Initial Results from HRPPD B-field Campaign at BNL

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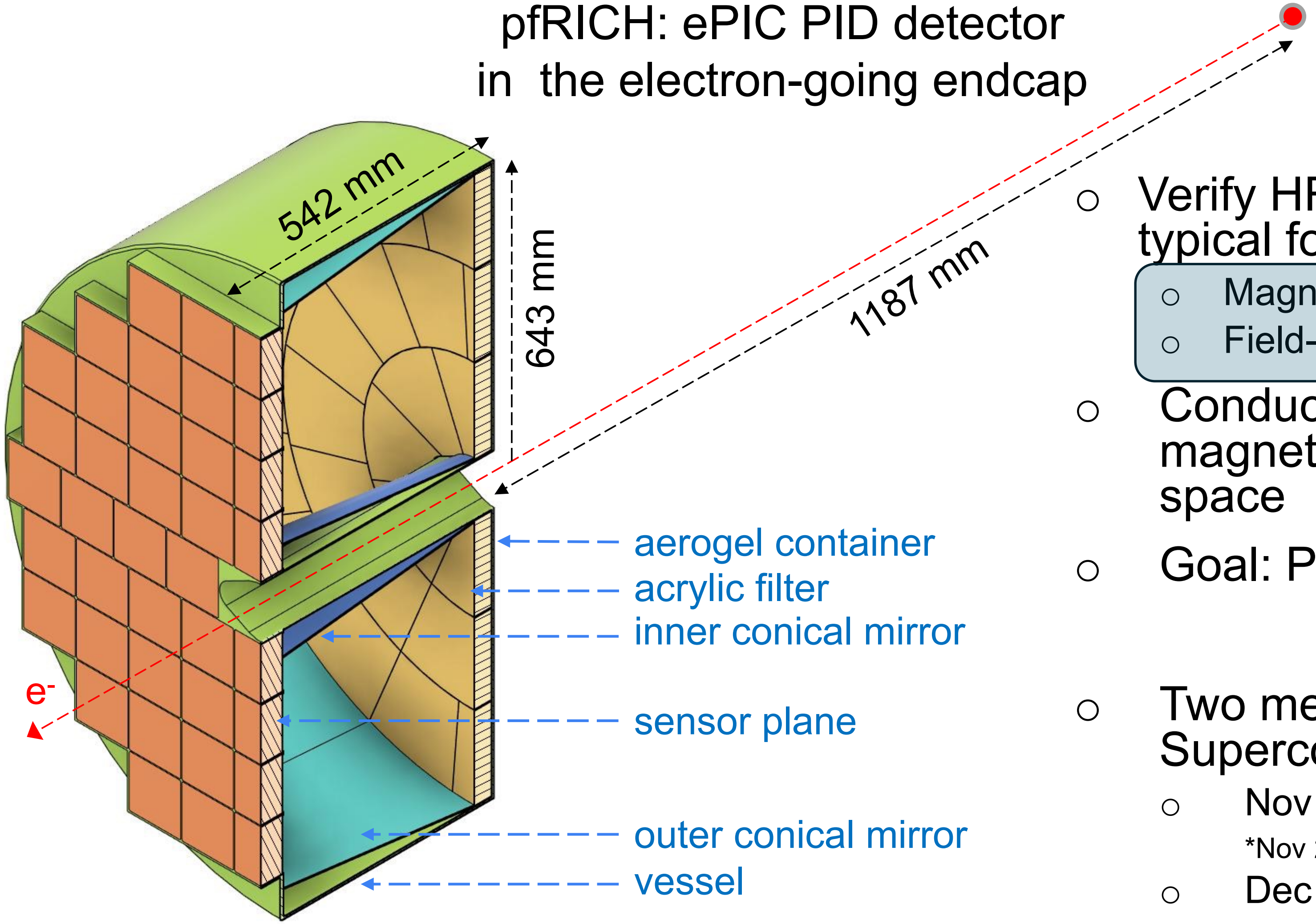
2026/01/12

ePIC TIC Meeting – HRPPDs in magnetic field

Motivation

pfRICH: ePIC PID detector
in the electron-going endcap



- Verify HRPPD operation in magnetic fields typical for the pfRICH sensor location in ePIC
  - Magnetic field strength up to ~1.3 T
  - Field-to-HRPPD window normal angles up to ~13°
- Conduct a systematic study over (HV, magnetic field, inclination angle) parameter space
- Goal: Produce publishable-quality results
- Two measurement campaigns @ Superconducting Magnet Division at BNL
  - Nov 17–26* (installation and dry runs included)
    *Nov 20–21 (CERN Director-General Visit SMD at BNL)
  - Dec 11–12

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Team


Alexander


Andrew (Yale)


Bob

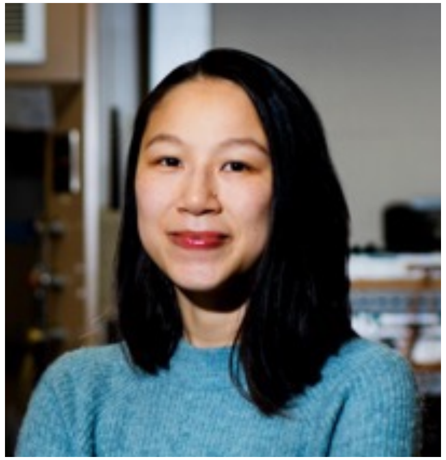

Brian


Craig


Jihee


Mark (Incom)


Martin


Ping


Yifan

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Participated remotely: Alexey Lyashenko (Incom), Yordanka Ilieva (South Carolina)
Local support @ SMD: Vikas Teotia, Chris Tamagro, Ray DeSalvo

Facility and Experimental Area

Superconducting
Magnet Division (SMD)
at BNL

warm dipole

HRPPD enclosure mounted on a sled

PiLas laser; Hall probe controller

10’ long rails

rack with HV, digitizers, NIM logic

DAQ PC

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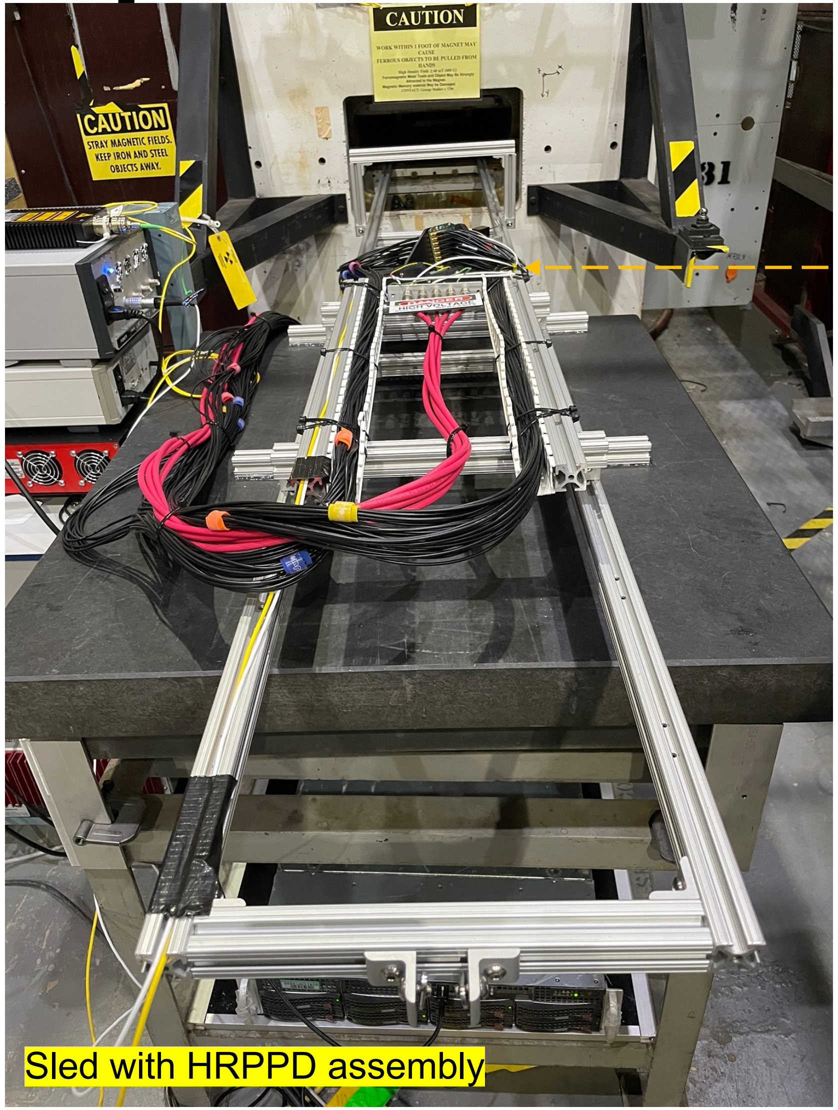
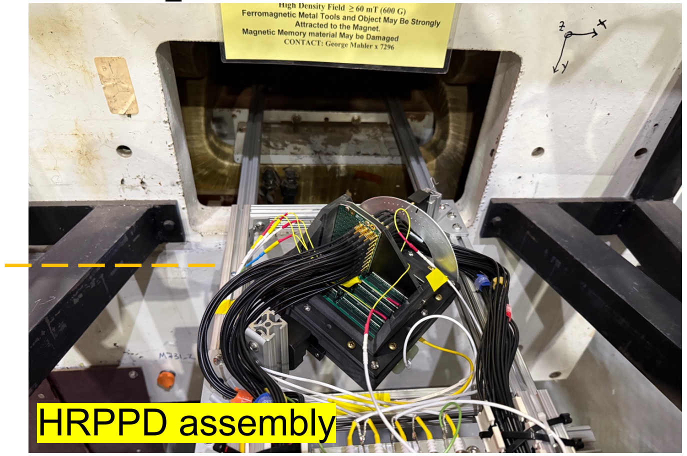
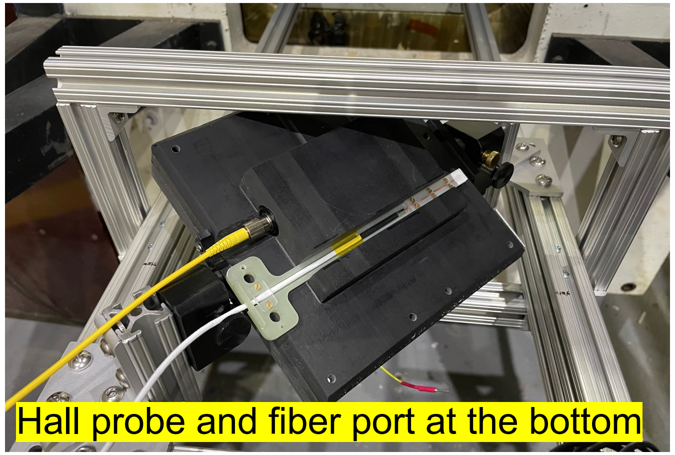
Experimental Setup details



Sled with HRPPD assembly



HRPPD assembly



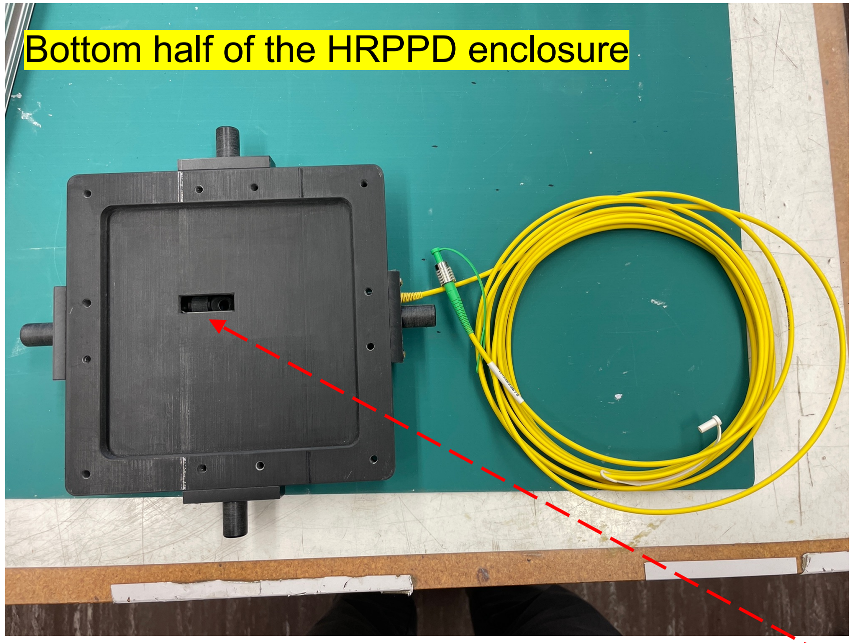
Hall probe and fiber port at the bottom

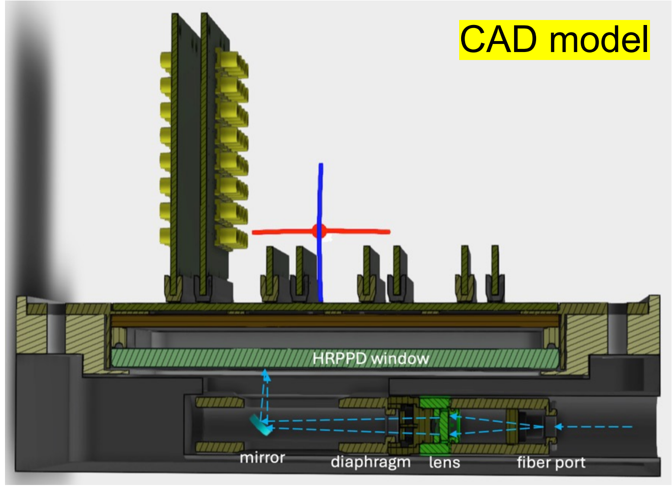
- Retractable sled with an optically tight HRPPD assembly
- Protractor with pin holes (2.5° step) to fix a tilt angle
  - Assembly can be rotated around XY-axes and flipped upside down

- PiLas laser is SM-fiber coupled to the enclosure
- 3D Hall probe attached (rotates together with the assembly)
  - Readings are included in the event file headers

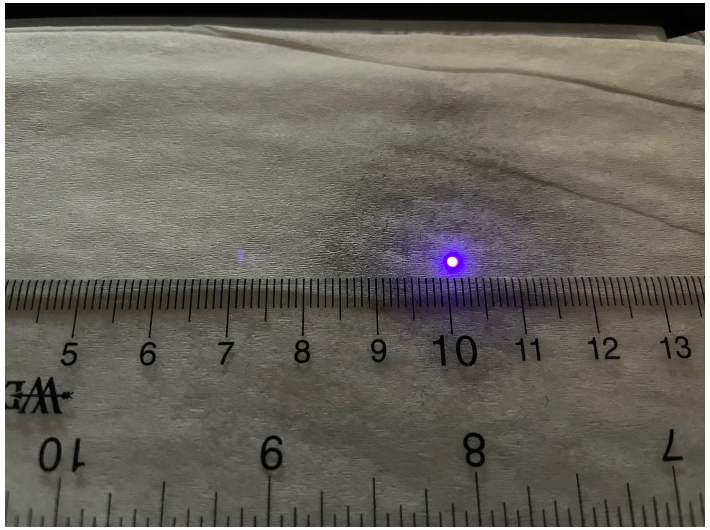
- A single 8×8 pad spot equipped with MCX adapter cards
  - Remember, HRPPD anode has a 32×32 uniform pixellation
- 10’ long RG-174 cables to V1742 CAEN digitizer(s)
  - Most part of the data taken with a single digitizer (6×6 - 4 pad area)

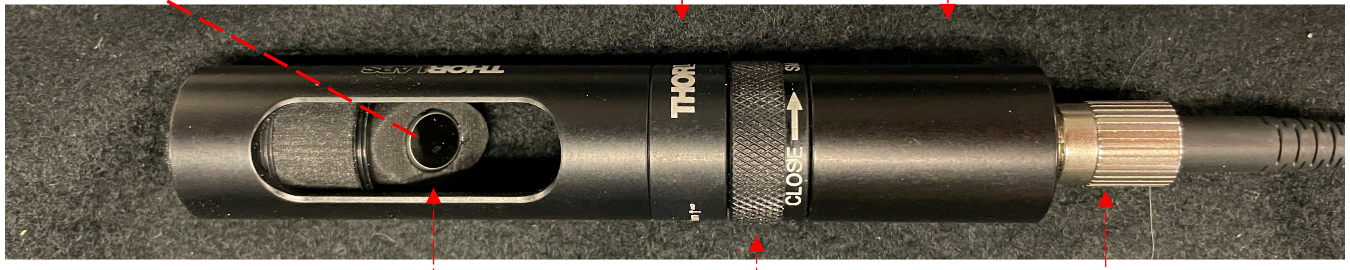
Optical configuration details





- Use F=20mm plano-convex lens in a close to “2F-2F” configuration
- OD4 filter, diaphragm fully open
- At a 40% laser tune get 5-7 % useful events
- Beam spot size ~1.5mm diameter
  - See backup slides

