Laser Beam Asymmetry and HV switch study at UVa

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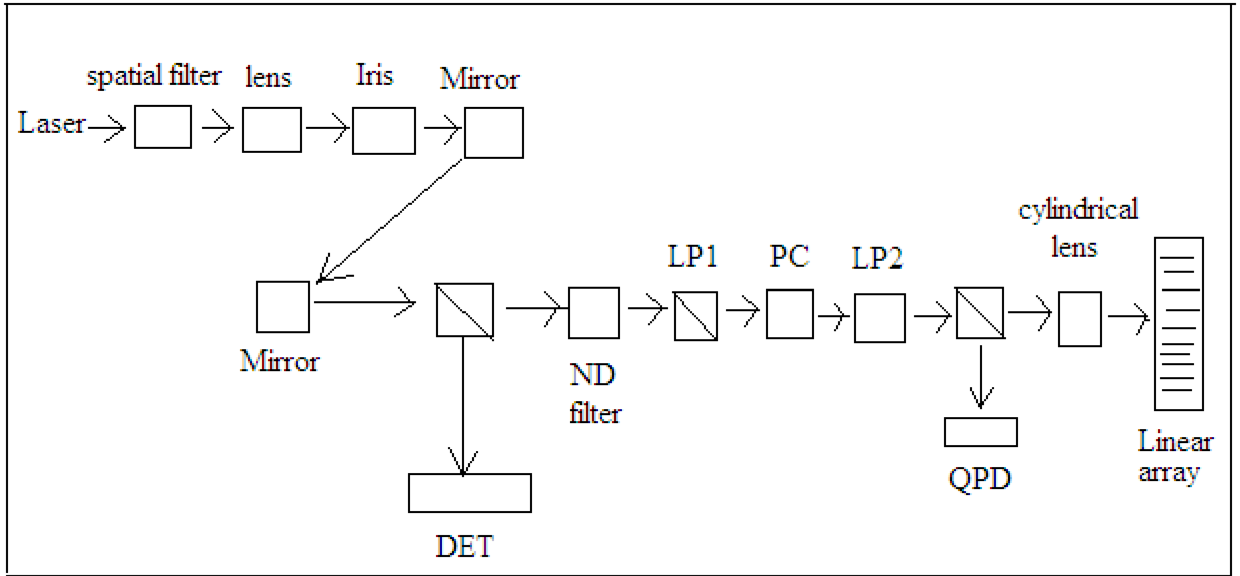
Optical Setup



- The spatial filter, lens and iris upstream of the mirrors are used to improve the beam profile. Ideally we would get a Gaussian beam out of the setup, but our beam is not entirely Gaussian (discussed later).
- The DET receives the pickoff beam, which acts as a baseline for changes in laser intensity normalization in our data.
- LP1 and LP2 (analyzer) are linear polarizers, which are crossed to maximize extinction. This setup ensures that we are maximally sensitive to any residual linear polarization.
- PC (Pockels Cell) is set up with its fast and slow axis at +- 45 degrees to the polarization axis of the upstream beam, and modulated using a high voltage (HV) switch to convert the linearly polarized light into right and left circular polarization states, corresponding to the TTL high and low on the HV-switch.
- LP2 provides close to 100 % analyzing power (the strain on the photocathode induces an analyzing power typically of about 3-4% at jlab)

Beam Asymmetry

The phase change of a beam propagating through a uniaxial crystal is given as

$$(\delta_{PC})_{R/L} = \pm \frac{\Pi}{2 V_{\lambda/4}} V_{PC}$$

But there is always some amount of residual linear polarization in the circularly polarized beam. It is convenient to write the phase shift as

$$\delta^R = -\left(\frac{\Pi}{2} + \alpha\right) - \Delta\,; \quad \delta^L = +\left(\frac{\Pi}{2} + \alpha\right) - \Delta$$

ά being the asymmetric phase shift deviation from quarter-wave shifts does not contribute to the asymmetry (cancels out).

The asymmetric phase shift deviation from quarter-wave shifts Δ does contribute to the asymmetry

- Δ phase shift arises mostly due to stress on the PC and optics downstream of the PC
- Δ phase can vary across the beam spot, resulting in HC position differences.
- Δ phase shifts can be the dominant contribution to the HCBA, if left unchecked.
- But $\Delta \propto V_{PC}$ so we can zero out the Δ phase contribution to asymmetry by adjusting the voltage properly.

What if the beam is not normal to the PC longitudinal axis?

$$(\delta_{PC})_{R/L} = \pm \frac{\Pi}{2\,V_{\lambda/4}} V_{PC} + \mathbf{a}\,(\rho^2 - \theta^2)\ ;\ \mathbf{a} = \frac{\Pi l n_o}{\lambda} \cdot \frac{n_o^2 - n_e^2}{n_e^2}$$

- ρ being the angle made by the rays to z-axis in the y-z plane, and θ being the angle made by the rays to the z-axis in the x-z plane, with the beam propagating along the z-axis.

For a single ray going through the PC,

$$I_{R/L} = \sin^2\left(\frac{\Pi}{4}\frac{V}{V_{\lambda/4}}\right) \pm \frac{a}{2}(\rho^2 - \theta^2)\sin\left(\frac{\Pi}{2}\frac{V}{V_{\lambda/4}}\right) + \left(\frac{a}{2}(\rho^2 - \theta^2)\cos\left(\frac{\Pi}{4}\frac{V}{V_{\lambda/4}}\right)\right)^2$$

$$A_q = \frac{I_R - I_L}{I_R + I_L} = \frac{a(\rho^2 - \theta^2)\sin\left(\frac{\Pi}{2}\frac{V}{V_{\lambda/4}}\right)}{2\sin^2\left(\frac{\Pi}{4}\frac{V}{V_{\lambda/4}}\right) + \left(a(\rho^2 - \theta^2)\cos\left(\frac{\Pi}{4}\frac{V}{V_{\lambda/4}}\right)\right)^2}$$

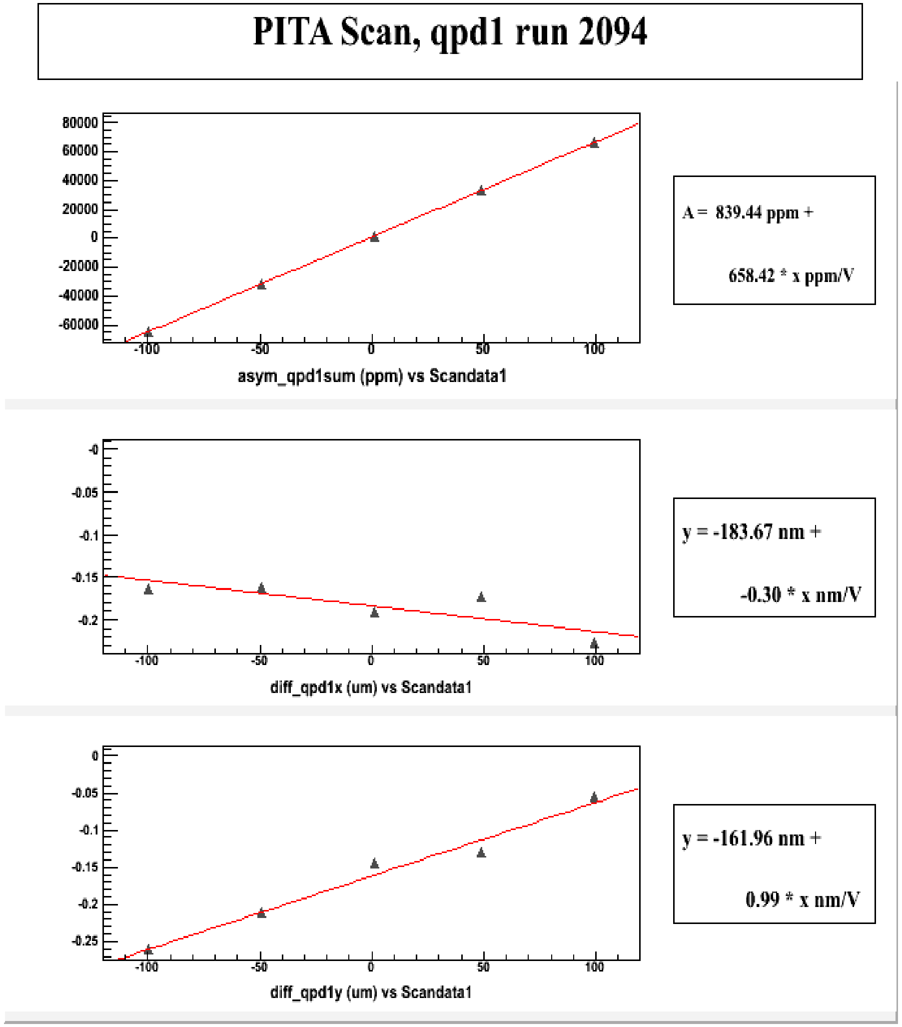
If we distribute this ray over a Gaussian profile (rough approximations),

$$\overline{x} \approx \left(\int I_R\, Ix\, dx - \int I_L\, Ix\, dx\right) \propto -\frac{4\,\Pi^2}{lw^4}\theta_o$$

$$x_{rms} \approx \left(\int I_R\, Ix^2\, dx - \int I_L\, Ix^2\, dx\right) \propto \left(\frac{\Pi}{l^2\, w^6} + \frac{4\,\Pi}{w^4}(\rho_o^2 - \theta_o^2)\right)$$

