Development of Beam Conditions Monitor for the ATLAS experiment

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Motivation

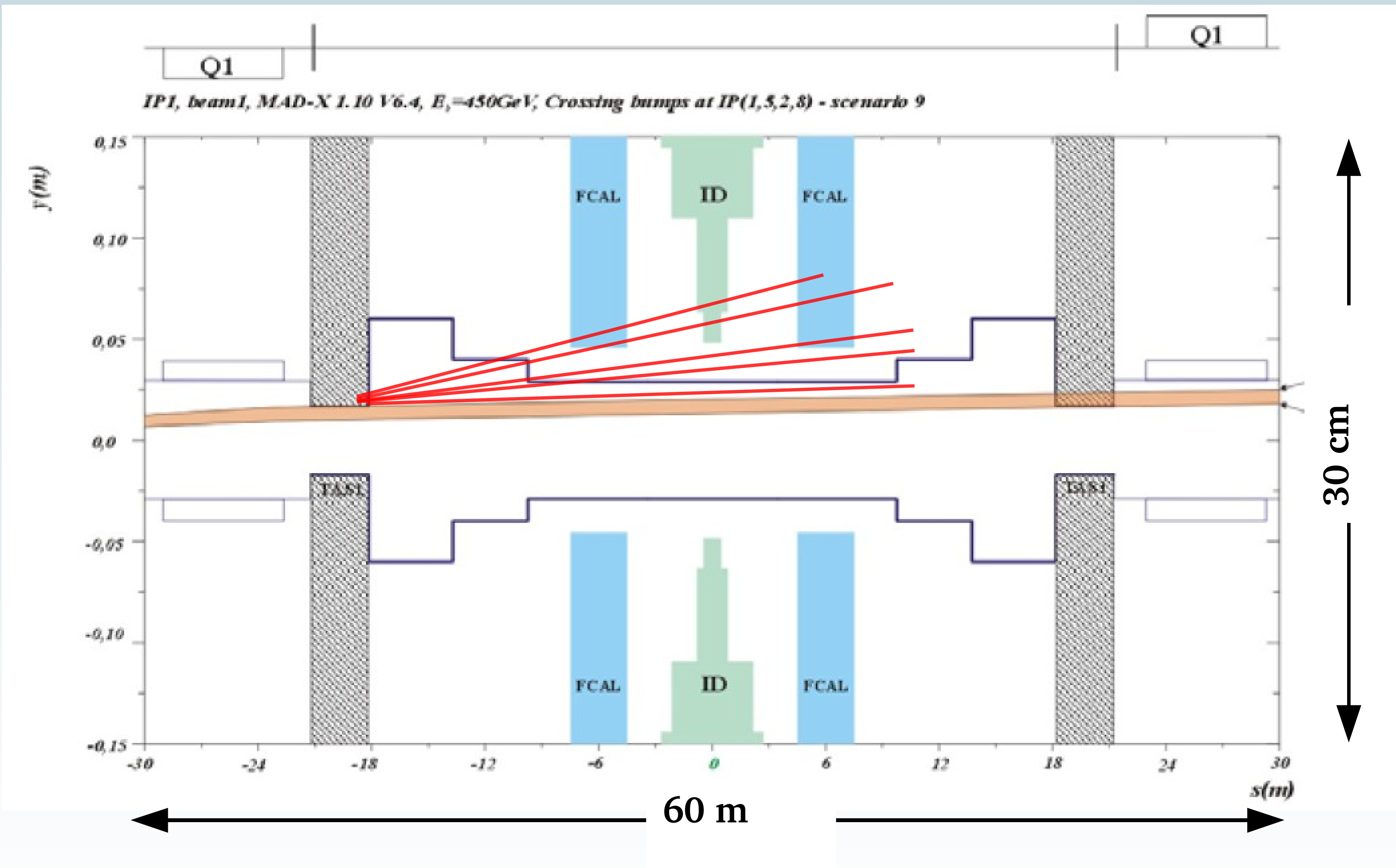
The goal of beam conditions monitor (BCM) system inside the ATLAS Inner Detector:

- Monitor the particle rates and distinguish each bunch crossing between **normal collision** and **background events** during normal running
  - measure background rate (beam halo hitting TAS collimator, beam gas interaction…) close to the interaction point (IP)
  - measure collision rate and provide (bunch by bunch) relative luminosity information (additional measurement to LUCID, ATLAS main luminosity monitor)

- Primary goal: **protection** in case of larger beam losses
  - if there is a failure in an element of accelerator the resulting beam losses can cause damage to the inner detectors of experiments
  - fast detection of early signs of beam instabilities (due to incorrect magnet settings, trips, ...)
  - Issue a beam abort signal if necessary

Beam Loss Scenarios

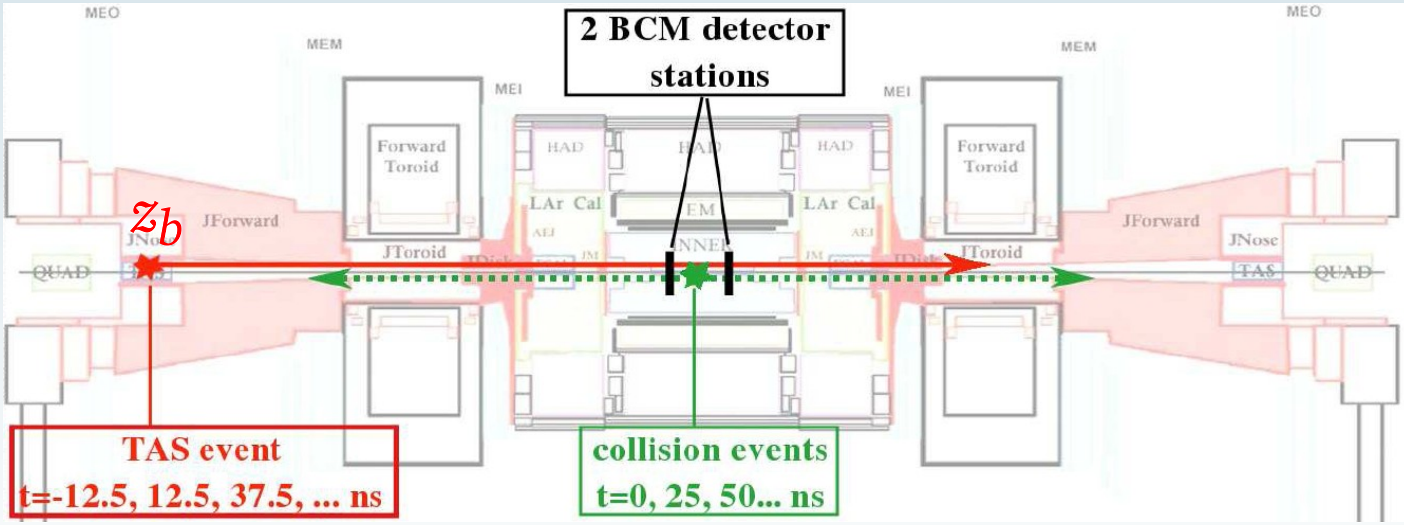
simulations of beam orbits with wrong magnet settings (D. Bocian) exhibit scenarios with beam scrapping TAS Cu collimator



ATLAS BCM principle of operation

Time of flight measurement to distinguish between normal collision and background events (beam gas, halo, TAS scraping)

