ICATPP 2009 *- 11th International Conference on Advanced Technology and Particle Physics*
5th - 9th October 2009, Villa Olmo, Como, Italy

The ATLAS Beam Condition and Beam Loss Monitors

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on behalf of the ATLAS BCM group

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

Motivation

- LHC equipment failure: resulting beam losses potentially dangerous to the ATLAS Inner Detector (ID)

- Experience show that beam accidents can happen

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

- Total energy stored in one LHC beam (2808 bunches with 10^{11} protons at 7TeV → 350MJ) more than 100-times higher than in previous accelerators like Tevatron or HERA

- Time constants of magnets: shortest ~ few LHC turns (order of ms) → if beam losses detected early enough, the beam can be dumped in time to prevent beam accident (beam is dumped within 3 turns ~ 270μs)

ATALS BCM and BLM goal

Protection

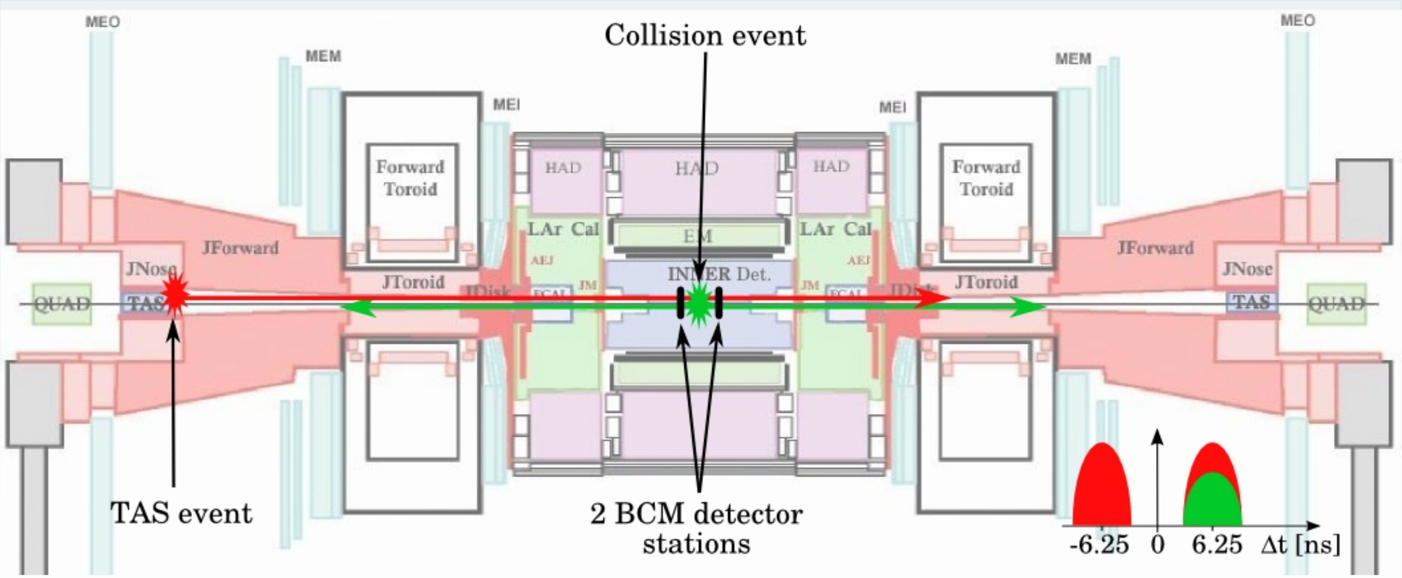
- Passive:
  - ATLAS and CMS have **TAS collimators**: protects Inner Detector from direct beam incidences
  - TAS (Target Absorber Secondaries) collimators: at $z=\pm 18$m which protect the Inner Triplet of quadrupoles from secondaries produced in p-p collisions
- Active:
  Machine Beam Loss Monitors, Beam Positions Monitors… can fire beam abort

- ATLAS **Beam Condition 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 beam failures
    - **BCM**
      - Particle counter
      - Will additionally provide a coarse relative **luminosity** measurement (complementary information to LUCID-ATLAS main luminosity monitor)
    - **BLM**
      - Induced current measurement

ATLAS BCM: principle of operation

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

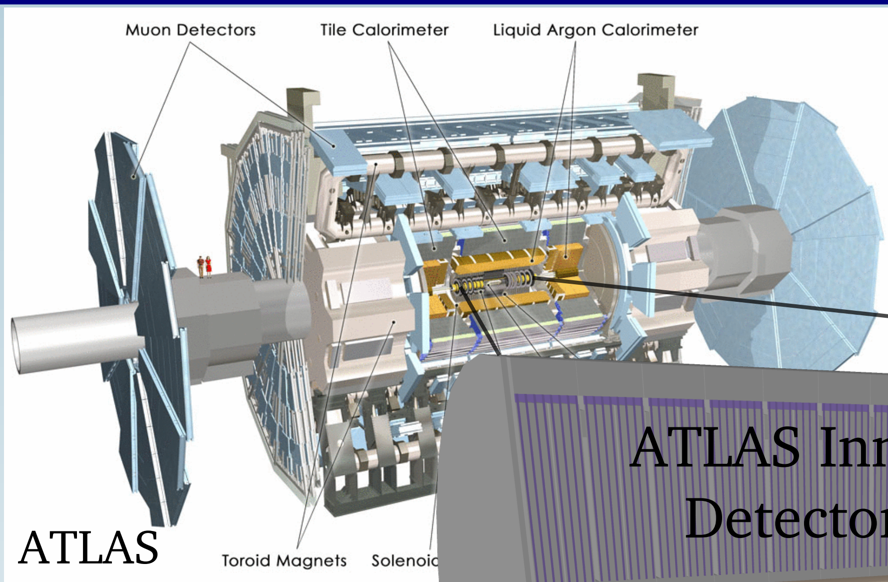
- measurement every proton bunch crossing (BC - 25 ns)
- place 2 detector stations at $z=\pm 1.9$m:
  - particles from **collisions** reach both stations at the same time (6.25ns after collisions themselves) every BC
  - particles from **background** interactions
    - reach the nearest station 12.5ns (½ BC) before particles from collisions (6.25ns before collisions themselves)
    - reach the furthest station at the same time as particles from collisions
  - > use "**out of time**" hits to identify the background events
  - > use "**in time**" hits to monitor luminosity

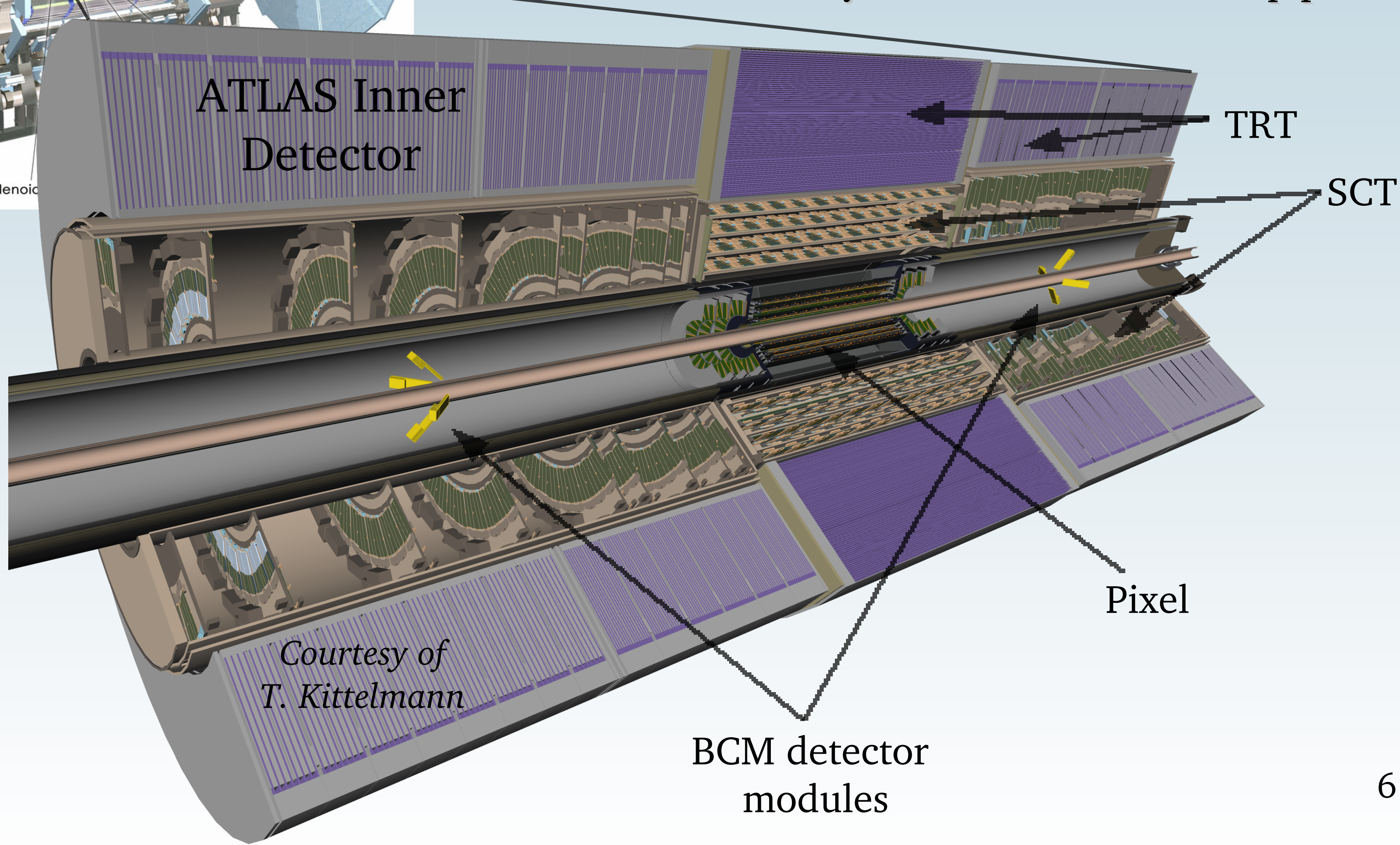


Requirements:
- fast and radiation hard detector & electronics:
  - >rise time ~1ns
  - >pulse width ~3ns
  - >baseline restoration ~10ns
  - >ionization dose ~0.5 MGy, 10^{15}particles/cm^2 in 10 years
- MIP sensitivity

