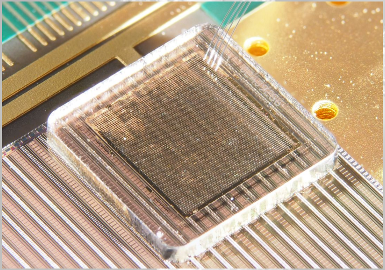
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



New Test Beam Results of 3D and Pad Detectors Constructed with Poly-Crystalline CVD Diamond

Vienna Conference on Instrumentation

Michael Reichmann

19th of February, 2019

Table of Contents

1. Motivation
2. Introduction
3. 3D Pixel Detectors
4. Pad Detectors (Rate Studies)
5. Conclusion
6. Outlook

Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers $\rightarrow$ highest radiation damage $\mathcal{O}\left(\text{GHz/cm}^2\right)$
- current detectors is designed to survive $\sim$12 month in High-Luminosity LHC
- $\rightarrow$ **R/D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material

- innermost tracking layers $\rightarrow$ highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive $\sim$12 month in High-Luminosity LHC
- $\rightarrow$ **R/D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerant
  - isolating material
  - high charge carrier mobility
  - **smaller signal than in silicon with same thickness (large bandgap)**

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive ~12 month in High-Luminosity LHC
- → **R/D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerant
  - isolating material
  - high charge carrier mobility
  - **smaller signal than in silicon with same thickness (large bandgap)**

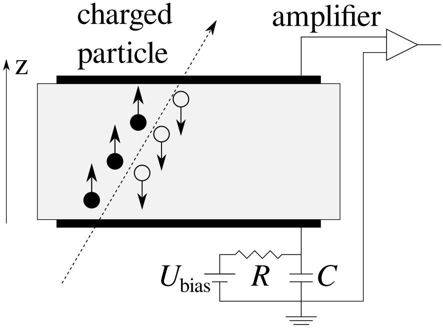
Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
  - **pad** → full diamond as single cell readout
  - pixel → diamond sensors on state-of-the-art pixel chips
  - **3D pixel** → detector with design to reduce drift distance

Section 2

Introduction

Diamond as Particle Detector

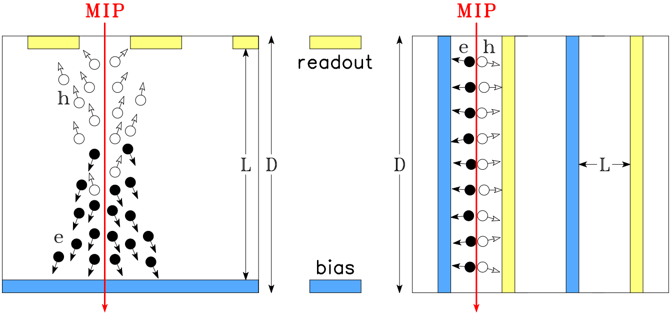


(a) Detector Schematics

(b) 15 cm pCVD Diamond Wafer

- detectors operated as ionisation chambers
- poly-crystals produced in large wafers
- metallisation on both sides

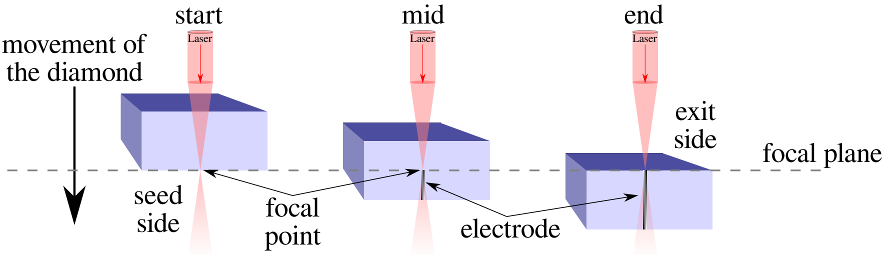
Working Principle



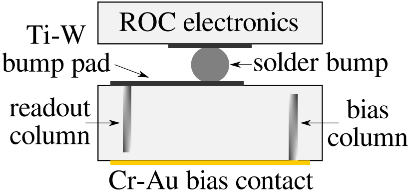
- after large radiation fluence all detectors become trap limited
- bias and readout electrode inside detector material
- same thickness $D \rightarrow$ same amount of induced charge $\rightarrow$ shorter drift distance L
- **increase collected charge in detectors with limited mean free path**

