CVD diamond sensor research at ETHZ

Dmitry Hits

ETH Institute for Particle Physics

Outline

- Why diamond is a good detector
- Examples of application of diamond detectors
- Diamond detector research at ETH

Why use diamond as detector

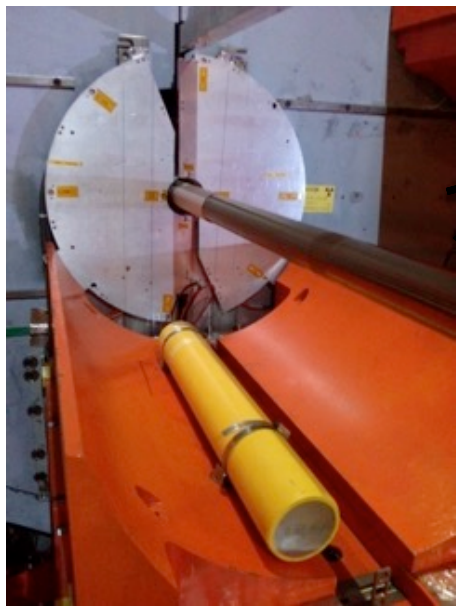
- Intrinsic Properties
  - High thermal conductivity (good heat spreader)
  - Wide band gap (no thermally generated noise)
  - Large single atom displacement energy (radiation hardness)
  - Large mobility and large saturation velocity (fast signals)
- Device Advantages
  - Intrinsically simple device
    - ➡ can fabricate robust, compact devices
  - High temperature operation (no need for cooling)

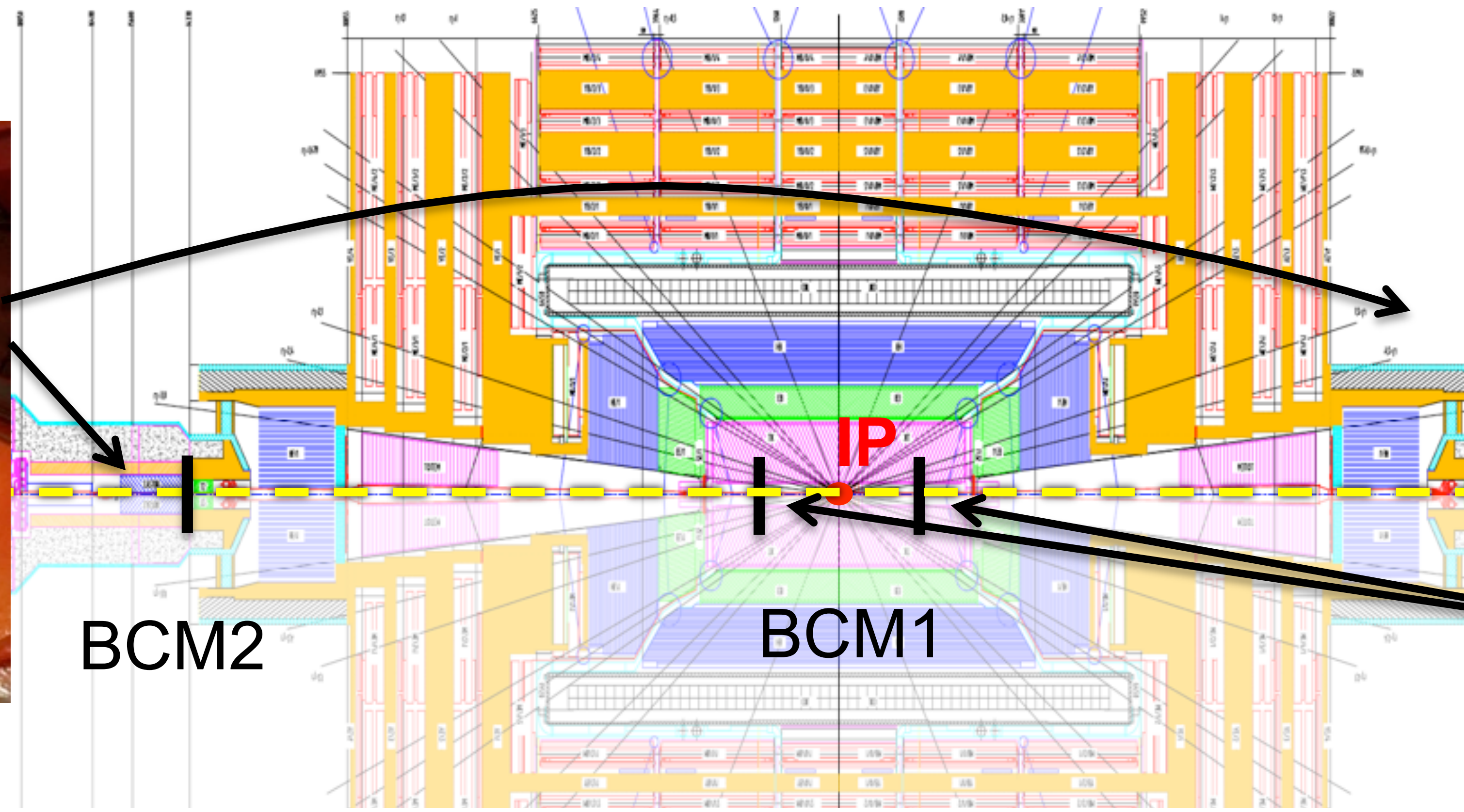
Why aren't we all use diamonds

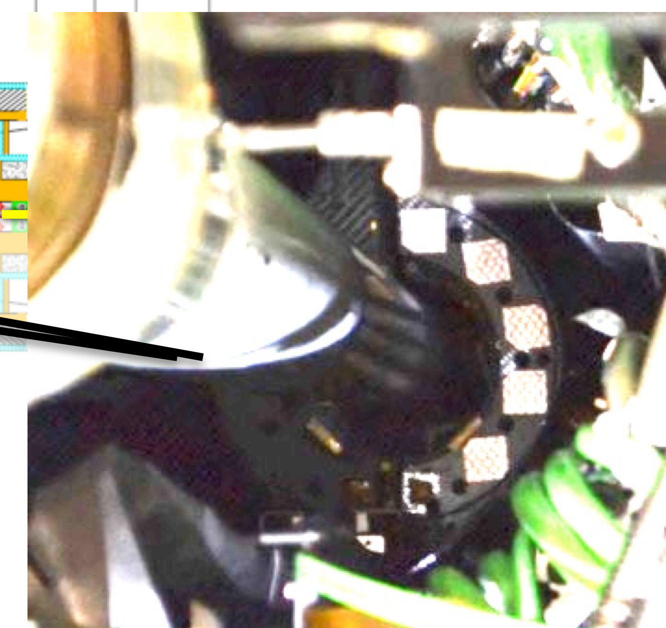
- Electronic grade diamond is still a "research" type device
  - Production is expensive
  - Good quality samples are scarce and selecting them is not an easy process
  - Electronic properties are not fully understood
    - ➡ for example, it is very difficult to precisely simulate impurities in diamond

Few examples of where diamond detectors are used

Pad Diamonds at CMS





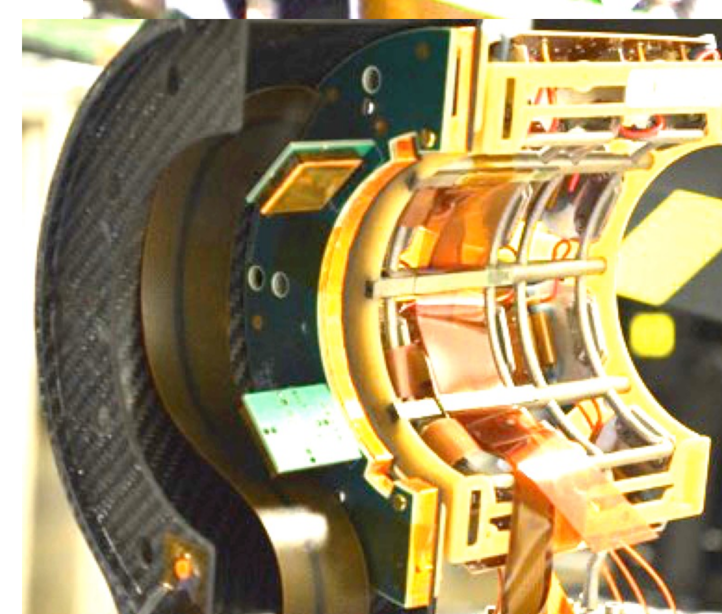


BCML(1/2)

- Leakage current measurement.
- Beam loss monitoring for
  - active protection
  - Short intense events monitoring
- Readout identical to LHC BLM system.
- 16 10x10mm² pCVD diamonds

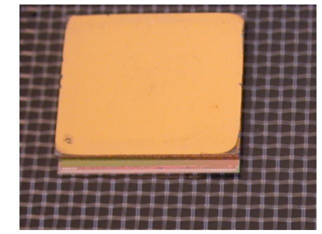
BCM(1)F

- Single particle counter.
- Histograms particle hits in time domain
- Luminosity and beam gas measurement.
- 14 5x5mm² diamonds (4 sCVD 10 pCVD)

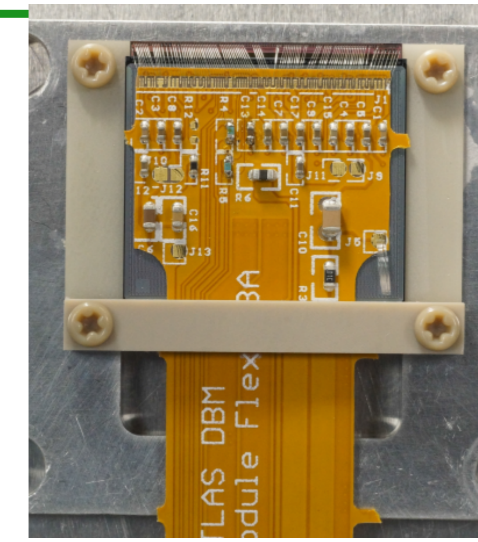


Pixelated Diamonds at ATLAS

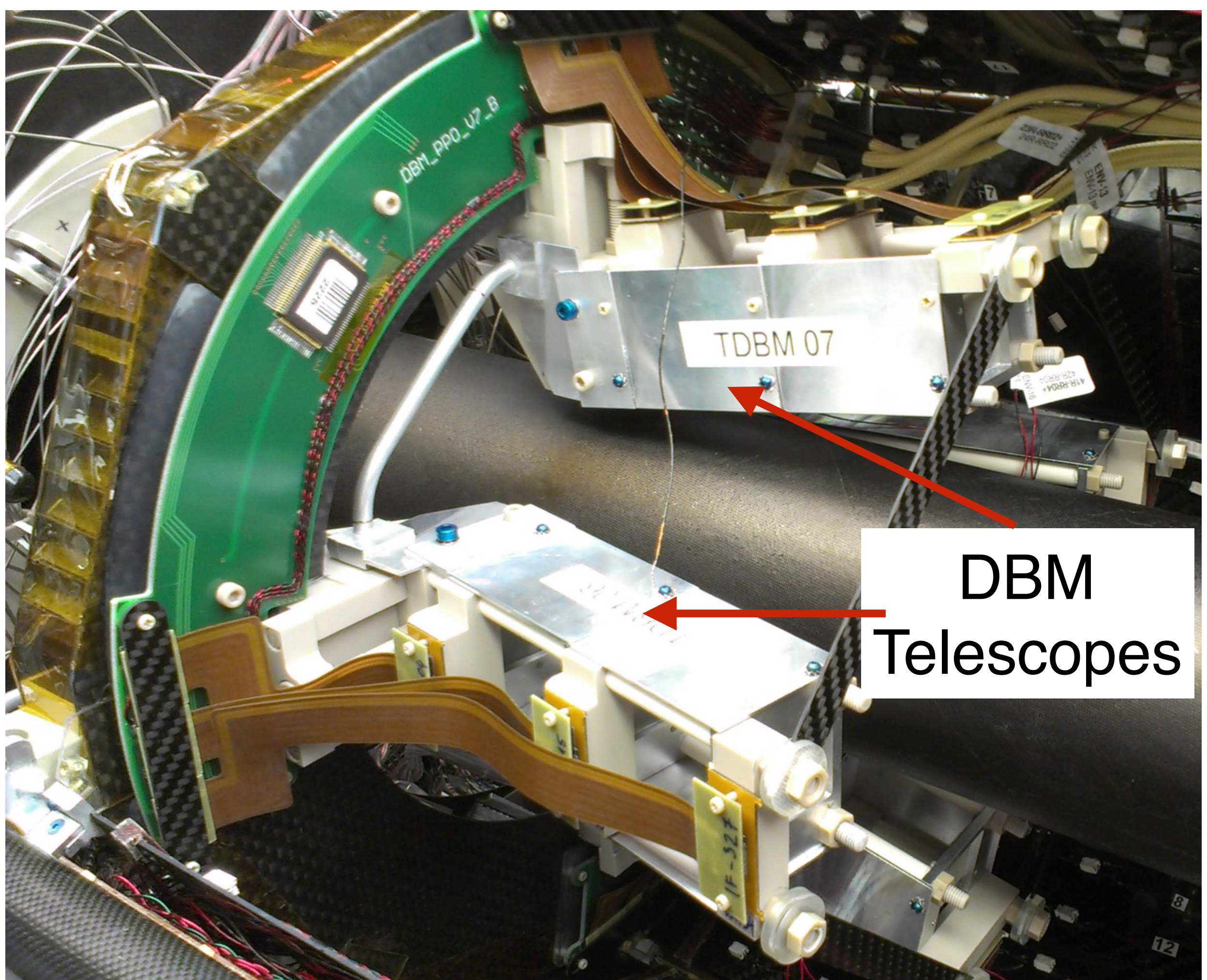
- Diamond Beam Monitor (DBM)
  - 8 Telescopes (4 per side) 24 modules total
  - 18 equipped with pCVD 20 x 20 mm^2 diamond sensors
  - Bunch by bunch luminosity monitoring with <1% precision per bunch per lumi block
  - bunch by bunch beam spot monitor



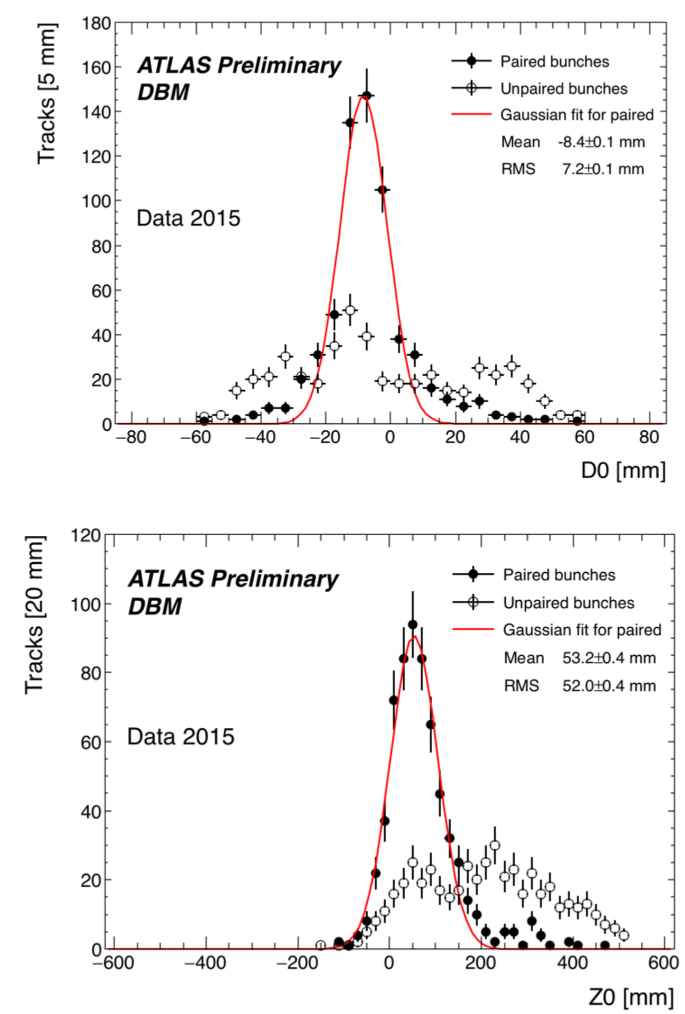
pCVD diamond bump-bonded to FE-I4 chip



DBM Module



Beam spot reconstruction

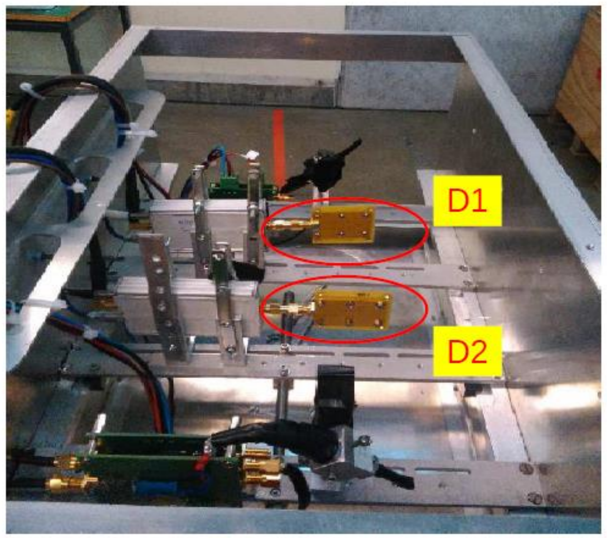


radial

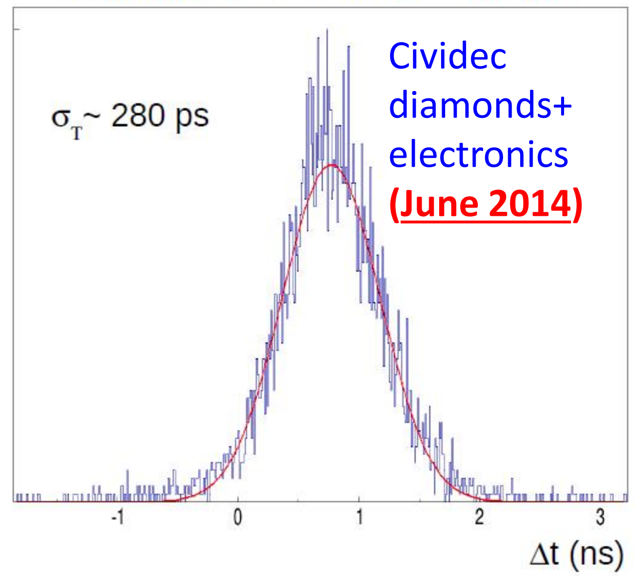
longitudal

Diamonds for timing in TOTEM

Two diamonds detectors ~4mm x 4mm, 500µm thick

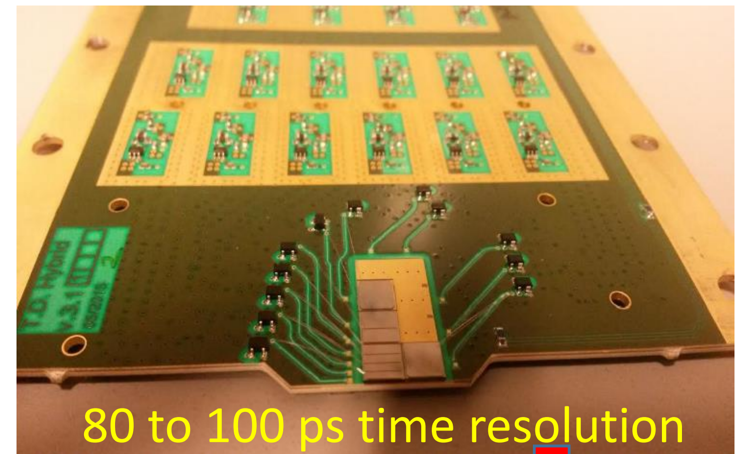


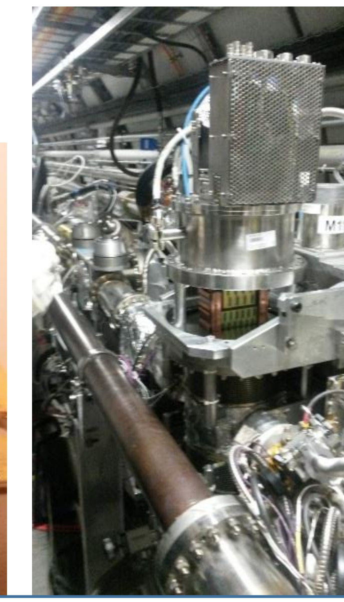
Time difference between the 2 detectors



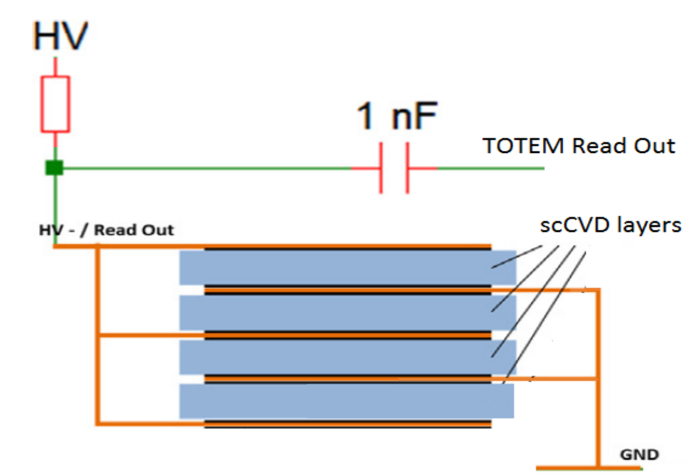
Cividec diamonds+ electronics (June 2014)

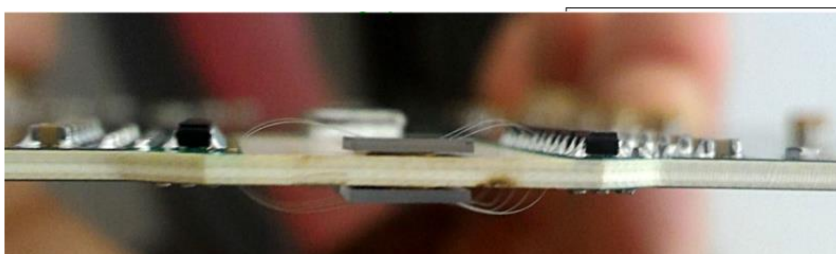
Final vertical diamond plane with achieved time resolution (End 2015)

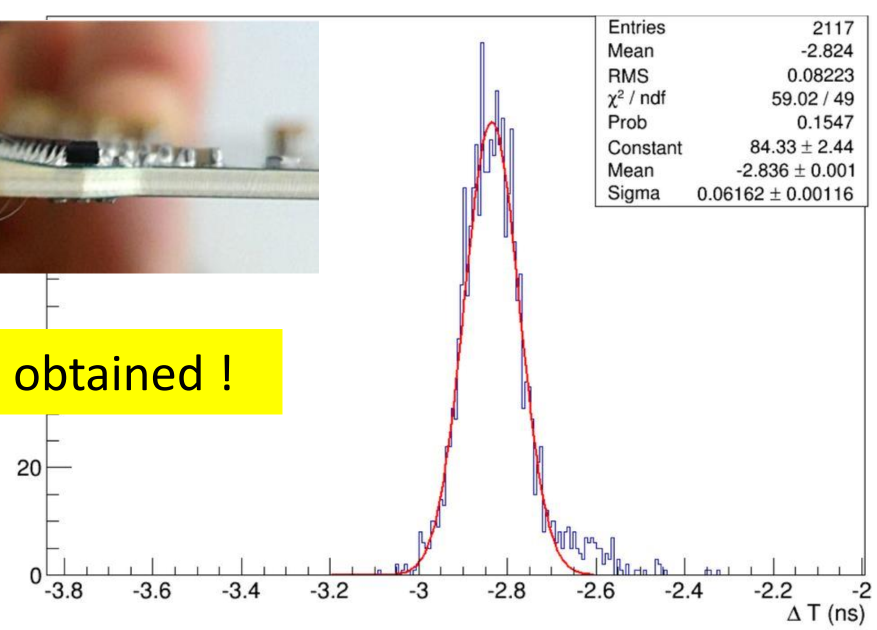




Development of a double layer geometry (End 2016)



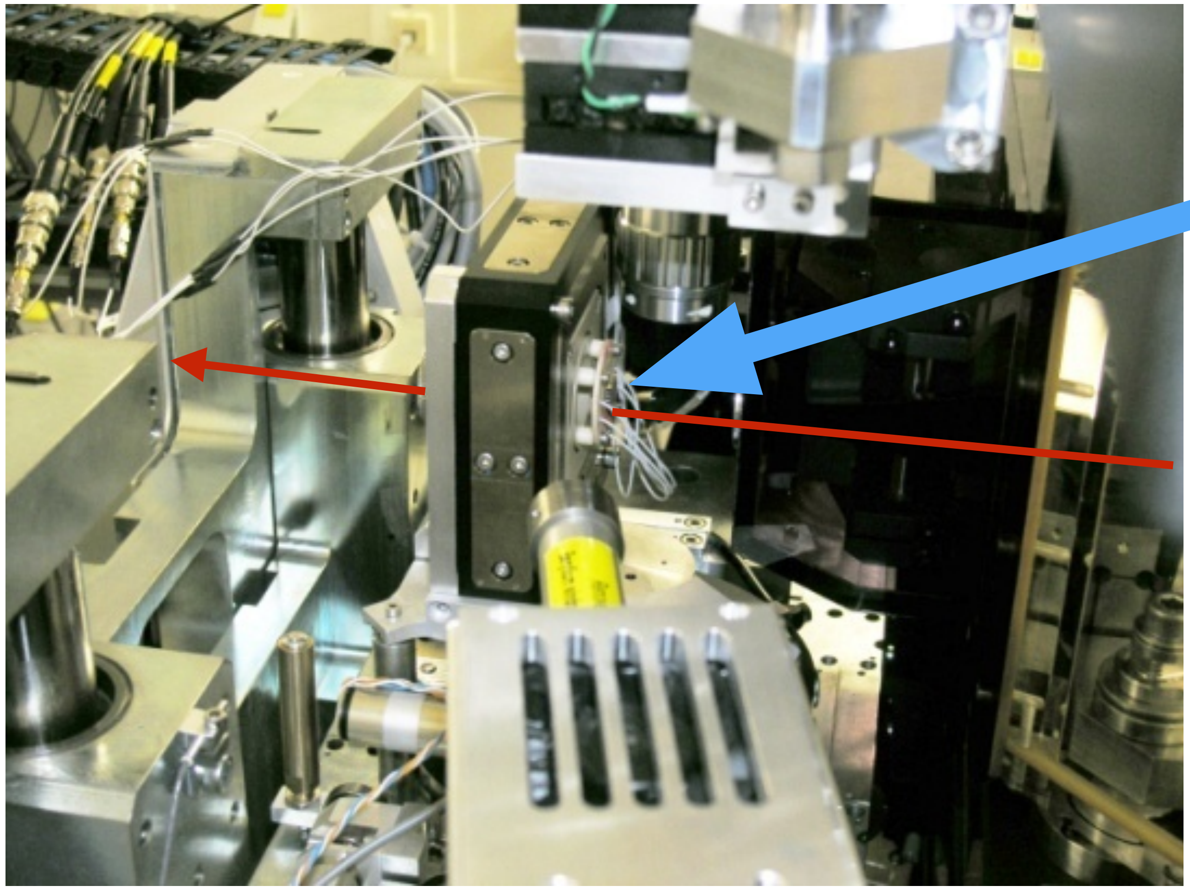


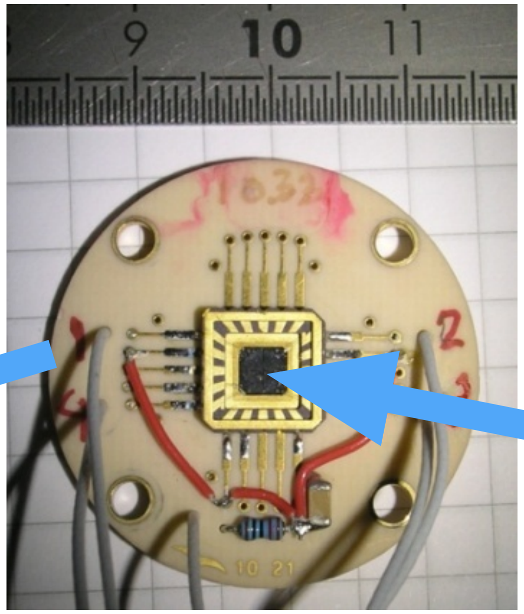


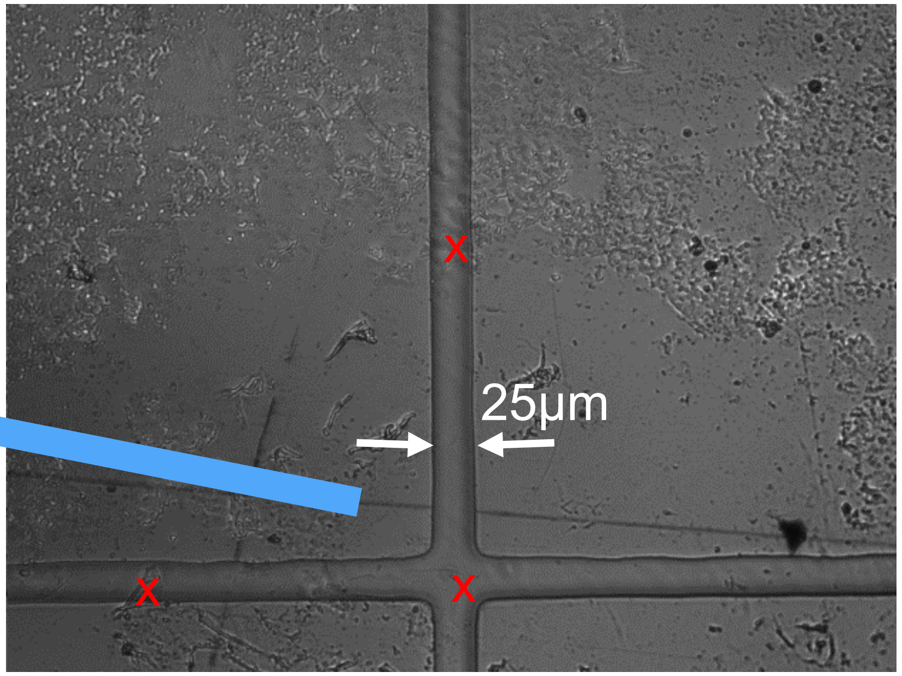
σ_T ~ 50 ps/plane obtained !

Diamonds for X-rays at ESRF

ID22 nanofocus beamline,
5-6 Sept 2012:



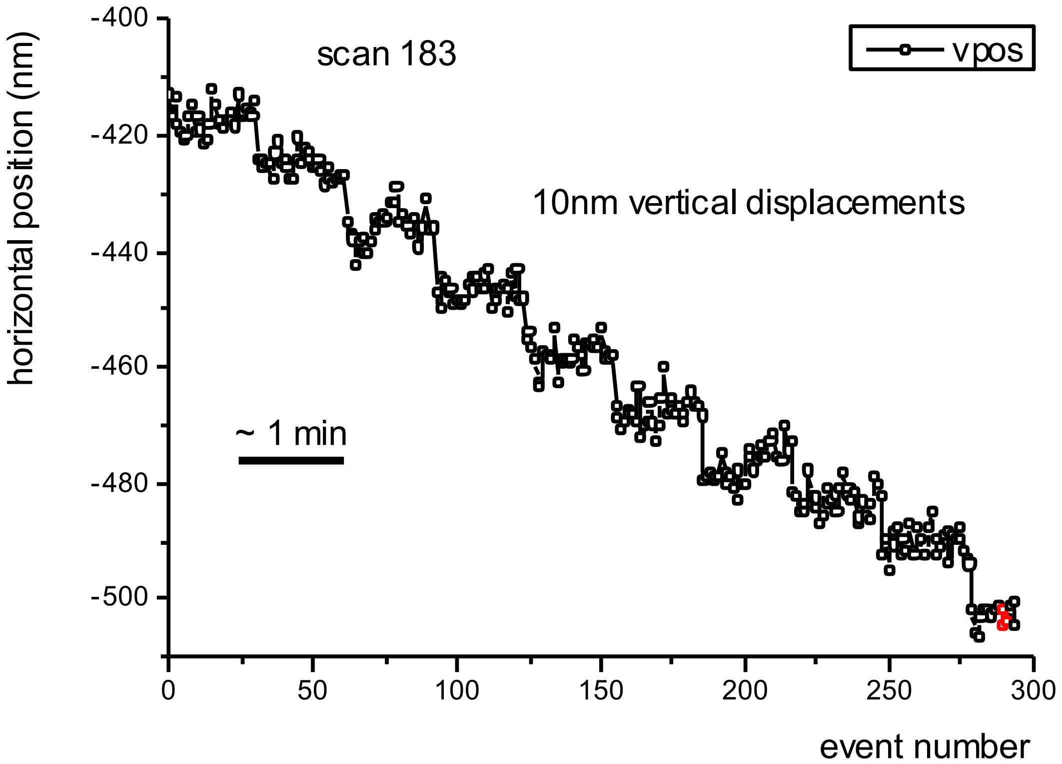




17keV, flux 2.5x 10^9 ph/sec

~50 nm beam spot on diamond detector

diamond piezo stage
step-displaced vertically:
10nm steps clearly visible



from J. Morse presentation at ADAMAS workshop (2012)

Diamond detector research at ETH

- Radiation hardness study
- Study of detector response at various rates
- Study a new (more radiation tolerant) device concepts
  - 3D diamond detectors
- Study of transport properties of diamond sensors
  - edge-TCT with femtosecond laser
- Developing in house methods for constructing diamond detectors

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Study of the radiation hardness of CVD diamonds

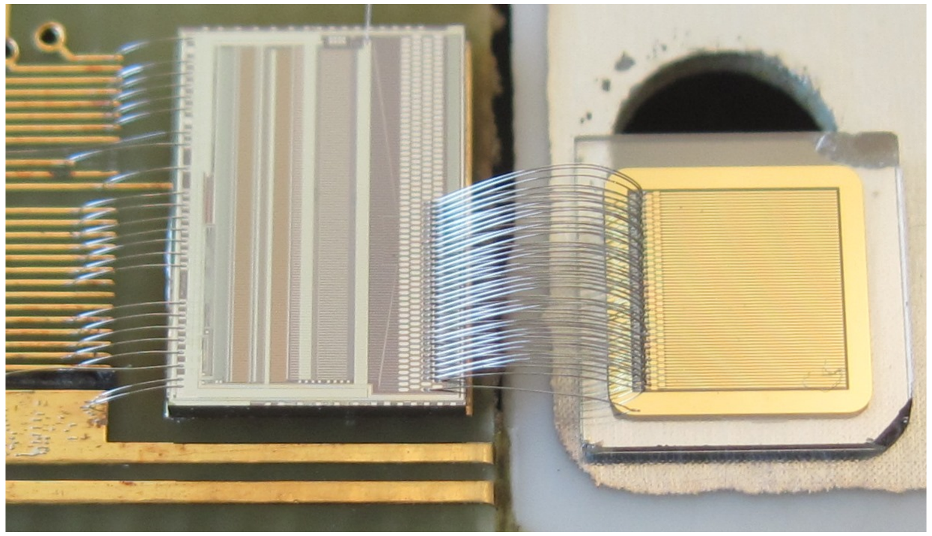
Diego Alejandro Sanz Becerra (present)

Felix Bachmair, Lukas Bäni (past)

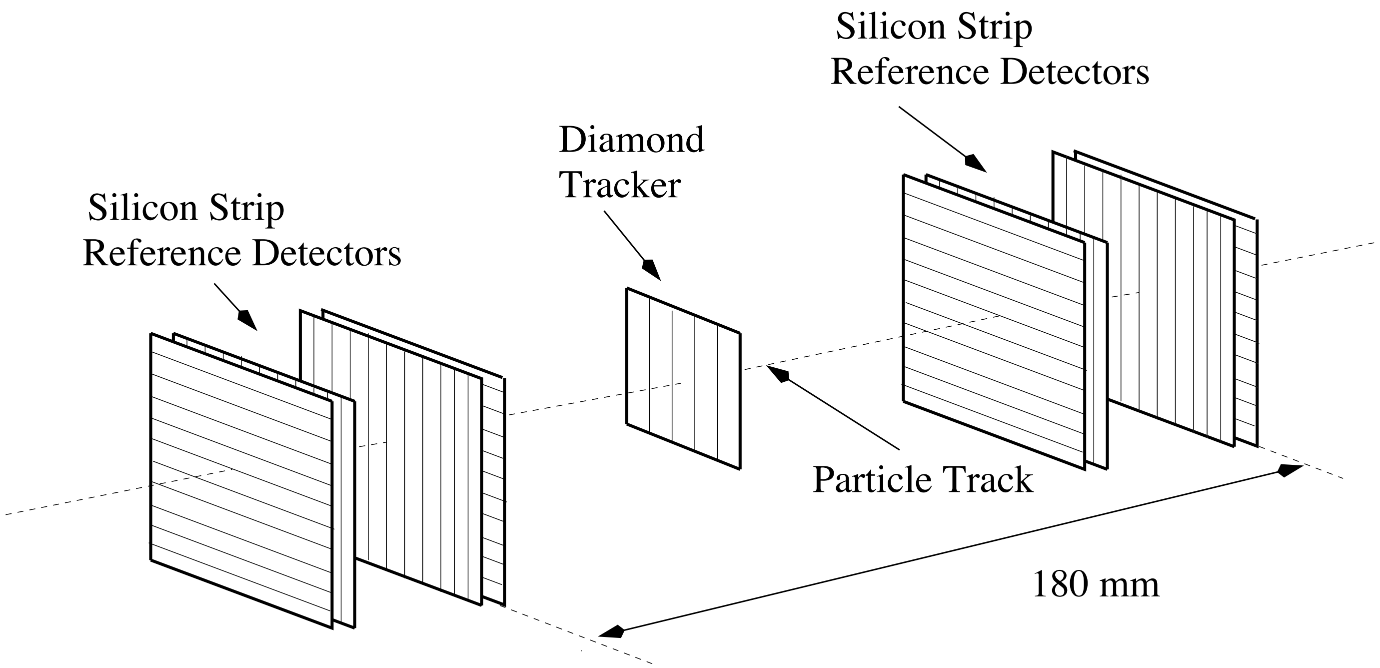
ETH Institute for Particle Physics

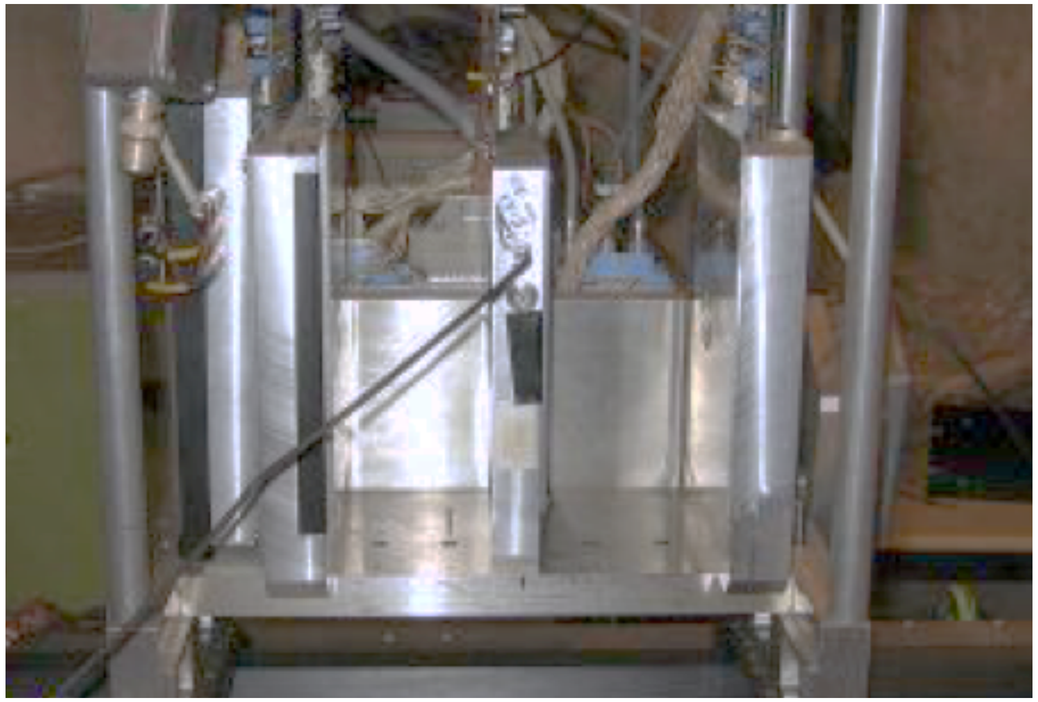
Testing of radiation hardness of CVD diamonds

- Samples are irradiated prior to the measurement
  - 25MeV, 70MeV, 800MeV and 24 GeV protons
  - reactor neutrons
- On each sample a strip detector is build with a low noise VA2 readout
  - Noise is only 80 electrons after common mode subtraction
- Samples are pumped to fill the active traps before the test
- Relativistic charged particle beam
  - CERN SPS beam line 120 GeV protons or pions
- Beam telescope reconstructs particle tracks and predicts their impact position in the device under test with ~2 μm precision



