The Diamond Beam Monitor for Luminosity Upgrade of ATLAS

Richard Kass
Ohio State University

November 22, 2012

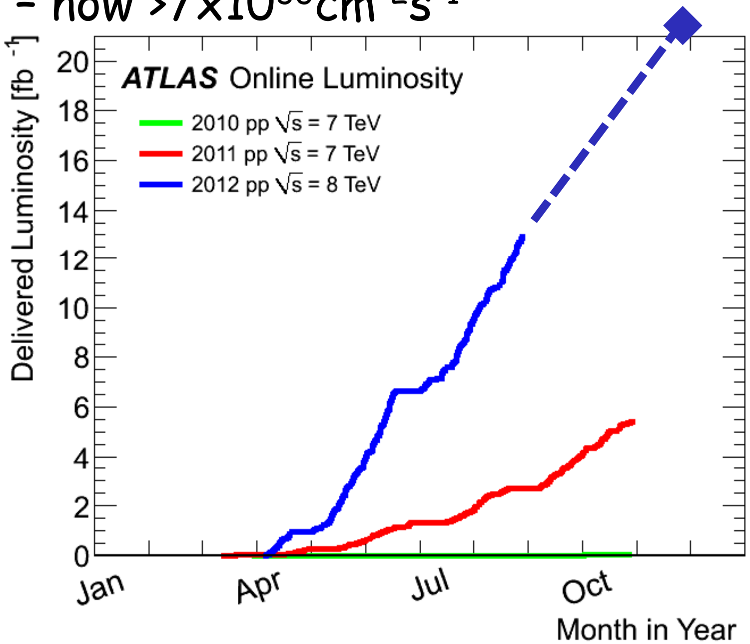
<u>Outline of Talk</u>

Motivation
The ATLAS DBM Concept
DBM Design
DBM Status
Summary

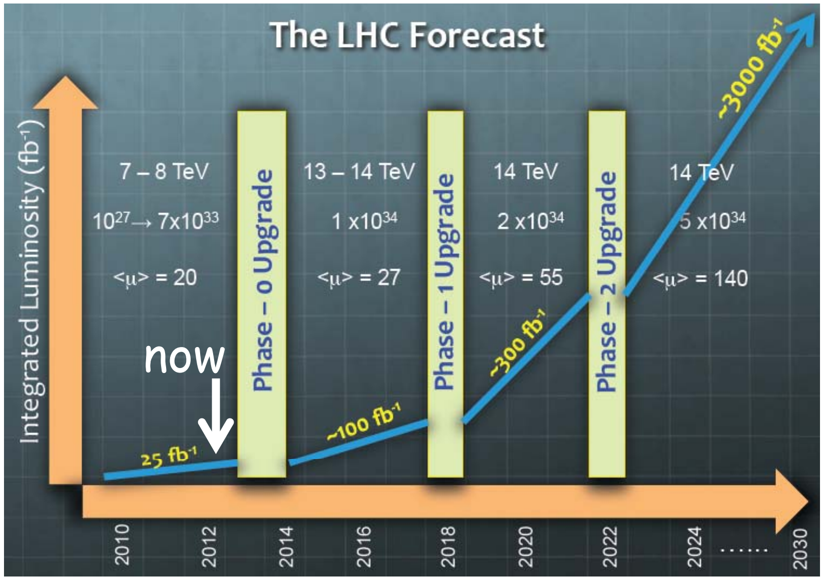
Diamond Beam Monitor Motivation

Many precision measurements limited by luminosity determination (e. g. absolute cross section measurements, pp→ZX, WZX,..)

Rapid increase in LHC Luminosity
- now >7×10^{33} cm^{-2}s^{-1}



….And L will continue to grow!



$$L = \mu(n_b f_r)/\sigma_{inel}$$

μ=average # of inelastic interactions per bunch crossing

n_b= # of colliding bunch pairs
f_r= machine revolution frequency
} LHC parameters

σ_{inel}= inelastic cross section

Luminosity is a counting issue: requires good segmentation in space or time

Problems occur when μ can not be reliably measured

Diamond Beam Monitor Motivation

In order to make a precise determination of the luminosity at the highest instantaneous luminosity & energy we need a detector that is:

- radiation hard: accumulate $2\times10^{15}\ n_{eq}/cm^2$
- fast: ~nsec resolution, resolve beam bunches
- stable/reliable: last for ~ "10 years"
- sensitive to charged particles: prefer min. ionizing

Diamond is a good sensor candidate...

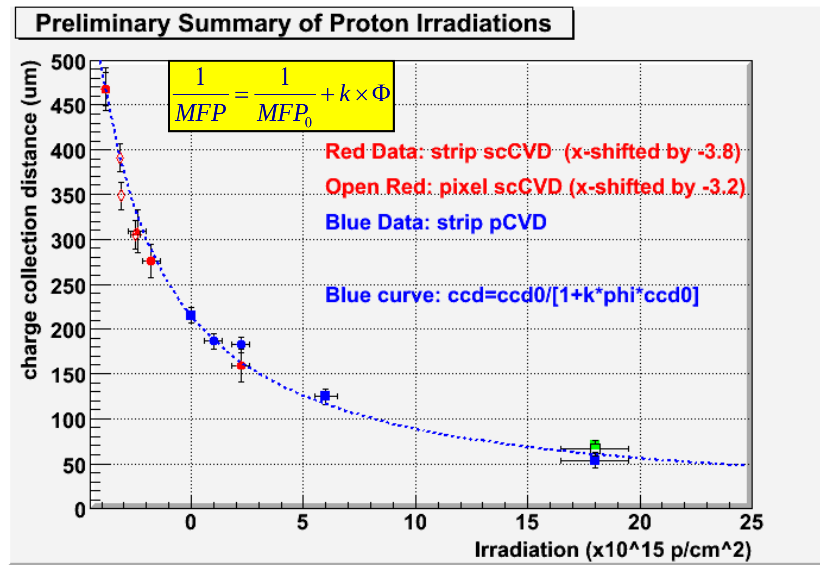
Chemical Vapor Deposition Diamond

The properties of diamond make it interesting/useful for particle detectors:
radiation hard, short collection time, low leakage current, high thermal conductivity

Diamond as sensor material

Property	Diamond	Silicon
Band gap [eV] □ Low leakage	5.5	1.12
Breakdown field [V/cm]	10^7	3×10^5
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	2.3×10^5
Intrinsic carrier density [cm^{-3}]	$< 10^3$	1.5×10^{10}
Electron mobility [cm^2/Vs]	1900	1350
Hole mobility [cm^2/Vs]	2300	480
Saturation velocity [cm/s]	0.9(e)-1.4(h)x 10^7	0.82x 10^7
Density [g/cm^3]	3.52	2.33
Atomic number - Z	6	14
Dielectric constant – ε □ Low cap	5.7	11.9
Displacement energy [eV/atom] □ Rad hard	43	13-20
Thermal conductivity [W/m.K] □ Heat spreader	~2000	150
Energy to create e-h pair [eV]	13	3.61
Radiation length [cm]	12.2	9.36
Interaction length [cm]	24.5	45.5
Spec. Ionization Loss [MeV/cm]	6.07	3.21
Aver. Signal Created / 100 μm [e_0] □ Low Noise, Low signal	3602	8892
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323

Radiation Studies



Single-crystal CVD & poly CVD fall along the same damage curve

Proton damage well understood

At all energies diamond is >3x more radiation tolerant than silicon

ATLAS Already has 2 Diamond Based Systems

The Beam Condition Monitor (BCM)

The Beam Loss Monitor (BLM)

Both of these systems monitor the LHC beams:

- **can abort the LHC beams**
- **useful for determining luminosity**

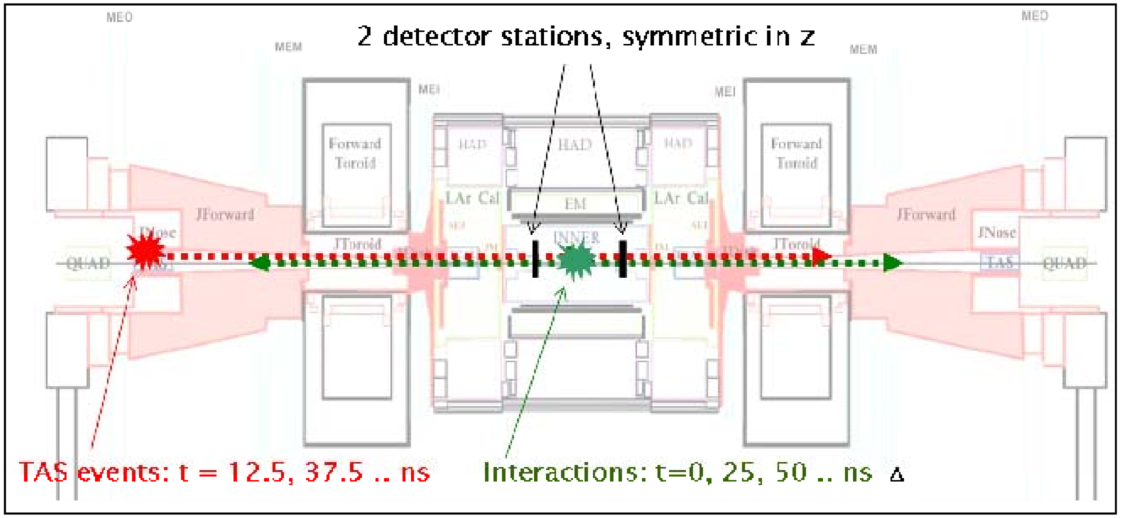
ATLAS Beam Conditions Monitor

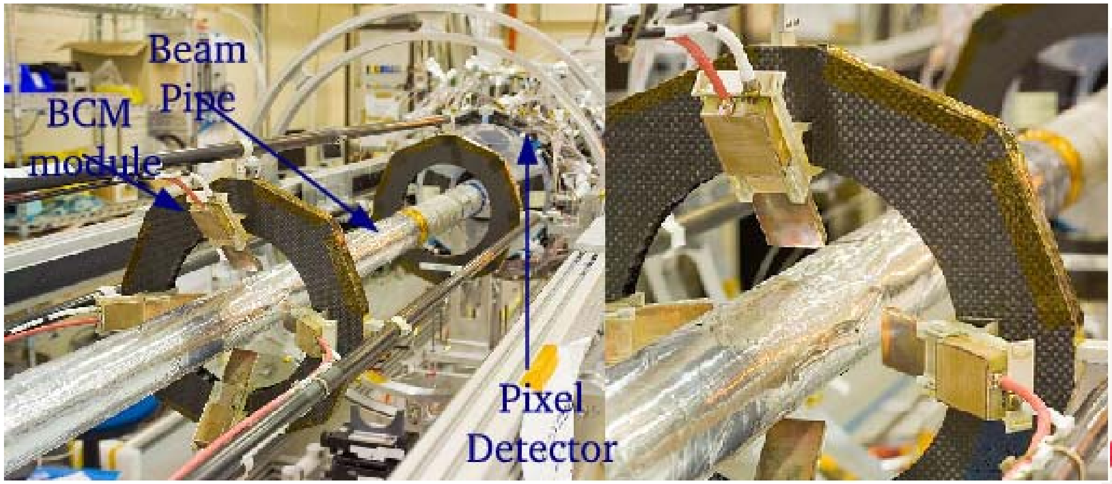
The ATLAS BCM plays a key role in data taking

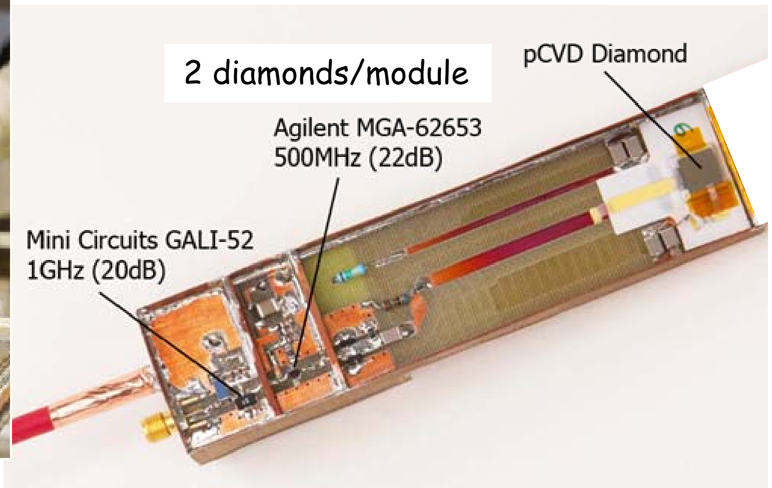
luminosity measurement + protection

BCM uses 16 pCVD diamonds (1 x 1 cm^2)

z=±184 cm
r=5.5 cm
|η|=4.2

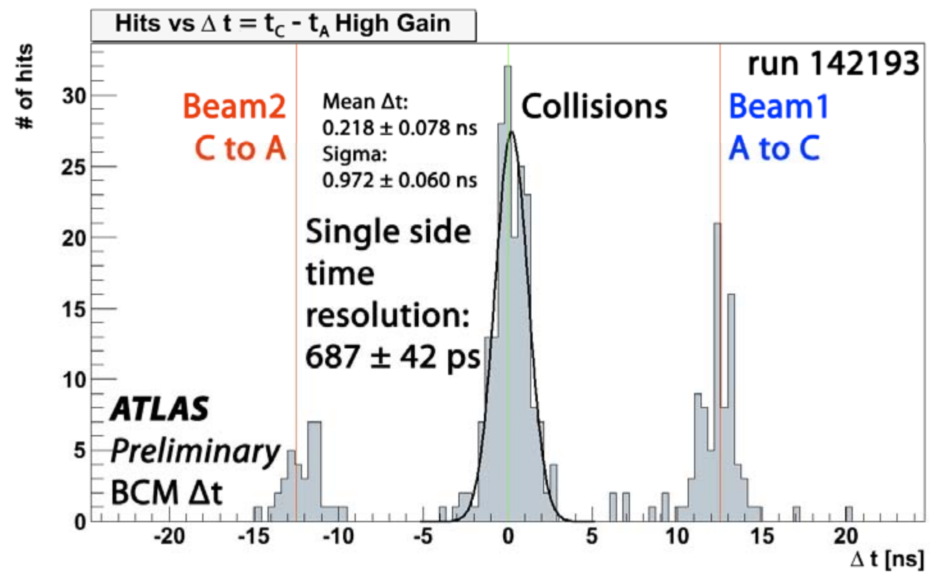




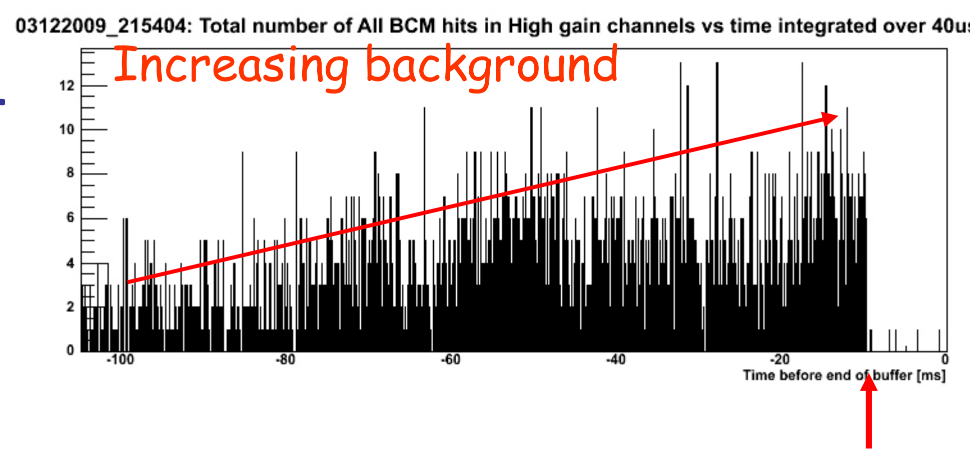


Data taking with the ATLAS BCM

- BCM achieved 687ps timing
- BCM can distinguish real collisions from background

