Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders

RD42 Status Report

Harris Kagan
for the RD42 Collaboration

LHCC Meeting – May 10, 2017

Outline of Talk

- The RD42 Collaboration
- The RD42 Program
- Collaboration with LHC Experiments: CMS BCM1F
- Collaboration with LHC Experiments: ATLAS BCM'
- Diamond Device Development – 3D Diamond
- Rate Studies
- Summary

The 2017 RD42 Collaboration

The 2017 RD42 Collaboration

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130 participants

32 institutes

The RD42 Program, Publications, and more

Areas of work in RD42:

- Characterization of diamond (materials work)
- Work with manufacturers (feedback)
- Development of machine devices (BLM, lumi)
- Development of detectors (pad, strip, pixel, 3D)
- Irradiation (JSI,LANL) and Beam tests (CERN, PSI)
- Work with LHC experiments

RD42 meetings: https://indico.cern.ch/category/3177/

- 11 published papers in the last year; 11 the year before
- 9 conference talks in the last year
- 2 Ph.D. student graduated in the last year
- 12 Ph.D. students continuing in 2017

LHCC Milestones/Priorities of Research-2016

- Continue to develop pCVD and scCVD material.
- Expand sensor grade manufacturing capability.
- Beam tests of the highest quality material.
- Test radiation tolerance and rate tolerance of highest quality pCVD and scCVD material.
- Develop diamond devices for the LHC (BLM's) and LHC experiments (pixel detectors, lumi).
- Develop diamond devices for future HL-LHC experiments (3D diamond devices) and machine.
- Record publications/talks/theses/students

The RD42 Program, 2016 Referees Report

2016 LHCC Referees Report (CERN/LHCC 2016-008)

The RD42 collaboration is to be commended for its publication record this year, with 11 publications and 11 conference submissions. The progress in the development of 3D diamond sensors looks promising. The prioritized goals for the coming year are to work with CMS to prove the diamond-based beam loss monitor concept and to continue the study if pCVD is an option for future luminosity telescopes. Scaling up a 3D detector by another factor of 10 and constructing a 3D-diamond based pixel module will be initiated. The study of rate effects will be continued.

The value of diamond detectors for the community is well recognized and we congratulate the collaboration on the progress this year. Following the successful model of the other large RD collaborations, it is suggested RD42 create a slightly tighter collaboration to advance the overall scientific output.

Summary

1-Work w/CMS on beam loss monitor ✓
2-Study if pCVD is an option for future luminosity measurements ✓
3-Scale up 3D by factor of 10 factor of 4 done - ongoing
4-Construct 3D-diamond based pixel module ✓

Collaboration with experiments: CMS BCM1F

BCM1F Upgrade Motivation:

- Avoid HV trips seen with previous scCVD system.

Potential problem areas:

- pcb's, scCVD diamonds

Modification of pcb layout:

- not possible.

Production of new pcb:

- only yielded 2 out of 6 produced.
- 2 old spares used; HV adapter pad (kapton) used.

Diamonds:

- replaced with 10-12 pCVD ← RD42 collaborated on this
- added 2 3D diamond detectors ← RD42 provided these

Collaboration with experiments: CMS BCM1F

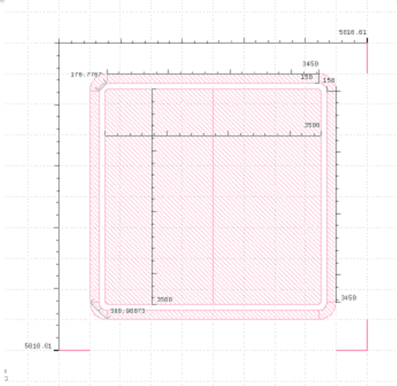
Sensor production

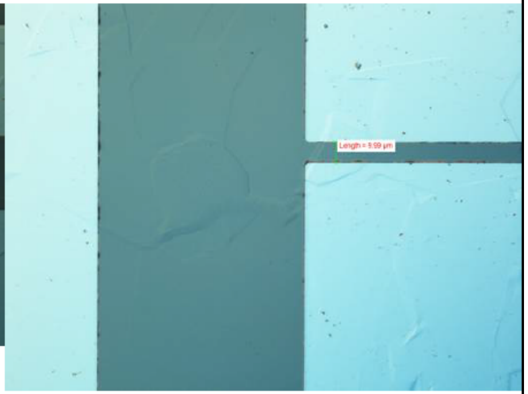
- Pre-selection by Harris
- Cleaning and backplane metallization in OSU
- Readout metallization in Princeton
  - Split pad -> 2 channels per diamond
- The odyssey of the diamonds:
  - II-VI to Harris for tests (normally sent back to II-VI for sales)
  - Harris implements final back metal and sends to Princeton
  - Princeton puts readout metal, sends back to Harris
  - Harris to II-VI
  - II-VI officially sales to CERN (shipment to CERN)
  - Received by Dmitry, picked up by us.
  - Shipped to DESY for testing and finally mounting on PCB
  - Final detector to CERN for integration.

➢ **Great effort by everyone to achieve production in time**

Collaboration with experiments: CMS BCM1F

Sensors, metallization



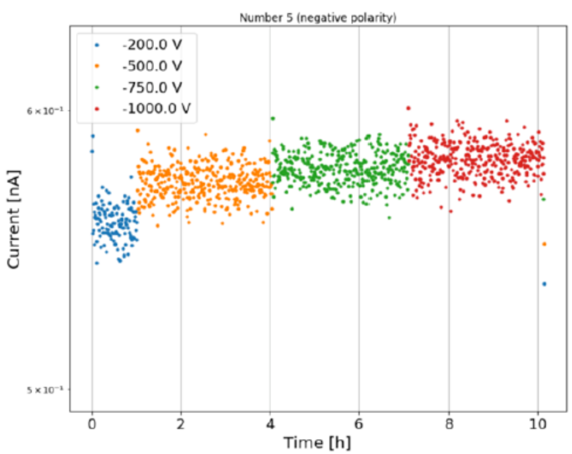


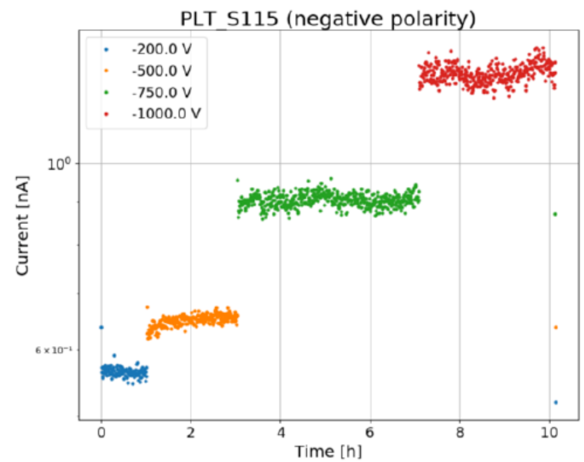
- Geometry provided by Harris.
- Princeton made a split pad version of the same geometry (10um gap)

M.Guthoff 7

Collaboration with experiments: CMS BCM1F

Sensor tests: I(t) single





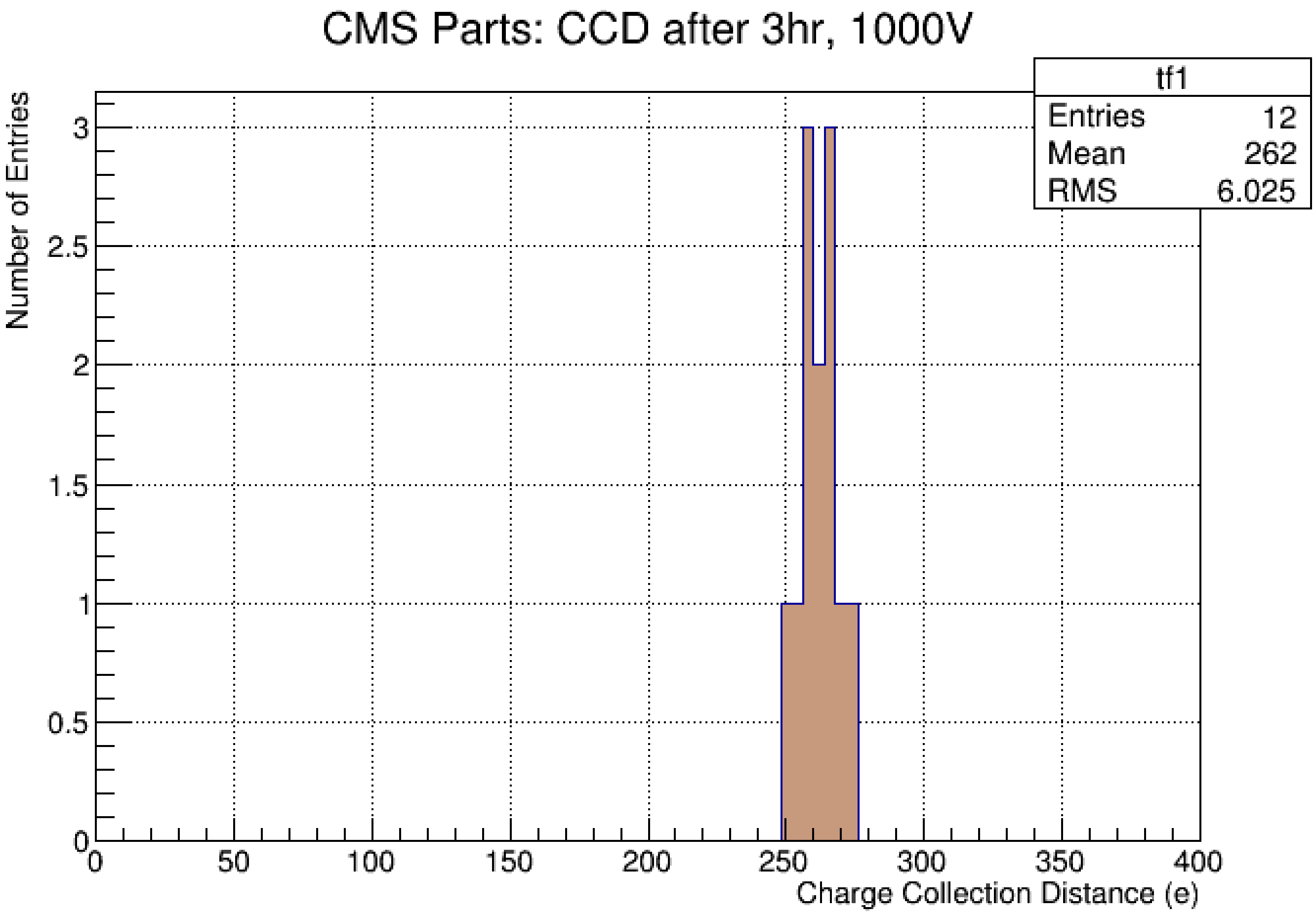
- Perfect result, much better than anything we had in the last production run