Diamond strip detector
wire bonded to VA2 readout





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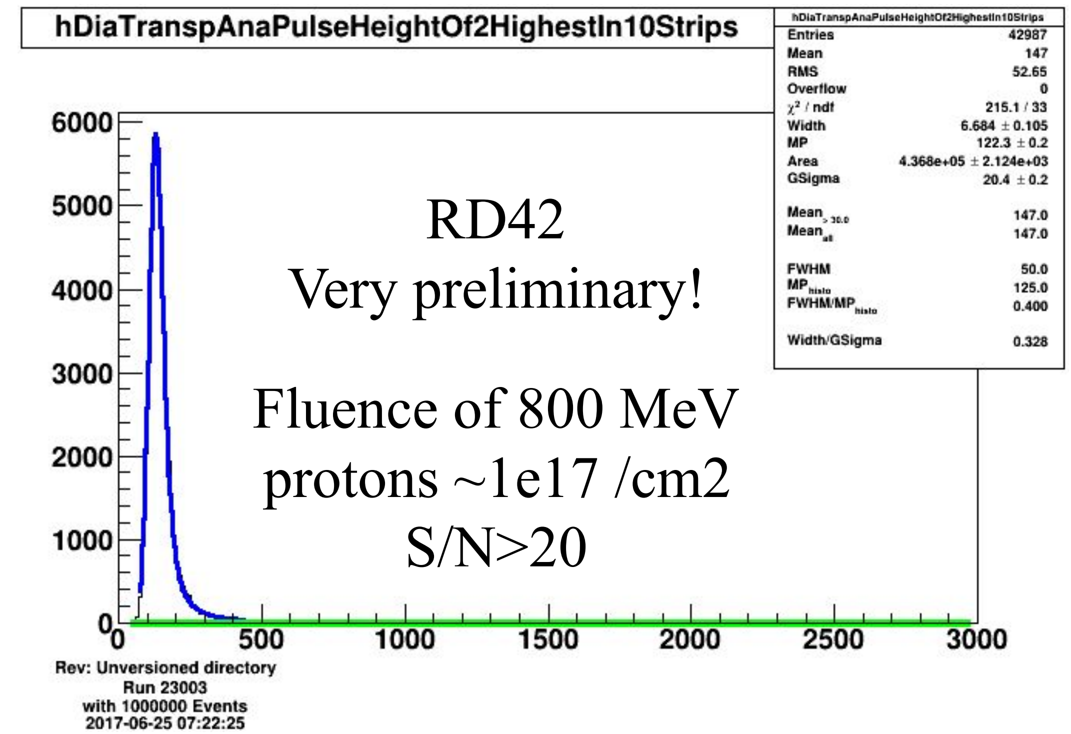
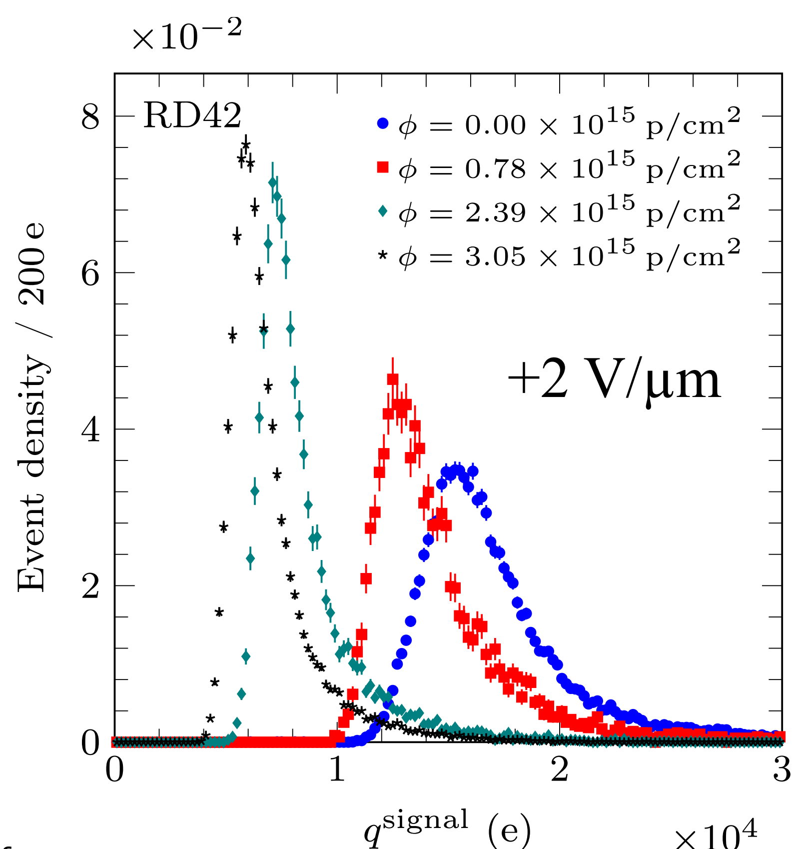
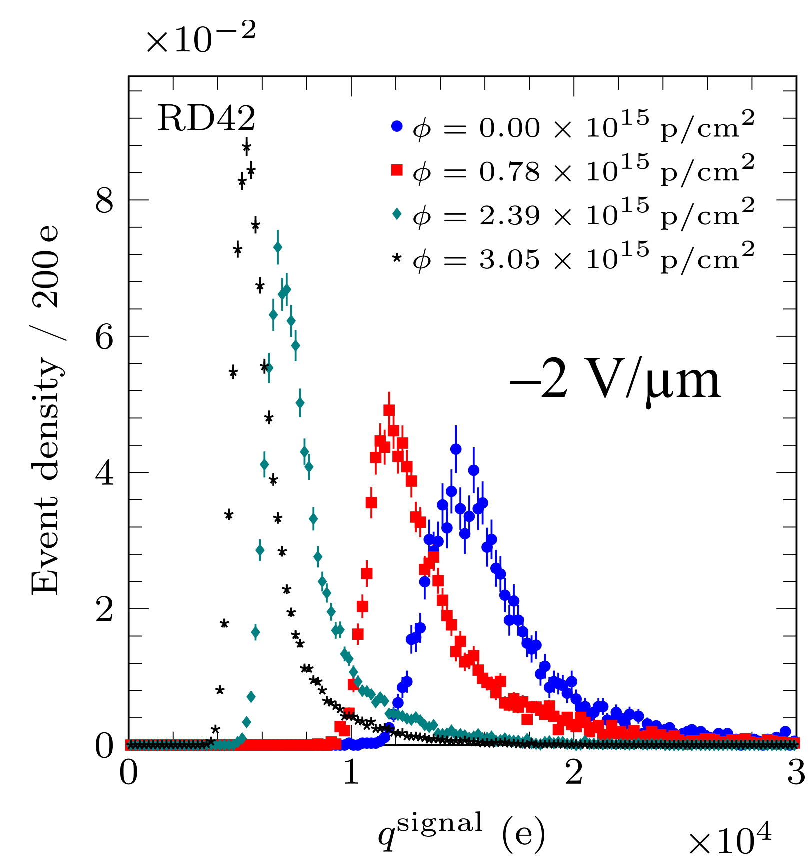
Radiation hardness

- Transparent analysis
  - After telescope alignment and pedestal subtraction
  - Look in the 10 strips closest to the hit position
  - Select 2 neighboring strips with the largest charge
- The CCD is deduced from the Landau mean

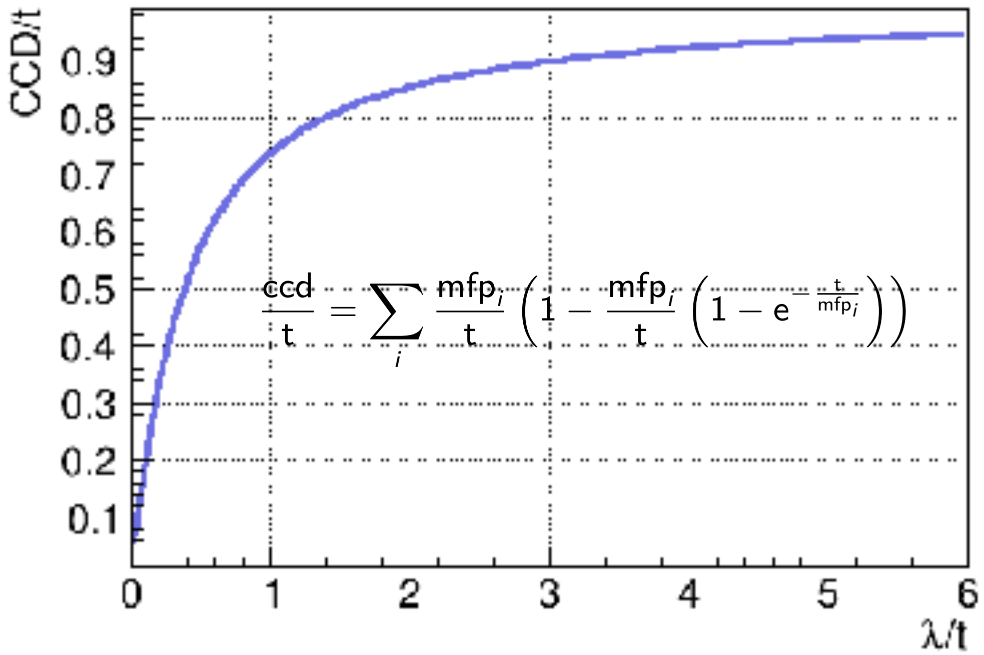


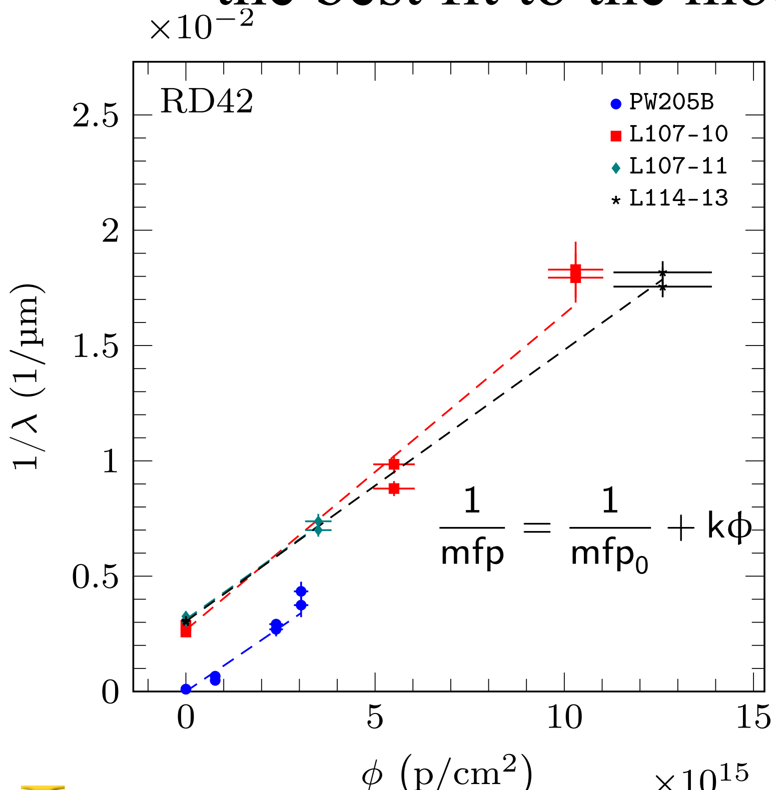


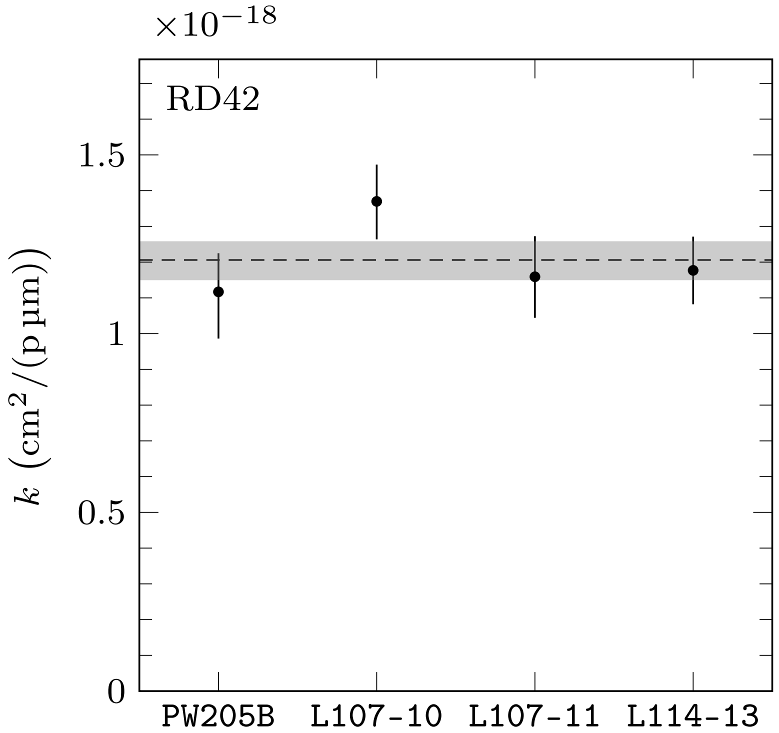


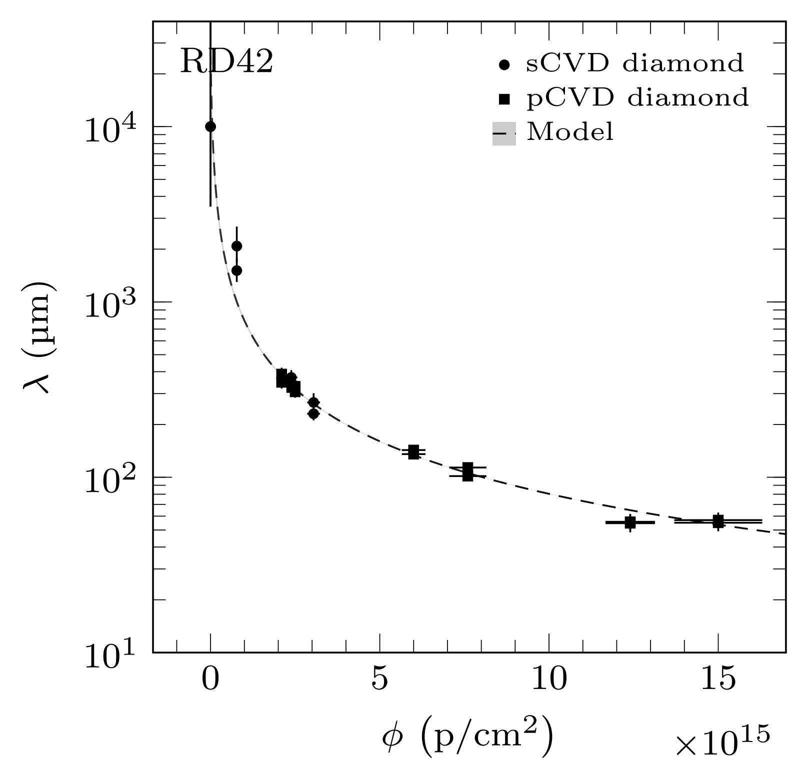
Radiation hardness (800 MeV protons)

- Convert CCD to mean free path
  - $$\frac{\text{ccd}}{\text{t}} = \sum_i \frac{\text{mfp}_i}{\text{t}}\left(1 - \frac{\text{mfp}_i}{\text{t}}\left(1 - e^{-\frac{\text{t}}{\text{mfp}_i}}\right)\right)$$
- Fit mfp vs fluence for each sample individually
  - $$\frac{1}{\text{mfp}} = \frac{1}{\text{mfp}_0} + k\phi$$
- Damaged factor is average between all samples
- The initial "damage" offset for pCVD diamonds is adjusted individually to provide the best fit to the model



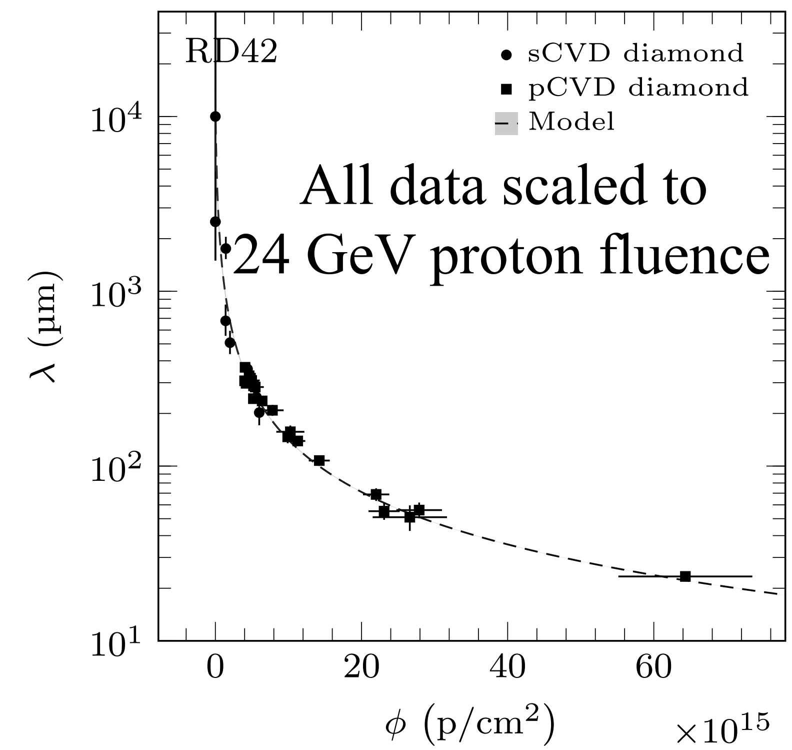




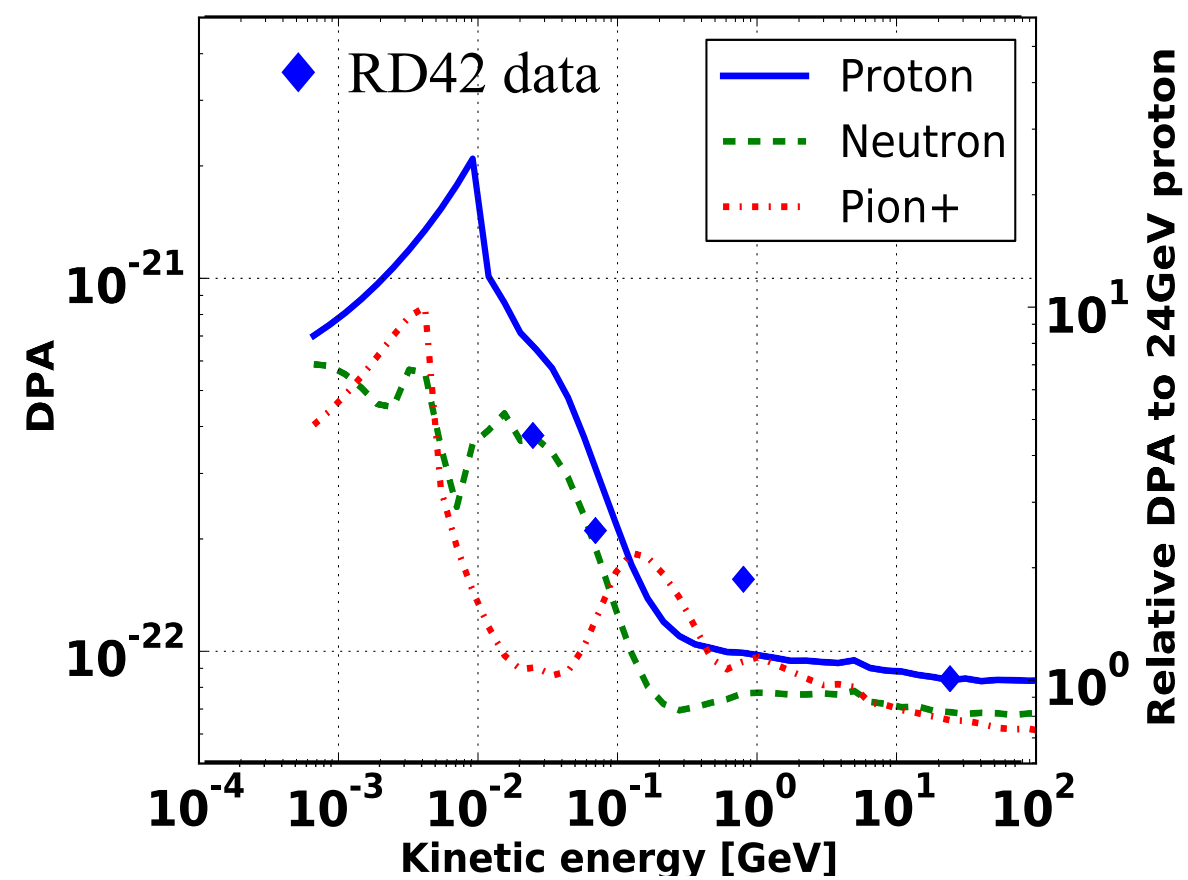


Summary of radiation hardness tests

Particle species	k (cm^2/µm)	κ
24 GeV protons	$0.67\,^{+0.04}_{-0.04} \times 10^{-18}$	1
800 MeV protons	$1.24\,^{+0.04}_{-0.04} \times 10^{-18}$	1.85 ± 0.13
70 MeV protons	$1.64\,^{+0.25}_{-0.27} \times 10^{-18}$	2.5 ± 0.4
25 MeV protons	$3.02\,^{+0.42}_{-0.36} \times 10^{-18}$	4.5 ± 0.6
Fast neutrons	$3.05\,^{+0.27}_{-0.27} \times 10^{-18}$	4.5 ± 0.5



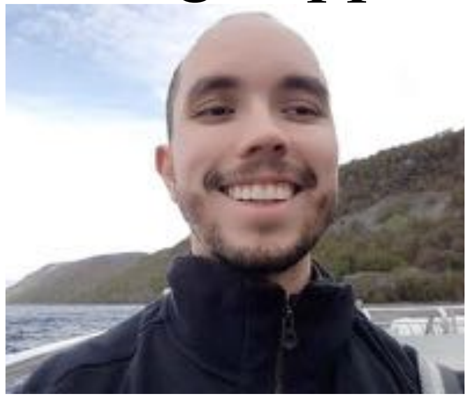
- Lukas Bäni and Felix Bachmair PhD theses
- Damage constants do not seem to follow theoretical models



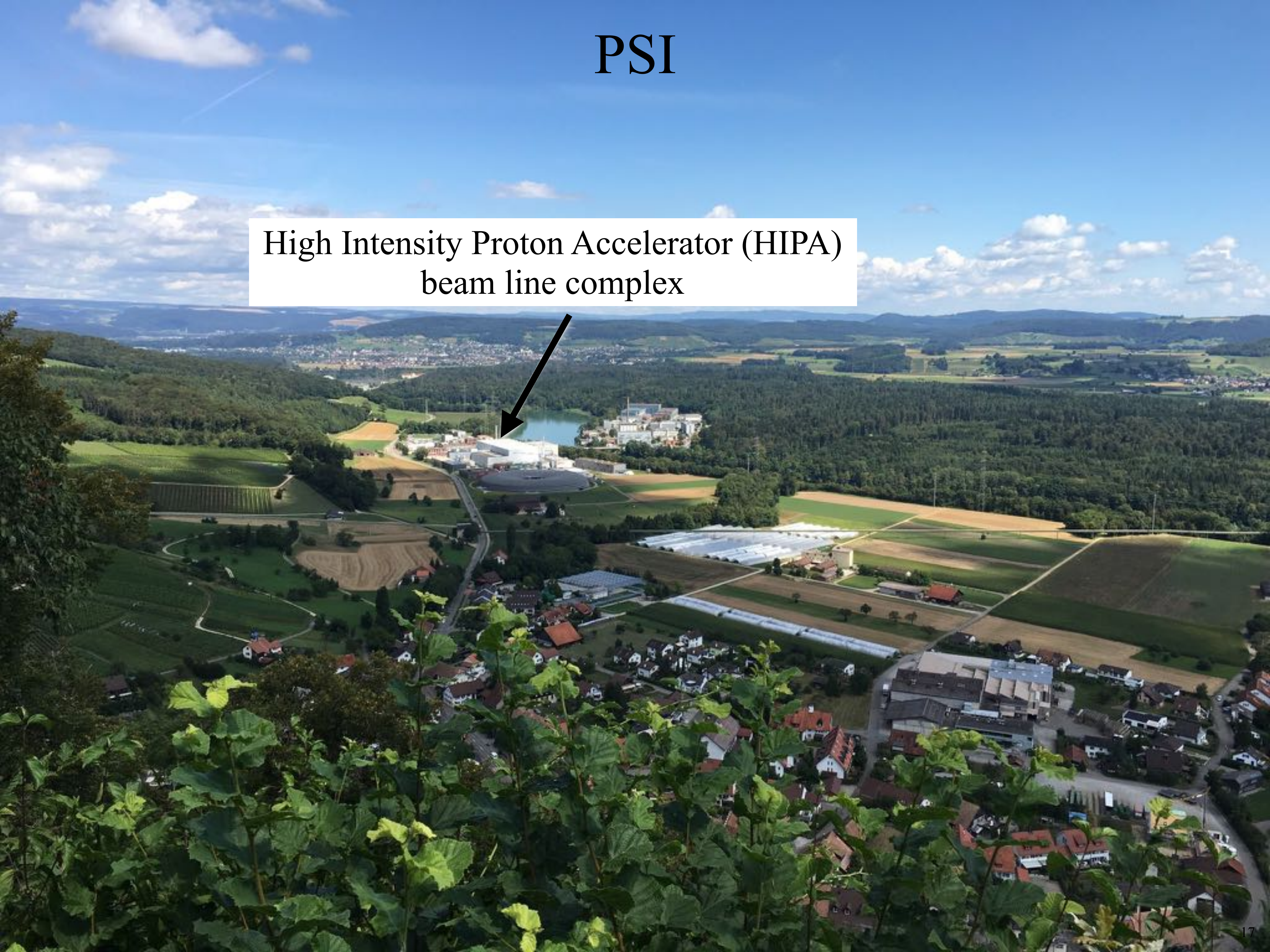
High rate tests at PSI

Micha Reichmann

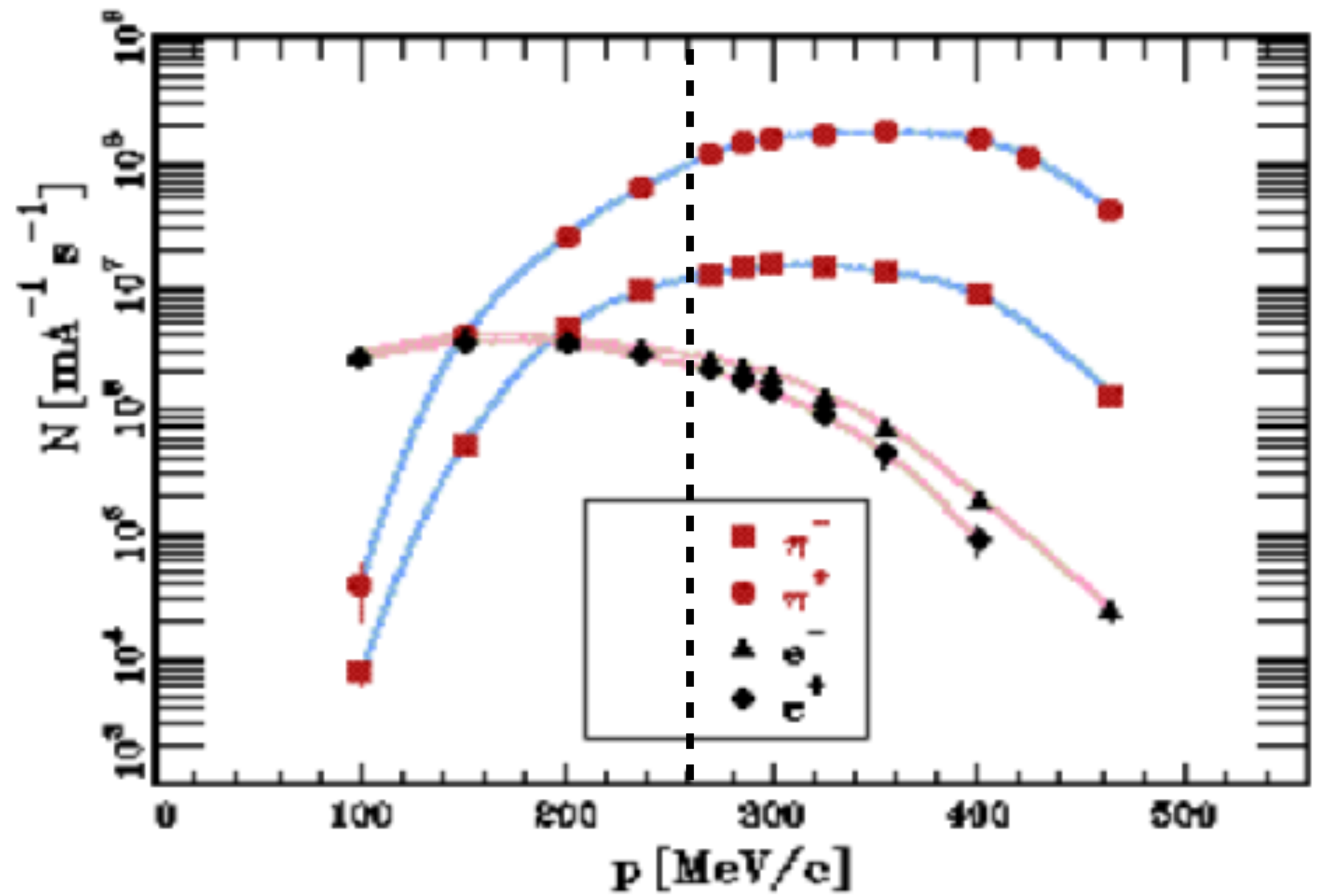
With a strong support from the rest of the crew



PSI



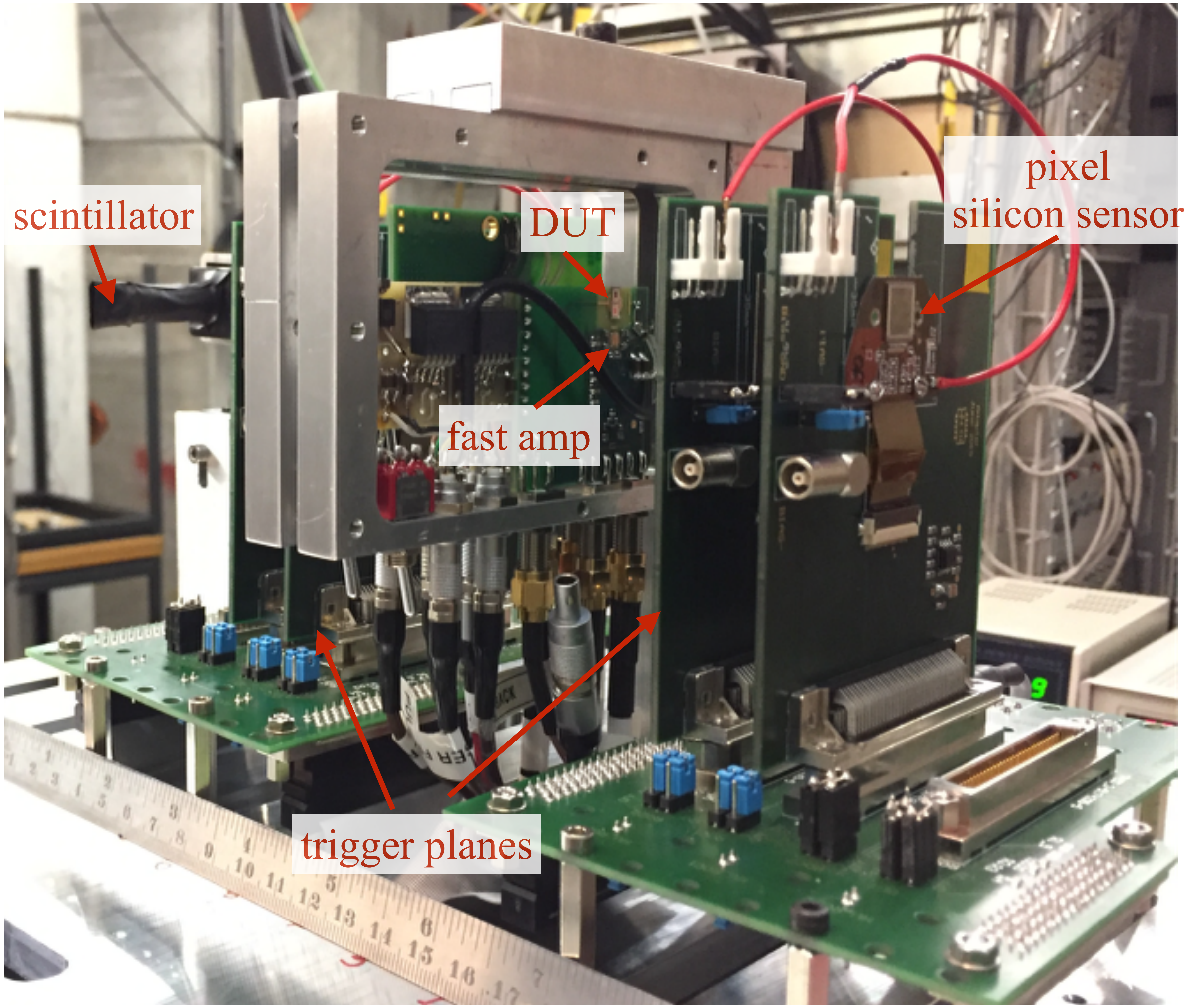
Beam conditions



- PSI HIPA accelerates ~10^{16} protons/sec to 590 MeV on two fixed targets ((É)paisse and (M)ince)
- πM1 beam line with beam optics tuned to π+ at 260 MeV/c
- Rate controlled with two sets of collimators from 2 kHz/cm^2 to 10 MHz/cm^2

Test setup (pads)

- Modular reconfigurable telescope
  - 100 μm x 150 μm pixels
  - 4 tracking planes
    - up to 6 possible
  - inner tracking planes provide masked trigger
  - coincidence with scintillator for precise ~ 1 ns event timing
  - ~70 μm position resolution at PSI
    - limited by multiple scattering
- 2 detectors under test
  - 5 mm x 5 mm CVD diamonds, thickness 500 μm
  - pulse height amplified by fast CERN/OSU amplifier (a.k.a. CVDFE1), 3-6 ns rise time, pulse goes in under 20 ns



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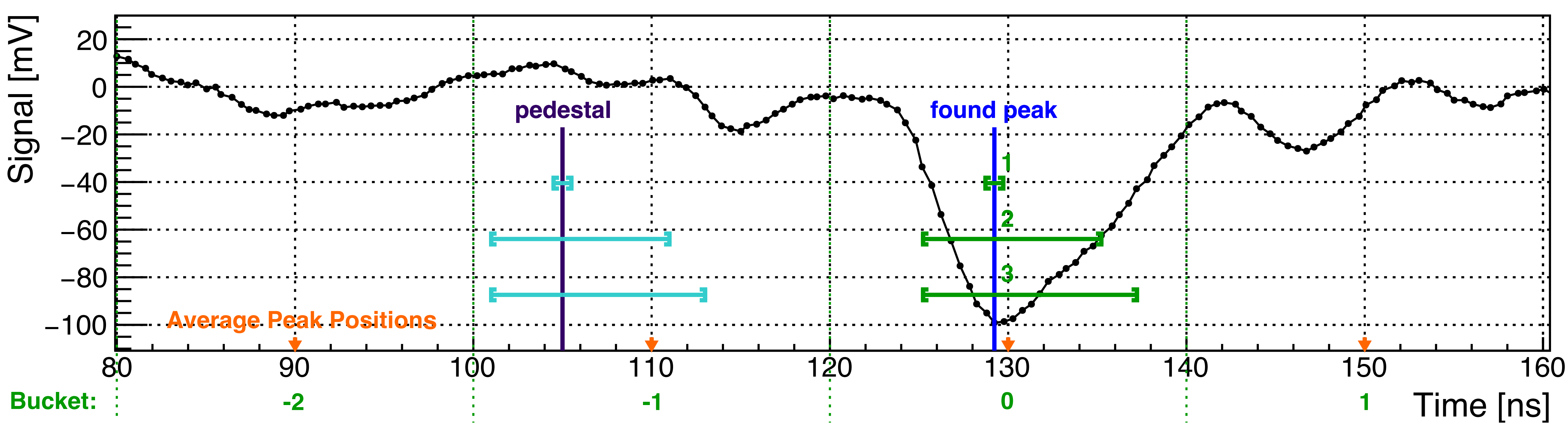
Analysis procedure (waveform)

- Pulse height amplified with CVDFE1 fast amp
  - 3-6 ns rise time, goes away in under 20 ns
- Digitized by DRS4 evaluation board
  - 1024 sampling points
  - Sampling speed 2 GSPS
- Find peak in the signal region
- Integrate in the window around the peak
  - Integration window optimized to provide best signal to noise ratio
- Subtract pedestal integral
  - Pedestal integrated exactly one bucket in front of the signal



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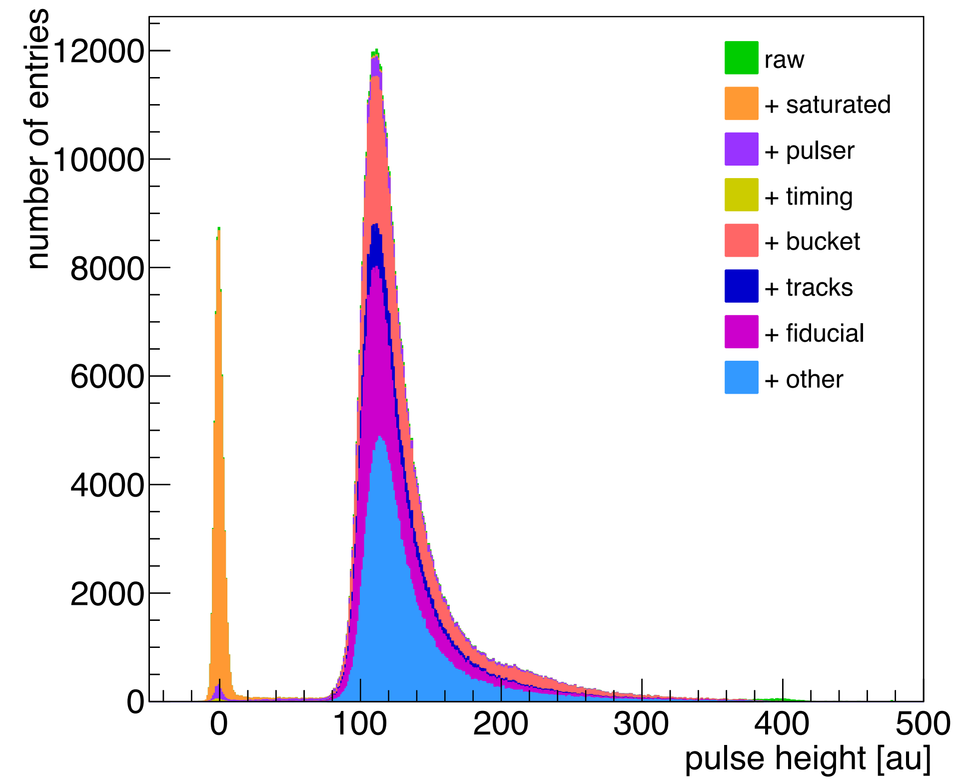
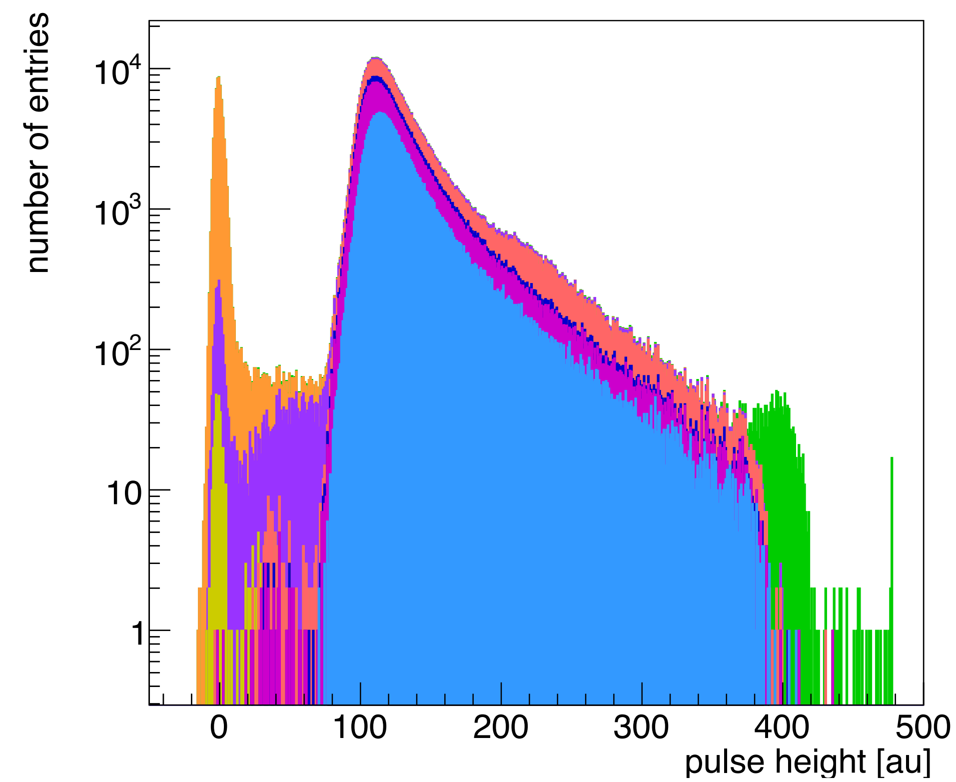
Pad detector specific cuts

- Careful handling of systematic effects
  - **Remove saturated wave forms (heavy ionizing particles)**
  - **Remove calibration pulser events**
  - **Remove residual trigger jitter**
  - **Remove events in wrong bucket**
  - **Accept only events with one hit in each plane**
  - **Accept only tracks predicting into the fiducial area**
- Remaining pulse height distribution **shown in blue** is clean with no remaining pedestal events





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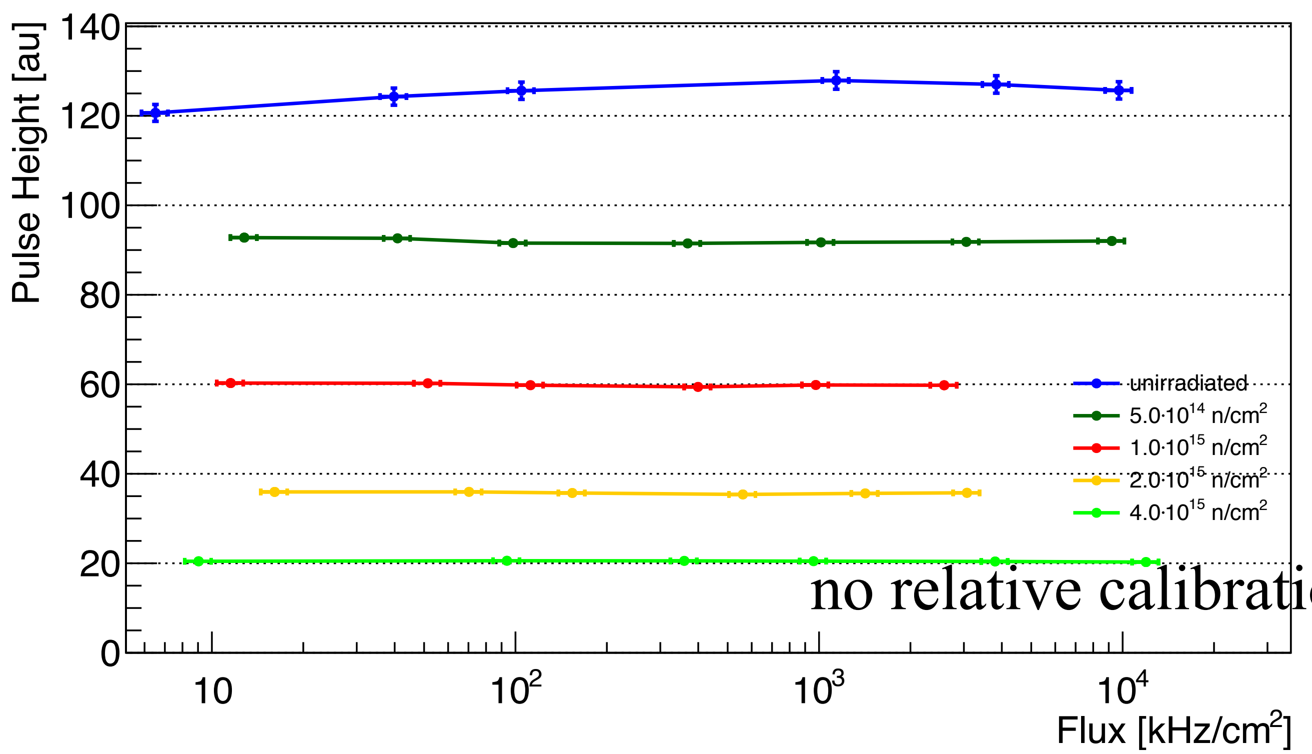
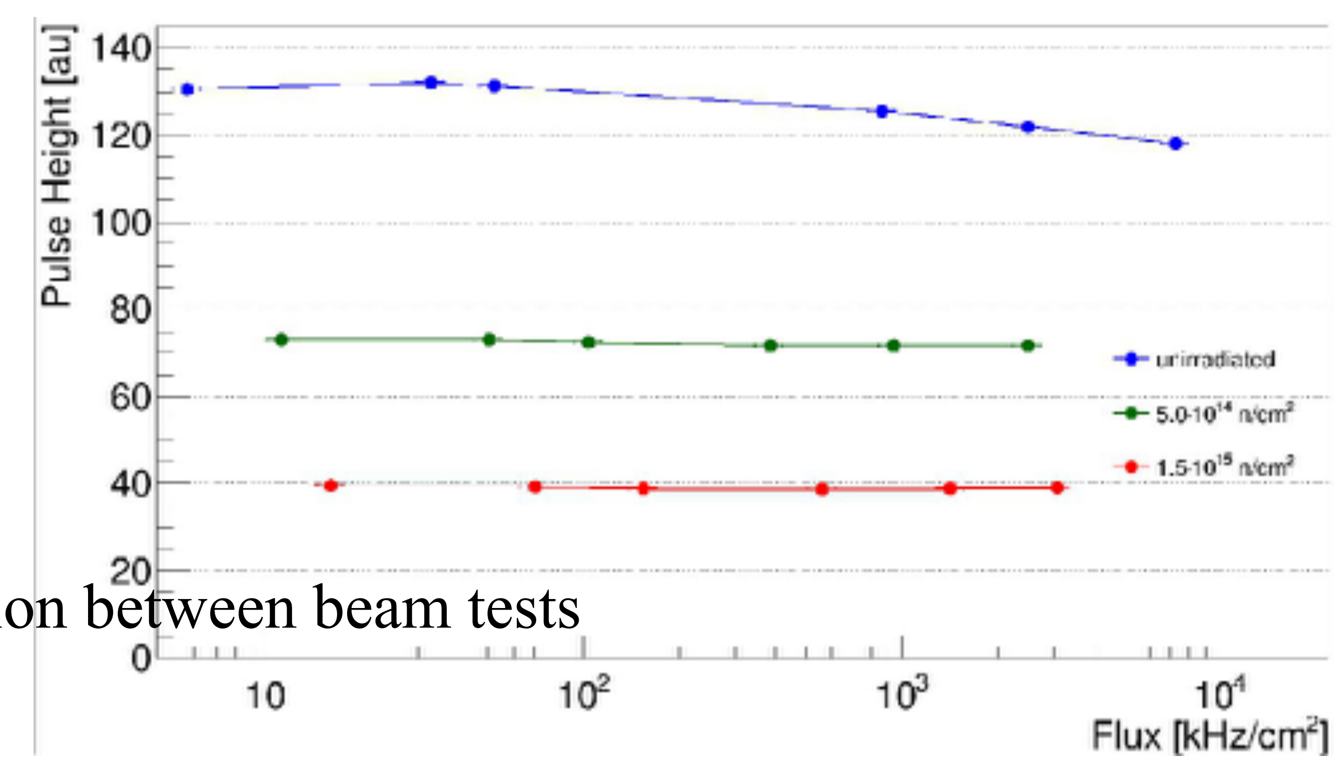
Results (pCVD - pad detector)