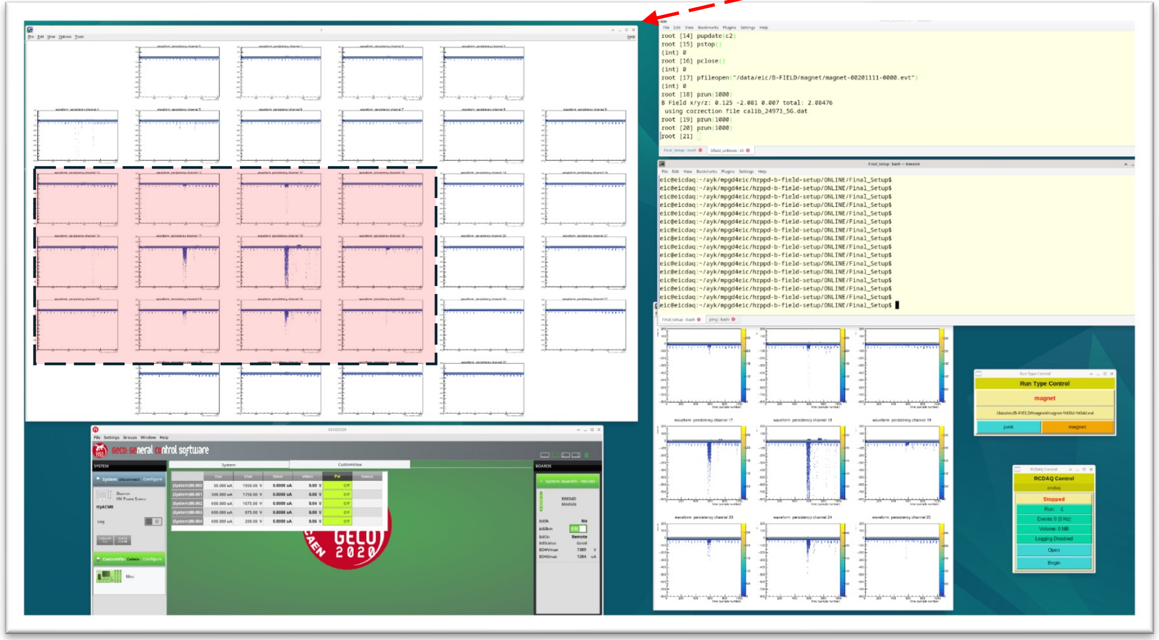




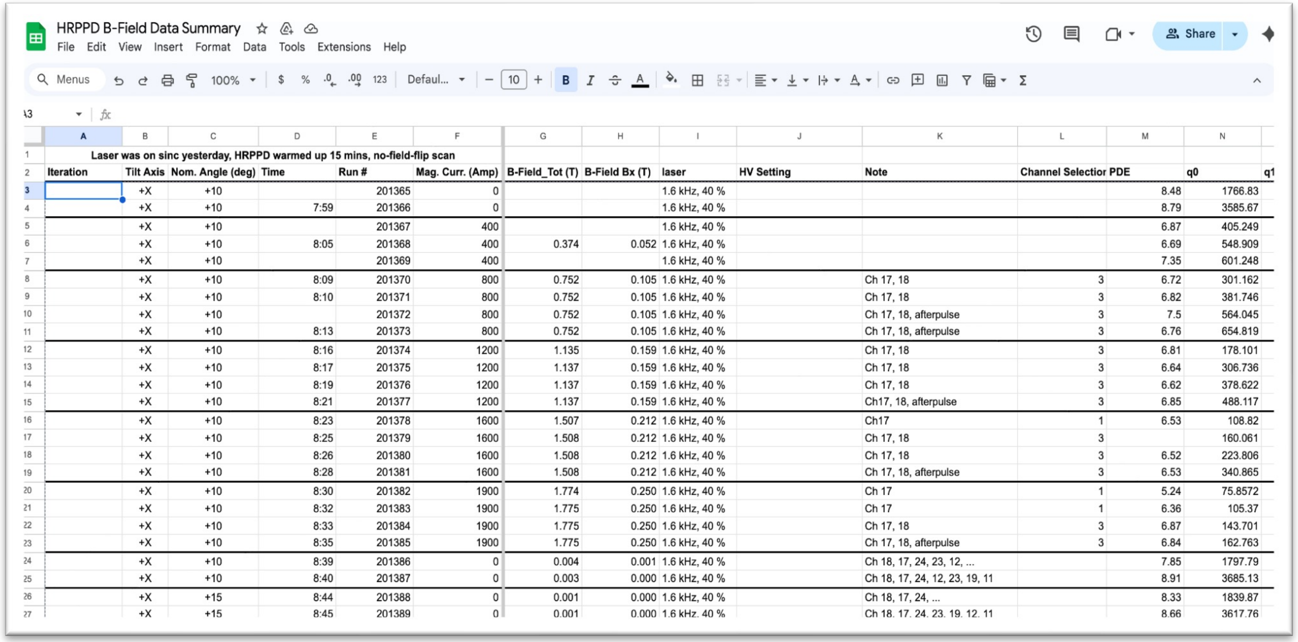
Data Taking and Online Monitoring

Online Monitoring VNC display

A 6x6-4 instrumented pad area



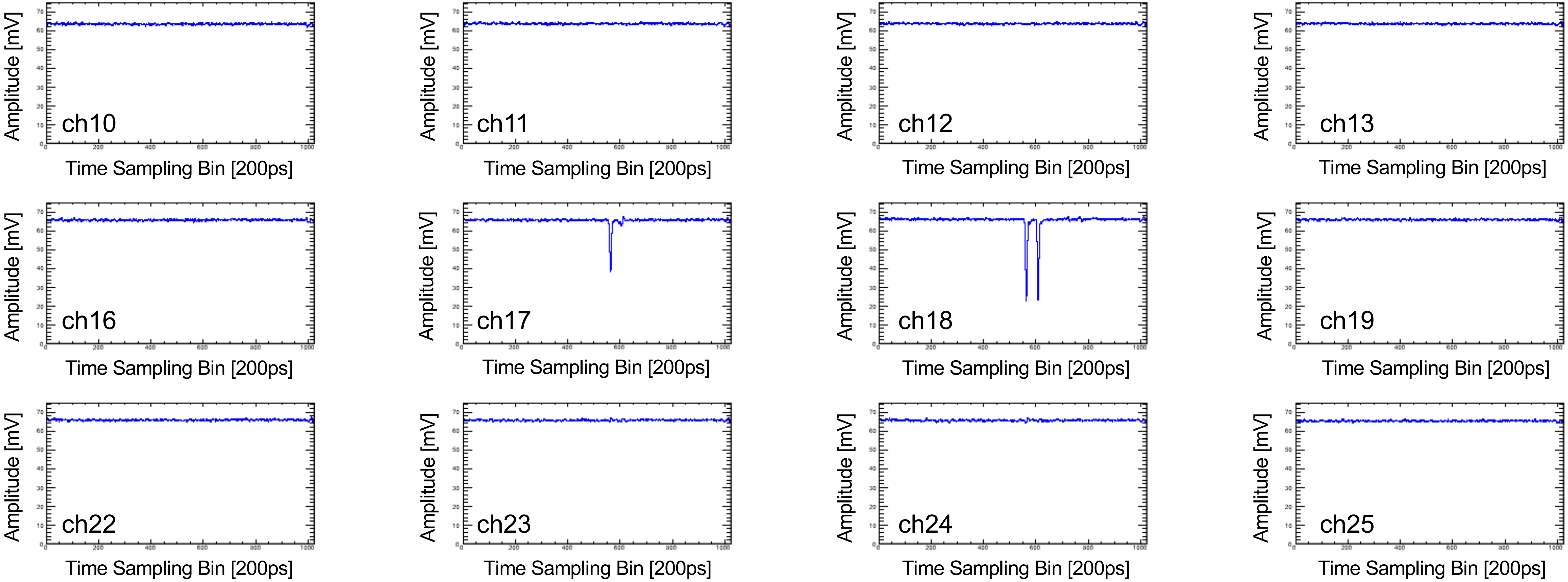
Data Summary Google sheet



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
1	Laser was on sinc yesterday, HRPPD warmed up 15 mins, no-field-flip scan														
2	Iteration	Tilt Axis	Nom. Angle (deg)	Time	Run #	Mag. Curr. (Amp)	B-Field_Tot (T)	B-Field Bx (T)	laser	HV Setting	Note	Channel Selectior	PDE	q0	q1
3		+X	+10		201365	0			1.6 kHz, 40 %				8.48	1766.83	
4		+X	+10	7:59	201366	0			1.6 kHz, 40 %				8.79	3585.67	
5		+X	+10		201367	400			1.6 kHz, 40 %				6.87	405.249	
6		+X	+10	8:05	201368	400	0.374	0.052	1.6 kHz, 40 %				6.69	548.909	
7		+X	+10		201369	400			1.6 kHz, 40 %				7.35	601.248	
8		+X	+10	8:09	201370	800	0.752	0.105	1.6 kHz, 40 %		Ch 17, 18	3	6.72	301.162	
9		+X	+10	8:10	201371	800	0.752	0.105	1.6 kHz, 40 %		Ch 17, 18	3	6.82	381.746	
10		+X	+10		201372	800	0.752	0.105	1.6 kHz, 40 %		Ch 17, 18, afterpulse	3	7.5	564.045	
11		+X	+10	8:13	201373	800	0.752	0.105	1.6 kHz, 40 %		Ch 17, 18, afterpulse	3	6.76	654.819	
12		+X	+10	8:16	201374	1200	1.135	0.159	1.6 kHz, 40 %		Ch 17, 18	3	6.81	178.101	
13		+X	+10	8:17	201375	1200	1.137	0.159	1.6 kHz, 40 %		Ch 17, 18	3	6.64	306.736	
14		+X	+10	8:19	201376	1200	1.137	0.159	1.6 kHz, 40 %		Ch 17, 18	3	6.62	378.622	
15		+X	+10	8:21	201377	1200	1.137	0.159	1.6 kHz, 40 %		Ch17, 18, afterpulse	3	6.85	488.117	
16		+X	+10	8:23	201378	1600	1.507	0.212	1.6 kHz, 40 %		Ch17	1	6.53	108.82	
17		+X	+10	8:25	201379	1600	1.508	0.212	1.6 kHz, 40 %		Ch 17, 18	3		160.061	
18		+X	+10	8:26	201380	1600	1.508	0.212	1.6 kHz, 40 %		Ch 17, 18	3	6.52	223.806	
19		+X	+10	8:28	201381	1600	1.508	0.212	1.6 kHz, 40 %		Ch 17, 18, afterpulse	3	6.53	340.865	
20		+X	+10	8:30	201382	1900	1.774	0.250	1.6 kHz, 40 %		Ch 17	1	5.24	75.8572	
21		+X	+10	8:32	201383	1900	1.775	0.250	1.6 kHz, 40 %		Ch 17	1	6.36	105.37	
22		+X	+10	8:33	201384	1900	1.775	0.250	1.6 kHz, 40 %		Ch 17, 18	3	6.87	143.701	
23		+X	+10	8:35	201385	1900	1.775	0.250	1.6 kHz, 40 %		Ch 17, 18, afterpulse	3	6.84	162.763	
24		+X	+10	8:39	201386	0	0.004	0.001	1.6 kHz, 40 %		Ch 18, 17, 24, 23, 12, ...		7.85	1797.79	
25		+X	+10	8:40	201387	0	0.003	0.000	1.6 kHz, 40 %		Ch 18, 17, 24, 12, 23, 19, 11		8.91	3685.13	
26		+X	+15	8:44	201388	0	0.001	0.000	1.6 kHz, 40 %		Ch 18, 17, 24, ...		8.33	1839.87	
27		+X	+15	8:45	201389	0	0.001	0.000	1.6 kHz, 40 %		Ch 18, 17, 24, 23, 19, 12, 11		8.66	3617.76	

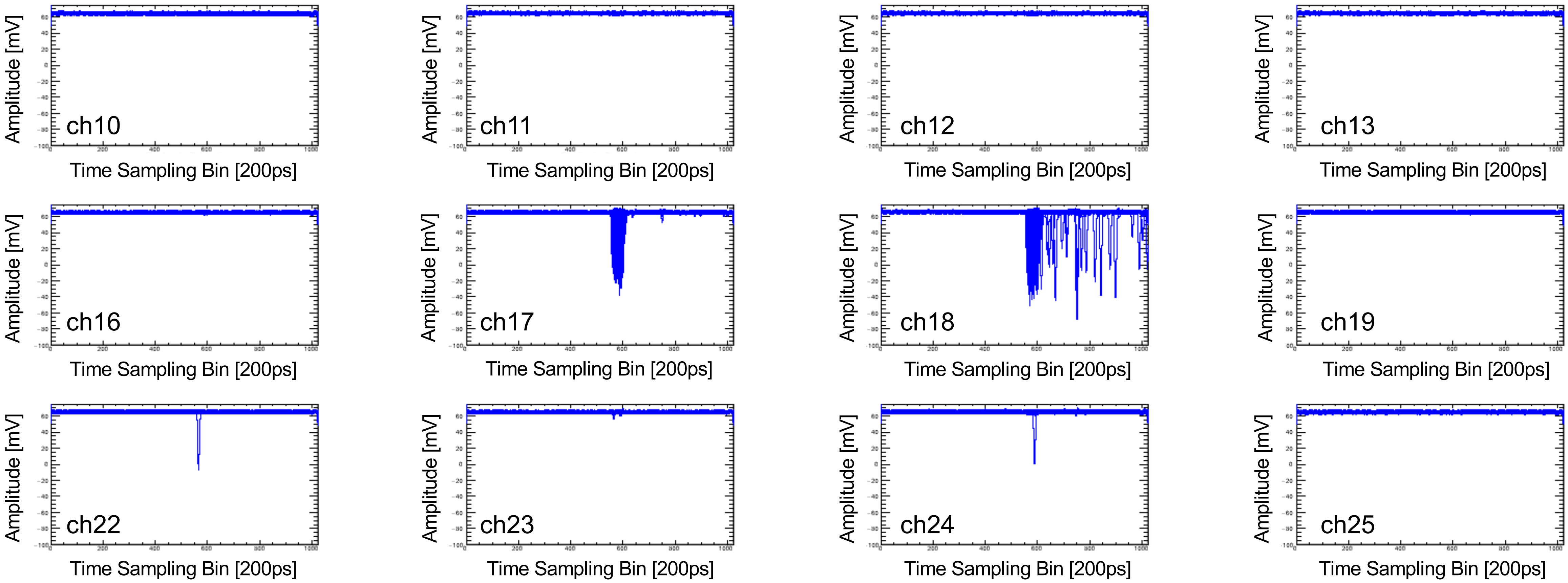
- RCDAQ data acquisition by Martin Purschke, VNC, elog, HV control, online display
  - Fully automated data taking in a batch mode (except for magnet ramp-up and ramp-down)
- ~1.5 kHz on tape, typically 100k events per setting, ~1500 runs, ~7.5TB of data
  - A typical "beam test" environment (*and a very useful exercise before going to a pfRICH beam test @ CERN*)
- Near-online data analysis, with subsequent data productions on BNL SDCC

Typical Waveforms (Single Event)



- ~200 ns full range (1024 samples @ 5 GS/s); few dozens of mV signals (gain-dependent of course)
- **Charge sharing** between channels 17 and 18, with an **afterpulse** observed in channel 18

Typical Accumulated Waveforms



- **Charge sharing** between channels 17 and 18, with **afterpulsing** observed in channel 18
- Other channels also show some activity when several waveforms are accumulated (stray photons?)

Run Configuration Parameters

- **Tilt axis**: +/-X, +/-Y, +/-X with assembly flip imitating B-field sign change
- **High voltage (HV)**: MCP symmetric, MCP asymmetric, PC HV variation
- **Magnetic field**: 0–1.86 T (magnet current 0–2000 A)
- **Inclination angle (θ)**: -30° to +30° (actual range tilt axis dependent)
  - Only a fraction of results will be shown today; also see the backup

- **Laser repetition rate**: 600 Hz, 1 kHz, 1.6 kHz (default), 2 kHz, 10 kHz
  - A NIM trigger pulse signal gets digitized by the V1742 along with the HRPPD pad signals
- **Laser tune**: 30 %, 40 % (default)
  - **Single photon mode**: typically, ~5-7% of "useful" events out of 100k events / run

- **Notation**: 0V 200 – 675 – 200 – 675 – 200V

anode - → photocathode

MCP#2 (Exit) MCP#1 (Entry)

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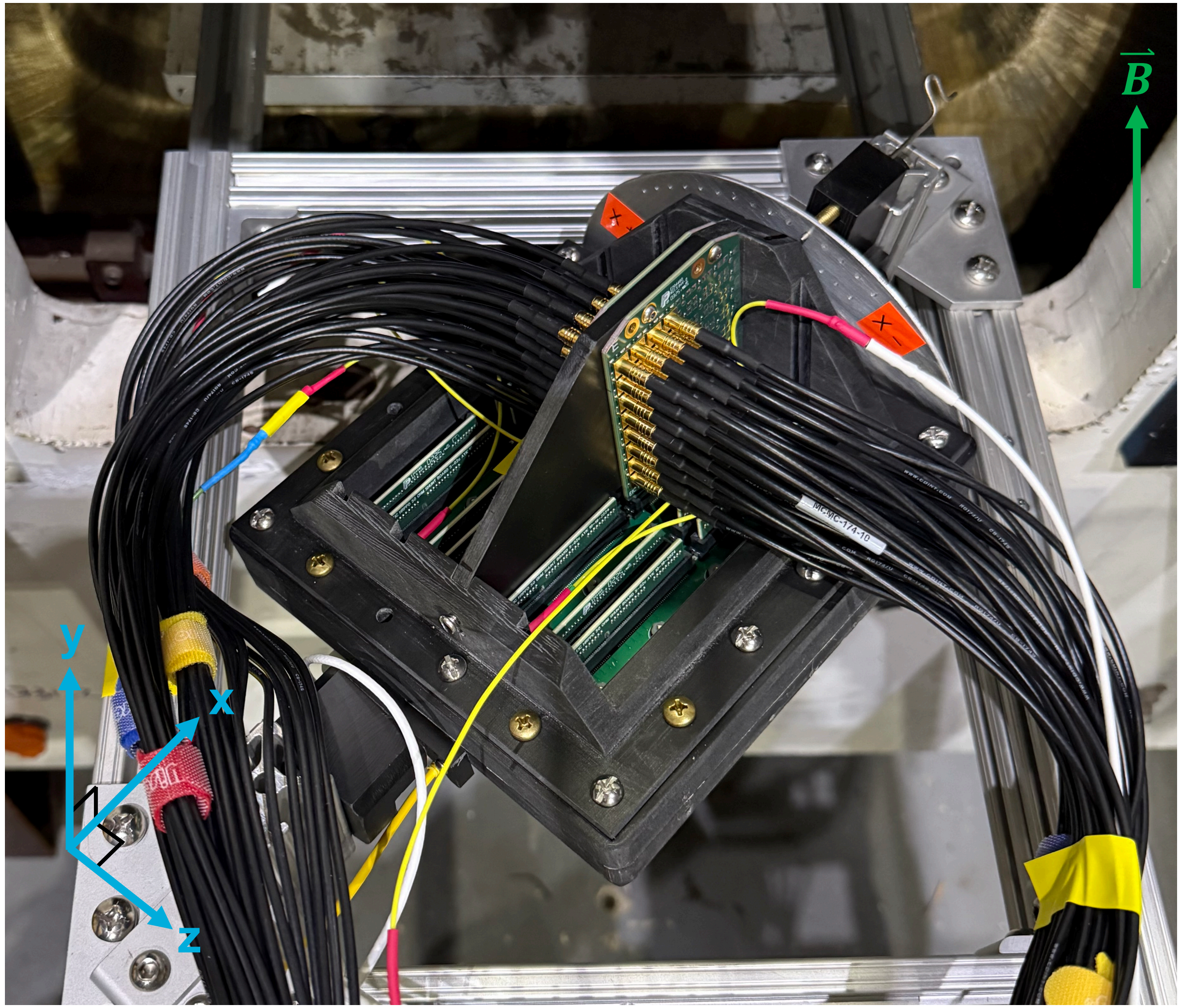
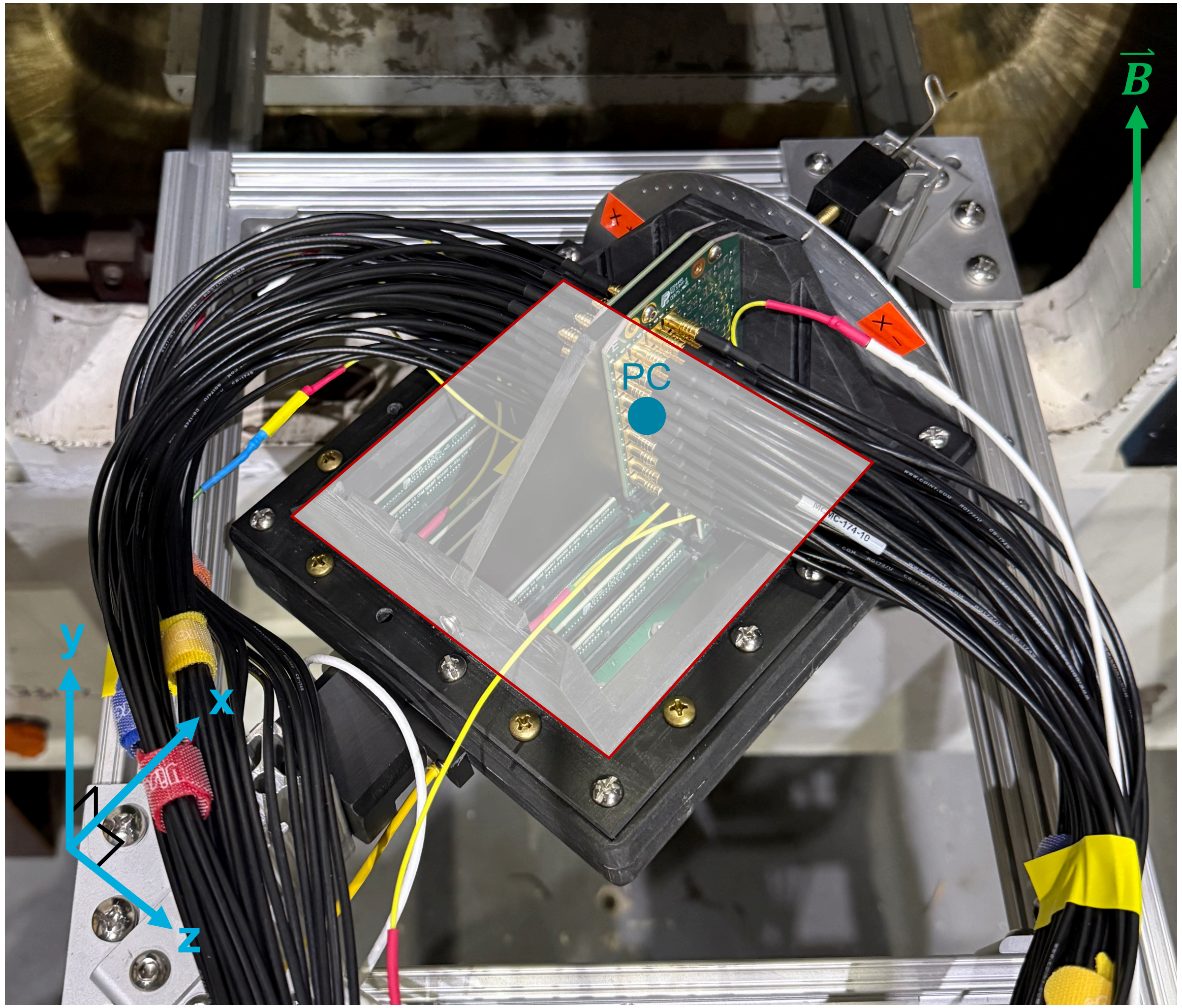
HRPPD assembly rotation axes

HRRPD facing down, +/-X rotation (“main” axis)



HRPPD assembly rotation axes

HRRPD facing down, +/-X rotation (“main” axis)