- Stable and low current, complies with selection criteria
- Clearly more current

M.Guthoff 10

Collaboration with experiments: CMS BCM1F

Charge Collection Distance



Collaboration with experiments: ATLAS BCM'

Abort and Luminosity Functions

Abort

- Require out-of-time and in-time signals above threshold signifying beam background at the danger Level
- Danger levels can be very high

  ATLAS SCT 25k/cm^2/BC i.e. ~4000x lumi signal
- Need to keep flexibility for threshold settings

Luminosity

- Main algorithm: (absence of) in-time hits

  Max sensitivity ~1.6 hits/cell
- Need robust device, signal stability paramount

Collaboration with experiments: ATLAS BCM'

Present BCM suffers from abort-lumi incompatibility

- Abort thresholds can not be set higher without abandoning lumi
- Fast timing needed for abort lowers S/N thus limiting lumi stability

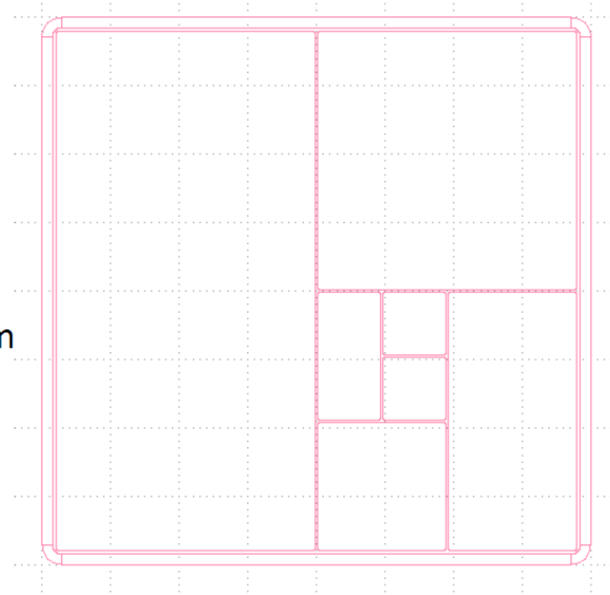
Separate functions at the HL-LHC

- Two fast devices from sensor to off-detector
- Keep as much commonality as possible
- 4 stations/side with abort, lumi-BCM', BLM

Collaboration with experiments: ATLAS BCM'

Sensor design

- Build in dynamic range into sensor design
- 6 different pads from 1 to 32 mm^2
  - occupancy from 0.06 to 2 at μ=200
    - covers sweet spot for lumi
  - 250 to 80000 MIP's at the declared SCT danger level (25k/cm^2/BC)
  - need to update the ballpark danger level for ITK asap !
- pCVD diamond substrate 300-500 μm thick
- Pads bonded to chip
- Prototype produced, to be tested in PSI TB at 5-10 MHz/cm^2 end of May



RD42, CERN, 29/3/2017 M. Mikuž: BCM' 8

Prototype detector built w/RD42
Prototype electronics from RD42
} Test @PSI next week!

Collaboration with experiments: ATLAS BCM'

Start with RD42 fast amp used in rate studies

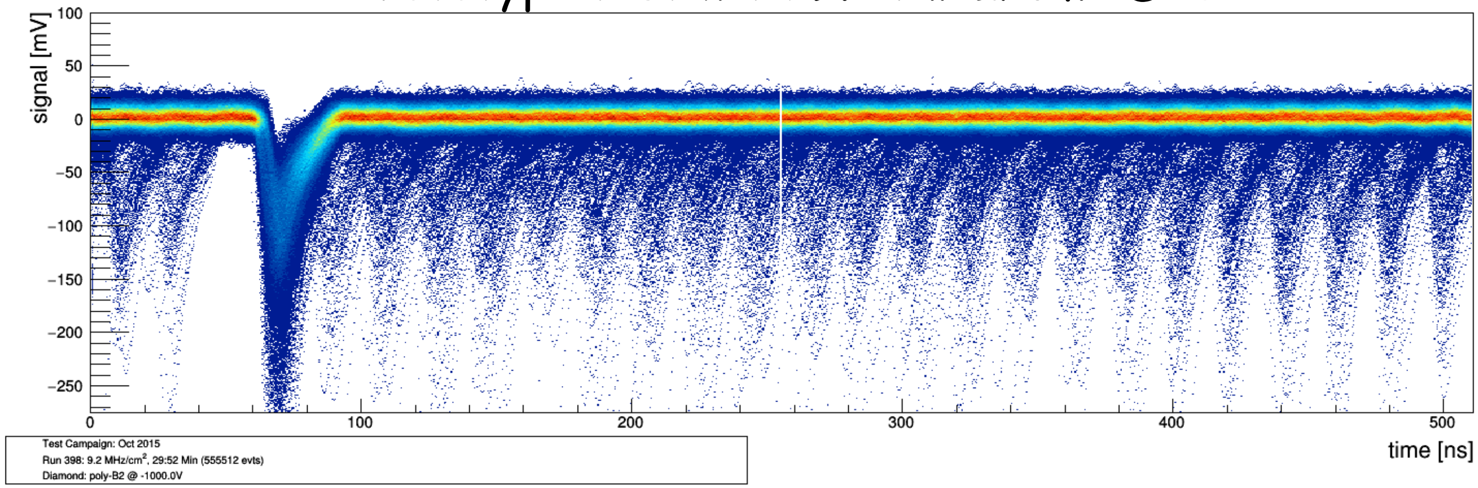
- Designed in 130nm; will be updated to 65nm
- Rise time 3-6ns; Baseline recovery time 12-18ns
- Noise for 2pf input ~550e

ATLAS electronics ideas

- Two preamp designs since otherwise large dynamic range (10^4) needed to cover lumi and abort in same channel
- High gain for lumi; low gain for abort. Optimize gain and speed vs SNR for lumi and abort separately
- Rise time ~few ns; return to baseline 10ns
- Tune parameters based on beam tests
- 16 channels (8/8 lumi/abort)

Collaboration with experiments: ATLAS BCM'

