CMS Luminosity Monitor using CVD Diamond Pixel Detectors

- Overview
- Technology of Diamond Detectors
- CMS Pixel Luminosity Telescope (PLT)
  - Design
  - Construction
  - Readout DAQ
  - Simulations and Performance
  - Status

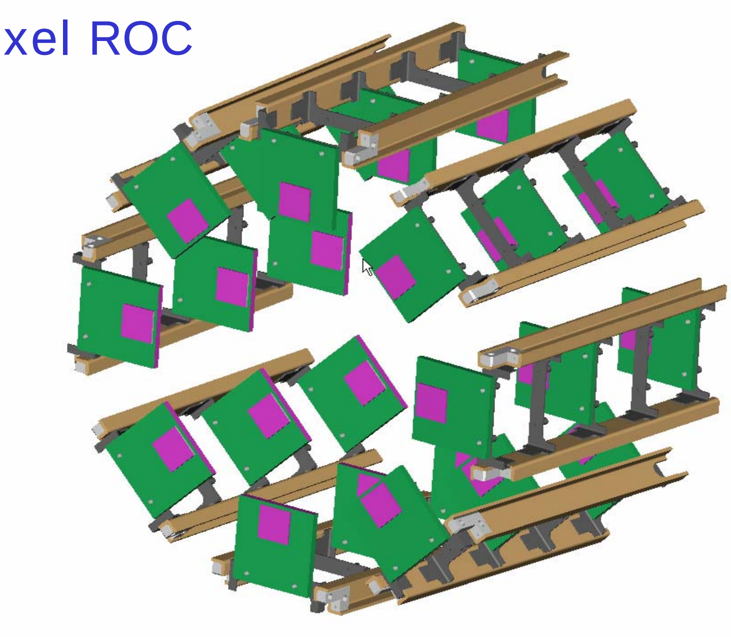
R. Stone Rutgers University

Pixel 2008

CMS Pixel Luminosity Telescope (PLT)

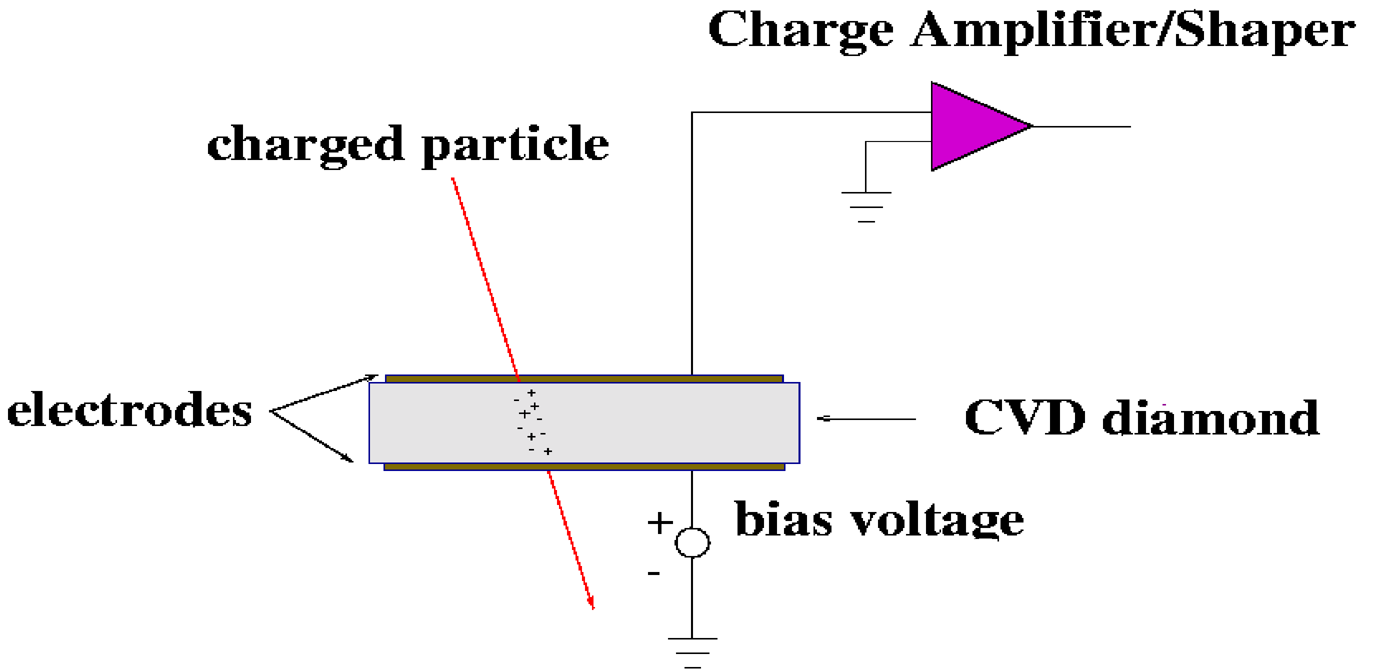
Measure relative luminosity bunch-by-bunch

- Small angle (~1^o) pointing telescopes
- Total length 9 cm, located at
  r ~ 5 cm, z +- 1.7 m
- Three planes of single-crystal CVD diamond
  sensors (4 mm x 4 mm) active area
- Diamond pixels bump-bonded to CMS pixel ROC
- Eight telescopes per side
- Form 3-fold coincidence from ROC
  fast 'hit' signal
- Rutgers, Princeton,
  UC Davis, CERN, Vanderbilt,
  Tennessee, DESY-Zeuthen, Vienna



Count 3-fold coincidences
for each bunch crossing

A Simple Diamond Detector



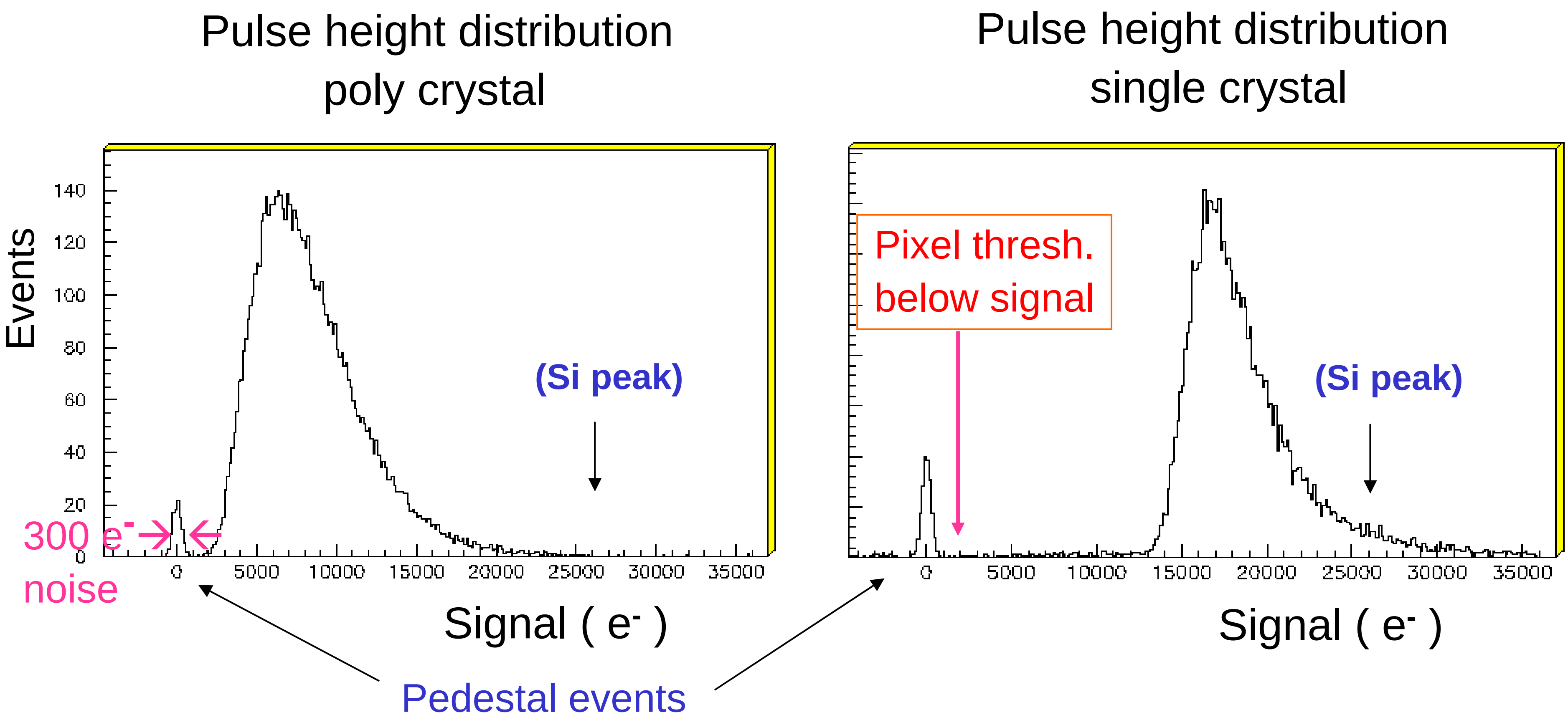
- No reverse-bias PN junction: Diamond is an extremely good insulator
- Charge deposited: 36 $e^- h^+$ pairs / micron thickness
- Signal collected may be less due to charge traps

