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The ATLAS Beam Diagnostics System

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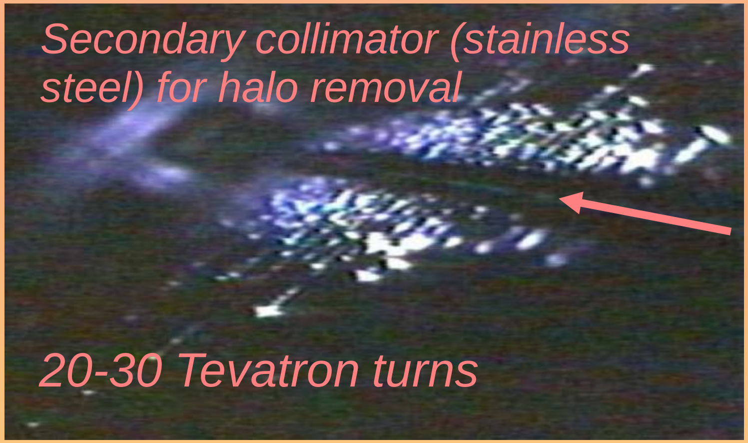
ATLAS BCM/BLM web page: https://twiki/cern.ch/twiki/bin/view/Atlas/BcmWiki

Motivation for ATLAS Beam Diagnostics

- LHC equipment failure: resulting beam losses potentially dangerous to the ATLAS Inner Detector (ID)
- Tevatron experience shows beam accidents DO happen

Tevatron Beam accident:
caused by Roman Pot re-inserting itself in the beam after it had been issued retract commands



- Total energy stored in a single LHC beam (2808 bunches with 10^{11} protons of 7 TeV → 350 MJ) more than 100-times higher than in previous accelerators (Tevatron, HERA), equal to a Jumbo Jet (B-747) when landing
- Time constants of magnets: order of ms
- LHC beam can be dumped within 3 turns ~ 270 μs; i.e in time to prevent beam induced damage if anomalous losses are detected early enough

ATALS BCM and BLM Goal

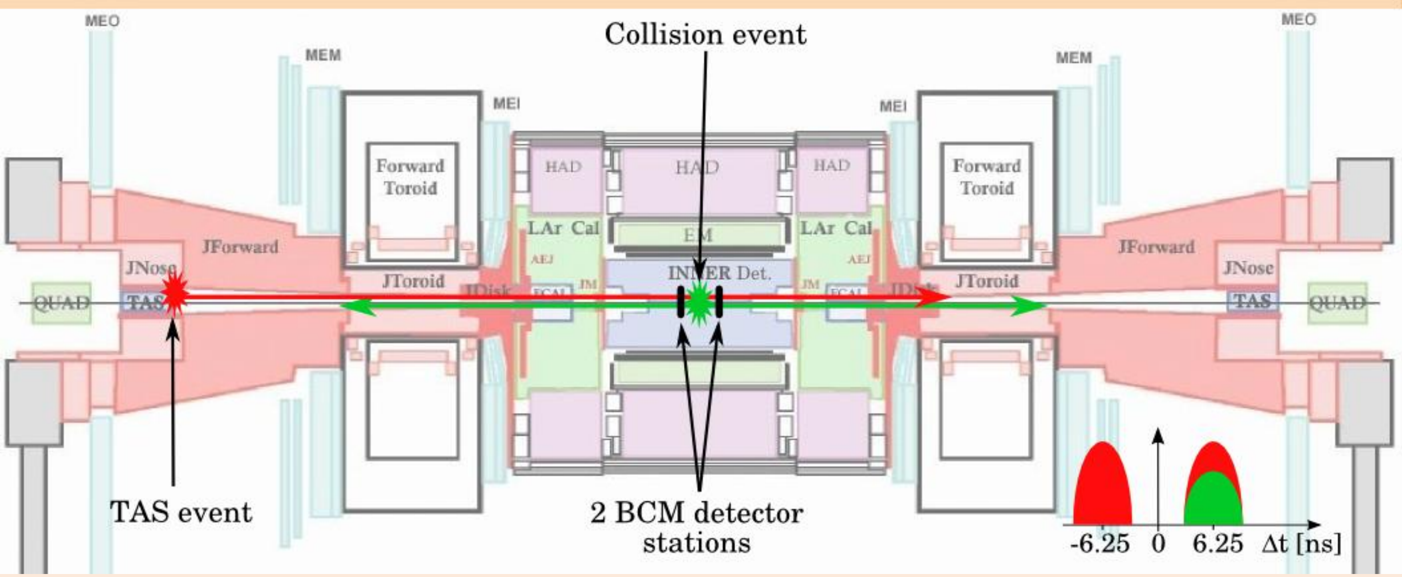
Protection

- Passive:
  - ATLAS, CMS use TAS collimators to protect from direct beam incidences
    - TAS (Target Absorber Secondaries) collimators**:** at z = ±18 m; protecting the Inner Triplet of quadrupoles from secondaries produced in p-p collisions
- Active:
  - LHC Machine
    - Beam Loss Monitors (BLM), Beam Positions Monitors (BPM)... can fire beam abort
  - ATLAS Beam Conditions Monitor (BCM) and Beam Loss Monitor (BLM)
    - Designed for fast detection of early signs of beam instabilities (due to incorrect magnet settings, magnet trips, failures...)
    - Issue a beam abort in case of threatening beam failures
      - **Beam Conditions Monitor - BCM**
        - Particle counter with sub-ns time resolution
        - Will additionally provide a coarse relative **luminosity** measurement bunch-by bunch (complementary info to LUCID - ATLAS main luminosity monitor)
      - **Beam Loss Monitor - BLM**
        - Measurement of beam-induced ionization current

ATLAS Beam Conditions Monitor: Principle of Operation

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

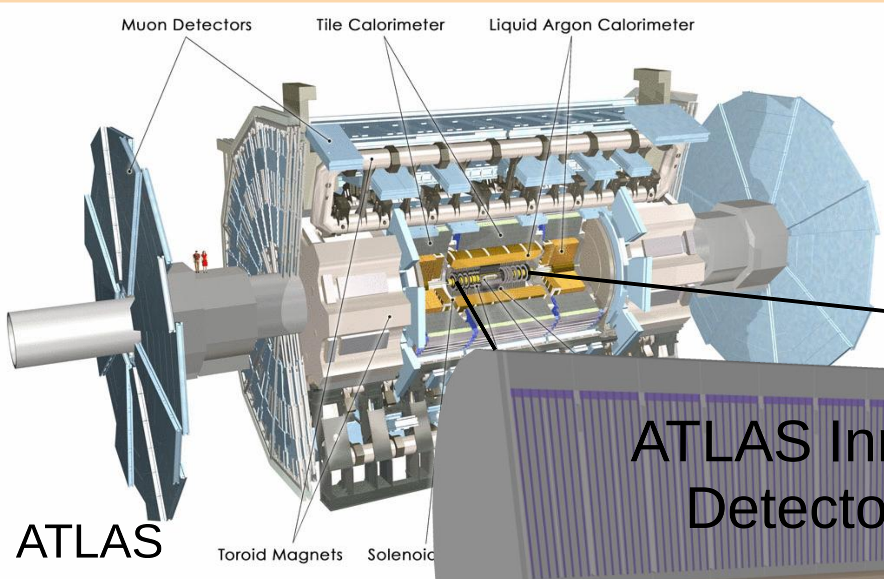
- Measurement every proton bunch crossing (BC = 25 ns)
- Two BCM stations with 4 modules each placed symmetrically to collision point at $z \sim \pm 1.9$ m:
  - particles from **collisions** reach both stations at the same time (6.25 ns after collisions)
  - particles from **background** interactions
    - reach the up-stream station 12.5 ns (½ BC) before particles from collisions (6.25 ns **before** the collision)
    - reach the down-stream station at the same time as particles originating from collisions
  - > use **out-of-time** hits to identify background events
  - > use **in-time** hits to monitor luminosity

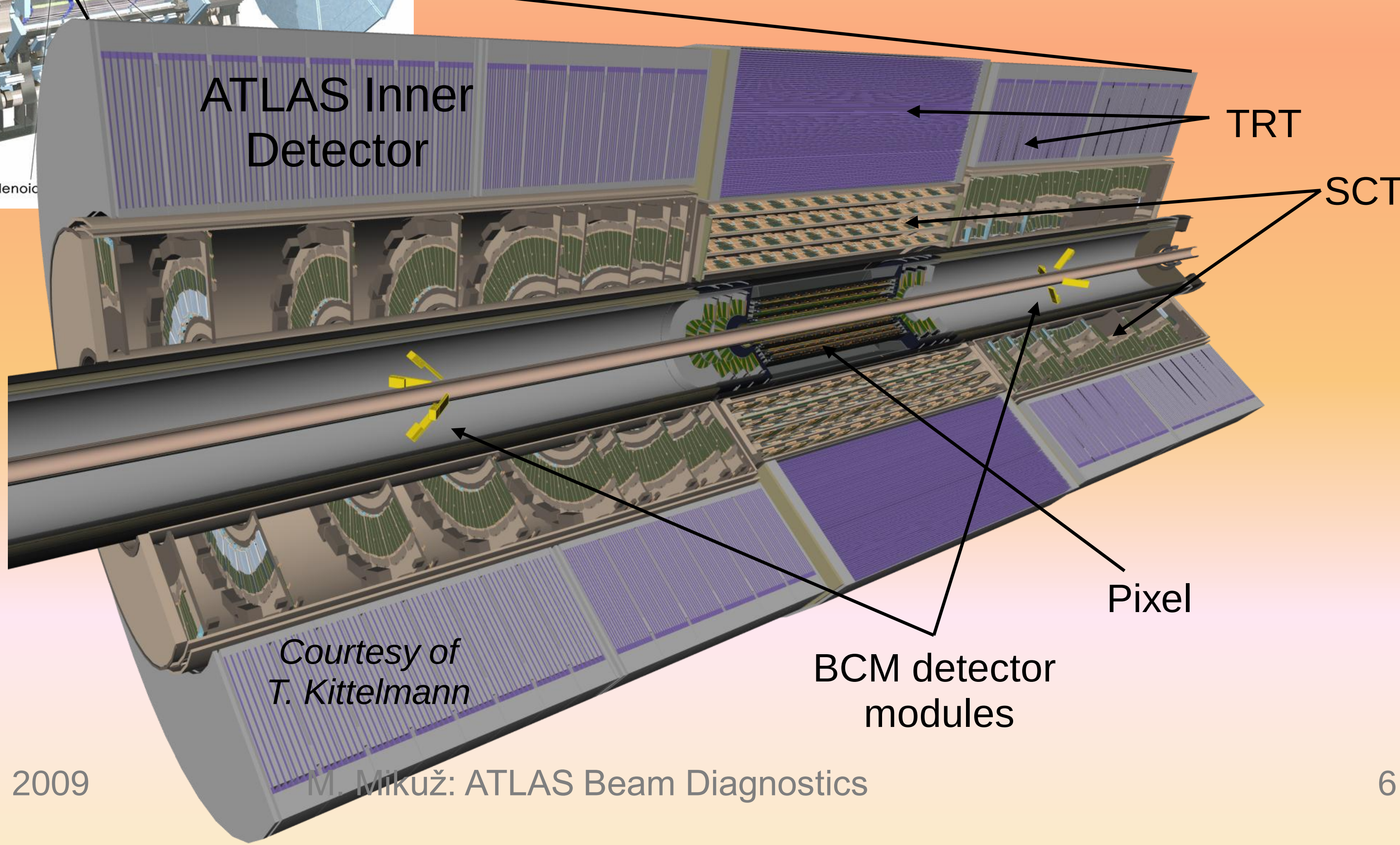


Requirements:
- fast detector & electronics:
  - > rise time ~1ns
  - > pulse width ~3ns
  - > baseline restoration ~10ns
- radiation hard
  - > ionization dose ~0.5 MGy
  - > 10^{15} pions/cm^2 in 10 years
- MIP sensitivity