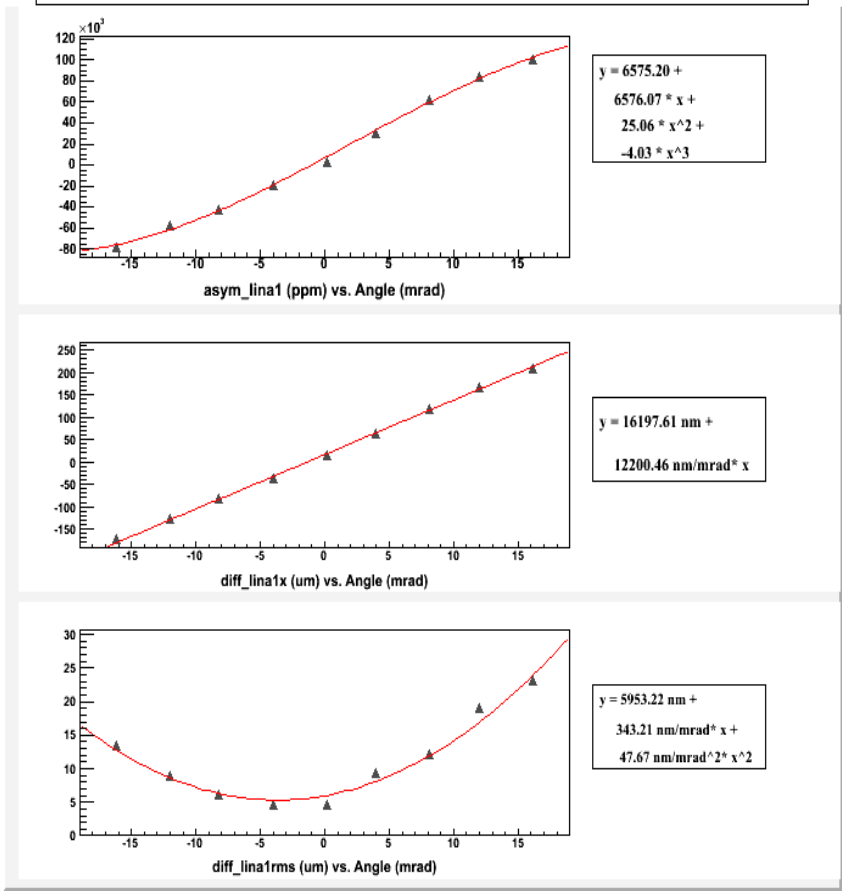
PITA scan on a well aligned PC

- PC is aligned using PITA scans, along with PC pitch/yaw scans to minimize the asymmetry and position differences.
- The asymmetry is less than 1000 ppm.
- The position differences are about 200 nm or less (which is well within the accuracy of PC stage of ~ 1 um)
- There is very little dependence of the position difference on applied voltage.

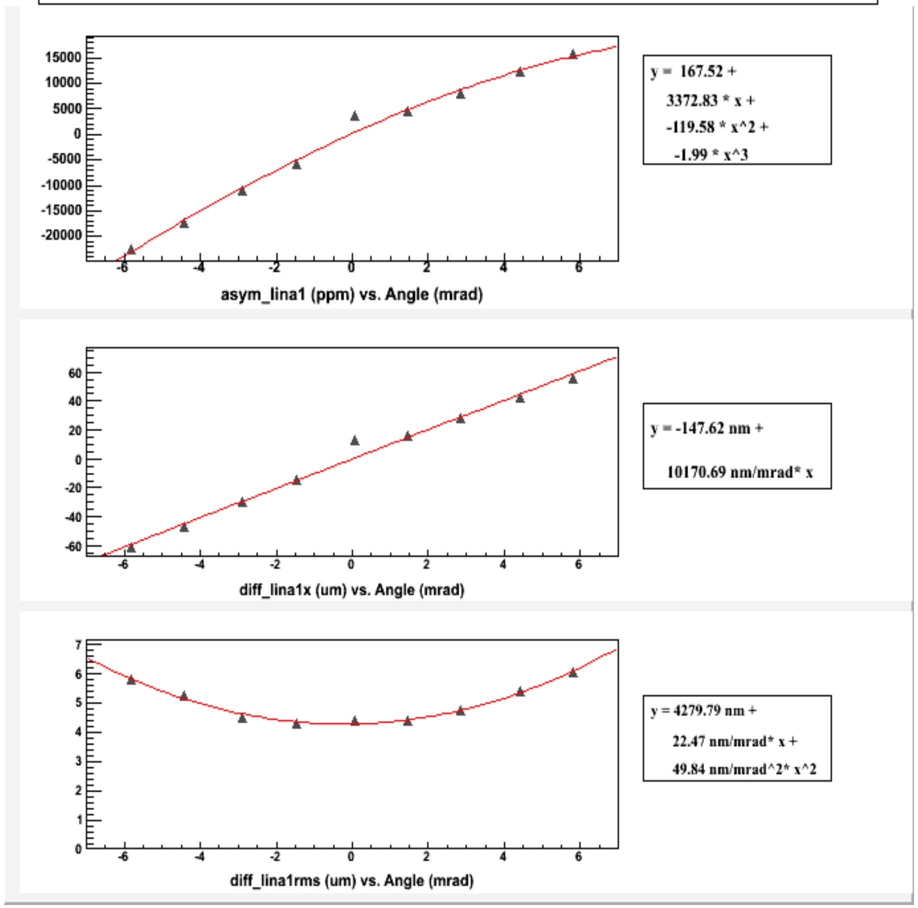


PC rotation scans (linear array @ 45 deg)

PC Pitch Scan, lina run 1962

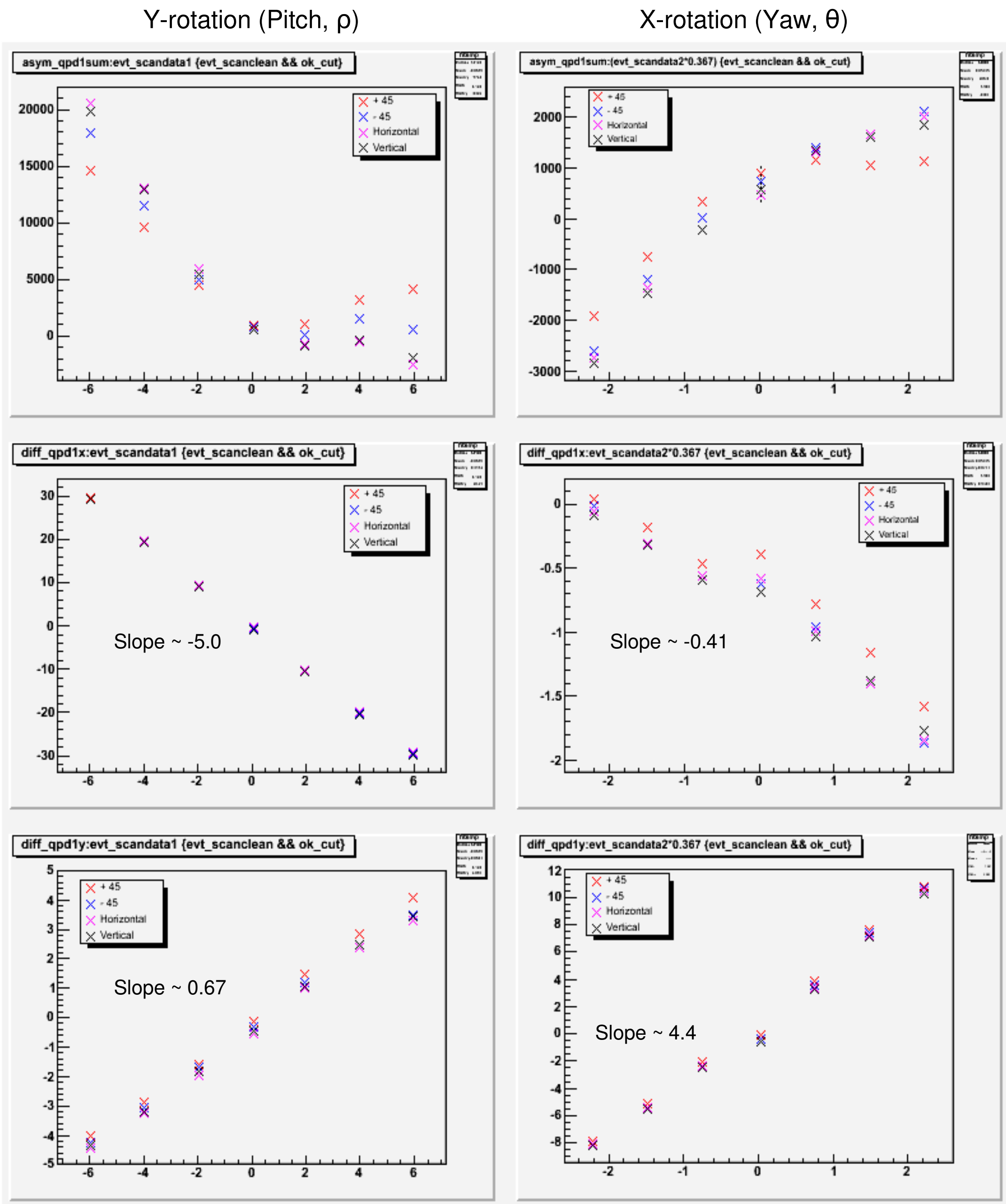


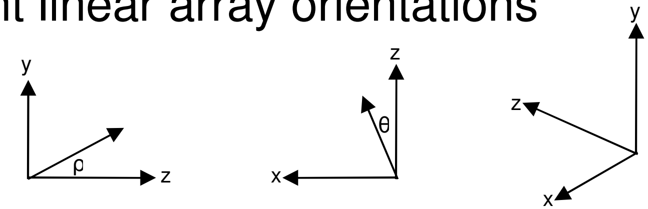
PC Yaw Scan, lina run 1963



- These plots demonstrate the importance of proper pitch and yaw PC alignment. Any slight misalignment of the PC axis leads to a huge contribution to HCBA, and the position and rms differences.
- The position difference scales linearly with the angle of rotation.
- The spot size difference scales in quadrature with the angle of rotation. The PC cannot be aligned to zero the spot size differences. There is a constant offset in spot size differences even when the PC is perfectly aligned in pitch and yaw, since we are observing the breathing modes.

