SLAC ATCO Testing @ GSFC Update 2

12/18/2023

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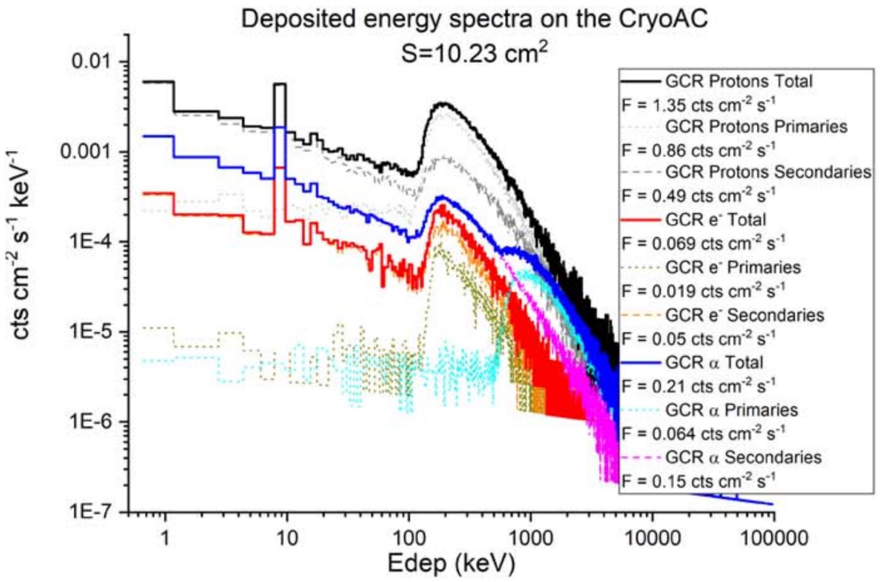
LEM ATCO

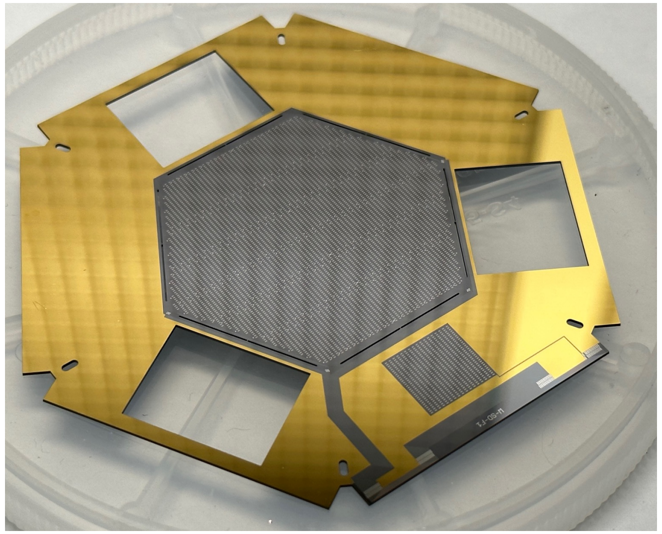
Baseline requirements:

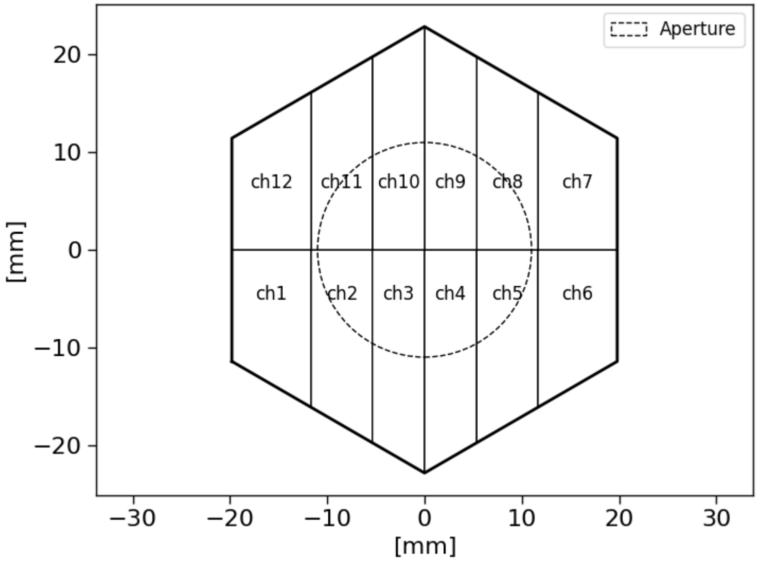
- ***Low-energy threshold ≤ 20 keV***
- ***Detection efficiency ≥ 95%***
- ***No explicit spatial resolution requirement, but sub-channel resolution is desirable***



Simulations shown for Athena cryoAC

- different count rate expected for LEM but same energy depositions
  - ➢ Peak expected around 200 keV





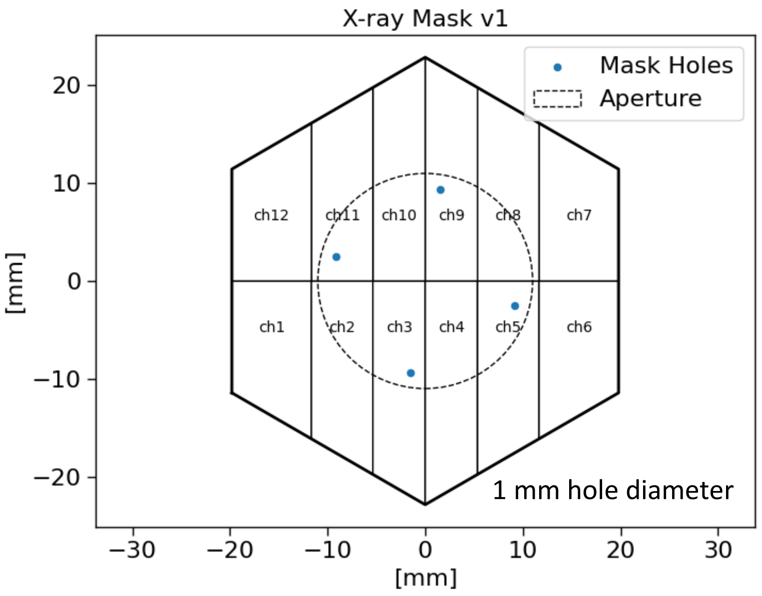
SLAC Prototype ATCO

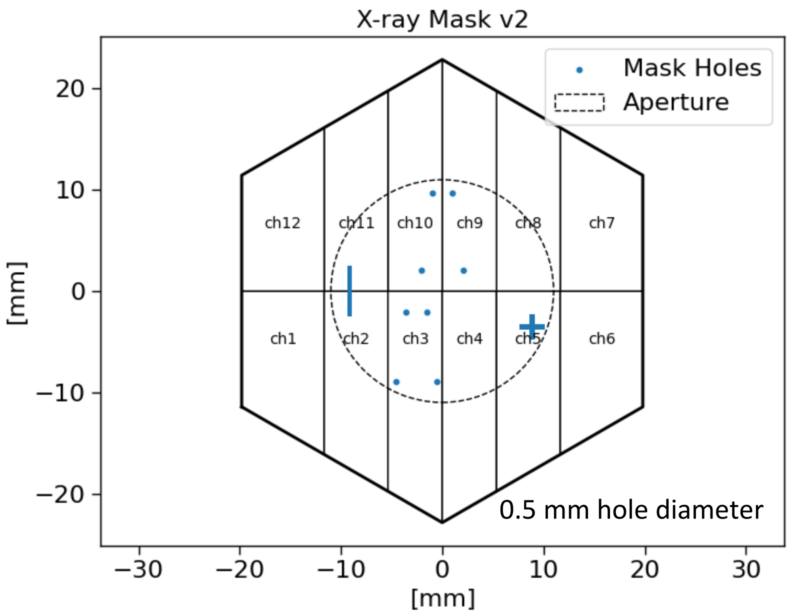
- 12 TES parallel network W-TES channels
  - Aperture of current testing setup does not allow for all 12 channels to be illuminated
- All testing shown here with SLAC ATCO-2
  - received Al wet etch, so poor Al trace quality and presumably high probably of some broken traces
- Utilizing GSFC-fabbed, high-R shunt chips
  - Design goal = 5 mOhm, actual estimated ~ 8 mOh
    - Only measured R on 10 shunt channels in series, and have observed some variability in this measurement between chips
- Operating at Tb = 53 mK

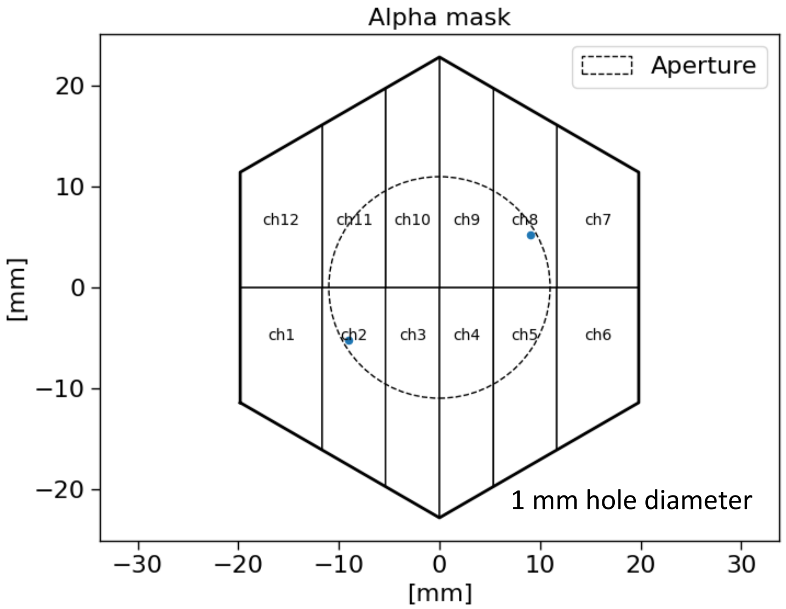
Testing Configurations

Same chip has now been tested with four different source/masking configurations

- Two different X-ray masks with holes/slots (Run #1 and #3)
  - Masks are 0.5 mm thick Cu, fully blocking low energy X-rays ≲ 30 keV
- One run with Am-241 alpha source (5.5 MeV alphas + 60 keV gammas) inside cryostat, directly behind detector wafer (Run #2)
  - Alphas fully masked except at two locations
- One run with no mask - detector fully uncovered (Run #4)



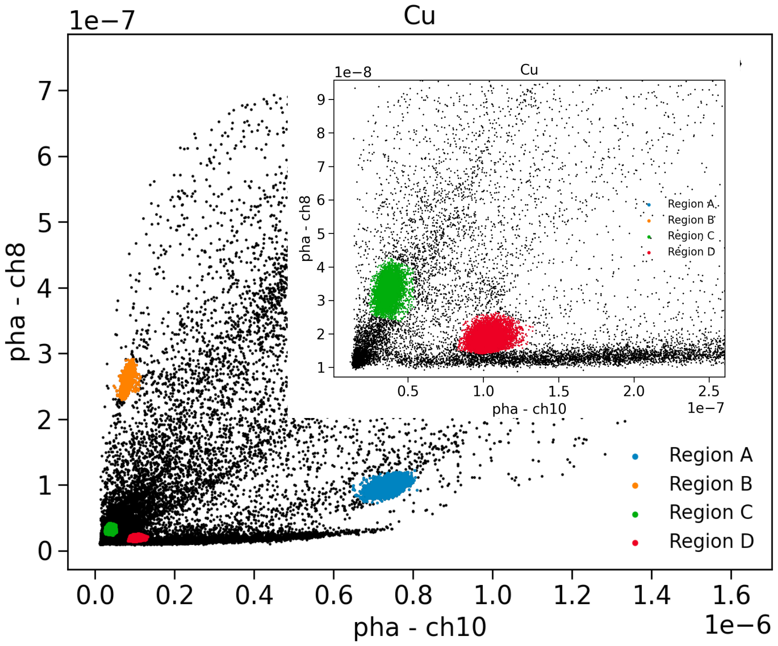




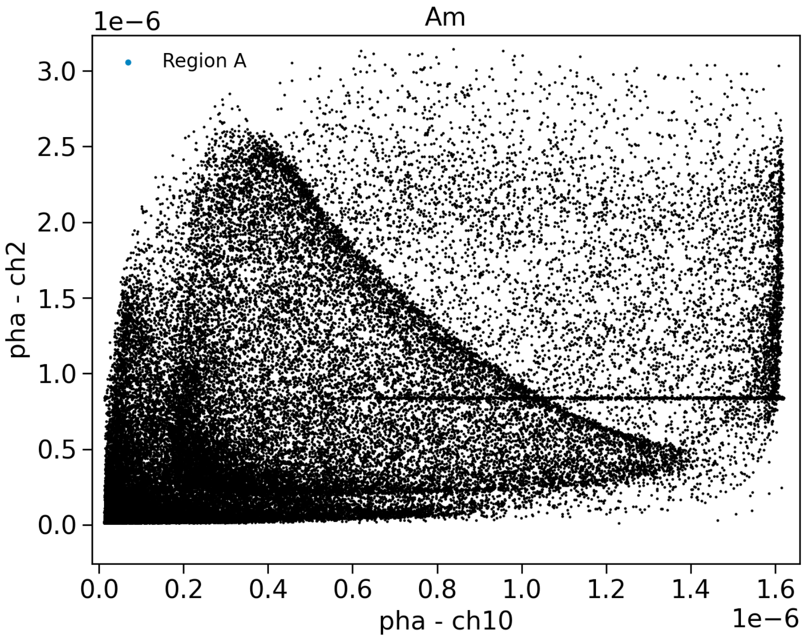
*alpha mask was not precisely mounted relative to detector, so positions are not exact (+/- ~ 0.5 mm)

