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DG CIRCUITS: GIANLUIGI DE GERONIMO
SYOSSET, NY
&
Brookhaven National Laboratory
Stony Brook University

Diaphanous Diamond for X-ray Beam Imaging Update
DOE STTR DE-SC0019705 (RMD C20-30)

- Started in 2020
- CoVID: BNL closed, RMD open
- Appointment change (RI Change: SBU to BNL)

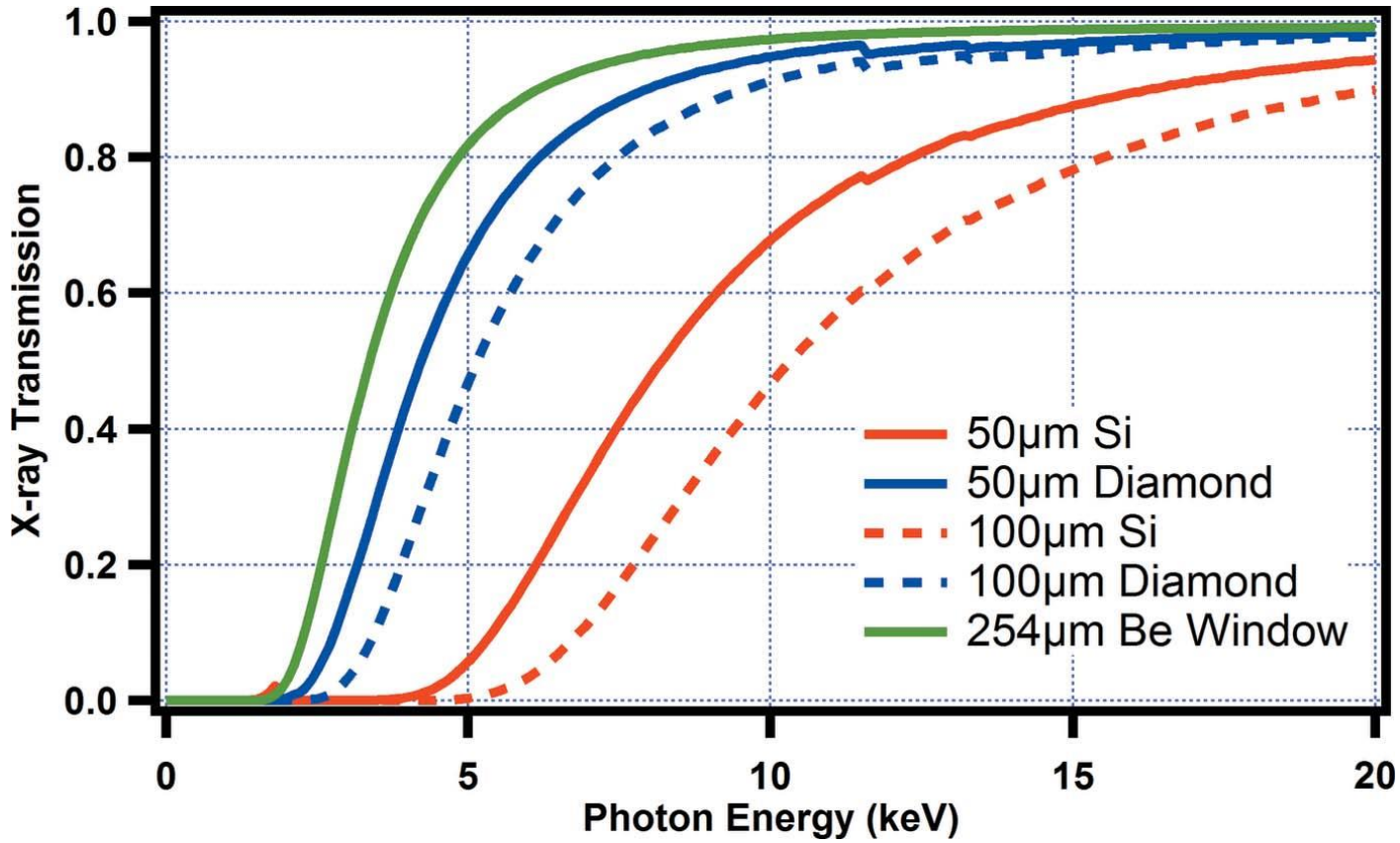
August 20, 2023

X-ray beam monitor introduction: cross-strip imaging

Next-generation synchrotron sources trend toward use of high-flux beams and/or beams which require enhanced stability and precise understanding of beam position and intensity from the front end of the beamline all the way to the sample.

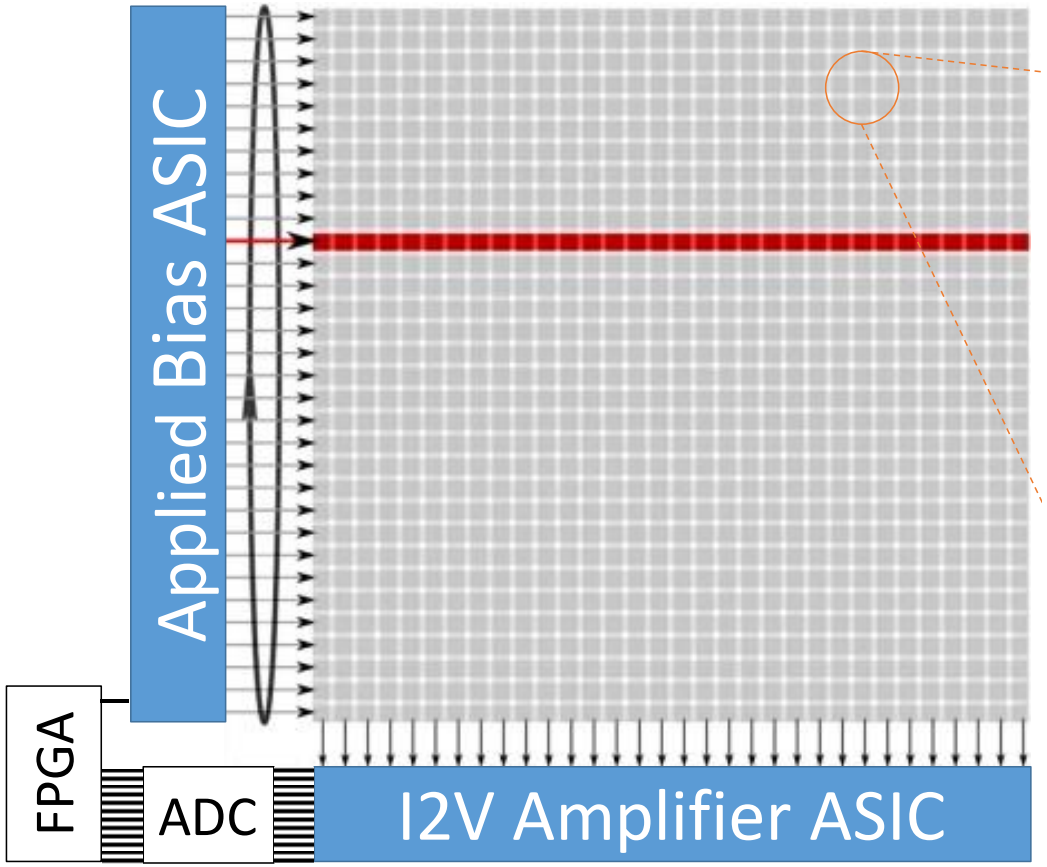
Imaging beam-line monitors needed

- Withstand radiation environment
- Withstand high temperatures
- Minimize beam interaction below 20 keV



Thin, "diaphanous" diamond an ideal candidate

Concept: Crossed-strip readout



- Bias applied row-by-row
- Current in each col read out
  - NOT photon counting
  - Discrete components
  - Application Specific Integrated Circuit (ASIC)
- Diamond detectors
  - 100-um thick poly-crystalline from E6:
    - requires 10 V bias for readout
    - Leakage/Dark Current per area: 6 fA/mm^2
    - Capacitance per area: 0.5 pF/mm^2
  - 70-um thick single crystalline from Innovative Carbon:
    - requires 20 V bias for readout
    - Leakage/Dark Current per area: 12 pA/mm^2
    - Capacitance per area: 0.72 pF/mm^2

Phase-2 Objectives and Tasks

1. Transfer photolithographic fabrication technology
    - Fabricate test structures at RMD (RMD)
    - Order diamond substrates and thin if necessary (RMD)
    - Fabricate devices at RMD (RMD & SBU)
    - Fabricate control devices at Stony Brook (SBU)
    - Test at NSLS light source using existing electronics (SBU)
2. Continue Exploration of alternative sources of electronic grade diamond (RMD)
    - Evaluate diamond fabrication options
3. Develop and transfer readout technology
    - Modify external/discrete ADC and Interface (RMD)
    - Front-end ASIC

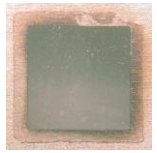
Demonstrate the performance of the prototype

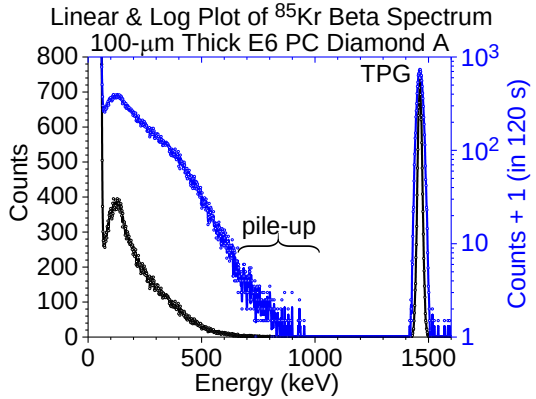
- Integrate components (RMD)
- Modify firmware and software (RMD)
- Test at NSLS light source (BNL)