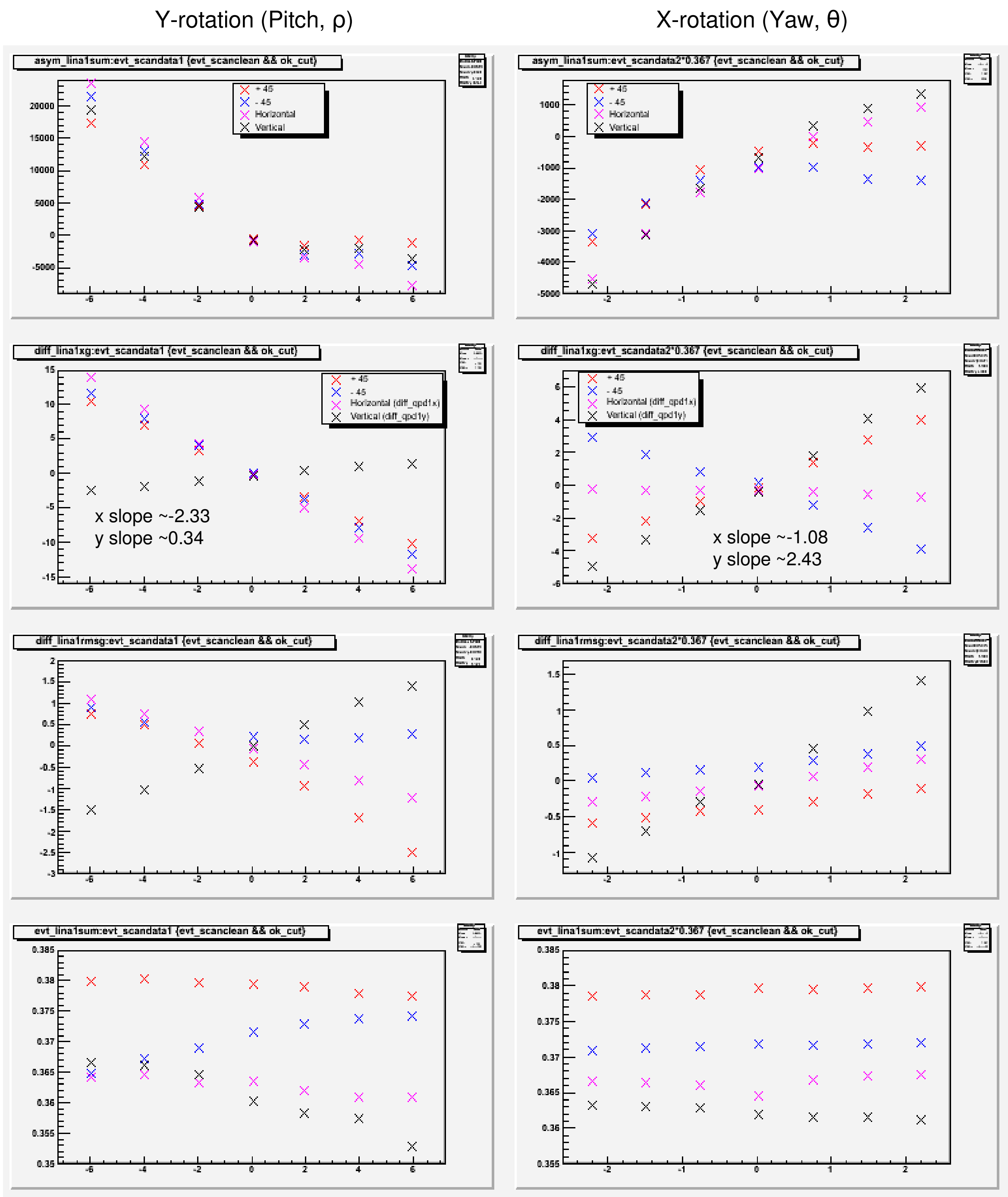
PC rotation scan on QPD @ 4 different linear array orientations





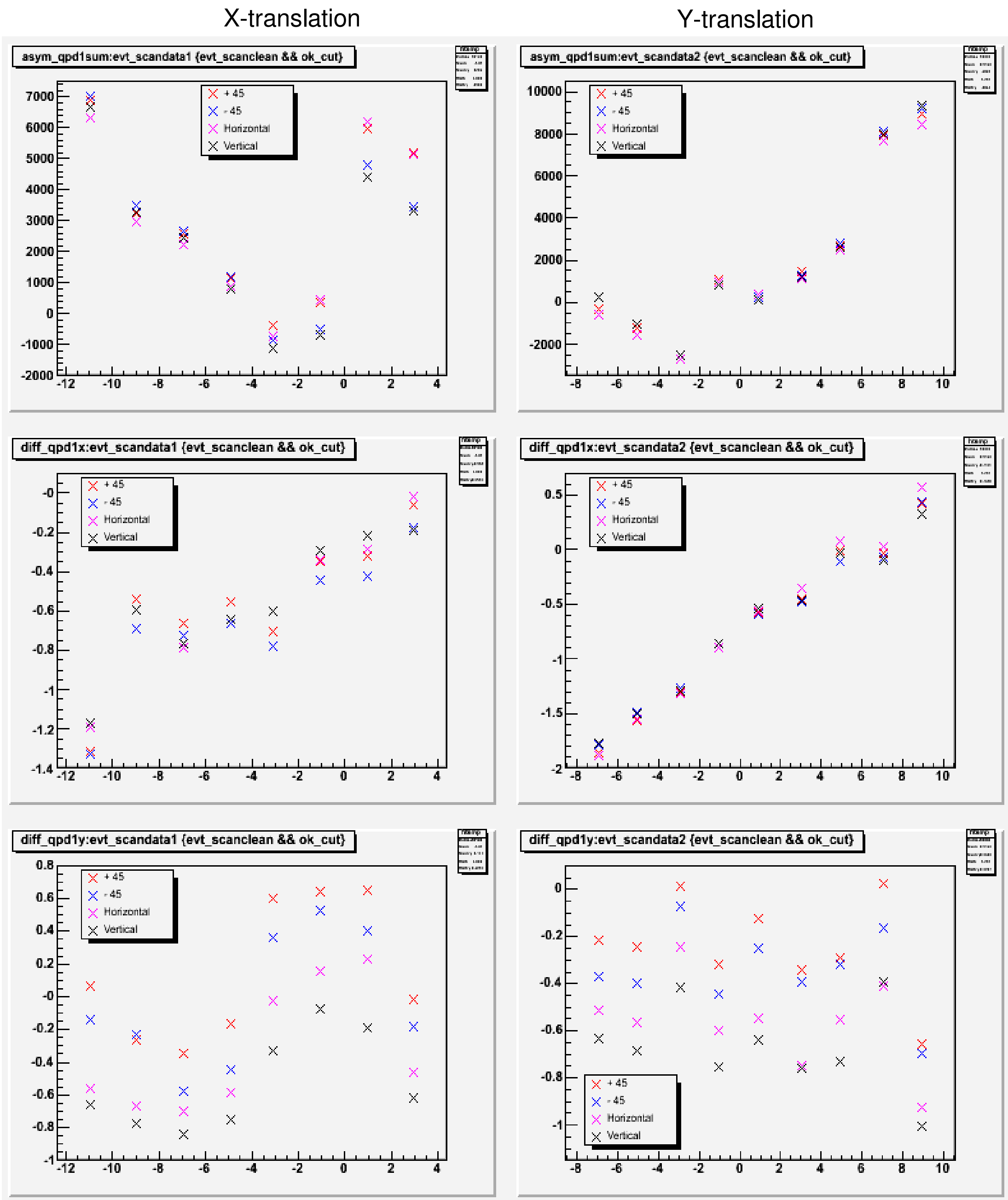
- Consistency check between the 4 sets of runs.
- The position differences scales linearly with angle.
- But the x-position difference depends much more strongly on the PC rotation in y-z plane, and the y-position difference depends much more strongly on the PC rotation in the x-z plane
- diff_qpd1x pitch scan rotated 90 degrees clockwise about z becomes –diff_qpd1y yaw. The magnitude of the slopes , 5.0 and 4.4 agrees to within 6.4 %.
- Considering that the PC stages are precise to only about 0.7/8 mrad every time we change the angle the agreement is really good.
- The agreement between the diff_qpd1y pitch slope and diff_qpd1x yaw is about 24.1 %, which is not way off taking into account the precision of the PC stage.