Recap from Run #1 results shown at from previous meeting

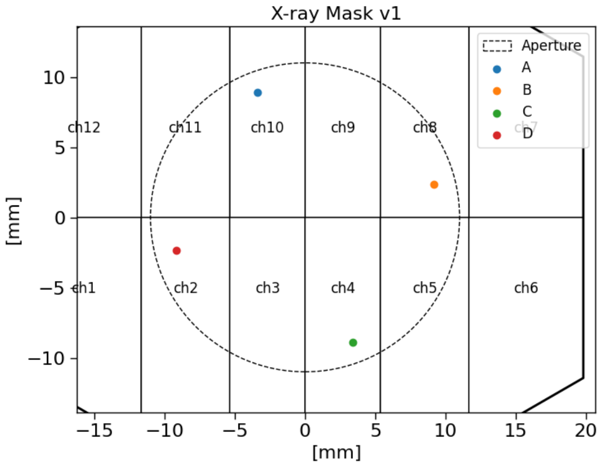
- Using mask with 4 holes, able to locate 4 distinct regions in rawPH-rawPH plots for lower energy sources, showing good spatial discrimination at even large distances from hole locations
- “banana” type structure seen in PHA-PHA plots from higher energy X-ray sources also indicative of continues, fine spatial discrimination between channels
- Able to detect X-rays as low as 5.9 keV in all working channels, indicating threshold far below 20 keV
- Soft saturation (non-linearity) observed in pulse shapes at all X-ray energies (for incident channels), so “gain curve” appears quite nonlinear

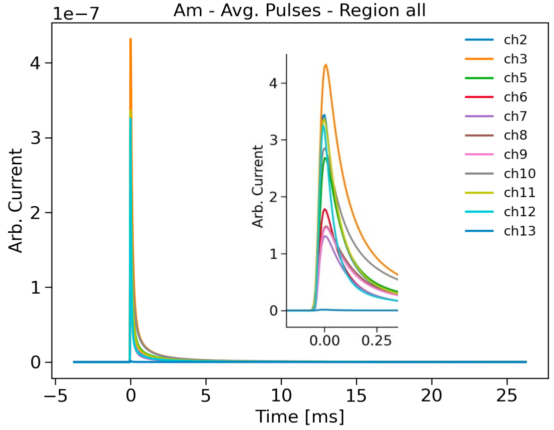


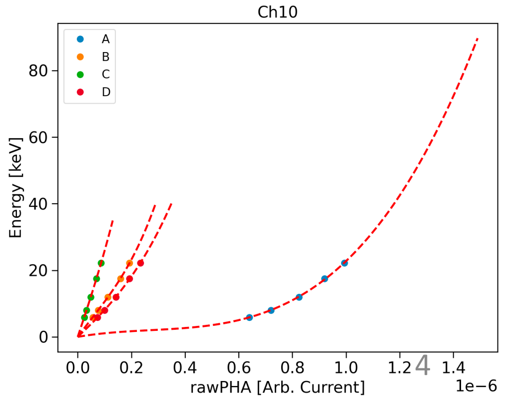
8 keV

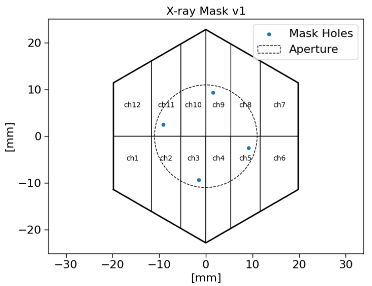


60 keV



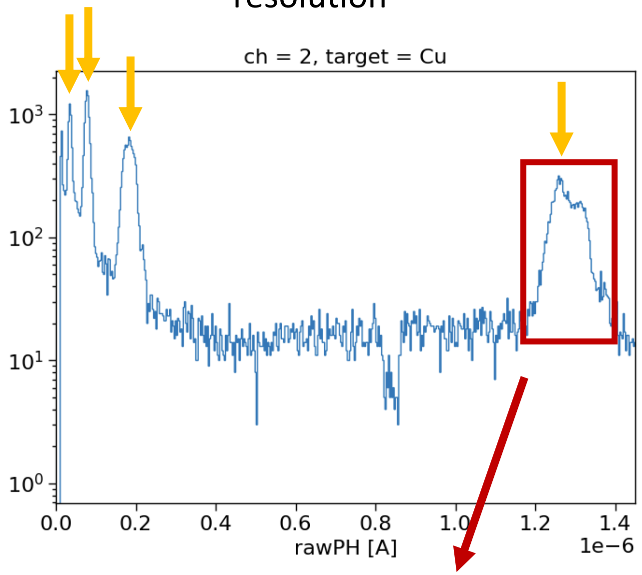






Further results from Run #1 – Energy Resolution

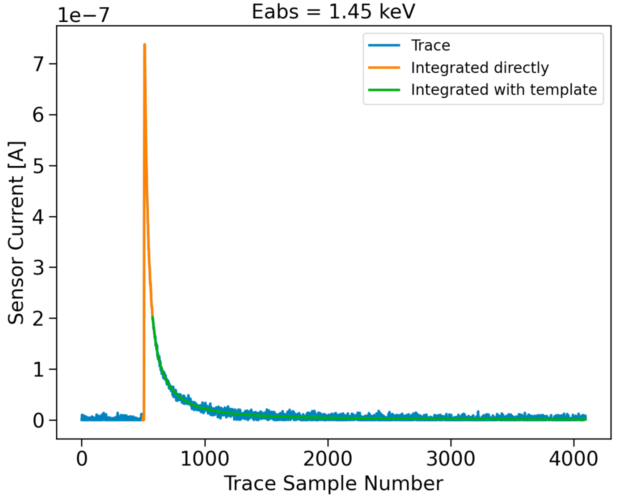
- Individual rawPH spectra have 4 clear peaks, but line shape are not very Gaussian with poor resolution

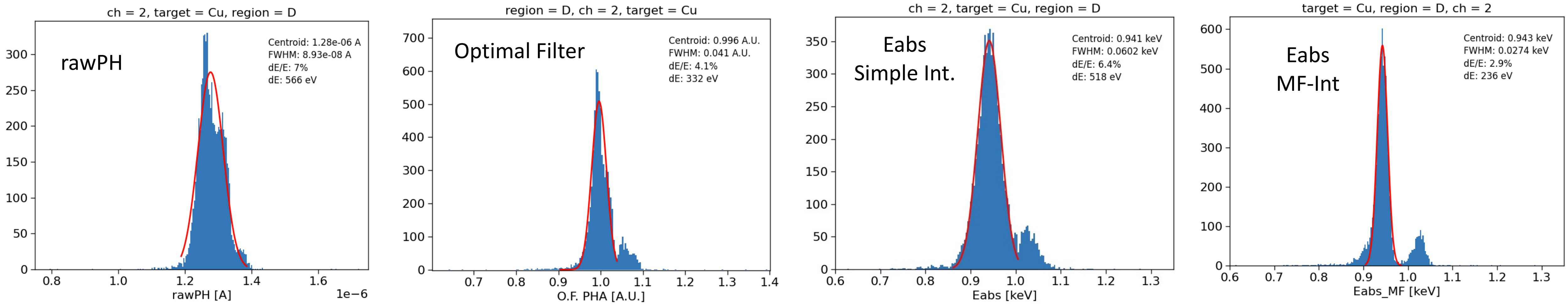


- Spectral shape and resolution can be improved with standard frequency-domain optimal filtering
- Also calculated energy absorbed by TES using following equation from Ren et al. 2021 (via Irwin and Hilton)
  - Corresponds to E_ETF, so will diverge from true absorbed energy as pulses become more saturated with increasing energy

$$E_{abs} \approx \left(1 - 2\frac{R_\ell}{R_\ell + R_0}\right) I_b R_{sh} \int \delta I_s(t)dt \ + R_\ell \int \delta {I_s}^2(t)dt$$

- In some cases, resolution can be further improved with matched-filter integral (MF-Int) estimator: e.g. integrating the pulses only above a certain threshold, and then fitting to a pulse template below it

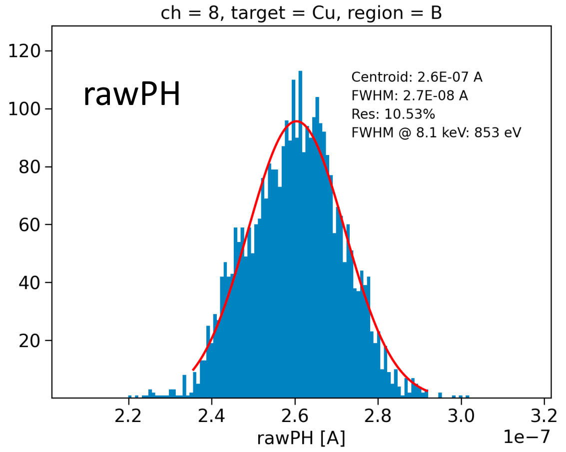


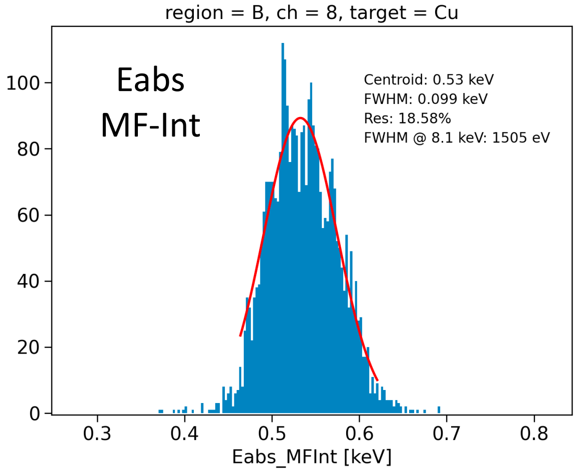


Cu – 8 keV

Further results from Run #1 – Energy Resolution

- MF-Int works best with large signal-to-noise; less effective in situations with poor signal-to-noise (e.g. spatially distant from incident X-ray hit; higher TES operating point/Tc)
    - In best case—channels close to X-ray hit and low R0/Rn—individual channel resolution as good as few hundred eV
    - NEP/baseline resolution as low as ~ 25 eV
- Standard optimal filter is better with smaller signal-to-noise
    - MF-Int tends to be better with summed spectra; hybrid approach would probably be ideal
- Regardless of analysis method, 20 keV threshold requirement easily being met for all channels, even those with low Tc and detecting X-ray signal originating from a spatially distant location





NEP

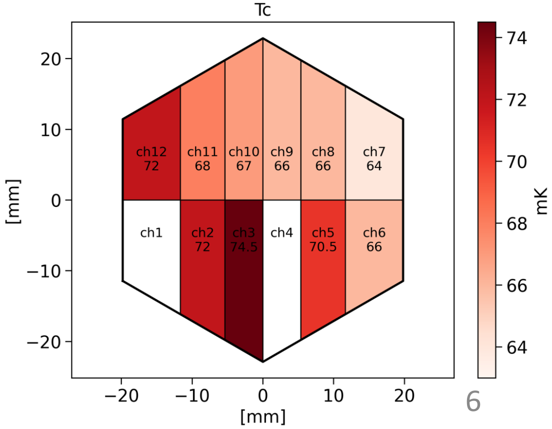
region ch	A (eV)	B (eV)	C (eV)	D (eV)
2	588.8	1322.4	256.3	25.6
3	560.8	707.2	62.8	98.4
5	1120.7	133.0	54.8	697.8
6	1308.3	184.7	307.3	1074.8
7	757.3	74.8	1193.3	2102.0
8	319.2	76.0	992.3	1908.3
9	168.3	695.8	2925.9	2516.7
10	41.3	551.4	1260.7	401.5
11	60.8	661.7	1044.3	116.8
12	266.8	883.1	1162.4	208.6
13	21095.4	13465.0	21423.4	20199.1

ΔE @ 8.1 keV OF

region ch	A (keV)	B (keV)	C (keV)	D (keV)
2	1.18	1.62	1.45	0.34
3	1.39	1.27	1.87	1.90
5	1.76	1.60	1.70	1.20
6	1.90	1.79	1.29	1.60
7	1.26	1.56	1.75	2.68
8	1.51	0.92	1.52	2.44
9	1.57	1.64	3.33	2.86
10	0.55	1.22	1.73	1.40
11	1.58	0.99	1.40	1.84
12	1.21	1.10	1.43	1.64
13	5.95	6.43	6.00	6.95
Summed	0.88	0.88	1.01	1.20