- Average pulse height vs pion rate
- Pulse height was measured at several rate points between 2 kHz/cm^2 and 10 MHz/cm^2
  - scanned up and down up to 4 times to check repeatability
- Pulse height very stable after irradiation
  - slight change in pulse height, ~5-8% before irradiation,
  - could be due to the inadequate surface preparation (we are checking that)

pCVD1: II6-B2 Bias: -1000 V



pCVD2: II6-97 Bias: -1000 V



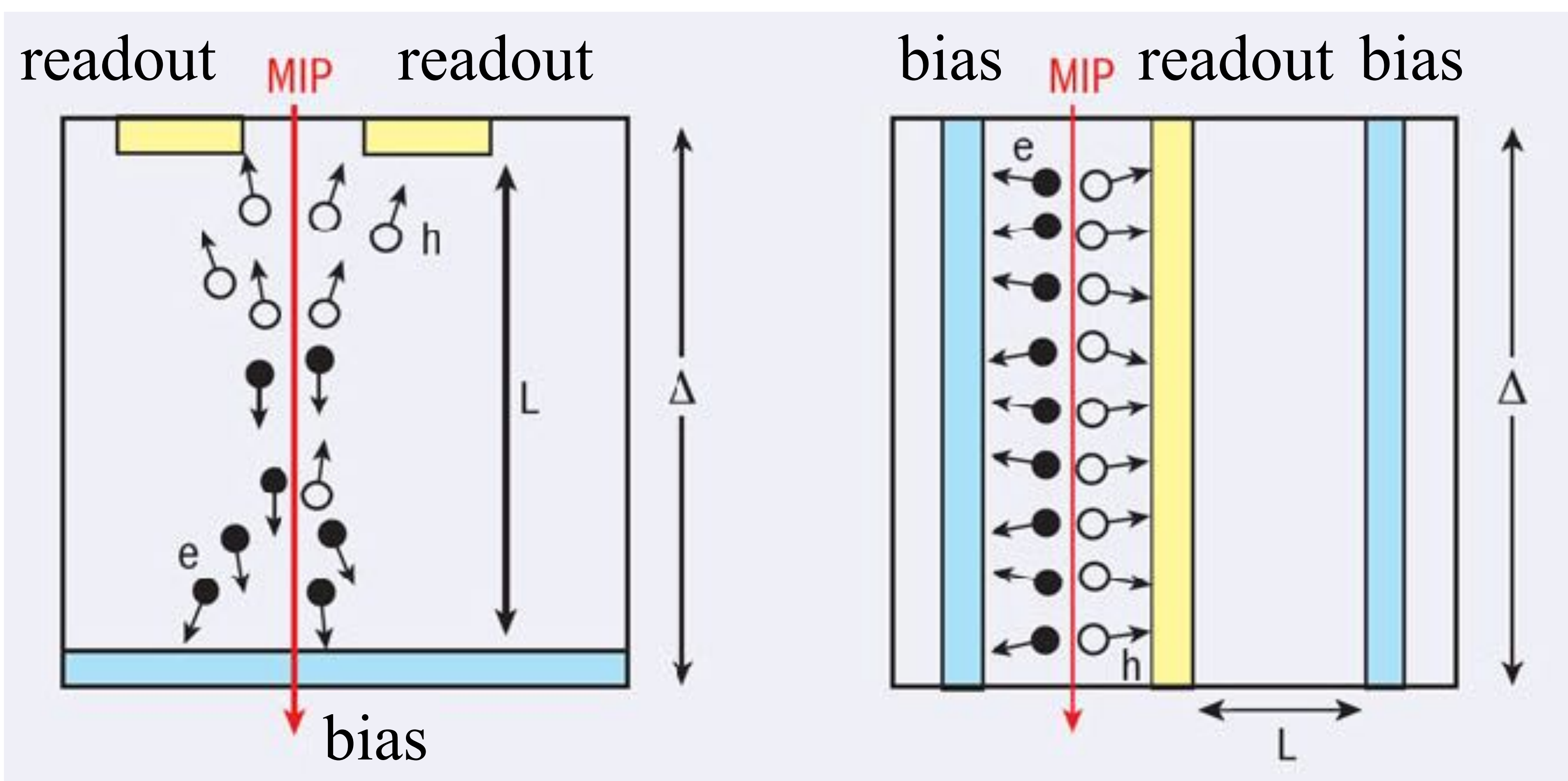
no relative calibration between beam tests

3D CVD diamond Detectors

3D detector concept

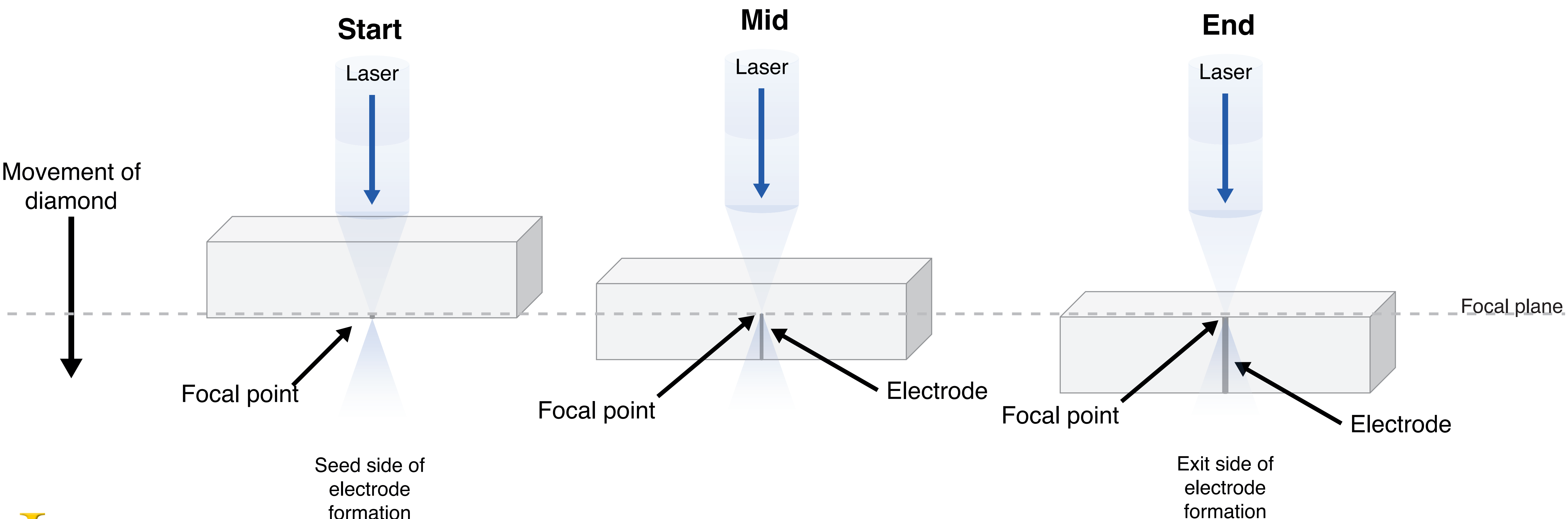
[Parker et al., NIM A395 (1997)]

- Incorporate bias and readout electrodes into detector's bulk
- Same detector thickness - Δ
  - same amount of charge induced by an ionizing particle
- Shorter drift distance in 3D detectors - L < Δ
  - reduced probability of charge trapping in radiation damaged and/or polycrystalline detectors



3D detector fabrication

- Femtosecond laser converts insulating diamond into a resistive mixture of various carbon phases: DLC, amorphous carbon, graphite, etc
- Early detectors had 90% column yield [Bachmair et al., NIM A, 786 (2015)]
  - recently ~100% has been achieved using Spatial Light Modulation to correct for aberration in diamond



3D detector fabrication

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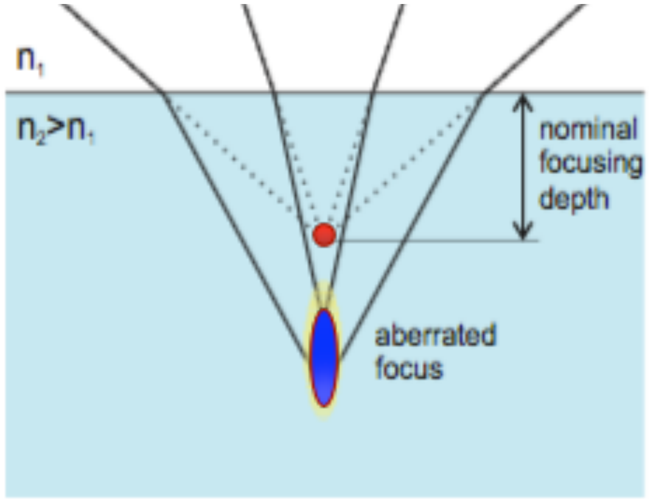
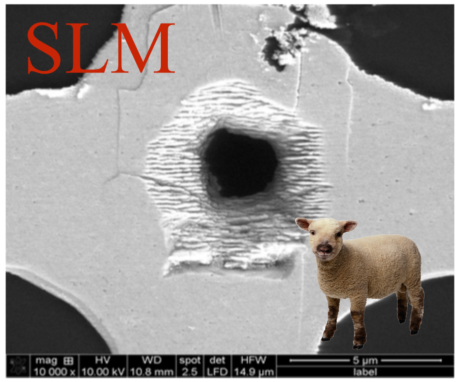
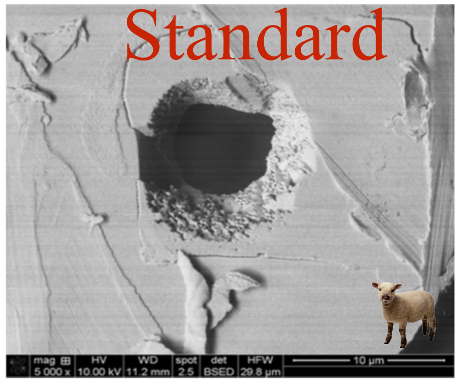
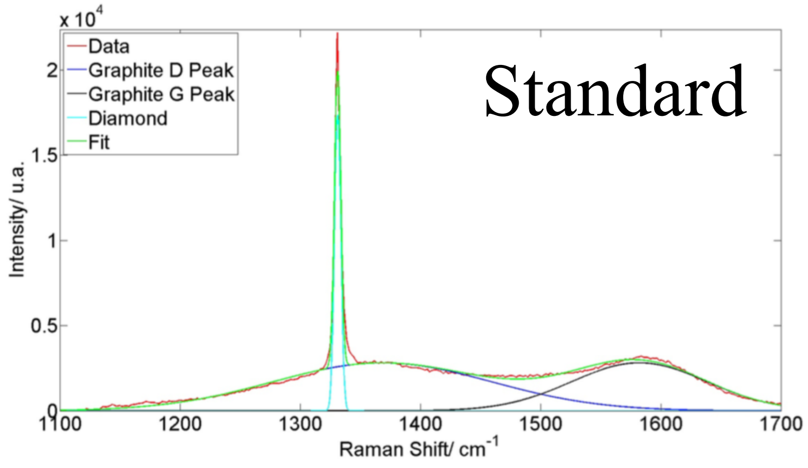
  - recently ~100% has been achieved using Spatial Light Modulation (SLM) to correct for aberration in diamond

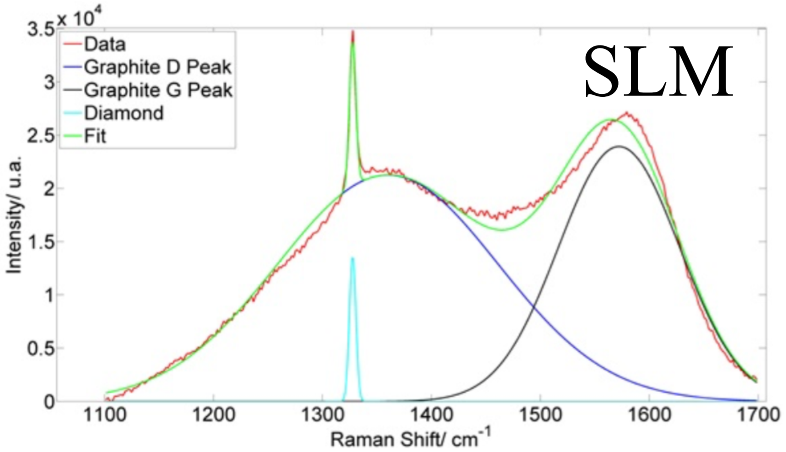








(a)



	Standard	SLM
Resistivity	1 Ωcm	0.1 Ωcm
Diameter	~3μm	~1μm
Diamond to graphite ratio	~4	~0.2

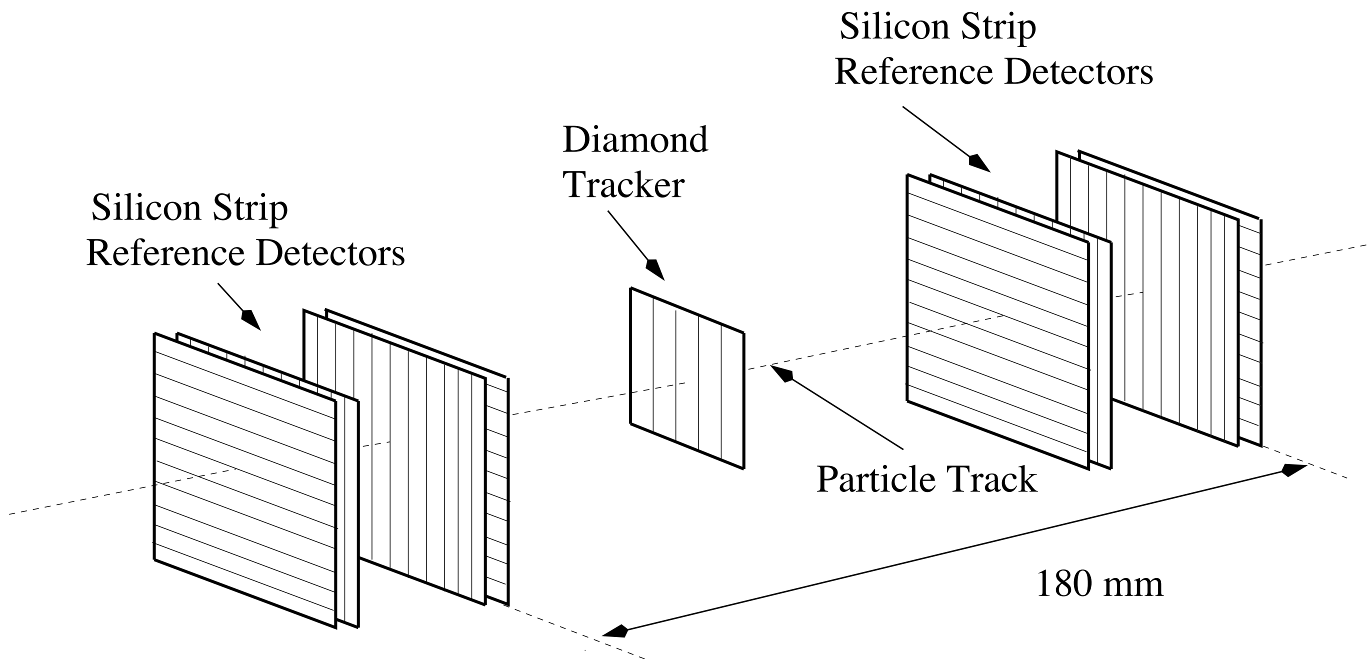
Testing 3D detectors at CERN

Diego Alejandro Sanz Becerra (present)

Felix Bachmair, Lukas Bäni (past)

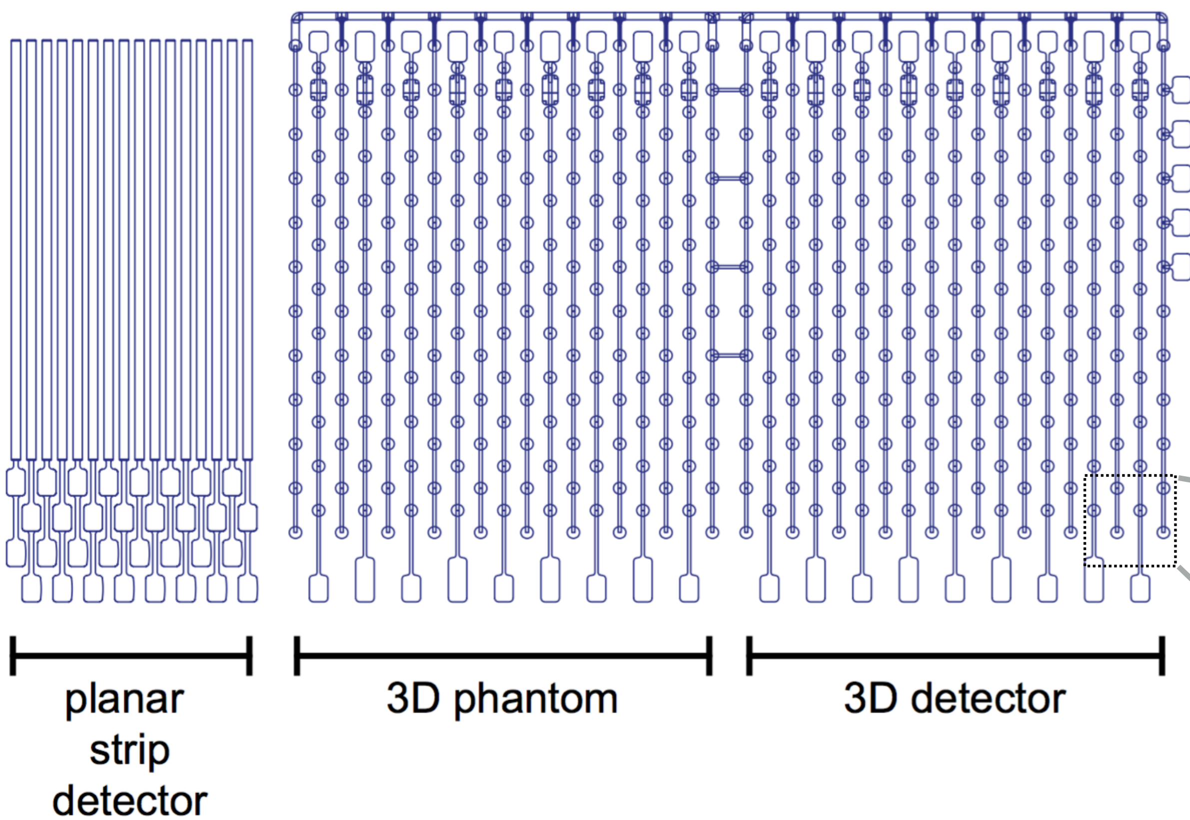
Testing of radiation hardness of CVD diamonds

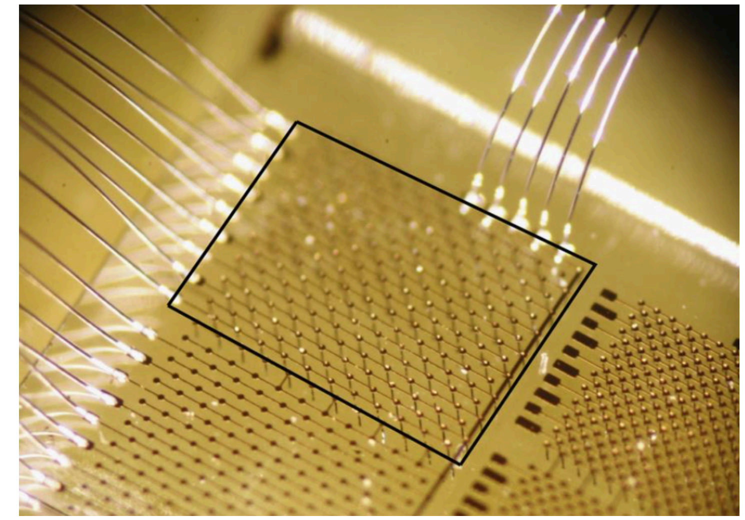
- On each sample a strip detector is build with a low noise VA2 readout
  - Noise is only 80 electrons after common mode subtraction
- Samples are pumped to fill the active traps before the test
- Relativistic charged particle beam
  - CERN SPS beam line 120 GeV protons or pions
- Beam telescope reconstructs particle tracks and predicts their impact position in the device under test with ~2 μm precision



3D detector in single crystal CVD diamond

[Bachmair et al., NIM A, 786 (2015)]



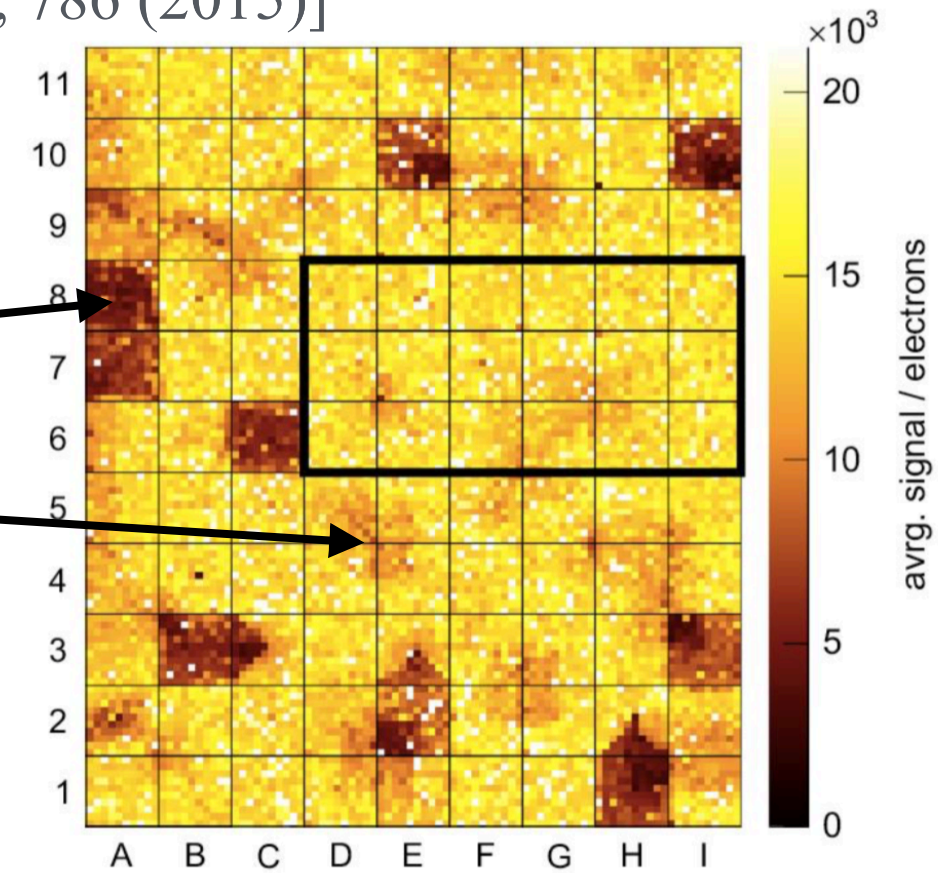


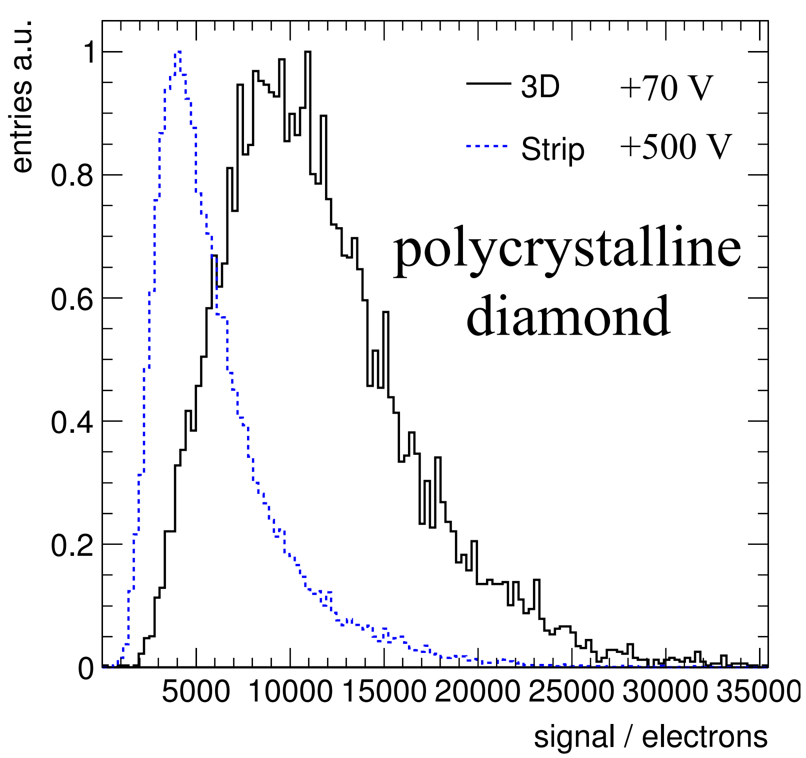
- 3 detectors
  - strip with backside contact for bias
  - 3D with bias and readout contacts on the same side (150μm cell size)
  - 3D phantom (same metal pattern as 3D but without graphitic columns)
- Some broken columns in the detector (90% success rate in column drilling)

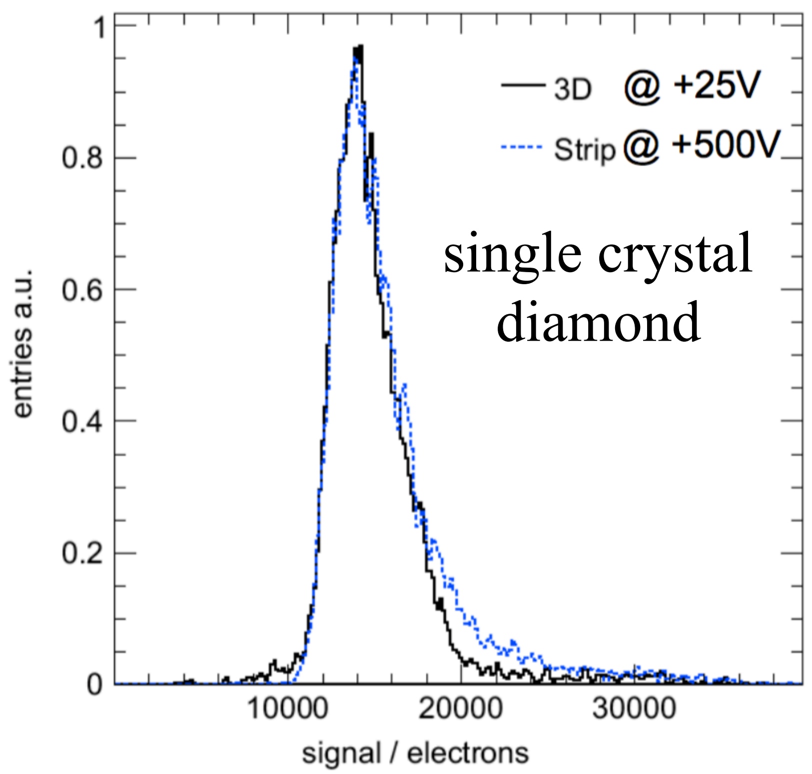
3D detector in single crystal CVD diamond

[Bachmair et al., NIM A, 786 (2015)]

- Some broken columns in the detector (90% success rate in column drilling)
  - Broken readout columns result in cell with low signal
  - Broken bias column result in region with lower signal
- For comparison with the strip detector use contiguous region with no broken signal columns



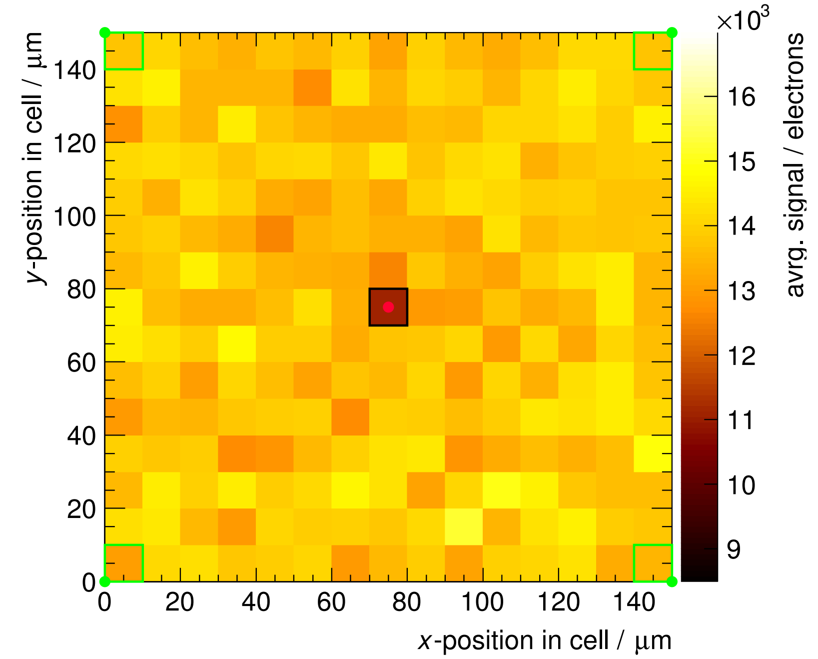




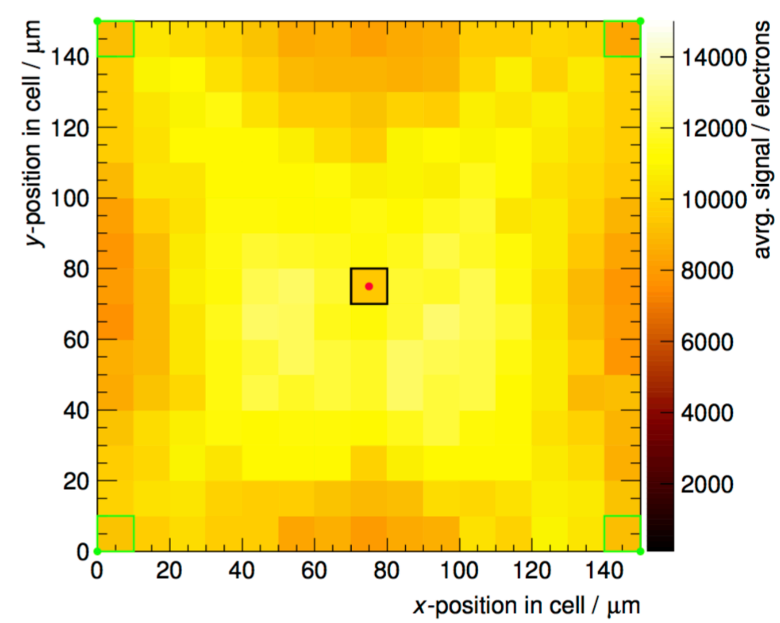
Charge collection efficiency with a cell

- Overlay average charge collected in all "good" cells
- 3D scCVD
  - Charge collected uniformly throughout cell, except for location of columns
- 3D pCVD
  - Charge collection is not uniform over the cell
  - low field regions collect less charge

good 3D cell in single crystal diamond

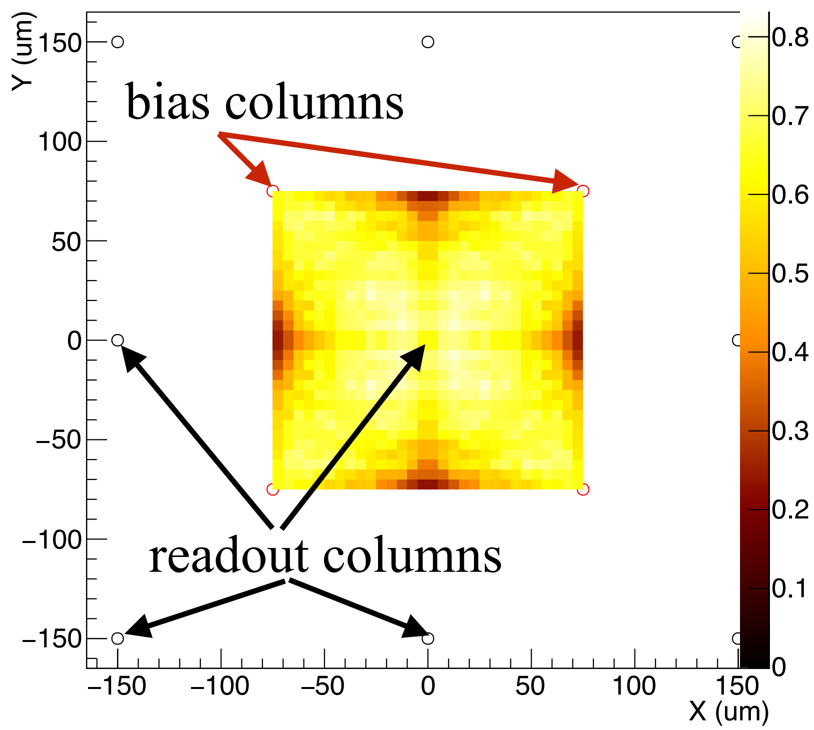


good 3D cell in polycrystalline diamond

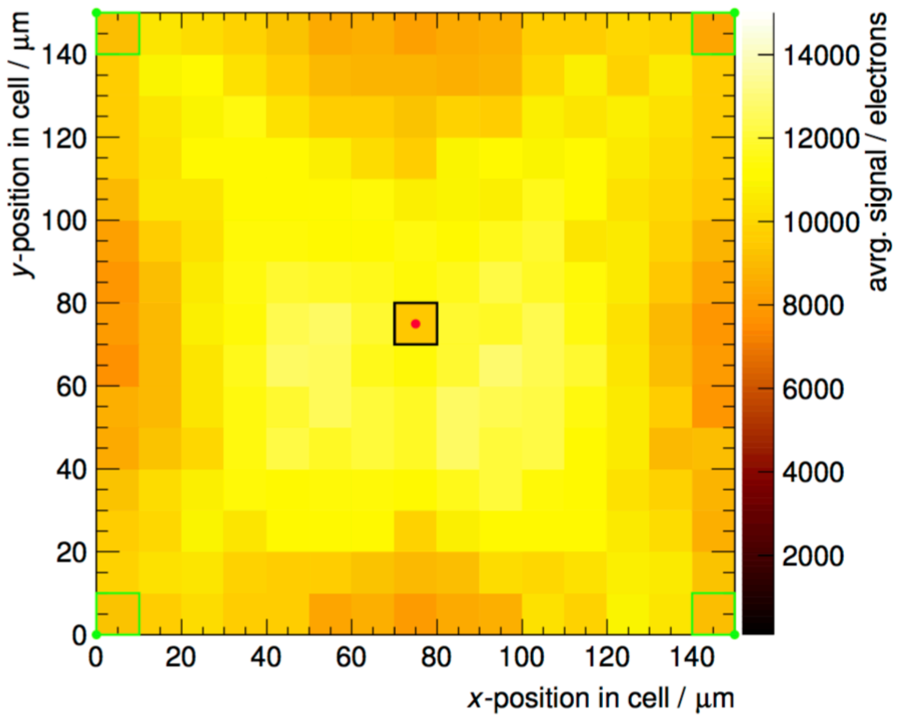


Comparison between data and simulations

Simulation (G. Forcolin)



Data (F. Bachmair)

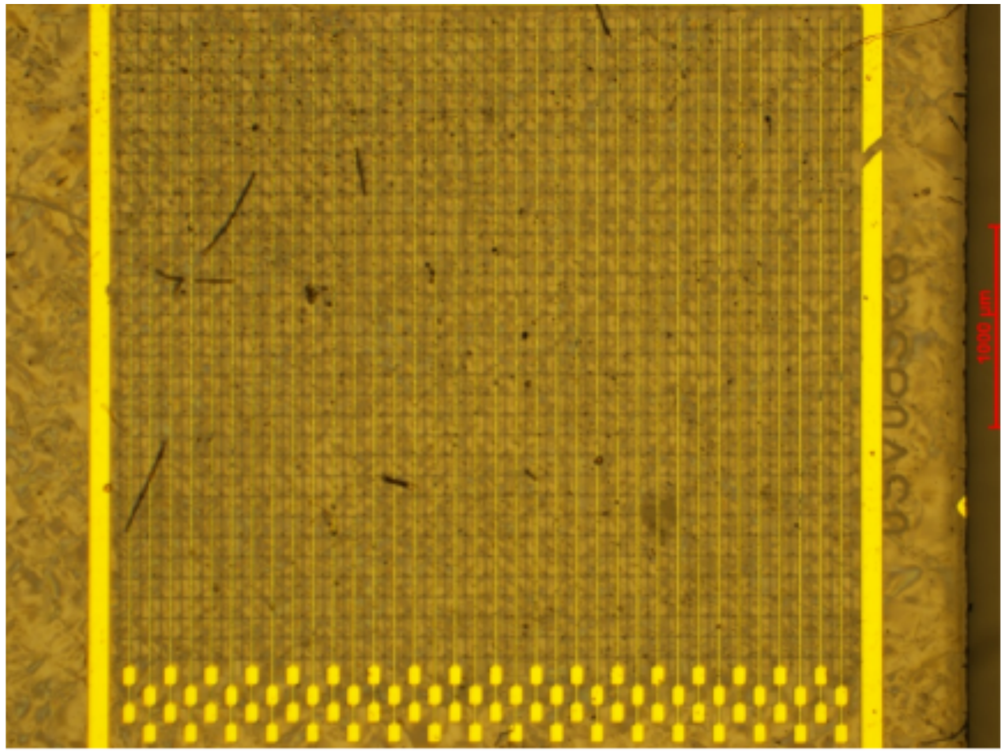


- Simulated ionizing particle passing through the quarter cell
  - Divided the area into 7.5x7.5 µm bins, and simulated an ionizing particle hit at the center of each bin
- Limit charge lifetime to simulate effects of charge trapping
- Plot the charge collected as function of hit position
- Good qualitative agreement between simulation and data

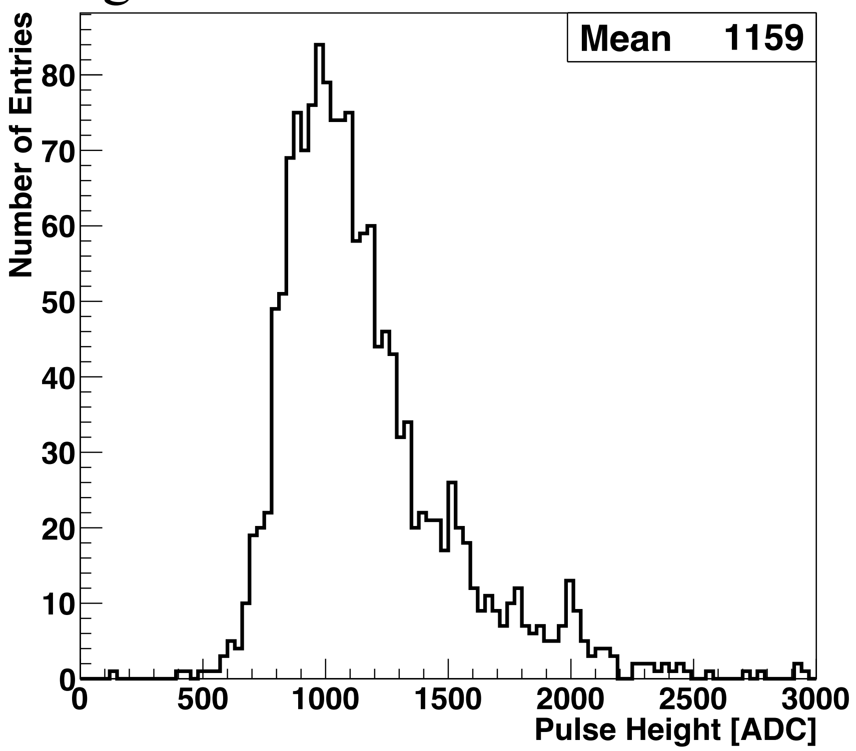
Full 3D detector in polycrystalline CVD diamond

- 3 dramatic improvements compared to previous generation 3D
  - an order of magnitude more cells: from 99 to 1188
  - smaller cell size: 100 µm × 100 µm
  - higher column efficiency: from 92 % to 99 %
- analysis in progress
  - some cells are not connected due to problems with metallization (too thin strips)
  - contiguous region shows >80% of charge collection