PC rotation on linear array

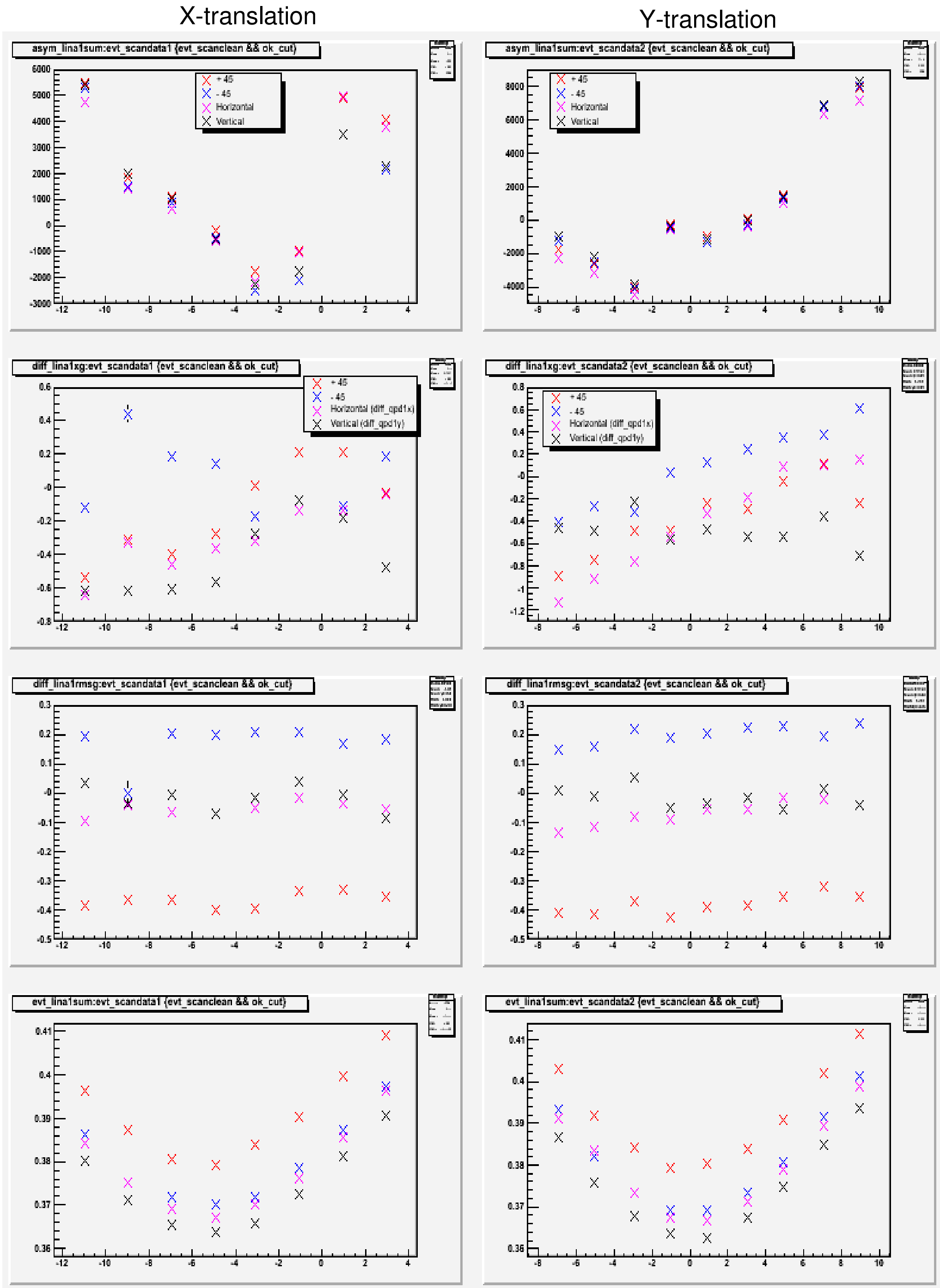


- Spot size on the liner array is calibrated to match the spot size measured on the qpd.
- The x and y position differences slope on the linear array should be identical to the qpd1x and qpd1y position difference slopes
- But the linear array slopes are consistently difference by a factor of ½, except for diff_lina1x yaw, which is a factor of 2 of the qpd1_y yaw
- All the position differences intersect at around 0 in pitch and yaw, indicating that the PC is fairly well aligned
- The rms does not have the quadratic behavior that we would expect, but the +- 45 data does seem to indicate opposite offsets
- The intensity stays fairly constant for the yaw scan, but does change for the pitch scan by as much as ~ 1.7 %

PC translation scan on qpd @ 4 different linear array orientations



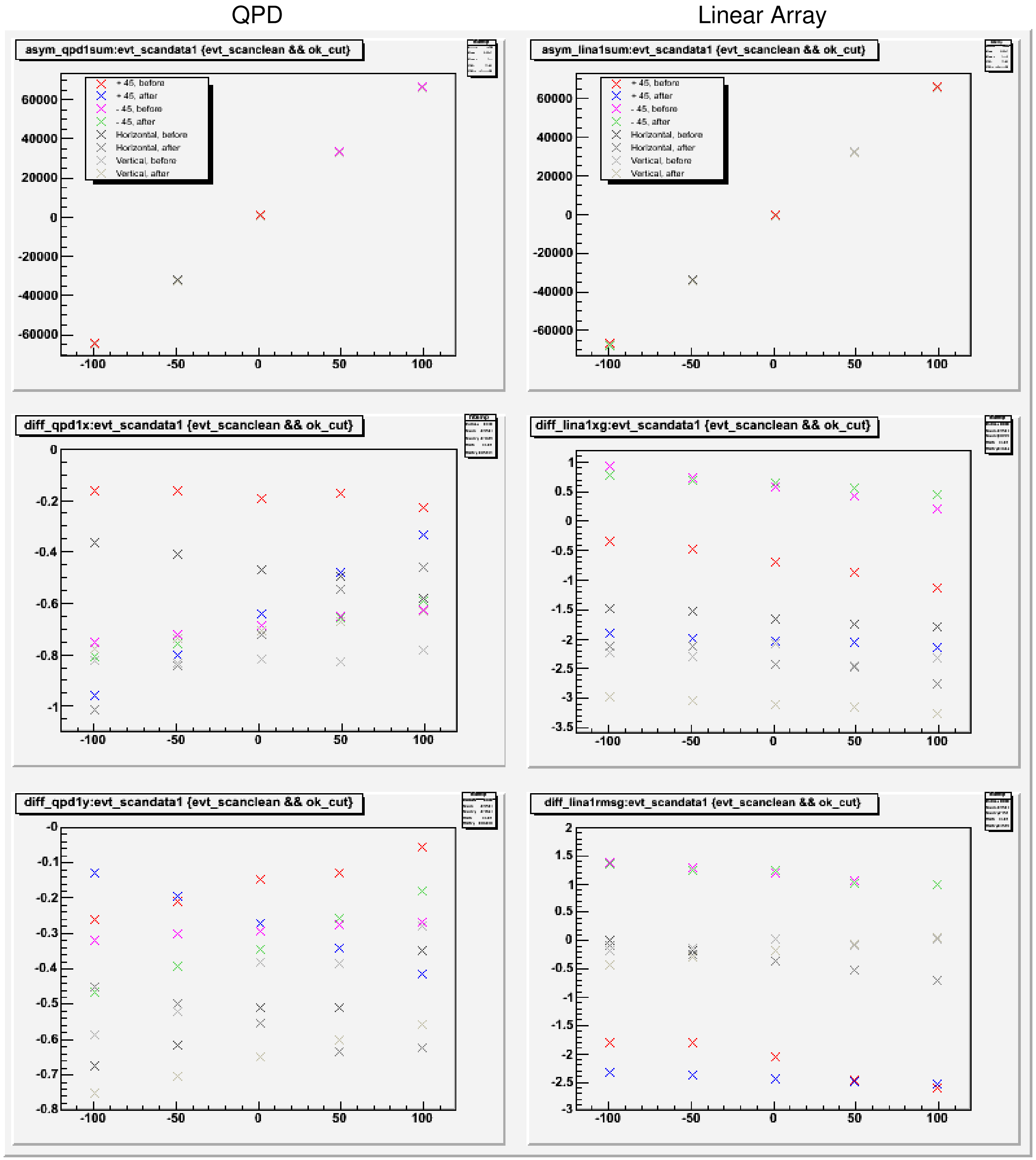
- We essentially expect the position differences in the direction of scan to scale as the slope of asymmetry
- For x-translation scan, we would expect diff_qpd1x to roughly correspond to the asymmetry slope, while diff_qpd1y should stay about constant
- For the most part diff_qpd1y is random and small.
- This relationship would tell us that changes in the beam position scales with the slope of the asymmetry in that direction.
- But, can hardly make out any such correlation from these plots!
- Probably because spot size (300 um) is far too small when we are scanning by 2mm steps.



PC translation scan on the linear array

- The asymmetry pattern matches the one observed on qpd.
- Again, the x and y position differences do not seem to have much correlation to the asymmetry curve. Probably because the spot size is too small compared to the scan step size, so the contribution due to Δ phase gradient is suppressed.
- The rms differences is small, and stays roughly constant throughout each scan.
- The +- 45 rms difference changes sign, which is what we would expect along the breathing modes.
- The x and y rms differences are 0 or very close to it.
- The bottom two plots are intensity plots. The peculiar shape may be the result of α phase shift contribution.

PITA scan before and after each of the PC scans



- Linear array rms not normalized to qpd rms. The differences are suppressed by a factor of about 4 (maybe 5) when normalized.
- The asymmetry values remain constant for different runs.
- The position differences changes to some extent (1 um max.) but this is well within the precision of the stage holding PC which is 1 um.
- rms changes between the runs is small (250 nm max), but for any particular run rms is fairly constant.