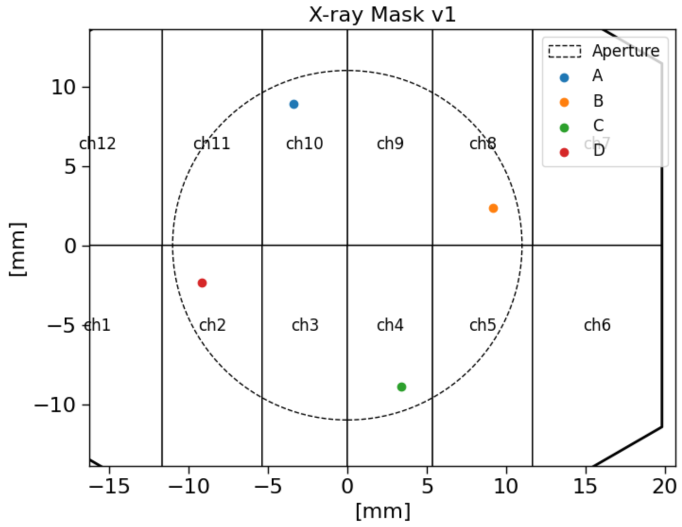
ΔE @ 8.1 keV MF-Int

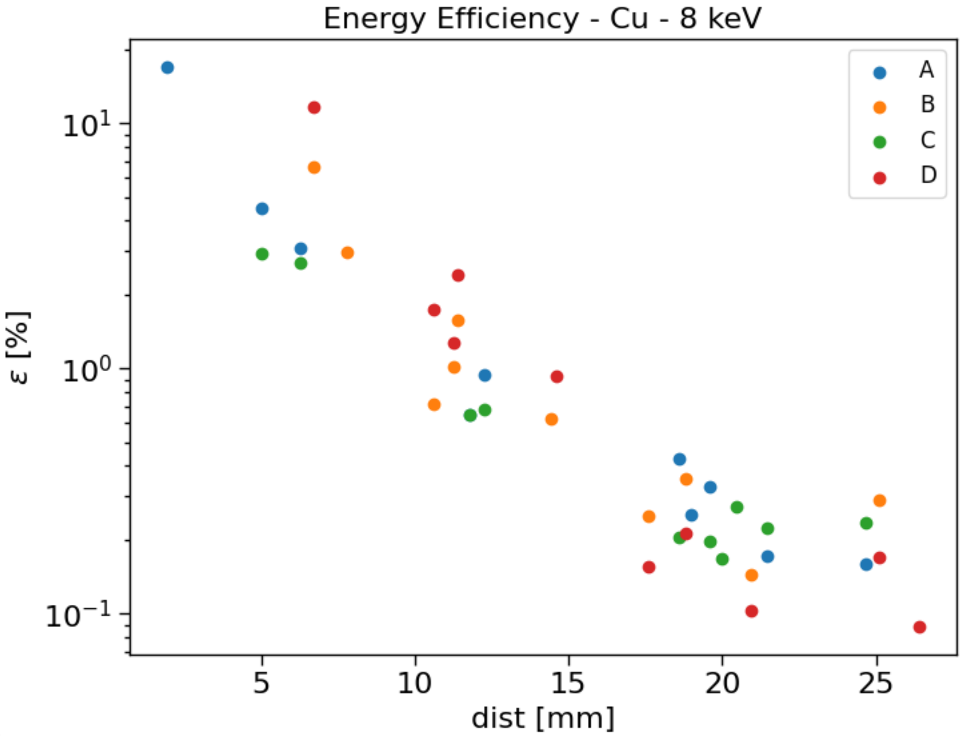
region ch	A (keV)	B (keV)	C (keV)	D (keV)
2	4.00	6.37	1.57	0.23
3	3.70	2.31	2.22	2.19
5	6.34	2.21	2.23	2.57
6	4.36	1.98	1.73	3.66
7	2.51	2.14	3.66	5.12
8	1.82	1.40	3.14	4.71
9	2.26	2.29	5.56	4.65
10	0.41	1.82	3.30	1.93
11	2.16	2.13	2.97	2.32
12	1.41	2.40	3.20	1.78
13	22.73	-	21.06	20.88
Summed	0.49	1.08	0.96	0.60

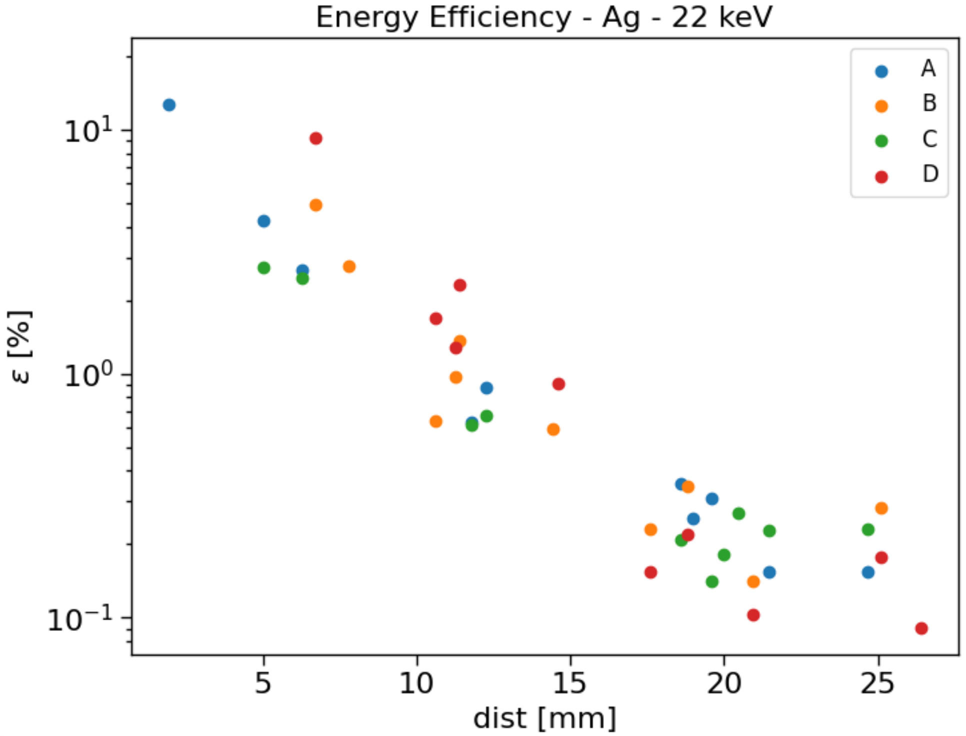


Further results from Run #1 – Energy Efficiency

- Can evaluate energy efficiency as Eabs/Eph and plot as function of distance away from incident X-ray
  - Probably not especially accurate due to soft saturation of pulses, particularly at higher energies and smaller dist

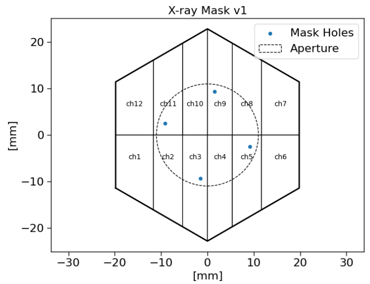






dist = distance between centroid of a channel and a given hole location

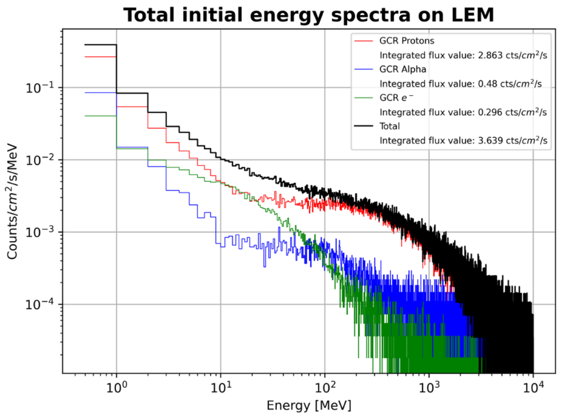
Further results from Run #1 – Deadtime



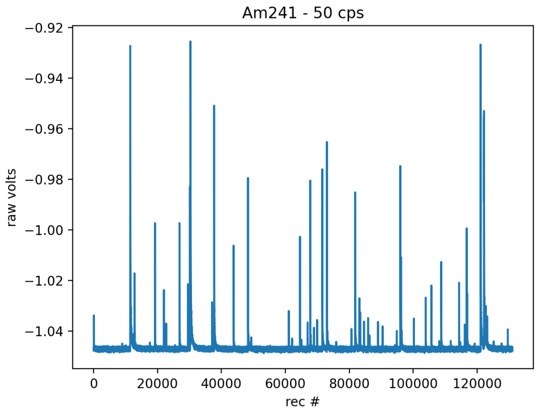
- From simulations, expected total background rate (R) on ATCO is ~ 50 cps
  - Assuming Poisson statistics, fraction of accepted events F :

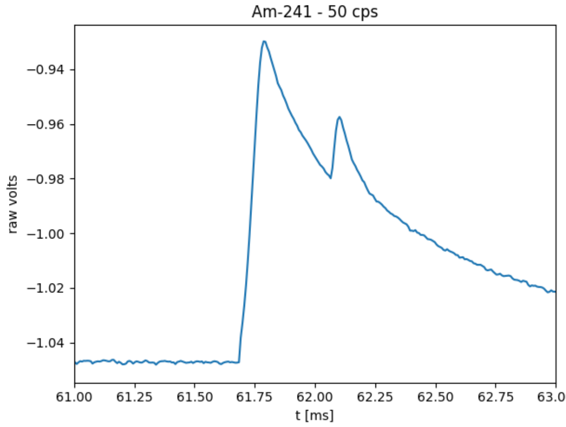
$$F = e^{-dt * R}$$

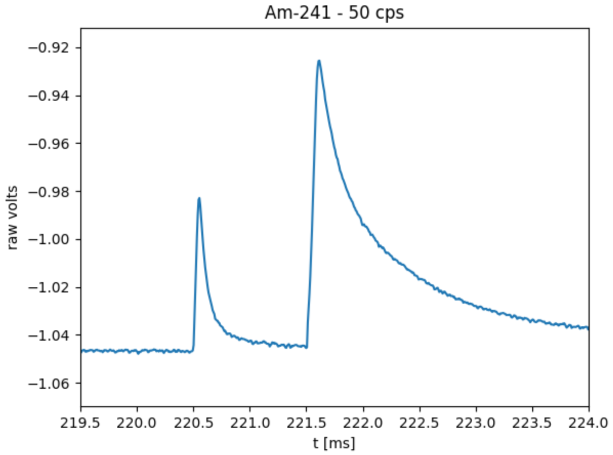
  - For F ≥ 95%, need dt (deadtime) to be ≲ 1 ms

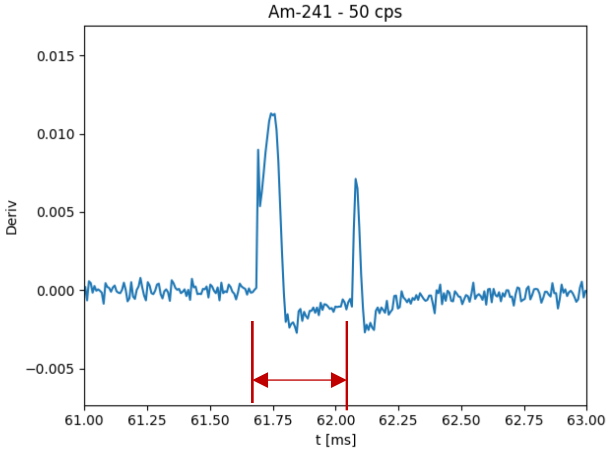


- Took ~ 50 cps data with Am-241 source (60 keV) to investigate deadtime at flight-like rates
  - Despite the highest energy pulses having very long tails, we think using a simple (difference) derivative trigger will allow for detection of secondary pulses while the pulse is still far above the baseline
  - Even for largest pulses, deadtime appears to be no more than ~ 0.5 ms with this method

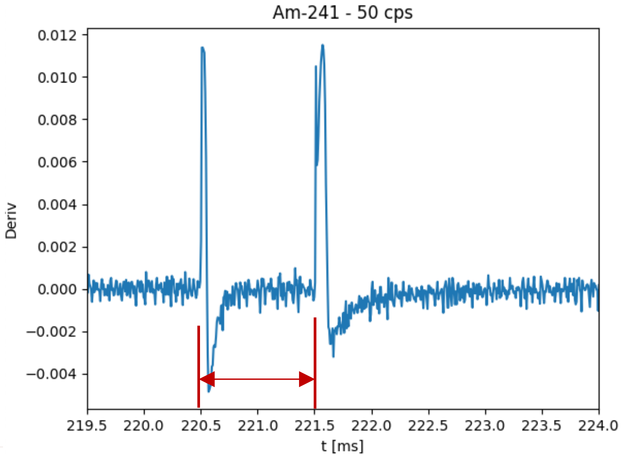






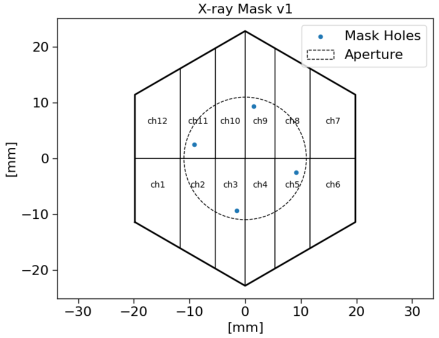


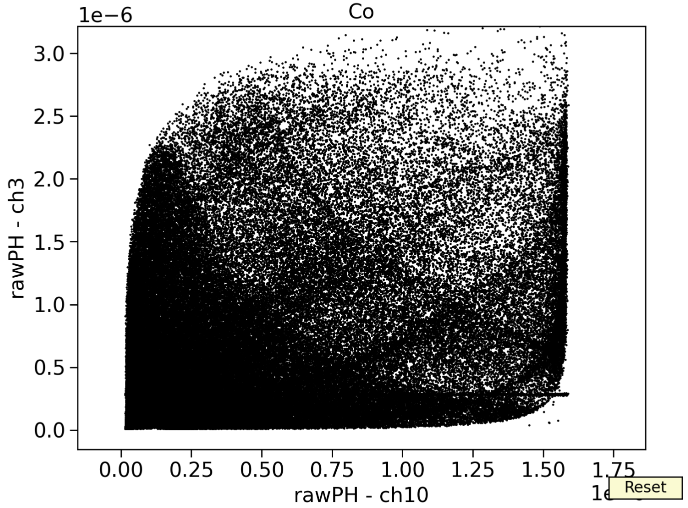
dt ≈ 0.35 ms



dt ≈ 1 ms

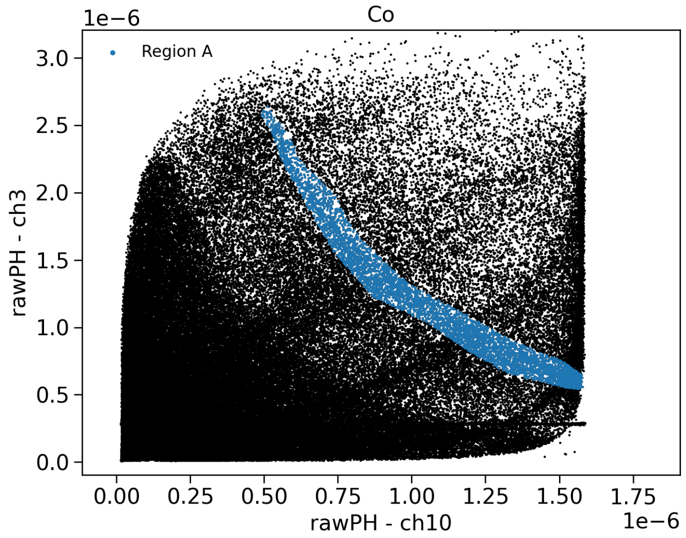
Further results from Run #1 – Co-57 source (122 keV)