Diamond Detectors: ^{85}Kr beta emission (251 keV avg., 687 keV endpoint)

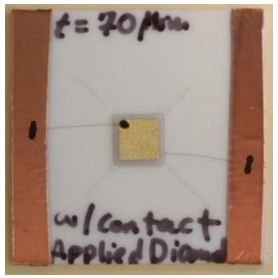
Table 1. Diamond Vendors.				
Vendor	Material	Area (mm^2)	Thickness (um)	
Element 6	Poly-crystal	5x5	100	
Applied Diamond (Delaware Diamond Knives)	Grown	5x5	70	
IIa Technologies				
Innovative Carbone Group, LLC	Grown	5x5	70	

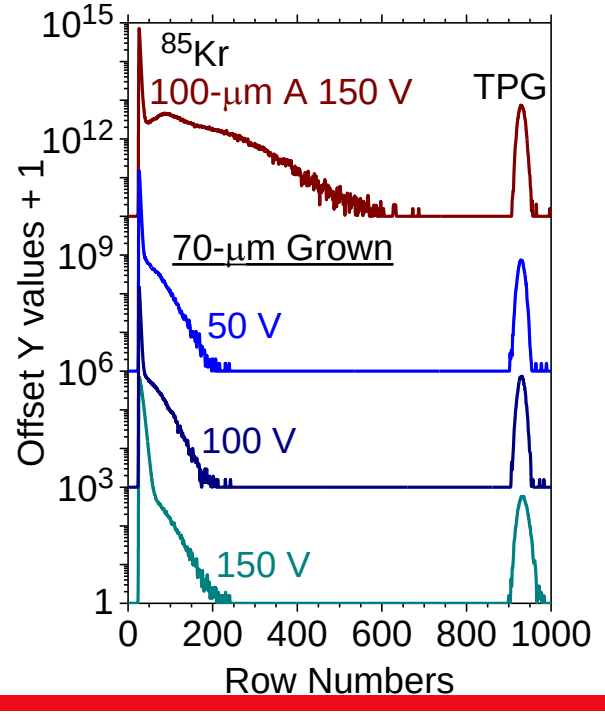
E6 thinned by Applied Diamond



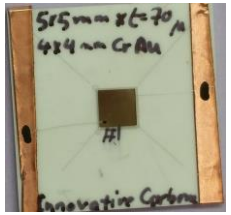


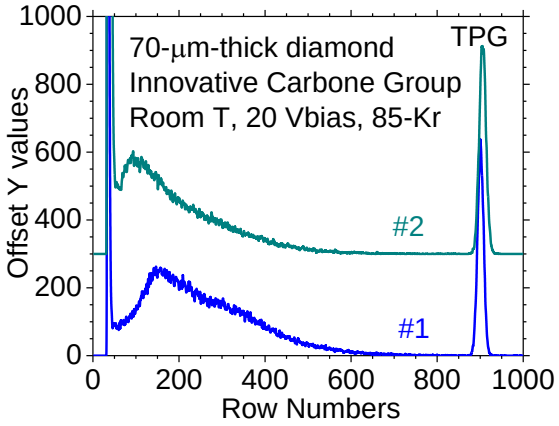
Grown by Applied Diamond





Innovative Carbone Group





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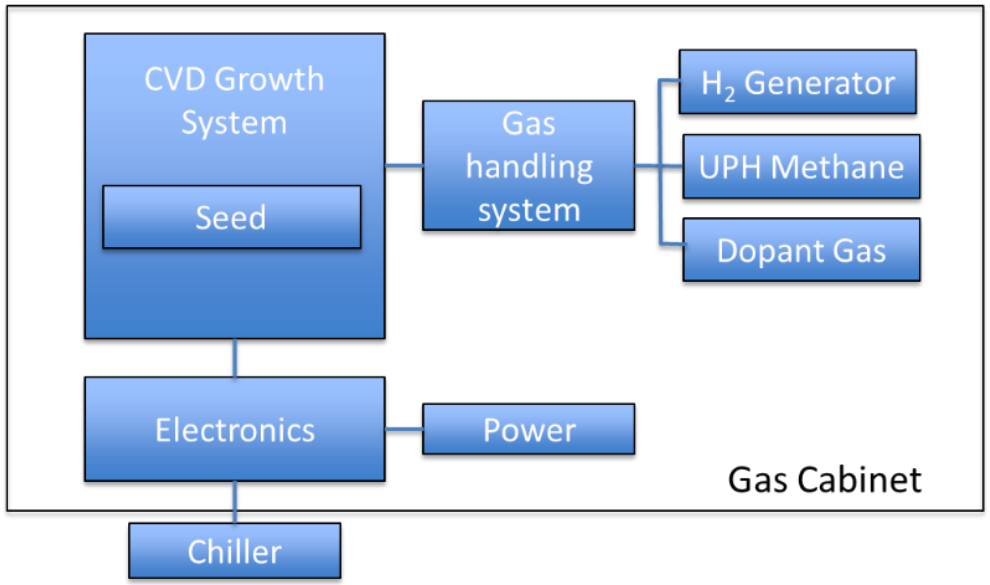
Electronic grade diamond (fabrication options)

Electronic Grade CVD Growth Concept



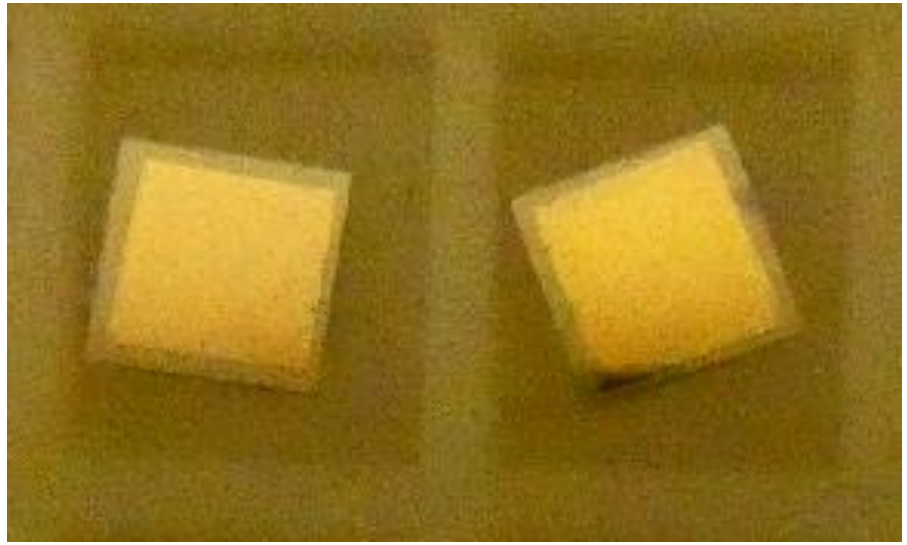
- Reactors commercially available
- Need UHV: low N_2
- Seeds for single crystal (best for thin)

➢ Use Innovative Carbon (access to large seeds)

Name	Website	Address	Comments
ElementSix	https://e6cvd.com/us/	Element Six Technologies Ltd Kings Ride Park Ascot, Berkshire UK SL5 8BP	4.5x4.5x0.5 mm^3 $2,260
Innovative Carbon Group LLC (C6 Materials)		Innovative Carbon Group LLC 717 Forest Ave. 2nd Floor Lake Forest, IL 60045 USA	7x7x0.15 mm^3 $2,400
Ziemer	www.shine-on-me.ch	Ziemer Swiss Diamond Art AG Allmendstrasse 11 2562 Port Switzerland	5x5x0.2mm^3 ppb
Diamond Elements	http://www.diamondelements.com/	Diamond Elements Pvt. Ltd. 2nd Floor Sham House, Opp Science Center, Citylight, Surat-395007, Gujarat, India.	4.5x4.5x0.3 mm^3 $2,480
Chenguang	https://cnchenguang.en.made-in-china.com	Chenguang Machinery & Electric Equipment Co., Ltd. Changsha, China /product/uXvnxCcMnqro/China-Electronic-Grade-Single-Crystal-Diamond-Plates-for-Quantum-Optics.html	Products not listed on website
Applied Diamond, Inc.	http://usapplieddiamond.com/	3825 Lancaster Pike, Wilmington, DE 19805	Limited charge collection
Great Lakes Crystal Technologies	https://glcrystal.com	4942 Dawn Ave, East Lansing, MI 48823	Products not listed on website

Thin UHP Diamond Substrates

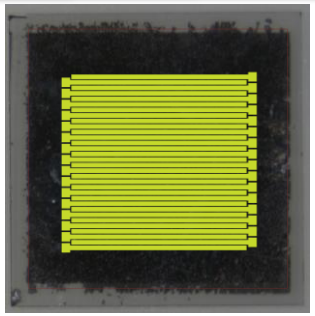
- A couple 5 mm x 5 mm x 0.15 mm
- Processed
  - 7mm x 7 mm
  - ~60-100 nm finish (best effort)
  - 50 nm thick metal



- Diamonds at BNL/SBU
  - UHP 190 um thick 5 mm x 5 mm (#9)
  - UHP ~80 um thick 5 mm x 5 mm (#8)
  - 70-um thick sample (#2) from Innovative Carbone 5 mm x 5 mm
  - 100-um thick sample polyxtal from E6, 5 mm x 5 mm
  - 100-um thick sample polyxtal from E6, 1 cm x 1 cm