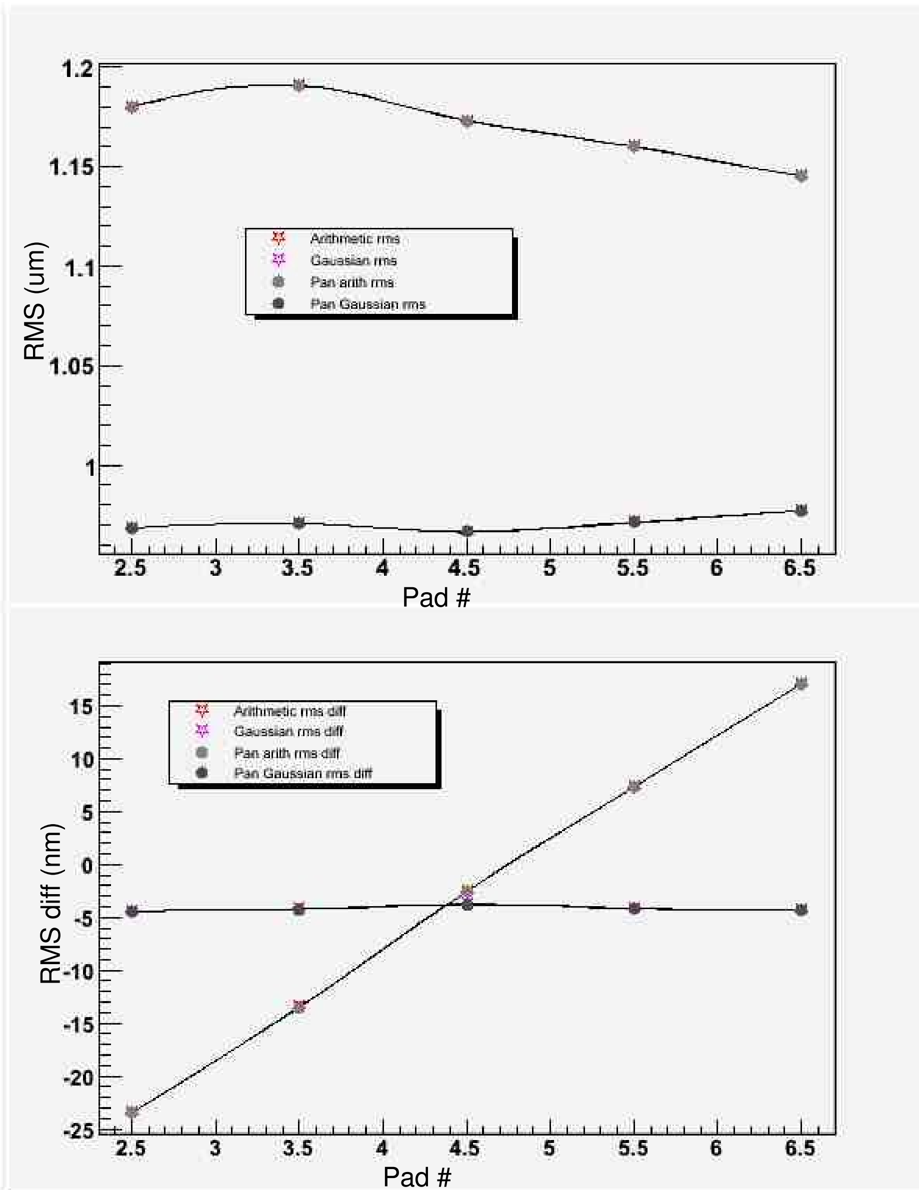
Conclusion of 4-axes study

- Fair to say that we can align the PC to within ~200 nm position differences with the 100 % analyzing power that we have.
- The spot size variations fluctuate to within < 250nm even when we move the PC around.
- Limited by the accuracy and precision of the PC stage currently used, probably.
- In jlab, these differences are decreased by a factor of about 20 since typical analyzing power of the photocathode is 3-4 %.
- Locating the beam waist at the PC and minimizing it can decouple the helicity correlated position and spot size differences to some extent.

Spot Size correlation to linear array position

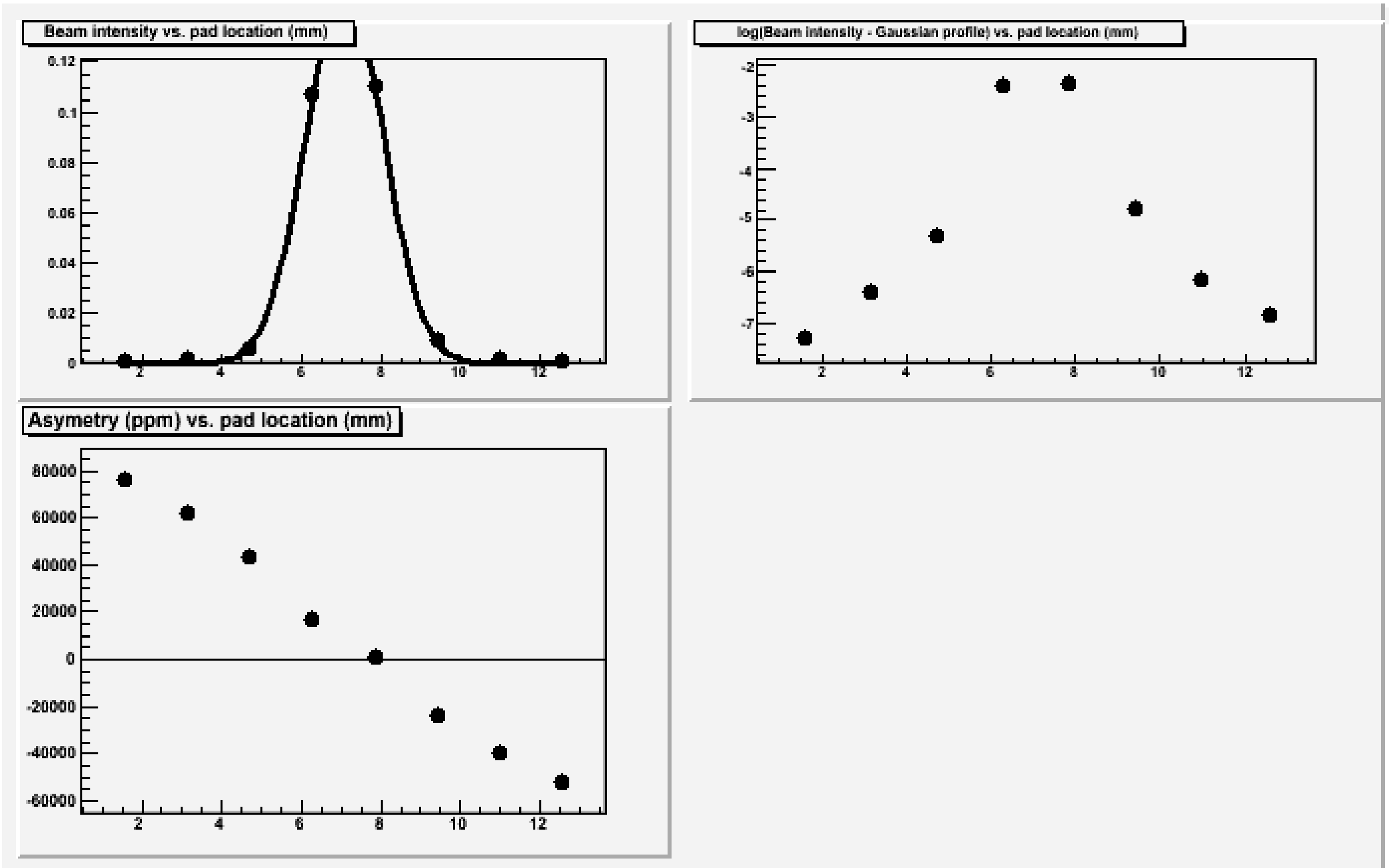
- Is the beam spot size and differences correlated to the linear array position?
  i.e. Does the rms and rms difference depend on which pad receives most of the light?
- Obviously, the answer should be NO, it should not.