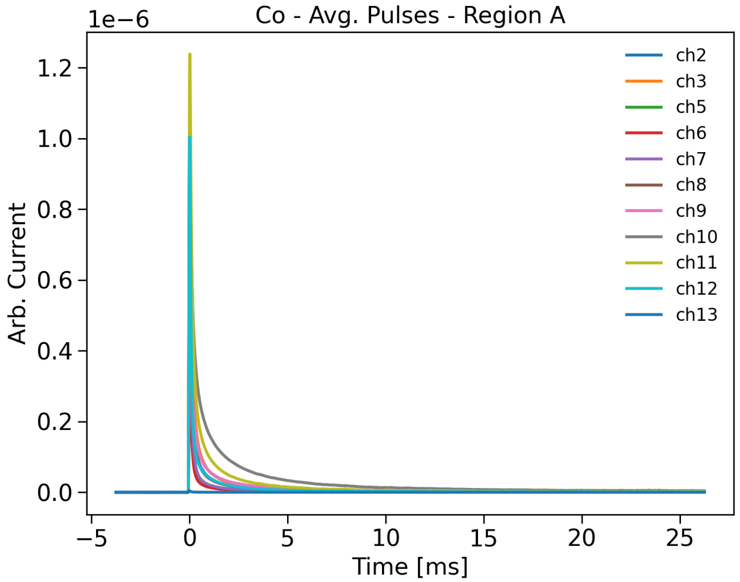


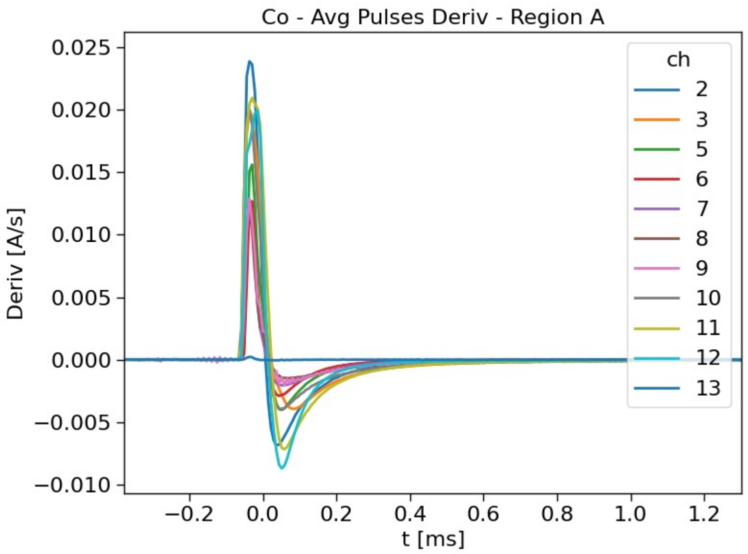


Used borrowed Co-57 source to attempt to look at 122 keV X-rays

- Vast majority of detected X-rays appear to be Compton scattered to lower energies
- Some faint banana-type structure that could be the 122 keV line – very roughly lines up with extrapolated PH based on “gain” fitting
- Average pulses from this region show that derivatives essentially return to baseline within ~ 0.5 ms, supporting previous conclusion that deadtime will satisfy requirement

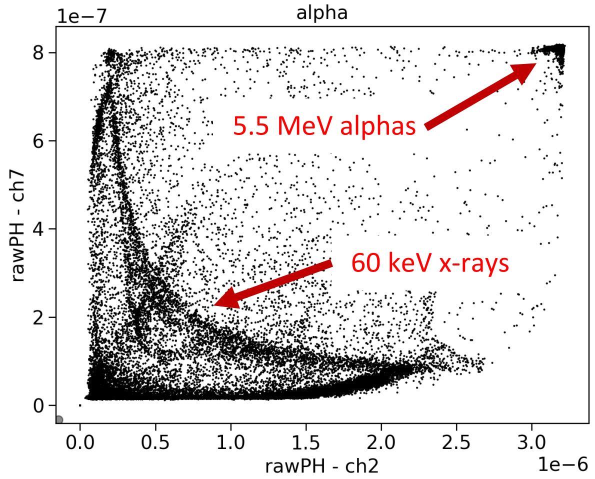


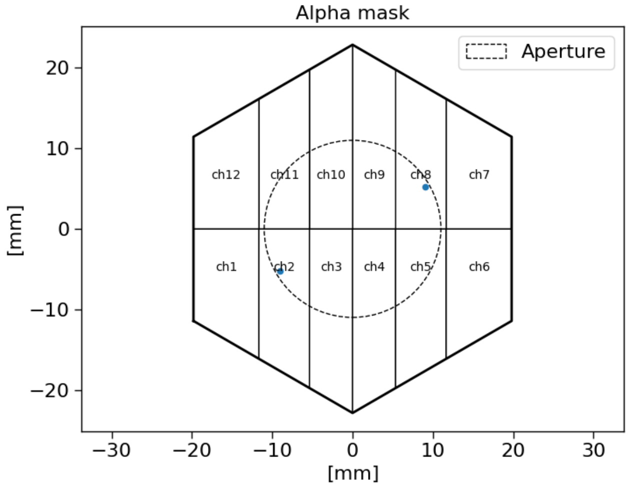


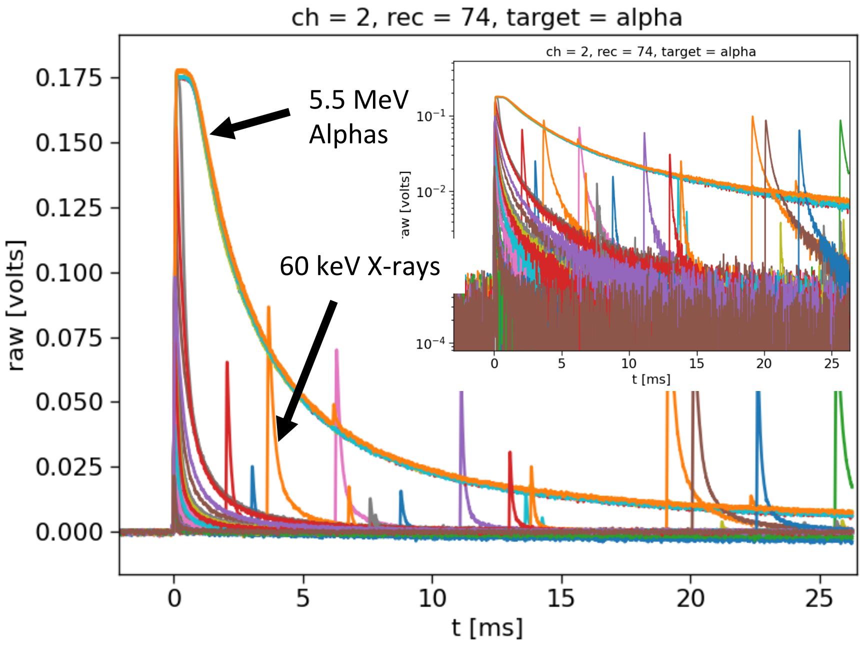


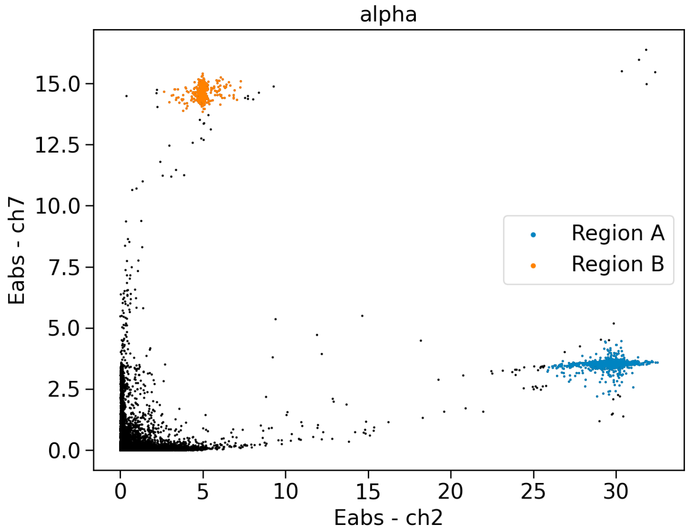
Run #2 – Alpha Source

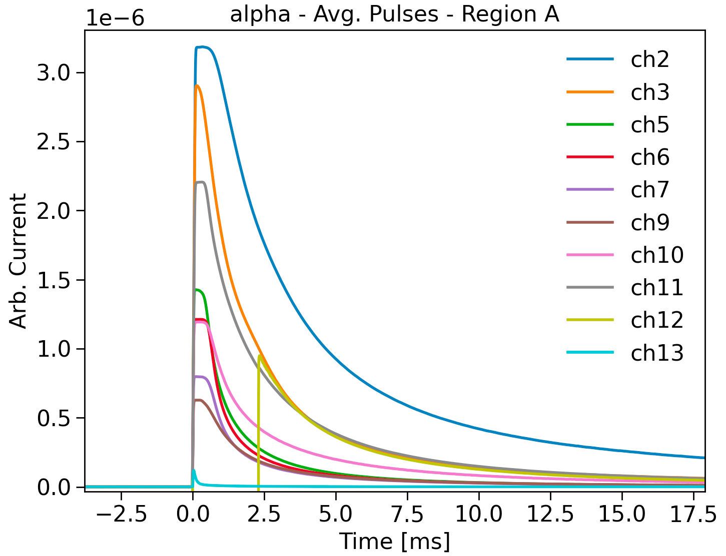
- Motivation: investigate deadtime and spatial resolution beyond upper limit of ATCO energy range
- 5.5 MeV alphas masked to 2 locations - ch2 and ch8
    - Alpha source is mounted directly behind detector, with no shielding for 60 keV, so very high X-ray background
- Alphas are fully saturated for period of time in all channels, and have very long tails
    - Obviously cannot spatially discriminate between two alpha locations in rawPH, but integrating pulses (Eabs) shows two clear distributions



