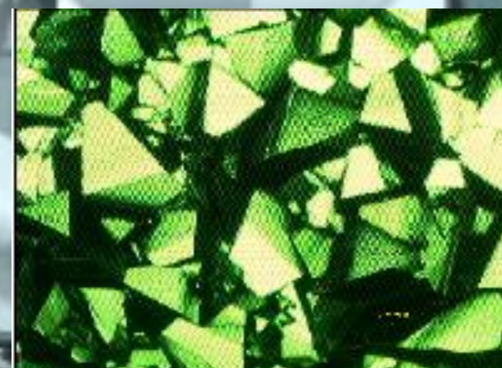
# Diamond Sensors

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**for the CERN RD-42 Collaboration**

**and ATLAS BCM/BLM & DBM Groups**


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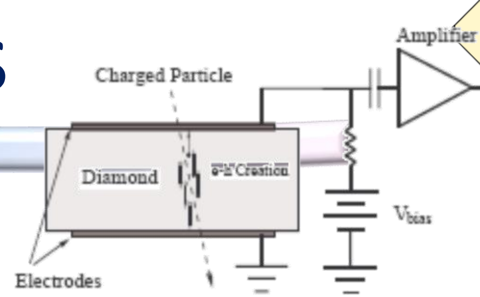
# Outline

- Diamond as sensor material
- RD-42
  - Diamond suppliers
  - Radiation hardness
- Diamond sensor applications - ATLAS
  - Radiation detection – beam monitors
    - Beam Conditions Monitor
    - Beam Loss Monitor
  - Particle tracking
    - Diamond Beam Monitor

# Diamond as Sensor Material

| Property | Diamond | Silicon | |
|---|---|---|---|
| Band gap [eV] | 5.5 | 1.12 | |
| Breakdown field [V/cm] | $10^7$ | $3x10^5$ | |
| Intrinsic resistivity @ R.T. [Ω cm] | > $10^{11}$ | $2.3x10^5$ | ☺ Low leakage |
| Intrinsic carrier density [$cm^{-3}$] | < $10^3$ | $1.5x10^{10}$ | |
| Electron mobility [$cm^2$/Vs] | 1900 | 1350 | ☺ Fast signal |
| Hole mobility [$cm^2$/Vs] | 2300 | 480 | |
| Saturation velocity [cm/s] | 1.3(e)-1.7(h)x 107 | 1.1(e)-0.8(h)x $10^7$ | |
| Density [$g/cm^3$] | 3.52 | 2.33 | |
| Atomic number - Z | 6 | 14 | |
| Dielectric constant - ε | 5.7 | 11.9 | ☺ Low capacitance |
| Displacement energy [eV/atom] | 43 | 13-20 | ☺ Radiation hard |
| Thermal conductivity [W/m.K] | ~2000 | 150 | ☺ Heat spreader |
| Energy to create e-h pair [eV] | 13 | 3.61 | |
| Radiation length [cm] | 12.2 | 9.36 | |
| Spec. Ionization Loss [MeV/cm] | 6.07 | 3.21 | |
| Aver. Signal Created / 100 μm [$e_0$] | 3602 | 8892 | ☹ Low signal |
| Aver. Signal Created / 0.1 $X_0$ [$e_0$] | 4401 | 8323 | |

# Signal from CVD Diamonds

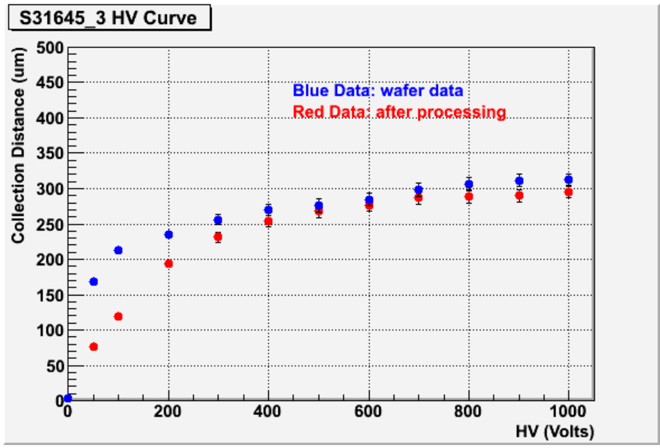



- No processing: put electrodes on, apply electric field
  - Surface preparation and metallization **non-trivial !**
- Trapping on grain boundaries (pCVD) and in bulk
  - Much like in heavily irradiated silicon
- Parameterized with Charge Collection Distance, defined as

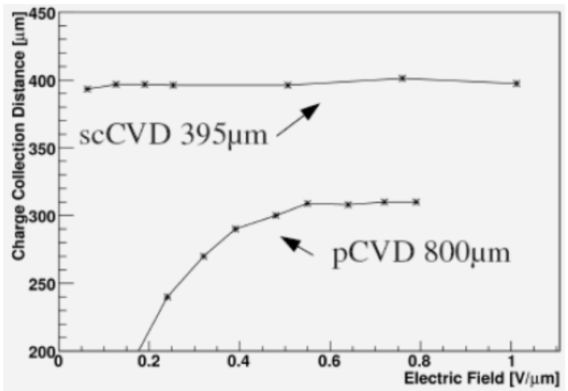
$$CCD = \frac{< Q_{col} >}{36 \frac{e_0}{\mu m}}$$

☝ **mean** not **most probable**

- *CCD* = average distance e-h pairs move apart




***CCD*** **measured on recent 1.4 mm thick pCVD wafer from E6, and after thinning to 0.8 mm**




***CCD*** **vs. field for pCVD and scCVD diamond**

# Diamond Sensors for HEP: RD-42

RD42 Collaboration 2012

K. Andeen[17] ,M. Artuso[25], F. Bachmair[29], L. Bäni[29], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], S. Blusk[25], A. Borgia[25], J-M. Brom[10], M. Bruzzi[5], M. Cadabeschi[19], G. Chiodini[32], D. Chren[23], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[24], A. Dabrowski[3], R. D'Alessandro[6], W. de Boer[13], M. Dinardo[24], D. Dobos[3], W. Dulinski[10], V. Eremin[9], R. Eusebi[30], H. Frais-Kolbl[4], A. Furgeri[13], C. Gallrapp[3], K.K. Gan[16], J. Garofoli[25], M. Goffe[10], J. Goldstein[21], A. Golubev[11], A. Gorisek[12], E. Grigoriev[11], J. Grosse-Knetter[28], M. Guthoff[13], D. Hits[17], M. Hoeferkamp[26], F. Huegging[1], H. Jansen[3], J. Janssen[1] , H. Kagan[16,♦], R. Kass[16], G. Kramberger[12], S. Kuleshov[11], S. Kwan[7], S. Lagomarsino[6], A. La Rosa[3], A. Lo Giudice[18], I. Mandic[12], C. Manfredotti[18], C. Manfredotti[18], A. Martemyanov[11], H. Merritt[16], M. Mikuz[12], M. Mishina[7], M. Moench[29], J. Moss[16], R. Mountain[25], S. Mueller[13], A. Oh[27], P. Olivero[18], G. Parrini[6], H. Pernegger[3], R. Perrino[32], M. Pomorski[14], R. Potenza[2], A. Quadt[28], S. Roe[3], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], S. Seidel[26], S. Smith[16], B. Sopko[23], S. Spagnolo[32], S. Spanier[31], K. Stenson[24], R. Stone[17], C. Sutera[2], M. Traeger[8], W. Trischuk[19], D. Tromson[14], J-W. Tsung[1], C. Tuve[2], P. Urquijo[25], J. Velthuis[21], E. Vittone[18], S. Wagner[24], R. Wallny[29], J.C. Wang[25], R. Wang[26], P. Weilhammer[3,♦], J. Weingarten[28], N. Wermes[1]

♦ Spokespersons

~100 Participants

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2 INFN/University of Catania, Catania, Italy
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8 GSI, Darmstadt, Germany
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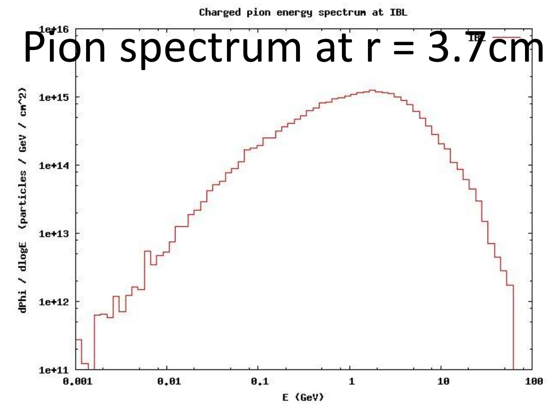
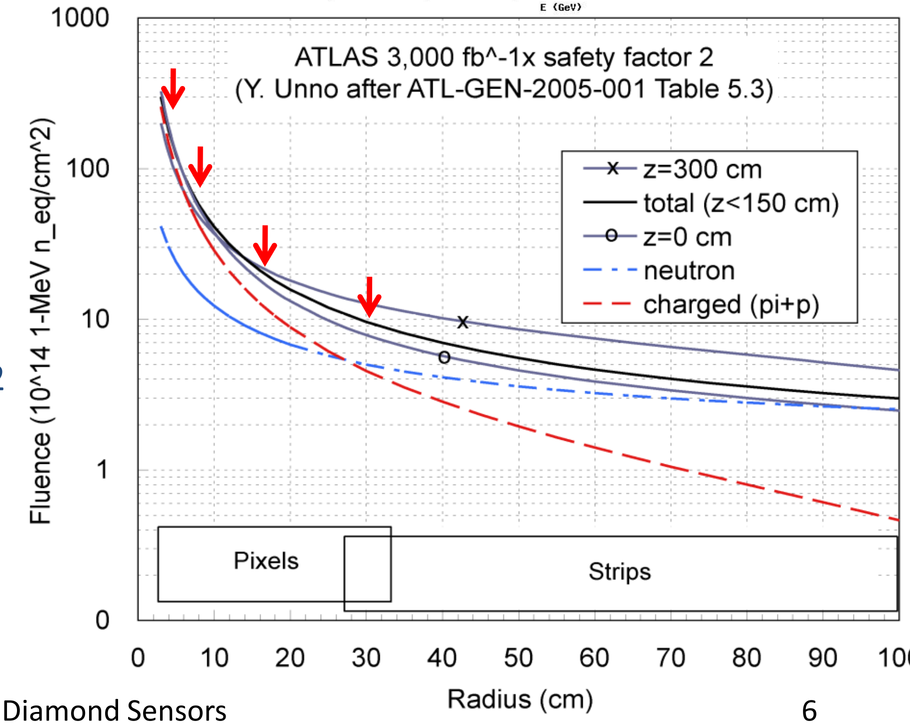
31 University of Tennessee, Knoxville TN USA
32 INFN-Lecce, Lecce, Italy

32 Institutes

# The Challenge

- Sensors for 1st (& 2nd ?) tracking layer of experiments at the LHC and more importantly at the HL-LHC
- Diamond offers:
  - Radiation Hardness
    - ➢ Survive to the end of the experiment
  - Low dielectric constant
    - ➢ Low capacitance → low noise
  - Low leakage current
    - ➢ Decreases with irradiation
    - ➢ Low readout noise
  - Room temperature operation
    - ➢ Low mass construction
  - Fast signal collection
- Fluence of interest is $O(10^{16})$ cm$^{-2}$
  - For 1st pixel layer at R ~4 cm
  - For R < 25 cm charged particles dominate

