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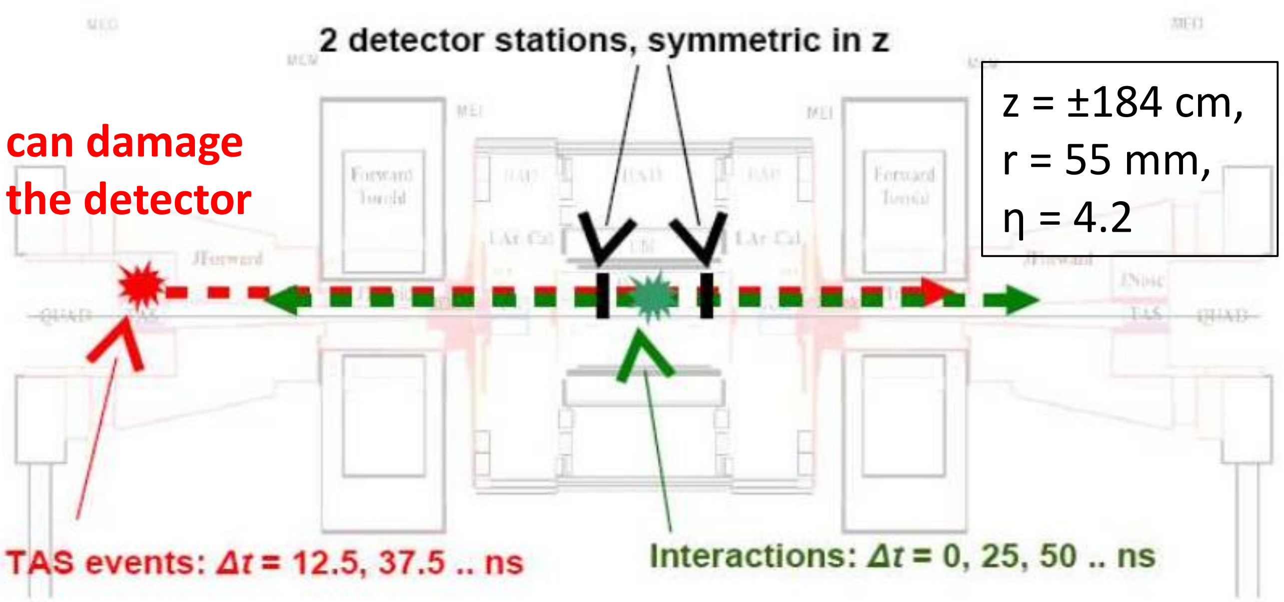
Development of the BCM' abort and luminosity system at the HL-LHC based on poly-crystalline CVD diamond pixel-pad detectors

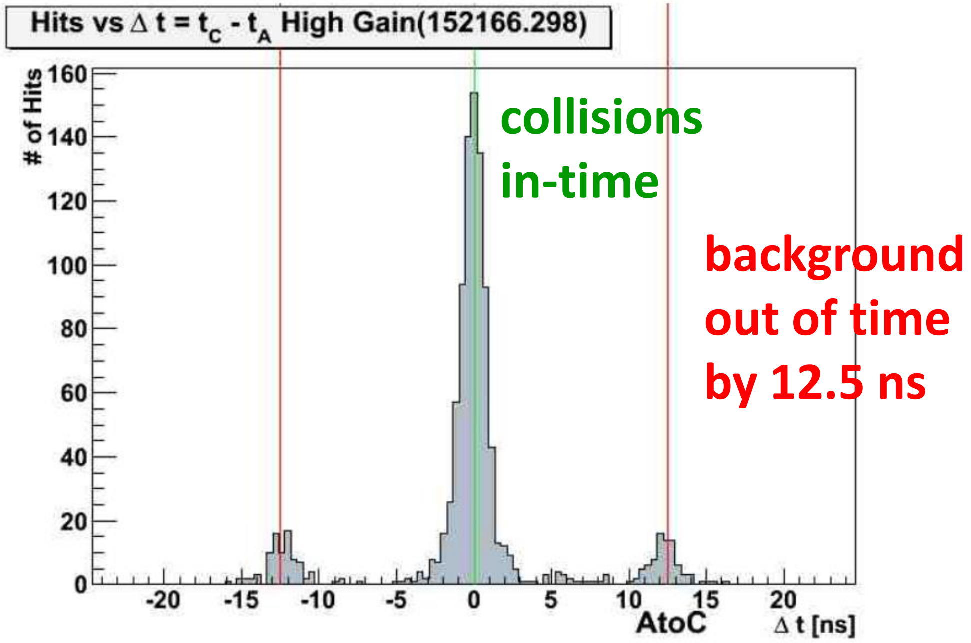
14th Trento Workshop on Advanced Silicon Radiator Detectors, 25. 02. 2019

Bojan Hiti (Jožef Stefan Institute, Ljubljana, Slovenia) for ATLAS BCM'

ATLAS BCM and BCM'

- Current ATLAS **abort** system: Beam Condition Monitor (BCM)
  - 2 stations **6.25 ns** from IP
  - Dumps the LHC beam if ATLAS endangered (scattered beam – out of time measurements ± 12.5 ns)
  - Also used for luminosity measurement
- **10 x 10 mm²** single pad pCVD diamond sensor → occupancy at high pile-up is problematic (1.5 MIPs / *pp* collision)
- After HL-LHC upgrade (2024—2026) luminosity will increase by factor 5

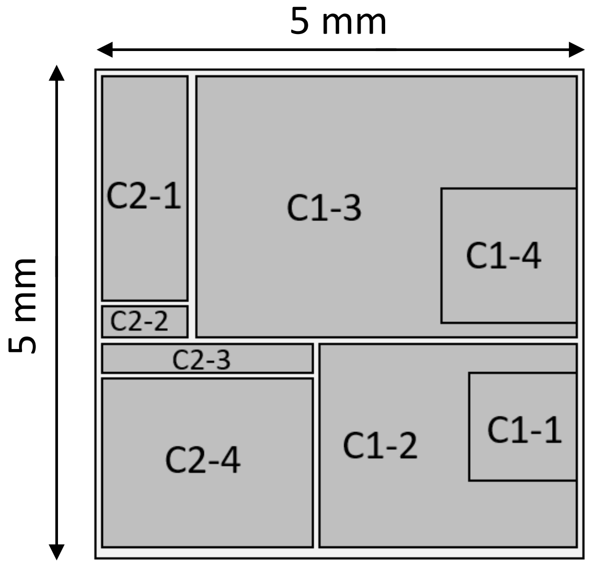




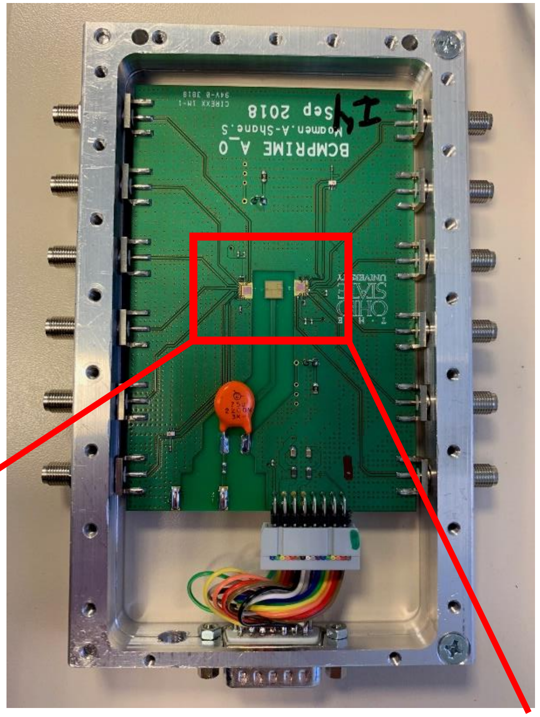
Robust solution for HL-LHC→ BCM' (BCM Prime)

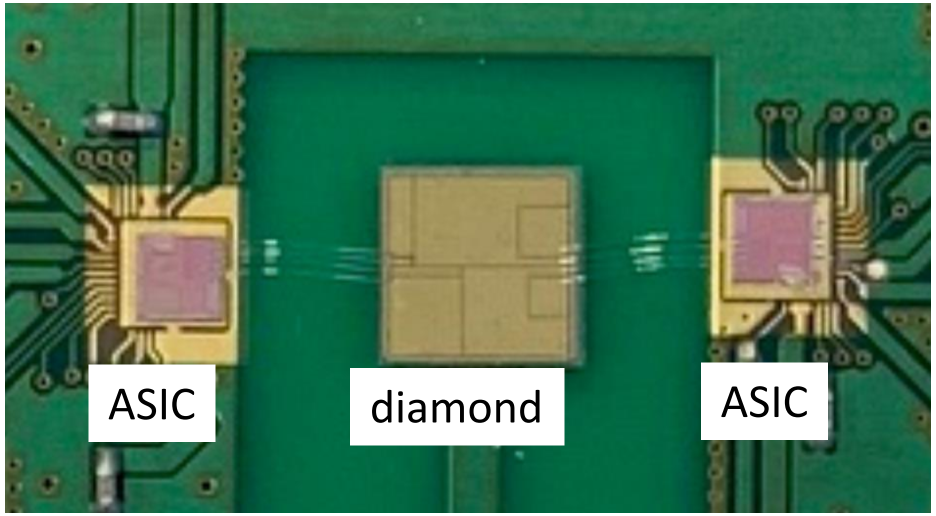
BCM' upgrade for HL-LHC

- pCVD diamond sensor, segmented into **8 pads** → flexible acceptance
- Custom analogue front end **BCM' ASIC** (designed by OSU)
  - 65 nm TSMC process, 4 readout channels
  - Separate front end functionality for **Abort** (high signals) and **Luminosity** (low noise)
  - Current amplifier; < 1 ns rise time, fast (~10 ns) baseline restoration
  - Desired sub-ns time resolution for beam diagnostics
  - Large pitch bump bonding or wire bonding
- First prototypes available in September 2018
- Presenting first results from beam tests at CERN SPS and PSI in October 2018



