Beam Conditions Monitoring at CMS

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On behalf of the

CMS BCM project

Outline

- Why fast beam conditions monitoring within CMS
- The CMS BCM
- Location, location, location
- PCVDD as a sensor
- BCM Testbeam results and PCVDD benchmarks
- Back end logic
- Observations and Outlook

Radiation Monitoring: What CMS requires

- **Provide an on-line monitor for beam conditions => BCM**
  - **Protection of sub- detectors from adverse beam conditions**
  - **Ability to request beam-abort**
  - **Optimization of beam Conditions**

- **Provide mapping of the radiation field => BCM + active/passive monitors**
  - **Benchmark activation simulations**
    - **There is a factor 3 uncertainty in the FLUKA simulations**
    - Small and cheap active/passive monitors to measure dose (ionization) and particle fluence (displacement damage)
  - **Identify leaks in the shielding**
  - **Map out activity prior to first shutdown**

- **Provide a long-term monitoring of integrated radiation exposure =>active/passive monitors +RAMSES**
  - **Post-mortem diagnosis in case of device failure**
  - **Tool for corrective measures for background mitigation**
  - **Activation levels for access**

Fast Monitoring: The Beam Conditions Monitor

The BCM is to be the central component of the monitoring system

- Sensors placed close to beampipe (within the Pixel service-tube volume)
- Sensors have to discriminate bad beam conditions over normal running conditions
  - ⇒ Other radiation monitors (passive or long sampling) will not see beam losses

Conditions at z=3m,r=4cm

- Normal pp background = 31mGy/sec => ~2.7 MIP equivalent/cm^2 per bunch crossing
- 1 proton on the TAS generates ~0.65nGy =>~2.3 MIP/cm^2 per bunch crossing
  - In the process of simulating # hits and energy distribution per bunch crossing
    - Attempting to model of low energy looper density

The Role of the BCM

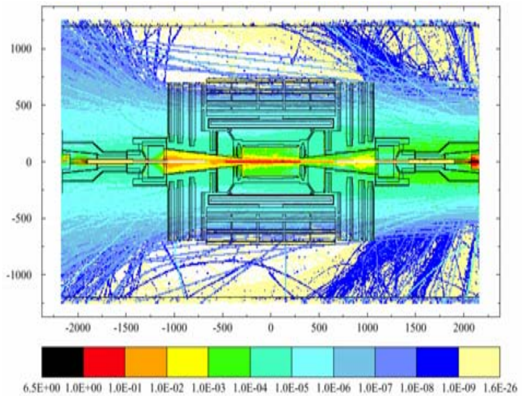
- Allow to protect equipment during instabilities/accidients
- Provide fast feedback to the machine for optimization of beam conditions
- Provide high time resolution diagnostics for beam accidents/ bad background conditions

If all is well, the BCM should a completely redundant system:
ie the LHC machine protections should be more than sufficient.
However: Machine protection group strongly encourages us to implement a system within the experimental volume.

Beam Conditions Monitoring

Operational requirements

- BCM to be designed for both beam monitoring and as a protection system for the inner tracker region of CMS
- Completely reliable system
- Measure beam conditions under standard operating conditions
- Monitor the beam for the onset of unsuitable beam conditions
  - Identified by increased per bunch crossing flux
  - Post mortem analysis required:
    =>Time stamping on the bunch crossing time scale
- Monitor the environment during the Pilot Run
- Monitor the inter-bunch spacing during normal operations
- Survive the extreme burst irradiation conditions
  associated with beam abort failures
  - ie fluxes of ~10^8 per cm^2 per bunch crossing



BCM Front end requirements

Should be fast

- Has to be able to handle normal operation hits within 8-10ns
- Sensors AC coupled to amplifers have to restore to baseline under 12ns
- Use Std 40MHz CLK to sync with CMS (assumes intelligent FE electronics)

Should be able to monitor within the inter-bunch spacing

- Restricts the positioning from the IP ie z=12.5ns
- Use 40MHz CLKing, but with inverted clock
- Need to single MIP sensitivity in interbunch spacing

Should provide flexible inputs to the BCM backend

- Adjustable threshold (done in terms of counters)
- Analog pulse amplitude to be sampled

Should be able to see the onset of adverse beam conditions

- Should not tie ourselves to particular accident scenarios

Should be able to see normal and startup conditions

- Monitoring single 450GeV pilot bunch => Single MIP sensitivity

Should be able to survive unsynchronised beam aborts and other blasts

- FE amplifier protection (for bursts and sustained bursts)

Should have a minimal material budget

- Use existing structures and thermal enclosure at $\eta \sim 4.5$
- Difficult challenge: find space for services routing on tracker bulkhead

Must be reliable

- CMS BCM is to be a 3-fold system

The 3 Component BCM

The BCM must be a simple and ultra reliable system with a dynamic range of

1 to 10^8 MIPs per cm^2 per bunch crossing

⇒ We do not want to require this of a single subsystem

The 3 subsystem being proposed are:

Subsystem 1: The intelligent ammeter approach

- Digitize the DC level coming from a simple sensor
  - Look for sustained time above threshold
  - Needs careful grounding
  - Allows for tunable time-over-threshold window (0.5 to several orbits)

Subsystem 2: Bunch by bunch sampling. Minimal processing

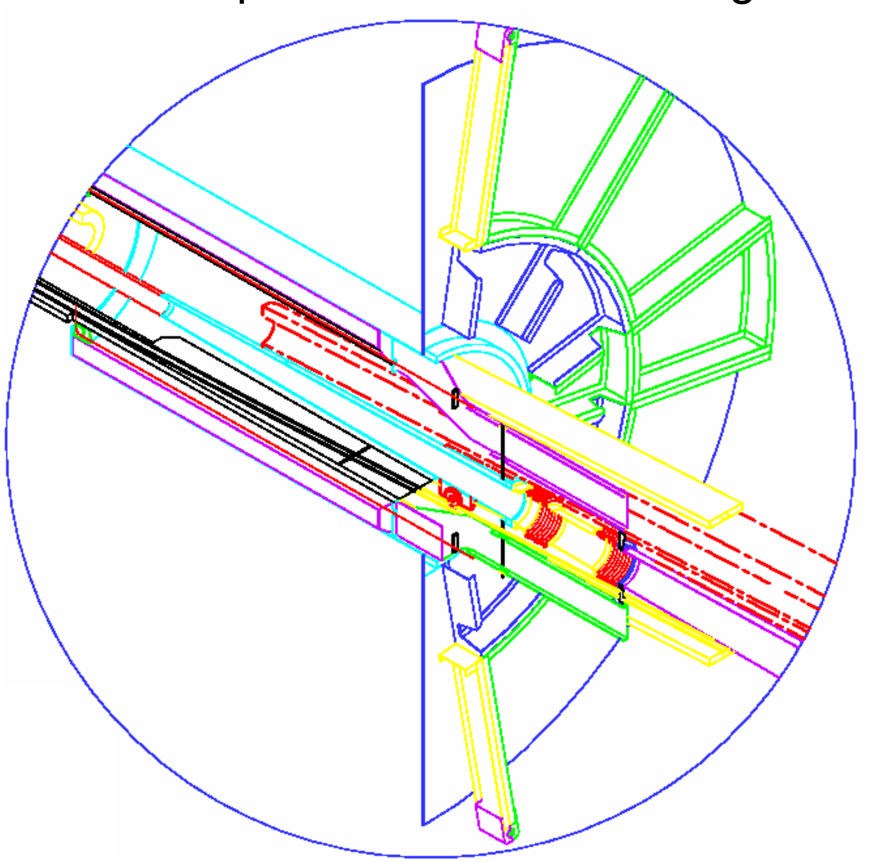
- Simple sensor AC coupled to fast amplifier (~1GHz)
- Pass signal through staggered discriminators to assess levels
- Use discriminator outputs to form logical AND over BCM array
- Feed logical AND into Staggered circular buffers (different time scales)
  - Trigger abort signal on a majority level in buffer
  - Time scales set by active buffer depth (10 bunch crossings to 1 orbit)