BCM: Realization

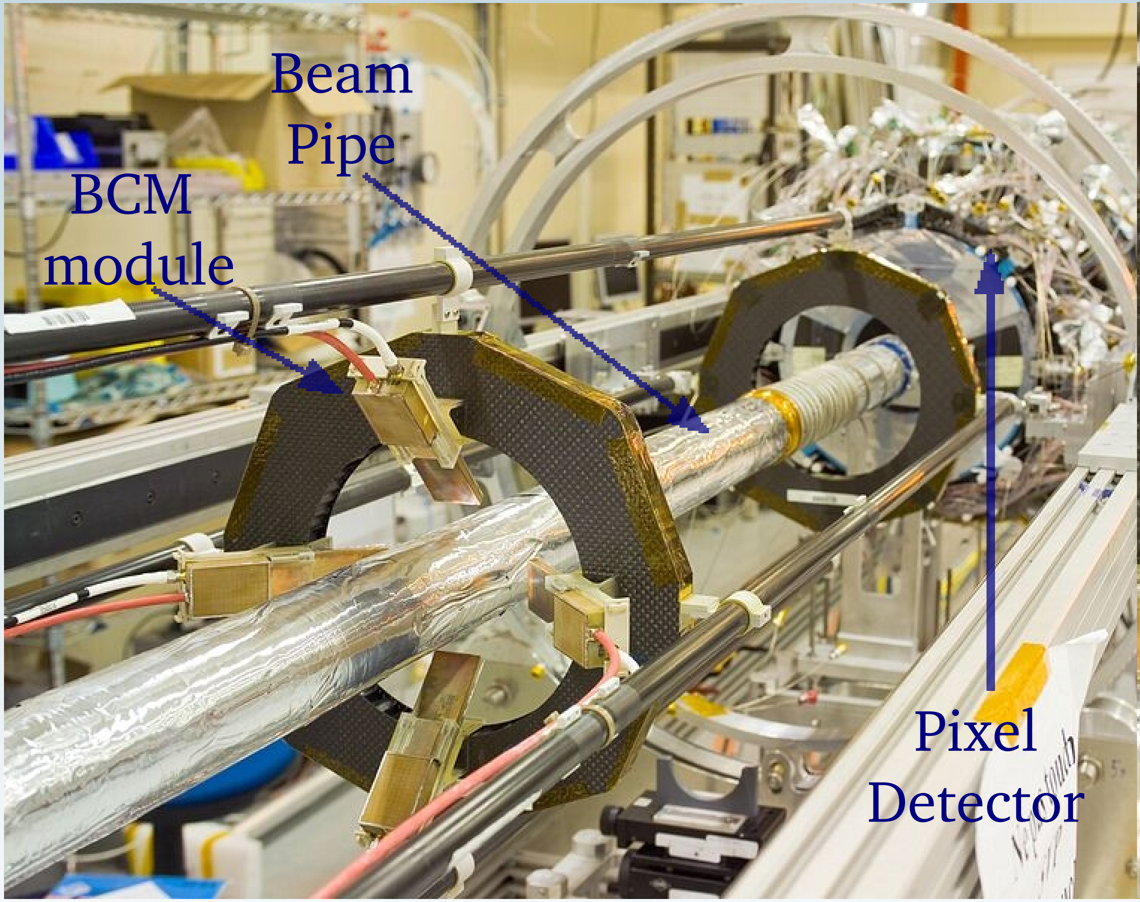
- 4 BCM detector modules on each side of the Interaction Point
- Mounted at $z=\pm183.8$cm and $\varphi=0^o$, 90^o, 180^o, 270^o, sensors at $r=5.5$cm ($\eta\approx4.2$)
- Modules tilted by 45^o towards the beam pipe

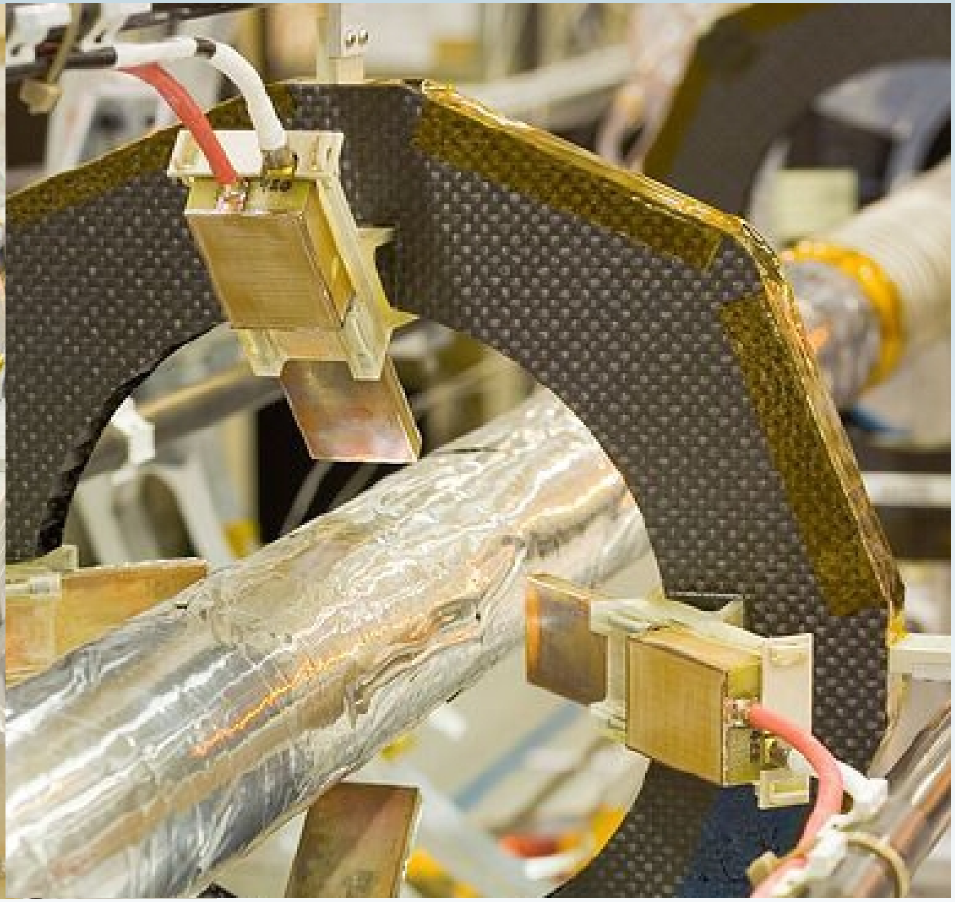




BCM: Detector Modules Installed

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





BCM Detector modules

Poly-crystalline CVD diamond sensors

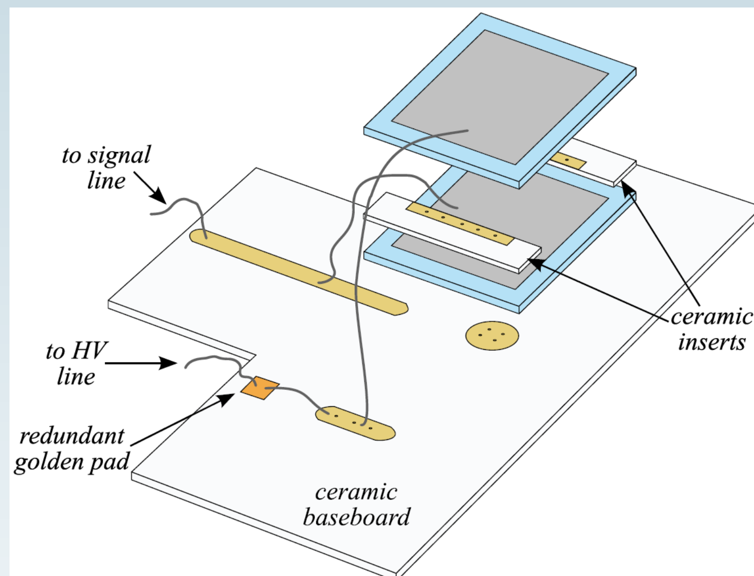
- developed by RD42 and Element Six Ltd.
- radiation hard: shown to withstand 10^{15}p/cm^2
- low leakage current → no cooling required
- operated at high drift field 2V/µm → fast and short signals

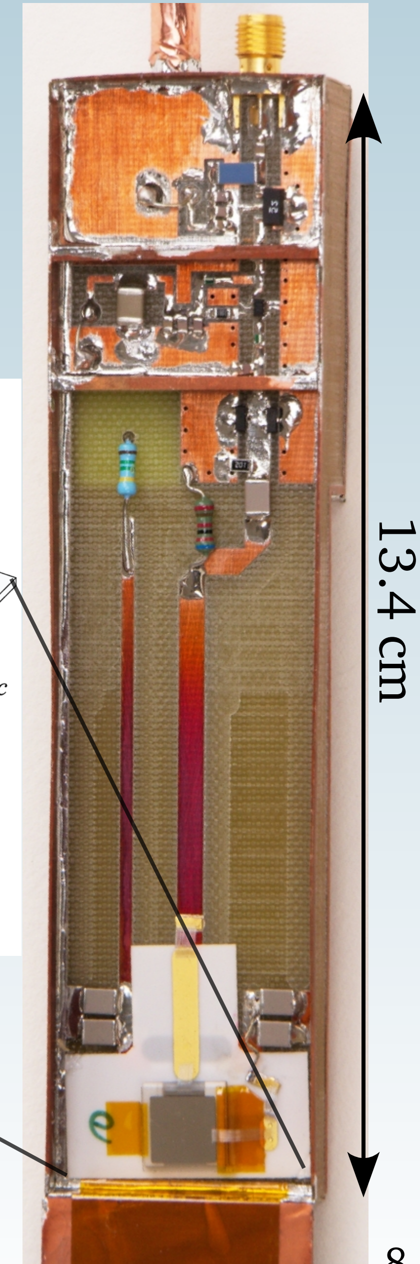
Double – decker assembly

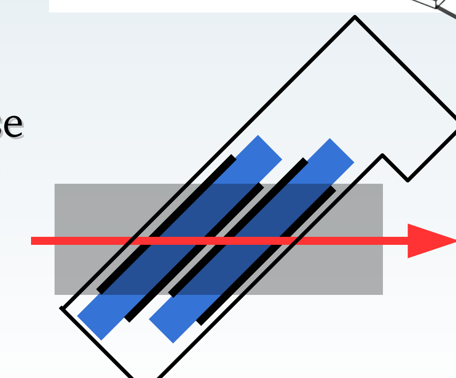
- 2 back-to-back sensors each with
  - Thickness 500µm,
  - CCD @1V/cm ~220µm
  - Size: 10×10 mm^2
  - Contact size: 8×8 mm^2
  - Operated at 2V/µm (1000V)