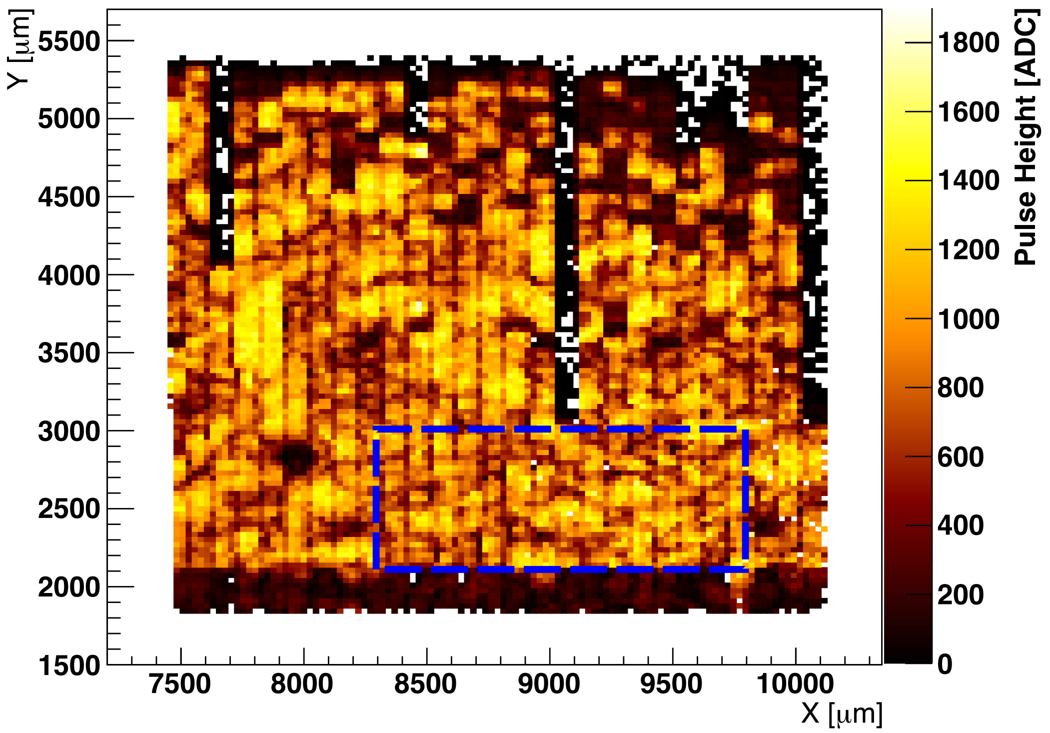
front contact



pulse height distribution in continuous region



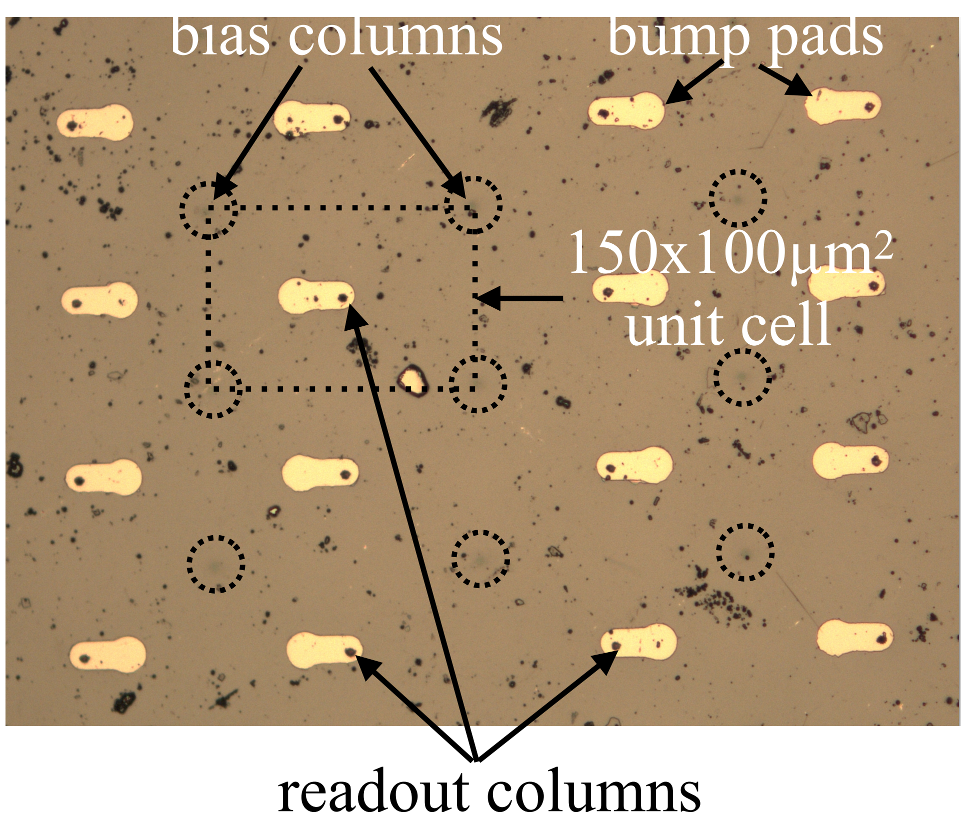
average pulse height in one strip vs hit position

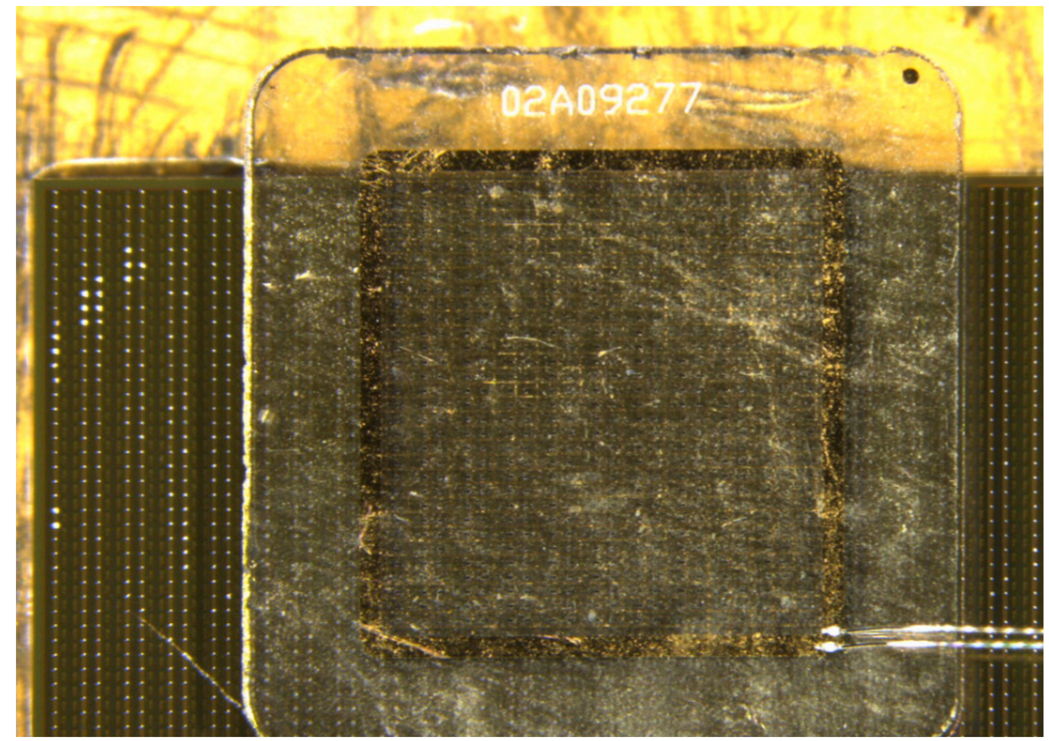


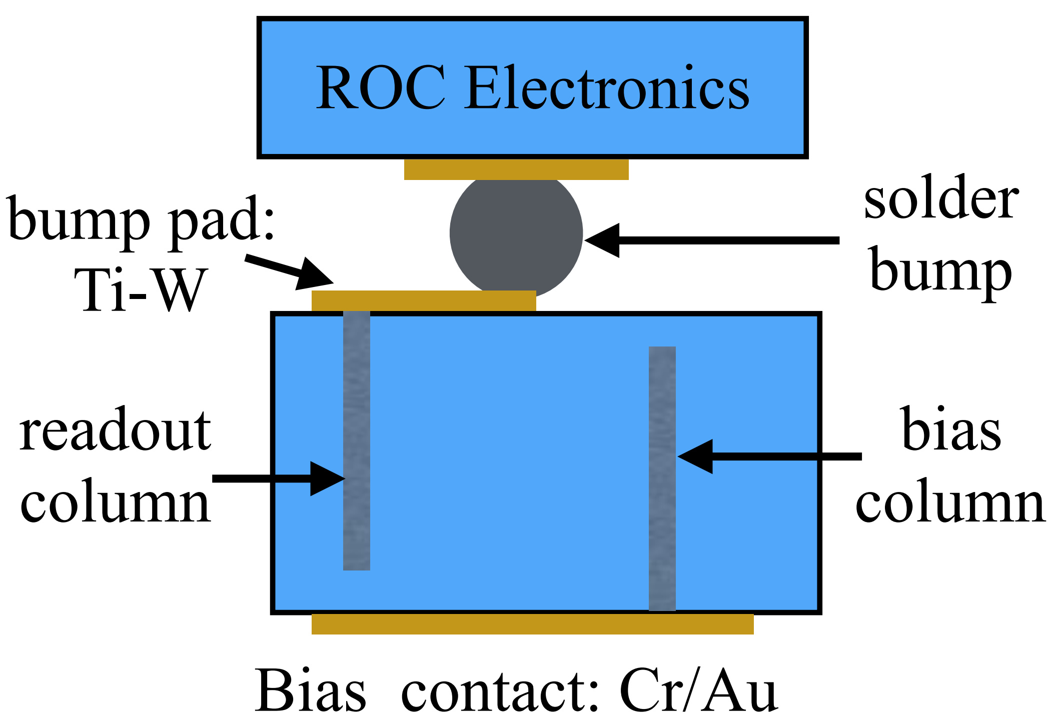
Testing 3D detectors at PSI

Micha Reichmann

1. 3D poly diamond with pixel readout

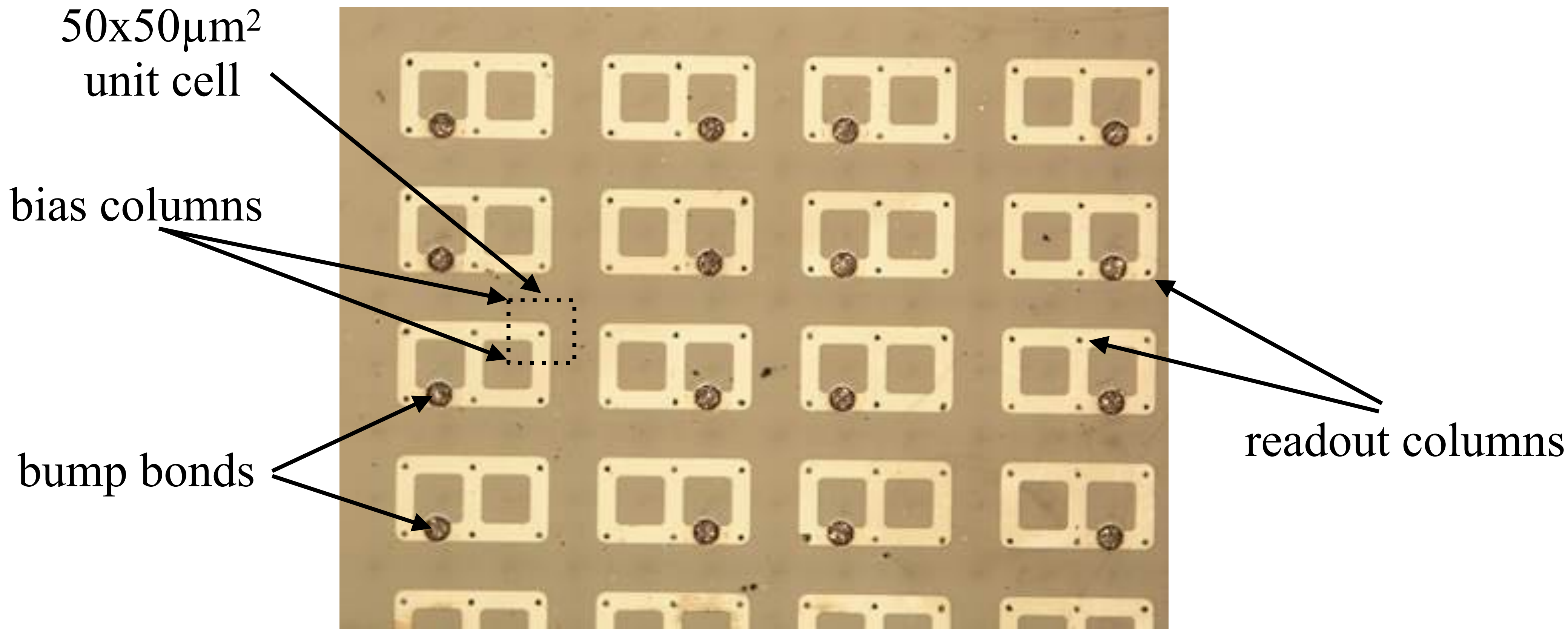


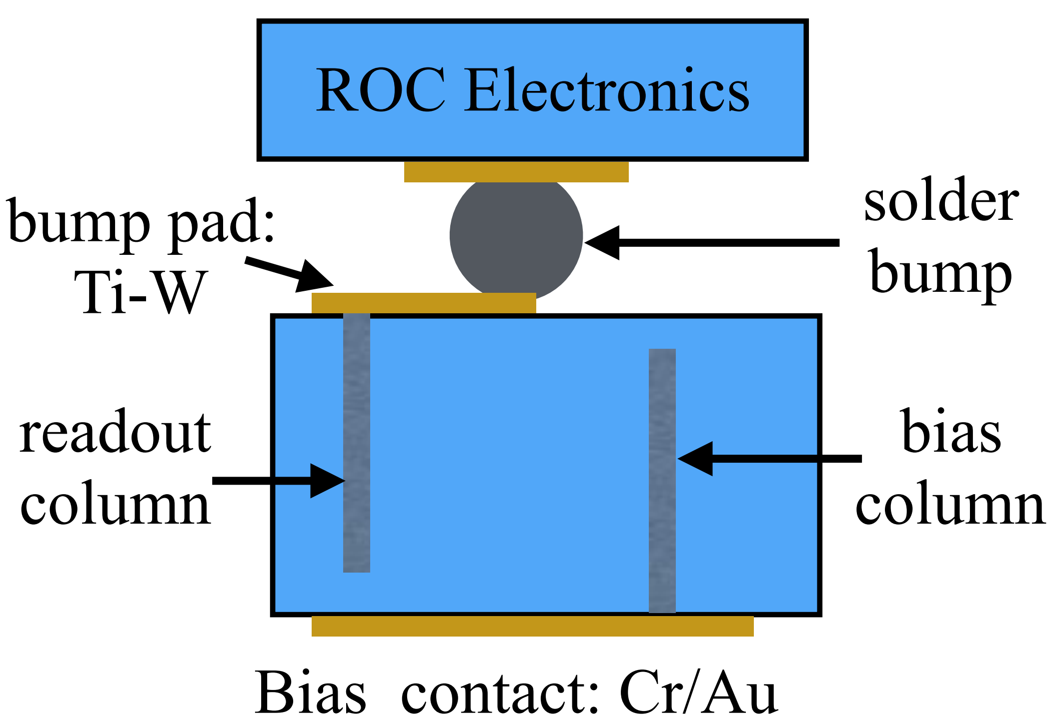




- First assembly with pixel readout chip and 3D pCVD diamond produced
  - Bump bonded by B. Harrop, Physics Department, Princeton University to the latest CMS digital pixel chip with low threshold (~1500 electrons)
- 3D columns were designed to stop 15μm before the end of the material and drilled from both sides
  - produced by: Dr. P. Salter, Prof. M. Booth, Department of Engineering Science, University of Oxford

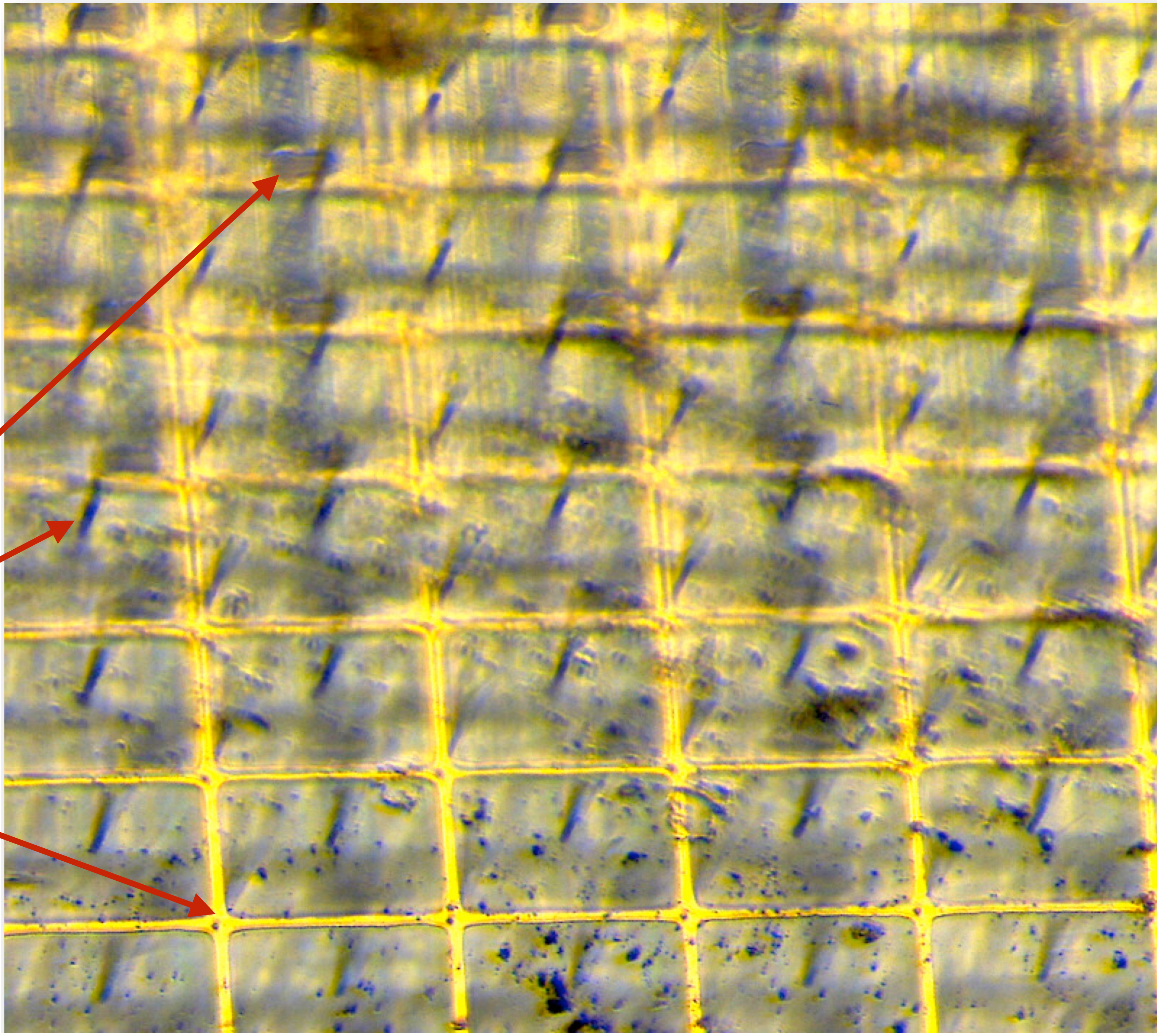
2. 3D poly diamond with pixel readout





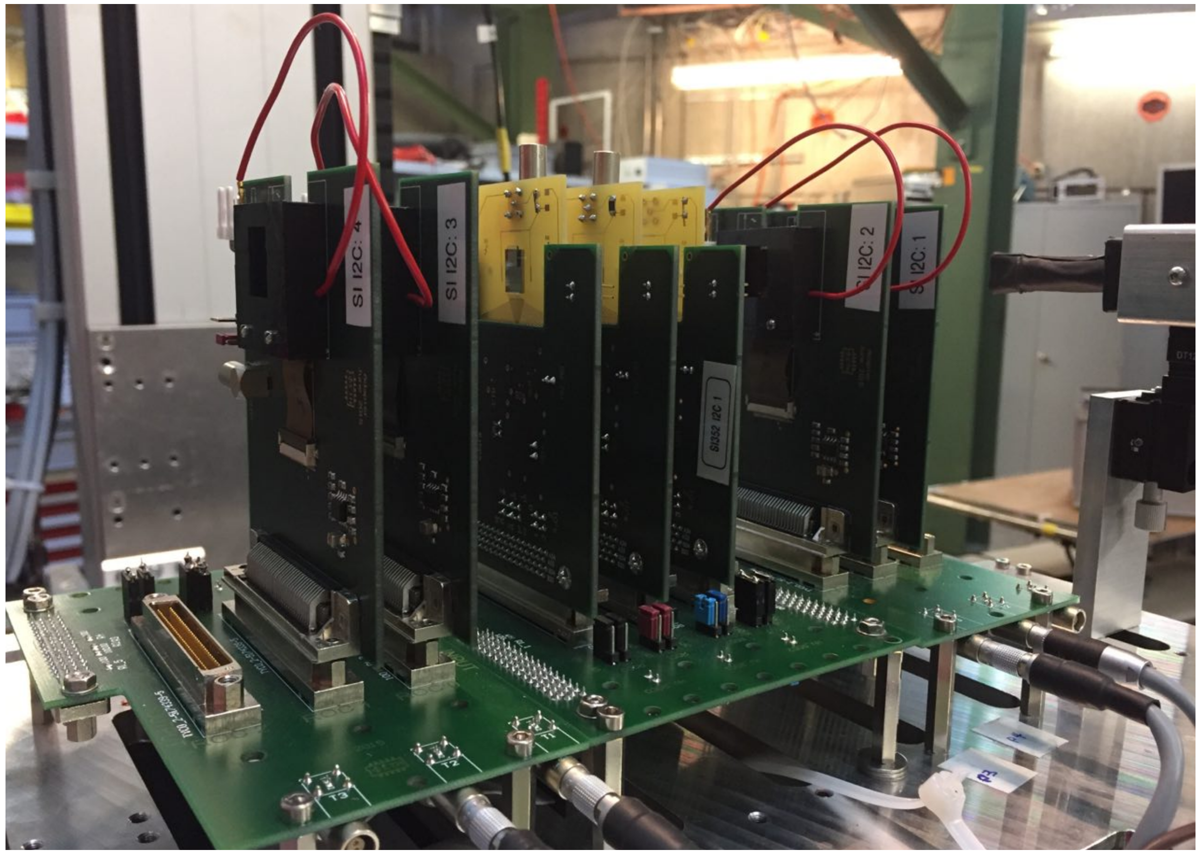
- Second assembly with pixel readout chip and 3D pCVD diamond produced
  - Bump bonded by B. Harrop, Physics Department, Princeton University to the latest CMS digital pixel chip with low threshold (~1500 electrons)
- 3D columns were designed to stop 15µm before the end of the material and drilled from both sides
  - produced by: Dr. P. Salter, Prof. M. Booth, Department of Engineering Science, University of Oxford

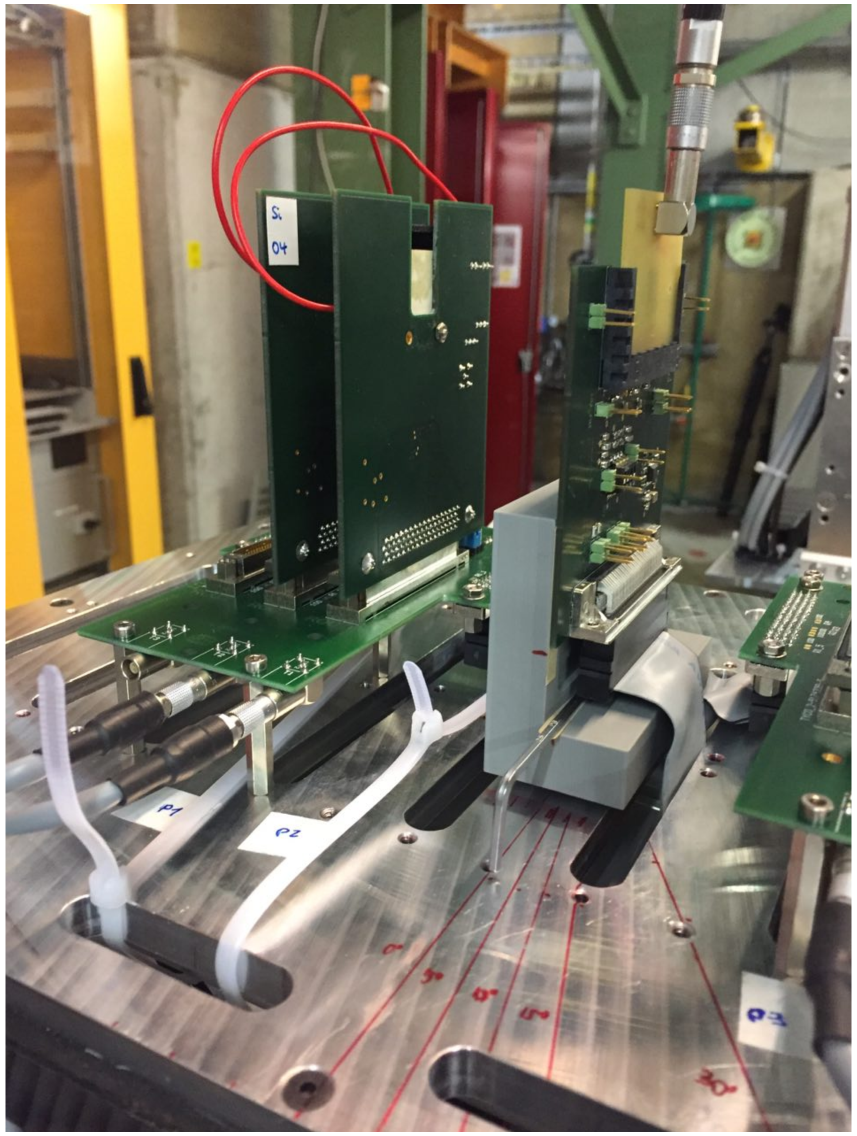
Tilted view of the 3D poly diamond pixel chip assembly



- Tilted image, focus on:
  - Bump pads
  - Columns
  - Bias grid

Beam test of 3D pixel detector





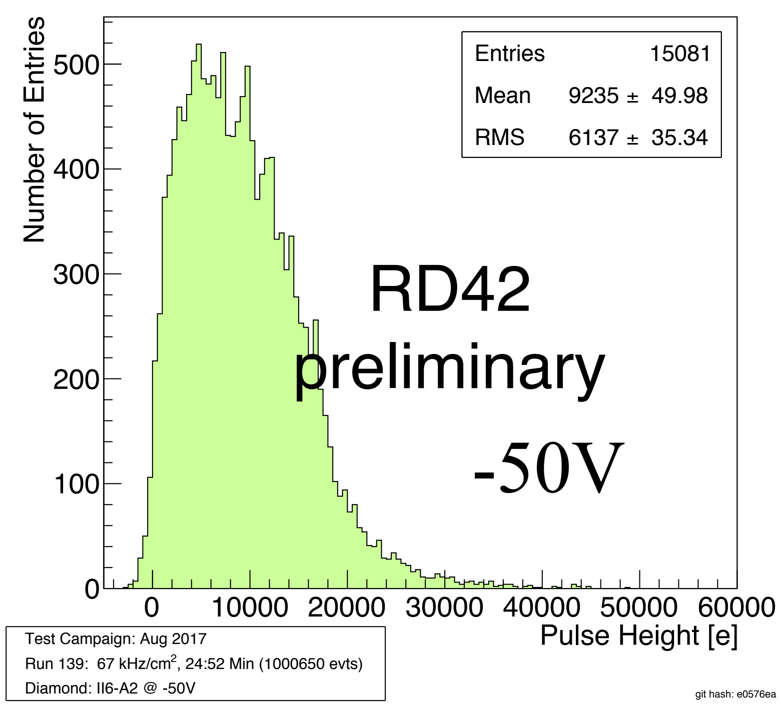
Rotation stage setup
for 50x50μm² cell 3D

- Latest (August 2017) testbeam at PSI
  - 260 MeV/c positive pions
- Read-out chip setup
  - Threshold for accepting hits: ~1500 electrons
- Test performed:
  - rate scan from 7 kHz/cm2 — 7 MHz/cm2
  - Bias scan from 0V to -55V
  - Angle scan 0 — 30 degree
  - rise time scan (varying CMS-Pixel DAC to increase rise time of the ROC)

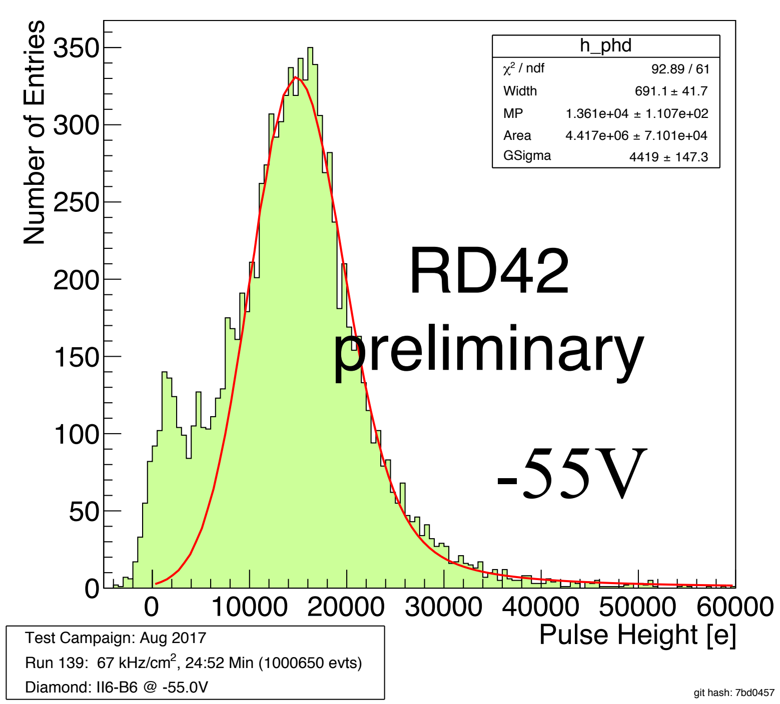
Beam test of 3D pixel detector

- All results are very preliminary!
  - The peak at 0 we are not yet able to explain
- Pulse height calibration for diamond samples is approximate
- Silicon sample was calibrated with X-ray fluorescent lines
- Mean of the fit for 50x50μm^2 is 16ke
  - ~90% charge collection

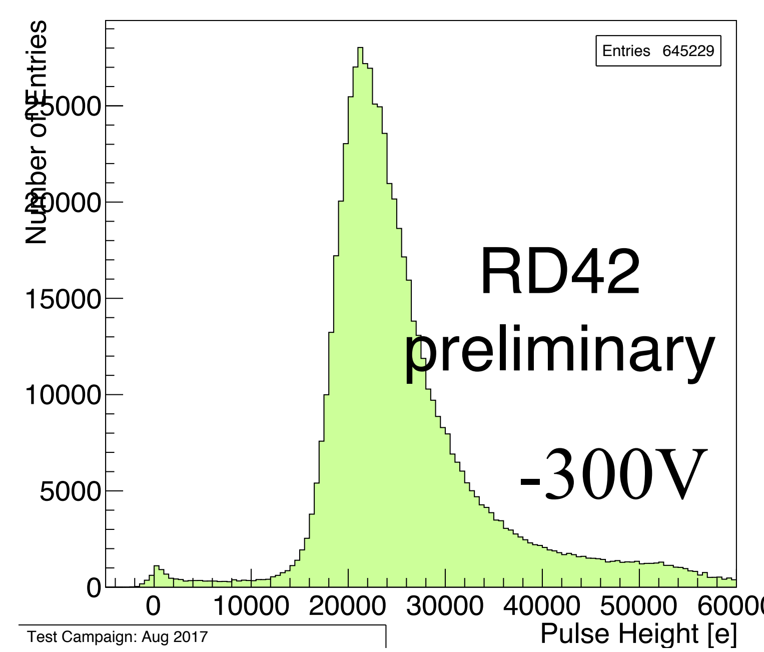
150x100μm^2
3D pCVD diamond



50x50μm^2
3D pCVD diamond



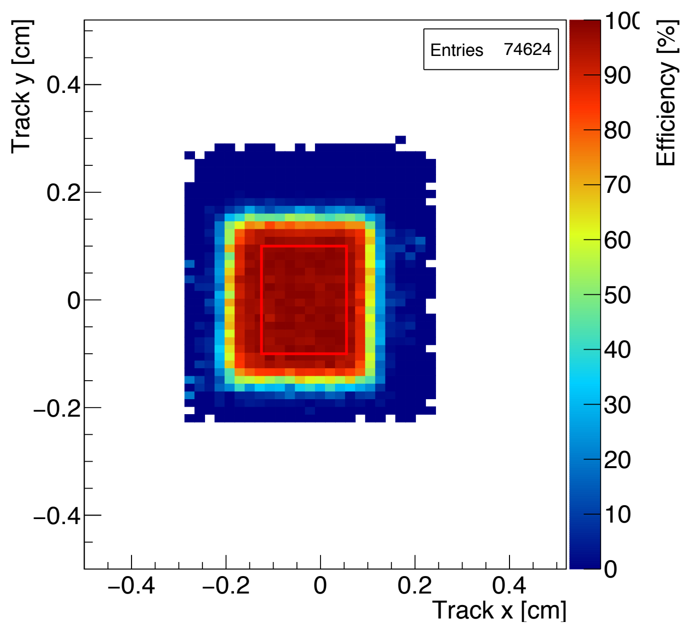
planar Si



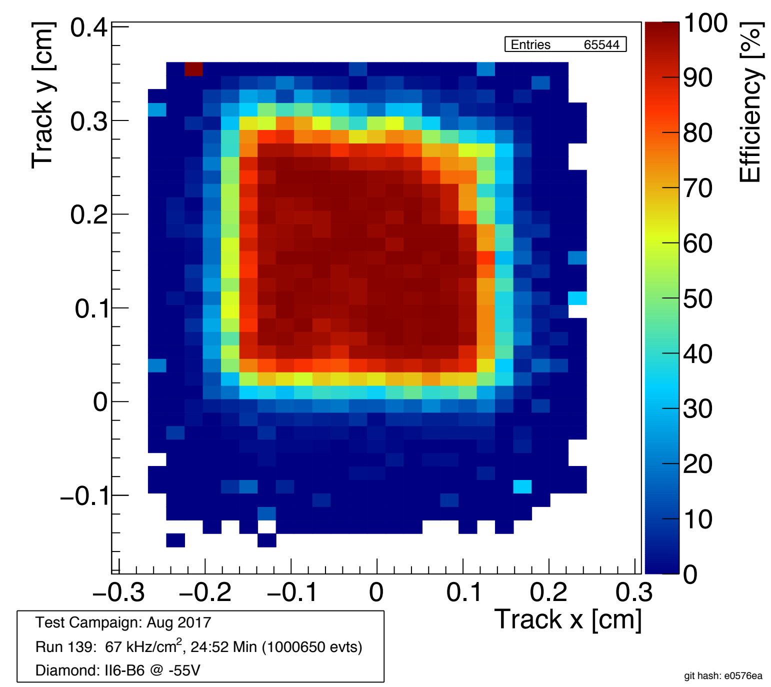
Hit efficiency

- Efficiency checked by counting all hits in the device under test and dividing them by the number of tracks predicted by the telescope within a fiducial area
- Efficiency very high for all 3 devices
  - 150x100μm² — 98.5%, 50x50μm² — 99.4%, planar Si — 99.9%
- We expect that efficiency will be even higher for the tilted 3D device

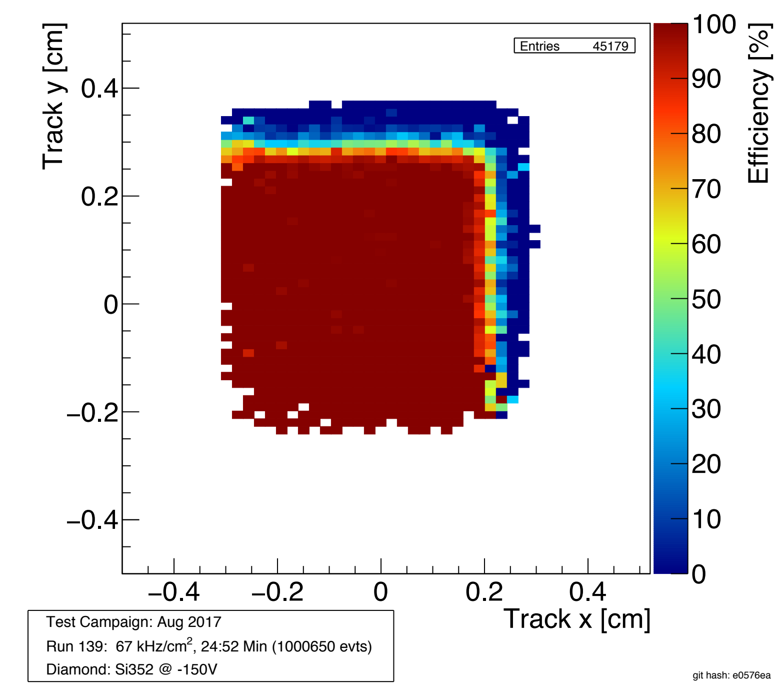
3D, 150x100μm² cell



3D, 50x50μm² cell



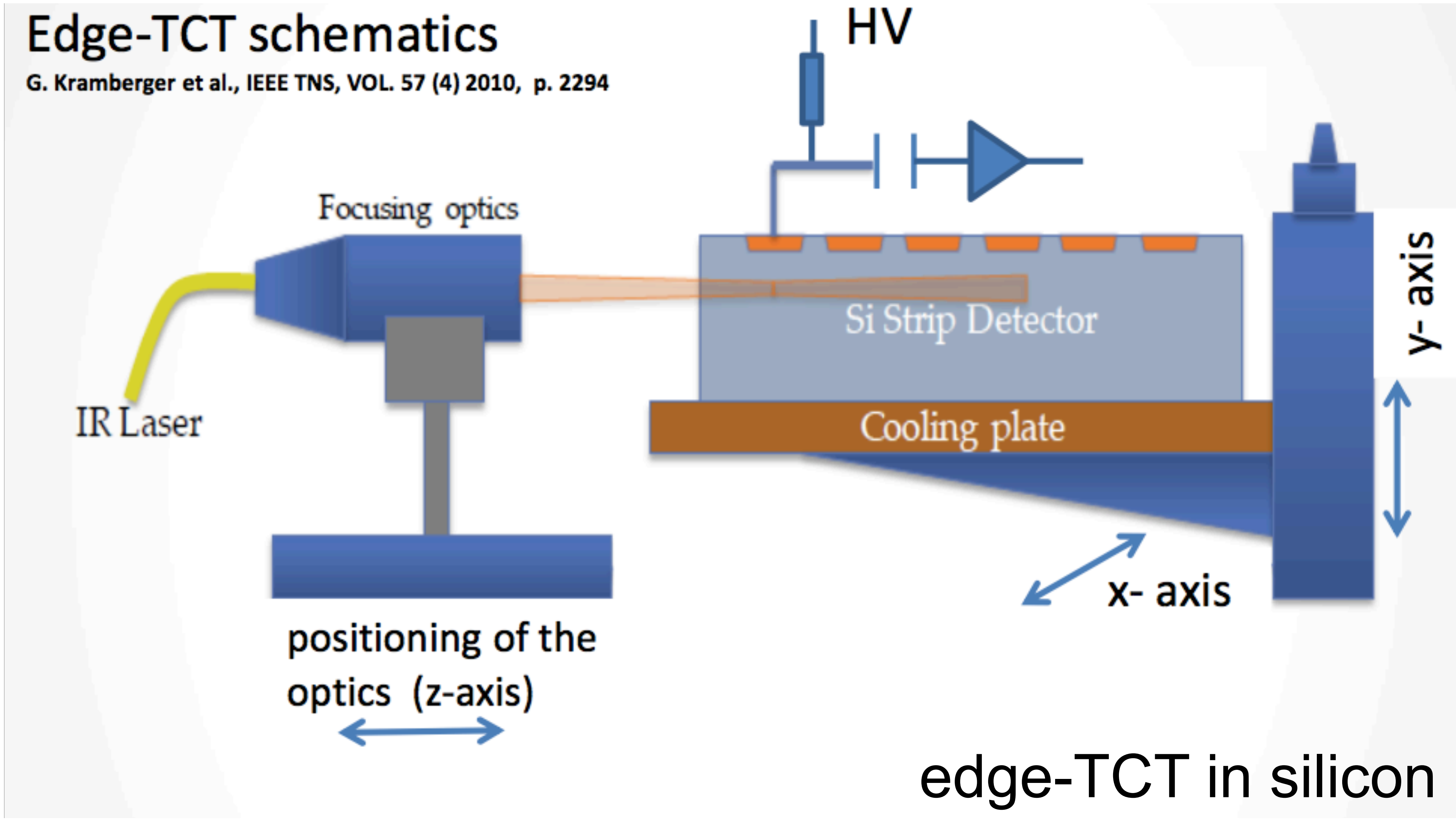
planar Si



edge-Transient Current Technique

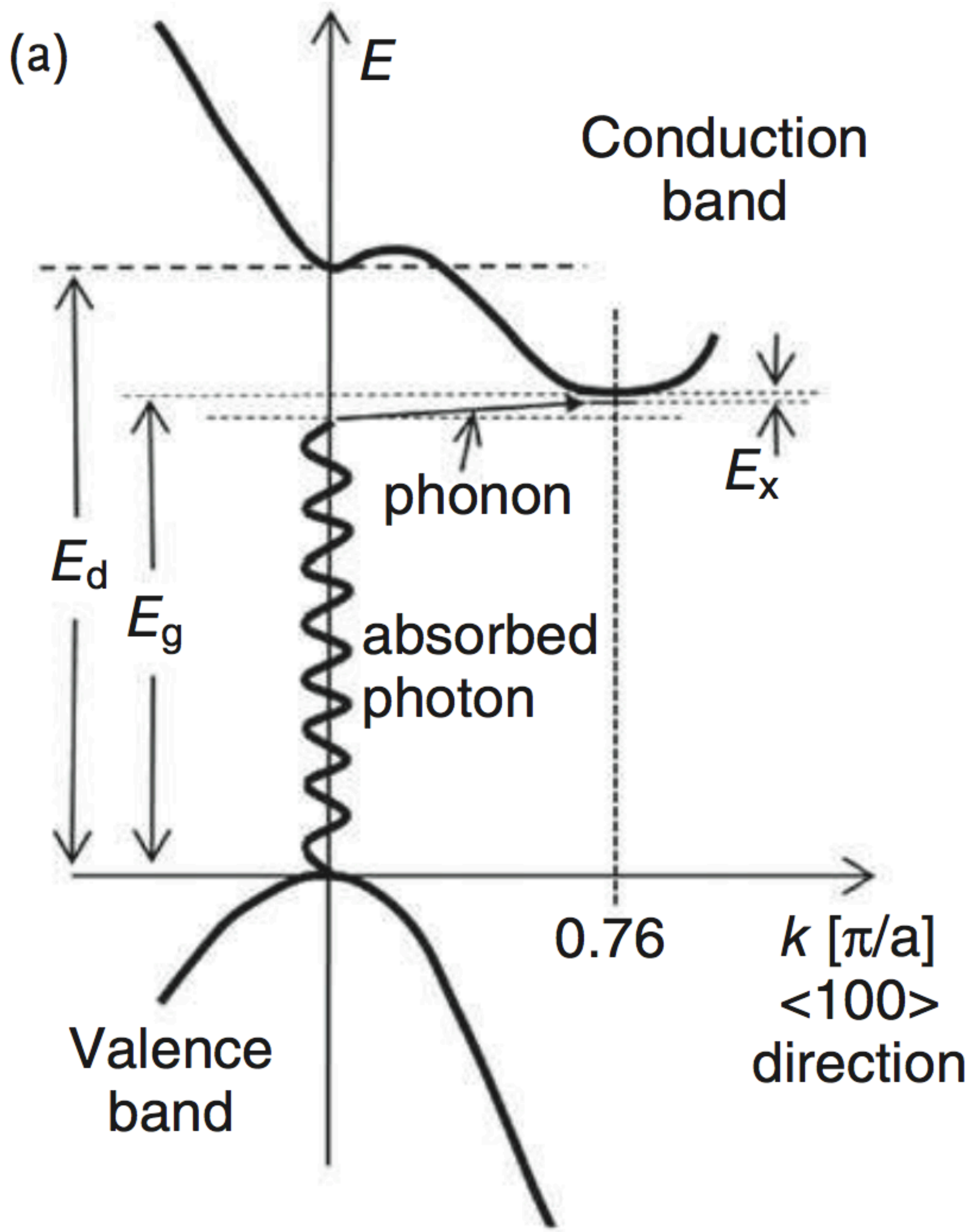
Christian Dorfer

edge-TCT (pads)



- Powerful tool to demystify the charge transport properties of (irradiated and unirradiated) sCVD diamond:
  - space charge thus the electric field
  - trapping times
  - charge collection efficiency (CCE)
  - saturated velocity
  - mobility electrons and holes

Electronic band gap of diamond



Electronic band diagram of diamond showing photon absorption by the indirect band gap.