Prototype test with 9.2 MHz/cm^2 @PSI

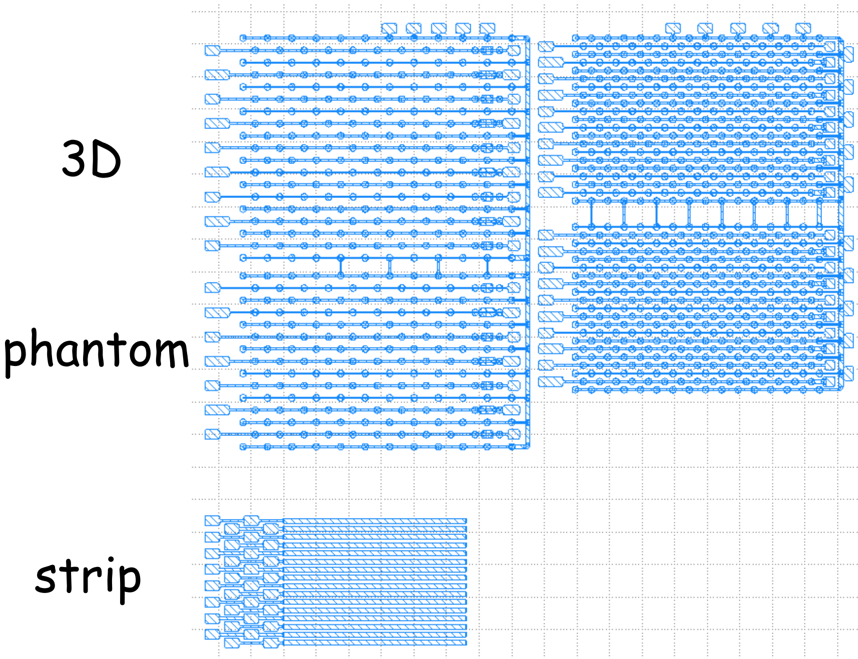


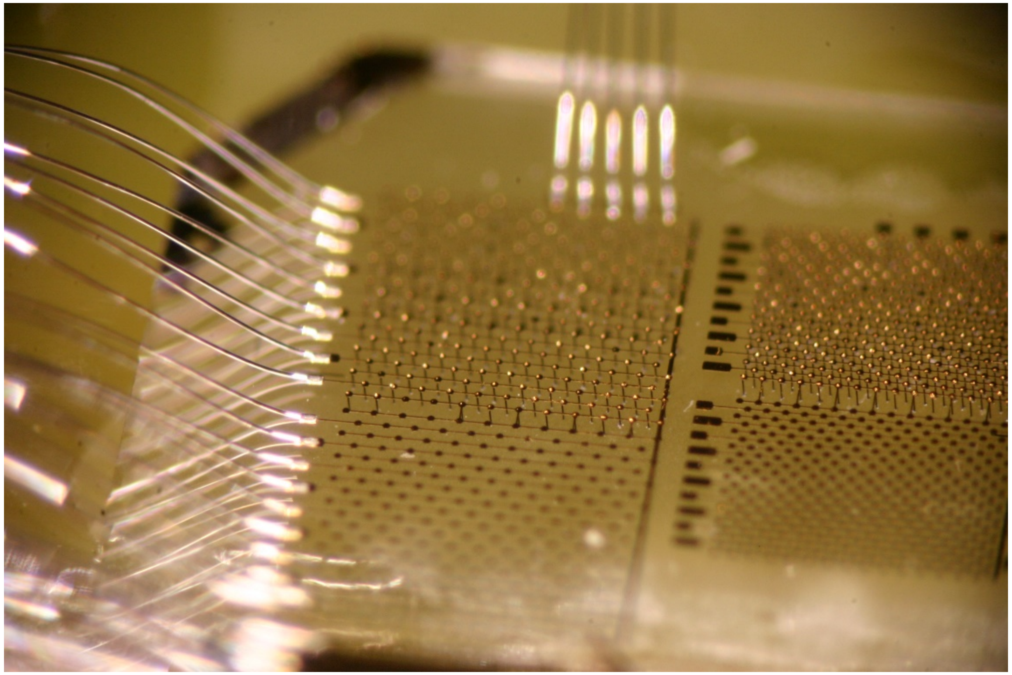
- Bunches 19.8ns apart clearly separated
- Trigger is at 69ns
- Hits in bunch before trigger not allowed

Diamond devices in experiments

- Beam Conditions Monitors
  - Alice, ATLAS, CMS, LHCb
- Current generation Pixel Detectors
  - ATLAS DBM (low threshold operation)
- Future HL-LHC Trackers
  - ATLAS
  - 3D diamond

3D device in pCVD diamond

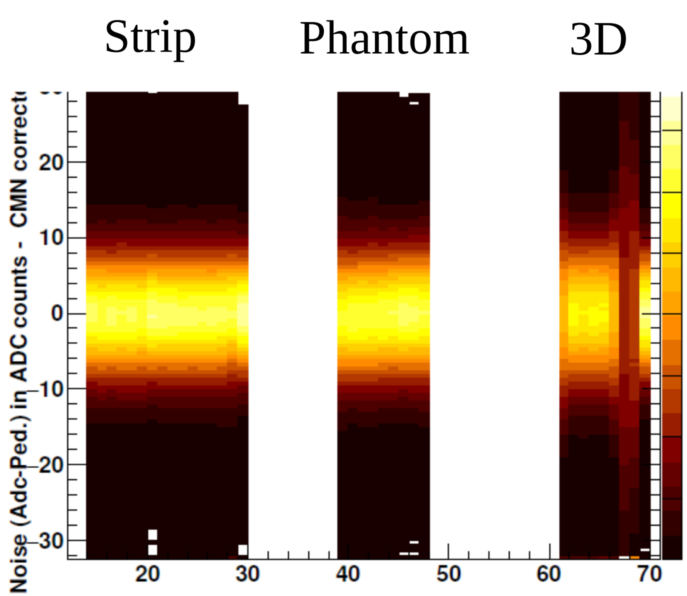


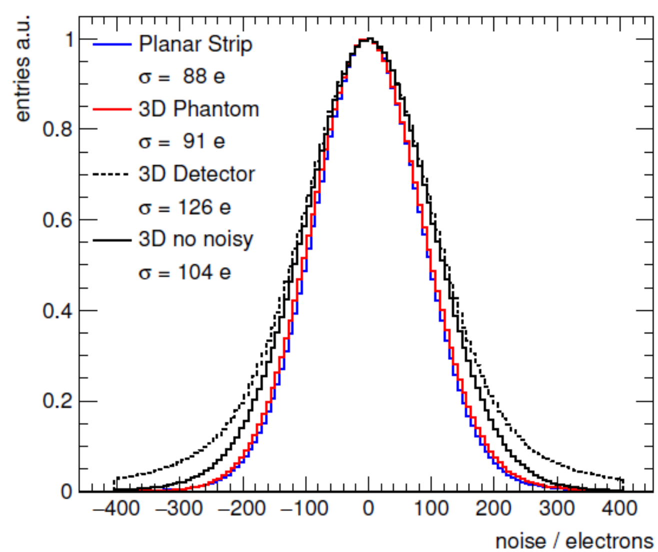


- Two years ago we showed the results in scCVD diamond
  - -Compared scCVD strip detector (500V) with 3D (25V)
- Last year the first 3D device in pCVD diamond
  - -Compare pCVD strip detector (500V) with 3D (60V)
- This year the first 3D pixel detector in pCVD diamond

3D device in pCVD diamond

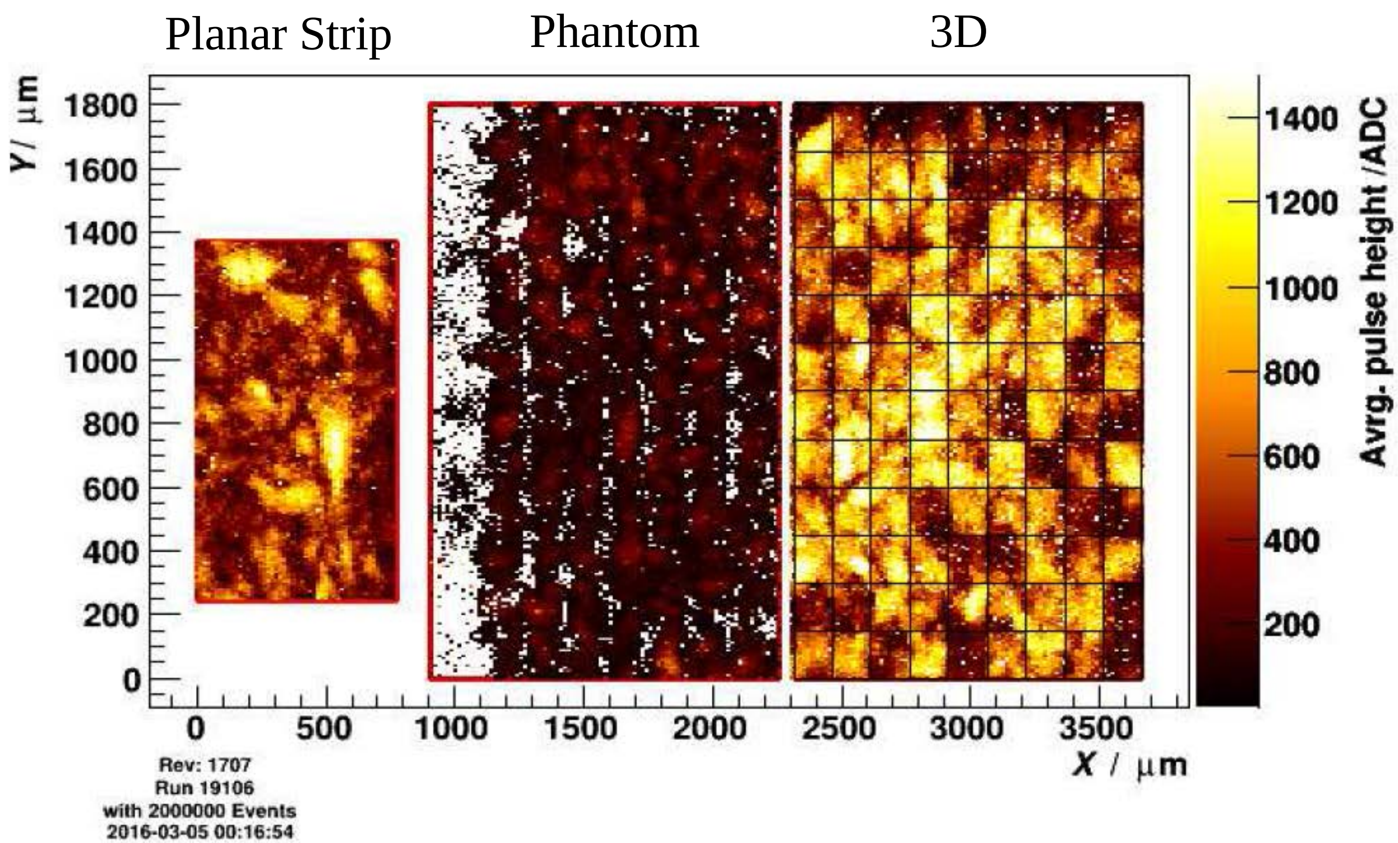
- Measured noise:
  - Planar strip: 88e
  - Phantom: 91e
  - 3D no noisy strips: 104e





