Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

# Diamond is a Beam's Best Friend

John Smedley
Brookhaven National Laboratory

Diamond x-ray sensors
Transparent x-ray camera
Sensors for radiation therapy

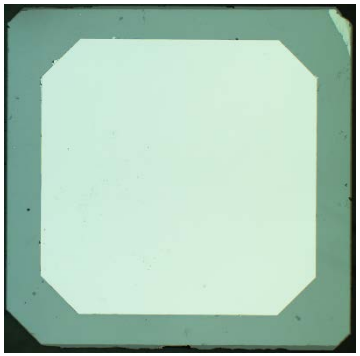
# Diamond as an X-ray Sensor

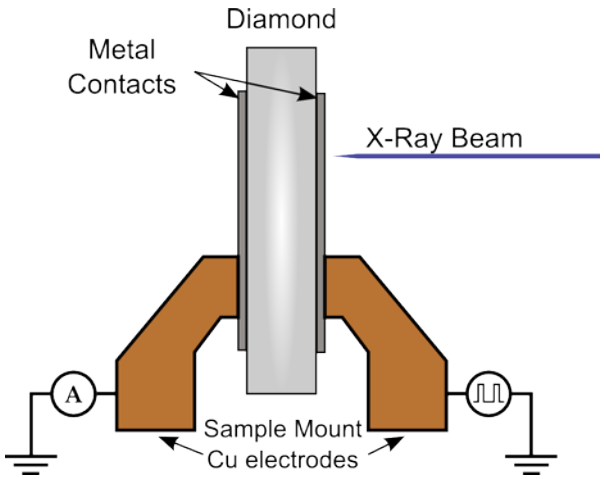
**Diamond Advantages:**

- Low X-ray Absorption
- High Thermal Conductivity
- Mechanical Strength
- Radiation Hardness
- Indirect bandgap

**Sample Information:**

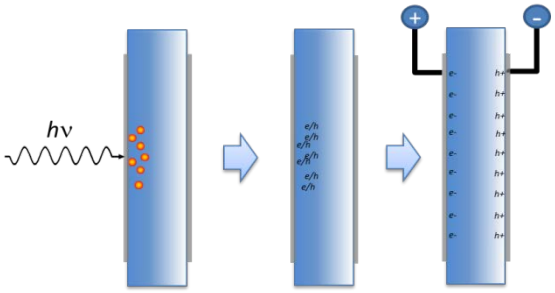
- Electrical grade CVD single crystal diamond
- (100) surface orientation
- ~1 ppb nitrogen impurity
- Typical size: 4mm x 4mm x 50µm