- Double signal compared to assembly with one sensor, but noise not measured to be two times higher

- For 45^{o} particle incidence signal increase by factor √2 → modules installed at 45^{o} to the beam pipe





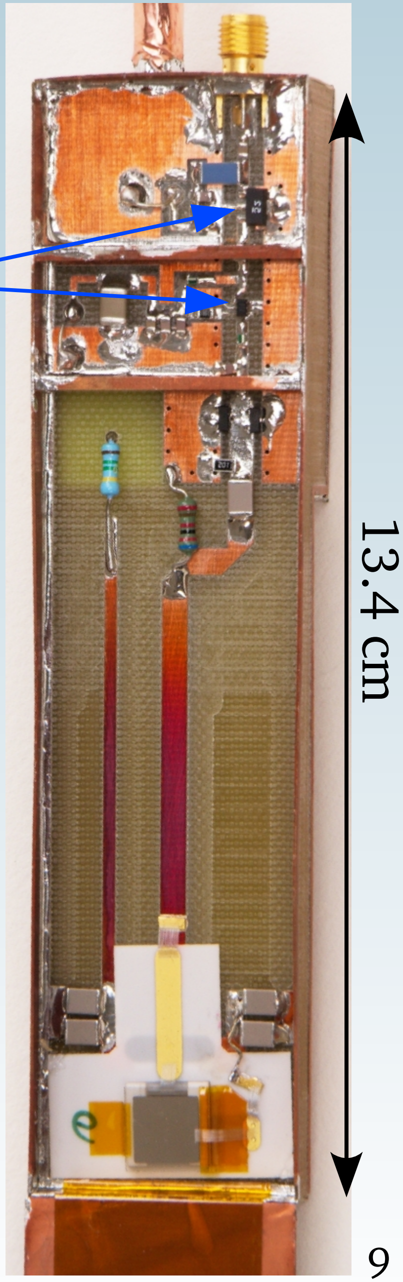


BCM Detector modules

Front end electronics

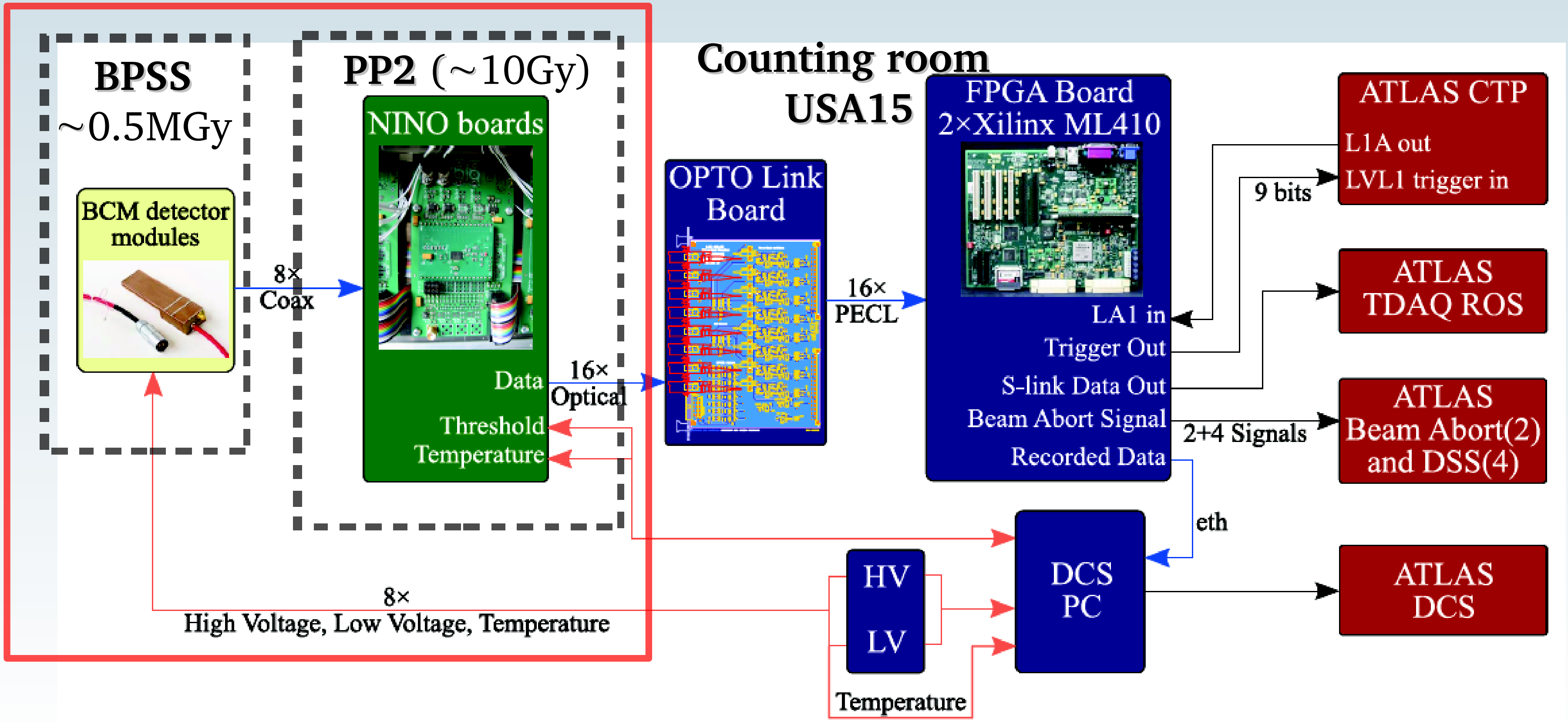
- **2 stage amplifier:**
  - 1st stage: Agilent MGA-62653, 500MHz (22db)
  - 2nd stage: Mini Circuit GALI-52, 1GHz (20dB)

- Measurements showed (confirmed with simulation):
  - Limiting BWL to 200MHz improved S/N by 1.3
  - rise time worse by 70% and FWHM by 60%, but still fit to requirements
  - → 4th order 200MHz filter integrated on digitisation board before digitisation (NINO chip)



BCM: Readout chain

- Analogue signals from BCM detector modules routed behind calorimeter (lower radiation levels) where they are "digitised" by custom made board based on **NINO chip**
- Each module connected to separate NINO electronics board