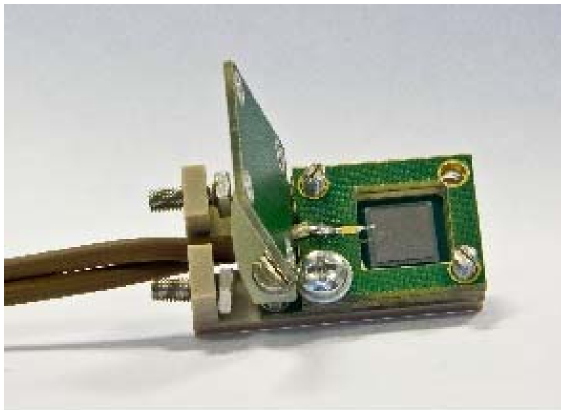


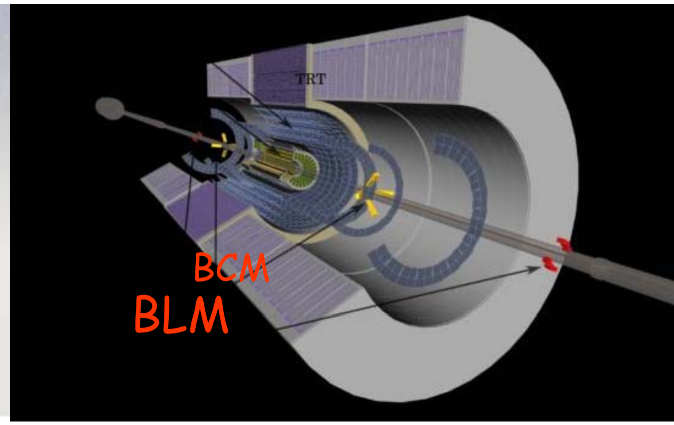
- BCM stores a record of 1177+100 orbits
- BCM sensitive enough to abort the beams

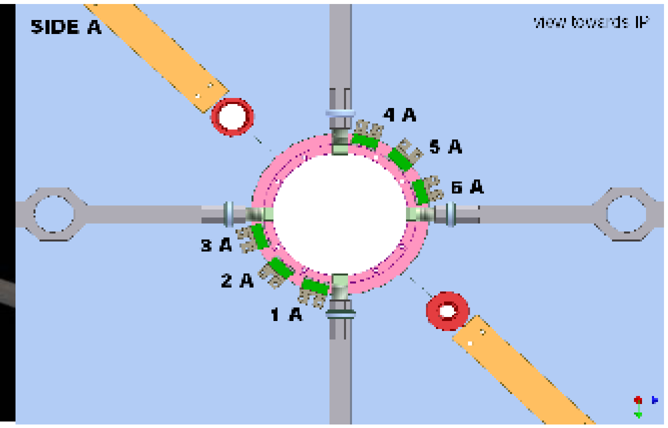


ATLAS Beam Loss Monitor

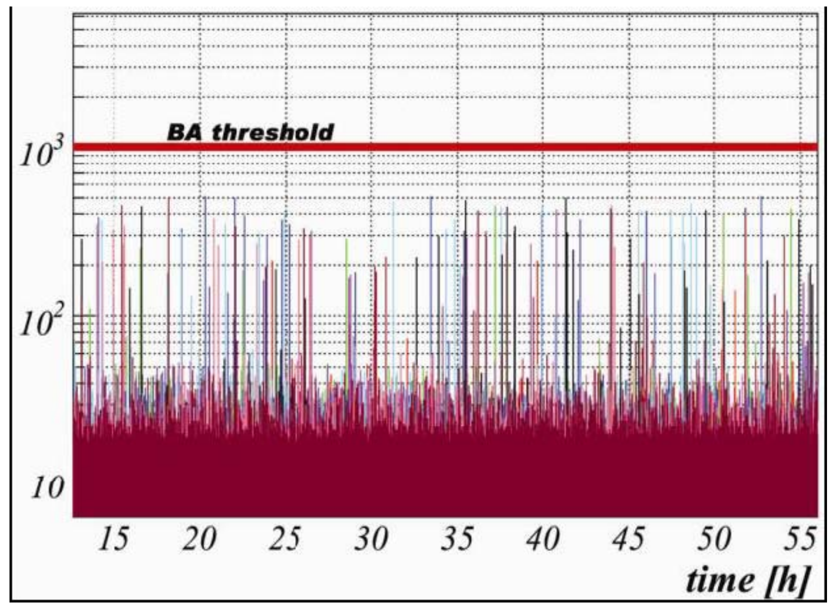
BLM uses 12 pCVD diamonds, 6 per side
z=±345cm, r=6.5 cm







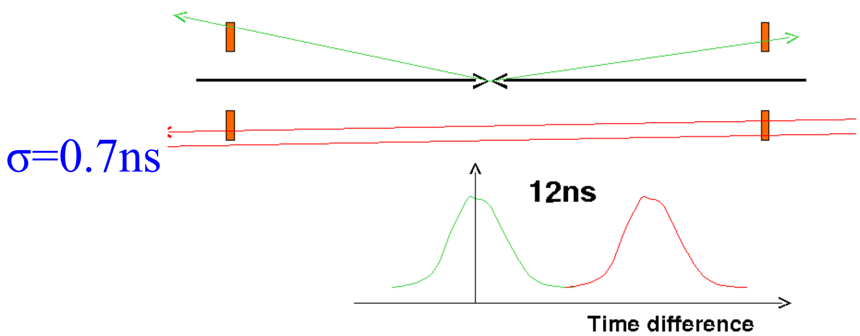
- BLM extends the range of the BCM and adds redundancy
- BLM running sums give count rate for a given time interval (μs to s)
- Both BCM and BLM operate continuously
- Aborts beam when necessary

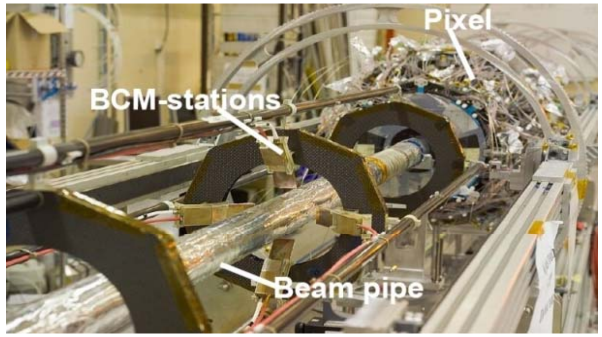


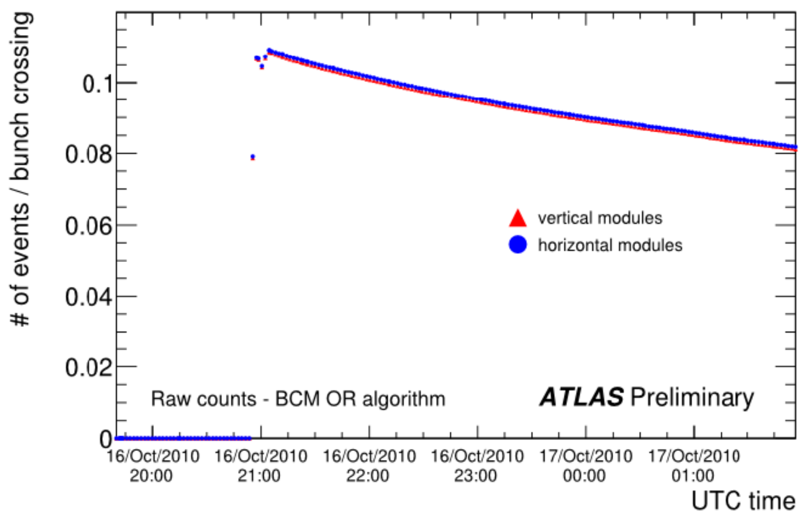
DBM Motivation: lessons learned

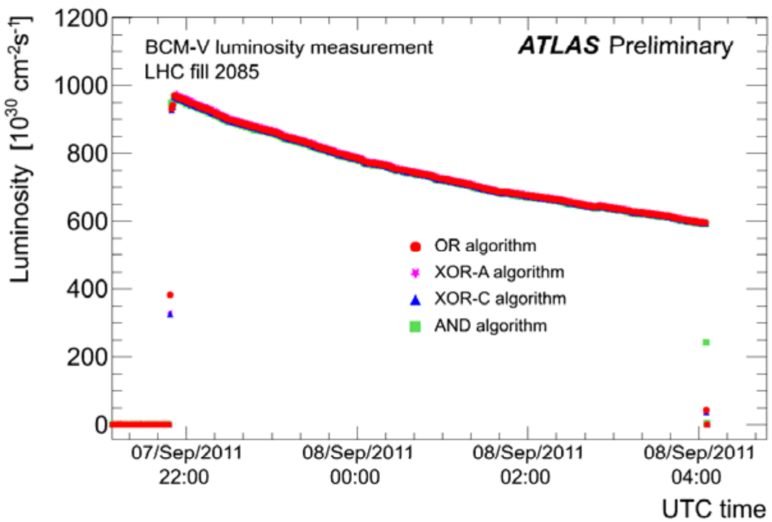
Luminosity measurement with the ATLAS diamond BCM

Single Particle Counting: in-time Luminosity & out-of-time Background
Flexible: Can run as "OR", "AND", horizontal, vertical