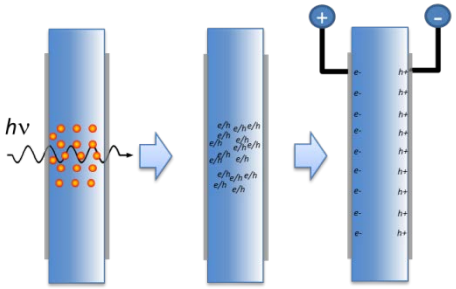

**X-ray generated charge carriers**

Low energy x-ray



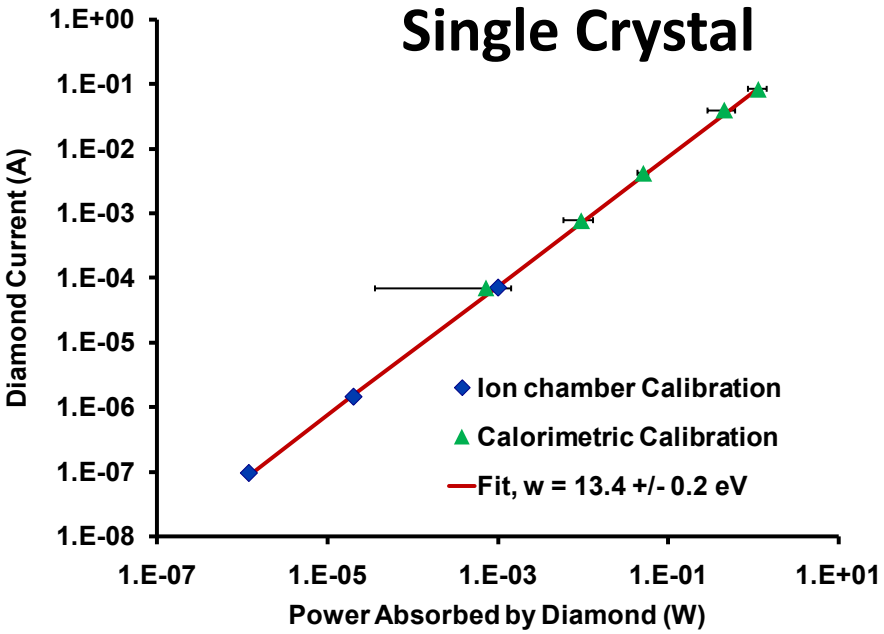

Electron hole pairs created near incident electrode: must move entire thickness of the diamond

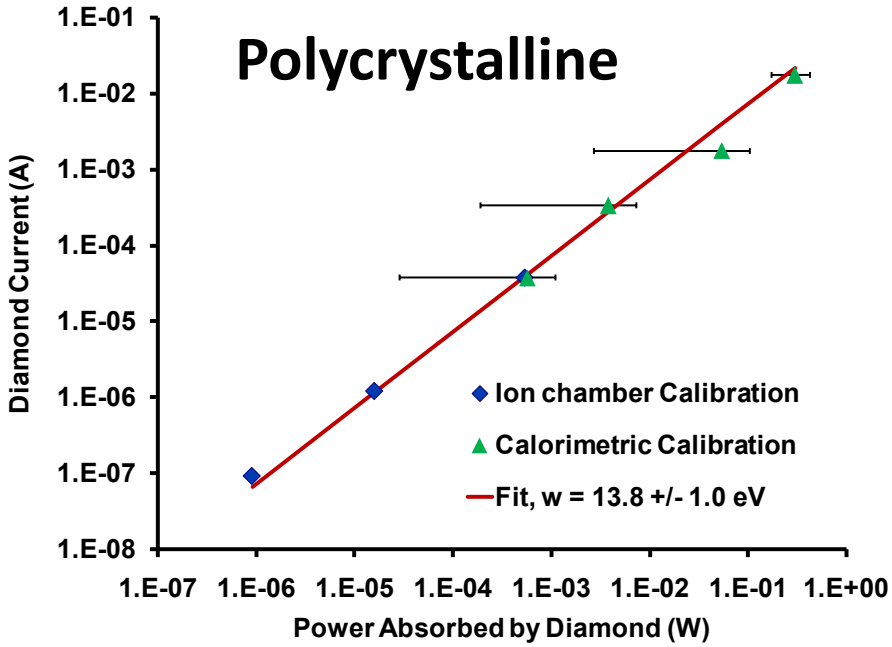
High energy x-ray



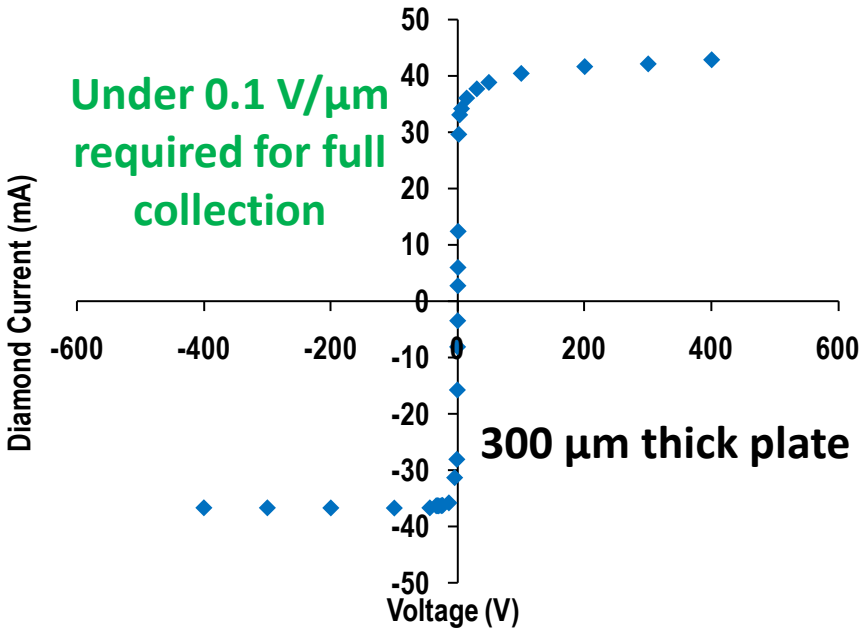

Electron hole pairs created throughout the thickness creating a column of electron-hole pairs