Advantages/Disadvantages of CVD Diamond

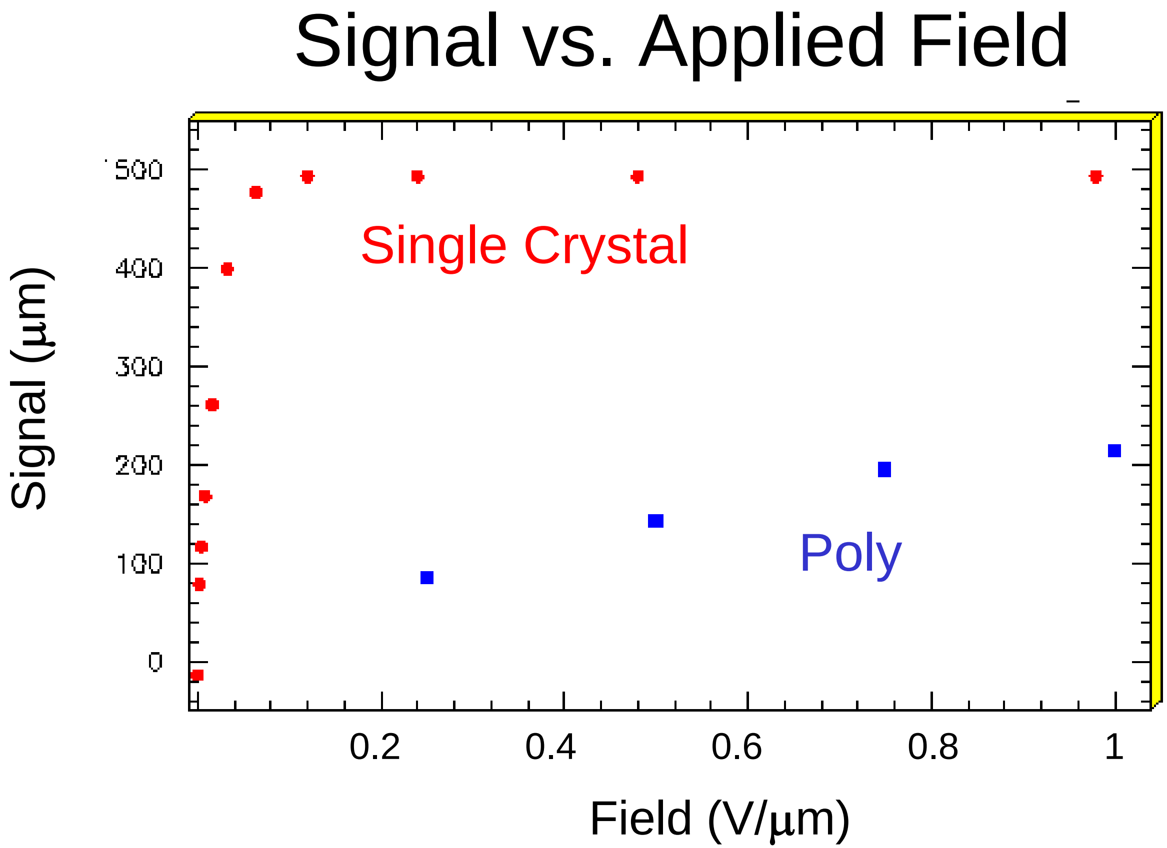
- High mobility: fast signal collection (~1ns for 500 microns)
- High resistivity: insignificant dark current → lower parallel noise
- Low dielectric constant → lower series noise
- Chemically inert:
- Reusable: solid electrodes, then remove metal, then pixel electrodes
- High thermal conductivity:
- **No need for extensive cooling**
- **High radiation tolerance: survives > 2 x 10^{15} protons/cm^2**

- Smaller signal: < ½ of silicon
- Relatively new material:
  - few manufacturers can produce detector quality diamond
  - higher cost than silicon

Comparison of Poly vs. Single crystal Diamond (500 μm thick)



Comparison of Poly vs. Single-crystalline Diamond (500 μm thick) (2)



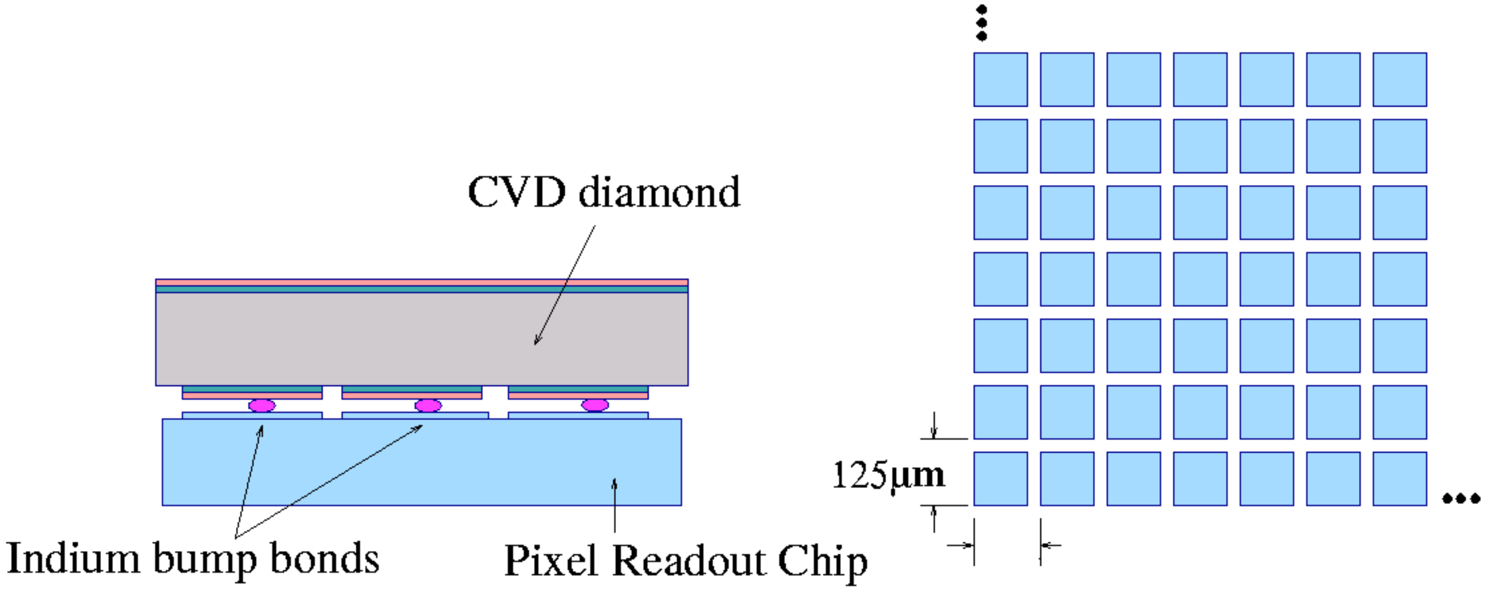
Comparison of Single vs. Poly-crystalline Diamond (3)

- Poly Crystal:
  - 6 inch wafers: suitable for large scale pixel module production
  - Less expensive than single crystal diamond (but more than Si)
  - Stable particle flux measurement (within large B field)

- Single Crystal:
  - 1 cm^2 largest produced so far, but 5mm x 5mm a production item
  - Full charge collection at less than ¼ the electric field needed for poly
  - Charge distribution much narrower than poly, ~half that of Si
  - Excellent signal separation from noise for threshold setting

Both show decrease in dark current after irradiation

Structure of a Diamond Pixel Detector



- Diamond thickness: ~500 microns
- Diamond metallization: Ti-W, 1 micron thick
- Bump bond: Indium, 15 micron diameter
- **Note: no guard rings needed (diamond is near-perfect insulator!)**

Indium Bump Bonding Process

- Current technique (based on process developed at UCD) done at PRISM nano-fabrication facility at Princeton University

Grow Indium bumps on both Diamond and ROC

- Apply thick (15 μm) photoresist
- Wipe off edge bead of photoresist
- Expose and develop 15 μm diameter holes for In bumps
- Evaporate 10 μm Indium
- Liftoff photoresist
- Flip chip bonding, w/o reflow

