Diamond detector technology: status and perspectives

Harris Kagan
for the RD42 Collaboration

12^{th} Trento Workshop
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Outline of Talk

- The RD42 Program
- Development of Material and Production Capabilities
- Diamond Devices in the LHC and Experiments
- Diamond Device Development – 3D Diamond
- Rate Studies
- Summary

Additional info in talks by Giulio Forcolin and Iain Haughton on Wed

The 2016 RD42 Collaboration

The 2016 RD42 Collaboration

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31 Institutes

The RD42 program

Focus Areas of 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)

This talk will try to bring you an overview of this work.

Development of material and production

- E6/II-VI provided first sensors for ATLAS DBM in 2013
  - 200-225um charge collection distance (ccd) (t=500um)
- Wafer production capabilities expanded/higher quality
  - 300-325um ccd in production (t=500um); 5% uniformity
  - 400um ccd goal in sight!

2013 2016

Diamond devices in the LHC

Plan

1. **Cryogenic BLMs**
2. **Fast diamond BLMs**

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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.

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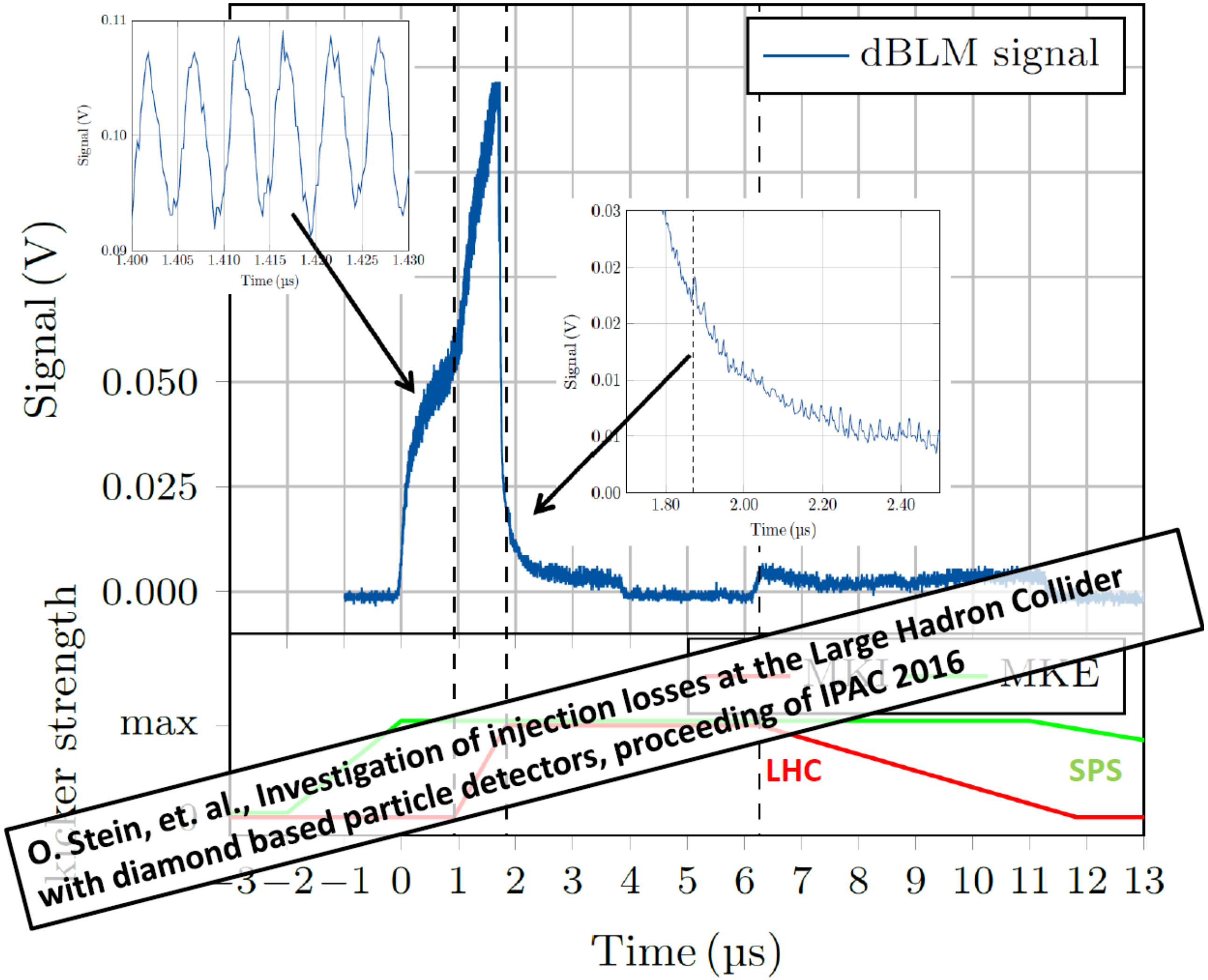
Diamond devices in the LHC



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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.**

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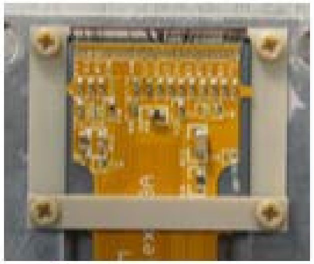
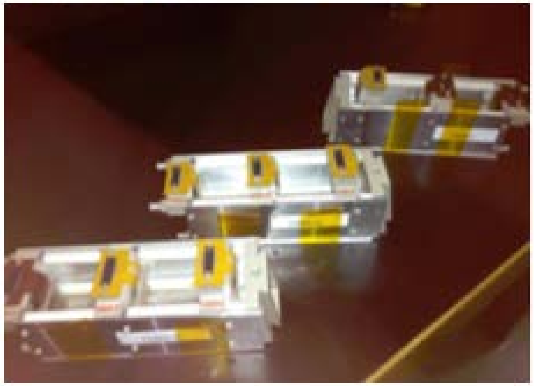
Diamond devices in experiments

- Beam Conditions Monitors/Beam Loss Monitors
  - Essentially all modern collider experiments
- Current generation Pixel Detectors
  - ATLAS DBM (low threshold operation)
- Future HL-LHC Trackers
  - 3D diamond

Diamond devices in experiments

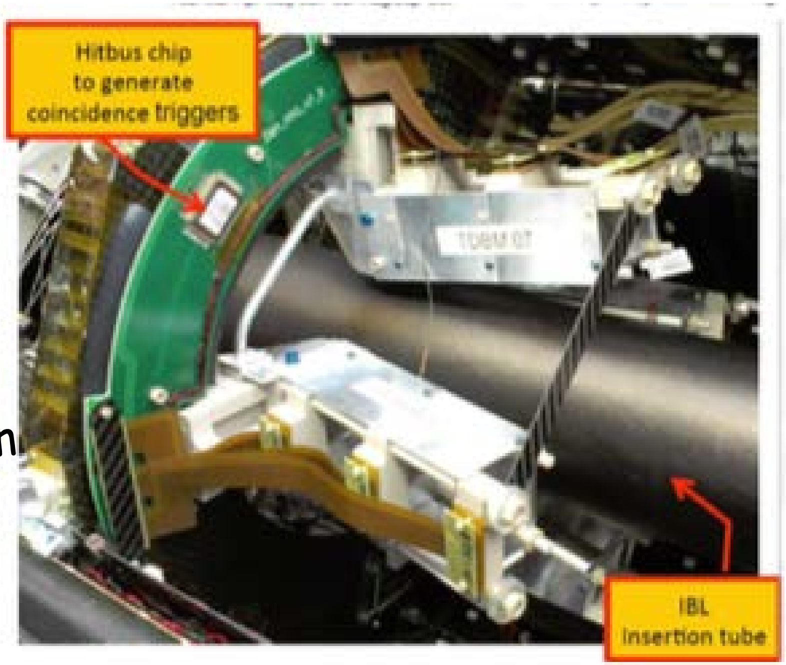
- ATLAS DBM: diamond pixel detectors in ATLAS (tracking)
- Total production: 45 diamonds (500 μm thick) w/FE-I4b
- Modules Assembled at CERN
- Installed during LS1