BCM: Realization

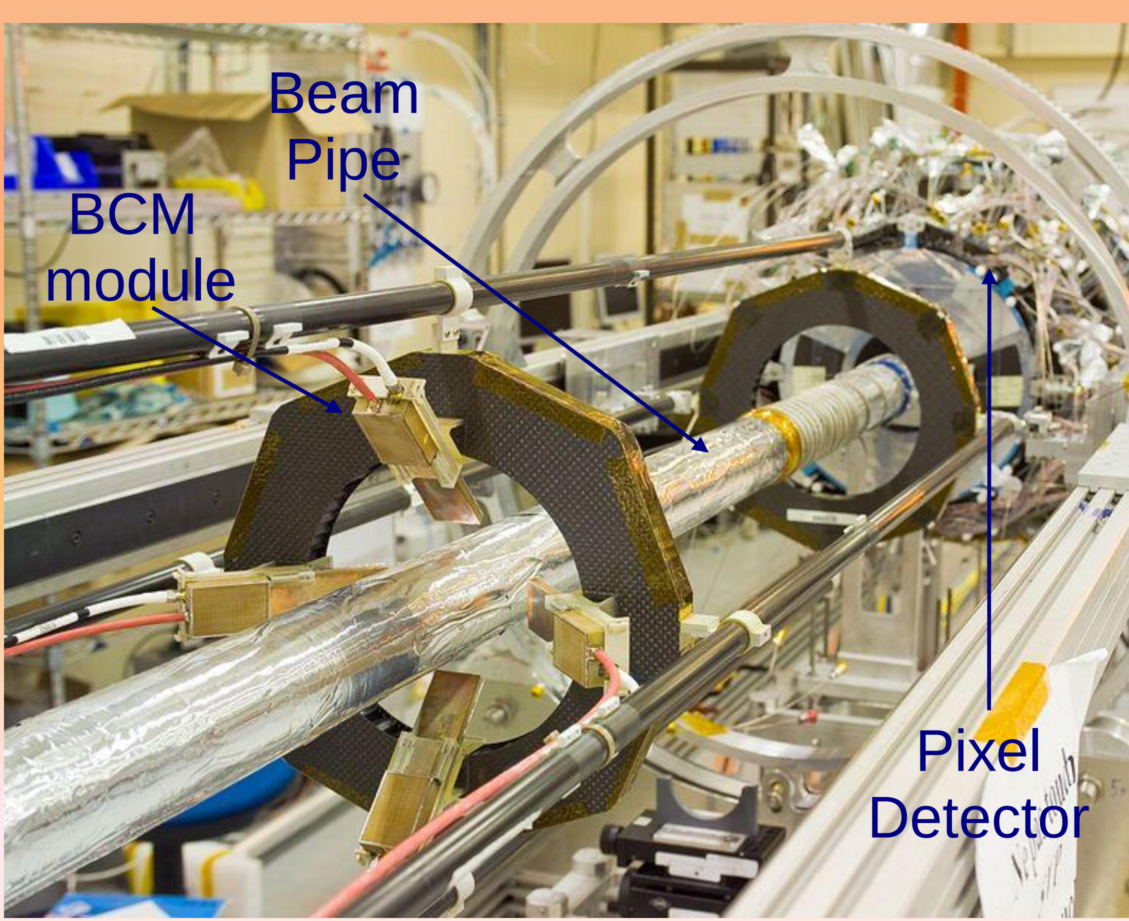
- 4 BCM detector modules on each side of the Interaction Point
- Mounted at $z=\pm183.8$cm and $\phi = 0^o, 90^o, 180^o, 270^o$, sensors at $r \approx 5.5$cm ($\eta \approx 4.2$)
- Tilted at 45^o to the beam pipe





BCM: Detector Module Installation

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



BCM Detector Modules

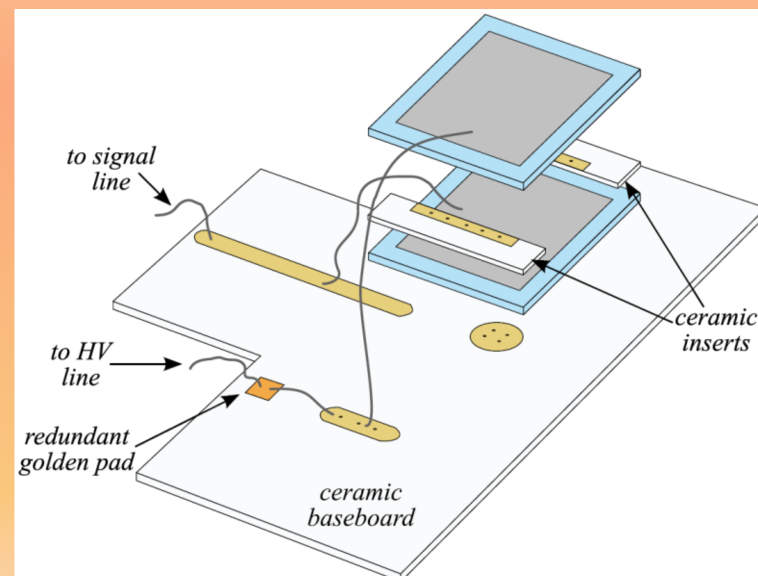
Poly-crystalline CVD diamond sensors

- developed by RD42 and Element Six Ltd.
- radiation hard: shown to withstand 10^{15} p/cm^2
- low (pA) leakage current → no cooling required
- operated at high drift field 2V/µm → fast signals

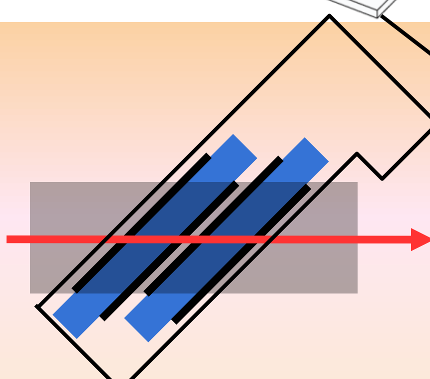
Double–decker assembly

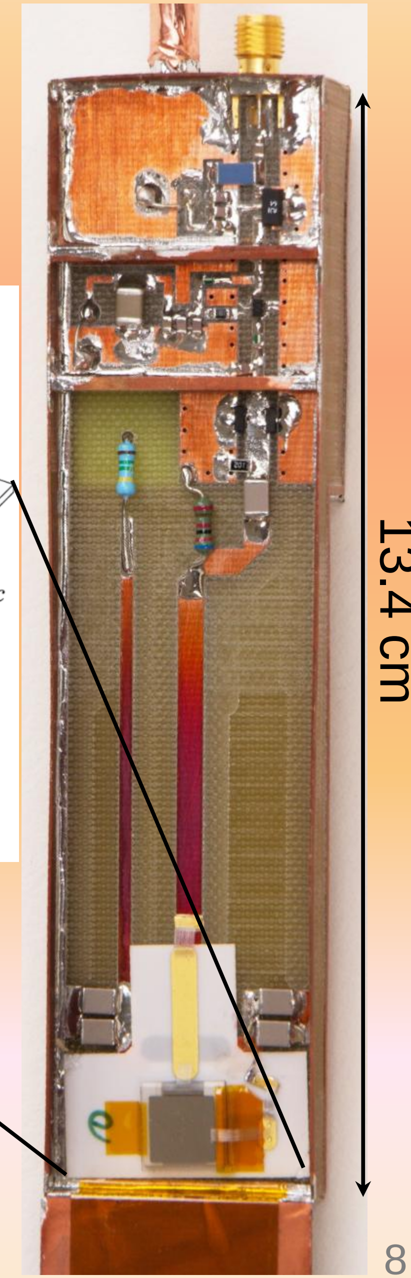
- 2 back-to-back sensors
  - 500 µm thick
  - CCD @1V/µm ~220 µm
  - Size: 10×10 mm^2
  - Contact size: 8×8 mm^2
  - Operated at 2V/µm (1000 V)

- Double signal compared to single sensor assembly, noise increasing only by ~40 %



- For 45^o incidence signal increases by √2 → modules installed at 45^o to beam pipe

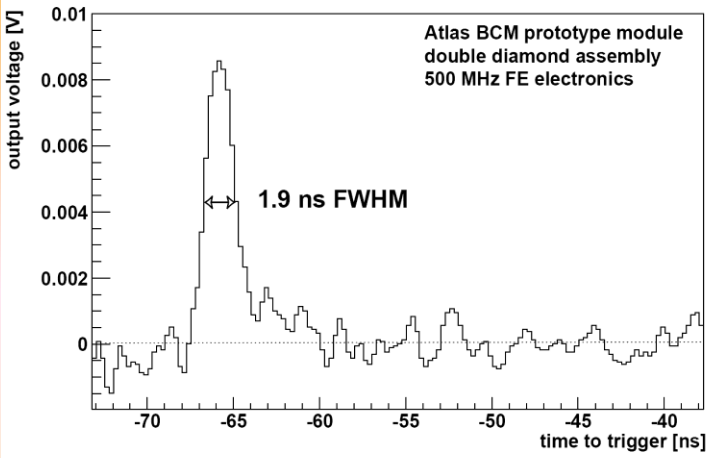




Front end electronics

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

- Measurements showed (confirmed with simulation):
  - Limiting BWL to 200 MHz improved *SNR* by 1.3
    - Rise time increases by 70% and FWHM by 60%, but still complies to requirements
  - 4th order 200 MHz filter integrated on digitisation board

