Use of Single Crystal Diamond for the Fast Beam Conditions Monitor and the Pixel Luminosity Tracker for CMS at the LHC

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On Behalf of CMS-BRM and CMS-PLT Groups

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CARAT09 Worskhop
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Primarily based upon these 2 papers:

Fast Beam Conditions Monitor BCM1F for the CMS Experiment

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Abstract

The CMS Beam Conditions and Radiation Monitoring System, BRM, will support beam tuning, protect the CMS detector from adverse beam conditions, and measure the accumulated dose close to or inside all sub-detectors. It is composed of di erent sub-systems measuring either the particle flux near the beam pipe with time resolution between nano- and microseconds or the integrated dose over longer time intervals. This paper presents the Fast Beam Conditions Monitor, BCM1F, which is designed for fast flux monitoring measuring both beam halo and collision products. BCM1F is located inside the CMS pixel detector volume close to the beam-pipe. It uses sCVD diamond sensors and radiation hard front-end electronics, along with an analog optical readout of the signals. The commissioning of the system and its successful operation during the first beams of the LHC are described.

Key words: LHC, CMS, beam conditions, sCVD diamonds, radiation hard sensors

(Submitted NIM A)

Results from a Beam Test of a Prototype PLT Diamond Pixel Telescope

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Abstract

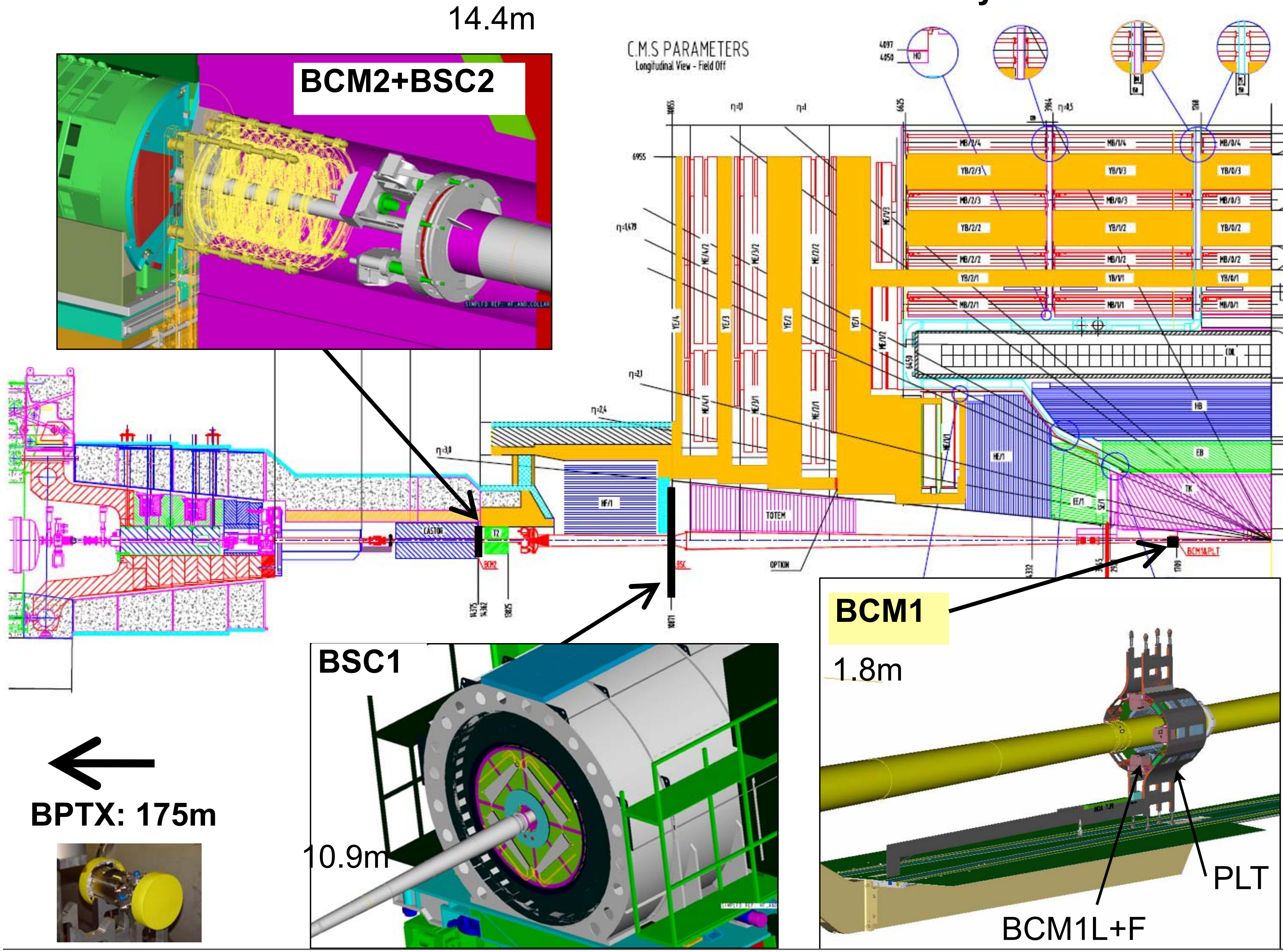
We describe the results from a beam test of a telescope consisting of three planes of single-crystal, diamond pixel detectors. This telescope is a prototype for a proposed small-angle luminosity monitor, the Pixel Luminosity Telescope (PLT), for CMS. We recorded the pixel addresses and pulse heights of all pixels over threshold as well as the fast-or signals from all three telescope planes. We present results on the telescope performance including occupancies, pulse heights, fast-or efficiencies and particle tracking. These results show that the PLT design concept is sound and indicate that the project is ready to proceed with the next phase of carrying out a complete system test, including full optical readout.

(about to be submitted)

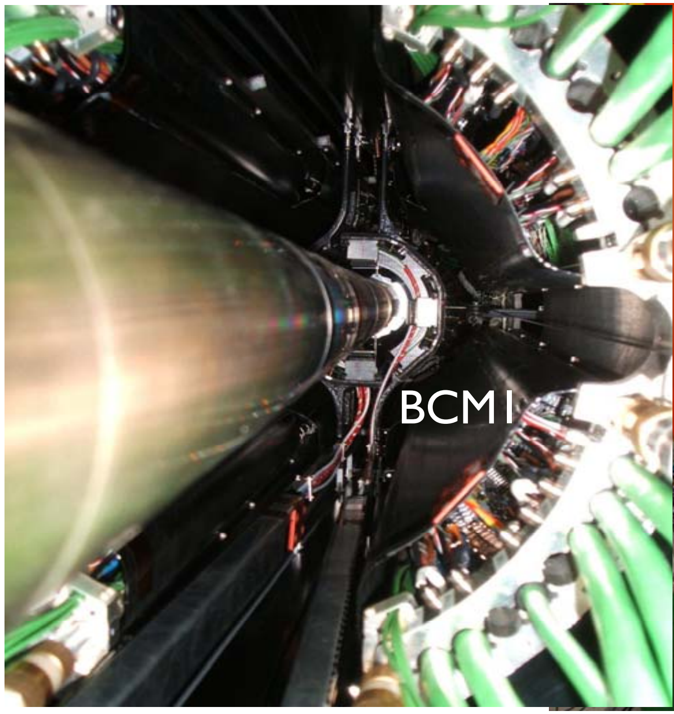
Diagram of Location of BRM+PLT Subsystems

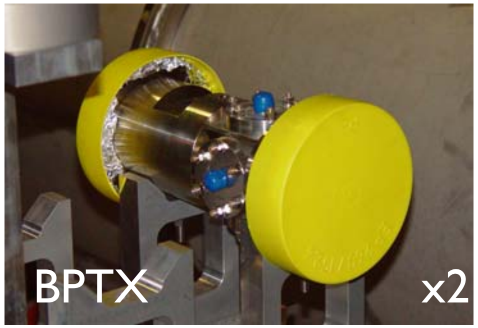
RADMON: 18 monitors around UXC

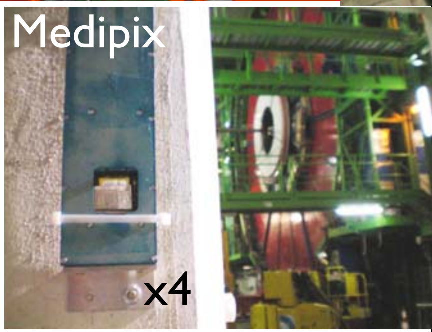
PASSIVES: Everywhere



... and the reality ...







BRM Subsystem Hardware Summary

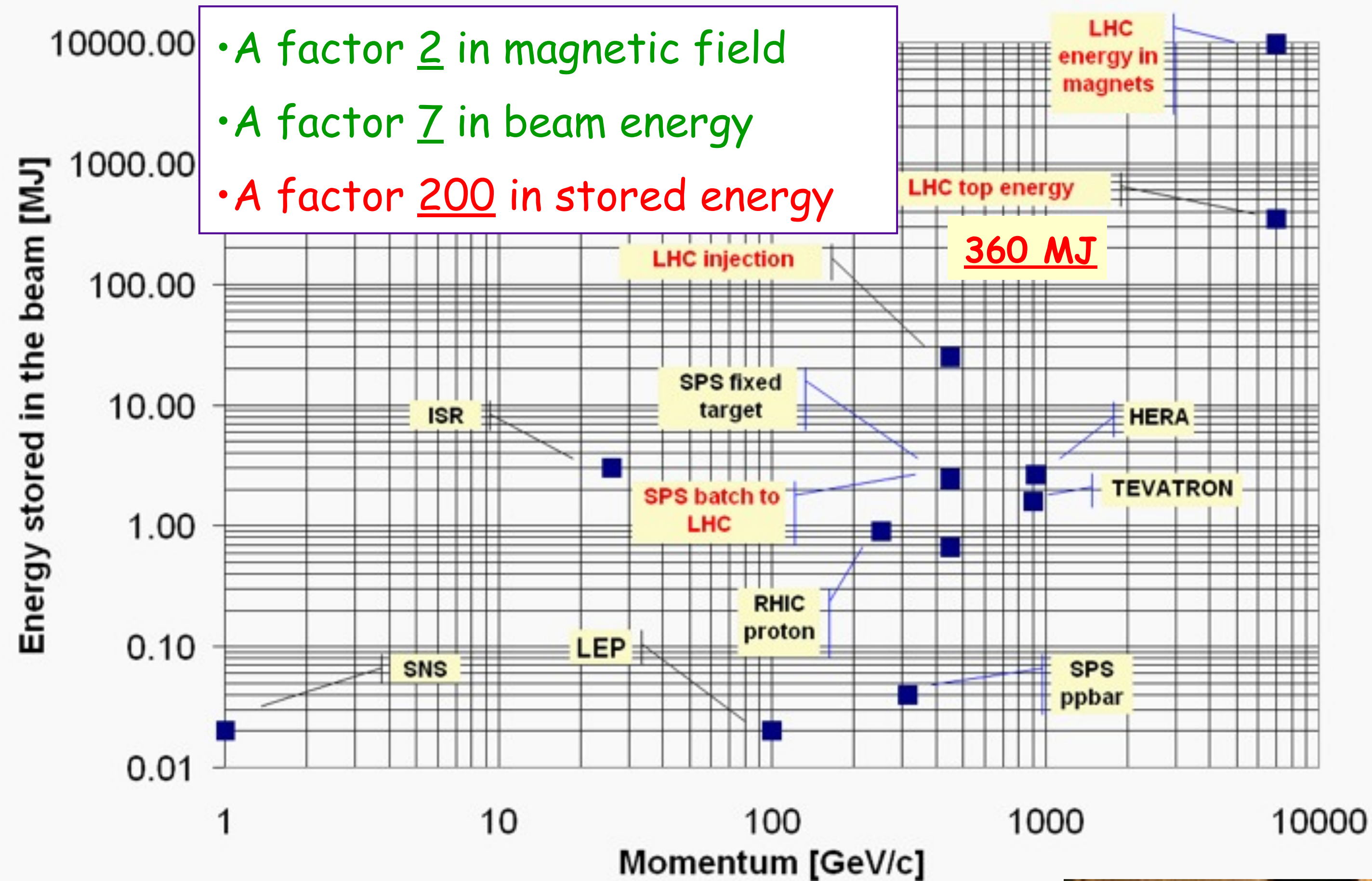
Emphasis on detectors that are relative flux monitors

Subsystem	Location	Sampling time	Function	Readout + Interface
Passives TLD + Alanine	In CMS and UXC	Long term	Monitoring	---
RADMON	18 monitors around CMS	1s	Monitoring	Standard LHC
BCM2 Diamonds	At rear of HF z=±14.4m	40 us	Protection	CMS + Standard LHC
BCM1L Diamonds	Pixel Volume z=±1.8m	Sub orbit ~ 5us	Protection	CMS + Standard LHC
BSC Scintillator	Front of HF z=±10.9,14.4 m	(sub-)Bunch by bunch	Monitoring	CMS Standalone
BCM1F Diamonds	Pixel volume z=±1.8m	(sub-)Bunch by bunch	Monitoring + protection	CMS Standalone
BPTX Beam Pickup	175m upstream from IP5	200ps	Monitoring	CMS Standalone

Increased time resolution

Systems are independent of CMS DAQ, and on LHC UPS power

Why do we need beam monitoring?



Slide from Jorg Wenninger

Stored Energy

Large damage potential from uncontrolled beams means that comprehensive protection system is needed

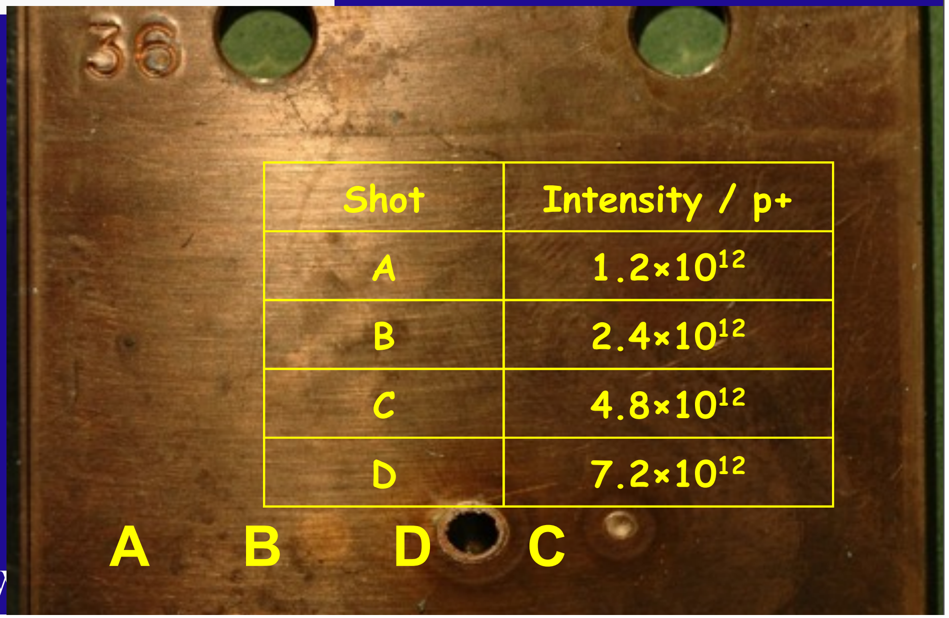
BCM Systems perform this role for the experiments

Damage Potential of High Energy Beams

Controlled experiment with 450 GeV beam shot into a target (over 5 μs) to benchmark simulations:

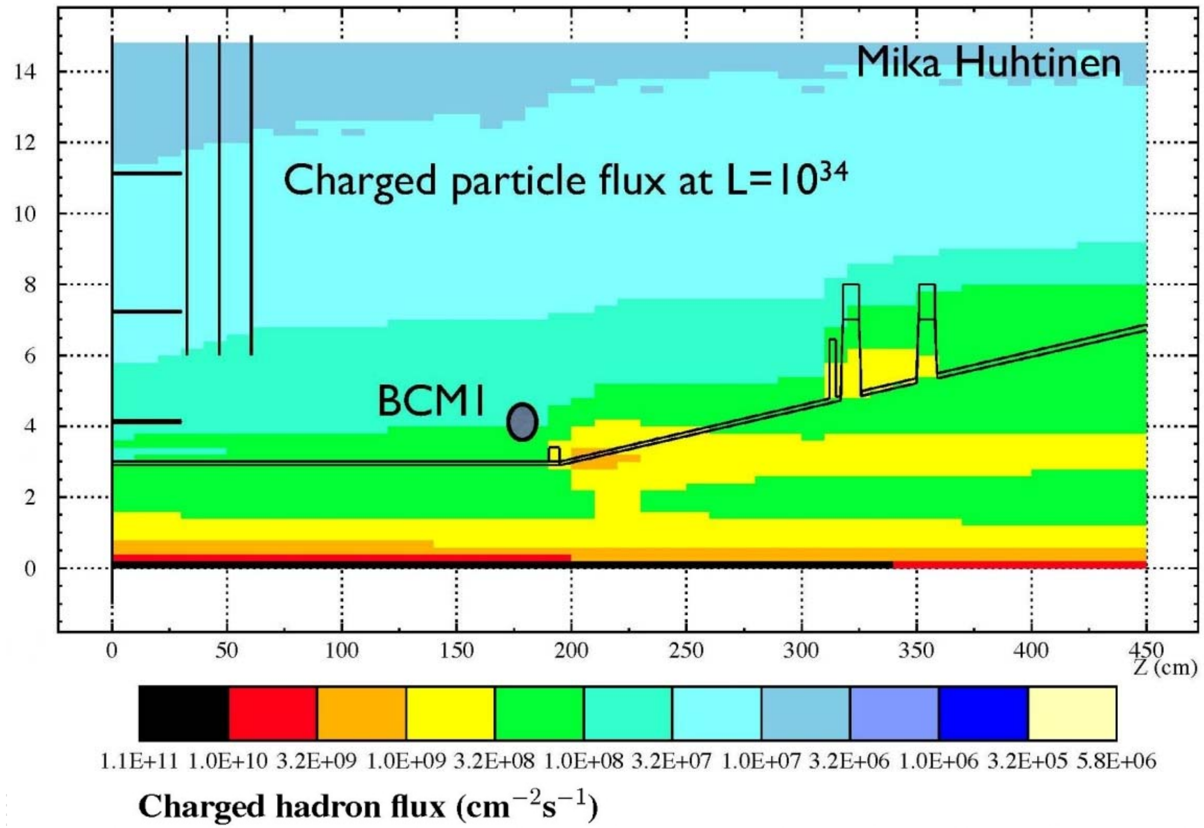
- Melting point of Copper is reached for an impact of ≈ 2.5×10^{12} p, damage at ≈ 5×10^{12} p.