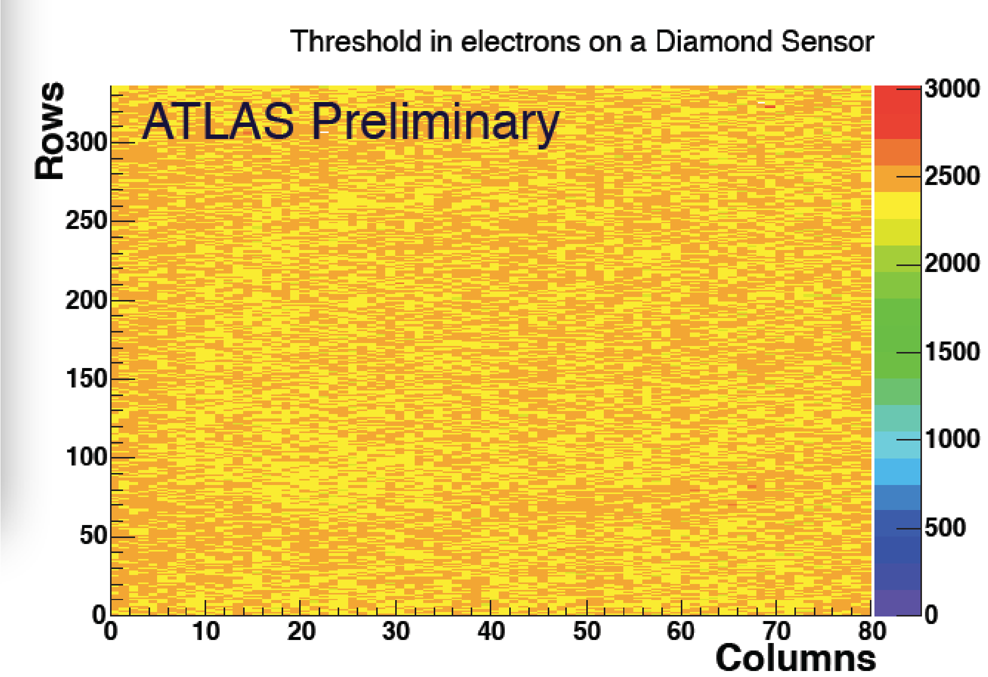
8 telescopes
(2 Si\6 Diamond)
symmetric
around ATLAS IP

$854\text{mm} < |z| < 1092\text{mm}$
$3.2 < |\eta| < 3.5$



Diamond devices in experiments

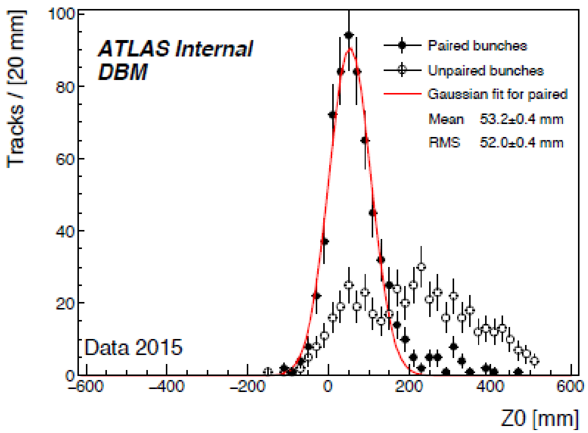
- ATLAS DBM integrated in ATLAS readout in 2015
- Thresholds tuned to 2500e



  - Would like to lower this (1100e possible on bench)
- Took data – found operation issues

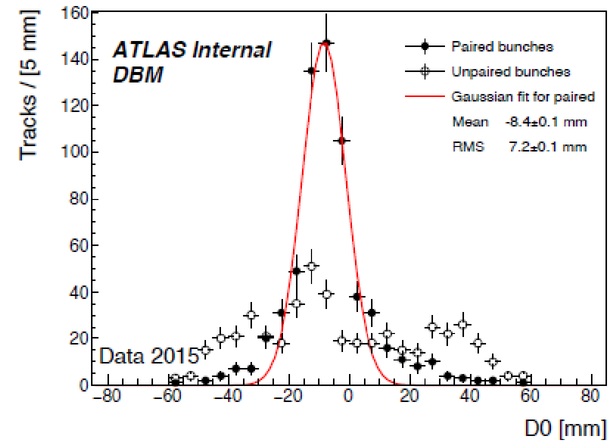
Diamond devices in experiments

- Use hits from the 3 modules for reconstructing tracks



Run of July 2015
clear separation:

Collisions:
vs
Background:



Longitudinal distance of the projected particle tracks to the interaction point

Radial distance of the projected tracks of the closest approach to the interaction point

- Can discriminate between IP and background particles
  - Plots above use initial alignment (final still to be done)
- 2 electrical incidents in 2015 caused loss of modules(Si/D)
  - now in re-commissioning phase

Diamond devices in experiments

Testbeam Results of ATLAS DBM Modules at CERN SPS

RD42 Meeting
CERN

13.05.2016

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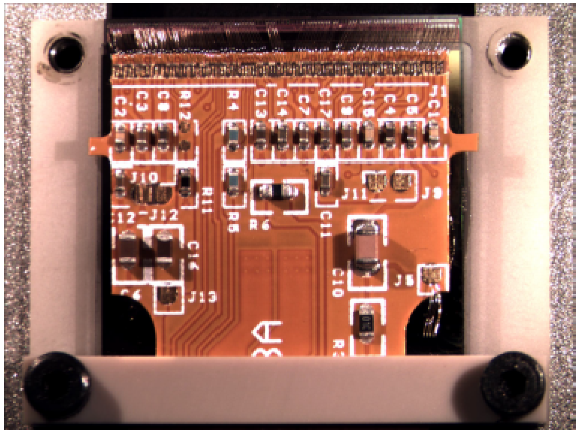
universitätbonn