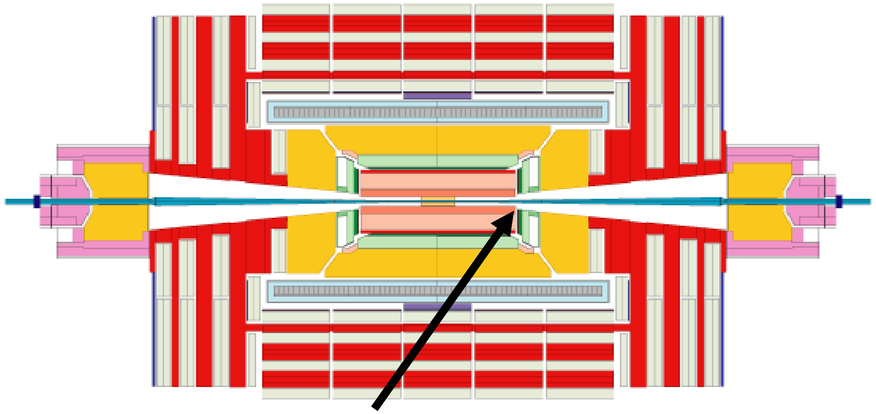
Subsystem 3: Fast and full readout

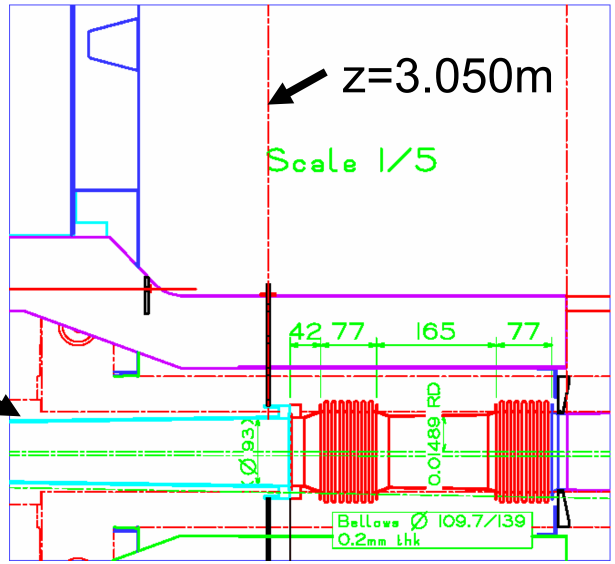
- Use more complex system based on the CMS Pixel electronics: Sensitivity: 0 to ~10 MIPs per bunch crossing

Location, location, location

For this talk, focusing on
Beam Pipe/Tracker bulkhead region

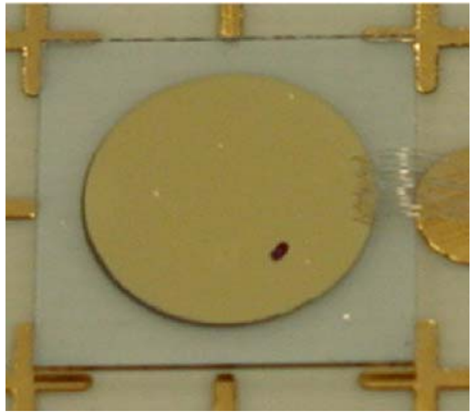






Developing BCM proposal using the "fishing arm" as a support for placing the BCM near the beam pipe bellows/Tracker bulkhead region

BCM sensors: CVD Diamond



CMS BCM has opted for synthetic CVD Diamond
- Sensor does not require cooling
- Fast signal response: sub nano-second risetime
- Fast recovery: FWHM of MIP signal: O(2ns)
- Sensor Response covers required dynamic range
- Radiation tolerance
  - ~20% loss in signal after charged hadron flux of $2x10^{15} \cdot cm^{-2}$

- Used poly-crystalline CVD diamond (PCVDD)
  - Commercially available in 1cmx1cm and 300 -500 μm thick
  - For 300μm thick sensor ~ 7000 electrons/MIP: Sufficient for BCM
  - Nominal signal collection done with bias of 1V/μm
- Single Crystal CVDD: A possibility
  - Not easily available yet (size and cost). Expect developments in 2005.
  - No grain boundaries => Significant increase in signal, increased efficiency
    - For 300μm thick sensor ~ 18000 electrons/MIP. cf 22500 for Si
  - Lower Bias voltages (<100V)