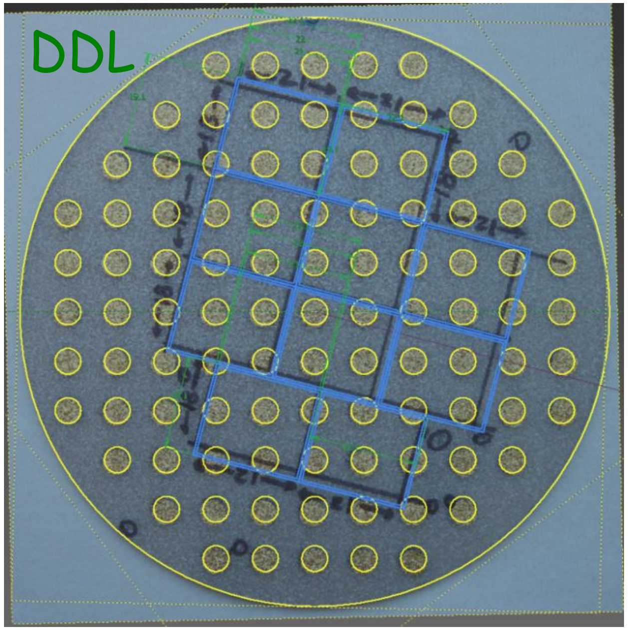


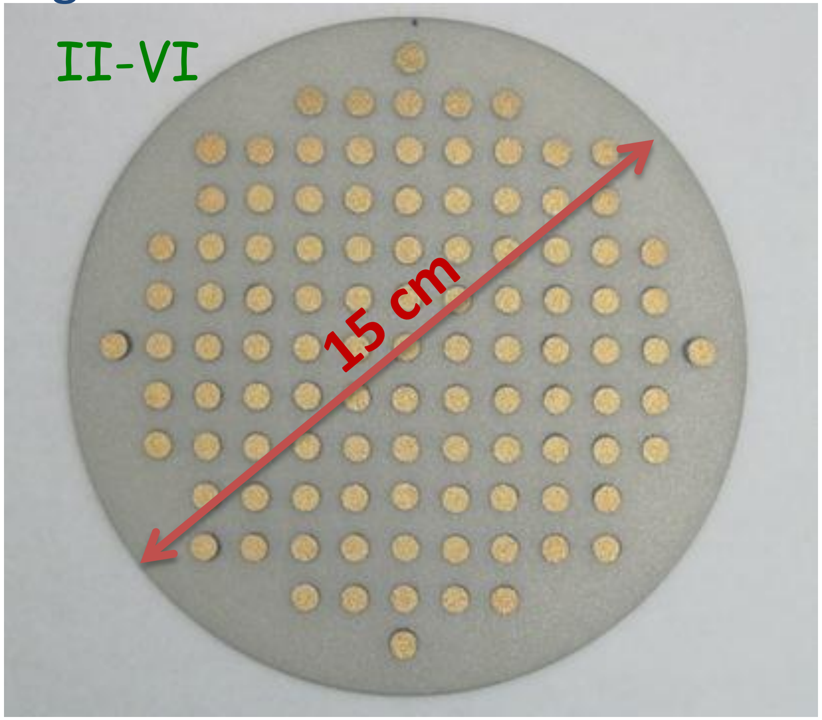



# Diamond Manufacturers

- Many large (~2 cm x 2 cm) sensors delivered in the last year:
  - Diamond Detectors Ltd, UK
    - 10 ATLAS Pixel sensors ordered
  - II-VI Infrared, USA
    - 4 ATLAS Pixel sensors received
    - 10 ATLAS Pixel sensors ordered, 10 as option
- Now in position to build 30-50 tracking devices ☞ ATLAS DBM

II-VI INFRARED ...the world leader in $CO_2$ laser optics



# Radiation Damage Parameterization

- Traditionally *CCD* was fitted with the ansatz
  - We measure *CCD*
- Radiation-induced traps in fact decrease the mean free path *mfp*
  - $CCD \sim mfp_e + mfp_h$ in thick detectors $t >> mfp$, *CCD*
  - CCD degradation formula not applicable to scCVD since $CCD_0 = t$; $mfp_0 \rightarrow \infty$
  - Also for high-quality pCVD $CCD_0 \rightarrow t$
- Relation $CCD \leftrightarrow mfp$ for homogeneous material

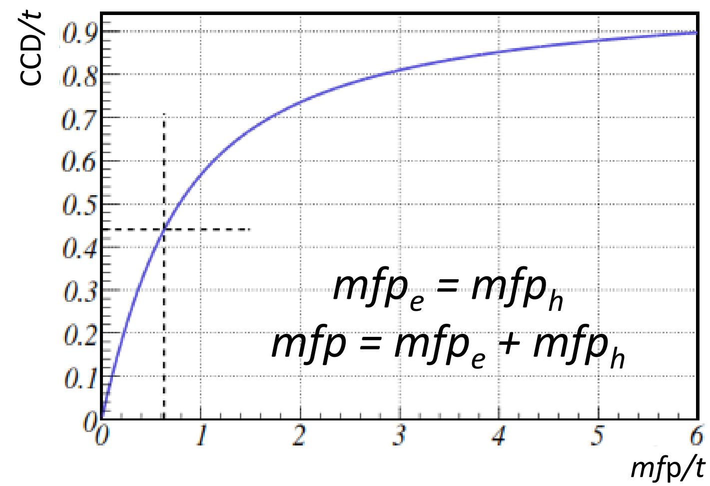
$$\frac{1}{CCD} = \frac{1}{CCD_0} + k \times \Phi$$

$$CCD = \frac{<Q_{col}>}{36 \frac{e_0}{\mu m}}$$

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k_{mfp} \times \Phi$$

$$CCD = \sum_{e,h} mfp_{e,h} \left[ 1 - \frac{mfp_{e,h}}{t} \left(1 - \exp\left(-\frac{t}{mfp_{e,h}}\right)\right) \right]$$

- For lack of data assume $mfp_e = mfp_h$
  - Symmetry of strip *CCD* to field reversal supportive of the assumption
  - $k_{mfp}$ robust to $mfp_e / mfp_h$ variation anyway



# Irradiation: 24 GeV Protons (PS)

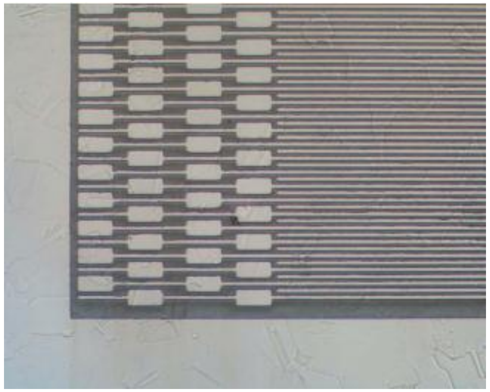
- *CCD* evaluated with strip detectors in CERN test beam
- For mean free path expect

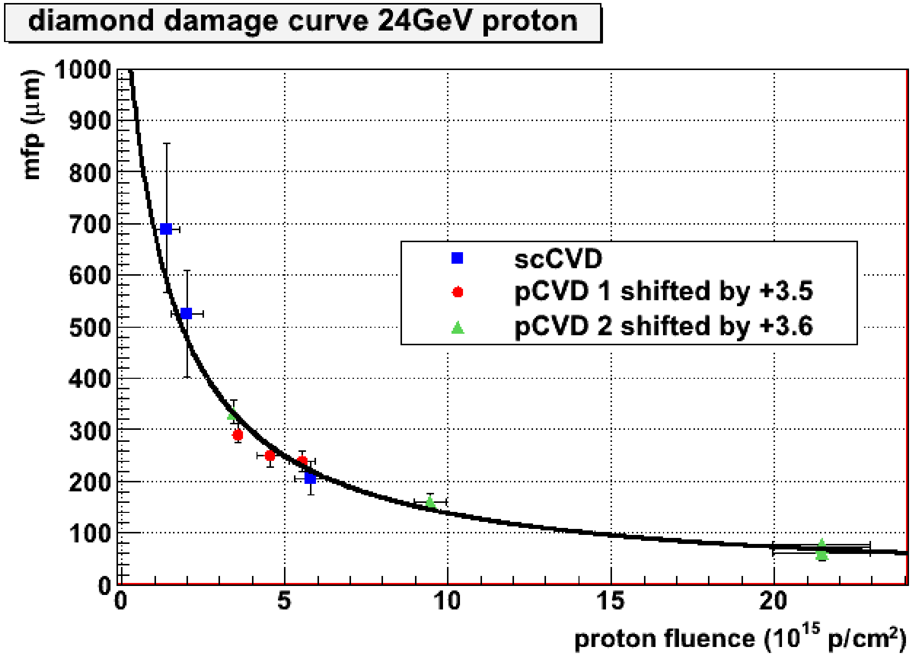
$$\frac{1}{mfp} = \frac{1}{mfp_0} + k_{mfp} \times \Phi$$

- With $mfp_0$ initial trapping, deduced from $CCD_0$
- $k_{mfp}$ the damage constant
  - Can turn 1/ $mfp_0$ into effective "initial" fluence (x-shifts)
  - expect $mfp_0 \sim \infty$ for scCVD
  - **pCVD and scCVD diamond follow the same damage curve**

➢ $k \sim$ **$0.66 \times 10^{-18}$ µm$^{-1}$cm$^{-2}$**

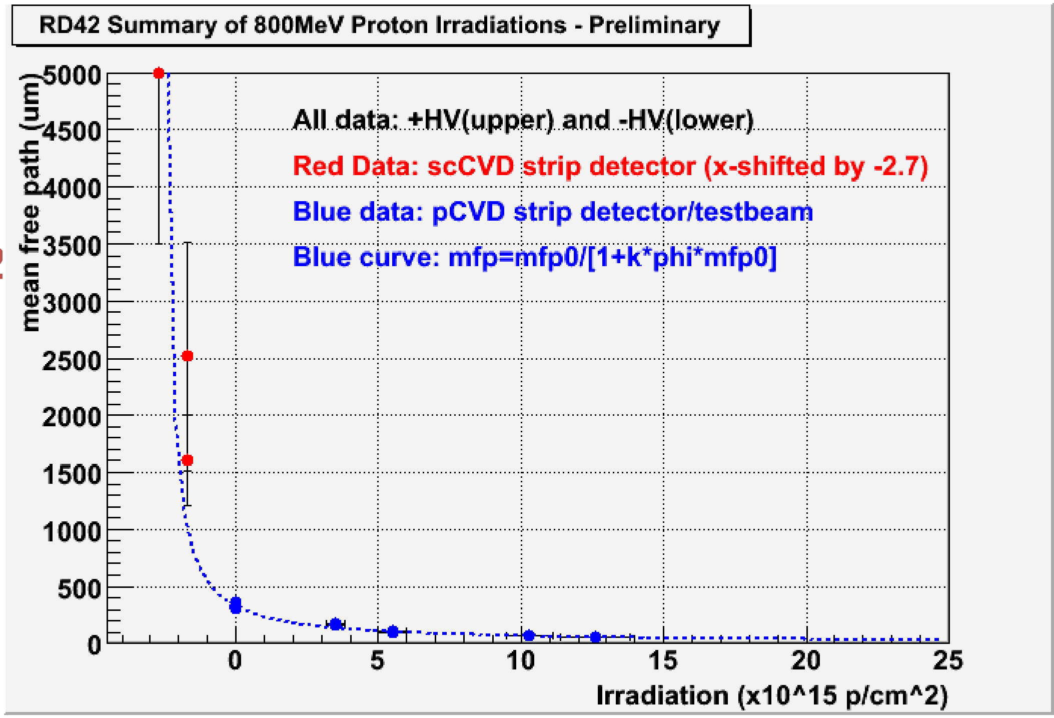
Test beam results with strip detectors





# Irradiation: 800 MeV Protons (LANL)

- Recent irradiations with 800 MeV protons at LANSCE Facility in Los Alamos, US
- ➢ $k \sim$ **1.2x10$^{-18}$ µm$^{-1}$cm$^{-2}$**
- ~1.8x more damaging than PS protons
- Consistent with NIEL prediction



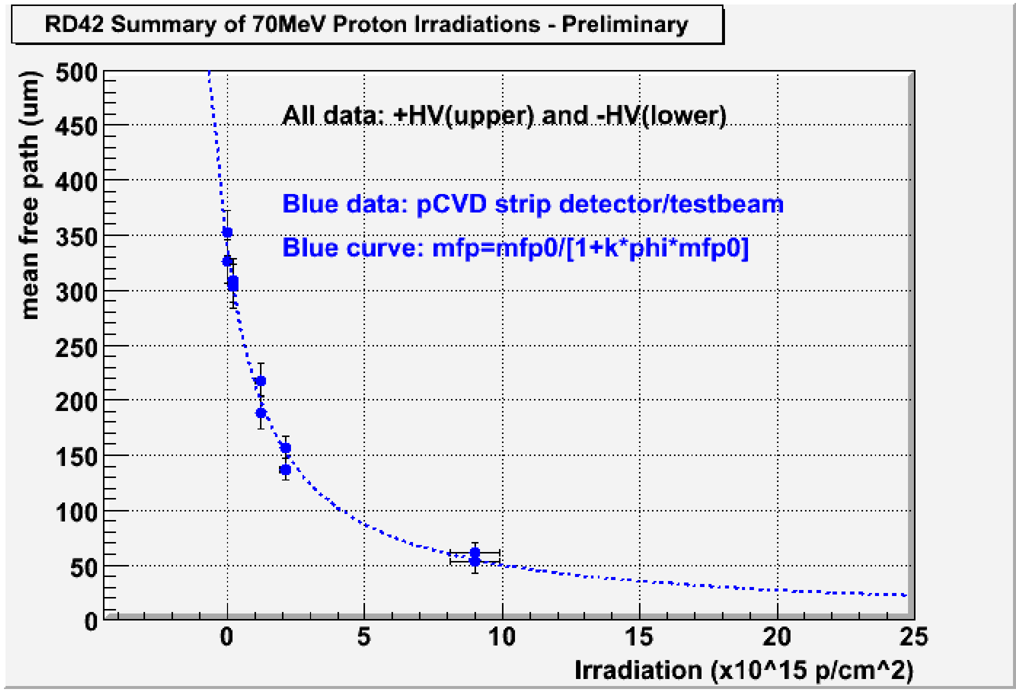

Test beam results

# Irradiation: 70 MeV Protons (Sendai)

- Recent irradiations with 70 MeV protons at Cyric Facility in Sendai, Japan

➢ ***k* ~ 1.7x10$^{-18}$ μm$^{-1}$cm$^{-2}$**

- ~3x more damaging than PS protons
- NIEL prediction
  - factor of 6
  - NIEL violation ?!