SI LAB Silizium Labor Bonn

Diamond devices in experiments

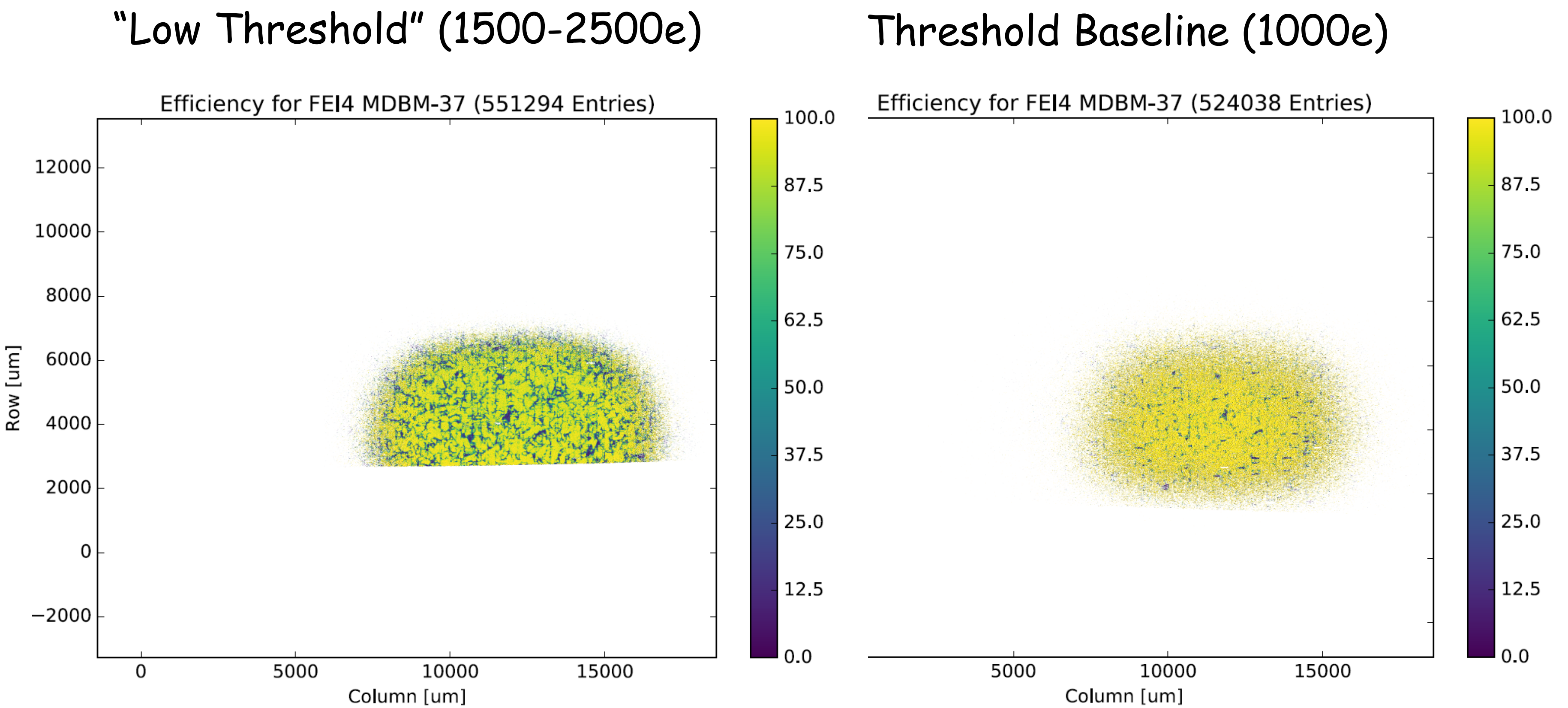
- Test beam campaigns at CERN SPS to study the DBM characteristics:
- Lower charge from diamond necessitates low threshold operation of FE chip
- Developed a new tuning algorithm for FE-I4B not using Pulser DAC: Threshold Baseline Tuning

MDBM-120



Threshold tuning	Method	Threshold
Standard ATLAS	Pulser DAC	~ 3-4 ke (Si)
Standard Threshold Tuning	Pulser DAC	~ 1.5-2.2 ke (Diamond)
Threshold Baseline Tuning	Noise Occupancies	~ 1 ke (Diamond)

Diamond devices in experiments



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

DBM Summary

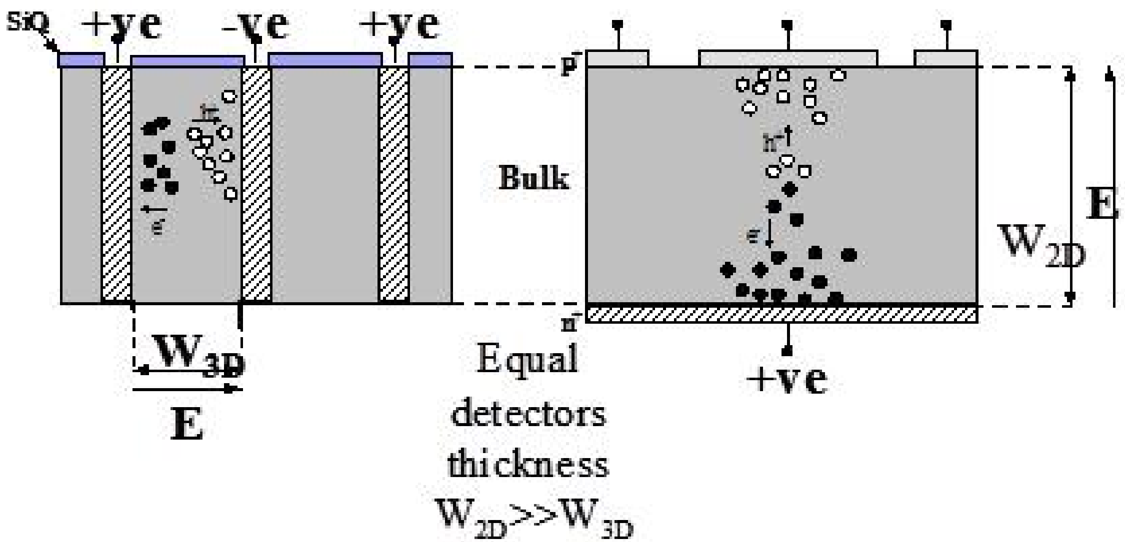
- Low threshold method developed
- DBM Modules perform as expected in test beam
    - Ave efficiency of planar Si modules 97.5%,
    - Ave efficiency of planar Diamond modules 94%
- Now re-commissioning DBM in ATLAS

3D device in pCVD diamond

After severe radiation damage all detectors are trap limited
- Mean free paths < 75μm
- Would like to keep drift distances smaller than mfp

Comparison of 3D and planar devices

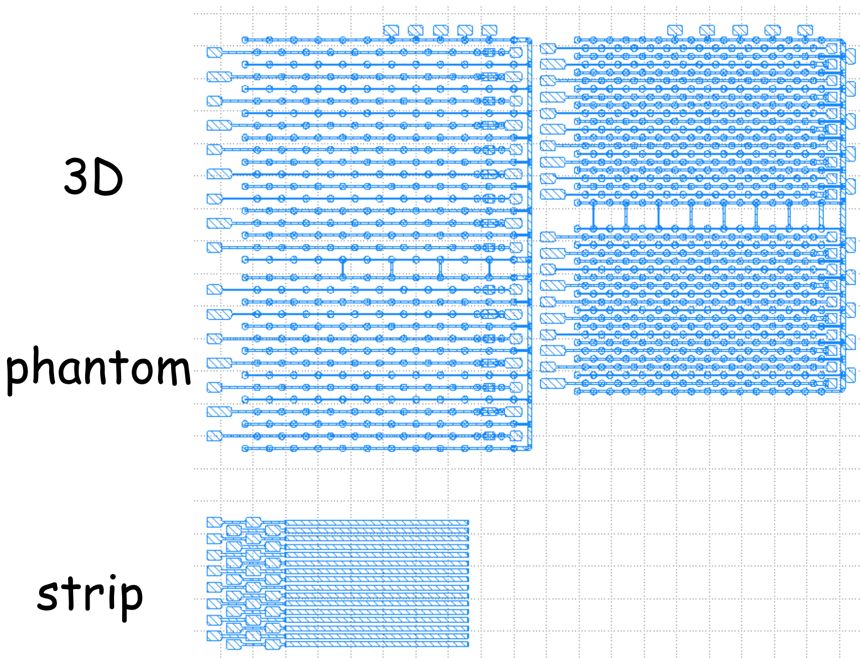
Can one do this in pCVD diamond?