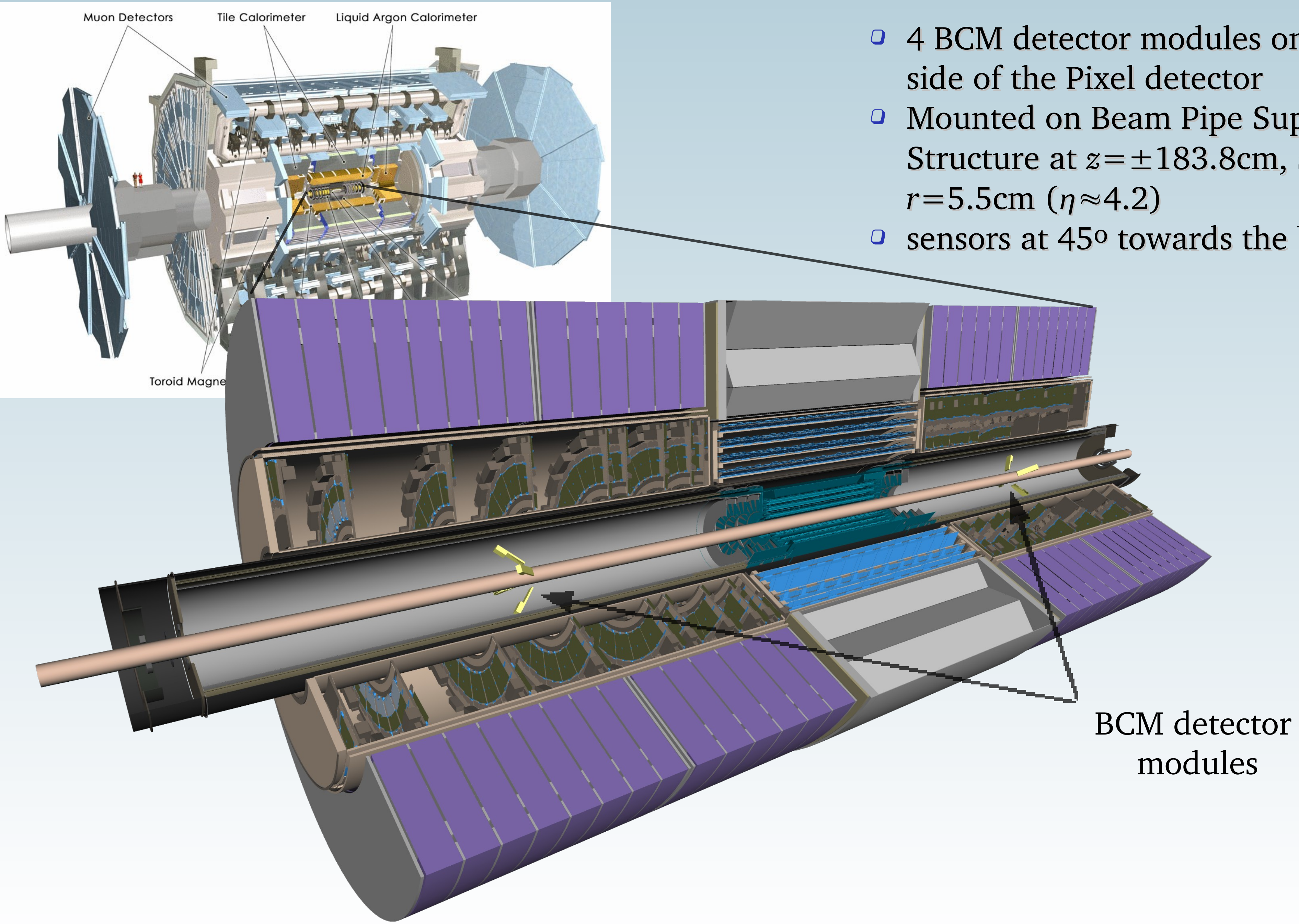
- place 2 detector stations at $z_{BCM}=\pm 1.9$m:
  - particles from **collisions at interaction point** (IP) reach both stations at the same time (6.25 ns after collisions at IP) → **"in time" hits**
  - particles from **background** interactions occurring at $|z_b|>|z_{BCM}|$ reach nearest station 12.5ns before particles from collisions at IP (6.25 ns before collisions) → **"out of time" hits**
  - use **"out of time"** hits to identify the background events
  - use **"in time"** hits to monitor luminosity
- measurement every proton bunch crossing (25 ns)



Requirements:
- fast and radiation hard detector & electronics:
  - rise time ~1ns
  - pulse width ~3ns
  - baseline restoration ~10ns
  - ionization dose ~0.5 MGy, 10^{15}particles/cm^2 in 10 years
- MIP sensitivity

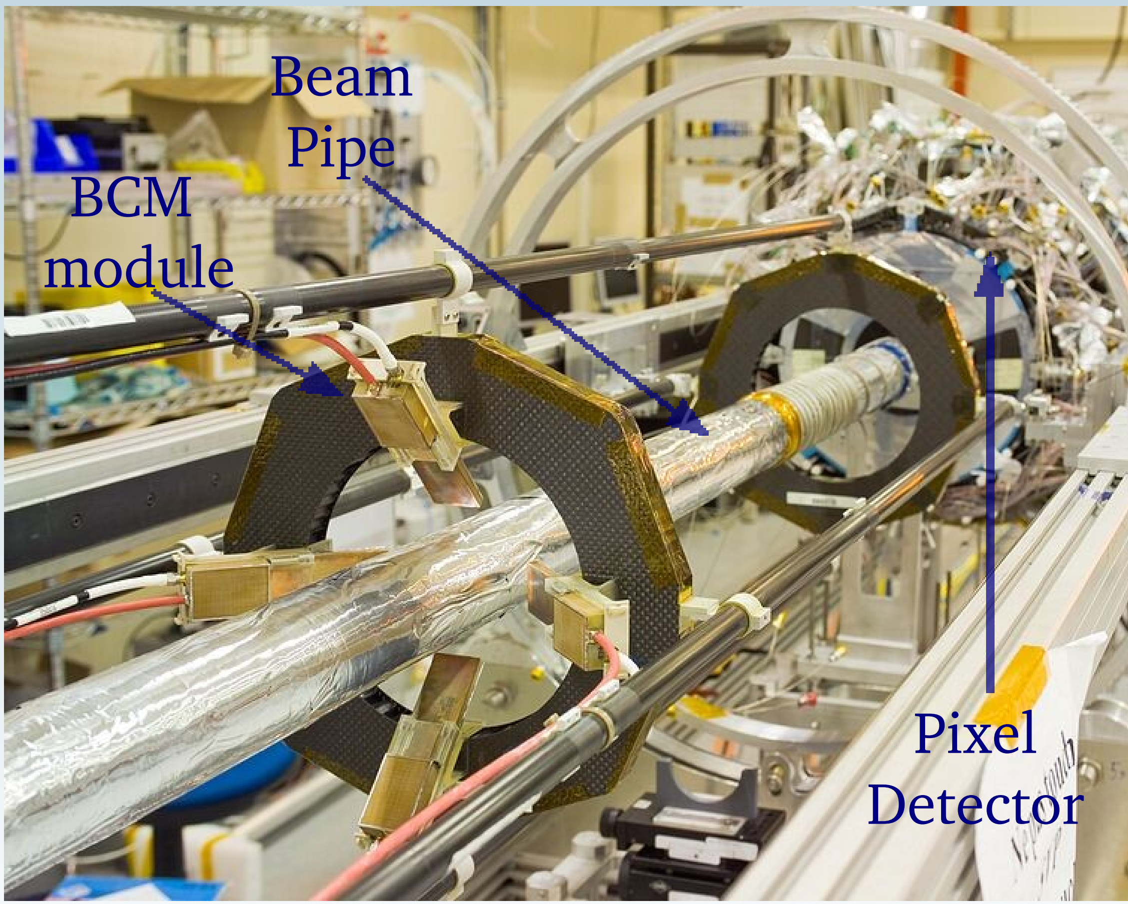
Realization

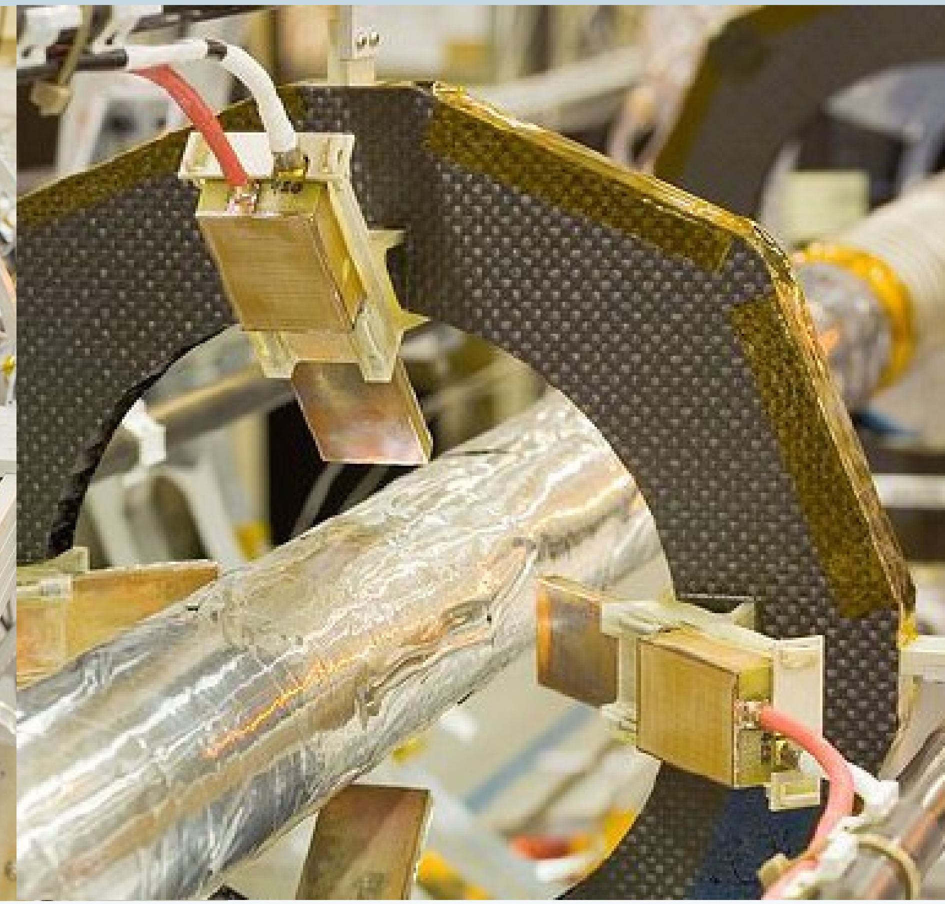
- 4 BCM detector modules on each side of the Pixel detector
- Mounted on Beam Pipe Support Structure at $z=\pm183.8$cm, sensors at $r=5.5$cm ($\eta\approx4.2$)
- sensors at 45^{o} towards the beam