Indirect Bandgap

required energy ≈ 5.47 eV / 226 nm
(minus phonon contribution and exciton energy)
1-photon absorption
2-photon absorption: $E_\gamma \approx 2.74$ eV / 453 nm

Direct Bandgap

required energy = 7.3 eV / 170 nm
1-photon absorption
2-photon absorption: $E_\gamma = 3.65$ eV / 340 nm
3-photon absorption: $E_\gamma = 2.43$ eV / 510 nm

Attoline Laser

- ~ 25 fs
- 0.1 – 5 nJ pulse energy, equivalent to $2 \cdot 10^8 - 10^{10}$ photons/pulse
- photon energy of 3.1 eV (400 nm)

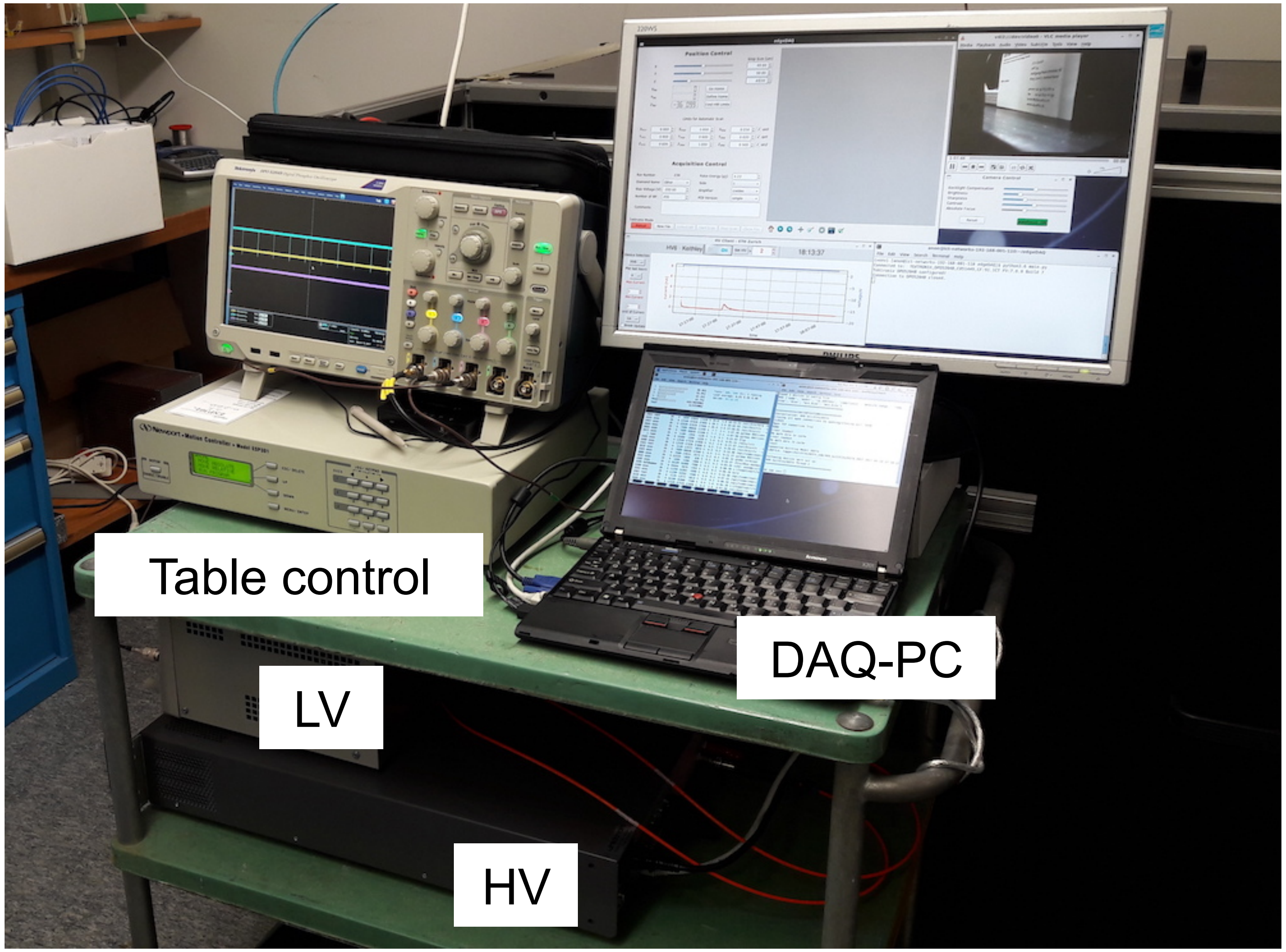
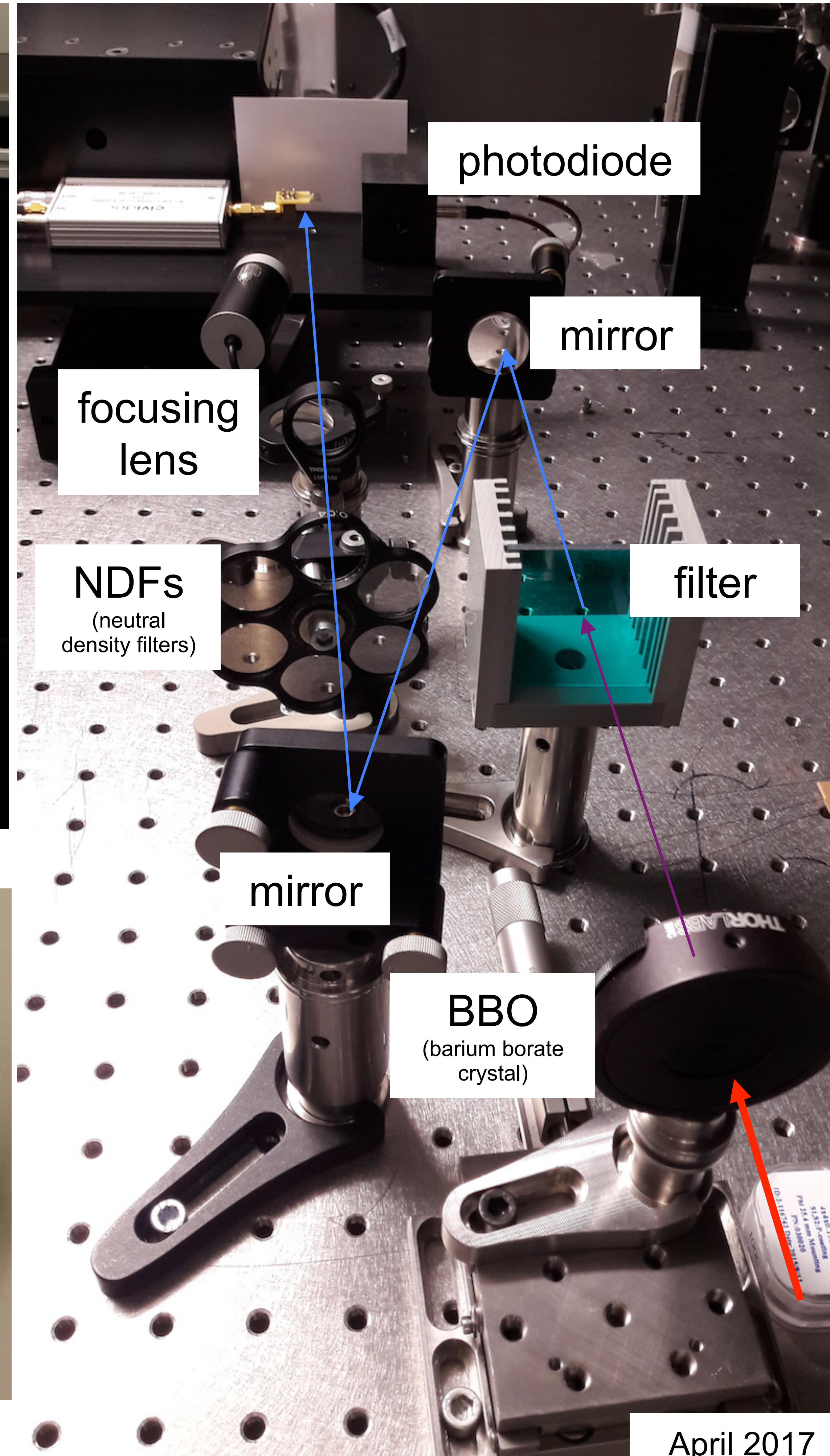
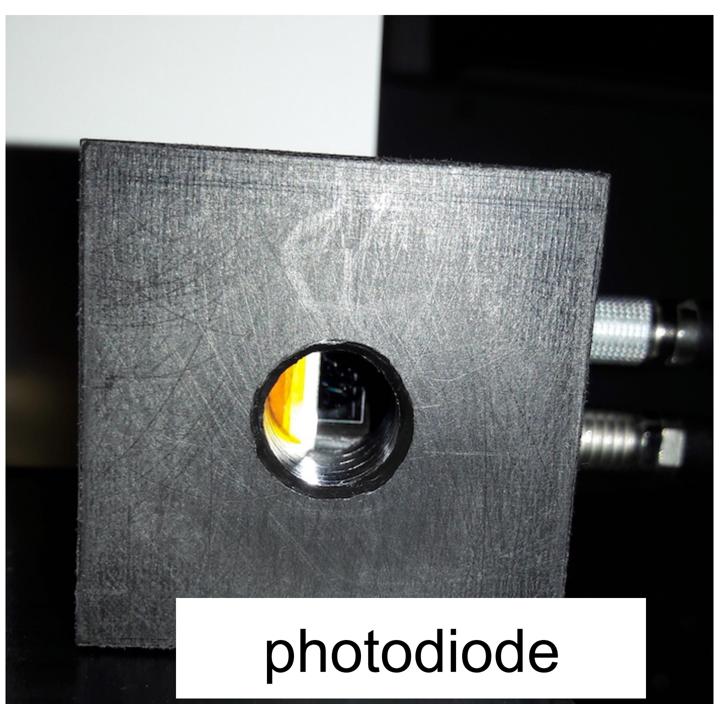


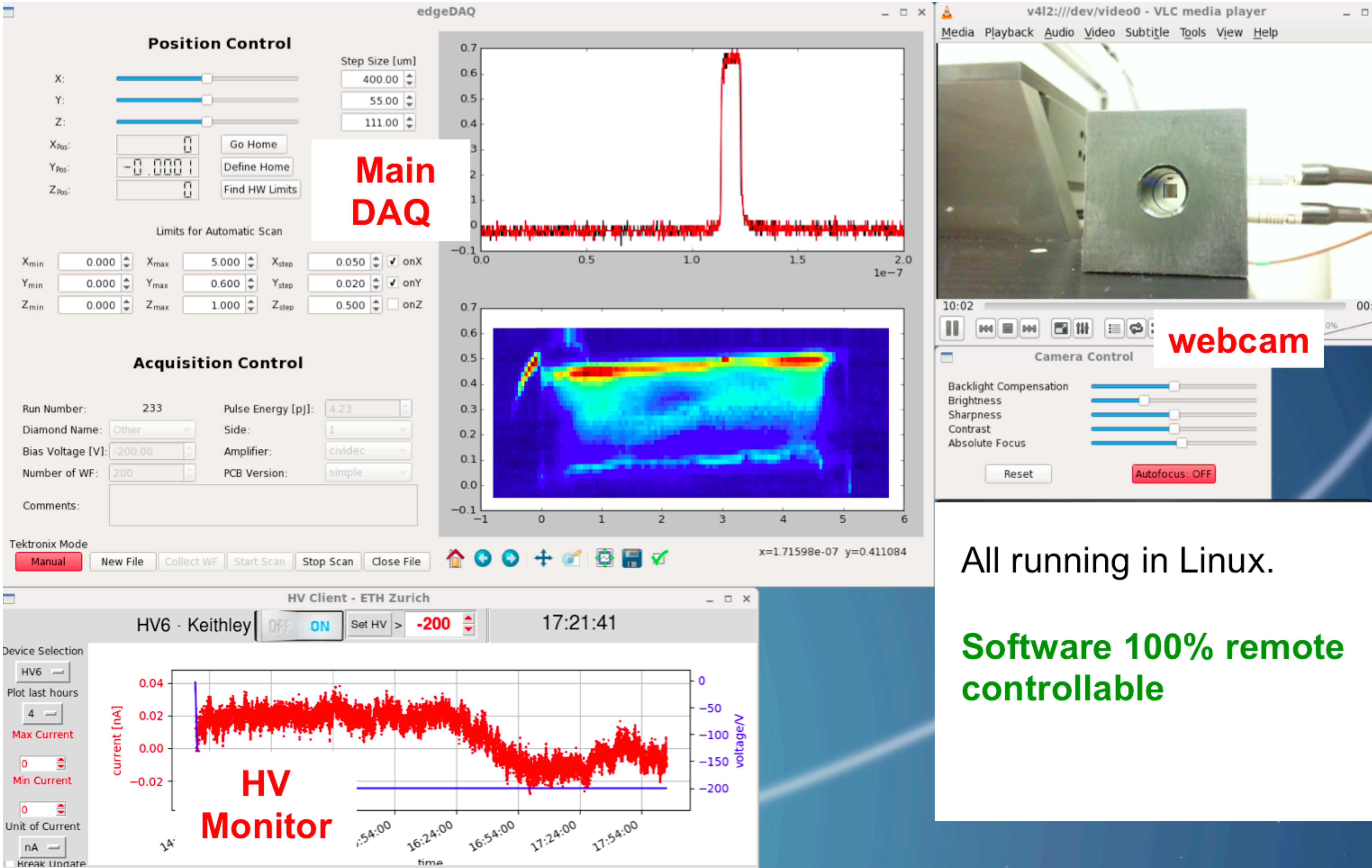
Table control
DAQ-PC
LV
HV


photodiode
mirror
focusing lens
NDFs
(neutral density filters)
filter
mirror
BBO
(barium borate crystal)
April 2017


photodiode


‘old’ diamond holder

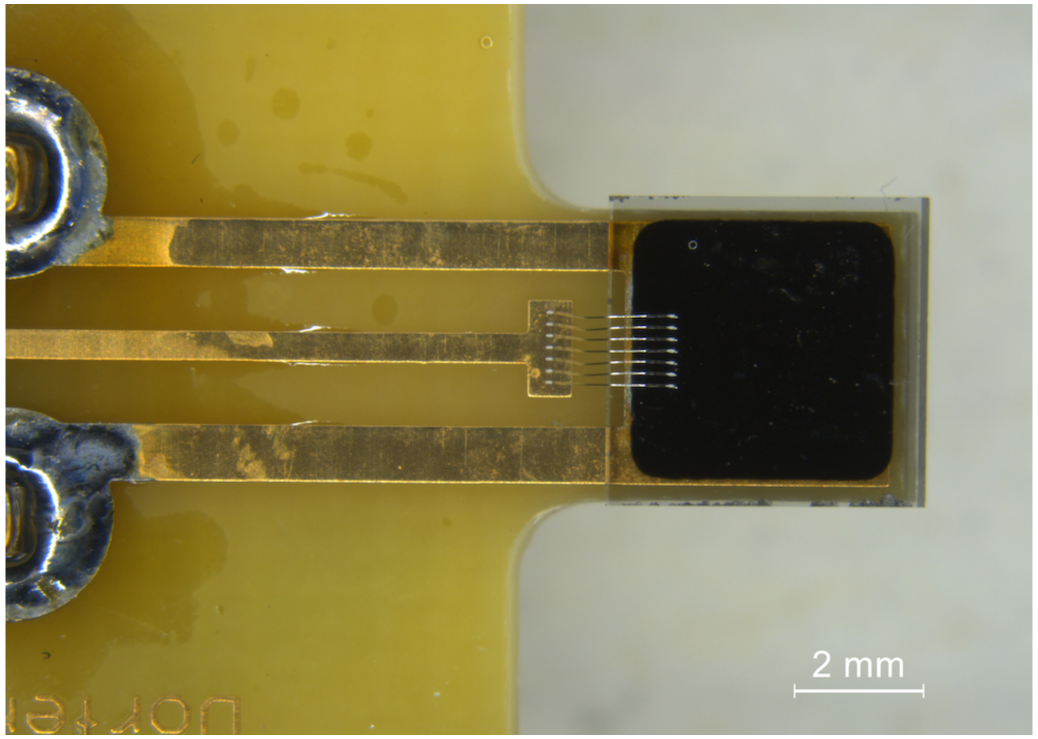
DAQ screenshot

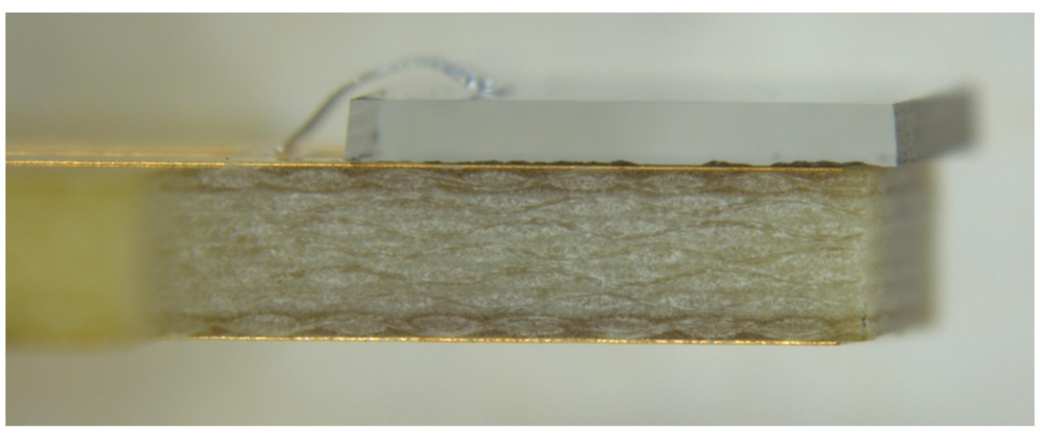


All running in Linux.

Software 100% remote controllable

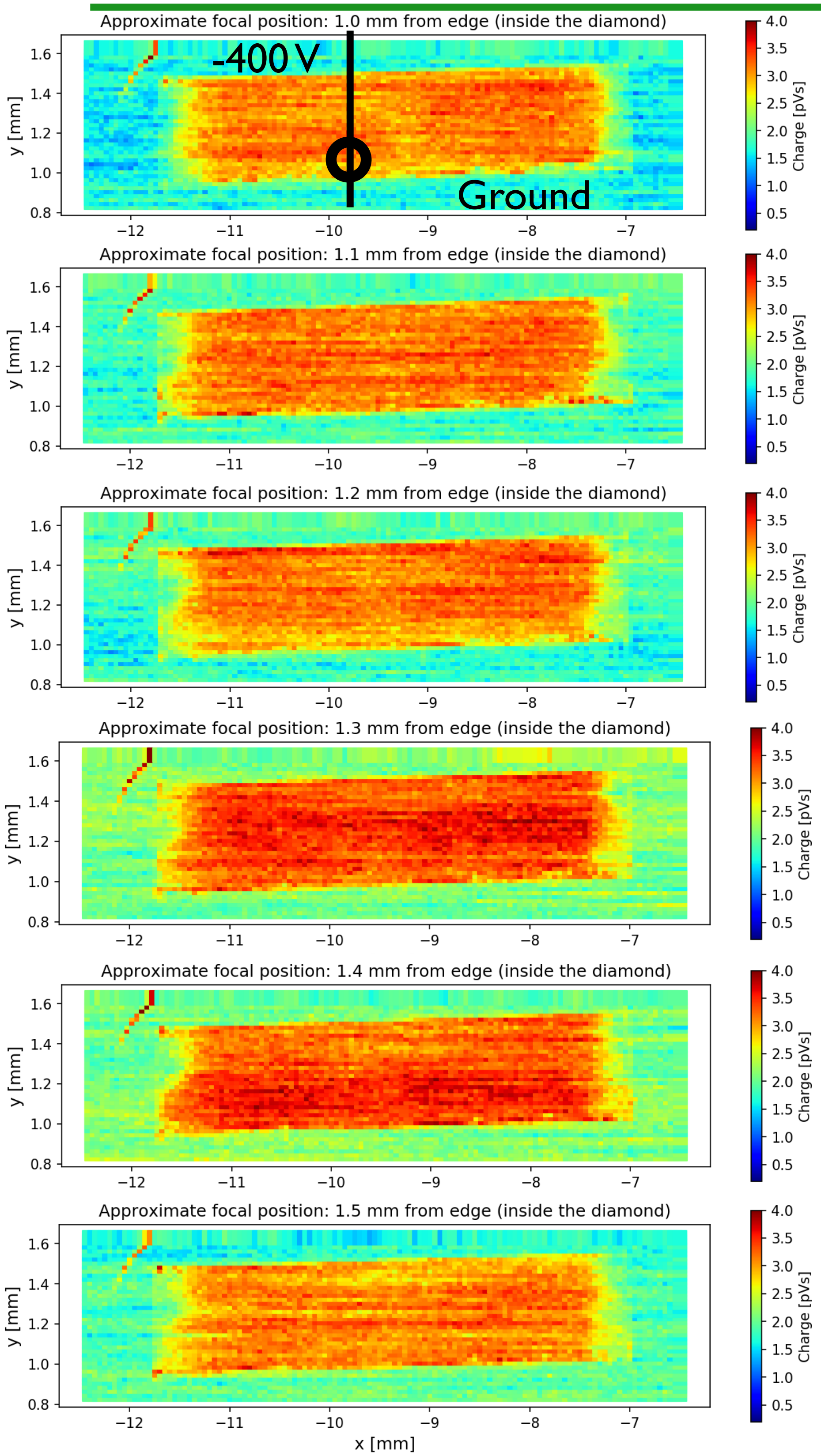
scCVD sample

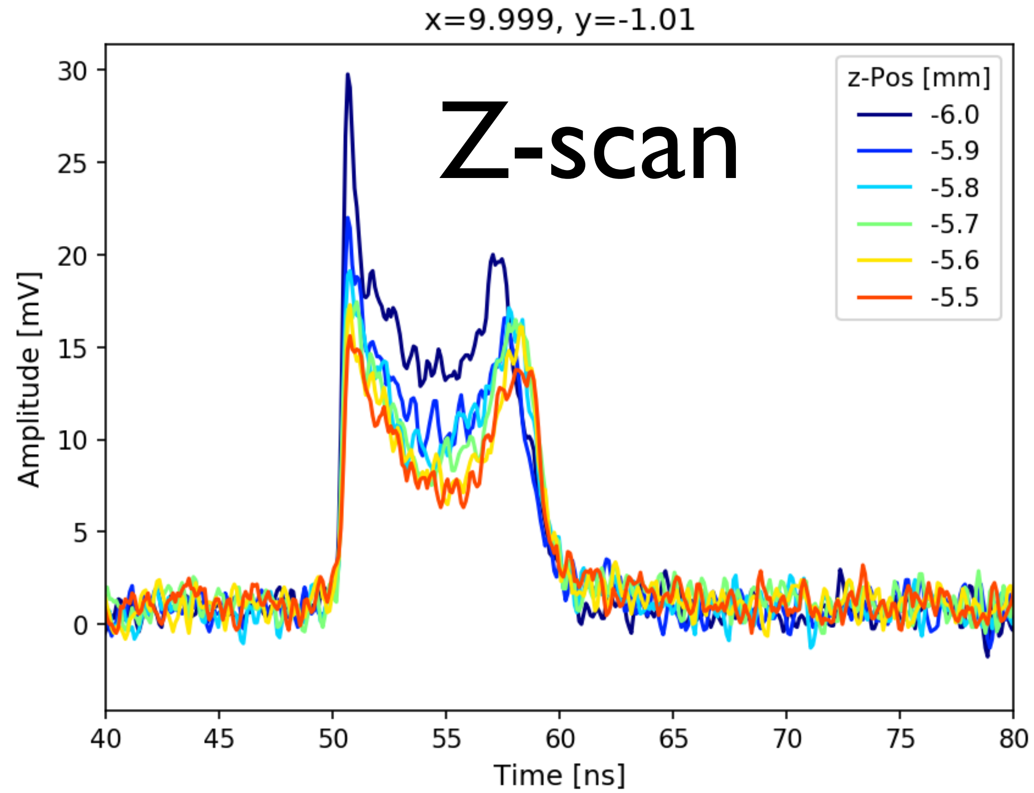


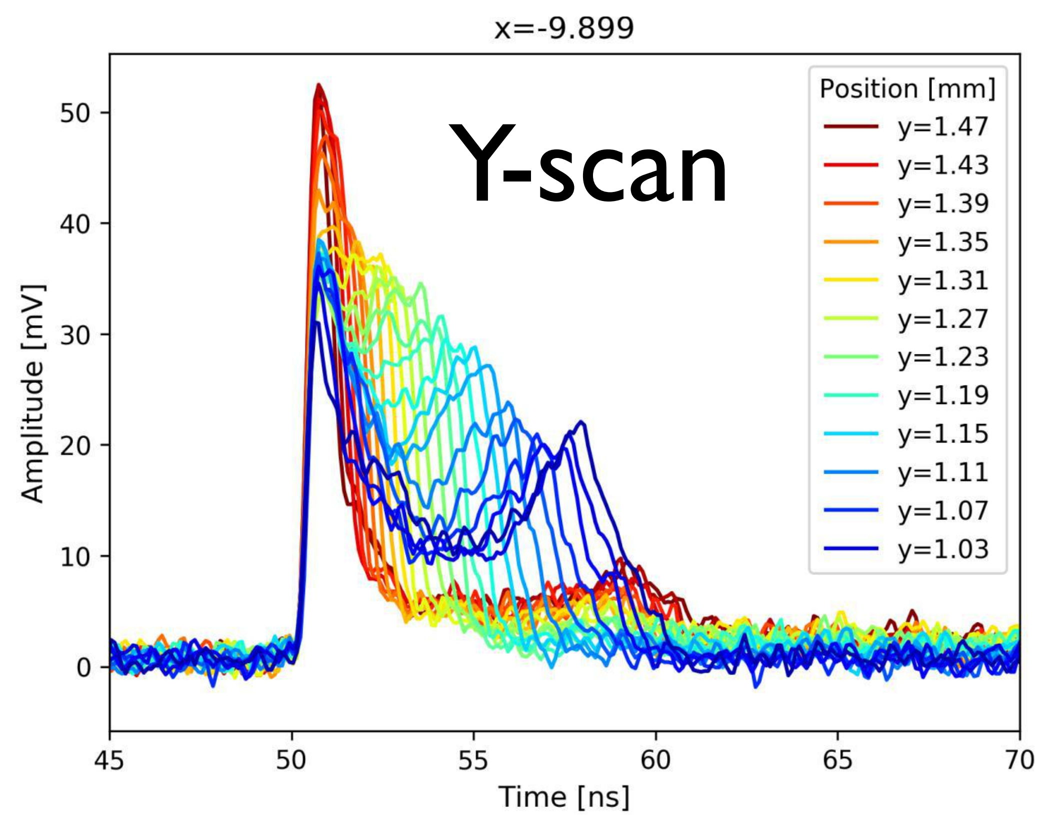


- un-irradiated
- bought from Element 6 (through DDL)
- pad metallized by Rutgers University (TiW sputtered with shadow mask)
- metallization distance from edge ≈400 µm
- Not used in PLT due to poor CCD performance
  - requires high field to collect full charge
- 2 edges polished

1st 3D scan



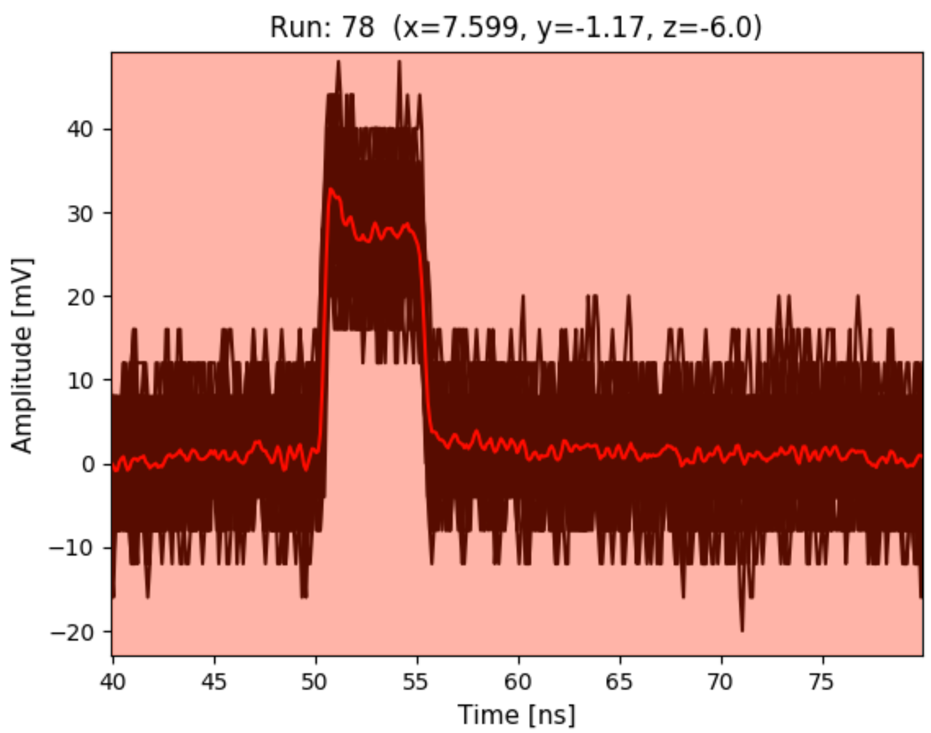


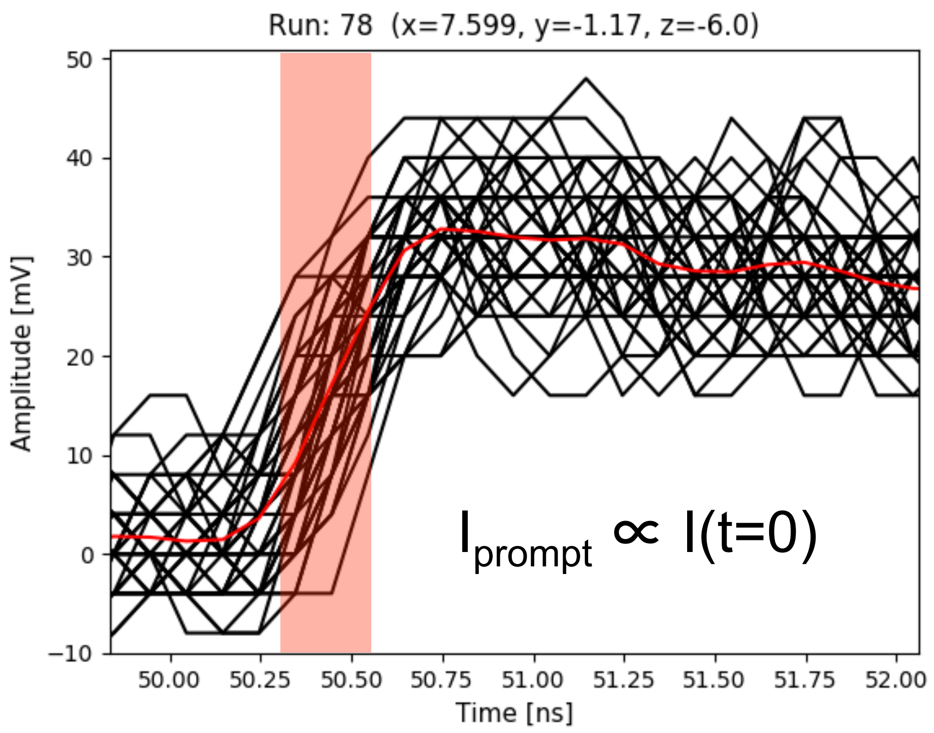


- Test parameters:
  - Bias voltage: -400V
  - 50 waveform averaging, 3993 scan points (~0.4s each)
  - Laser pulse energy: 0.2 nJ
- Parameters to extract:
  - electrons seem to drift differently than holes (uniform positive space charge?)
  - drift speed
  - electrical field configuration
  - trapping rate
  - …

ETH zürich

Waveform analysis

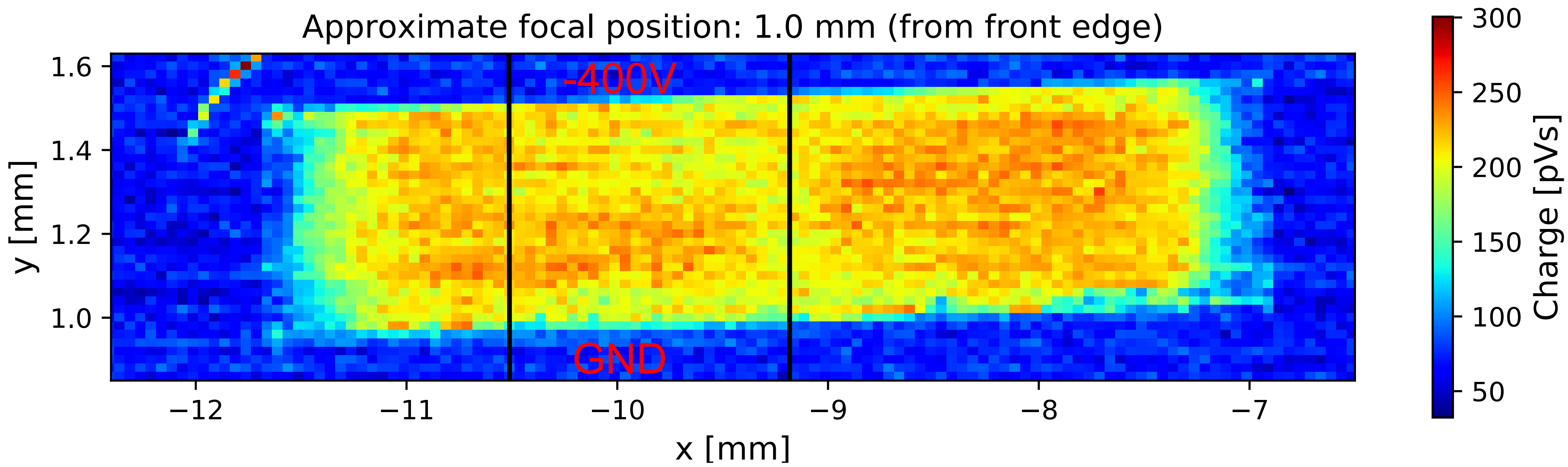


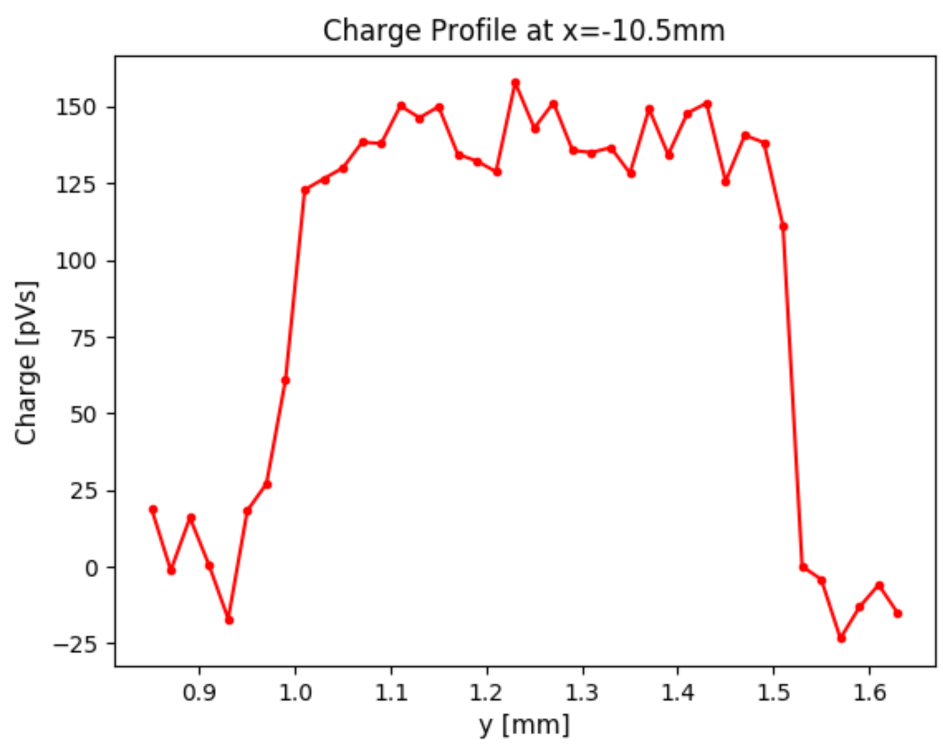


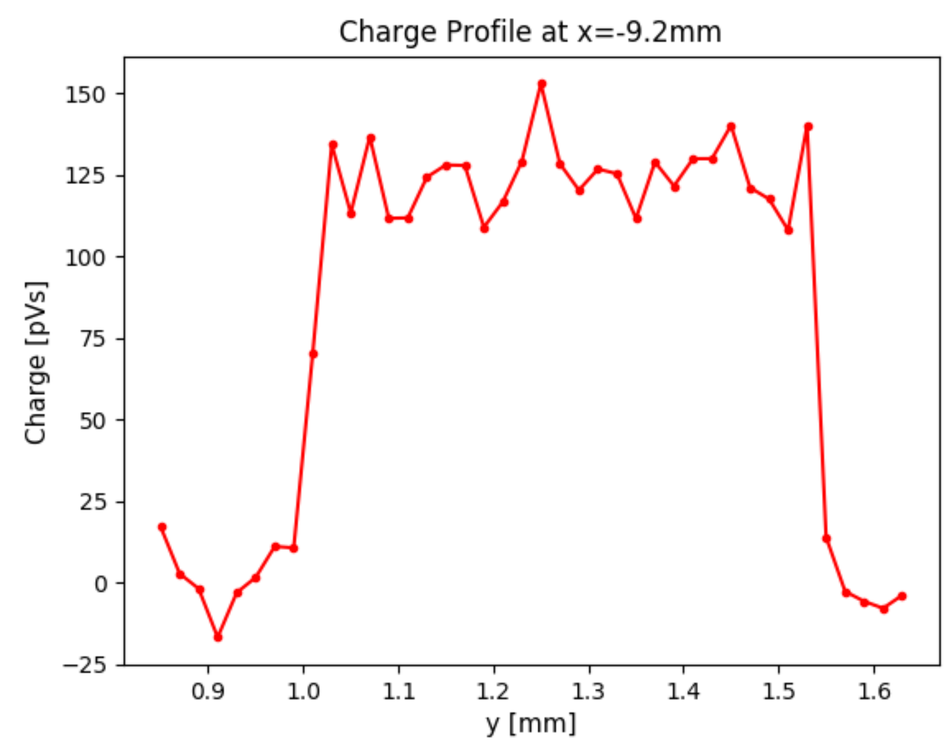
- Total charge
  - Integral of the complete baseline corrected waveform