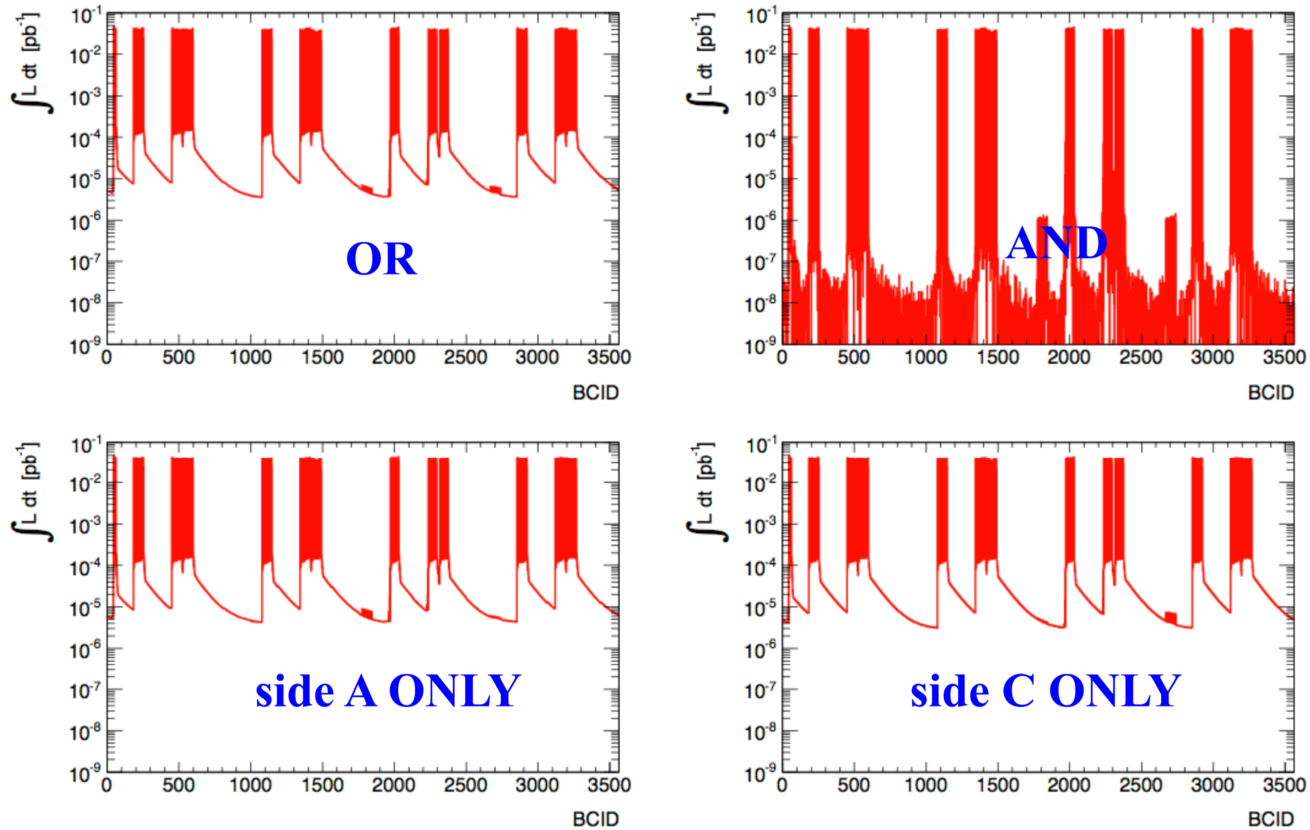




Speed, robustness, stability required for good luminosity measurement

DBM Motivation: lessons learned

The BCM rate (speed) is Beam Crossing ID aware

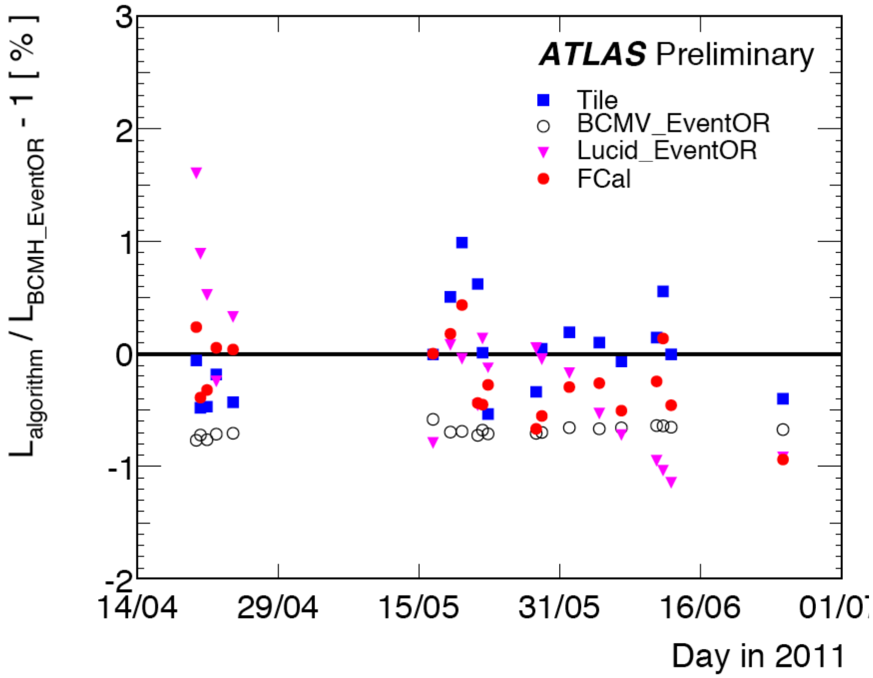


Provides robust rate measurements, ~ 10^{-3} backgrounds

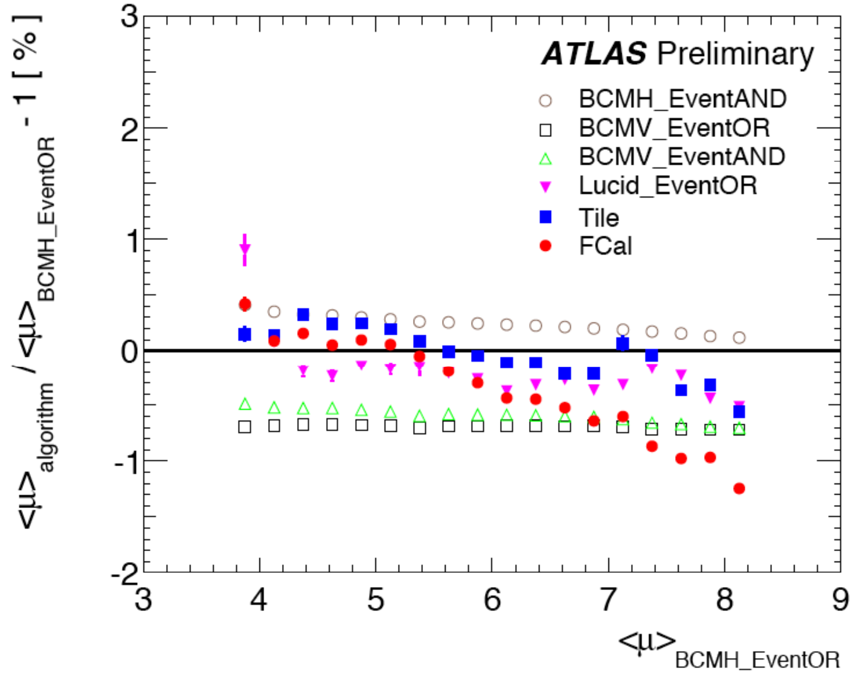
DBM Motivation: lessons learned

Two independent luminosity measurements BCMH & BCMV:
(H=horizontal, V=vertical)

Stable over months



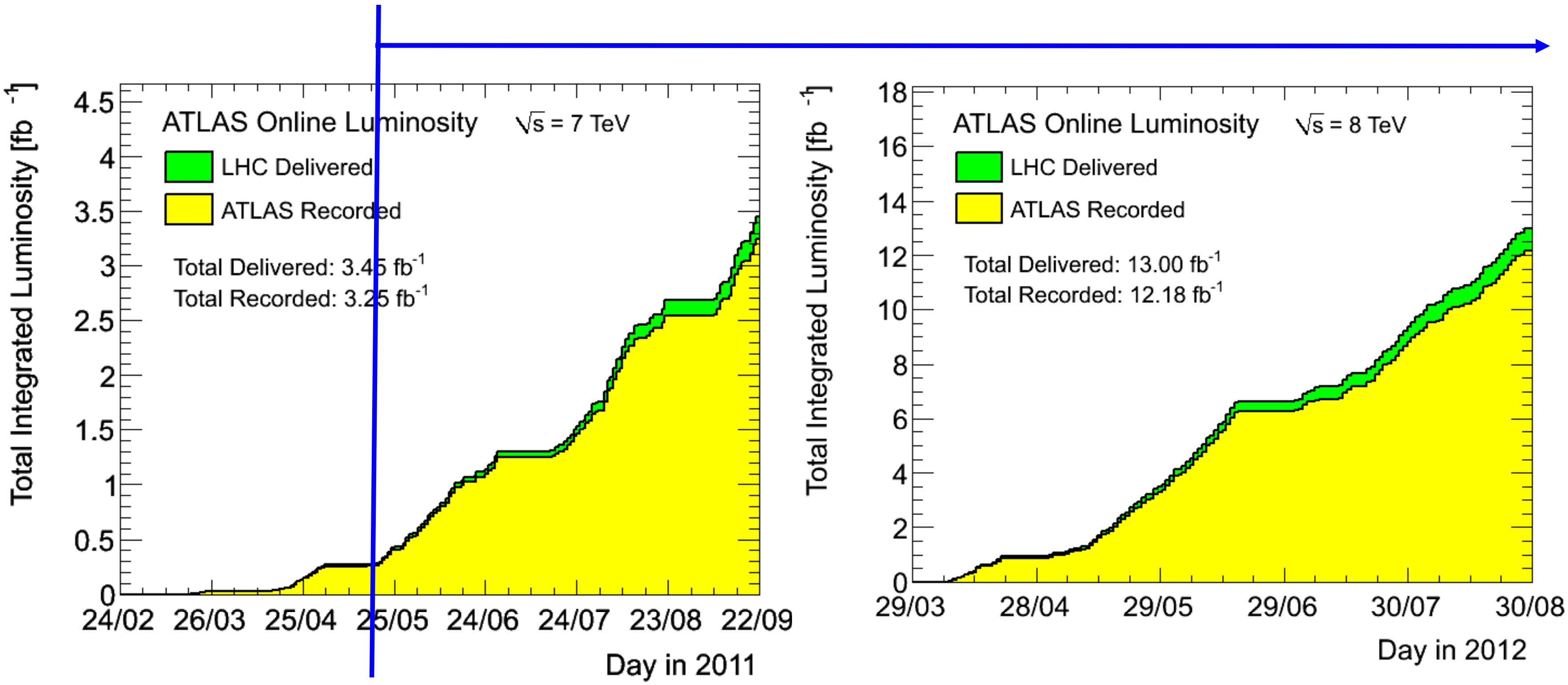
Stable against pile-up



In 2011 BCM achieved a 1.9% luminosity measurement!
(BUT issues with vDM scans increased systematic error to ~3.5%)

DBM Motivation: lessons learned

The BCM is preferred ATLAS luminosity device since early 2011:

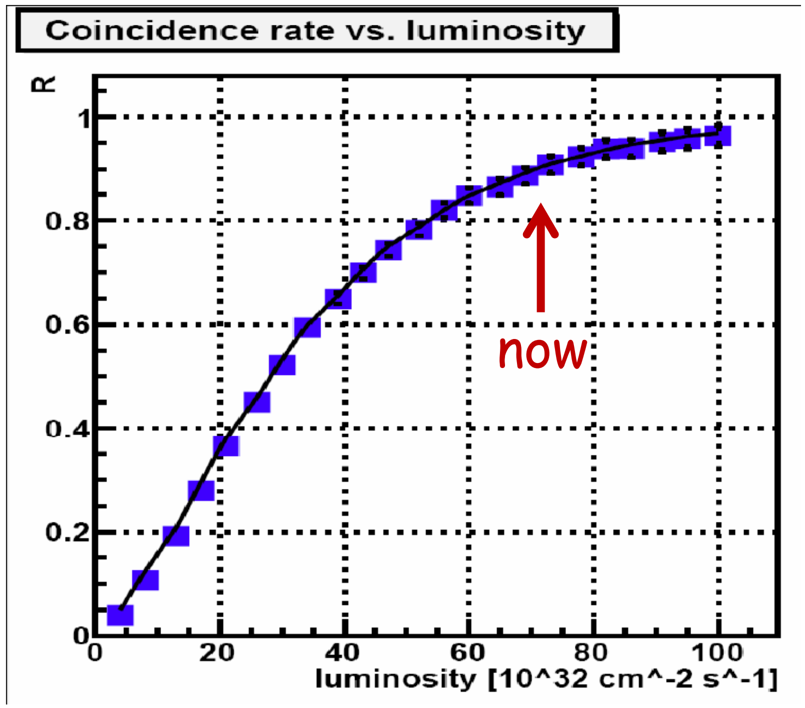


Calibrated in Van der Meer scans

Operates when other systems are not active!

DBM Motivation

The BCM will begin to saturate at ~10^{34} $cm^{-2}s^{-1}$:



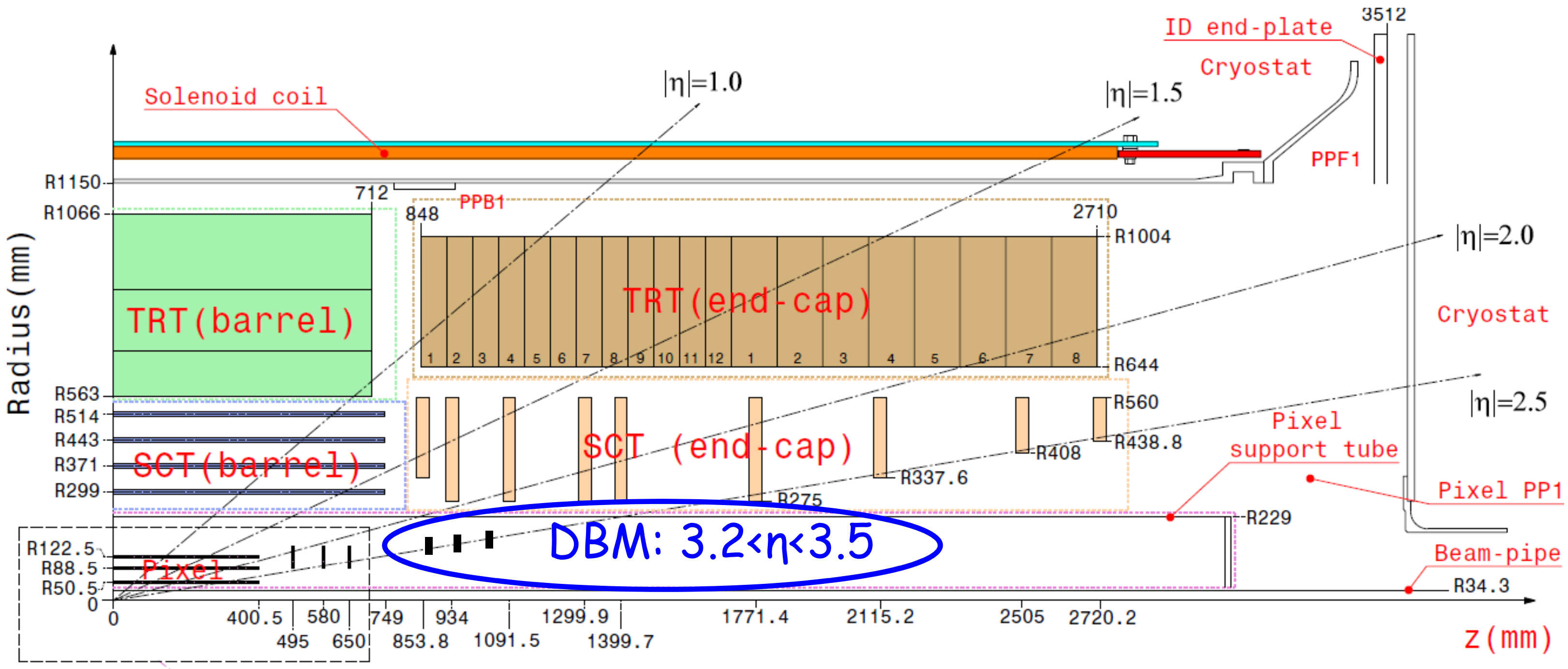
More segmentation → Diamond Beam Monitor (DBM)

Increase number of channels by ~ 10^5

The ATLAS DBM Concept

Build on success of BCM – pixelate the sensors

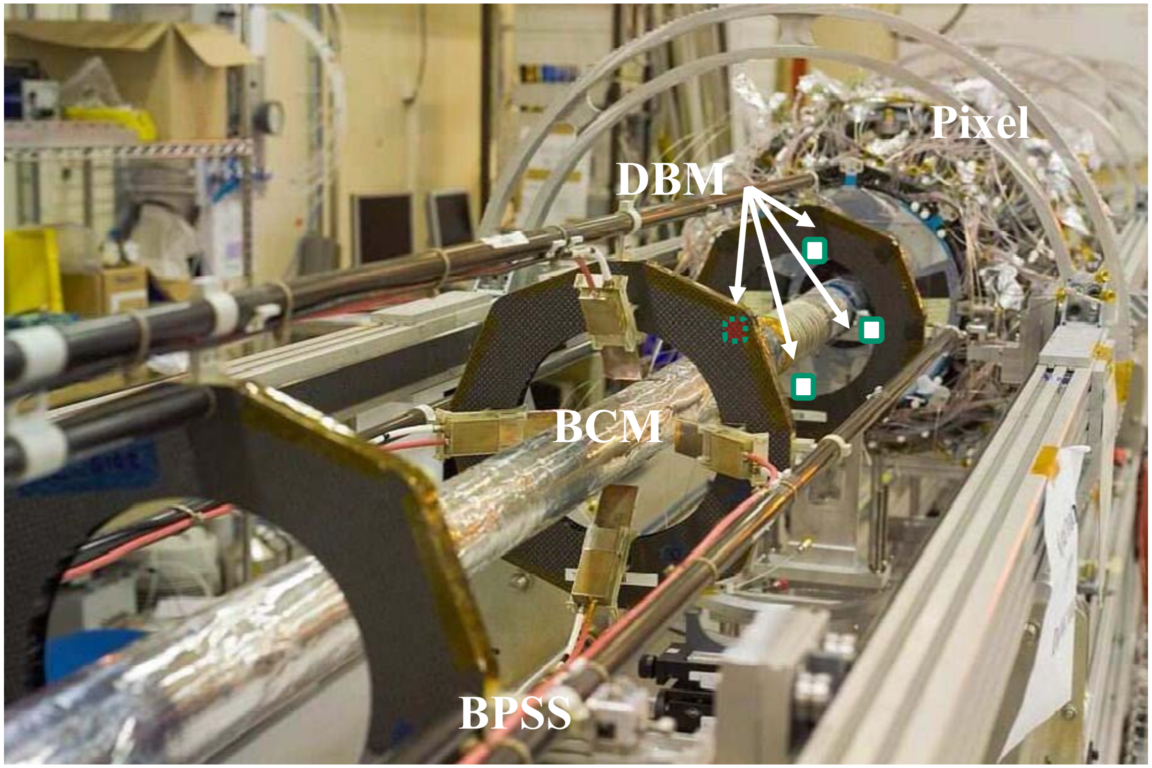
- Use IBL diamond pixel demonstrator module
  - use many of the same pieces (FEI4, etc) as IBL to save time/money
  - same segmentation as IBL sensors, 50 x 250 μm^2
- Install during new Service Quarter Panel (nSQP) replacement
- Four 3-plane stations on each side of the IR