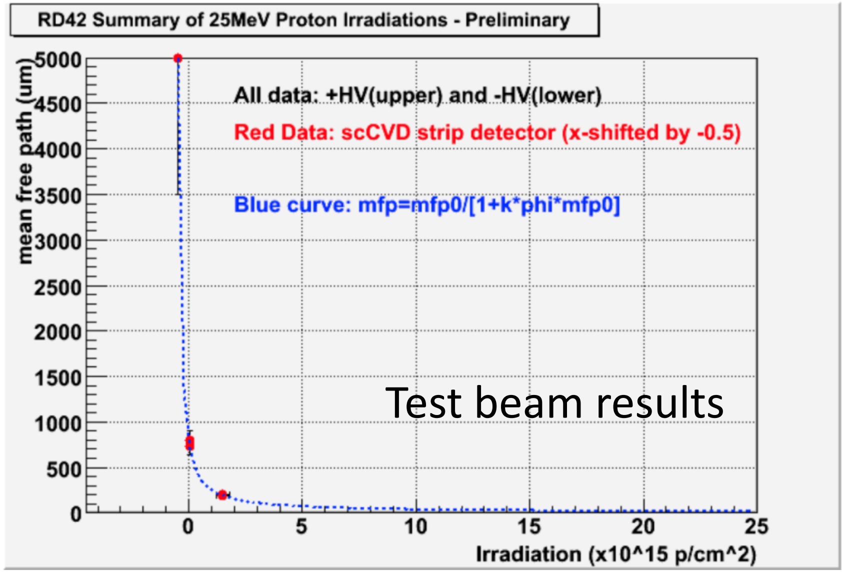

Test beam results

# Irradiation: 25 MeV Protons (KIT)

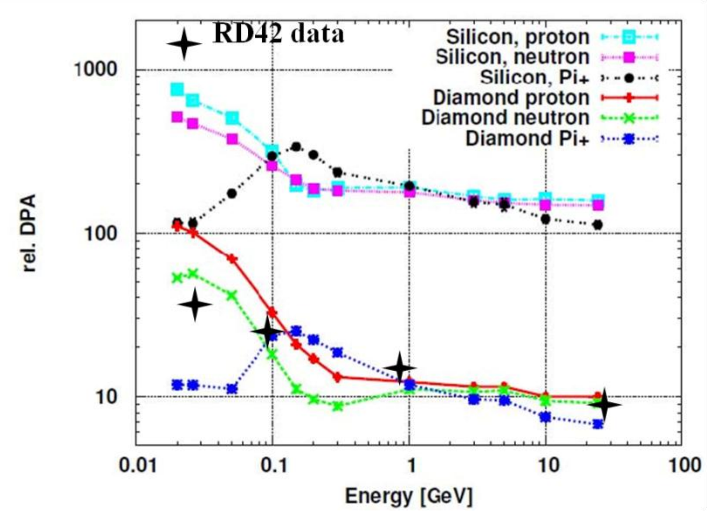
- Recent irradiations with 25 MeV protons at Karlsruhe, Germany

➢ ***k* ~ 2.6x10$^{-18}$ μm$^{-1}$cm$^{-2}$**

- 4x more damaging than PS protons
- NIEL prediction
  - factor of 15
  - NIEL violation !
- Work in progress




Test beam results



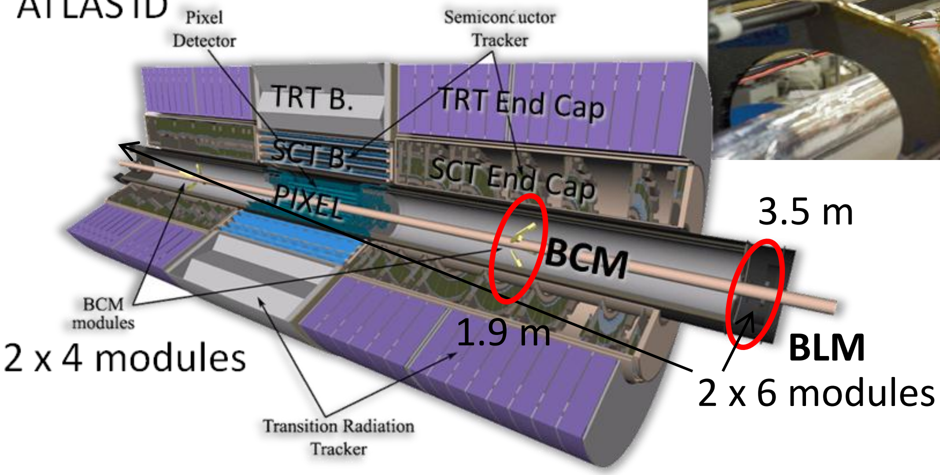

Steffen Mueller – PhD Thesis.

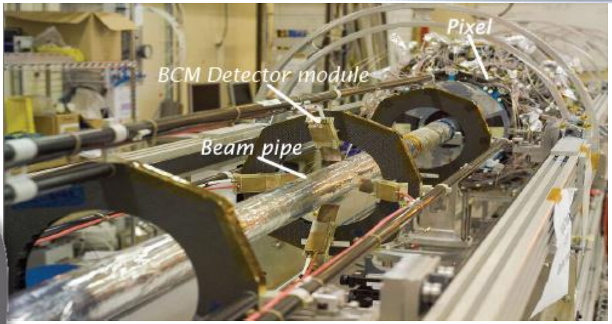
# Diamond Sensor Applications in HEP

- All LHC exp's use diamonds for beam monitoring & accident protection
  - Current and counting mode operation, TOF capability
  - *O*(100) diamond sensors employed
- CMS is building Pixel Luminosity Telescope
  - 48 scCVD pixel modules (5 mm x 5 mm)
- ATLAS is building Diamond Beam Monitor
  - 24 pCVD pixel modules (21 mm x 18 mm)
- Upgrade plans include diamond as candidate for innermost pixel tracker layer(s)
- Elaborate on ATLAS projects, CMS covered in separate talk
  - Beam monitoring: ATLAS BCM/BLM
  - Particle tracking: ATLAS DBM

# ATLAS BCM/BLM

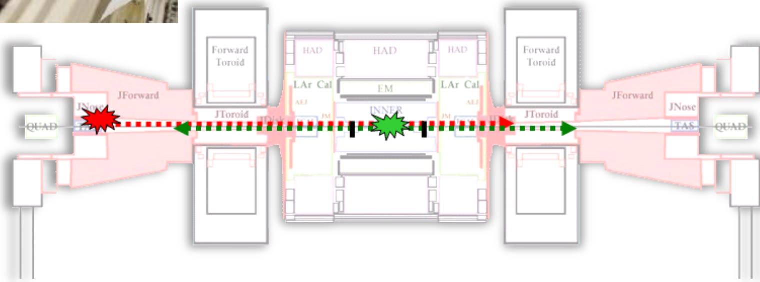
ATLAS ID



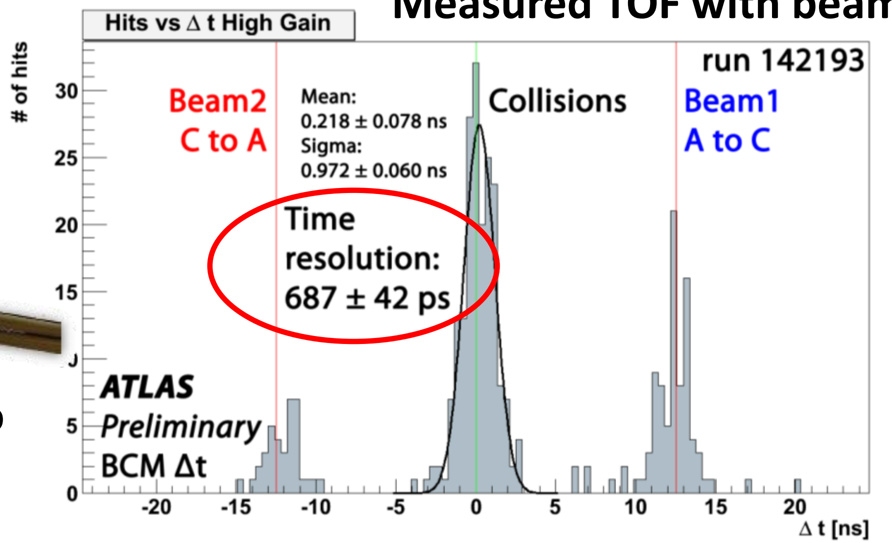




**BCM TOF concept**

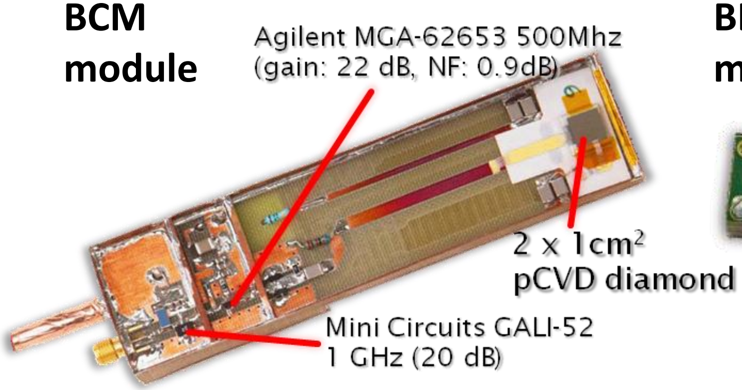
- **Collisions: in time**
- **Background: out of time**