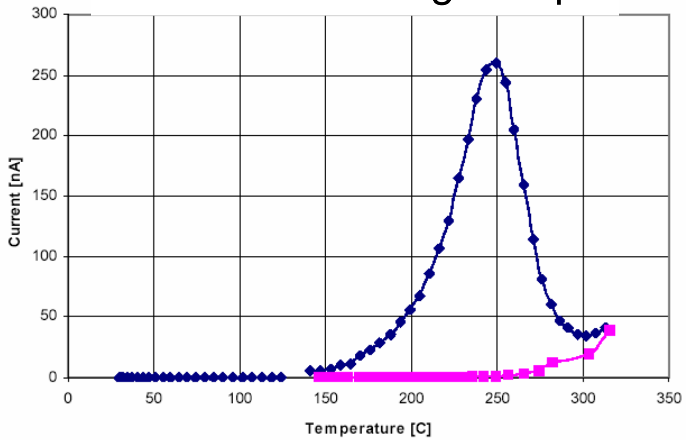
Radiation damage in PCVD

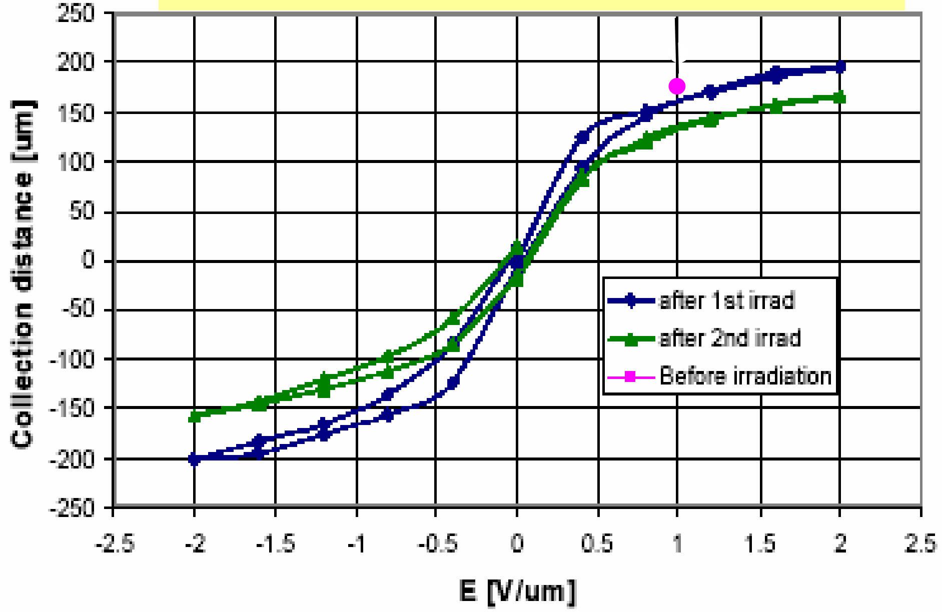
- Use a simple pragmatic evaluation of radiation damage
- Measure sensor response to ^{90}Sr characterisation stand
  - decrease in collection distance
    collection distance = measure of signal response

Fluence of $1x10^{15}$ protons/cm^2
~14% signal degradation
Fluence of $1.8x10^{15}$ protons/cm^2
~20% signal degradation

CDS116 at 1 V/µm	
Before irradiation	~175 µm
After 1st irradiation ($1x10^{15}$)	~155 µm
After heating (TSC to 300deg C)	~180 µm
After 2nd irradiation ($1.8x10^{15}$)	~143 µm

TSC Measurement
Release of Charge Traps





=> Signal after ~$2x10^{15}$ is still sufficient for the BCM

Evaluation of PCVD: East Hall Test Beams

- Use the PS East Hall for testing PCVD sensor response
- Use dedicated “fast extraction” beam structure to test response and dynamic range of PCVD Diamond to particle bursts
  - Only possible due to Michael Hauschild (PS Coordinator) ,Rende Steerenberg (PS Operations), Luc Durieu (East Hall Coordinator)
  - Used both T7 Primary zone and T7 Secondary Zone
  - Also used T11 for calibration and cross check work

T7 Primary Beam:

24 GeV protons

Intensity: 8×10^{11}protons per spill

Flux on PCVDD: 2.2 $\times 10^{8}$ protons/cm^2/spill

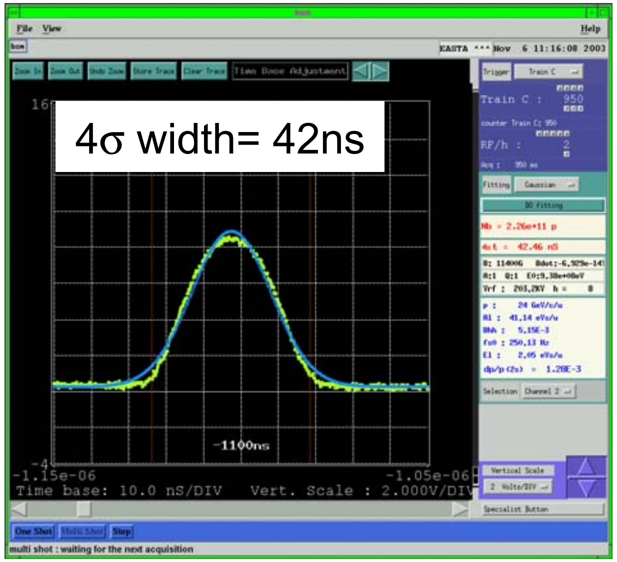
Time structure: ~Gaussian. σ ~10.5ns

T7 Secondary beam:

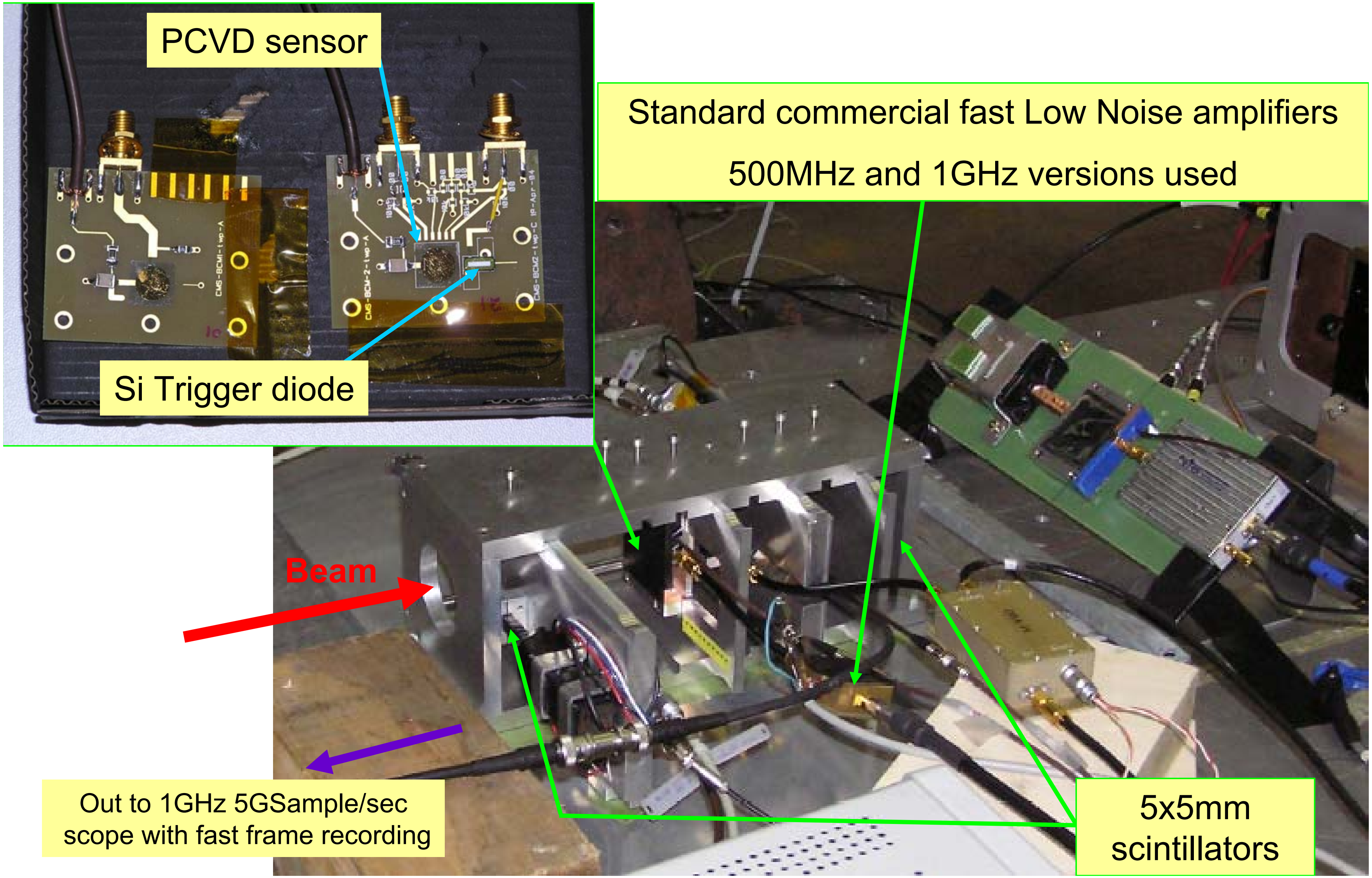
1-10 GeV protons/ pions (selectable)