Laser drilling

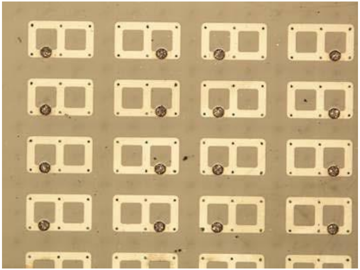
- "drilling" columns with $\sim$15 µm gap to the surface using fs-laser (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of spatial light modulation (SLM) to correct for aberration
- initial column yield $\sim$90 % $\rightarrow$ now $\geq$99 %
- initial column diameter $6 \sim 10$ µm $\rightarrow$ now 2.6 µm



Bump Bonding



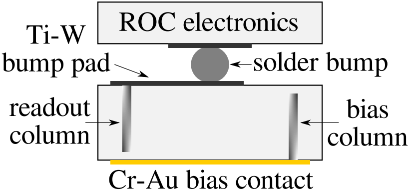
(a) Bump bond schematics



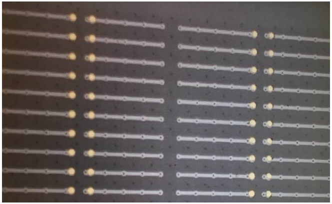
(b) 3×2 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap to the surface to avoid a break-through

Bump Bonding



(a) Bump bond schematics



(b) 1×5 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap to the surface to avoid a break-through

Progress in Diamond Detectors

3D Detectors:

- proved that 3D works in pCVD diamond
- scale up the number of columns per detector: $\mathcal{O}(100) \rightarrow \mathcal{O}(1000)$ (x40)
- reducing the cell size: $150\,\mu\text{m} \times 150\,\mu\text{m} \rightarrow 50\,\mu\text{m} \times 50\,\mu\text{m} \rightarrow 25\,\mu\text{m} \times 25\,\mu\text{m}$ (soon)
- reducing the diameter of the columns: $6 \sim 10\,\mu\text{m} \rightarrow 2.6\,\mu\text{m} \rightarrow 1 \sim 2\,\mu\text{m}$ (soon)
- $\rightarrow$ increasing column yield: $\sim$90 % $\rightarrow \geq$99 %
- recently tested first irradiated $50\,\mu\text{m} \times 50\,\mu\text{m}$ 3D detector ($3.5 \cdot 10^{15}\,\text{n/cm}^2$)

3D Pixel Detectors:

- visible improvements with each step reducing the cell size
- all worked as expected (to first order)

Rate Studies in Pad Detectors:

- particle fluxes from $1\,\text{kHz/cm}^2$ up to $20\,\text{MHz/cm}^2$
- irradiations up to $4 \cdot 10^{15}\,\text{n/cm}^2$

Section 3

3D Pixel Detectors

1×5 Ganging

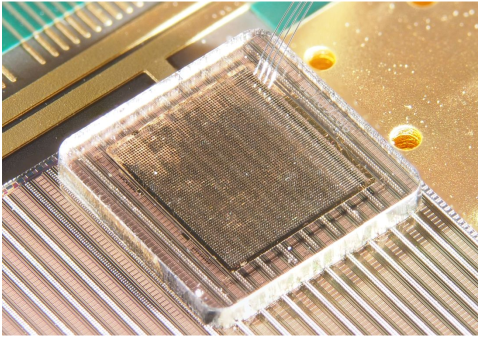
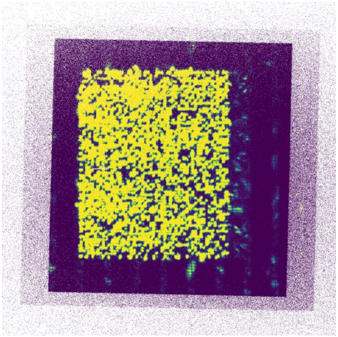