PRISM Facility

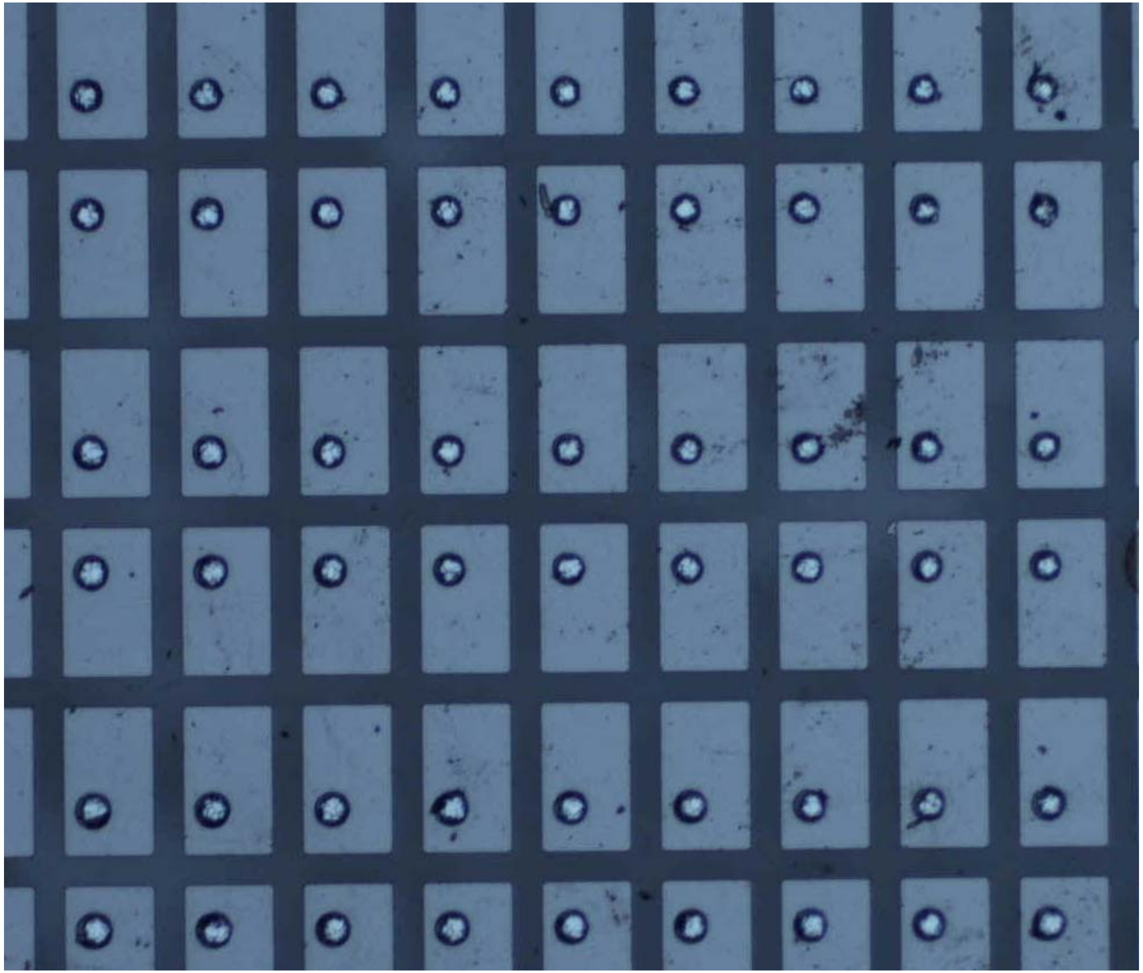
PRISM photolithography facilities

Karl Suss MA-6 6" mask aligner at PRISM

Edwards E306A Thermal Evaporator at PRISM

Research Associates M8A at PRISM

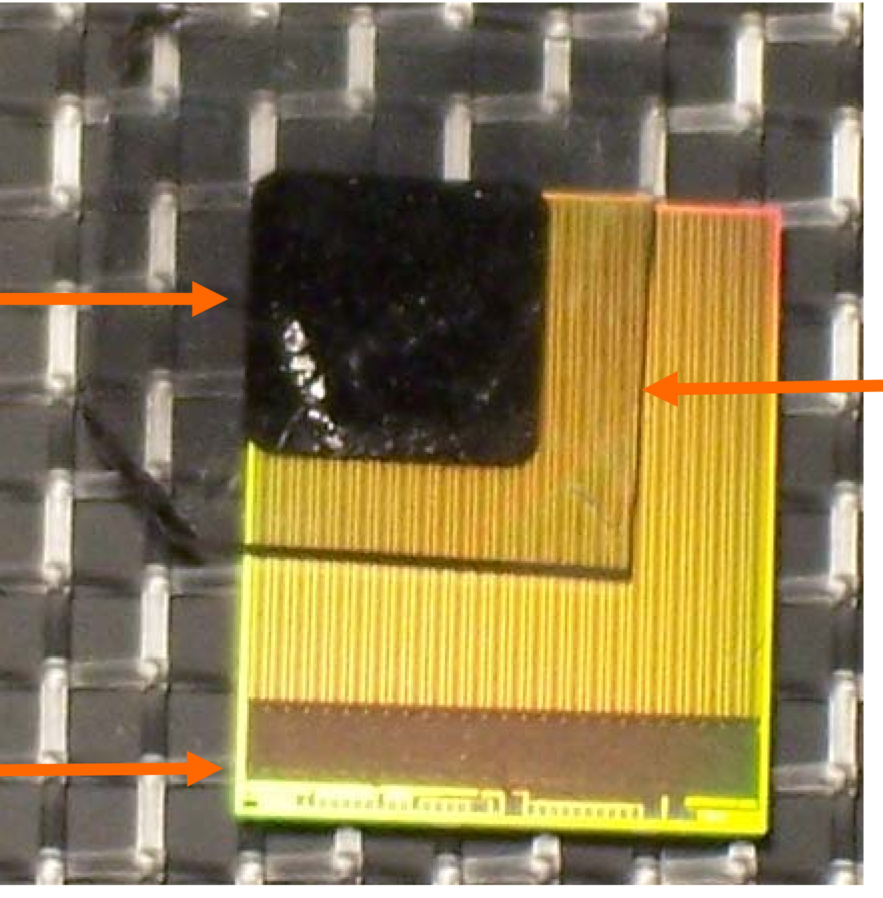
Indium bumps on diamond pixel pattern



100μm x 150μm
pixel pitch (CMS)

Diamond Bump Bonded to ROC

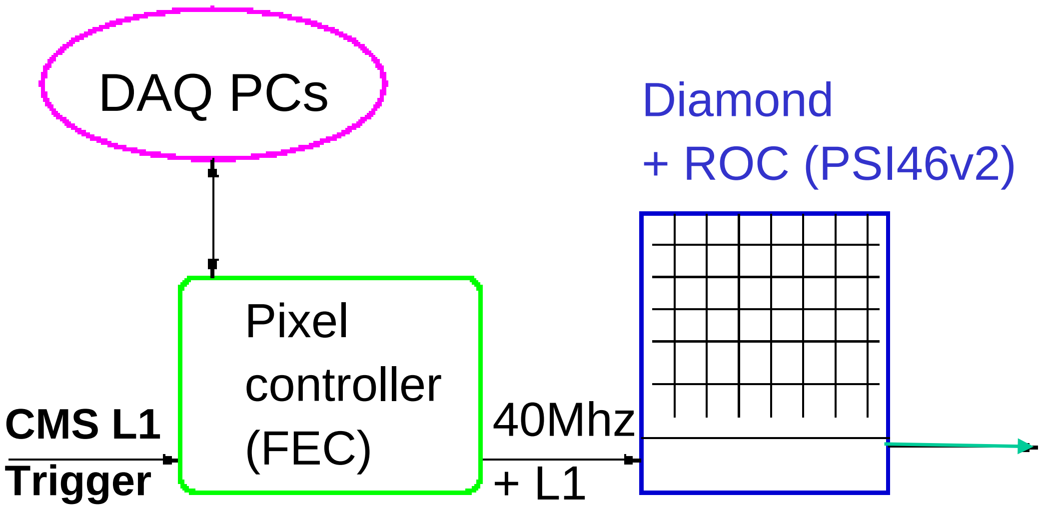
4 x 4 mm^2
Backplane
Electrode
Covering pixels