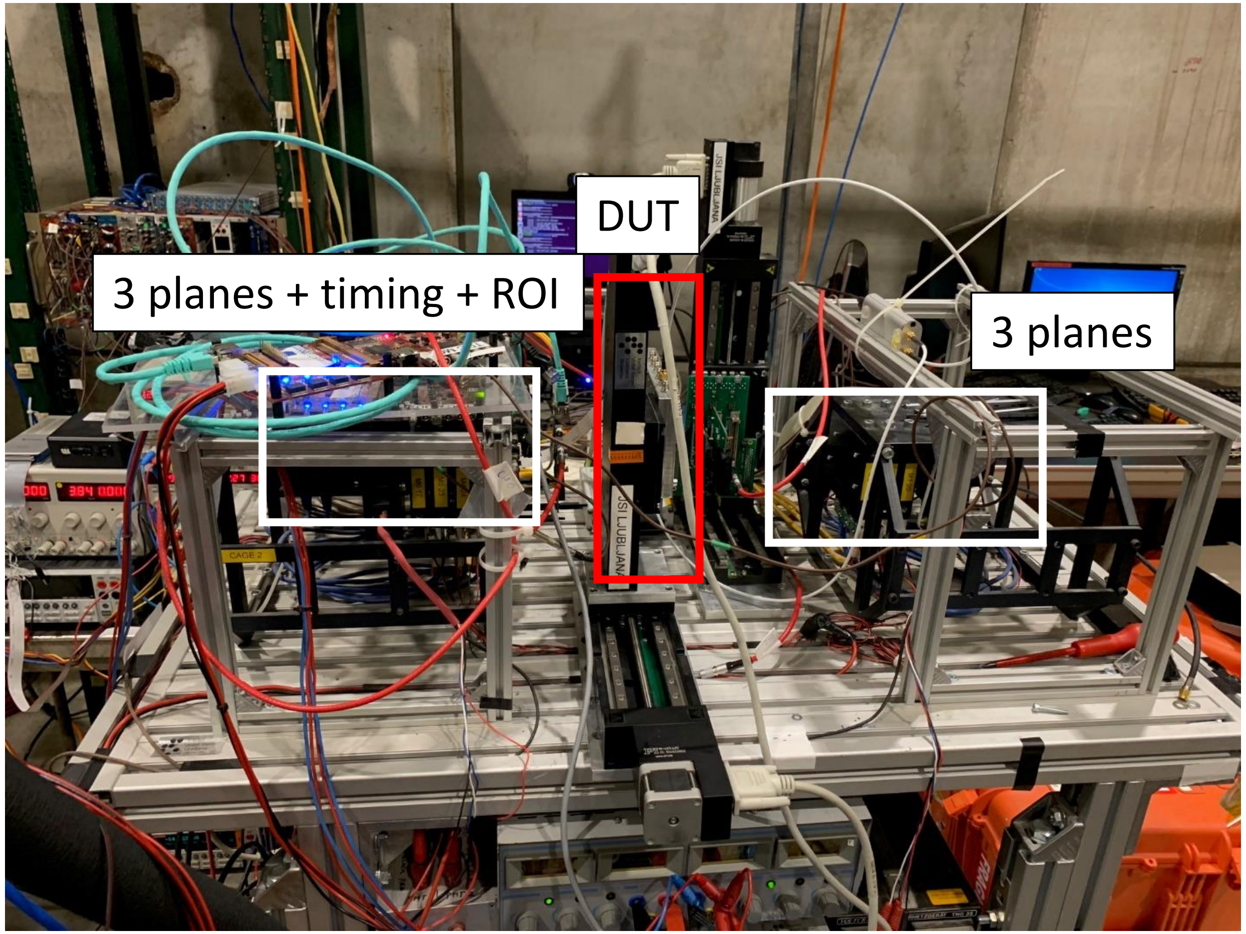
thickness 500 µm



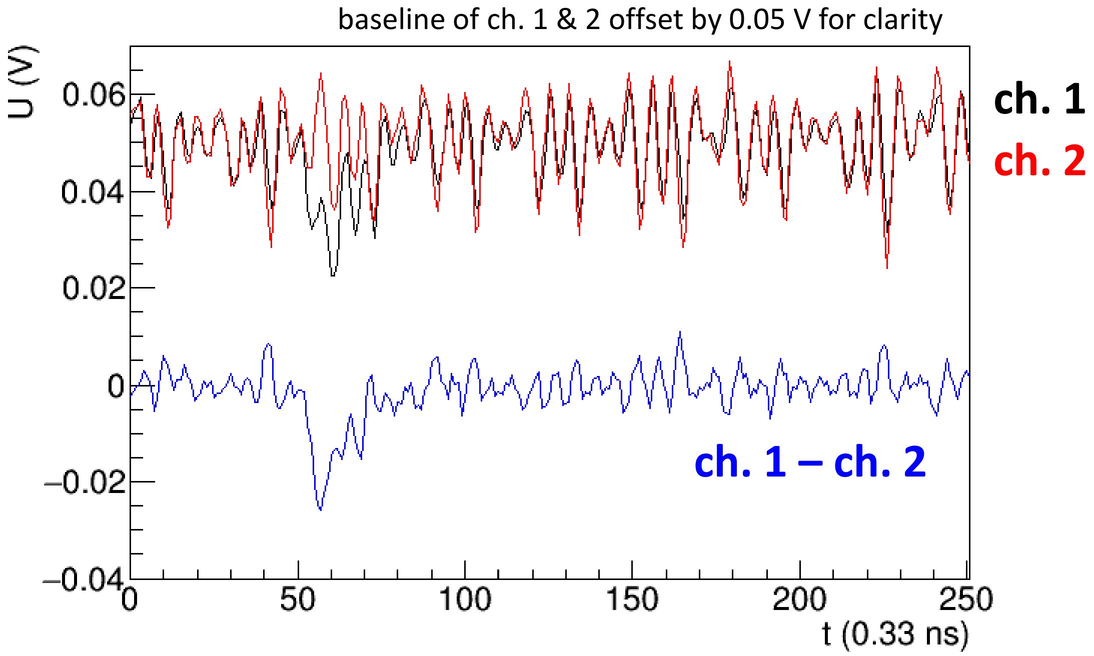


CERN H6 test beam

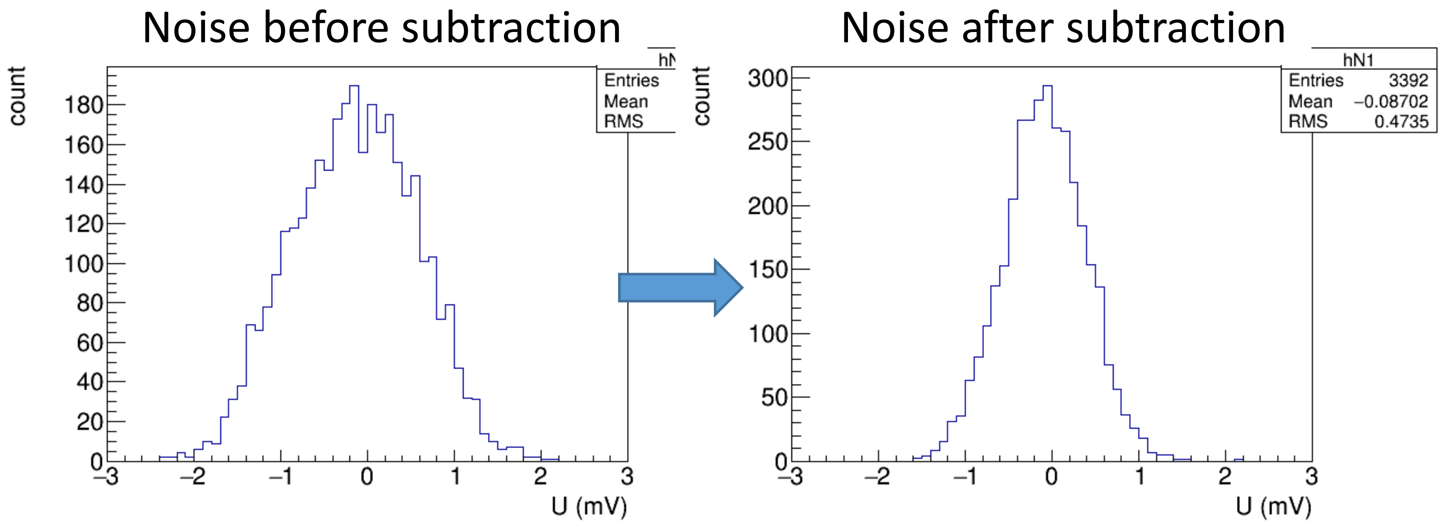
- CERN SPS H6 test beam: 120 GeV hadrons
- KarTel (Mimosa) beam telescope
  - Tracking resolution ≈ 3 μm
- DRS 4 analog readout
  - 3 GS/s acquisition rate, 700 MHz bandwidth
- DUT:
  - + 1000 V bias voltage
  - DUTs pumped with Sr90 before measurements
  - Output oscillated if more than one channel per chip active → Recorded two channels per run
- Dataset:
  - All channels measured (separate runs)
  - several 10k tracks per channel



Signals and pick-up



- Large pick-up from the setup/environment
- Same shape in all channels → Mitigation by subtracting two waveforms
- (ch1 – ch2) or (ch2 – ch1) depending on track position
- Pick-up reduced by factor 2