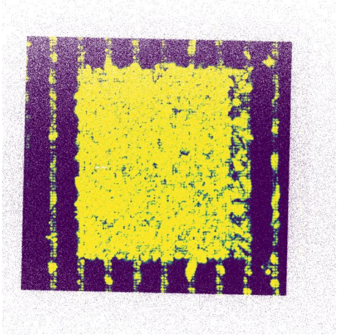
Figure: Final Detector

- readout chip (ROC): ATLAS FEI4
- Size: $5\,\mathrm{mm} \times 5\,\mathrm{mm}$
- active area $3\,\mathrm{mm} \times 3\,\mathrm{mm}$
- tin-silver bump bonding at IFAE (Barcelona)

Efficiencies



(a) High treshold



(b) Low threshold

- efficiencies

Time over Threshold

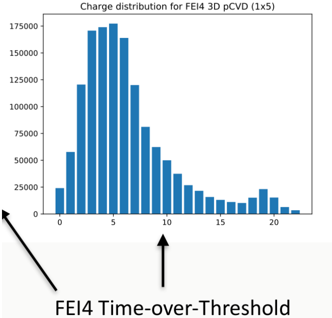


Figure: Time over Threshold

- tot

2 × 3 Ganging

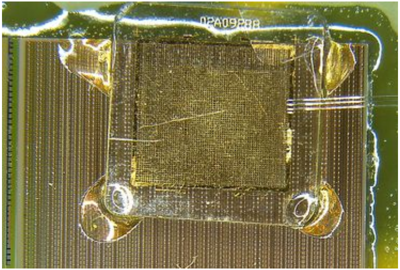
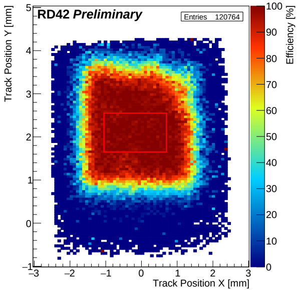


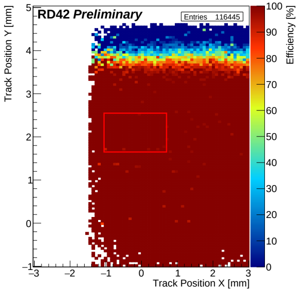
Figure: Final Detector

- readout chip (ROC): CMS PSI46digv2.1repspin
- Size: 5 mm × 5 mm
- active area 3.5 mm × 3.5 mm
- indium bump-bonding (Princeton)

Efficiencies - First PSI Beam Test



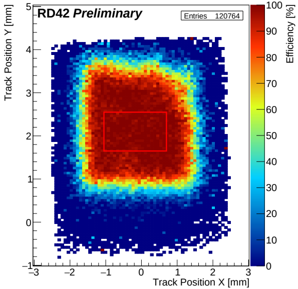
(a) Efficiency Map Diamond



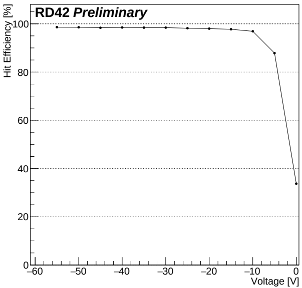
(b) Efficiency Map Silicon

- top right corner of the diamond badly bump bonded
- efficiency in red fiducial area: Diamond: 99.1 %, Silicon: 99.9 %

Efficiencies - First PSI Beam Test



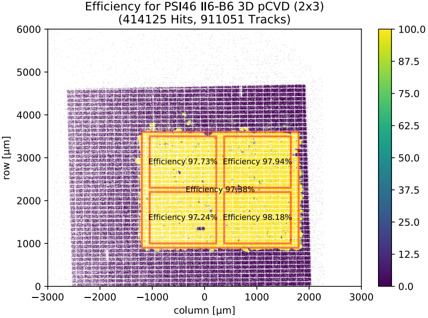
(a) Efficiency Map



(b) Efficiency vs. voltage

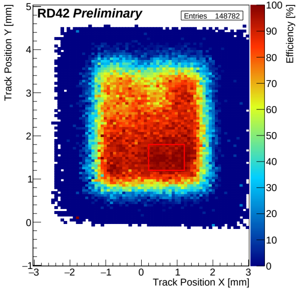
- top right corner of the diamond badly bump bonded
- effective efficiency in red fiducial area: 99.2 %
- already fully efficient at 20 V
- ROC malfunctioned after this beam test