8 x 8 mm^2
sCVD
diamond

ROC
PSI 46 v2

Nominal CMS Pixel Readout Mode



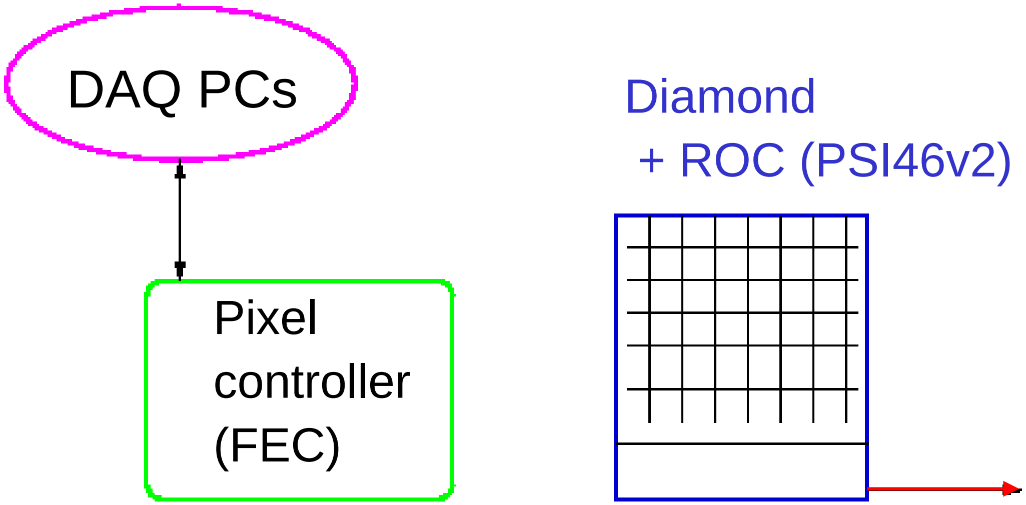
40MHz Pixel Analog out:

- **event hdr**
- **col,row 1st pixel**
- **1st pulse height**
- **col,row 2nd pixel**
- **2nd pulse height**

….

- **event trailer**

Fast Hit Output



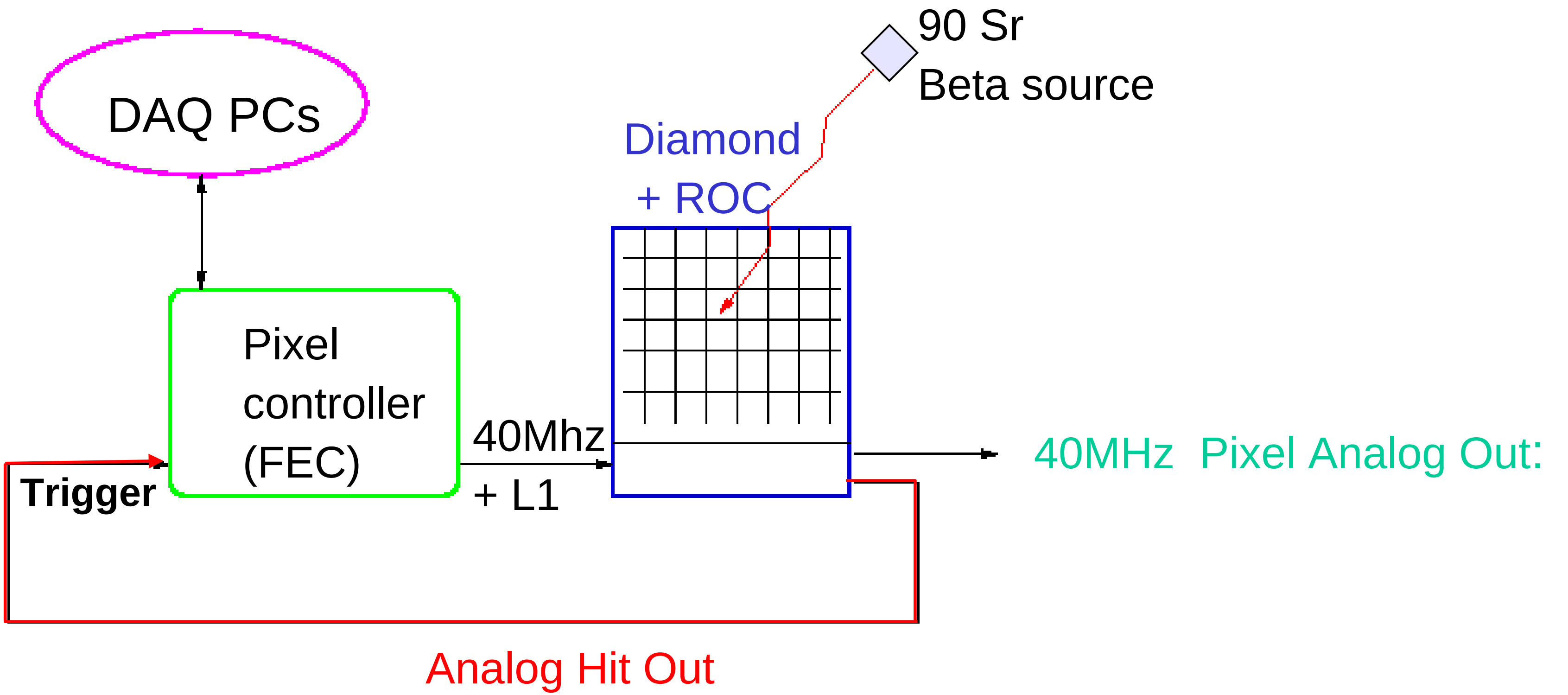
40 MHz Analog Hit Out:

- proportional to number of columns having >=1 pixel hit

Note: designed years ago to provide input to
a hardware Level 1 trigger processor,
but not currently in use in CMS pixel system

Can form the basis of a Luminosity measurement

Pixel Diagnostic Readout Mode



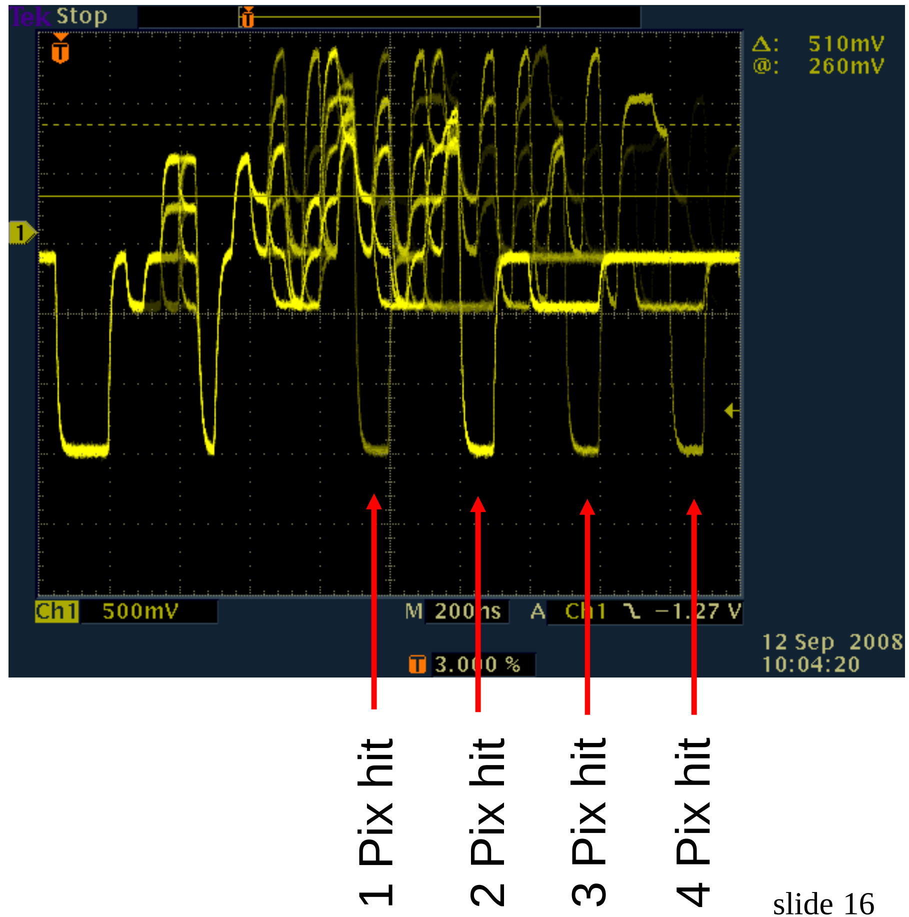
Diamond+ROC self-trigger on
- **stopping electrons (mostly)**
- **(or noise)**

Pixel Diagnostic Readout Mode

- Spectrum from stopping betas:
  - Some deposit many times min I
  - Some deposit less than min I

- Likely to have charge on >1 pixel due to multiple scattering

- Scope trace of Pixel A out: Stopping beta signature of working detector



Pixel Diagnostic Readout Mode

- Analyzed pixel hit multiplicity →

- 90Sr self triggering benefits:
  - Pixel to pixel uniformity of gain and efficiency
  - Bump yield
  - Single detector production testing