60:40 ratio of $p:\pi^+$

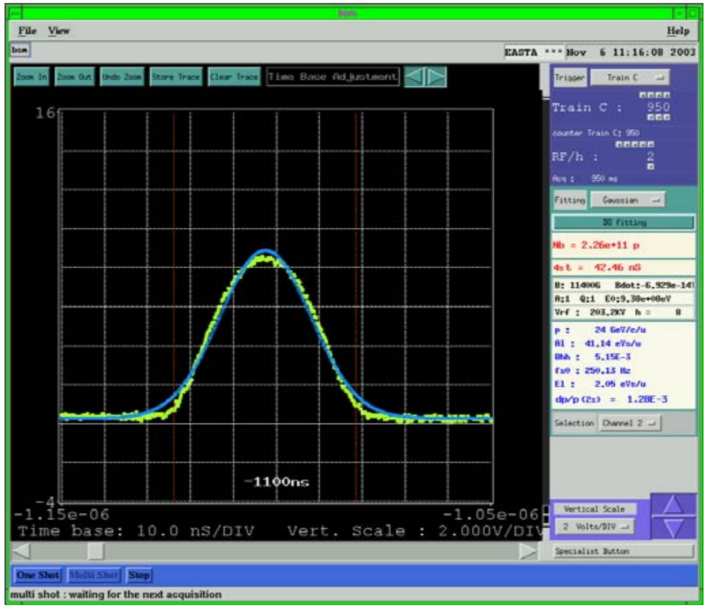
Flux: max ~5×10^{6} protons/cm^2/spill



Evaluation of PCVD: East Hall Test Beams

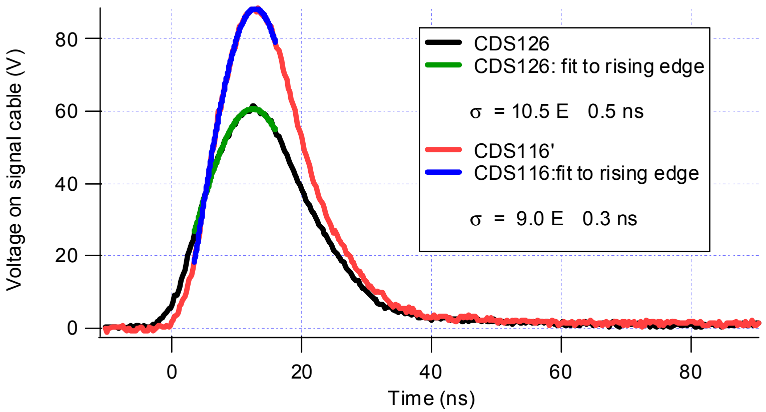


The primary beam: 2.2×10^8 protons/cm^2 per spill



<u>Single pulses from diamond</u>

- Bias on Diamond = +1 V/um
- Readout of signal:
  - 16m of cable
  - no electronics