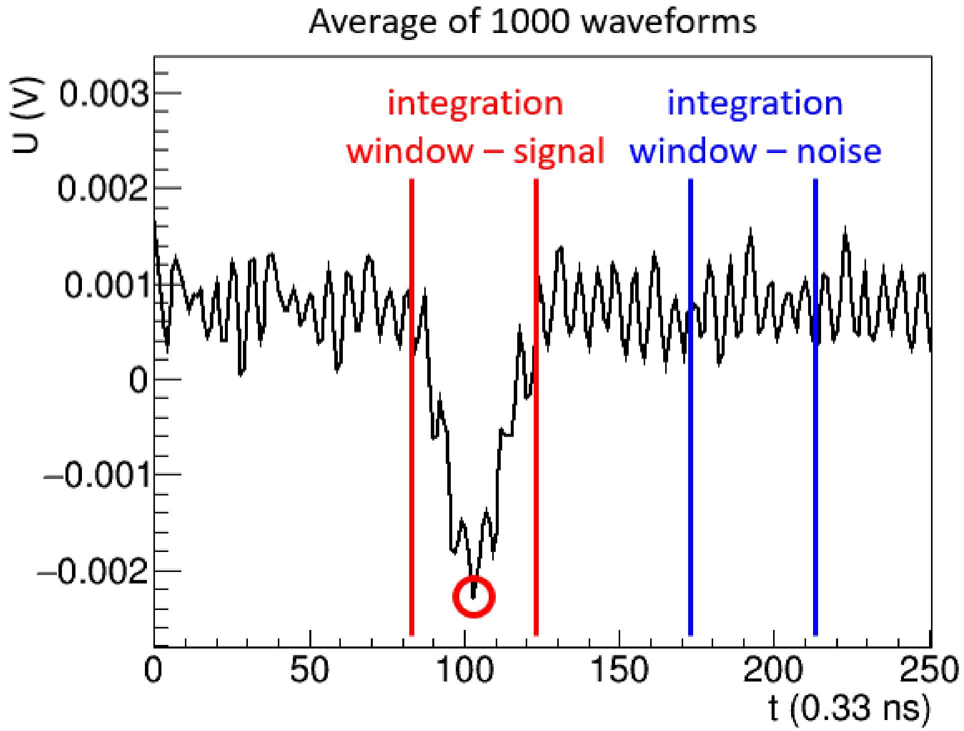


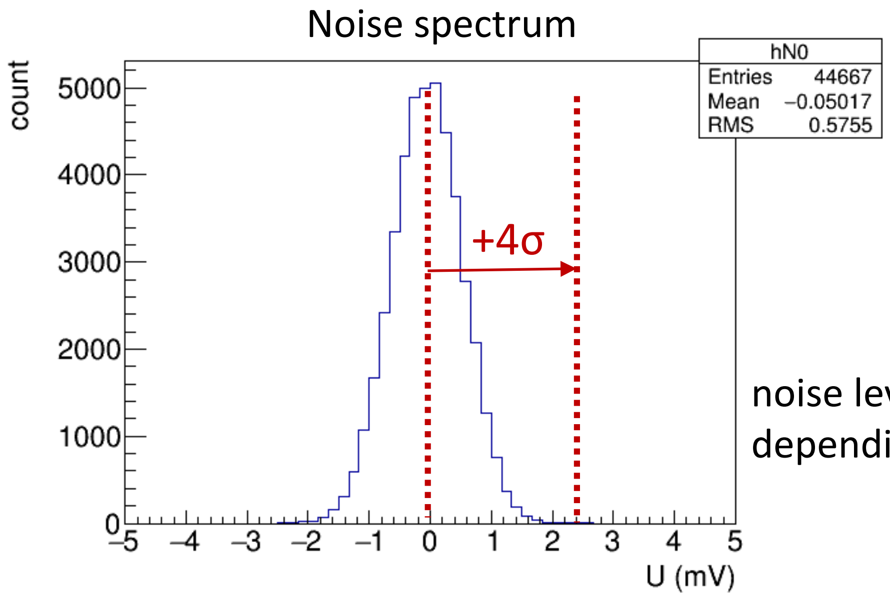
Signal measurement

- Average waveform of 1000 acquisitons
- Select an integration window around the peak [t_{min}, t_{max}]
- Signal = Integral around the peak

$$S = \frac{1}{t_{max} - t_{min}} \int_{t_{min}}^{t_{max}} U \mathrm{d}t$$

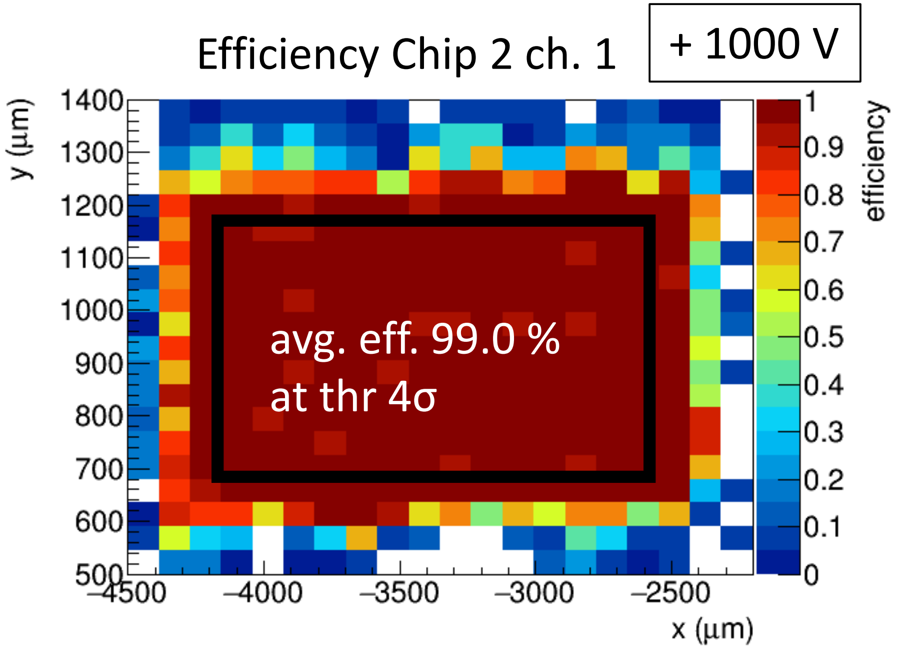
- Long integration window [– 6 ns, 6 ns] to mitigate for noise
- Hit criterium: signal threshold = 4σ above noise

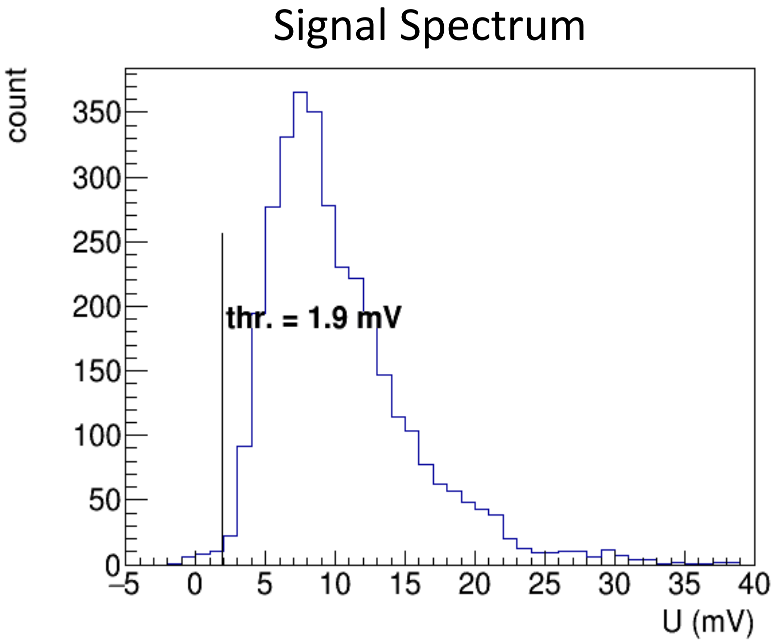




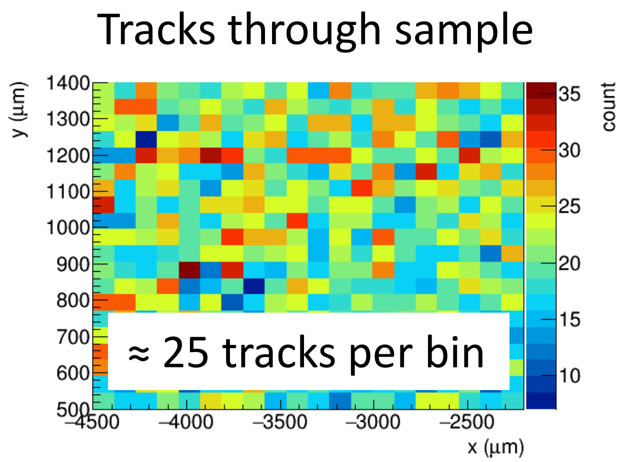
noise level varies by factor 2, depending on the channel

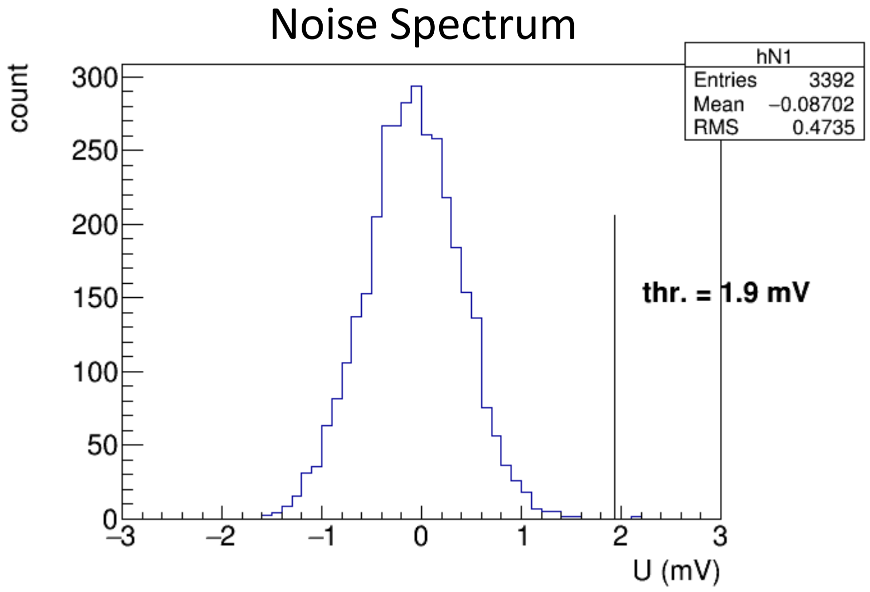
Efficiency measurement Chip 2 channel 1 (1000 V)