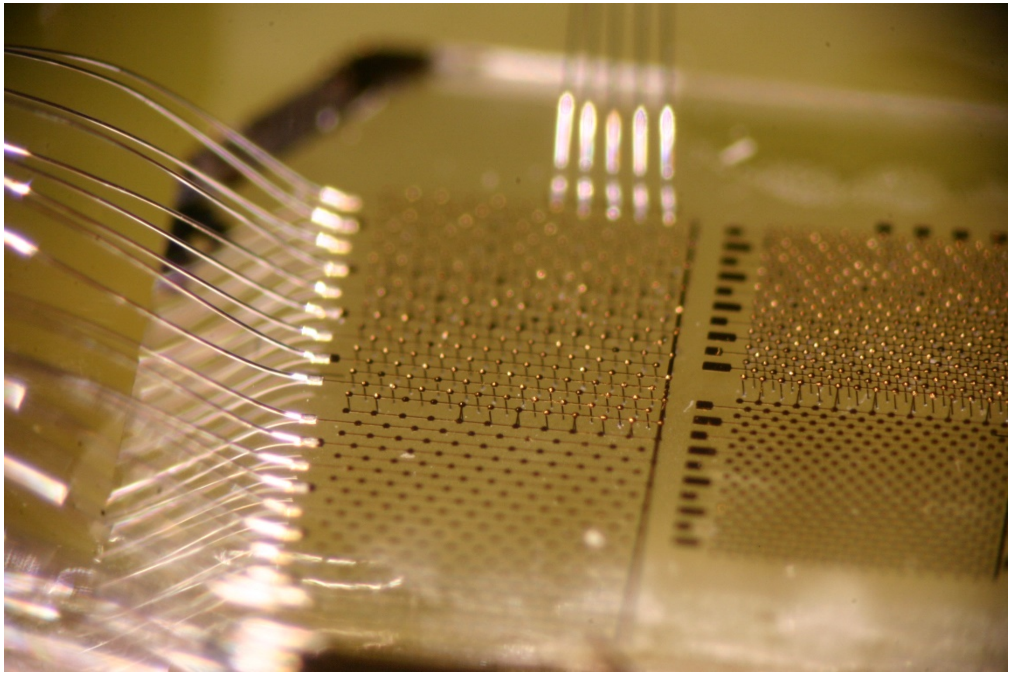


Have to make resistive columns in diamond for this to work
- -columns made with 800nm femtosecond laser
- -initial cells 150μm x 150μm; columns 6μm diameter

3D device in pCVD diamond

Simultaneously readout all 3 devices

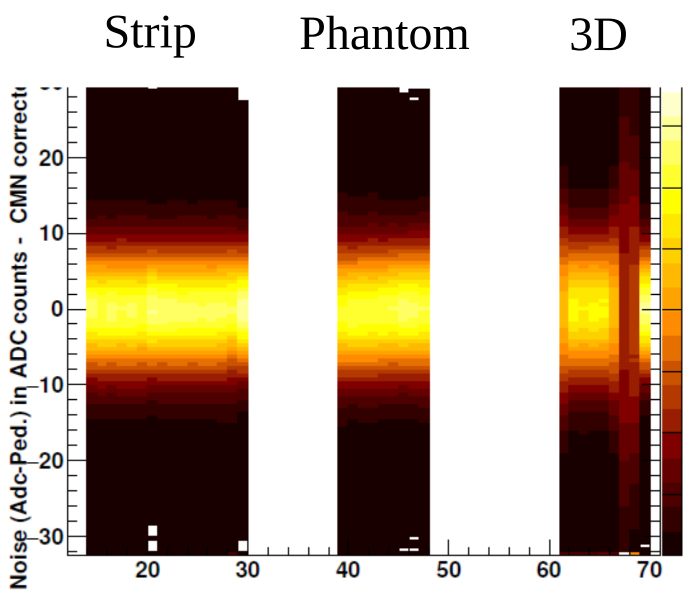


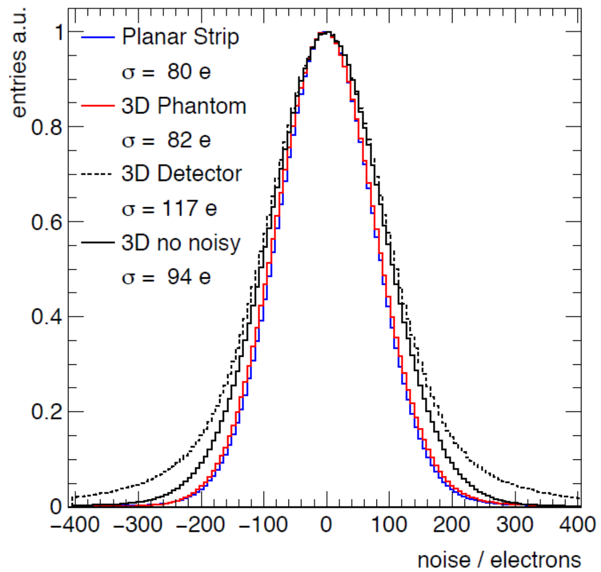


- Last year results of 3D scCVD diamond published
  - -Compared scCVD strip detector (500V) with 3D (25V)
- This year the first 3D device in pCVD diamond
  - -Compare pCVD strip detector (500V) with 3D (60V)
- See talk by Giulio Forcolin for full details and simulation

3D device in pCVD diamond

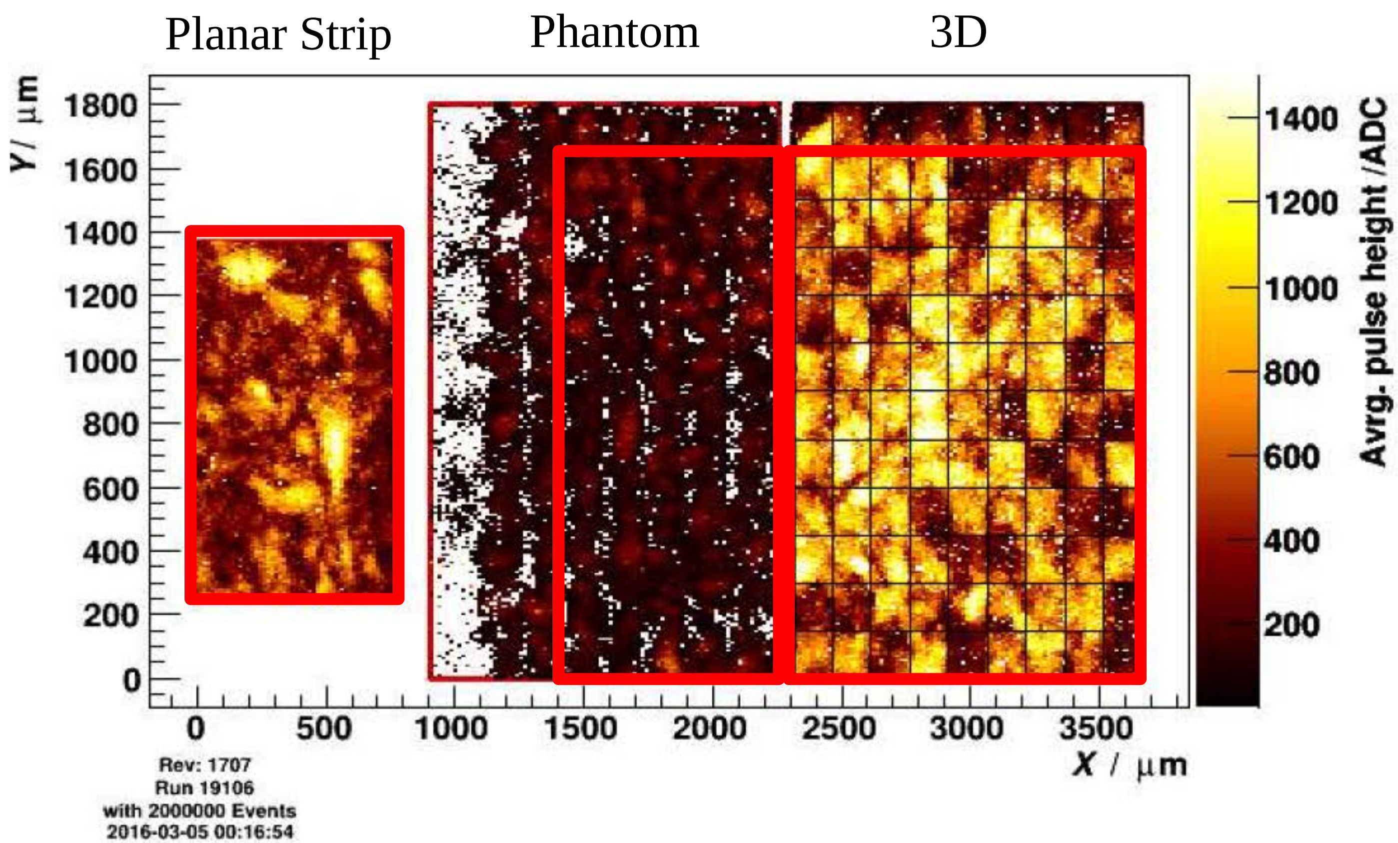
- 3D cells are 150μm x 150μm
- Measured noise (~proportional to capacitance):
  - Planar strip: 80e
  - Phantom: 82e
  - 3D no noisy strips: 94e