➢ Test device fabrication and characterization measurements in progress reports

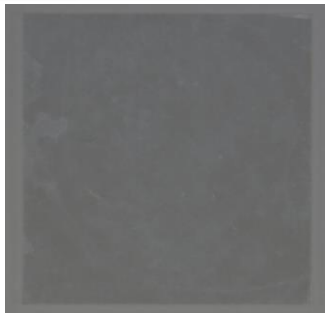
From Stony Brook



- #2 – Inn. Carbon
- 5.2 mm x 5.2 mm

- #4
- 5.2 mm x 5.2 mm

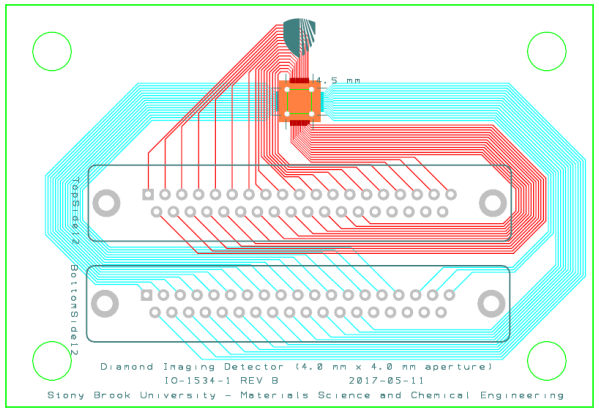
- SC ppb
- 5.0 mm x 4.8 mm

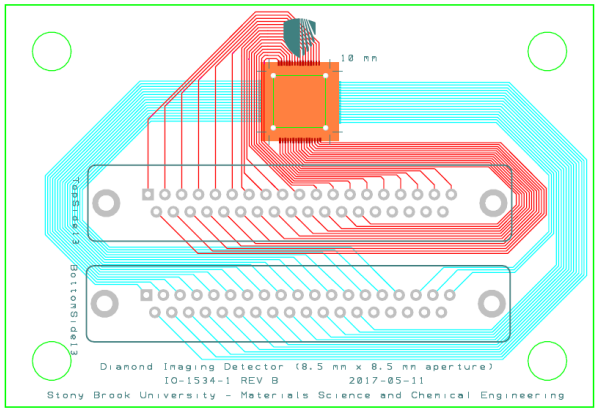


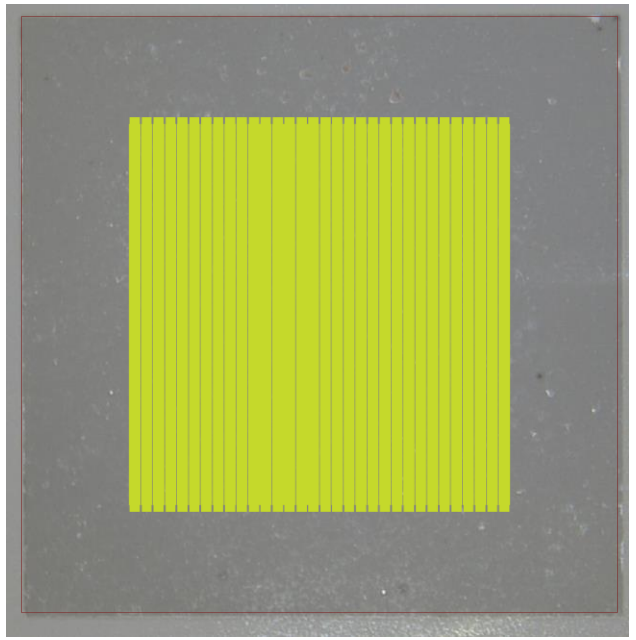
- *AL
- 5.0 mm x 4.9 mm

Suggested Pattern

- 100 µm pitch
- 20 µm gap
- 3.2 mm active area







- #5
- 10.2 mm x 10.2 mm

Suggested Pattern

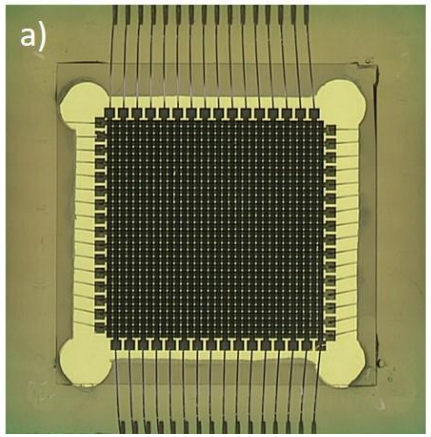
- 200 µm pitch
- 20 µm gap
- 6.4 mm active area

List from my email

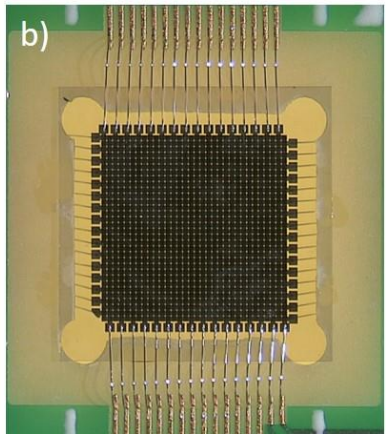
1. UHP 200 um thick 5 mm x 5 mm
2. UHP ~80 um thick 5 mm x 5 mm
3. 70-um thick sample (#2) from Innovative Carbone 5 mm x 5 mm
4. 100-um thick sample polyxtal from E6, 5 mm x 5 mm
5. 100-um thick sample polyxtal from E6, 1 cm x 1 cm

Diaphanous diamond x-ray beam imaging

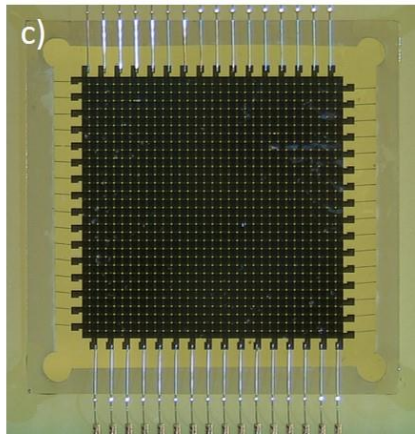
Fabrication and Testing at Stony Brook University and BNL (NSLS-II, CFN)



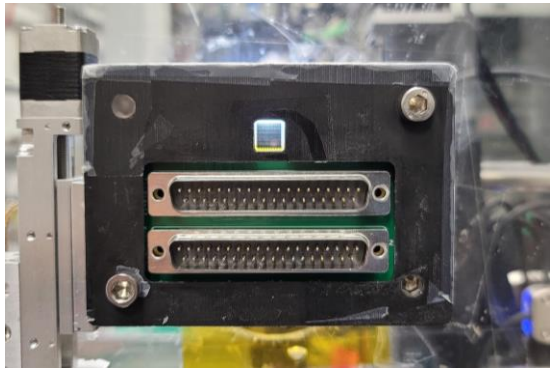
Innovative Carbon (size: 5.2 mm x 5.2 mm x 0.07 mm and pitch: 100 µm)

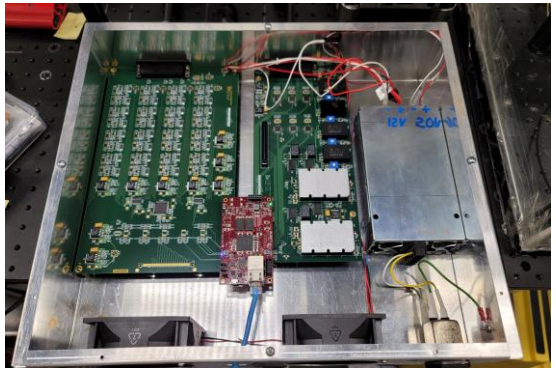


UHP – Poly Diamond (size: 5 mm x 5 mm x 0.08 mm and pitch: 100 µm)