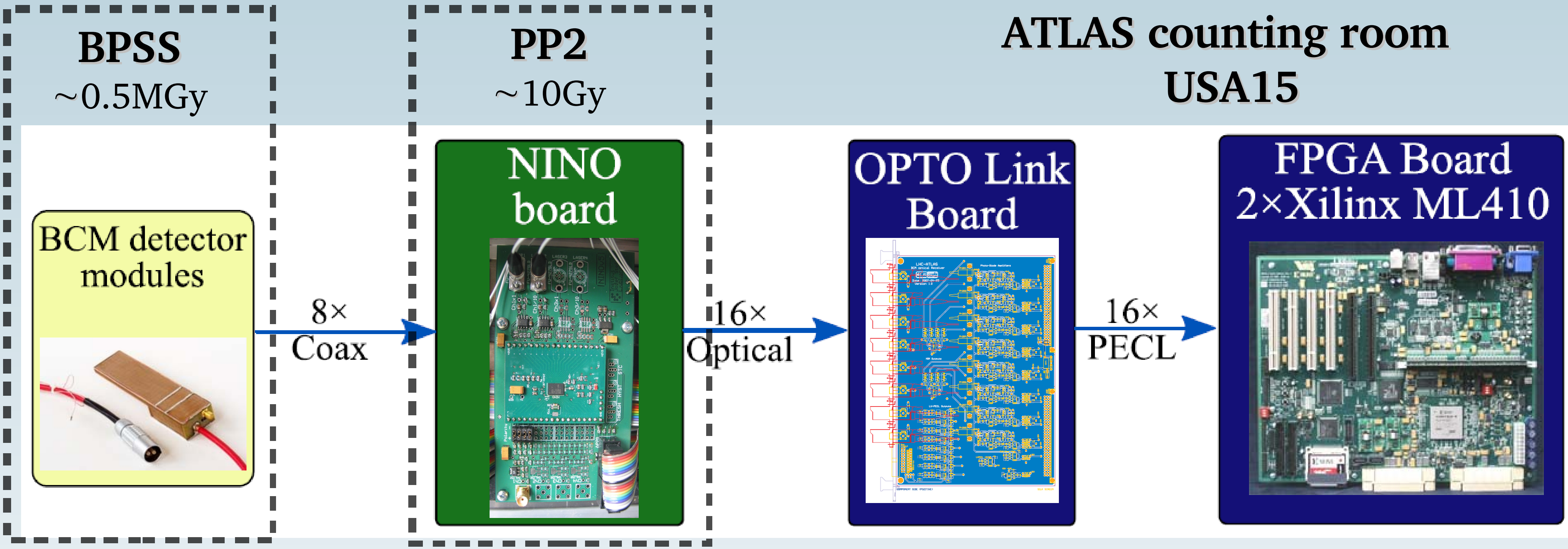
BCM Detector Modules Installed

BCM modules were installed on Beam Pipe Support Structure in November 2006 and lowered into ATLAS pit in June 2007





BCM System - Schematics



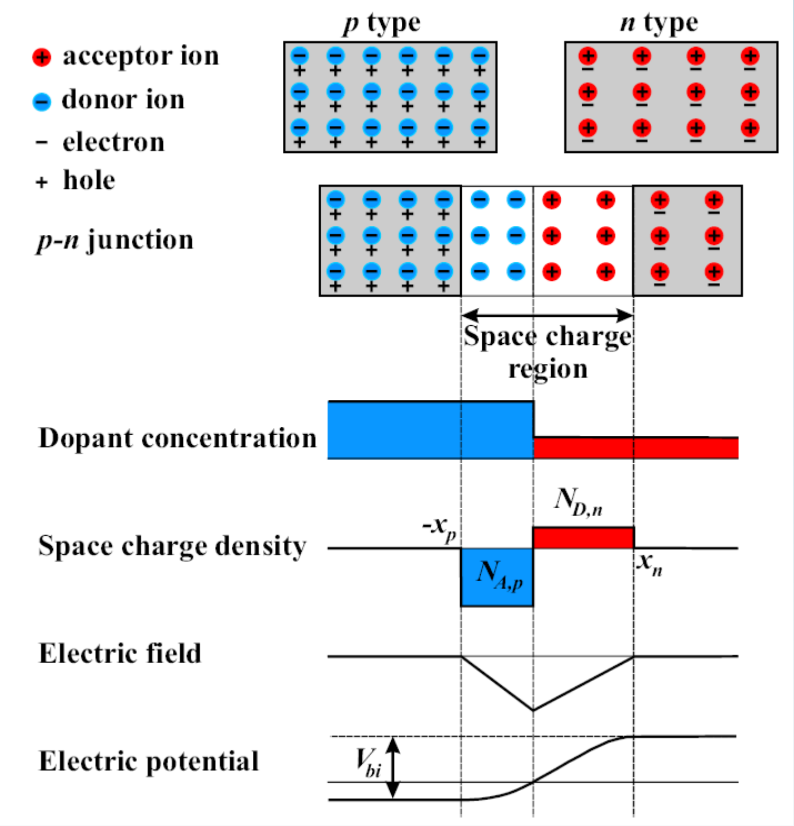
BCM sensors

2 candidates for BCM sensor material

- pCVD (polycrystalline chemical vapour deposition) diamond
- epitaxial silicon

Silicon detectors

- ionising particle: drifting of *e*-*h* pairs in el. field induces a current signal
- diode (*p*-*n* junction): acts as ionization chamber
- space charge region (SCR):
  - lower leakage current → lower noise
  - ionised dopants → electric field
- reverse bias voltage: increase sensitive volume
- **epi silicon:**
  - annealing studies at elevated temperatures (Hamburg group) indicated higher radiation tolerance compared in terms of N_{eff} to standard high resistivity *n*-type FZ silicon detectors → candidate for BCM
  - Annealing studies performed at 20°C (closer to annealing scenarios at LHC) to verify these promising results

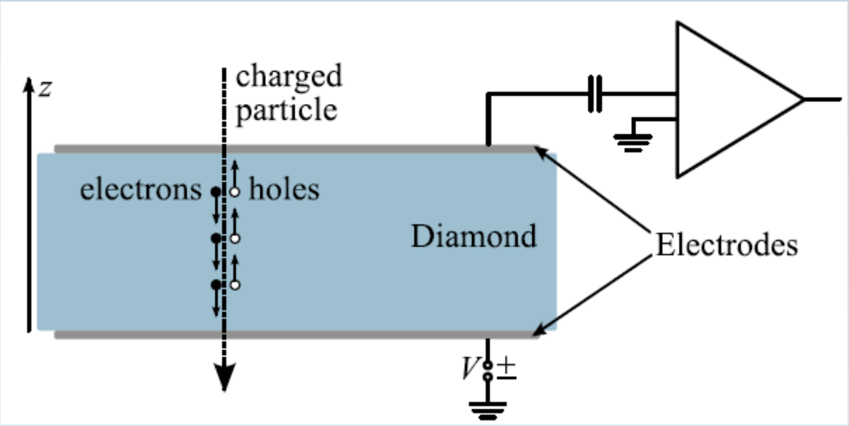


BCM sensors

Property	Silicon	Diamond
Atomic number	28.09	12.01
Mass density ρ_m [g/cm^3]	2.329	3.515
Protn number	14	6
Breakdown electric field ε^{br} [V/cm]	$\sim 3\times 10^5$	1–20×10^6
Dielectric constant ϵ	11.9	5.7
Energy gap E_g [eV]	1.12	5.47
Intrinsic resistivity ρ [Ωcm]	3.3×10^5	$>10^{15}$
Mobility $\mu_{e,h}$ [cm^2/Vs] electron hole	1420 470	2150 ± 200 1700 ± 280
Saturation velocity $v_{e,h}^{sat}$ [cm/s] electron hole	10^7 9×10^6	1.5×10^7 1.05×10^7
Displacement energy E_R [eV]	11–25	37–48
Average number of e–h pairs in 100 μm created by 1 MIP	8000	3600
Energy to create electrion-hole pair [eV]	3.6 eV	13 eV
MIP ionisation loss [MeV/cm]	2.9	4.7

Diamond sensors

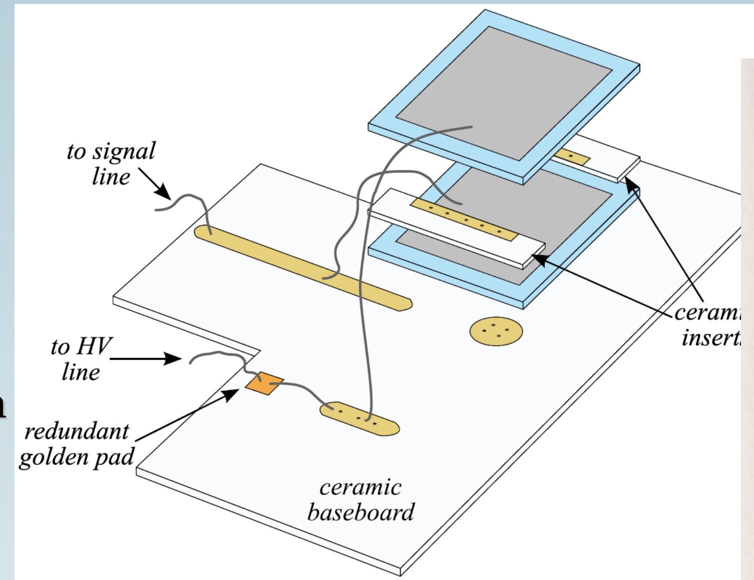
- larger band gap: higher resistivity → low leakage currents, no SCR needed