The ATLAS DBM Concept

24 diamond pixel modules arranged in 8 telescopes provide
- Bunch by bunch luminosity monitoring
- Bunch by bunch beam spot monitoring

Installation in summer 2013



The ATLAS DBM Specs and Collaboration

Specs:

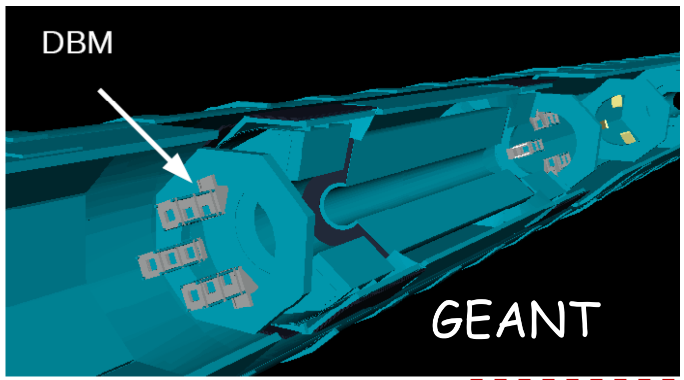
- Bunch by bunch luminosity monitoring (<1% stats/sec)
- Bunch by bunch beam spot monitoring (unbiased sample, ~ 1cm)

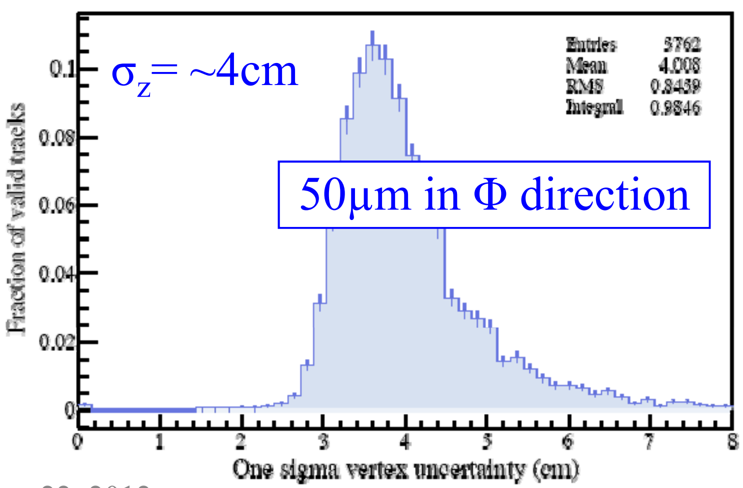
Bonn CERN Göttingen Ljubljana N.Mexico OhioSt Toronto

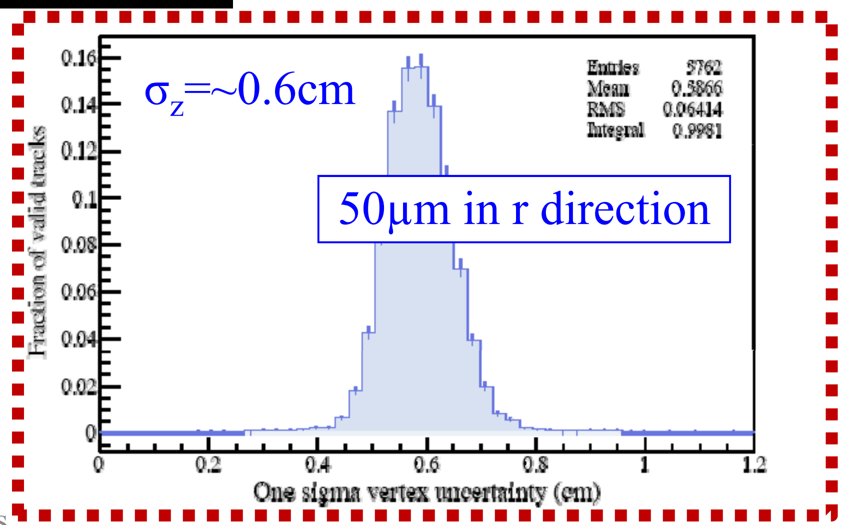
The ATLAS DBM Tracking Simulation

Simulate DBM to find best orientation and resolution

- Focus on z vertex resolution (momentum resolution bad)
- 3 layers of tracking with 50 x 250 μm^2 pixel cell
- Two choices of pixel orientation, pick the one that gives the best z-vertex resolution



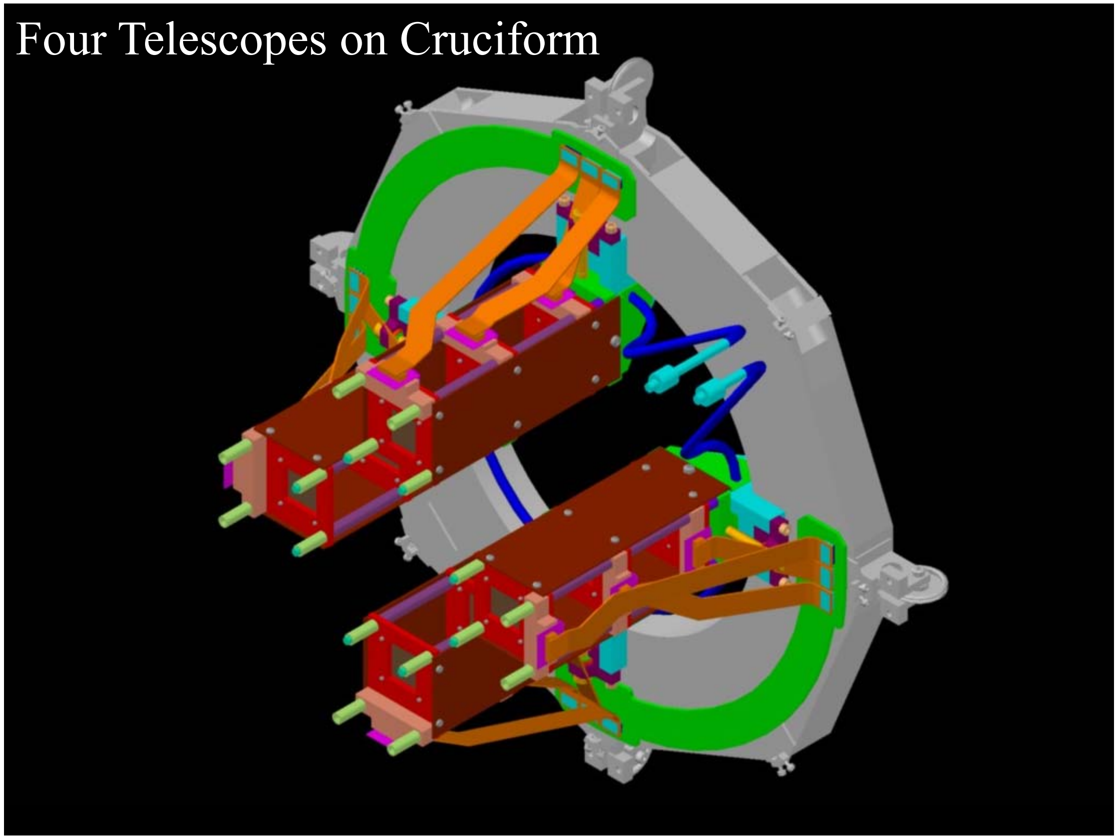


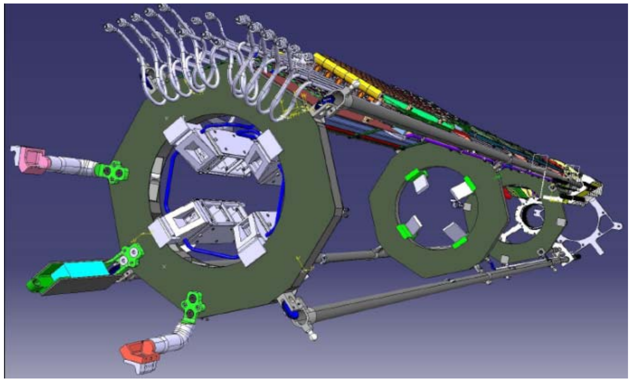


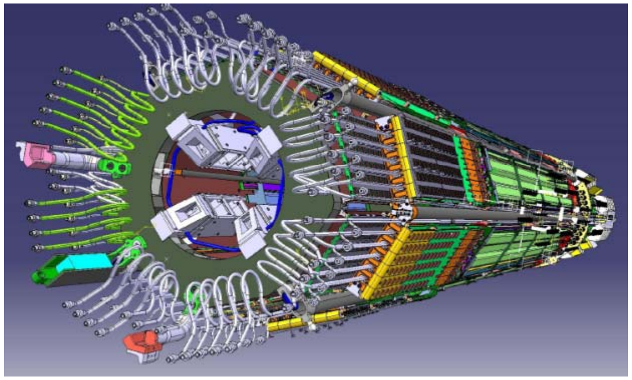
The ATLAS DBM Concept

Mechanics finalized – use as many IBL parts as possible

Mechanical simulations complete → Al, AlN, Peek

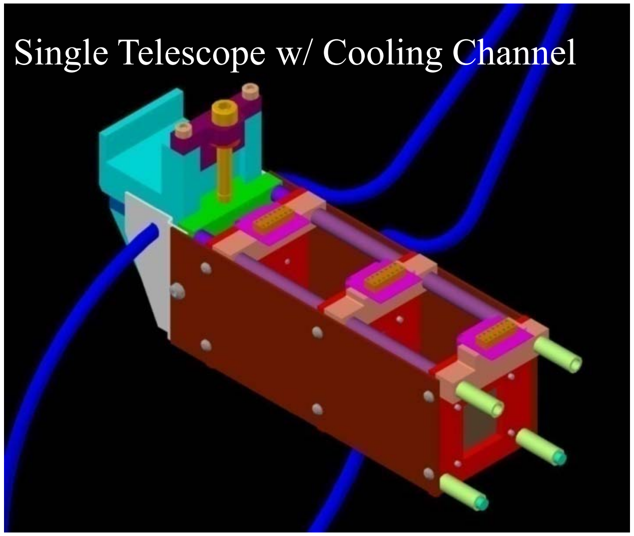


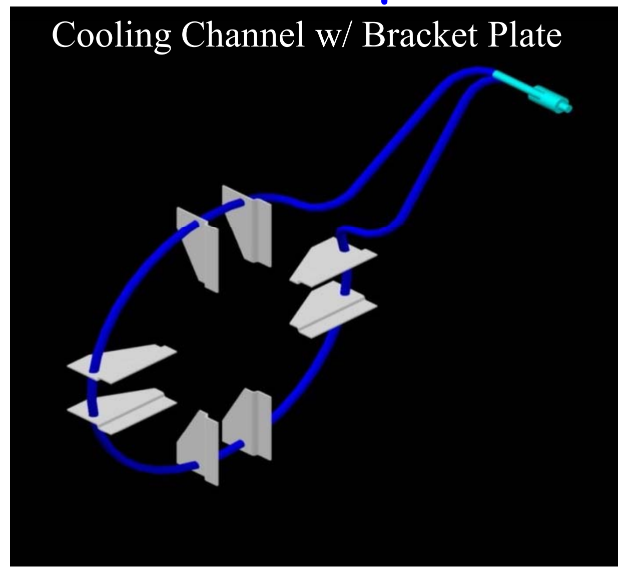


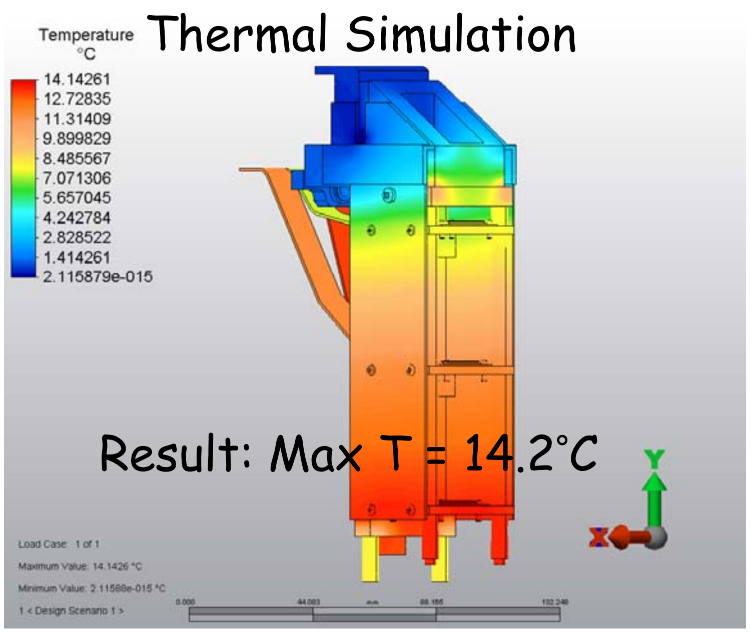


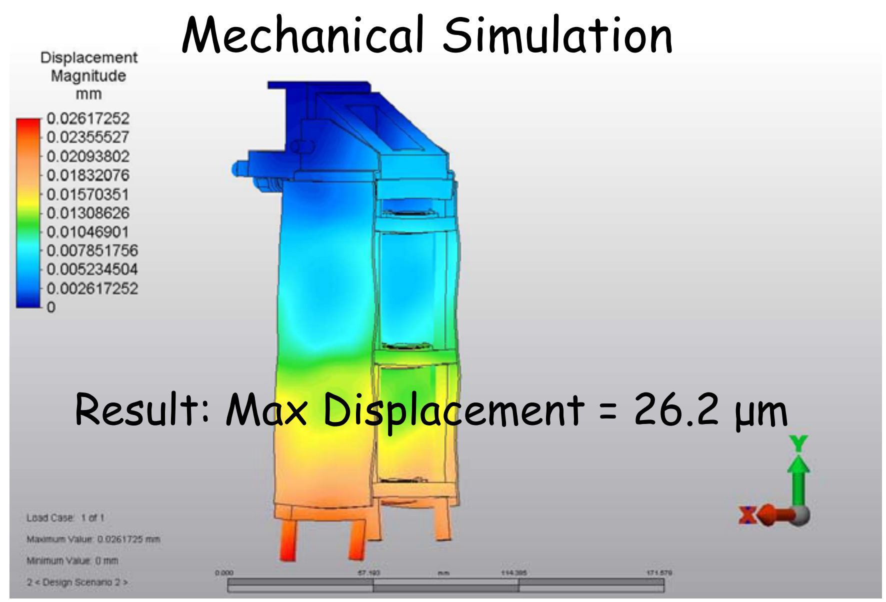
The ATLAS DBM Concept

Thermal & mechanical simulations complete









DBM Diamond Sensor Plan

Diamond Sensors for DBM:

Type: polycrystalline CVD diamond
Charge collection distance > 250 μm
(as measured with Sr90 source)
Size: 21 x 18 mm^2, 525 ± 25 μm thickness
Number: 24 for DBM modules + spares
5 for Irradiation studies

21 x 18 mm^2 pCVD diamond

Two diamond suppliers involved:

Diamond Detectors Limited (DDL)/E6 (UK based)
II-VI (US based)

How much Diamond is in the DBM?