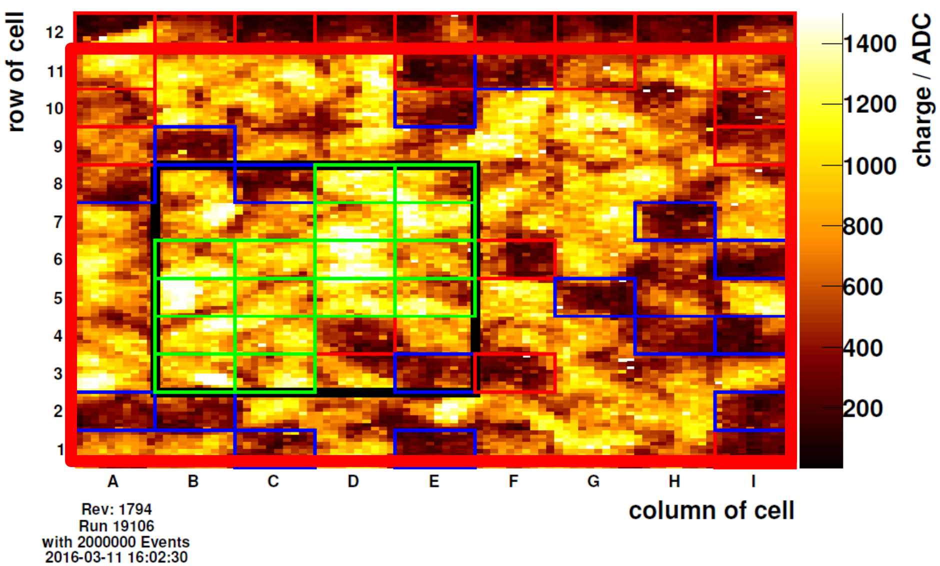
3D device in pCVD diamond

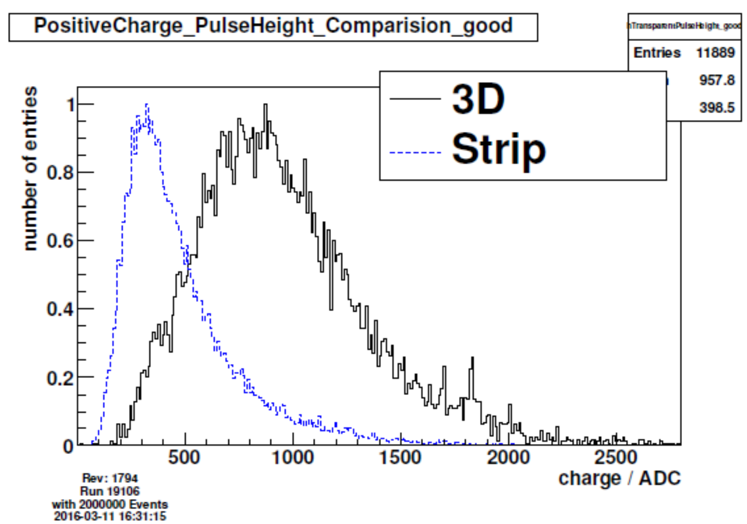
- Measured column efficiency: 92%
- Measured Signal:
  - Visually 3D gives more charge than planar strip!



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_{eq}=350-375um
- For the first time collect >75% of charge in pCVD

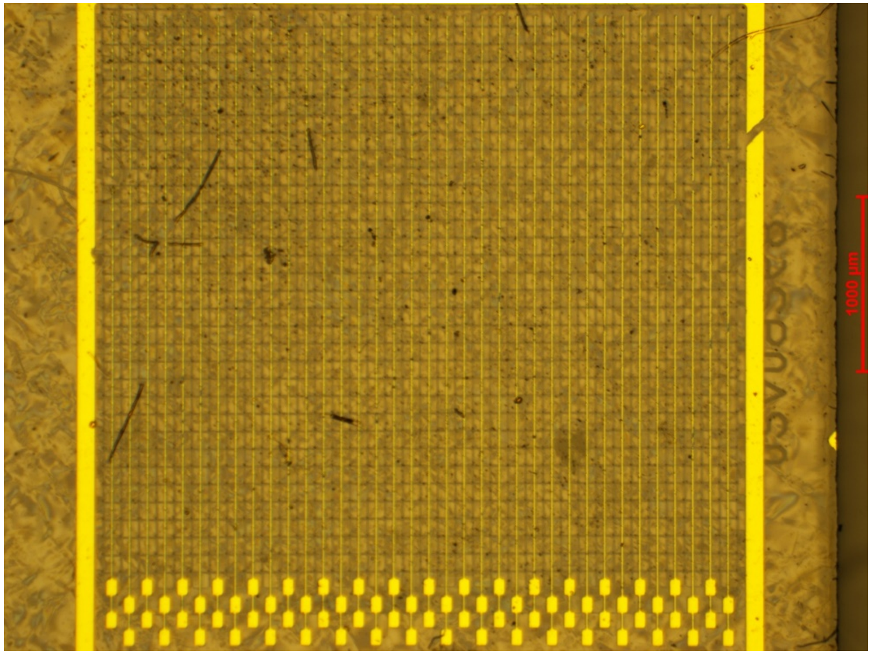




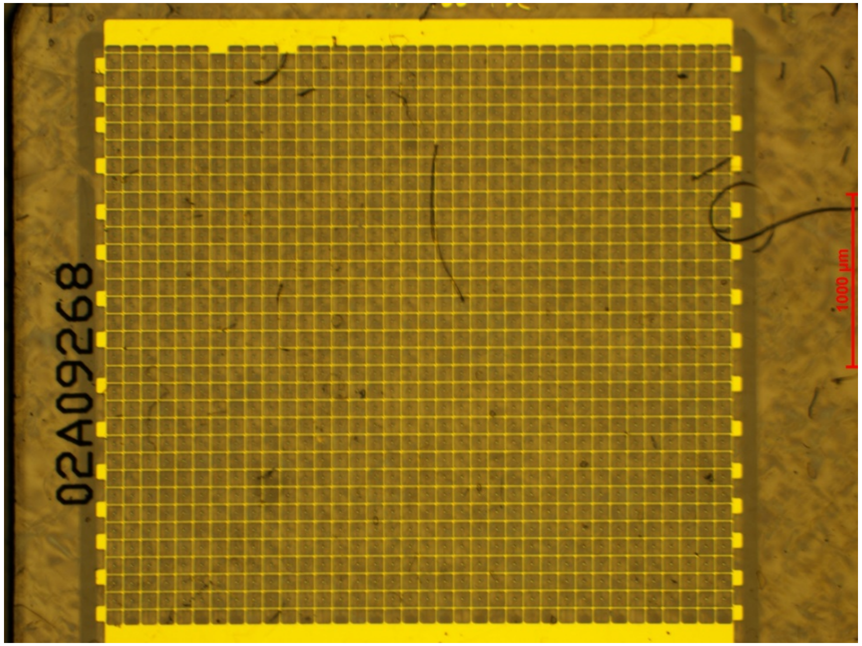
3D device in pCVD diamond

- In May/Sept 2016 tested first full 3D in pCVD with three dramatic improvements
  - An order of magnitude more cells (1188 vs 99)
  - Smaller cell size (100um vs 150um)
  - Higher column production efficiency (99% vs 92%)