- lower dielectric constant: lower capacitance → lower noise
- lower displacement energy: potentially radiation hard
- higher energy to create *e-h* pair: lower signal charge
- pCVD diamond:
  - trapping of signal charge even before irradiation
  - quality of pCVD diamond given in terms of measured charge collection distance CCD
    $$CCD=D(Q_{ind}/Q_{gen})$$
  - tested with 24GeV/c protons, 2.2×10^{15}particles per cm^2 (15% signal charge degradation)

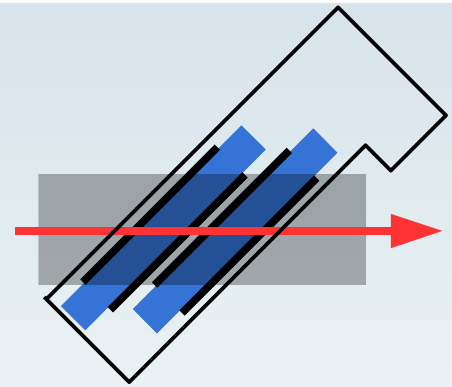
BCM Detector modules

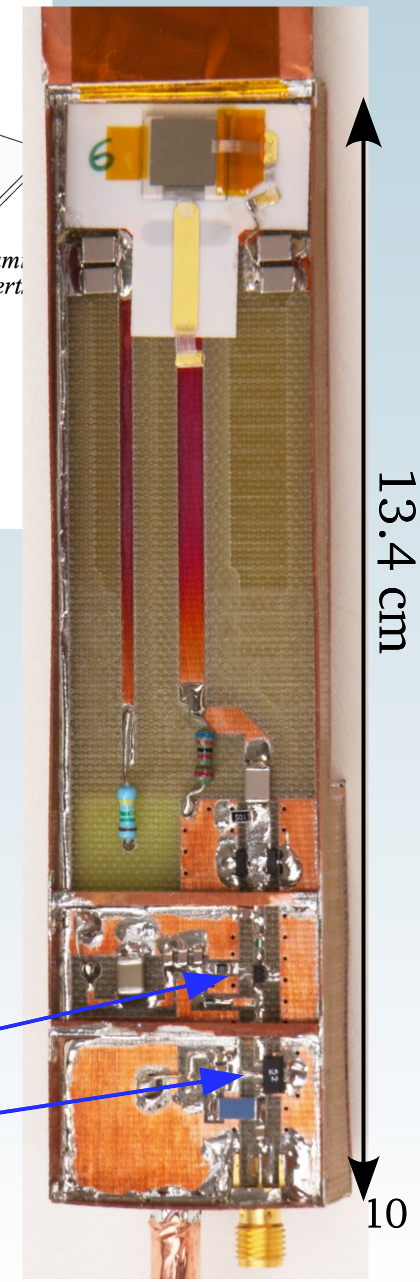
pCVD diamond sensors chosen for ATLAS BCM



Double – decker assembly

- signal passively summed before amplification
- 2 back-to-back sensors each with
  - thickness 500µm,
  - CCD @1V/µm ~220µm
  - Size: 10×10 mm^2
  - Contact size: 8×8 mm^2
  - Operated at 2V/µm (1000V)
    - → fast & short signals





Front end electronics

- **2 stage amplifier:**
  - 1st stage: Agilent MGA-62653, 500MHz (22db)
  - 2st stage: Mini Circuit GALI-52, 1GHz (20dB)

Mesurements with epi silicon: radiation hardness

Radiation damage in Si:

- Bulk damage is cause by non-ionising energy loss (NIEL) resulting in displacement of Si atoms out of their lattice site
  - resulting defects introduce energy levels in the bandgap altering the electrical characteristics of the bulk
- Bulk damage changes detector properties
  - Change of $N_{eff} \rightarrow$ increase of V_{FD} $$N_{eff} = \frac{2\epsilon_{Si}\epsilon_0}{e_0 D} V_{FD}$$
  - Increase of leakage current → increase of noise and high power consumption
  - Deterioration of charge collection efficiency due to trapping of signal charge
- NIEL depends on the type of incoming particles and material
  - equivalent fluence ϕ_{eq} = fluence of 1MeV neutrons that would cause the same NIEL as the actual fluence ϕ_A of particles A

    $\phi_{eq} = \kappa_A \, \phi_A$, κ_A=hardness factor

Mesurements with epi silicon: radiation hardness

Annealing studies with epi diodes:

- Results obtained by Hamburg group at elevated annealing temperatures (60°C, 80°C): epi silicon more radiation tolerant in terms of N_{eff} compared to standard high resistivity FZ silicon, but picture of damage creation not clear at the beginning of our study
- Annealing studies performed at 20°C (closer to annealing scenarios at LHC) to verify these promising results
- *n*-type epi diodes (25μm, 50μm, 75μm) irradiated with reactor neutrons (JSI, Ljubljana, $\kappa \approx 0.9$) and 24GeV/c protons (SPS, CERN, $\kappa \approx 0.62$) with particle fluences up to 10^{16} cm^{-2}
- Annealing behaviour of N_{eff} (V_{FD}) and leakage current after irradiation measured for time period of 3.5 years
- N_{eff} and leakage current determined from capacitance-voltage and current-voltage measurements

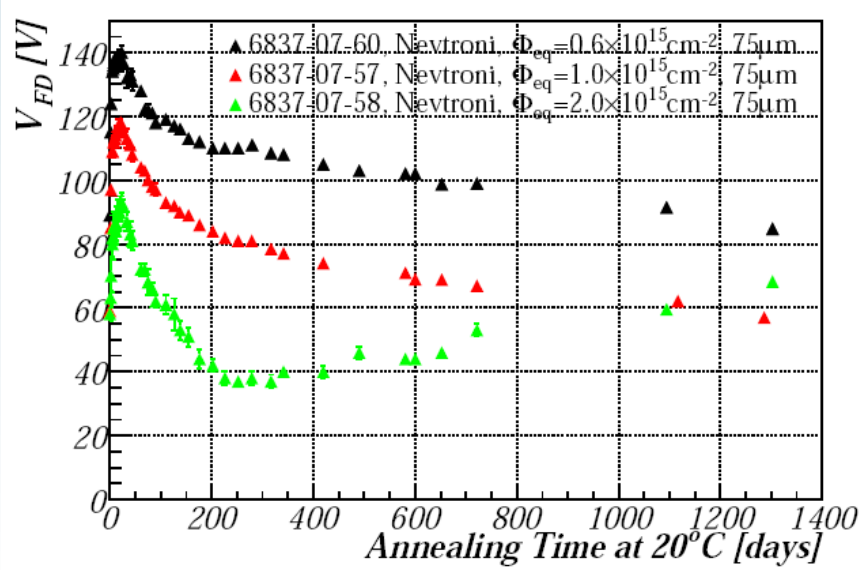
$$C(V) = S\sqrt{\frac{e_0\epsilon_0\epsilon|N_{eff}|}{2V}} = S\frac{\epsilon\epsilon_0}{w_{scr}}, \quad N_{eff} = N_D - N_A$$

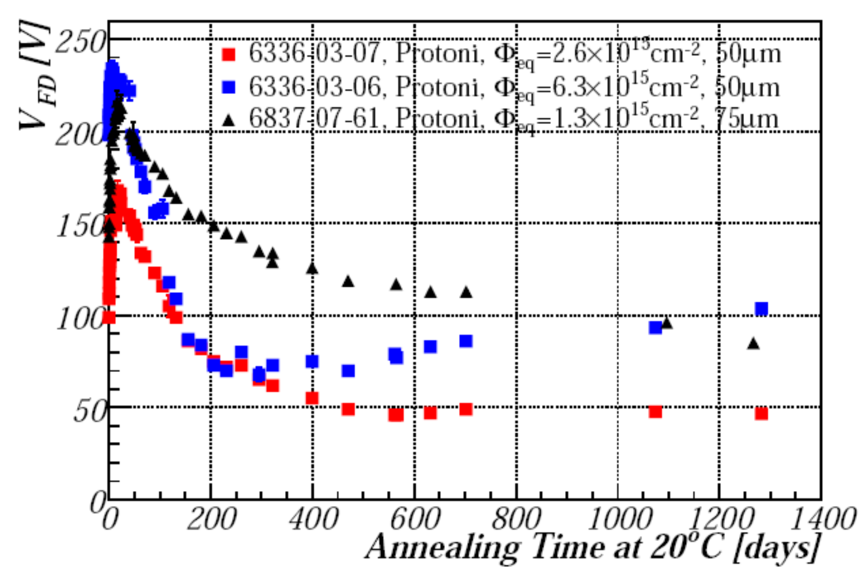
$$N_{eff} = \frac{2\epsilon_{Si}\epsilon_0}{e_0 D}V_{FD}$$

Mesurements with epi silicon: radiation hardness

Annealing of N_{eff}

- **3 components:** short term, long term, stable
- **High resistivity *n*-type FZ silicon:**
  - highly irradiated samples: type inversion immediately after irradiation (more electrically active acceptors than donors created during irradiation)
  - after irradiation:
    - initial decrease of V_{FD} (annealing of acceptors) → short term component
    - followed by slow increase of V_{FD} (generation of acceptors) → long term component
- **Epi silicon:**
  - opposite behaviour for both *n* and *p* irradiation: initial increase of V_{FD}, followed by slow decrease → **explained by** creation of **donors** during irradiation, **no type inversion** immediately after irradiation