Spot size variations with linear array pad position



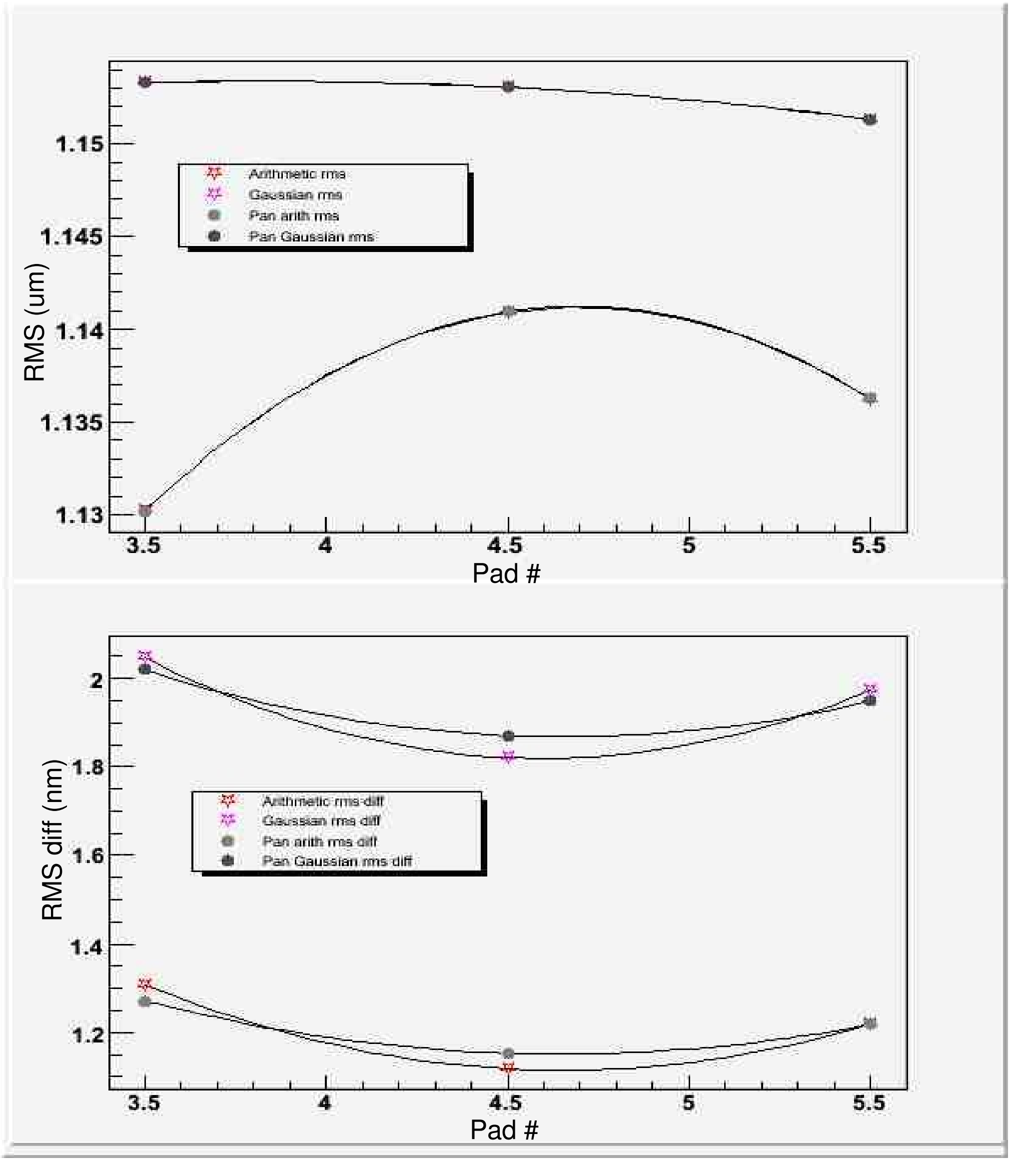
- Scan the linear array across the beam without changing any other parameters.
- Initially had pan evaluate rms using the arithmetic method. The arithmetic rms is evaluated as $\sum(x-x_{mean})^2 I_x/I$, where x is the pad position, I_x the intensity of beam on that pad, and I is the total beam intensity.
- The arithmetic rms varies ~ 3.4 %, and the rms difference increases linearly with pad position!
- Use Gaussian rms instead, which is obtained by fitting Gaussian profile to the beam intensity
- The Gaussian rms variation is ~ 1.3 % with the difference essential constant across the pad position.
- Something is wrong, either with the beam or our technique of evaluating the arithmetic rms (most likely suspect is the beam profile: beam fringes contribution)

Linear array pad beam profile



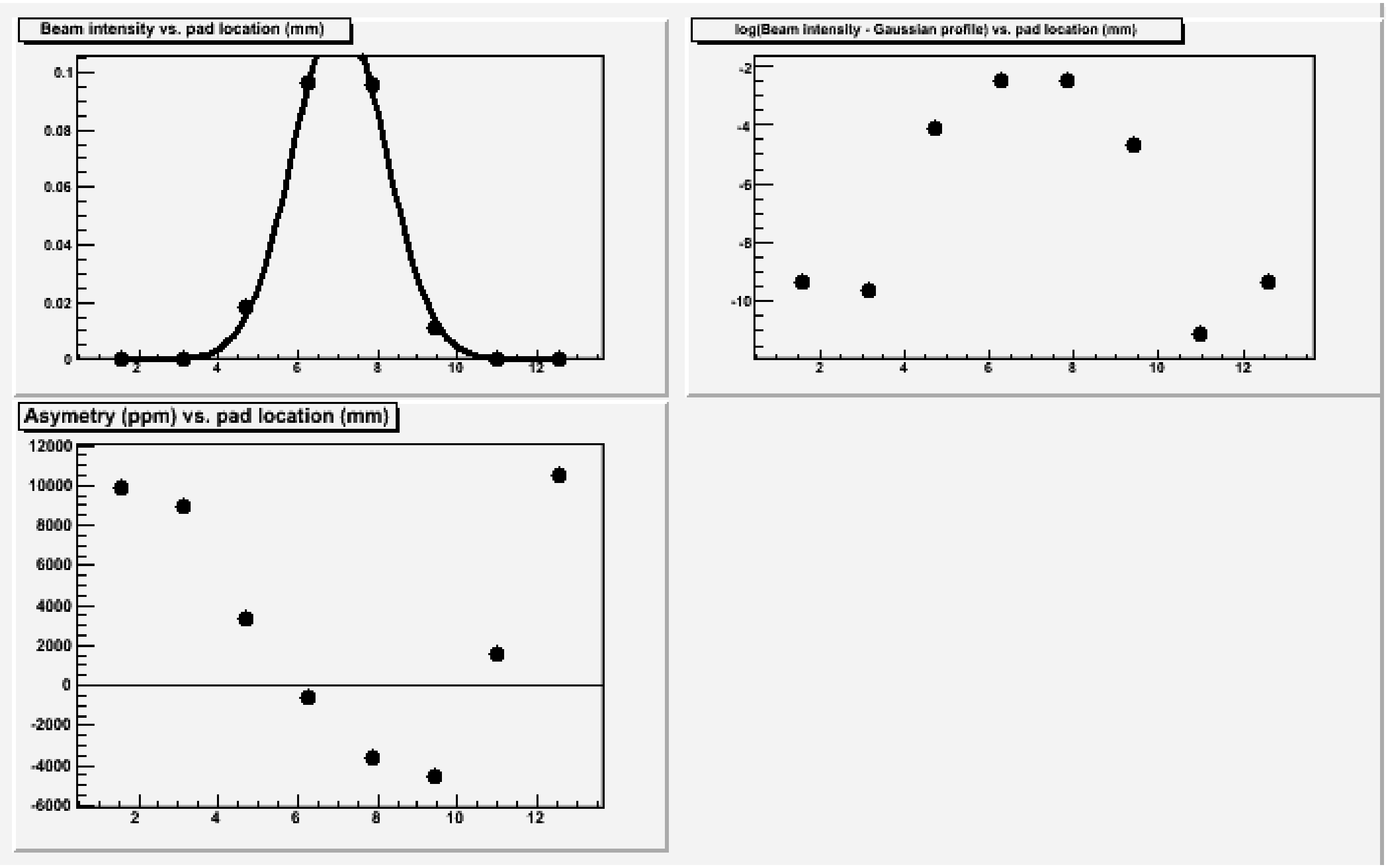
- Looks like the beam fits the Gaussian profile well, but when subtracted from an ideal Gaussian beam, the discrepancy is visible (graph on the right).
- The intensity of the tails is much bigger than we would expect of a Gaussian beam.
- These tails have huge asymmetry, as can be seen on the bottom graph.
- Even though the asymmetry is weighted by intensity on each pad, the tail intensity is big enough to contribute significantly to throw off arithmetic rms.
- Just to quantify the tail effect, the spot size is ~ 1.5 mm, Gaussian diff_rms is -3.77 um, arith diff_rms is -2.52 um with all 8 pads. If the 8th pad is removed then the Gaussian rms_diff is -3.77 um, while the arith dif_rms is 7.45 um!

Spot size variations on the linear array with a 5 mm iris immediately before the cylindrical lens



- The rms values obtained from the gaussian and arithmetic method are much closer now.
- The rms differences no longer scale linearly with the pad number!
- The arithmetic rms differences agree to within 6.1 % and the gaussian rms difference agree to within 5.1 %.

Linear array data with 5mm iris



- The tails on the Gaussian fit of the intensity across the pads fits much better now, but the beam is still not very Gaussian
- The asymmetry is at least of the same sign at the tails.
- Rms ~ 1.5 mm.
- For all 8 pads, Gaussian diff_rms is 1.82 um, arith diff_rms is 1.12 um.
- For pads 1-7, Gaussian diff_rms is 1.82 um, arith diff_rms is 1.02 um.
- Arith diff_rms still changes by 9.3 %, but much smaller than for the case without the iris.