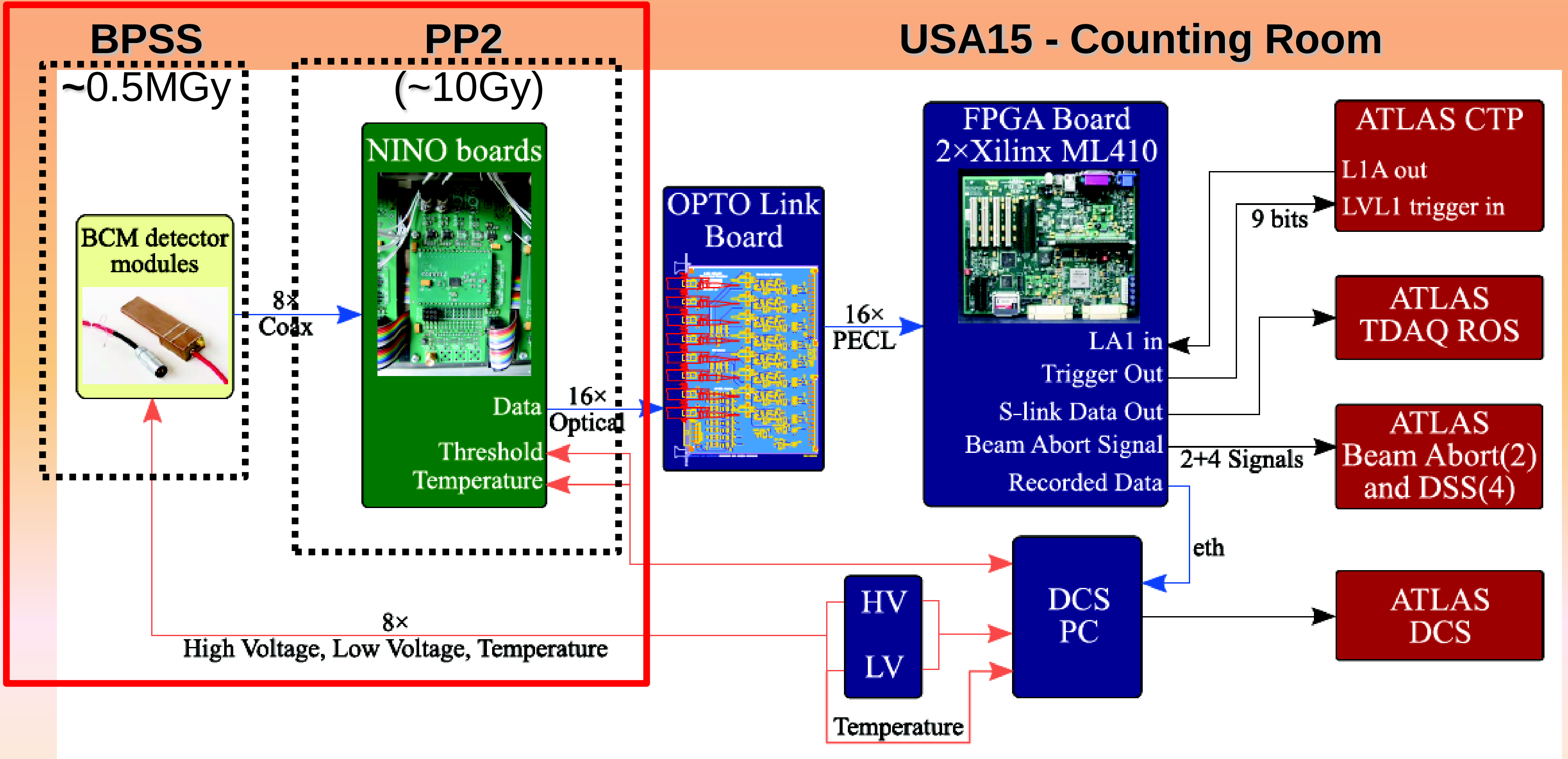


Typical MIP signal from BCM module before filtering

13.4 cm

BCM: Readout Chain

- Analogue signals from BCM modules routed behind calorimeter (lower radiation levels) and "digitized" by custom board based on **NINO chip**
- Each module connected to separate NINO electronics board, each channel fully floating

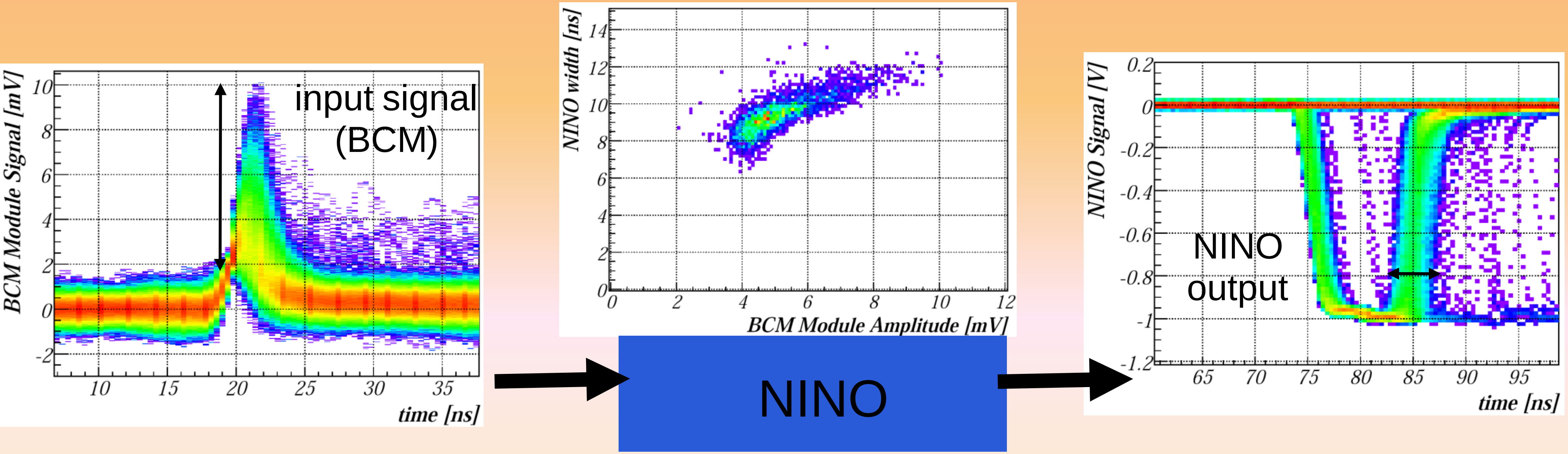


BCM: “Digitization” Electronics Board

NINO chip

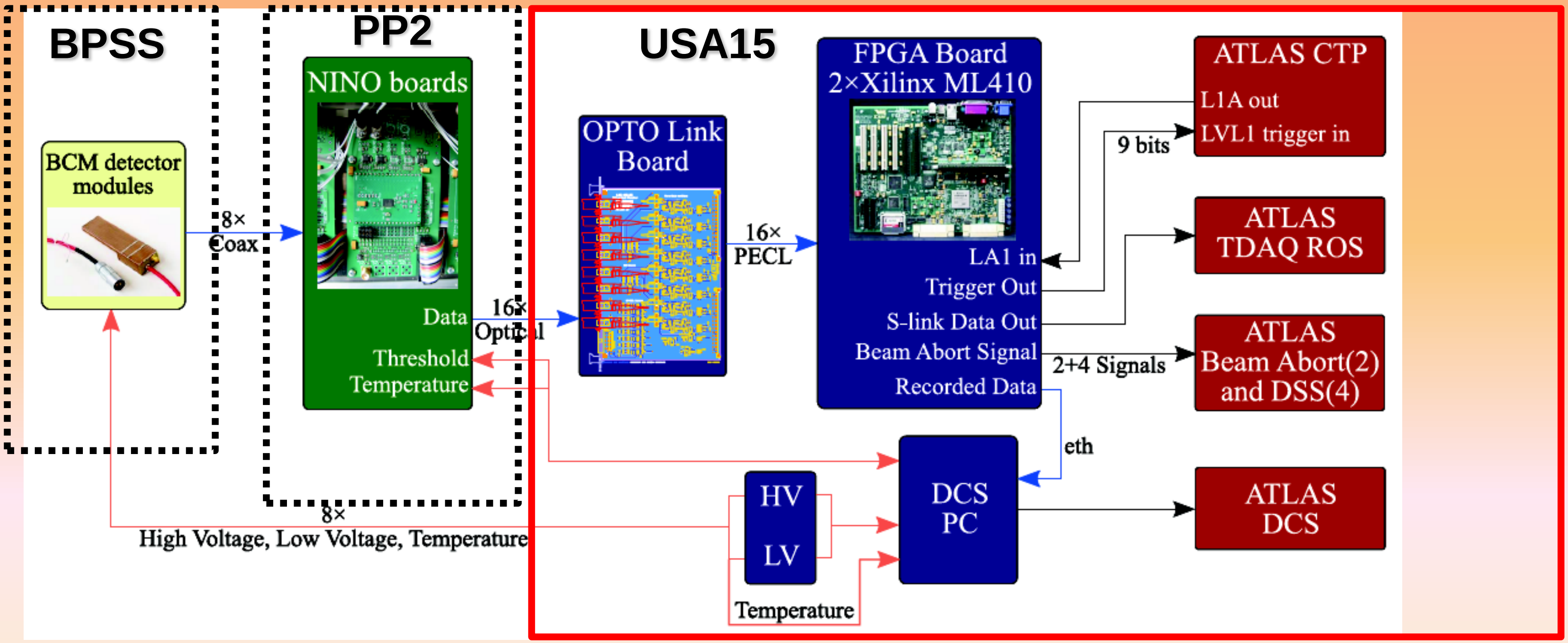
- Developed for ALICE ToF (F. Anghinolfi et al.)
- Radiation tolerant, fabricated in ¼ µm IBM process
- Rise time < 1 ns, jitter < 25 ps, min. detection threshold 10 fC

- **Time-over-threshold amplifier-discriminator** chip
- Width of LVDS output signal depends on input charge
- Before input to NINO chip: signal charge split into two channels in ratio of 1:11 to increase the dynamic range → **high** and **low attenuation channels** (HA/LA)
- High attenuation channels need ~10 times more charge from MIPs traversing the sensor to exhibit the signal than low attenuation channels



BCM: Readout Chain

- Optical signals routed over 70 m of optical fibres to USA15 counting room
- Transformed to PECL in 2 optical receiver boards
- Fed into 2 data processing units (ROD) – each gets 4 LA & 4 HA from all 8 modules
- Processing units (based on Xilinx Vitrex-4 FPGA) connected to
  - ATLAS Central Trigger Processor (CTP): BCM provides 9 bits (temporarily 6)
  - ATLAS Data acquisition (TDAQ): on trigger signal (LVL1A) from CTP, BCM data from 31 bunch crossings is formatted and sent off to ATLAS DAQ readout chain
  - ATLAS Detector Control System (DCS): monitoring rates, conditions etc.
  - Detector Safety Systems (DSS), Beam Interlock System (through CIBU-Control Interlocks Beam User)

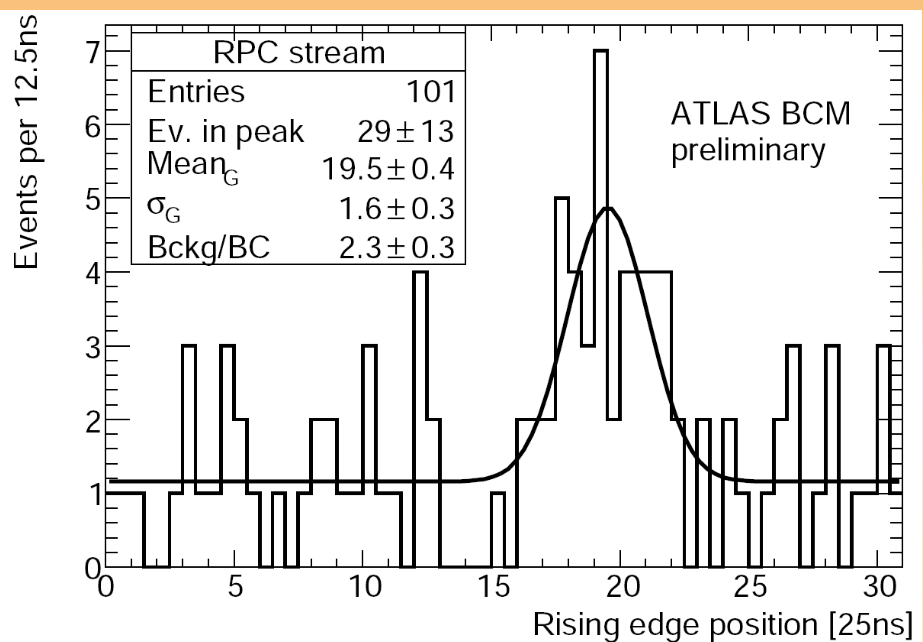


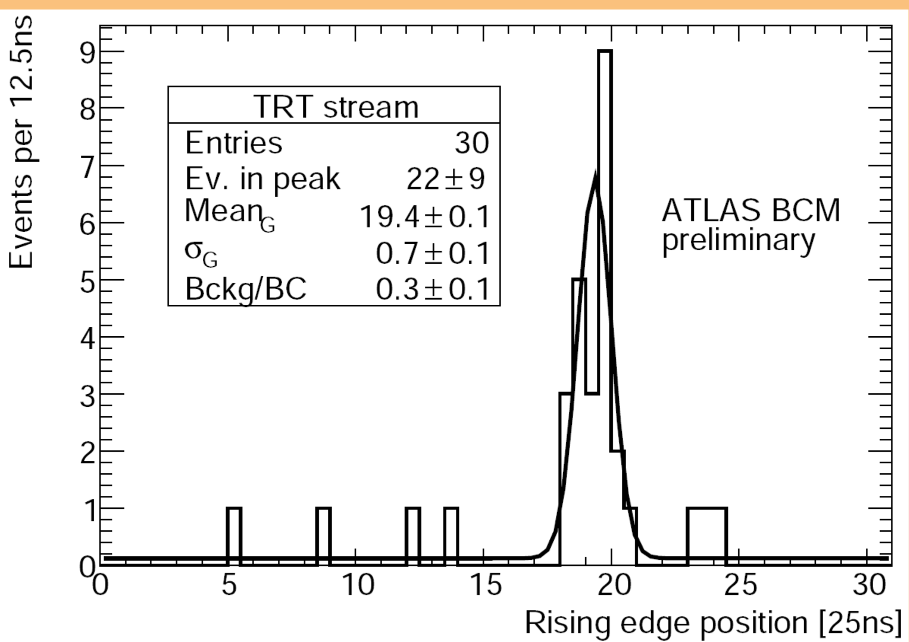
BCM Commissioning: Cosmic Data

November 2008: combined ATLAS Inner Detector cosmic data taking

- Two different triggers:
  - Resistive Plate Chambers (RPC) of Muon system
  - Fast-OR feature of Transition Radiation Tracker (TRT)
- On each trigger received from CTP BCM sends data (rising edge and width of BCM signals) from 31 BCs to ATLAS DAQ chain
- Timing distribution of RPC- and TRT-triggered BCM hits:
  - Superimposed is a fit to Gaussian signal and a flat random background.
  - Gaussian peak wider with RPC trigger; better jitter of TRT trigger
  - Probability of noise hit per BC: ~10^{-7}
  - RPC: about 10M triggers needed for 9 genuine BCM hits
  - TRT: about 1M triggers needed for 9 genuine BCM hits

N.B.:BCM represents only **2 cm²** active surface per side !