Experiments-Machine W

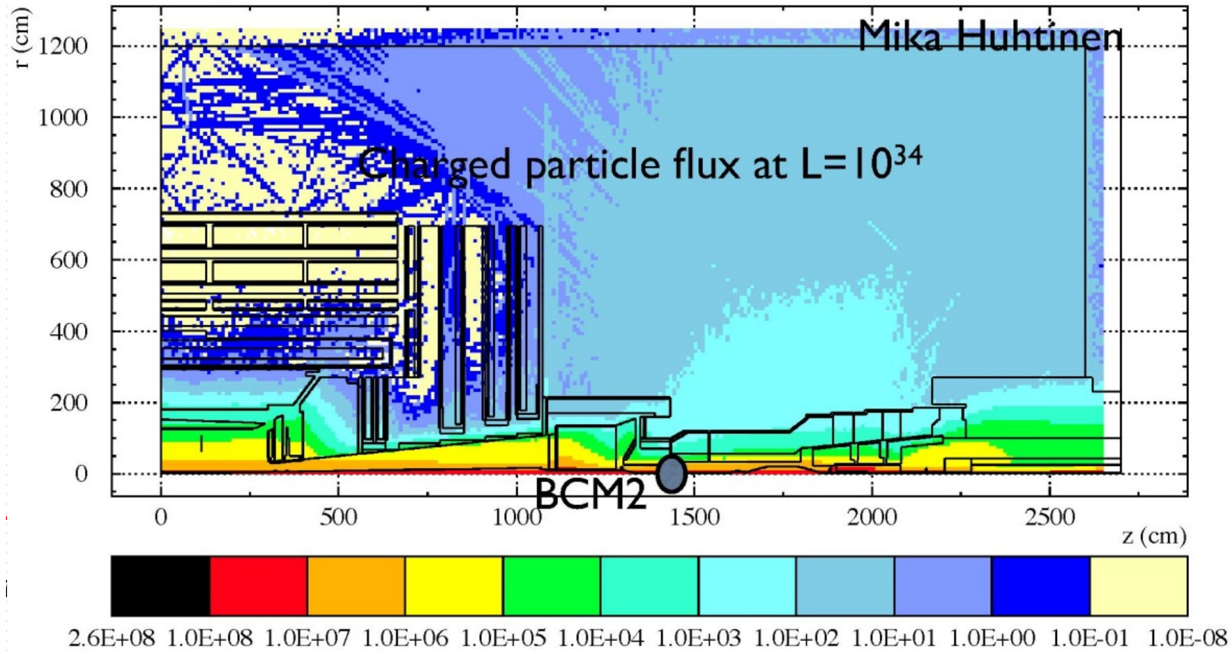


Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

Expectation of charged particle flux at nominal LHC luminosity



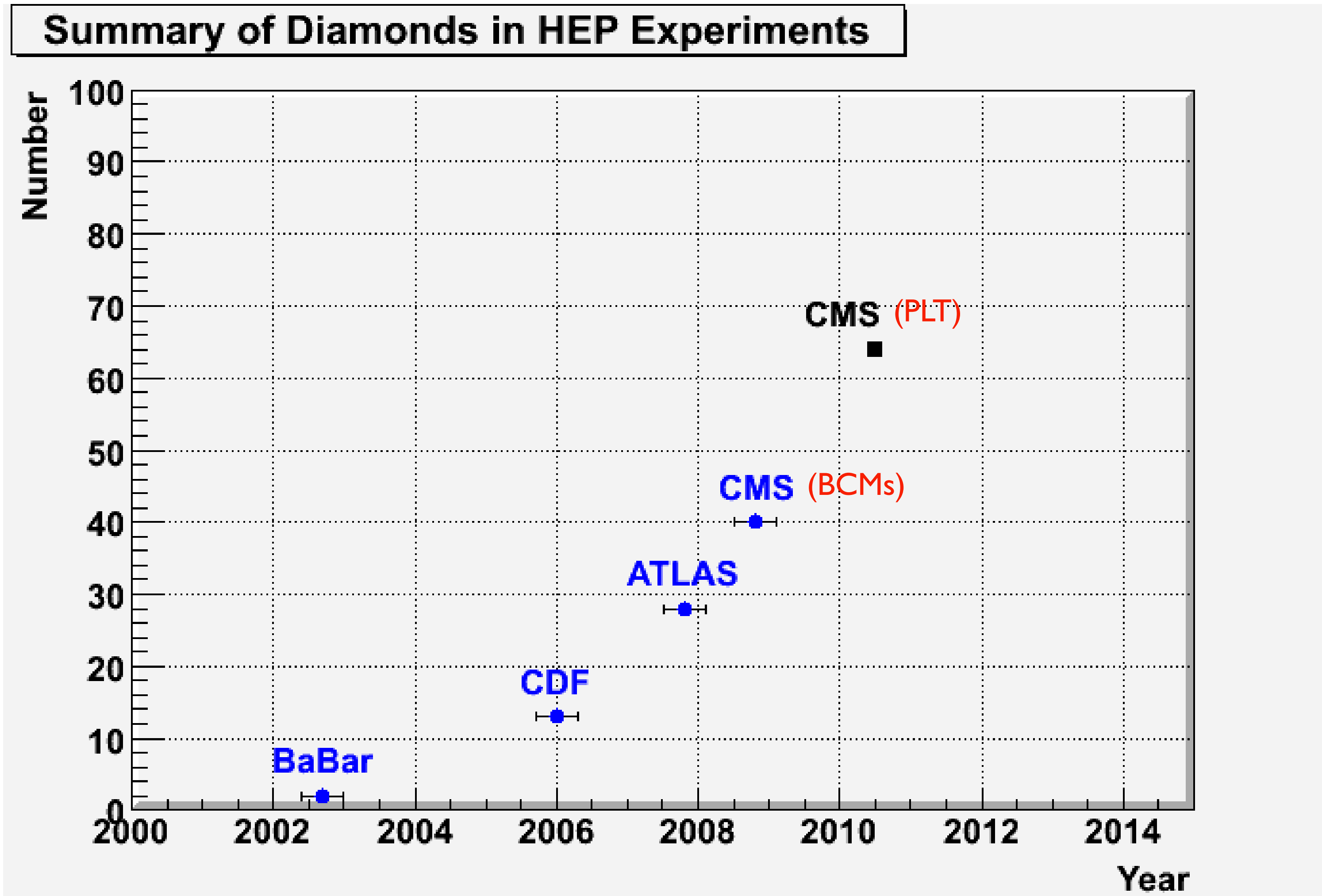
Location of beam conditions monitors and inner layer pixel detectors ca. 4-5cm radius



At nominal luminosities, fluxes of charged hadrons of 3.10^8 $cm^{-2}s^{-1}$ expected

Diamonds in CMS

Diamond in HEP Experiments



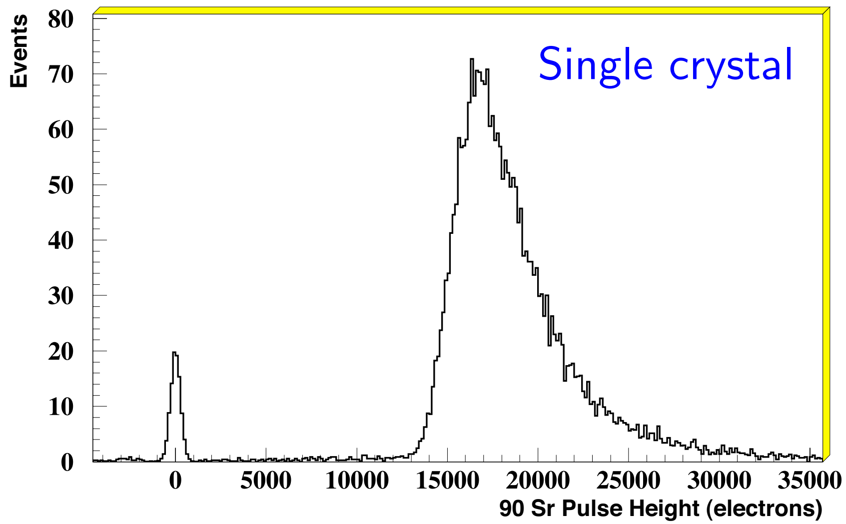
(Plot Courtesy of H. Kagan/RD42)

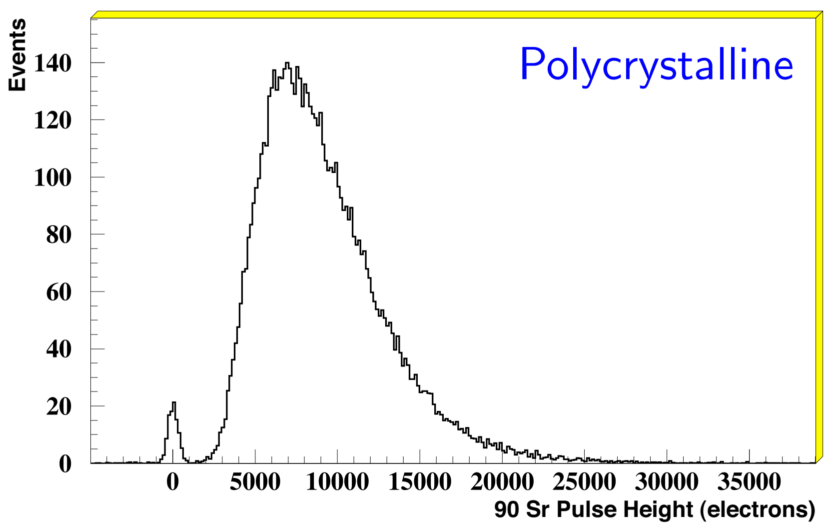
Fast Beam Conditions Monitor

Fast Beam Conditions Monitor

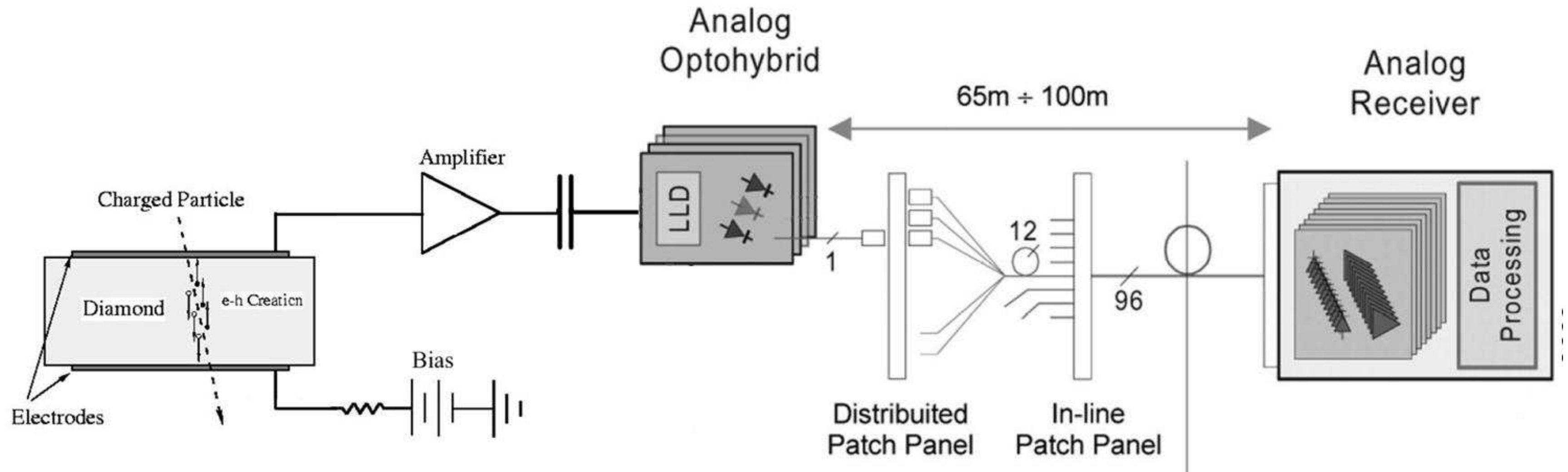
- Purpose: Give bunch-by-bunch (and sub-bunch) MIP-sensitive measurements of losses inside pixel detector volume
- Measure both beam halo losses and collision losses
- Location is very restricted and crowded
  - No cooling or slow control possible
  - Test pulse shares HV lines
  - Needs to be insensitive to environmental conditions
  - Needs to have an optical readout to backend
- sCVD diamond (from DD) used
  - 5x5x0.5mm sensor
  - Choice due to signal size
  - Radiation hardness “sufficient” for LHC (...maybe not be SLHC (see Wim’s talk) ..)