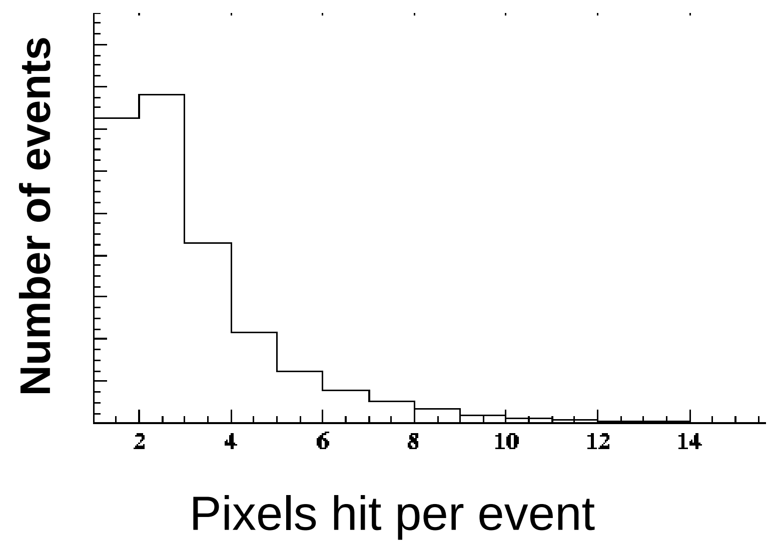
- Still need Min I (beamtest) for:

  Overall detector hit efficiency

  Pulse height distribution

  Gain calibration

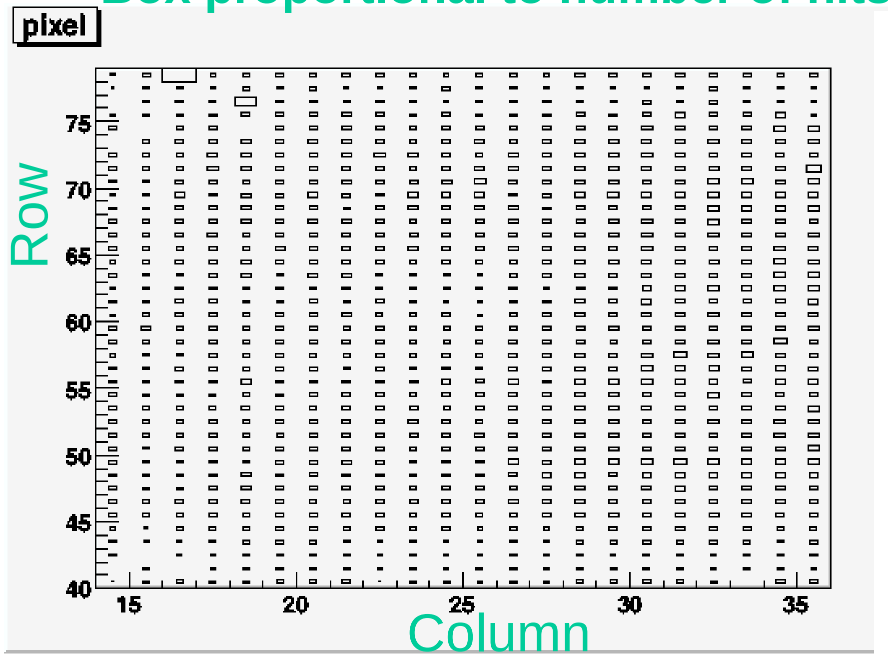
  Hit spatial resolution



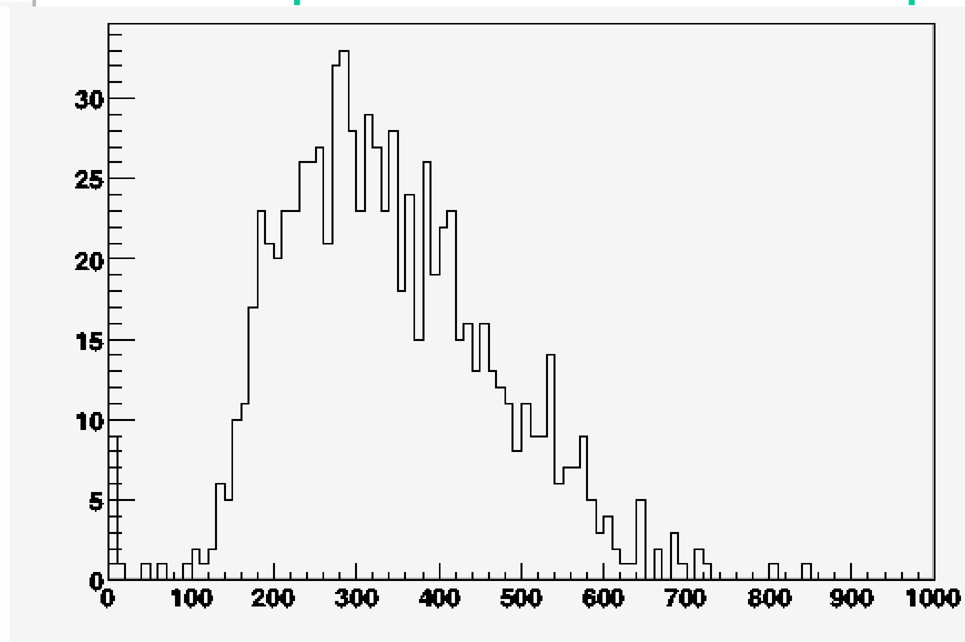
Pixel Detector Uniformity

Preliminary

Box proportional to number of hits



Number of pixels vs. number of total hits/pixel



~ <1% bad pixels

Dual Readout of PLT

Unique dual readout capability:

1) fast (bunch-by bunch) hit information
2) full pixel tracking information

1) Luminosity mode:

Fast output level (every 25ns bunch crossing)

- **0, 1, 2, 3, … double column hits**
- **individual pixel thresholds adjustable**
- **individual pixels can be masked**

2) Tracking mode:

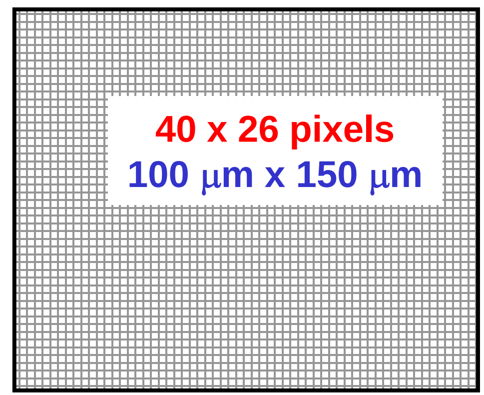
Full pixel readout (~ 1kHz)

- **pixel address and pulse height of each hit**
- **diagnostic of fast out signal**
- **determination of track origin**
- **determination of IP location**