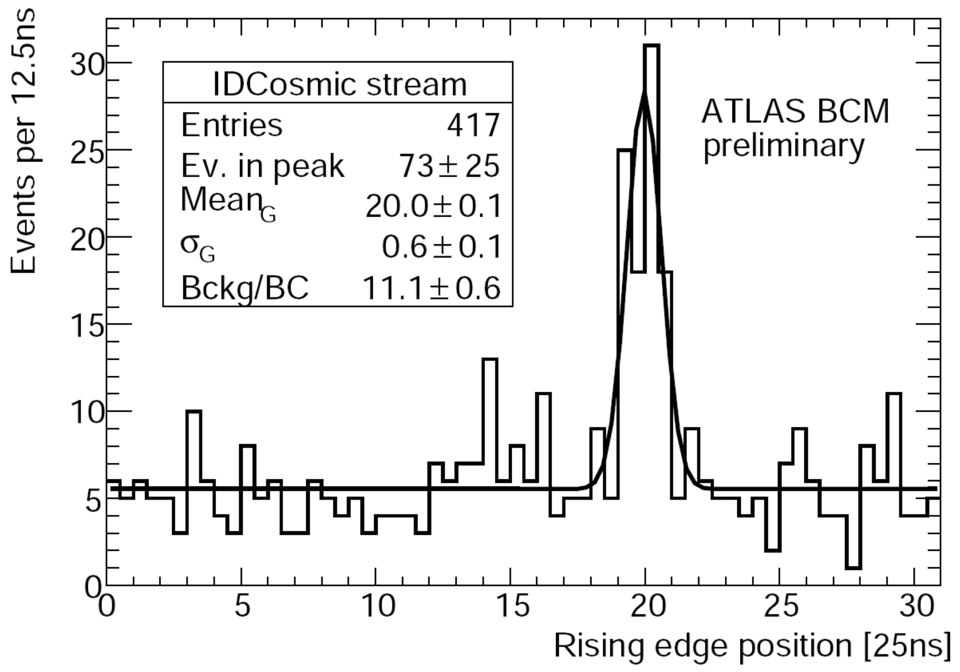


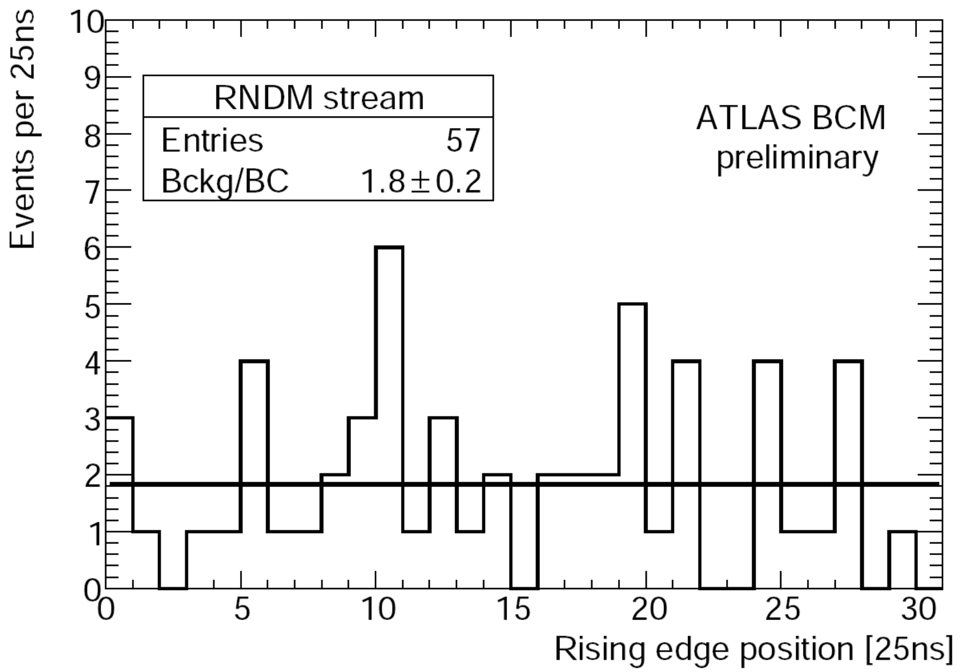


Cosmic Data (cont.)

June 2009: ATLAS cosmic data taking

- IDCosmic trigger stream: selects events with at least one track reconstructed in Inner Detector from LVL2 trigger
- RNDM trigger stream: random trigger
- Timing plots:
  - RNDM stream: flat as expected
  - IDCosmic stream: Gaussian with width ~ as for TRT stream in November cosmic run
- Probability for noise hit per BC: 7-8 times higher than in November 2008 run, due to higher thresholds in 2008
- Signal: 1M IDCosmic triggers give 6 true BCM hits



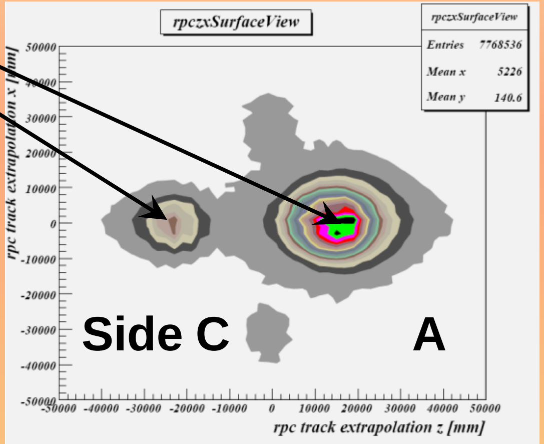


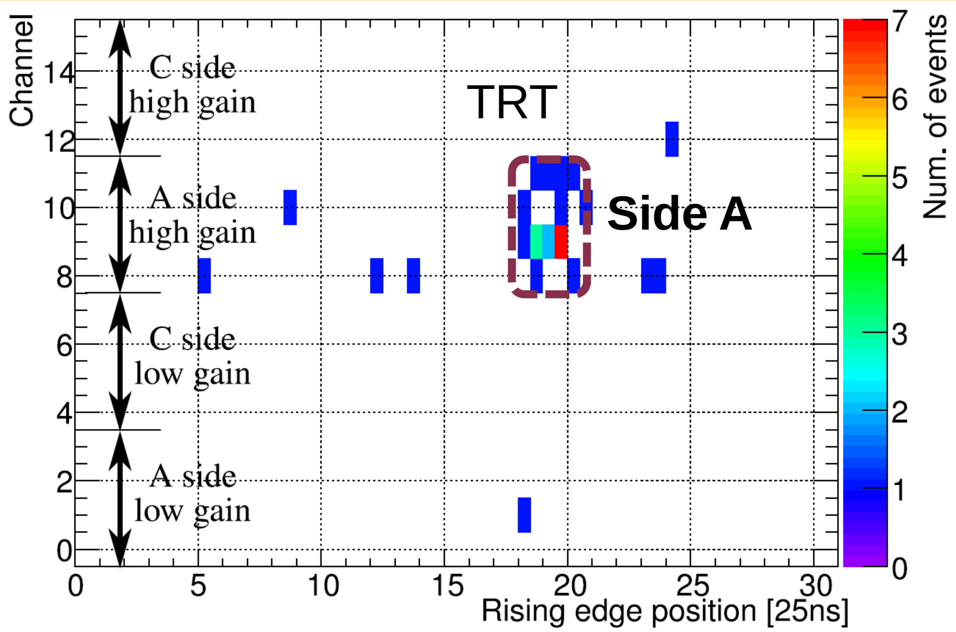
Cosmic Data (cont.)

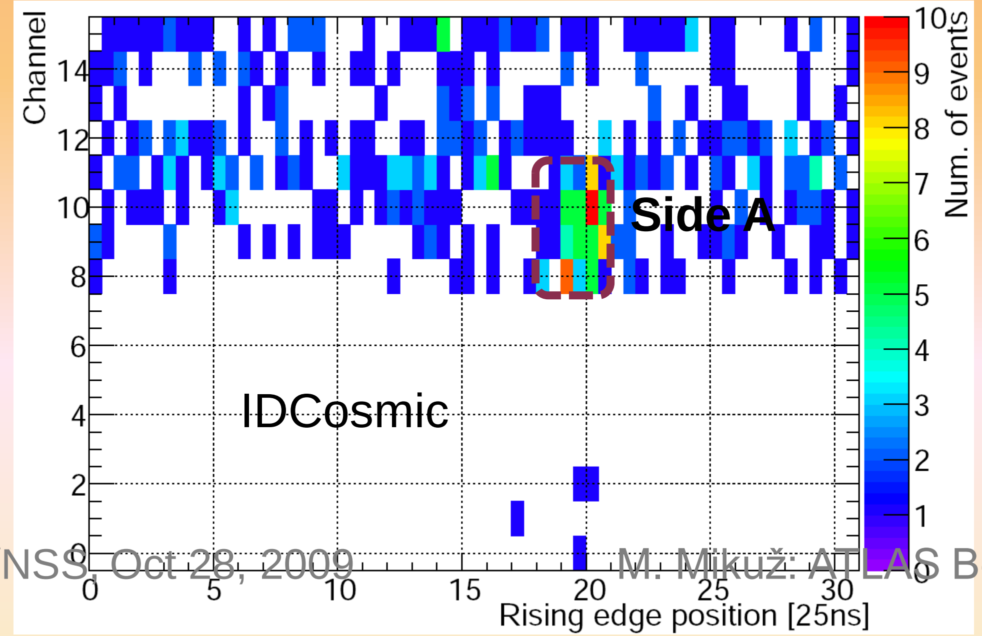
Timing distribution of BCM hits over channels:

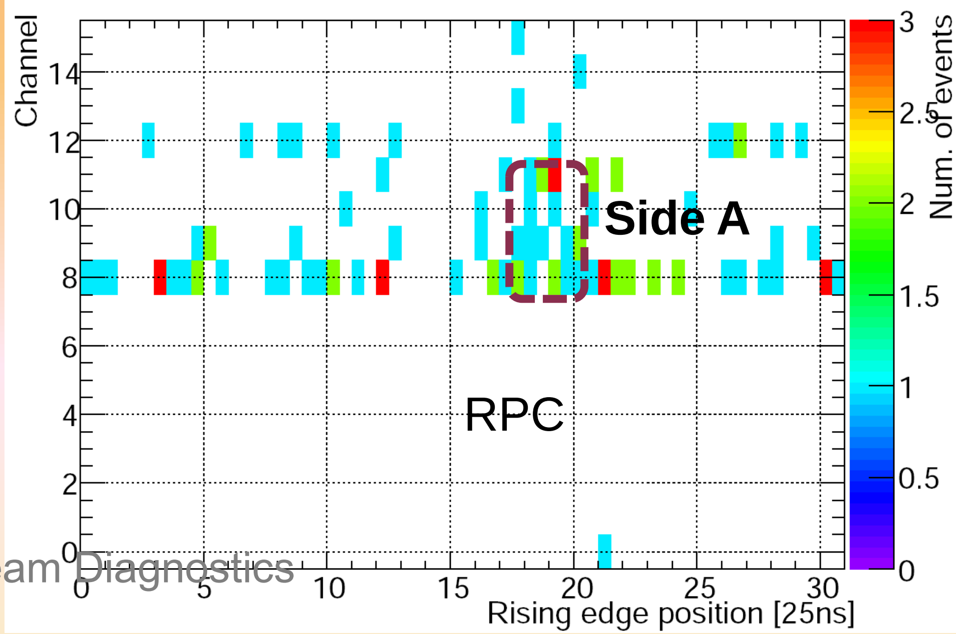
- Almost no hits on side C
- Attributed to unequal size of 2 main ATLAS shafts

***From:** M. Bianco,"ATLAS RPC commissioning status and cosmic ray test results", PIC2008*





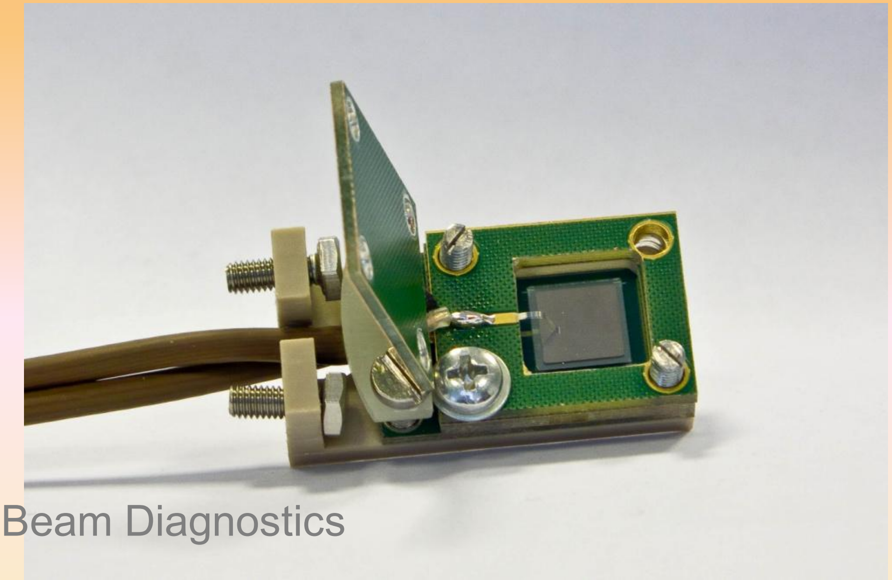




ATLAS Beam Loss Monitor – ATLAS BLM

- Independent system
- Recently added as a supplement to ATLAS BCM
- Goal: protection only → much simpler than BCM
- Used standalone, complementary information to BCM
- Measurement of ionization current
- Readout electronics a “straight” copy of the LHC BLM system
  - Major difference: ATLAS BLM uses **diamond sensors** instead of ionization chambers (LHC BLM)
  - Other: different LV powering scheme, firmware changes in the readout cards,...

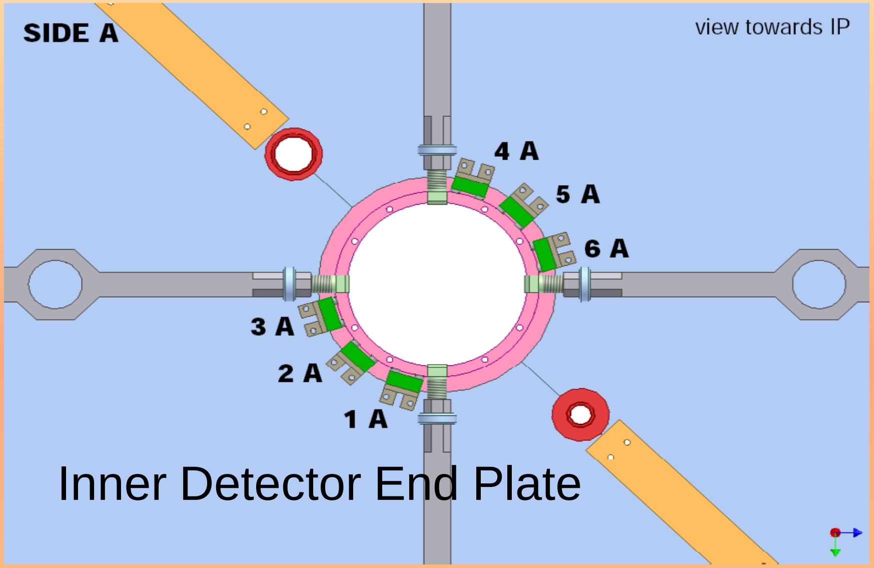
- **Sensors:**
  - one pCVD 8×8 mm^2 diamond, 500 µm thick, metallization 7×7 mm^2
  - operated at +500V
  - current @ 500 V typically < 1-2 pA

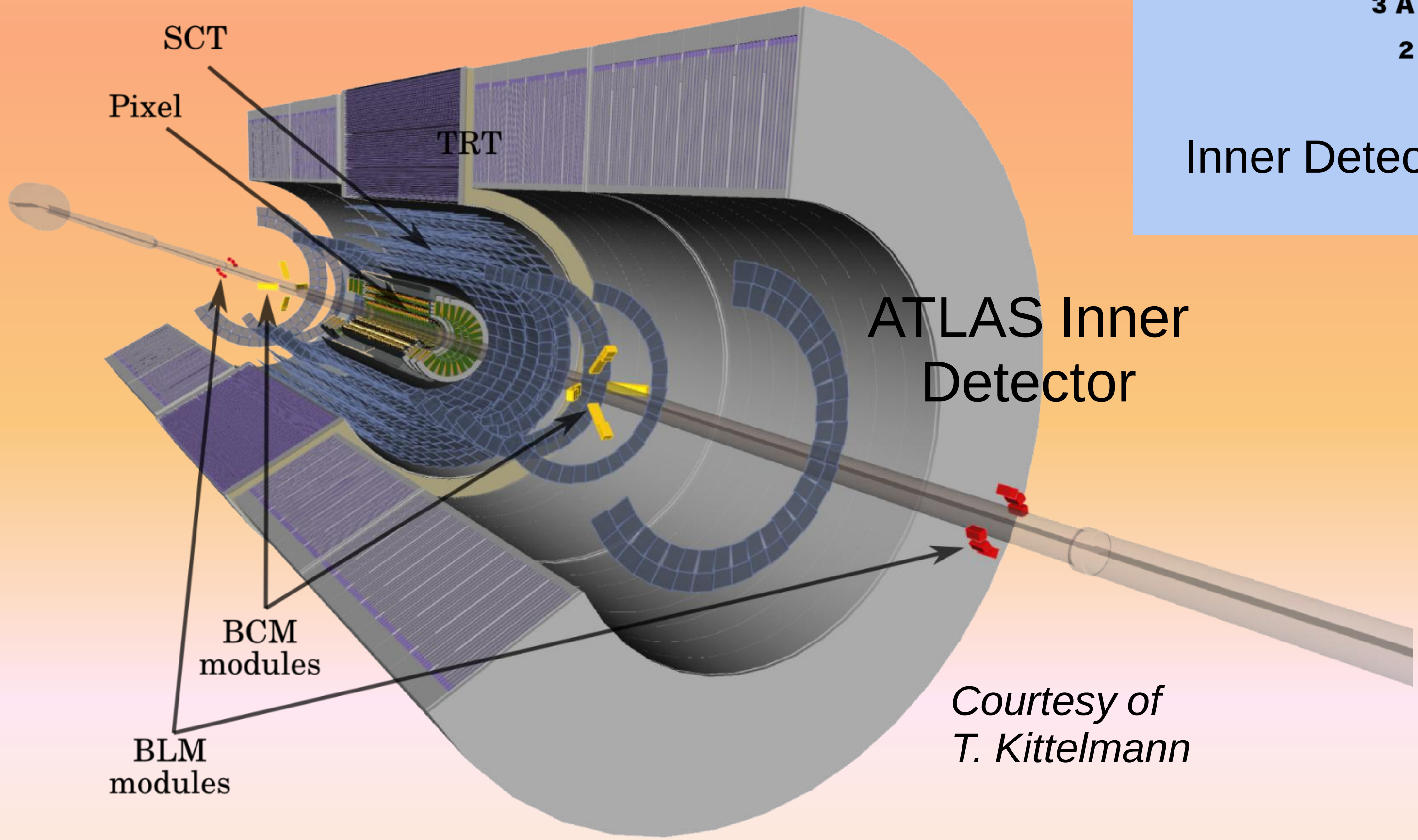


ATLAS BLM: Detector modules

12 detector modules installed in May 2008

- 6 on each side of IP, installed on Inner Detector End Plate
- Close to IP: $z = \pm 3450$ mm, $r = 65$ mm

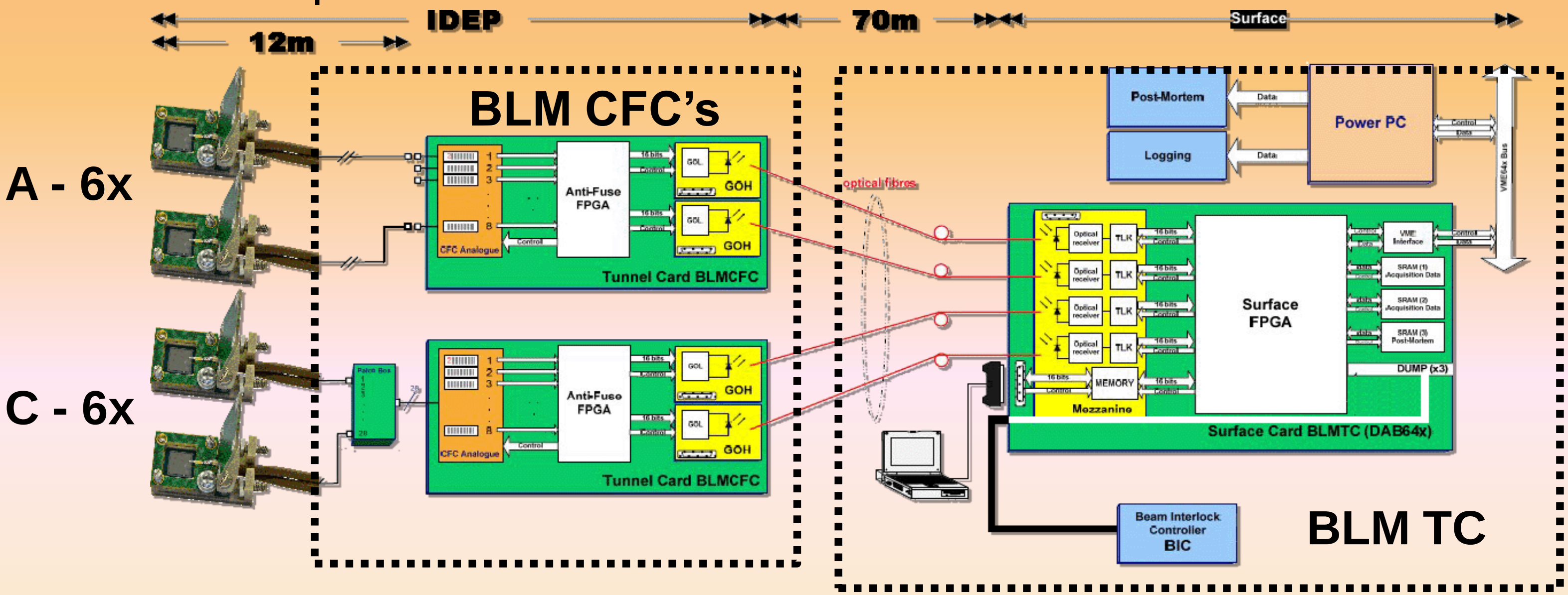




Courtesy of T. Kittelmann

ATLAS BLM: Readout

- Measurement of radiation **induced current** in sensors, integrated over predefined time constants ranging from 40 μs to 84s.
- Current converted to frequency in radiation tolerant BLMCFC (**“CFC card”**) behind calorimeter
- Digitized information transmitted through optical fibres to USA15 counting room, **recorded** by BLMTC (**“threshold card”**) based on Altera FPGA:
  - BLMTC inserted in VME crate
  - VME bus used to transmit the **post mortem buffer** to the Single Board Computer and for **monitoring readings** sent to ATLAS Detector Control System
  - Connected to ATLAS BIS**:** beam abort issued if readings from 2 modules on one side exceed a predefined threshold