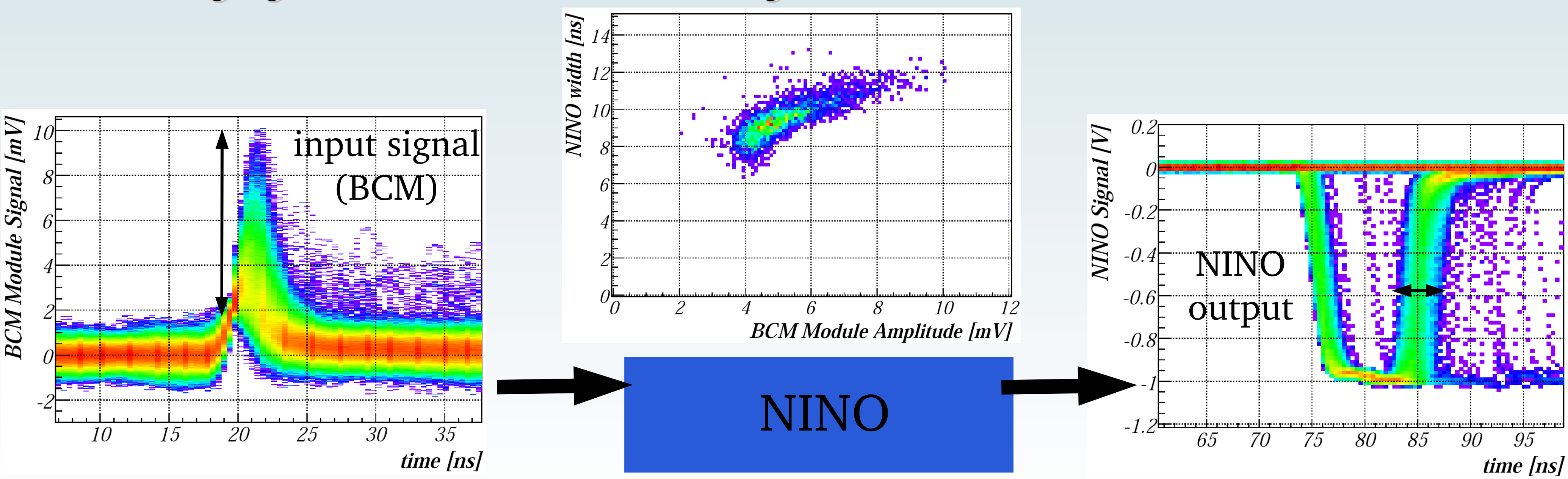


BCM: "Digitisation" electronics board

NINO chip

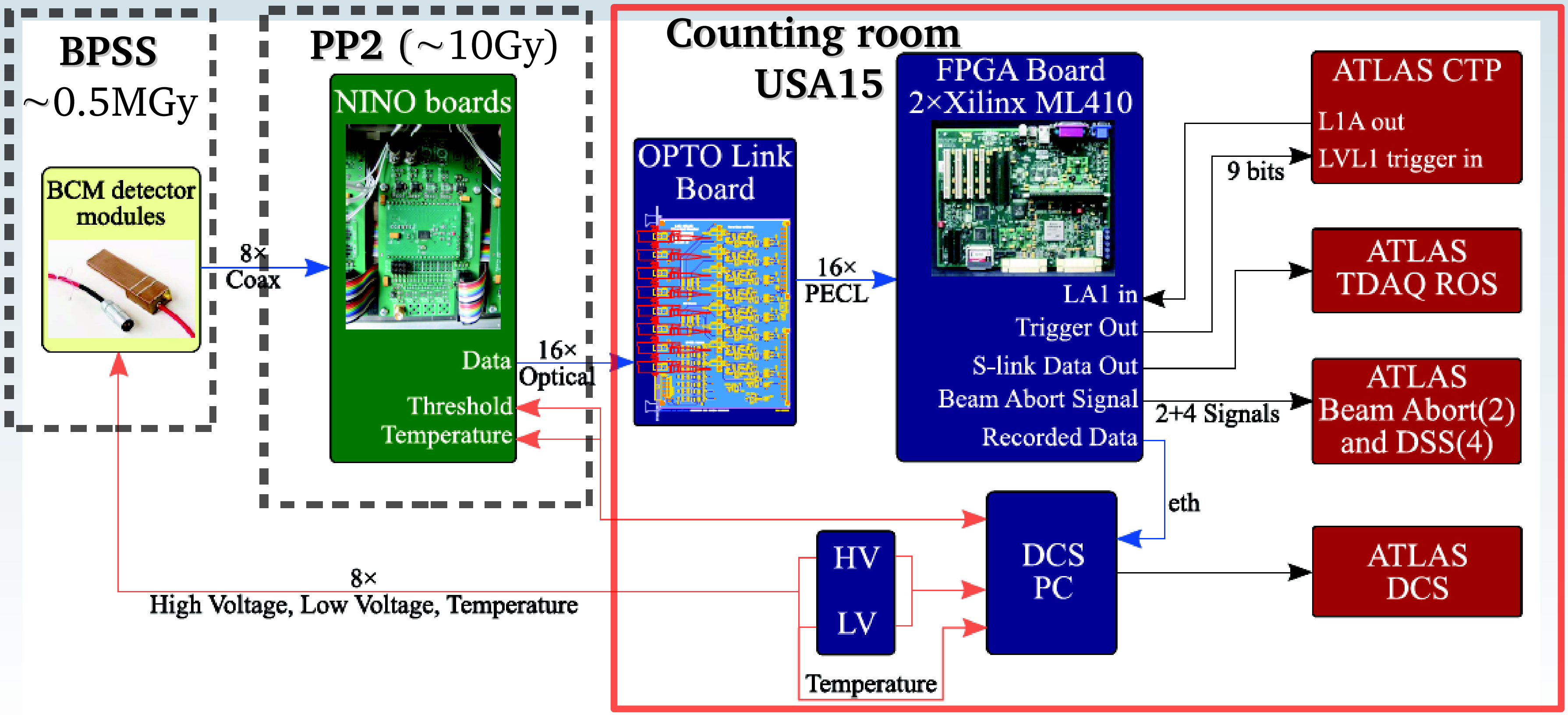
- Developed for ALICE ToF (F. Anghinolfi et al.)
- Radiation tolerant, fabricated in 0.25µm IBM process
- Rise time < 1ns, jitter <25ps, Min. detection threshold 10fC

- **Time-over-threshold amplifier-discriminator** (adjustable threshold) chip
- Width of LVDS output signal depends on input charge
- Before input to NINO chip: signal charge split in two channels in ratio of 1:11 to increase the dynamic range → **high** and **low gain channels**
- Low gain channels need ~10 times more MIPs traversing the sensor simultaneously than high gain channels to show the signal



BCM: Readout chain

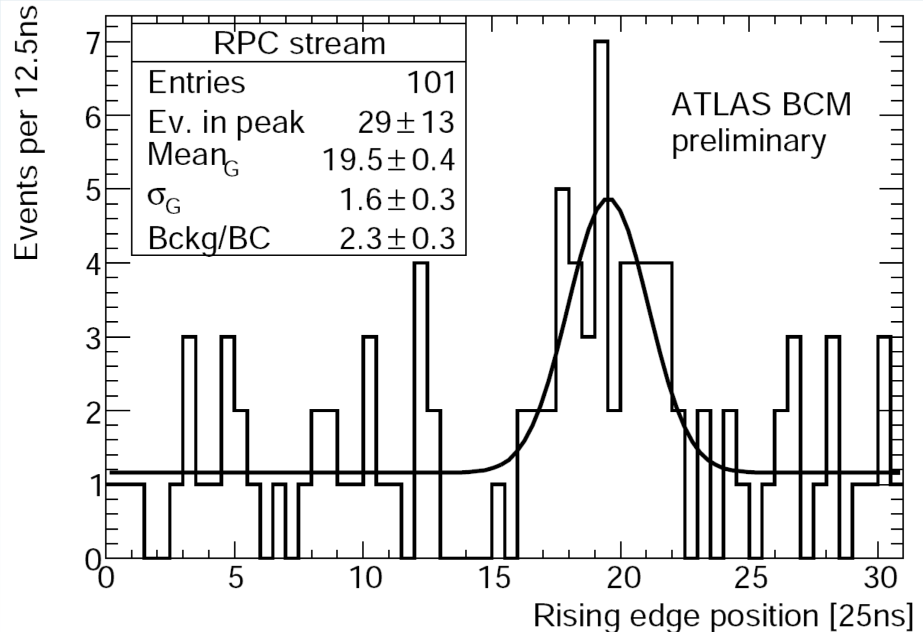
- Optical signals transmitted through 70m of optical fibres to USA15 counting room
- Optical signals transformed to PECL (2 optical receiver boards) and connected to 2 data processing units based on Xilinx Vitrex-4 FPGA
- Processing units connected to
  - ATLAS Central Trigger Processor (CTP): BCM provides 9 bits
  - ATLAS Data acquisition (TDAQ): on trigger signal (LVL1A) from CTP, BCM data from 31 bunch crossings is formatted and sent of ATLAS DAQ readout chain
  - ATLAS Detector Control System (DCS): monitoring rates,...
  - Detector Safety Systems (DSS), Beam abort system (through CIBU-Control Interlocks Beam User)

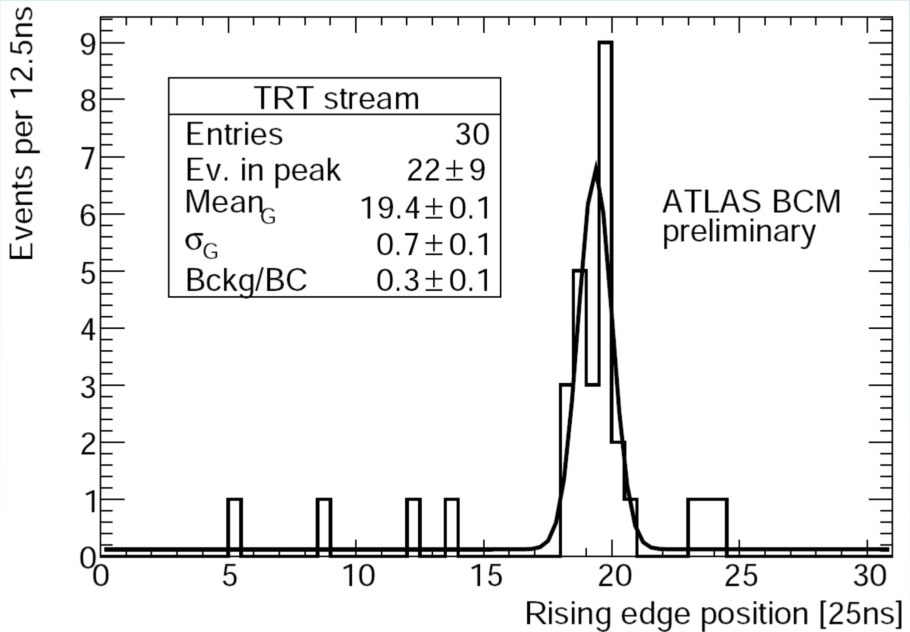


ATLAS BCM: Cosmic data

November 2008: combined ATLAS Inner Detector cosmic data taking

- Two different triggers:
  - Resistive Plate Chambers (RPC) of Muon system
  - Fast-OR mechanism of Transition Radiation Tracker (TRT)
- On each trigger from CTP: BCM sends data (signal rising edge and width) 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 random background.
  - Gaussian peak wider with RPC trigger: better jitter of TRT trigger
  - Probability for noise hit in BC: ~10^{-7}
  - RPC: about 10M triggers needed for 9 true BCM hit
  - TRT: about 1M triggers needed for 9 true BCM hit