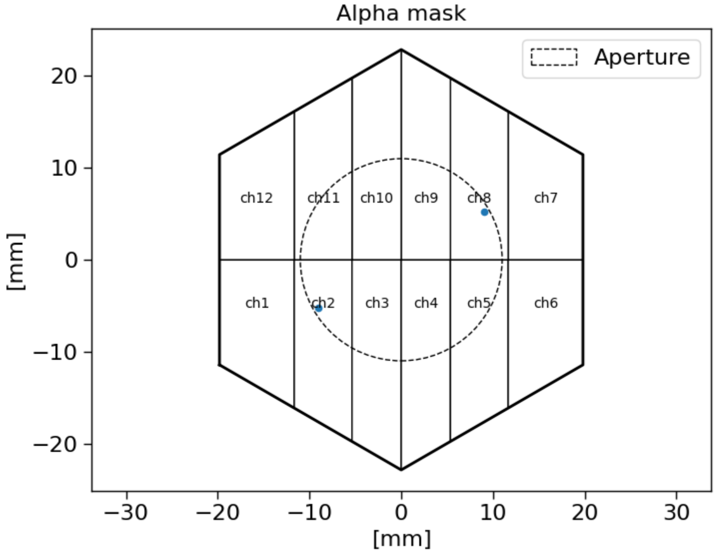




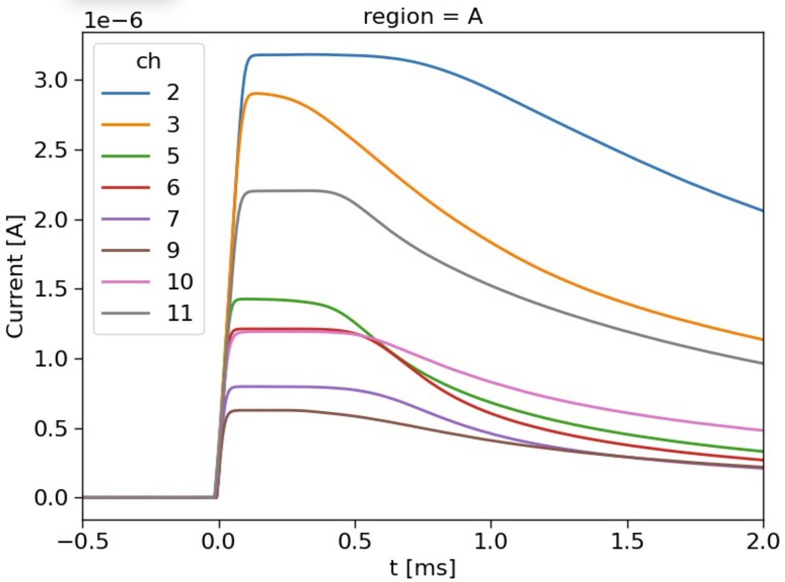


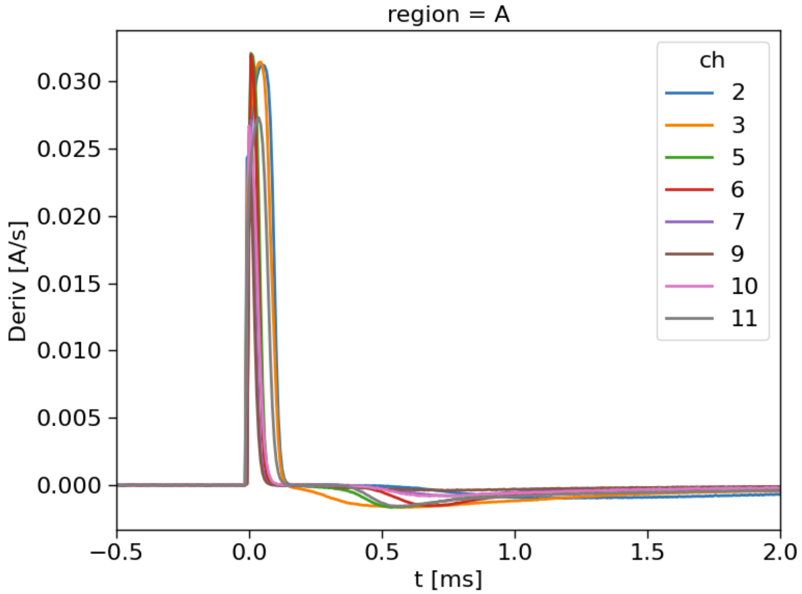


Run #2 – Alpha Source



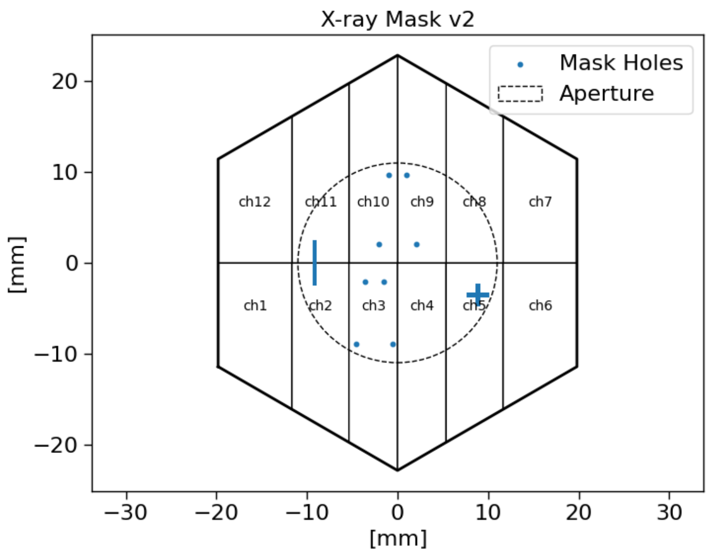
- Results support conclusion that 95% deadtime requirement likely to be satisfied even at 5.5 MeV
  - Hard saturation time typically still less than 1 ms
  - Derivative trigger will still work well on long tails
- Planning to run a simulation to calculate deadtime as a function of primary/secondary energy using measured pulse shapes at multiple different energies as input



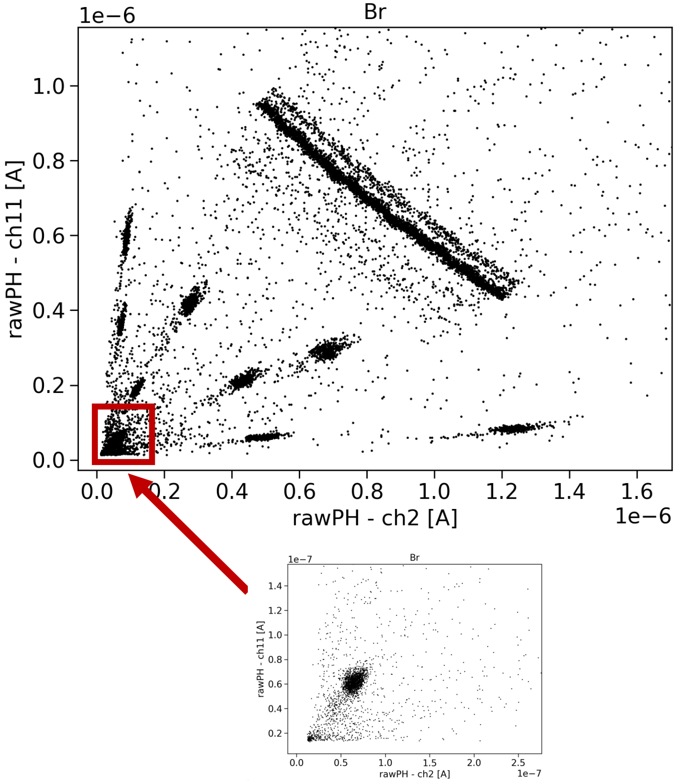


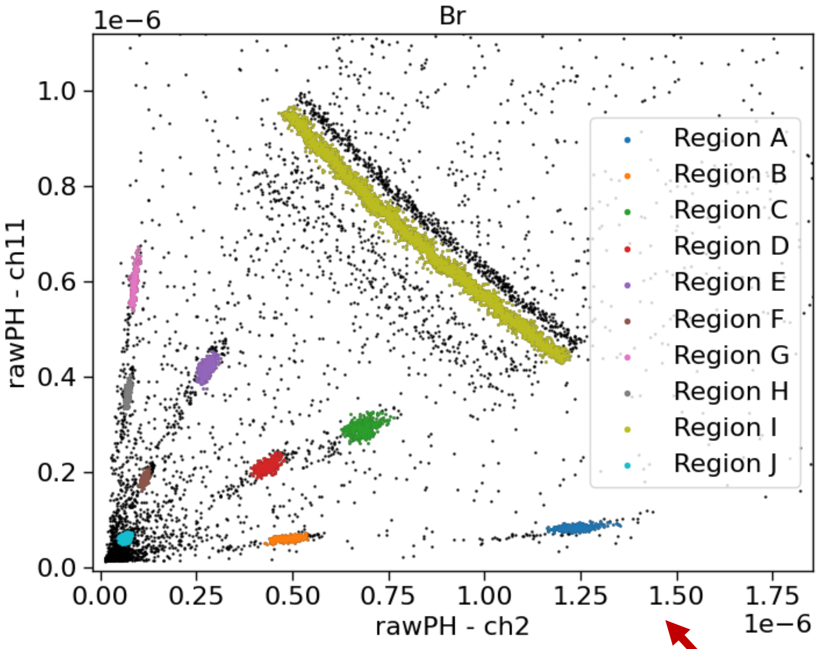
Run #3 – X-ray mask V2

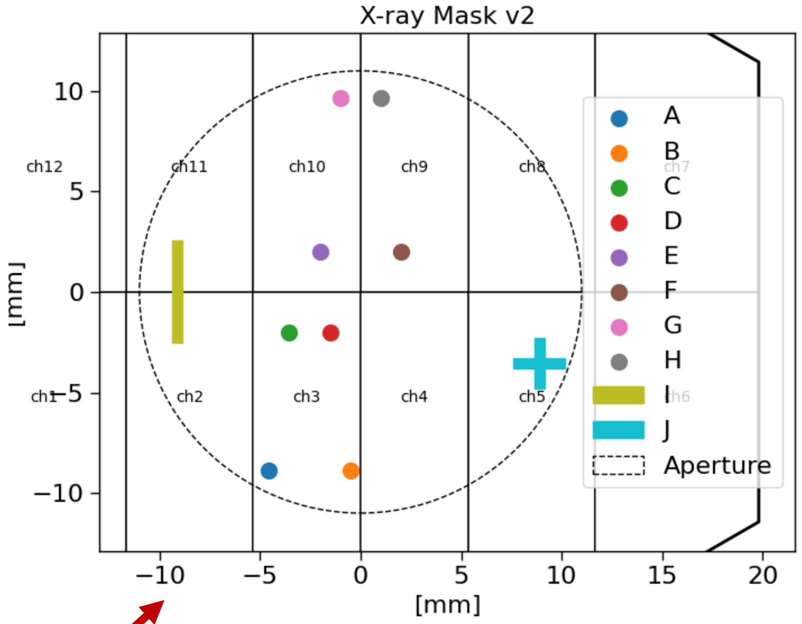
Hole/Slot diameter = 0.5 mm



- X-ray mask with 8 holes plus a vertical slot and cross shape
  - Pairs of holes with different separations to investigate discrimination ability in different situations (e.g. inter-channel vs across channel)
    - 2 mm and 4 mm hole separations
  - Slot across channels to look for any discontinuities at boundary
  - Cross to investigate differences along x vs y axis
- Resulting rawPH-rawPH plots show 10 distributions with clear separation
  - Manually identified regions with hole locations below by comparing across many such PH-PH plots