<u>Time response</u>

Fit Gaussian to leading edge of pulses

σ (CDS126) =10.5 ± 0.5 ns

σ (CDS116) = 9.0 ± 0.3 ns

σ(PS)=10.5 ns with~6% distortion from the signal cable

<u>Output Signal in worst case scenario</u>

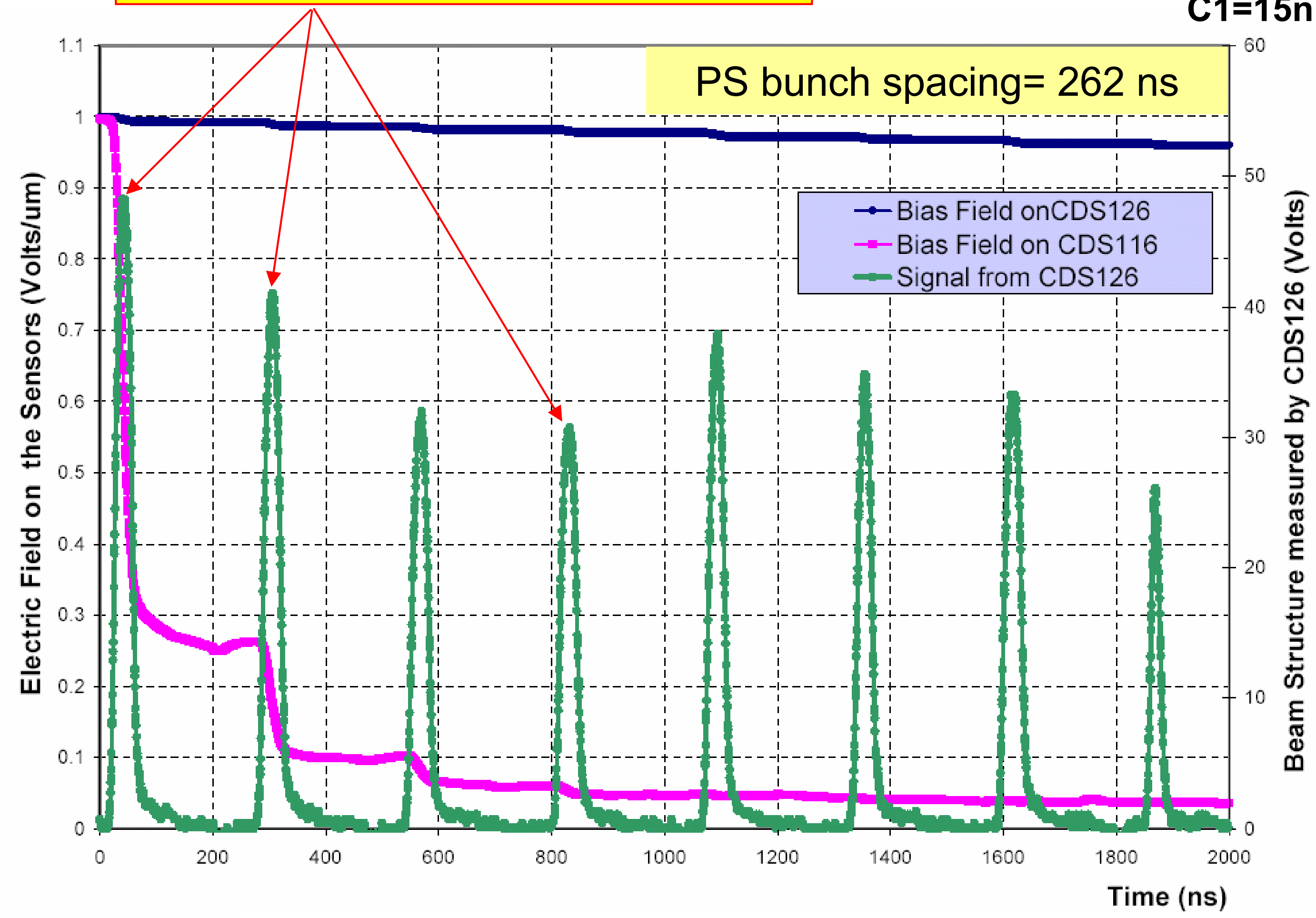
Signals from sensors are very large

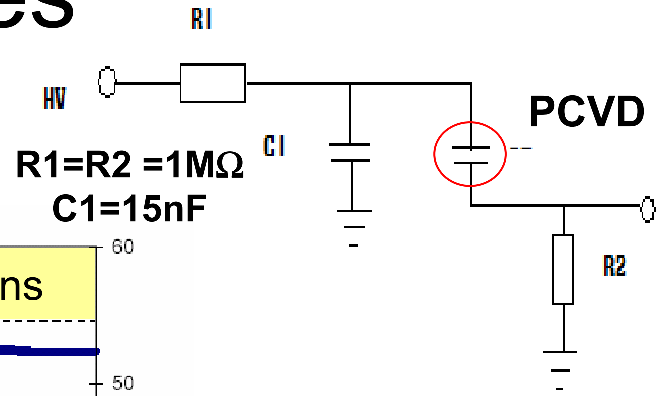
- V_max (CDS116) = 88 volts
  - => 1.8Amps into a 50 Ohm load

Typical CVD leakage current: O(10 pA)
=> Large signal maps to large FE load!!

Multiple Bunches

PS primary beam structure with ~ 10^8 protons/cm^2 per bunch





τ_{C1R1} ~15 ms

C1 maintains bias for > 10 spills

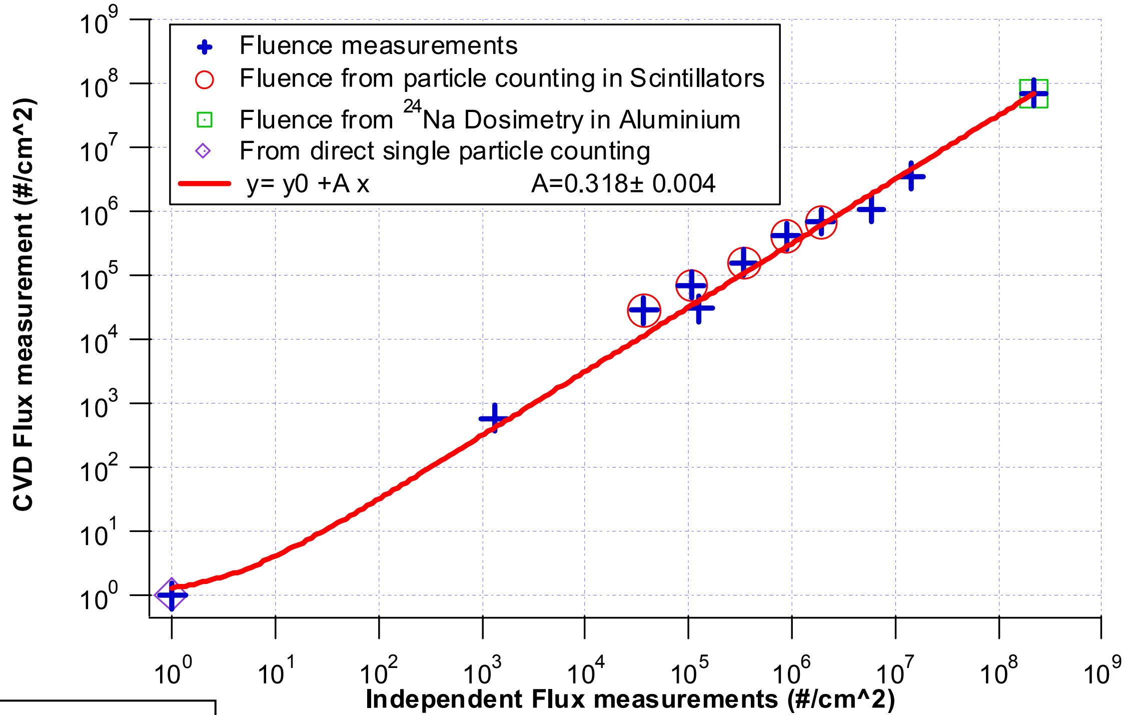
C1=15nF => bias drops from 300V to 288V after 8 spills

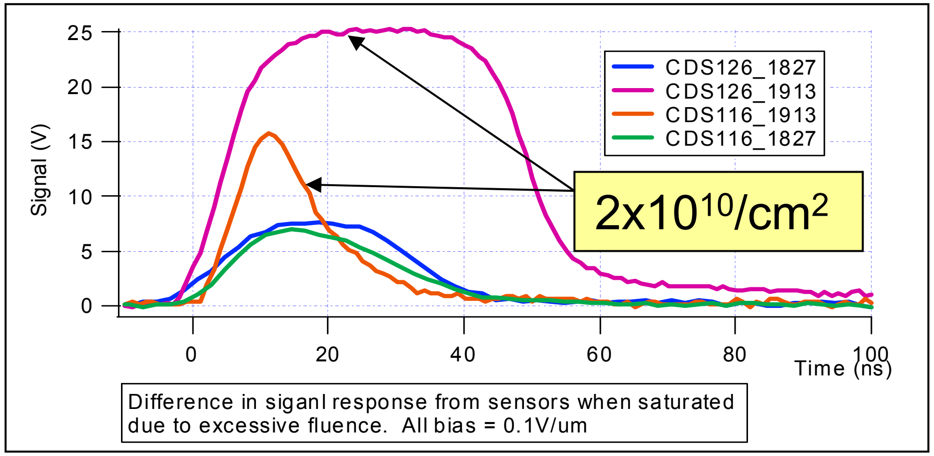
Multi-bunch variation seen for all fast extraction intensities
=> Could identify PS kicker malfunctions online!!

PCVDD Response and Linearity

PCVDD response to beam is approximately linear over 10 orders of magnitude!!