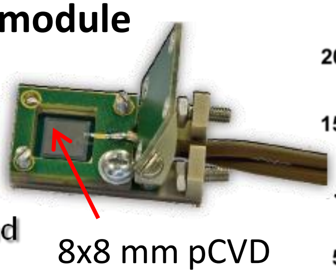
**Measured TOF with beam**




**BCM module**

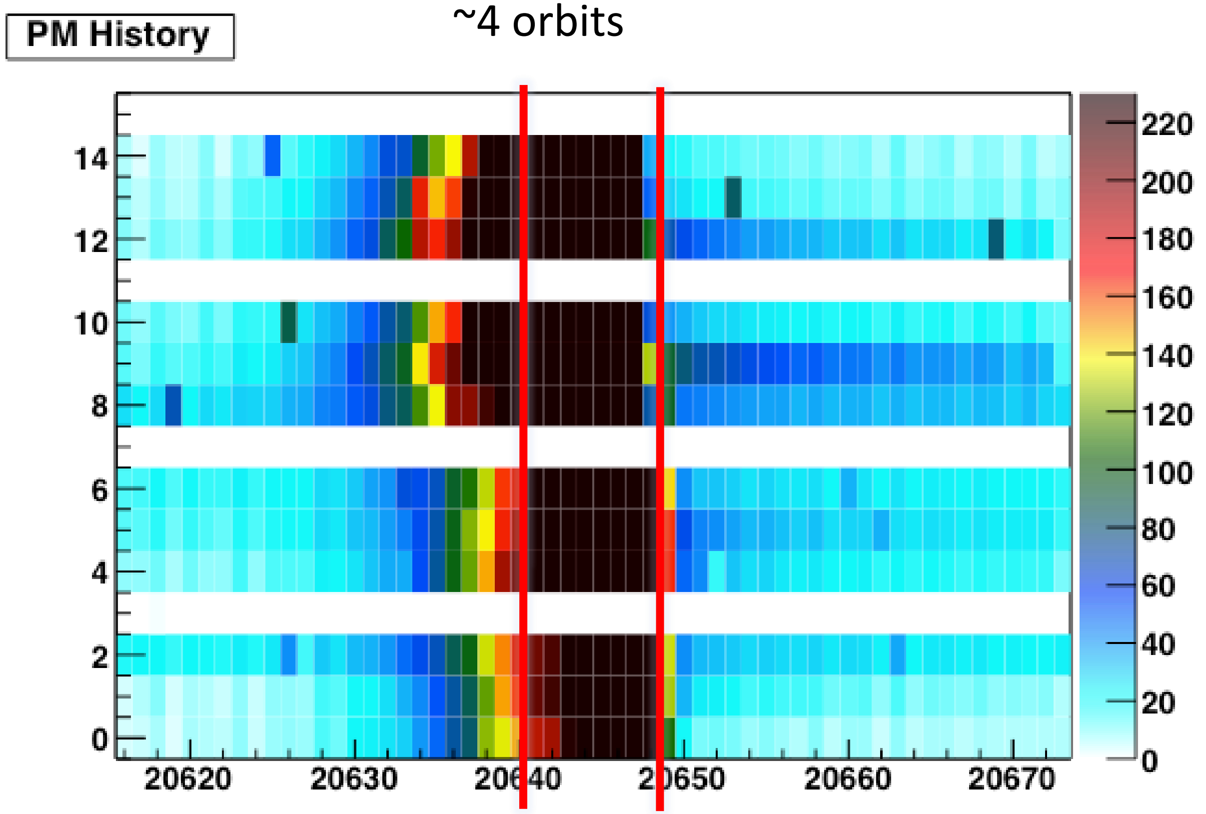



**BLM module**



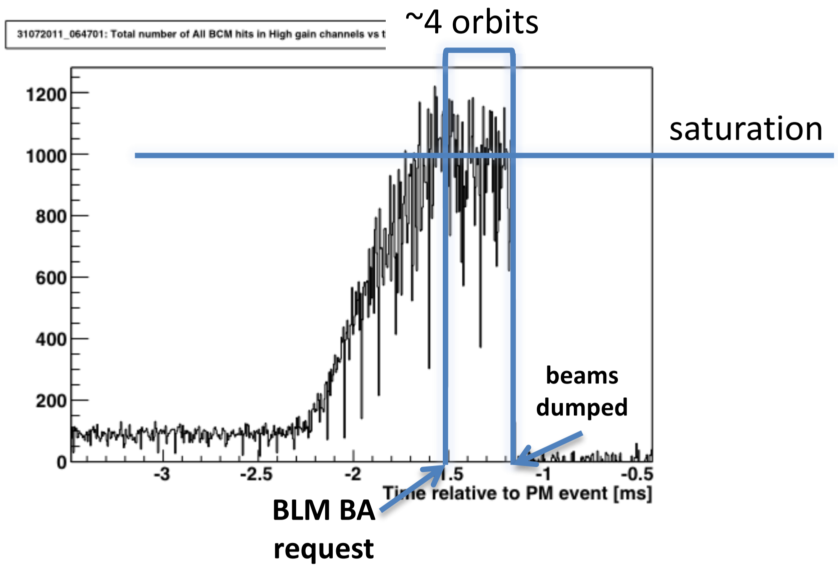
# BLM Beam Dumps – Summer 2011

- The LHC beams were dumped twice by BLM due to UFO–like events: 31/07/2011 @ 6:47 and 17/8/2011 @ 9:48
- Abort condition: 230 counts on both sides, simultaneous in 2 channels (i.e. 2+2)
- No aborts this year yet, threshold risen from 230 to 350 due to increased lumi



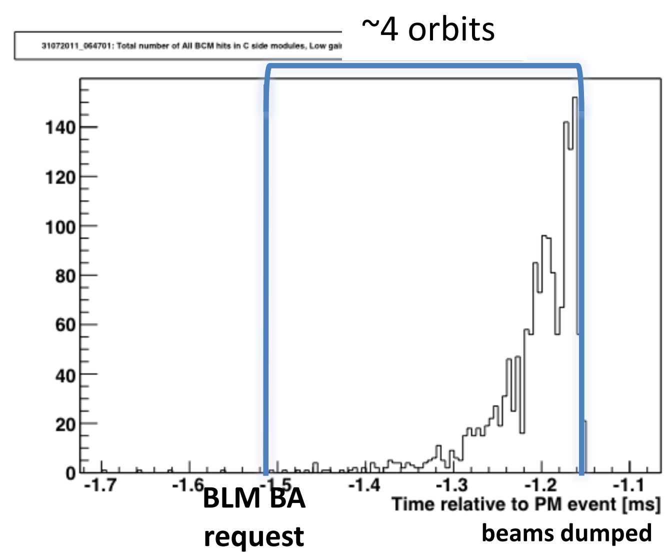
# BLM dump – BCM Post Mortem Info

- Single MIP sensitive channels – saturate at ~1k in 5µs bin

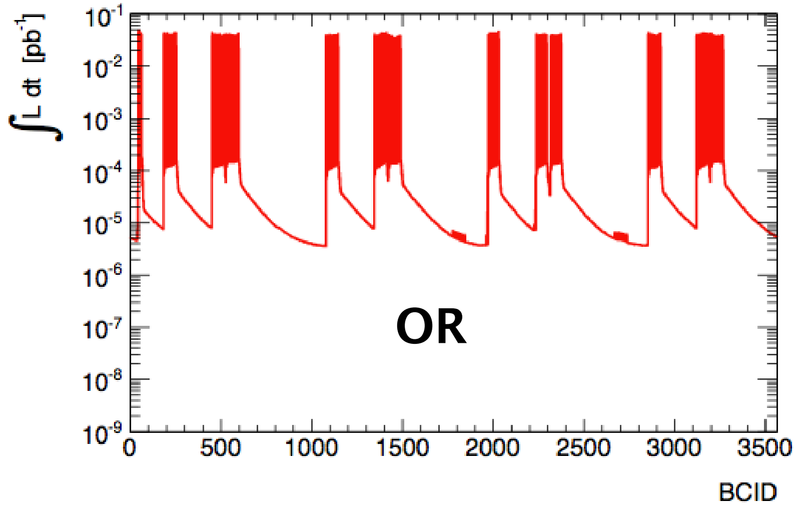


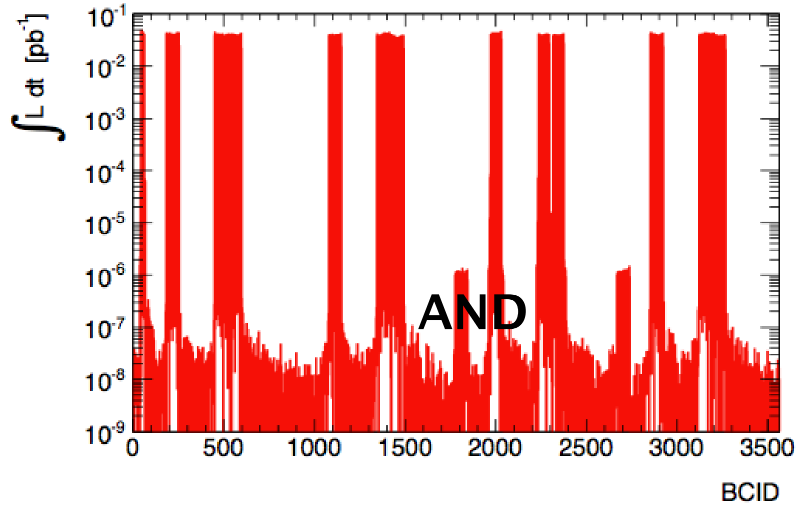

- 100 MIP sensitive channels – far from saturation. Substantial signal which is ~exponentially increasing before beams were extracted (~140/1k).

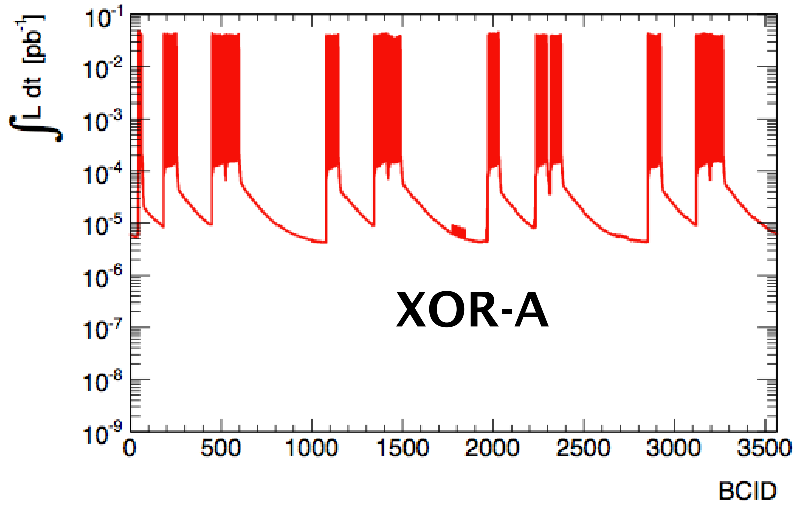
  Note: when BLM fired – there was almost no signal in HT BCM channels