About as much as in the diamond Richard Burton bought for Liz Taylor in 1969

~ 70 carats

Auctioned in 1978 for $5M

http://en.wikipedia.org/wiki/Taylor-Burton_Diamond

Each DBM sensor is ~ 3.2 carats

(1 carat= 200 mg)

Entire DBM: 24 sensors

~ 76 carats!

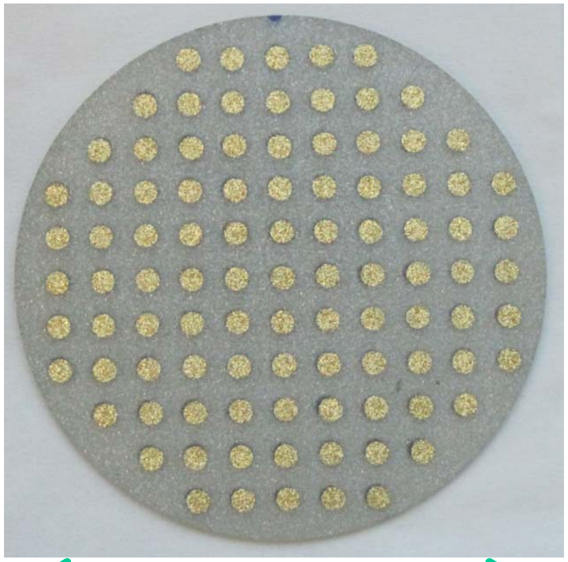
Price of all DBM diamond < $150k

DBM Diamond Sensor Qualification

At OSU we put conducting contacts ("gold dots") on the diamond & measure the charge collection properties in the region of each dot.

Use Sr90 as a source of particles for charge collection measurements

A wafer from DDL



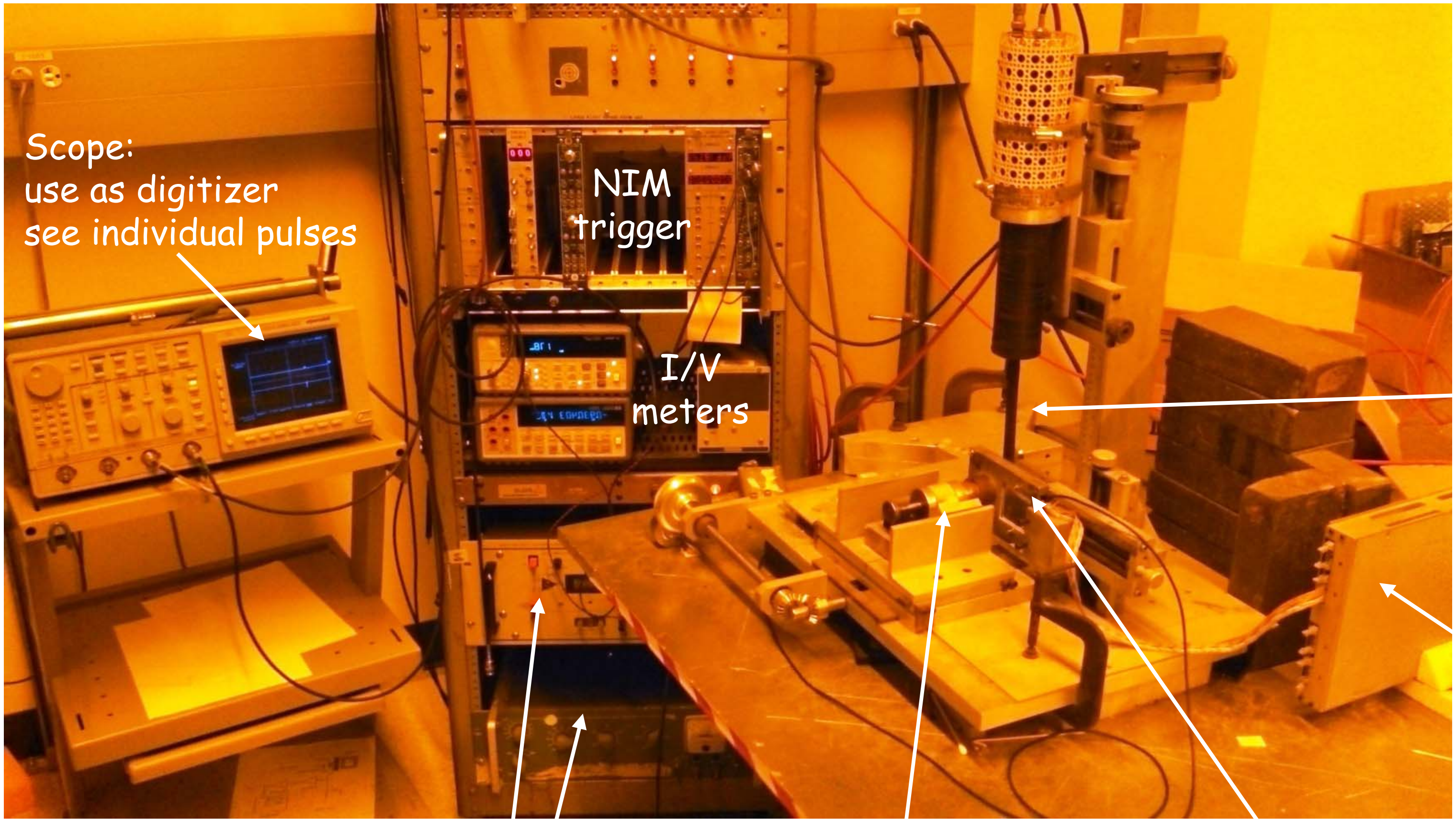
5 inches

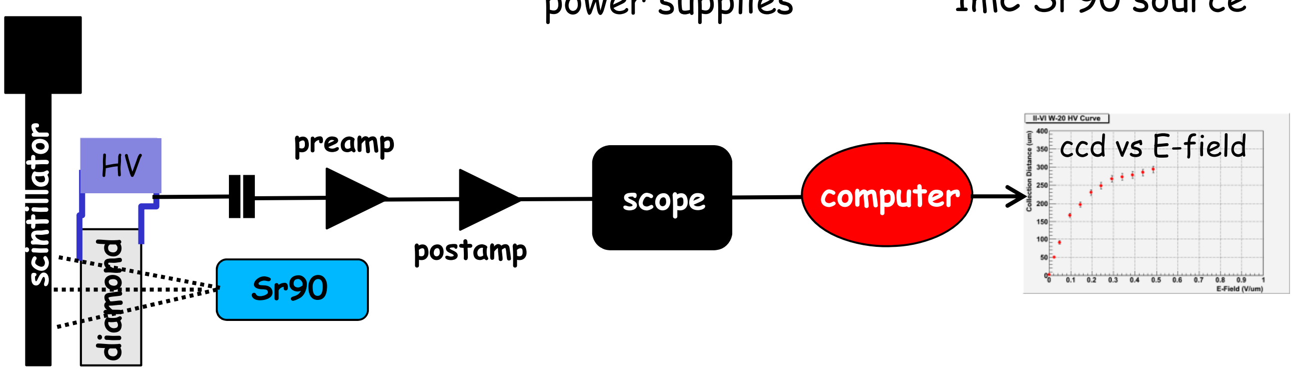
5 inches

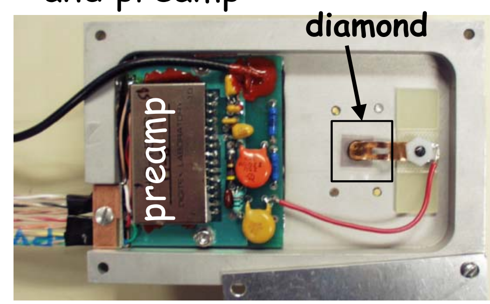
We also make a map of the current draw as we measure CCD

Good regions have I < 5 nA at 1000V in air

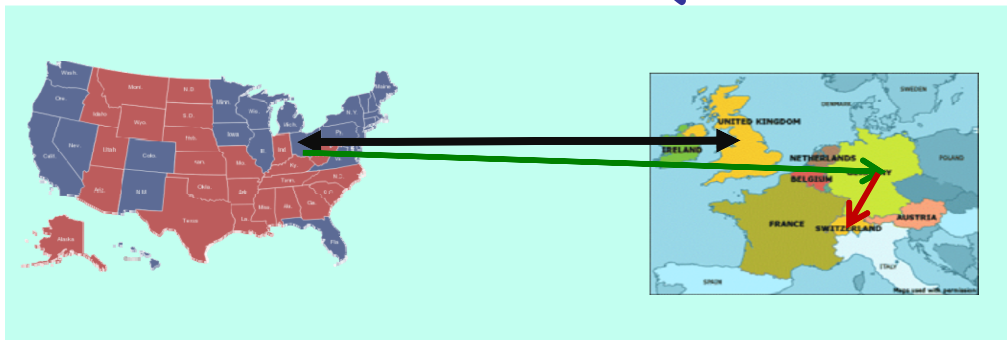
CCD measurement with Sr90 @ OSU

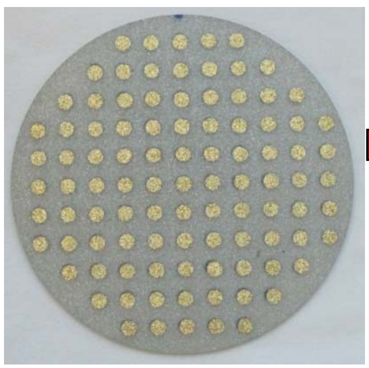




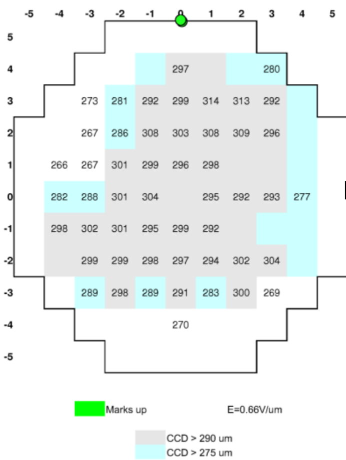


DBM Diamond Sensor Qualification

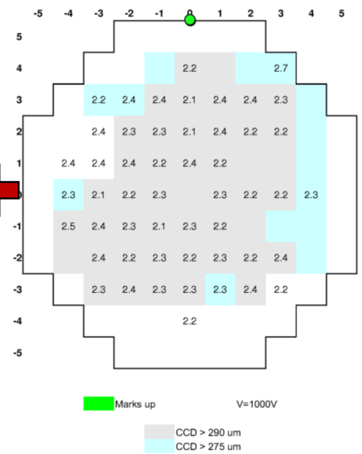




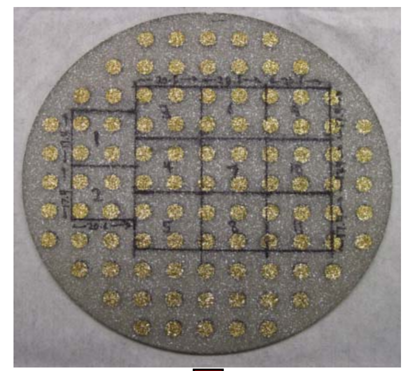
Map of charge collection distances



Map of current draw

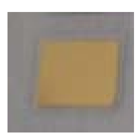


"Cut" map
This wafer will be cut into 11 sensors



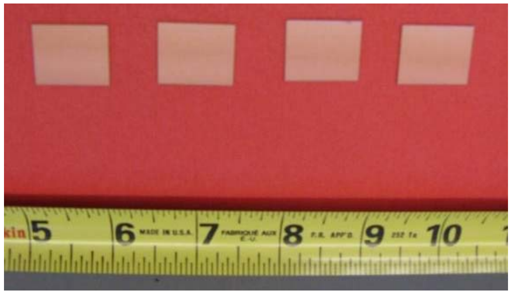
Back to manufacturer for dicing & thinning

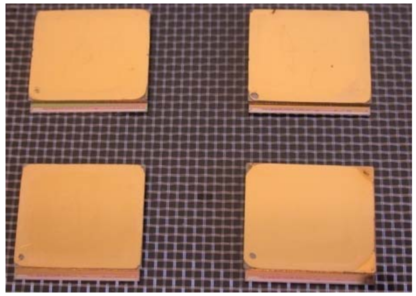
Back to OSU re-test with Sr90, metalize backplane

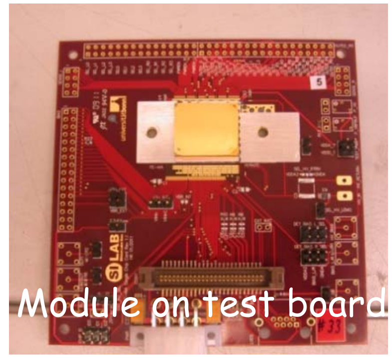


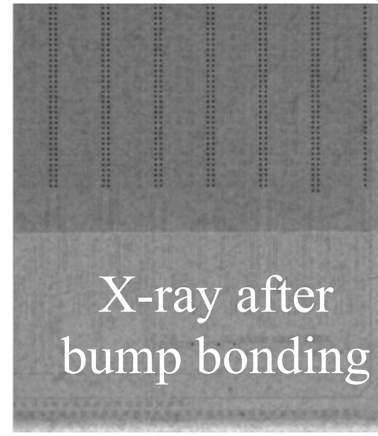
To IZM for bump bonding, etc

DBM Module Production



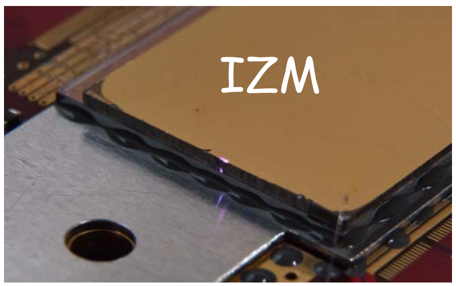


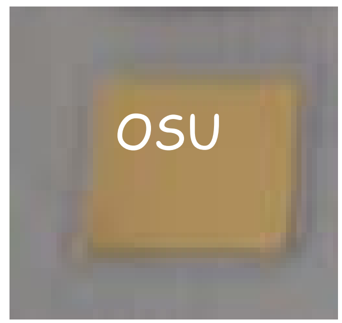




HV Problems with first modules from IZM

- Backside metalization goes to the edge of diamond and breaks down
- Fixed by changing back metalization procedure
  - no longer performed by IZM, performed at Ohio State