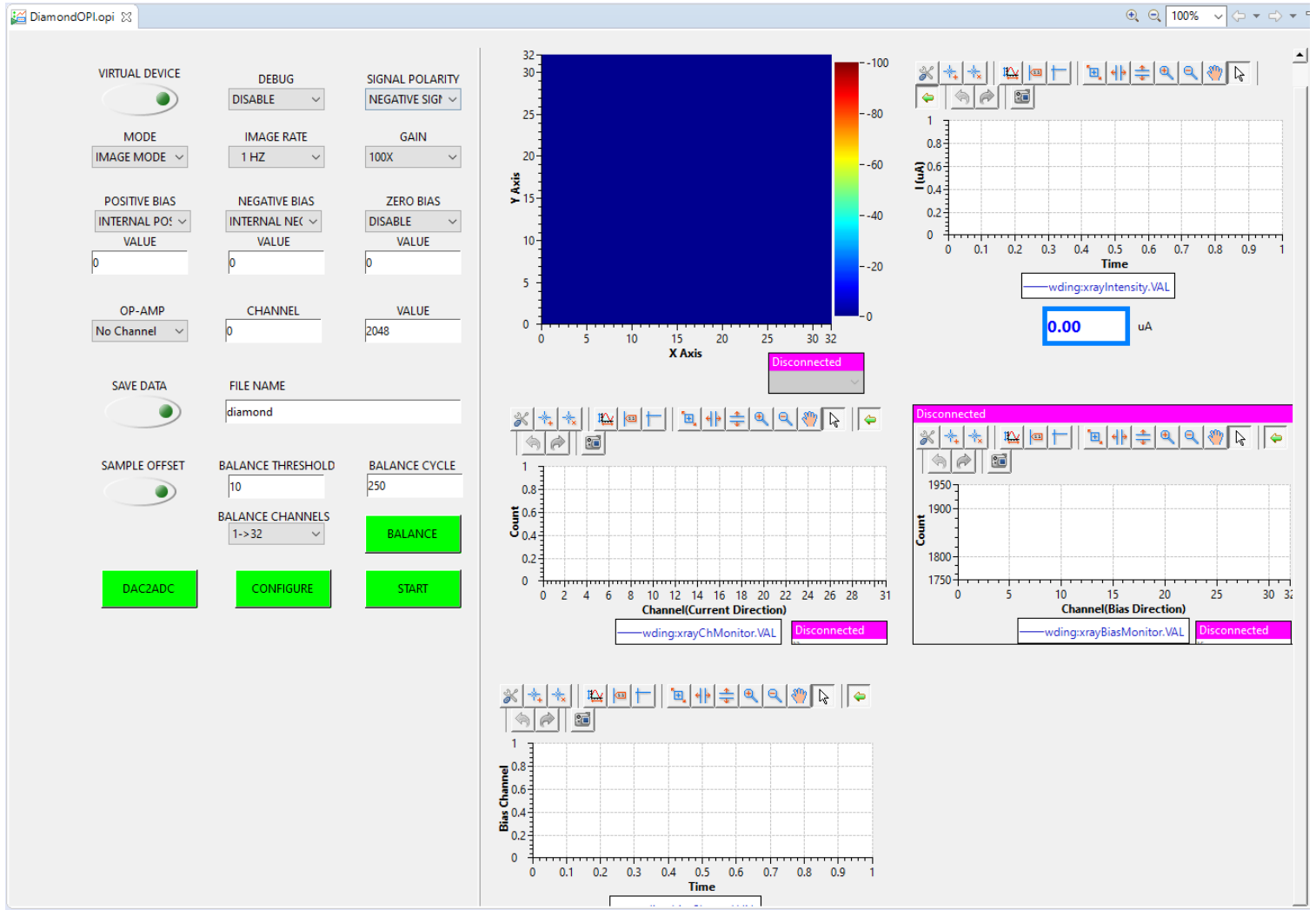
E6 – Poly Diamond (size:1 cm x 1 cm x 0.1 mm and pitch: 220 µm)





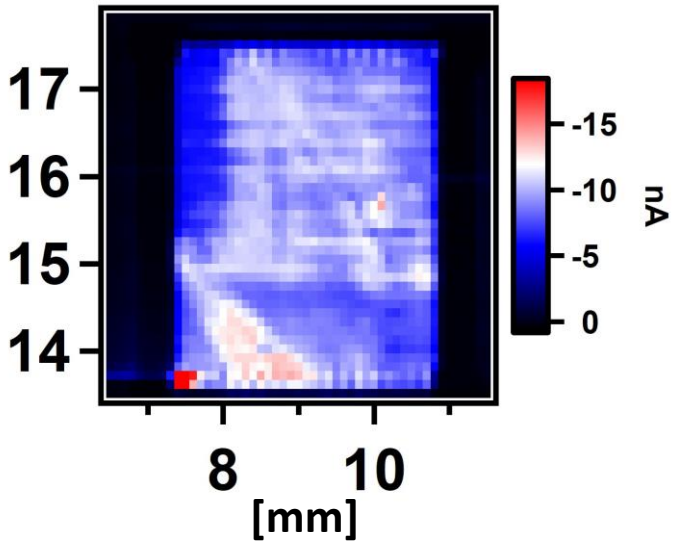
- **Initial phase**: to fabricate and test diamonds using our existing diamond Imaging system.
  - Larger area, polycrystalline, new vendors
- Testing centered on imaging and x-ray beam-induced current (XBIC).
  - XBIC determines the material's charge collection and uniformity which is critical for a good x-ray imaging sensor.
- Three imaging detectors are shown to the left that were fabricated using facilities at BNL (Instrumentation Division, CFN).
- Several beamtimes were used to study this material, however, the SBU electronics could not be used because the Xilinx FPGA failed and was not available (end of 2021).

Screenshot of SBU control panel

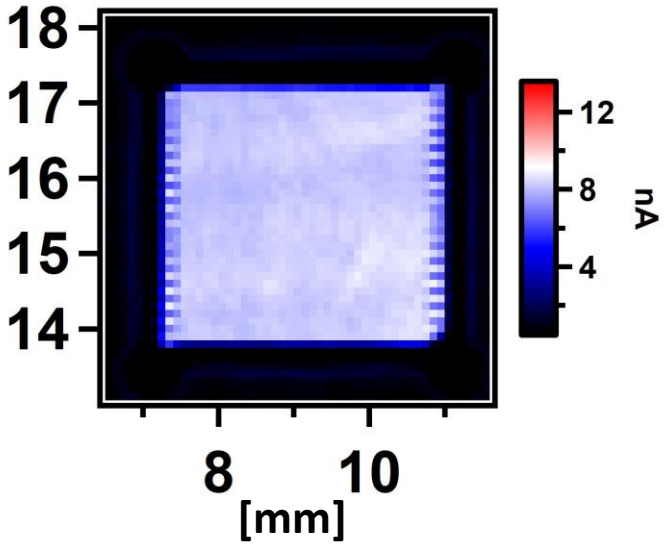


XBIC at the XFP Beamline, NSLS-II early results

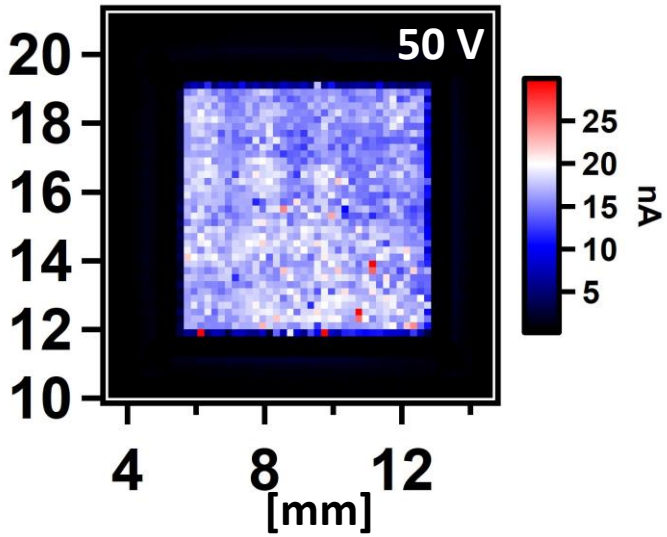
Innovative Carbon Single Crystal



UHP Poly Crystal



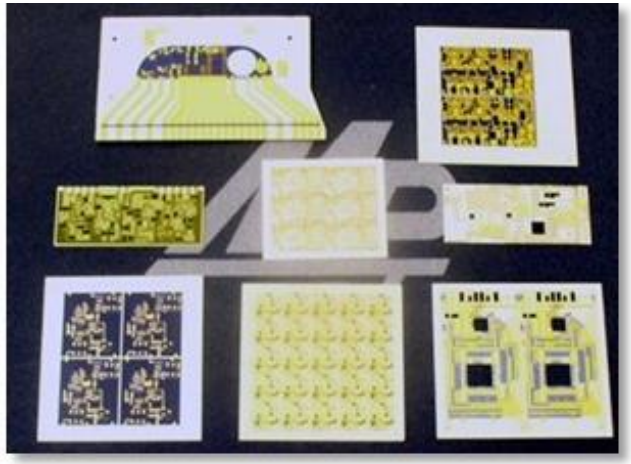
E6 Poly Crystal



- **All diamond material showed promise, but there were still some uniformity issues at some biases**