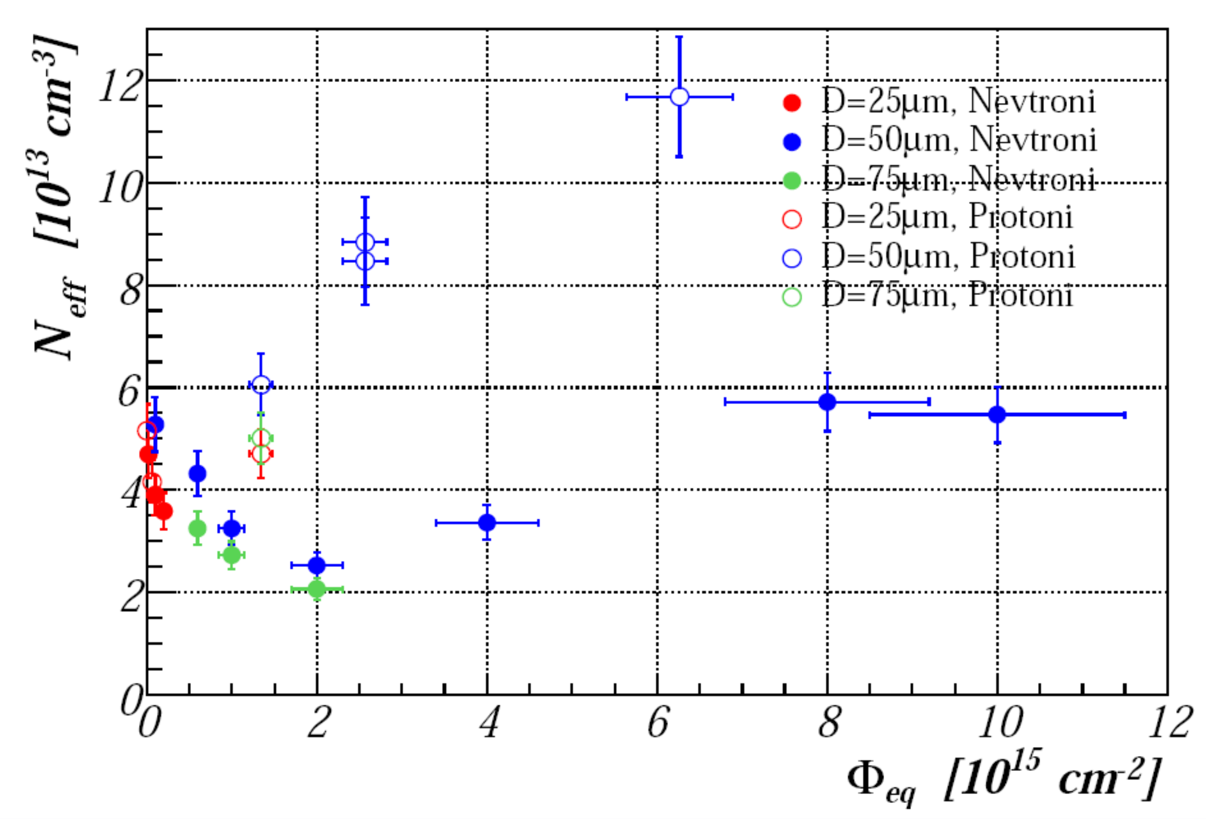


Mesurements with epi silicon: radiation hardness

Annealing of N_{eff}

$|N_{eff}(\phi_{eq})|$ at the end of the short term annealing (stable damage dominating)

- if no type inversion immediately after irradiation:
  - donor removal at low ϕ_{eq}(present in FZ as well): exponential saturation with ϕ_{eq} due to exhaustion initial doping (donors) in *n*-type material
  - at higher ϕ_{eq}: possible creation of acceptors during irradiation (observed in FZ) overcompensated by creation of donors



Mesurements with epi silicon: radiation hardness

Annealing of N_{eff}

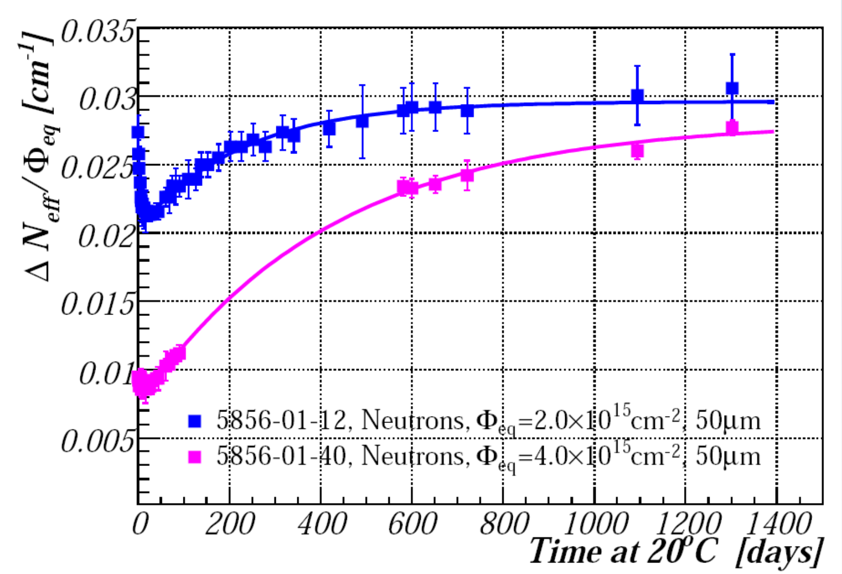
Hamburg parametrisation:

$$\begin{aligned}\Delta N_{eff}(\Phi_{eq}, t(T_a)) &= N_{eff,0} - N_{eff}(\Phi_{eq}, t(T_a)) \\ &= N_A(\Phi_{eq}, t(T_a)) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq}, t(T_a))\end{aligned}$$

- Short term annealing: $N_A = N_{A,0}\exp(-t/\tau_A)$
- Long term annealing: $N_{Y1} = N_{Y1,0}\exp(-t/\tau_{Y1})) = g_{Y1}\Phi_{eq}\exp(-t/\tau_A)$
- Stable damage: $N_C = N_{c,0}(1 - \exp(-c\Phi_{eq})) + g_C\Phi_{eq}$

Donor removal

Effective stable donor creation



Mesurements with epi silicon: radiation hardness

Annealing of N_{eff}

Extracted parameters:

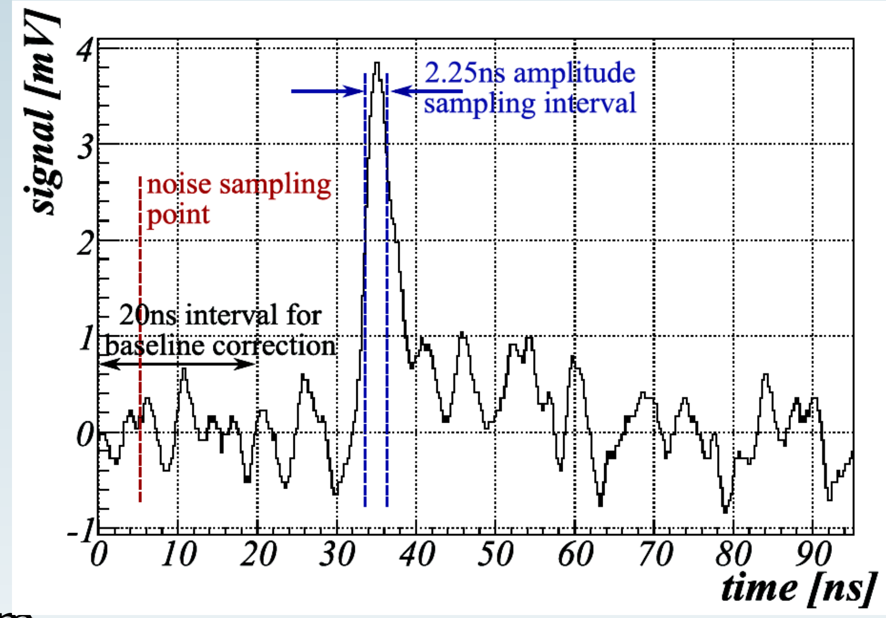
- Results for stable damage agree with the results reported by Hamburg group
- Long term annealing:
  - τ_{Y1} and g_{Y1} slightly lower than expected from results presented by Hamburg (Hamburg: τ_{Y1}=440 days at 20°C, $g_{Y1}=2.9\times10^{-2}cm^{-1}$)

Damage Parameter	Neutron Irr.	Proton Irr.
$N_{C,0}$ [10^{13}cm^{-1}]	5.6±1.0	
c [10^{-15}cm^{-2}]	1.3±0.2	
g_C [10^{-2}cm^{-1}]	−0.63±0.15	−1.7±0.2 (50 μm samples)
g_{Y1} [10^{-2}cm^{-1}]	1.5±0.4	2.2±0.7
τ_{Y1} [days]	330±60	190±60

Signal analysis

- **baseline correction**: average value in ~20ns time interval before the pulse used to shift the event waveform