HRPPD assembly rotation axes

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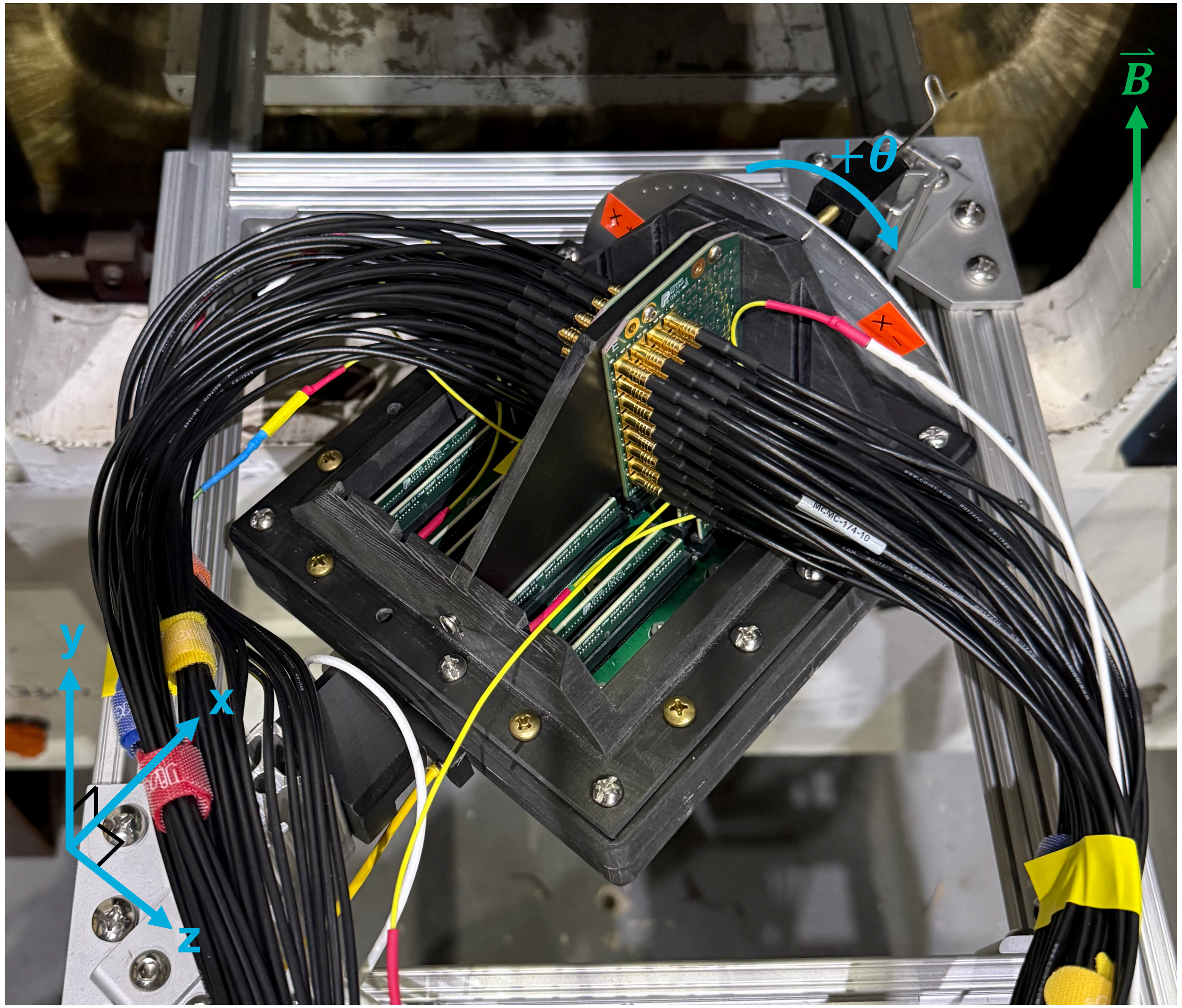
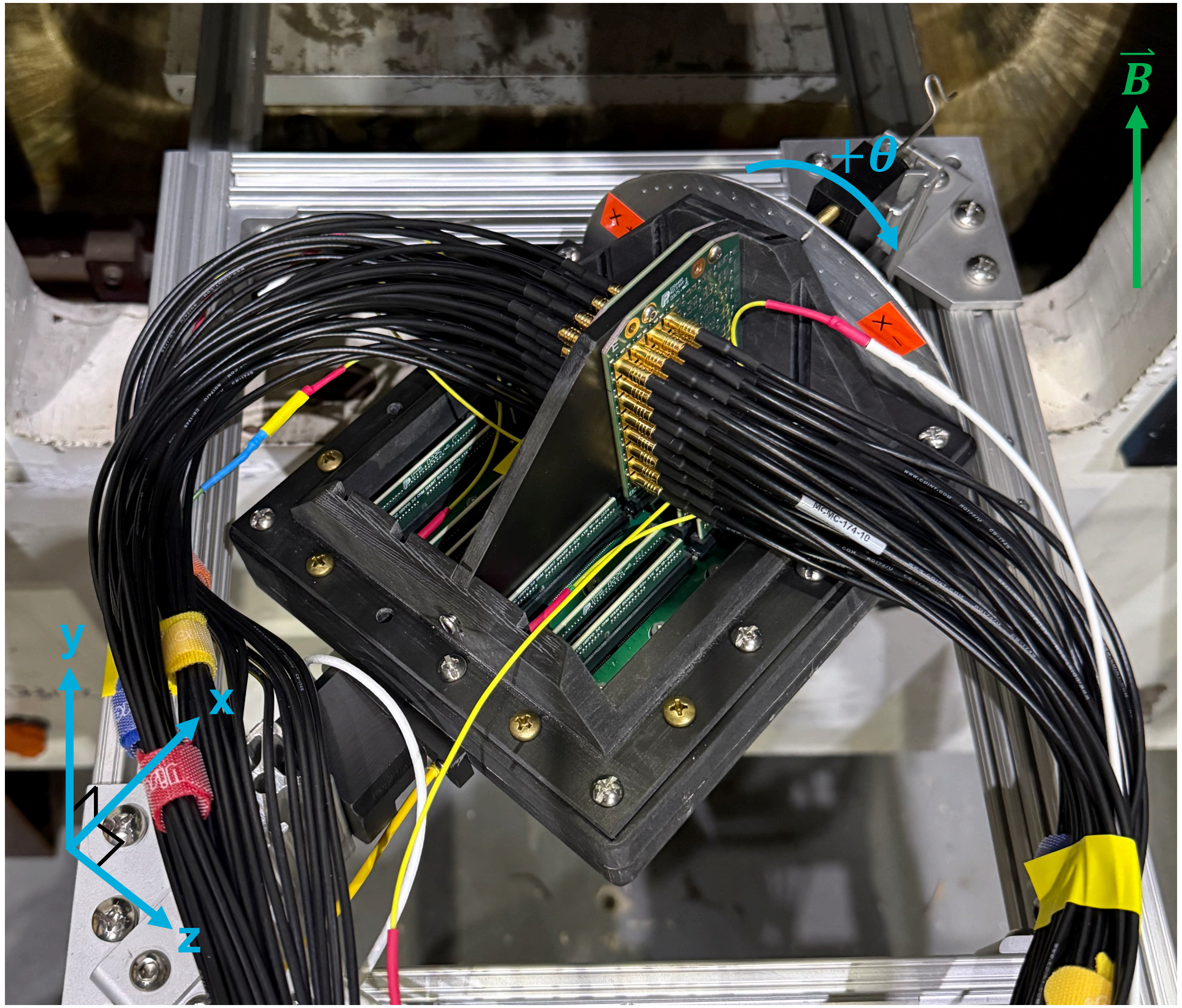
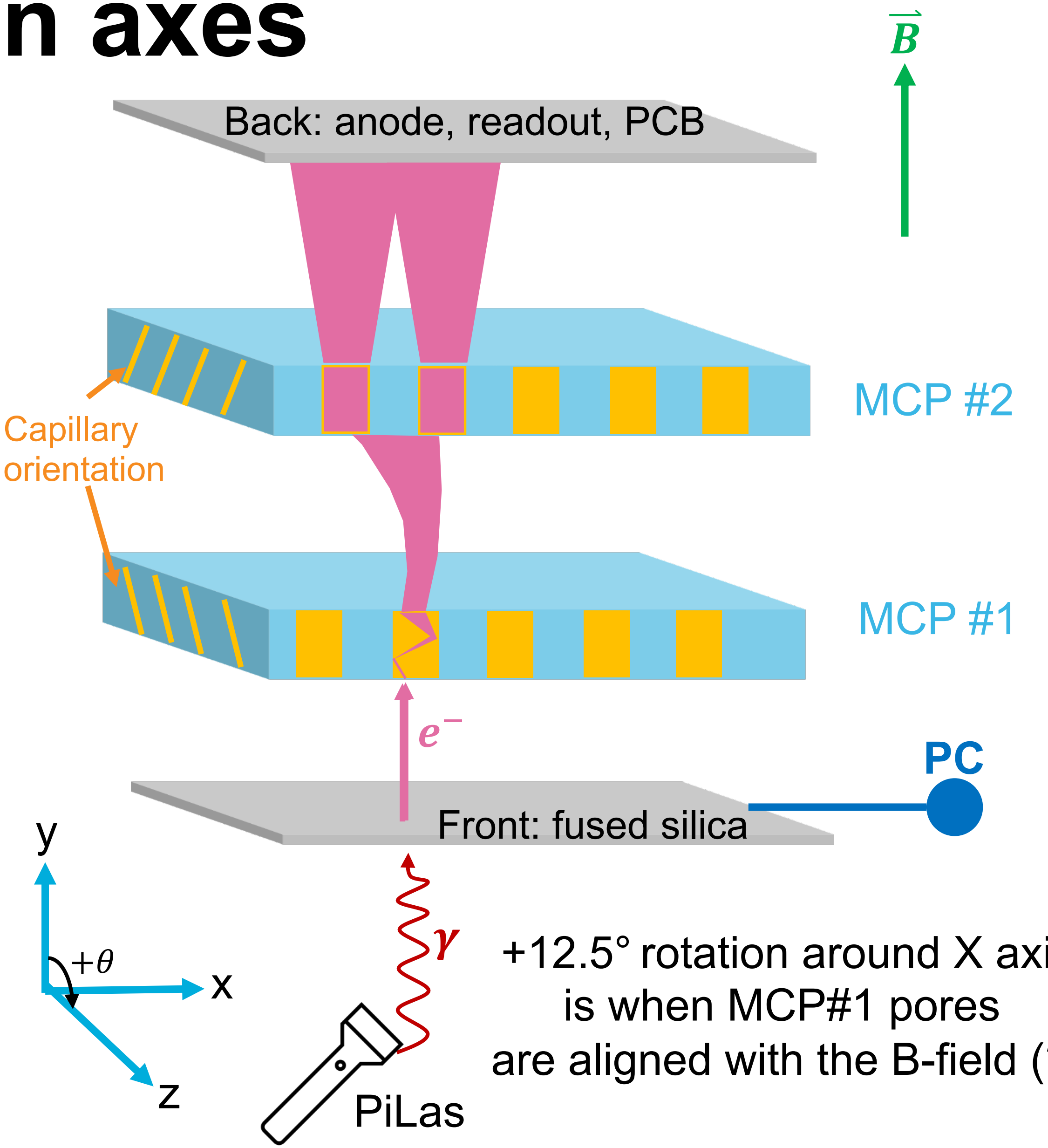


HRPPD assembly rotation axes

HRRPD facing down, +/-X rotation ("main" axis)





+12.5° rotation around X axis is when MCP#1 pores are aligned with the B-field (?)

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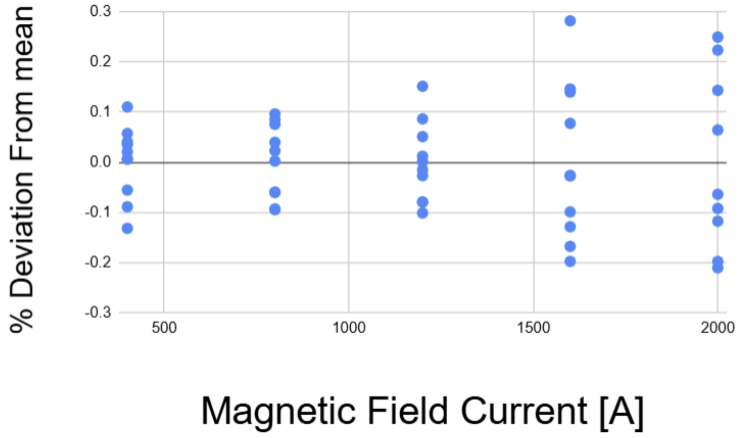
Yet MCP#1 & MCP#2 chevron capillary orientation needs to be clarified

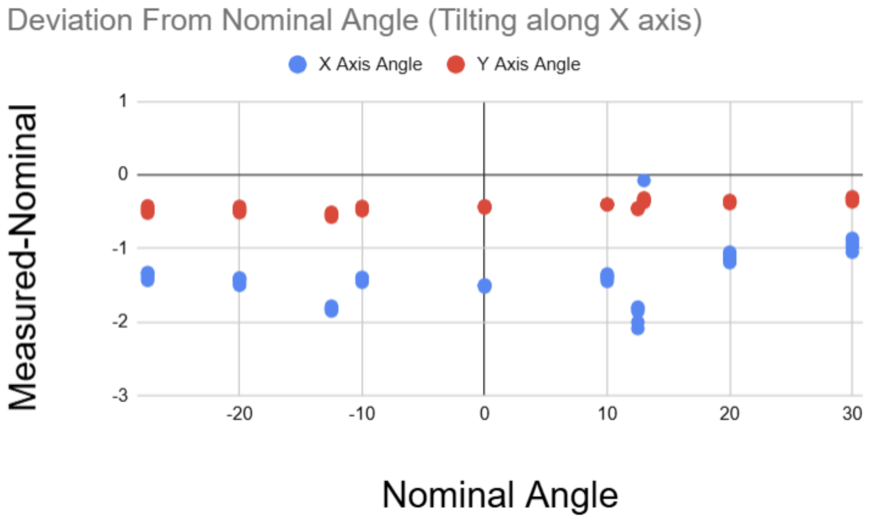
Hall probe orientation / misalignment

Use mounted Hall probe readings to measure magnetic field components on a run-by-run basis to correct the "nominal" angles

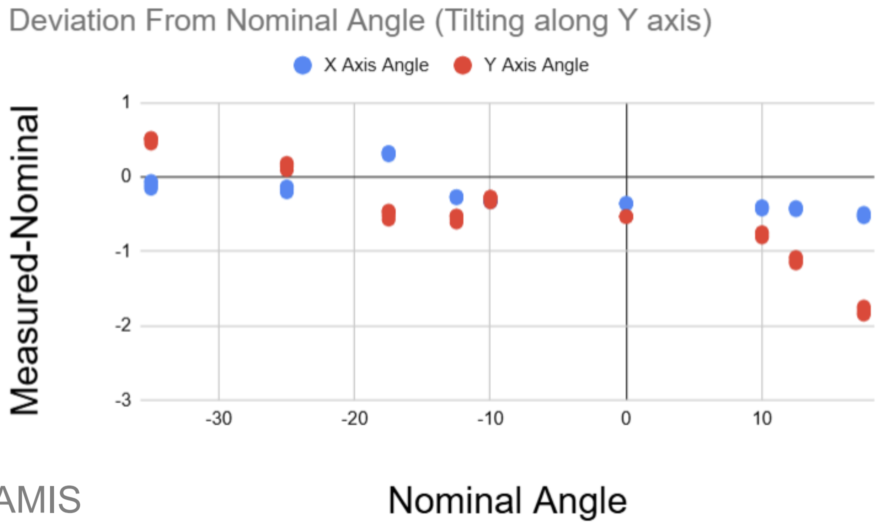


Absolute field values are reproducible within ~0.3 % throughout the whole data taking period

- Tilting Along X axis
  X axis avg. offset: -1.4° (Protractor error)
  Y axis avg. offset: -0.4° (Hall probe misalignment)

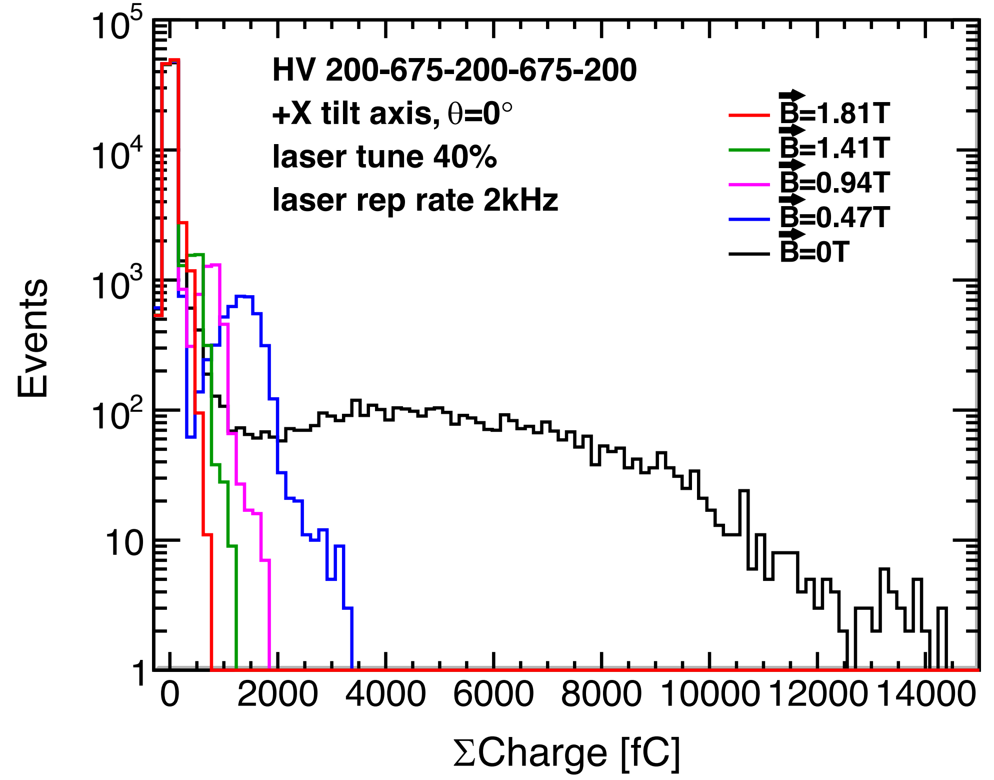


- Tilting Along Y axis
  Offset has small dependence on nominal angle due to slight misalignment

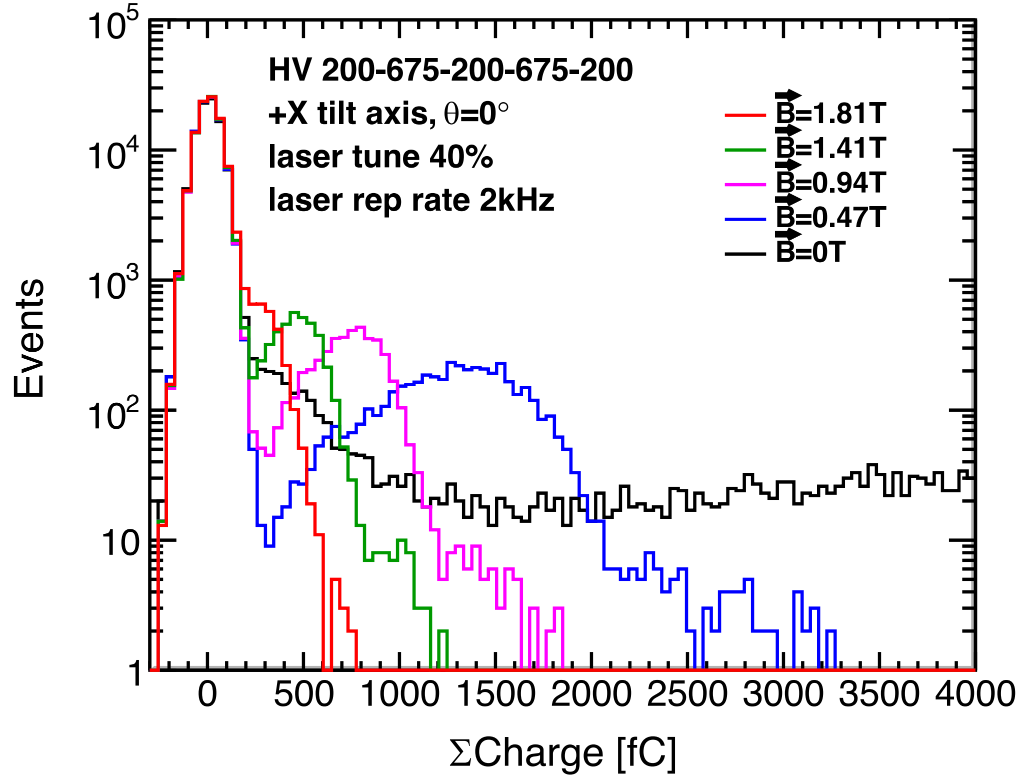


Example charge Spectra vs Magnetic Field

With a 0T Spectrum included



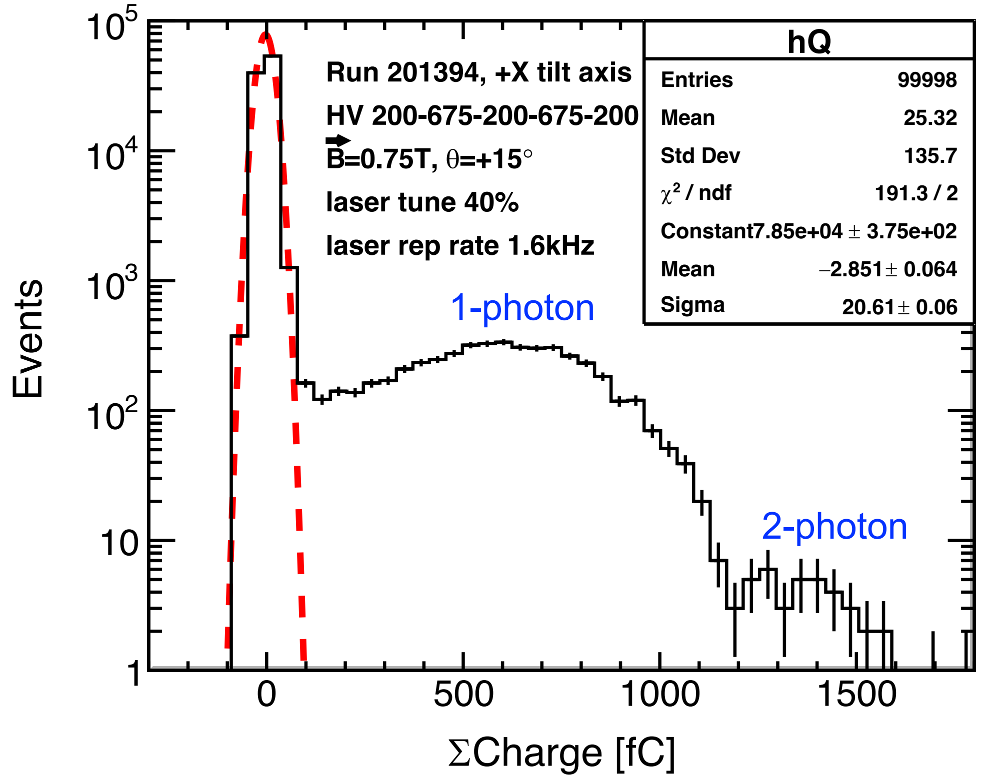
Zoomed in non-zero B-field data



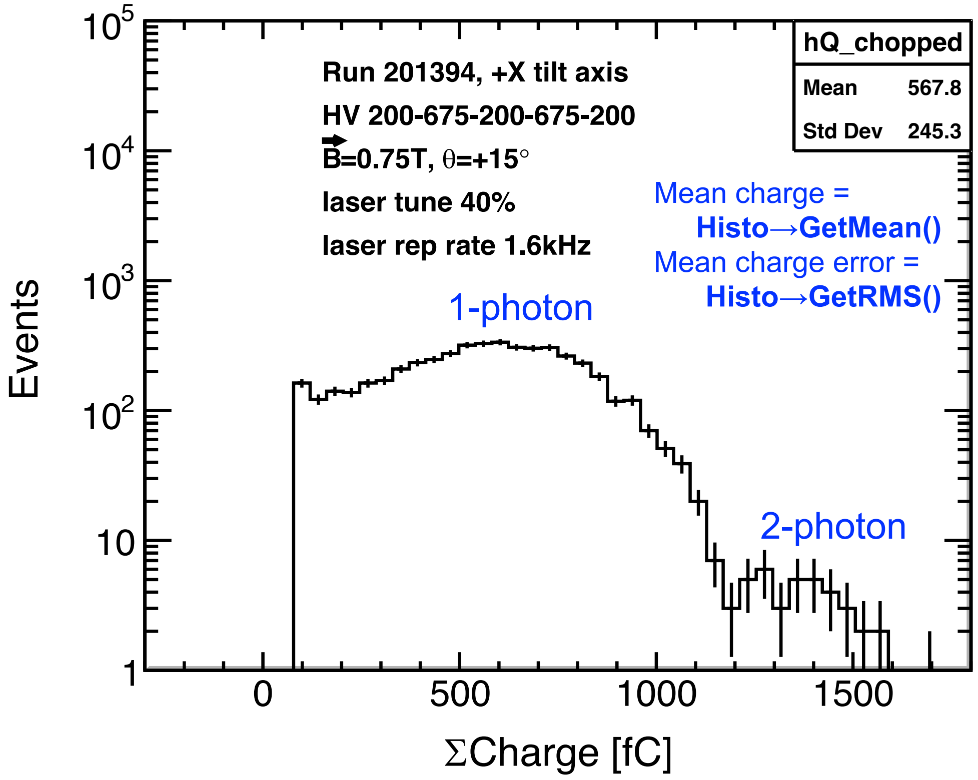
- **Charge calculation**: a sum of 3×4 neighboring pad signals in a 4ns wide window (20 time bins)
- **Gain reduction** with increasing magnetic field is seen (see backup: full magnetic field set)
- Units: 1600 fC is equivalent to a gain of 10^7

Mean Charge Extraction (Gain)