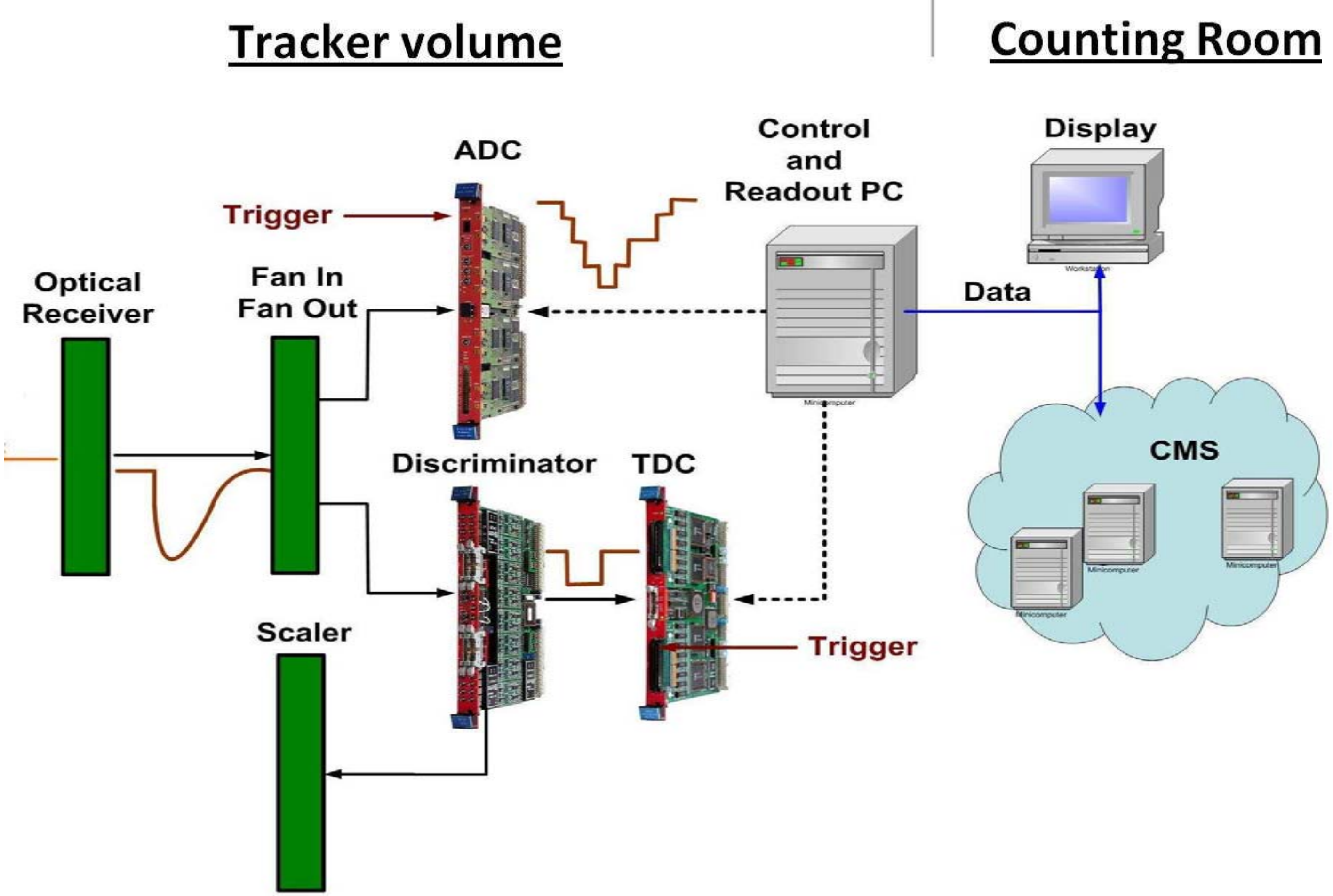
^{90}Sr results





Schematic of BCM1F

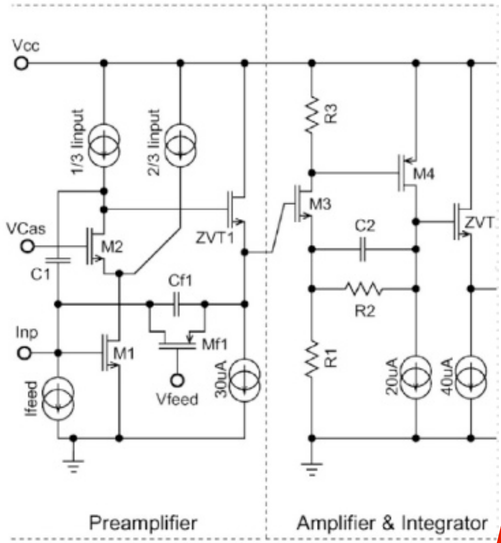


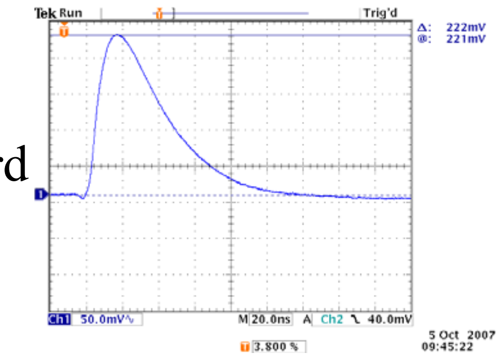


BCM1F components in detail - PREAMP + OPTOBOARD

JK16 (CERN) [IEEE TNS 52-2005 2713]:

- 0,25 µm radhard CMOS process
- Transimpedance design
- Charge sensitive preamp + shaper (20 ns peaking time)
- 4 pF input capacitance (open loop)
- 10 mV / fC ⇒ ~ 60 mV / MIP for the sCVD sensor
- ENC ~ 500 e^- + 40 e^- / pF
- Sensor glued onto PCB and (wire)bonded directly to the preamp
- Leakage currents of < 1 nA achieved
- Supply cable soldered directly to the PCB
- Piggy back connection to the analog optical hybrid (AOH) board
- Optical transmitter supplied via preamp board



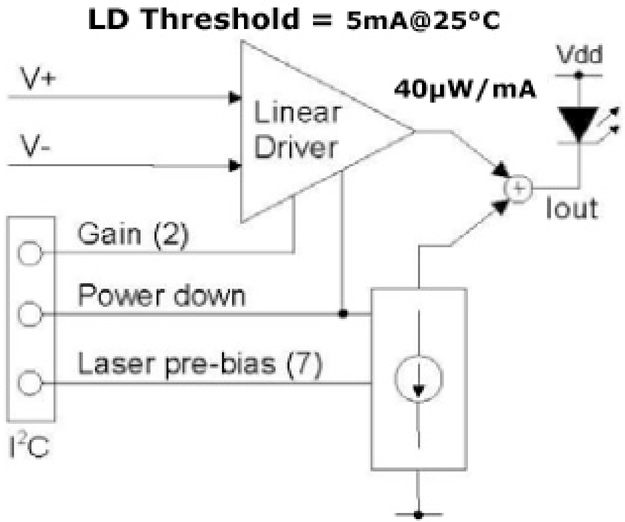


BCM1F components in detail - SIGNAL TRANSMISSION

Analog optical hybrid:

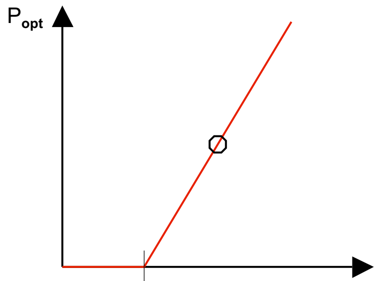
- Adjustment of laser pre-bias current
- Optimal setting for modulation of signal
  - ⇒ Attention paid to possible degradation

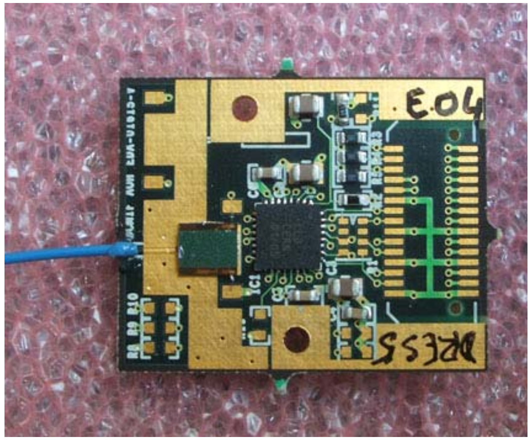
…laser, pigtail, patch panel, ribbon…

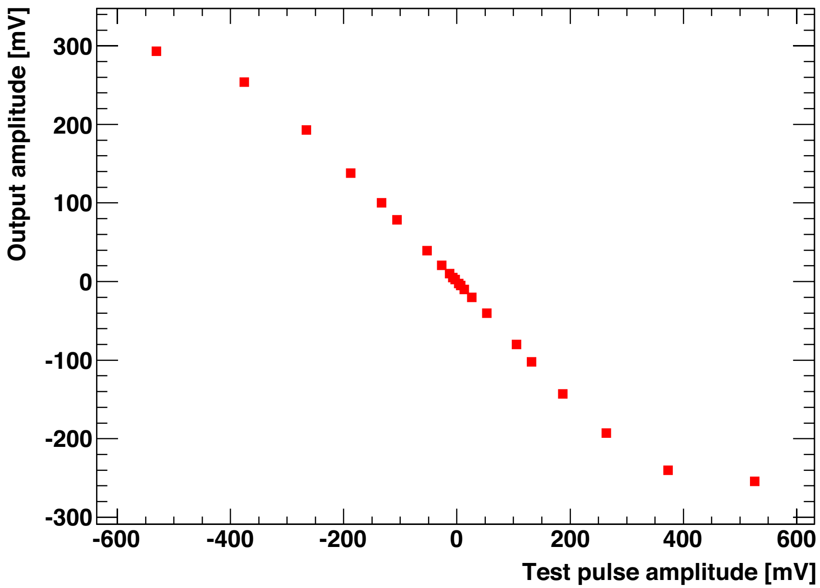


Optical receiver:

- Adjustment of offset compensation
- Fan-out of electrical signal

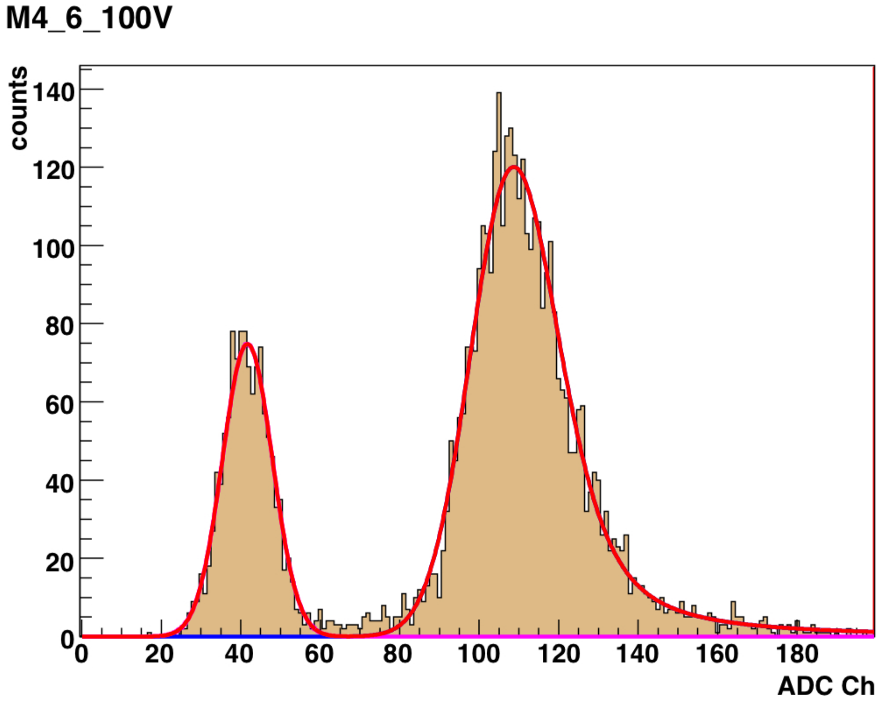


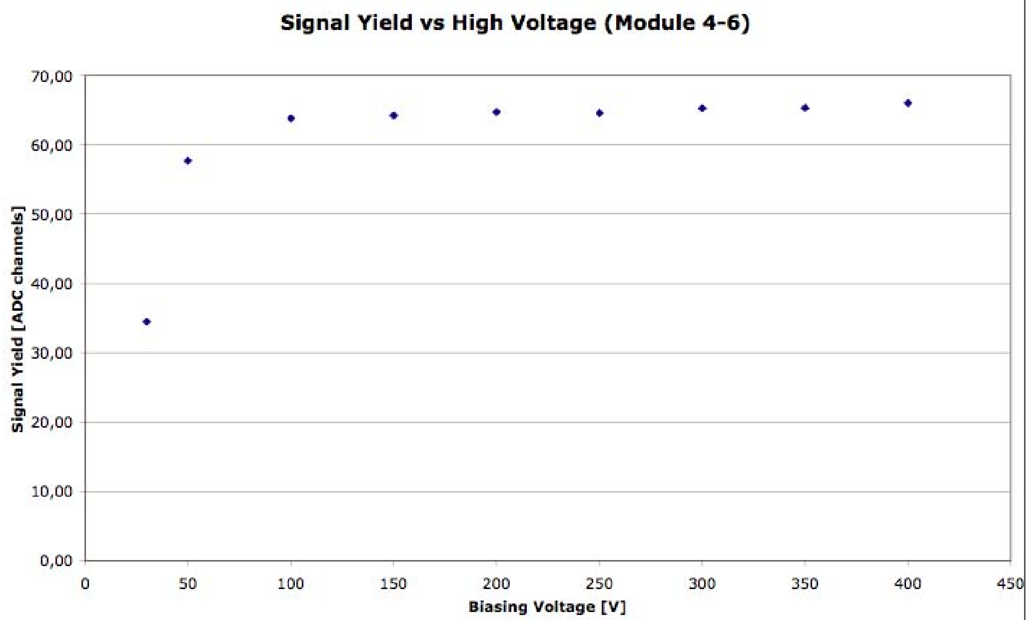




Response of whole readout chain
Linear 2.3 MIPs
Saturates >5 MIPs

Final Detectors



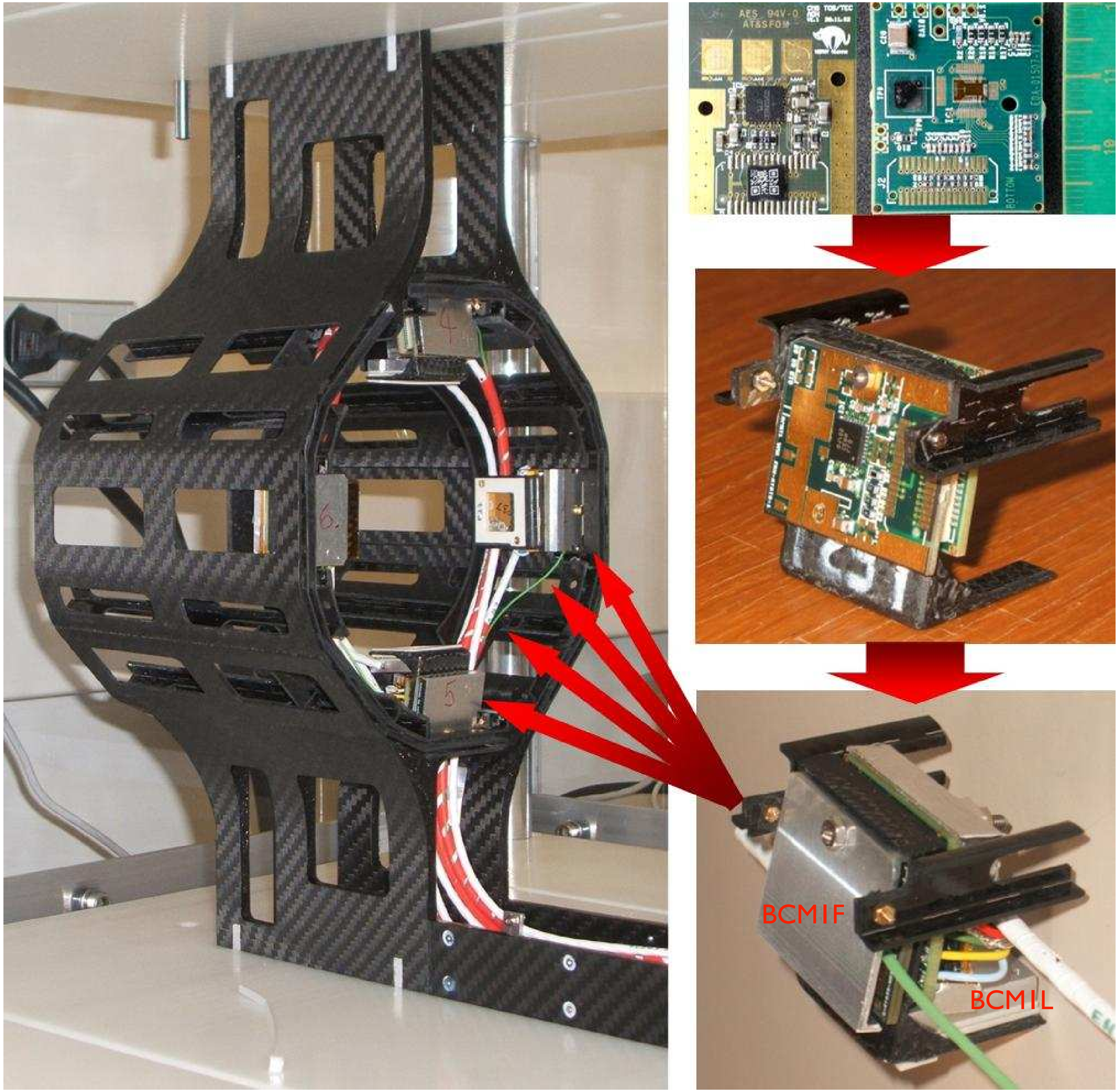


- Good separation S/N
- Signal saturates <100V
  - <0.2V/um

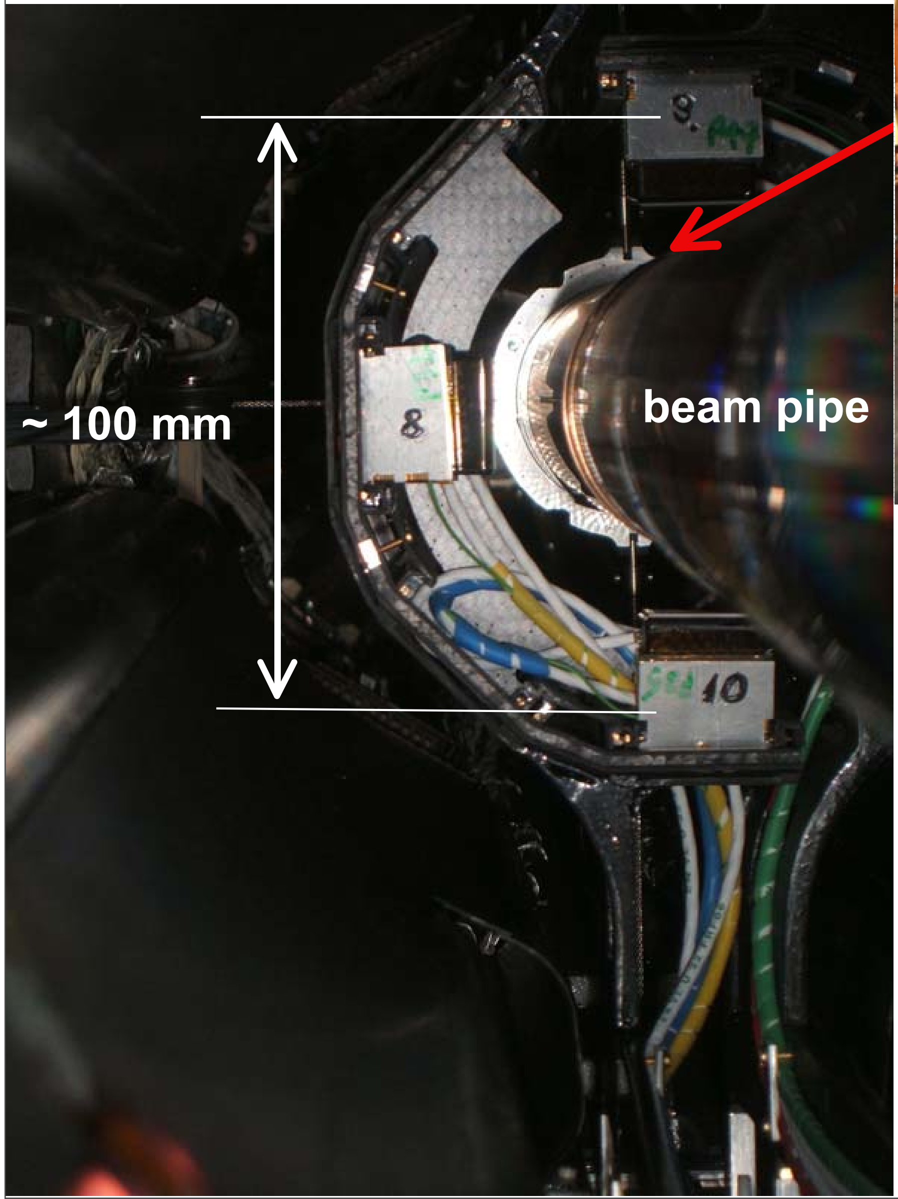
Mechanics

Shown is 4 detectors mounted on 1 "end"

Total of 8 detectors

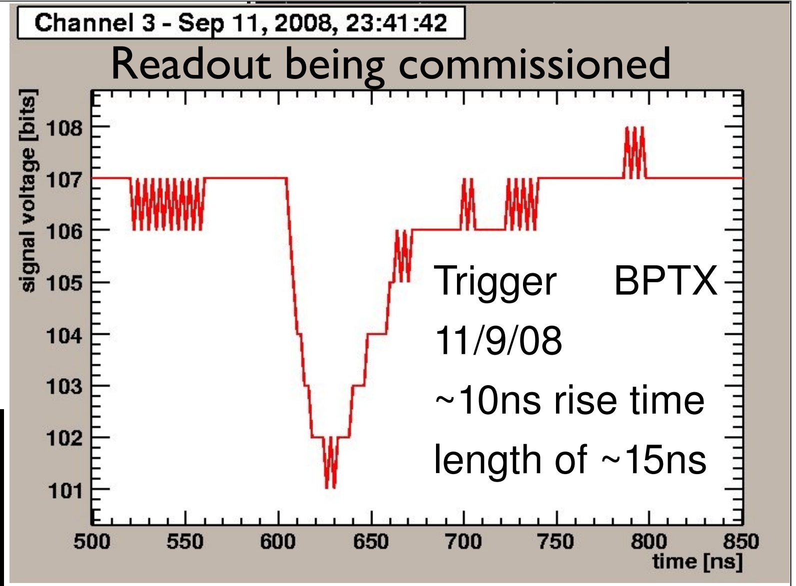


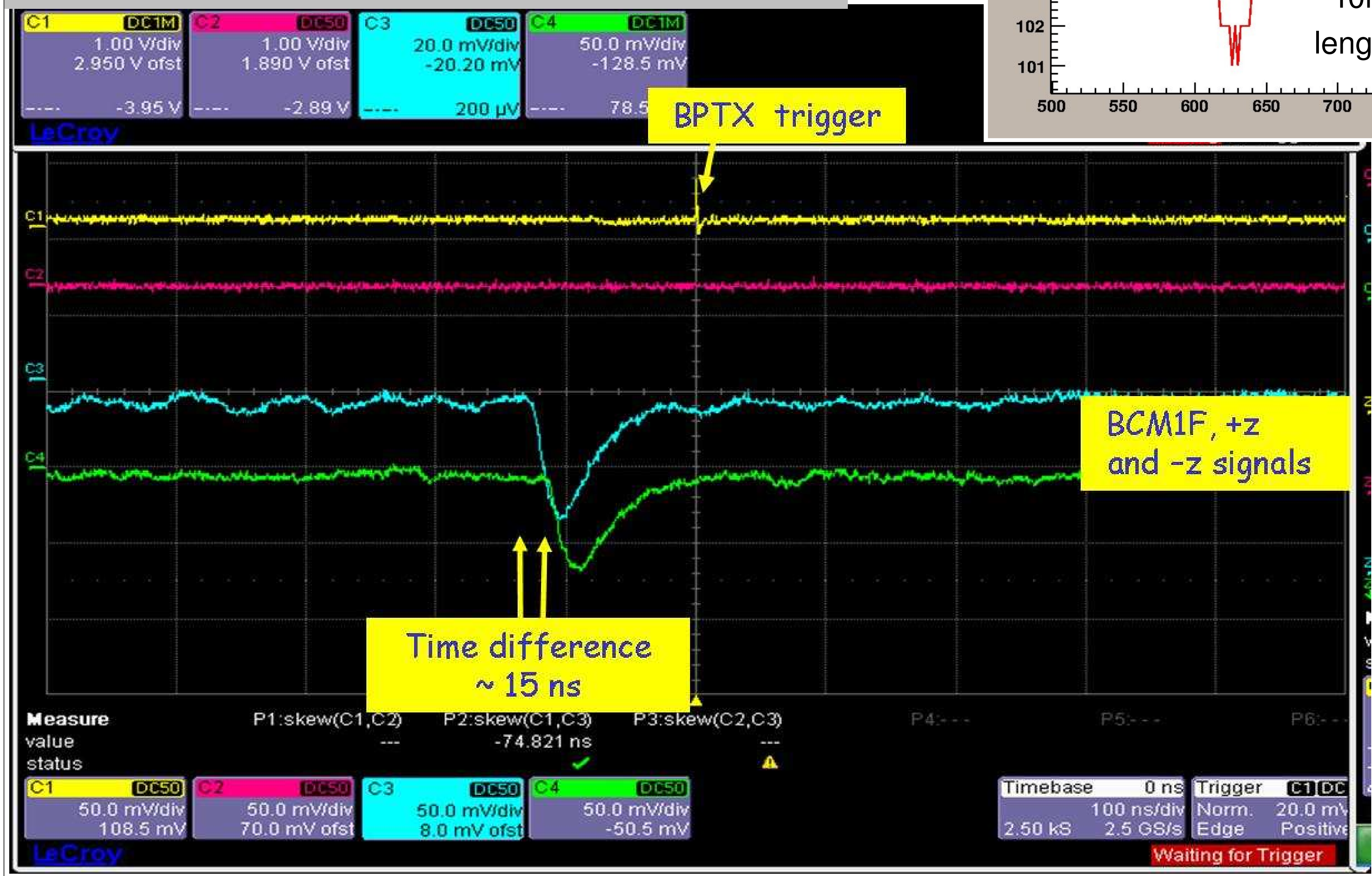
BCM1F Installation



First signals 2008 - Beam 1 on scope

+Z side gives signal ~15ns before -Z side (time of flight of particle)