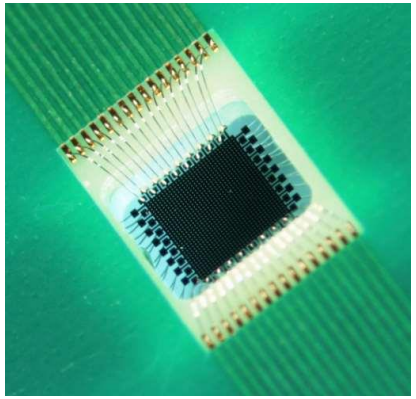
100 µm pinhole, 3mm Al

Ceramic Printed Circuit Boards

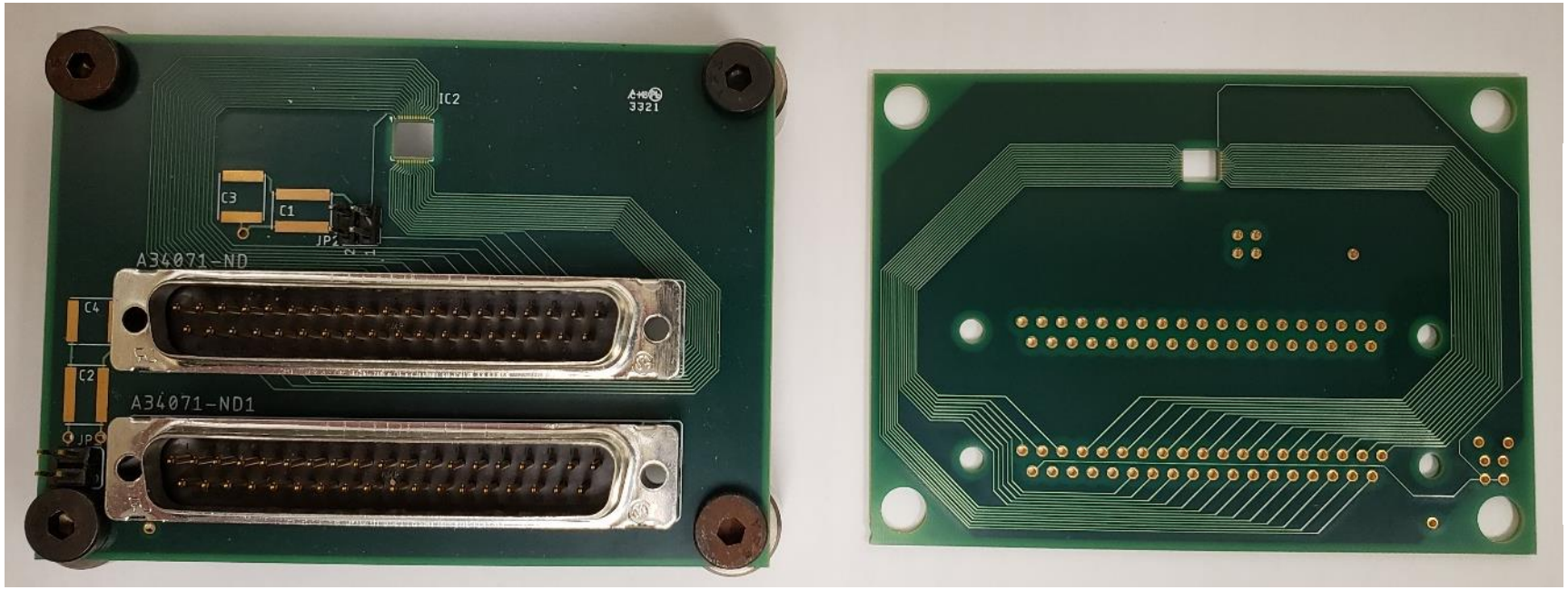


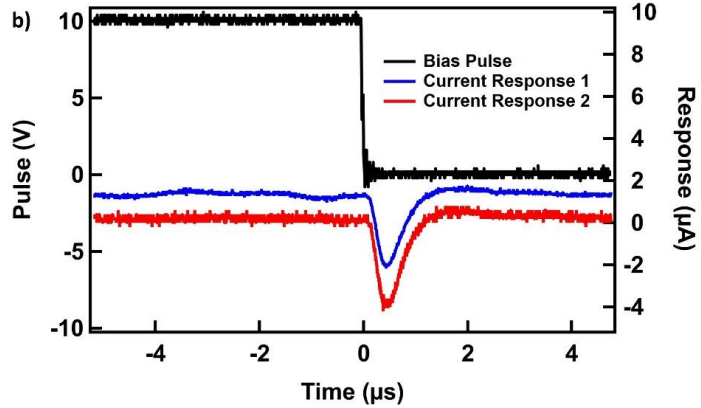
MPT
Micro-Precision Technologies, Inc.
10 Manor Parkway, Suite C
Salem, New Hampshire 03079
603-893-7600
www.micropt.com

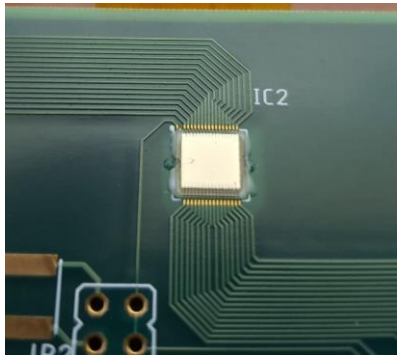
- Exotic PCB material expensive
- Good wire-bonding

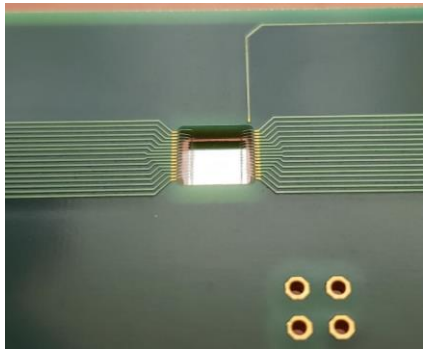


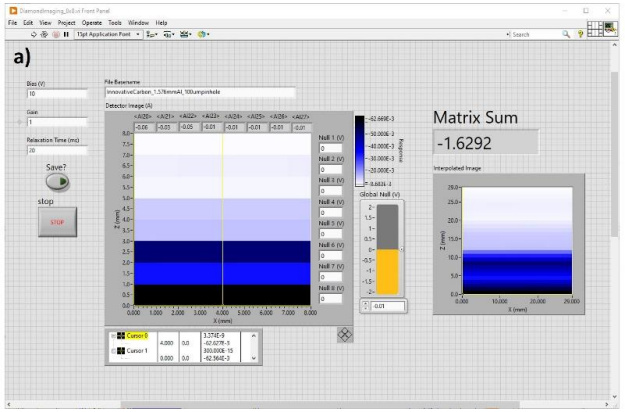
Initial test PCB



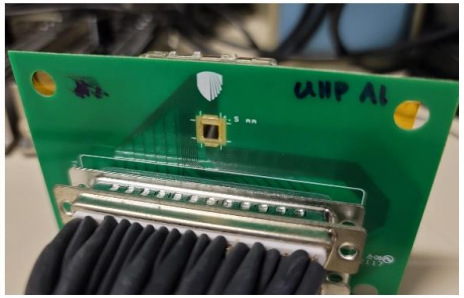




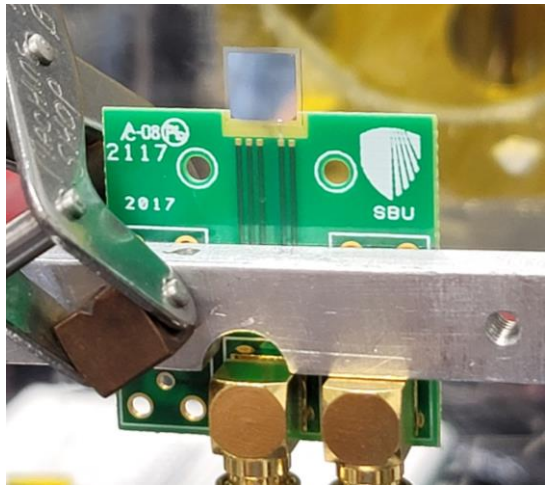


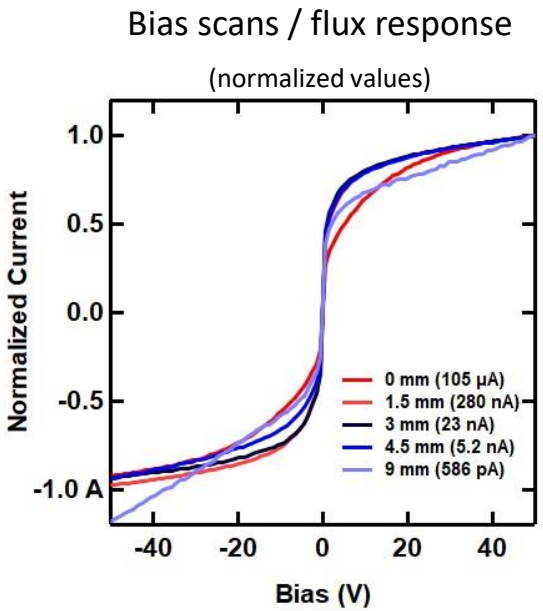


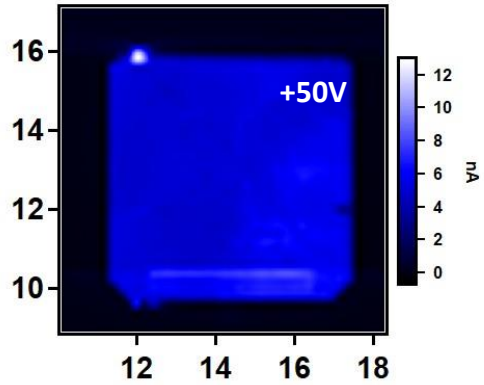
b)