Readout side

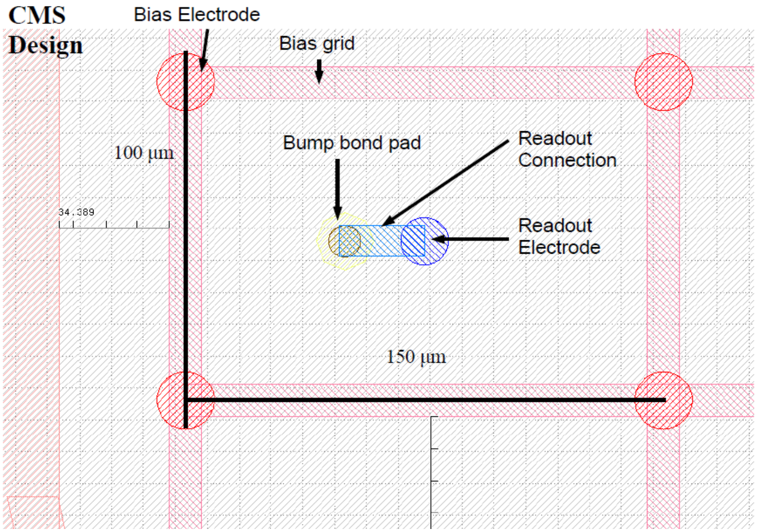


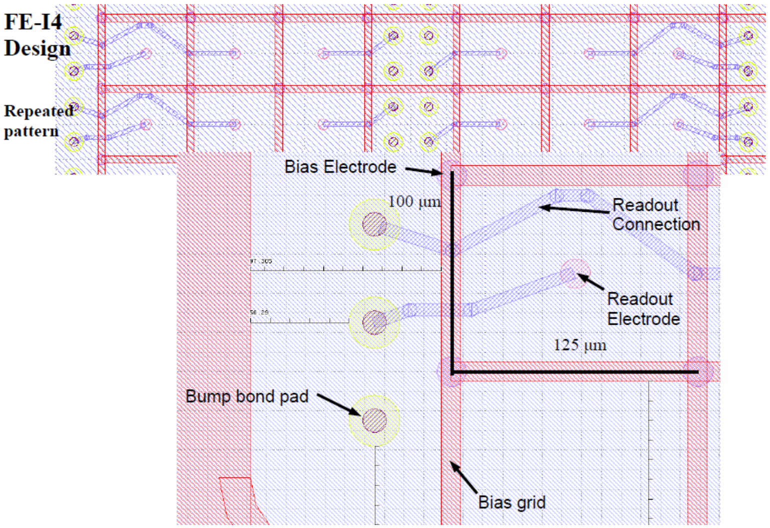
HV bias side



Production Plans: ATLAS, CMS 3D pCVD Pixels

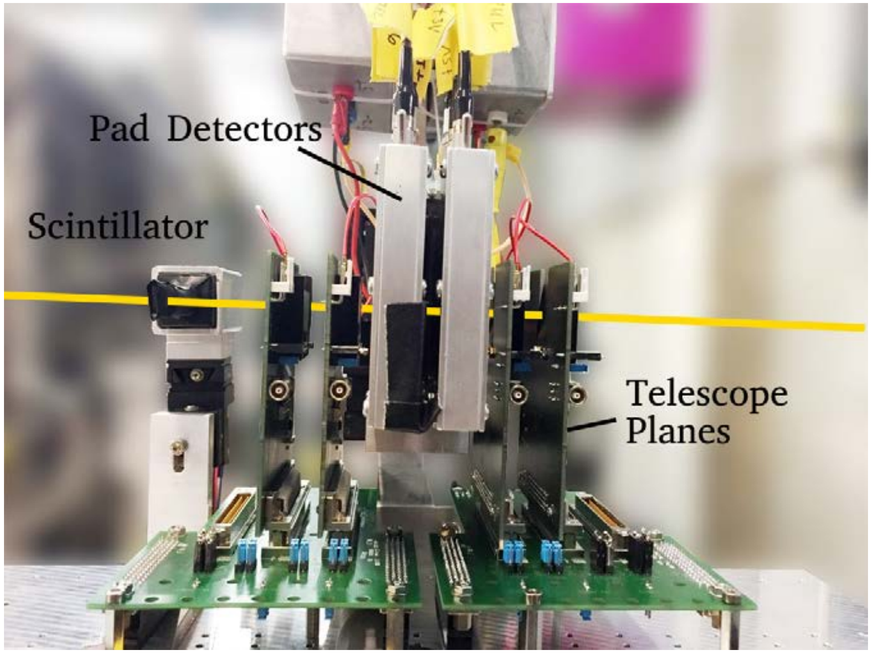
- Laser fabrication of resistive columns: Oxford(in progress)
- Mask set: Manchester(in progress)
- Cleaning/Metallization: Ohio State(next week)
- Bump Bonding: Princeton(Oct), CNM(2017), later IZM
- Module Building/Testing:ETH-Z, Rutgers(CMS),Bonn(FE-I4)
- Irradiation: JSI/Ljubljana
- Beam Tests:ETH-Z, JSI, Göttingen [Oct 20-24, 2016 (PSI)]

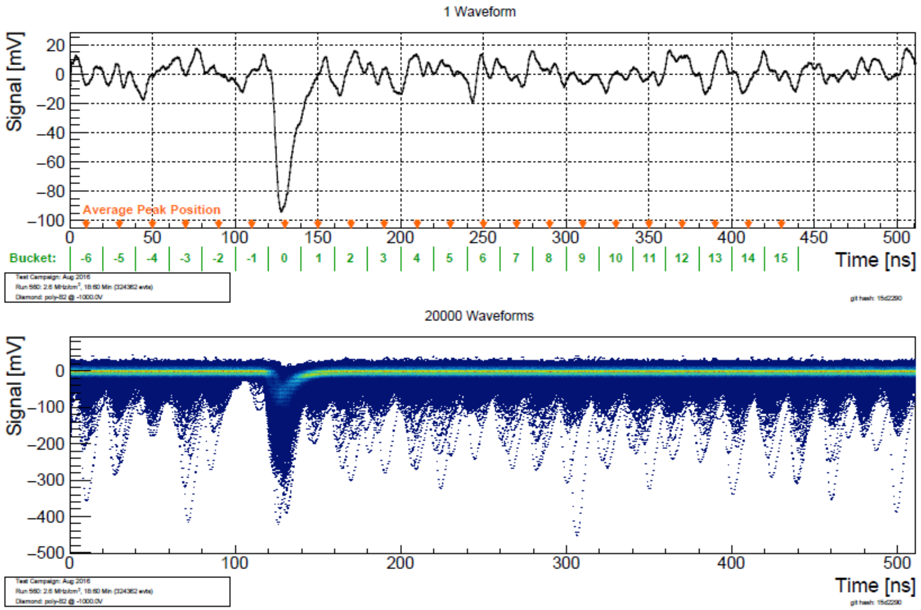




Rate studies in pCVD diamond

- Done at PSI - Last year published rates up to 300kHz/cm^2
- This year w/new electronics, rates up to 10-20MHz/cm^2
- Pad detector tested in ETH-Z telescope (CMS Pixels)
- Electronics is prototype for HL-LHC BCM/BLM