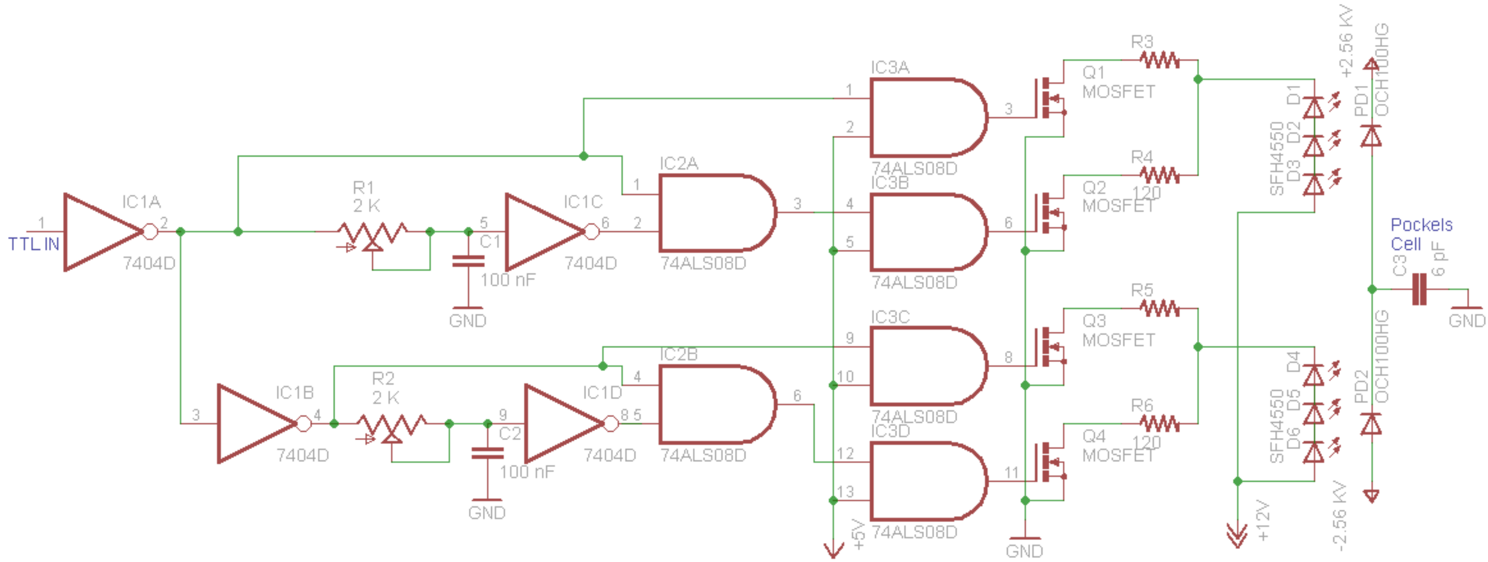
Conclusion of the spot size dependency study on linear array position

- The beam we are using is not very Gaussian. As a result, using arithmetic method to calculate the rms and position differences is misleading.
- We can still get reasonable results using the Gaussian fit to extract the beam position and spot size.
- If the beam has a lot of tail then getting rid of the tail using an iris significantly improves the beam profile, and asymmetry data.
- If the source of the fringes is PC, then it is very likely that the fringes are present on the laser setup in jlab as well.
- But the source of the fringes is very likely the filter we have used to improve the beam profile.
- Take a similar run soon enough with the laser coupled to a fiber, which should give us a much better Gaussian beam profile. Hopefully we do not see the tails anymore.

Transition time studies

- Define transition time as the net time taken by the laser beam to switch between the helicity states as observed in the detector.
- Important to study this because the degree of circular polarization (DoCP) of the laser beam leaving the PC is much smaller during transition time
- Data from the transition time window has a much larger asymmetry.
- Data from this period is unusable for precision parity-violating experiments which usually requires laser beam circular polarization of 99.99 % or better.
- Hence, there is a dead time associated with every helicity flipping.
- The old switches had a dead time of around 100 us. For PREX, which is being run at 250 Hz (500 Hz data run, with helicity flipping every 2 ms), the dead time is 5 %.
- But for QWEAK, which is being planned to run at 1000 Hz data run, 100 us would be a 10% dead time, which is unacceptably big amount of data loss.

Switch setup



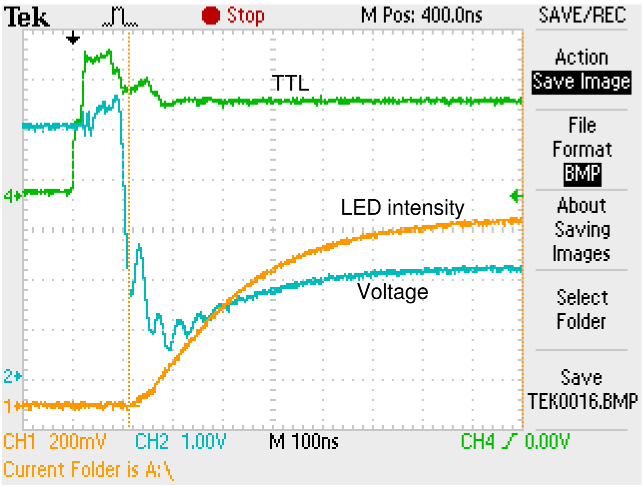
•Switch designed based on John Hansknecht's switch

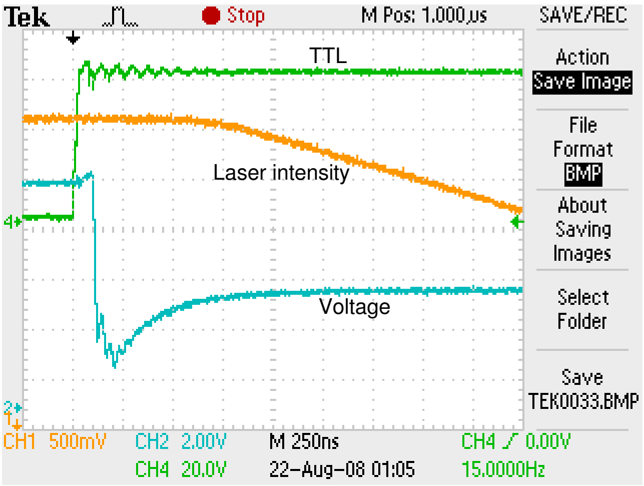
- The SFH4550 LED triplets are turned on/off based on TTL high/low.
- The optodiode only transmits current through it when illuminated by the SFH4550 LED.
- Only one optodiode is turned on during a helicity window.
- R3 and R5 are pulsed for about 20-100 us (high current pulses)
- R4 and R6 stays open for the entire TTL window (low current pulses)

Transition time contributors

- Net transition time is the sum of following:
  - Optocoupler-photodiode (optodiode) initiation time delay (i.e. time taken by the logic circuit to initiate the optodiode after receiving TTL signal)
  - response time of the optodiode (i.e time taken by the optodiode to let sufficient amount of current through it for voltage drop across PC after it receives light from the illuminating SFH4550 LEDs)
  - transition time due to the capacitance of the PC (dominant contributor)

Optodiode Initiation Time Delay & Optodiode response time





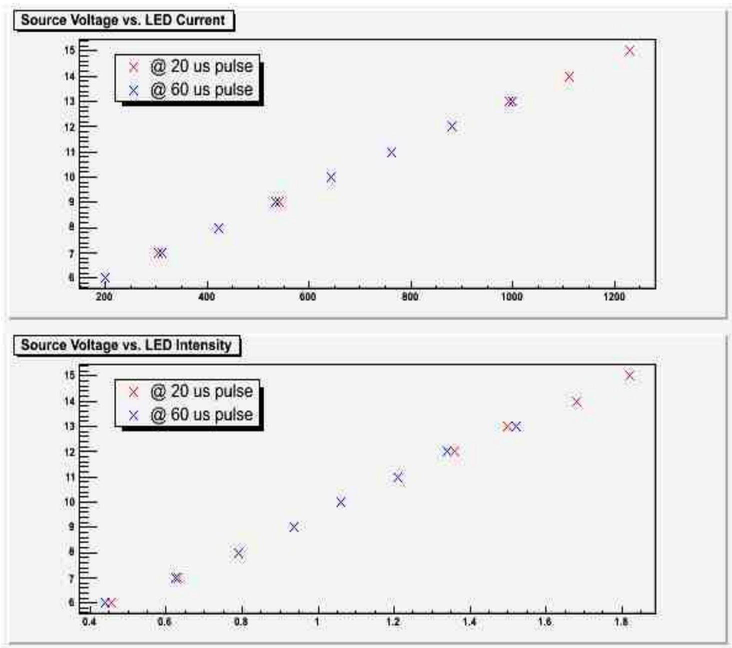
- Response time of the TTL drive circuit + SFH4550 LED response time (~ 110 ns)
- Delay between the circuit output and the start of LED light emission is about 20 ns. Considering that the detector has about 14 ns of rise time, this delay is probably smaller in actuality.

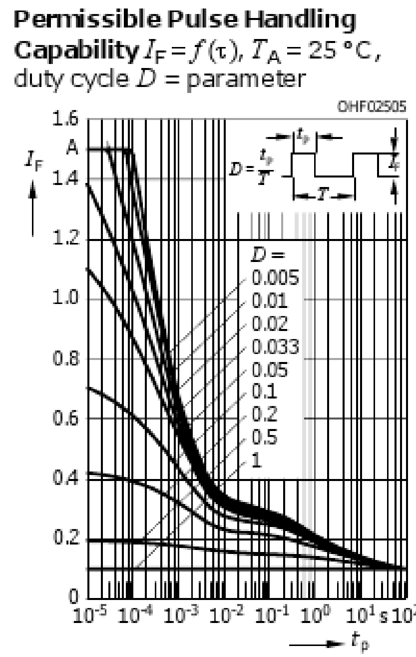
- Spec-sheet claims the response time of the optodiode to be about 2 us.
- But from the second graph, read off the response time of the optodiode < 750-110 = 640 ns.
- Delay between the arrival of TTL and the initiation of laser intensity change ~ 750 ns.

PC transition time contribution

- Response time of the PC is < 350 ps
- So the dominant contribution to the transition time from PC is due its capacitive delay given as
  - $\Delta\tau = \Delta V * C/I$
- C ≈ 6 pF is the total capacitance of the PC (≤ 5 pF) and the wires
- ΔV = 5.12 KV is the total voltage change across the PC during helicity flip
- I is the current through PC (the same as the reverse leakage current through the optodiode, and is determined by the quantity of illumination from SFH4550 LED)
- C and ΔV depend on the PC material and laser beam wavelength, so not adjustable
- Can reduce Δτ by maximizing I
- So need to pump as much light out of SFH4550 without burning it out, or at least illuminate the optodiode maximally without saturation.