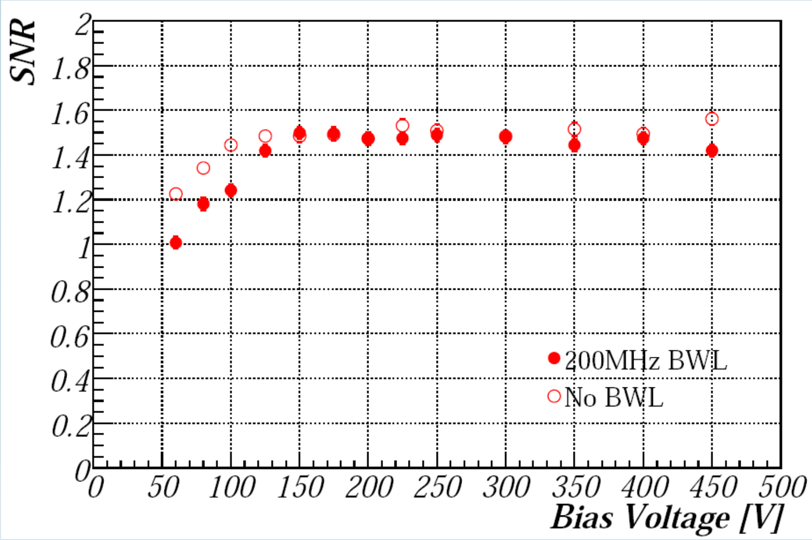
- **Analogue signals**:
  - **SNR** = (MP amplitude)/σ
  - **noise σ** = width of Gaussian function fitted to distribution of signal sampled at a fixed point before the signal pulse (noise distribution)
  - **MP amplitude**: extracted from the Landau-Gauss convolution fitted to the amplitude distribution (amplitude=maximum reading in ~2ns around the average pulse)



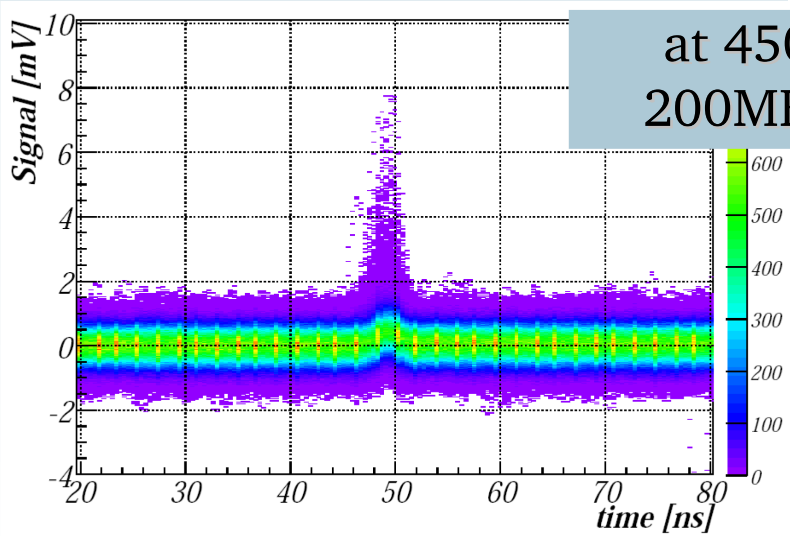
- **Digital signals:** sampled on a 20ns interval

Mesurements with epi silicon: BCM module performance

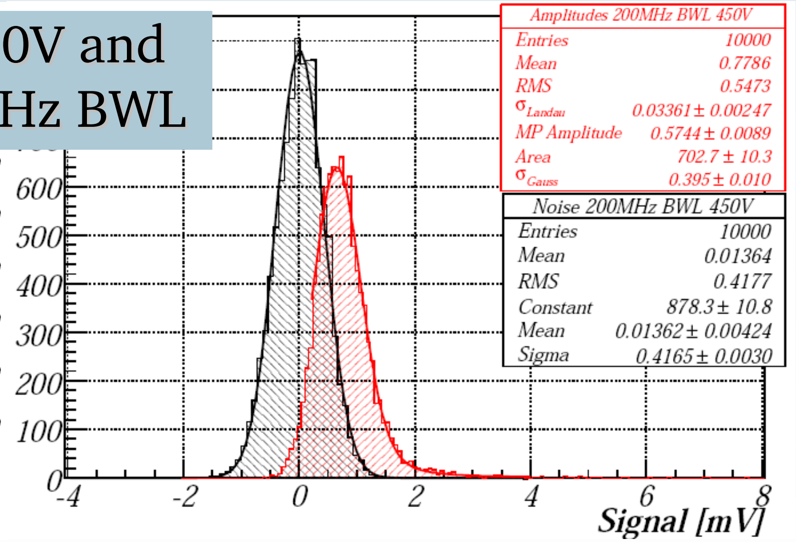
BCM detector module tested with 50µm epi diode (V_{FD}≈130V)



- 500MHz BWL:
  - MP amplitude above V_{FD} around 1.2mV,
  - noise above V_{FD} around 0.8mV, SNR≈1.5
- 200MHz BWL at readout:
  - MP amplitude and noise both two times lower, same SNR
- very low amplitudes, MP amplitudes overestimated
- better SNR performance with pCVD diamond → pCVD diamond chosen for BCM sensor



at 450V and 200MHz BWL



Mesurements with pCVD diamond

Numerous measurements during the development phase of BCM with or without digitisation electronics included

- laboratory measurements with ^{90}Sr
- Test beam:
  - with 125MeV (3.8MIP) and 200MeV (2.7MIP) protons at MGH, Boston
  - 1MIP pions at CERN SPS and PS, KEK

Measurements with pCVD diamond: analogue signals

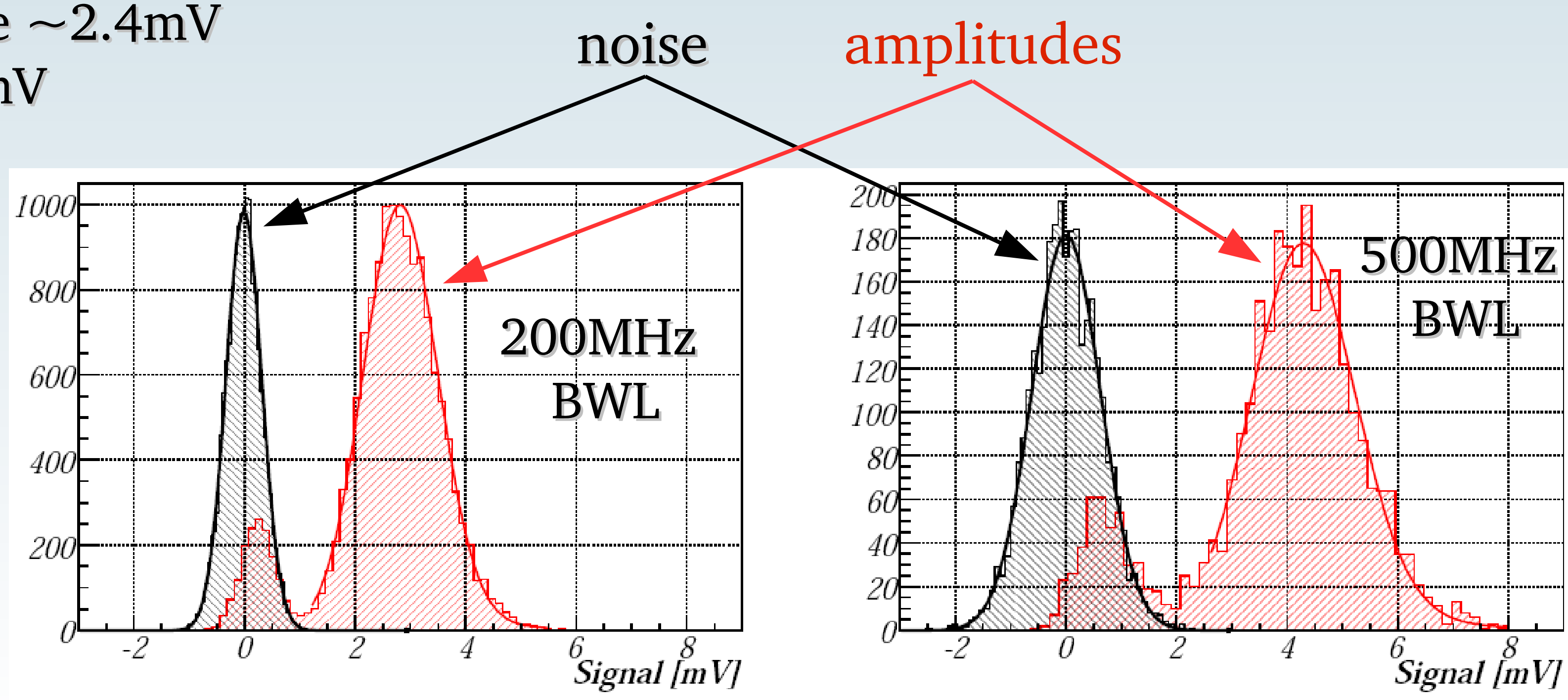
Test beam measurements

- At 2V/μm **double decker** assembly gave
  - ~2× higher MP amplitude compared to an assembly with **one diamond**
  - noise increased by ~30% compared to one diamond
  - SNR increase by more than 50%
- Improvement of SNR when bandwidth limited (BWL) from 500MHz to 200MHz;
- No significant dependence of signal **rise time** and **width** (FWHM) on electric field strength up to 2V/μm
  - Limiting BWL from 500MHz to 200MHz
    - increase of rise time from 0.85ns to 1.5ns (70% increase)
    - increase of FWHM from 1.75ns to 2.8ns (60% increase)
- **Timing resolution** of analogue signals (measured with 300MHz BWL at the readout) better then 400ps on a threshold range 0.1-2MP amplitude