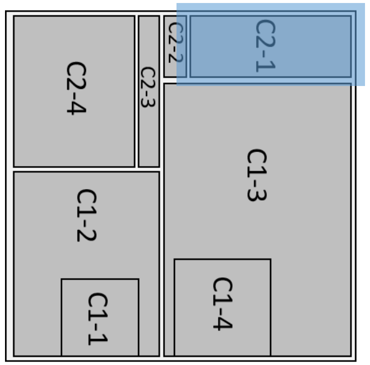




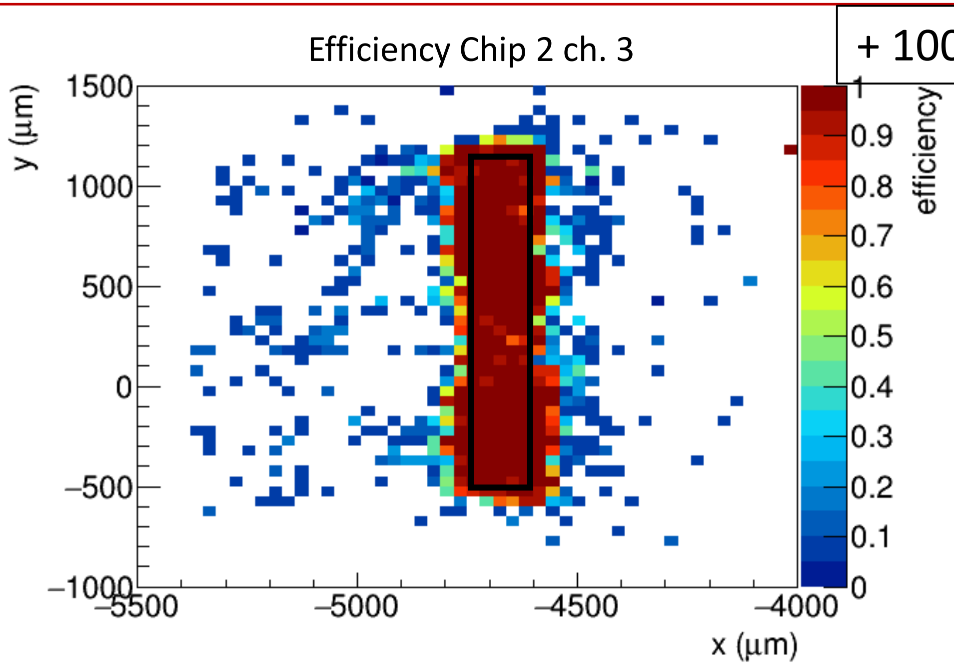
- > 99 % hits above threshold
- Measured in the fiducial region at + 1000 V
- MPV = 7.5 mV, mean 9.8 mV
- Noise RMS = 0.5 mV
- S/N ratio (mean) ≈ 20

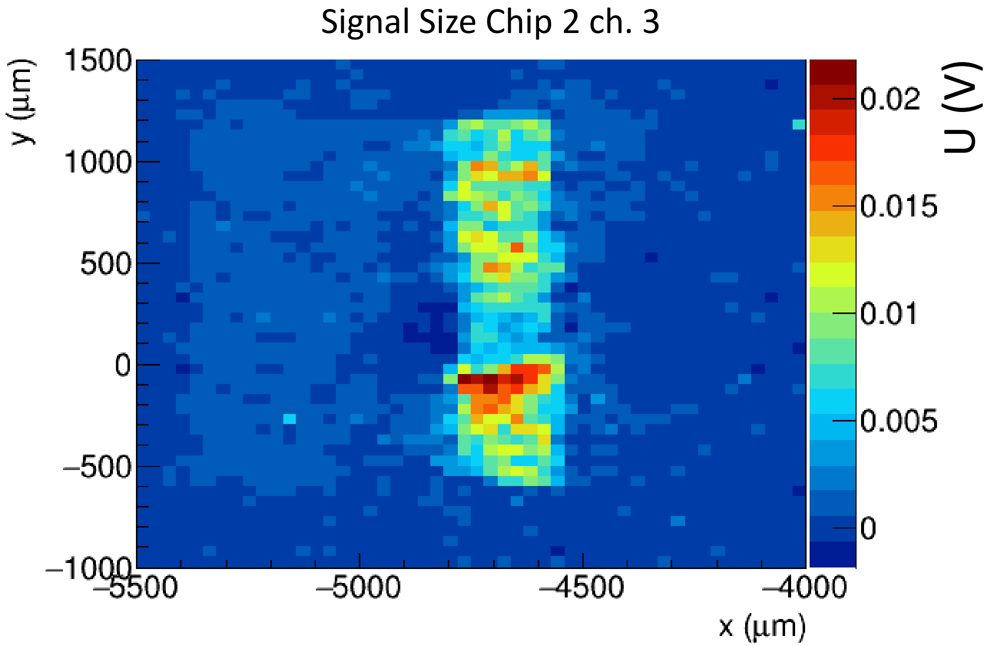


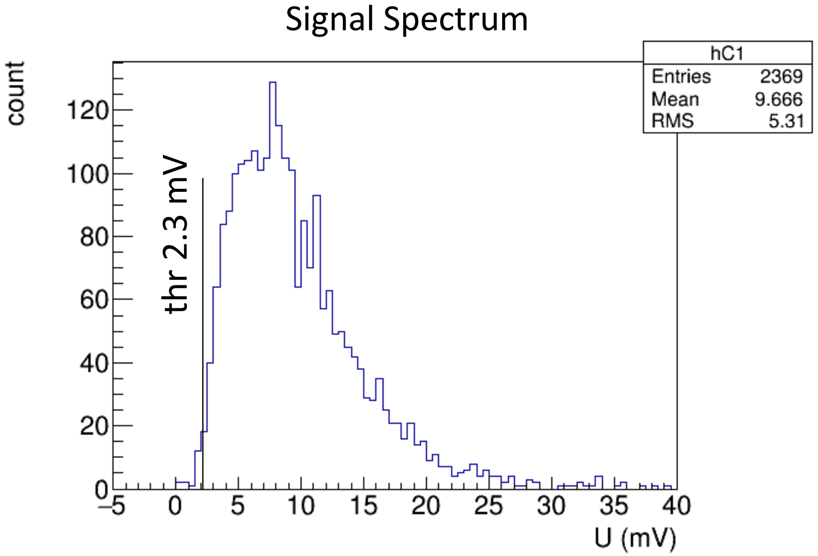




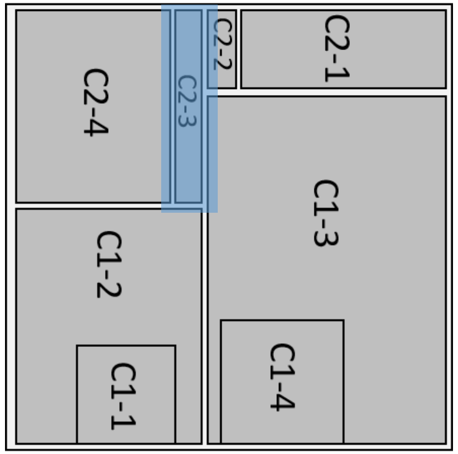
Chip 2 channel 3





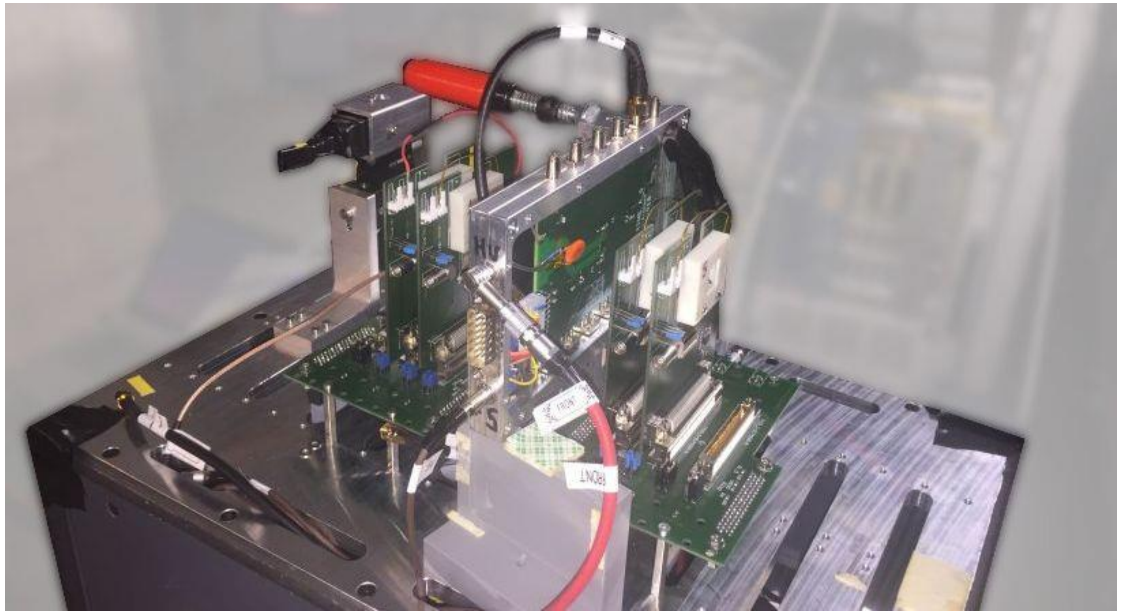


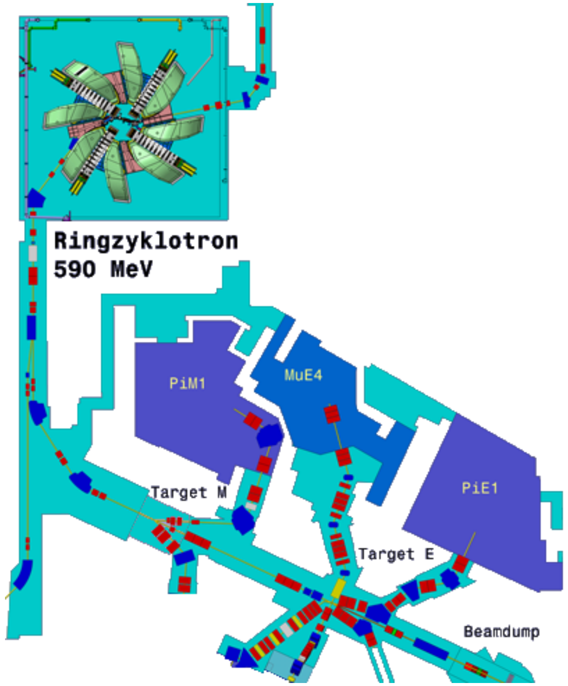
- High resolution run on a small pad
- Efficiency > 99 % in fiducial region at thr. 4σ
- Signal size varies with position (pCVD diamond)
- Should average out over large pad