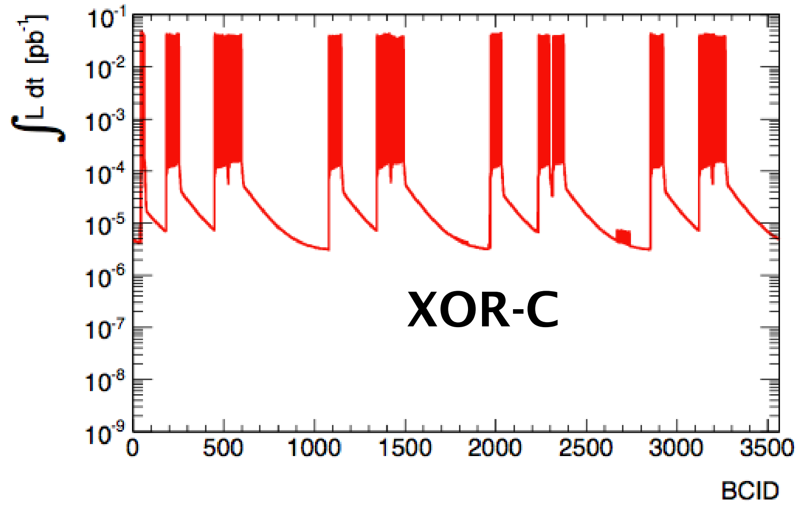


# BCM - BCID Aware Luminosity



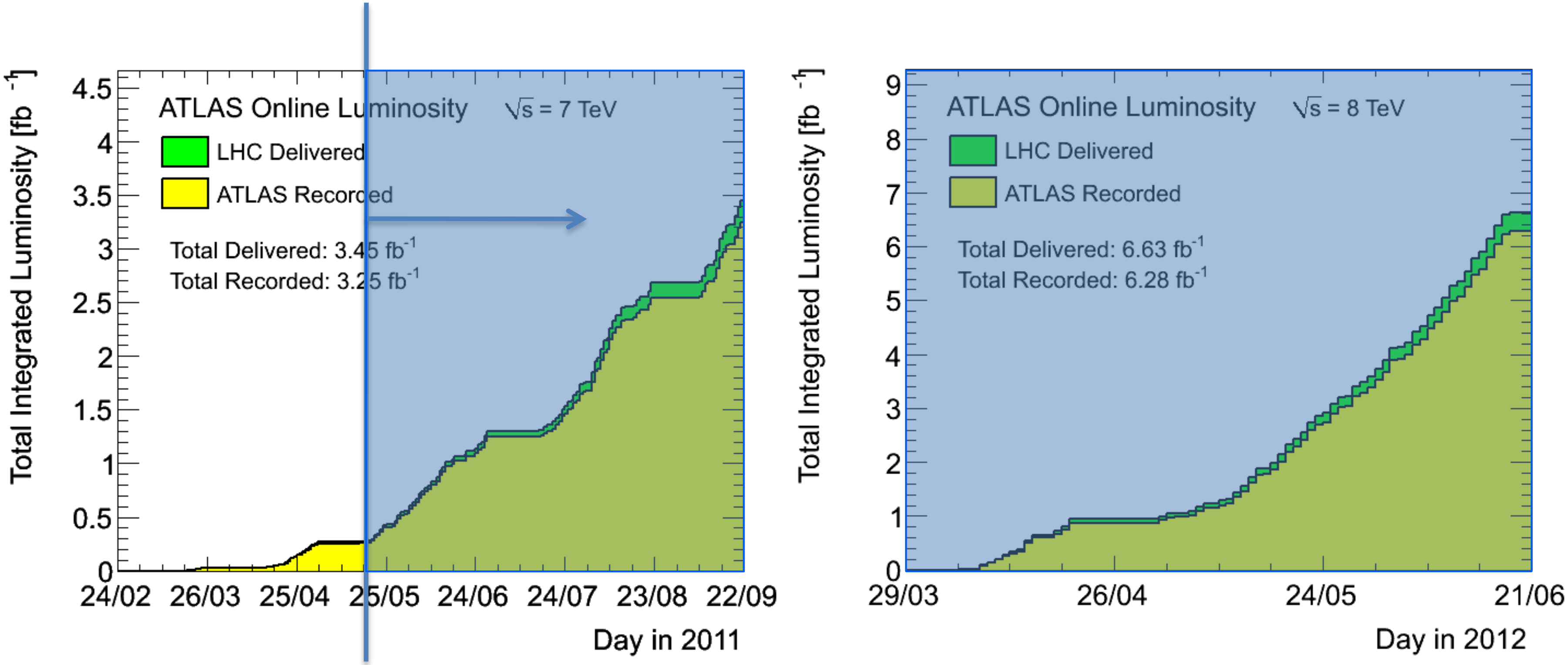



# BCM – Preferred ATLAS Lumi Monitor

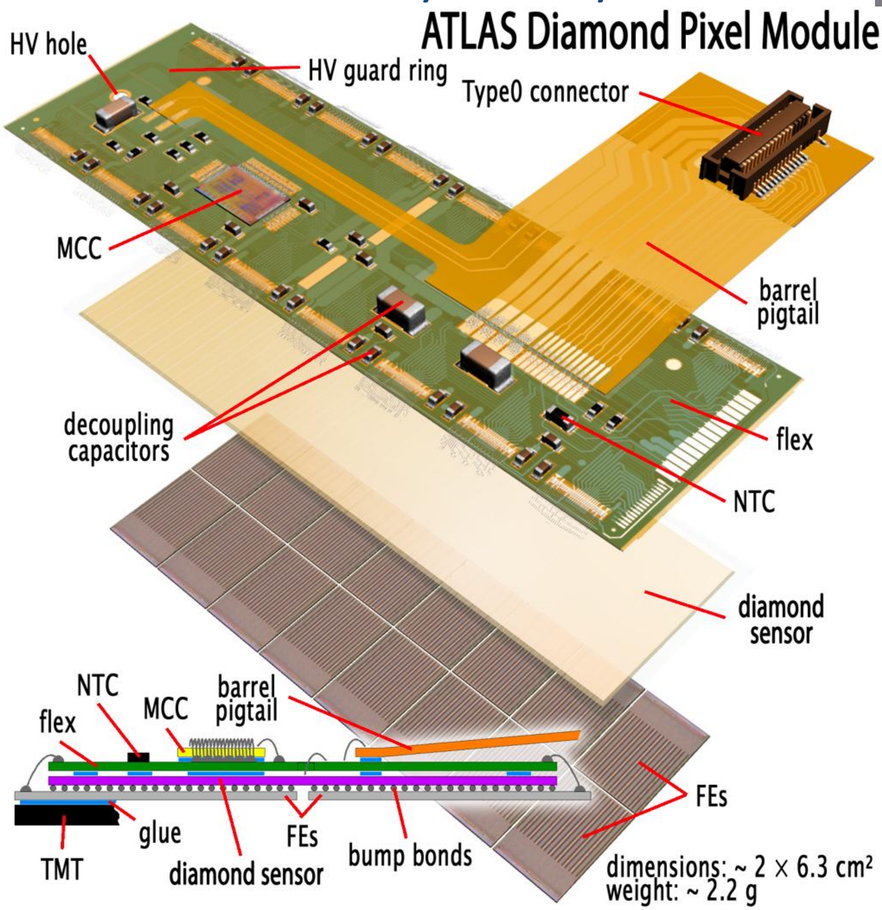
- Robust, stable, (very) low background
- Insensitive to pile-up

BCM – preferred lumi monitor

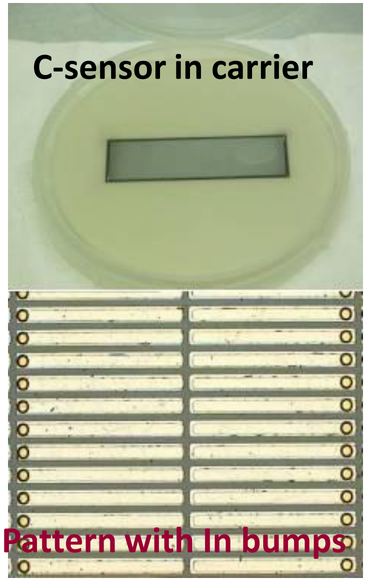


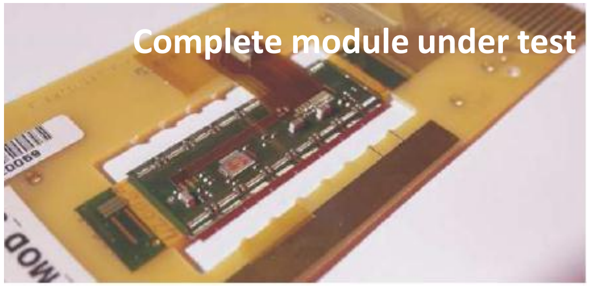
# Diamond Pixel Modules

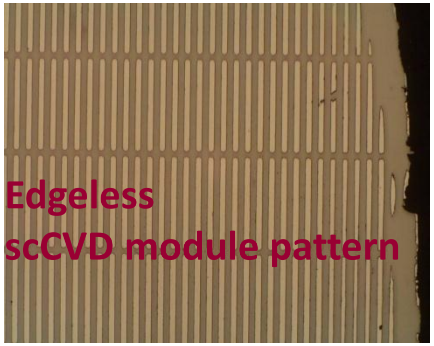
- Full modules built with I3 pixel chips @ OSU, IZM and Bonn
- Last of those fully built by IZM