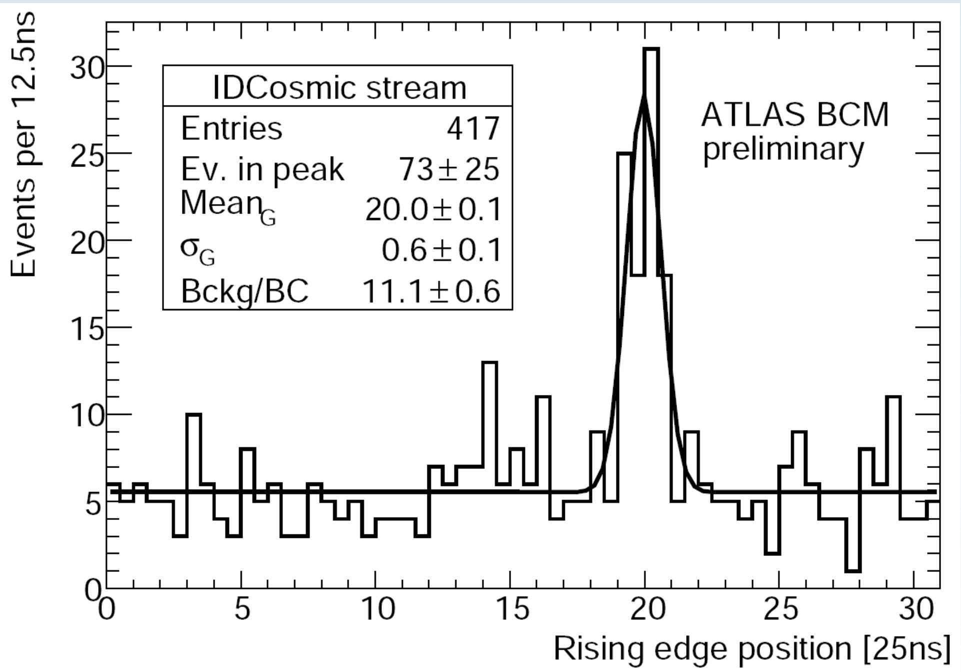


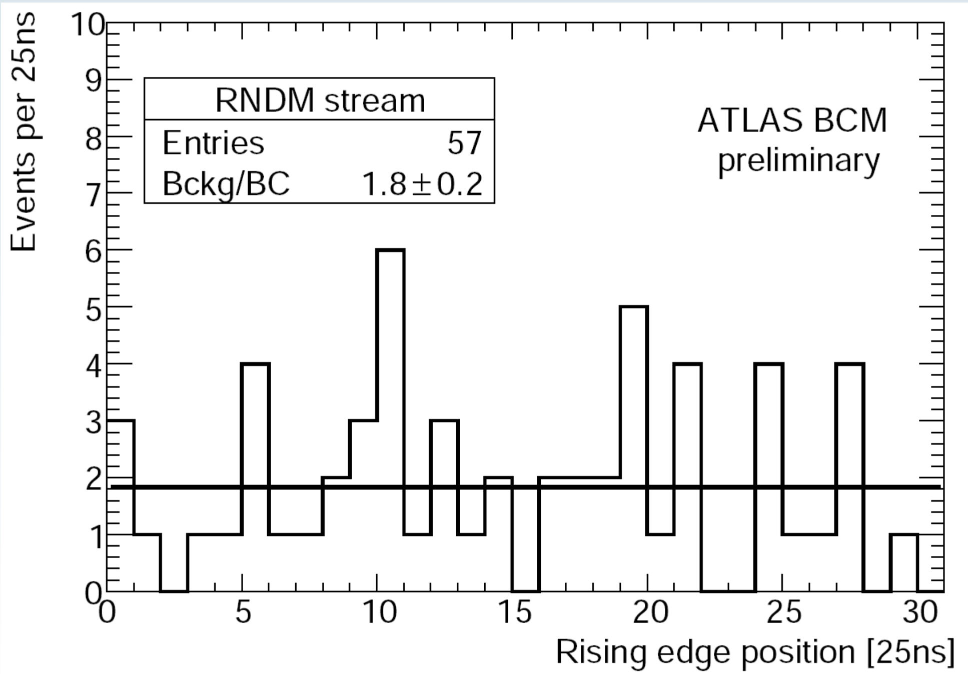


ATLAS BCM: Cosmic data

June 2009: ATLAS cosmic data taking

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



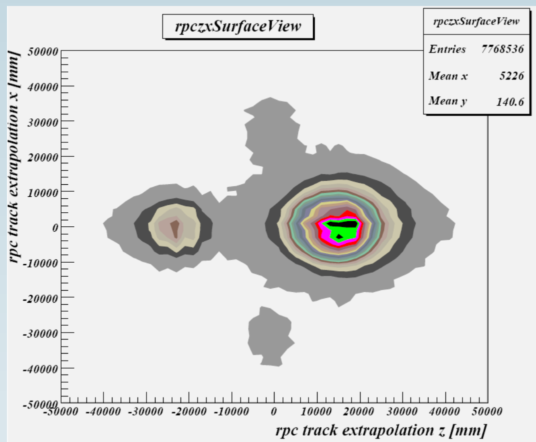


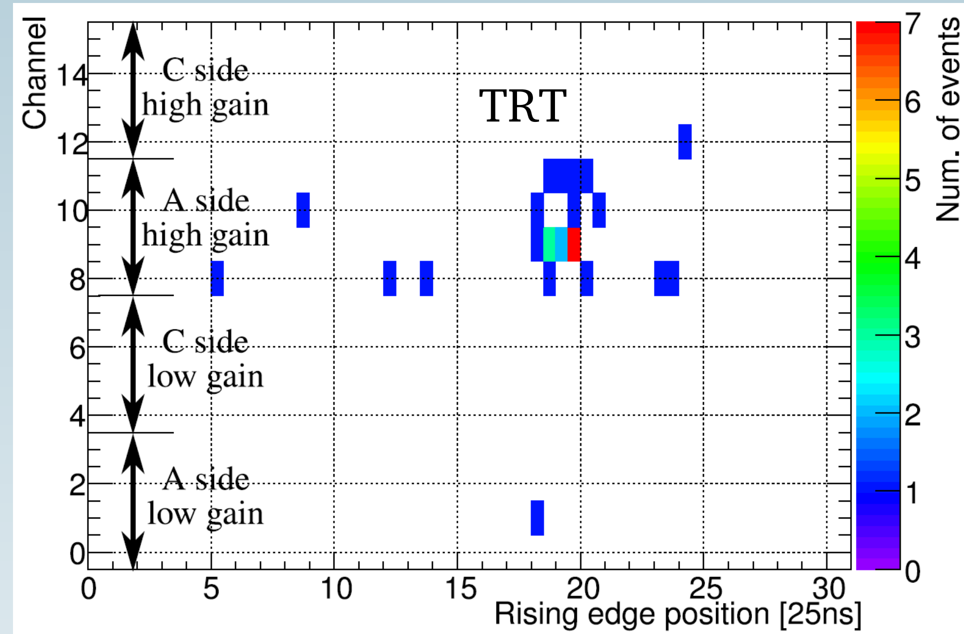
ATLAS BCM: Cosmic data

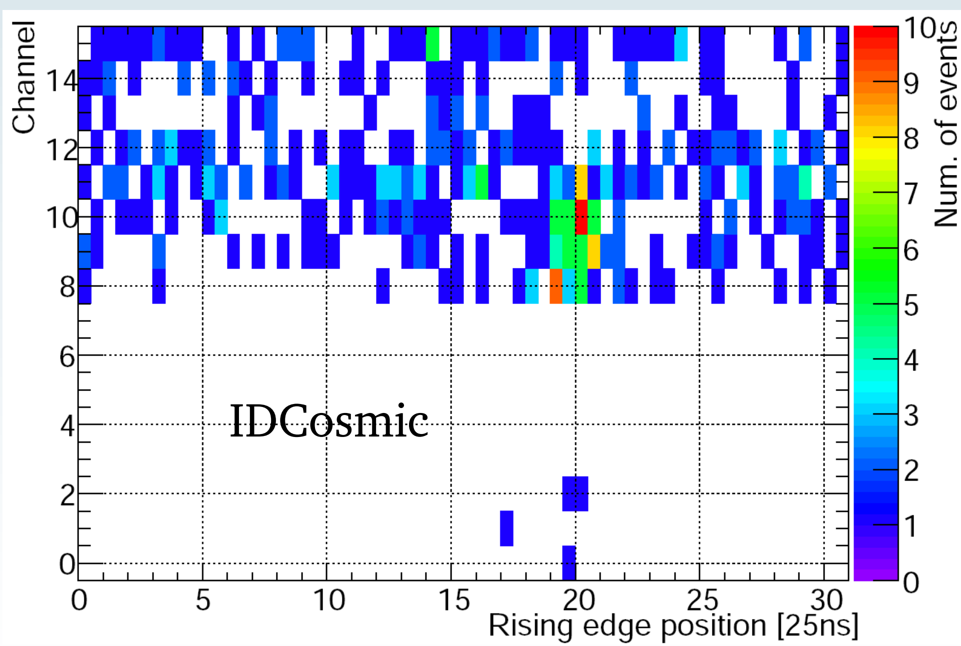
Timing distribution of BCM hits over channels:

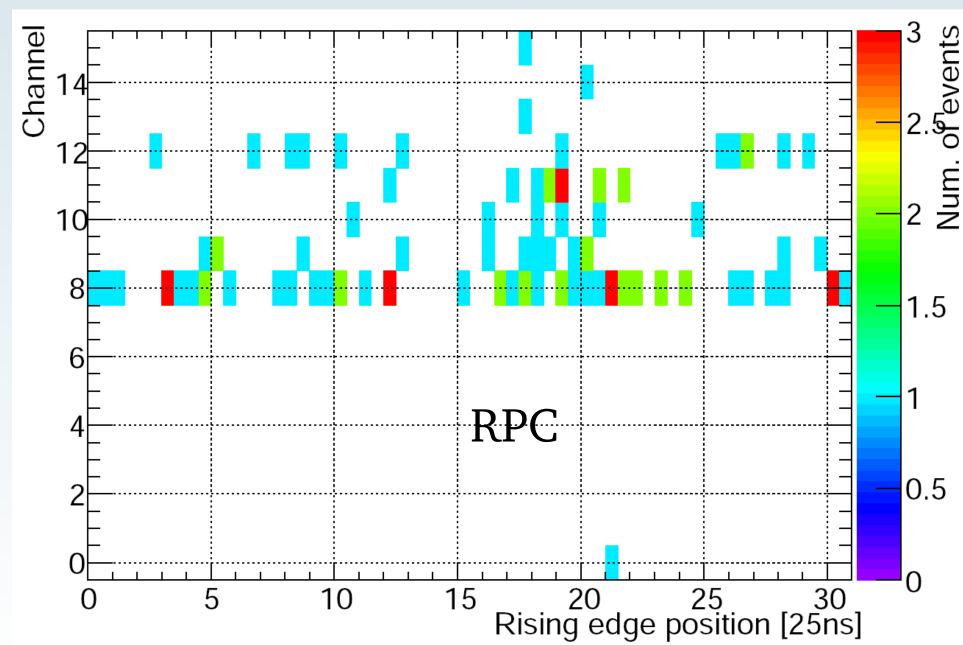
- Almost no hits on C side (attributed to unequal size of 2 main ATLAS shafts)

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





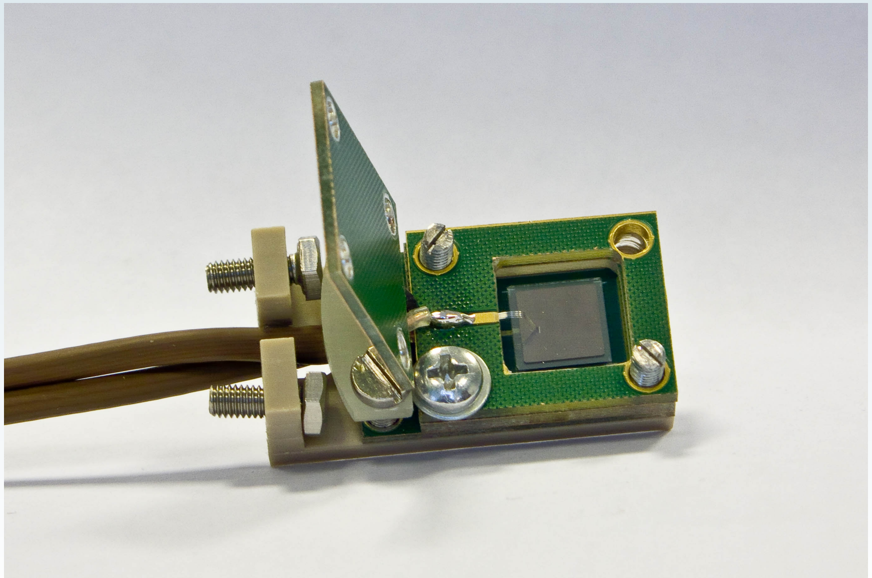




ATLAS Beam Loss Monitor – ATLAS BLM

- Independent system
- Recently added as a backup for ATLAS BCM
- Goal: only protection → much simpler than BCM
- Provide complementary information to BCM, but can be used as standalone in case of problems with BCM
- Readout electronics based on the LHC BLM system
  - Major change: ATLAS BLM uses diamond sensors instead of ionisation chambers (LHC BLM)
  - Other: different LV powering scheme, firmware changes in the readout cards,...