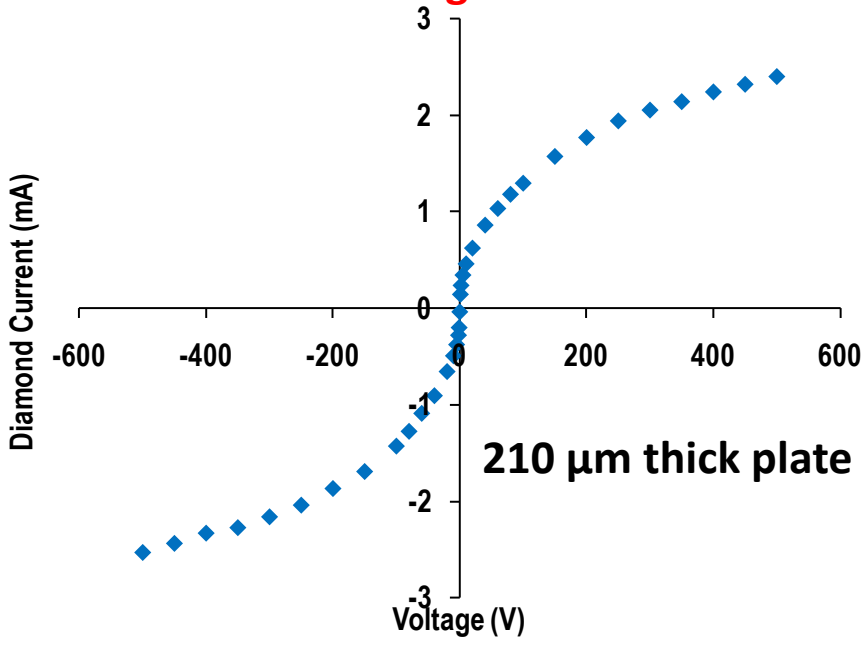
# Response vs Flux and Bias



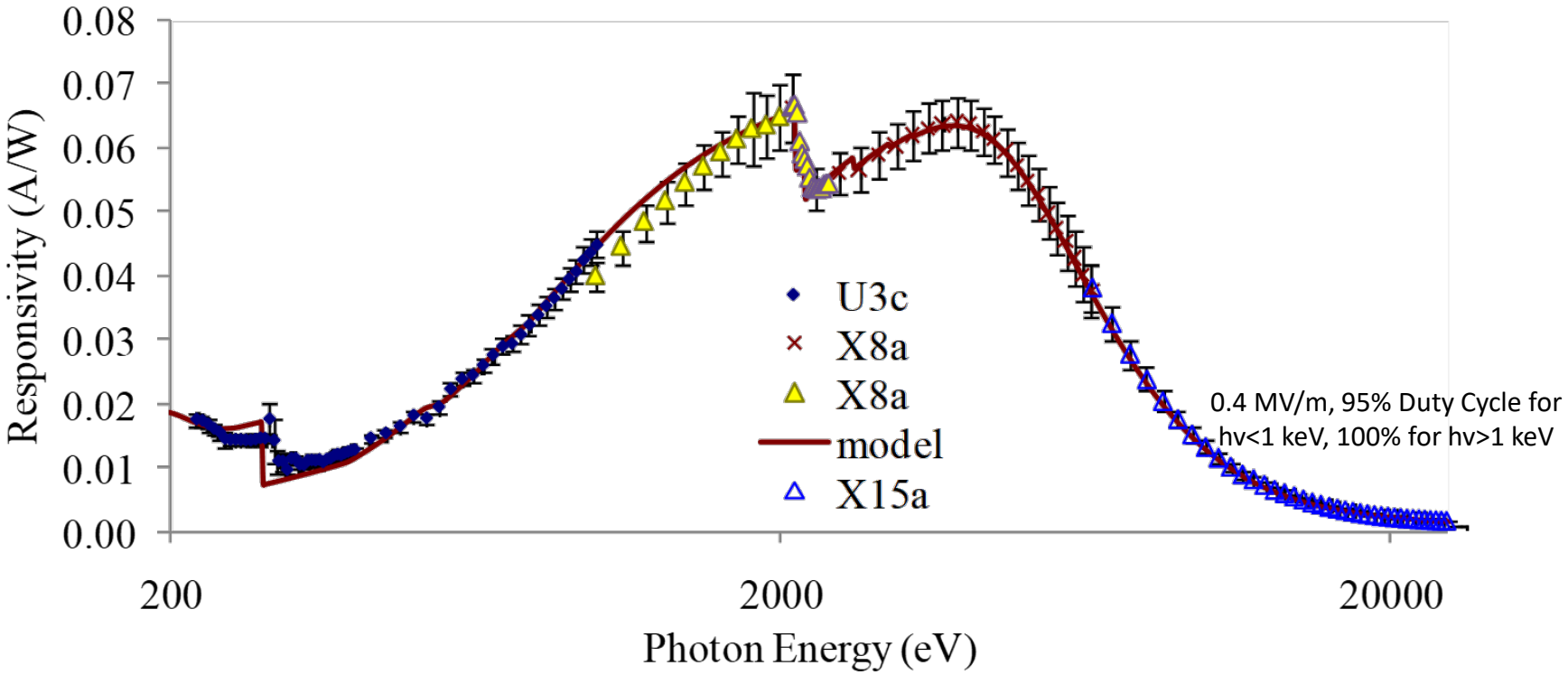

**Response to incident flux linear over 11 orders of magnitude**



# Responsivity vs Photon Energy

$$S = \frac{1}{w} e^{-t_{metal}/\lambda_{metal}} \left(1 - e^{-t_{dia}/\lambda_{dia}}\right) CE[v, F]$$




E.M. Muller et al, Appl. Phys. Lett. **104**, 093515 (2014)
J. Keister and J. Smedley, NIM A **606**, (2009), 774

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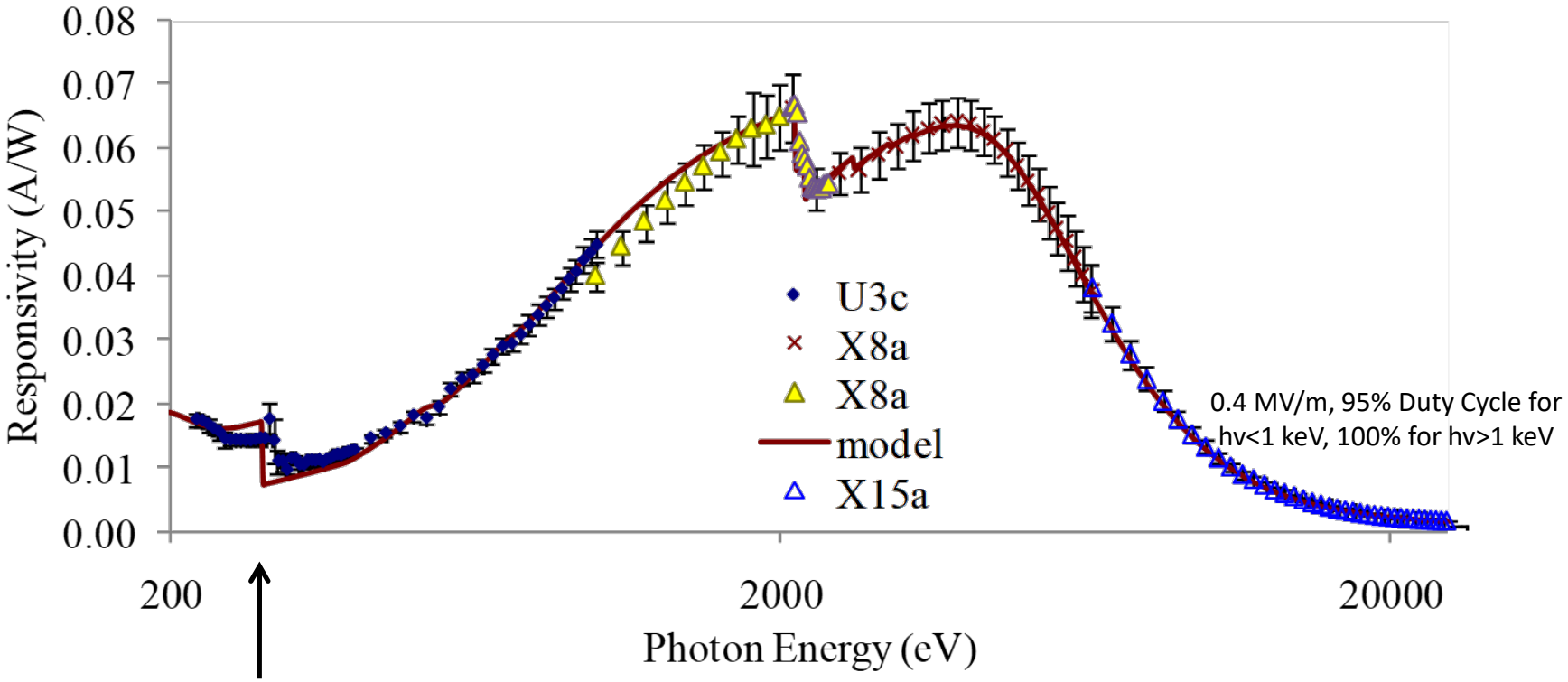