Efficiencies - CERN Beam Test

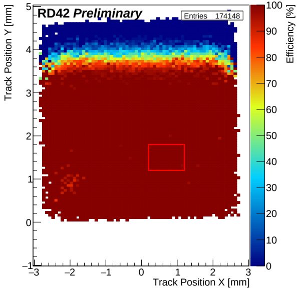


- high resolution measurement at CERN
- sensor twice re-bump-bonded with the same indium (no reprocessing)
- reduced efficiency

Efficiencies - Second PSI Beam Test



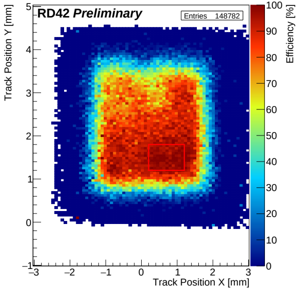
(a) Efficiency Map Diamond



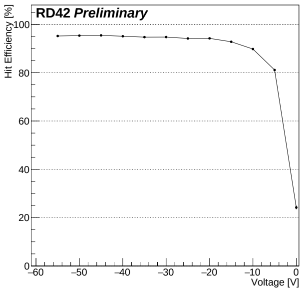
(b) Efficiency Map Silicon

- sensor twice re-bump-bonded with the same indium (no reprocessing)
- efficiency in red fiducial area: Diamond: 97.3 %, Silicon: 100.0 %

Efficiencies - Second PSI Beam Test



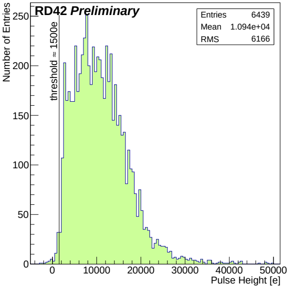
(a) Efficiency Map



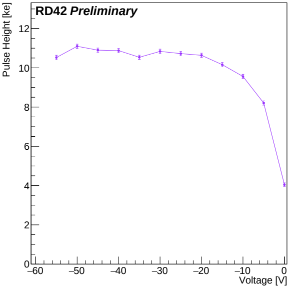
(b) Efficiency vs. voltage

- sensor twice re-bump-bonded with the same indium (no reprocessing)
- effective efficiency in red fiducial area: 97.3 %
- already fully efficient at 20 V
- only very small area working well → many bump bond problems

Pulse Height - Second Beam Test



(a) Signal Distribution



(b) Pulse height vs. voltage

- wrong pulse height calibration in first beam test
- full charge collection also at 20 V
- mean pulse height lower than expected: 11 000 e
- probably connected to bad bump bonding

Section 4

Pad Detectors (Rate Studies)

Leakage Currents

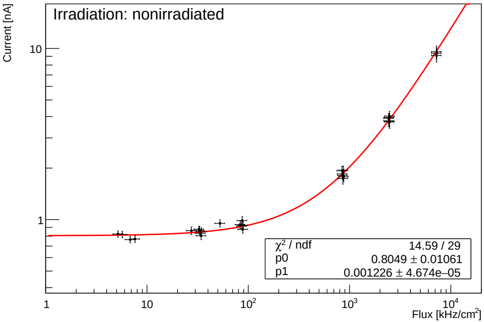
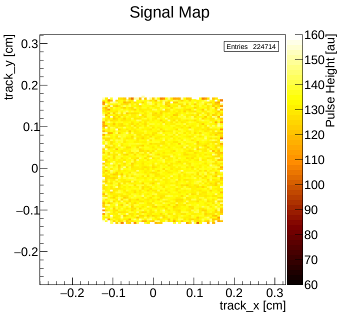