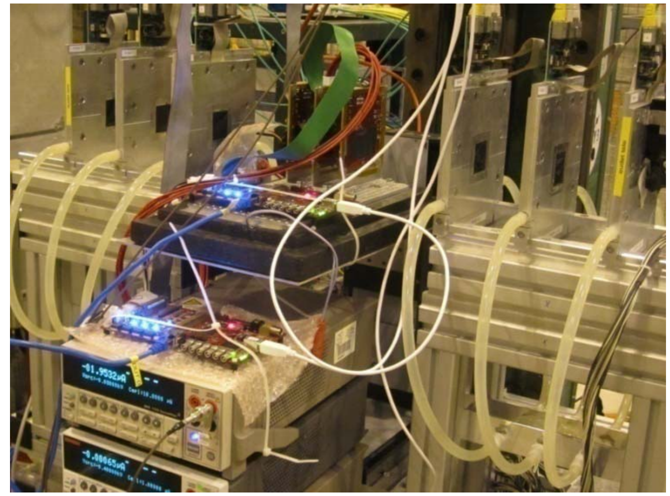


14 sensors currently at IZM

- put pixel pattern on diamond
- bump bond diamond to FEI4

DBM Module Testbeam

- Three Testbeam campaigns
  - Oct 11, Mar 12, Jun 12
- Learning about FE-I4 performance
  - Calibration/tunings for low threshold performance

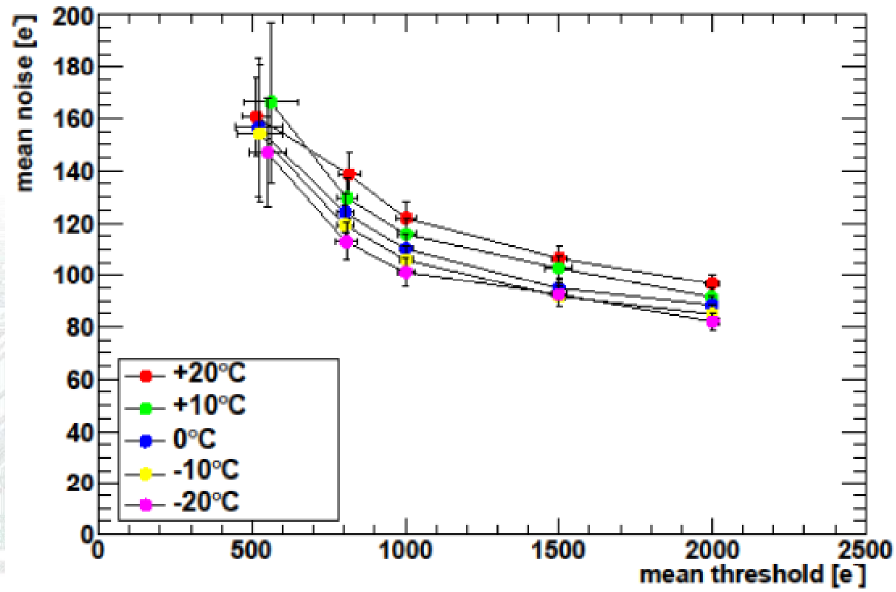


What is possible?

x = October 2011 DBM Test Beam

Gain \ Threshold	500e	800e	1000e	1500e	2000e
8ToT@3ke	x	x			
8ToT@5ke	x	x		x	
8ToT@8ke	x	x		x	x
8ToT@10ke		x			
8ToT@15ke					

„Green Valley“



DBM Module Testbeam

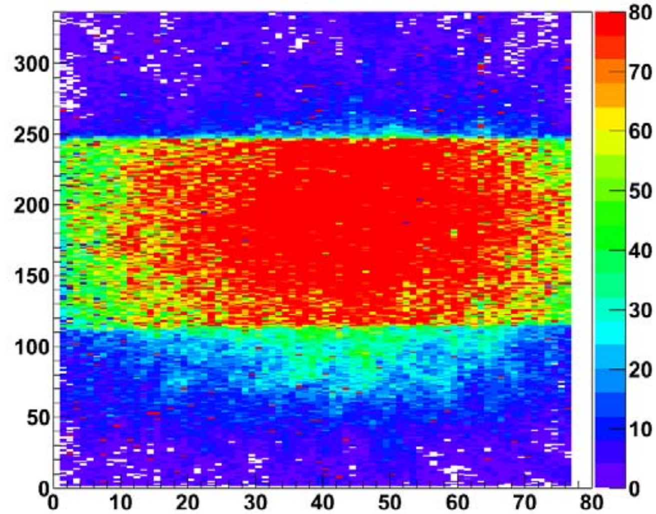
Prototype Modules Tested:

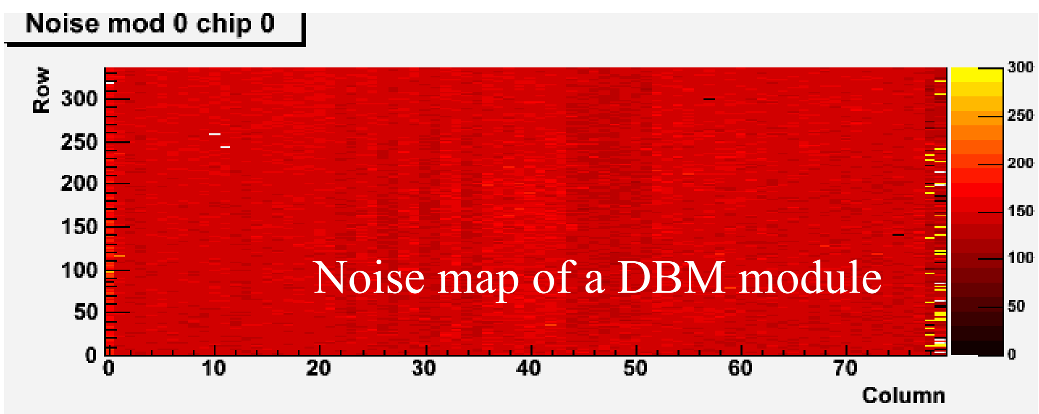
- 21mmx 18mm pCVD diamond w/FE-I4
- 336 x 80 = 26880 channels
- 50 x 250 μm^2 pixel cell

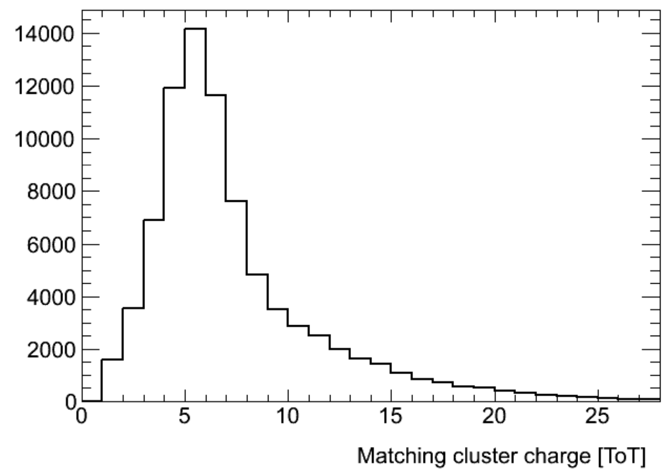
Results

- Noise map uniform
- Efficiency >95%

Hit Map







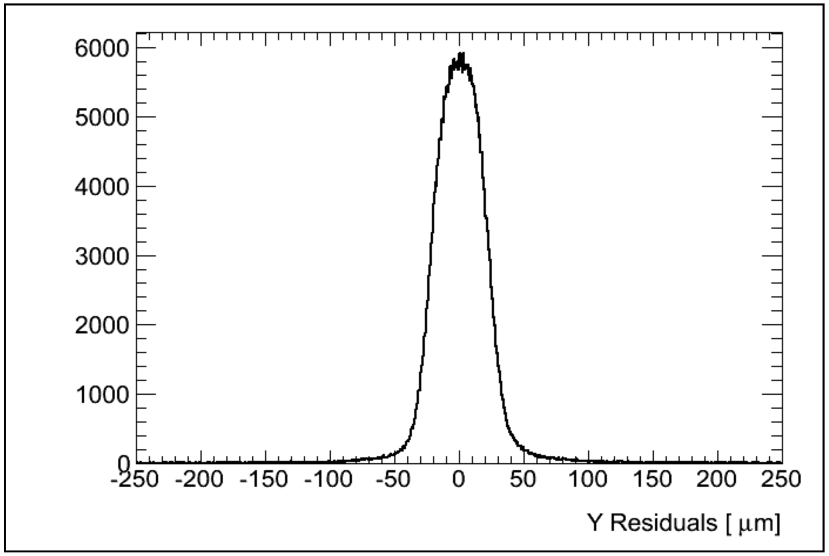
DBM Module Testbeam

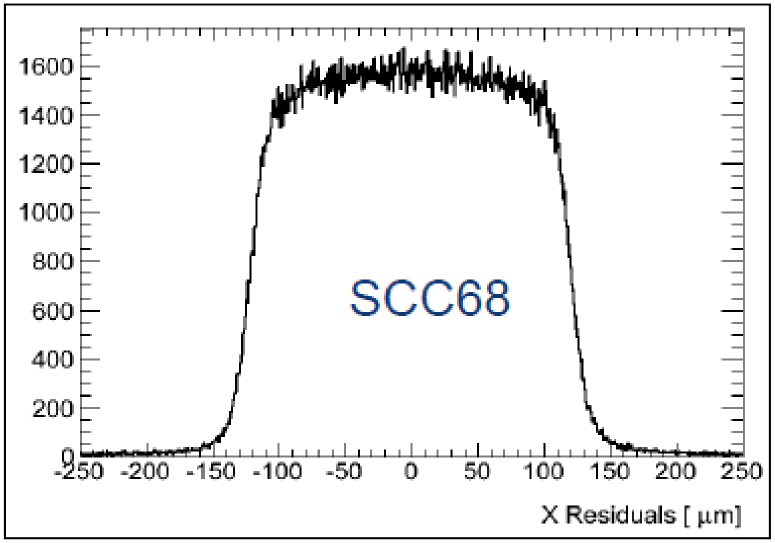
Prototype Modules Tested:

- 21mmx 18mm pCVD diamond w/FE-I4A
- 336 x 80 = 26880 channels
- 50 x 250 μm^2 pixel cell

Results

- Spatial resolution looks digital





OSU's DBM Hitbus Chip Overview

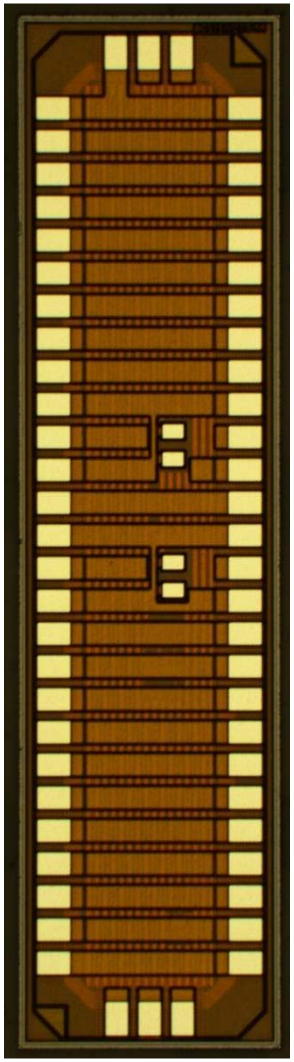
ASIC developed to provide L1A trigger for the DBM by using the FEI4 Hitbus outputs

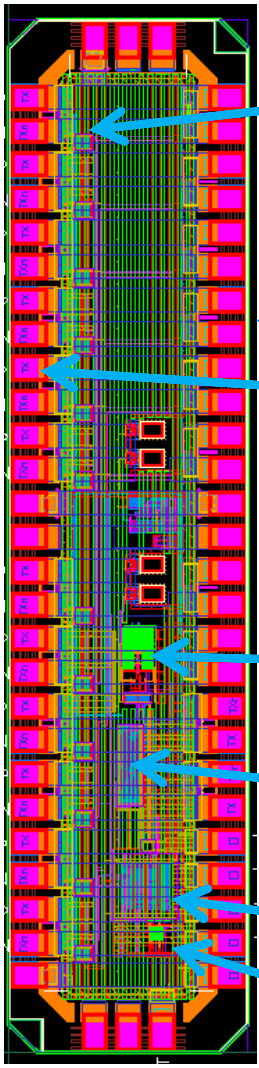
Each DBM hitbus chip services 2 telescopes so 4 chips needed for entire DBM