Summary

- **ATLAS BCM** will monitor beam conditions close to IP using **sub-ns TOF measurement**
  - Goal:
    - Protection
    - Relative luminosity measurement
  - **pCVD diamonds** as sensor material
    - 2 diamonds in back-to-back configuration at 45^{o} towards the beam
  - First experience with the system gathered in the last 1½ year

- **ATLAS BLM**:
  - Complementary system for additional safety
  - Ionization current measurement averaged over 40 μs
  - pCVD diamond sensors

Looking forward to using BCM & BLM with the real LHC beams !

Backup slides

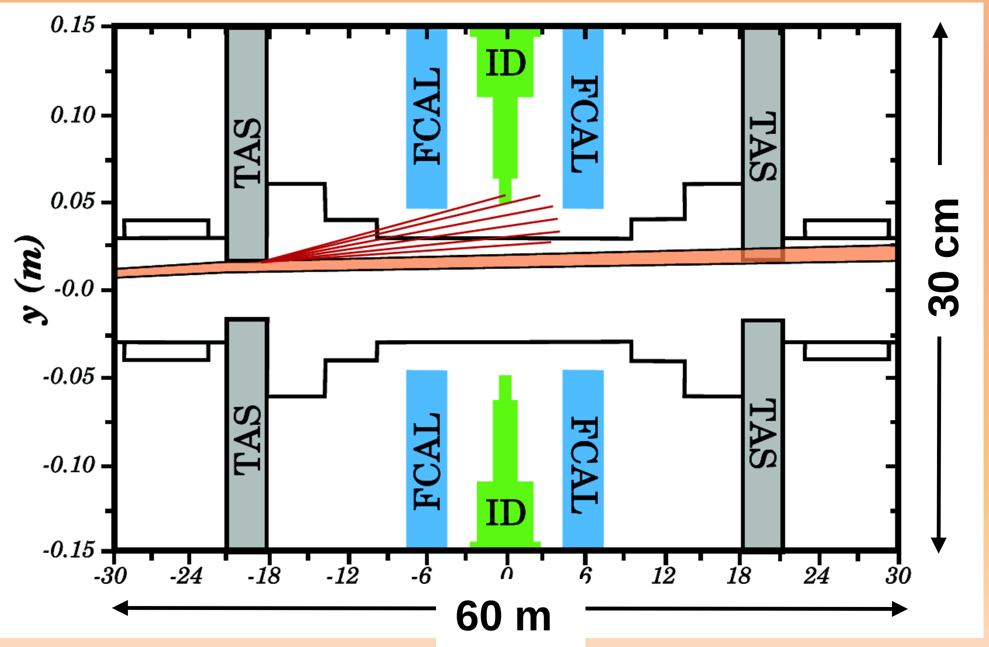
Beam Loss Scenarios

• Single-turn losses

- Likely to occur during injection or beam dump processes
- ATLAS can be rated the 'safest' of all LHC interaction points (far away from injection, dump)
- Pilot bunch (single bunch of low intensity, 5×10^9 p @ 450 GeV; 360 J) will be used to check the magnet settings

Simulation of beam orbits with wrong magnet settings (D. Bocian) *exhibit scenarios with pilot beam scrapping the beam pipe or TAS collimator (most likely scenario), no direct hitting of Inner Detector (ID)*

TAS (Target Absorber Secondaries) collimators: *at z = ±18 m which protect the Inner Triplet of quadrupoles from secondaries produced in p-p collisions*



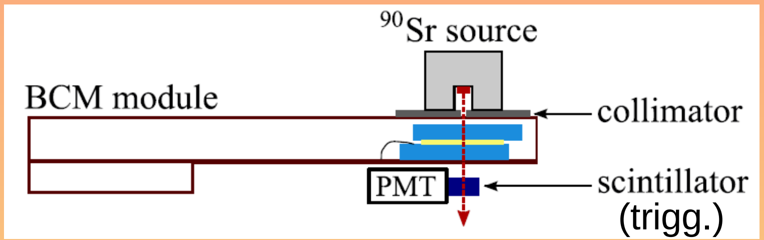
• Multi-turn losses

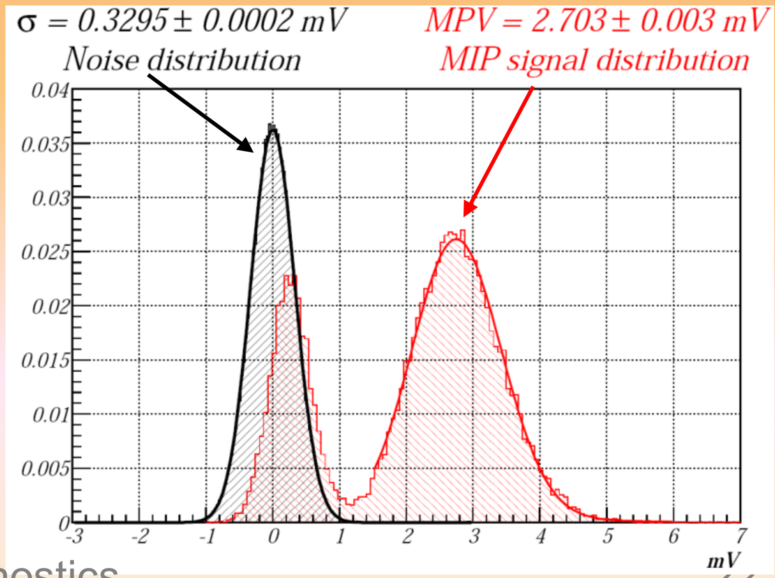
- Beam degradation due to equipment failure, magnet trips, wrong magnet settings...
- Time constants of magnets: shortest ~few LHC turns (order of ms) → can abort the beam if detected early (beam is dumped within 3 turns ~ 270 μs)

QA of BCM Modules

Qualification tests with final modules to select 8 for installation

- **Raw sensor characterization**:
  - I/V, CCD
- **Module performance**
  - All modules subjected to **thermo-mechanical test**
    - infant mortality test (12h @80^o)
    - accelerated ageing for one of the module (14h @120^o 10 years at 20^o)
    - thermal cycling (10 cycles from -25^o to 45^o)
  - **Module performance checked** before and after these tests with ^{90}Sr setup
    - no change in S/N observed
    - for normal particle incidence: typical S/N≈7–7.5



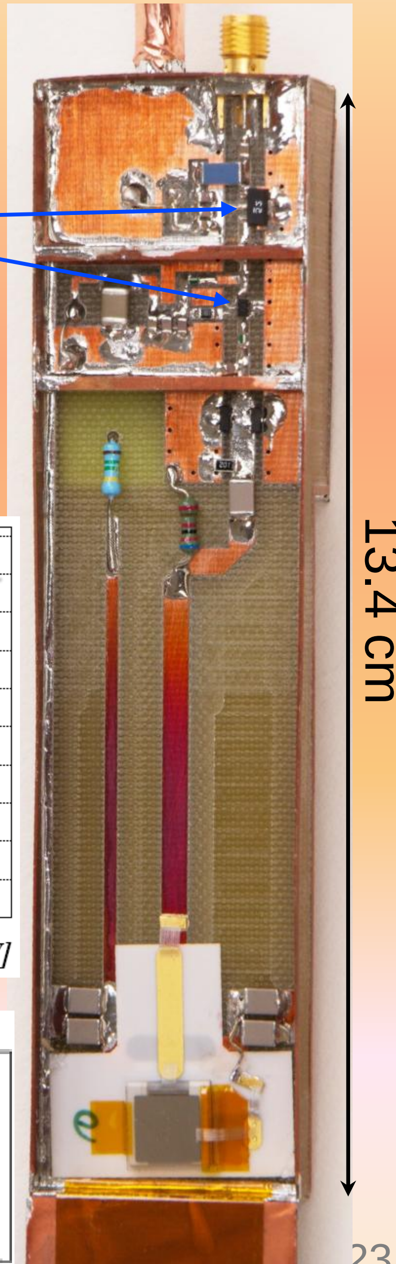


MODULE	404	405	408	410	413	420	422	424
Polarity	+	+	-	+	+	-	-	-
MPV [mV]	2.4	2.3	2.3	2.7	2.2	2.7	2.4	2.7
S/N	6.6	6.9	7.0	7.8	7.0	7.9	7.4	8.2
Current [nA]	70	35	20	25	250	200	40	10

