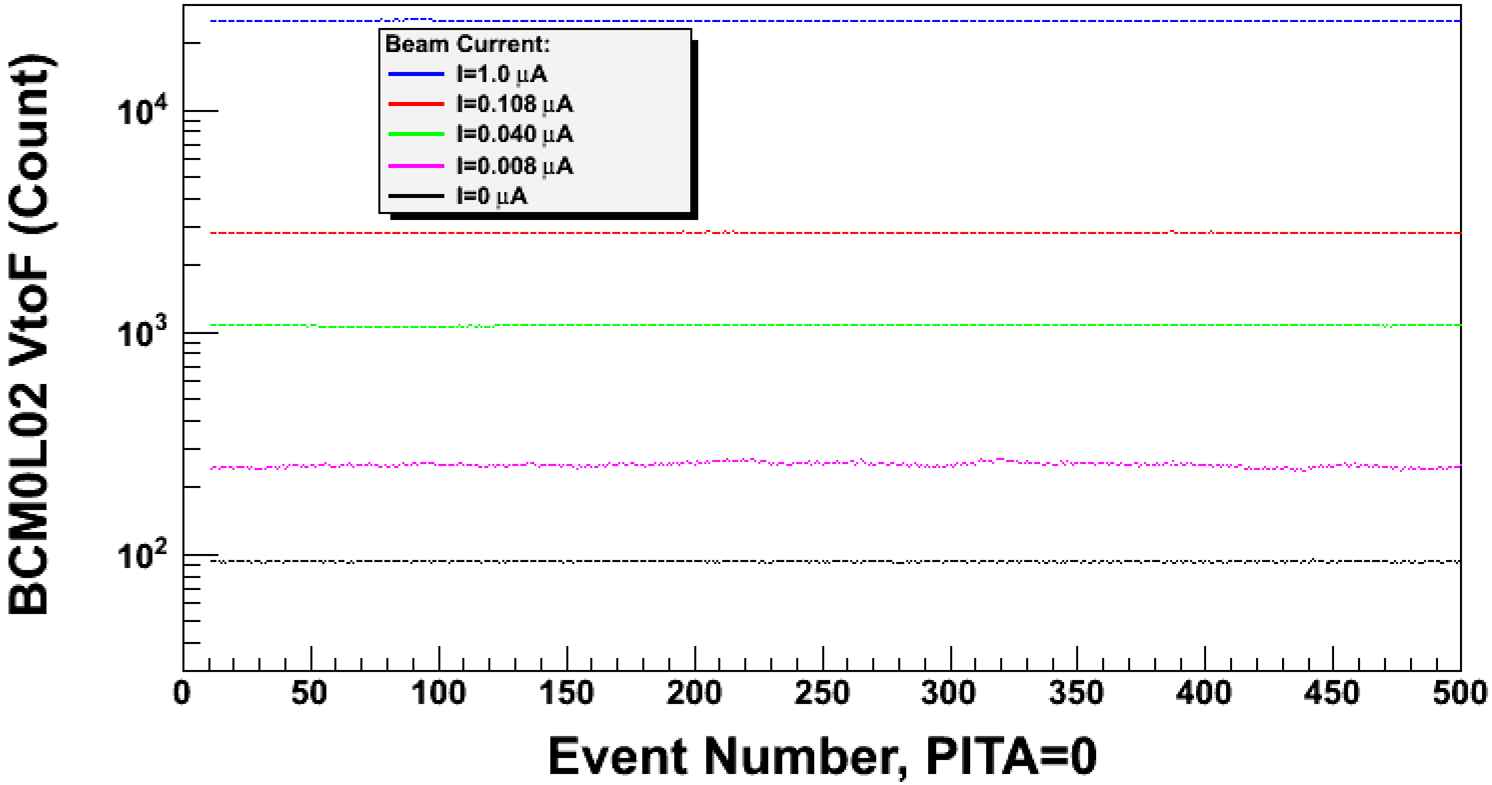
III. Charge Asymmetry Test:

   - PITA (Polarization Induced Transport Asymmetry): charge asymmetry depends on Pockels Cell HV
   - Experiments use PITA to implement charge feedback
   - Measure PITA slope at PITA = -2000, 0, +2000 DAC (Nominal 40000 – about 2.9 kV on Pockels Cell).