C K edge feature is field dependent, caused by incomplete carrier collection for carriers produced near incident electrode – electrons diffuse into incident contact and are lost

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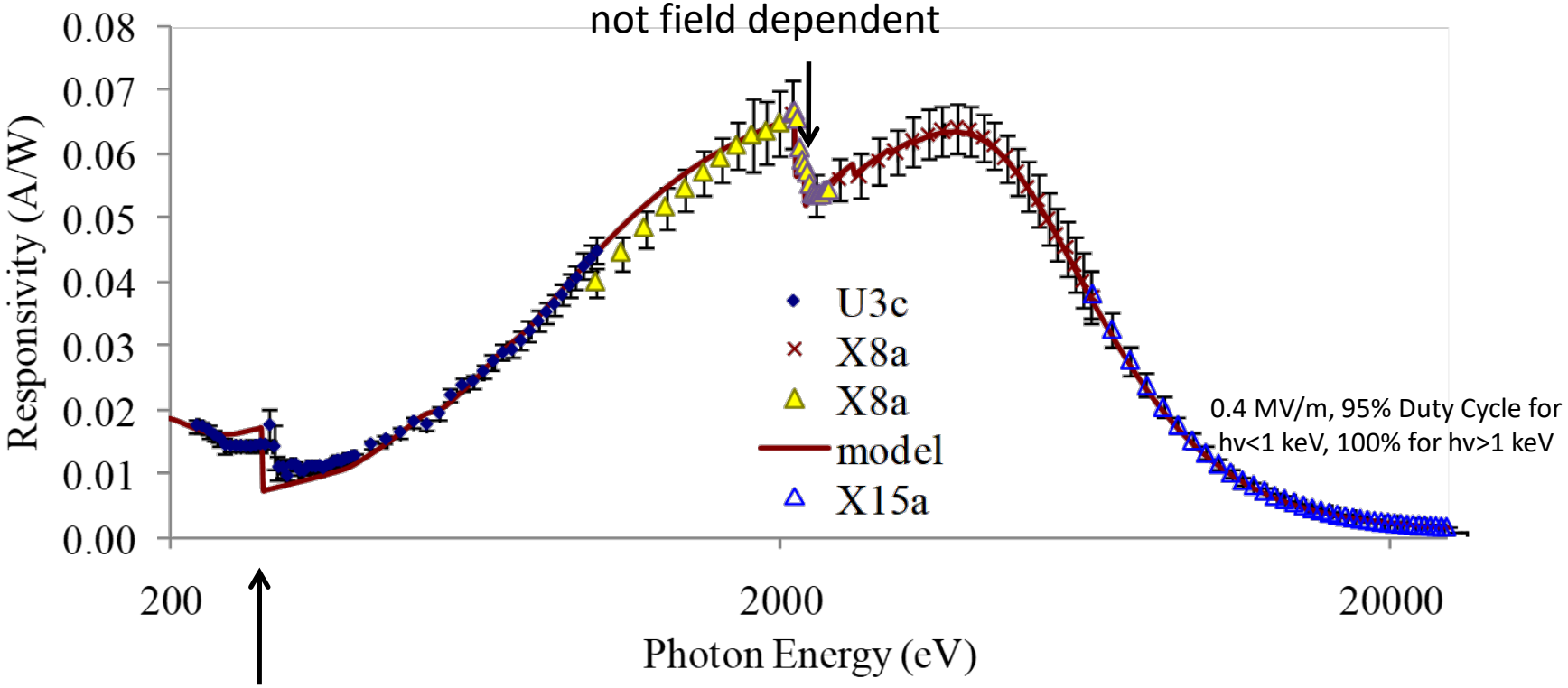