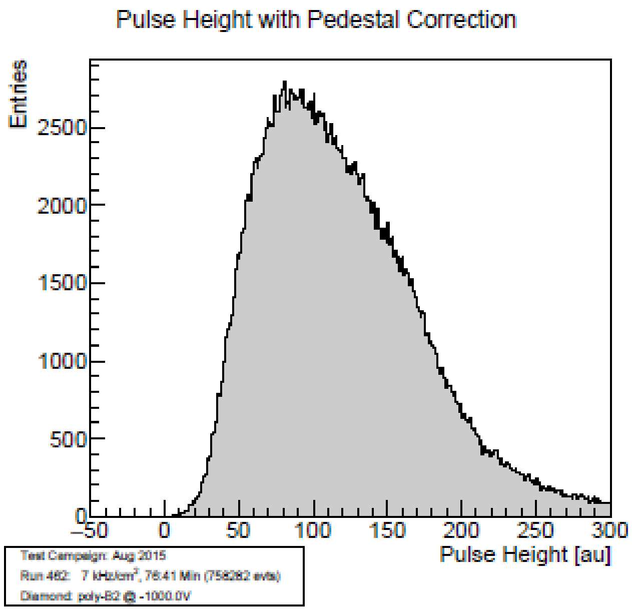


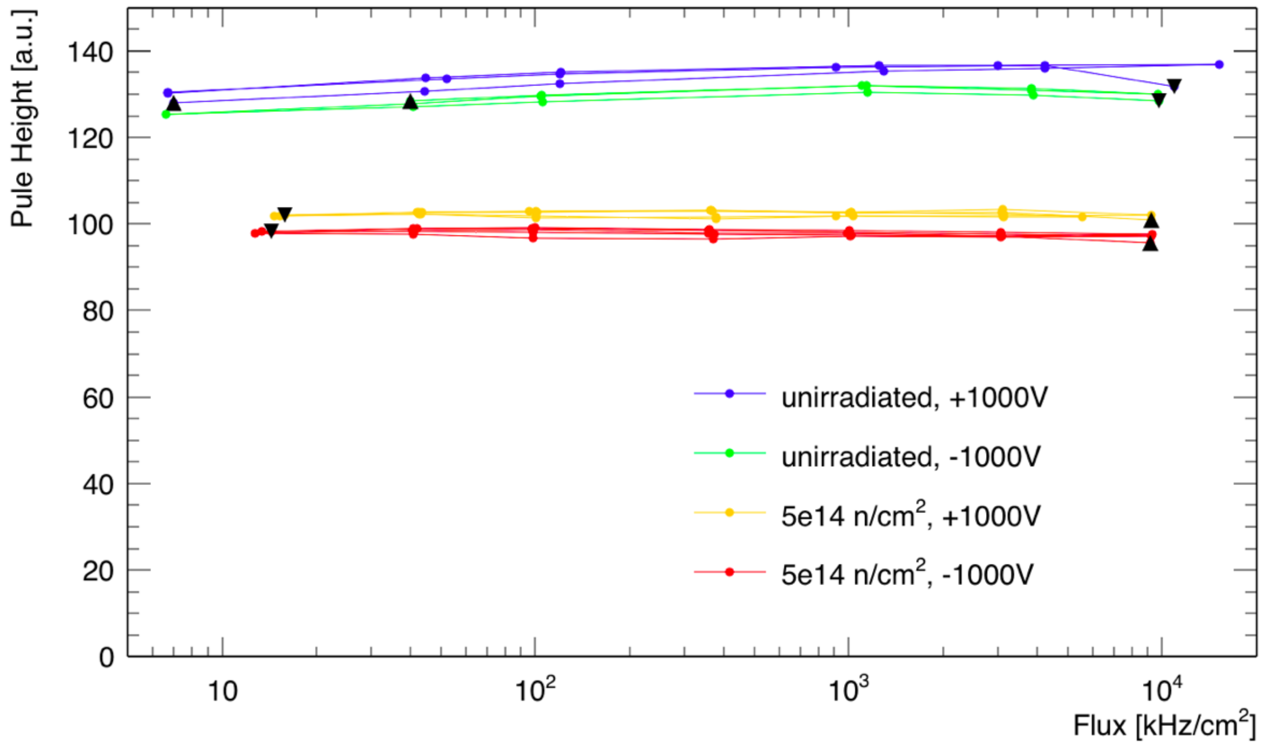


19.8ns bunch spacing clearly visible

Rate studies in pCVD diamond

- Done at PSI - Last year published rates up to 300kHz/cm^2
- This year w/new electronics, rates up to 10-20MHz/cm^2





No rate dependence observed in pCVD up to 10-20MHz/cm^2

Summary

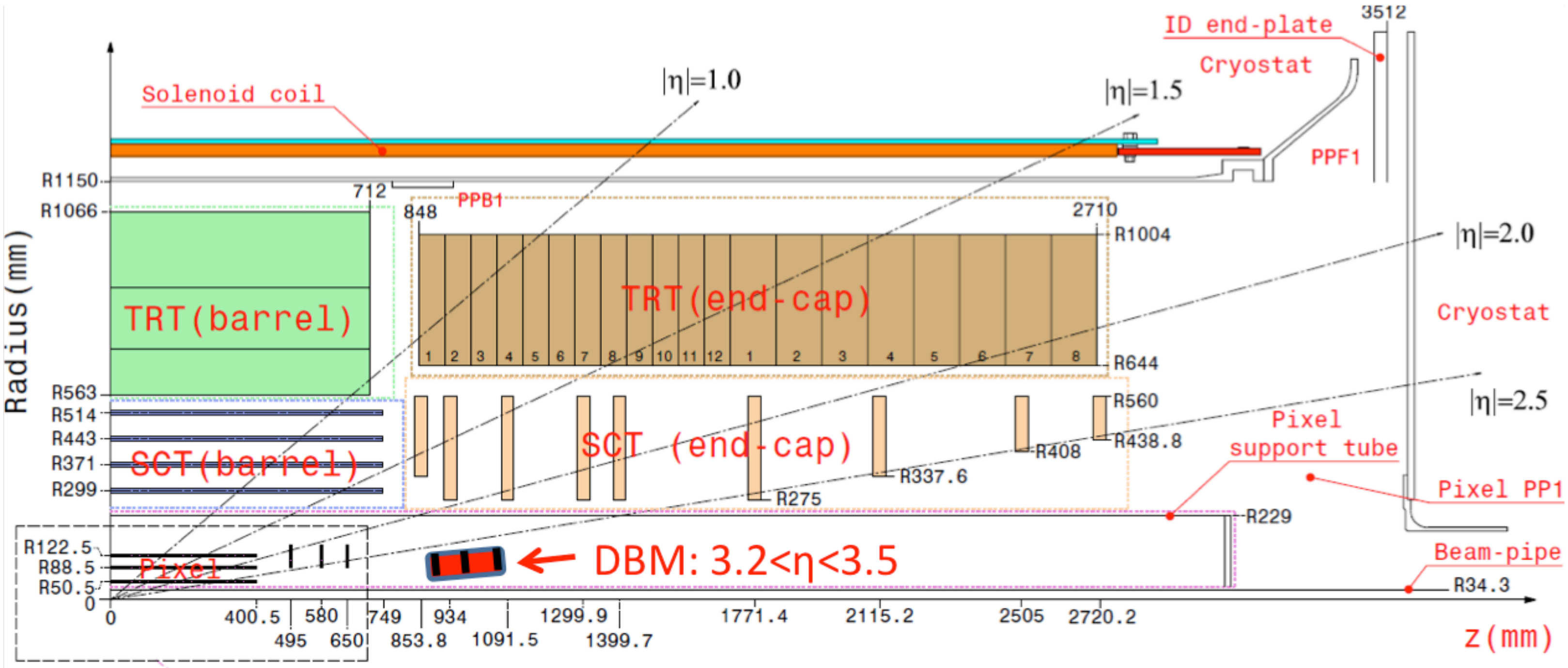
- Worked closely with manufacturers
  - Material quality increased
  - Production capabilities increased
- Diamonds in the LHC machine making impact moving forward
- ATLAS/CMS -BCM, BLM, DBM will see collisions again soon
  - Abort, luminosity and background functionality in all LHC expts
- First pixel project is about to start taking data
  - ATLAS DBM being commissioned for 13 TeV collisions
- 3D detector prototypes made great progress
  - 3D works in pCVD diamond; scale up worked; smaller cells worked
- Quantified understanding of rate effects in diamond
  - pCVD shows no rate effect up to 10-20MHz/cm^2
- 3D diamond pixel devices being produced (10^{17}/cm^2)