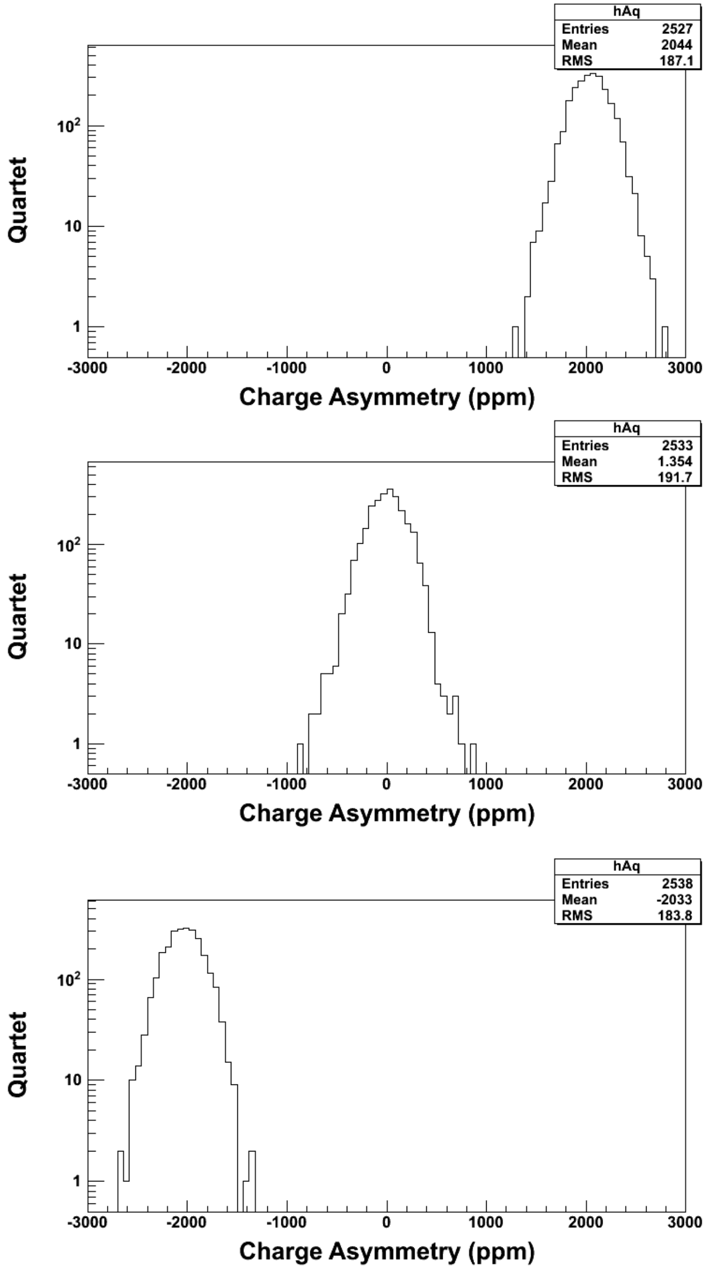
   - Measure PITA Slope for beam currents: 1.0 μA, 0.108 μA, 0.040 μA, and 0.008 μA