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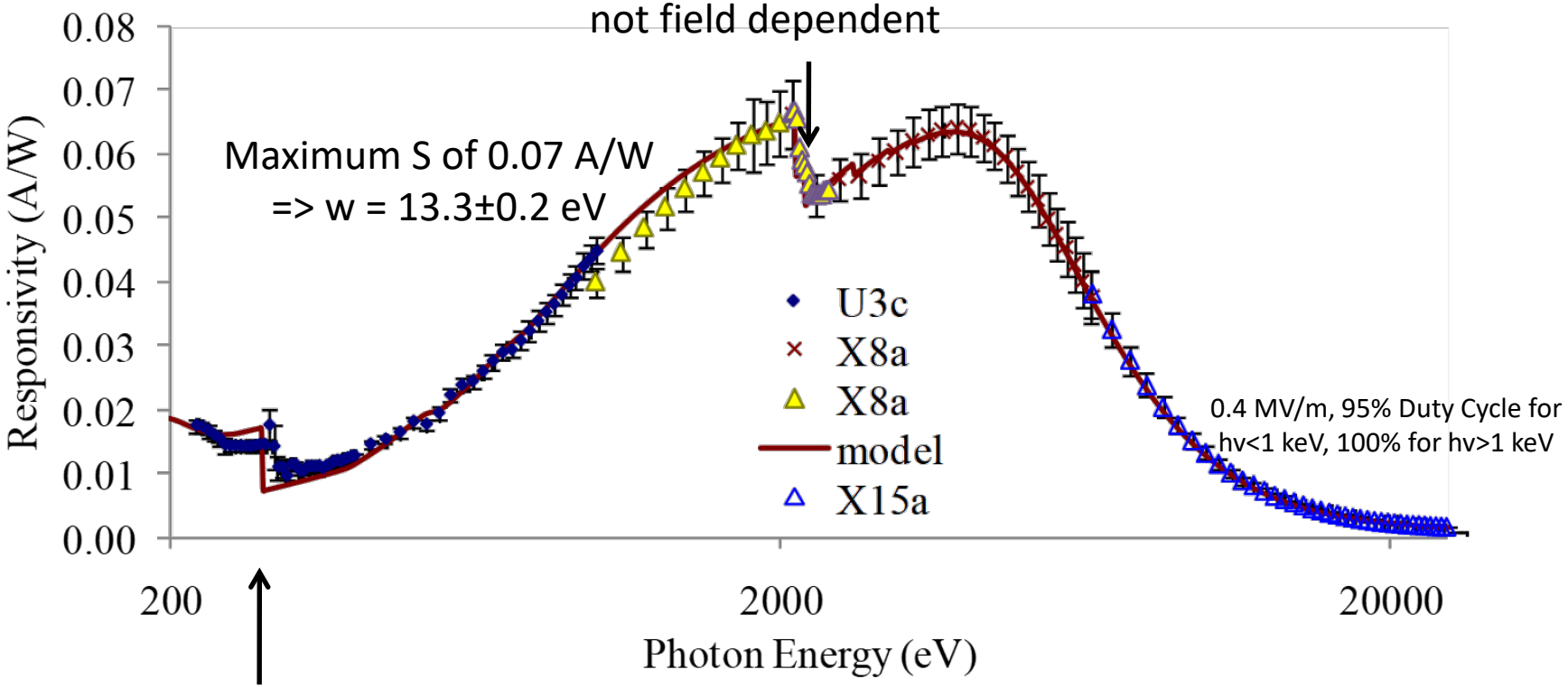