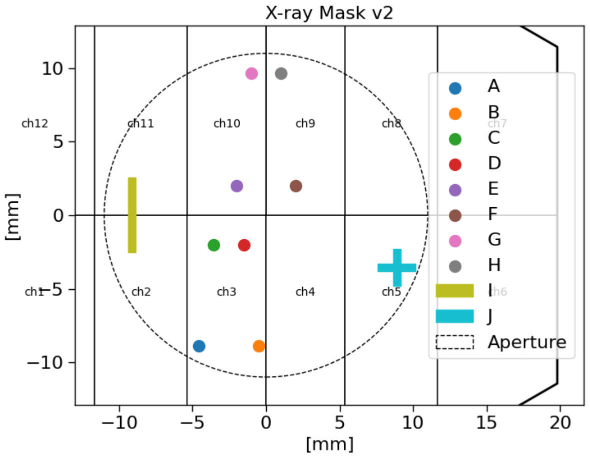




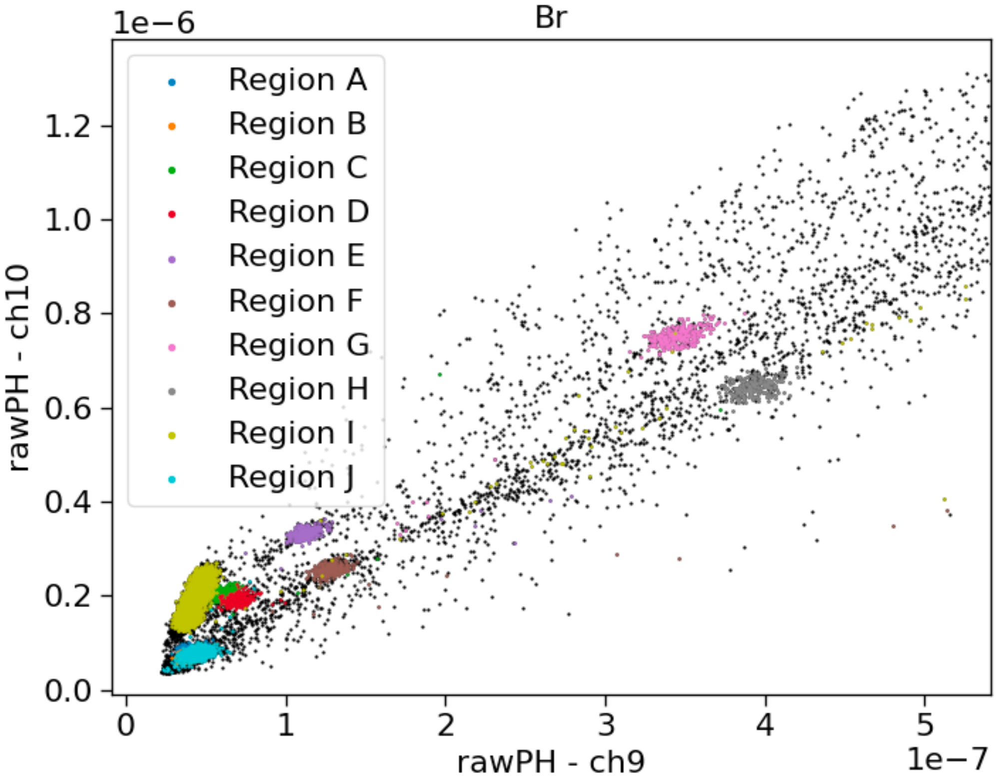


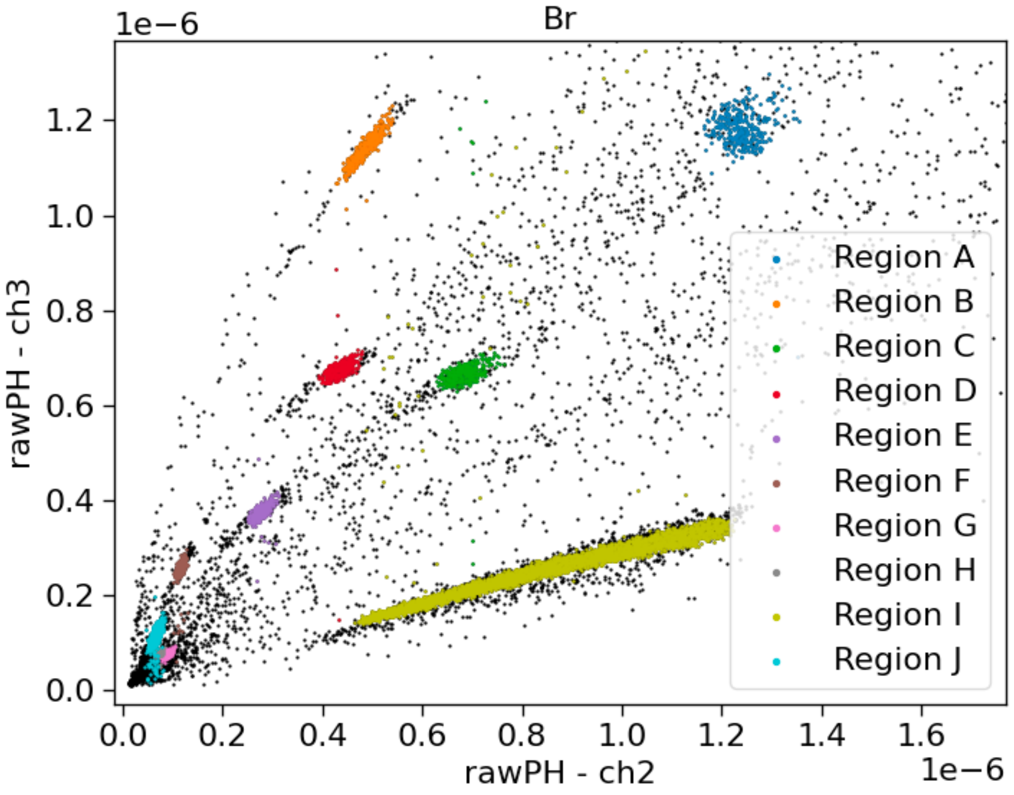
Color matched regions

Run #3 – X-ray mask V2



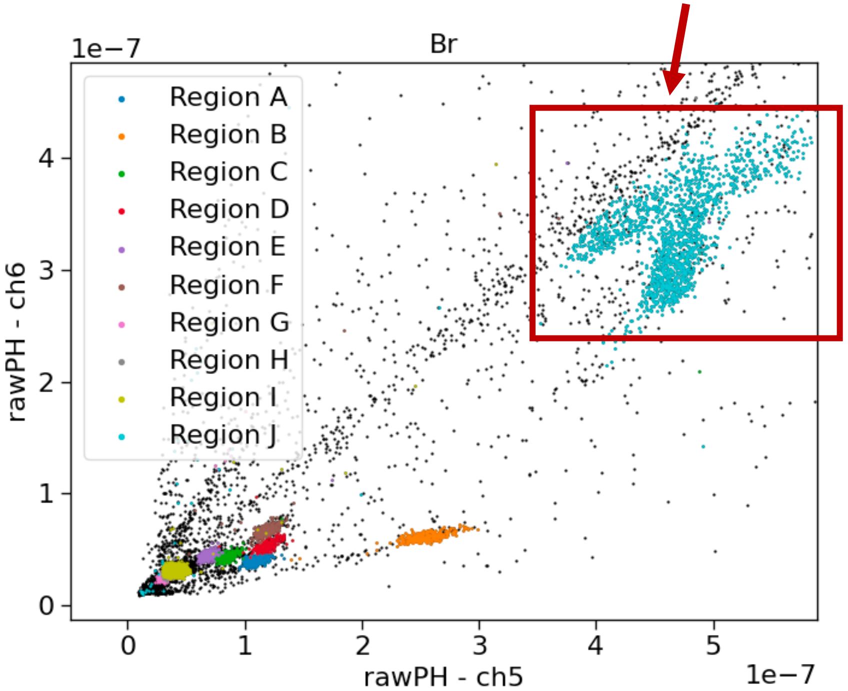
- Even most closely separated holes (2 mm) can easily be split into regions in rawPH vs rawPH plots
- Single neighboring channel (e.g. ch 2 lower right) can discriminate between multiple distributions on its own

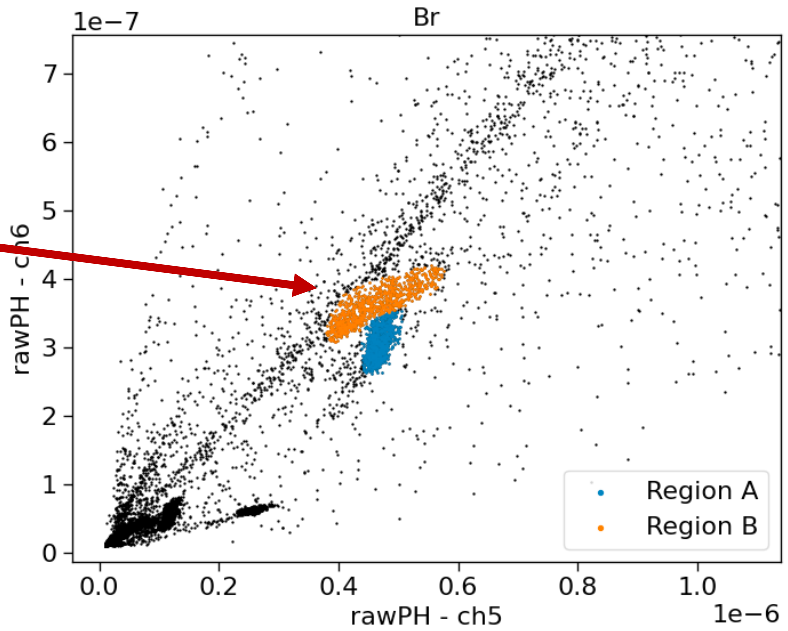


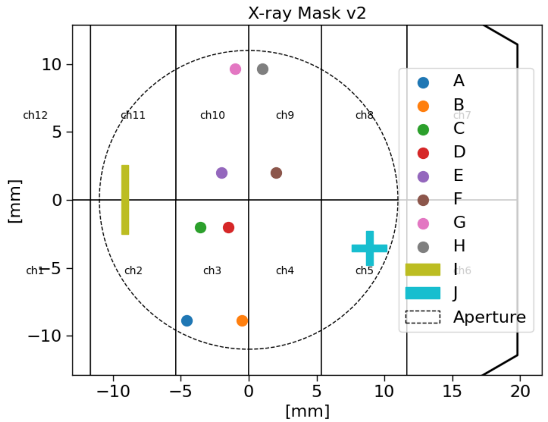


Run #3 – X-ray mask V2

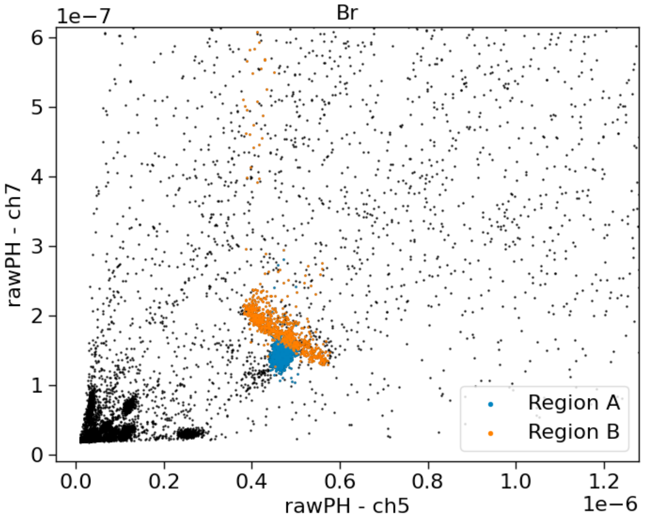
Splitting Region J into two sub regions

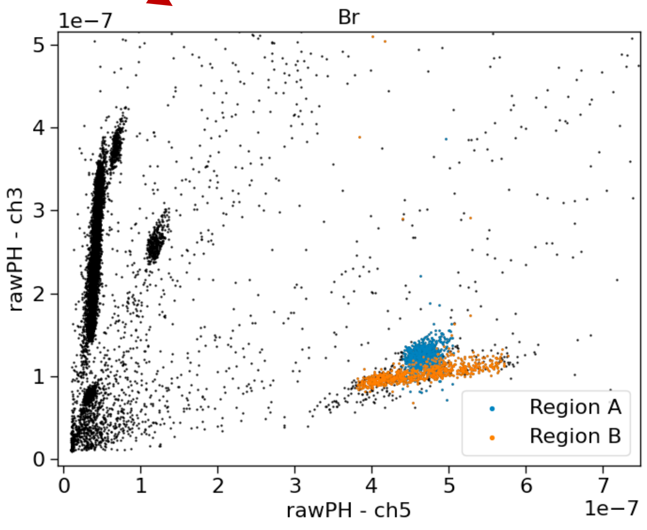




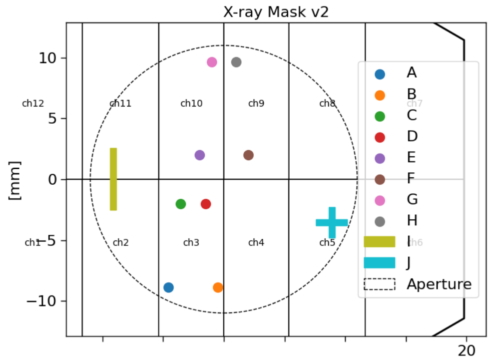


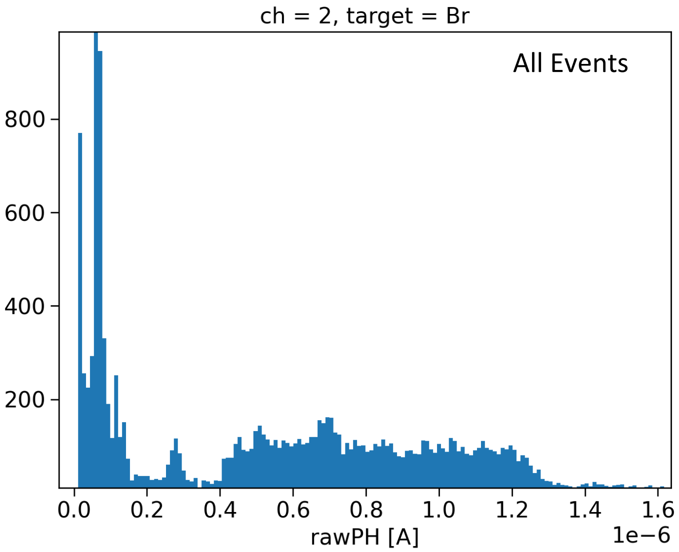
And then look at same subregions on other PH-PH plots