Use IBM 130nm 8RF CMOS

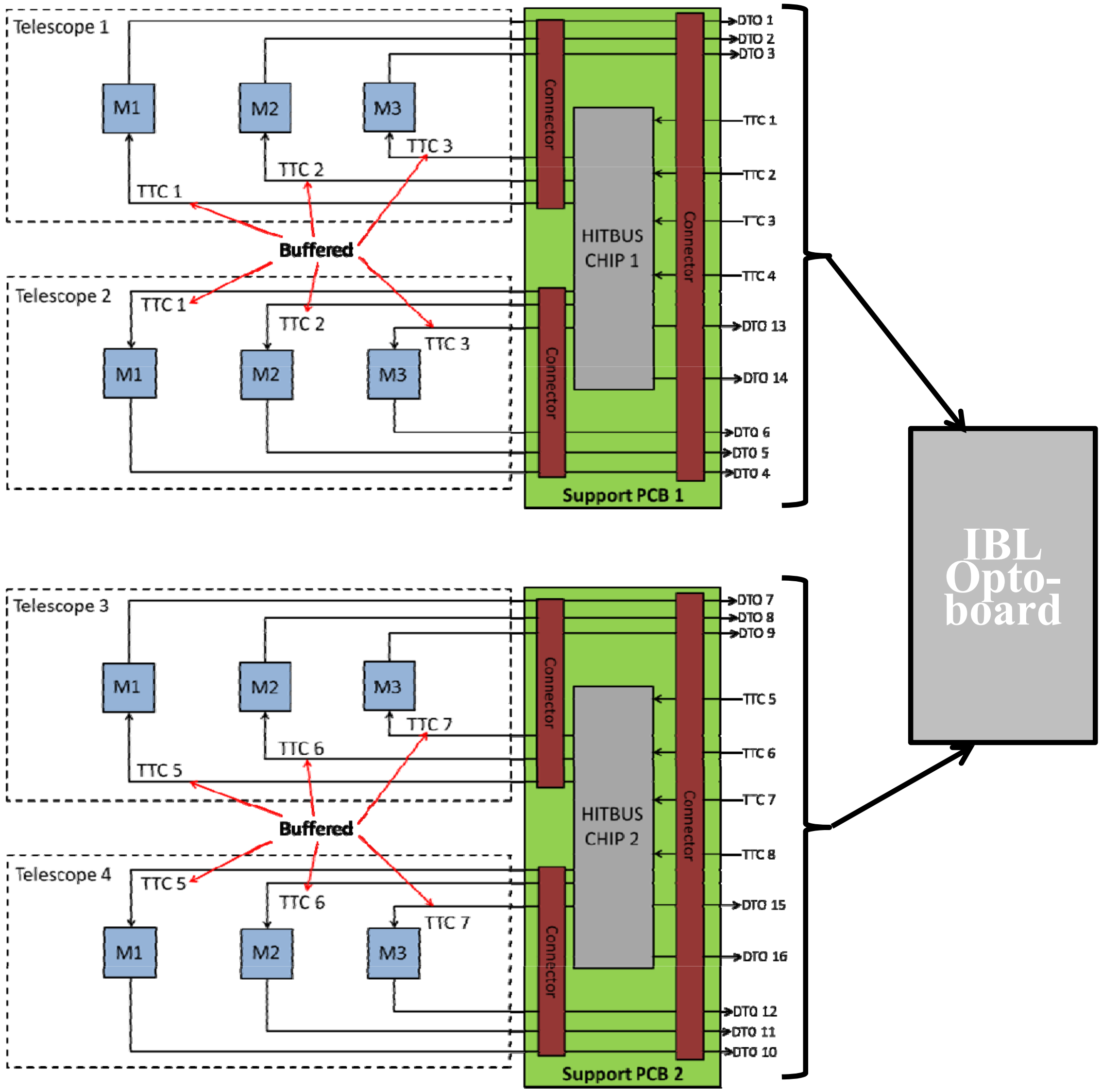
Size: 4.59 mm x 1.06mm

Incorporates shared circuit blocks from FEI4 collaboration & custom blocks designed at OSU

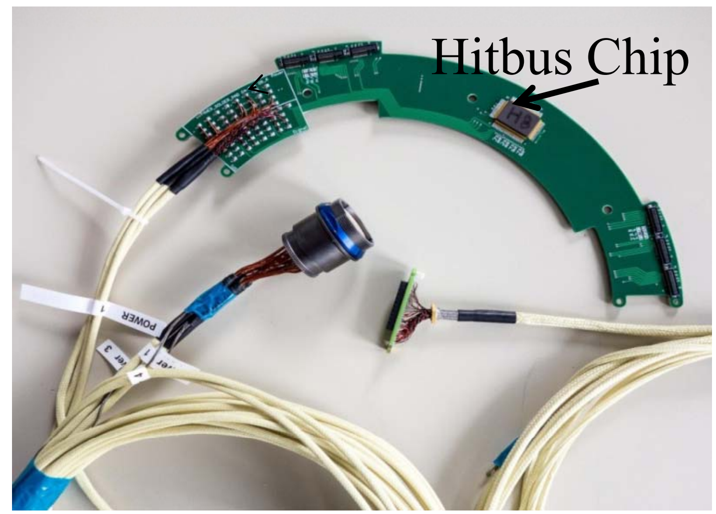




Half DBM System Block Diagram



2 Support PCBs/side

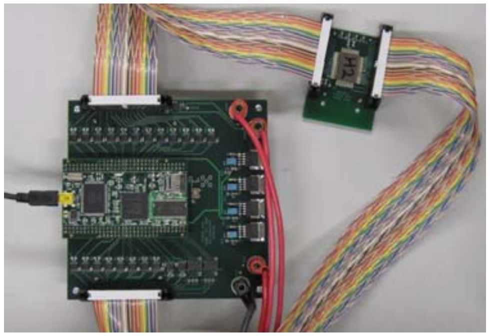


Hitbus Chip Irradiation

Need to certify that Hitbus Chip is rad hard

Irradiated 2 Hitbus chips to 4.3 x 10^{15} p/cm^2 (115 Mrad)

Used 24 GeV proton beam at CERN



Both chips survived

Slight increase in supply current consumption

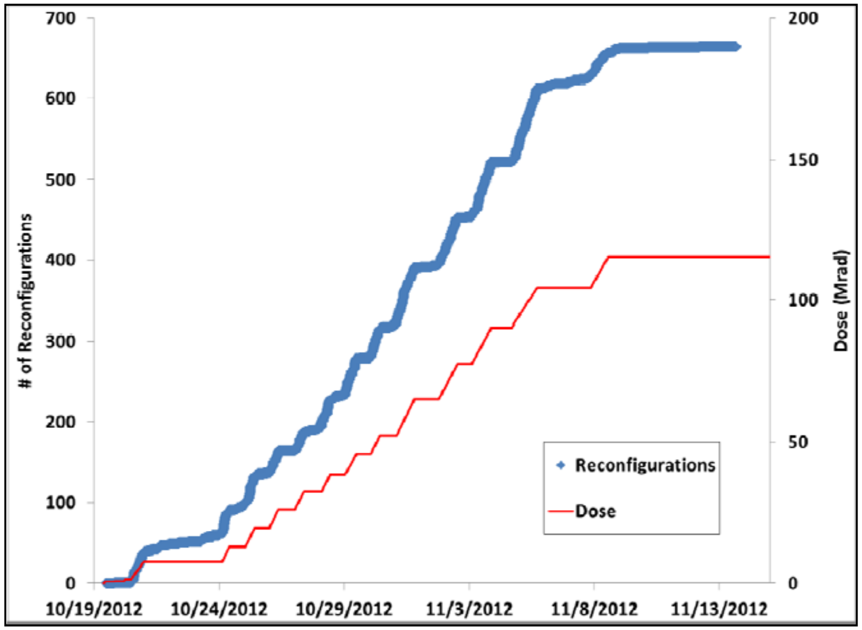
All functionality active during irradiation

Test system checked for SEU in the received data

Looked for flipped bits in SEU latches change of Hitbus desired function

Reconfigured the chip if error detected

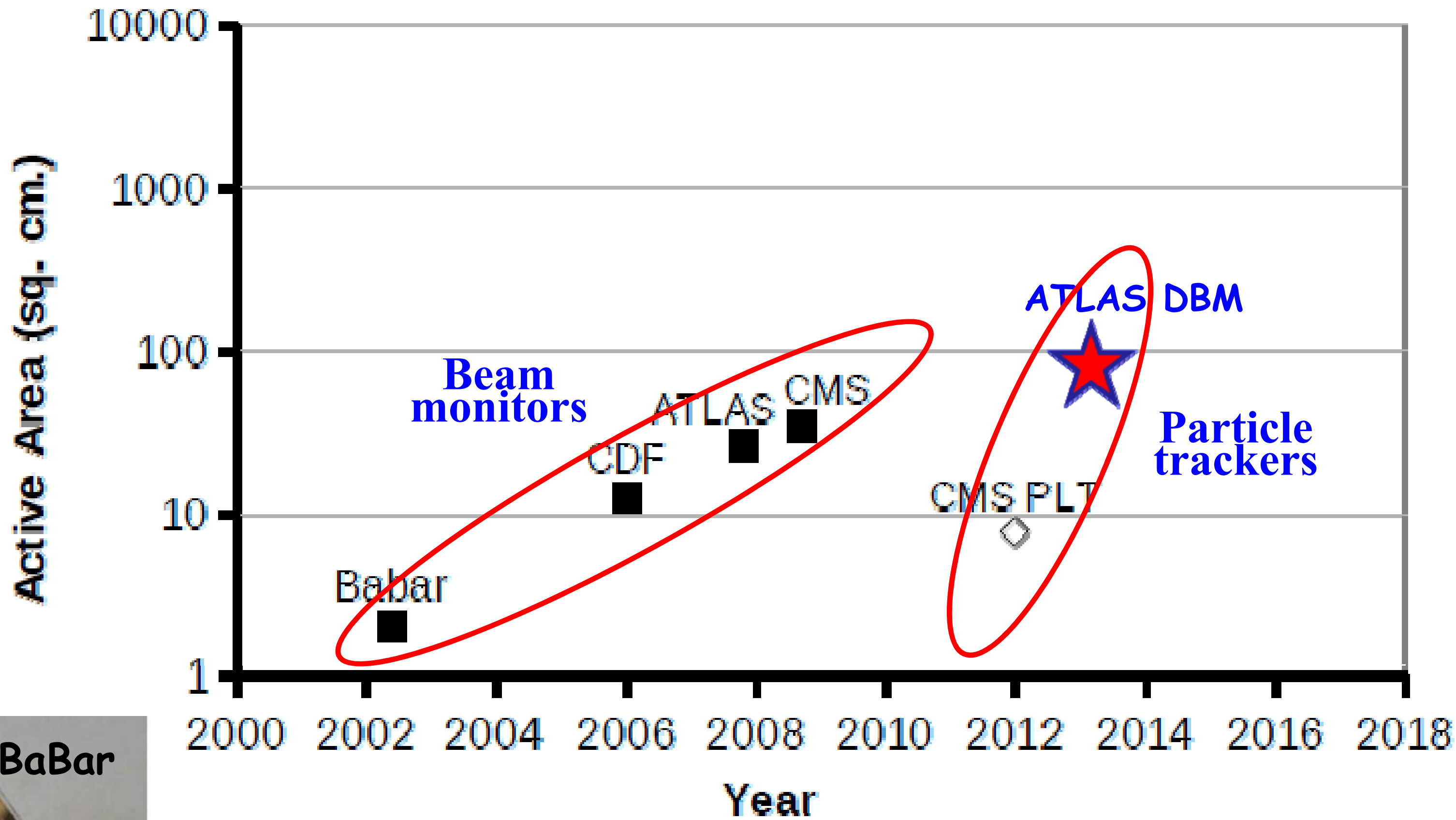
Only 664 reconfiguration events needed (for both chips)



DBM and Other Diamond Projects

DBM has ~ 6.25×10^5 channels

(DELPHI silicon pixel detector ~ 12×10^5 channels)



BaBar beam monitor:
two pCVD diamonds
1 cm x 1 cm x 500 μm

Summary

- Construction of the largest diamond pixel tracker underway
- Satisfies constraints for precision luminosity measurement
  - Bunch by bunch measurement
  - Background separation uses z resolution
- Should be robust against
  - Pile-up
  - Radiation damage

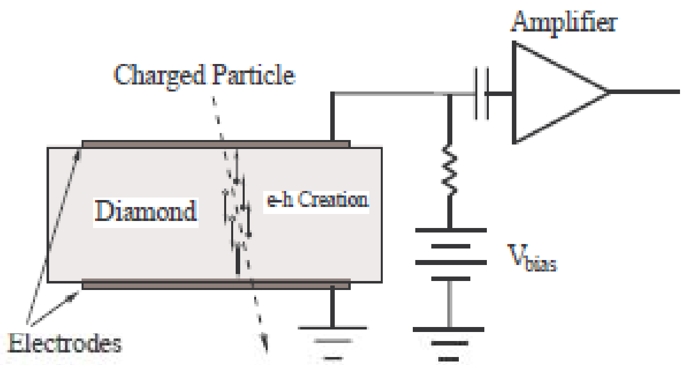
ATLAS Diamond Beam Monitor TDR: ATU-DBM-001

Backup Slides

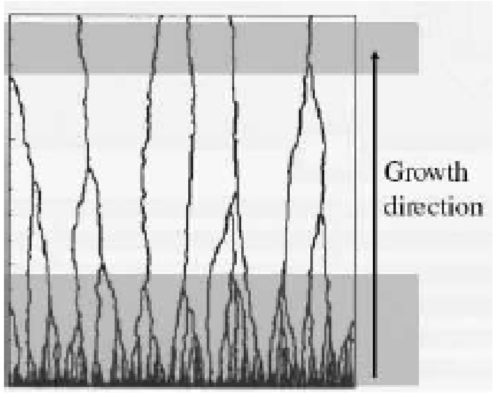
Charge Collection in CVD Diamond

Detectors Constructed with Diamond:

Signal formation



pCVD Schematic Side View



- $d=(\mu_e\tau_e + \mu_h\tau_h)E$ where d = collection distance = ave. dist. e-h pair move apart
- $d=\mu E\tau = v\tau$

  with $\mu = \mu_e + \mu_h \rightarrow v = \mu E$

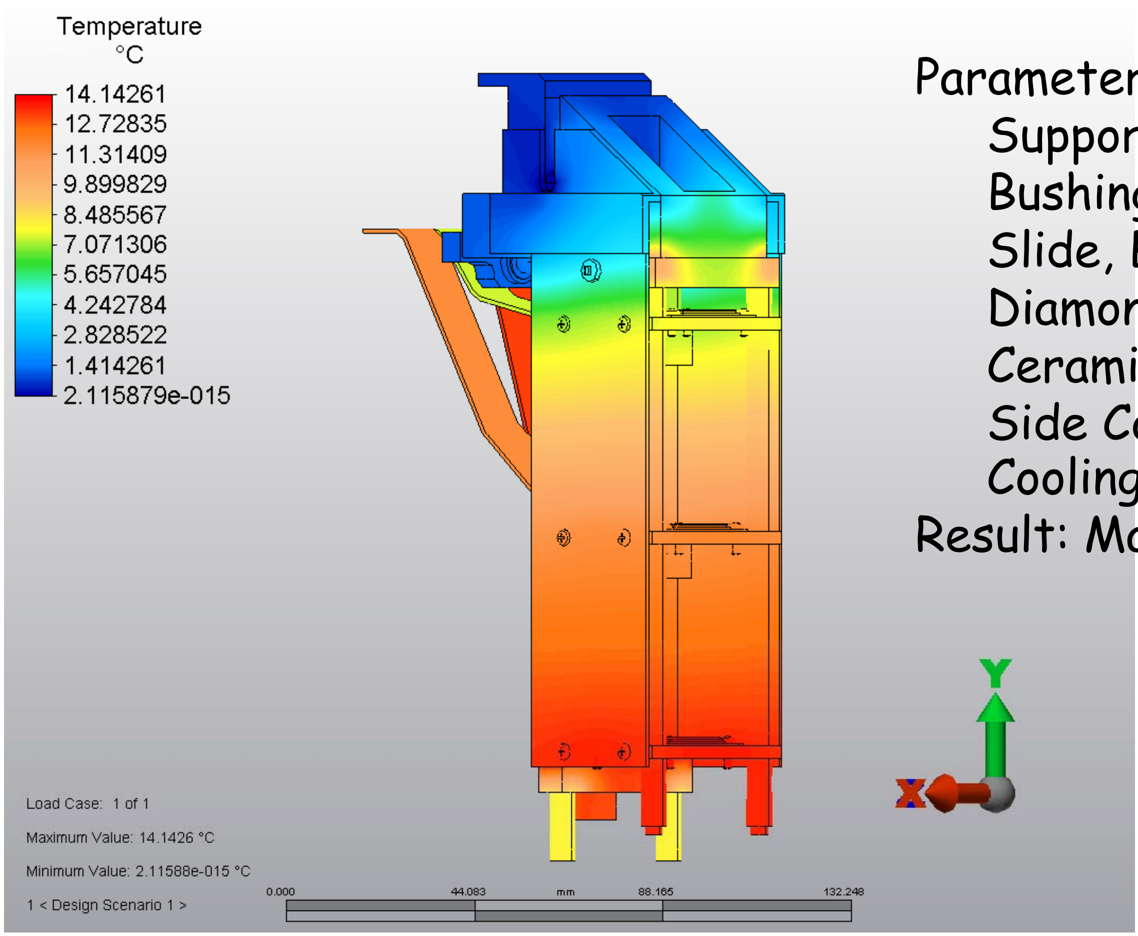
  and $\tau = \frac{\mu_e\tau_e+\mu_h\tau_h}{\mu_e+\mu_h}$
- $Q=\frac{d}{t}Q_0$ $\rightarrow$ for large charge need good collection distance - must maximize μ and τ
- $I=Q_0\frac{v}{d}$