Fit pedestal (Gaussian) alone

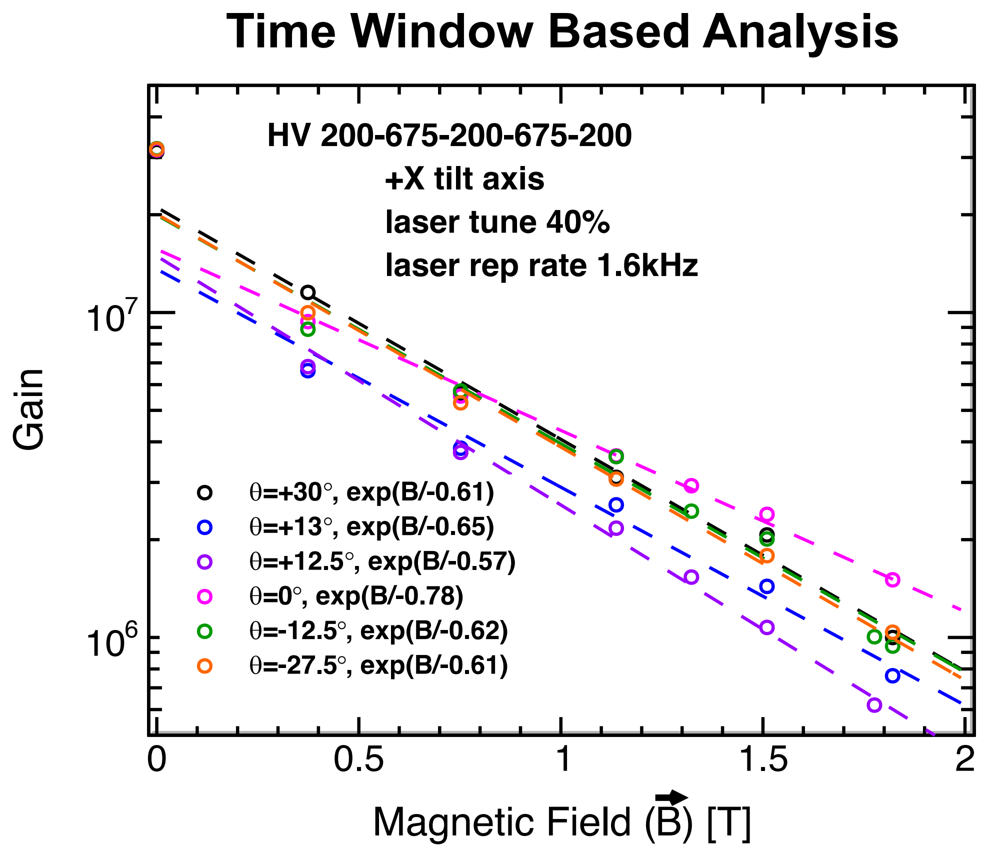


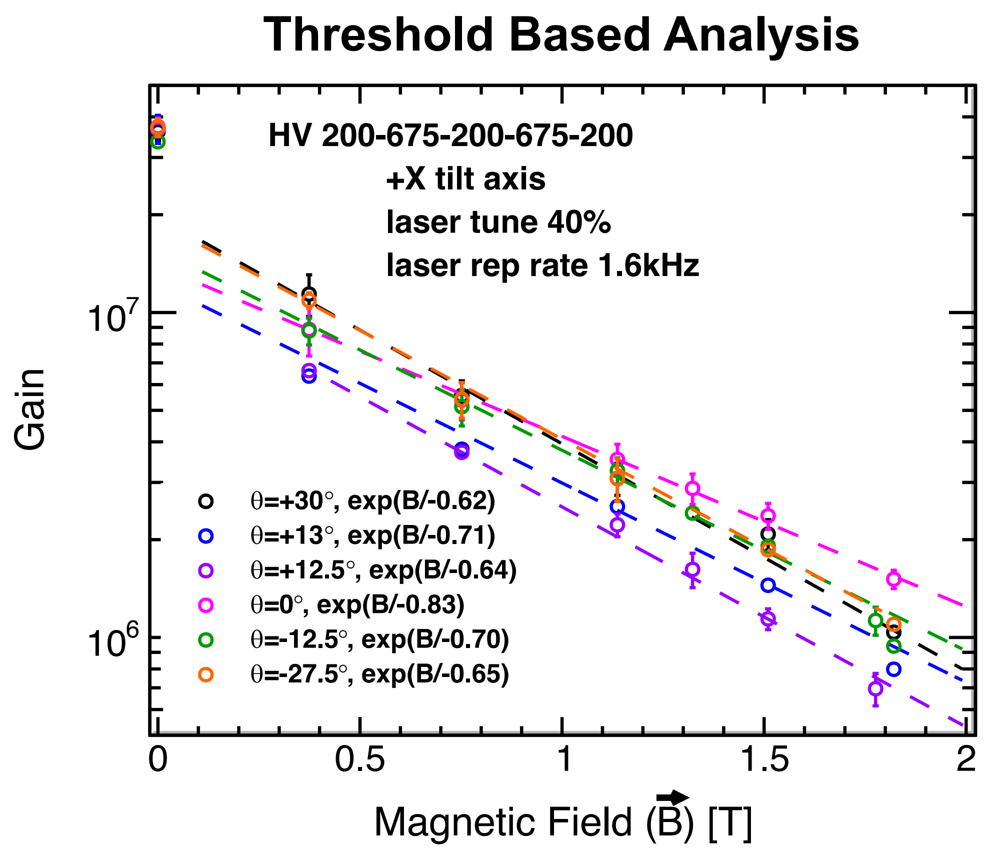
Apply a **4σ cut to remove the pedestal**



- Currently it is based on an average over 1-photon & 2-photon contributions
- Eventually, will account for 0-photon, 1-photon & 2-photon Poisson statistics and also go down to a ~2σ cut
- *Polya fit does not work well anyway* (see backup: gain saturation, no large amplitudes)

Gain vs Magnetic Field at various tilt angles

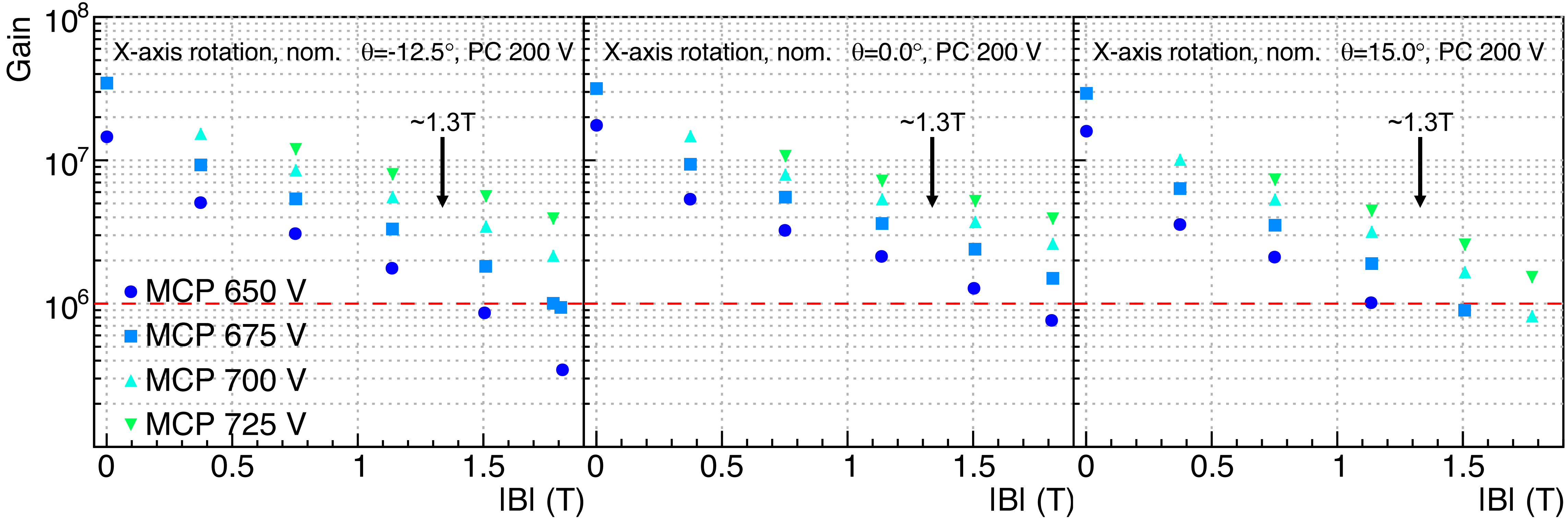




- Two independent analyses were conducted: time-window–based and threshold-based event selection
- **The mean charge values from both methods are consistent**

HRPPD Gain in a “pfRICH tilt angle” range of interest

pfRICH sensor plane location in ePIC: up to ~1.3T field, tilt angles up to 13°



- One can easily achieve >10^6 gain of few times 10^6 the whole tilt angle range of interest
  - Which may mean that all 68 HRPPDs can be oriented the same way
- *At these HV settings an HRPPD would not trip even at a zero field*
- We’ve taken this type of data in a range of a photocathode and transfer voltages, for a sake of completeness

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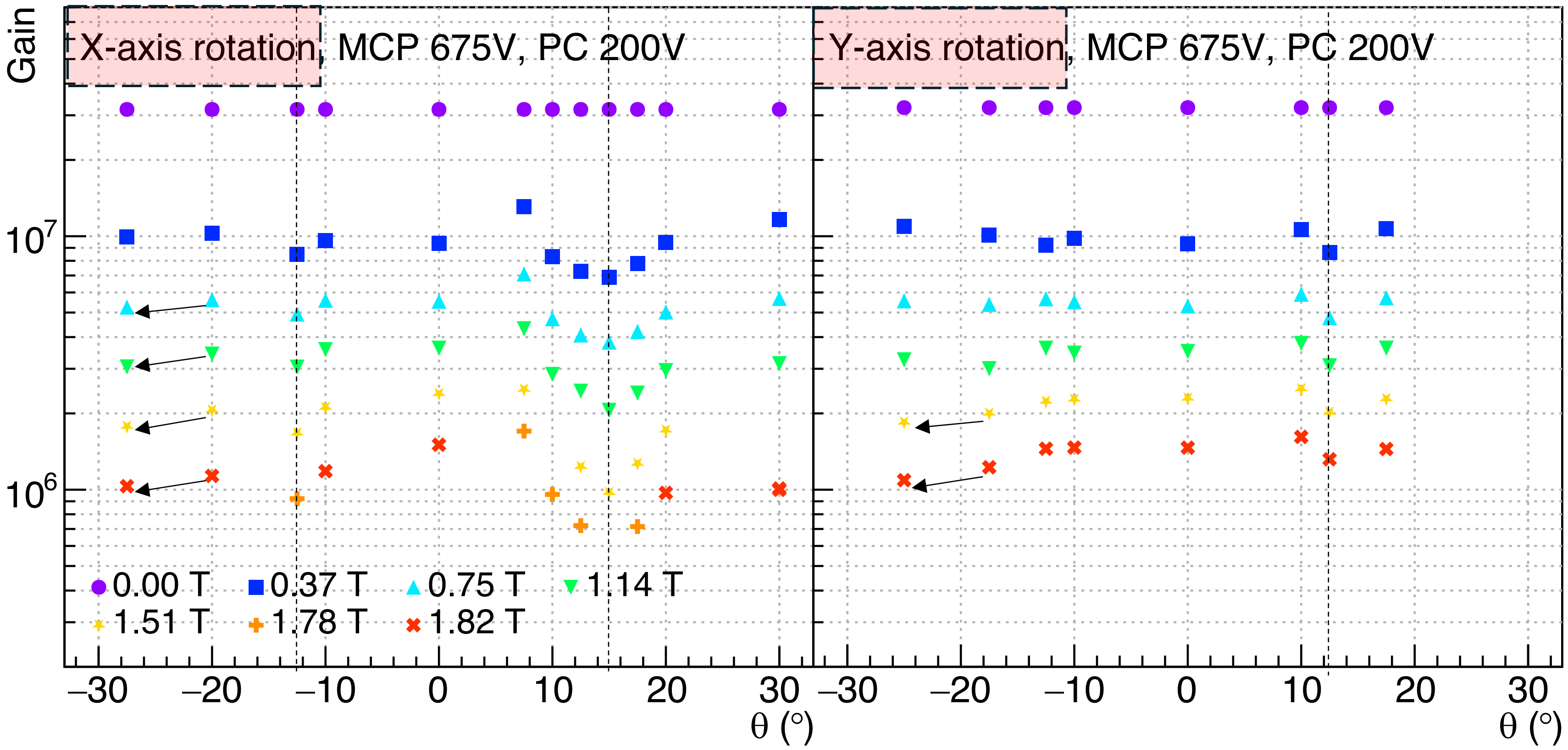
HRPPD Gain vs Tilting Angle



- X-axis: a minimum in gain is observed at approximately +15° *nominal angle* (B-fieldis roughly aligned with MCP#1 pores)
- X-axis: there is also a small dip at −12.5° *nominal angle* (B-field is roughly aligned with MCP#2 pores)

- Y-axis: a smaller angular dependence is observed

- Gain slightly decreases at large negative tilting angles (around −30°)

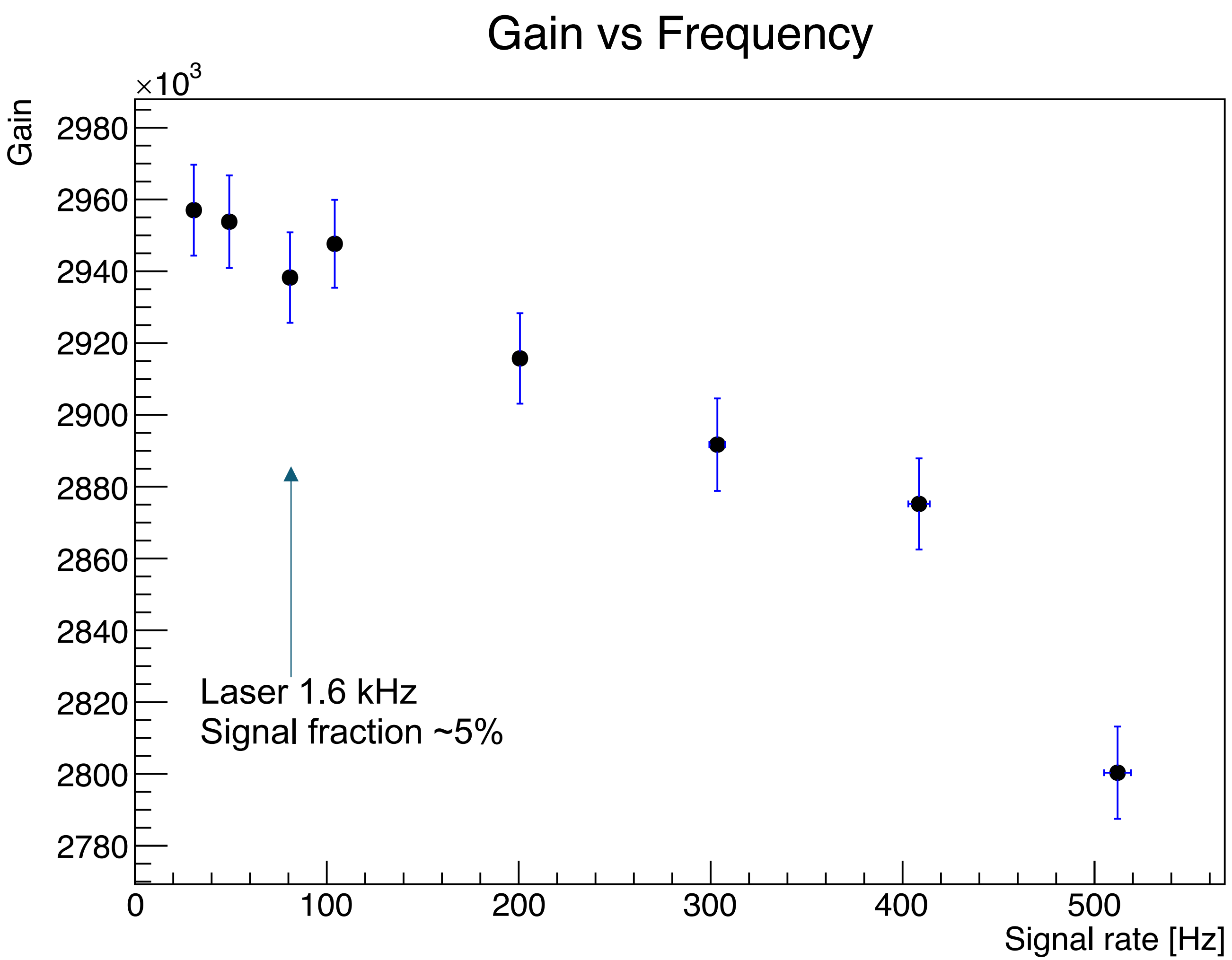
Repetition rate dependency

200-675-200-675-200V
1.3 T, 0° tilt angle

Signal rate = laser repetition rate * fraction of signal events in a run.

- Gain can be rate-dependent, especially in a high magnetic field, due to the electron avalanche focusing when only few of the MCP#2 pores are involved and can therefore saturate

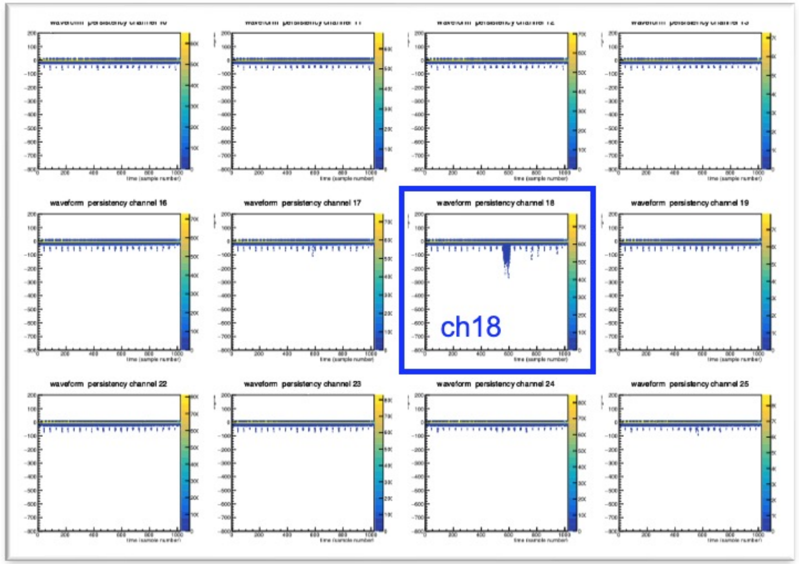
- One can indeed see a substantial rate dependency, however under the conditions we took data (1.6 kHz repetition rate, ~5-7% useful event fraction) *a respective correction will be very small*



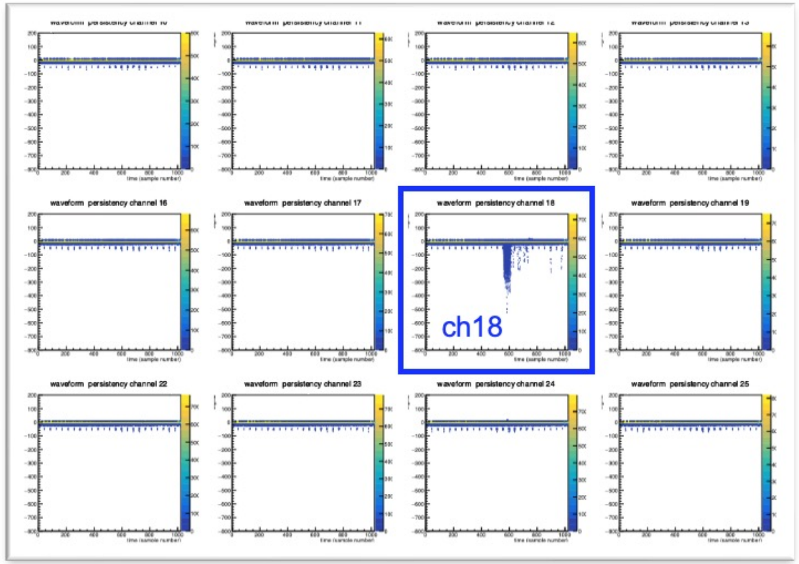
After-pulsing example: accumulated waveforms

+X tilt axis, $\vec{B}$ = 0.37T, $\boldsymbol{\theta} = -12.5°$, laser tune 40 %, laser rep rate 1.6 kHz

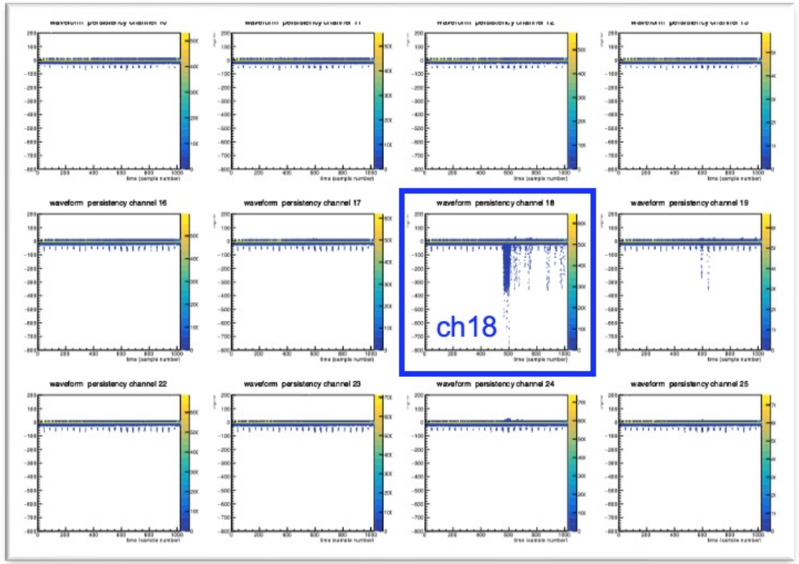
HV 200-**650**-200-**650**-200



HV 200-**675**-200-**675**-200



HV 200-**700**-200-**700**-200



- An increase in MCP bias voltage leads to more pronounced after-pulses
  - Which presumably means a faster photocathode aging
- As a rule of thumb, the after-pulsing rate should be kept <1% or so

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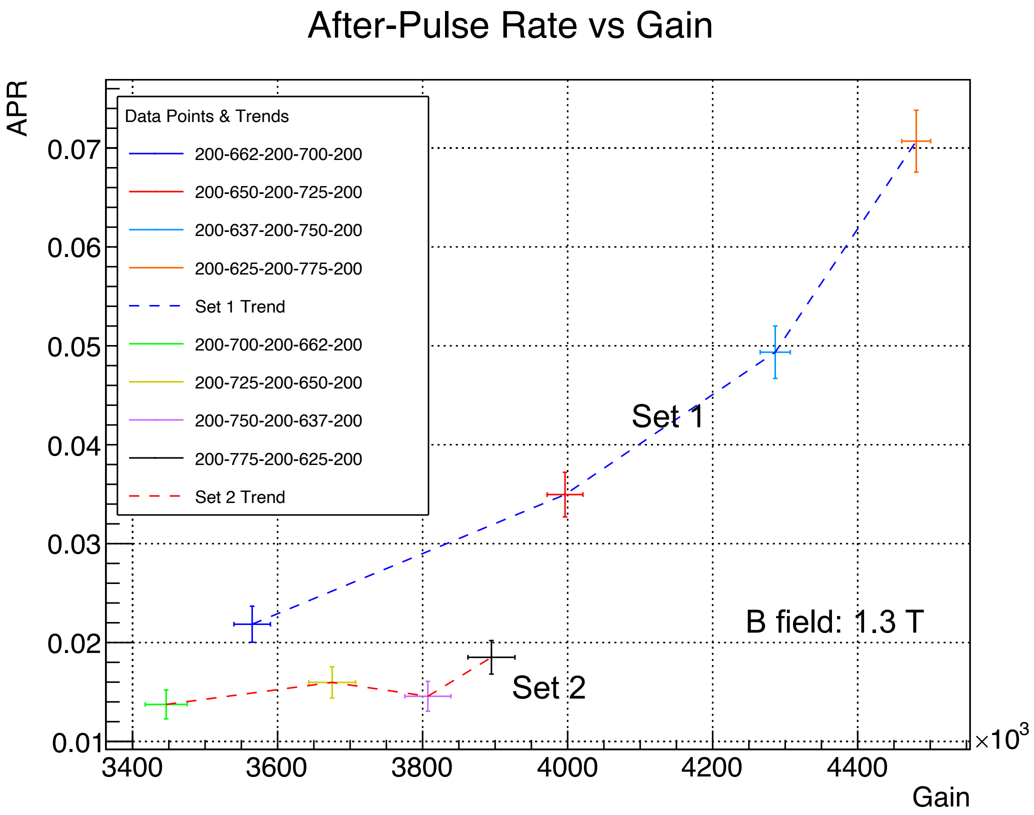
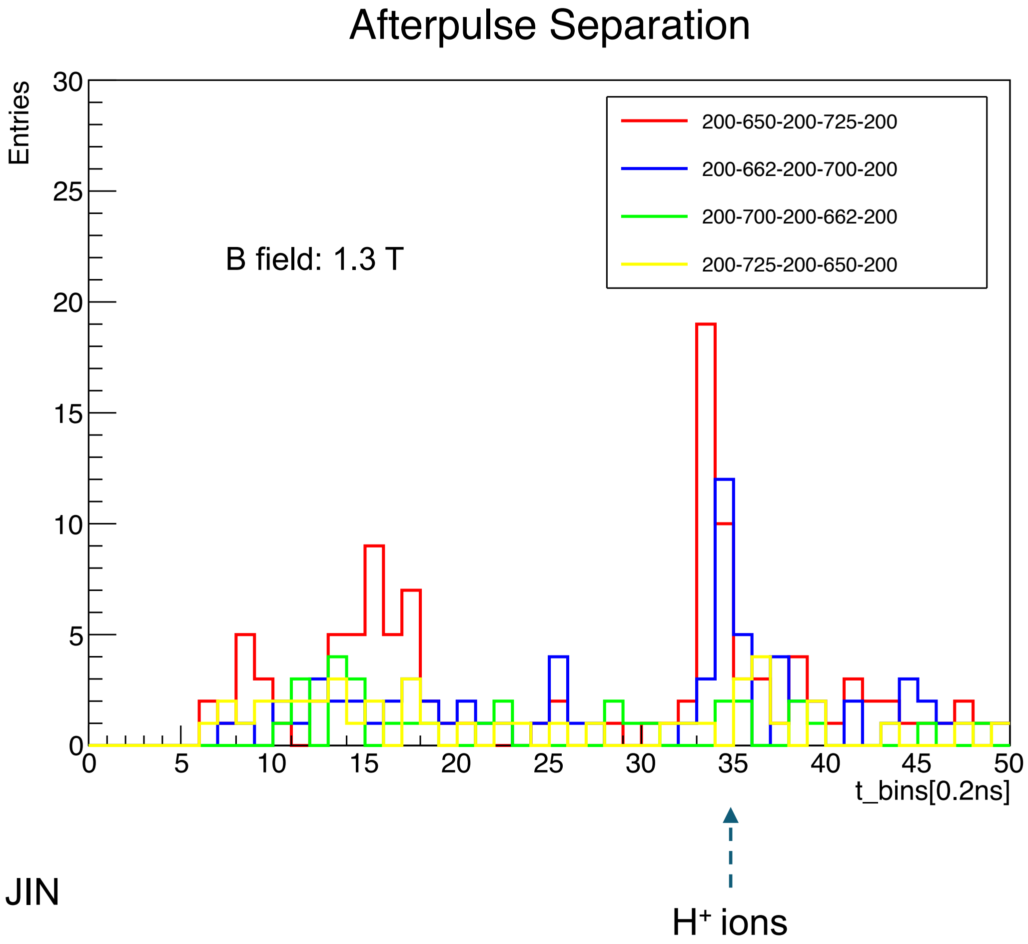
After-pulse rate