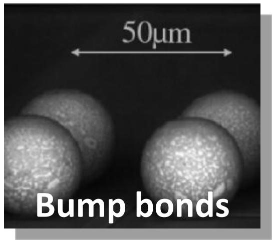






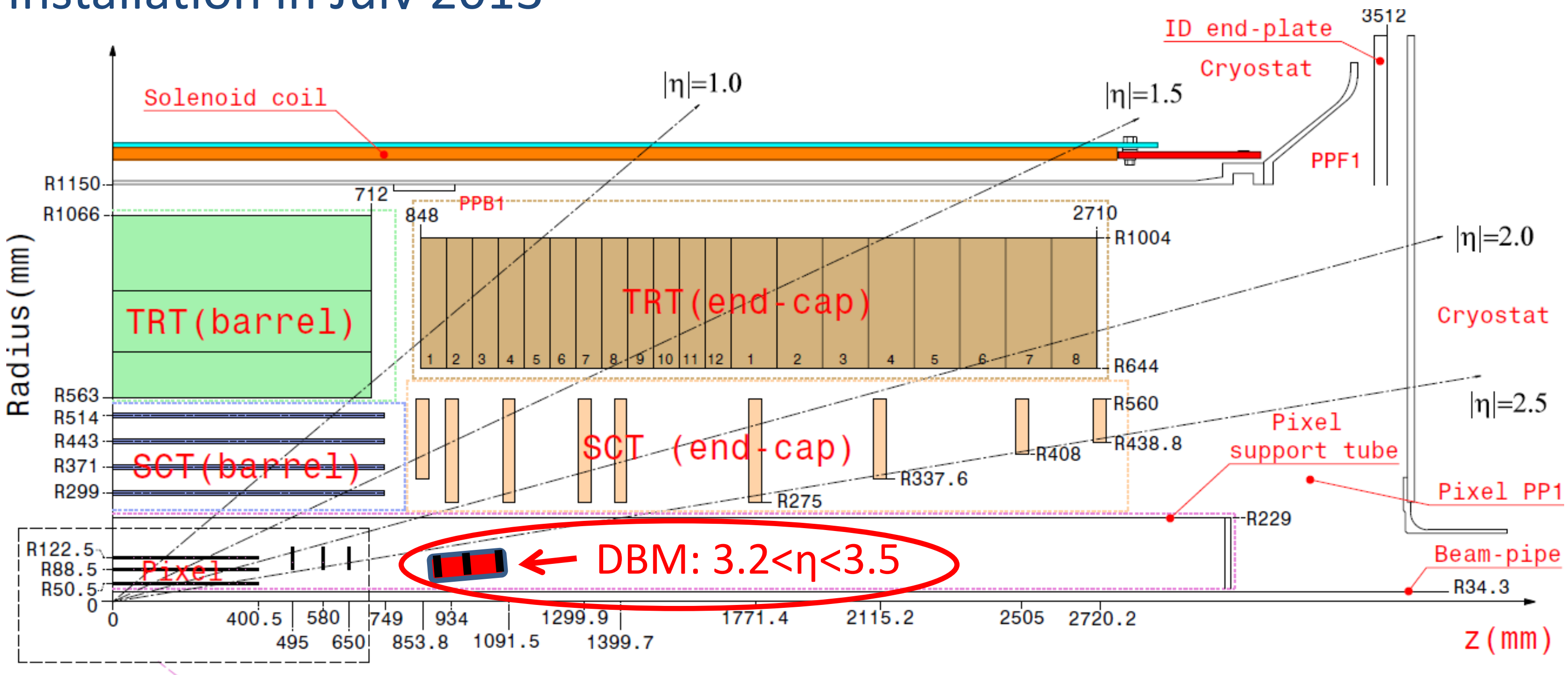



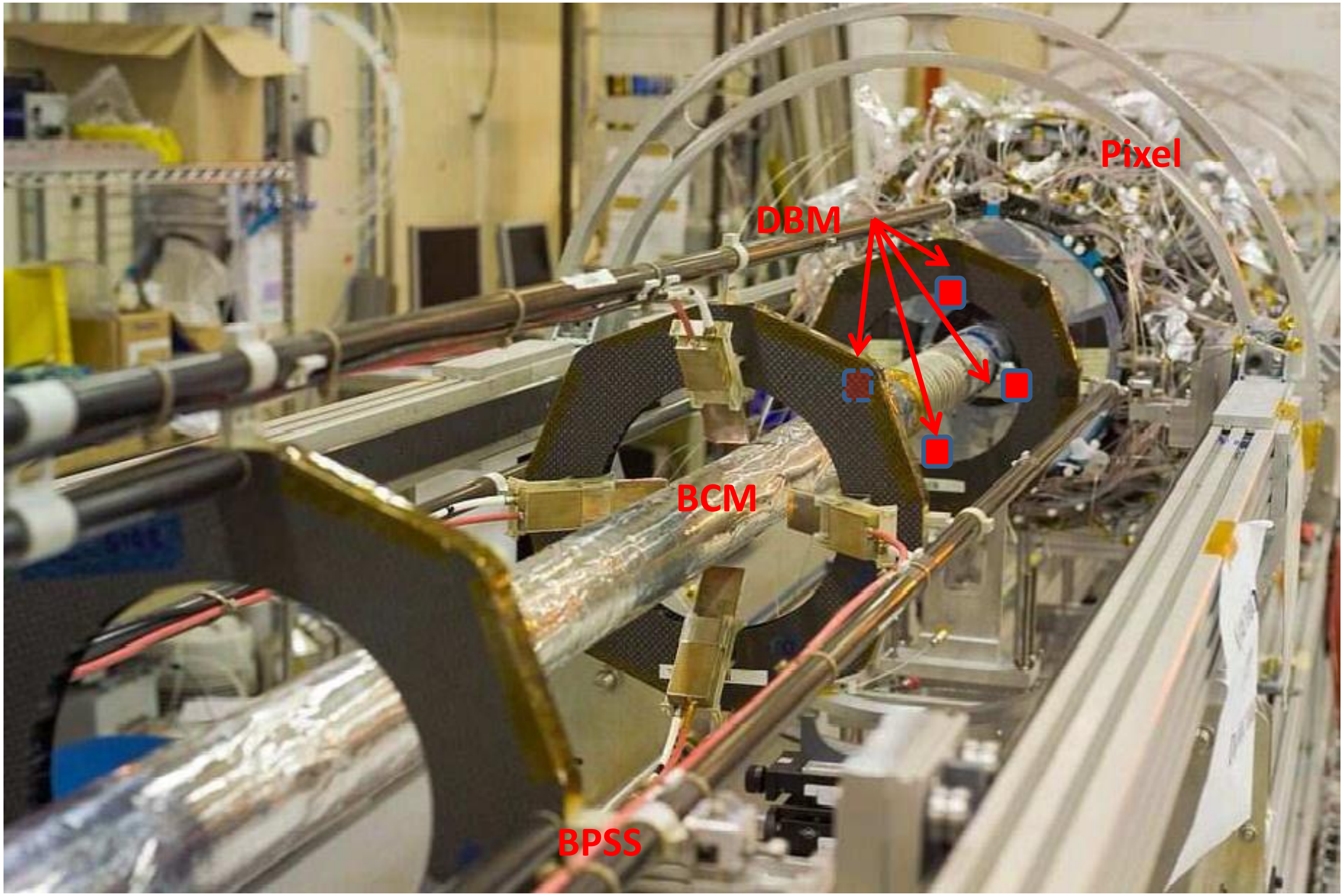
# ATLAS Diamond Beam Monitor

- Spin-off from diamond sensor bid for IBL
- 24 diamond pixel modules arranged in 8 telescopes around interaction point provide
  - Bunch by bunch luminosity monitoring
  - Bunch by bunch beam spot monitoring
- Installation in July 2013

- Accepted during last months as add-on to IBL
- Contingent on pixel services replacement in 2013

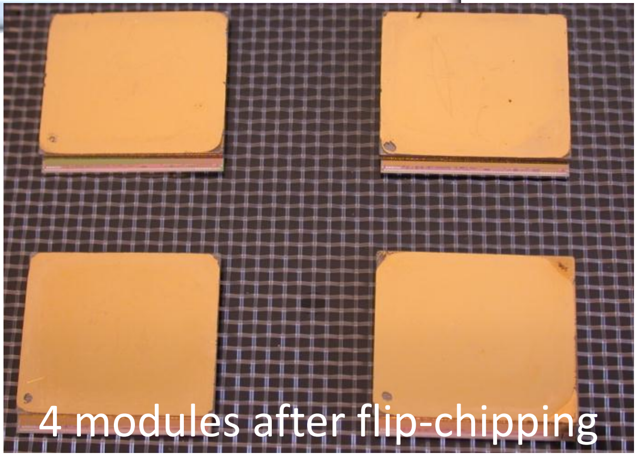


# DBM - Installation



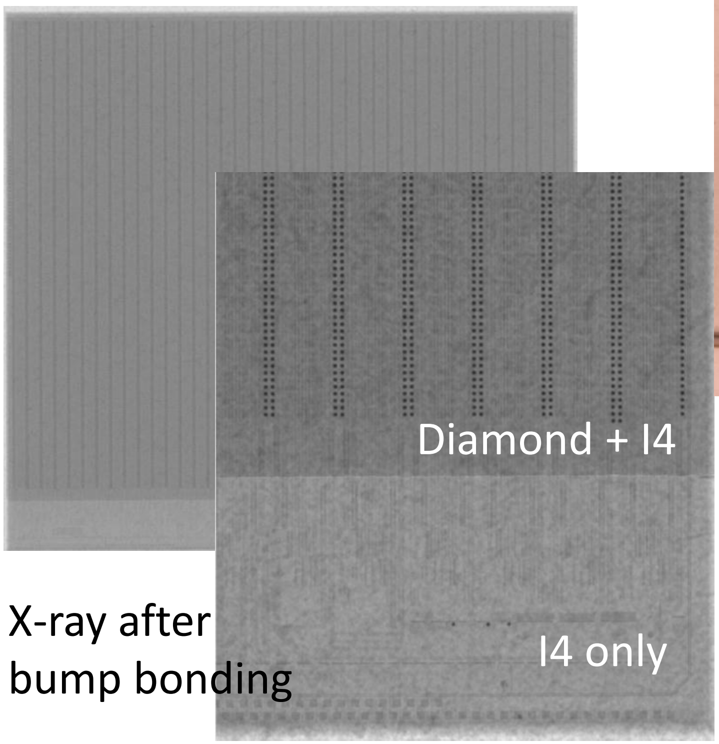
# First DBM Modules

- First four DBM modules built at IZM last year
  - 21x18 mm$^2$ pCVD from DDL, ~800 μm thick
  - FE-I4 ATLAS IBL pixel chip
  - 336x80 = 26880 channels, 50x250 μm$^2$
- Largest ASIC/diamond flip chip assembly
- Disassembled, sent to thinning

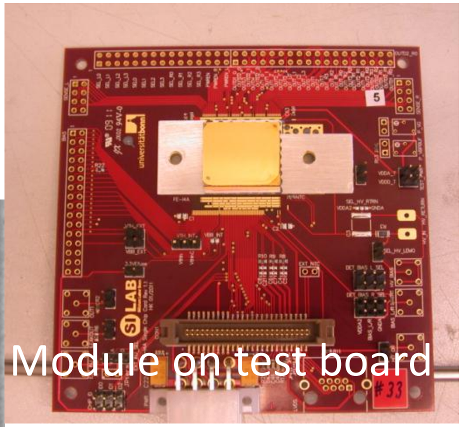


4 modules after flip-chipping

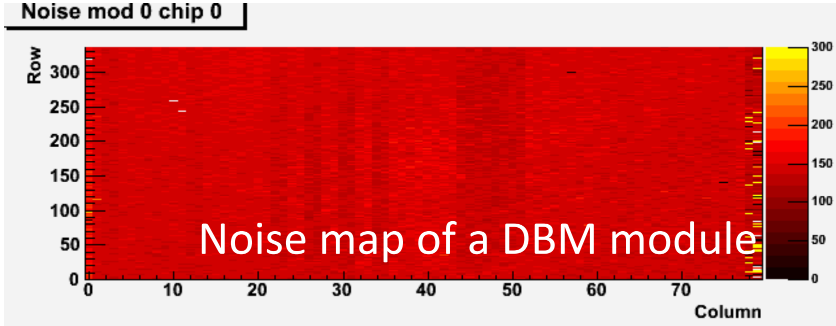
- ✓ X-ray perfect
- ✓ Noise map uniform
- ✓ Proof of large diamond module assembly
- ➢ More modules in pipeline now




X-ray after bump bonding



Module on test board




Noise map of a DBM module

# FE-I4 Tuning with Diamond

## What is possible?

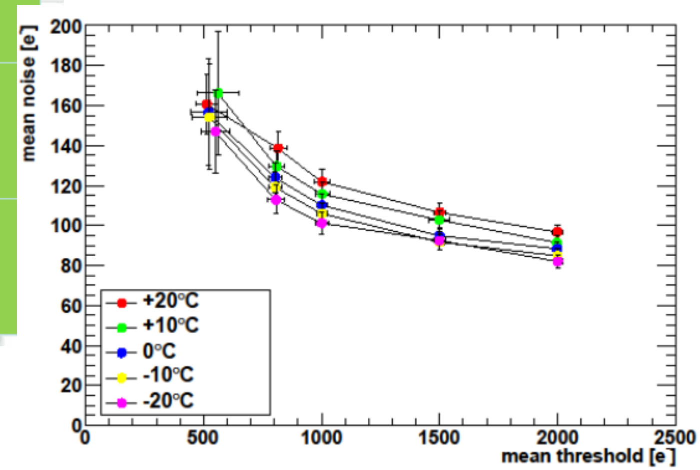
x = October 2011 DBM Test Beam

| Threshold / Gain | 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“

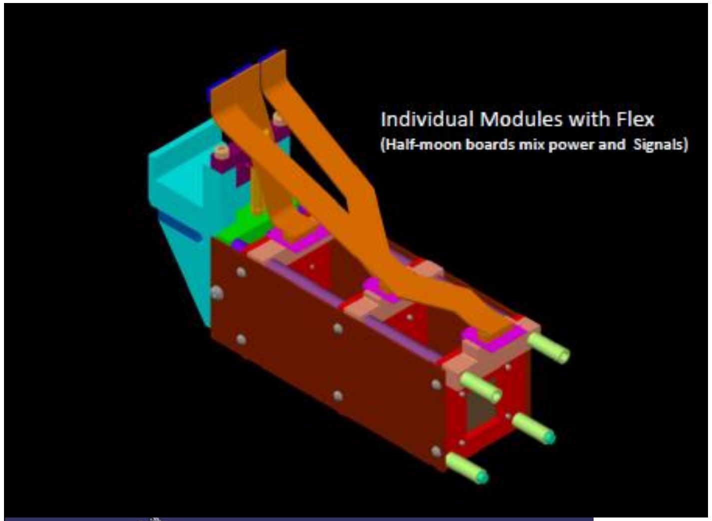
**Jens Janssen - Bonn**

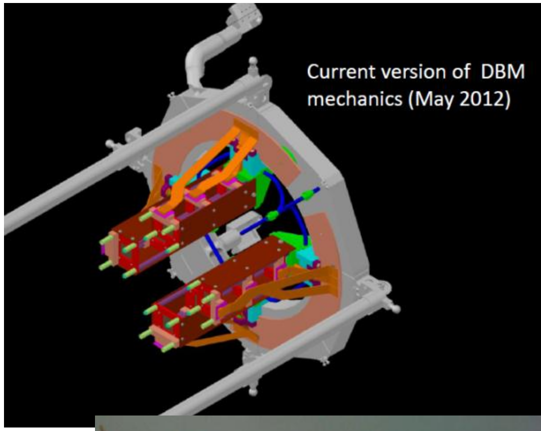
**Christian Gallrapp - CERN**

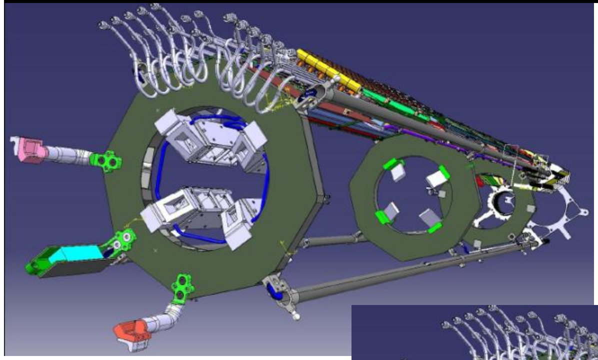


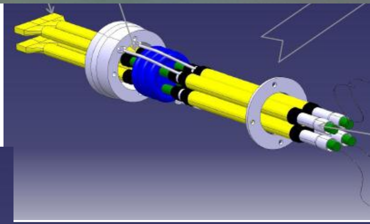
# DBM Mechanics & Integration

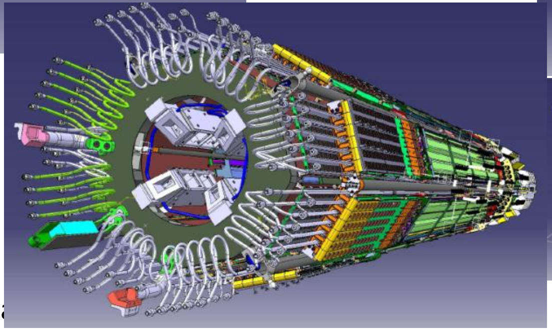
- Mechanics & cooling
  - Getting finalized
- Routing of cables from PP0 to PP1
  - Agreed
- Layout of Type 1 services
  - Agreed
  - Follow IBL design for wires
  - Addressing issues together with Su Dong
- PP0 board
  - Started with layout
  - Will produce board in the next weeks
- System Testing
  - Produce full on-detector DBM slice: i.e. Module – telescope – PP0 - type 1 services