- Based on several CVD samples
- Includes irradiated samples (fluence of 1.8×10^{15})
- Cross checked with indep measurement of fluence





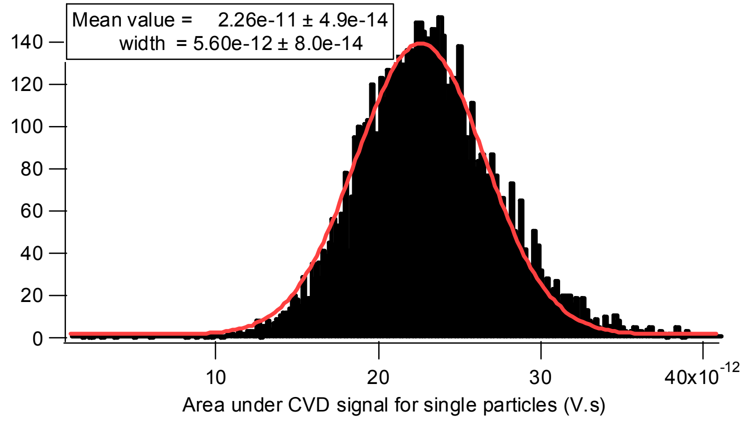
Linearity (above) extends to 10^{10}

Problem with measurement: Reservoir capacitor insufficient to maintain bias field
=> signal current plateaus until charge is drained off

Low Flux Measurements

- Single particle PCVDD response

  MIP signal: ~2.3x10^{-10}V.s



Fast extraction

- Look at ultra-low intensity run
- From calibrated TLD Dosimetry

  Spill flux= 600 particles/cm^2

=> number of particles through detector

- From TLD measurements

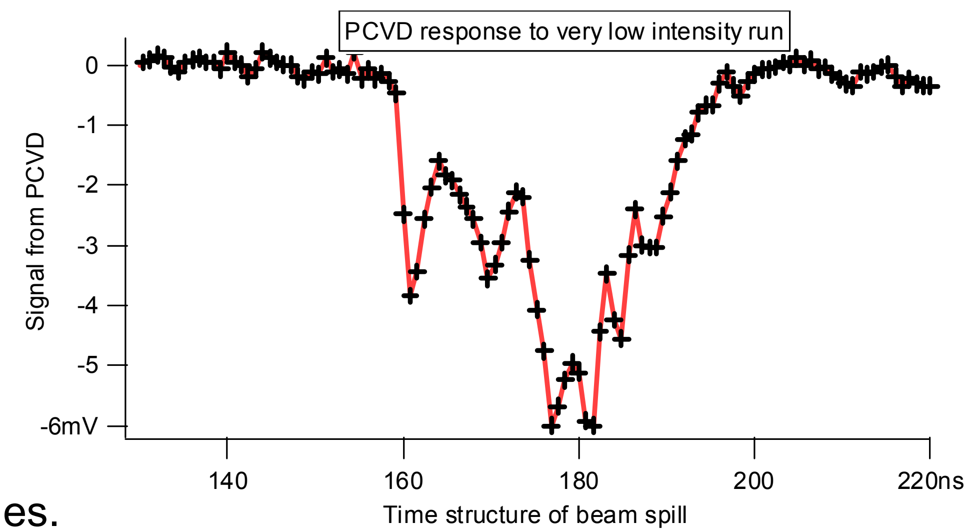
  Number expected = 6.2 particles

- From multiple/single signal area ratio

  Number measured = 5.1 particles

- From flux measurement on PCVD signal

  Number measured = 5.3 particles



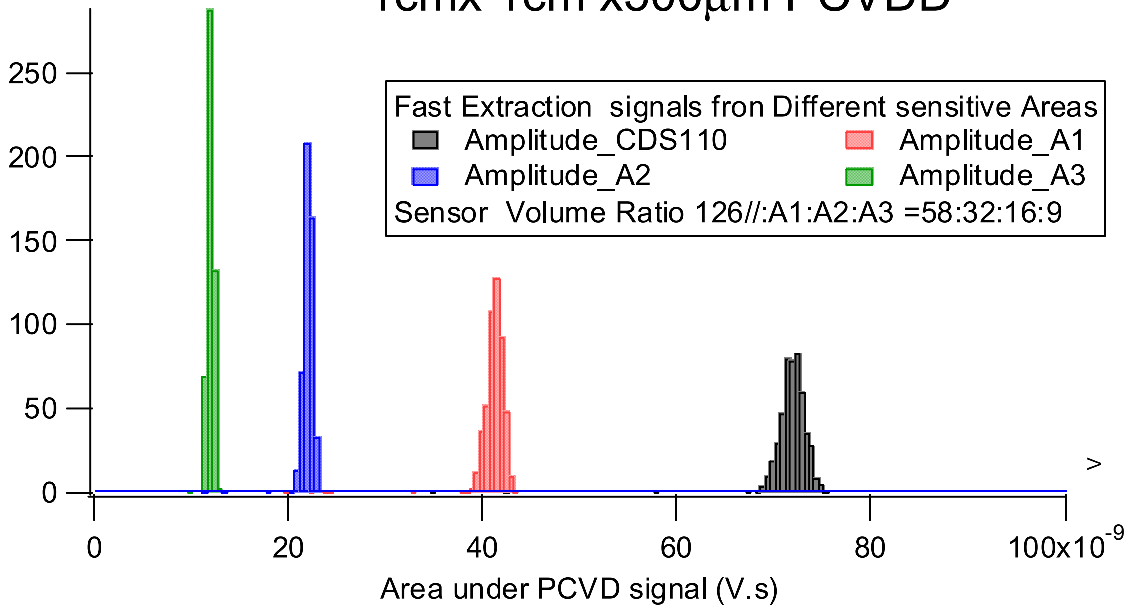
Time resolution: < 4 ns between single particles.

Different Sensor Volumes

PCVDD strip detector placed parallel to beam, beam traverses multiple strips

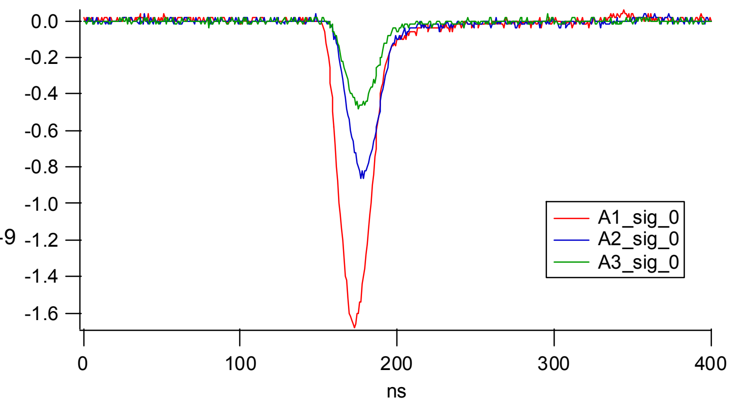
- PCVDD behaves as expected
- Under fast extraction, signals proportional to active volume of sensor