- For different HV setting, after-pulse rate ranges from O(1)% - O(10)%
- For “reference” pfRICH settings (200-675-200-675-200V @ 1.3 T and 0° tilting angle), after-pulse rate is ~1.3% in a 70ns window past the primary photoelectron pulse



After-pulse rate (for about the same gain) strongly depends on MCP#1 voltage



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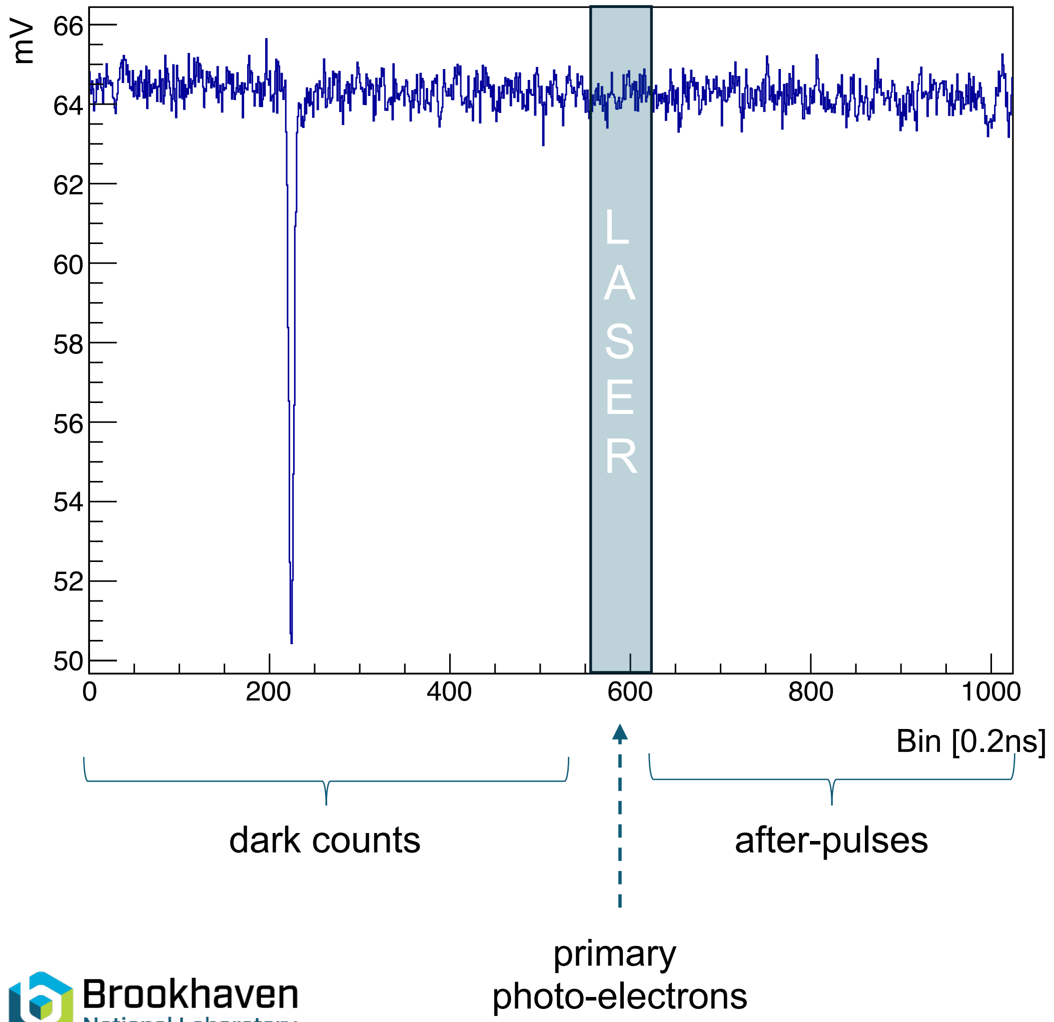
Dark count rate



pfRICH case

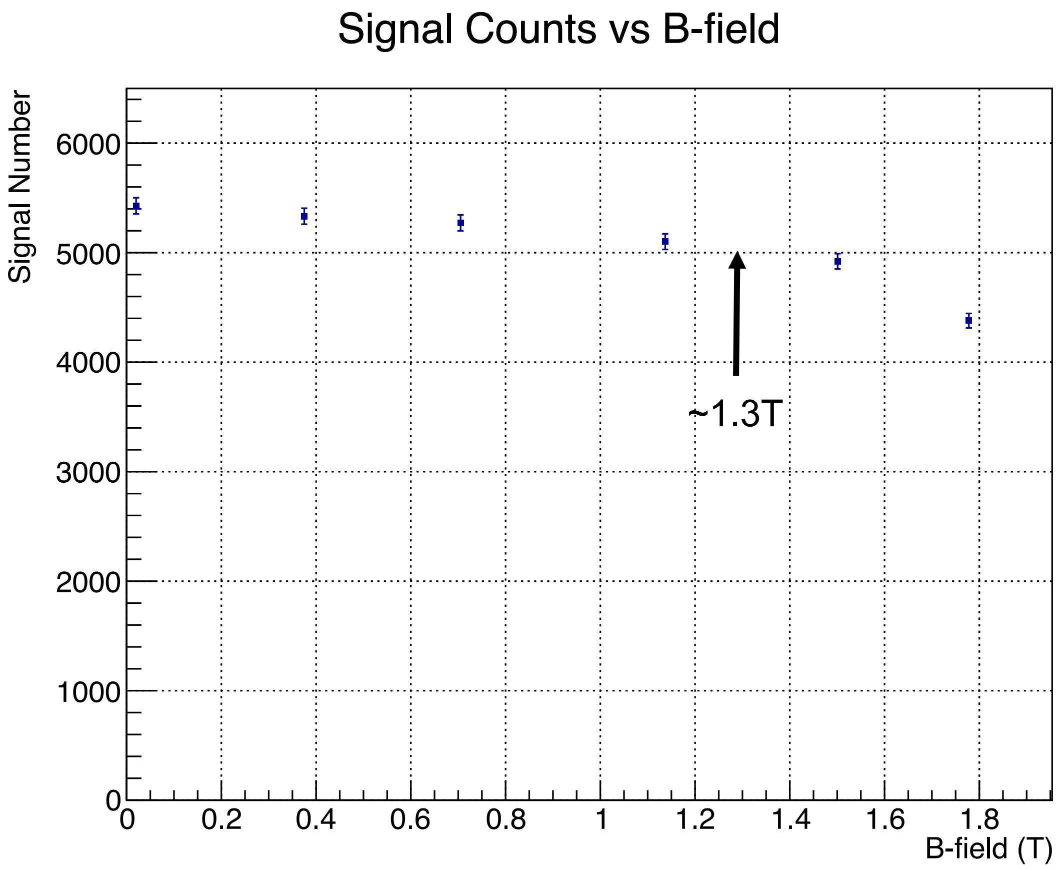
- Using 11 runs, each run has 100k events, 32 channels, first 500 bins in the waveform (laser shots around bin 600), with HV setting 200-675-200-675-200, **1.3 T** magnetic field, 0^o tilting angle: **10** dark count events are found.
- Thus, dark count rate (1.3T) = **~30 Hz/cm^2**

<u>Compare to a zero-field case:</u>

- With HV setting 200-675-200-675-200, **0 T** magnetic field, ~5700 dark count events are found in one run
- Thus, dark count rate (0 T) = **~170 kHz/cm^2**

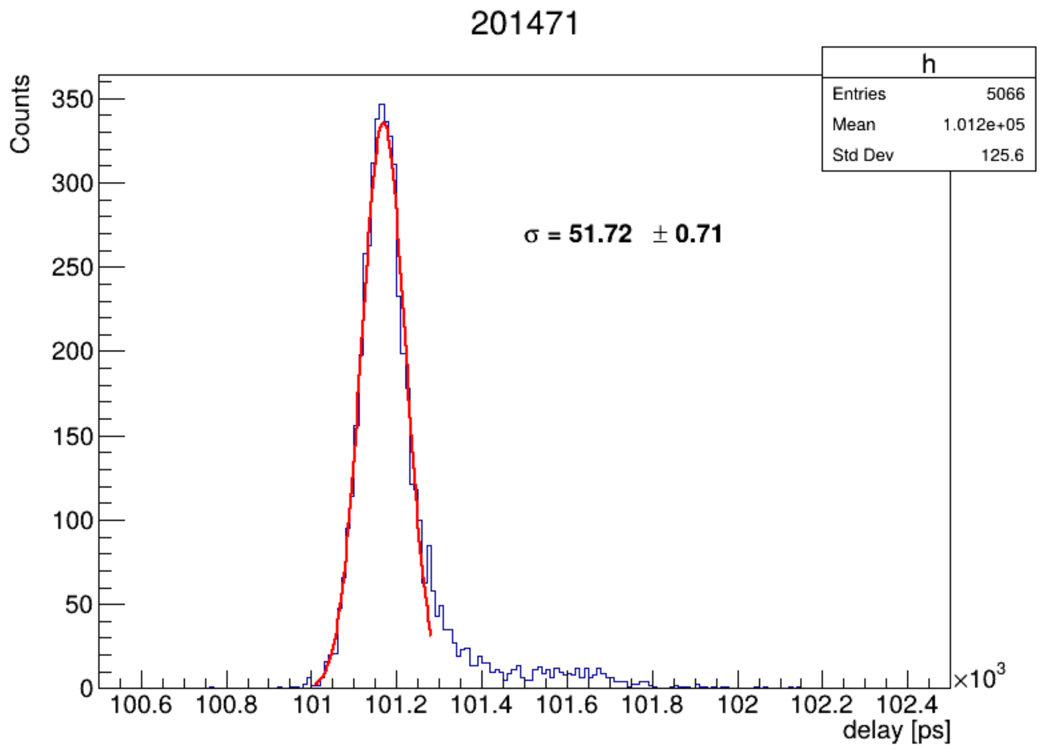
Detection efficiency

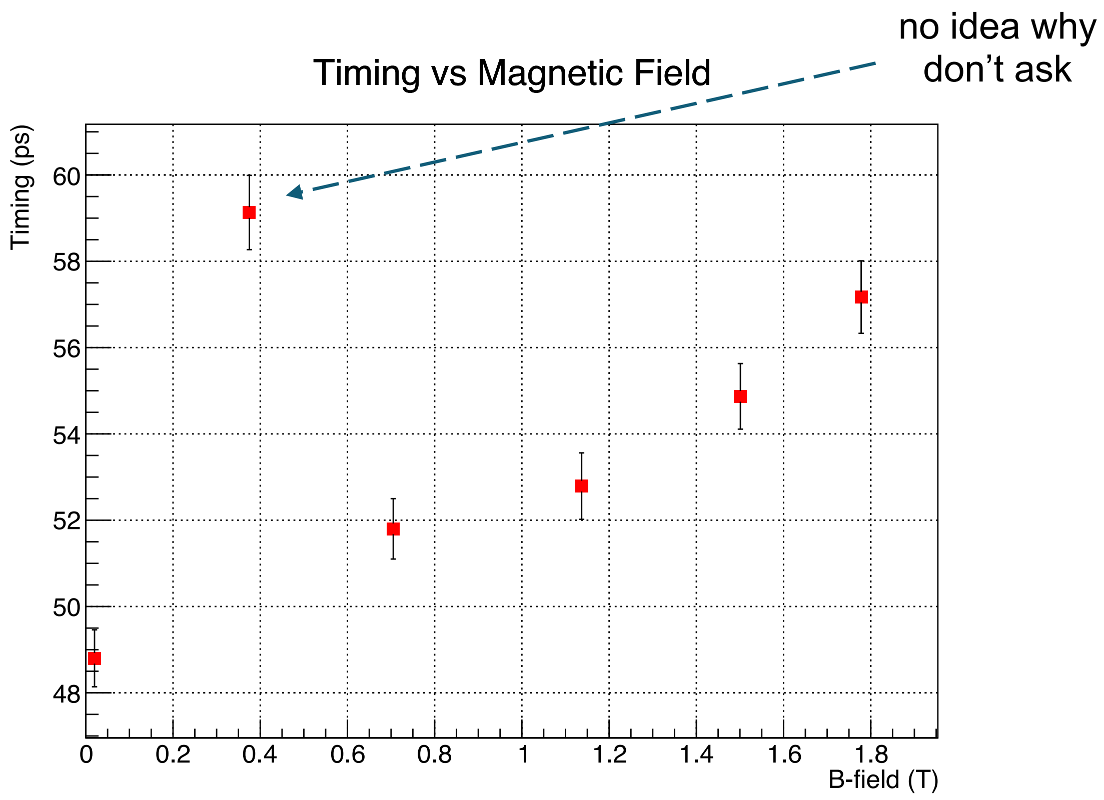
- HV setting 200-675-200-675-200, 0^{o} tilting angle



More studies needed (in a range of tilt angles and HV settings), but first impression is that there is no critical detection efficiency loss in a "typical pfRICH configuration"

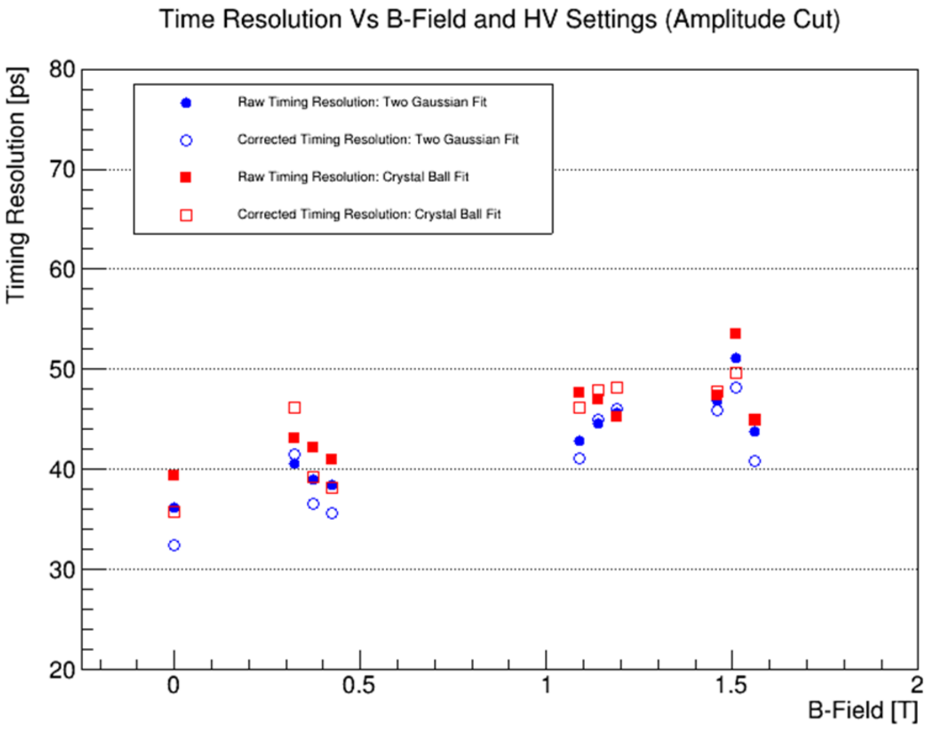
Timing resolution with a DRS4 readout

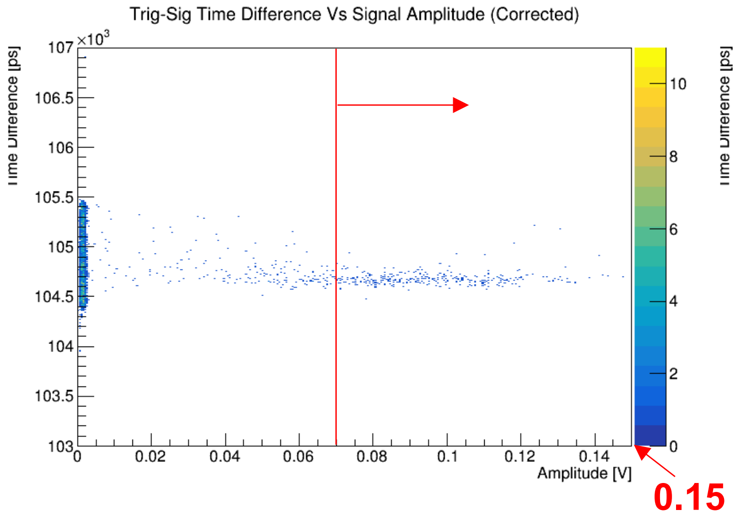


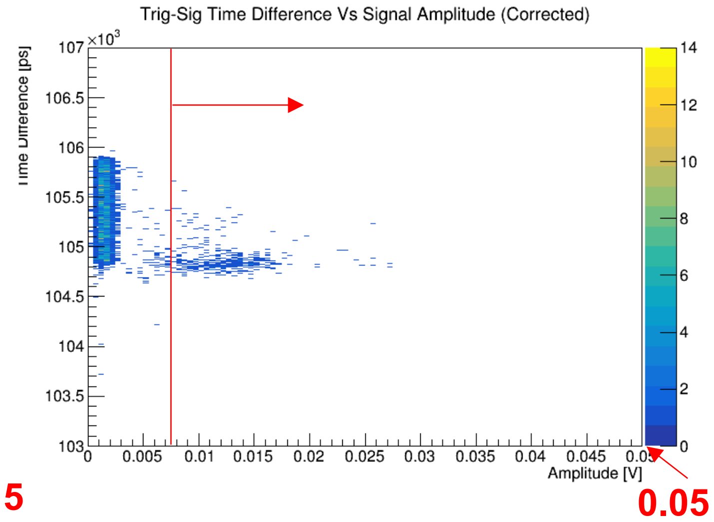


- In "typical" pfRICH conditions (1.3 T magnetic field, 0° tilting angle), with HV settings 200-675-200-675-200V (gain ~$3*10^6$), we observe ~52 ps timing distribution core Gaussian width
  - PiLas laser contribution, effect of DRS4 timing calibration and NIM trigger jitter not unfolded
- Weak dependence on a B-field is observed

Timing resolution using a 50 GS/s scope

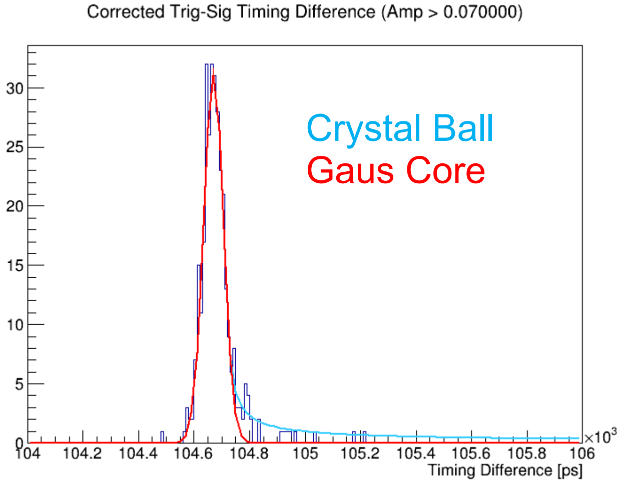


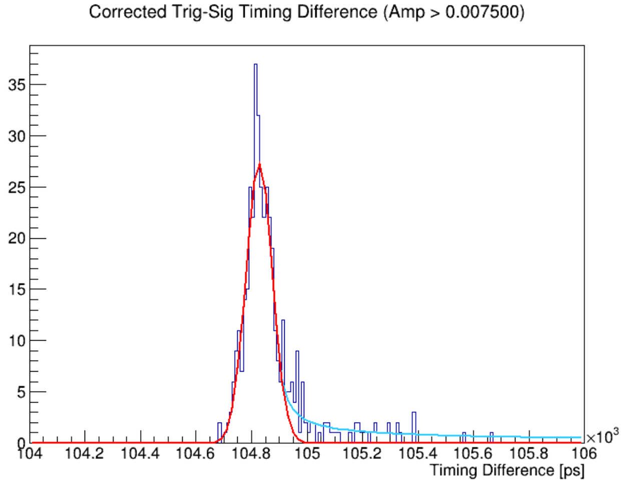




Zero Field

1.5 T (first point)





- ❑ Data taken at 0, 0.374, 1.138, and 1.509 T
- ❑ Zero field HV: MCP = 650, PC = 200 V
- ❑ Non-zero field HV (left to right):
  - ❑ MCP = 675, PC = 200
  - ❑ MCP = 675, PC = 400
  - ❑ MCP = 700, PC = 200

Outlook

- Need to perform a gain uniformity scan and other calibration measurements
- A thorough data analysis and paper drafting will take a couple of more months
  - All materials are available under this [Indico category]