IP
Scattering
Beam halo

CMS pixel chip has “fast” multiplicity counting built in

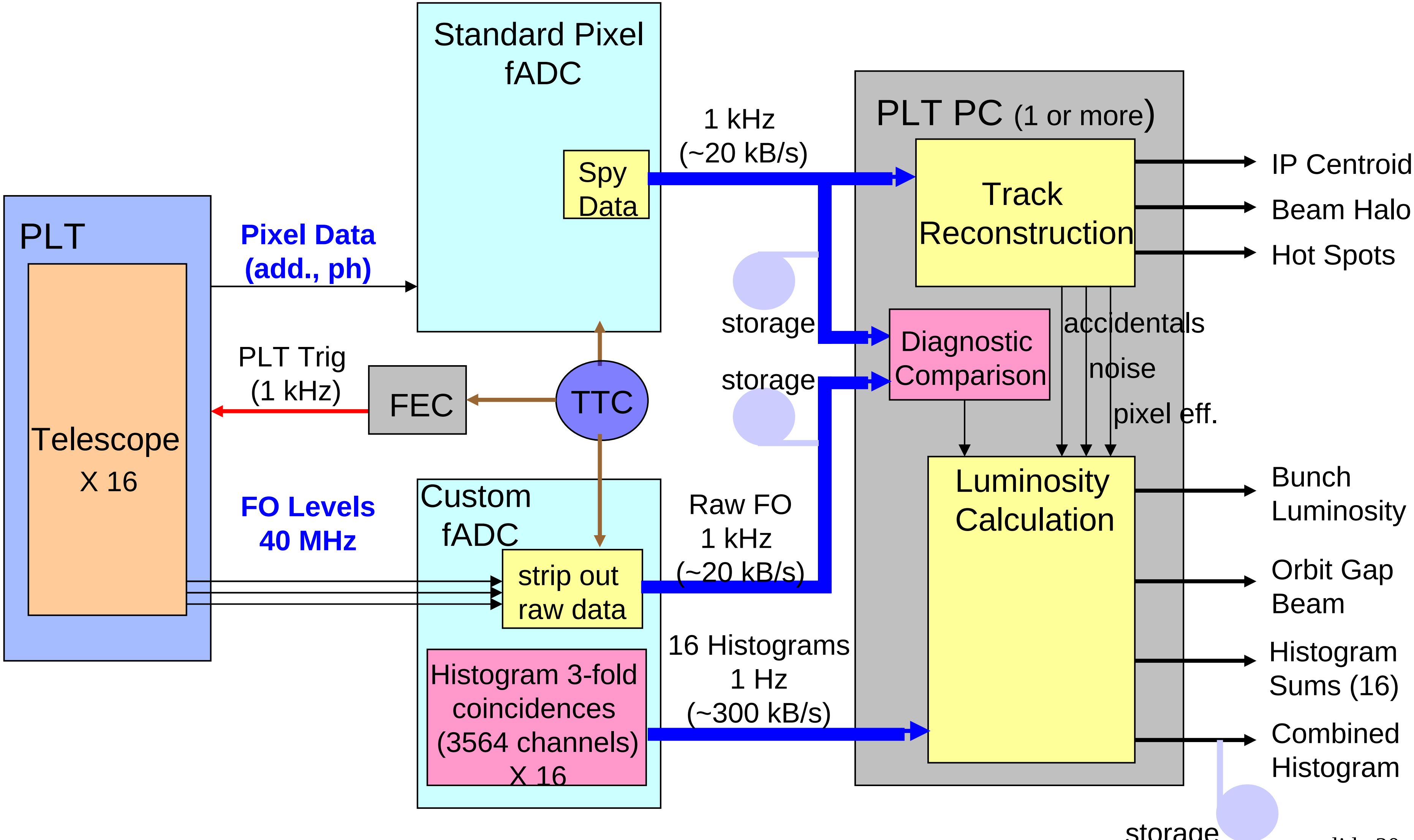
Diamond pixel active area



4 mm

4 mm

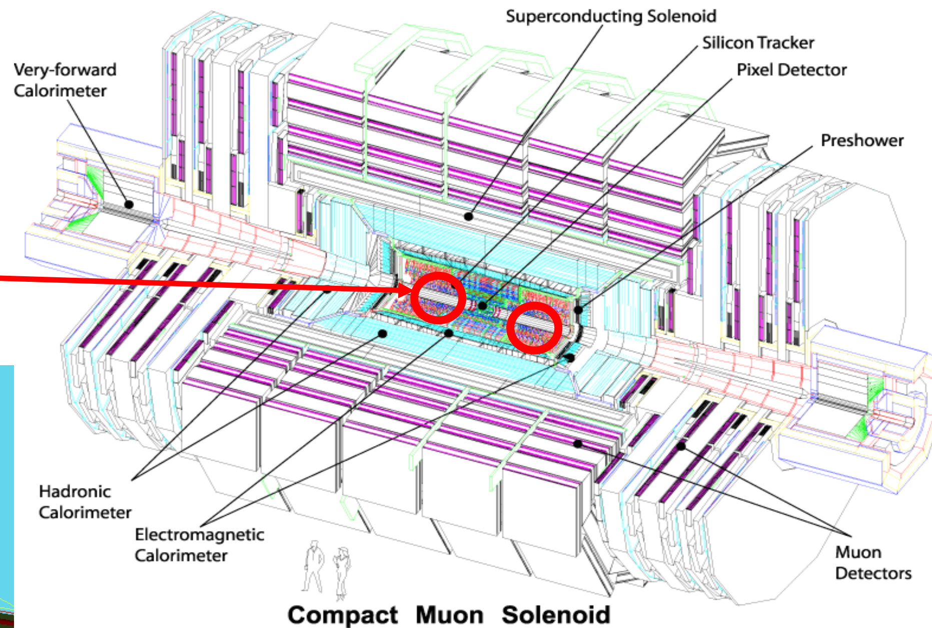
PLT Data Flow

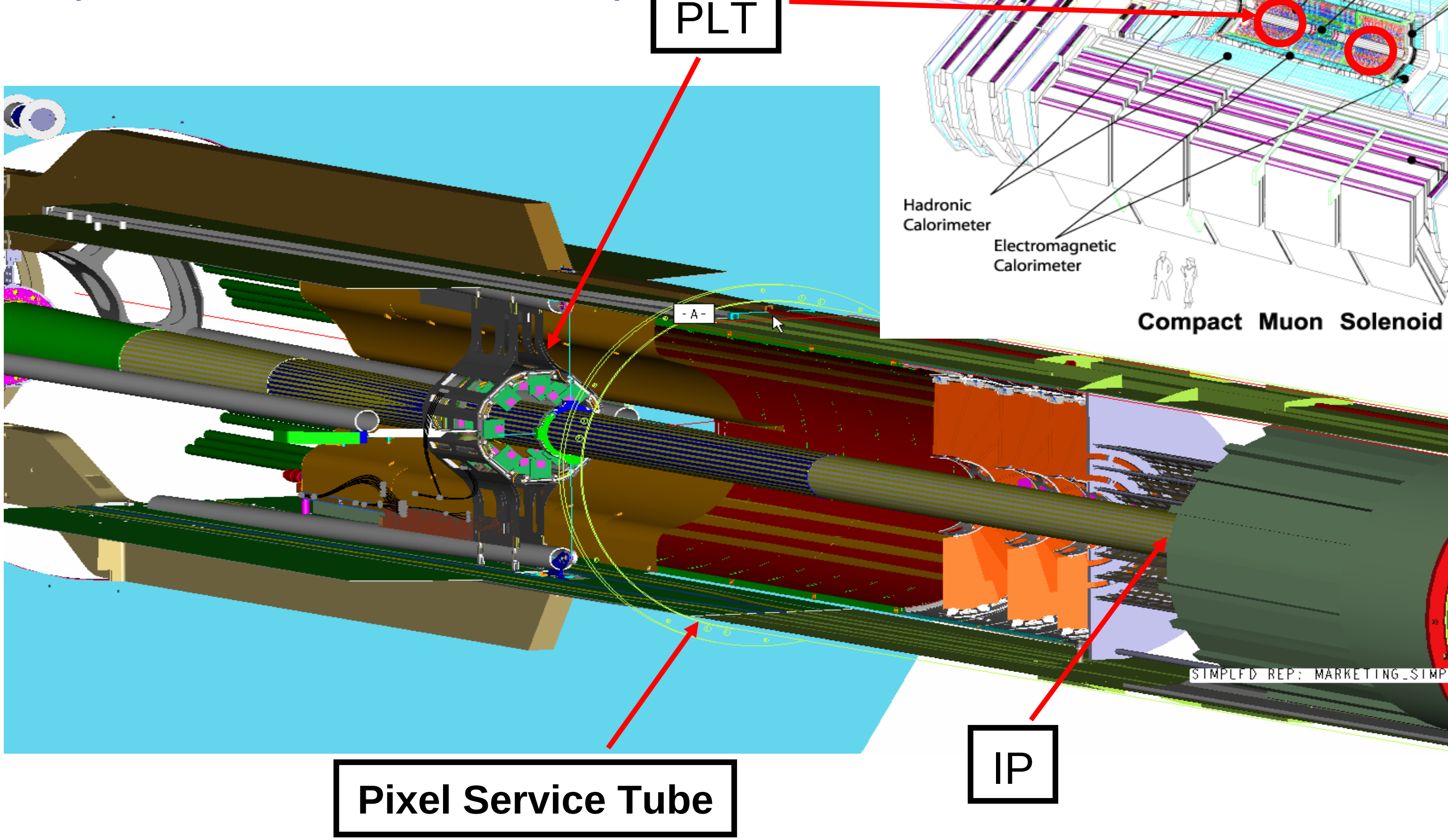


Location of Telescopes

- End of Be section of beam pipe
  (~ 1.7 m from IP)