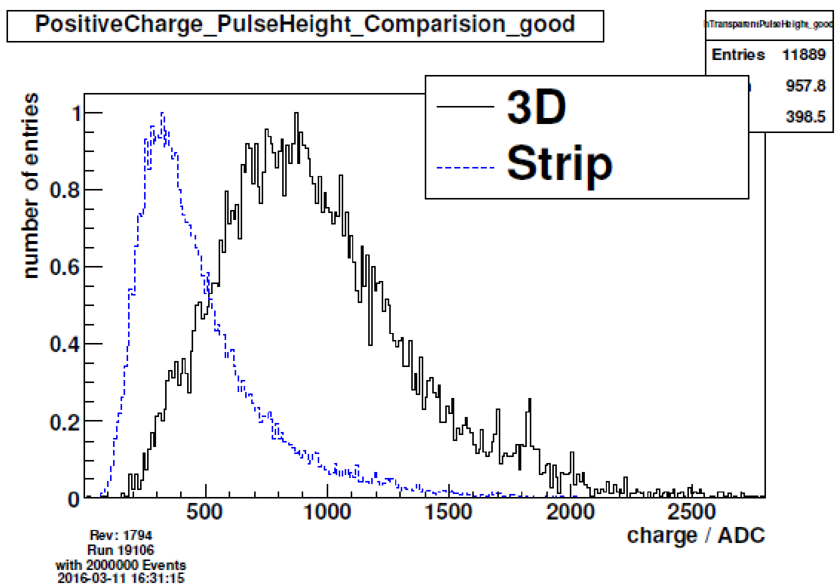
3D device in pCVD diamond

- Measured signal in first devices:
  - Visually 3D gives more charge that planar strip!



3D device in pCVD diamond

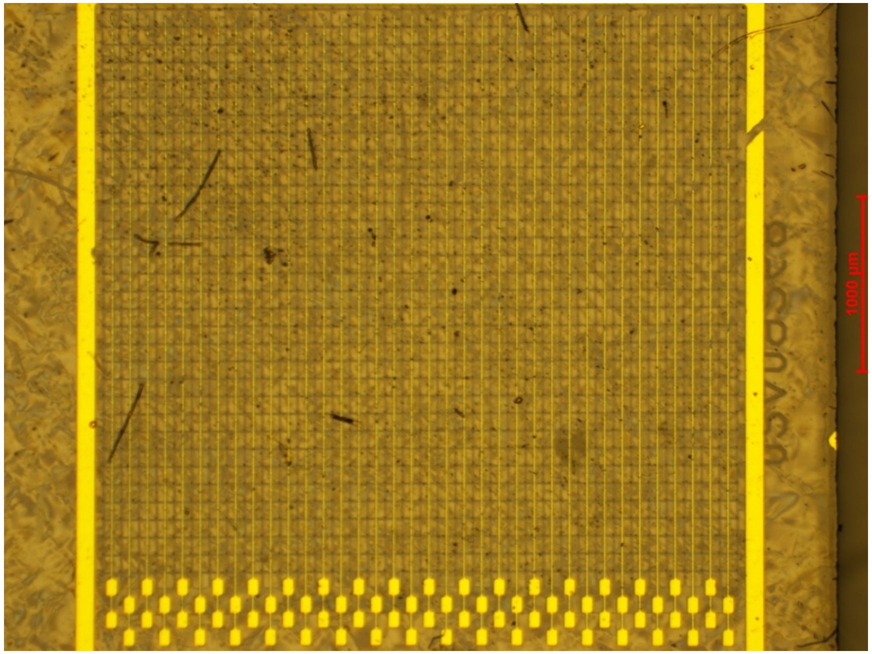
- Measured signal (diamond thickness 500um):
  - Planar Strip ave charge
    6,900e or ccd=192um
  - 3D ave charge
    13,500e or ccd=350-375um
- For the first time collect >75% of charge in pCVD



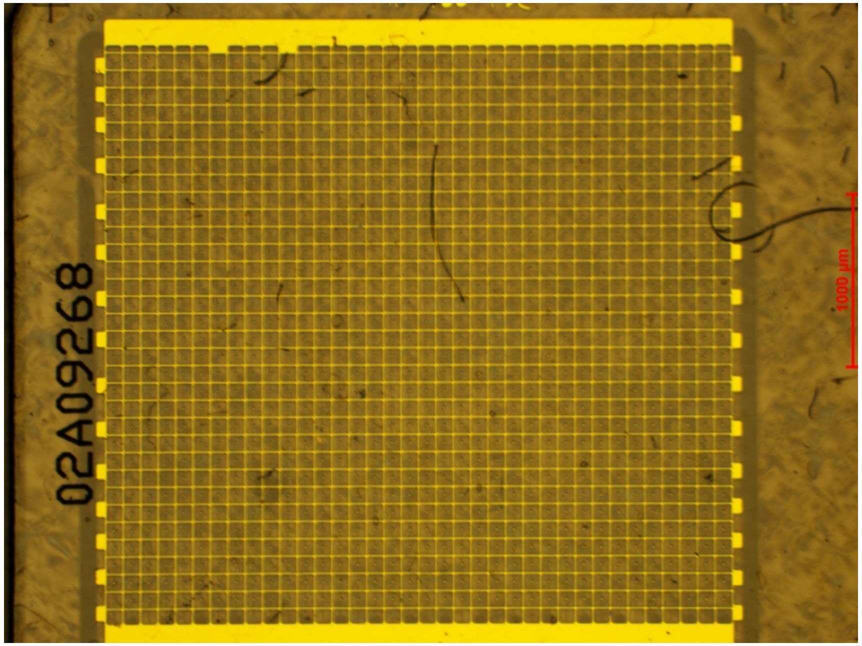
3D device in pCVD diamond

- In May 2016 tested first full 3D in pCVD (no planar or phantom) with two dramatic improvements:
  - An order of magnitude more cells (1188 vs 99)
  - Smaller cell size (100um vs 150um)