Mesurements with pCVD diamond analogue signals

Lab. measurements with ^{90}Sr, ~1MIP particles at normal incidence

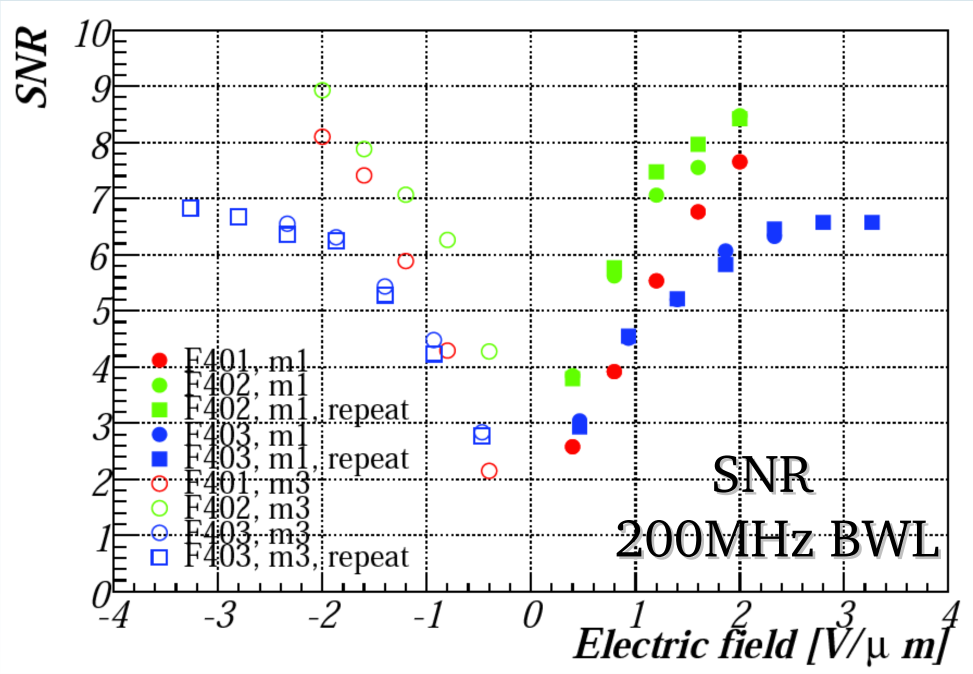
- Increase of SNR when **limiting the bandwidth** at the readout from 500MHz to 200MHz
  - MP amplitude decrease by ~30%
  - noise decreased by ~50%
  - → 4th order 200MHz filter integrated on NINO boards before digitisation
- For final modules at 2V/µm and 200MHz BWL typical
  - MP amplitude ~2.4mV
  - noise ~0.34mV
  - SNR~7-7.5

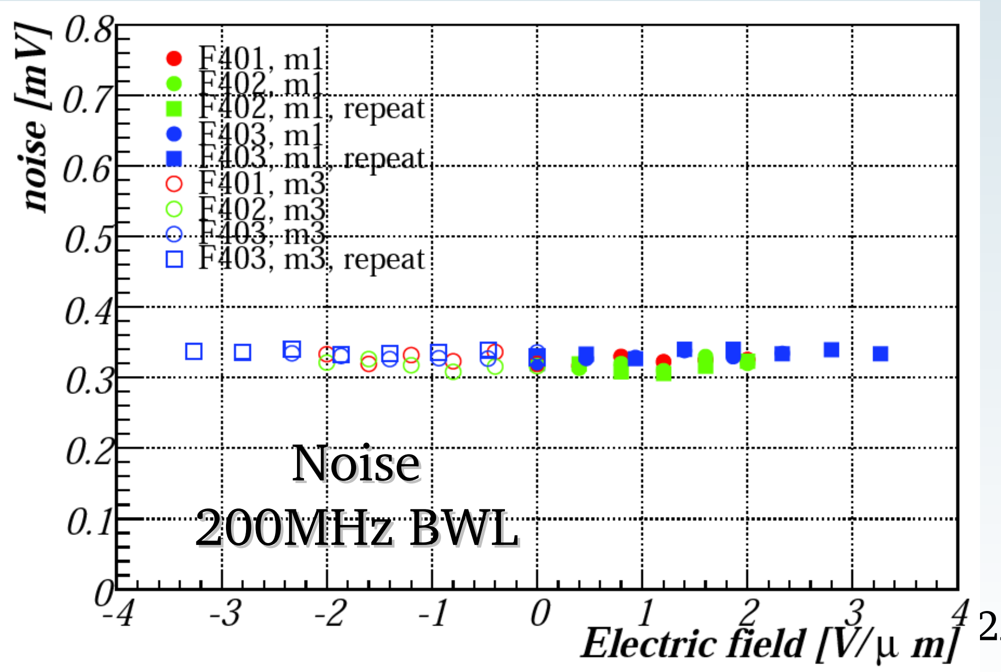


Mesurements with pCVD diamond analogue signals

Lab. measurements with ^{90}Sr and final modules, ~1MIP particles at normal incidence

- Noise independent of el. field for strengths up to 3V/µm (0.34mV at 200MHz BWL)
- Inferior performance of module with diamonds thinned to 300µm (blue symbols)

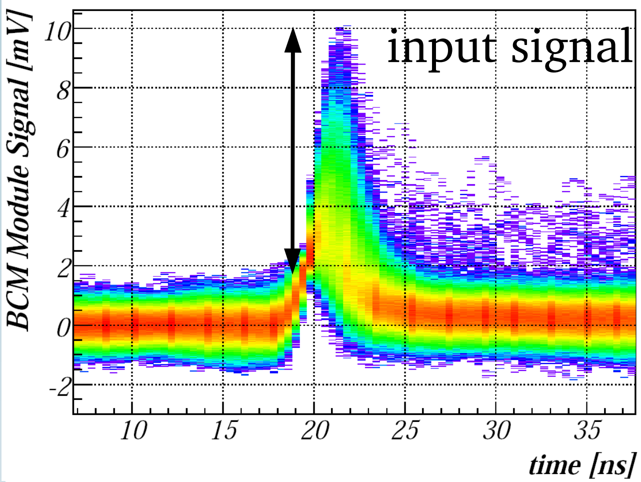


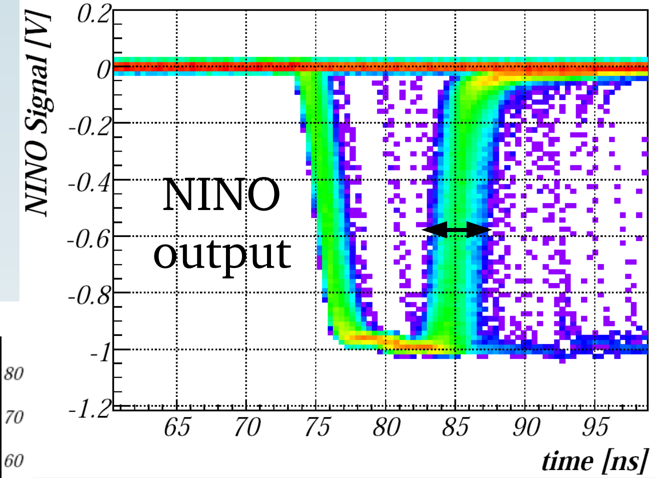


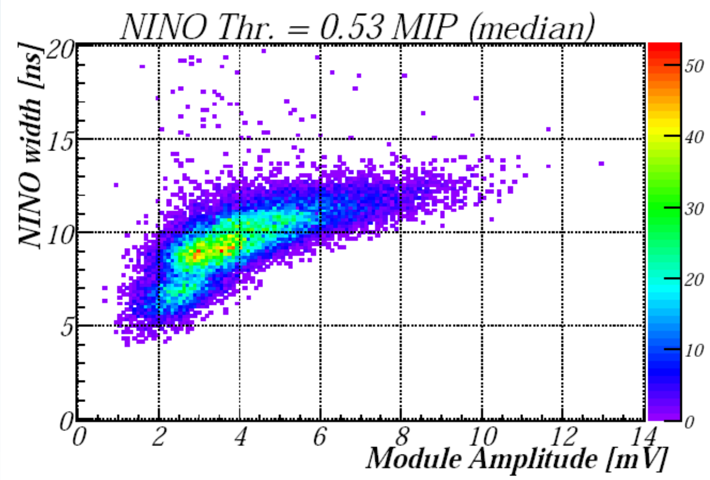
Mesurements with pCVD diamond: digital signals

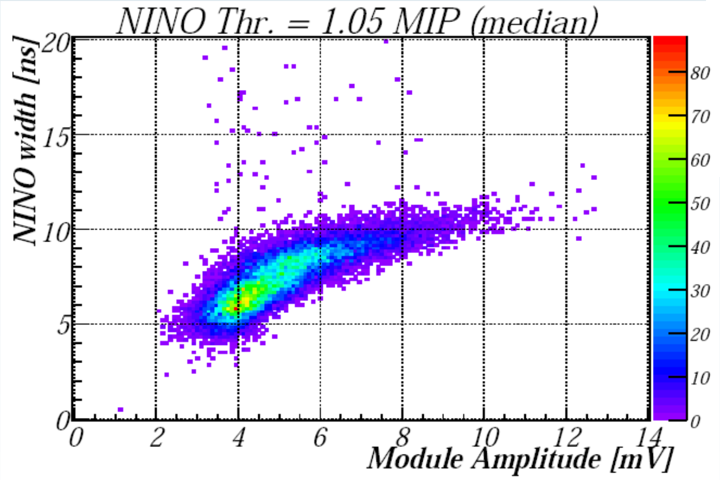
NINO chip

- Time-over-threshold amplifier-discriminator chip
- width of output signal depends on input charge
- The width of output signal as a function of NINO discriminator threshold saturates quickly
  - → input analogue signal is split into two parts in ratio of 1:11 in order to increase the dynamic range