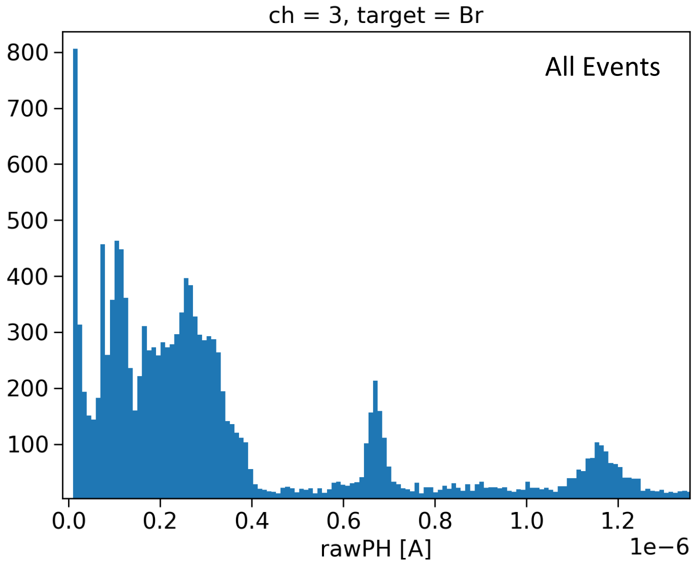


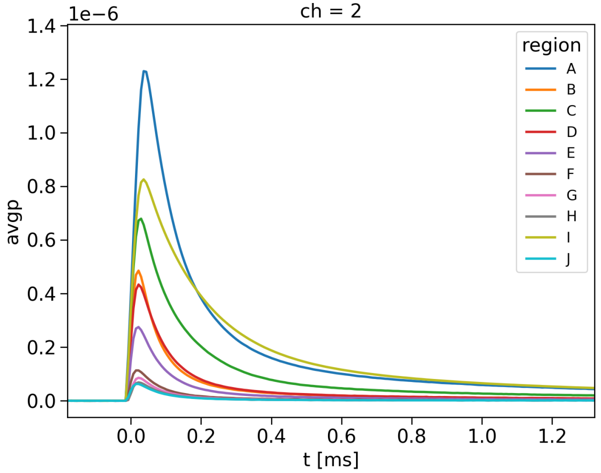


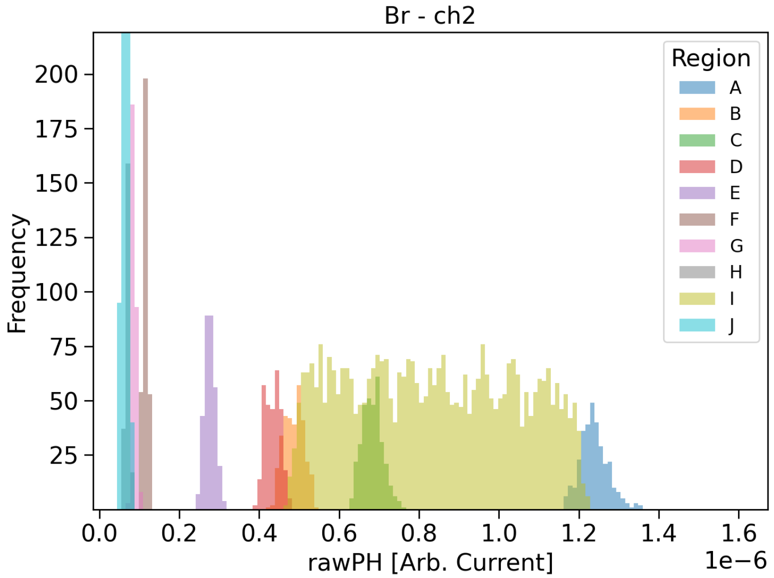
Run #3 – X-ray mask V2

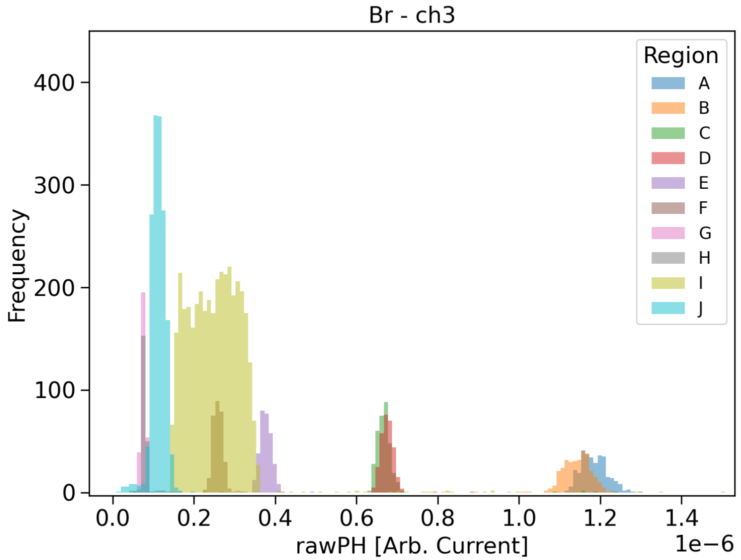


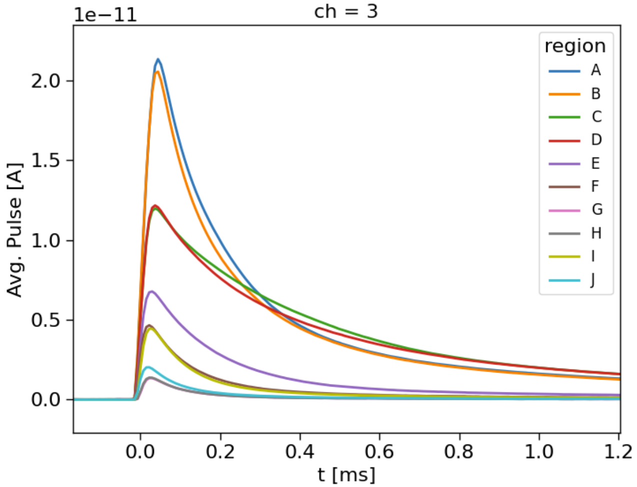






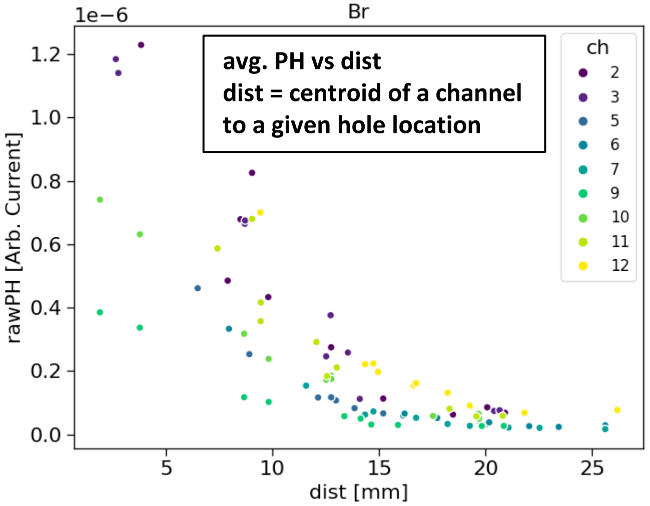




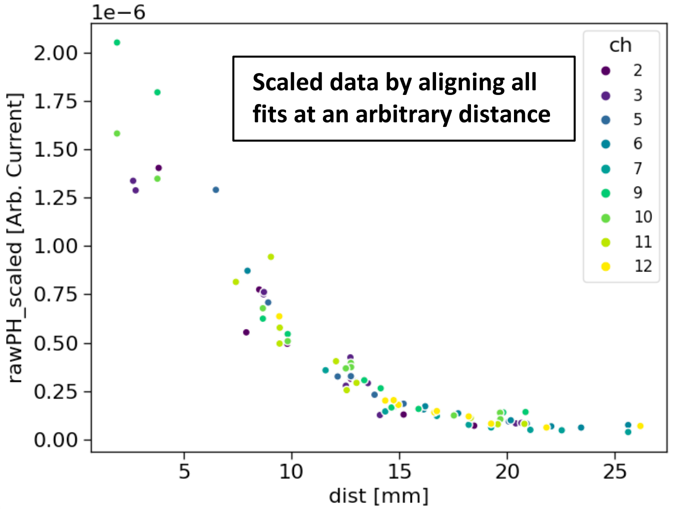


Run #3 – Spatial Resolution

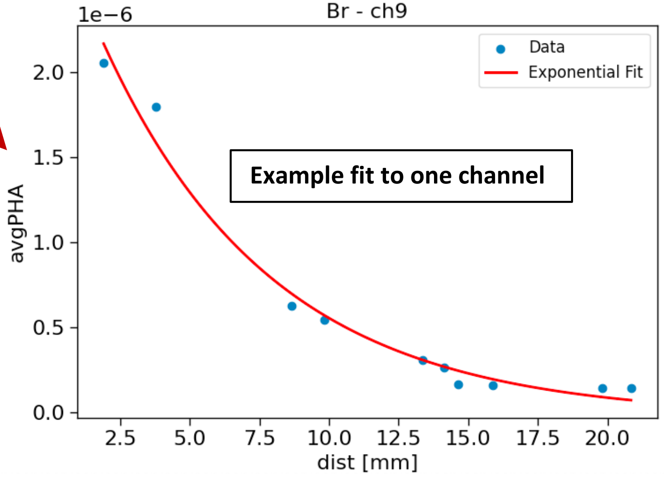
- Still struggling with best way to calibrate between channels; one quick-and-dirty attempt is aligning the distance vs average signal size for each channel



avg. PH vs dist
dist = centroid of a channel to a given hole location

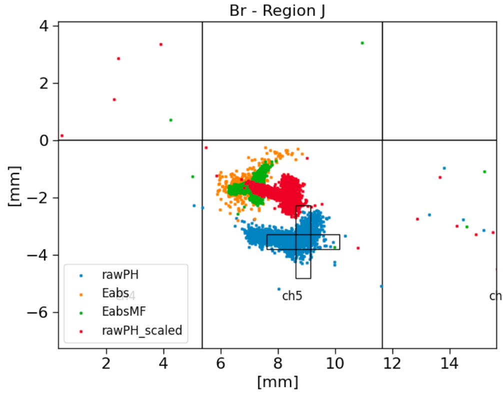


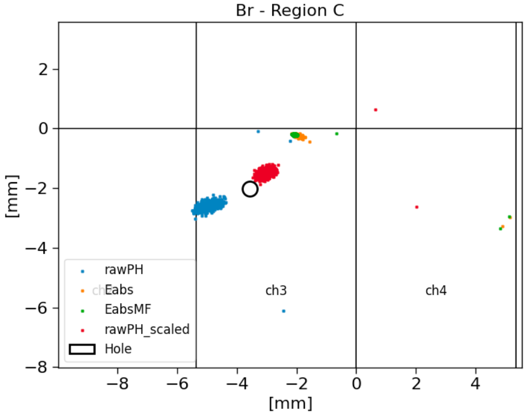
Scaled data by aligning all fits at an arbitrary distance

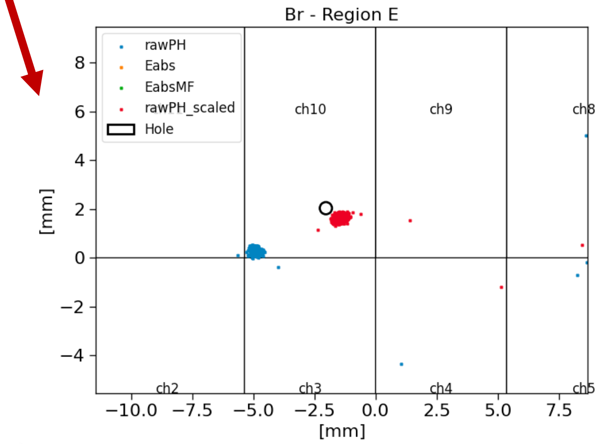


Example fit to one channel

This scaling often helps with more accurate centroiding, but not always

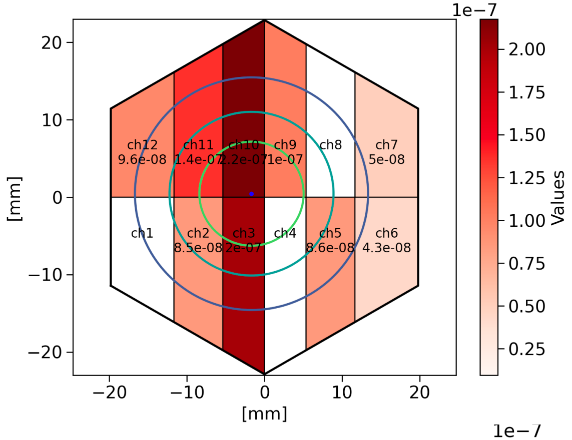






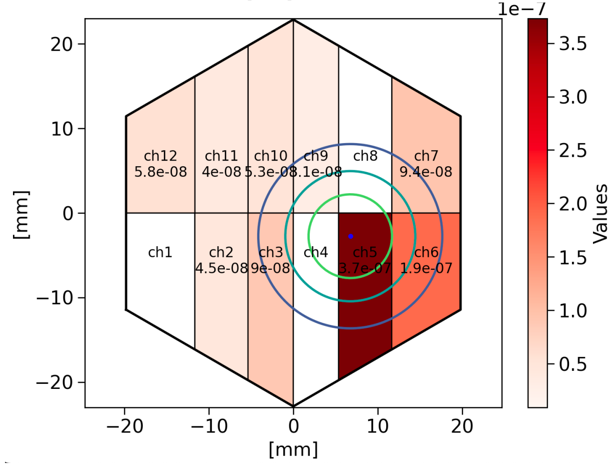
Run #3 – Spatial Resolution

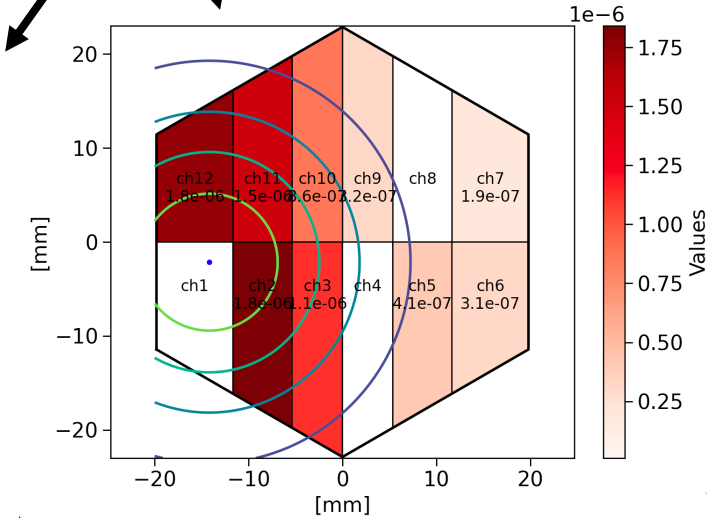
- First attempt to evaluate spatial resolution by fitting a 2d function to the distribution of signal over (x, y) position [e.g. Eabs(x, y)]
  - (x, y) channel position taken from geometrical centroid of each channel
  - Using 2D Gaussian function to start – though there is probably a better choice
- Only 12 channels to work with (and some of them are not working…) plus different TES operating points skewing the signal sizes
  - ➢ fitting is subject to high failure rate