Charge Asymmetry Test

- 30 Hz
- 8-window Delay
- Quartet



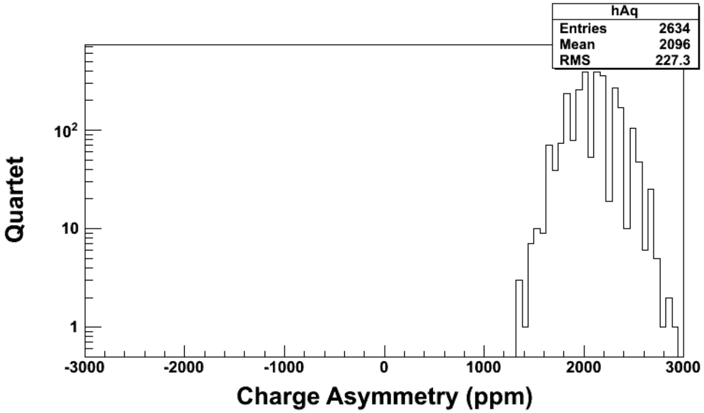
PITA Scan at 1.0 μA

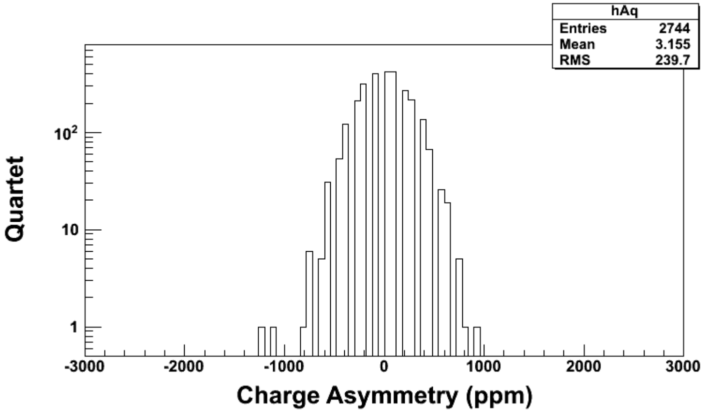


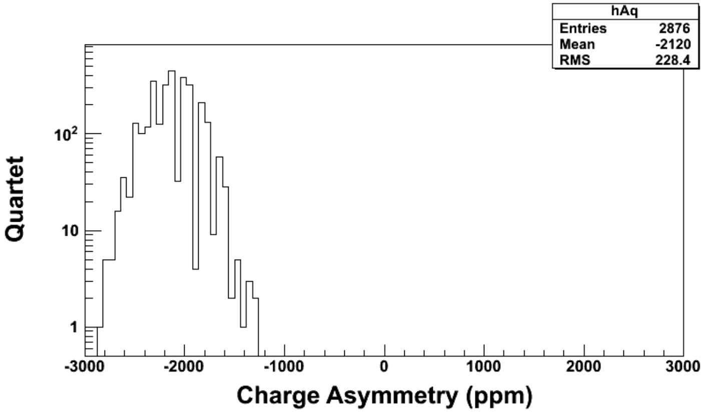
- Mott DAQ
  I. PITA Slope = -1.02 ppm/DAC