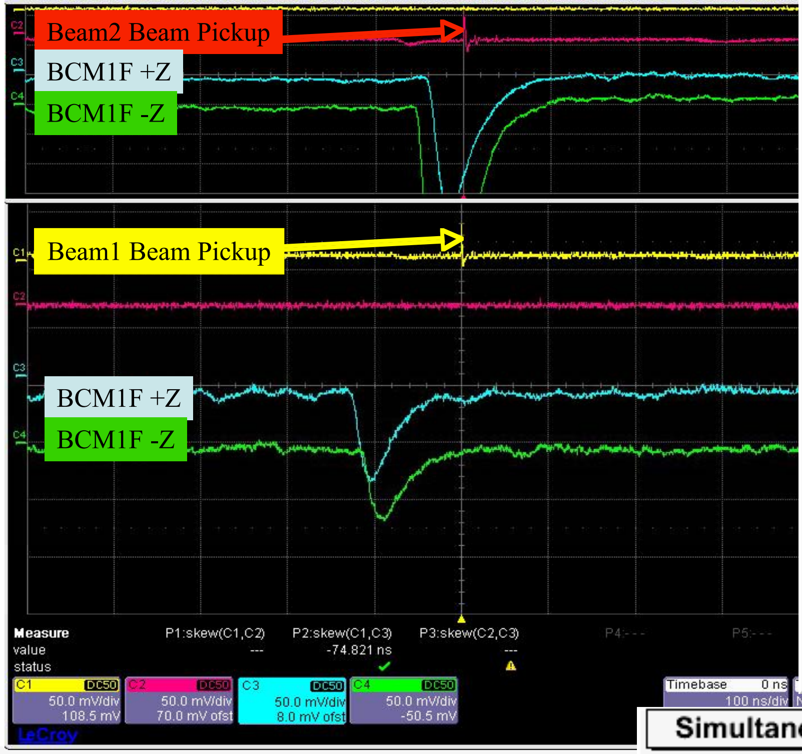


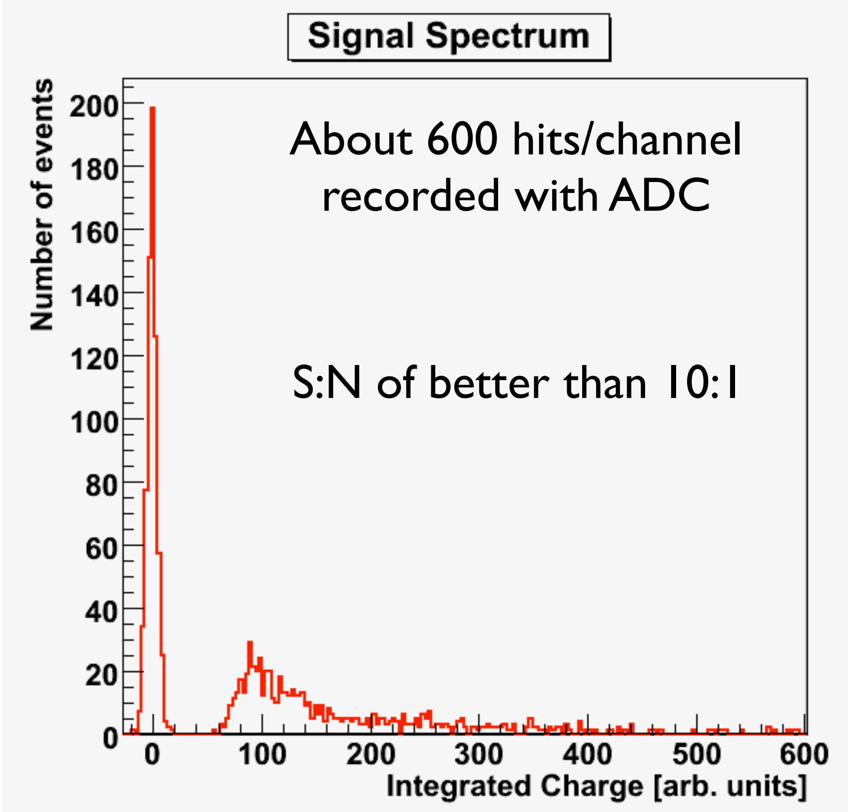
A Closer Look at BCM1F Data

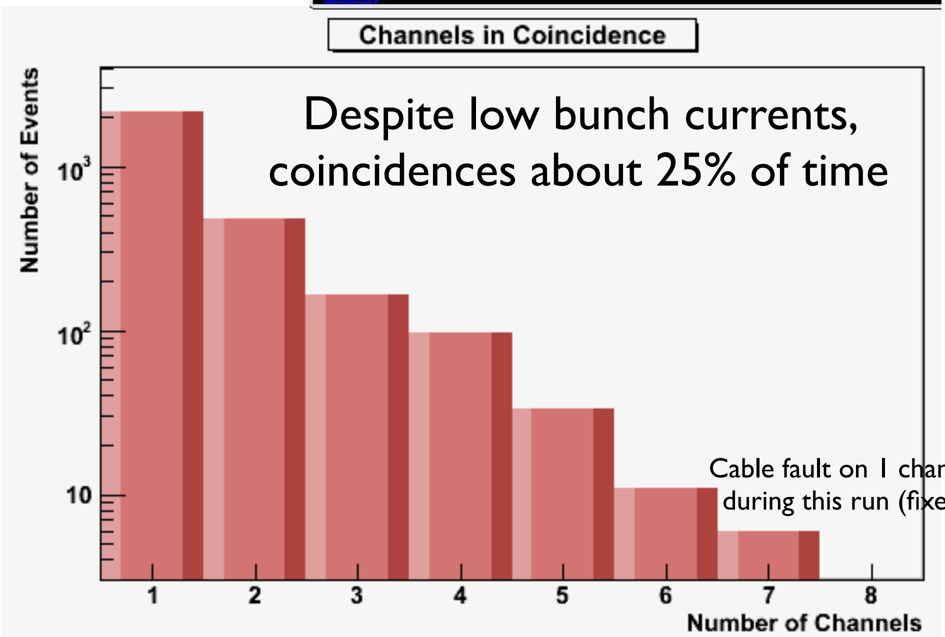
"Fast" System

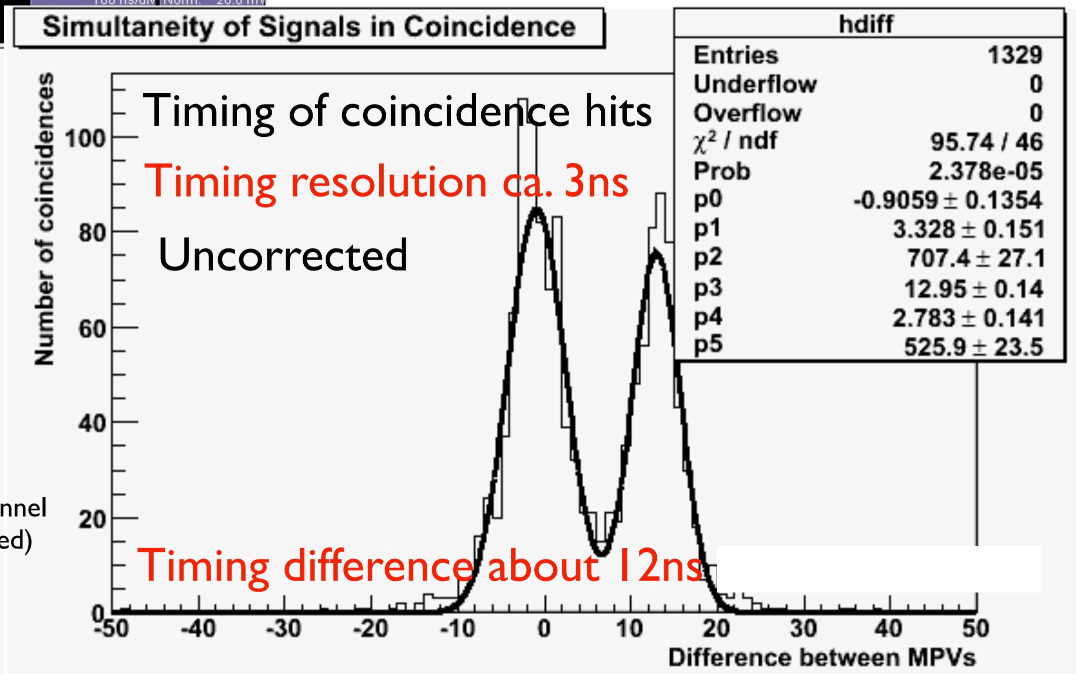
Based upon Single Crystal Diamond

2008

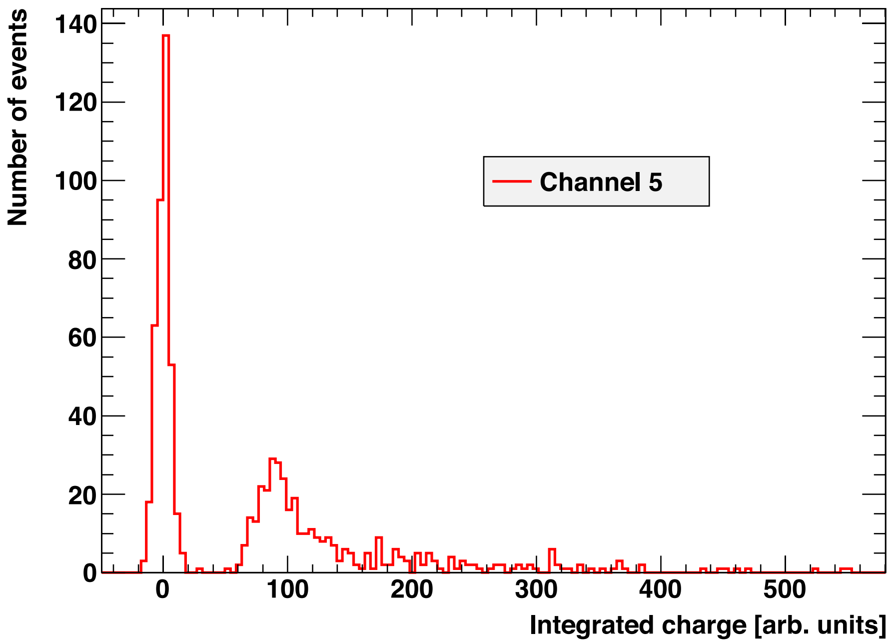


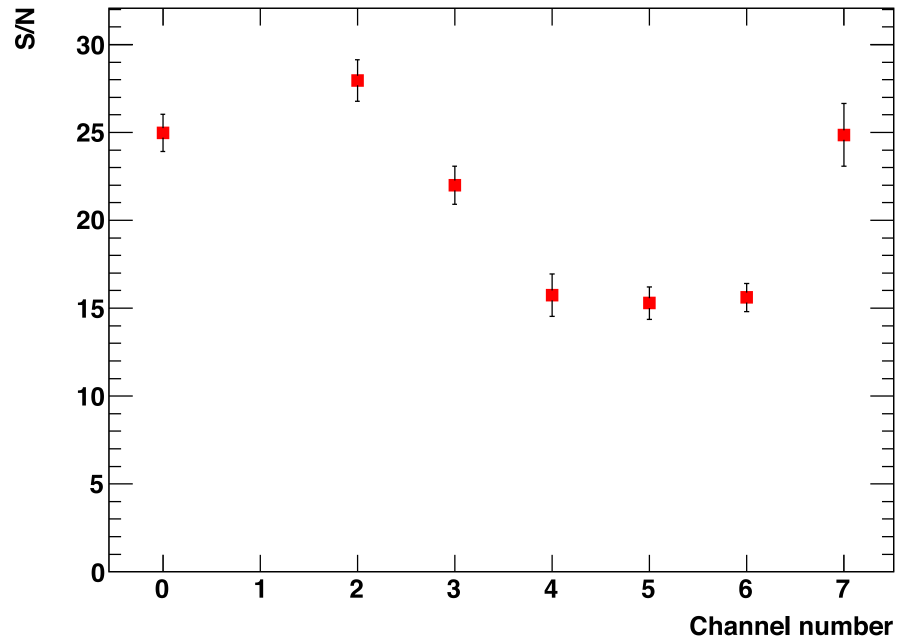




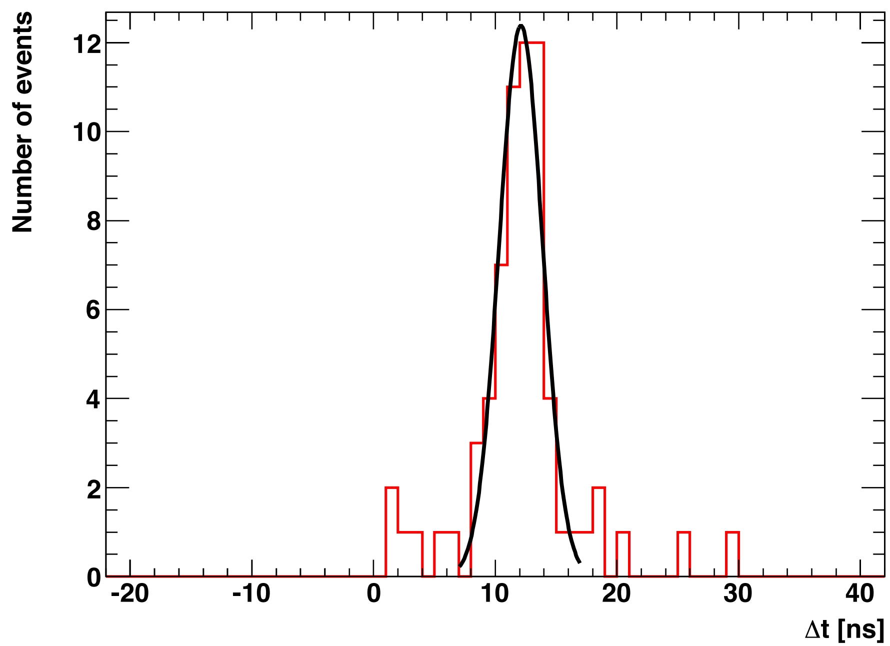


Detector performance with 2008 beam



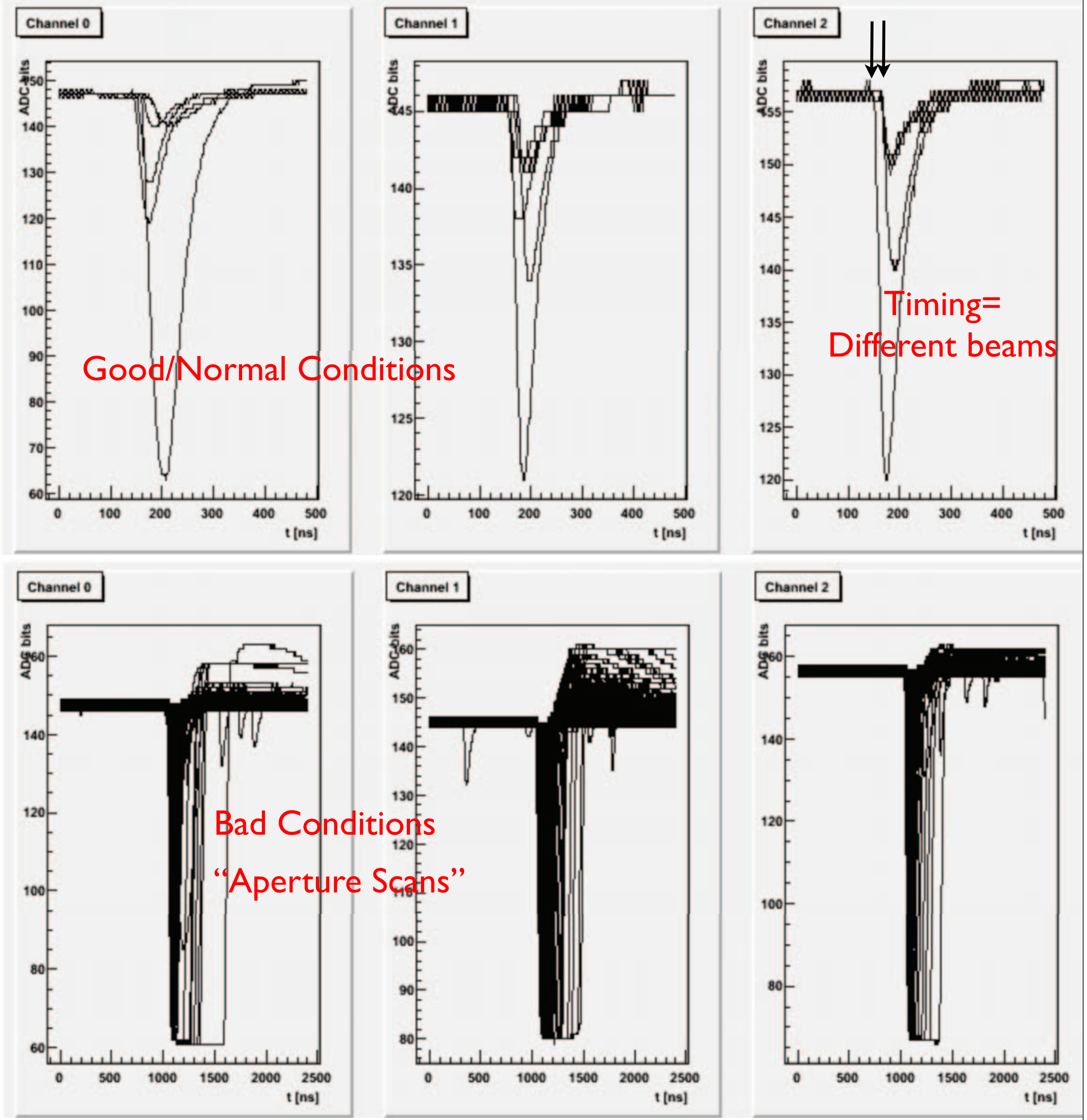


- Clear signals seen on all channels
  - S/N ranges from 15-28
- Timing shown difference of 12.4ns between hits on either side in agreement with time-of-flight
  - Width of difference is 1.8 ns
  - Implies a single hit timing resolution of 1.3 ns



Beam in 2009

- In good conditions, a few MIPs are seen
- Timing information visible
- With very high losses, see saturation
- (>40 particles/bunch crossing)
- Analysis ongoing
- Clearly a useful tool
- See Steffen's talk



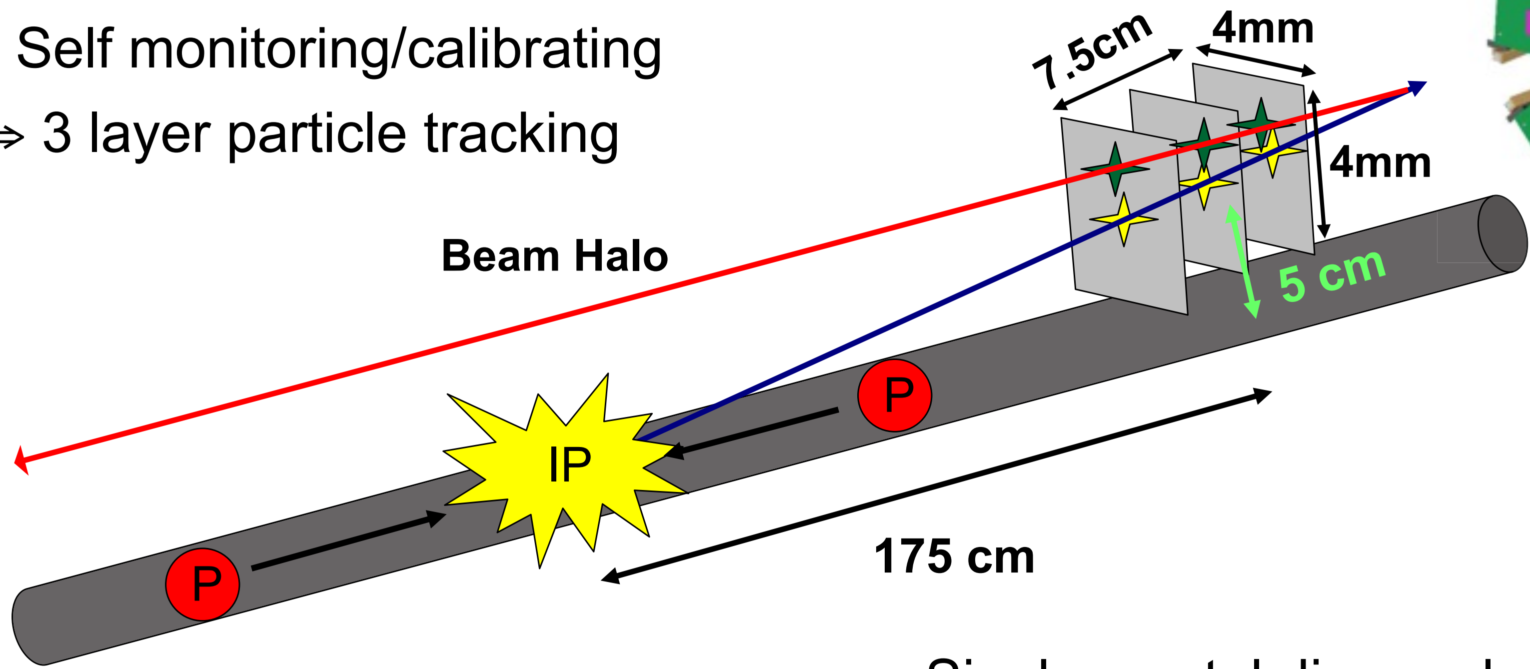
Pixel Luminosity Telescope

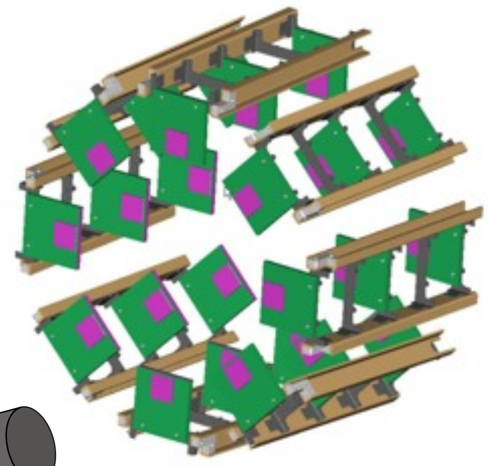
A dedicated “stand-alone” luminosity monitor for CMS

The Pixel Luminosity Telescope (PLT)

- Independent of CMS (self-triggered)
- Relative bunch-by-bunch measurements
- Precision at 1% level (stat, syst)
- Self monitoring/calibrating

⇒ 3 layer particle tracking





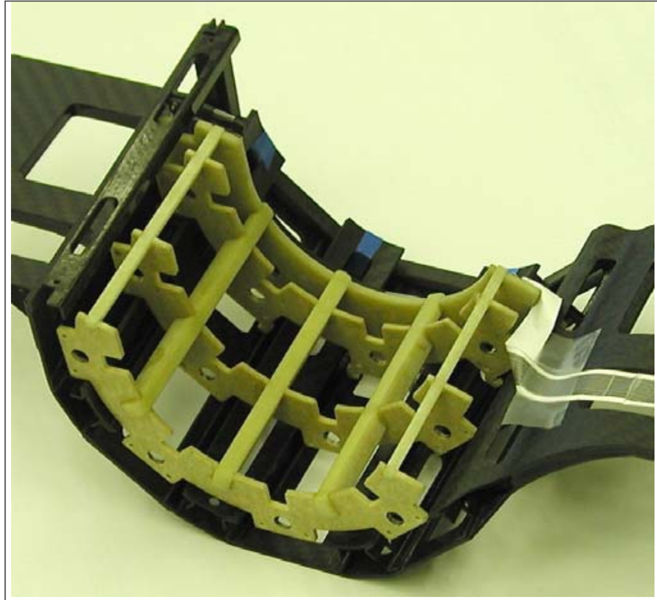
8 telescopes per "end"