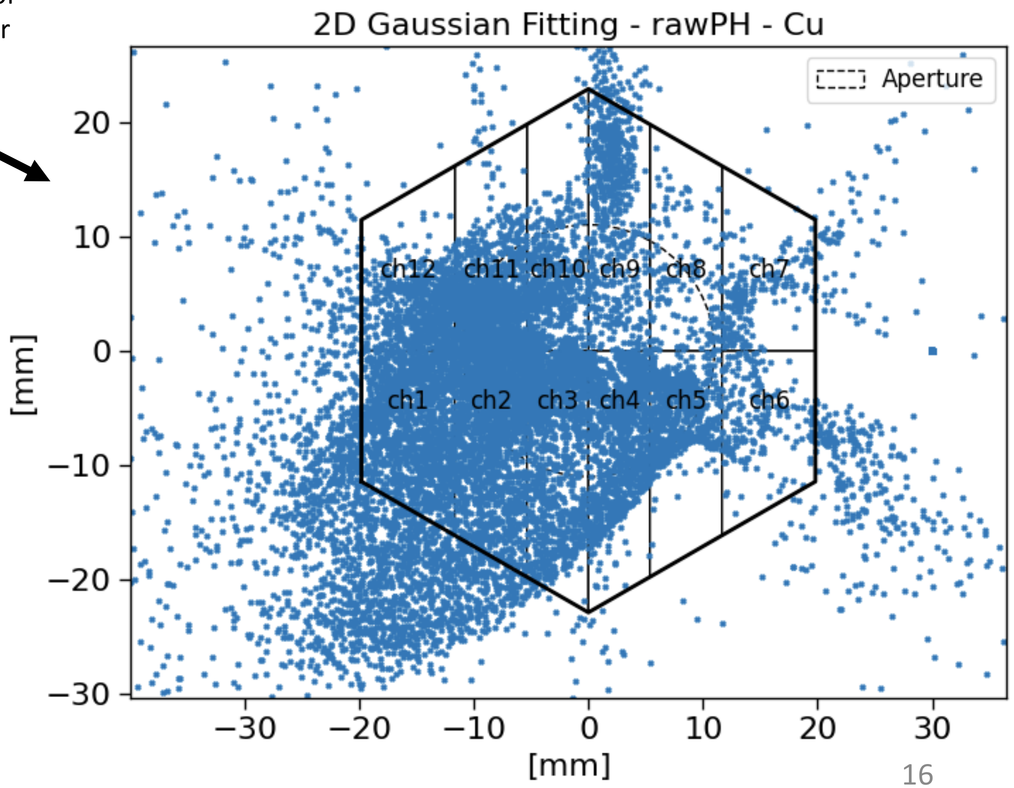


Scatterplot of spatial centroids of all events (with successful fit) for one dataset

Example Gaussian fits to individual events (rawPH)

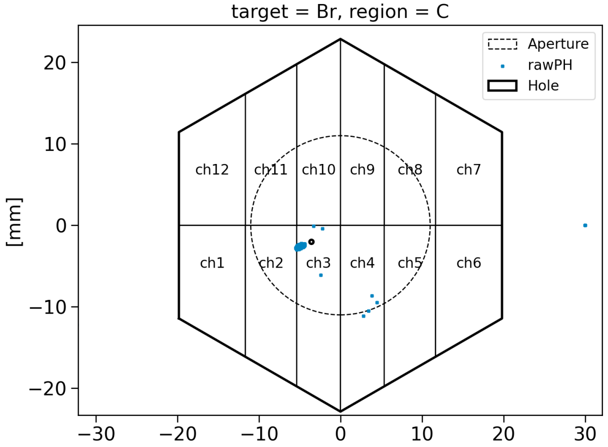


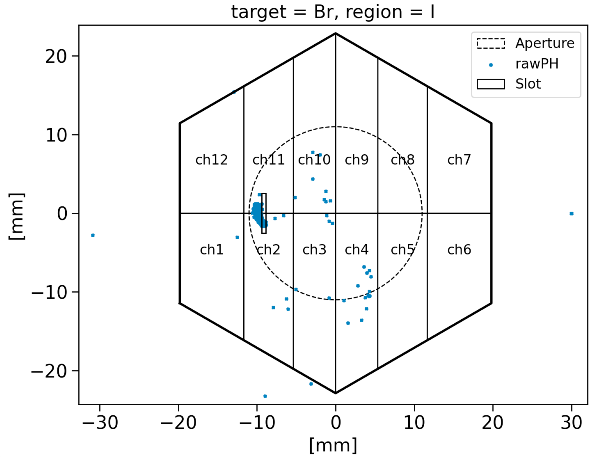


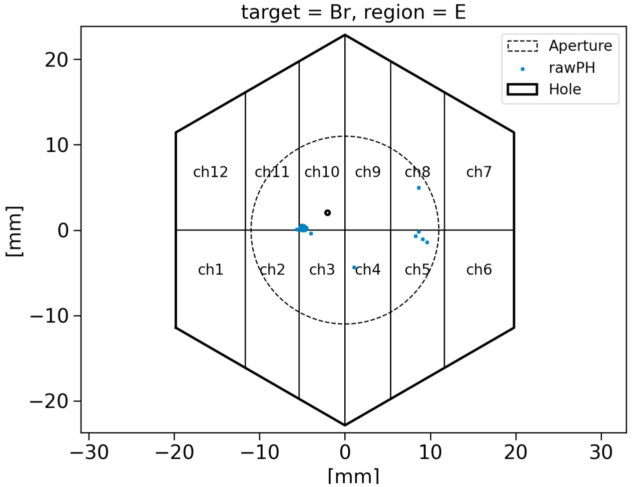


Run #3 – Spatial Resolution

- For most cases even this simple fitting method is somewhat effective; can locate the incident location to within a few mm and usually get correct channel
  - A few regions where not able to get many successful fits
  - Gain difference between channels (due to different operating points) likely skewing fit results


target = Br, region = C


target = Br, region = I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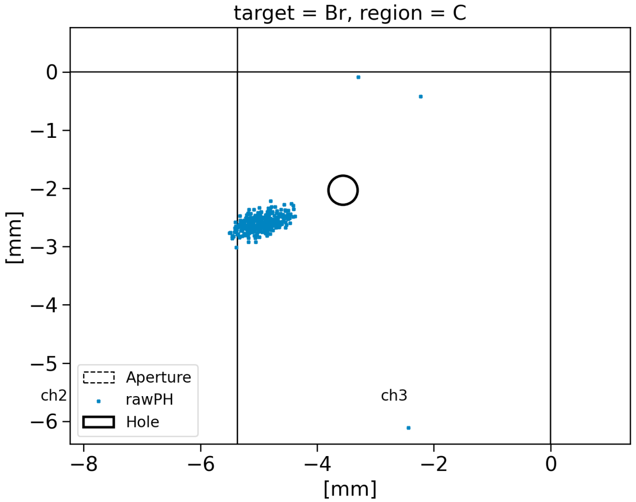
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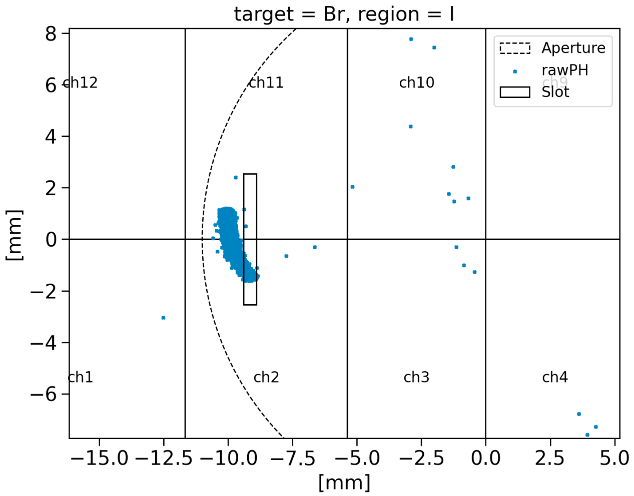
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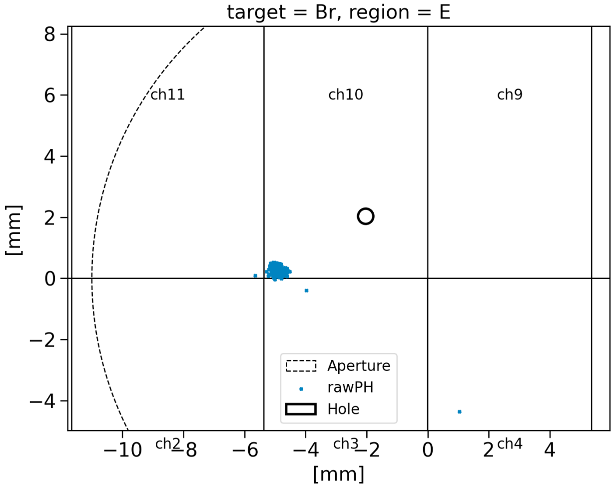
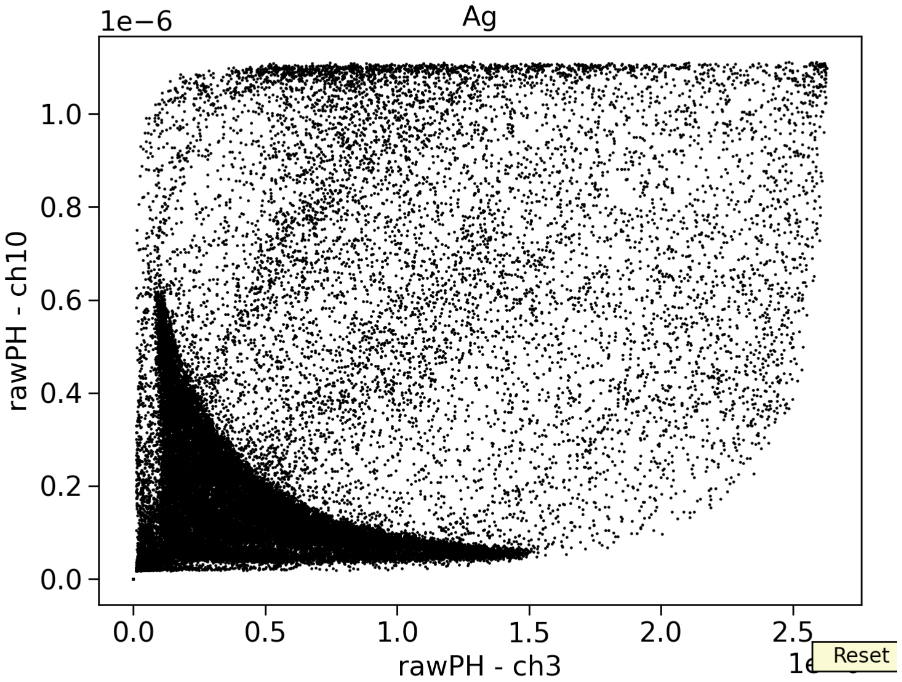
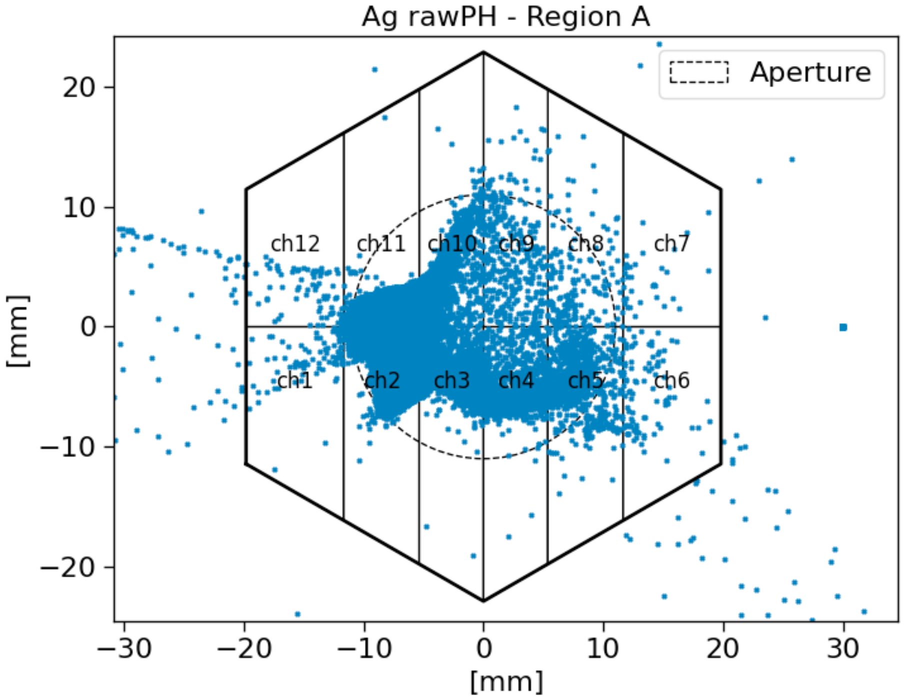

target = Br, region = E

Run #4 – No Mask

- Only really started taking data last week, so not much analysis completed yet
- Results do show expected "banana" type plots and other indicators of spatial discrimination
- Simple 2D Gaussian fitting does show most events are restricted to the aperture region, but with interesting structure
  - Using a better model and/or machine learning assistance will probably improve results





Other Oddities

- Lost one previously working channel (ch8) after the first run
  - Wire bonding issue during thermal cycling? Didn't see visible evidence of this, but didn't do any physical testing
- Significant changes in measured IVs between runs
  - Consistent Rn reduction over time across all channels
  - Also seeing Tc shifts that tend to go lower, but this is less consistent between channels
  - Also some differences in measured G values, but error on this measurement is high so hard to accurately correlate with these shifts