Readout side



HV Bias side

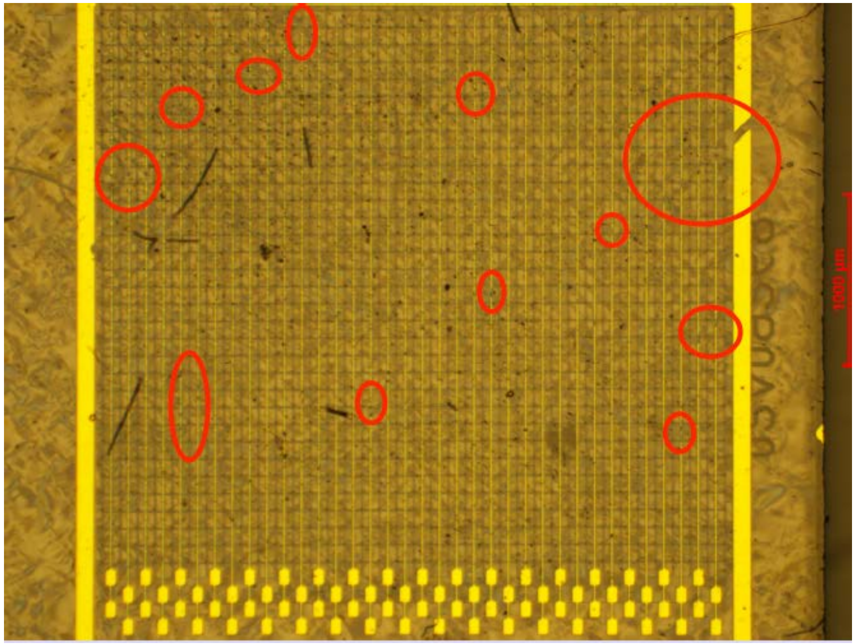


3D device in pCVD diamond

Proved viability (>99%) of new column fabrication procedure

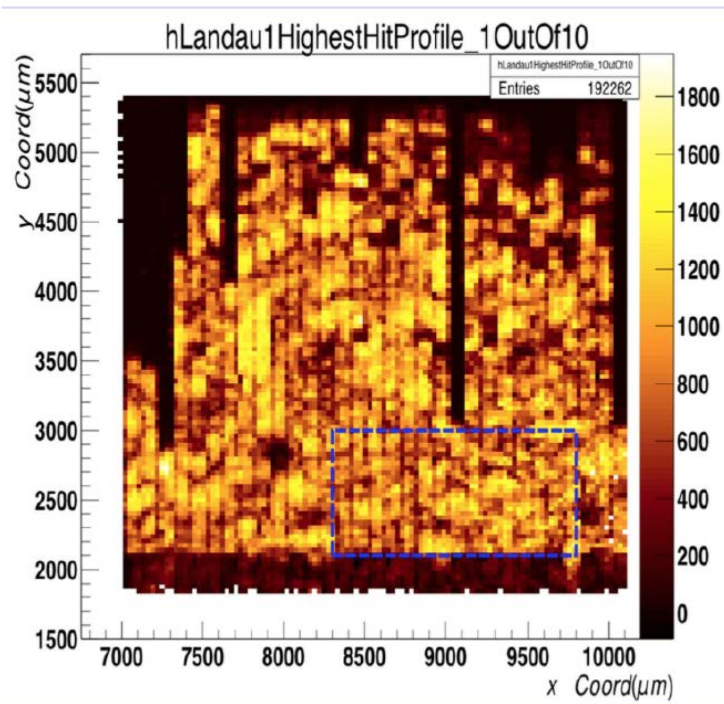
Issues mainly due to communications about handling procedures – led to:

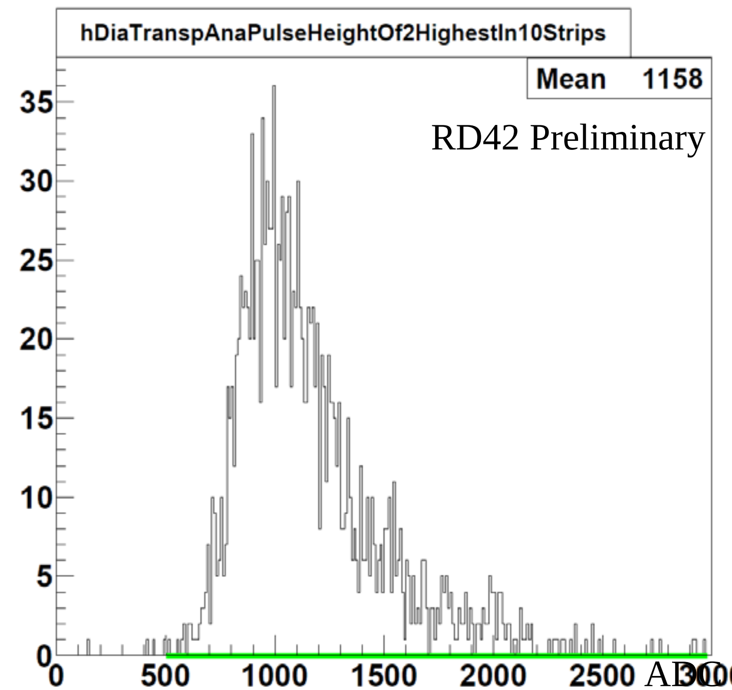
- Surface contamination
- Breaks in surface metallization
- All fixable



3D device in pCVD diamond

- Preliminary results of full 3D - device works well
  - First plot of 3D ave charge in entire detector
  - Largest charge collection in pCVD diamond
    - >85% of charge collected in contiguous region
- Analysis in progress of full detector





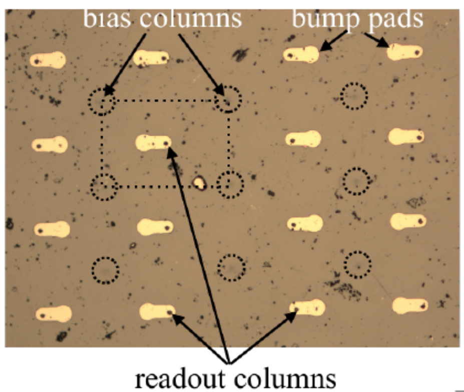
3D pixel device in pCVD diamond

- First 3D pixel device in pCVD – uses CMS pixel chip

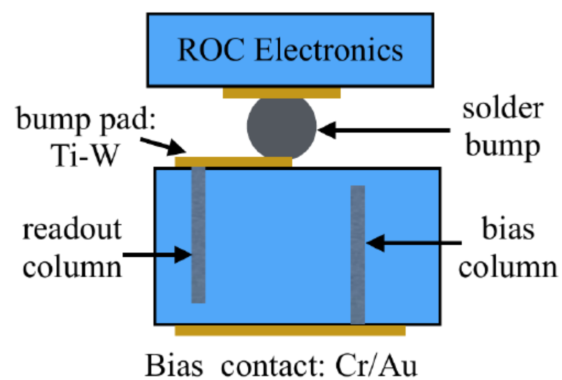
Fabrication

Metallisation & Bump Bonding

- connect to bias and readout with surface metallisation
- cleaned and prepared for photo-lithography at OSU
- photo-lithography and metalisation of HV back plane at OSU
- photo-lithography and metalisation of pixel readout at Princeton by Bert Harrop
- bump and wire bonding at Princeton



(a) pixel readout metalisation

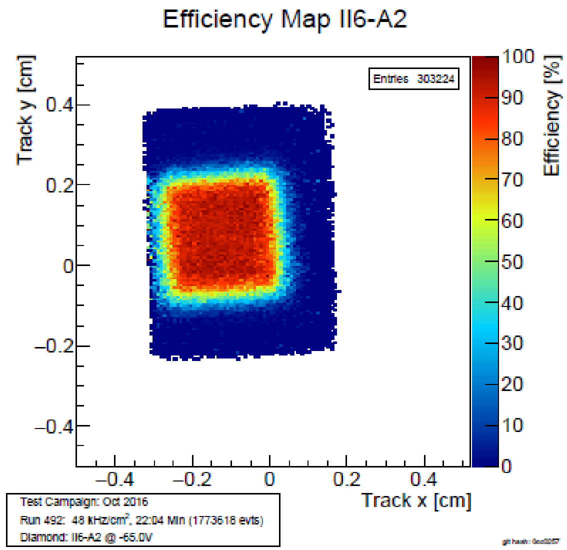


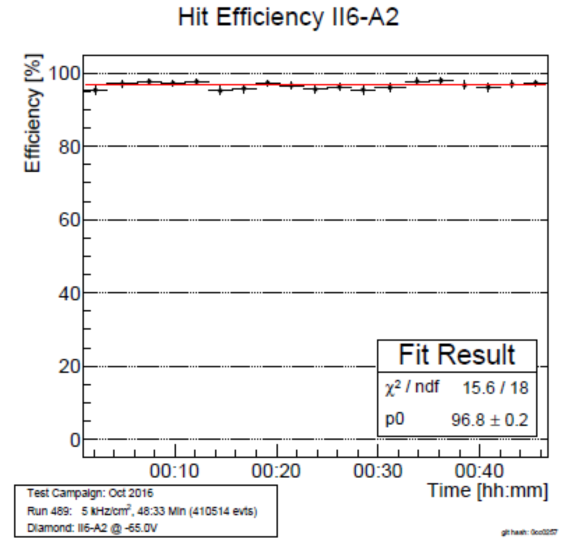
(b) final scheme

M. Reichmann (ETH zürich) CMS 3D Pixel Detector 11th April 2017 6 / 24

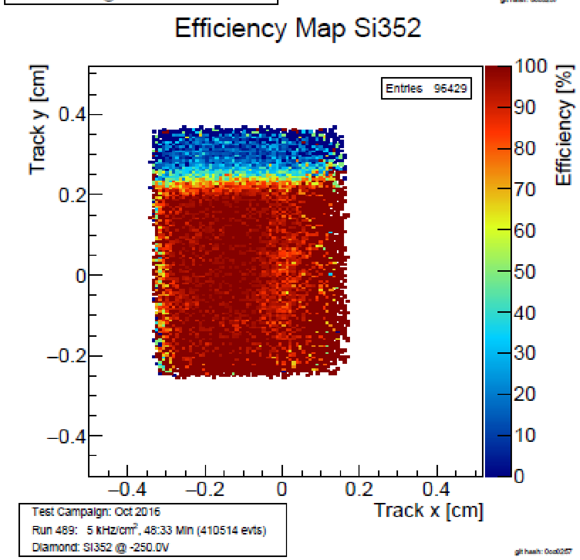
3D pixel device in pCVD diamond

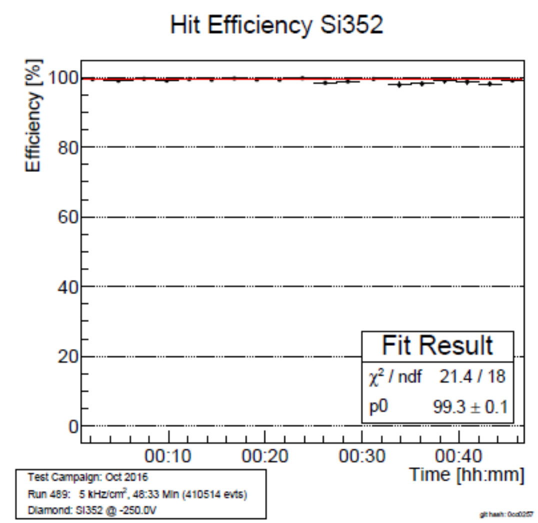
3D Diamond Pixel Efficiency (97%)