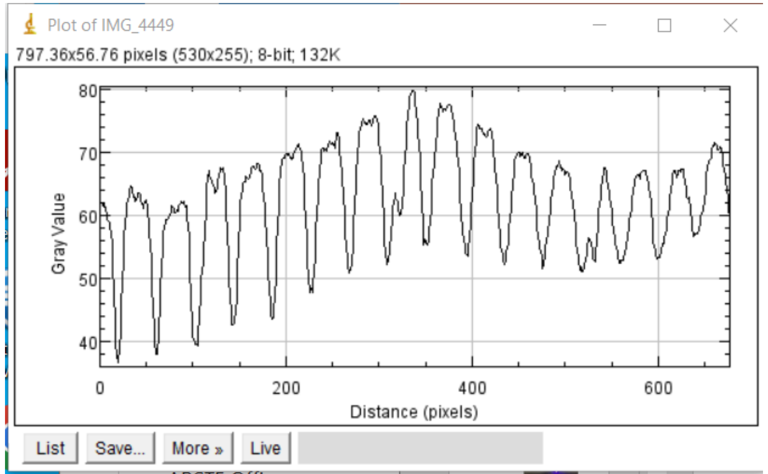
- The setup has been left intact and turnkey ready
- Would therefore like to come back and repeat the timing measurements using a femtosecond laser and a fast scope, some time in February
  - Eliminate PiLas laser timing jitter, DRS4 calibration contribution and NIM trigger jitter
  - Come up with a definitive statement about the expected HRPPD timing resolution in a pfRICH-like configuration

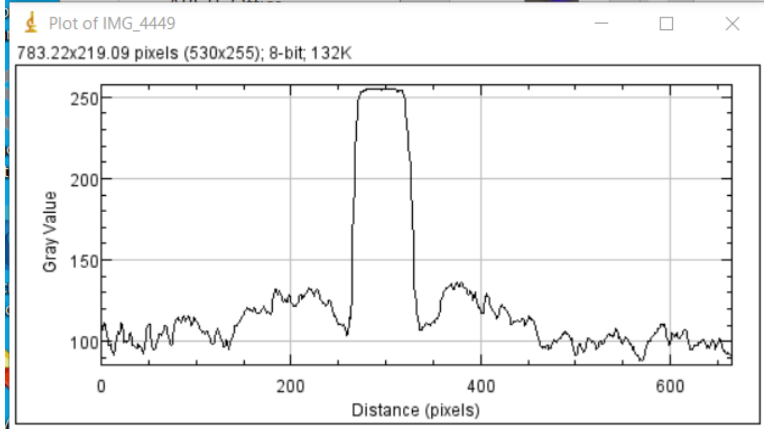
- *BNL SMD welcomes other ePIC groups to use the facility (but be aware about a 6” gap and <1.8 T field limitations)*

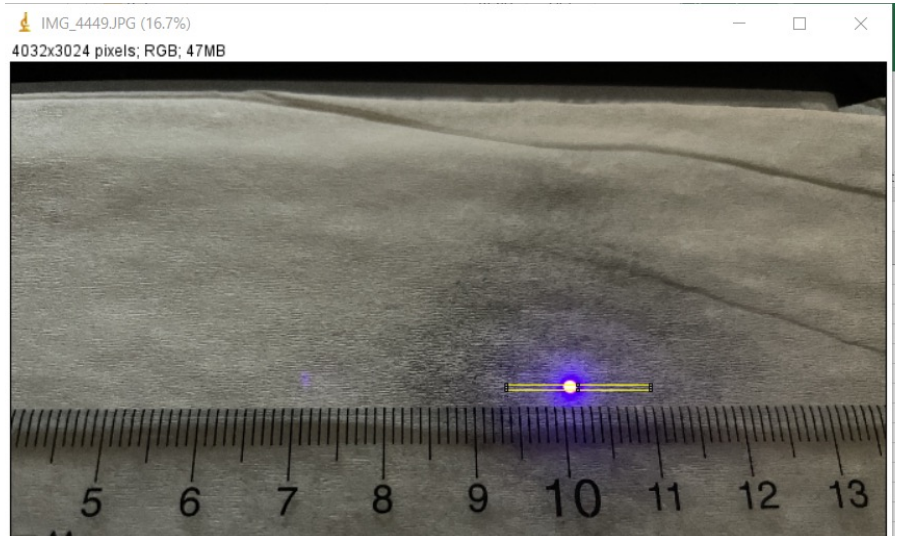
Backup Slides

IMG-4449.jpg
Small spot, vacuum side of window

No. of mm width: 1.5







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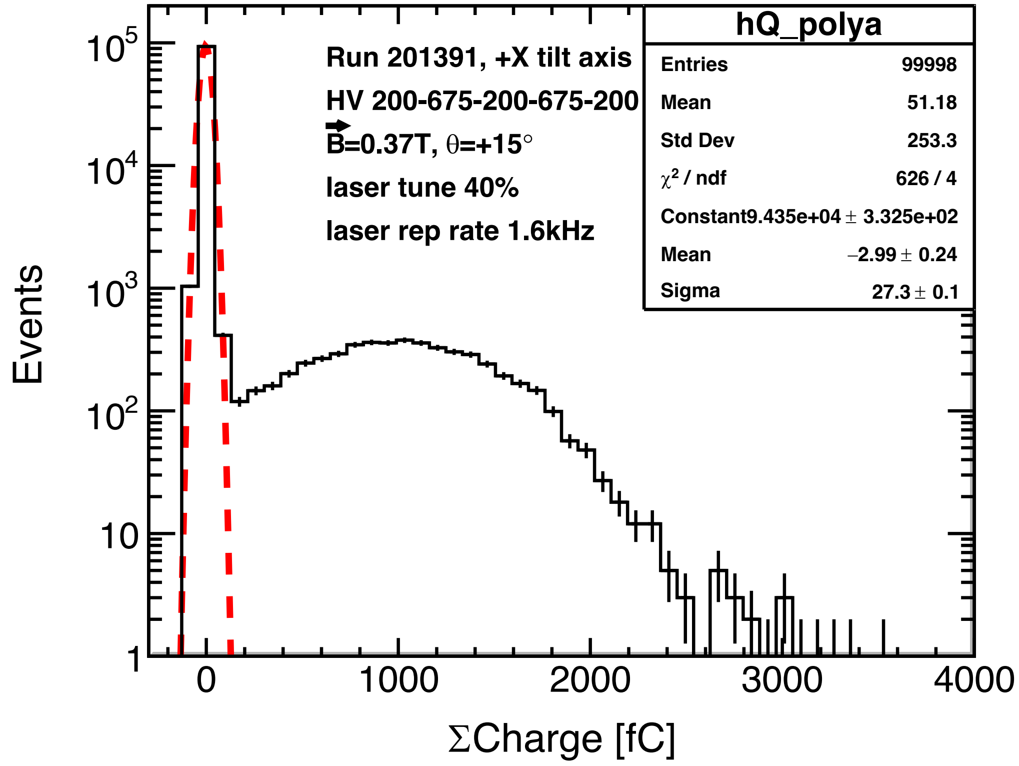
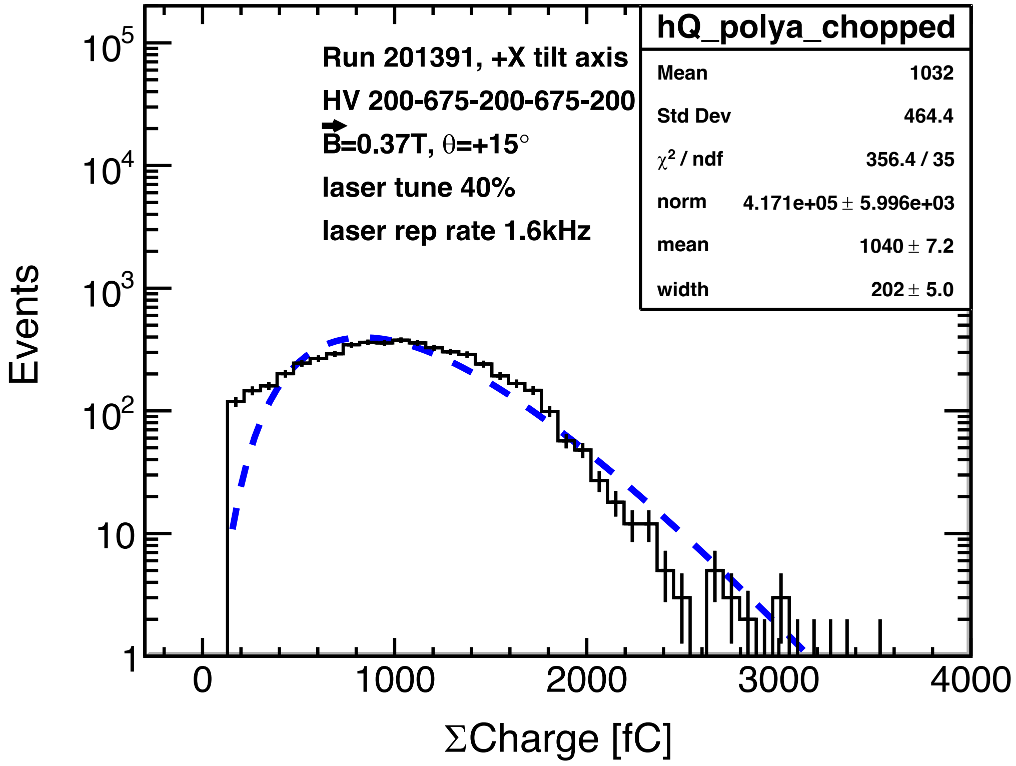
MARK POPECKI

Example – Mean Charge Extraction (Gain)

Fit pedestal (Gaussian) alone



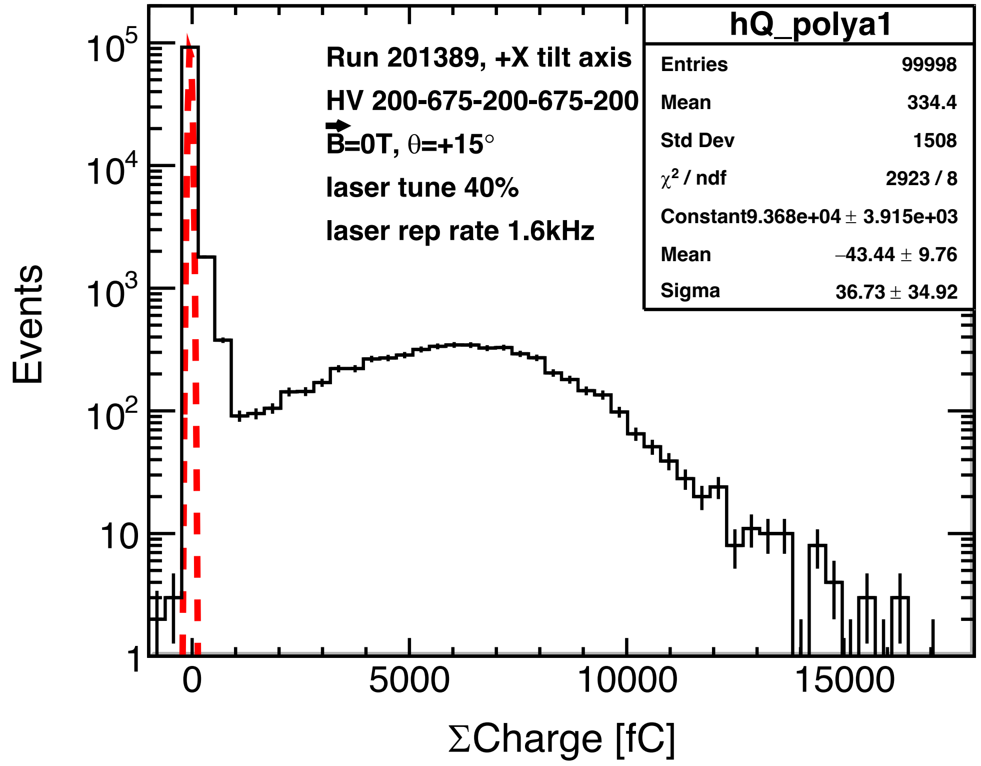
Apply a **4σ cut to remove the pedestal**
Fit polya function



- Define pedestal using Gaussian fit and apply a **4σ cut to remove the pedestal**
- Remaining distribution using polya fit to estimate mean charge. Not always works (case-by-case)

Example – Mean Charge Extraction (Gain)

Fit pedestal (Gaussian) alone



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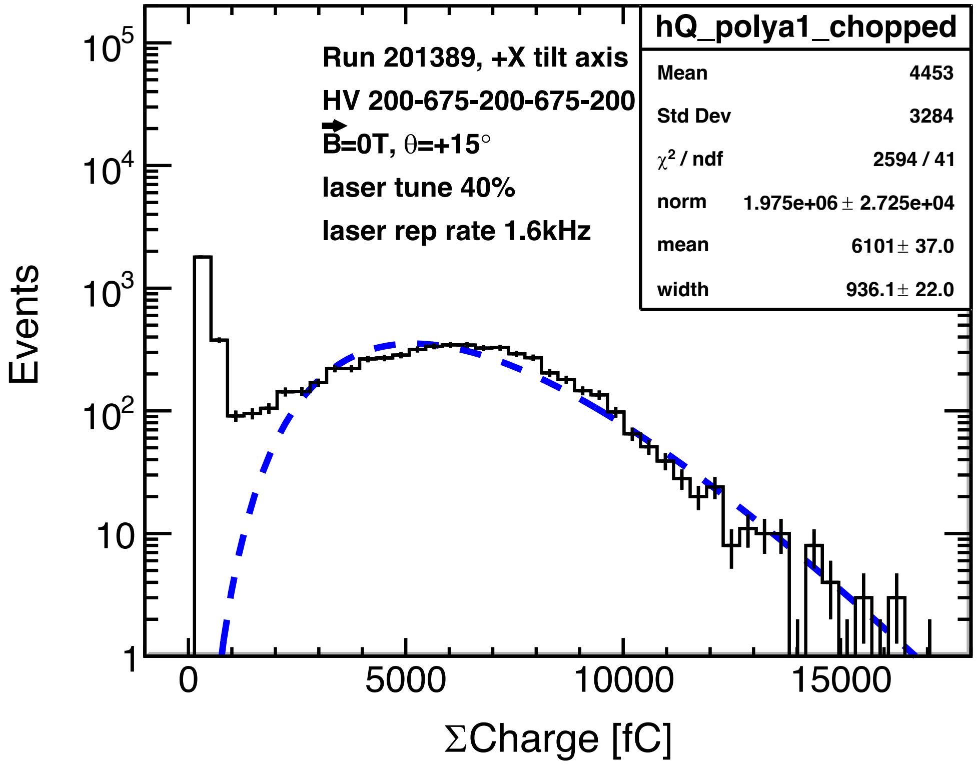

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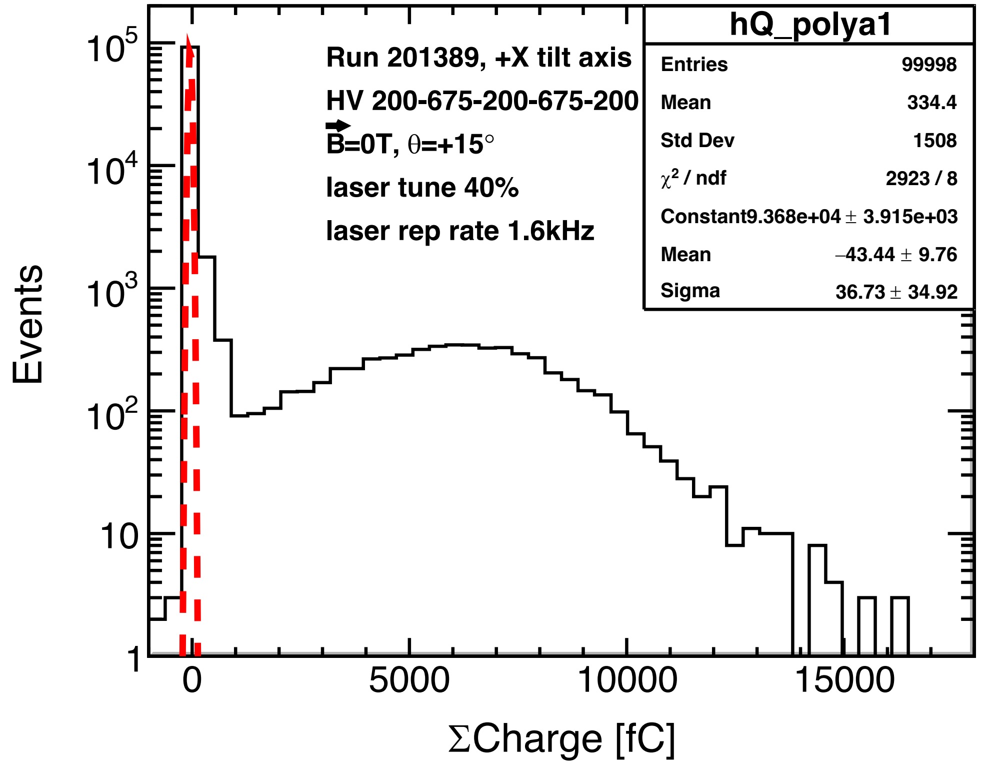
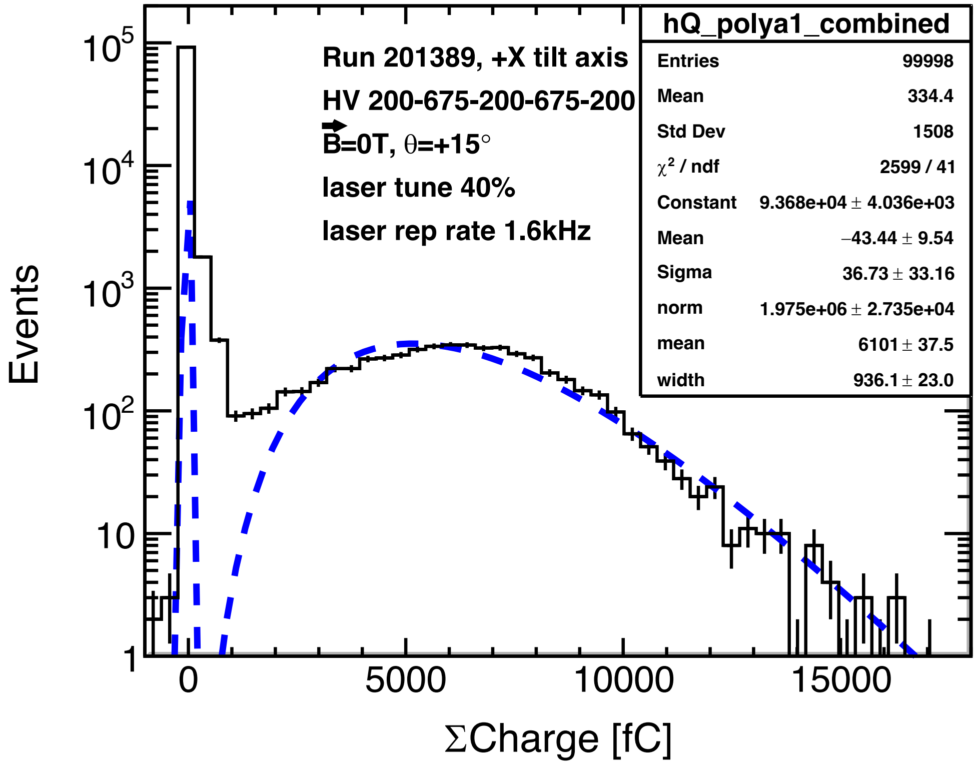


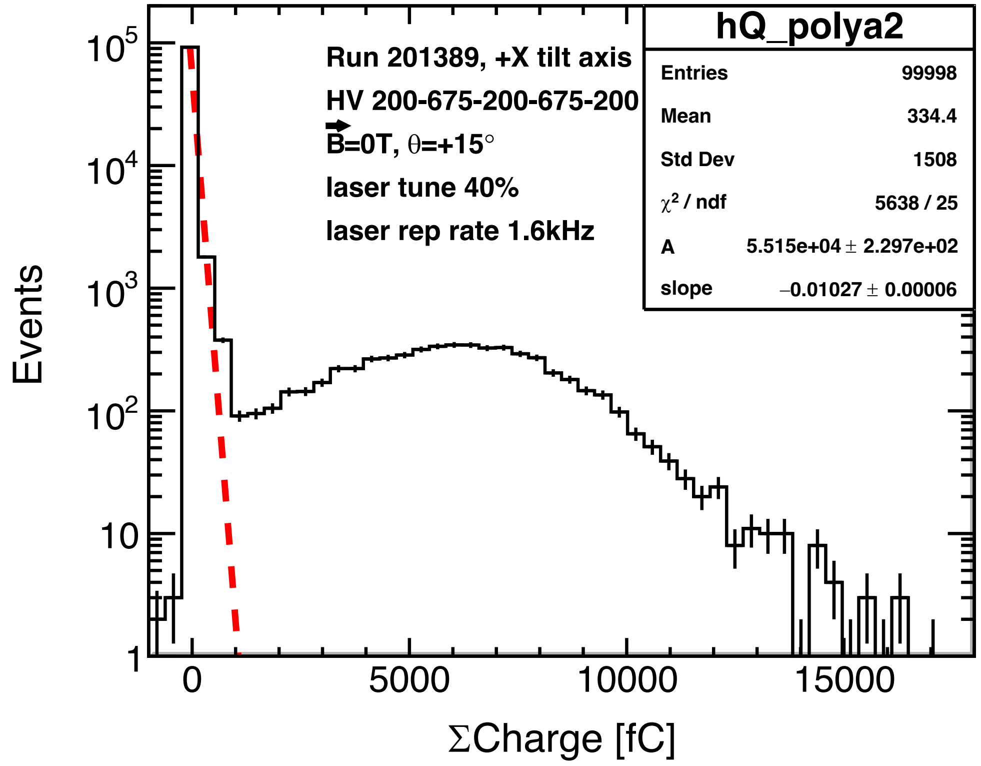
Fit combined Gaussian + Polya



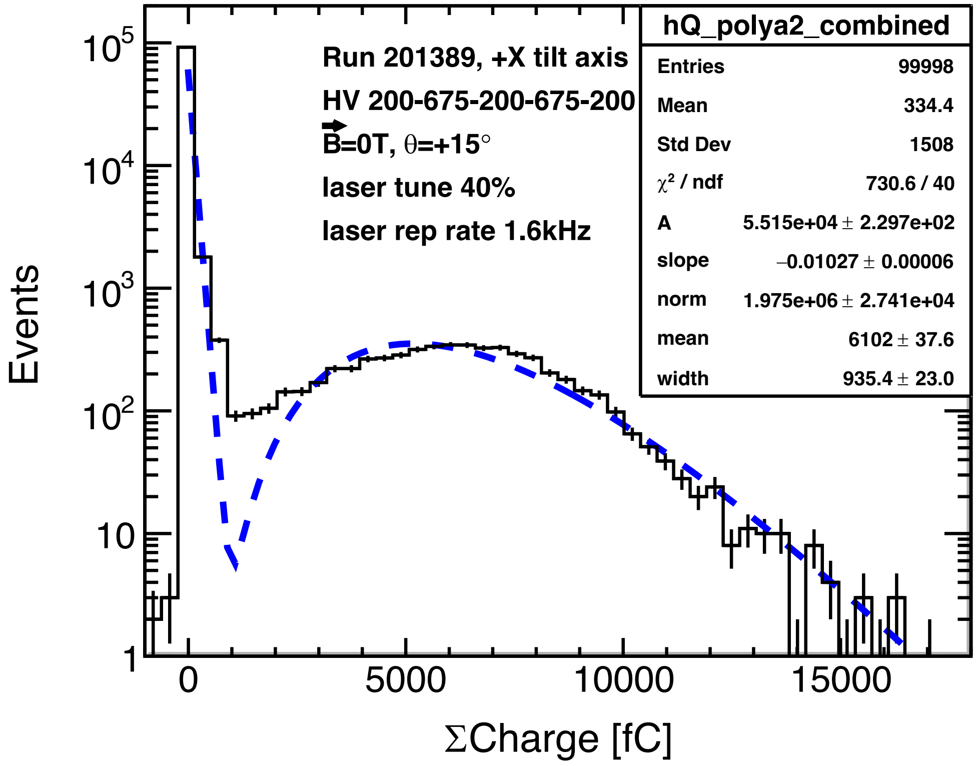
- Define pedestal using Gaussian fit and signal using Polya fit.
- Apply a combined fit (Gaussian + Polya)