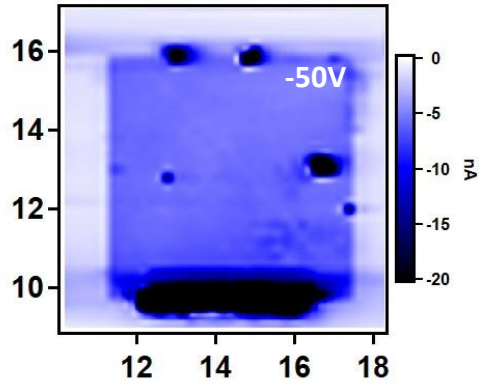


XFP Beamtime: 7mm x 7mm single crystal diamond





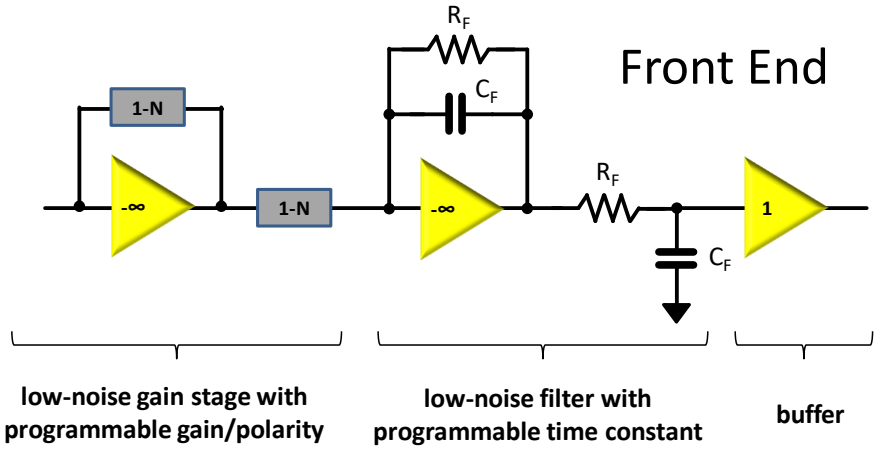


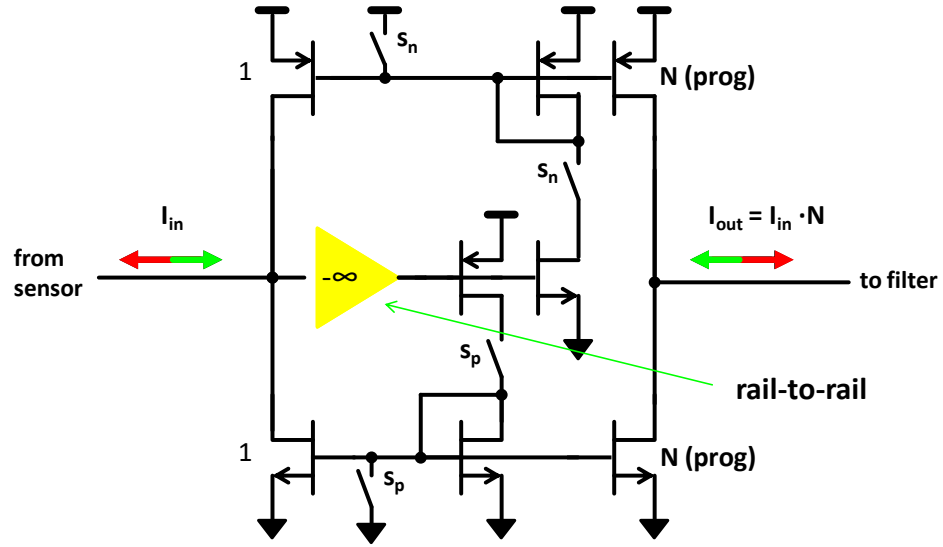


- Electronic grade single crystal diamond 7 x 7 mm^2 (0.1 mm thick)
- Promising new large area *single crystal* diamond
- Good bias response, uniformity, and flux response (in positive bias)

Multi-channel ASIC development for readout (G. DeGeronimo)

ASIC (Amplifier) Requirements			
Requirement	Units	Value	Comments
Number of channels		32	
Ranges		3	5 pA to 20 nA, 5 nA to 20 uA, 5 uA to 20 mA
Dynamic range		4×10^9	4000 each range
Readout rate	Hz	60	
Polarity		Selectable	
Noise floor	pA rms	1	
IC area	mm^2	25	Maximum
IC dimensions	mm	~5	Square
Max. power	mW/ch	2 to 40	Configuration dependent
Supply Voltage(s)	V	1.8	
Number of pads		128	Maximum
Process Technology			TSMC 0.18 um HV, DFE





Current Amplification Stage

- Current for x-ray beam imaging (cross strip electrodes)
  - Bias strip (scan) and orthogonal readout strip
  - Number of channels and ranges
- Front-end amplifier designed and simulated

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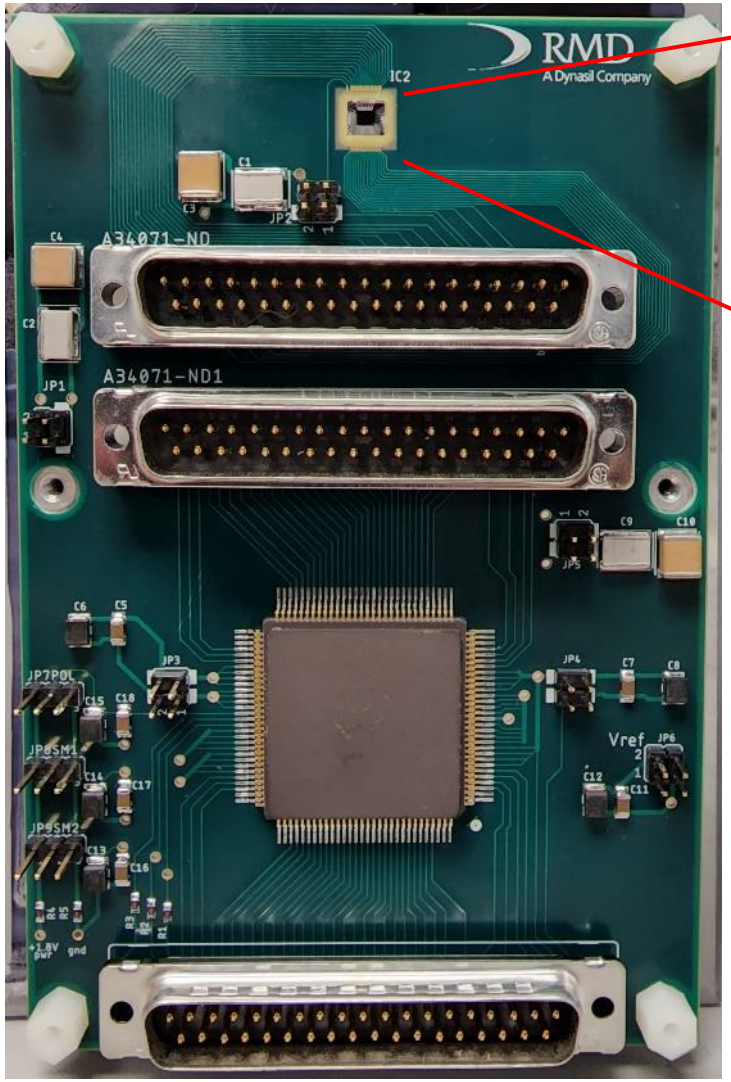
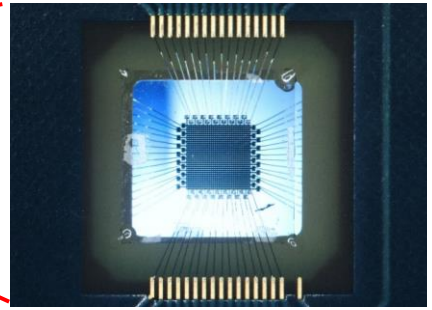
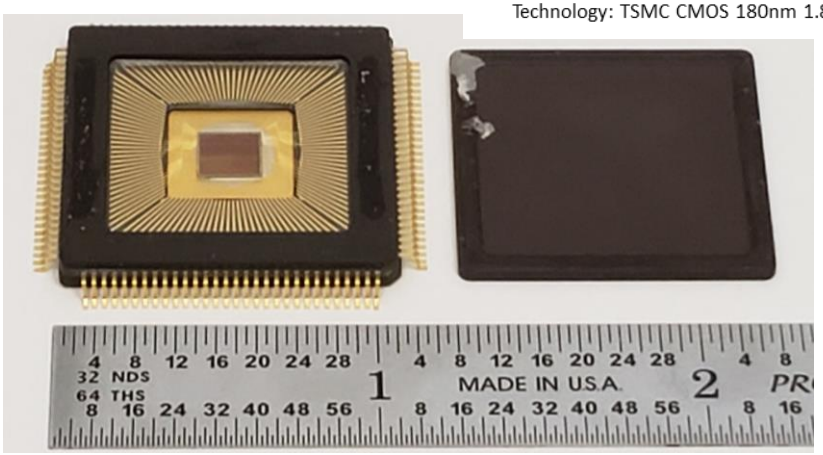
Test PCB with DMFE ASIC





Pin	Function	Type	Note
AS/AG	1.8V supply/ground	power	+1.8V±5%, max ~700mA
i1-i32	inputs	analog input	
o1-o32	output	analog output	output impedance 1kΩ // 100pF, settling time < 20µs
Vref	internal reference	analog reference	~900mV, recommended 100nF//10uF capacitors to AG
SP	polarity selection	CMOS input	SP=0: positive (entering current) SP=1: negative (exiting current)
SM2:1	range selection	CMOS inputs	SM=00 or SM=11: 5nA-20uA resolution: ~ 500pA rms SM=01: 5µA-20mA resolution: ~ 700nA rms SM=10: 5pA-20nA resolution: ~ 5pA rms

Technology: TSMC CMOS 180nm 1.8V 2fF/µm², 1P6M, 4X1U (20k UTM)