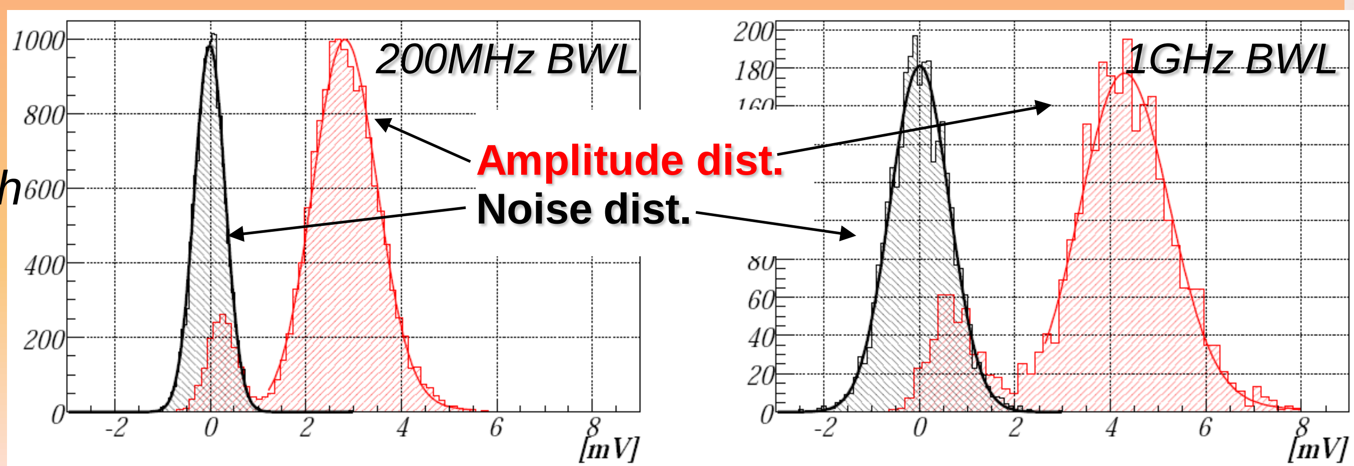
BCM Detector Modules

Front end electronics

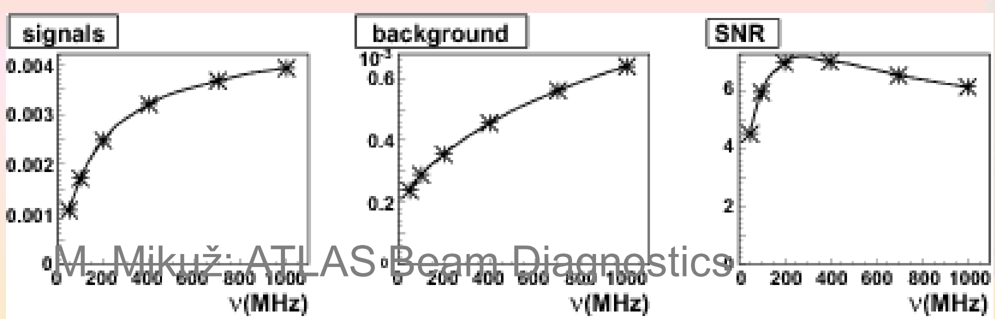
- **2 stage amplifier:**
  - 1st stage: Agilent MGA-62653, 500 MHz (22db)
  - 2nd stage: Mini Circuit GALI-52, 1 GHz (20dB)
- Limiting BWL to 200 MHz improved S/N by 1.3 (and rise time worse by 70% and FWHM by 60%, but still fit to requirements)
- ~ 4th order 200 MHz filter integrated before digitization (on NINO board)



Lab. Tests with MIPs at 90^o incidence

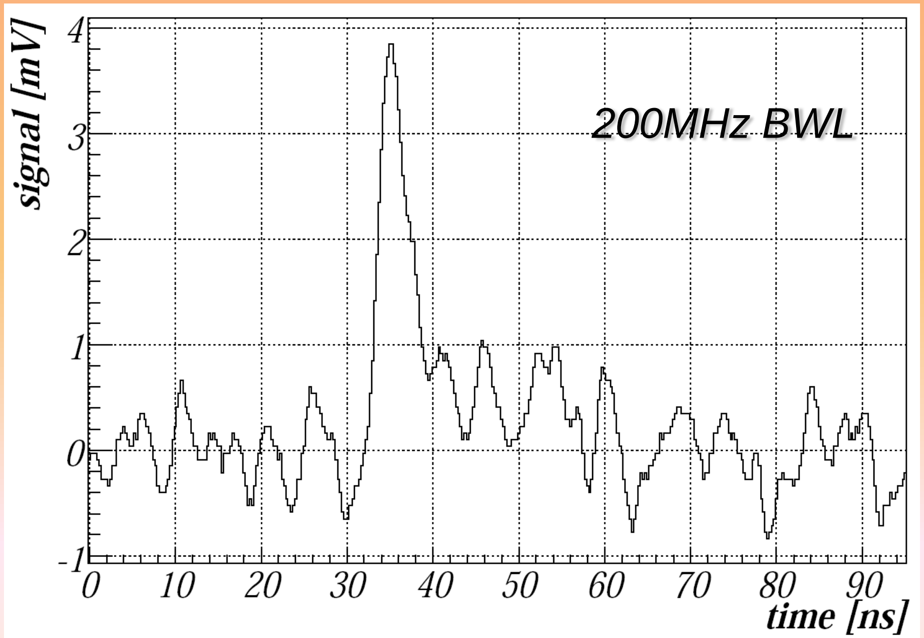


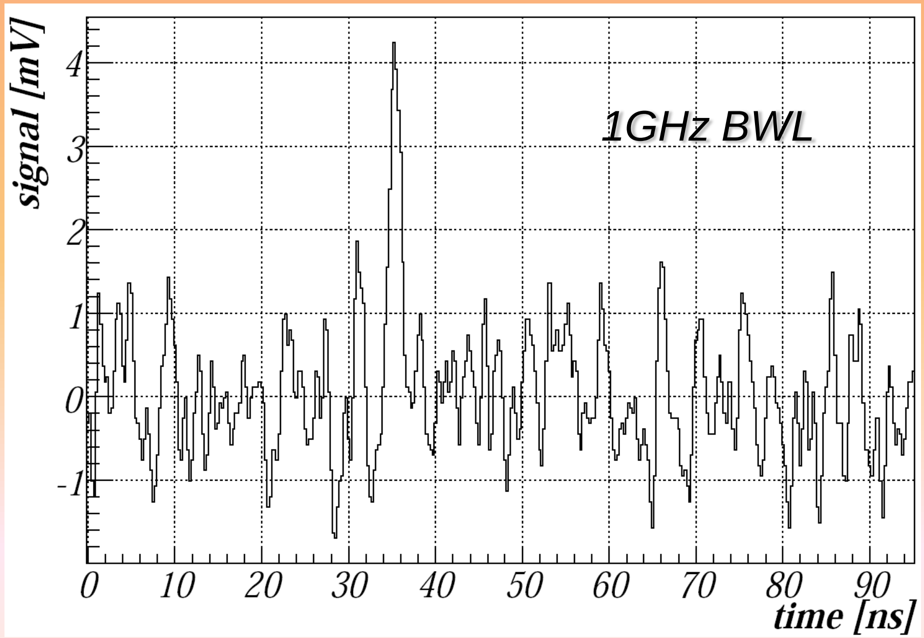
Off-line analysis of waveforms recorded at full BWL:
optimum S/N with 1st order filter with cut-off frequency 200-400 MHz



Signals recorded with 200 MHz BWL at the readout

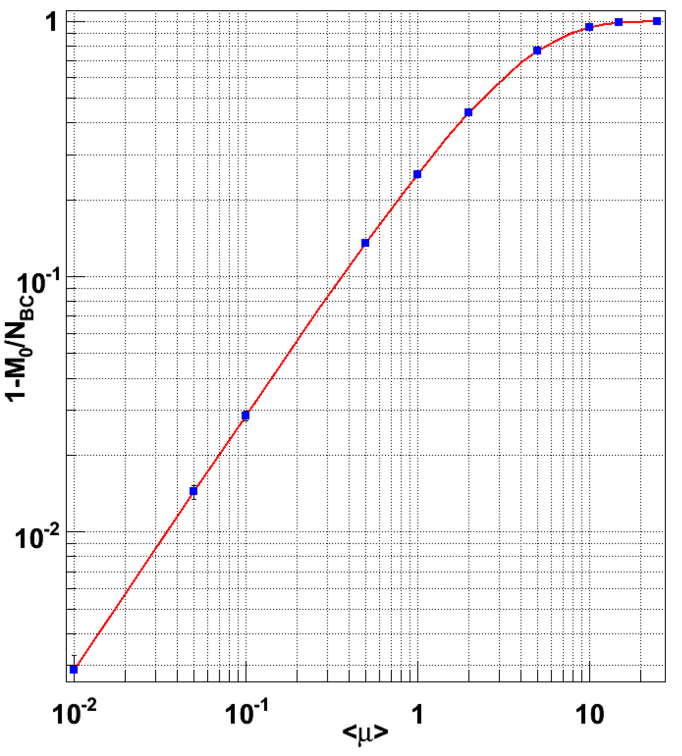
- Typical S/N with MIP at 90° incidence in the lab. tests: 7-7.5
- Most probable amplitude produced by MIP at 90°in the lab tests: 2.2 - 2.7 mV
- Mean rise time 1.4 ns
- Mean FWHM 2.9 ns
- Timing resolution better than 400 ps (thresholds: 0.1-2 MP amplitude)





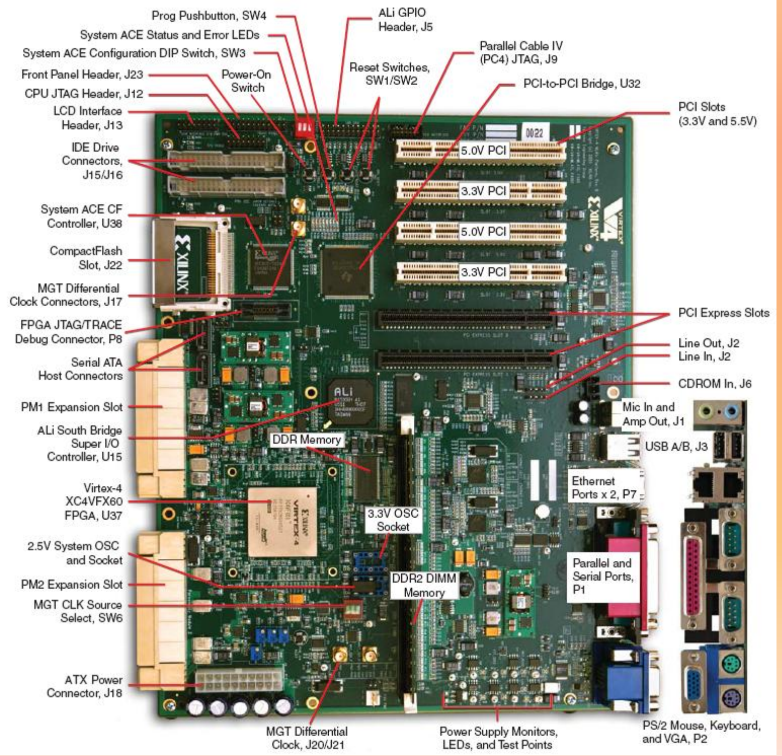
BCM: Luminosity

- BCM will contribute to luminosity monitoring with
    - Monitor instantaneous luminosity
    - Vertex position monitoring
    - Determination of dead time
    - Beam separation scans
- First algorithms will be based on non-empty event counting
    - Monitoring of luminosity per BCID
    - Providing instantaneous luminosity at Hz rate
- Monte-Carlo simulations under-way to provide initial calibration used before first beam-separation scans, and understanding systematics



BCM: Processing Units & Signal Analysis

- Input signal sampled with 2.56 GHz:
  64 samples of 390ps width for each proton bunch crossing (BC-25ns)
- Raw data stored in DDR2 circular buffer (for >more than 3×10^6 BCs $\rightarrow$ 1000 last LHC turns)
- For each BC:
  - Signal rising edge and width of at most first 2 signals are reconstructed and stored in DDR cyclic buffer (more than 2×10^6 BCs $\rightarrow$ 800 LHC turns)
  - On trigger signal (LVL1A) from CTP: BCM data from 31 Bunch crossings is formatted and sent of ATLAS DAQ readout chain
  - “In-time” and “out-of-time” coincidences, high multiplicity for low and high gain channels
    - 9 trigger bits to CTP
    - Beam abort (if beam conditions have reached unacceptable level)
    - Alarm and warning signals in less sent to DSS, DCS



BCM: Beam Abort

Beam abort algorithms:

- For initial phase:
  3 low attenuation channels (horizontal/vertical modules per ROD) and 3 high attenuation channels (vertical/horizontal)
- Data exclusive to each ROD → fire in both ROD's
  – loosely speaking 6/8 modules exceed ~5 MIP's