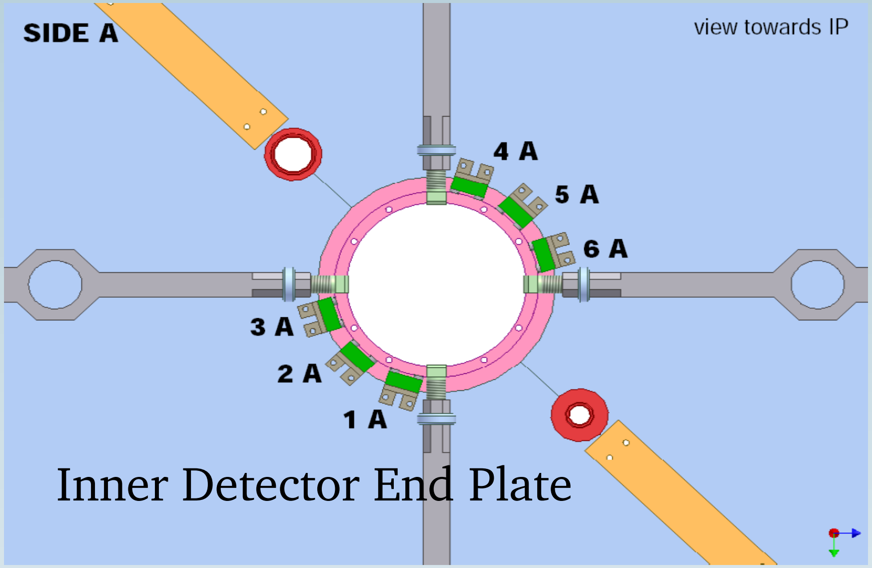
- **Sensors:**
  - one pCVD 8×8mm^2 diamond, 500μm thick. metallization 7×7mm^2
  - operated at +500V
  - current @500V typically <1-2pA

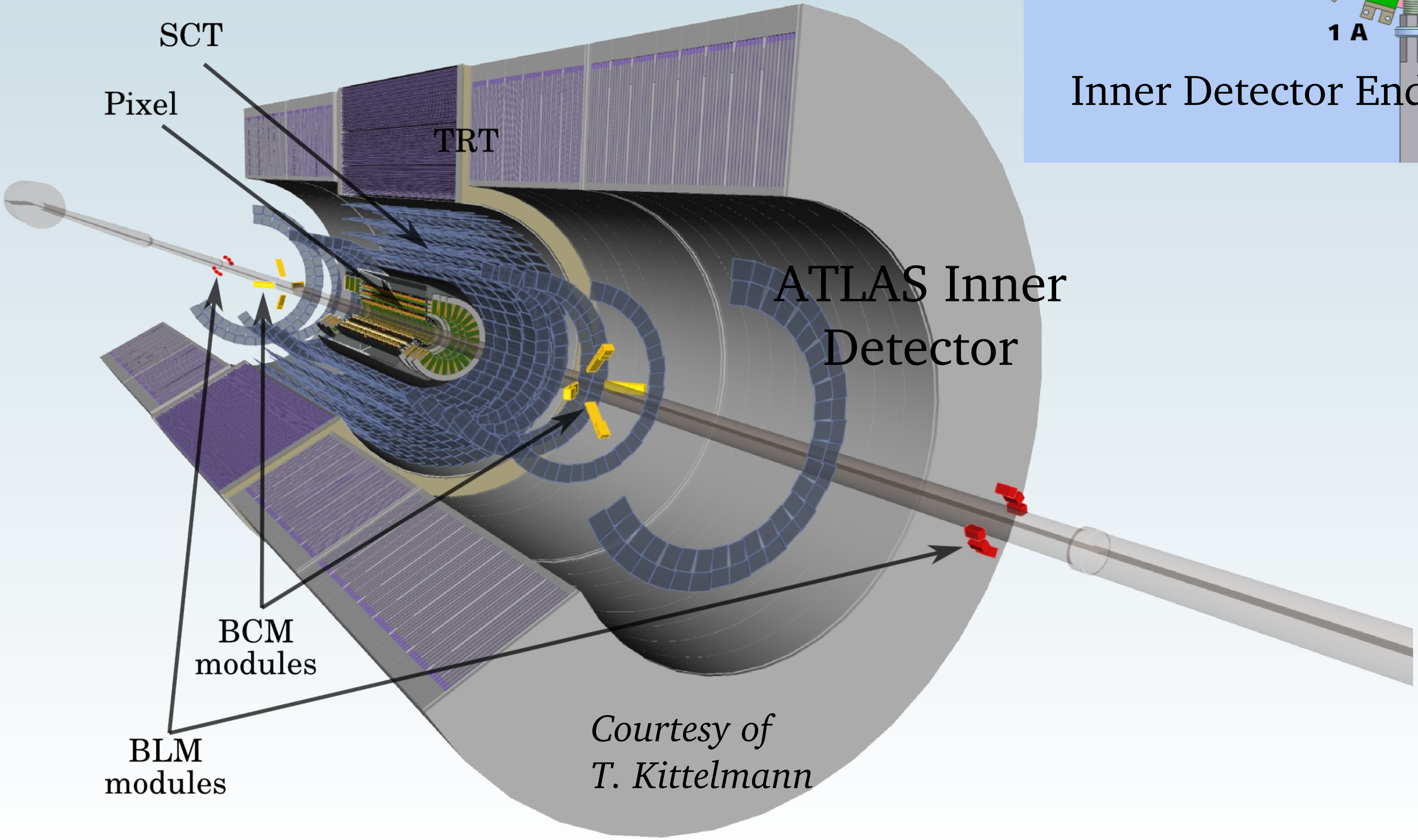


ATLAS BLM: Detector modules

12 detector modules installed in May 2008

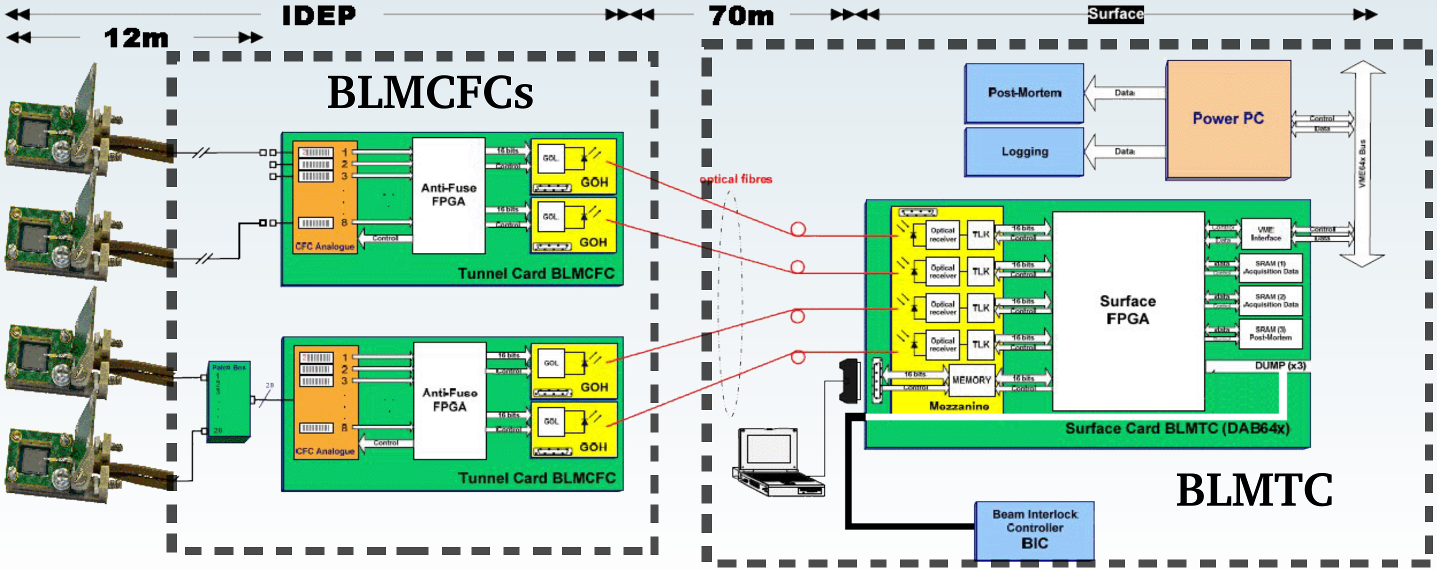
- 6 on each side of IP, installed on Inner Detector End Plate
- Close to IP: $z = \pm 3450$mm, $r = 65$mm





ATLAS BLM: Readout

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



Summary

- **ATLAS BCM** will monitor beam conditions close to IP using **TOF measurement**
  - Goal:
    - Protection
    - Additionally, relative luminosity measurement
  - **pCVD diamonds** as sensor material
    - 2 diamonds in a back-to-back configuration at 45° towards the beam
  - First experience with the system obtained in the last year and a half

- **ATLAS BLM**:
  - **Redundant** system for safety purposes
  - Induced current measurement
  - pCVD diamond sensors