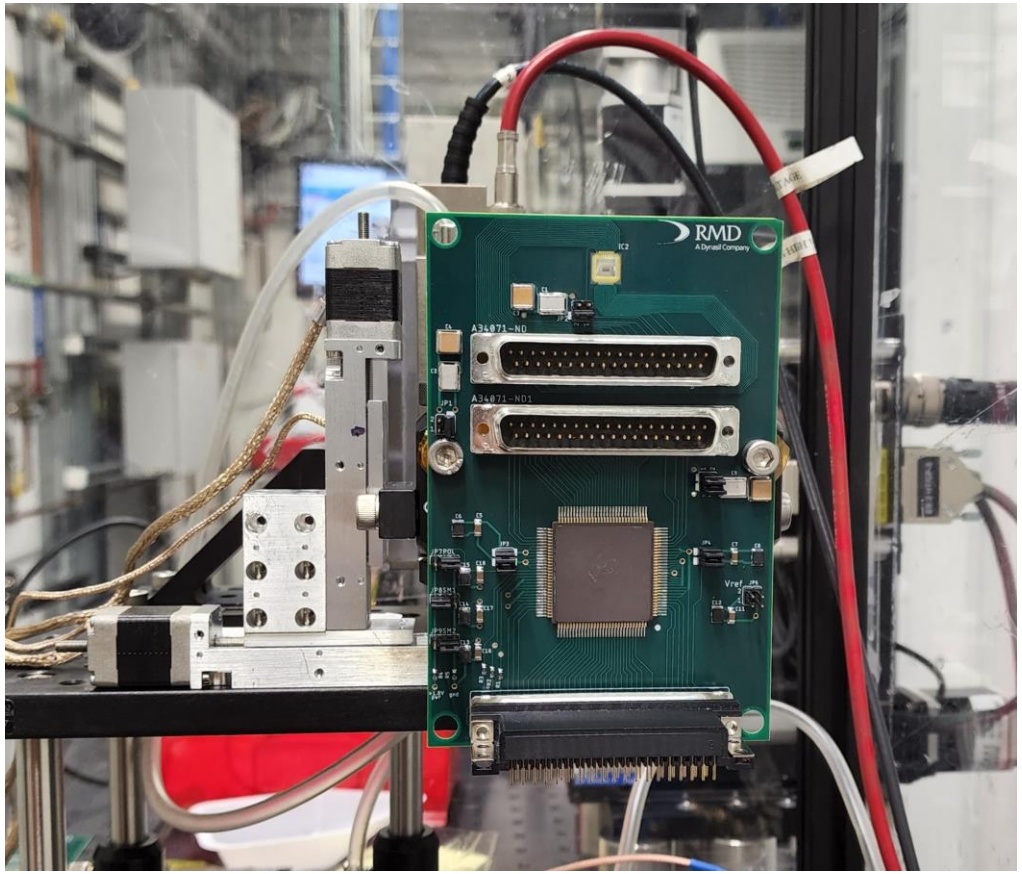


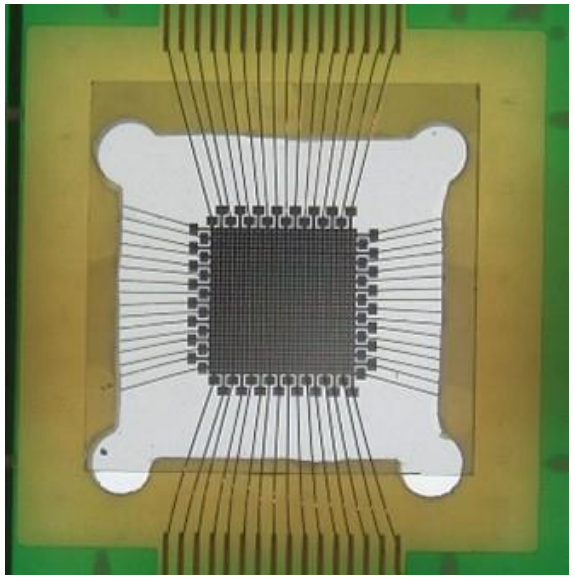
- PCB provide ASIC inputs and outputs – same pin out as previous PCB
- ASIC from RMD assembled and then tested at NSLS-II
- First beamtime we got preliminary data, but more testing is needed.
- Second beamtime planned for April 2023

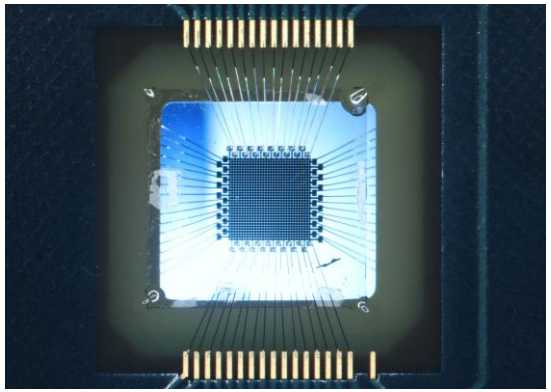
- Two more large area single crystal diamonds on order from Innovative Carbon – Has suffered several delays
- Planned to include in next round of imaging tests.

ASIC: TSMC 0.18um via Muse Semiconductor

Testing at NSLS-II: July 30 and 31, 2022

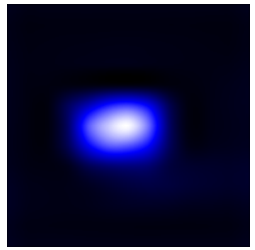


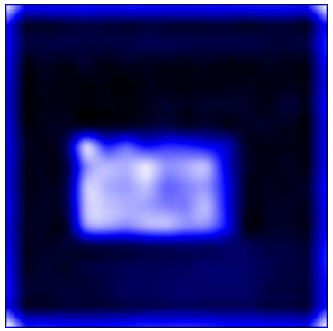


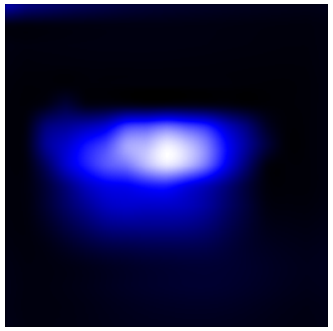


Results (July 30, 2022)