Planar Silicon Pixel Efficiency (99%)

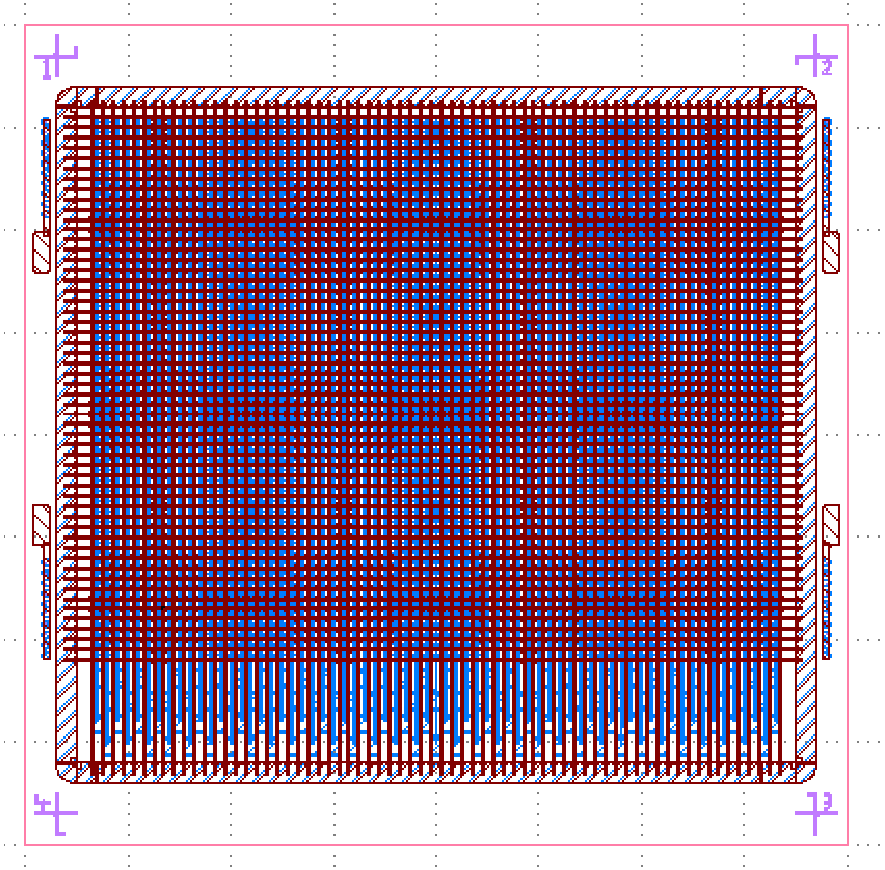




3D pixel device in pCVD diamond - scale up

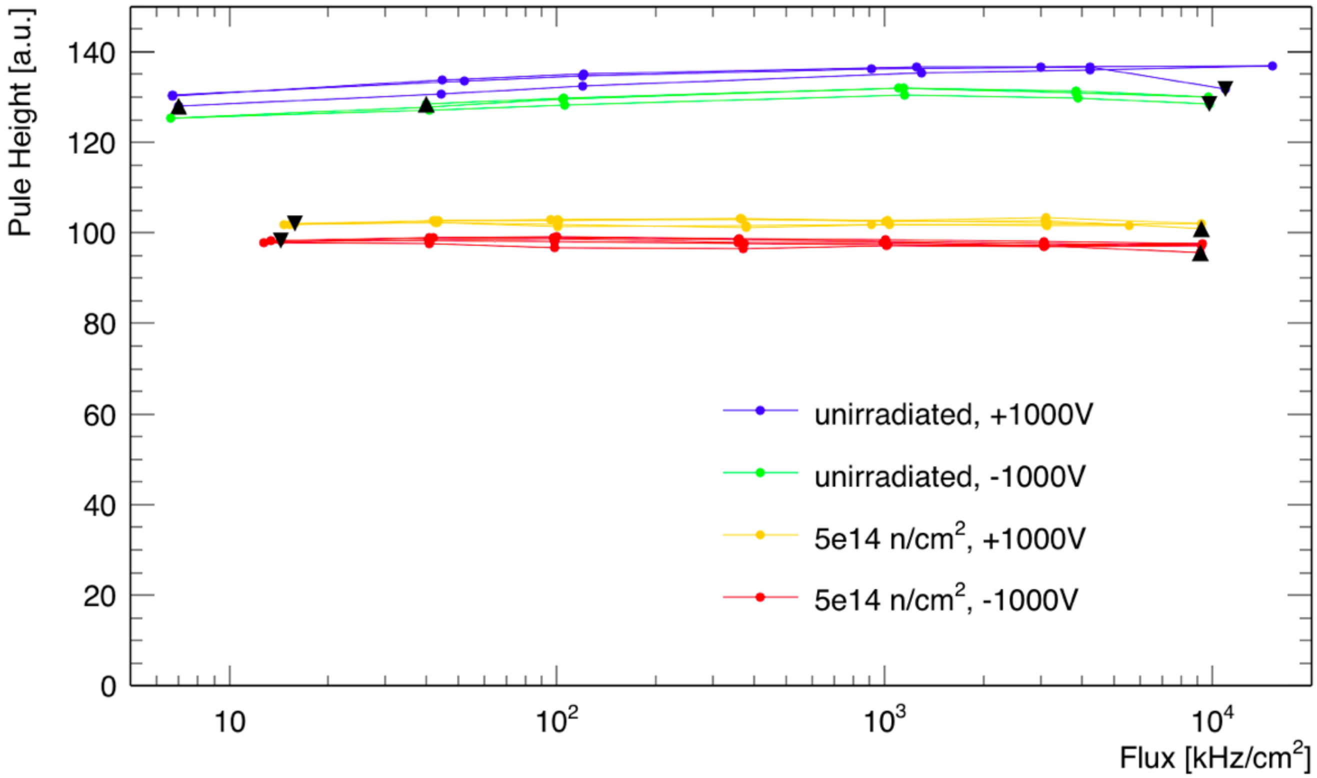
Presently producing 3500 cell pixel prototype

- Two being drilled now:
  - Oxford (complete May 10)
  - Manchester (June)
- Metalization @OSU
- Bump bonding
  - ATLAS @IFAE
  - CMS @Princeton
- Hope to be ready for June test beams



Rate studies in pCVD diamond

- Done at PSI - two years ago rates up to 300kHz/cm^2
- Last year w/new electronics, rates up to 10MHz/cm^2



No rate dependence observed in pCVD up to 10MHz/cm^2

RD42 Summary

- Worked closely with manufacturers to increase quality
- Diamonds in the LHC machine making impact moving forward
- ATLAS/CMS -BCM, BLM, DBM will see collisions again soon
  - Abort, luminosity and background functionality in all LHC expts
- CMS diamond upgrade completed successfully
  - I_L low; CCD ~265um
- Worked w/ATLAS on HL-LHC lumi/abort diamond upgrade
  - Prototyping now; TDR in August
- 3D detector prototypes made great progress
  - 3D works in pCVD diamond; scale up worked; smaller cells worked
- Construct first 3D diamond pixel detector
  - Efficiency looks good; PH analysis in progress
- RD42 played a pivotal role in making all this happen!