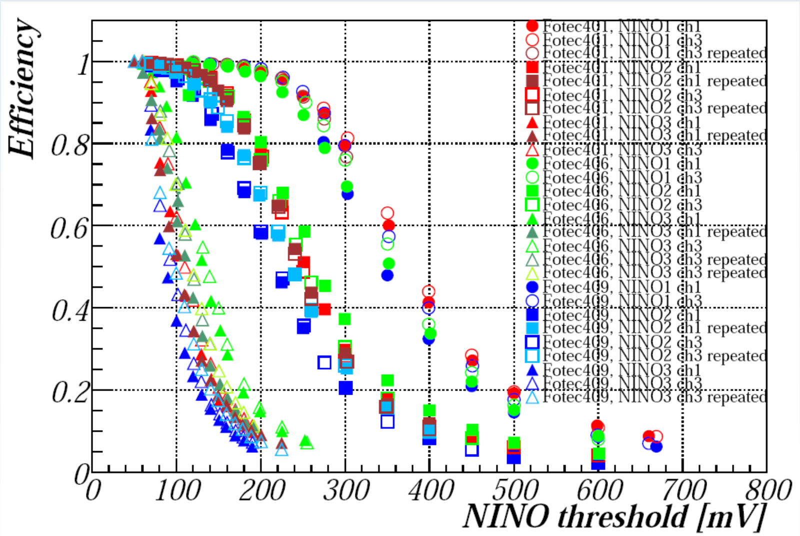
Mesurements with pCVD diamond: digital signals

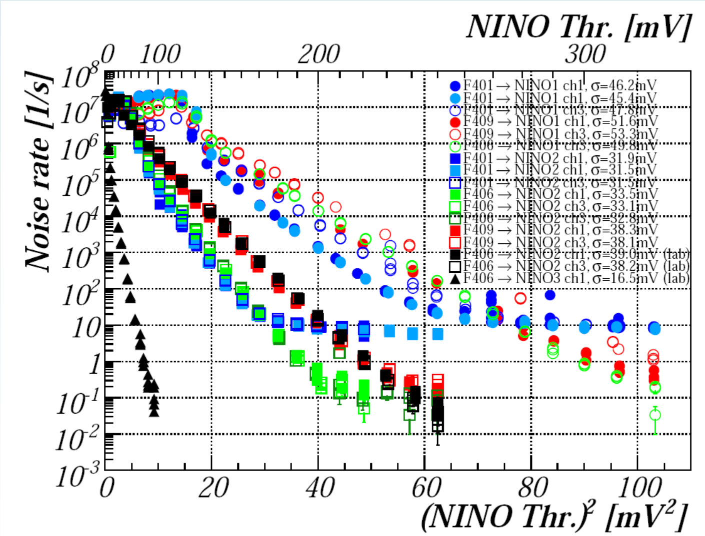
Test beam measurements

- 3 different prototype versions NINO board, spare final modules, final services
- **Efficiency** for 1MIP (45^{o} incidence) measured by varying the discriminator threshold on NINO board
  - threshold at 50% efficiency extracted: measure of median signal
- **Noise rate** dependence on NINO thresholds measured
  - noise σ in units of NINO threshold extracted

$$\mathrm{Ln}\,(\mathrm{Noise\,Rate}) \propto \frac{U_{THR}^{2}}{2\sigma^{2}}$$

- A measure of the BCM system performance at the end of readout chain
  - **median SNR**=(median NINO threshold)/(noise σ), 6-8.8 achieved
- NINO board (with filter and input resistance) with better SNR chosen for BCM system
  - **final boards**: new amplification added to make system more manageable
- **Timing resolution**: better than 800ps for NINO thresholds 0.5-1.8 median MIP signal





Mesurements with pCVD diamond: digital signals

Performance of the final NINO boards estimated from the lab. measurements (shorter signal cables)

- No test beam available for final NINO board

- **Noise rate** curve measured in lab, extracted noise σ_{lab} and K_{lab}
  - curve expected in ATLAS: estimation of σ_{atlas} *and* K_{atlas}
    - σ_{lab} scaled to σ_{atlas} by comparing test beam and lab results for one of the prototype modules: $\boldsymbol{\sigma_{atlas}}$**=64mV**
    - K observed to be the same in lab and test beam setup: K_{atlas} same as K_{lab}

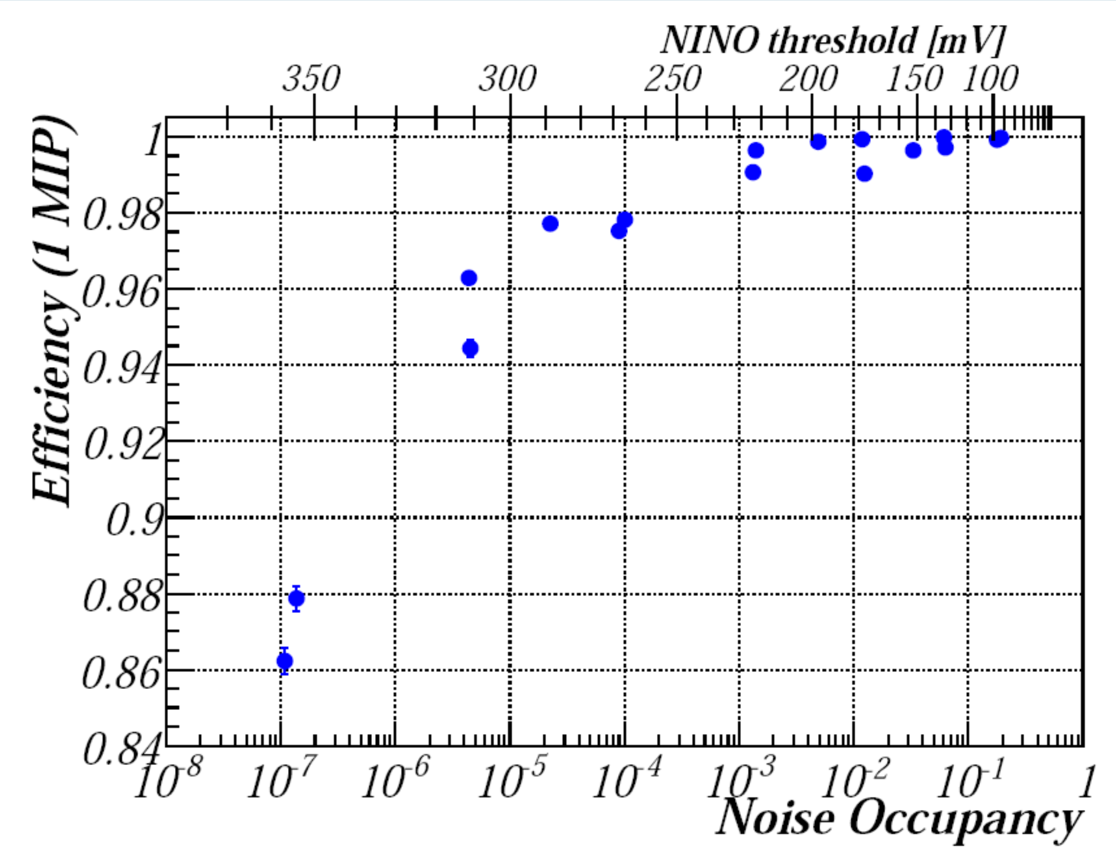
$$\ln(N_{NR}) = K\left[-\frac{U_{Thr}^2}{2\sigma^2}\right]$$

- **Efficiency** curve measured with a spare NINO board and a final module
  - ^{90}Sr source, trigger on analogue signal (**>1MIP** efficiency curve)
  - measured curve **scaled to curve for 1MIP** (scaling factor: comparing the median SNR obtained from test beam and ^{90}Sr measurements for one of the prototype NINO boards)
    → **median signal for 1MIP ≈ 575mV → median SNR≈9±0.5mV**

Mesurements with pCVD diamond: digital signals

Expected efficiency versus noise hits per bunch crossing (25ns)

- If noise rate small compared to bunch crossing rate (40MHz): noise hits per bunch crossing ≈ noise occupancy (probability for noise hit in one bunch crossing)



For the threshold range 230-300mV:

- efficiency 0.96 – 0.99
- occupancies 10^{-5}–10^{-3}

Summary

- ATLAS BCM will monitor beam conditions close to IP using **TOF measurement**
- 2 candidates for sensor material: **pCVD diamonds, epi silicon**
  - pCVD diamond chosen due its better performance in terms of SNR
- final modules:
  - 2 diamonds in a back-to-back configuration
  - at 45^{o} towards the beam
  - at 2V/μm and 200MHz BWL: SNR=7-7.5 for MIPs at normal incidence
- At the end of BCM readout chain: expected median SNR$\approx$ 9