- Prompt current
  - 0.3 ns-Integral around the center of the rising edge

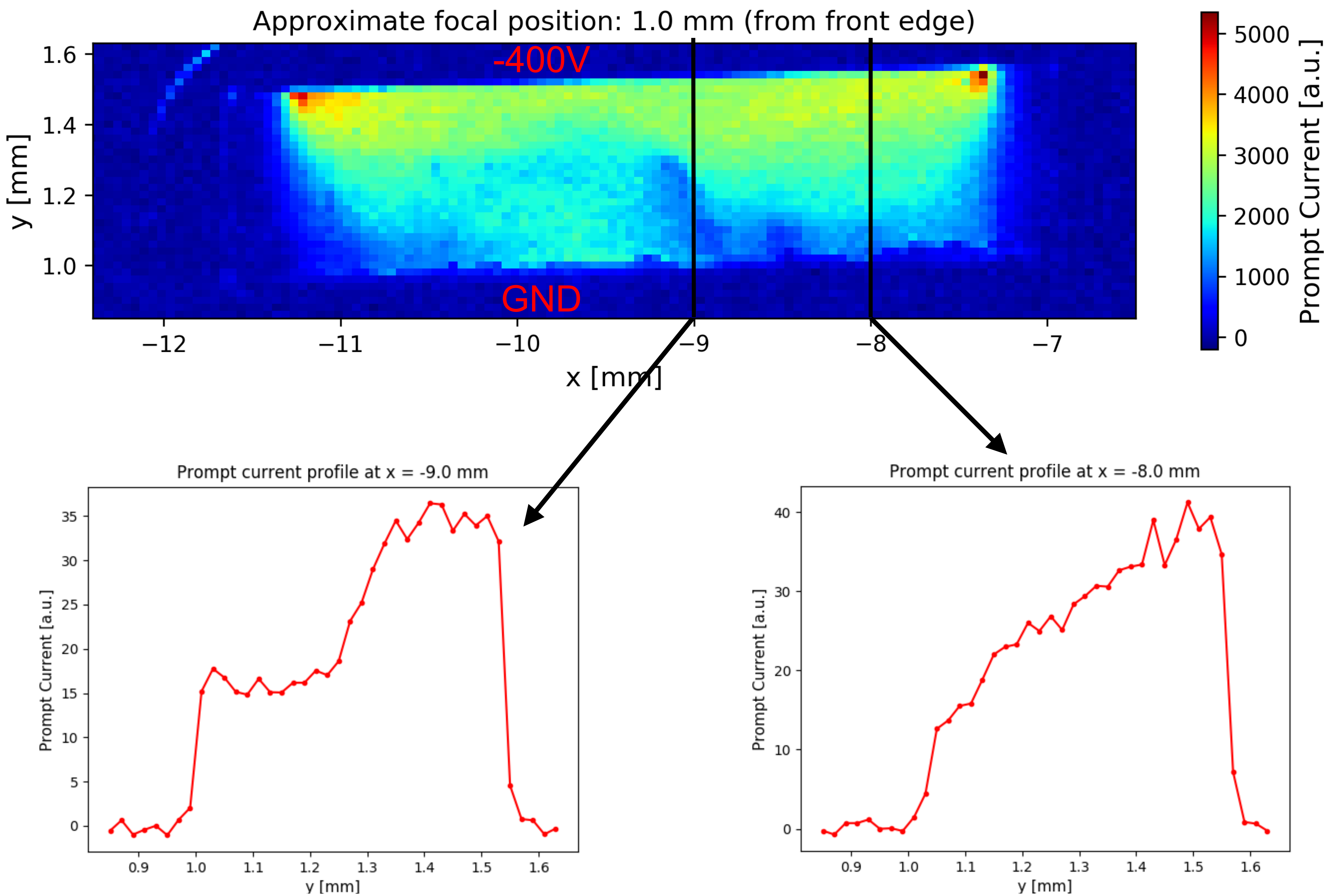
Total charge



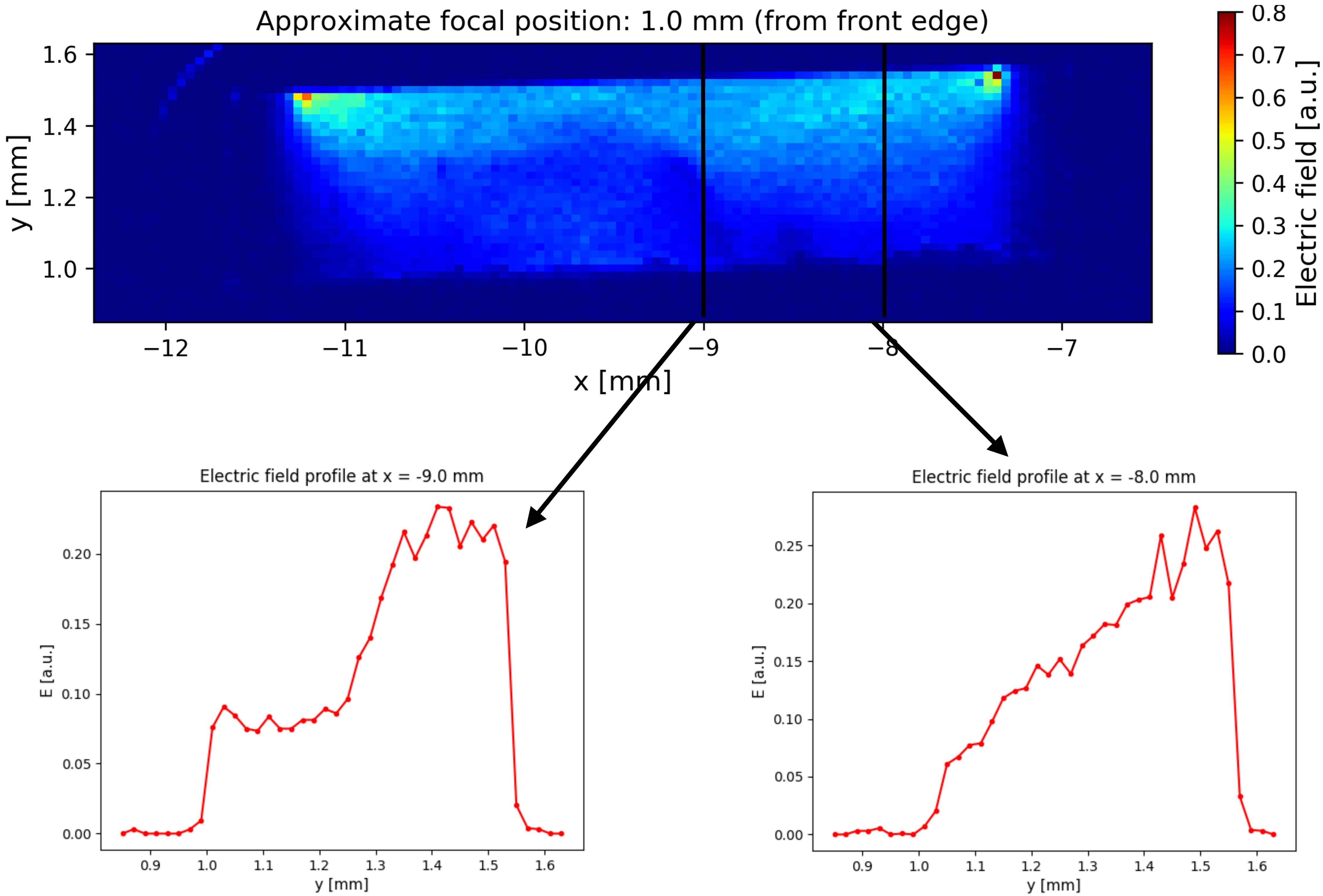




Prompt current



Electric field

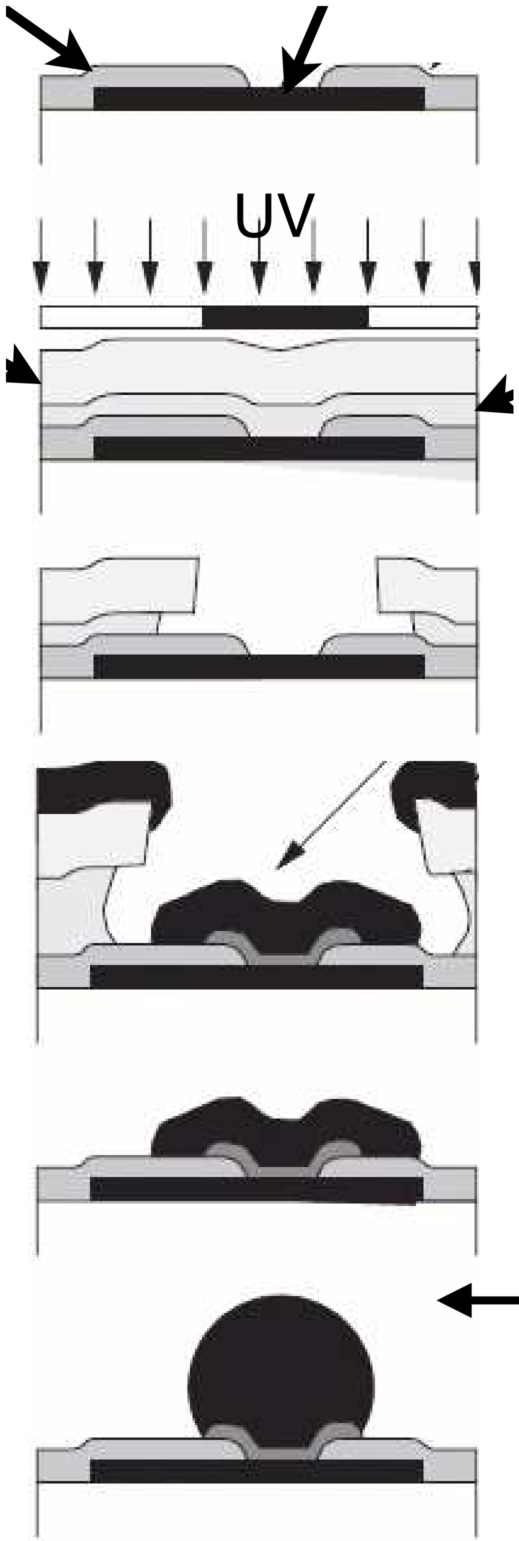


Development of in-house sensor bump bonding

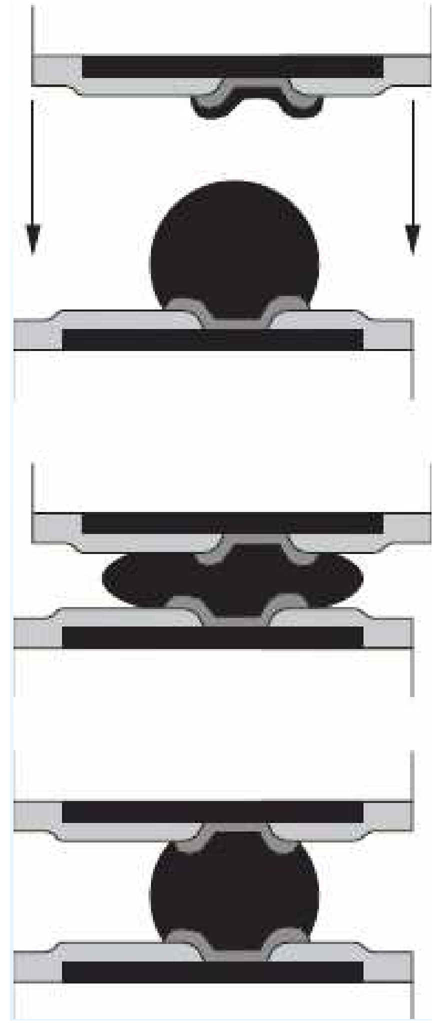
Diego Alejandro Sanz Becerra (present)

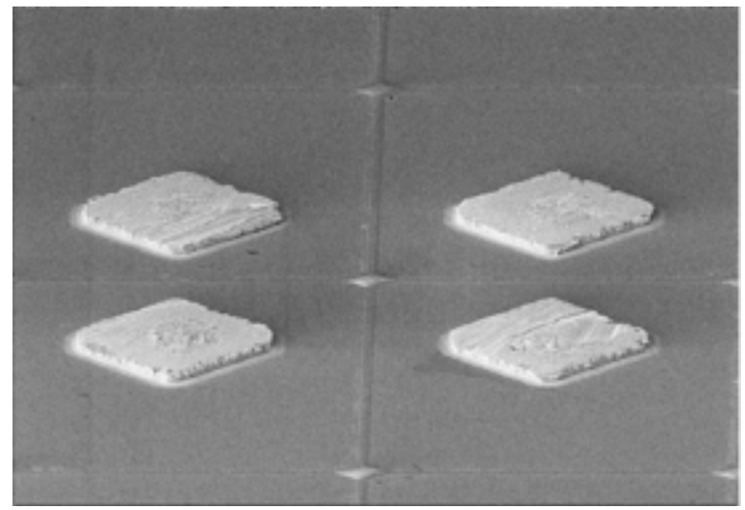
Felix Bachmair (past)

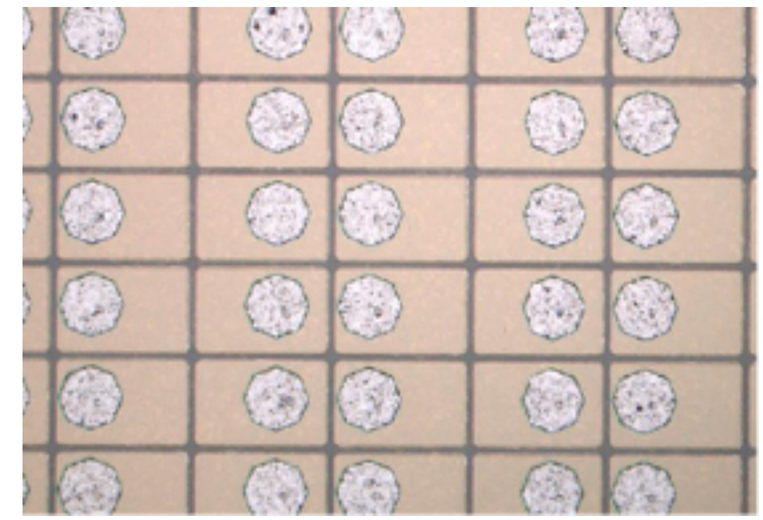
Bump bonding process



We were stuck here

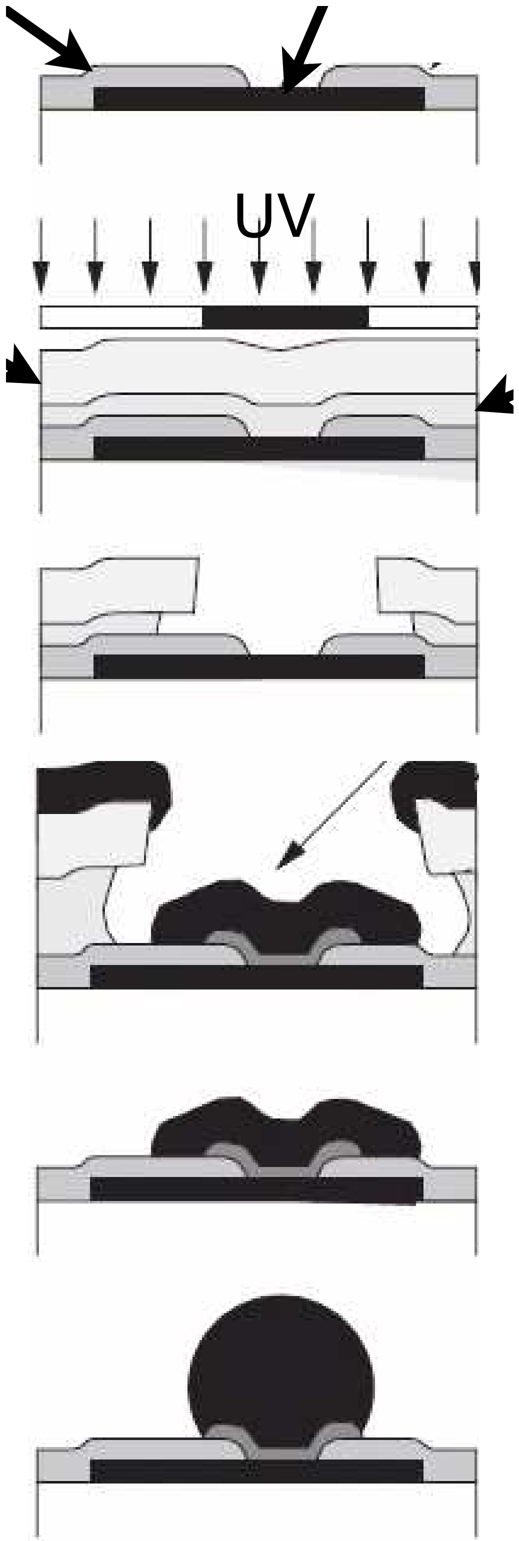


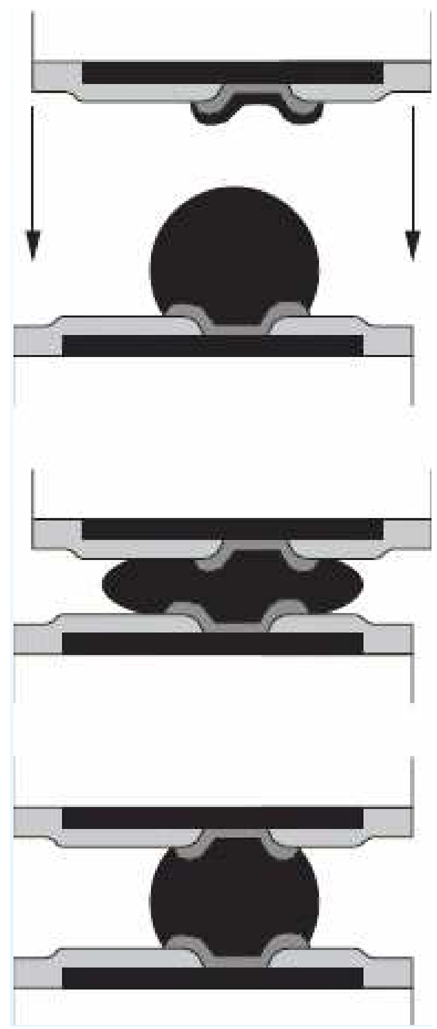




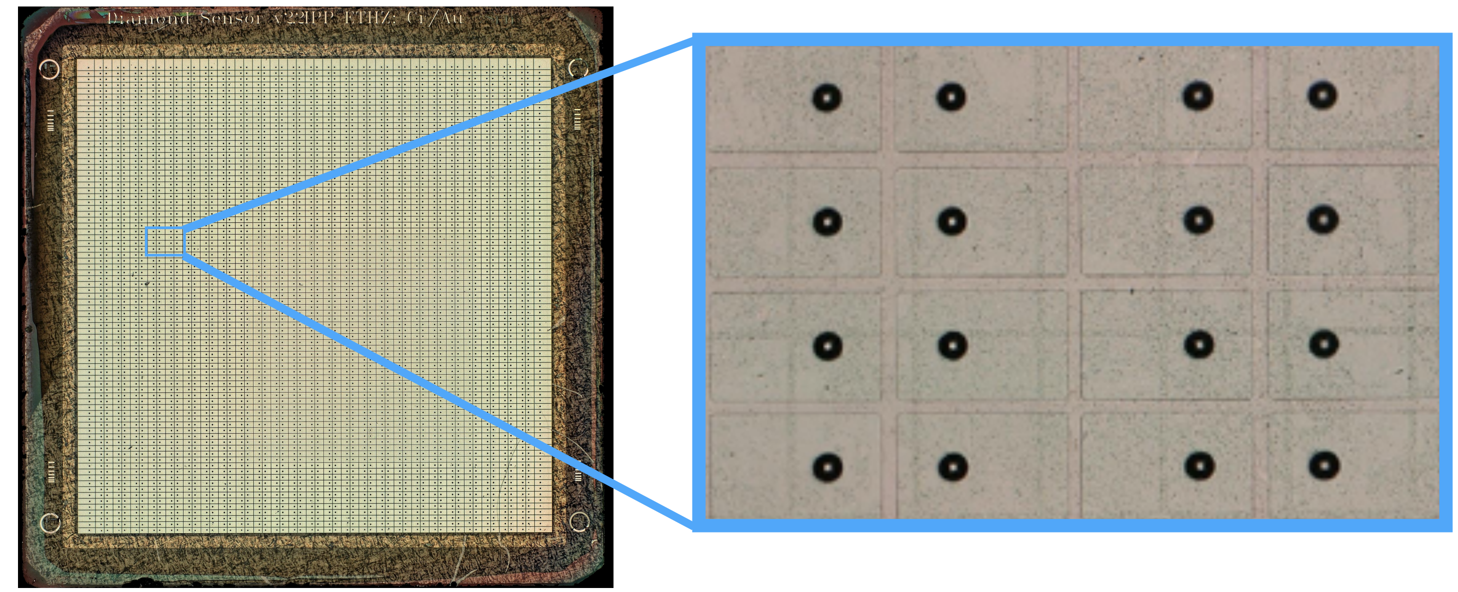
- Deposition of pixel and backside contact metal
  - Cr/Ni/Au (alternatives Ti, TiW, Al)
- Deposit passivation and etch window to contact metal
  - Al2O3, SiNx, SiON
- Deposition of extra UBM in the passivation window
  - Ti/Ni/Au
- Deposition of indium
- Reflow of indium
- Bump bonding and reflow the bump bonded device
- Process successful up to the reflow step

Bump bonding process



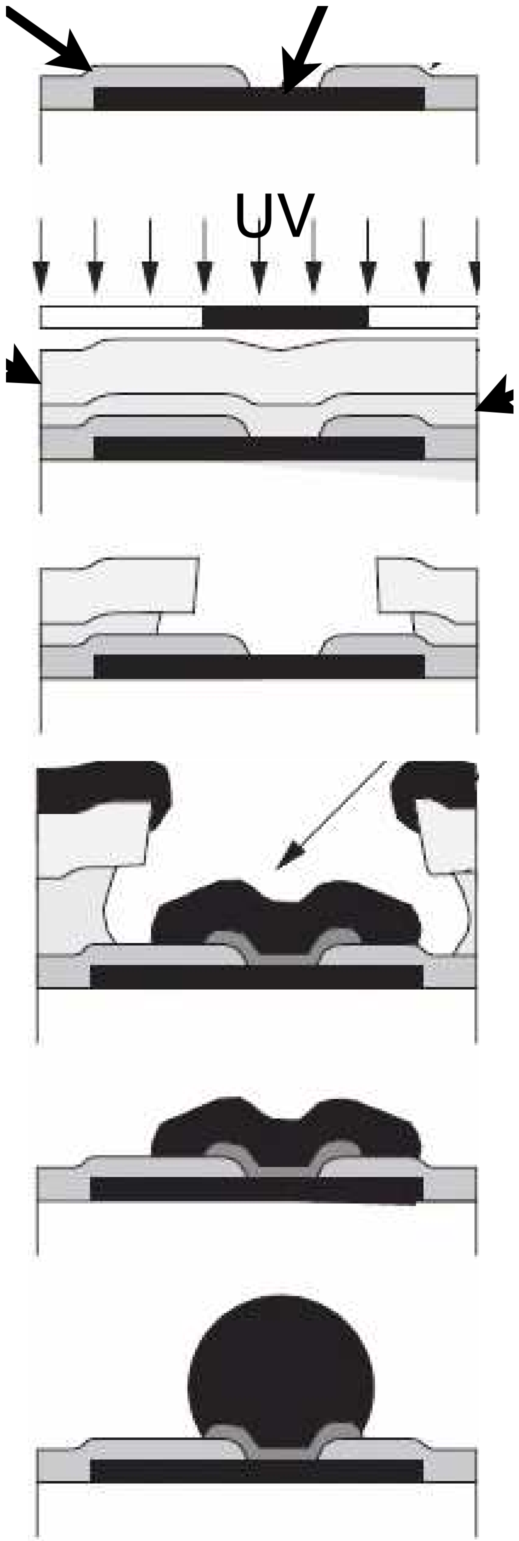


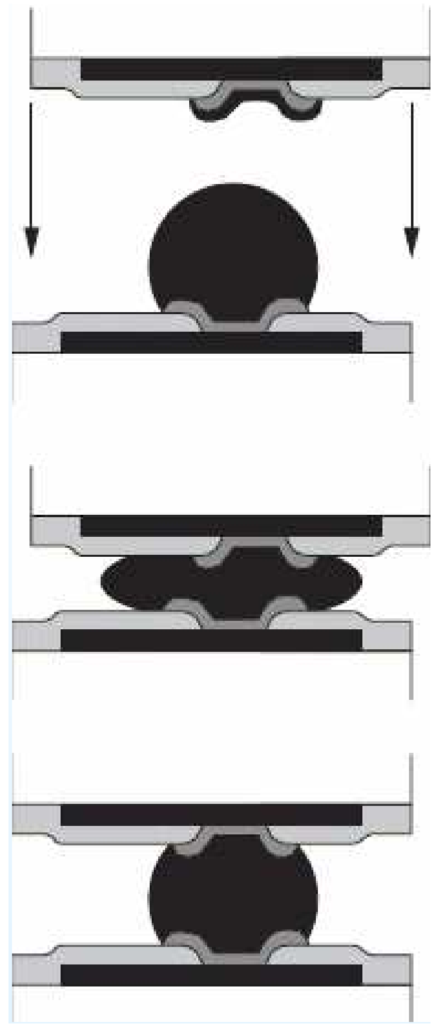
We are there!



- Deposition of pixel and backside contact metal
  - Ti/Al
- Deposit passivation and etch window to contact metal
  - SiON
- Deposition of extra UBM in the passivation window
  - Ti/Ni/Au
- Deposition of indium
- Reflow of indium
- Bump bonding and reflow the bump bonded device

Bump bonding process

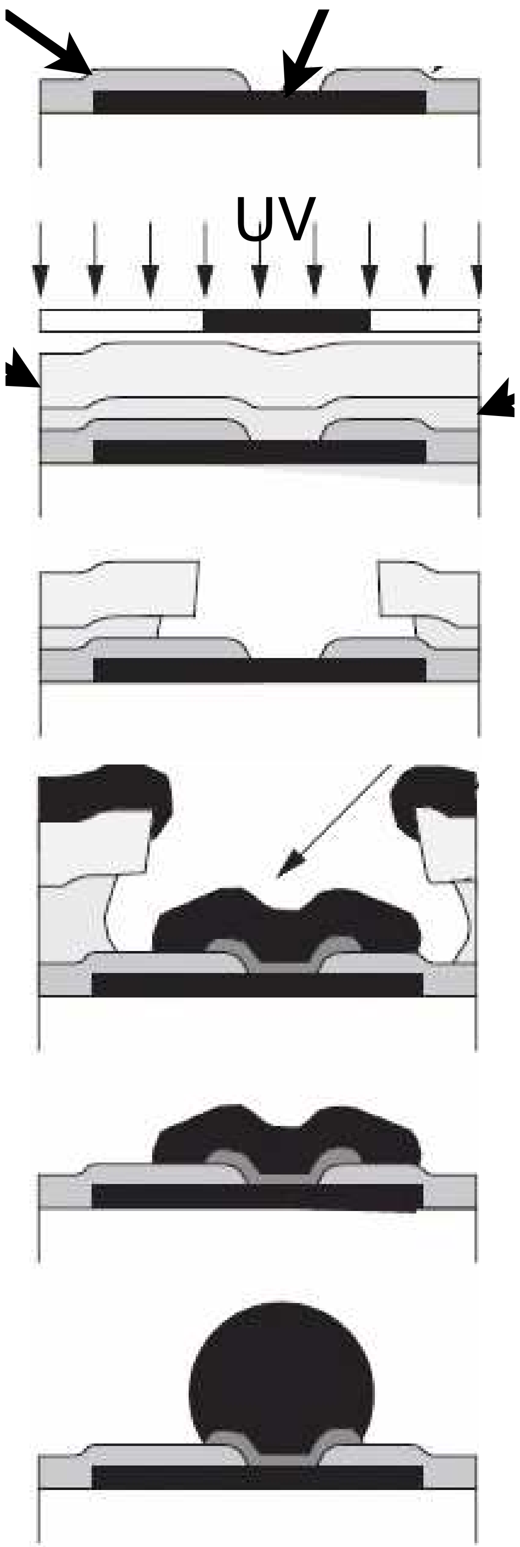


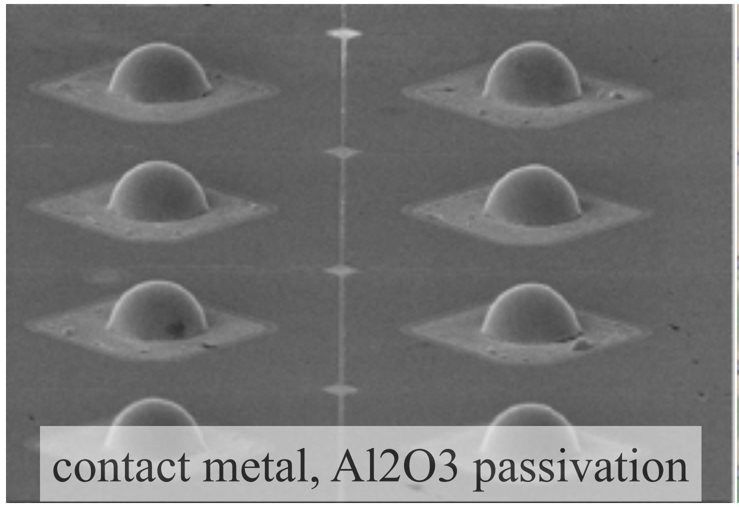


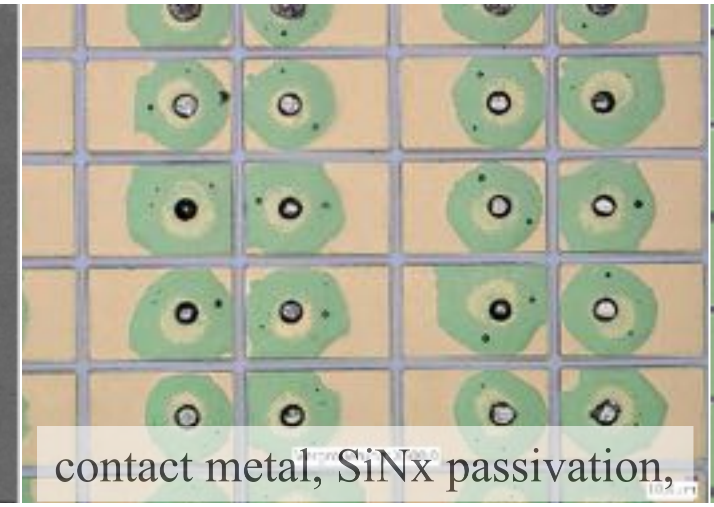
We are there!

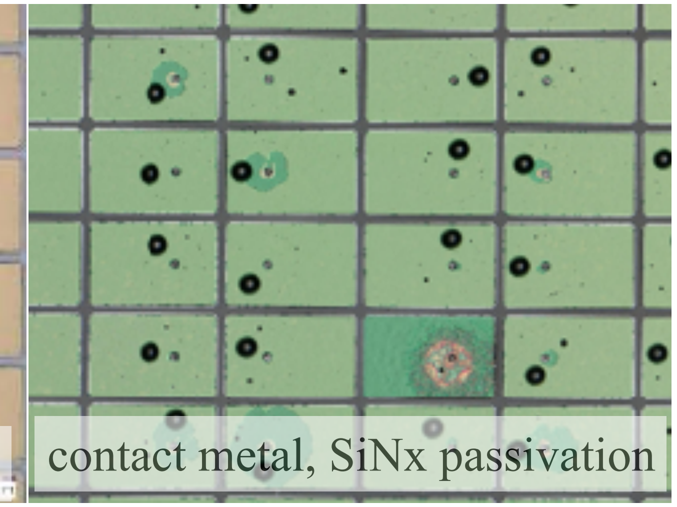
- 2 in house produced devices ready for testing!

Bump bonding (problems)

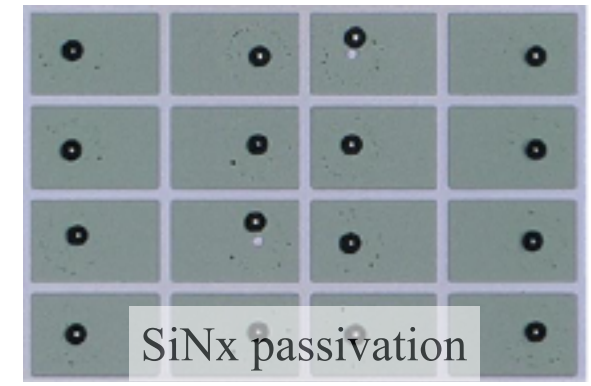


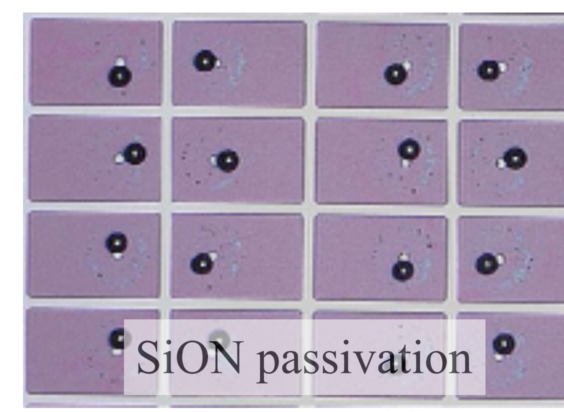

contact metal, Al2O3 passivation


contact metal, SiNx passivation,


contact metal, SiNx passivation

- Investigate matrix of many parameter
  - Varied sizes of under bump metallization opening
  - Varied sizes of the Indium pancakes
  - Different passivations
    - Al2O3 (natural oxide on Al),
    - SiNx, SiON (PECVD deposition followed by RIE)
  - With/without extra UBM in the passivation window
  - Varying top layer of contact metal
    - Au or Al on top of Cr and Ni


SiNx passivation


SiON passivation


contact metal,
SiON passivation, extra UBM

Conclusions

- Diamonds make good particle detectors
- They used in a wide range of applications
  - beam abort, particle timing, x-ray beam monitoring
- At ETH we are working to better understand the properties of the diamond sensors
  - Radiation hardness study extended to 10^{17} protons/cm^2
  - Study of rate behavior from 10 kHz/cm^2 to 10 MHz/cm^2 for diamonds irradiated to 4×10^{15} neutrons/cm^2
  - Successfully tested two 3D diamond sensors with pixel readout
    - ➡ 150μm x 100μm cells and 50μm x 50μm cells
  - e-TCT setup is fully operational
  - Bump-bonded our first diamond to a pixel readout using in-house process

Outlook

- Continue study 3D detectors
  - irradiate them to full HL-LHC dose
- Interpret our eTCT results and test irradiated diamonds with it
  - Test 3D diamonds with it
- Optimize our bump bonding procedure and produce a full CMS pixel module with a diamond sensor
- In more distant future investigate building electronics on diamond

Thank you for attention

Extra Slides

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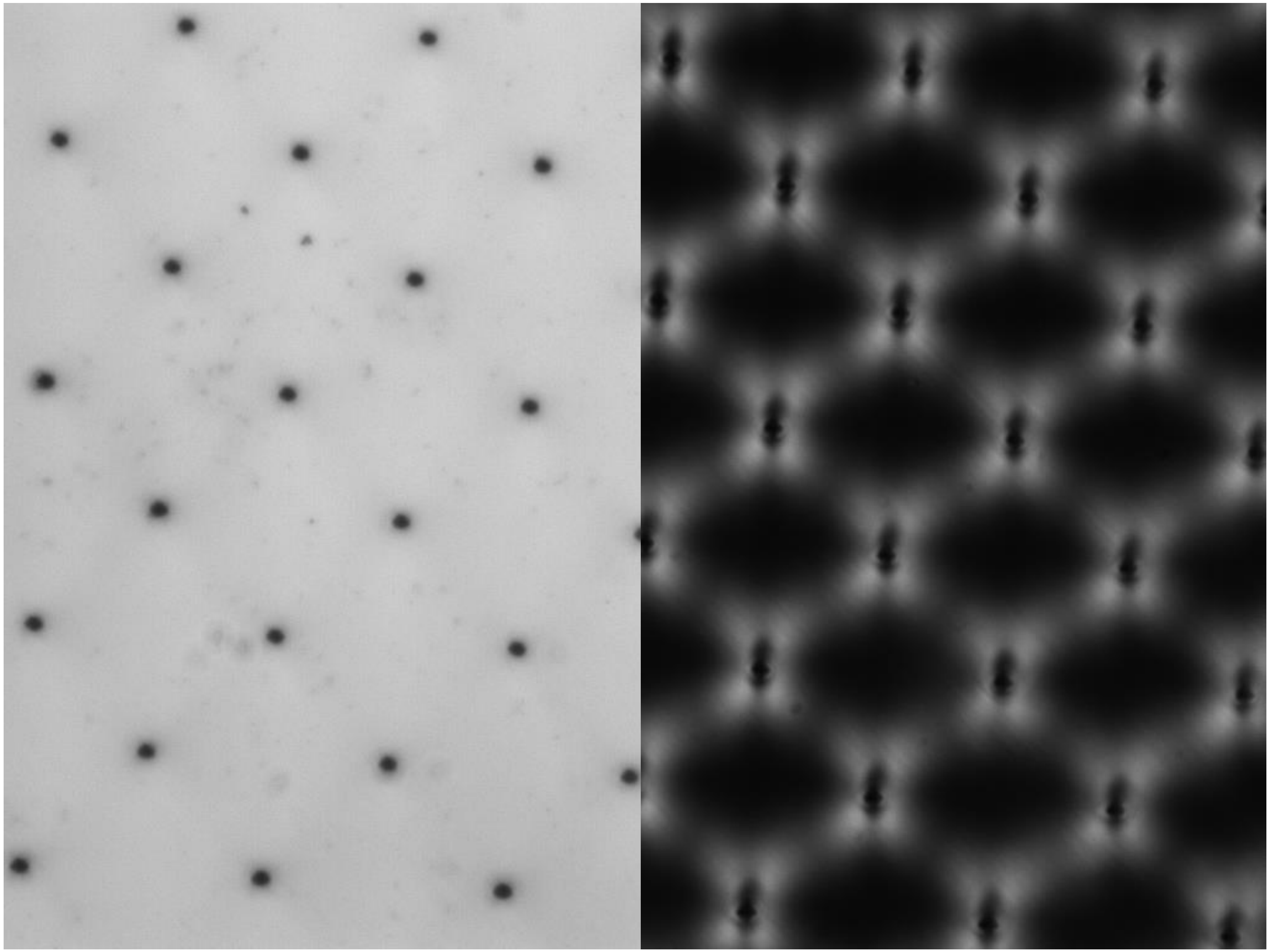
Properties of diamond compared to silicon

		silicon [a]		natural diamond [b]	
proton number	[ ]	14		6	
atomic number	[ ]	28.0855	[9]	12.011	[9]
lattice constant	[Å]	5.4310	[10]	3.5668	[10]
mass density	[$\mathrm{g\,cm^{-3}}$]	2.329	[10]	3.515	[10]
cohesive energy	[eV/atom]	4.63	[11]	7.37	[11]
melting point	[K]	1685	[10]	4100 [(c)]	[10]
band gap	[eV]	1.124	[10]	5.48	[10]
relative dielectric constant [d]	[ ]	11.9	[10]	5.7	[10]
resistivity	[Ωcm]	20×10^3 [(e)]		$> 10^{13}$	[11]
	[Ωcm]	5×10^{11} [(f)]	[3.2.3]	$> 10^{14}$ [(g)]	[3.2.3]
breakdown field	[V/μm]	30		1000	
electron mobility	[$\mathrm{cm^2\,V^{-1}\,s^{-1}}$]			1500..	[12]
		1450	[10]	..2400	[13]
hole mobility	[$\mathrm{cm^2\,V^{-1}\,s^{-1}}$]			1000..	[12]
		≈ 440	[10]	..2100	[13]
electron saturation velocity	[cm/s]			2×10^7	[13]
hole saturation velocity	[cm/s]			10^7	[13]
thermal expansion coefficient	[$10^{-6}\mathrm{K^{-1}}$]	2.59	[10]	0.8..1.0	[14]
thermal conductivity	[$\mathrm{W\,cm^{-1}\,K^{-1}}$]	1.4		20..23	[14]
energy to create *eh*-pair	[eV]	3.6	[15, 16]	13	[13, 17]
radiation length	[cm]	9.4	[9]	12.03	[3.75]
specific ionization loss	[MeV/cm]	3.9	[3.3.1]	6.2	[3.3.1]
ave. no. of *eh*-pairs/*mip*	[pairs/100 μm]	9000	[3.3.5]	3600	[11]
ave. no. of *eh*-pairs/*mip*	[pairs/300 μm]	27000	[3.3.5]	11850	[3.3.5]

Example of 3D detector drilling

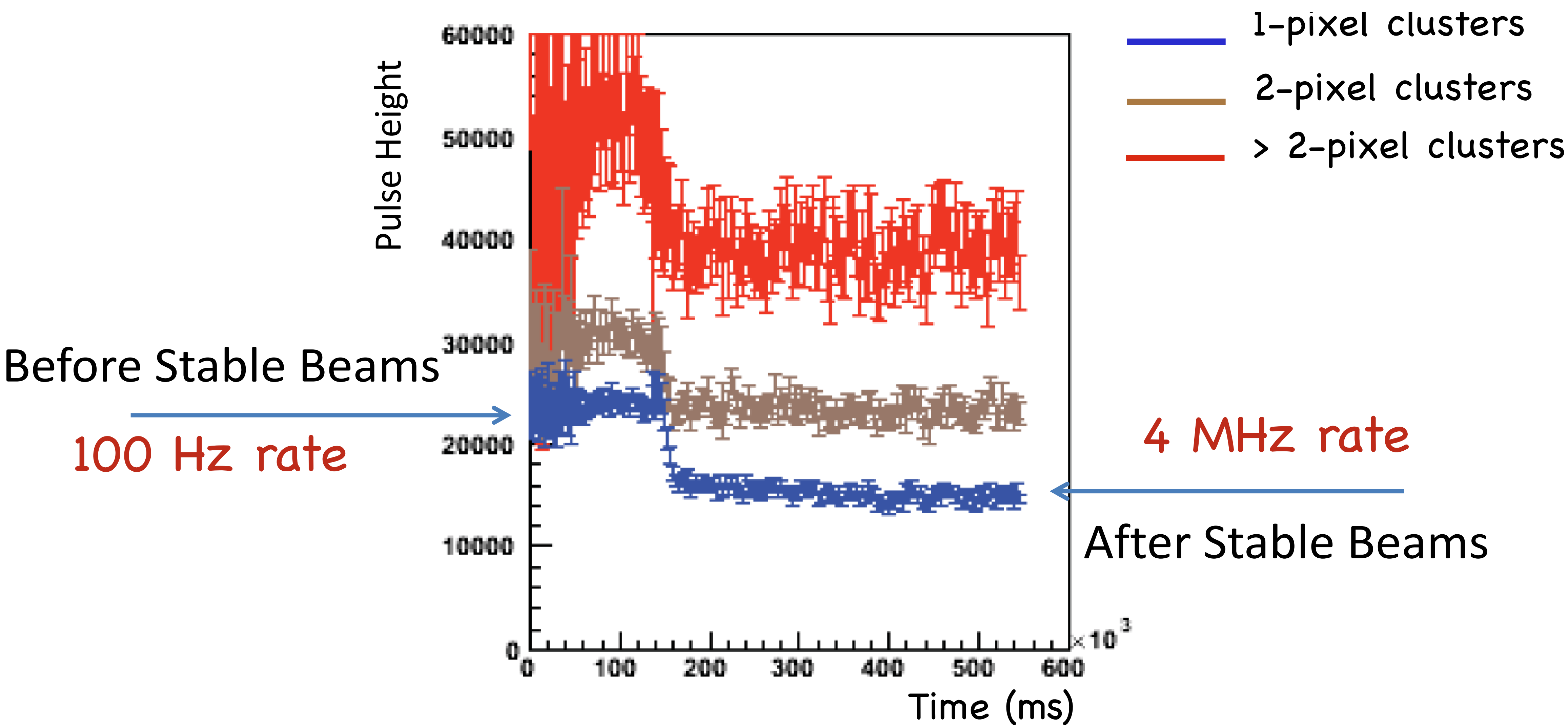


Array 3:
10× transmission microscope image without and with crossed polarisers.

Electrode diameter is ~4.5um.