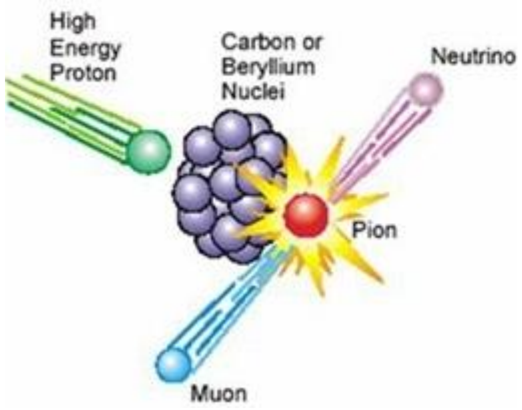


PSI test beam

- High Intensity Proton Accelerator (HIPA) at PSI, beam line PiM1, 260 MeV/c pions
- PSI beam telescope (150 x 100 μm pixels) + multiple scattering → lower resolution
- DRS 4 readout, modifications to reduce ringing
- Measurements at positive and negative bias voltage: ± 200 V, ± 300 V (sample 1), ± 500 V, ± 1000 V (sample 2)

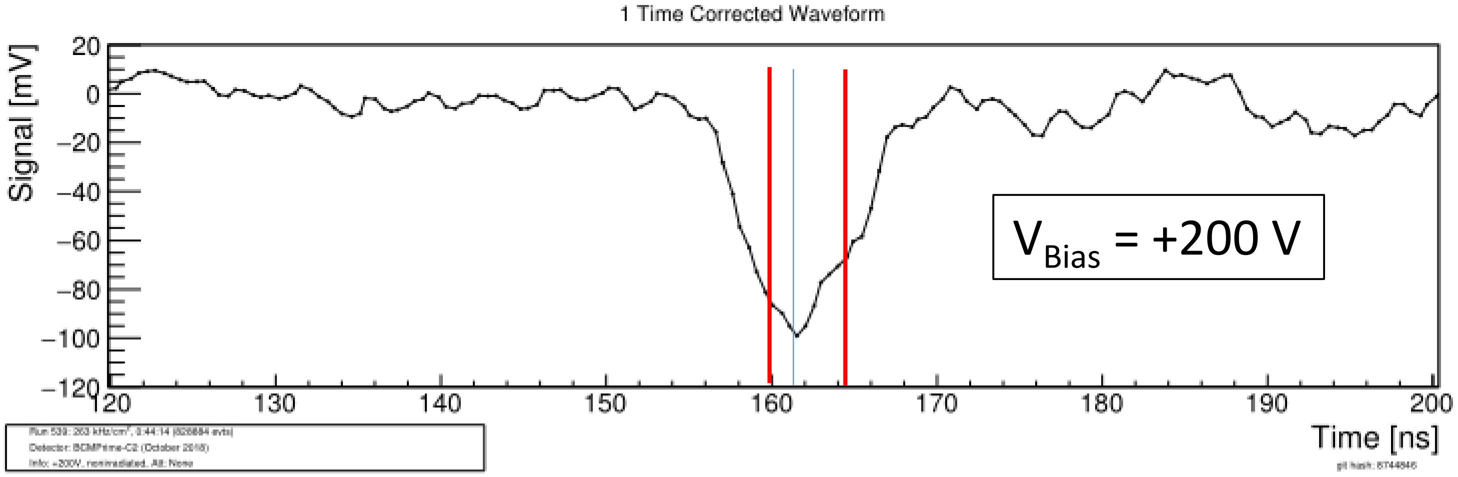


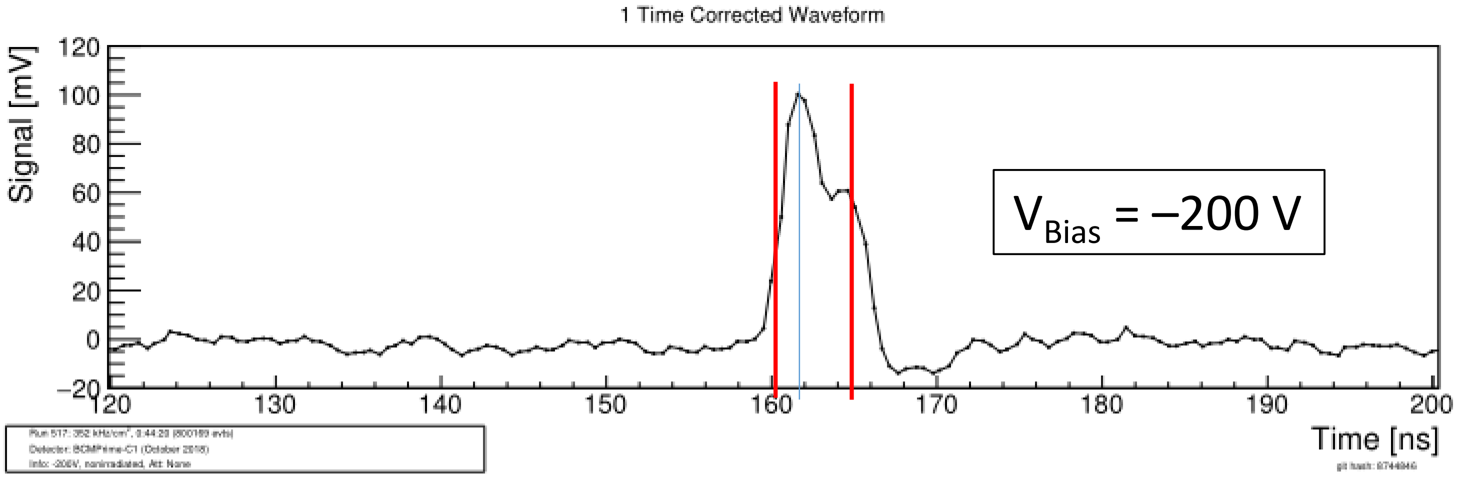




Thanks to ETH for measurements and analysis!