Diamond devices in experiments

Backup Slides

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

Beam Test at CERN SPS 2015

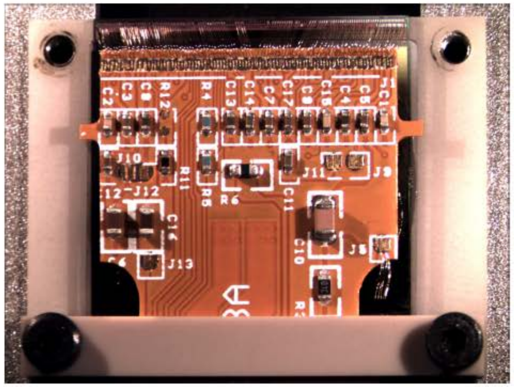
July/August 2015:
- 77 Mio triggers
- 57 runs

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



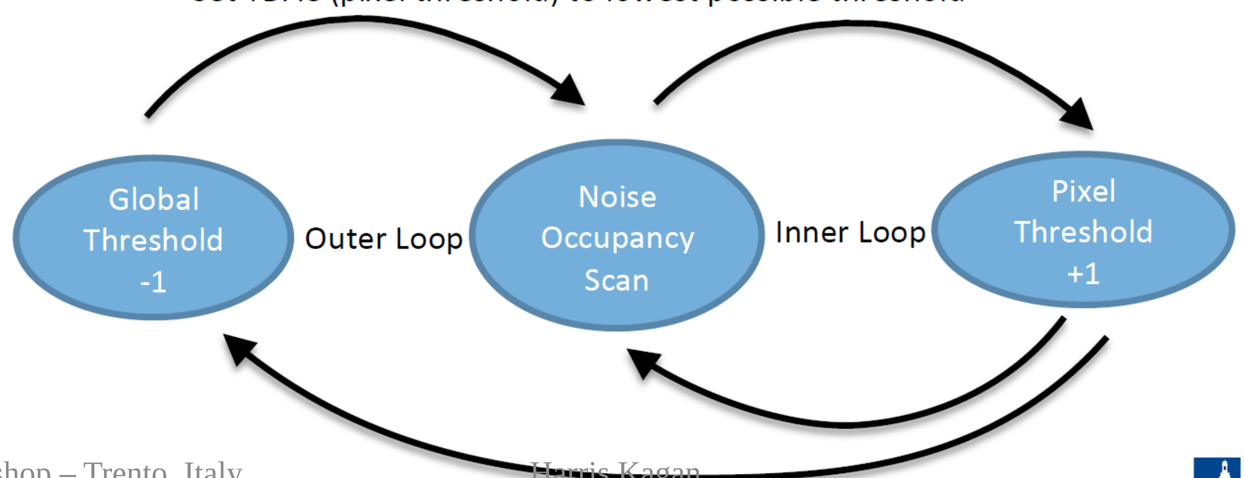
CD182

Diamond devices in experiments

Compare standard "Low Threshold" tuning (1500-2200e) and new Threshold Baseline tuning (1000e)

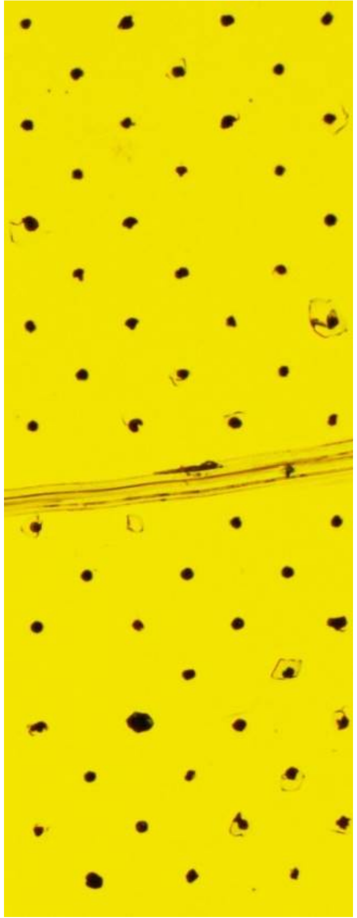
Threshold Baseline Tuning

- 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

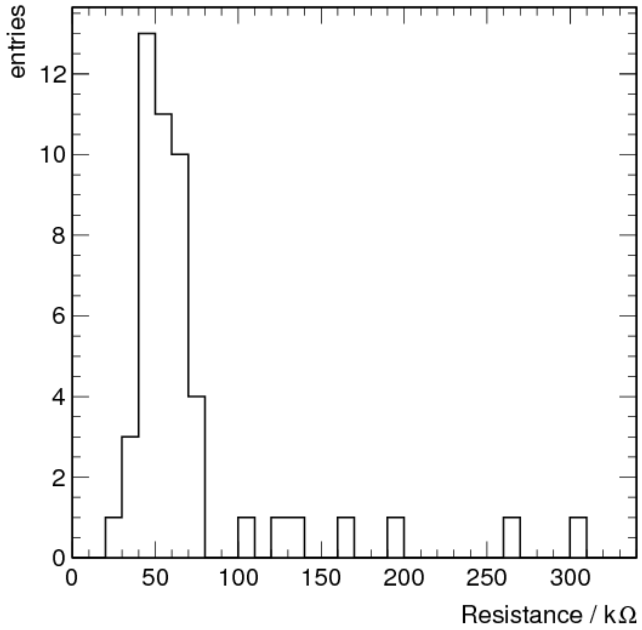


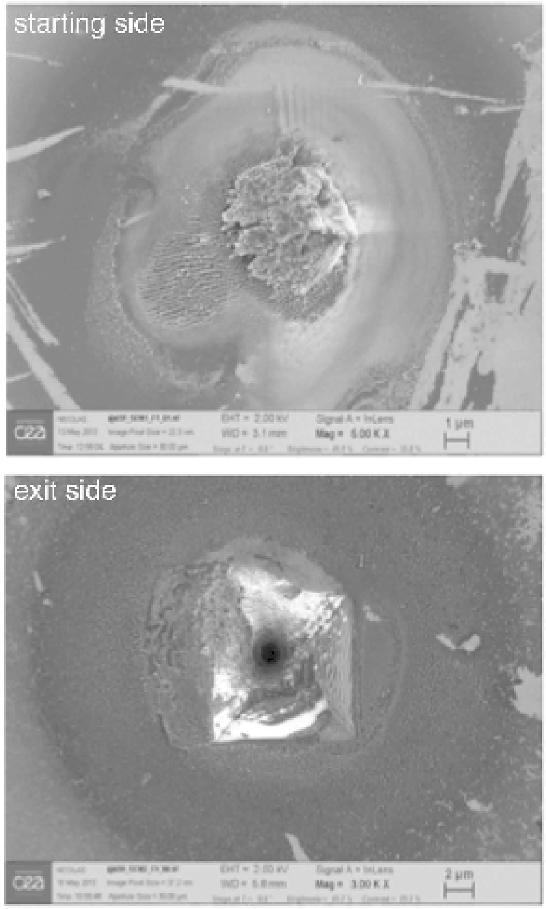
3D devices in pCVD diamond

Photos of holes and Resistance measurement



- Holes ϕ ~6μm
- Resistance ~50kΩ
- Efficiency 92+-3%





Production Plans: ATLAS, CMS 3D pCVD Pixels

- Collaboration: Bonn, CERN, ETH-Zürich, Göttingen, JSI/Ljubljana, Manchester, OSU, Oxford, Rutgers, UC Sacramento

First double-sided device