- Single-crystal diamond pixel
  - Fast pixel OR readout (3-layer coincidence)
  - Full readout (1-10 kHz)

Count 3-fold coincidences every bunch crossing (40 MHz)

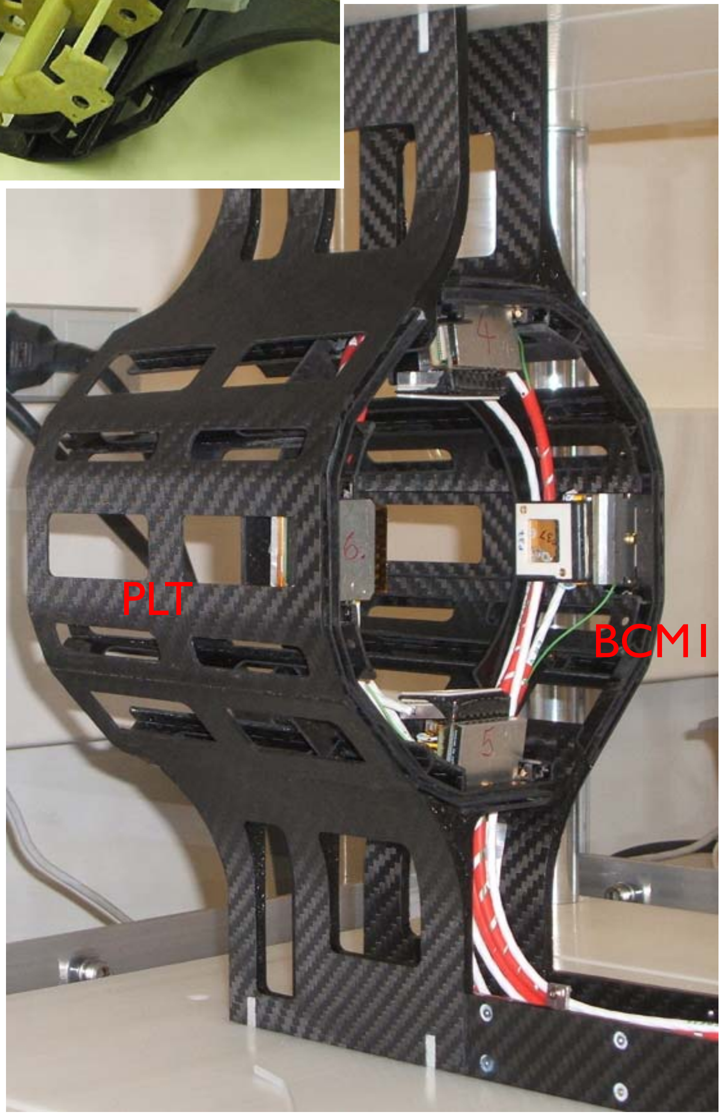
Count "tracks" from the IP

Proportional to luminosity

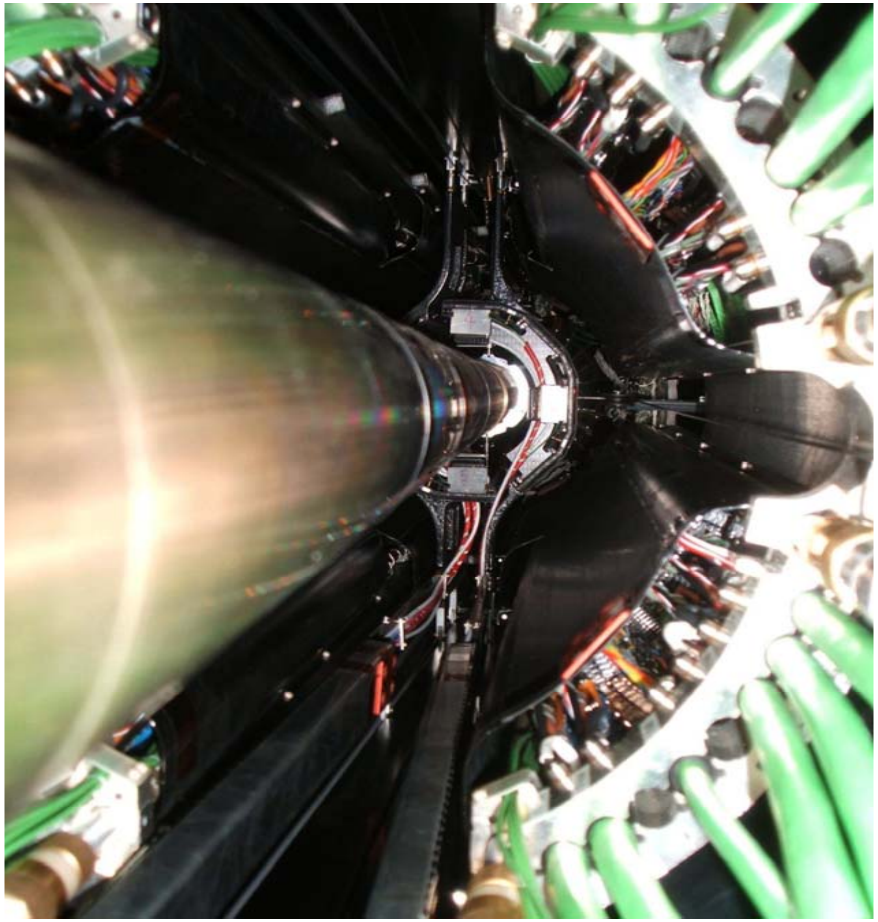


Mechanics already exists

slides on rails inside of
the pixel service cylinder

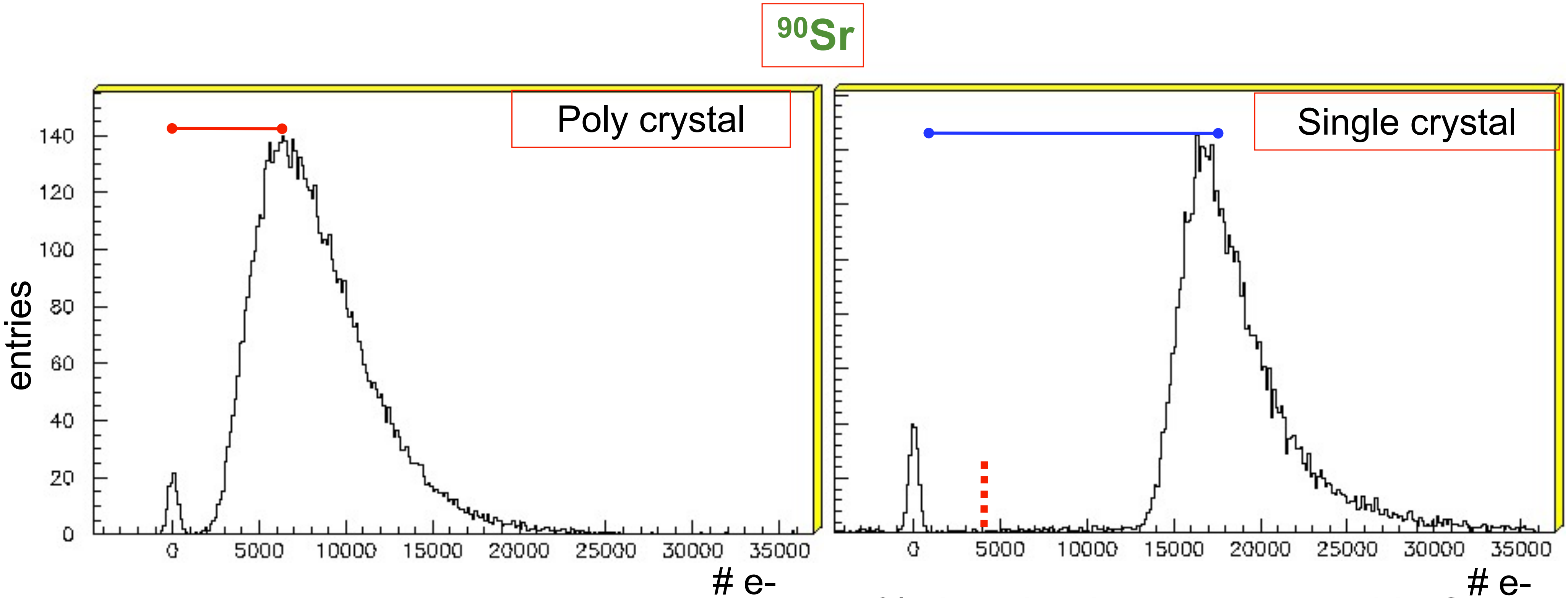


Fits in
BCM1
Carriage



Single-Crystal Diamond Detector (sCVD)

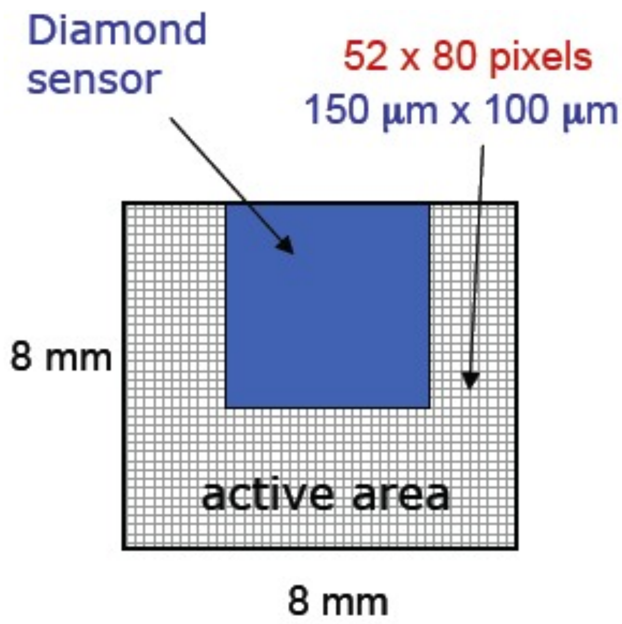
- Radiation hard (survives > 2 x 10^{15} p/cm^2)
- No need for cooling
- Full charge collection at E-field < 0.2V/um
- Fast signal collection (~1ns from 500 um)
- Pulse height well separated from pedestal



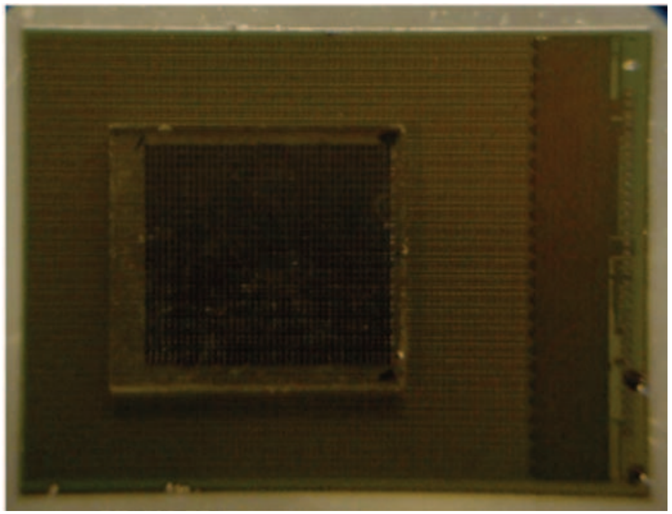
- 75% drop in charge collected before significant effect on efficiency

Readout

- CMS Pixel chip (PSI46v2) bump-bonded to sCVD
- Fast cluster counting in double-columns built in
- Individual pixel thresholds adjustable
- Individual pixels can be masked
- Self-triggered by fast pixel OR
- Full analog readout of
  - Hit address
  - Charge deposit
- Standard pixel readout (FEC, FED [ADC])

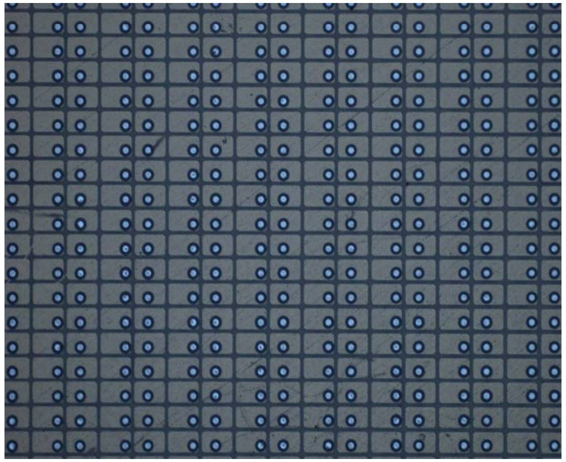


- Fast-Or Readout (40 MHz)
  - Bunch-by-bunch luminosity
  - Population of abort gap
  - Simulation: 1.6 tracks/BC at nominal luminosity
- Full pixel readout (1-10 kHz)
  - bunch integrated luminosity
  - IP centroid
  - Beam Halo Measurement

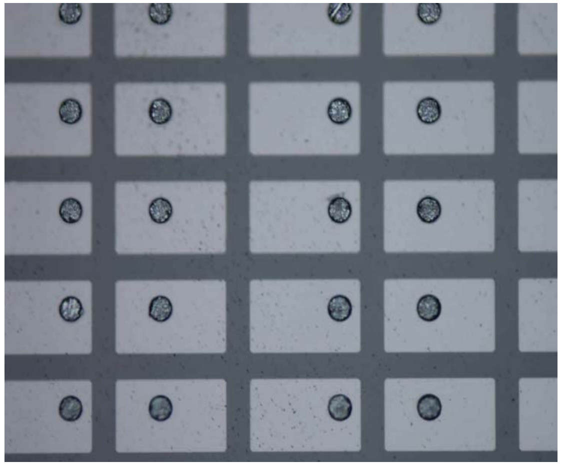


Bump bonded at Princeton micro-fab lab

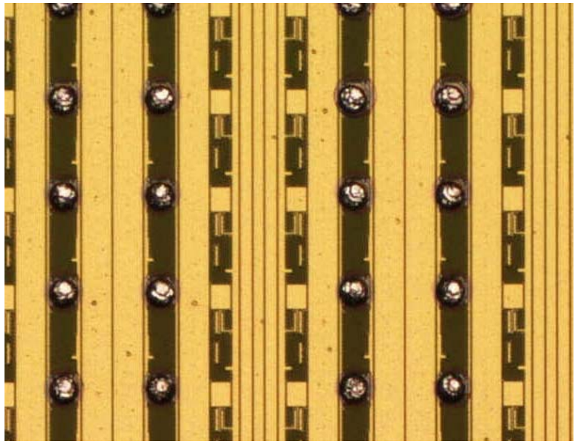
Detector Fabrication



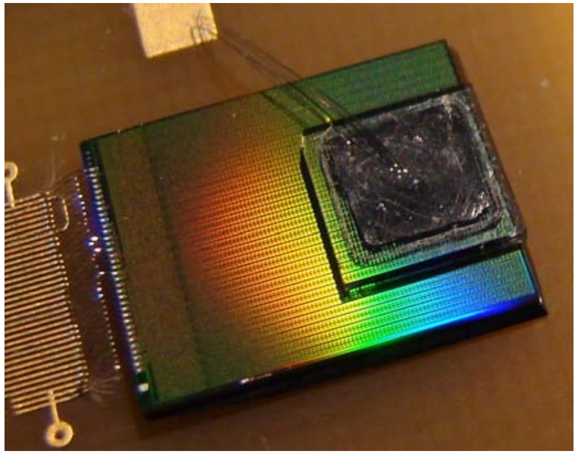
patterned diamond



indium bumps



bumped ROC

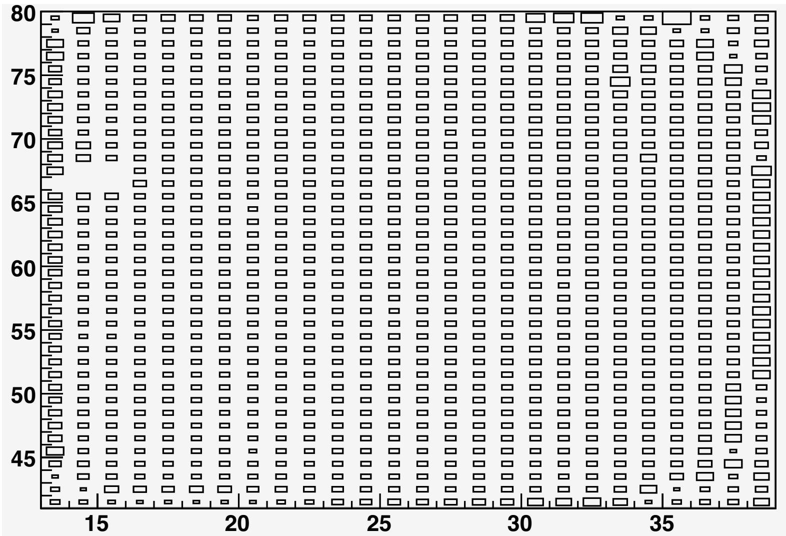


bumped detector

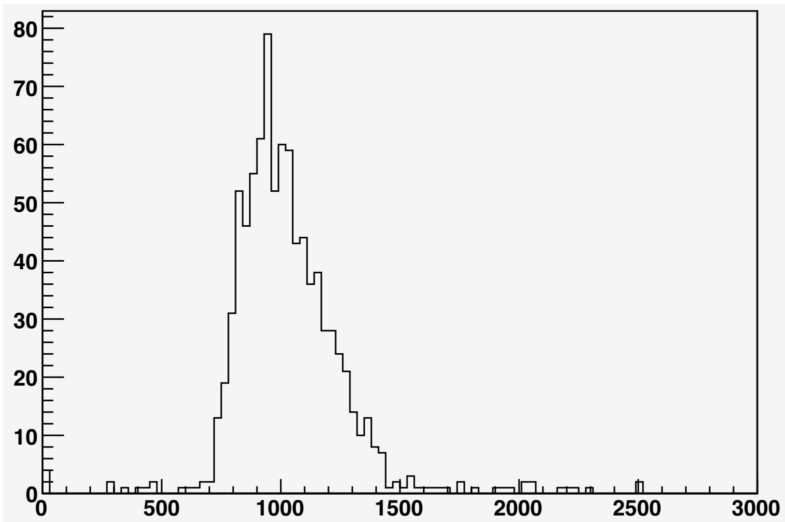
Bump Yield

1040 pixels in active area

- ^{90}Sr beta particles
- Fast-Or used as trigger
- mostly stopping beta's
- 3 to 4 pixels hit per beta