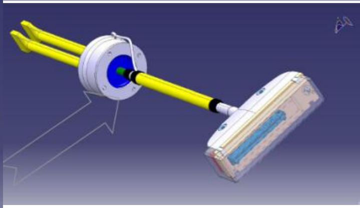


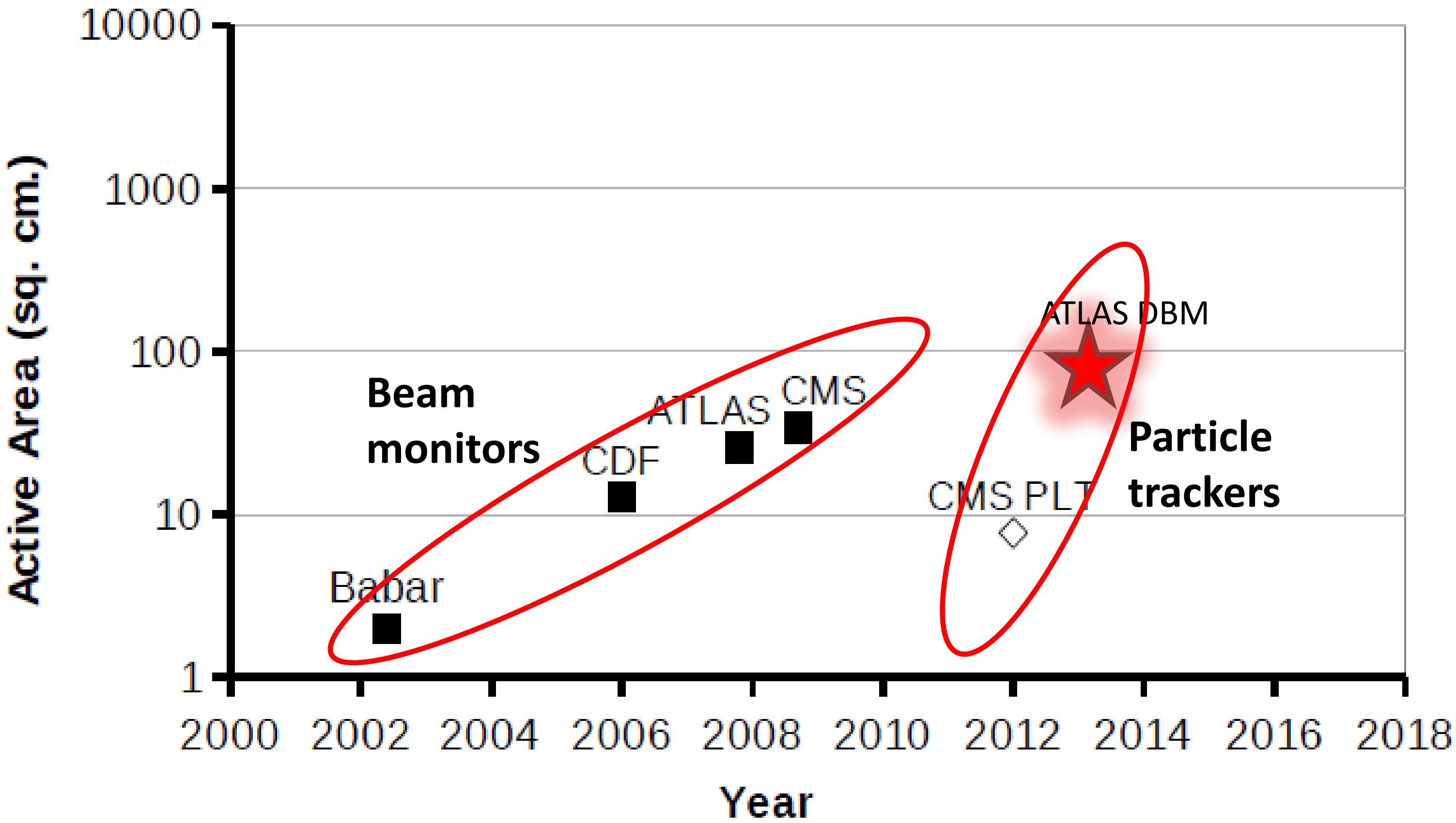









# Applications in HEP: wrap-up



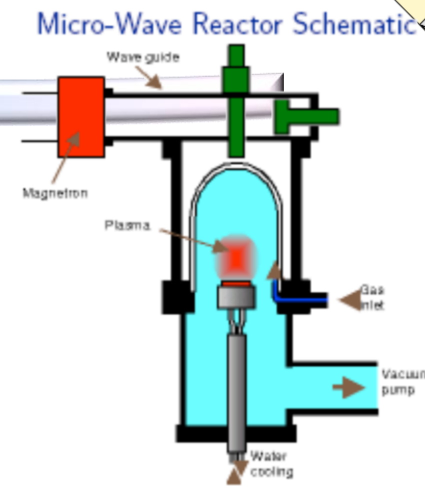
# Summary

- Recent progress in the diamond world
  - New promising manufacturers
  - Improved understanding of radiation damage
  - Application in all LHC experiments
  - Building of pixel modules in industry
  - Diamond trackers under way !

Very interesting times for diamond in HEP ahead of us !

# Backup

# Sensor Types - pCVD

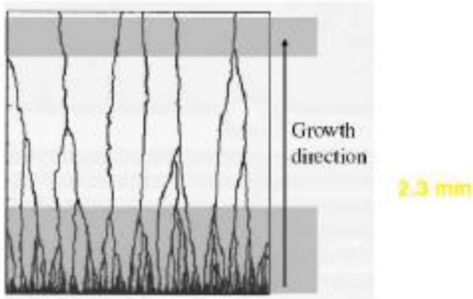


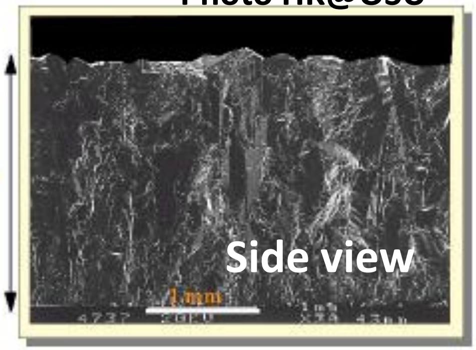

- Polycrystalline Chemical Vapour Deposition (pCVD)
  - Grown in µ-wave reactors on non-diamond substrate
  - Exist in Φ < 15 cm wafers, >2 mm thick
  - Small grains merging with growth
  - Grind off substrate side to improve quality
  
    → ~500-700 µm thick detectors

Surface view of growth side

Photo HK@OSU

Test dots on 1 cm grid

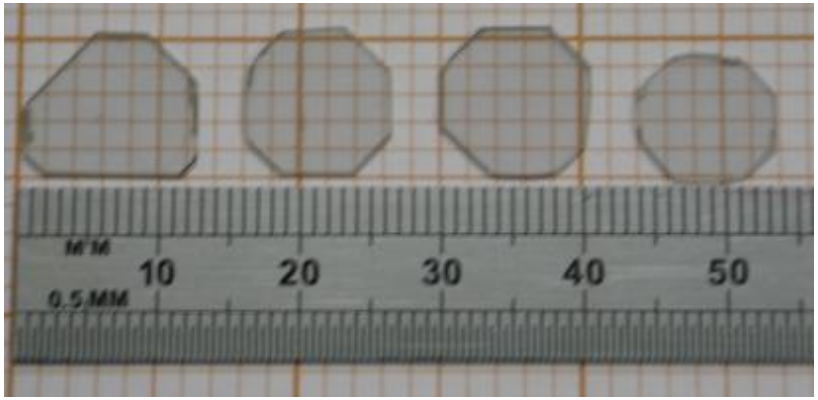


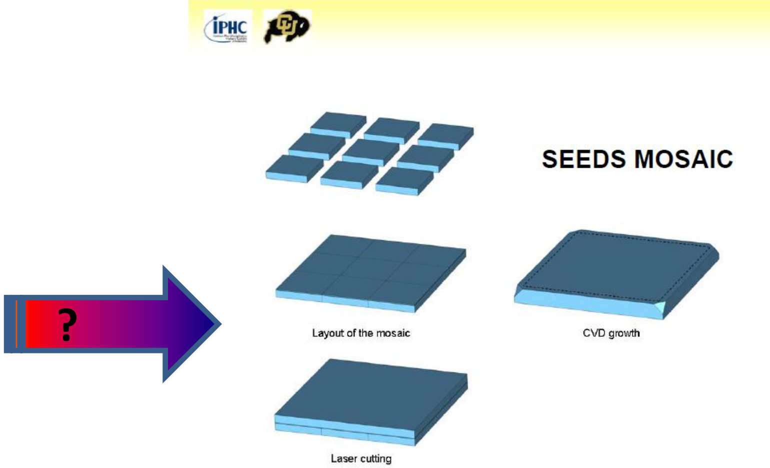




Photograph courtesy of E6

# Sensor Types - scCVD

- Single Crystal Chemical Vapour Deposition (scCVD)
  - Grown on HTHP diamond substrate
  - Exist in ~ 1 $cm^2$ pieces, max 1.4 cm x 1.4 cm, thickness > 1 mm
  - A true single crystal




☺ Fall-forward for HL-LHC pixel upgrade (single chips, wafers ?)
- ➢ Needs significant improvement in size & price, ideas are around
- ➢ After heavy irradiations properties similar to pCVD, headroom ~$3\times10^{15}$ p/$cm^2$

☹ Recent commercial developments in adverse direction
- ➢ Concentrate on max. ~5x5 $mm^2$ pieces & packaging, main target market: dosimetry

➢ Used on large scale in CMS PLT project

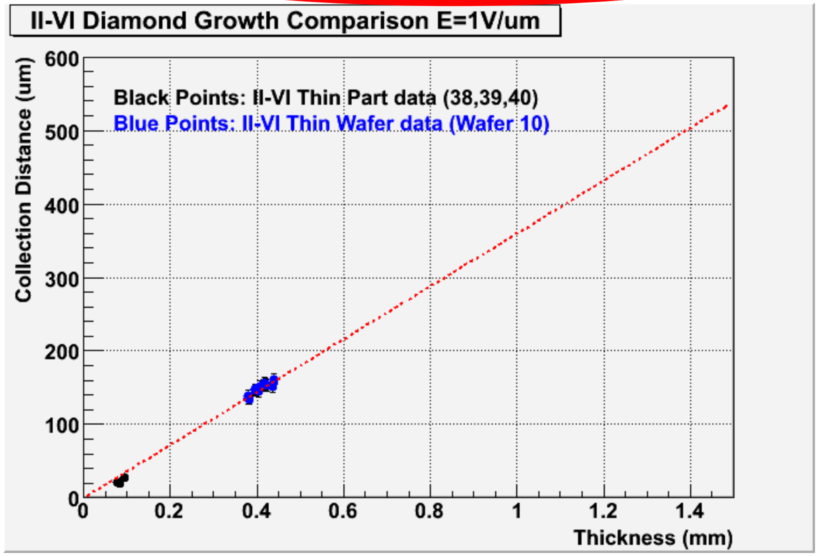
# Manufacturers: Good News

- A long lasting strive to identify an alternative supplier to DDL/E6
  - II-VI showed promising results ~2 y ago
- Order for 10 pcs (option for +10) placed in March with II-VI
  - Specified CCD > 250 µm at 500 µm thickness
- II-VI has grown several thin samples
  - <u>Very</u> promising CCD
    - 160 µm on as-grown 400 µm
- ☺ II-VI seems to know how to grow excellent detector grade diamond
  - ☞ Caveat: to be proven on thick (>1 mm) wafers
- Wafer delivered, tested @OSU now

**<u>Part Description</u>**

SPECIFICATIONS FOLLOW

Thickness: 0.500 +/- 0.050mm
Length: 21.000 +/- 0.200mm
Width: 18.000 +/- 0.200mm
Growth surface planarized with minimum possible material removal
Nucleation surface thinned to final thickness
Surface Roughness: Ra <5nm for both faces (average of 20 measurements on each side)
Wedge: <5 arcmin
Edge Chips: <0.1mm
Serialization: Nucleation surface marked with 0.2mm characters within 0.7mm of edge (~9 characters)
Charge collection distance of polished part: >250um (measured by OSU)



# Manufacturers: Bad News

- DDL has ceased operations
  - This was a business re-structuring
  - E6 has agreed to fill order outstanding for ATLAS
- Work with E6/DeBeers to remain a strong supplier

DIAMOND DETECTORS LIMITED

**DIAMOND DETECTORS LTD**

Dear Customer

**Diamond Detectors Limited**

It is with regret that we announce that we have taken the decision to close the business.