- Looking forward to using them in the real LHC environment

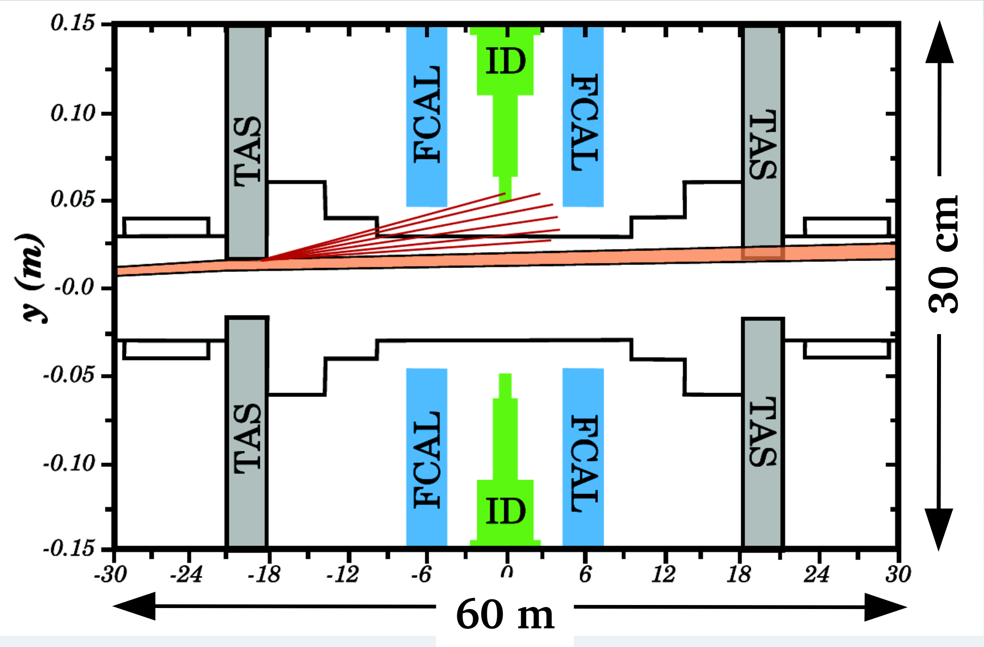
Backup slides

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@450GeV; 360J) 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 $z=\pm18$m which protect the Inner Triplet of quadrupoles from secondaries produced in p-p collisions*

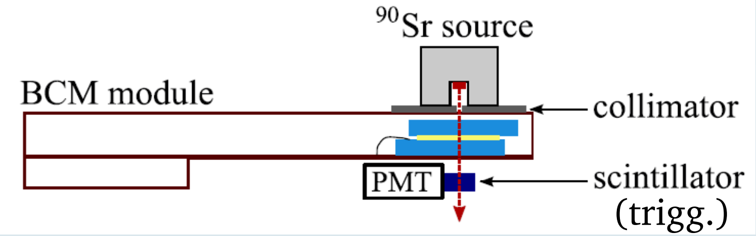


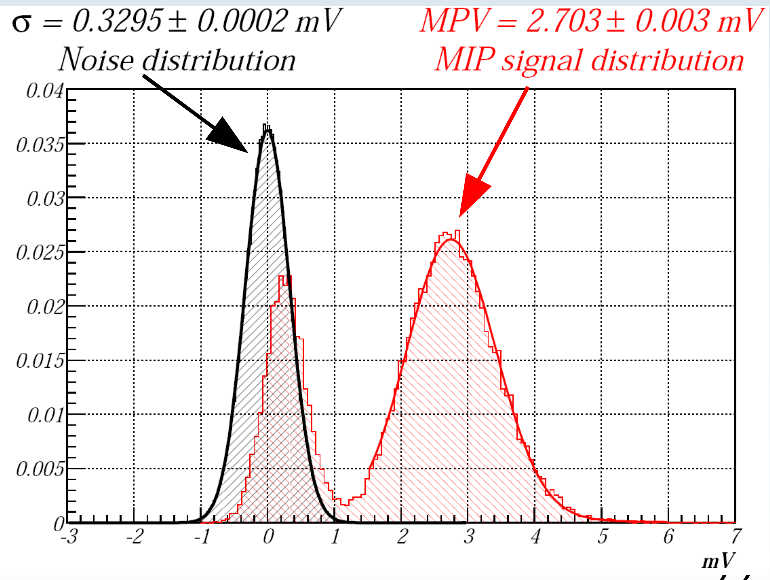
- **Multi-turn losses**
  - Beam degradation due to equipment failure, magnet trips, wrong magnet settings...
  - Time constants of magnets: shortest ~ few LHC turns (order of ms) → can abort the beam if detected early (beam is dumped within 3 turns ~ 270μs)

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

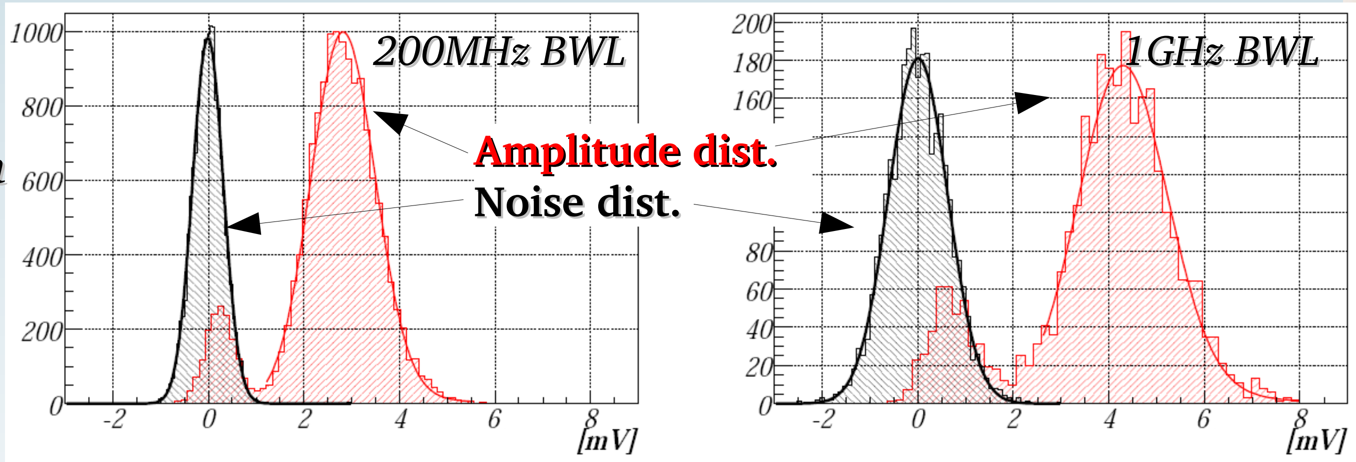
BCM Detector modules

Front end electronics

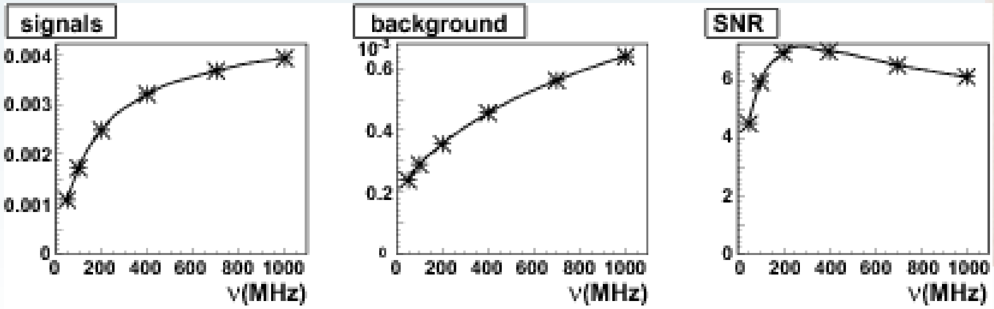
- **2 stage amplifier:**
  - 1st stage: Agilent MGA-62653, 500MHz (22db)
  - 2nd stage: Mini Circuit GALI-52, 1GHz (20dB)

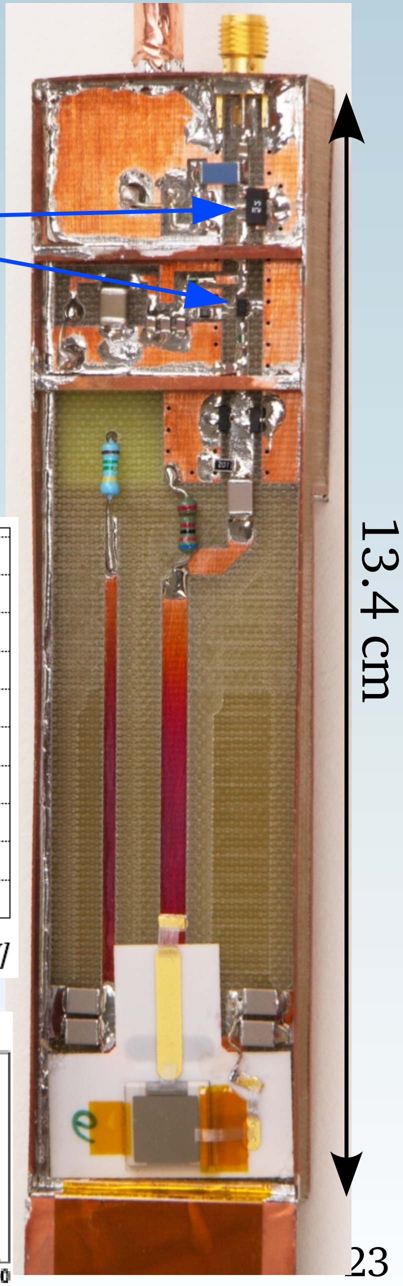
- Limiting BWL to 200MHz improved S/N by 1.3 (and rise time worse by 70% and FWHM by 60%, but still fit to requirements)
  → 4th order 200MHz filter integrated before digitization (on NINO board)