=> Can reliably use structured metallization on a
1cmx 1cm x500µm PCVDD



Signals: PCVDD strip detector in the T7 secondary zone

Beam: 5GeV proton/pion mix
Flux 9.5x 10^5 /cm^2 per spill



Similarly the “ linear volume ratio” for the strips is observed for single particle spills relations

Looking for MIPS

CMS BCM: Scenarios that require single particle sensitivity on a bunch by bunch basis

- Monitoring during the Pilot Run
- Monitoring the Inter-bunch spacing

Single particle detection design choices for subsystem 3:

- CVD diamond in "Standard" position perpendicular to beam, signal amplified by fast low noise amplifier.
  - Simple, but difficult to get decent S/N ratio. MIP in 300um PCVD => ~50uV signal
- CVD diamond parallel to beam, signal amplified by fast low noise amplifier.
  - Simple, decent S/N ratio. Use commercial amplifiers.
  - Reduced cross-sectional area of sensor
- Pixelized CVD sensor mounted in perpendicular to the beam.
  - More Complicated. Utilise complete CMS Pixel FE electronics => analog readout + fast out for bunch by bunch monitoring. Fully time stamped monitoring.
  - Location and services are key constraints (now under review)

Fast Out of CMS Pixel Chip

<u>CMS Pixels Fast-Out</u>

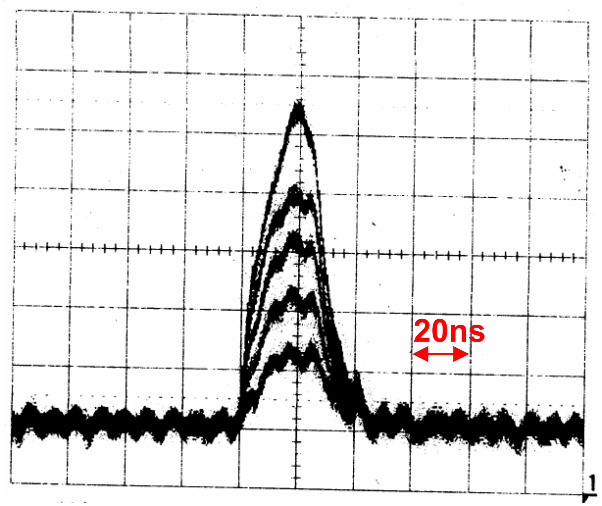
- Designed in Pixel chip to provide a Level 1 trigger input to CMS
- Treats the 8mmx8mm pixel array as 26 8mmx300um strips
- Gives fast-out signal if 1 or more "strips" is hit
- Multiple hits on a strip count as one

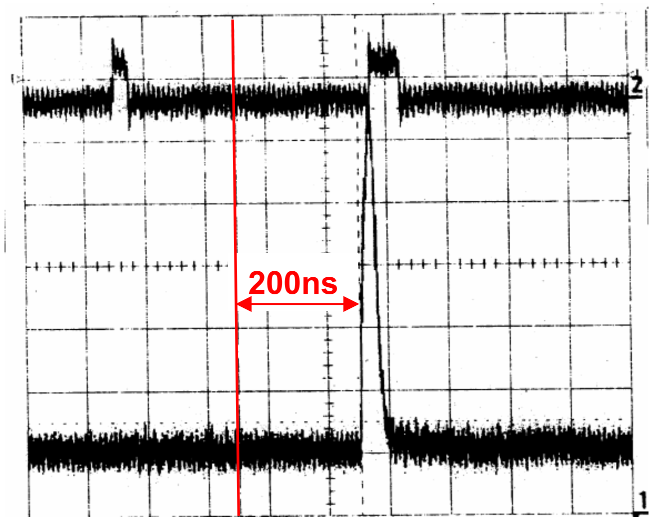
•DACs set the scale of the analog levels
  - Have tested 5 analog levels
  - Level increments tested:
    - 1 and 2 hit "strips" per chip

=> Per bunch crossing, have a range of 0 to 10 hit sensitivity on 8x8mm active area

- Can retain full CMS Pixel chip functionality

  =>Standard pixel readout (at lower rate),
  - Maskable pixels and "strips",
  - Adjustable pixel thresholds etc
  - Time stamping

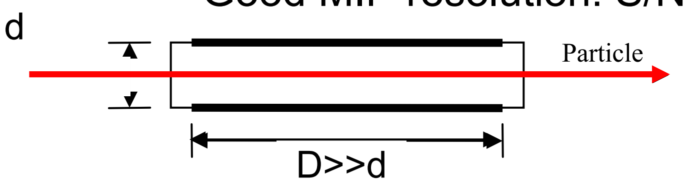


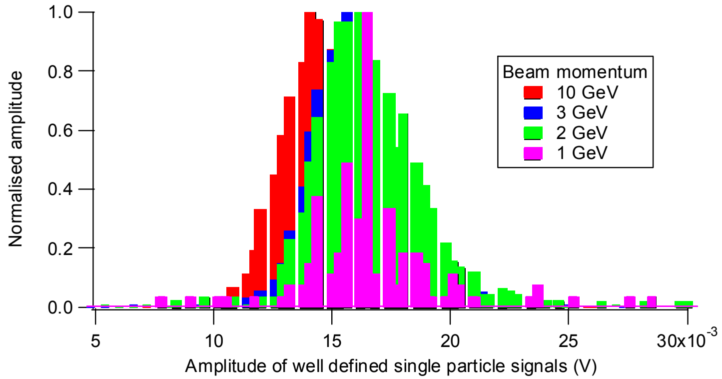


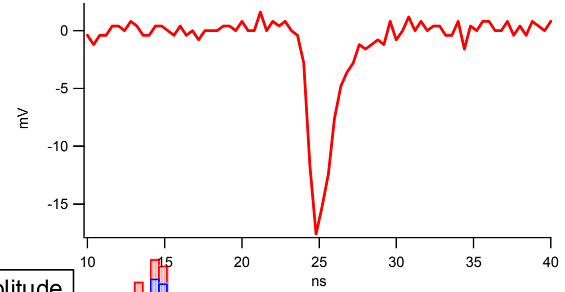
Single particle detection design choices