Example – Mean Charge Extraction (Gain)

Fit pedestal (Exponential) alone



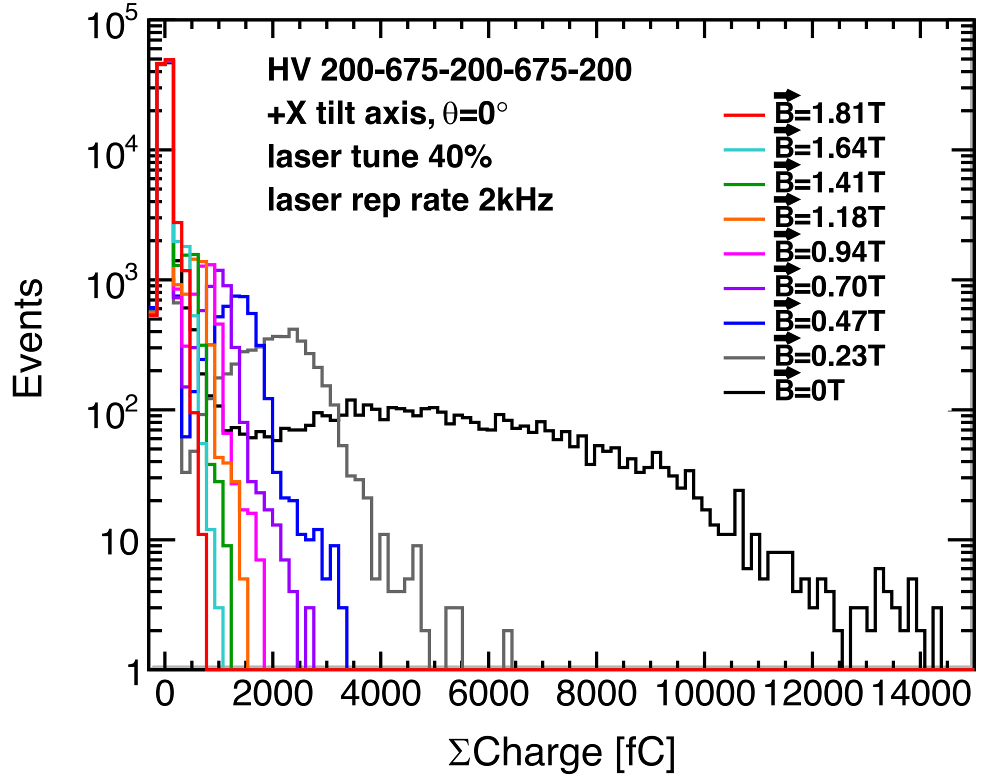
Fit combined Exponential + Polya



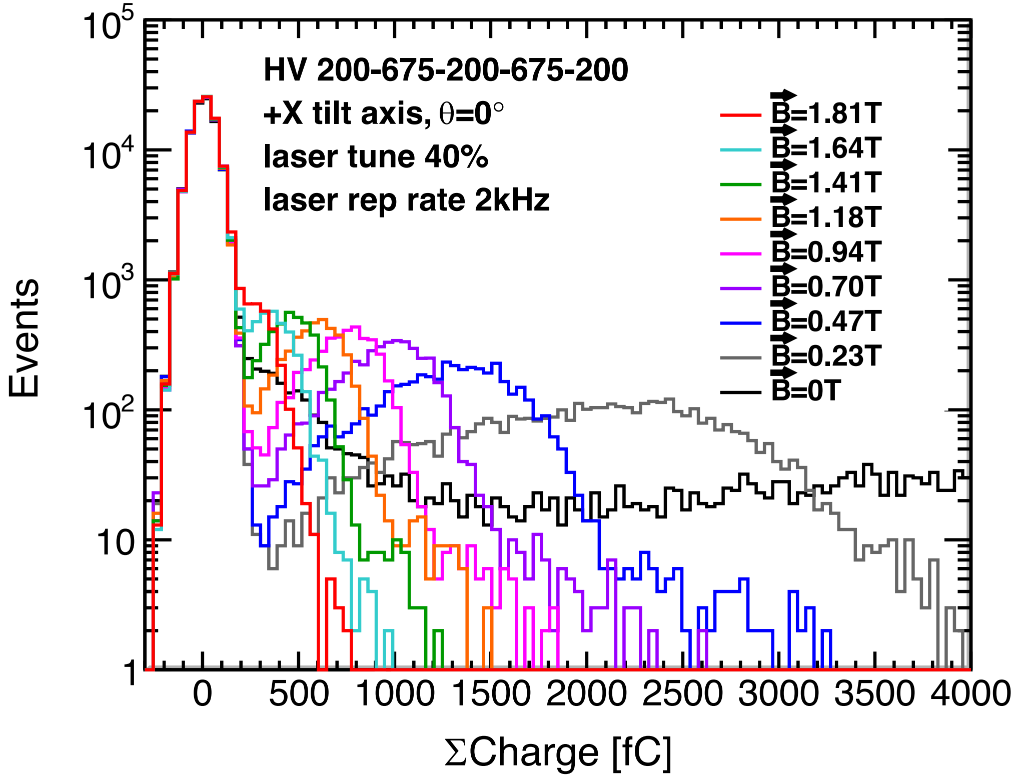
- Define pedestal using Exponential fit and signal using Polya fit.
- Apply a combined fit (Exponential + Polya)

Charge Spectra VS Magnetic Field

With 0T Spectrum



Without 0T Spectrum



- **Charge calculation**: 3×4 neighboring pad selection.
- Peak shifts toward **lower charge values**.
- **Gain reduction** with increasing magnetic field.

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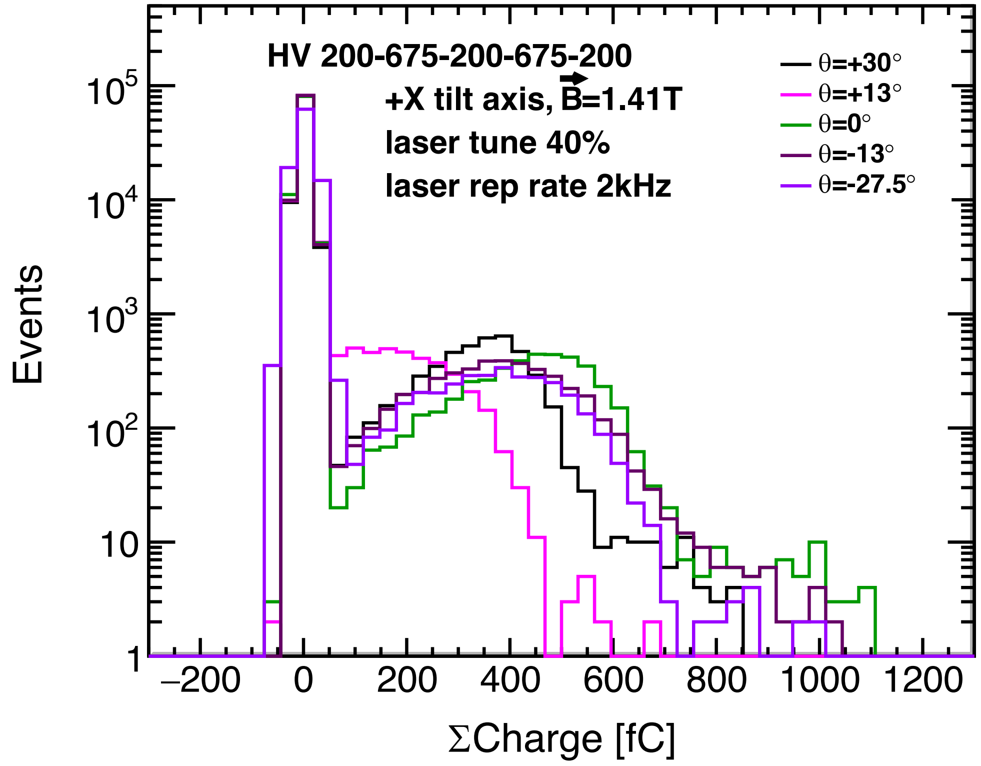
JIHEE KIM

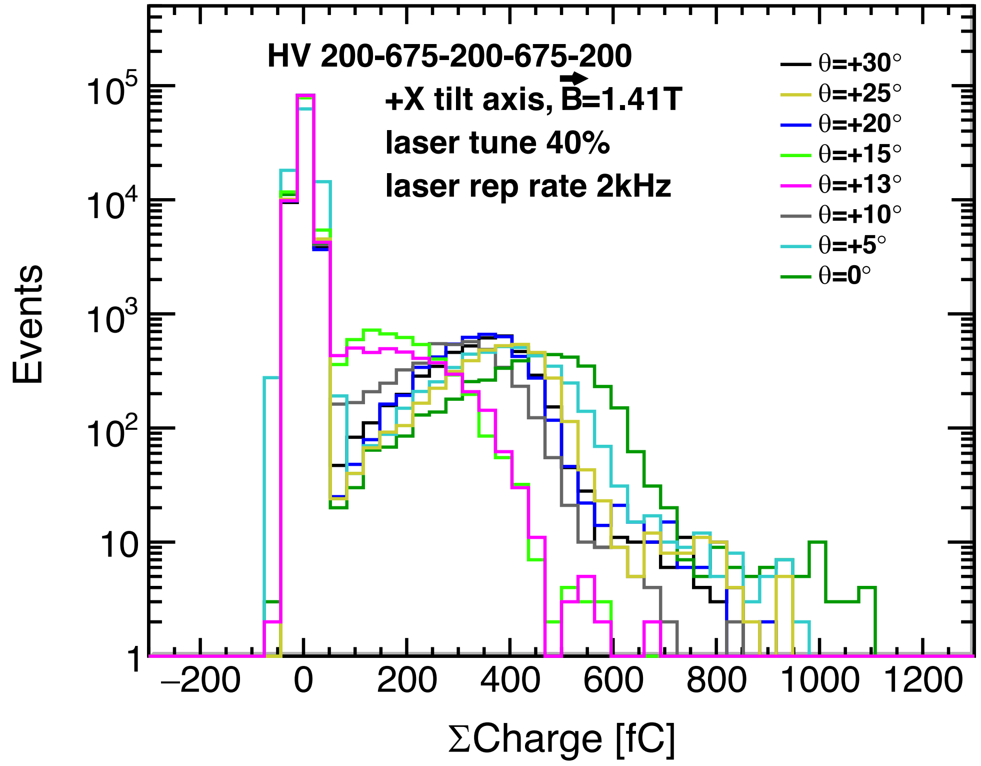
Charge Spectra VS Inclination Angle



Measured **charge spectra** at different **inclination angles** with **magnetic field $\vec{B}$ ~ 1.4 T**

- **Charge calculation**:
  - Major signal channel selection by accumulated signals
- **Observations**:
  - Mean charge remains consistent across most angles
  - **13° case shows behavior different** from other angles
- **Takeaway**:
  - Overall **angular dependence is weak**

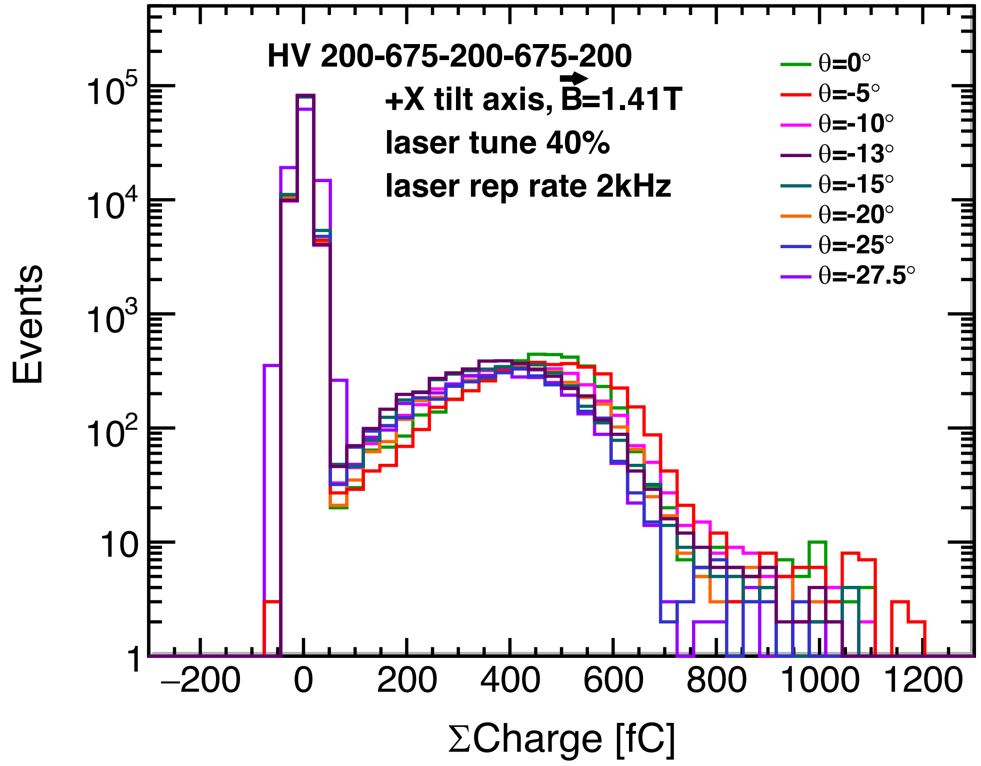
Charge Spectra VS Inclination Angle (+θ)



Measured **charge spectra** at different **inclination angles** with **magnetic field** $\vec{B}$ **~ 1.4 T**

- **Charge calculation**:
  - Major signal channel selection by accumulated signals
- **Observations**:
  - Mean charge remains consistent across most angles
  - **13°** and **15° cases show behavior different** from other angles
- **Takeaway**:
  - Overall **angular dependence is weak**

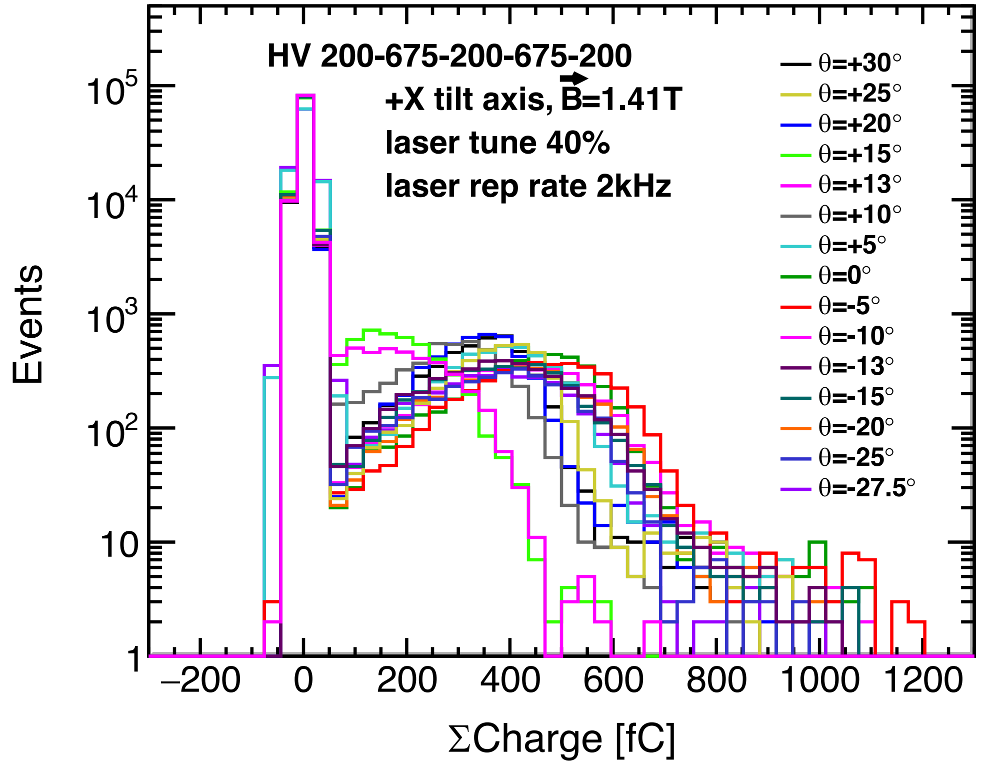
Charge Spectra VS Inclination Angle (-θ)



Measured **charge spectra** at different **inclination angles** with **magnetic field $\vec{B}$ ~ 1.4 T**

- **Charge calculation**:
  - Major signal channel selection by accumulated signals
- **Observations**:
  - Mean charge **remains consistent** across most angles
- **Takeaway**:
  - Overall **angular dependence is weak**

Charge Spectra VS Inclination Angle



Measured **charge spectra** at different **inclination angles** with **magnetic field $\vec{B}$ ~ 1.4 T**

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- **Takeaway**:
  - Overall **angular dependence is weak**

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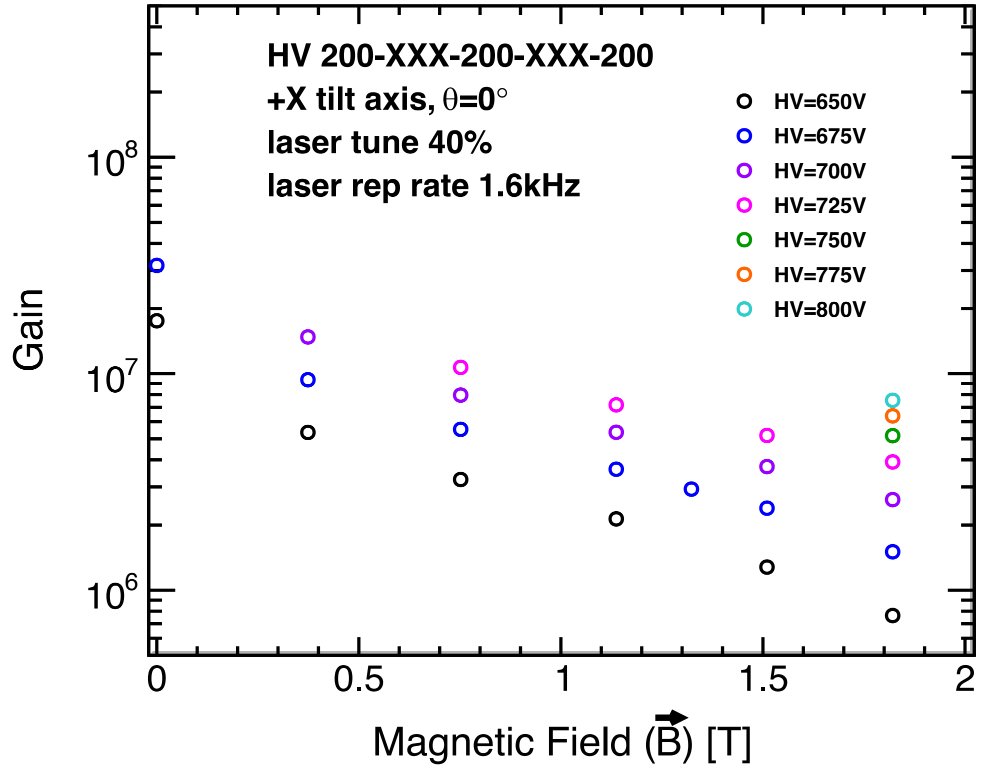
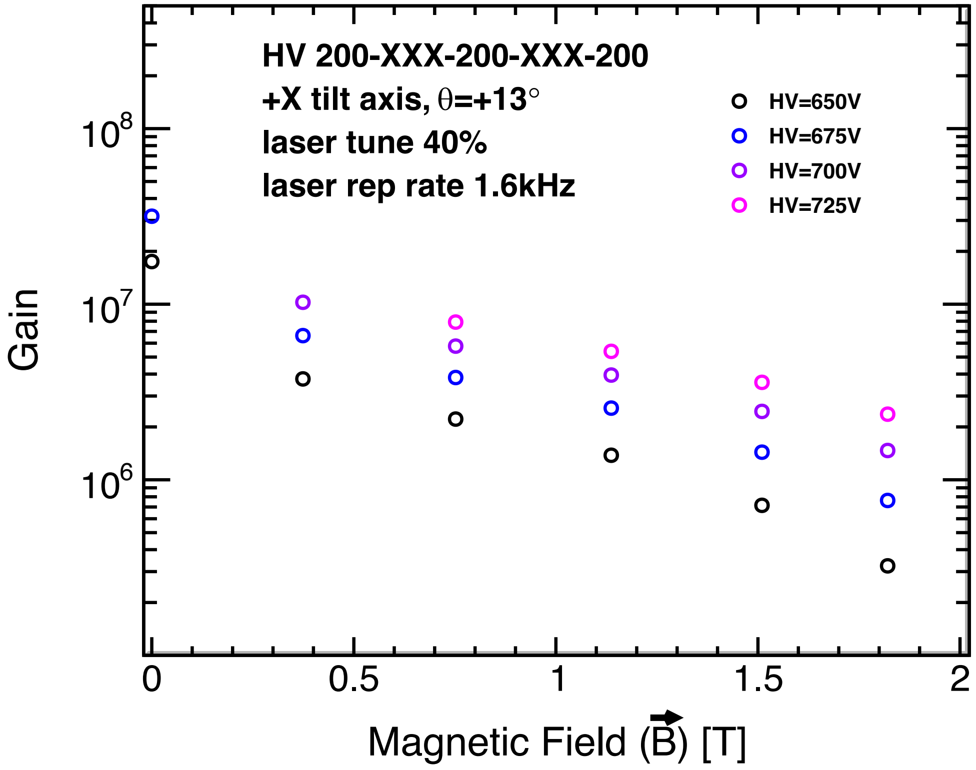
Gain VS Magnetic Field (w/ HV)@ θ=0°



Measured **mean charge as a function of magnet current** at different **bias voltage**

- **Charge calculation**:
  - Major signal channel selection by accumulated signals
- **Observations**:
  - Mean charge reduces as higher magnet current
  - Mean charge increases as higher bias voltage
- **Takeaway**:
  - **Gain partially recovered** by **increasing bias voltage**