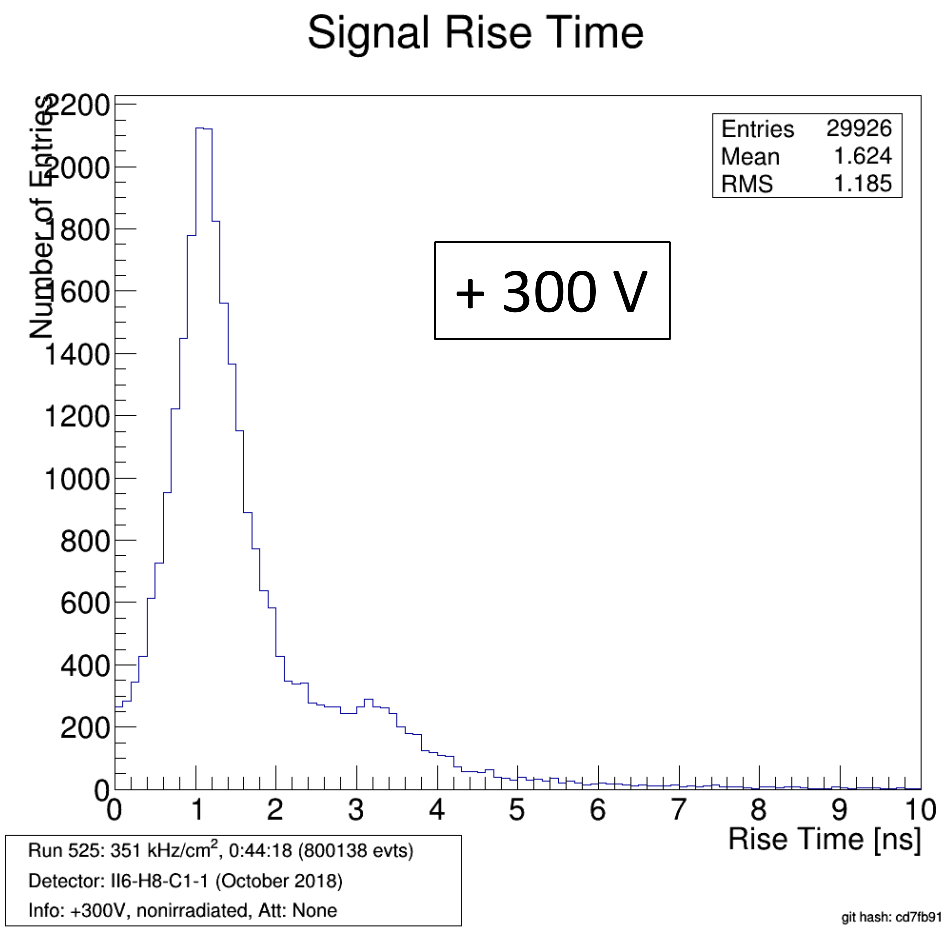
Waveforms at PSI

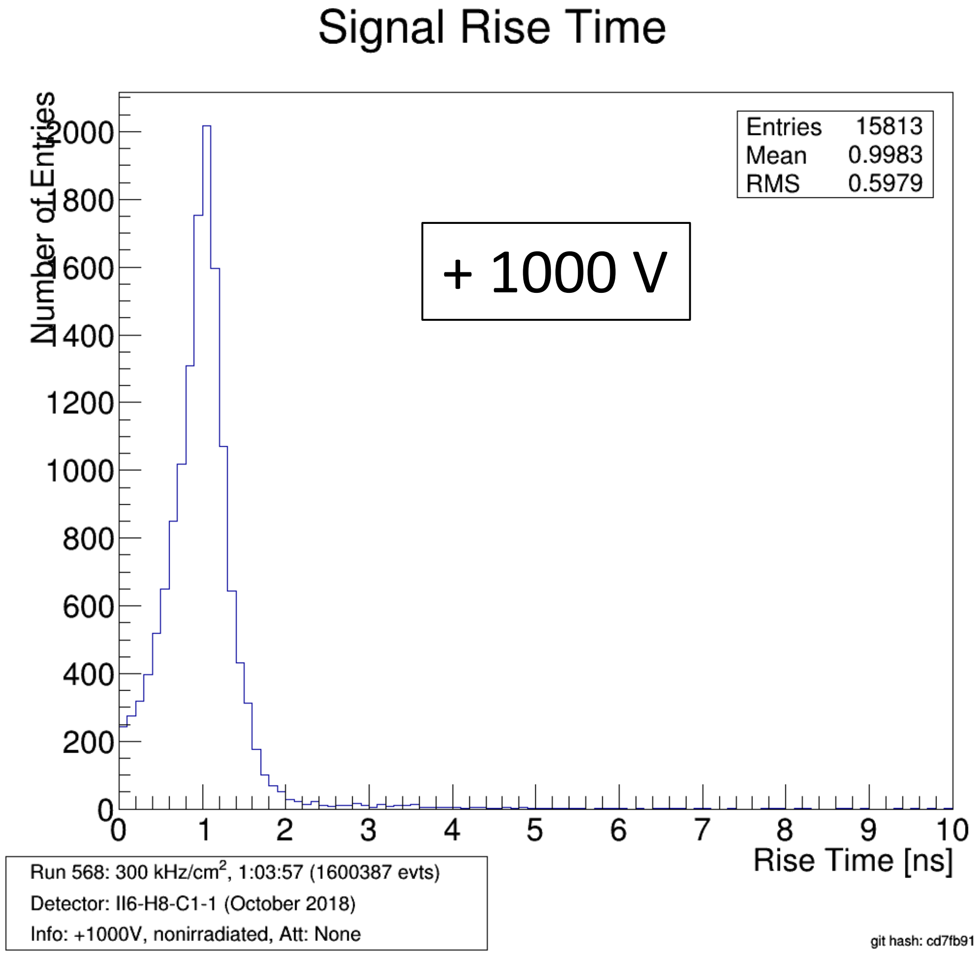




- Much lower noise than at CERN – no pickup
- ~ **1.4 ns** Average rise time (20 % – 80 %),
- DRS 4 analog bandwidth (700 MHz) may be the limiting factor in the rise time measurement
- Baseline restoration after 10 ns
- Analysis: Integration time [—1.5 ns, 3 ns]

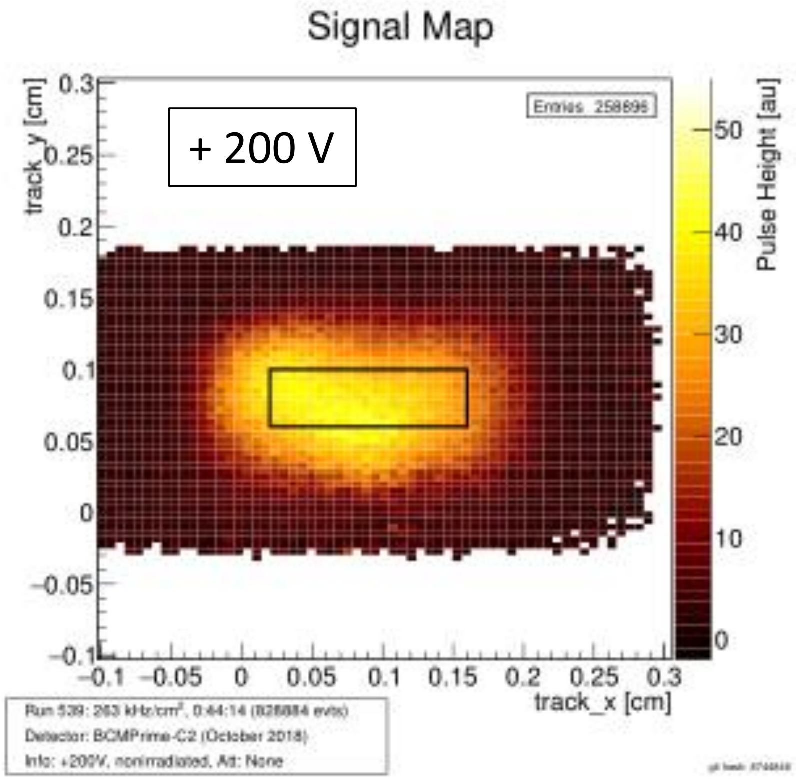
Signal Rise Time

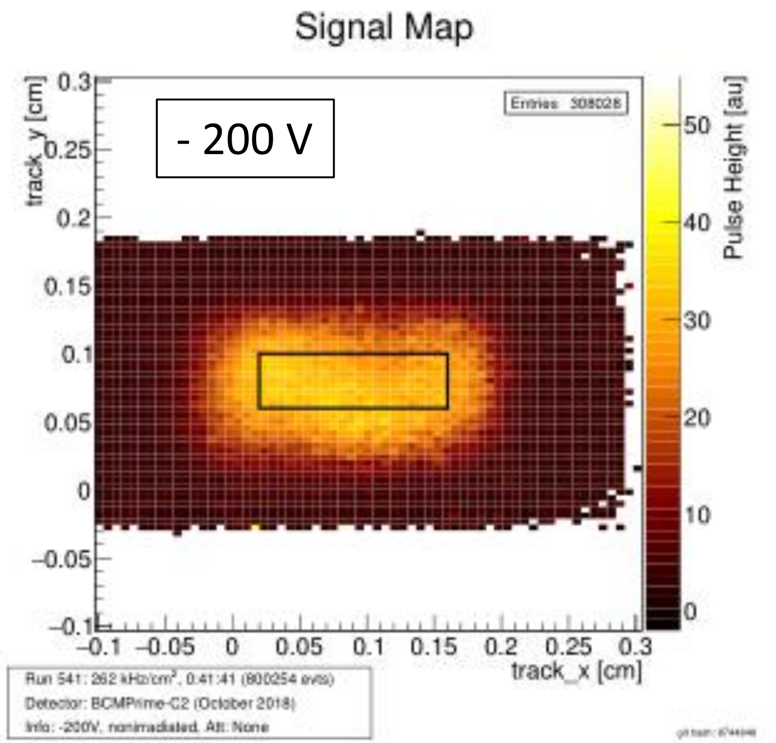


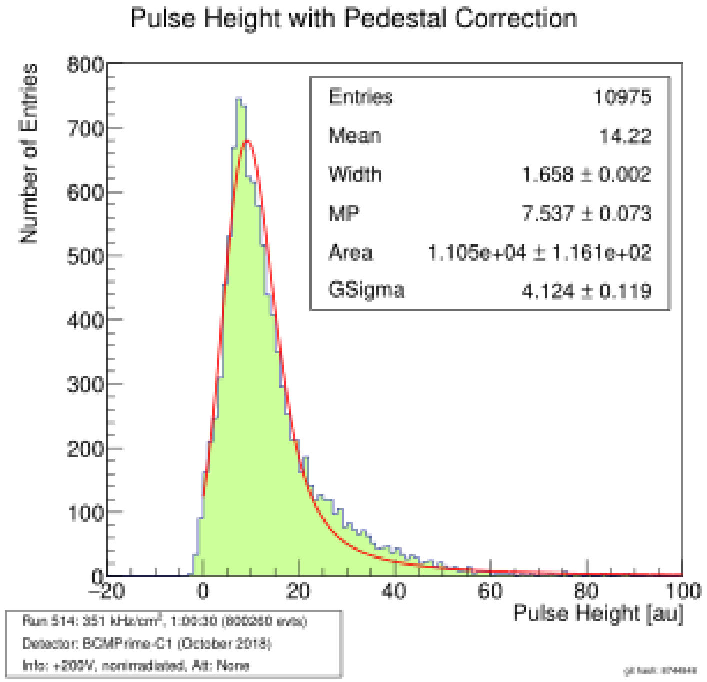


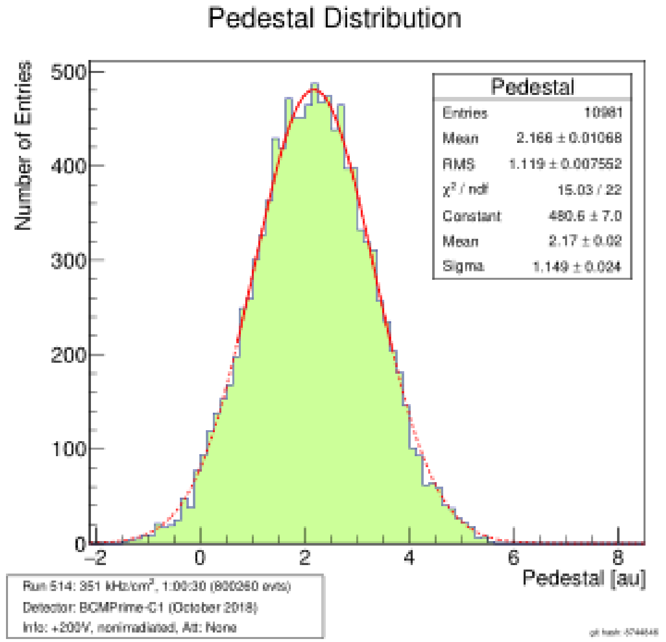
- Rise time (20 % – 80 %) ≈ 1 ns
- Improves with bias voltage – very few outliers at 1000 V