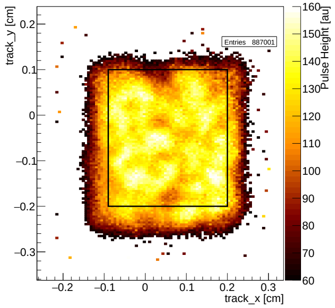
Figure: Leakage Current of a non-irradiated pCVD diamond

- leakage current of most of the diamonds linear in flux
- very low base leakage current (no beam) of $\mathcal{O}\,(1\,\mathrm{nA})$

Signal Maps



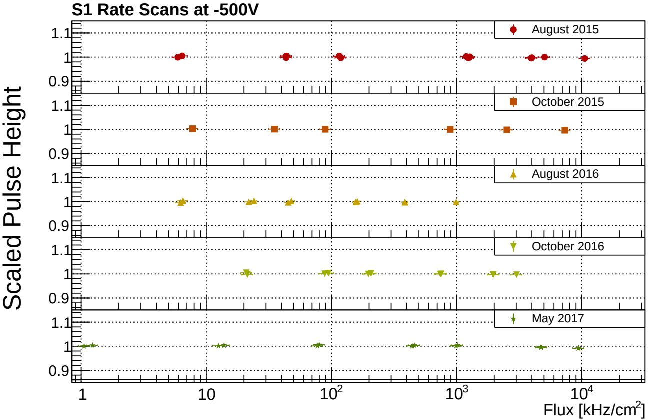
(a) scCVD (6 dB attenuation)



(b) pCVD

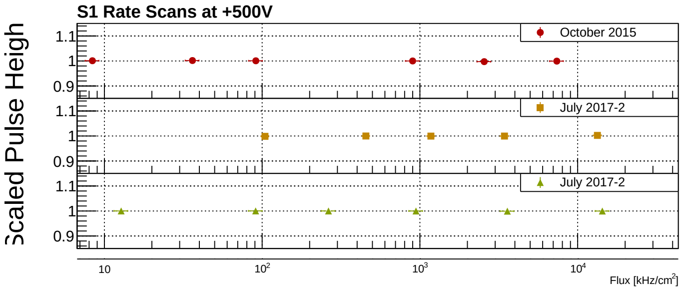
- uniform signal distribution in scCVD
- region dependent signal in pCVD

Non-Irradiated scCVD



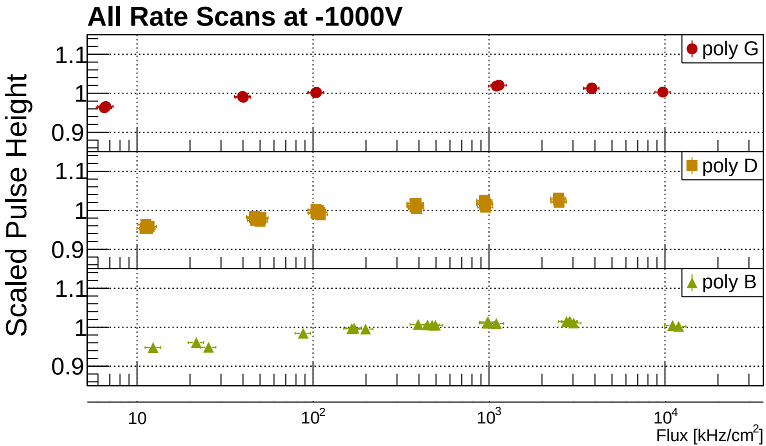
- rate scaled to the mean
- scCVD diamond shows now rate dependence within the measurement precision
- noise stays constant