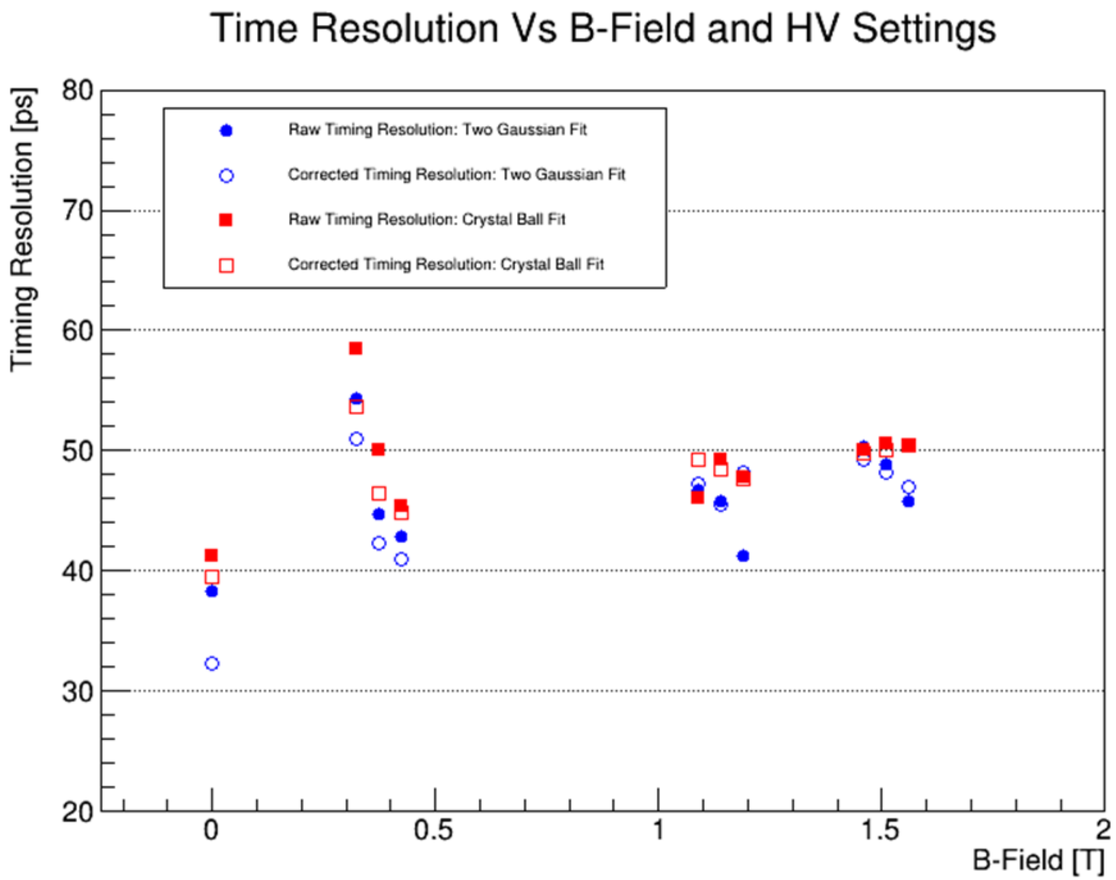
Gain VS Magnetic Field (w/ HV)@ θ=+13°



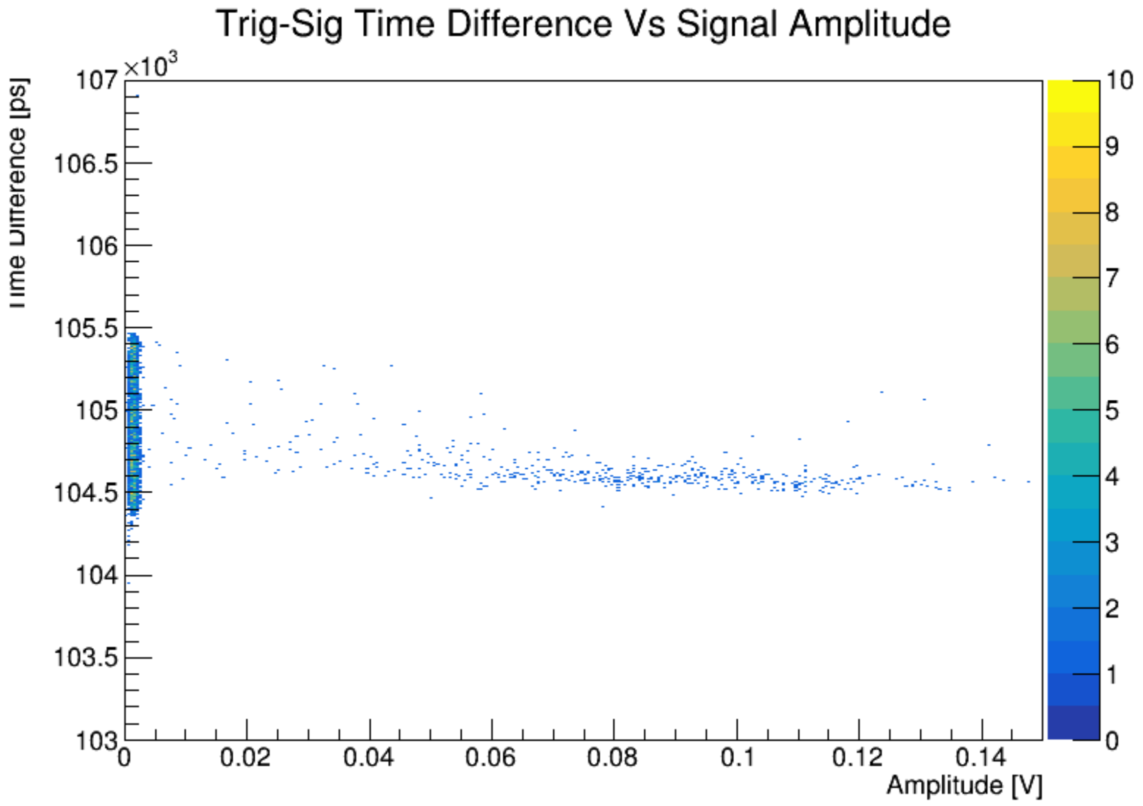
Measured **mean charge as a function of magnet current** at different **bias voltage**

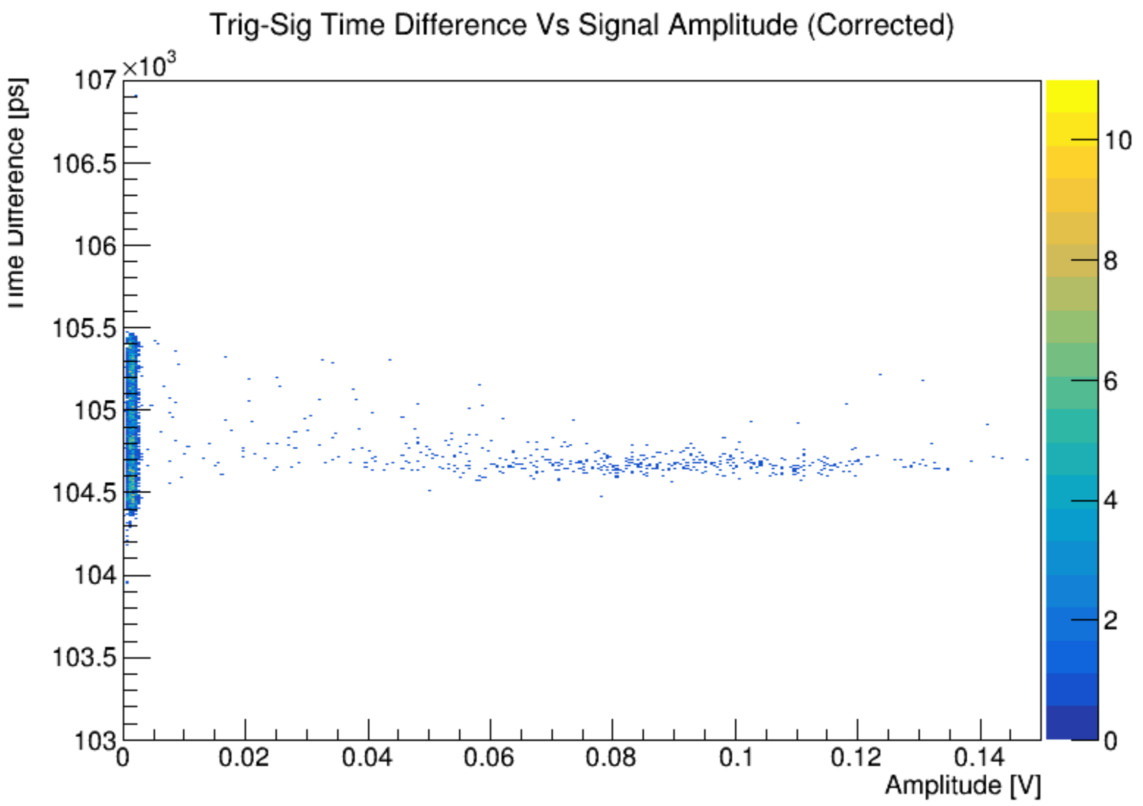
- **Charge calculation**:
  - Major signal channel selection by accumulated signals
- **Observations**:
  - Mean charge reduces as higher magnet current
  - Mean charge increases as higher bias voltage
- **Takeaway**:
  - **Gain partially recovered** by **increasing bias voltage**

Scope Timing resolution: Pedestal Cut Only



Scope Timing resolution: Amplitude Correction





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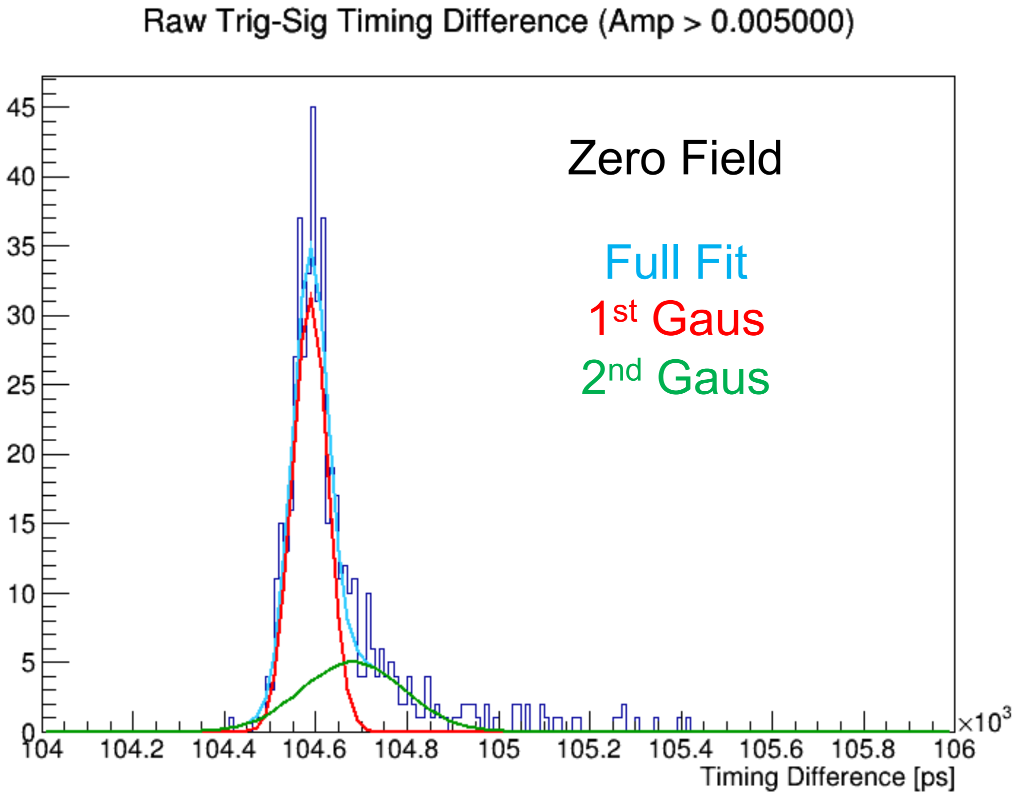
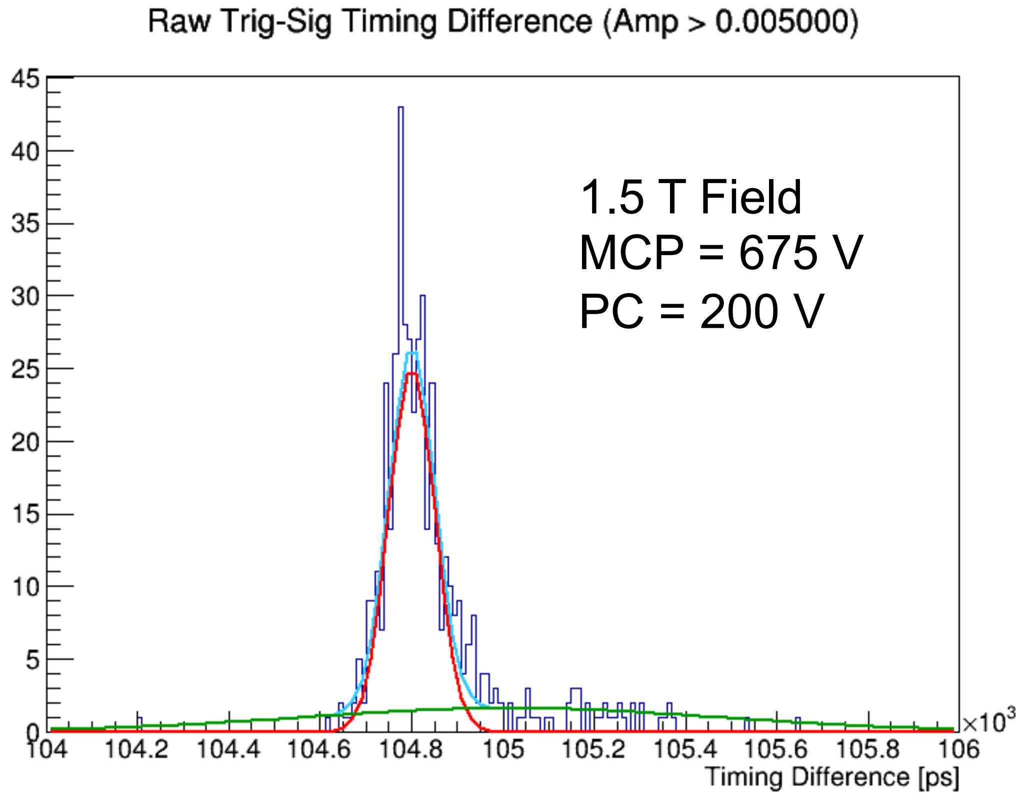
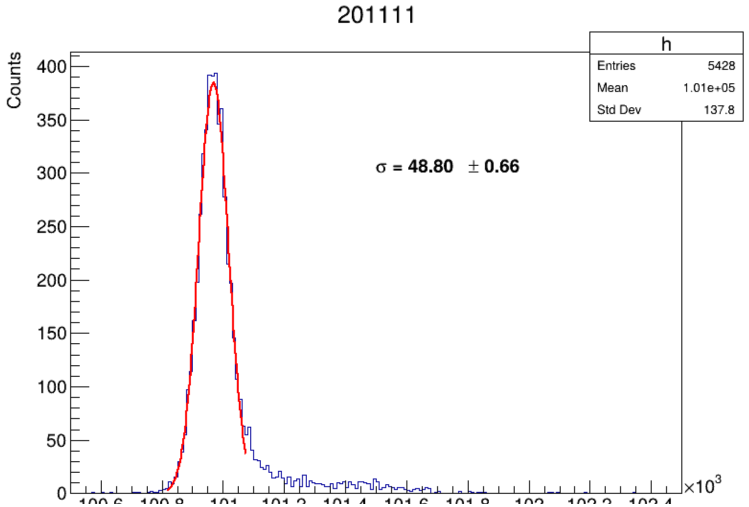
Scope Timing resolution: 2-Gaus Fit

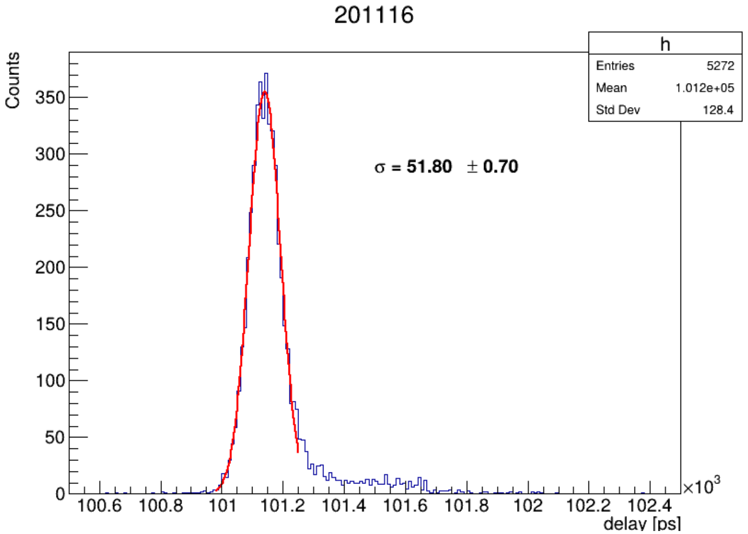


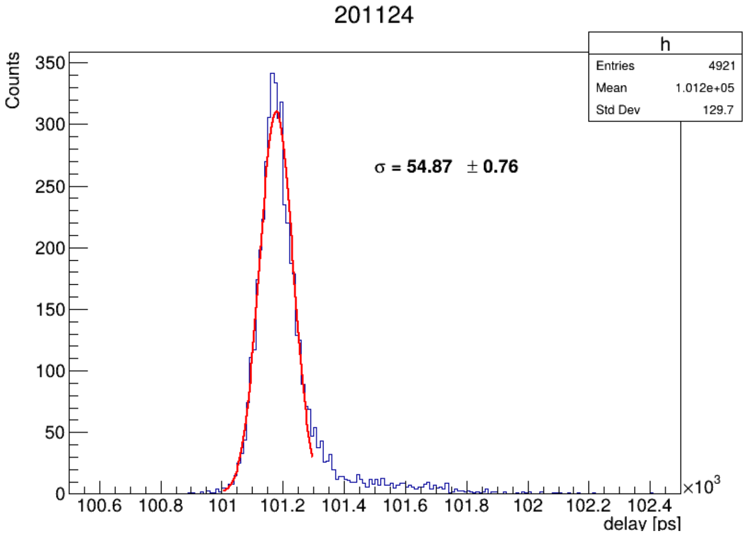


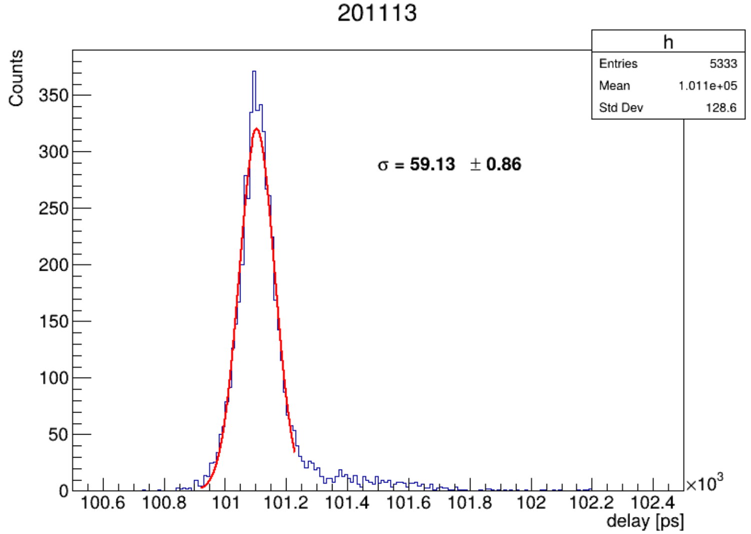
Scope Timing resolution: Laser Contribution

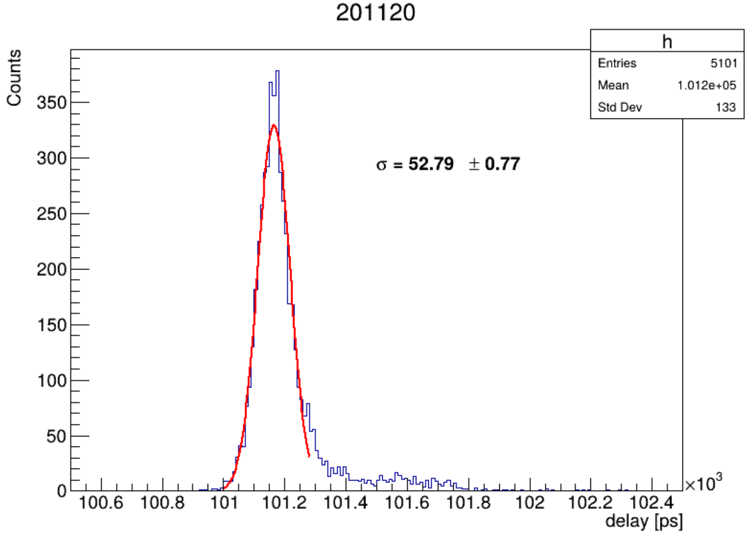
- In B-Field setup with PiLas laser and scope, measure time resolution of ~40 ps at zero field and ~50 ps at 1.5 T
- With femtosecond laser and scope in lab, measure time resolution of ~16 ps
- PiLas laser contribution to timing resolution = $\sqrt{40^2 - 16^2}$ = ~37 ps
- HRPPD timging resolution @ 1.5 T = $\sqrt{50^2 - 37^2}$ = ~34 ps
- Many assumptions and hand waving, but we could be seeing ~ a factor of 2 degradation in intrinsic HRPPD timing performance from 0 T to 1.5 T

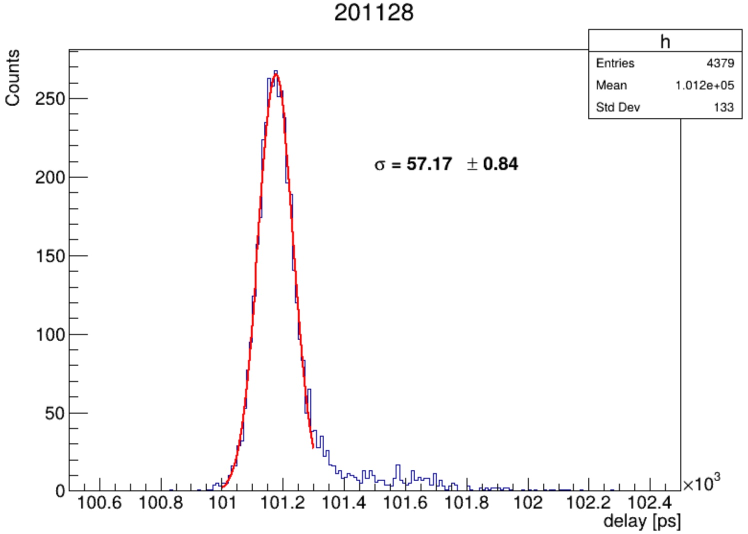












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Complimentary documents for timing VS B-Field.