Charge measurement + 200 V



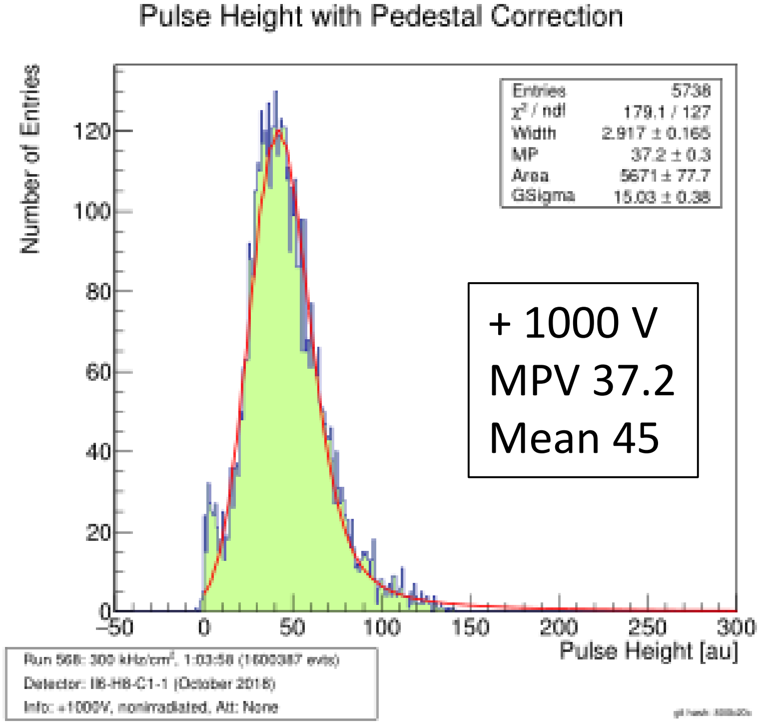


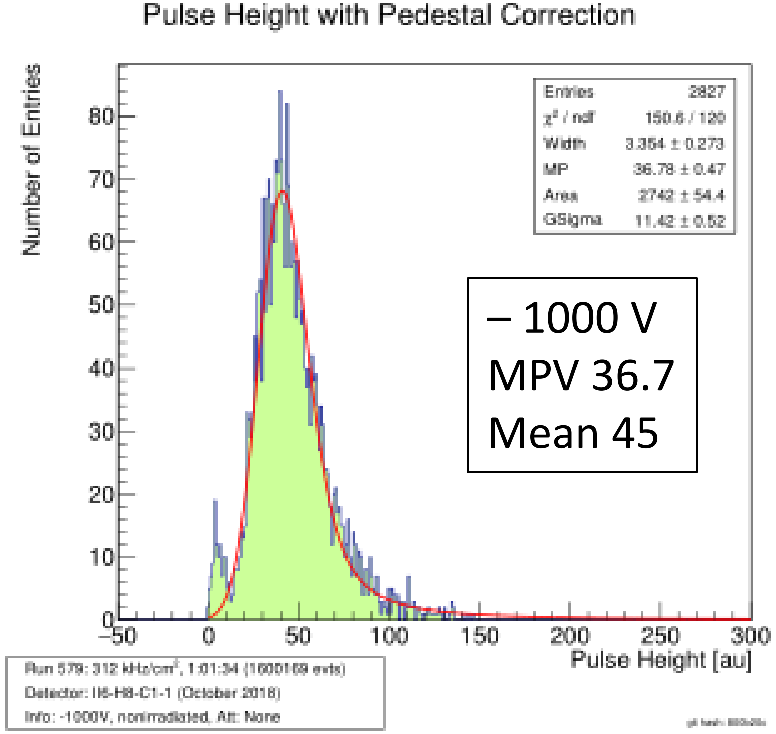


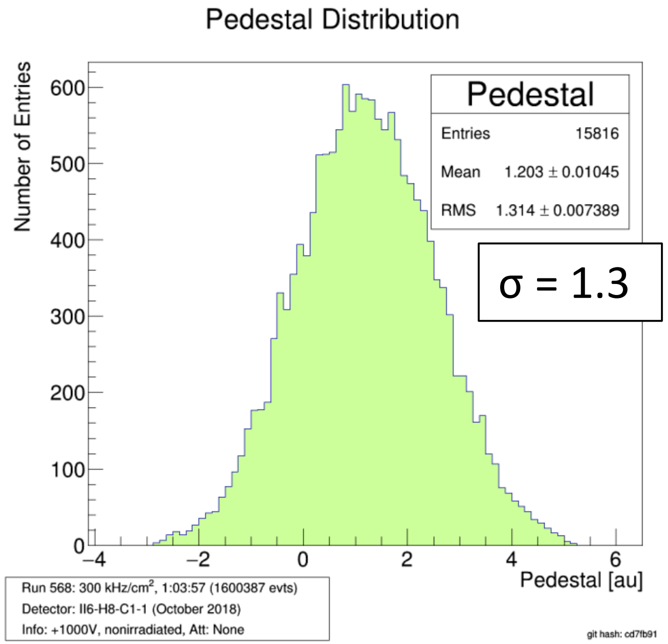


- Charge measurement in **fiducial region**
- 10 % difference for different sign of V_{bias} at low voltages (0.4 V/µm)
- Distribution fitted with convoluted Landau + gaussian
- Noise distribution independent of bias voltage, offset is a feature of DRS 4

Signal spectra at 1000 V







- At 1000 V signal spectrum is the same for both polarities
- Small pedestal – due to low tracking resolution

Signal summary

Diamond 1

Mean

Chip	Bias [V]	Signal [au]	Noise [au]	SNR
1	+200 V	14.07	1.15	12.23
2	+200 V	36.52	2.73	13.37
1*	+200 V	13.73	1.03	13.33
2*	+200 V	13.66	1.15	11.88
1	−200 V	12.04	1.28	9.40
2	−200 V	30.12	2.70	11.16
1*	−200 V	12.23	1.18	10.36
2*	−200 V	10.18	1.10	9.25
1	+300 V	21.93	1.21	18.12
2	+300 V	56.87	2.67	21.30
1	−300 V	16.53	1.26	13.12
2	−300 V	44.62	3.01	14.82

Diamond 2

Mean

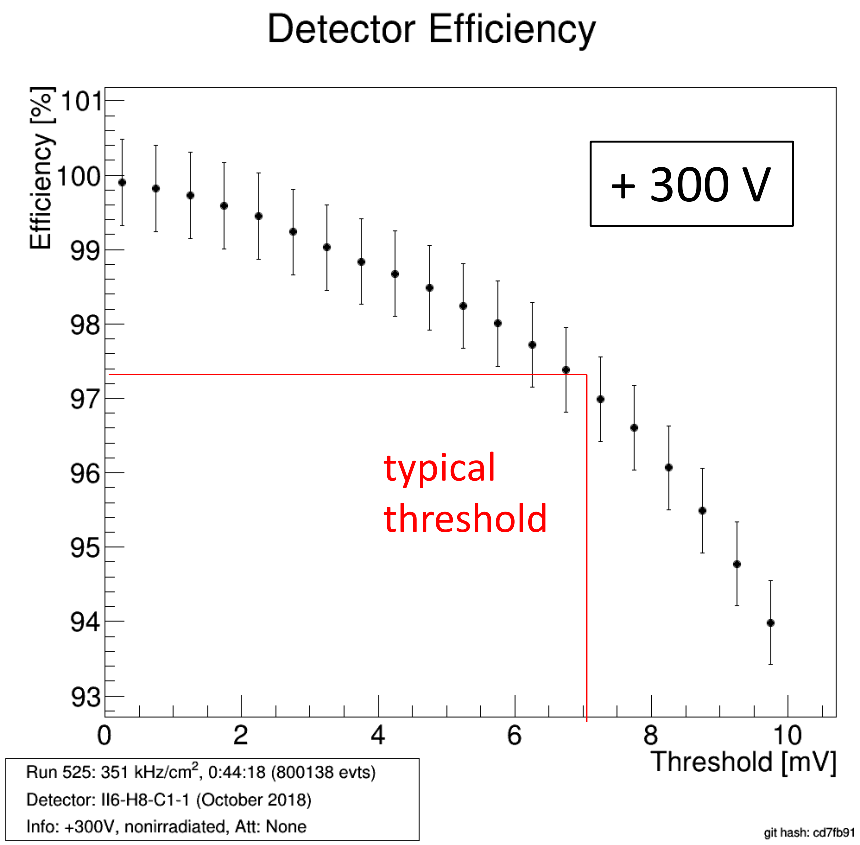
Chip	Bias [V]	Signal [au]	Noise [au]	SNR **(Mean)**
1	+500 V	35.16	1.02	34.47
2	+500 V	38.43	1.15	33.42
1	+1000 V	45.62	1.15	39.67
2	+1000 V	47.16	1.06	44.49
1	−500 V	33.10	1.18	28.05
2*	−500 V	24.32	1.21	20.10
1	−1000 V	44.96	1.12	40.14
2	−1000 V	45.75	1.12	40.85

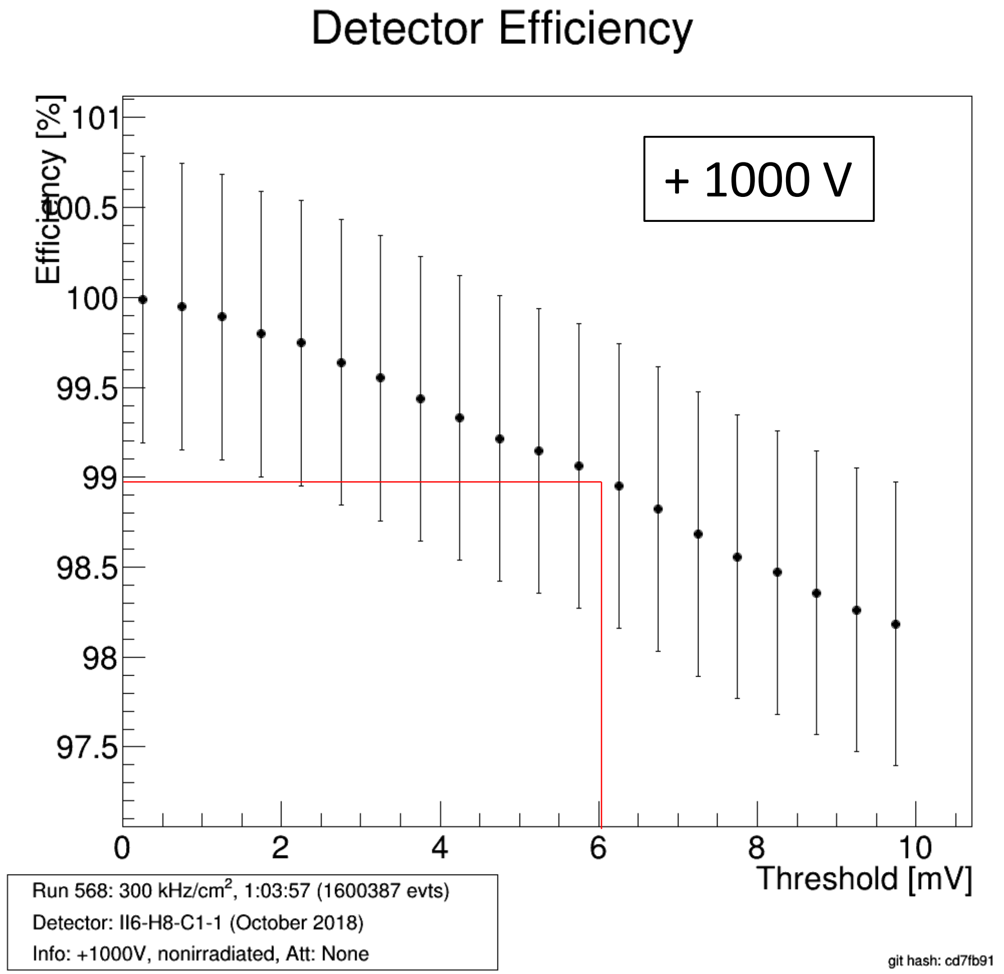
S/N ratio = **mean** signal / noise RMS

At highest bias voltages **S/N ≈ 40** (mean)