Diamond Specs

Property	Specifications
Sensor size	21mm x 18mm (active area 20mm x 16.8mm)
Sensor Thickness	400-500 microns
Minimum charge collection distance	200 microns
Minimum average charge	7200 electrons
Minimum collection distance/ charge after $2x10^{15}$ cm^{-2}	100 microns/3600 electrons
Minimum signal/threshold after $2x10^{15}$ cm^{-2}	3
Maximum operating voltage	1000 V
Maximum total leakage current (@1000 V)	100 nA

The ATLAS DBM Concept

- Cooling simulations for DBM telescope w/3 x 1W + AlN side plate



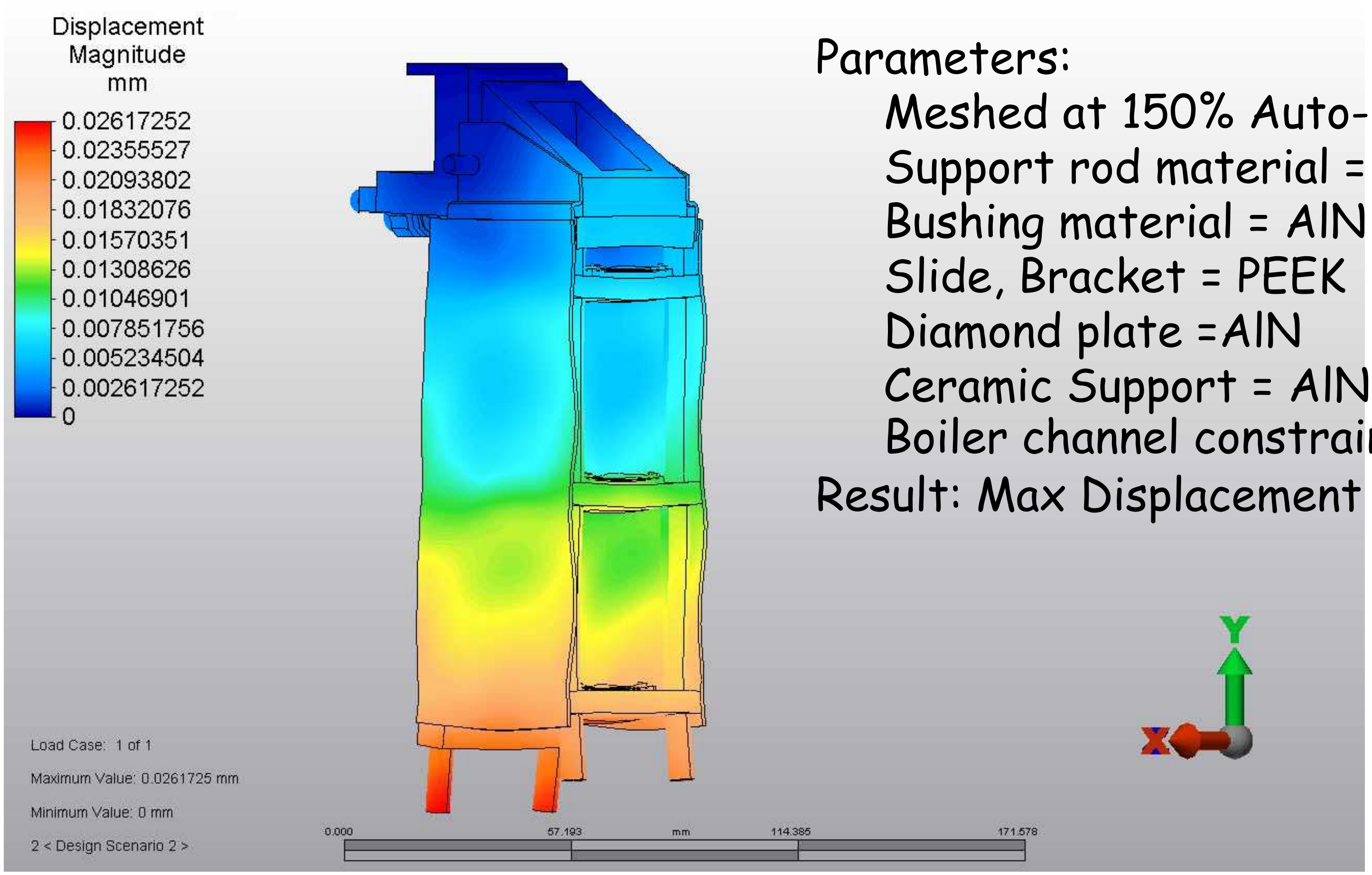
Parameters:

Support rod material = Aluminum
Bushing material = AlN
Slide, Bracket = PEEK
Diamond plate =AlN
Ceramic Support = AlN
Side Cooling Plate = AlN (1mm)
Cooling Pipe constrained to 0°C

Result: Max T = 14.2°C

The ATLAS DBM Concept

- Mechanical simulations for DBM telescope w/3 x 1W + AlN side plate



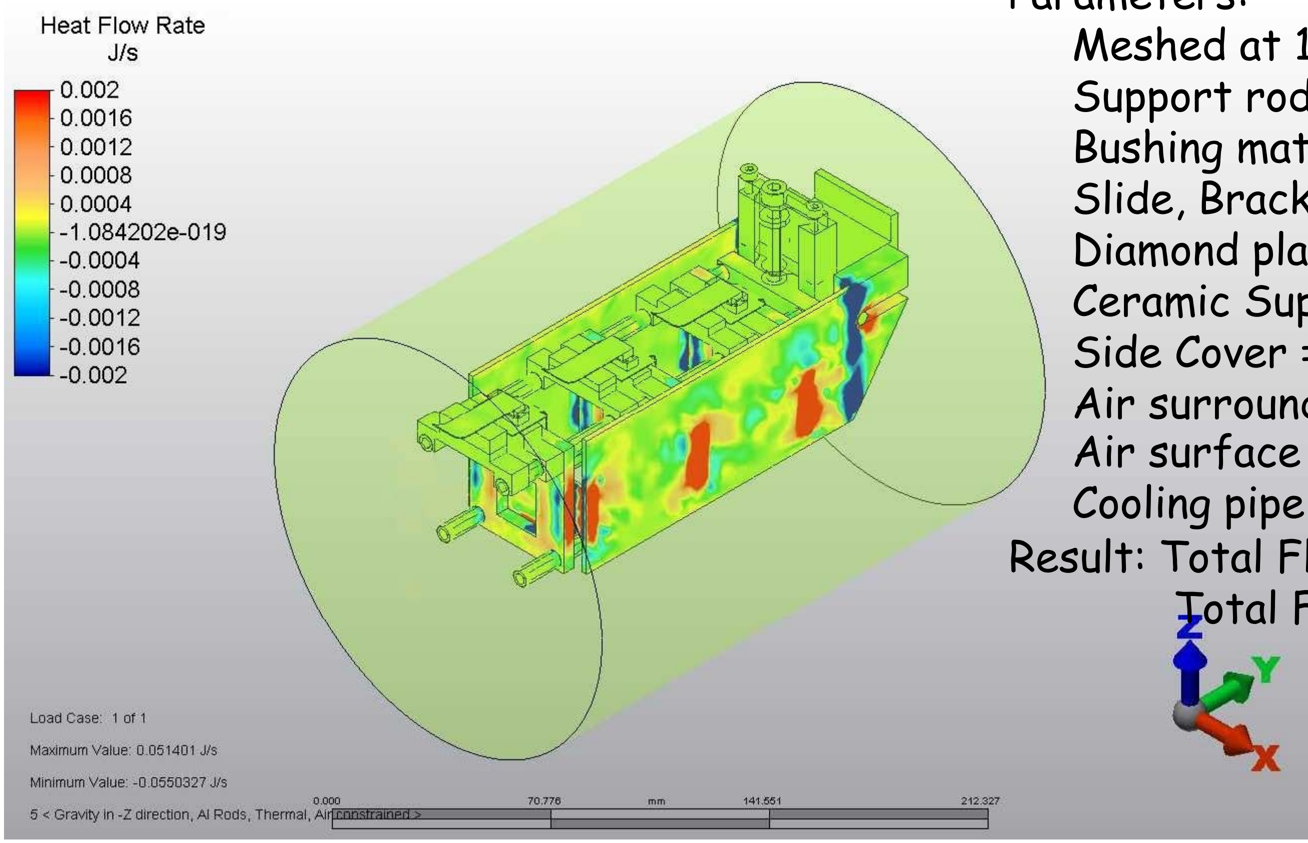
Parameters:

Meshed at 150% Auto-Mesh size
Support rod material = Aluminum
Bushing material = AlN
Slide, Bracket = PEEK
Diamond plate =AlN
Ceramic Support = AlN
Boiler channel constrained to 0°C

Result: Max Displacement = 26.2 μm

The ATLAS DBM Concept

- Heat Flux through a DBM telescope w/3 x 1W



Parameters:

Meshed at 150% Auto-Mesh size
Support rod material = Aluminum
Bushing material = Aluminum
Slide, Bracket = PEEK
Diamond plate =AlN
Ceramic Support = AlN
Side Cover = AlN
Air surrounding DBM – transparent
Air surface constrained to 0°C
Cooling pipe constrained to 0°C

Result: Total Flux Out = 0.12W
Total Flux In = 3W

Radiation Damage - Basics

Radiation induced effect	Diamond	Operational consequence	Silicon	Operational consequence
Leakage current	small & decreases	none	$I/V = \alpha\Phi$ $\alpha \sim 4\times10^{-17}$ A/cm	Heating Thermal runaway
Space charge	~ none	none	$\Delta N_{eff} \approx -\beta\Phi$ $\beta \sim 0.015\ cm^{-1}$	Increase of full depletion voltage
Charge trapping	Yes	Charge loss Polarization	$1/\tau_{eff} = \beta\Phi$ $\beta \sim 5\text{-}7\times10^{-16}\ cm^2/ns$	Charge loss Polarization

Charge trapping the only relevant radiation damage effect

NIEL scaling questionable *a priori*

E_{gap} in diamond 5 times larger than in Si

Many processes freeze out

Typical emission times order of months

Like Si at 300/5 = 60 K – Boltzmann factor

A rich source of effects and (experimental) surprises !

$$\frac{1}{\tau_{eff}} = \sum_t N_t(1-P_t)\sigma_t v_{th}$$

Summary of RD42 Test Beam Results for CVD Diamond

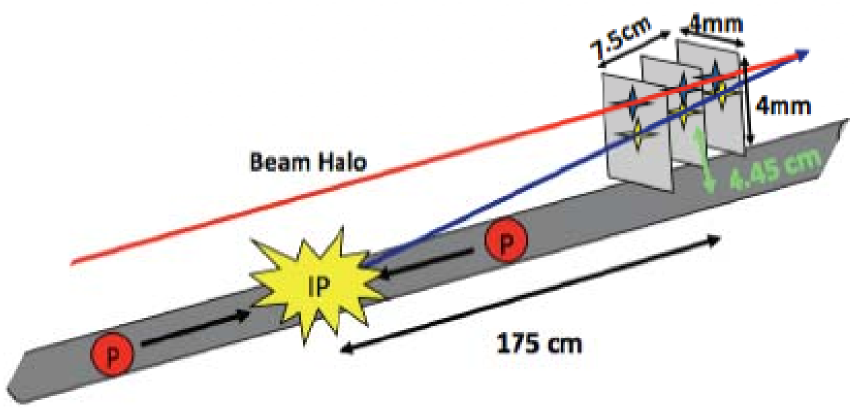
Particle	Energy	Relative k
p	24GeV	1.0
	800MeV	1.6-1.8
	70MeV	2.5-2.8
	25MeV	4.0-5.0
π	200MeV	2.5-3.0

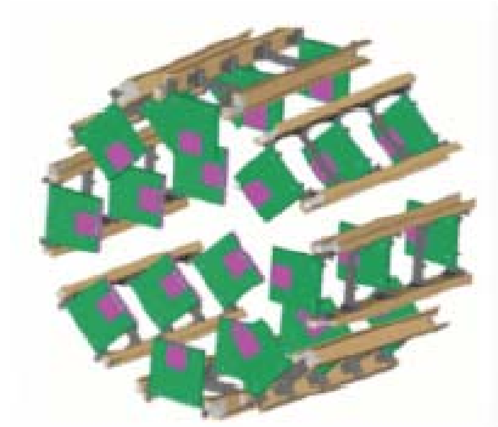
k is relative damage constant

CMS Pixel Luminosity Telescope

Dedicated stand-alone luminosity monitor for CMS

- High precision bunch-by-bunch luminosity
- Array of 3-plane telescopes each end of CMS
- Single-crystal diamond pixel sensors
- Measure bunch-by-bunch 3-fold coincidence rate
- Pixel readout for tracking and diagnostics





Install in CMS in 2013-2014 shutdown