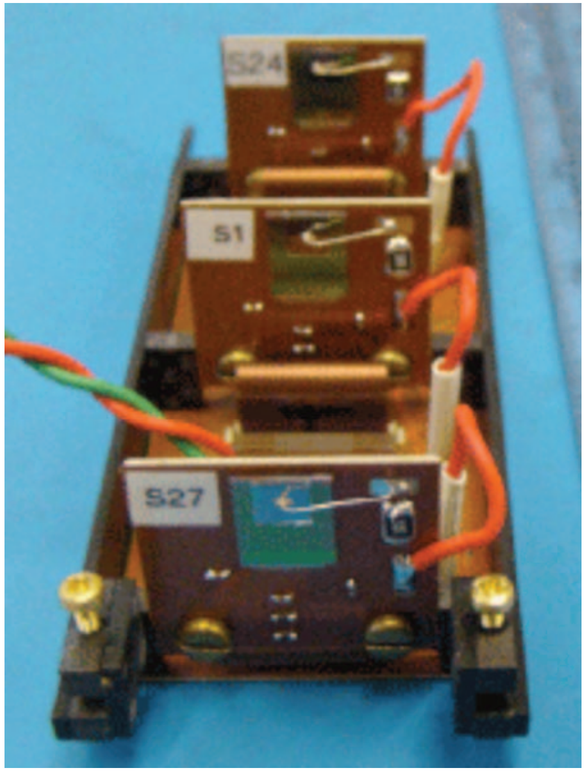
box area proportional to number of hits



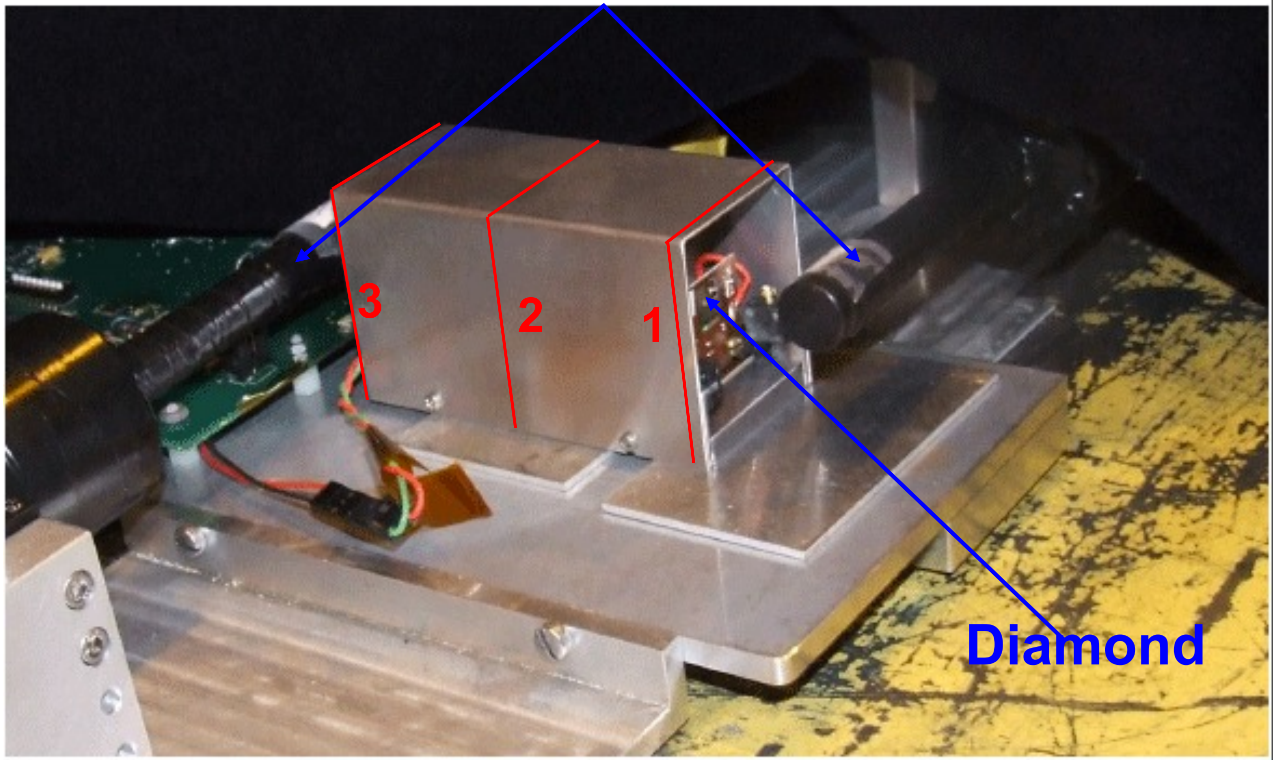
distribution of hits per pixel

Beam Test

- 1 full PLT telescope was successfully tested at CERN SPS
- 150 GeV/c $\pi+$
- 2 days of beam time



Small (6x6 mm) Scintillators
(used as triggers)



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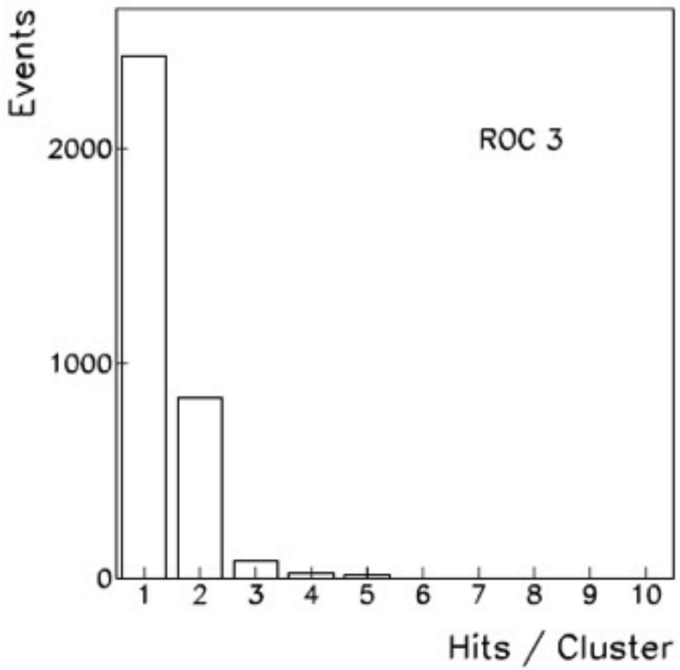
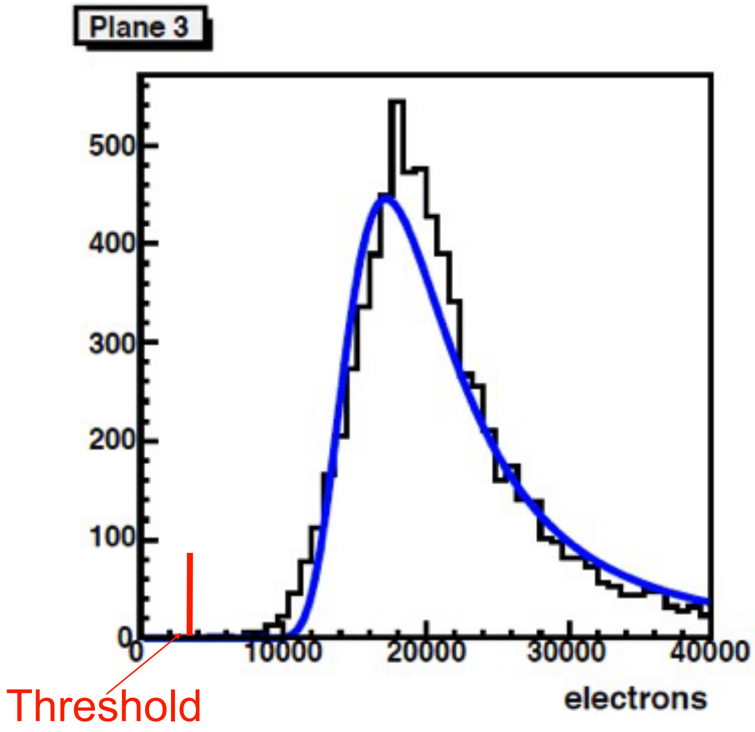
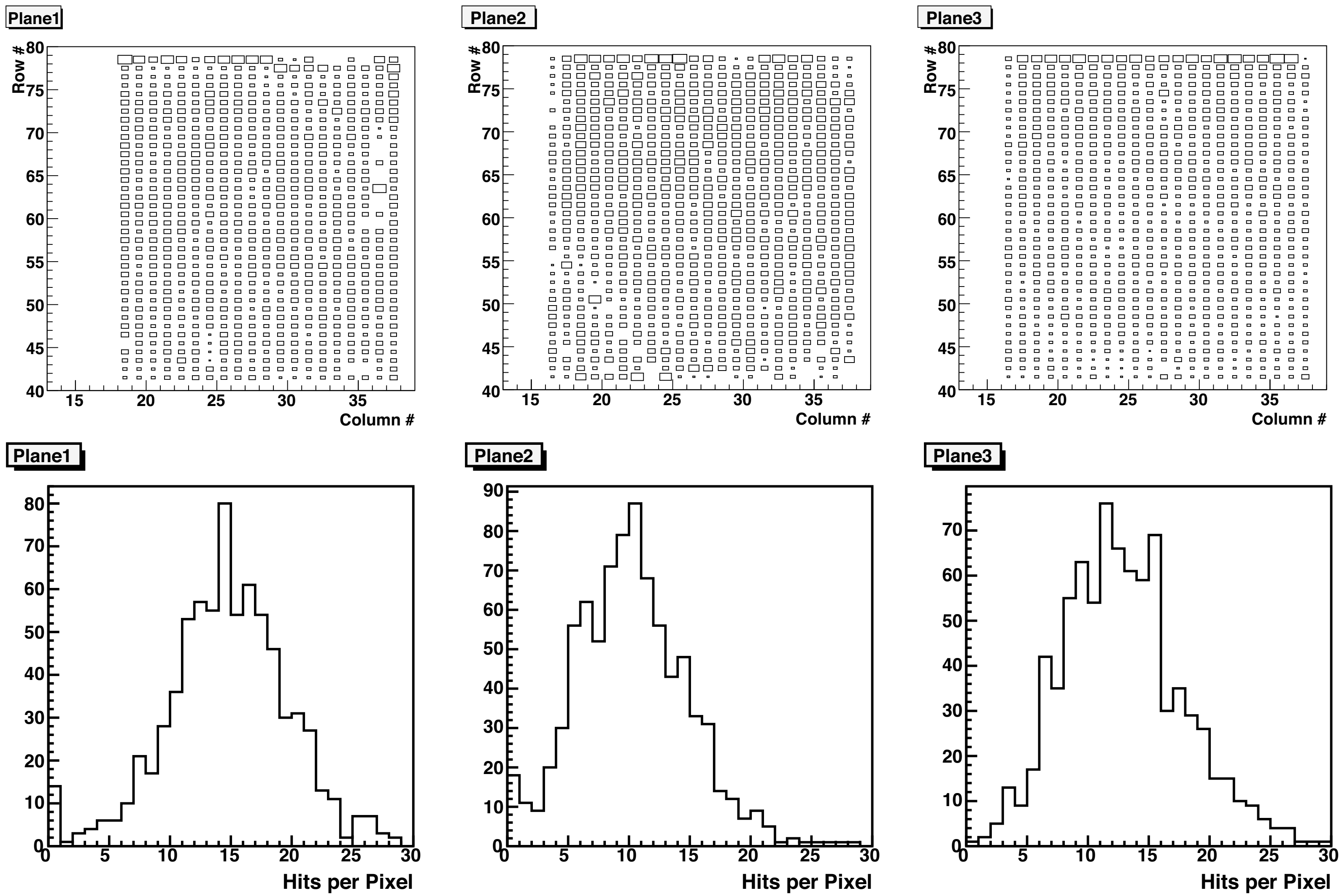
Charge Deposit

- Calibrated using charge injection feature of PSI42
- Require single cluster in all three planes
- Sum over cluster
- Most probable charge deposit: ~18,000 electrons (Si: ~28,000)





Pixel Yields

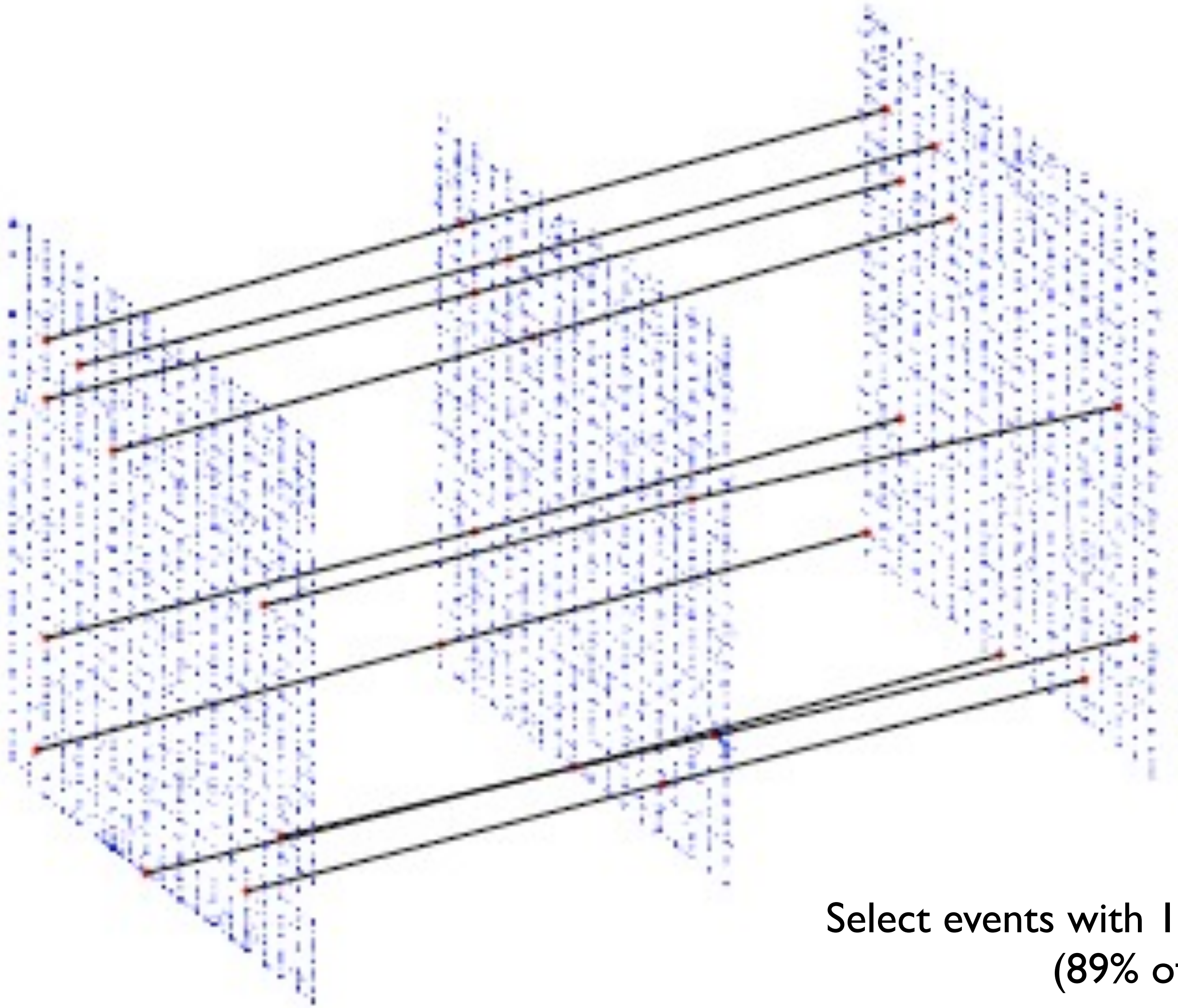


Percentage of pixels with no hits:

Plane 1: 1.8%   Plane 2: 2.2%   Plane 3: 0.1%

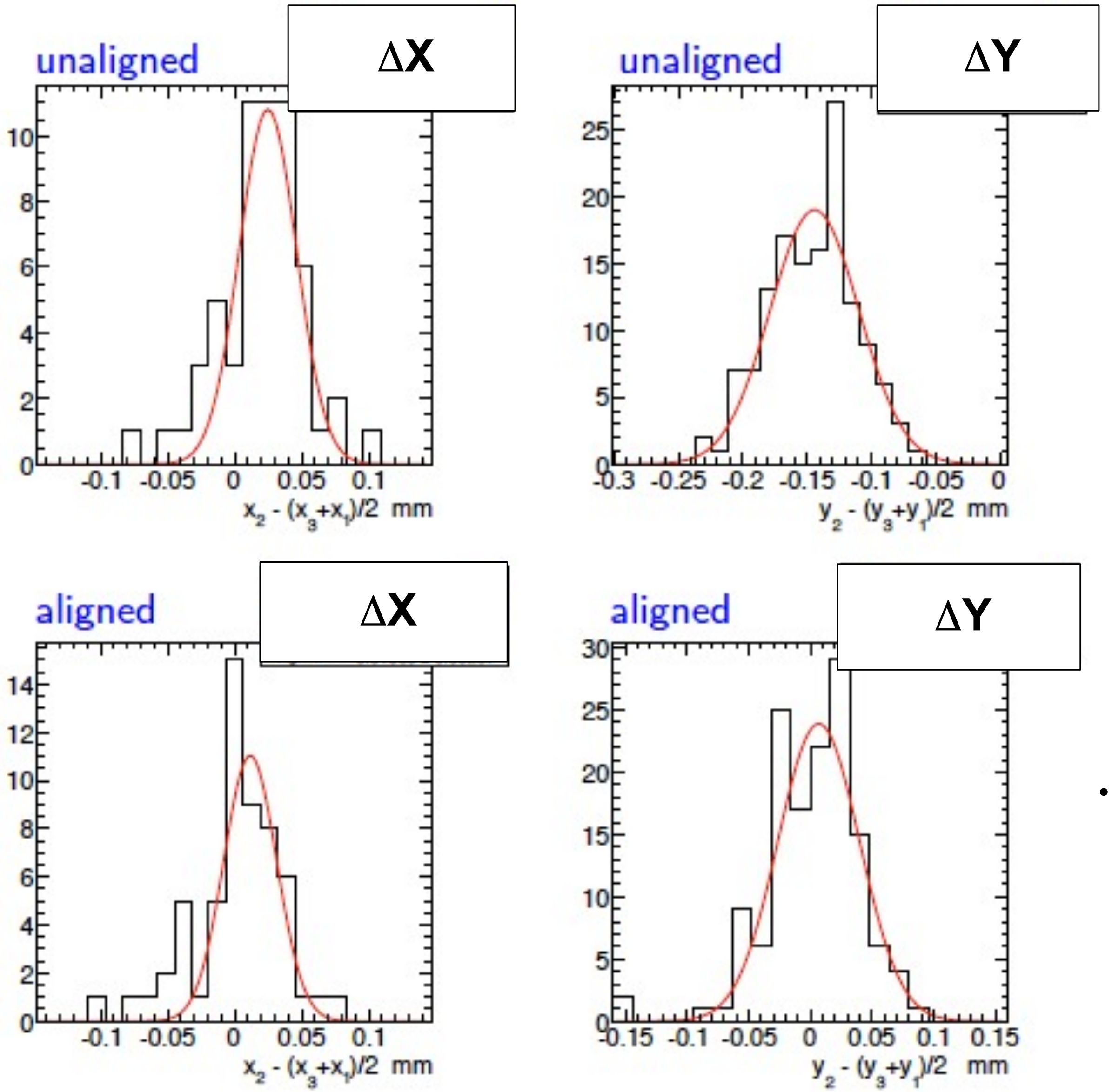
Fiducial area: masked border rows and columns and columns in shadow of entrance counter

Tracks Observed



Select events with 1 cluster in each plane
(89% of events)

Alignment

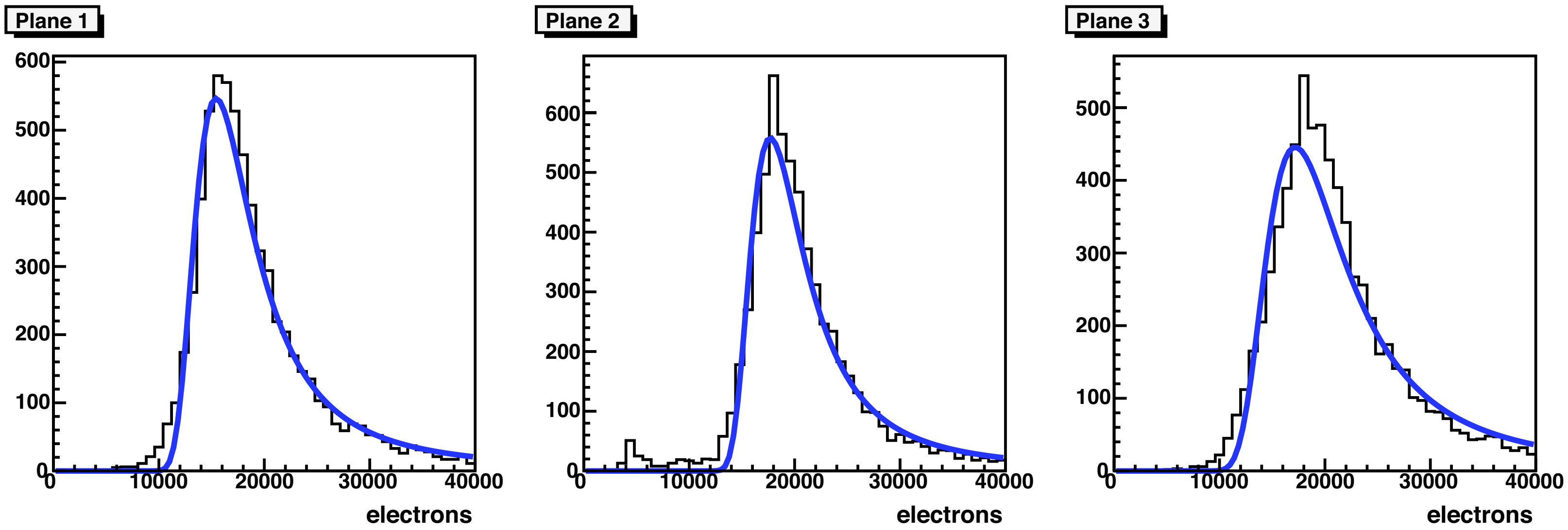


- Successfully reconstructed tracks
  - Hit position defined as the “center of charge” (charge sharing)

- Define residual: $x_2 - (x_3 - x_1)/2$
- Alignment
  - X offset: 25 ± 5 um
  - Y offset: 144 ± 3 um
- Rotation: 0.6 degrees
  - 40 um over 4mm
- Even with only a few tracks, a successful alignment was achieved
  - X alignment: 57 tracks
  - Y alignment: 140 tracks

Pulse Heights

- Require single cluster in all three planes
- For Plane c, require hit in regions of Planes a and b such that track is certain to pass through fiducial region of Plane c
- Plot pulse height summed over cluster

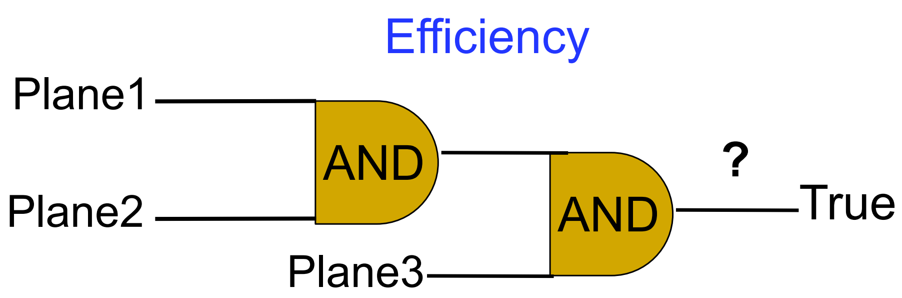


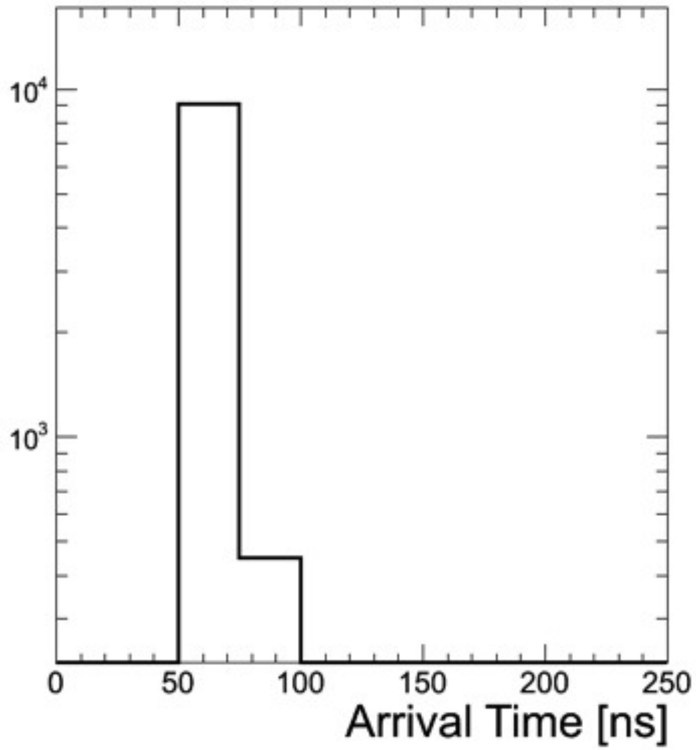
Most probable pulse heights:

Plane 1: 16,000 e^- Plane 2: 18,500 e^- Plane 3: 18,500 e^-

Fast-OR

- Test beam particles arrive at random times with respect to our clock
  - ⇒ count +- 1 time bin as the same event
- In CMS, particles arrive at a definite phase of the 40 MHz clock.
  - ⇒ fixed to 1 time bin



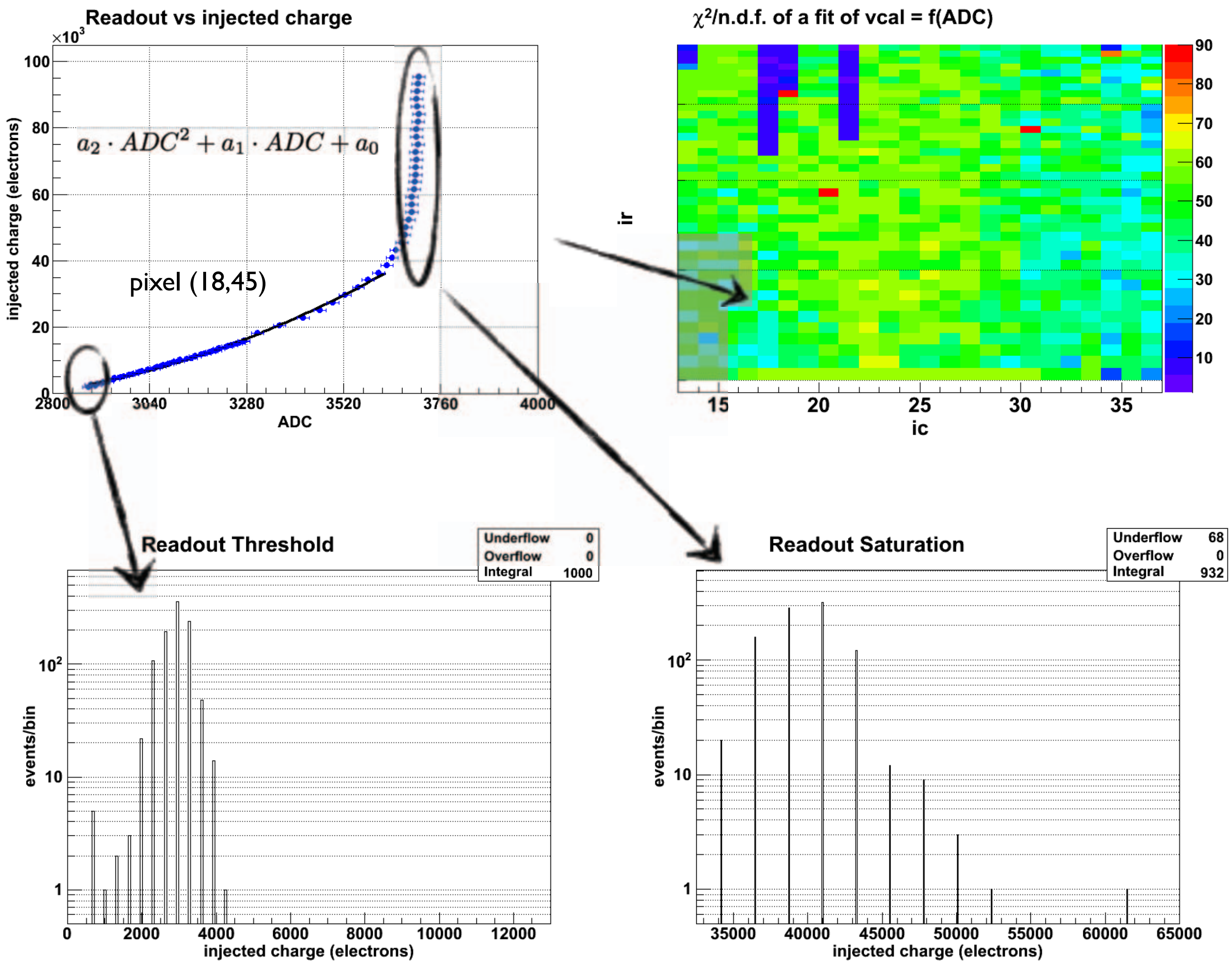


Time bin size = 25ns (40 MHz)

	Plane 1	Plane 2	Plane 3
Measured Efficiencies	99.3%	99.6%	99.9%

Calibration procedure defined for production

Calibration



Summary

- Outline of 2 MIP sensitive detectors using SCVD diamond for CMS shown
- Fast Beam Conditions Monitor
  - Built, installed and working
  - Meets the required specifications
  - Already proving useful in helping diagnosing beam conditions in the CMS experiment during this LHC run
  - Will prove to be an invaluable diagnostic tool
- Pixel Luminosity Telescope
  - Testbeam results show that design meets requirements
  - Demonstration of a diamond pixel tracker
  - Approved as a CMS project - construction started of 16 (+4) telescopes
  - Installation into CMS early 2011