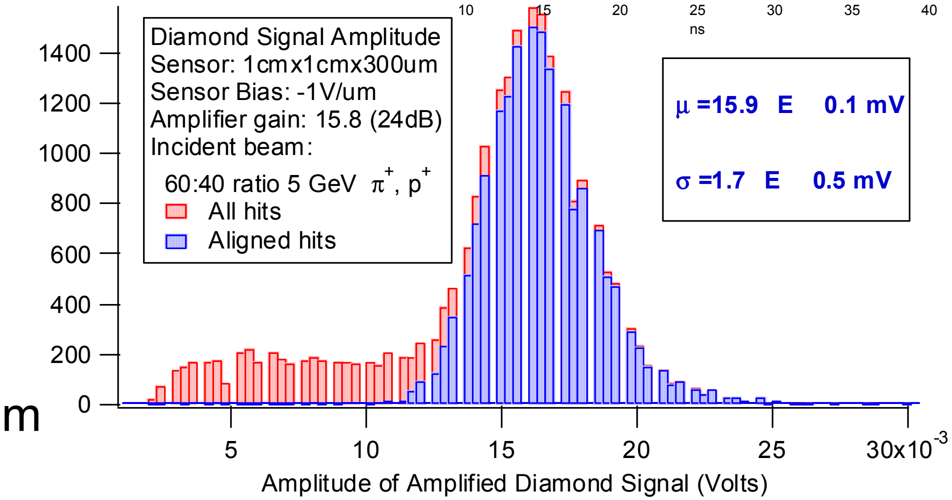
– Pixelized CVD sensor mounted in perpendicular to the beam.
  - Preferred design choice.
  - Currently evaluating mechanical/logistical constraints.
  - Potential for co-development with CVD-pixel luminosity monitor

– CVD diamond parallel to beam, signal amplified by fast low noise amplifier.
  - Backup single particle monitor solution.
  - Advantage: Use same amplifier readout chain as subsystem 1
  - Good MIP resolution: S/N~ O(100)









– CVD diamond perpendicular to beam
  - 2nd reserve option.

The BCM Backend

General Comments

- The BCM Backend Has to be a standalone system data logging, online updates and post mortem analysis abilities

Subsystem 1: The intelligent ammeter approach

- Not difficult to implement: Mostly software and controls issues

Subsystem 2: Bunch by bunch sampling. Minimal processing

- Build from commercially available components
- Need dedicated logic hardware and interface to CMS DCS and DSS
- Need dedicated conditioning of BCM output into LHC beam abort interface

Subsystem 3: Fast and full readout

- CMS Pixel solution
  - Need to understand bump bonding of CVD to pixel chips
  - Logistics of services and optical readout of BCM signals need to be sovled
  - Spy events. Readout pixel chip at spy rate. Need to understand if this could/should be integrated into standard data stream
- PCVDD parallel to the beam
  - Use BE similar to subsystem 2 but with dedicated online display

Observations and outlook

Comments: Extensive PCVDD sensor testbeam at the PS has just finished

- Very successful BCM programme: Large amount of data still to process
- Linearity of PCVDD sensors established over ~9 orders of magnitude
- Time response under beam monitor condition found to be sufficient
- Reproducibility of sensors response after repeated “worst case” beam spills
- Sufficient signal integrity after exposure to radiation levels comparable to that expected by BCM over 10 year lifetime of the experiment

Observations and outlook

- Now satisfied with choice BCM sensor, and availability of fast amplifiers
- Choice of 3-fold system key providing reliable system that addresses the requirements imposed by CMS Technical Coordination and CMS integration
- Subsystem 3 (pixelised CVDD) makes sense based on the CMS Pixels fast-out signal line. But it’s not trivial in terms of services and readout integration
- Identify subdetector protection procedures now that LV power supplies and cabling specified.
- CMS BCM Outlook

  Q1 of 2005: Finish testbeam analysis, Outline mechanical design of BCM

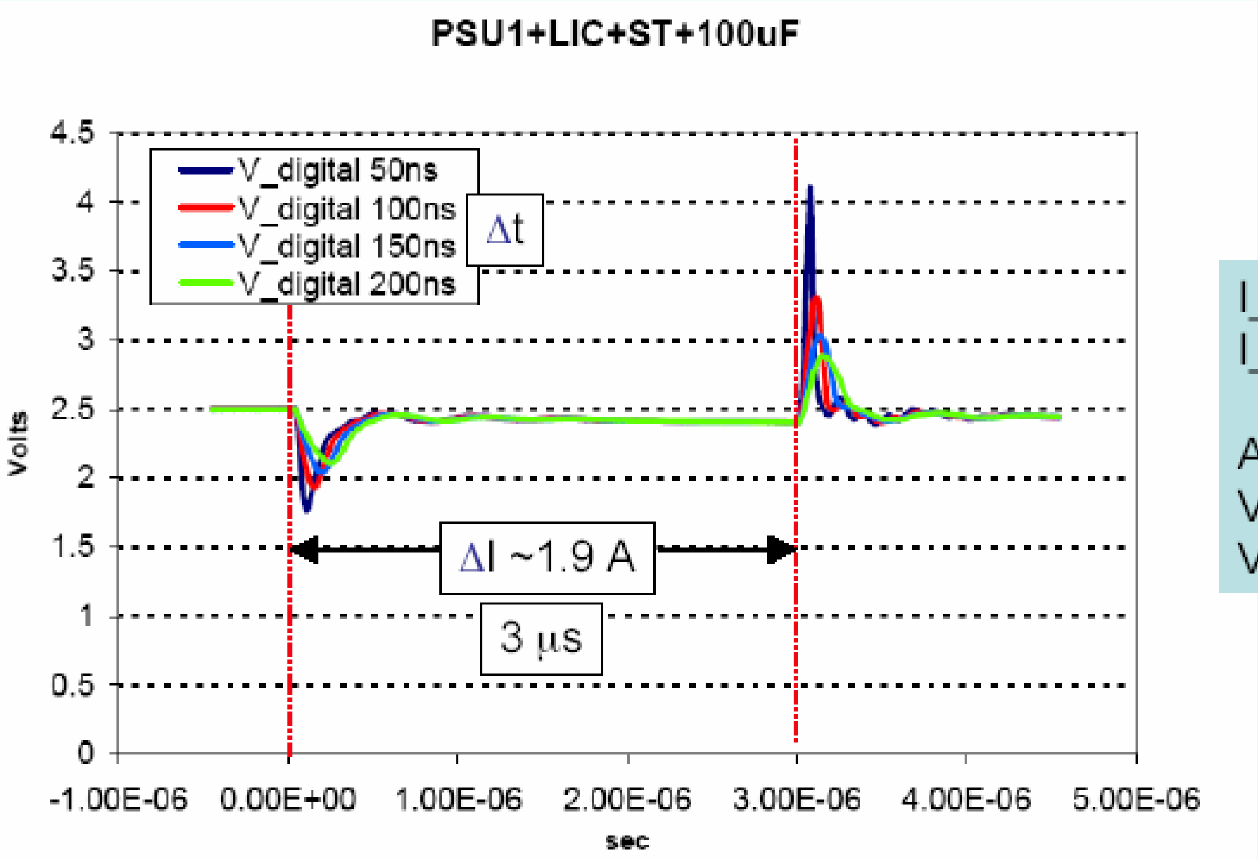
  Q2 of 2005: Preliminary design of backend. Finalise cabling. Prototype subsystem 3

  Mid 2005: Reassess status and review

Spare stuff

Measurements on voltage overshoot (fast)

Switch the I_digital by ΔI in a time Δt, passive load only on V_analog



Voltages probed at the active load

I_digital ~ 5.4 A
I_analog ~ 5.2 A

At the PSU:
V_digital ~ 4.4 V
V_analog ~ 4.3 V