- QWeak DAQ
  I. PITA Slope = -1.06 ppm/DAC

PITA at 0.108 μA

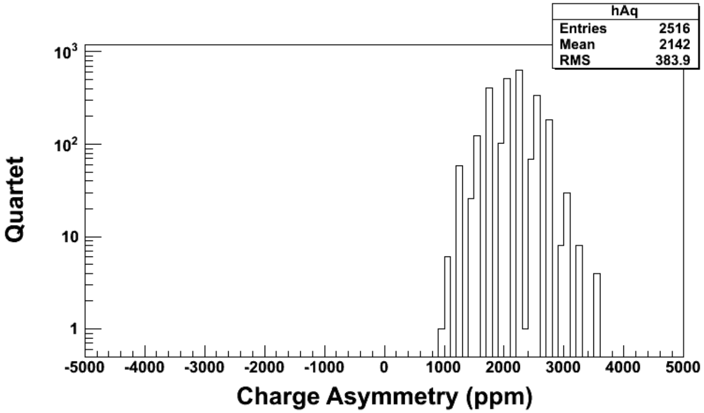


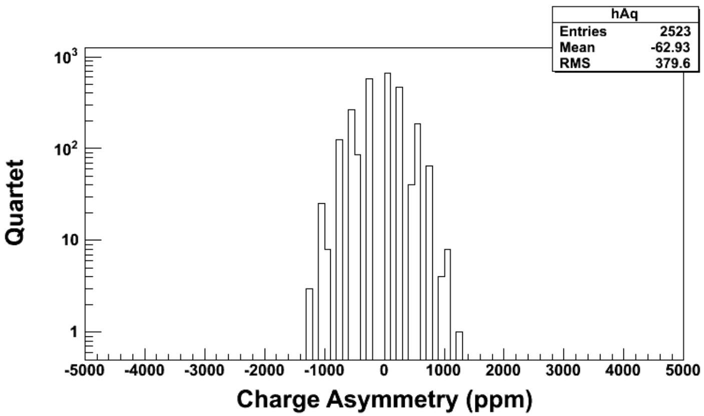


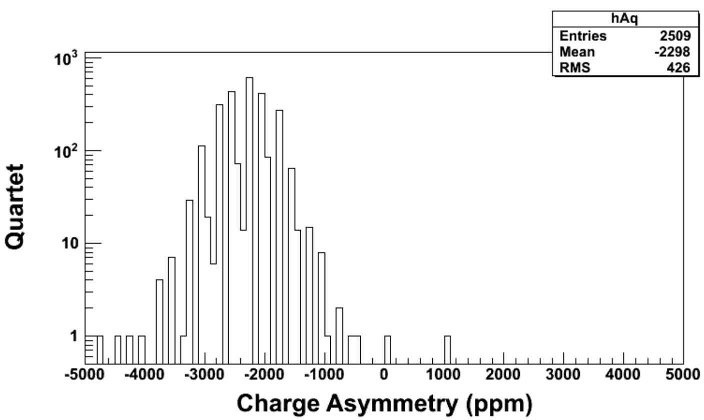


- Mott DAQ
  I. PITA Slope = -1.05 ppm/DAC

PITA at 0.040 µA

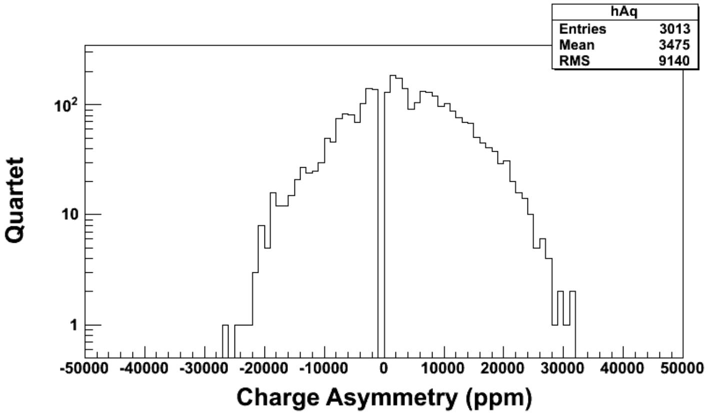


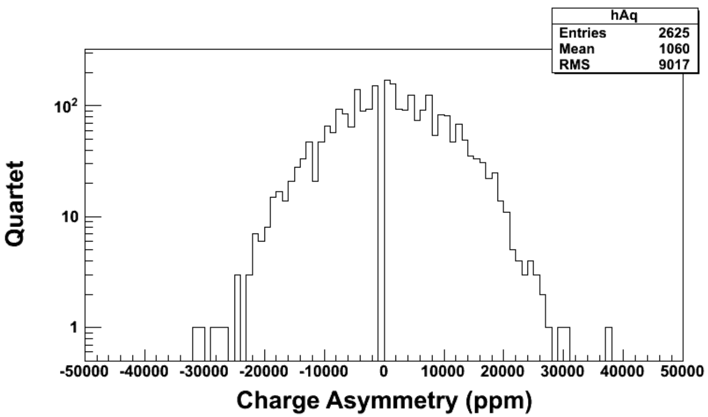


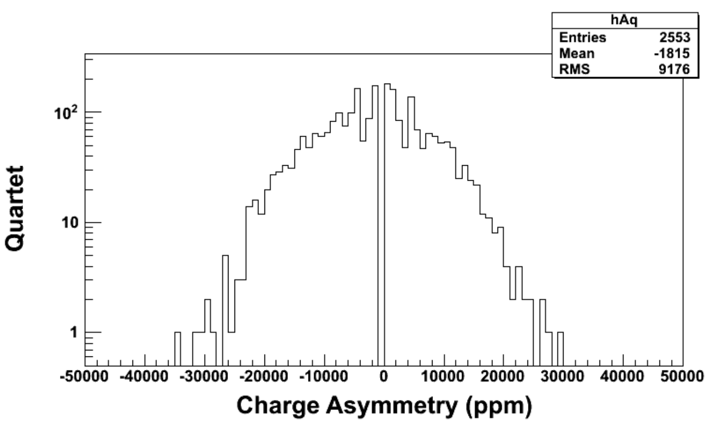


- Mott DAQ
  I. PITA Slope = -1.1 ppm/DAC

PITA at 0.008 μA







- Overwhelmed by noise

- Now, reliable charge asymmetry measurement to about 40 nA

Next, …

I. Calibrate Receiver to 100 nA FS
II. Measure charge asymmetry at 10 nA
III. For even lower beam currents:

    I. Measure charge asymmetry at 1 μA and at 10 nA → We know charge asymmetry at all currents

Precision Mott Electron Polarimeter

- Goal: Measure and publish electron polarization over range of 2 to 8 MeV with absolute uncertainty better than 1%.

$$P = \frac{A}{S}$$

  - Fast statistical measurements of experiment asymmetry (A) **<0.5%** vs. target thickness
  - Demonstrate instrumental false asymmetry **<0.3%**
    - Eliminate background events with Time-of-Flight (ToF) cut
    - Super-ratio calculation (double arm + helicity reversal)
  - New Data Acquisition system based on Hall D 250MHz FADC
  - Calculate the effective Sherman Function (S) **< 0.8%**

Effective Sherman Function	Error (ΔS/S)
Nuclear Corrections	0.5%
Target Thickness Extrapolation	0.6%
Scattering angle (0.1°)	0.1%
Electron Energy (0.5%)	0.1%

<u>Plan</u>

I. Theoretical support for Sherman function calculation

II. Measurements are collected "for free" parasitic to PEPPo in May/June, 2012

III. GEANT4 Simulation – No Extrapolation