SFH4550 LED characteristics

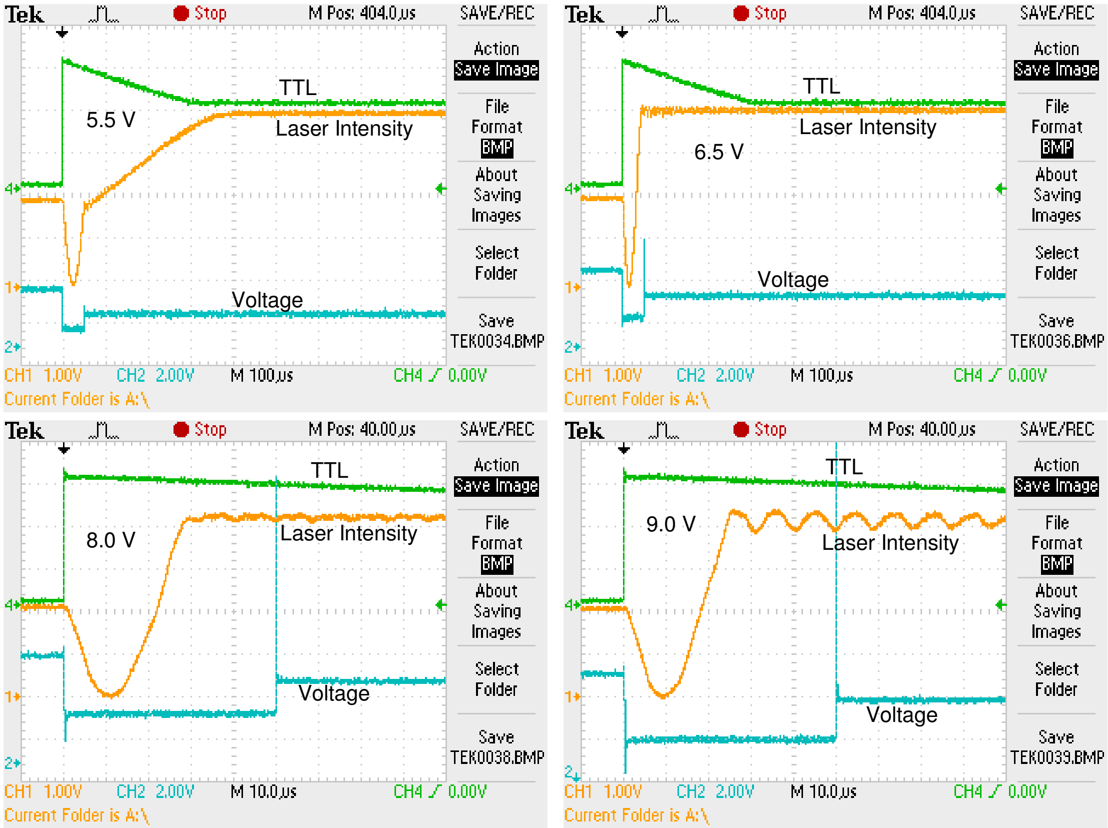




The current is measured across the resister/MOSFET (~5.1 Ω) on the pulsed line. Measurement of intensity is carried out on only one LED in one of the LED lines.

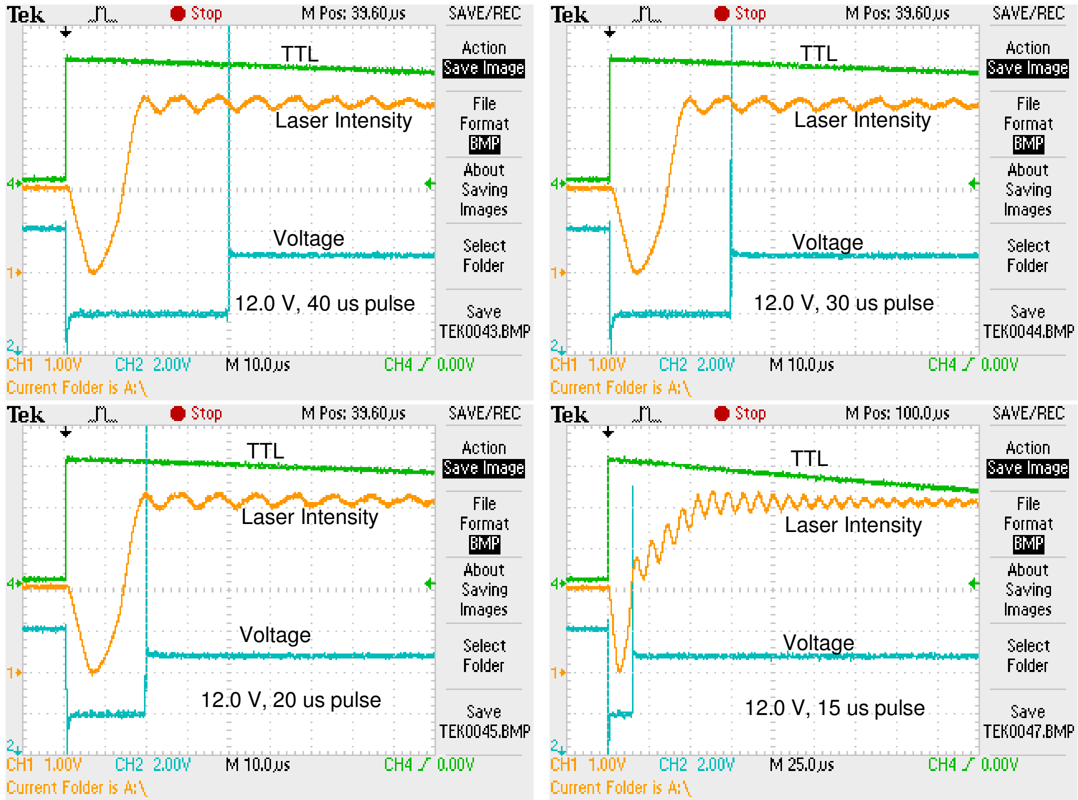
- The intensity produced by LED is limited by its threshold of thermal damage, which is summarized in the graph on the right for SFH4550
- At 15 Hz, the maximum current SFH4550 can handle for pulse length ≤ 100 us is 1.5A
- The LED current scales linearly with the applied voltage. It does not roll off or burn out within the investigated range.
- The LED intensity scales linearly with the applied voltage.
- Changing the pulse length does not change the LED behavior, which is what we expect to see.

Maximizing current through the LED



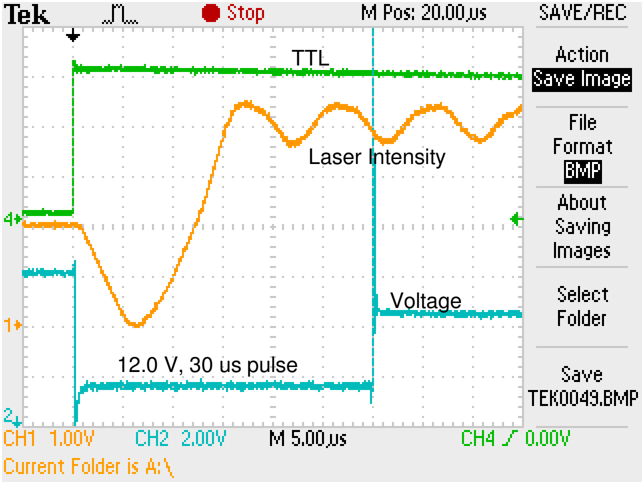
- The transition time decreases as we increase the LED pulse current
- There is a lot of ringing as the current is increased.

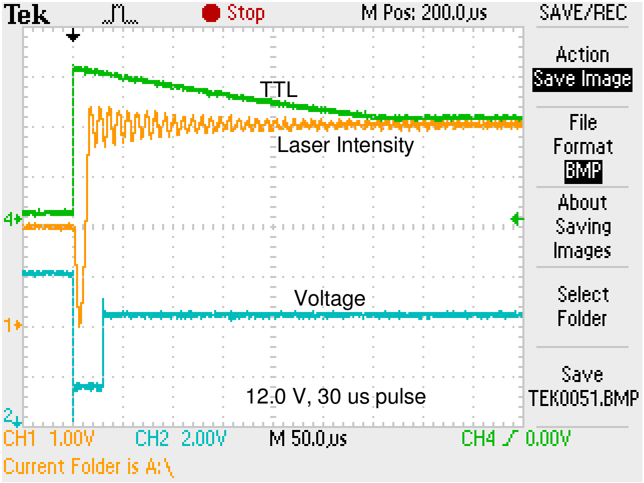
Can the pulse length be decreased without affecting the transition time?



- As long as the pulse length is long enough to drive complete transition, it does not matter how long or short the pulse length is.
- Looks like the transition time decreases as the amount of light illuminating optodiode is increased.

4-LED switch





- The transition time does go down from 20 us to about 17 us with this switch. More light on the optodiode decreases the transition time.
- But there the ringing gets worse as the optodiode is hit harder as well.

Conclusion of the transition time studies

- With this switch, the transition time can be driven to as low as 17 us (possibly lower), which is a significant improvement over the 100 us time scale with older switches used in jlab.
- The total contribution to the transition time from the logic switch and optodiode initiation delay is only about 750 ns, and the rest is due to PC capacitive delay.
- So, if we were to add another line of optodiode in parallel, effectively doubling the current through PC, then the transition time would be reduced by a factor of 2!
- Ringing of the PC is usually not a problem since we integrate the data for each helicity window, and usually modulate TTL in random mode. But, if it does turn out to be problematic, one solution is to try to ramp the pulse current through SFH4550 led, so that it is not driving the optodiode as hard.