Timing resolution: t_{rise} / (S/N) = 1.4 ns / 40 = 35 ps → very promising

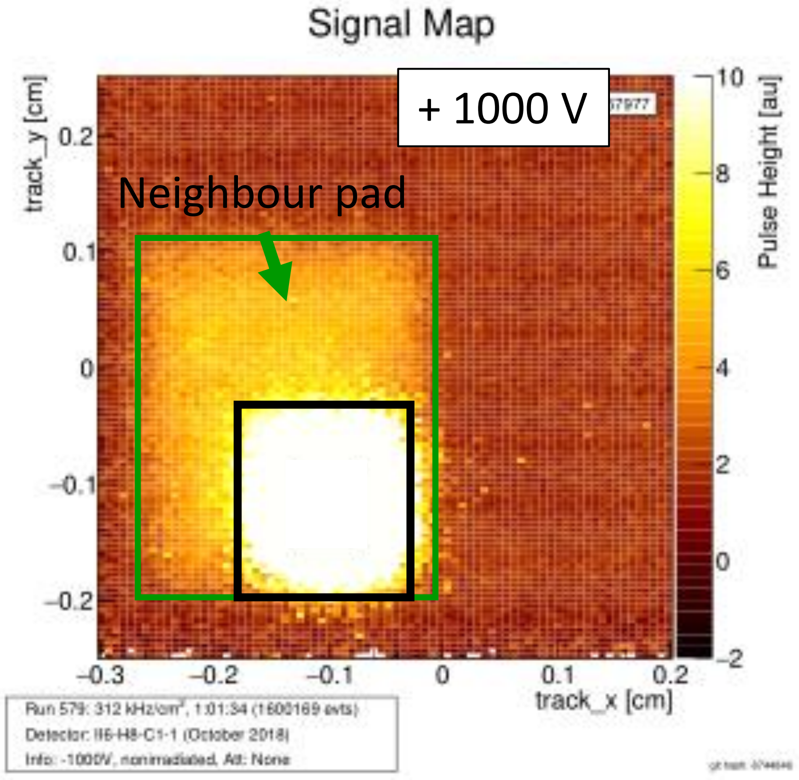
Efficiency vs. threshold

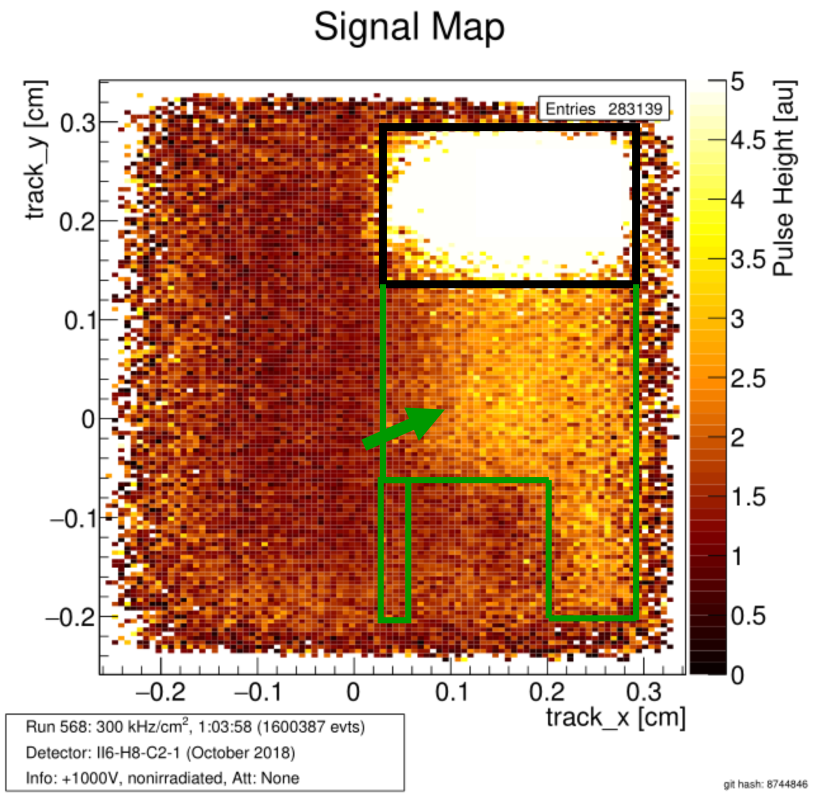




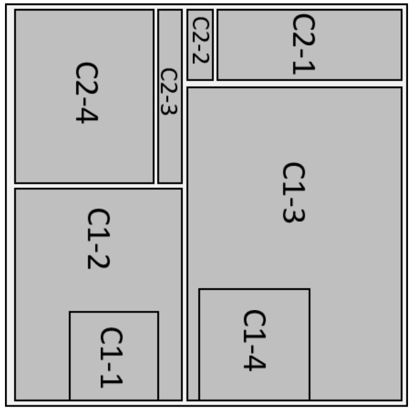
- Efficiency improves from 300 V (0.7 V/µm) → 1000 V (2 V/µm)
- Inefficiency in part due to low tracking resolution

Interchannel coupling



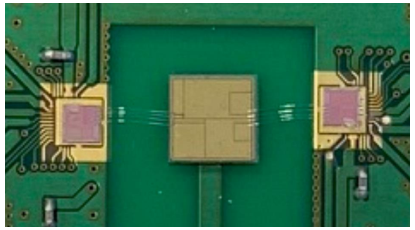


- Couplings to the neighbour pad observed – cross talk on the sensor suspected
- Similar behaviour observed at SPS
- Small signals every time a particle hits the neighbour pad

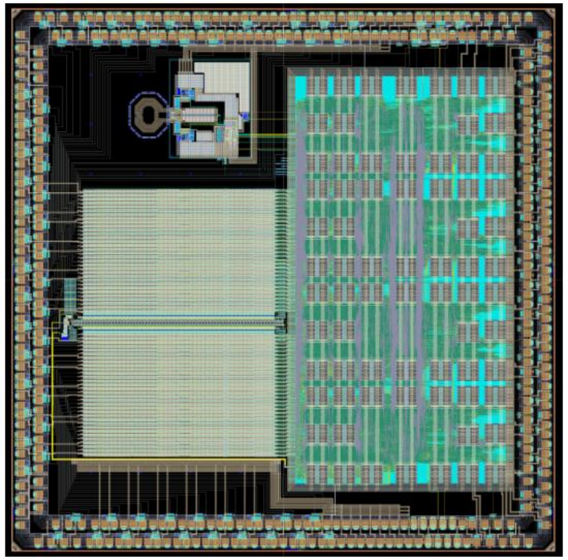


Toward the BCM' module

- Module = Sensor + analogue front end + digitization + data transmission



+ PicoTDC + lpGBT



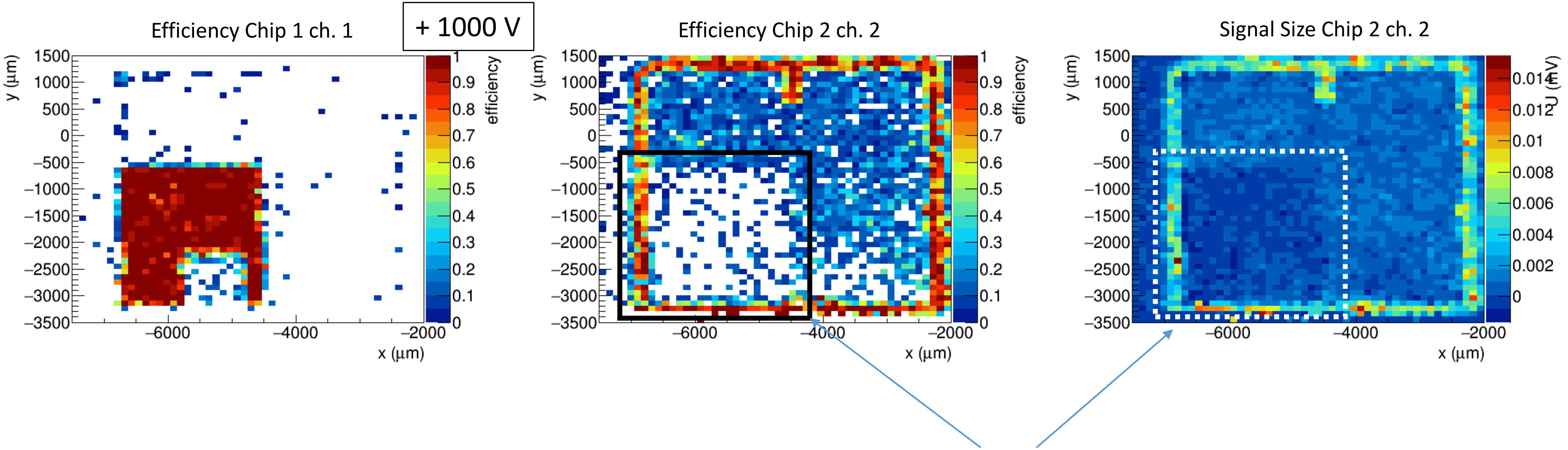
- Use "existing" components:
- PicoTDC: time-to-digital converter (TDC) developed by CERN
- Compatible with lpGBT
- 65 nm TSMC process
- 12 ps inherent time resolution
- 32 channels, selectable between measurement of
  - Time of arrival
  - Time over threshold
  - BCM' requires 16 channels

Summary and outlook

- Successfully demonstrated functionality of the first BCM' front end prototype
- > 99 % efficiency measured in the test beam
- S/N (mean) = 40 before irradiation
- Good timing performance
  - Rise time 1.4 ns
  - Baseline restoration 10 ns
  - < 100 ps timing resolution is already achievable
- Further analogue front end submissions planned
- Module production using common components: PicoTDC, lpGBT

BACKUP

Chip 1 ch. 2 + Chip 2 ch. 2



Cross talk ?

- Observed cross talk on the sample
- Separate readout chips, so cross-talk most likely from the sensor
- Noise level larger with larger pads → 2x higher threshold, efficiency slightly lower