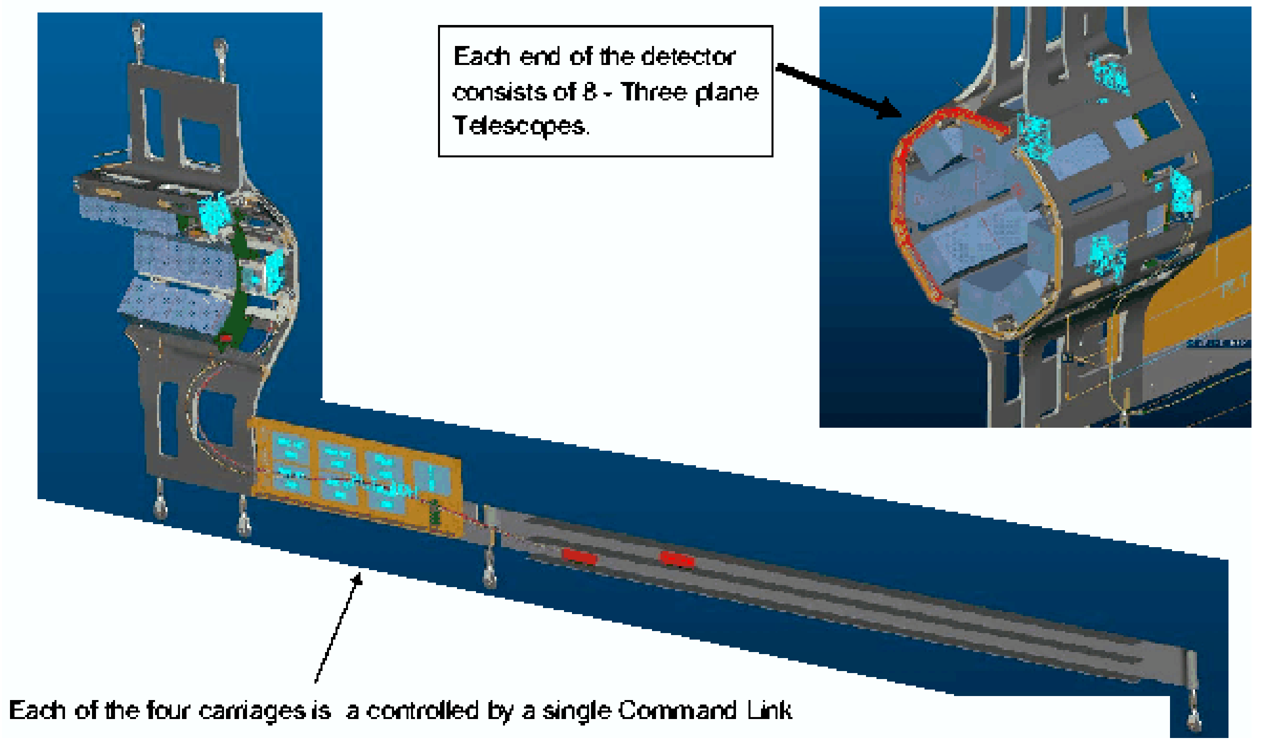
- Just outside of beam pipe
  (~ 5 cm from beam line)





PLT and BCM Carriage

carriage slides on rails inside of the pixel service cylinders



carriage already exists (houses BCM)

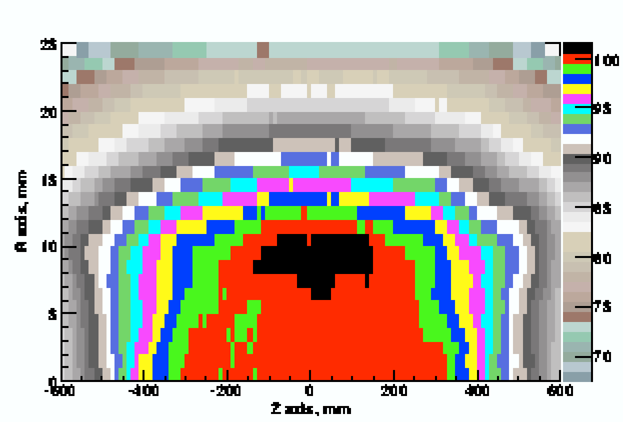
PLT Performance Capabilities

numbers for
$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$

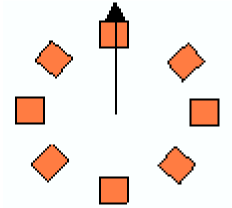
- 1.6 tracks per bunch crossing
  - **Pythia simulation**
- Relative bunch-by-bunch luminosity
  - **1% measurement each second**
- Interaction point centroid relative precision
  - **100 μm radially each second**
  - **2 mm longitudinally each second**

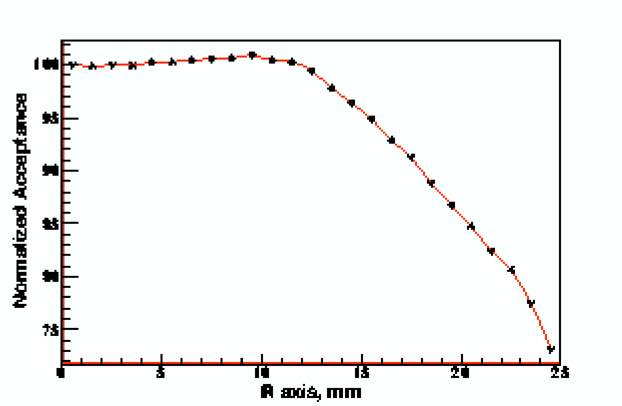
  } **scales as (time)$^{-1/2}$**
- Beam in abort gap identified
  - **crucial for CMS protection**
- Beam halo measured
  - **horizontal tracks**

Acceptance Uniformity

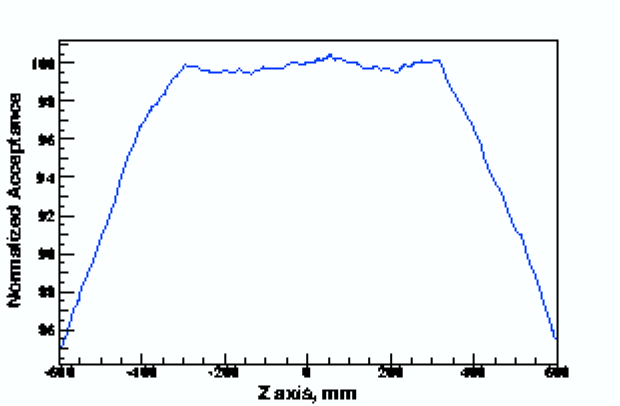


Uniformity of acceptance when beam is displaced in radial direction of a telescope



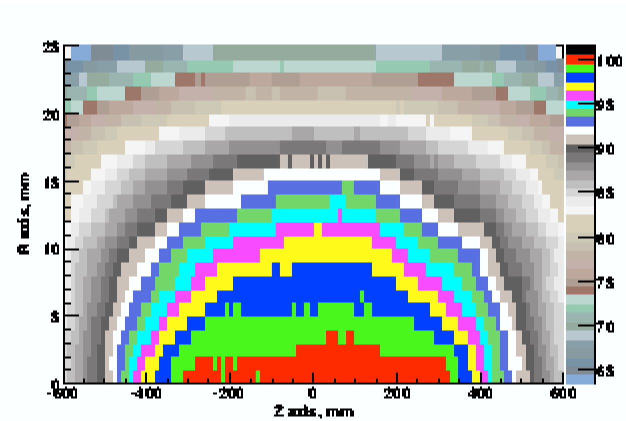


1% flat to 12 mm

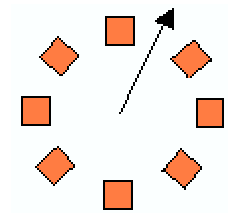


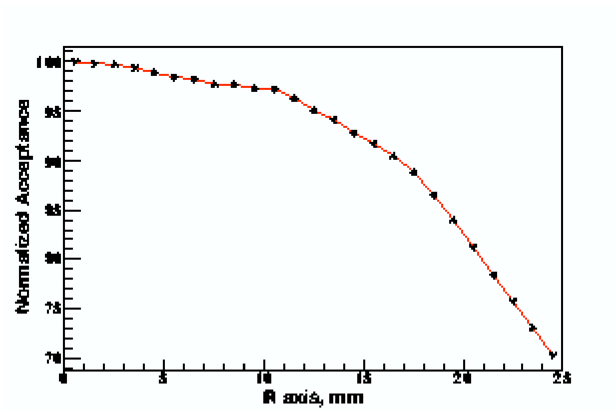
1% flat to ± 300 mm

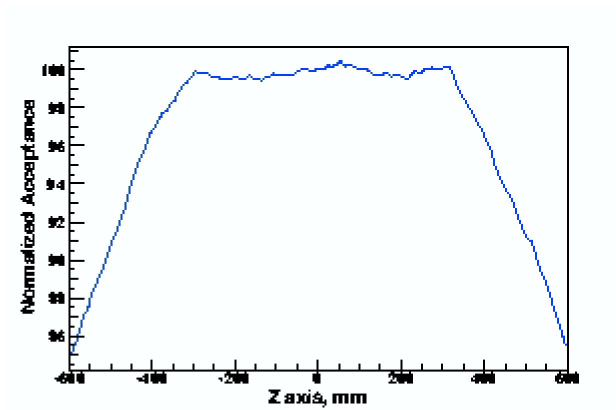
Acceptance Uniformity



Uniformity of acceptance when beam is displaced in radial direction midway between two telescopes





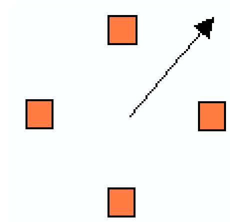


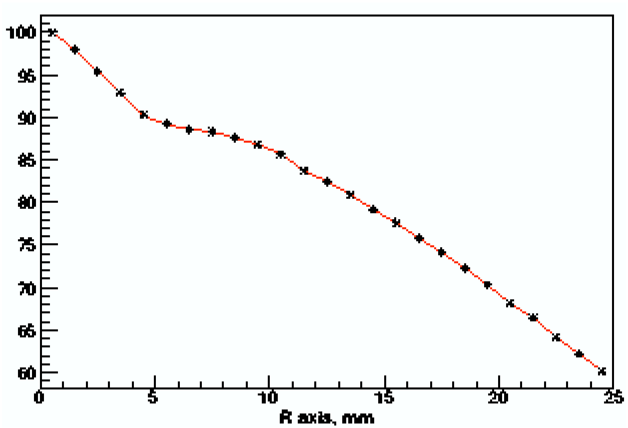
1% flat to 4 mm

1% flat to ± 300 mm

Only 4 telescope per side?