Operations will cease on 25 May 2012. Please be advised that existing orders will not be completed and no future orders will be accepted. We apologise for any inconvenience this may cause.

- Two steps forward, one step back…

# Radiation Damage in Diamond

| Radiation induced effect | Diamond | Operational consequence | Silicon | Operational consequence |
|---|---|---|---|---|
| Leakage current | small & decreases | none | $I/V = \alpha\Phi$<br>$\alpha \sim 4\text{x}10^{-17}$ A/cm | Heating<br>Thermal runaway |
| Space charge | ~ none | none | $\Delta N_{eff} \approx -\beta\Phi$<br>$\beta \sim 0.15$ cm$^{-1}$ | Increase of full depletion voltage |
| Charge trapping | Yes | Charge loss<br>Polarization | $1/\tau_{eff} = \beta\Phi$<br>$\beta \sim 4\text{-}7\text{x}10^{-16}$ cm$^2$/ns | Charge loss<br>Polarization |

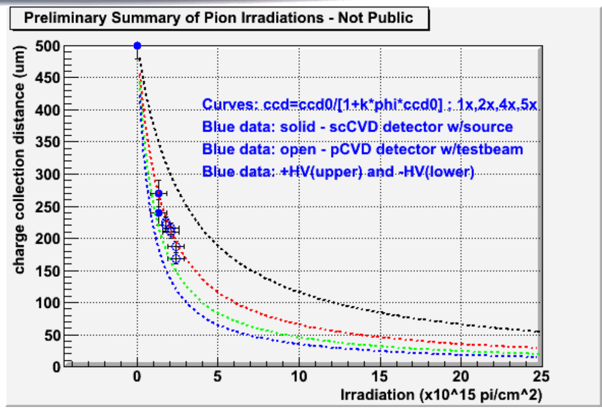
Charge multiplication

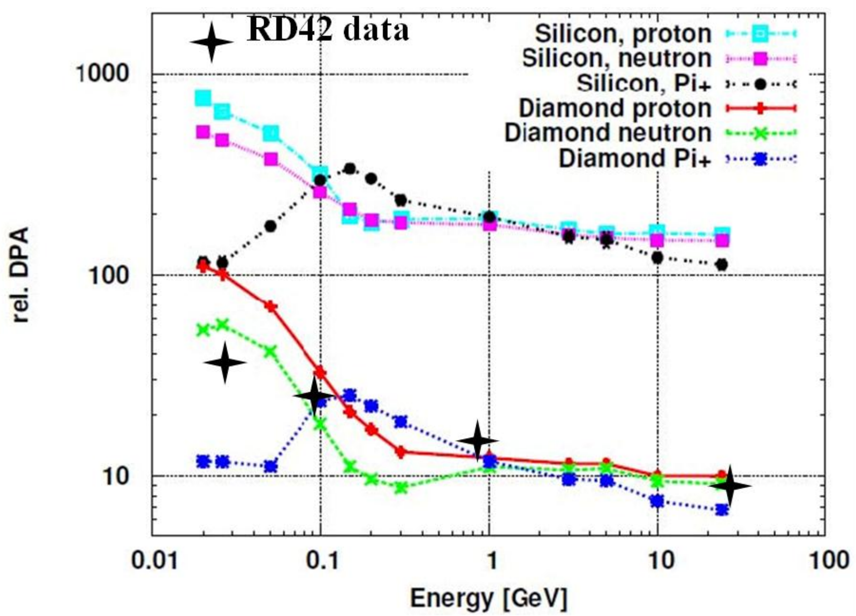
- At extreme fluences charge trapping the paramount radiation damage effect
- Difference O(10) in x-section between charged/neutral traps
  - Filled (neutral) traps trap less (of the opposite carrier)
  - Basics of "pumping"
- $E_{gap}$ in diamond 5 times larger than in Si
  - Many processes freeze out
  - Typical emission times order of months
- Works also in Si at 300/5 = 60 K – "Lazarus effect"

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

# Irradiation at PSI: 300 MeV pions

- Single scCVD, *d* = 500 µm, irradiated with 200 MeV pions at PSI, Villigen, CH
- Measured (source) *CCD* = 260 µm after $6.52 \times 10^{14}\ \pi/\mathrm{cm}^2$
- Turns into *mfp* of 420 µm
- **$k = 3.6 \times 10^{-18}\ \mu\mathrm{m}^{-1}\mathrm{cm}^{-2}$**
- Appears high, but DPA peaks at 200 MeV (Δ)
- Again, work in progress
  - Test-beam under way



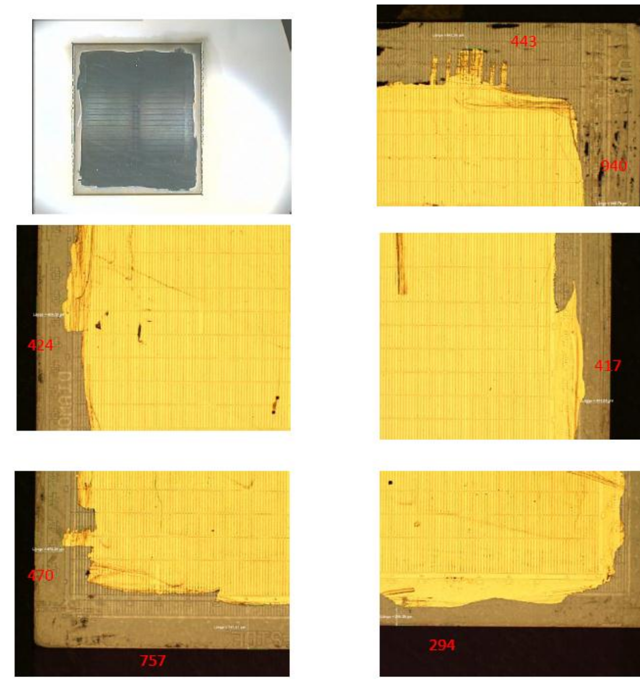




**Steffen Mueller – PhD Thesis.**

# Further DBM Modules

- Further 4 diamonds built @ IZM in Feb 12
  - ADBM01-4, 500 μm thick
  - Metallization stand-off “improved”
    - Uncovered pixels
    - Irregular pattern
  - Tested in Bonn, CERN, Gottingen
    - Limited success
    - Stable operation up to 500 V on 2 modules
      - Suspect backplane, PCB
      - Diamond(s) tested to 1000 V @OSU
  - Baseline module(s) for April DESY TB, CERN June TB

| |
|---|
| (1) Polishing done at OSU |
| (2) Acid cleaning done at OSU |
| (3) $O_2$-plasma cleaning |
| (4) Embedding in ceramic wafer |
| (5) Ar re-sputtering on bias side: TiW 230nm + Au 200nn |
| (6) Ar re-sputtering on pixel side: TiW 200nm + Cu 300nm |
| (7) Lithography of pixel structure |
| (8) Wet etch TiW between pixel |
| (9) Cutting out of wafer and cleaning |
| (10) Annealing 450°C for 4 min |
| (11) Flip-chip to pixel readout chip |

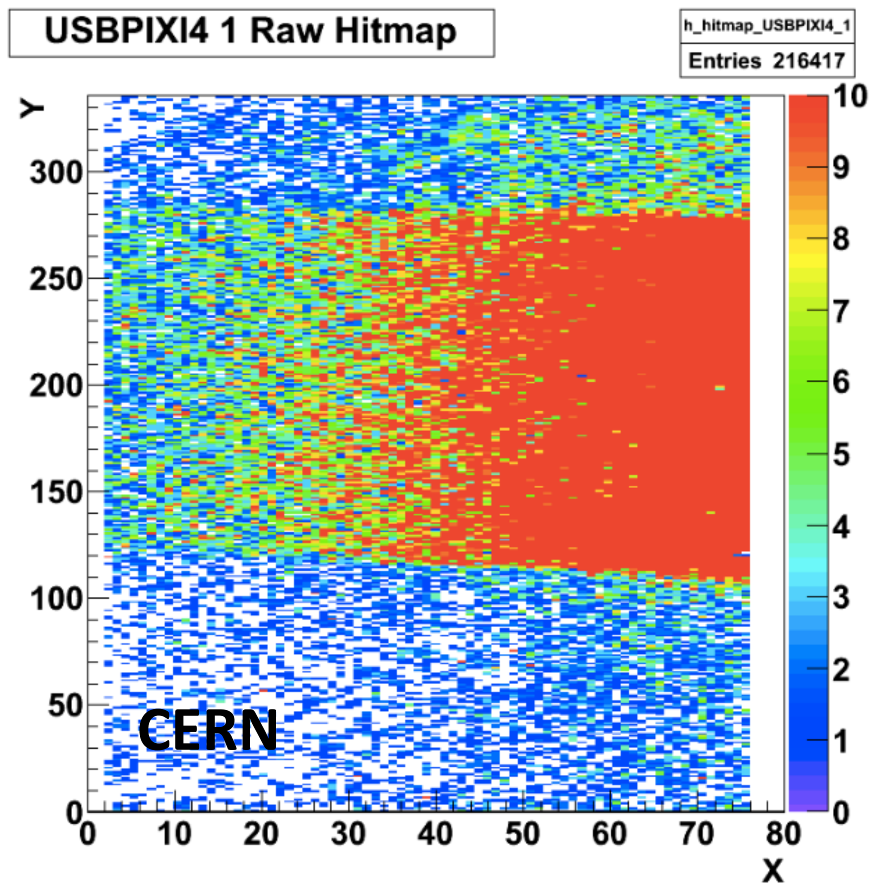



- Metallization moved to OSU
  - Photolithography
- Swap 4 and 5 in module work flow
- Steps 3&4 now @ OSU

# Test-Beam @ CERN

- $1^{st}$ week of June in SPS H6 high energy pion beam
- 3 modules as TB candidates
  - Readout problems
    - Only SCC148 could be accessed
- Module pumped at CERN
- Only hitmaps available so far
  - No obvious dips observable
  - Track-based analysis needed to confirm

800e, 8@5ke




Run range for SCC148 at 500V

| Threshold | ToT | GeoID | eta | phi | First Run | Last Run | Status |
|---|---|---|---|---|---|---|---|
| 2000e | 8@8ke | 44 | 0 | 0 | 70803 | 70821 | DONE |
| 2000e | 8@5ke | 45 | 0 | 0 | 70822 | 70839 | DONE |
| 1500e | 8@8ke | 36 | 0 | 0 | 70588 | 70624 | DONE |
| 1500e | 8@5ke | 40 | 0 | 0 | 70728 | 70745 | DONE |
| 1000e | 8@8ke | 38 | 0 | 0 | 79680 | 70697 | DONE |
| 1000e | 8@5ke | 37 | 0 | 0 | 70626 | 70699 | DONE |
| 1000e | 8@3ke | 39 | 0 | 0 | 70700 | 70727 | DONE |
| 800e | 8@3ke | 43 | 0 | 0 | 70784 | 70802 | DONE |
| 800e | 8@5ke | 42 | 0 | 0 | 70766 | 70782 | DONE |
| 800e | 8@8ke | 41 | 0 | 0 | 70749 | 70765 | DONE |