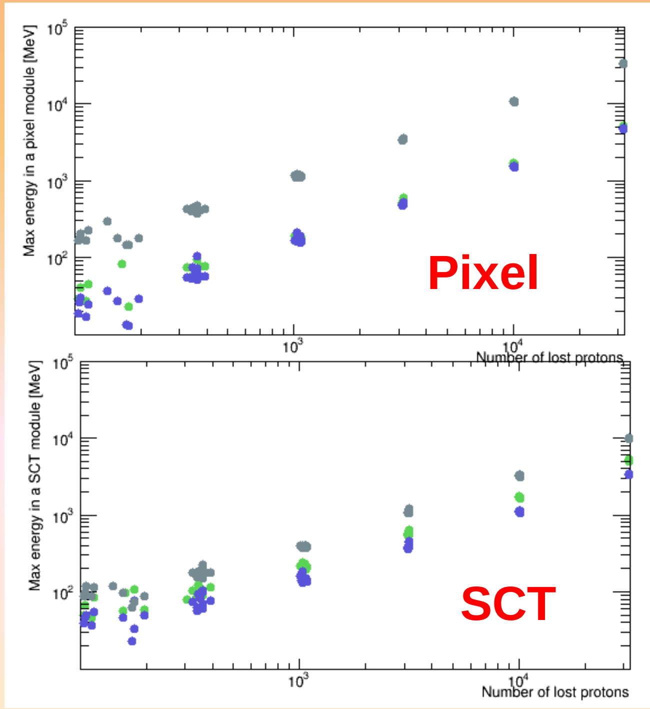
- Monitor and use later:
  - X out of Y
    - abort condition encountered in X out of last Y BC's
  - Leaky bucket Z(n) = X(n) + f.Z(n-1),
    - Abort condition X={0,1}, f – forgetting factor
    - Abort if $Z > Z_{max}$, set F, Z_{max} remotely

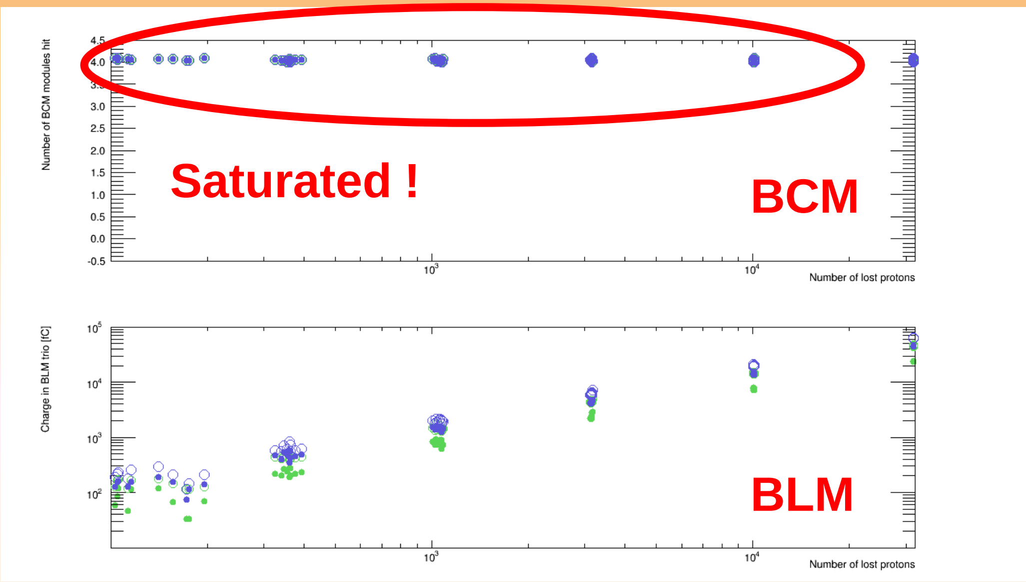
- Next year – full communication exchange between ROD's

Beam Accident Simulations

Full ATLAS simulation of 7 TeV protons hitting TAS

- BCM saturates before Pixel & SCT reach what they (nowadays) consider dangerous
- Initial abort condition does its job in protecting ATLAS ID ✓
  - Caveats:
    - Danger levels might change with improved detector understanding
    - Ratio BCM/ID might change with position of background source
  - **Good to start with plenty of headroom !**





BLM: Induced Current

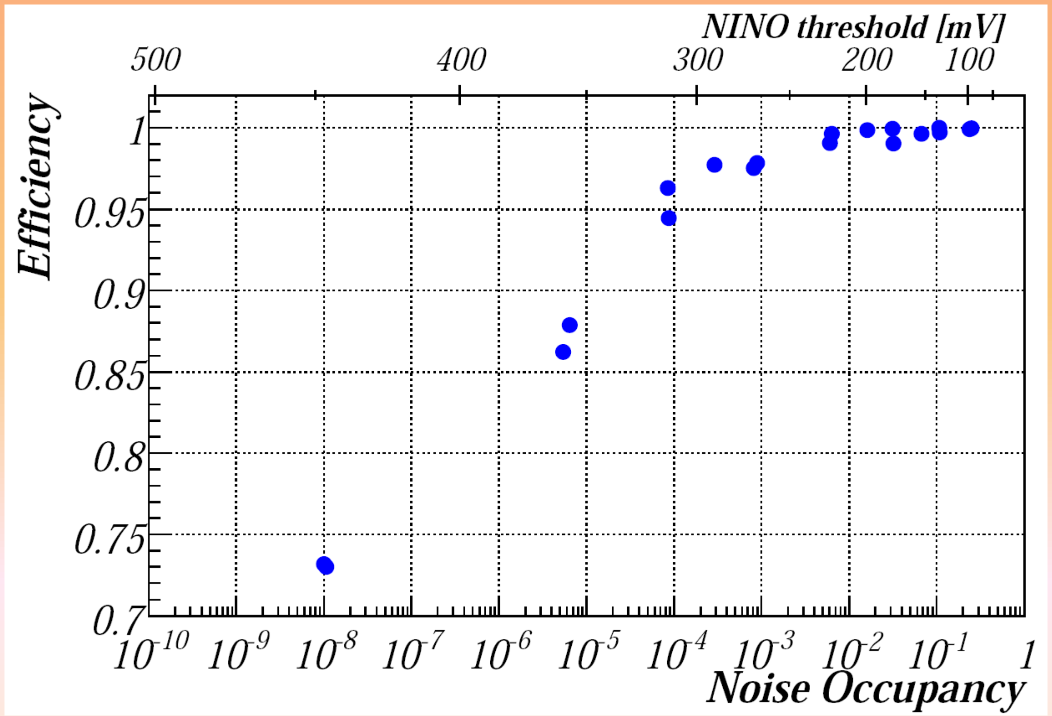
Currents in BLM modules:

- Current from 14TeV *p-p* collisions:
  - ~15nA/module (at design luminosity, 10^{34} $cm^{-2}s^{-1}$)
  - Estimated form the Total Ionisation Dose plots
  - Scales with luminosity
- Accidents (simulation)
  - 7 TeV p on TAS gives ~1 MIP/BLM module
  - 1 MIP in diamond generates ~1 fC of charge
    - 25 pA of current "spike" for single occurrence (1 bunch, possible for pilot bunch)
    - 40 nA of continuous loss every BC (much more likely for full LHC bunch structure)
- Diamond dark currents in magnetic field < O(10pA)
- Initially threshold for 40 µs reading: set to 50 nA

BCM Performance up to FPGA Input

Estimated performance of BCM system in ATLAS (up to FPGA input) for high gain channels:

- **Median S/N** (for MIPs at 45^{o} incidence) ~9
- Noise RMS σ ~64mV
- Median signal ~570mV

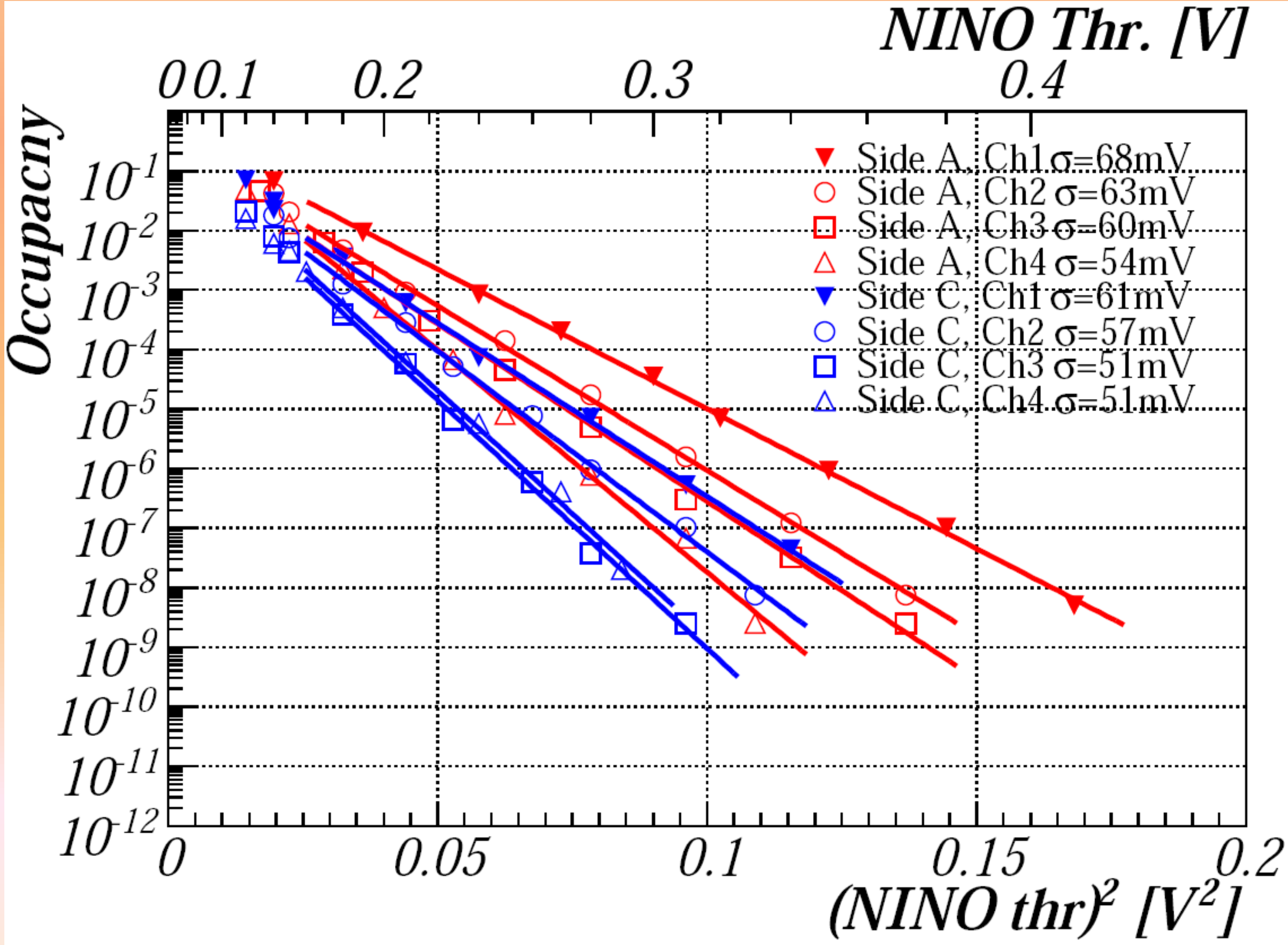


- 1MIP efficiency versus noise occupancy (noise rate scaled to 25ns interval – bunch crossing in ATLAS)
  - efficiency 0.95 – 0.99 for occupancies 10^{-3}–10^{-4}
- The exact level of fake rate depends on what kind of logical combination of signals will be used in ATLAS

BCM Noise Performance

Noise rate measured in ATLAS pit:

- extracted noise RMS σ 51-68mV (different det. modules and NINO boards) agrees with estimation (64mV)



Module	Sig Jul09	Sig Sep08	Delta
0	65.74	69.37	-3.63
1	61.36	61.52	-0.16
2	59.87	60.49	-0.62
3	63.84	63.90	-0.06
4	57.47	57.85	-0.38
5	58.72	59.86	-1.14
6	59.36	60.21	-0.85
7	60.63	61.26	-0.63

Noise stable to < 5 % in a year !