The case when there are only four telescopes per side





Acceptance falls 10% in 5 mm

No region where the acceptance is radially flat

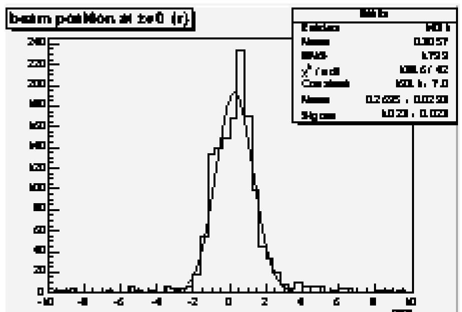
$\Rightarrow$ Need eight telescopes per side

IP Location

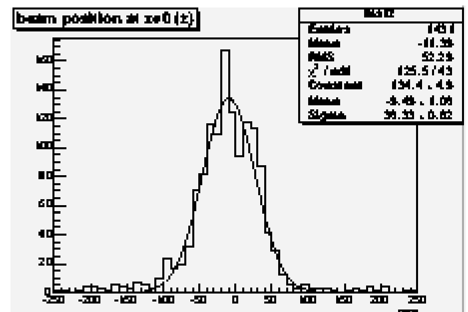
- Use pixel information to extrapolate tracks back to IP
- digital hit resolution (little or no charge sharing)
- linearly extrapolate tracks to $z = 0$
- smearing due to curvature of tracks

radial resolution | longitudinal resolution

no beam spread

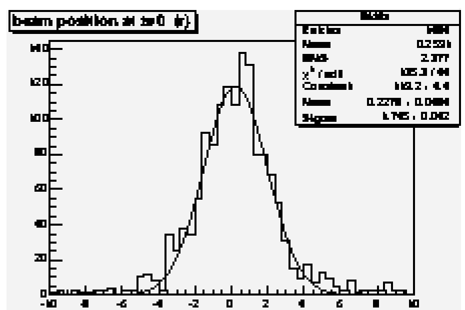


rms = 1.8 mm

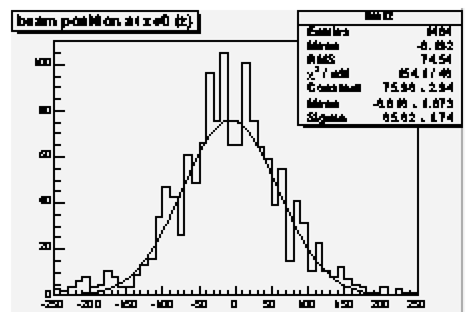


rms = 52 mm

beam spread $\sigma = 5.2$ cm



rms = 2.4 mm



rms = 75 mm

IP Centroid Precision

Resolution dominated by beam spread

- Assume 1 kHz of pixel information

  $\Rightarrow$ 100 tracks / second / telescope

- Use 4 telescopes to measure x or y position
- Use all 16 telescopes to measure z position
- radial rms = 2.4 mm
- longitudinal rms = 75 mm

Precision on relative centroid position
in one lumi section (93 s)

radially:	12 μm
longitudinally:	200 μm

PLT Status and Plans

Goal to have ~¼ PLT installed for 2009 run

Begin construction by Oct, 2008

Current status:

- **mechanical support structure installed (used for BCM also)**
- **cabling installed**
- **necessary ROCs plus aux. chips allocated**
- **power supply system purchased (same as pixel)**
- **conceptual design of DAQ (based on modified pixel VME module)**
- **conceptual plan for data logging and publishing (modeled on HF)**
- **first 12 of 48 diamond sensors in hand**

Milestones: **Oct '08:** - **Begin assembly of first 12 detector planes**

March '09:

- **Finish assembly of first 4 telescopes**
- **Complete test beam studies of 2 pixel telescopes**
- **Finish system tests and install in CMS → Need Help**

June '09:

- **Results analyzed from first 12 telescope planes**
- **Order remaining diamond sensors**
- **Begin production of remaining telescope planes**

Mar '10: - **Delivery of completed 16 telescope PLT to CERN**

PLT Summary

Luminosity monitor based on diamond pixel telescopes

- **Unique hybrid (fast coincidence, pixel) readout**
  $\rightarrow$ **most versatile luminosity monitor ever for hadron collider**
- **Precision bunch-to-bunch relative luminosity**
- **Precision measurement of IP location**
- **Measurement of beam hot spots, beam halo, and abort gap**
- **Stable reference for monitoring of CMS subdetectors and trigger**
- **Based largely on existing components: Modest cost**
- **Major milestone in development of radiation-hard detectors for SLHC and other high intensity colliders**

Long term test of diamond pixel detectors in high radiation environment under actual experimental conditions

Backup slides

Rates

Pythia simulation

0.0048 tracks / pp interaction / telescope

Taking 21 interactions per bunch crossing at $L = 10^{34}$ cm^{-2}·s^{-1}

$\Rightarrow$ 1.6 tracks in PLT / bunch crossing

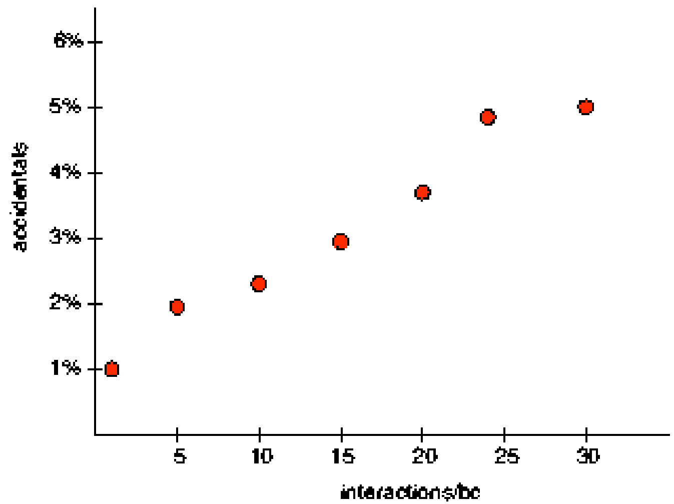
18,000 tracks per second for each of the 2835 filled orbit bunches

$\Rightarrow$ 0.75% precision in 1 second

More than sufficient

Accidentals

Accidental fraction vs. interactions per bunch crossing



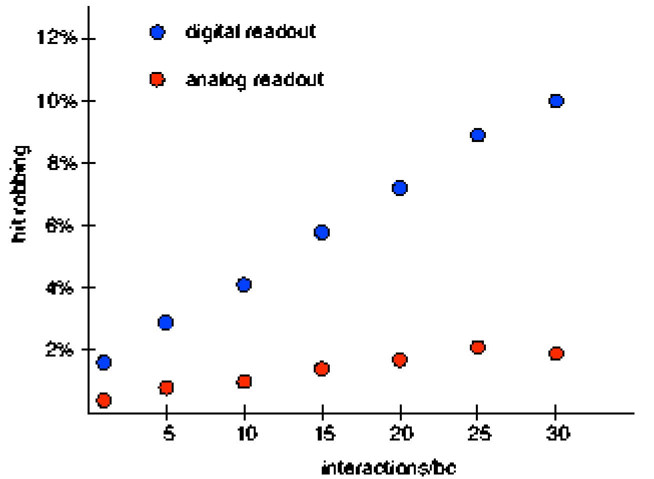
- about 4% at full luminosity
- correctable to few percent of itself using full pixel data
- can reduce active area if necessary

systematic error less than 1%

Caveat: repeat calculation with updated CMS geometry

Overlaps

Overlap fraction vs. interactions per bunch crossing



- about 8% at full luminosity (digital readout)
- about 1.5% at full luminosity (analog readout)
- correctable to few percent of itself using full pixel data

systematic error less than 1%