Reminder from the diamond past

- 2012 pilot run of PLT with single crystal CVD diamonds in the CASTOR region
- Reduction of pulse height at higher rate observed

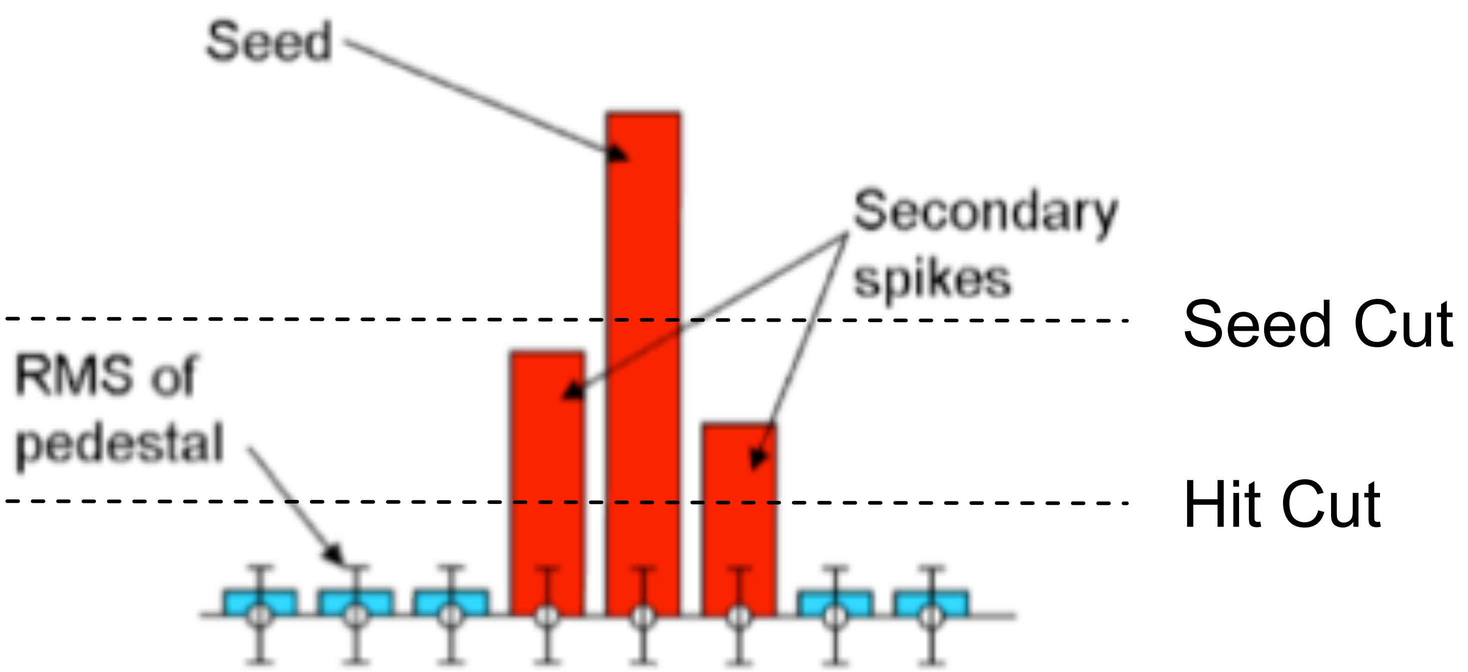


Analysis procedure

- Perform pedestal analysis and subtraction
  - Correct for the common mode
- Cluster channels above threshold(s)
  - “seed” threshold, “hit” threshold
- Select events with only one cluster in each telescope plane
- Align telescope
- Select events with only one cluster in each telescope plane and only one cluster in the diamond plane
- Align diamond plane to the telescope
- Transparent analysis
  - require only “good” tracks in the fiducial region of the telescope
  - no requirement on the diamond plane - unbiased

Beam test analysis: clustering

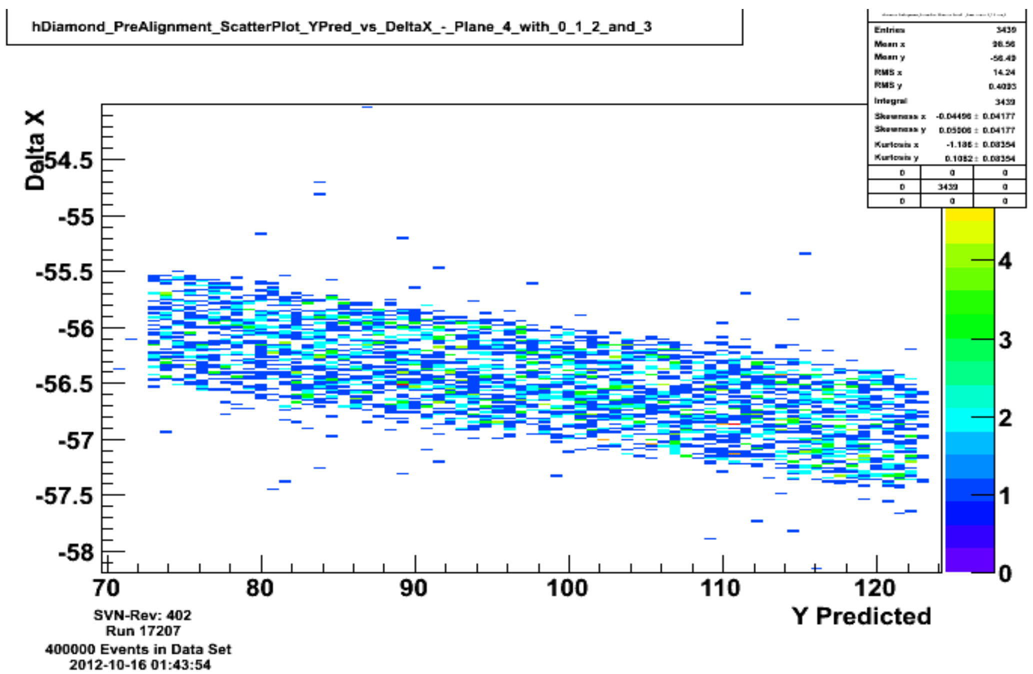
- pedestal subtraction
- clustering
  - seed cut in diamond plane is 5σ
  - hit cut 3σ

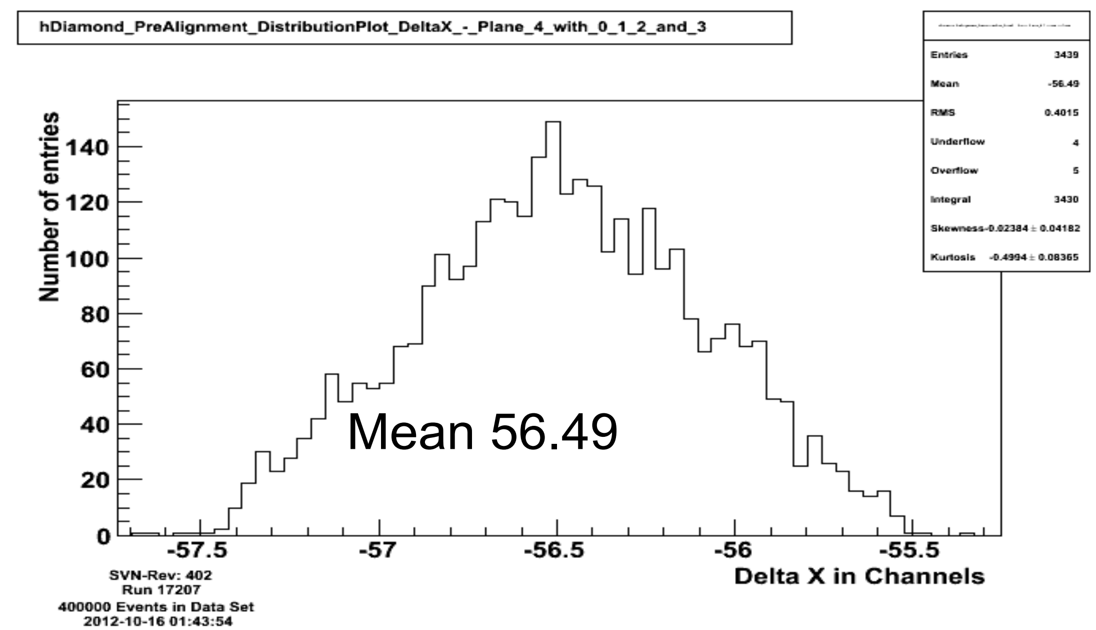


Alignment

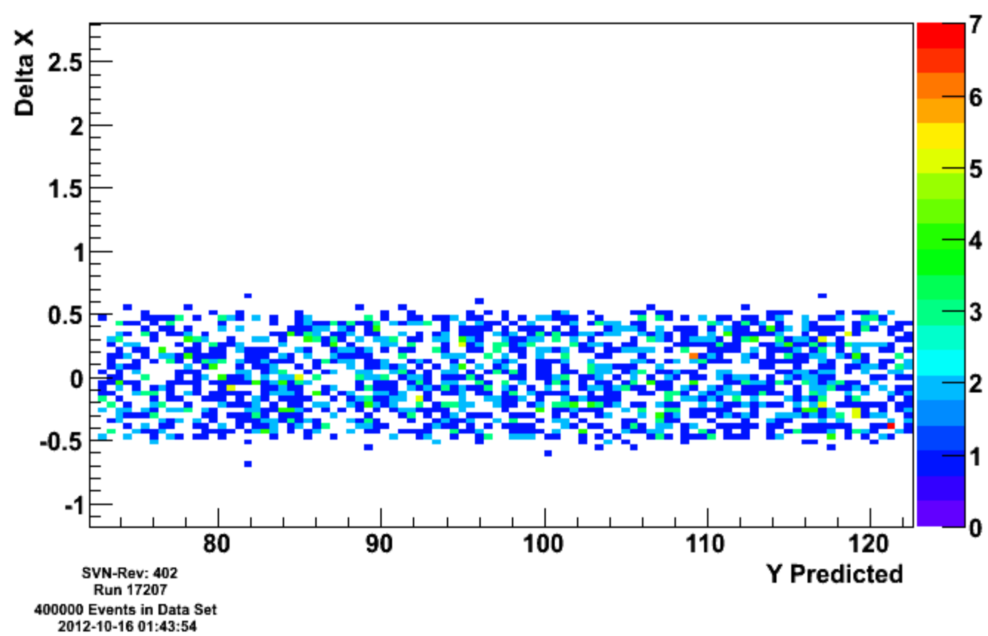
- Correct for shift and rotation in telescope and DUT planes

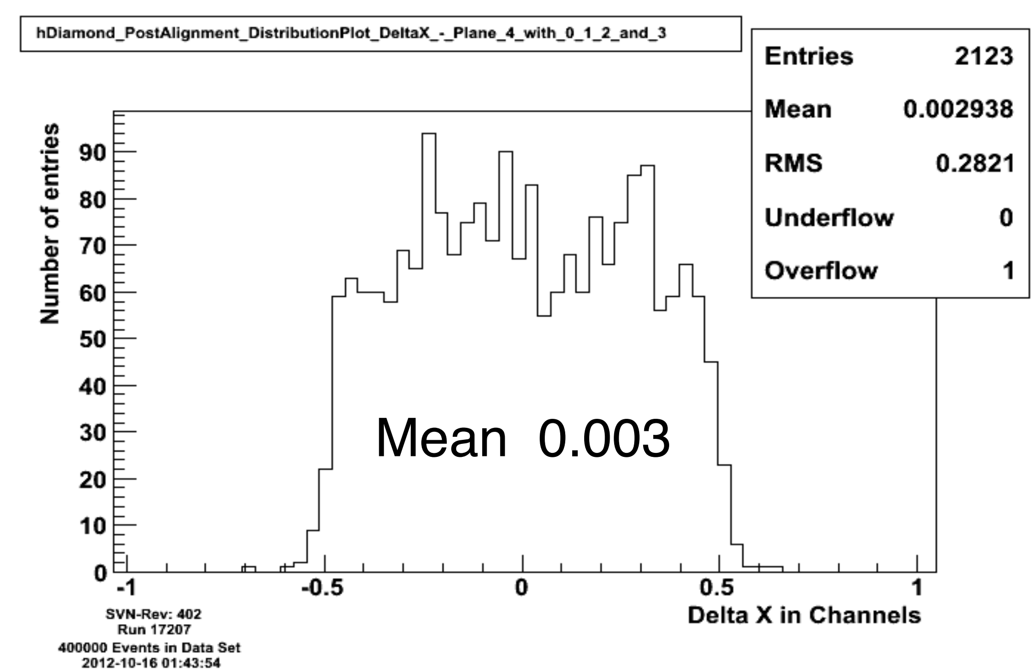
Before alignment





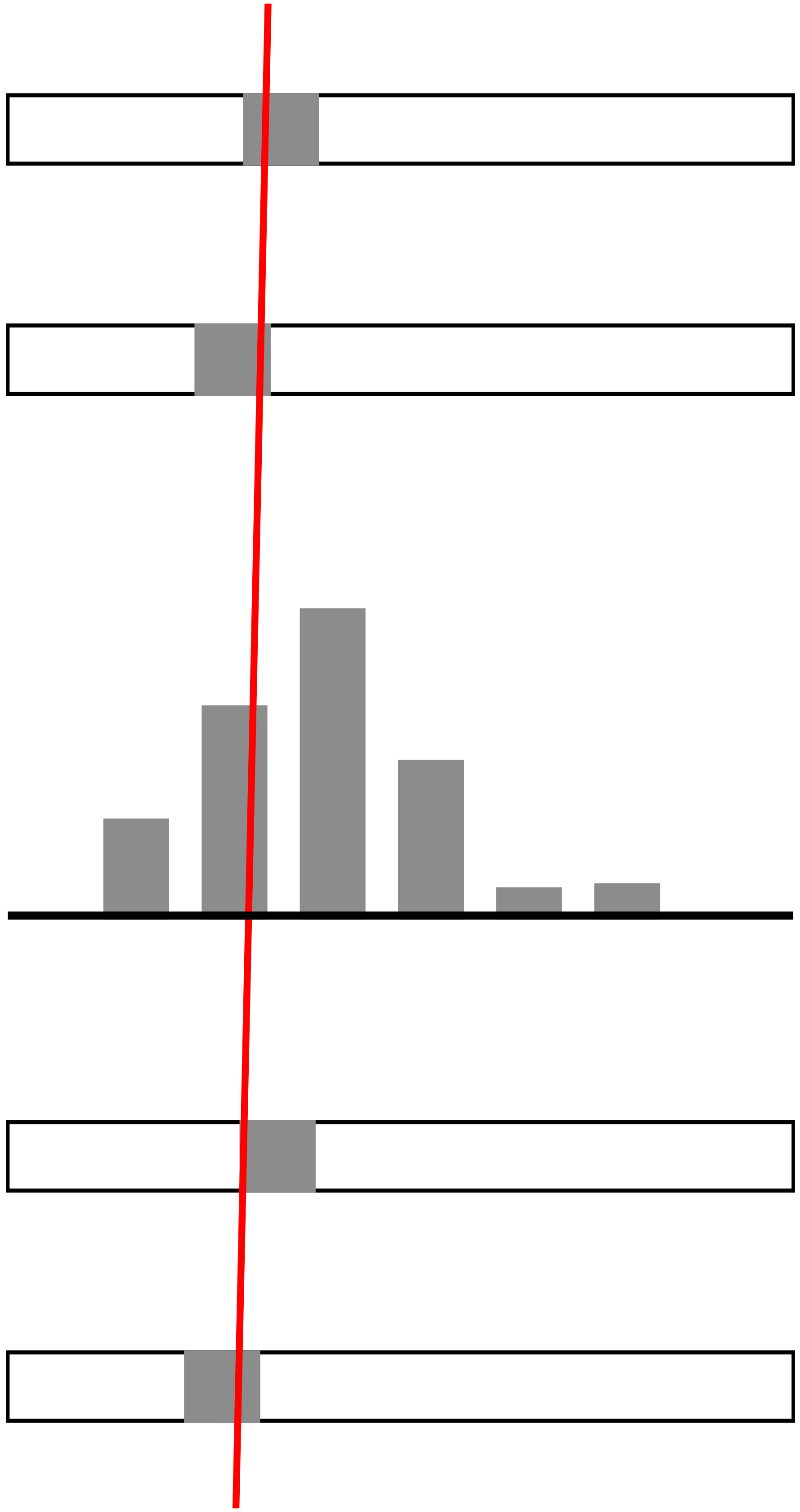
After alignment





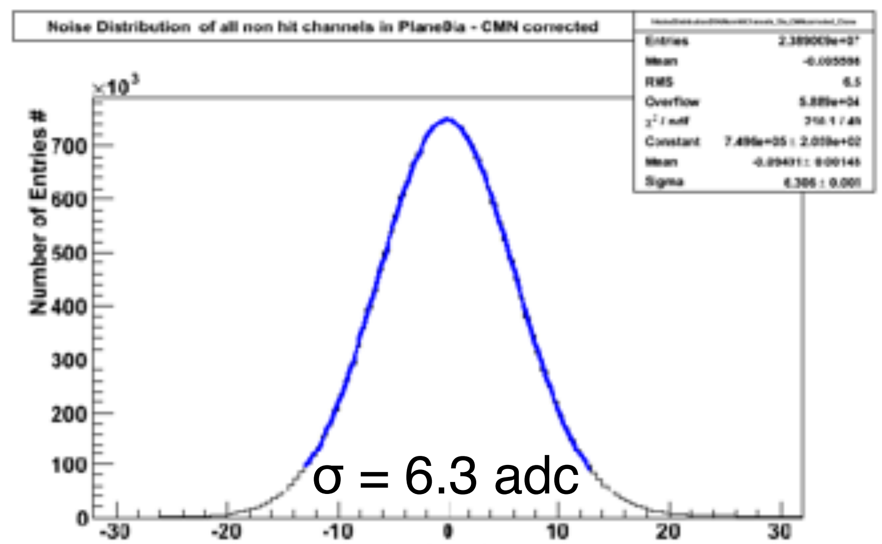
Transparent analysis

- Telescope plus DUT is aligned on a subset of tracks
  - not used in analysis
- Use telescope to predict hit position in the DUT
- In 10 strips surrounding the predicted position find two neighboring strips with the largest pulse heights
  - Measure cluster pulse height
  - Measure resolution

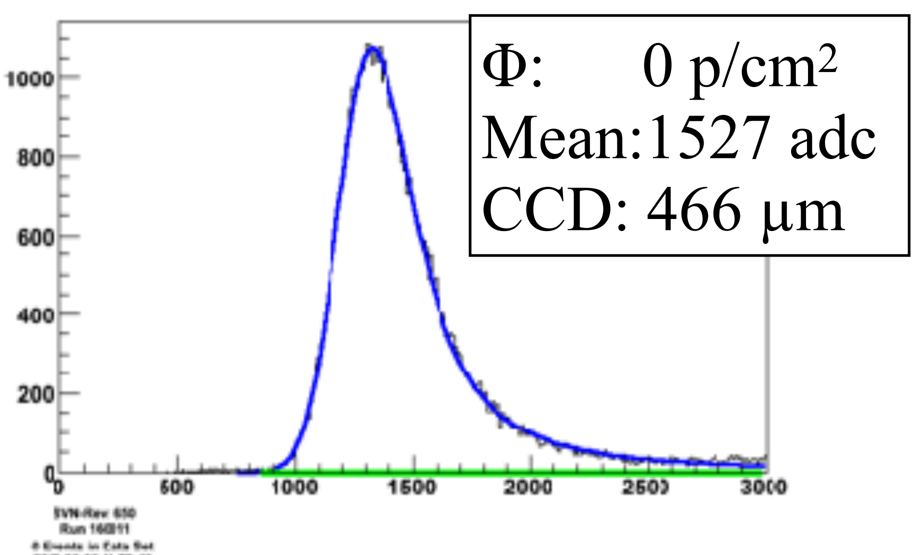


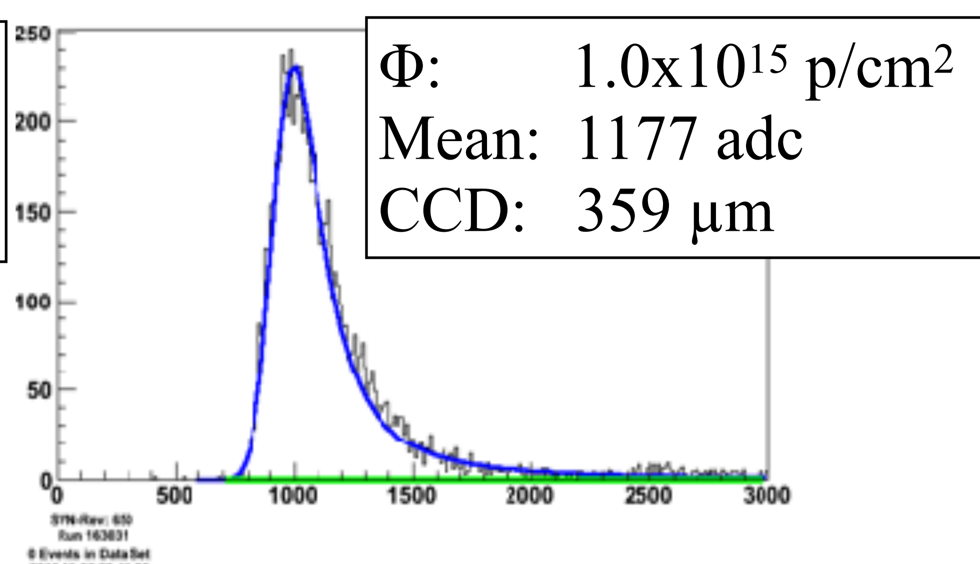
Pulse height: 800 MeV proton irradiation

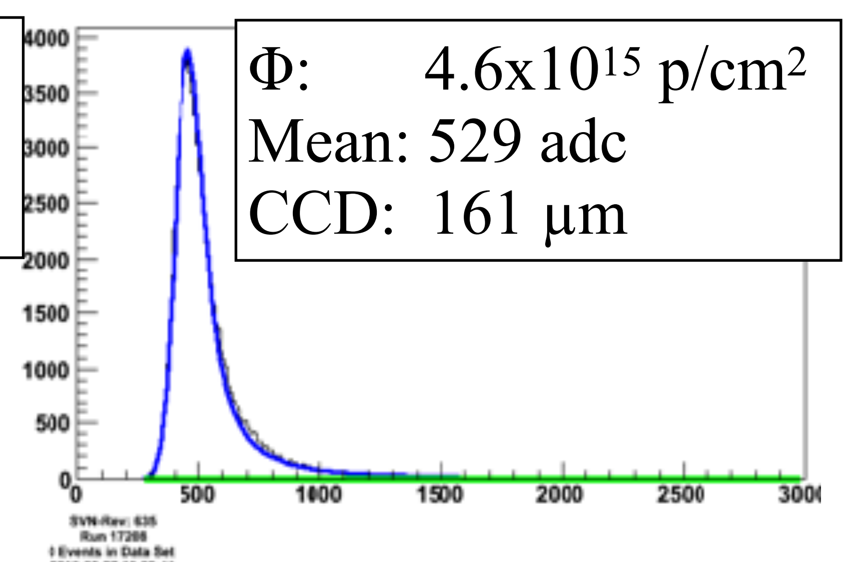
- scCVD diamond sample
  - CCD = is measured to thickness for unirradiated
- Noise is on the order 80-110 electrons
  - < 1.6% of the mean pulse height for the highest irradiation dose
- Pulse heights for 2 highest out of 10 strips closest to the predicted hit position
  - Pulse height shown for bias +1000 V (negative are similar)



Noise in non-hit channels
Common Mode corrected







Electric field calculations

no trapping

$$I_{e,h} = A \cdot e_0 \cdot N_{e,h} \cdot \cancel{e^{-\frac{t}{\tau_{eff}}}} \cdot v_{e,h} \cdot W$$

$$I_{e,h}(t=0) = A \cdot e_0 \cdot N_{e,h} \cdot v_{e,h} \cdot \frac{1}{d}$$

$$I_{e,h}(t=0) = A \cdot e_0 \cdot N_{e,h} \cdot \mu_{e,h}(E) \cdot E \cdot \frac{1}{d}$$

$$I_{e,h}(t=0) = constant \cdot \mu_{e,h}(E) \cdot E$$

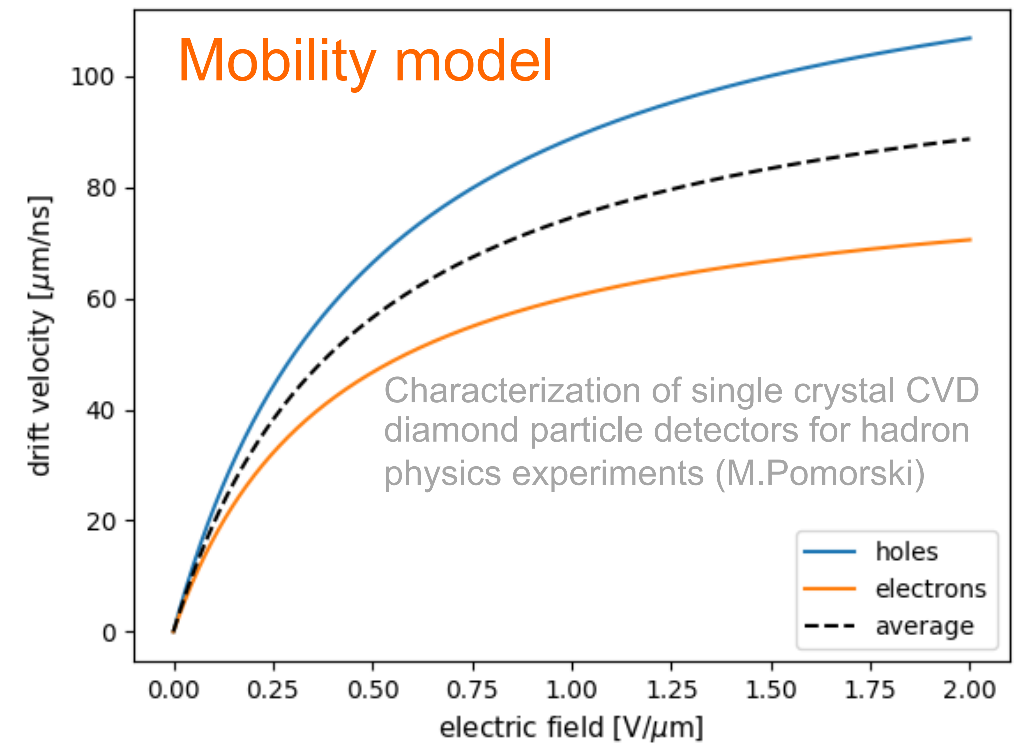
$$0 = I_{e,h}(t=0) - constant \cdot \mu_{e,h}(E) \cdot E$$

I_{prompt} from data

scaling

Mobility model

A .. Amplification
e_0 .. electron charge
$N_{e,h}$ .. number of e,h pairs
(constant in first order)
$v_{e,h}$ .. avg. drift speed of e&h
W .. weighting field (=1/thickness for 2 parallel infinite 2D electrodes)

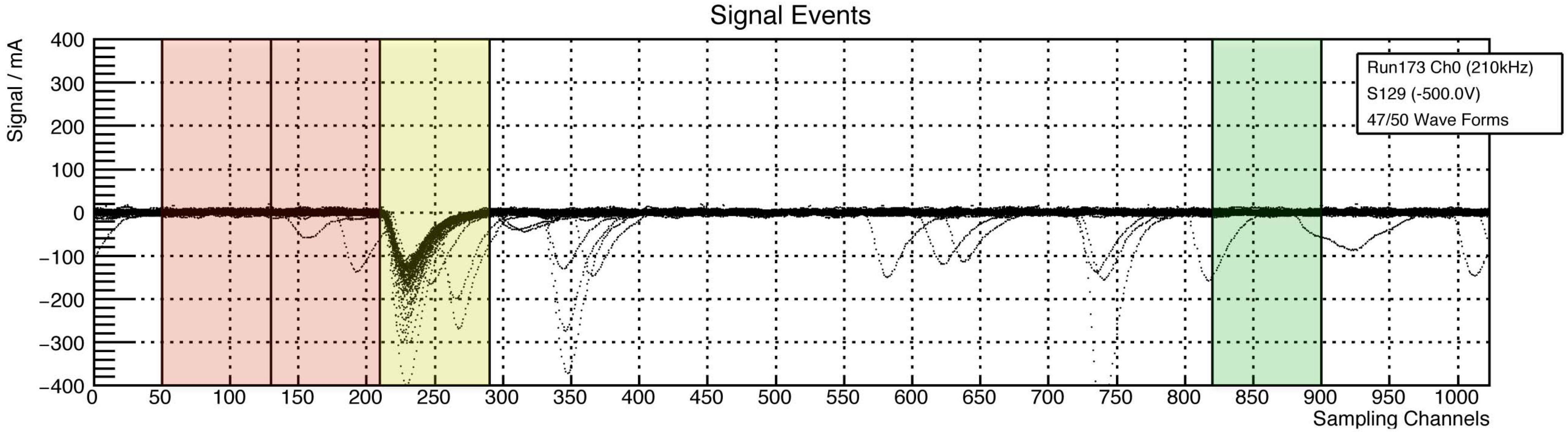


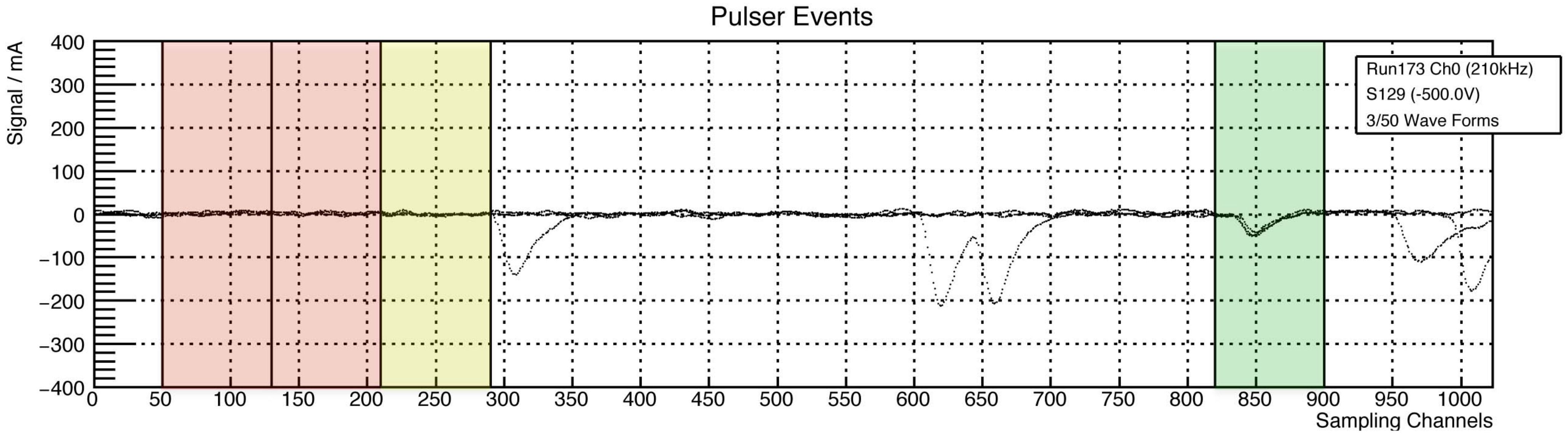
Use ‘Bisection Method’ to solve for **E** with the constraint that:

$$V_{Bias} = \int_0^d E \, dy$$

Analysis

- For each set of runs the signal region is set around most probable peak position for signal events
- Pedestal region is 40 ns or 2 bunch crossing in front of the signal region
- Pulser region is set around most probable peak position for pulser events

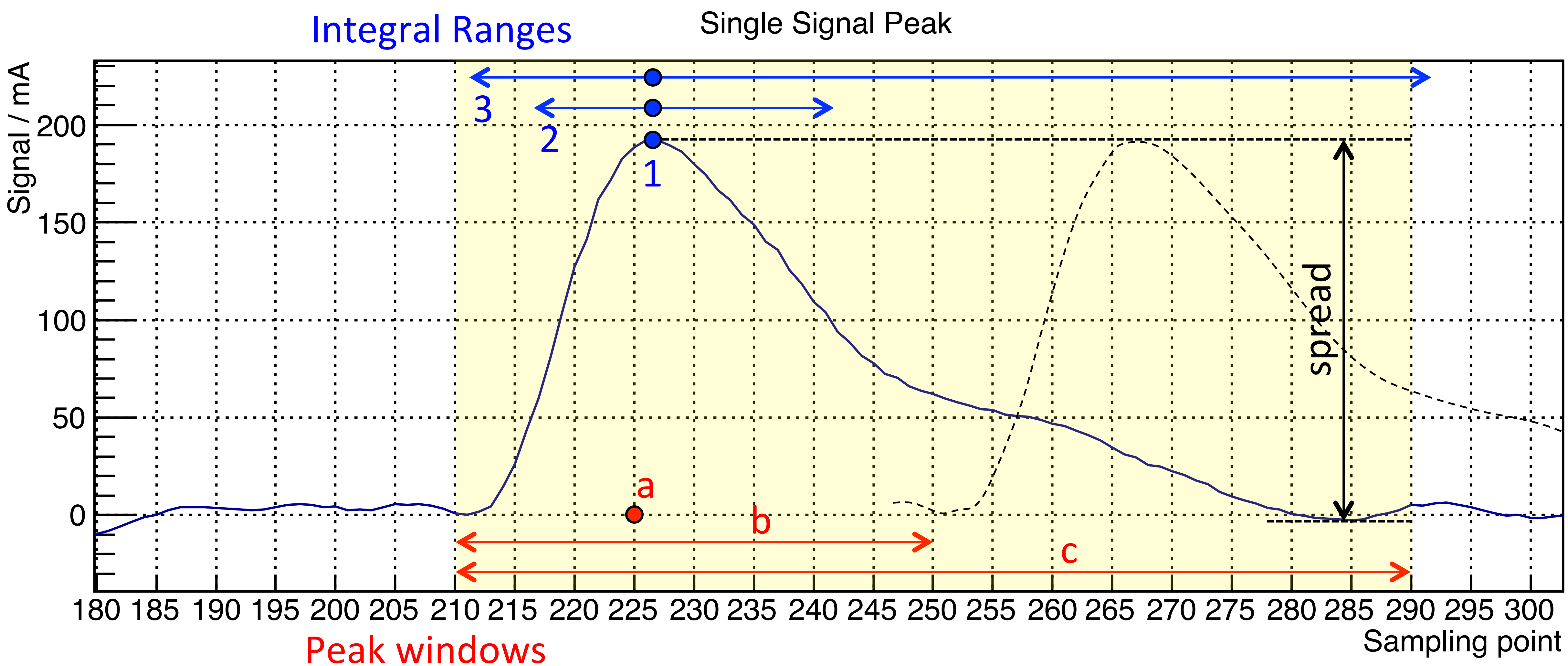




Analysis

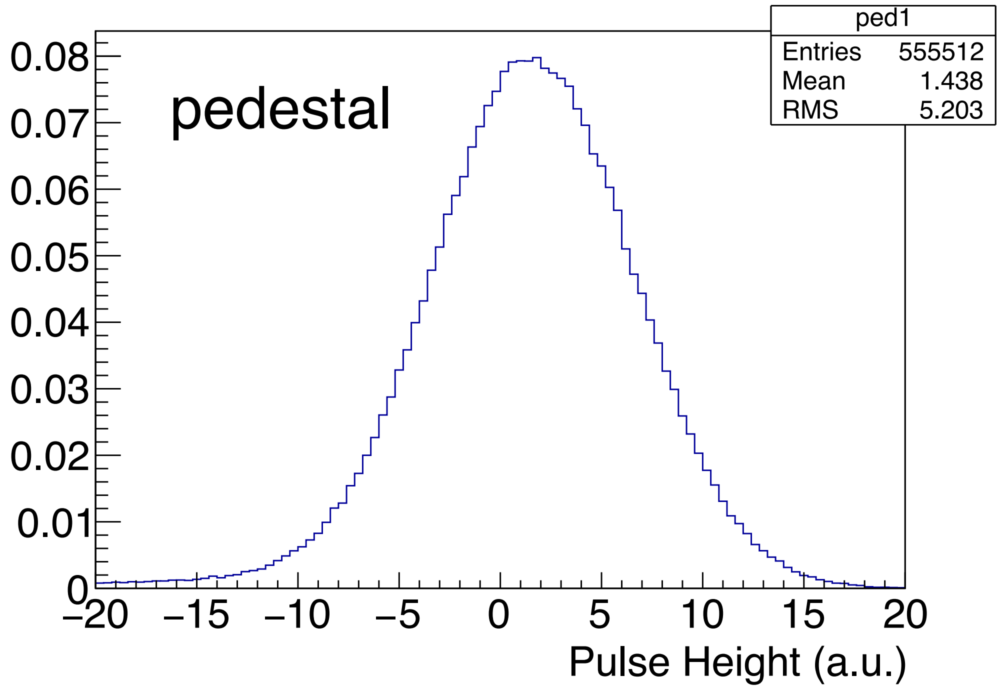
signal defintion

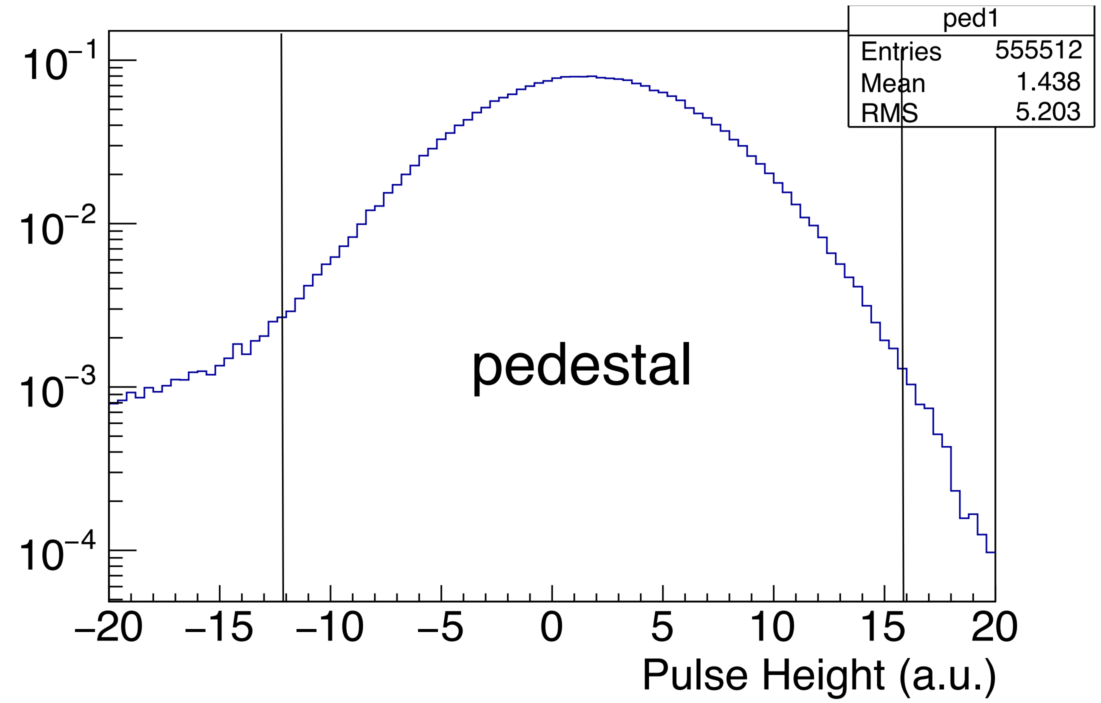
- Find a peak in the signal region
- Calculate an integral around the peak
  - for the following plots an integral (-5ns, +12.5ns) was used



List of cuts

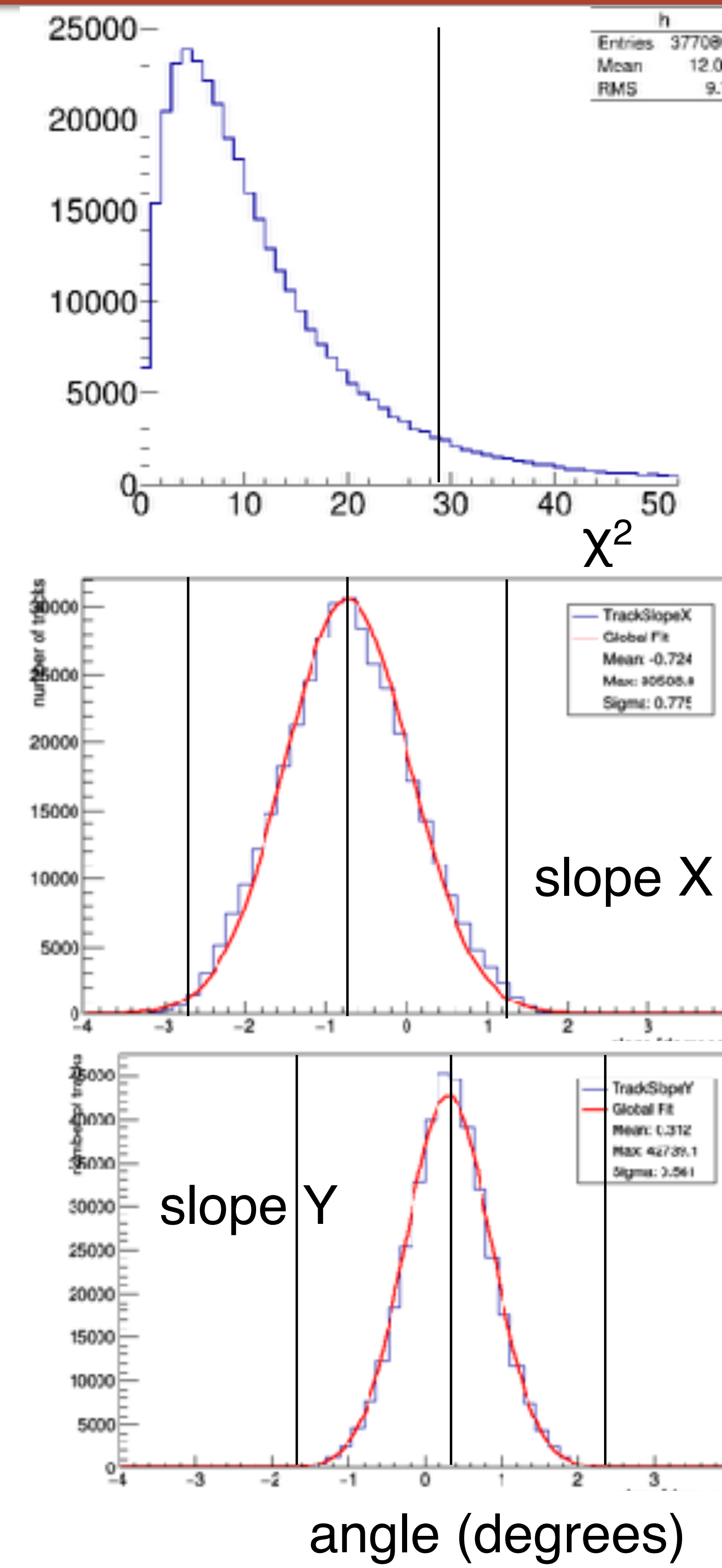
- Range cuts
  - cut out the beginning of the run where the beam stopper and/or collimator changes
- Beam interruptions
  - cut out regions beam interruptions
- Pedestal sigma cut
  - cut out events with pedestal > 3*sigma_pedestal
  - removes events with signal in the pedestal region
- Pulser
  - cut out pulser events



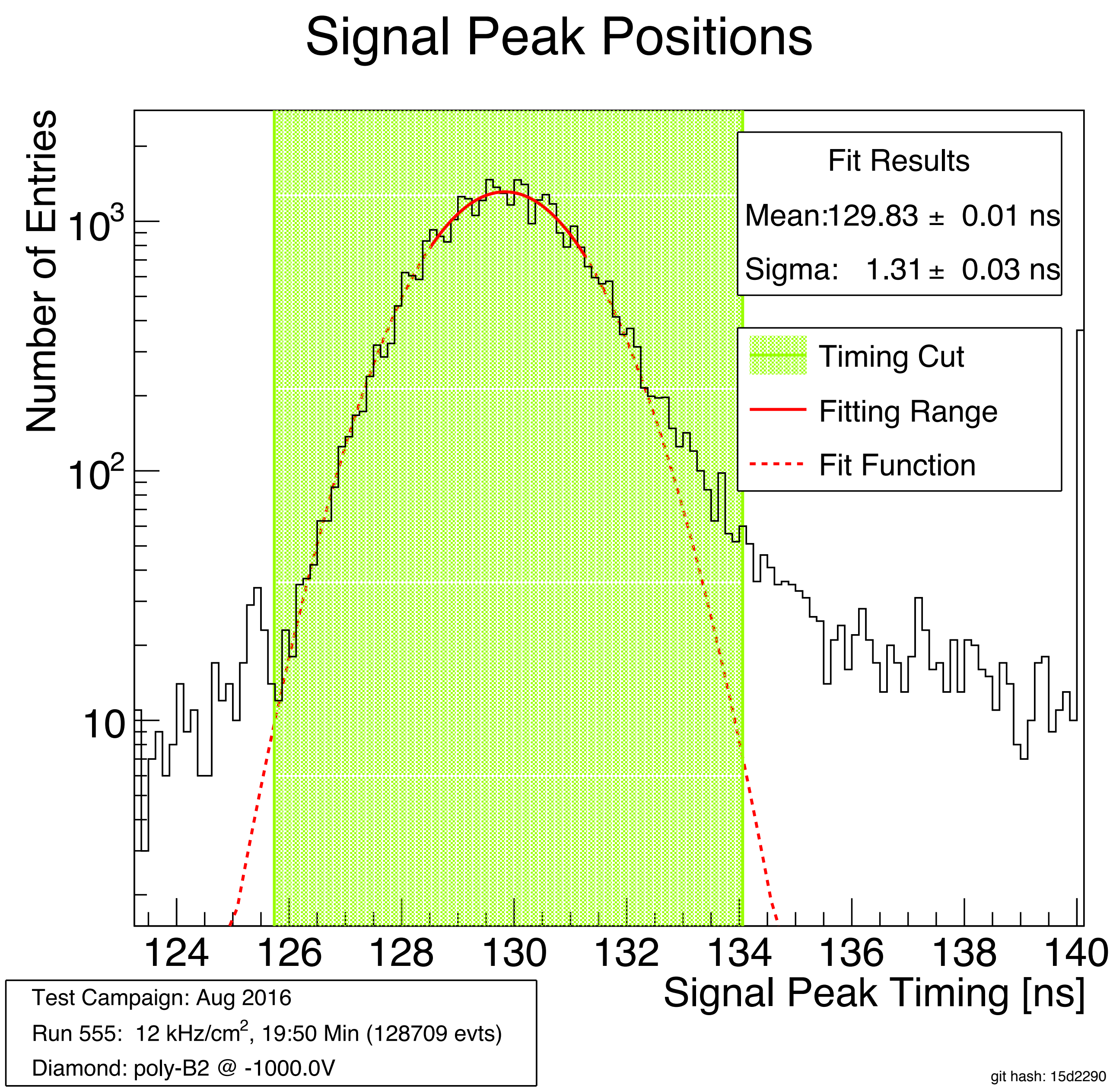


List of cuts (continued)

- Tracks
  - one and only one hit in each plane
- χ^2 of track fit
  - select good tracks
    - with χ^2 in the lower 90% quantile
- Track angle
  - select collinear tracks
    - < 2 degrees divergence in x and in y
- Saturated
  - cut out events reaching maximum ADC range at any point of the waveform