Non-Irradiated scCVD



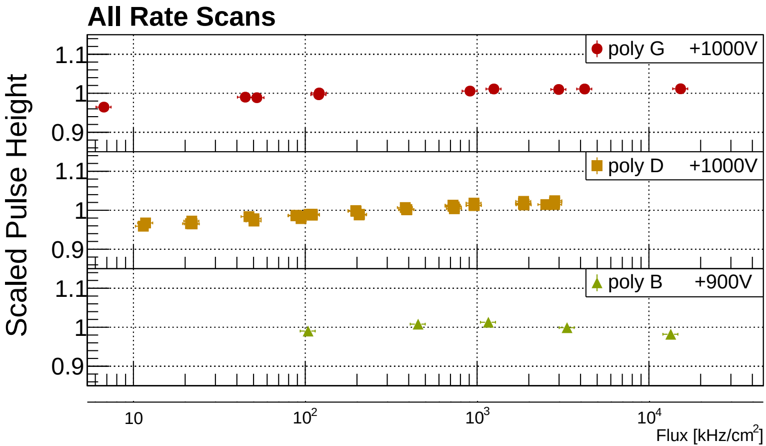
- rate scaled to the mean
- scCVD diamond shows now rate dependence within the measurement precision
- noise stays constant

Non-Irradiated pCVD



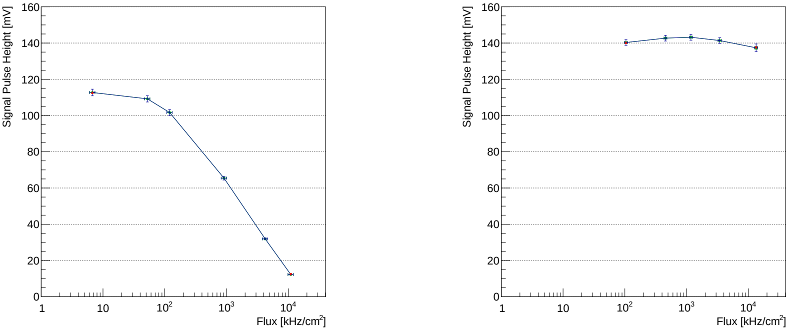
- rate scaled to the mean
- most non-irradiated pCVD diamonds have slight rate dependence (<5 %)
- behaviour very similar for both positive and negative bias voltage

Non-Irradiated pCVD



- rate scaled to the mean
- most non-irradiated pCVD diamonds have slight rate dependence (<5 %)
- behaviour very similar for both positive and negative bias voltage

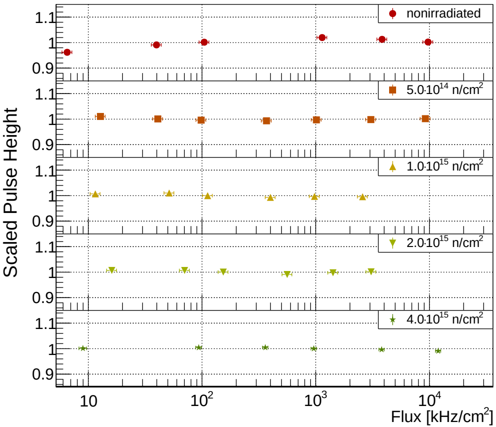
A Special Case



(a) First measurement (b) After reprocessing

- very large rate dependence at the first measurement (>90 %)
- after reprocessing and surface cleaning with RIE very stable behaviour (∼2 %)
- feasible to "fix" bad diamonds

Rate Studies in Irradiated pCVD



- rate scaled to the mean
- pulse height very stable after irradiation
- noise stays the same

Section 5

Conclusion

Conclusion

- strongly improved fabrication of 3D diamonds
  - 40x more cells
  - smaller cell size
  - smaller columns
- 3D Detectors work well in pCVD diamond
  - 99.2 % efficiency
  - nearly full charge collection
- possible to repair pCVD diamonds with surface issues
- rate tests of irradiated pCVD diamonds up to $4 \cdot 10^{15}\,\mathrm{n/cm^2}$
- irradiated pCVD diamond does not show rate dependence to $\mathcal{O}(2\,\%)$

Section 6

Outlook

Outlook

- results of $3.5 \cdot 10^{15}\,\mathrm{n/cm^2}$ irradiated $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ detectors
- continue irradiation up to $1 \cdot 10^{16}\,\mathrm{n/cm^2}$
- test both $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ and $25\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$ pixel detectors
- reduce cell diameter to $1 \sim 2\,\mu\mathrm{m}$
- build pixel device on newest RD53 chip ($50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ pixel pitch)
- continue scale up by 10x

Del Fin