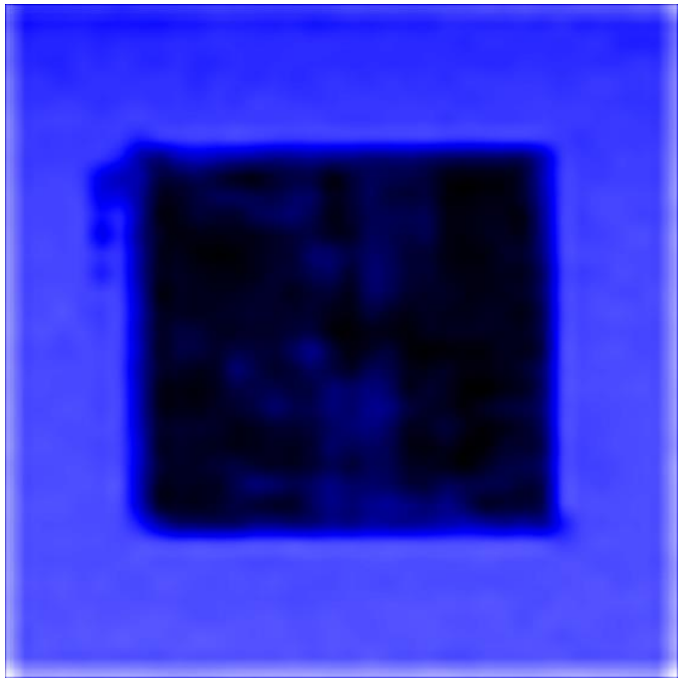
Tuning

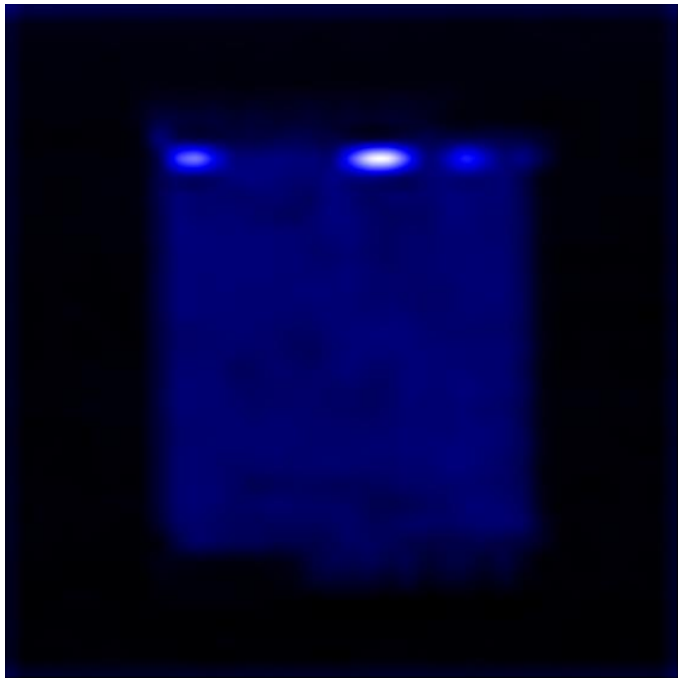






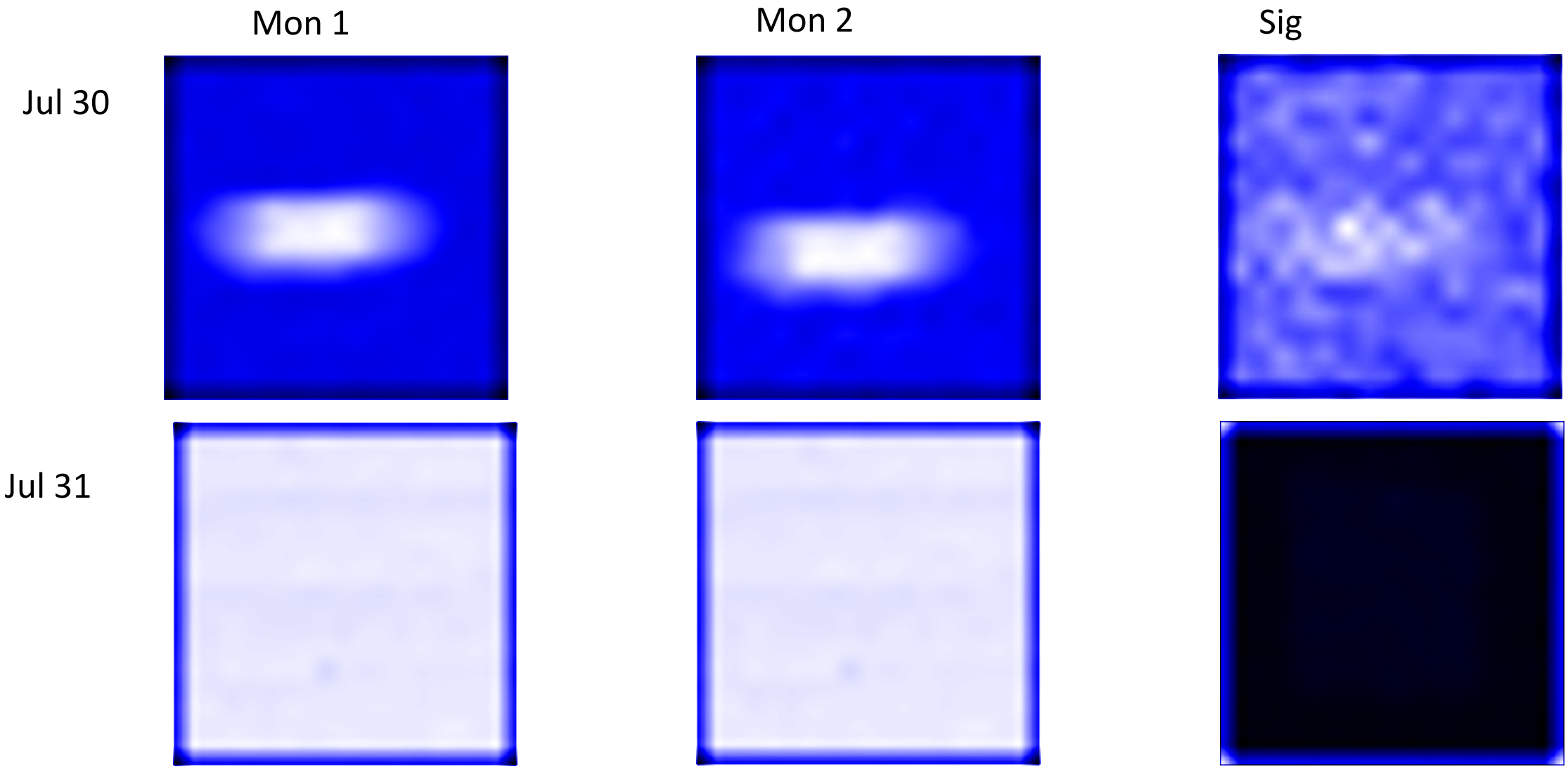
Detector Scans



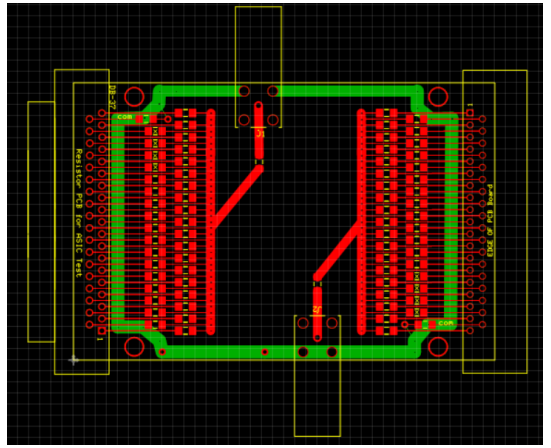


- Successfully scanned diamond detector
- ASIC not working as expected

With ASIC – no image



RMDs plans to debug ASIC



- Design and Build current input PCB
- Replace ASIC on existing PCB (or build a second PCB)
- Test ASIC and determine offset specifications for input and output
- If ASIC is responsive: Connect output to MUX (write VB.net code for MUX)

Summary

Current research Status

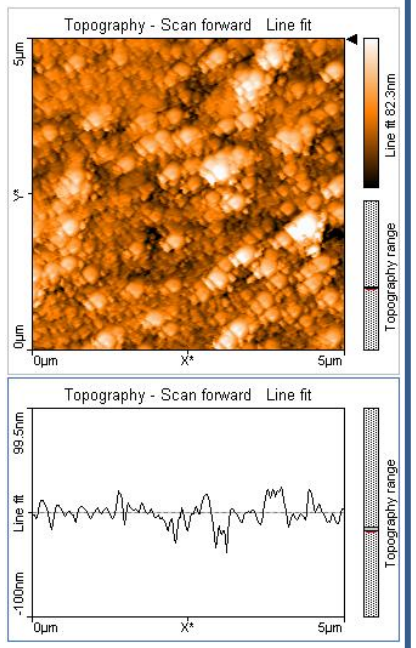
- Have acquired additional 7 mm × 7 mm substrates from Innovative Carbon, but problems (lost batch in polishing)
  - Have 5 mm × 5 mm substrates from E6 and UHP polycrystalline diamond
- Data acquisition and cabling

BNL/SBU status

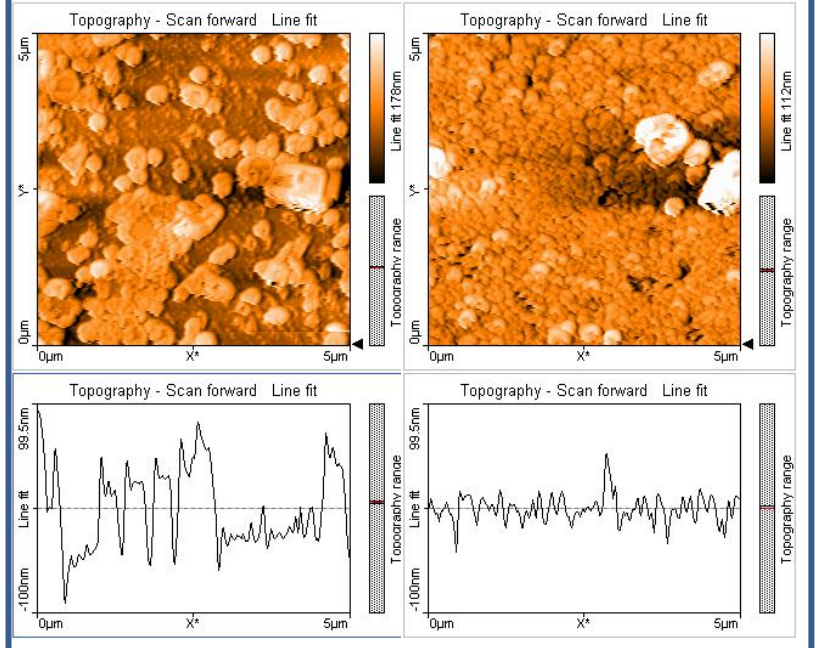
- Dr. Muller moved from Stony Brook University to Brookhaven National Lab.
- Changed Research Partner for STTR from SBU to BNL (approved by DOE: need subcontract with BNL)
- NCE to October to complete demonstration of ASIC measurements with X-rays
  - Allows additional beamtimes

➢ Funds remaining for RI: Covid de-phased efforts

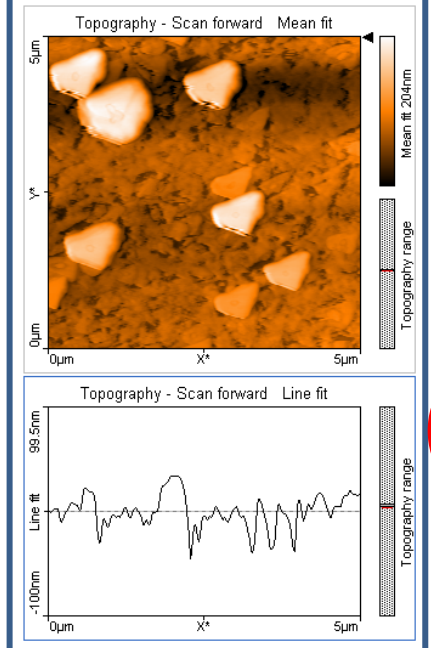
STM Comparison – BNL/SBU results



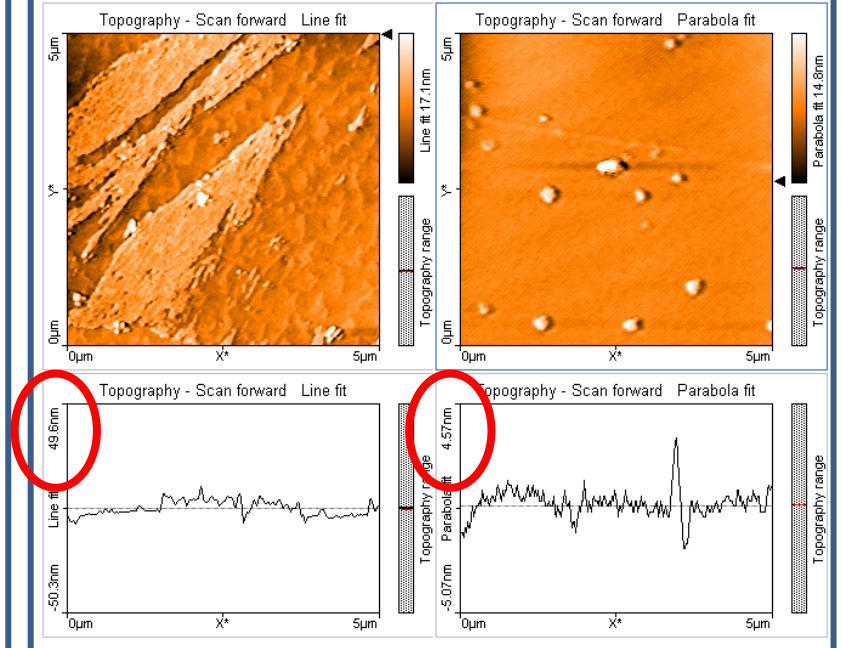
- UHP ~200 µm thick



- UHP ~80 µm thick



- E6 Poly 100 µm thick
- 5 mm x 5 mm



- E6 Poly 100 µm thick
- 1 cm x 1 cm