RD42 Research Priorities for 2017-18

- Characterization of diamond (materials work)
  - Quantify part quality: CCD, I_L, defects, rad tolerance
- Work with manufacturers (feedback)
  - Quantify wafer quality: as-grown CCD, uniformity
- Development of lumi/abort HL-LHC devices
  - Work w/ATLAS group to develop BCM'
    - characterize CCD, I_L, rate effects
  - Develop FE electronics (rate, lumi/abort)
- Development of detectors (pad, strip, pixel, 3D)
  - 3D pCVD devices:50umx50um cells, scale-up 2x, eff,ph
- Irradiation(JSI,LANL,CERN) and Beam tests (CERN,PSI)
  - Test new material to $5\times10^{16}/cm^2$ ($10^{17}/cm^2$)

Request of CERN LHCC

The RD42 Role at CERN

- Irradiations, development of new manufacturers, sample procurement, ~~test beams~~2013
- Central facilities for all experiments ➔ this worked for BCM's
- CERN Group in RD42 to be maintained

RD42 Request to CERN/LHCC

- RD42 is supported by many national agencies:
  - ➔ continuation of official recognition by CERN critical
  - ➔ ~200kCHF from outside CERN
- RD42 requires access to CERN facilities:
  - ➔ maintain the present 20 m^2 of lab space (test setups, detector prep, ...)
  - ➔ maintain present office space
  - ➔ test beam time (2014++) critical for next generation of proposals

RD42 & CERN play a critical role in diamond development

Backup Slides

Diamond devices in the LHC

Plan

1. **Cryogenic BLMs**

2. **Fast diamond BLMs**

Marcin Bartosik – RD42 Collaboration Meeting 2 13 May 2016

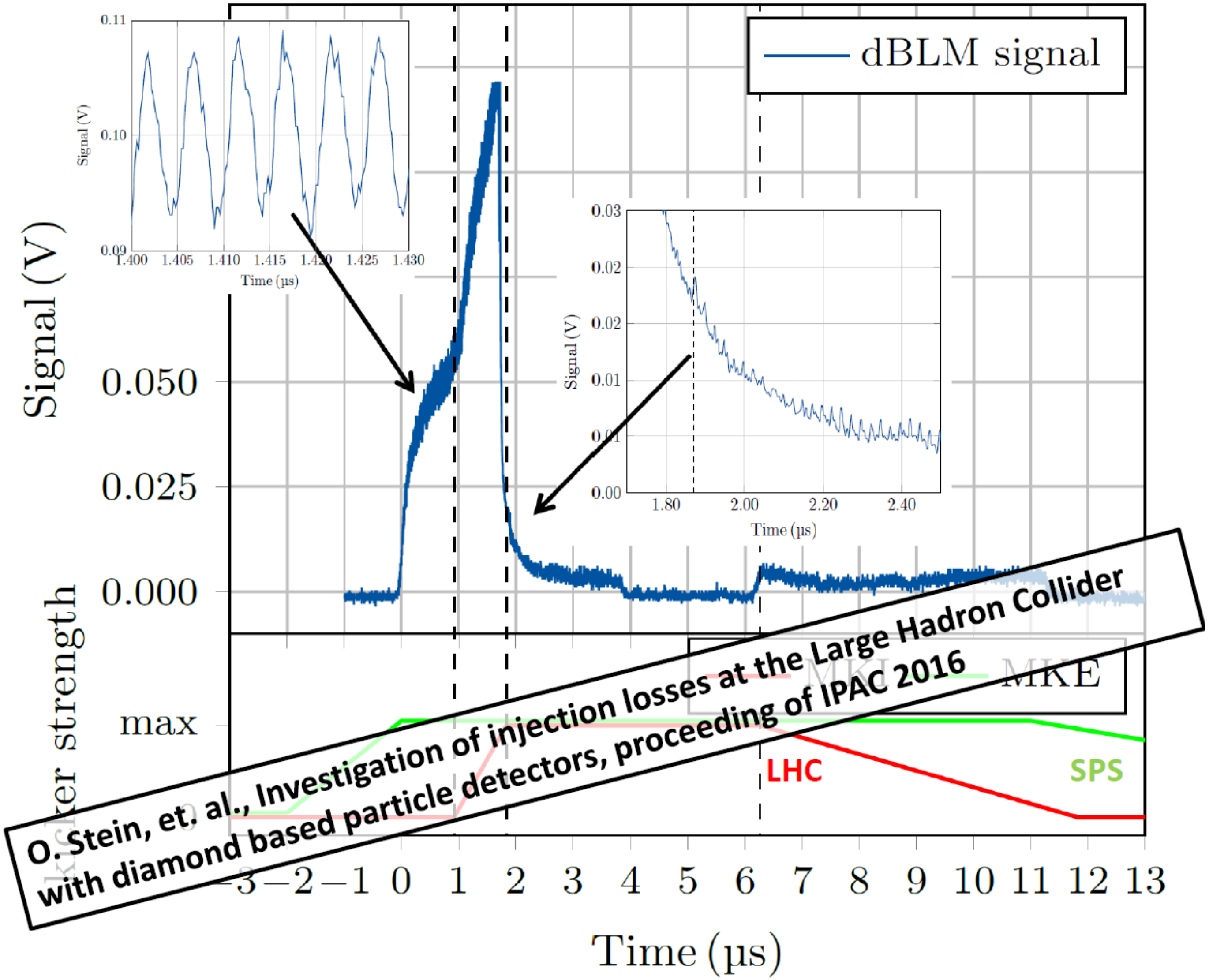
Diamond devices in the LHC

Fast diamond BLMs

- 2015 LHC beam commissioning
  - **high injection losses** were observed at the LHC internal beam absorber blocks (TDI) in IP2 and IP8.
  - Theses losses reached up to **90% of the dump threshold** of the respective beam loss monitors (BLM).
- **Diamond based particle detectors** are installed downstream of the TDIs in the injection regions of the LHC.

Marcin Bartosik – RD42 Collaboration Meeting 16 13 May 2016

Diamond devices in the LHC



O. Stein, et. al., Investigation of injection losses at the Large Hadron Collider with diamond based particle detectors, proceeding of IPAC 2016

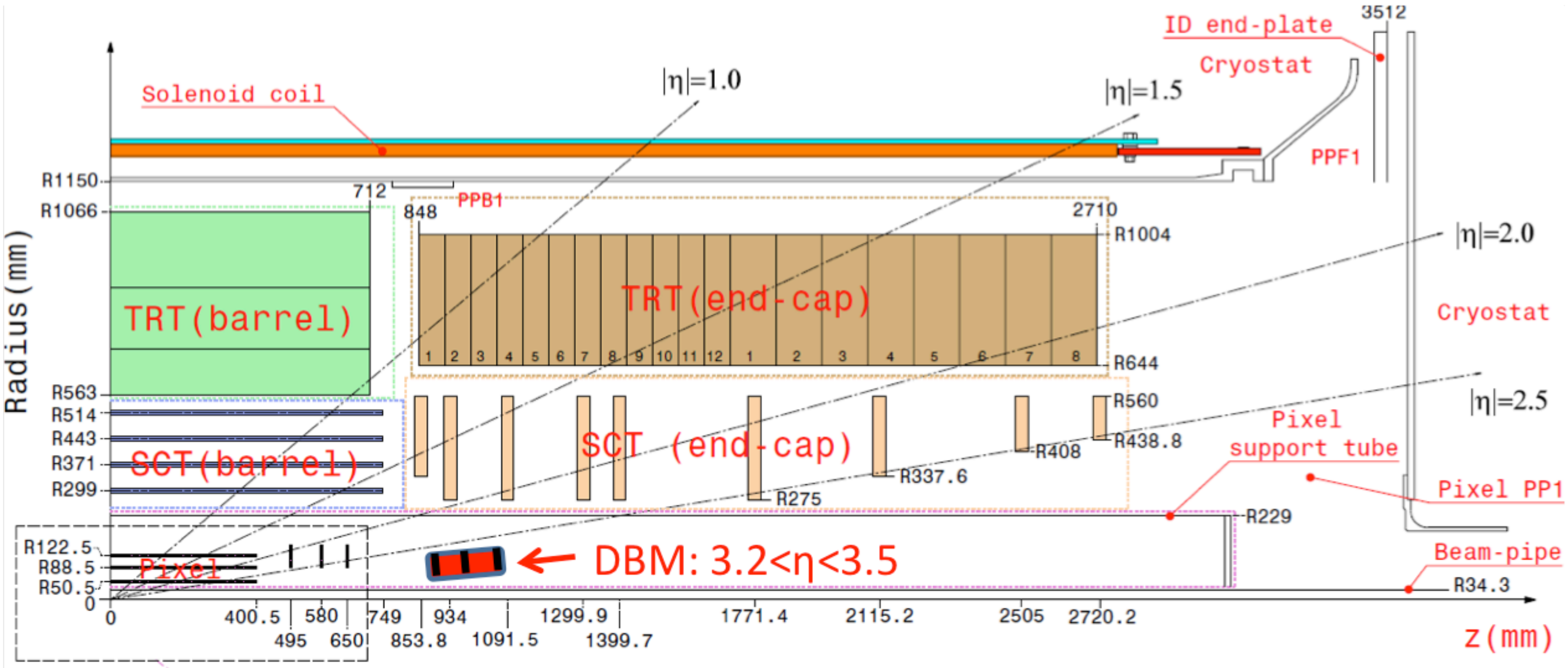
Diamond devices in the LHC

Fast diamond BLMs

- Their nanosecond time resolution allowed to **identify the time structure of the injection losses** for the first time.
- During dedicated beam time at the LHC methods for mitigating these injection losses were successfully demonstrated.
- By exciting the recaptured beam around the nominal bunch train with SPS tune kicker magnet **a reduction of the loss signal by 35% was achieved.**