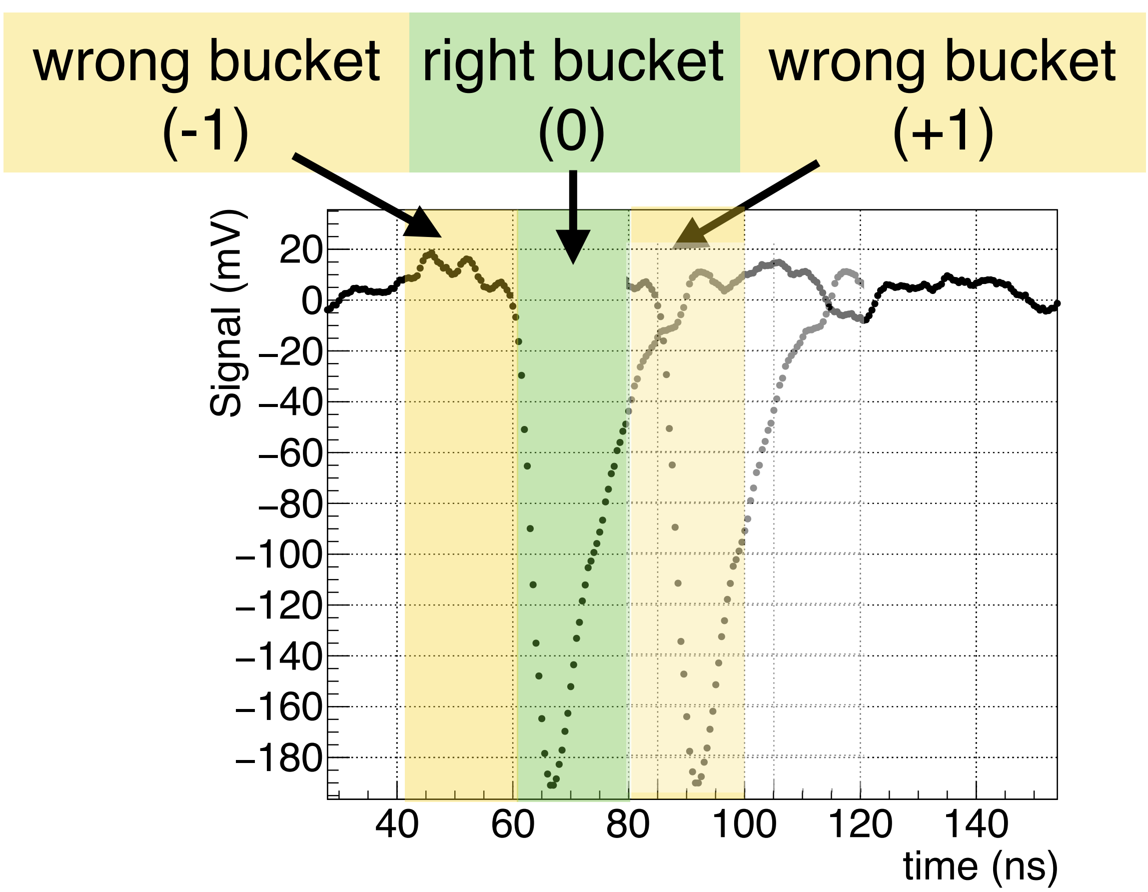
Timing cut

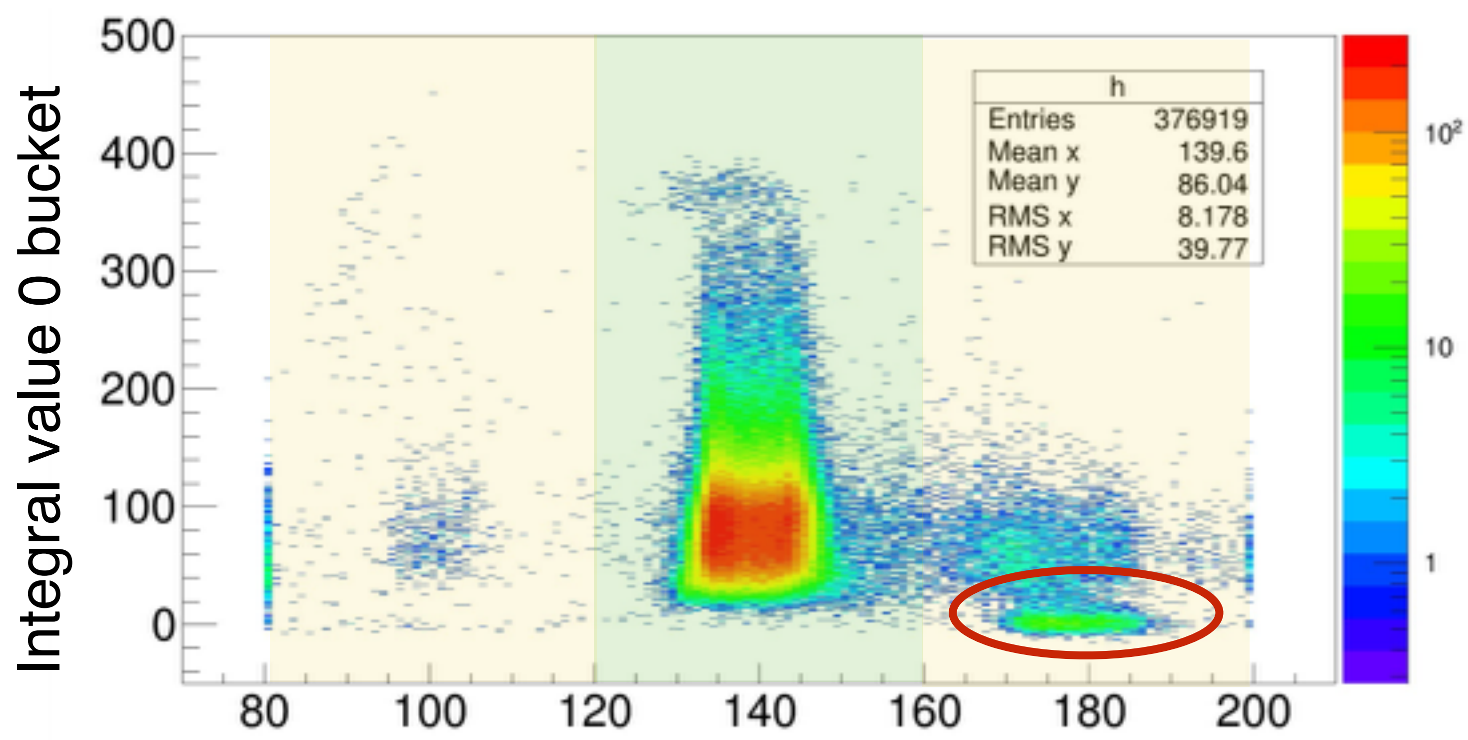


- timing follows Gaussian distribution with $\sigma = (1.31 \pm 0.03)$ ns
- use cut ($4\,\sigma$) based on this distribution to discard events with wrong timing
  - overlay of different buckets

List of cuts (continued)

- Bucket cut
  - due to 25 ns granularity of the fast-Or trigger and 20 ns bunch structure, coincidences between fast-Or in the later bucket and scintillator in the earlier bucket are possible
  - Only events with absolute peak in the right bucket are considered





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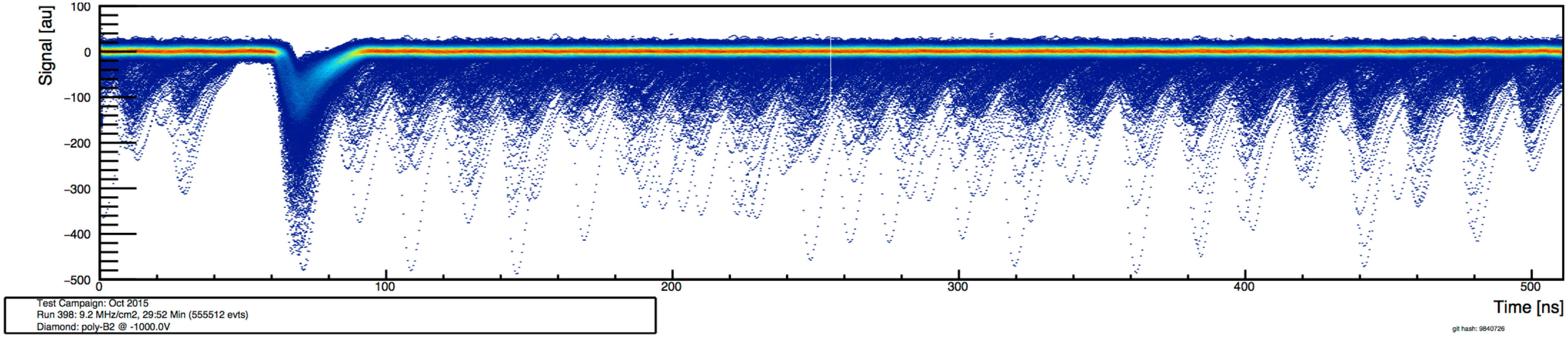
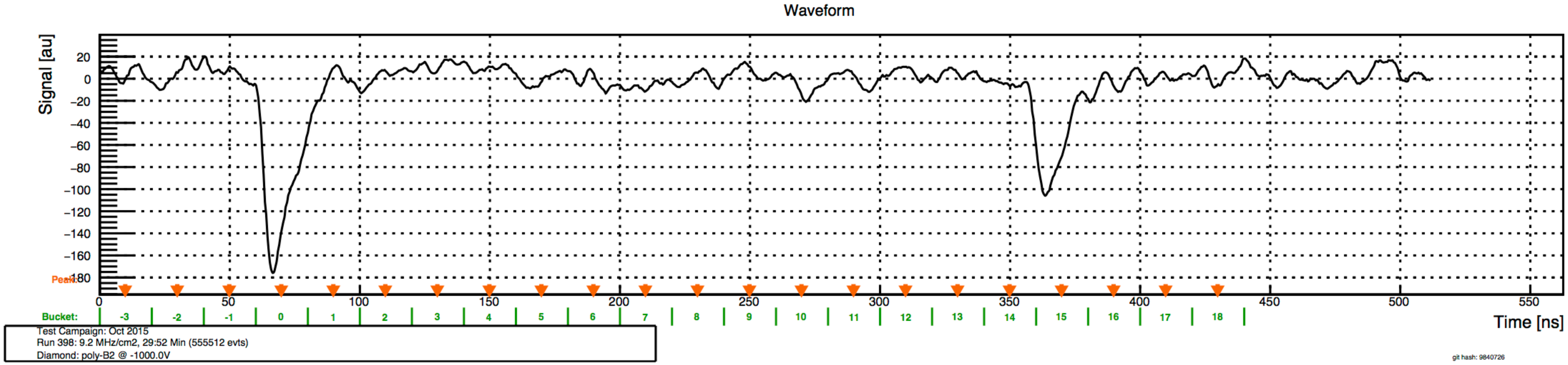
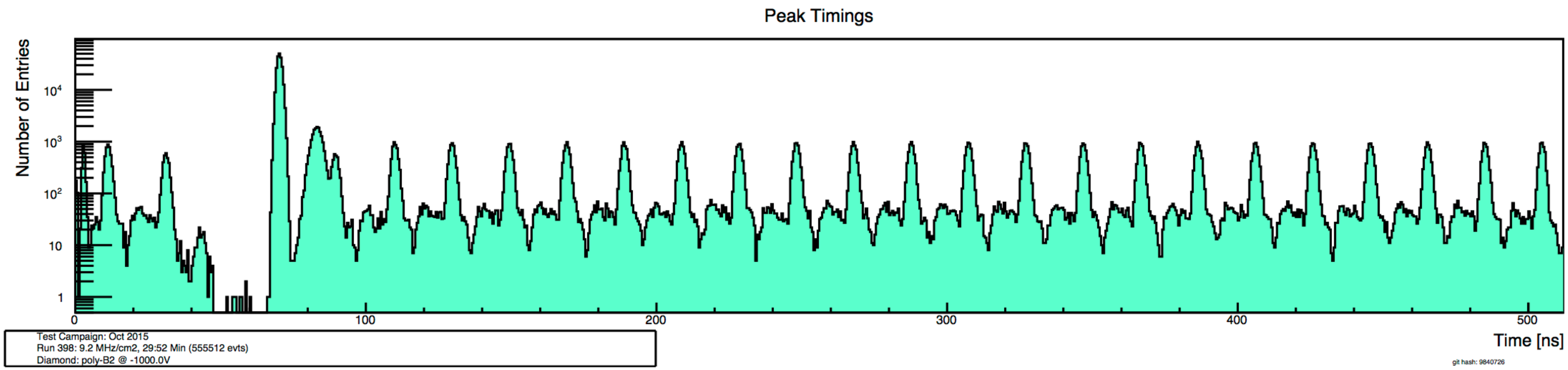
DRS4 signal traces

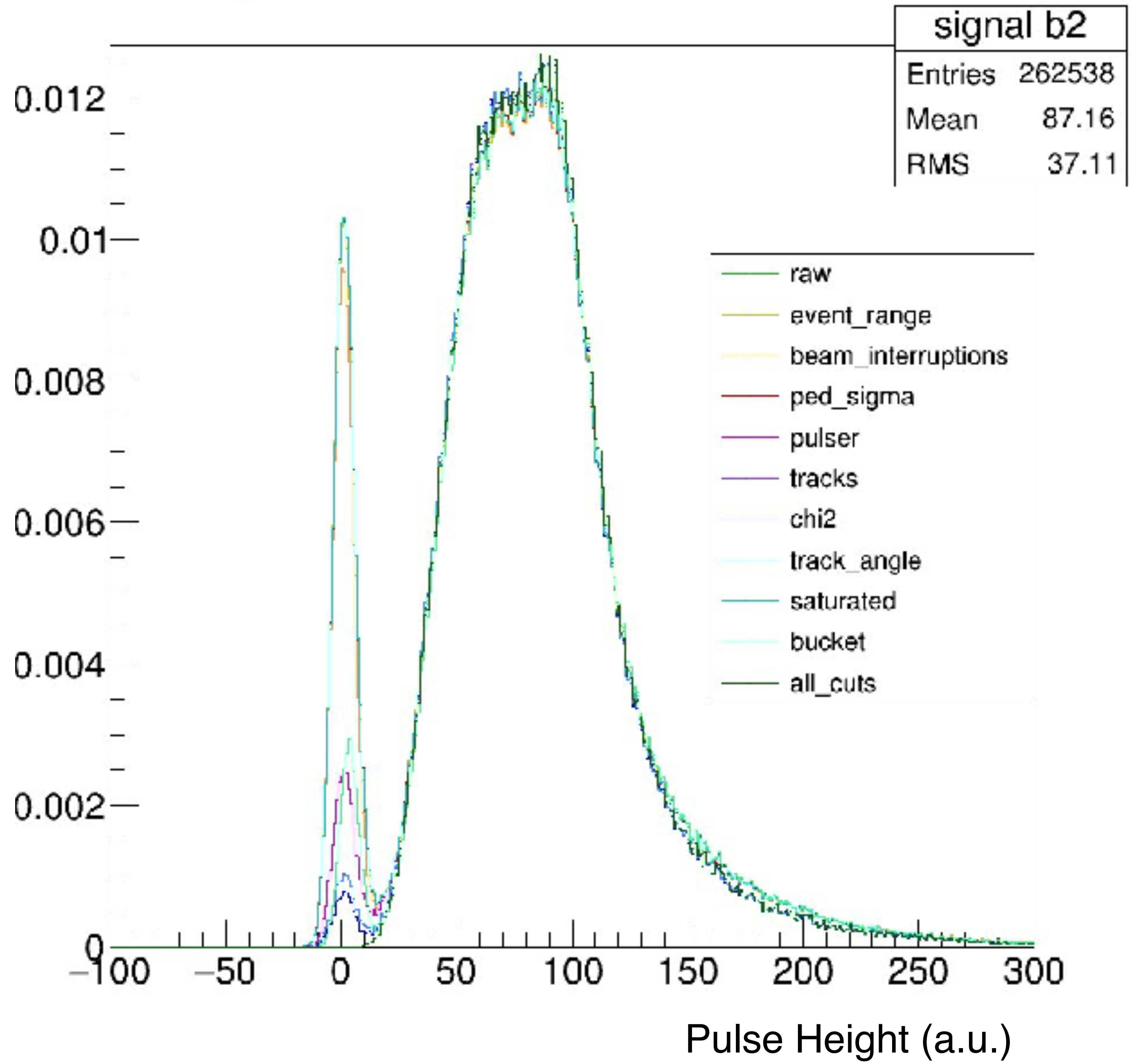




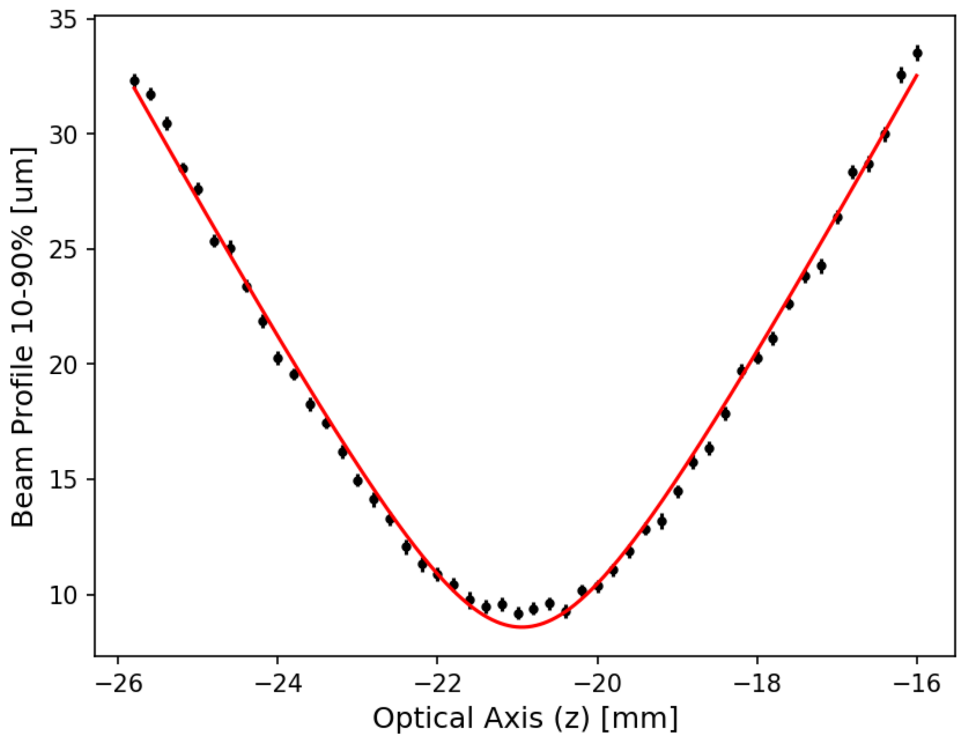


Analysis

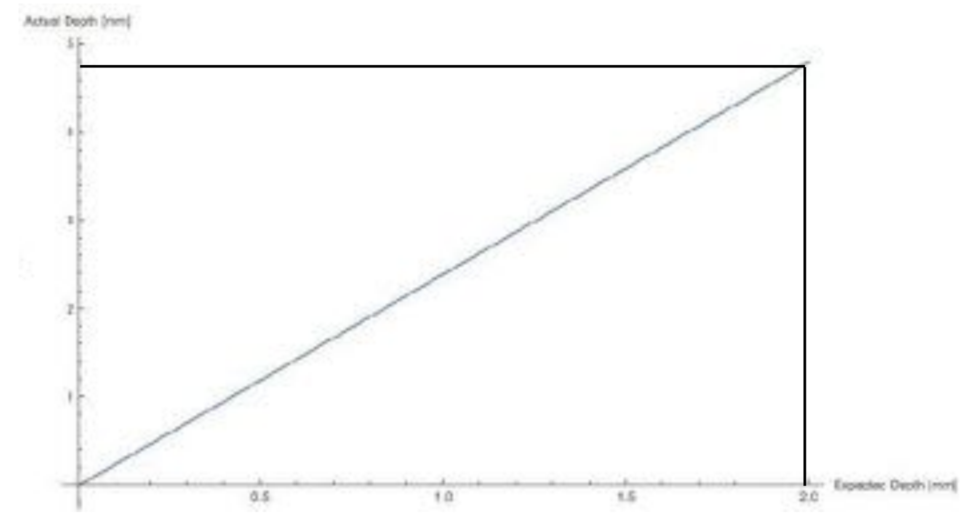
- Pedestal is removed completely by “all cuts”
- Basic shape of the Landau is not affected
- High end tail changes slightly after “track” cut

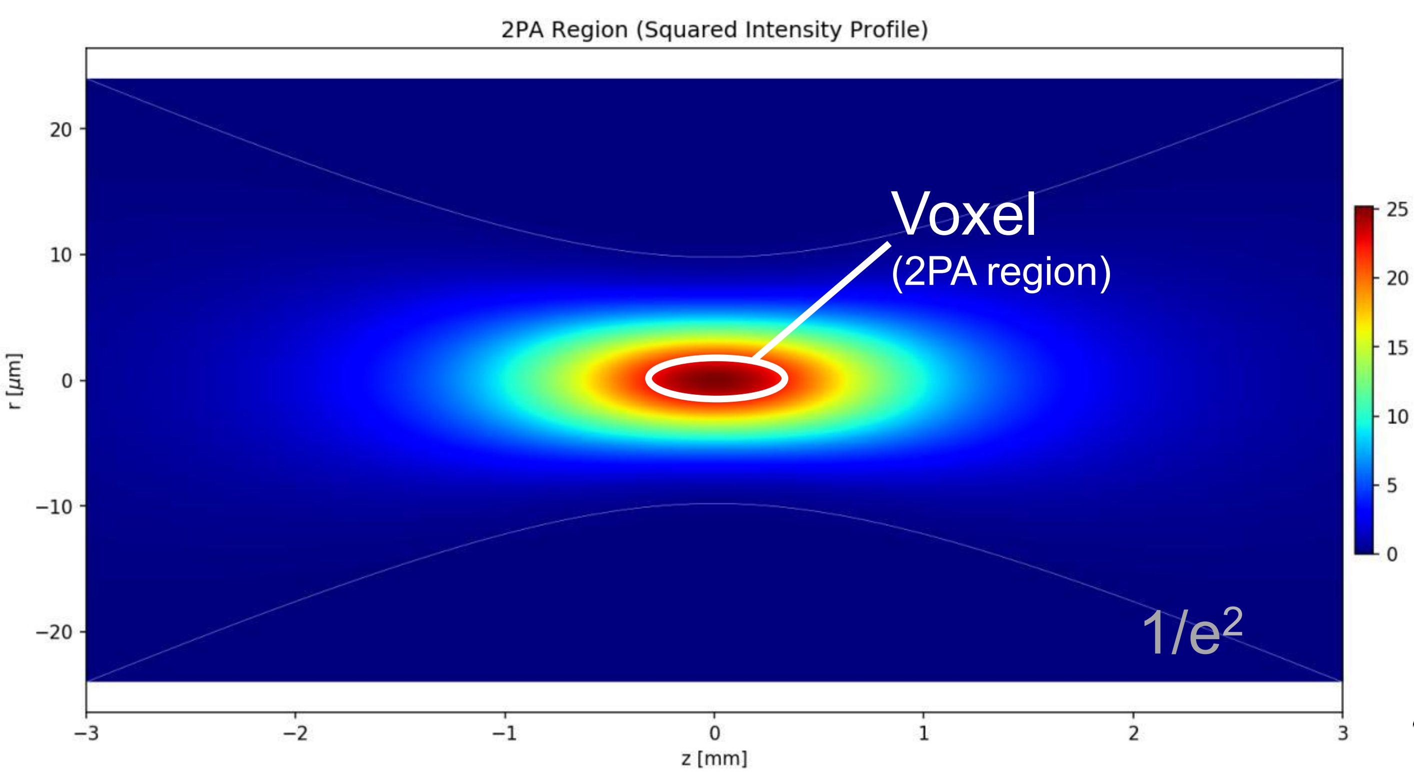


Charge generation volume



- Beam profile from the knife edge scan
  - in air, not accounting for aberration in diamond
  - 2.0 mm => 4.8 mm





- The charge profile is proportional to intensity squared for 2 photon absorption

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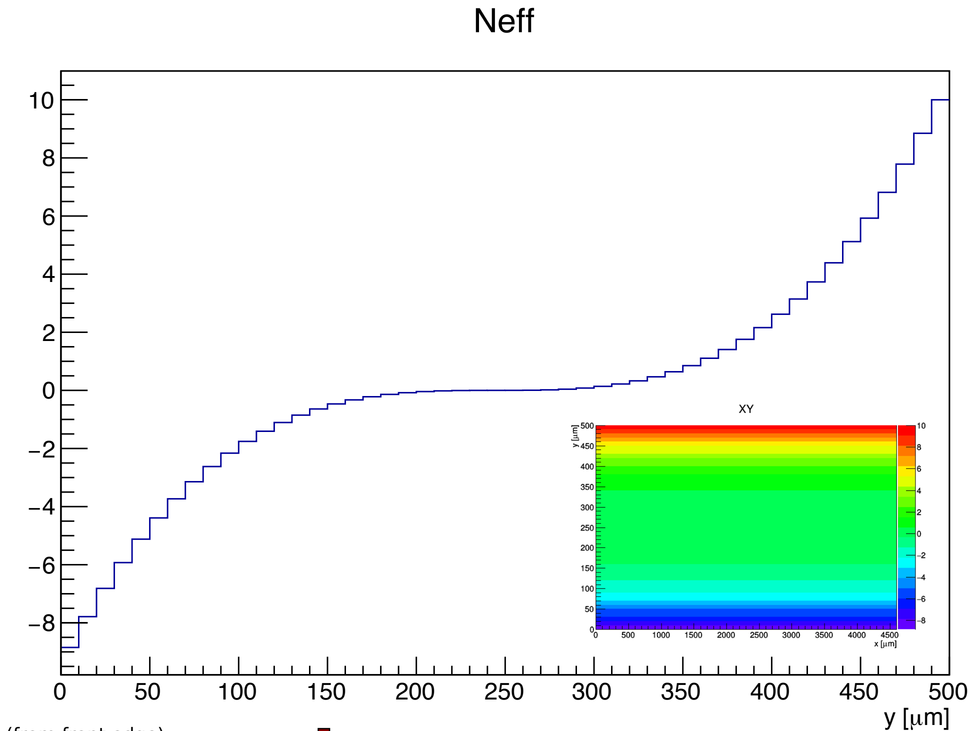
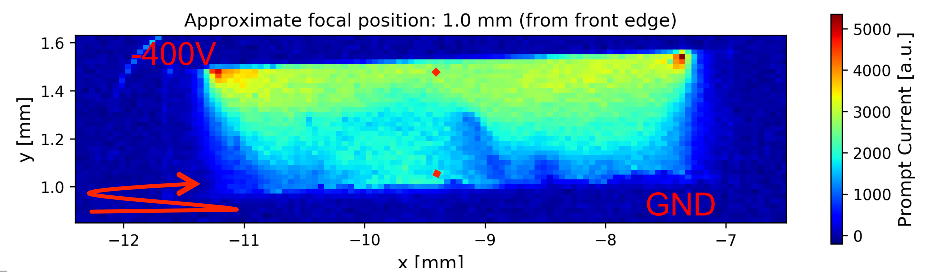
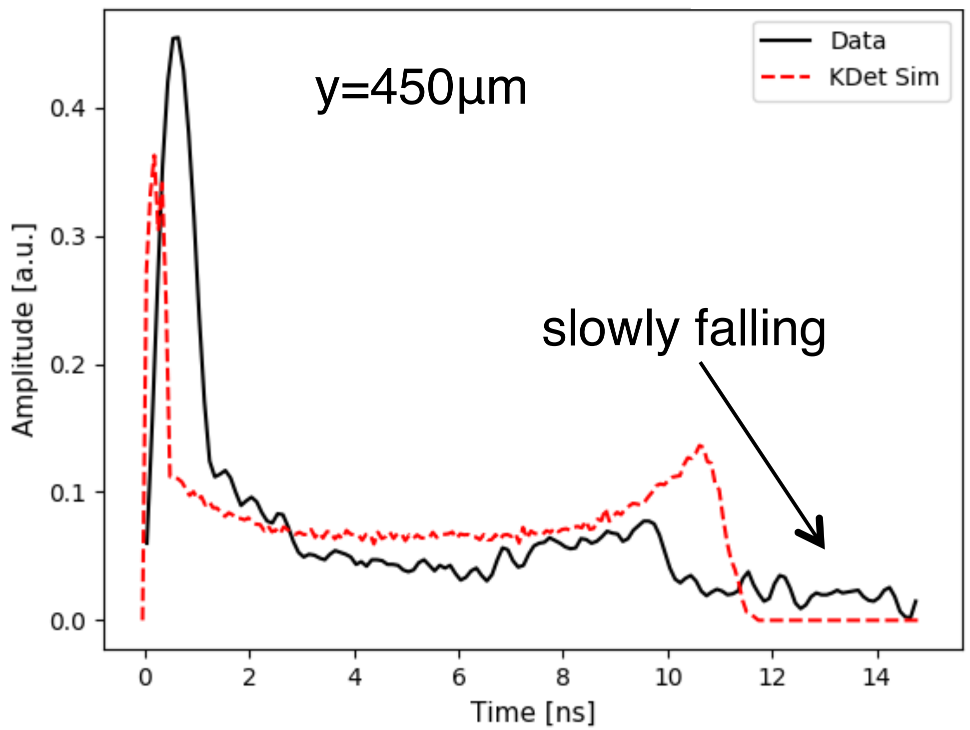
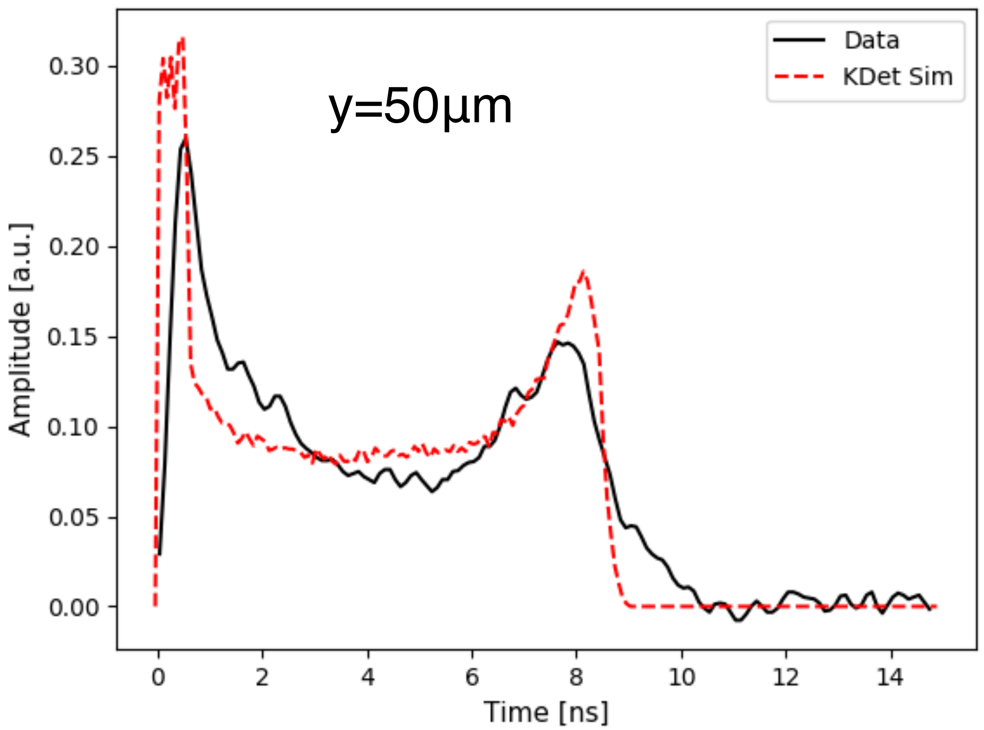
Preliminary simulation results

- Cubic space charge distribution
- Injection along a line
- Difusion = on
- No RC filter, no trapping

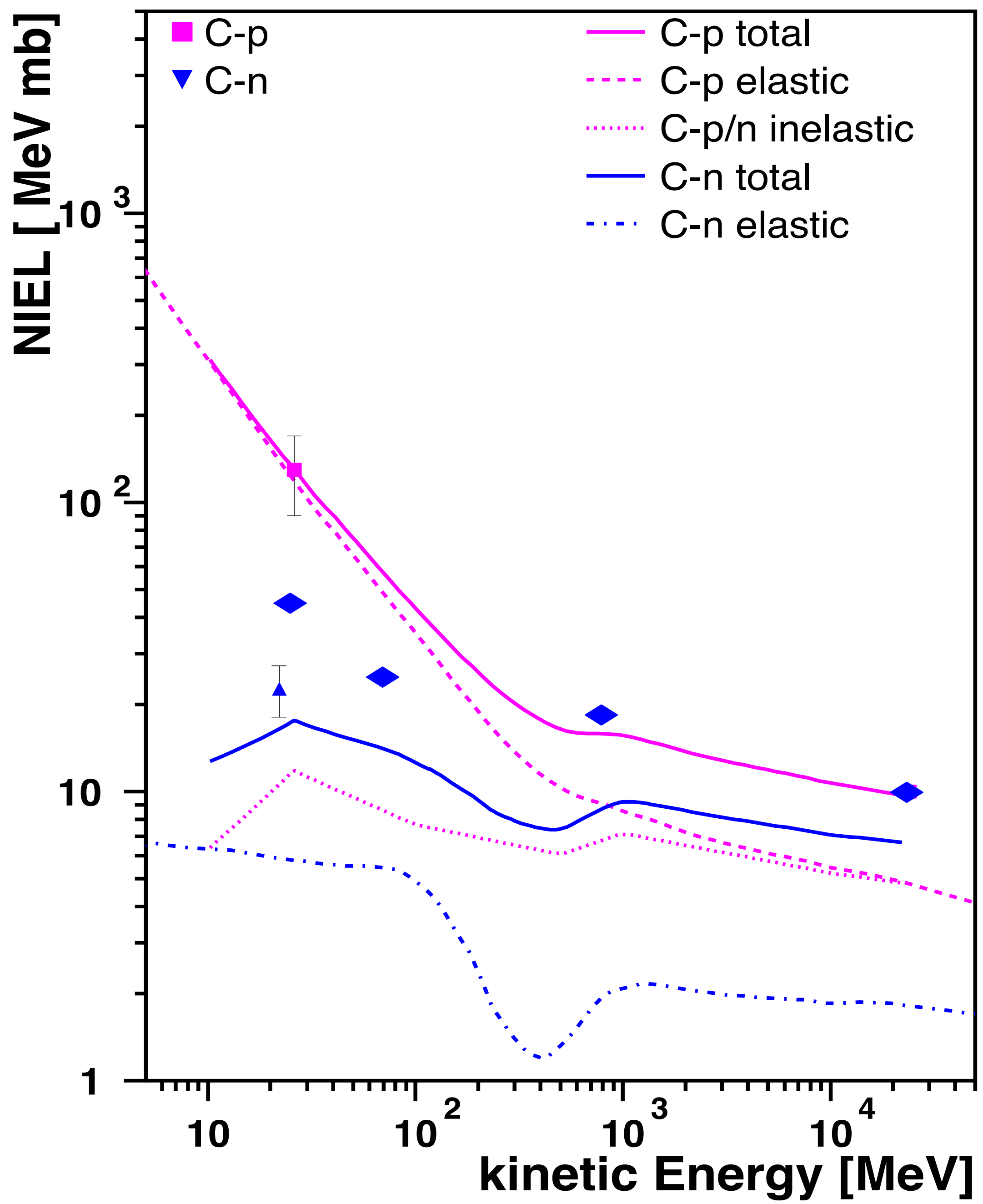






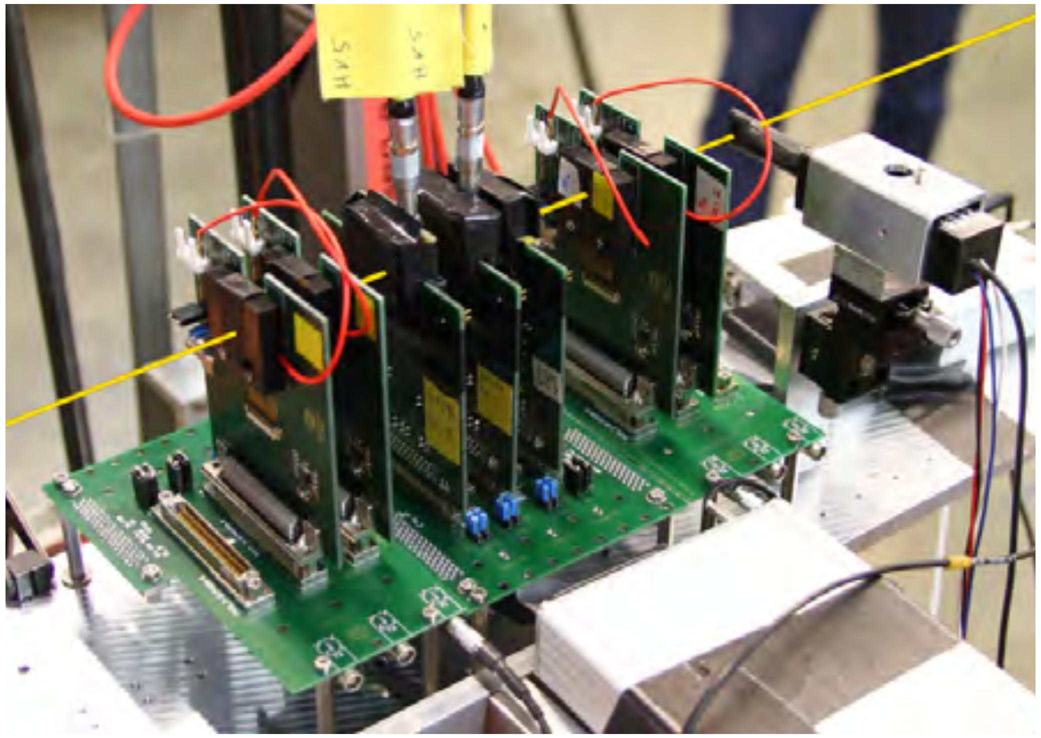


RD42 data compared to NIEL hypothesis

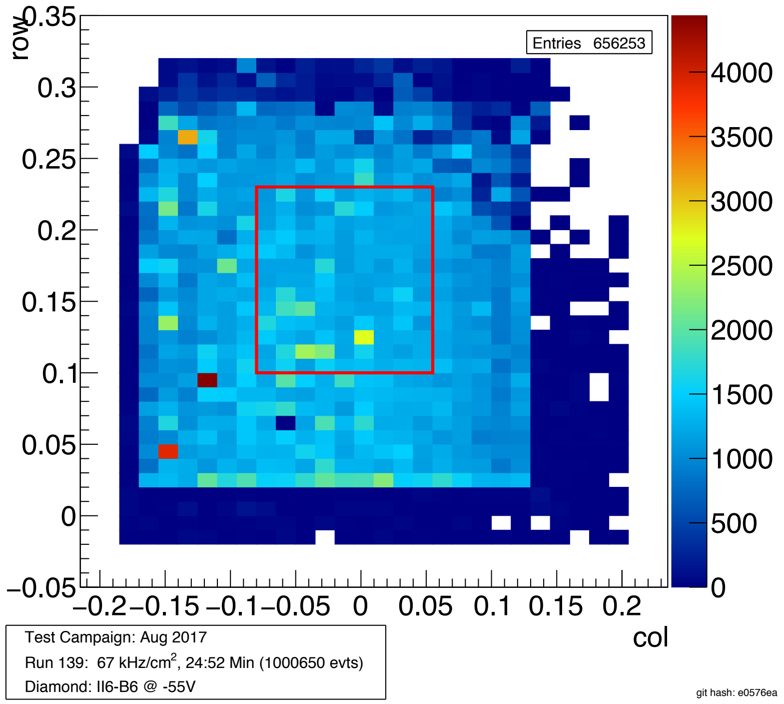


Beam test of 3D pixel detector

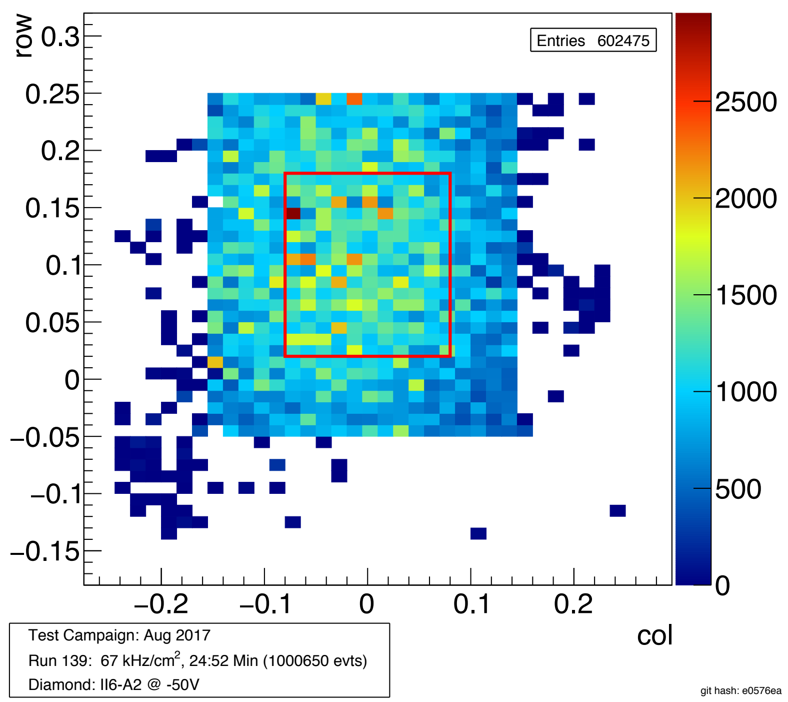
- Testbeam at Paul Scherrer Institute in October 2016
  - 260 MeV/c positive pions
- Read-out chip setup
  - Threshold for accepting hits: ~1500 electrons



hit occupancy of 50x50μm² 3D

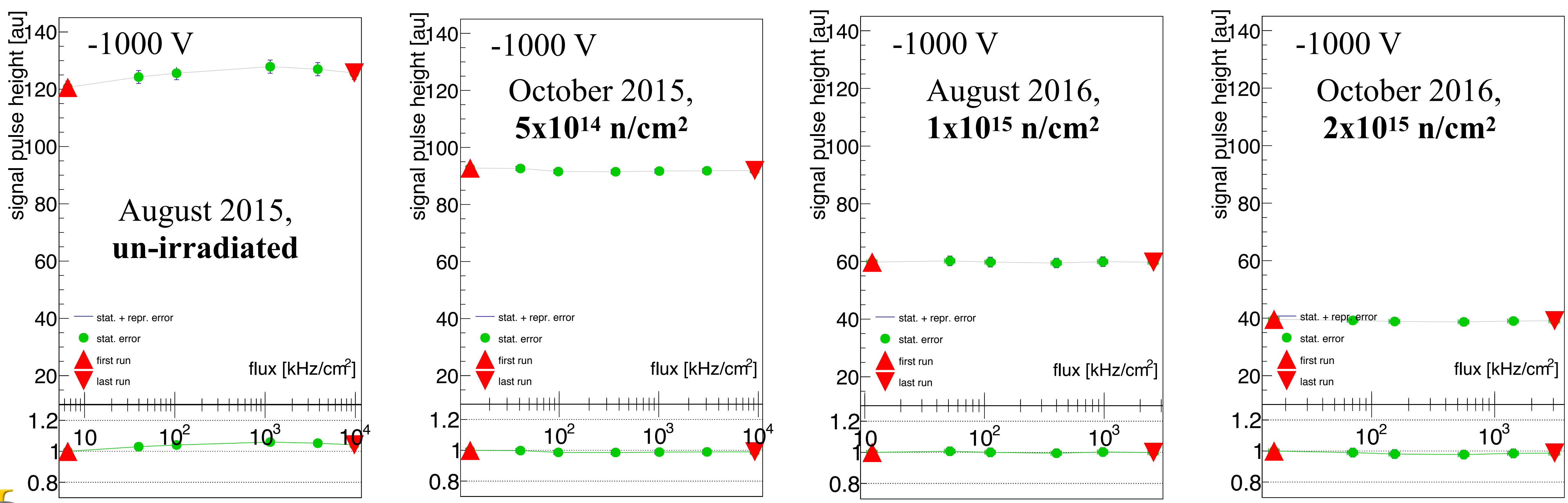


hit occupancy of 150x100μm² 3D



Results (II6-B2, pCVD - pad detector)

- Average pulse height vs pion rate
- Pulse height was measured at several rate points between 2 kHz/cm² and 10 MHz/cm²
  - no relative calibration between beam tests
  - scanned up and down up to 4 times to check repeatability
- Pulse height very stable after irradiation
  - slight rise in pulse height, ~5% before irradiation, probably due to surface preparation



Results (II6-97, pCVD - pad detector)

- Average pulse height vs pion rate
- Pulse height was measured at several rate points between 2 kHz/cm² and 10 MHz/cm²
  - no relative calibration between beam tests
  - scanned up and down up to 4 times to check repeatability
- Pulse height very stable after irradiation
  - slight change in pulse height, ~8% before irradiation, again surface preparation is a suspect, will check in the upcoming beam tests.