Lab. Tests with MIPs at 90° incidence



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

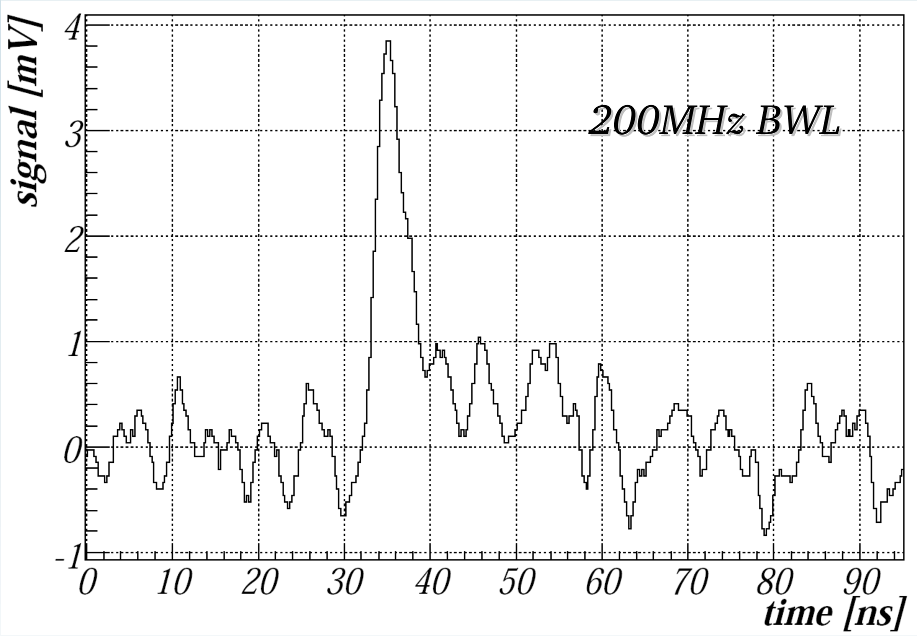


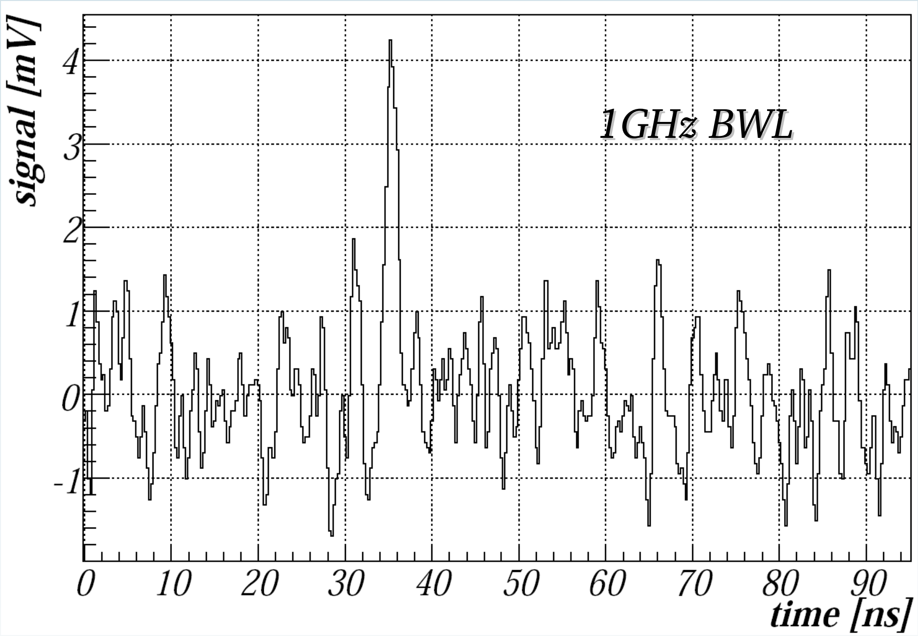


BCM: Analogue signals

Signals recorded with 200MHz BWL at the readout

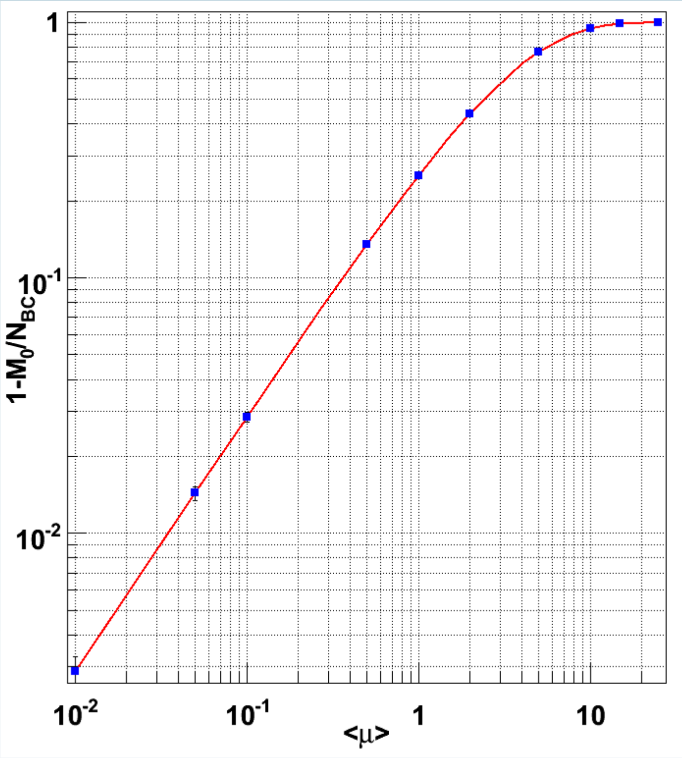
- Typical S/N with MIP at 90^{o} incidence in the lab. tests: 7-7.5
- Most probable amplitude produced by MIP at 90^{o}in the lab tests: 2.2 - 2.7mV
- Mean rise time 1.4ns
- Mean FWHM 2.9ns
- Timing resolution better than 400ps (thresholds: 0.1-2 MP amplitude)





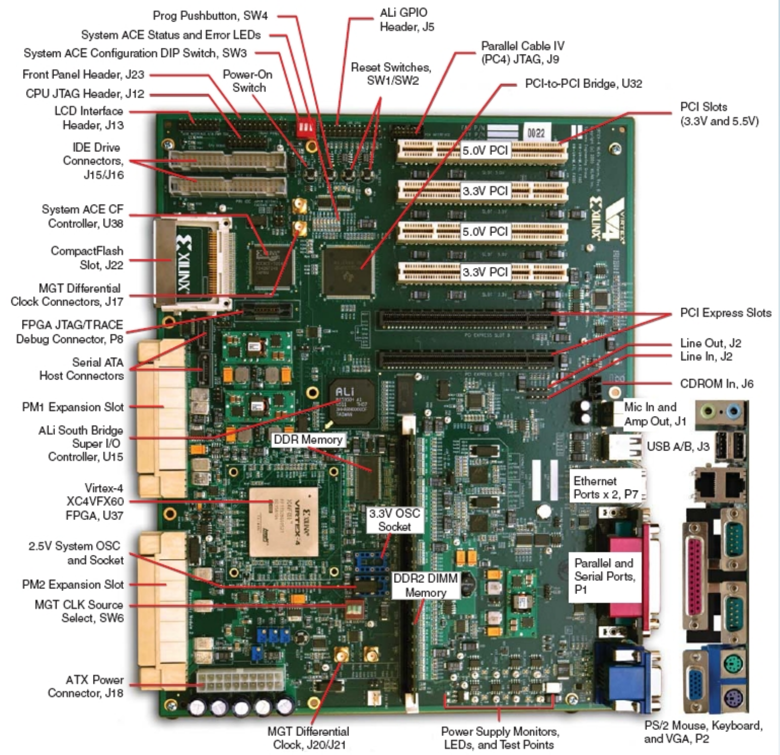
BCM: luminosity

- BCM will contribute to luminosity monitoring with
  - Monitor instantaneous luminosity
  - Vertex position monitoring
  - Determine 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 systematic



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 → 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\times10^6$1BCs → 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: 4 Low threshold channels (horizontal modules) + 3 high threshold channels (vertical modules)
- Monitor and use later:
  - X/Y (3+4 condition reached in consecutive X out of Y BCs)
  - Leaky bucket (X/Y with forgetting factor)

BLM: induced current

Currents in BLM modules:

- Current from 14TeV *p-p* collisions:
  - ~15nA/module (at design luminosity, 10^{34}/cm^{-1}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
    - 25pA of current "spike" for single occurrence (1 bunch, possible for pilot bunch)
    - 40nA of continuous loss every BC (much more likely for full LHC bunch structure)

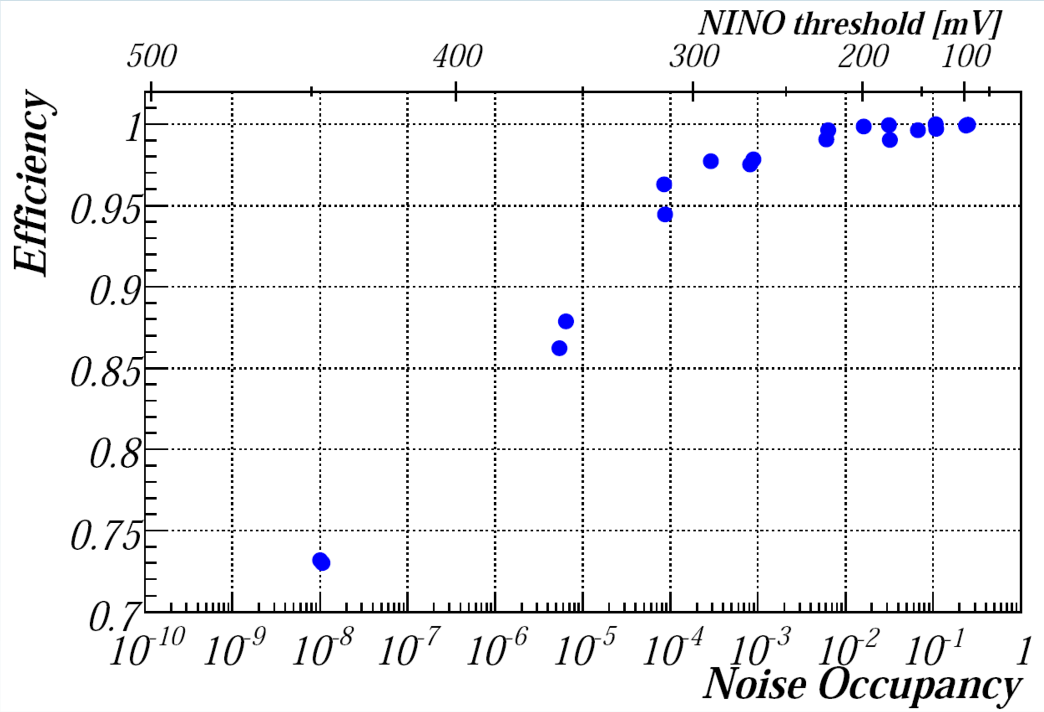
- Diamond dark currents in magnetic field O(10pA)

- Initially threshold for 40µs reading: set to 50nA

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: performance

Noise rate measured in ATLAS pit:

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