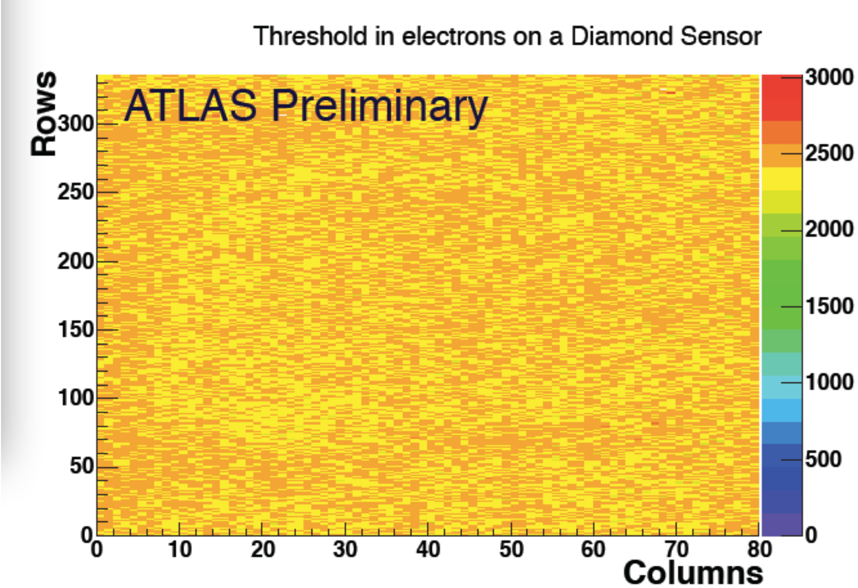
Diamond devices in experiments

- ATLAS DBM: built on success of BCM – pixelate the sensors
  - Use IBL demonstrator modules
  - Installed in 2013 during service panel replacement
  - Four 3-plane stations on each side of ATLAS



Diamond devices in experiments

- ATLAS DBM integrated in ATLAS readout in 2015
- Thresholds tuned to 2500e (lower than silicon)
  - Would like to lower this (1100e possible on bench)
- Took data – found operation issues with FE-I4
  - Revamped safeguards almost ready now



Diamond devices in experiments

Testbeam Results of ATLAS DBM Modules at CERN SPS

RD42 Meeting
CERN

13.05.2016

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SI LAB Silizium Labor Bonn

Diamond devices in experiments

Beam Test at CERN SPS 2015

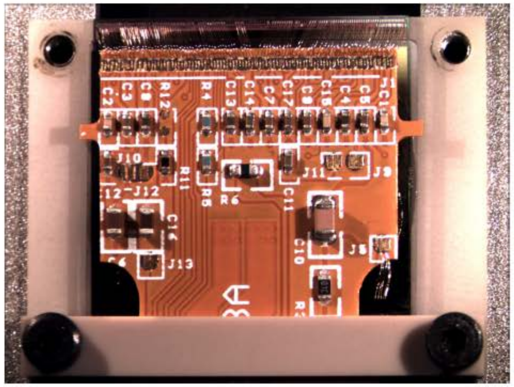
July/August 2015:
- 77 Mio triggers
- 57 runs

October 2015:
- 115 Mio triggers
- 56 runs

May 2016

Modules:
- MDBM-30 (ADBM-33 (E6-old), mounted in 2013)
- MDBM-120 (ADBM-58 (II-VI), mounted in 2014)
- MDBM-107 (ADBM-17 (E6), mounted in 2015)
- MDBM-37 (ADBM-19 (E6), mounted in 2015)
- MDBM-108 (ADBM-18 (E6), mounted in 2015)
- MDBM-119 (ADBM-60 (II-VI), mounted in 2015)
- CD182 (scCVD)
- DDL7 (scCVD)

MDBM-120



CD182

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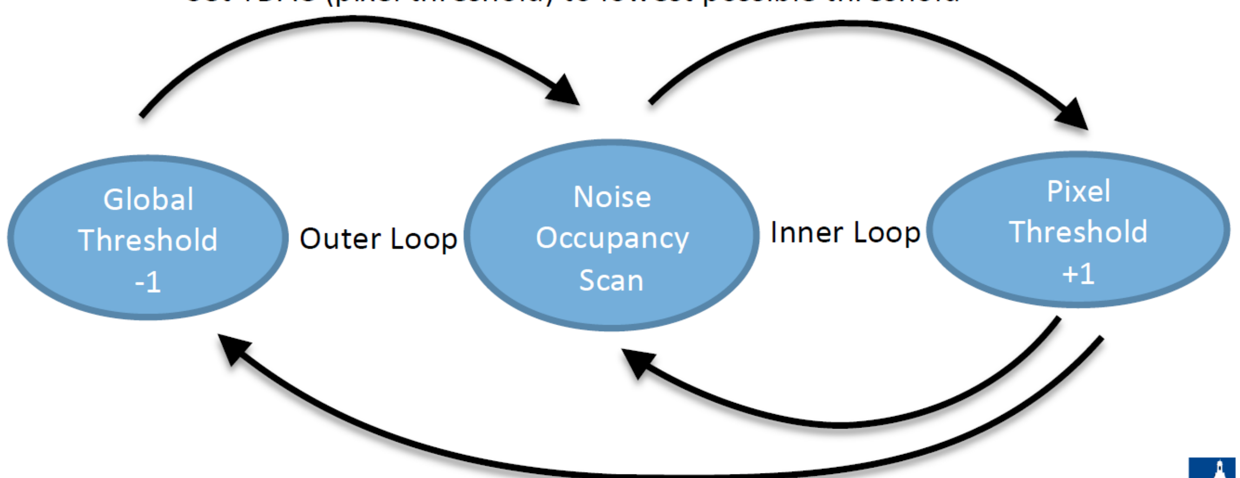
Diamond devices in experiments

Compare standard "Low Threshold" tuning (1500-2500e) and new Threshold Baseline tuning (1000e)

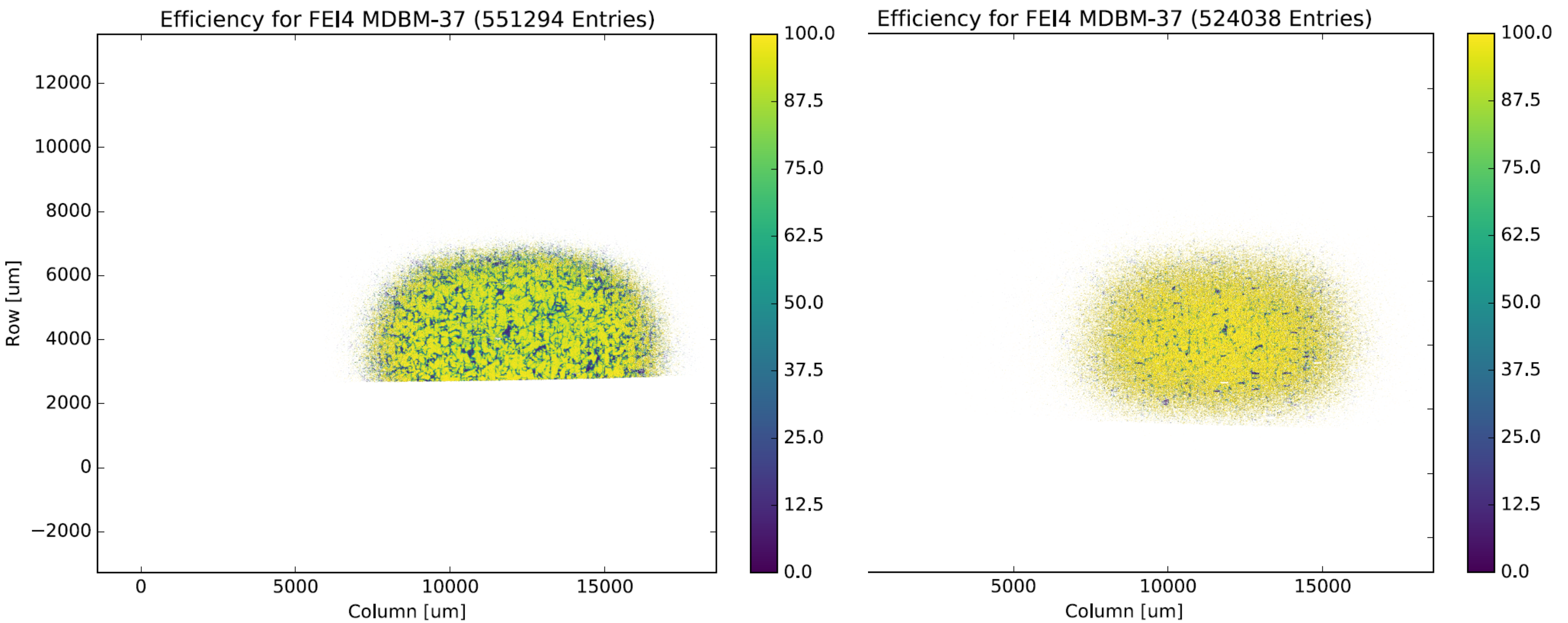
Threshold Baseline Tuning

- Avoid using on-chip charge injection circuit
- Two loops:
  - Outer loop **decreases global threshold**
  - Inner loop **increases pixel threshold**
- Initial condition:
  - Set GDAC (global threshold) to a rather high value
  - Set TDAC (pixel threshold) to lowest possible threshold



Diamond devices in experiments

"Low Threshold" (1500-2500e) | Threshold Baseline (1000e)



Results applicable in ATLAS – something like this will be necessary for irradiated silicon as well