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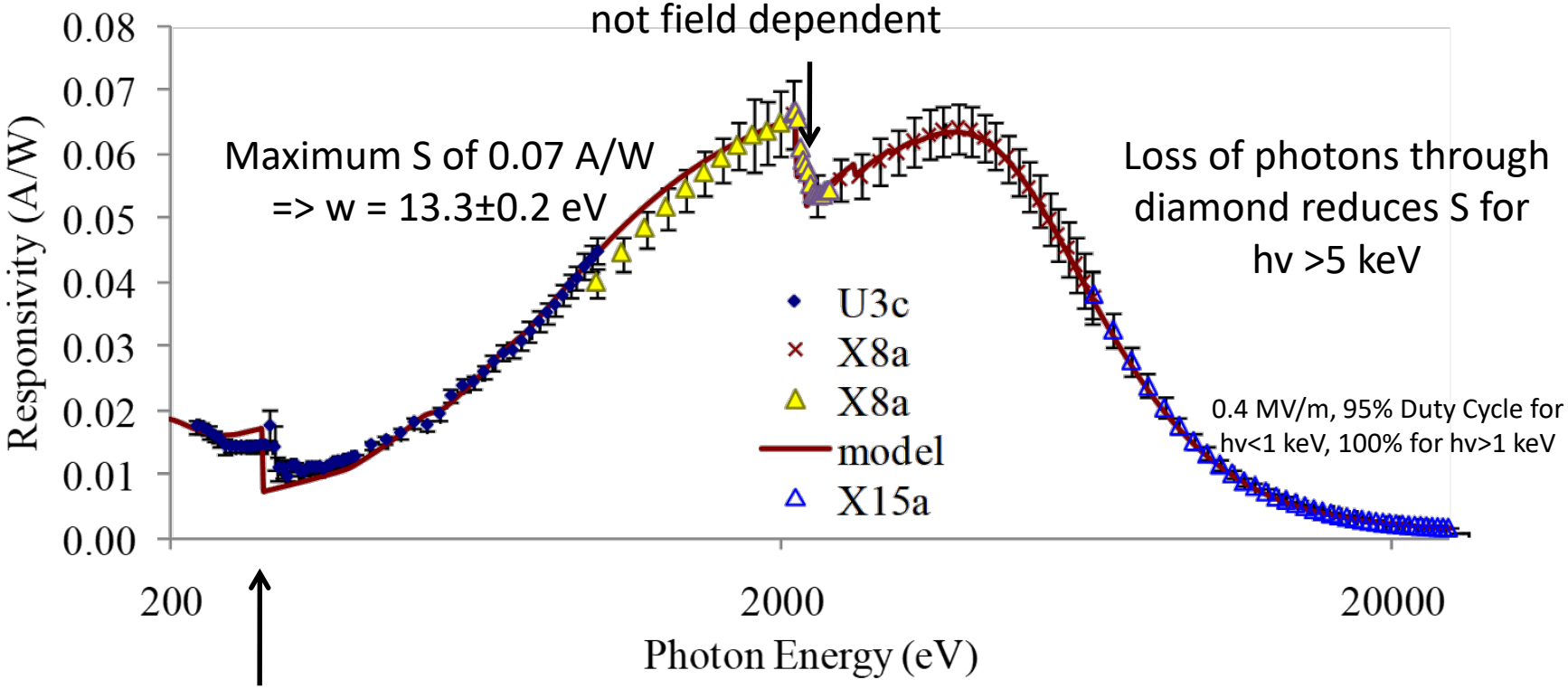


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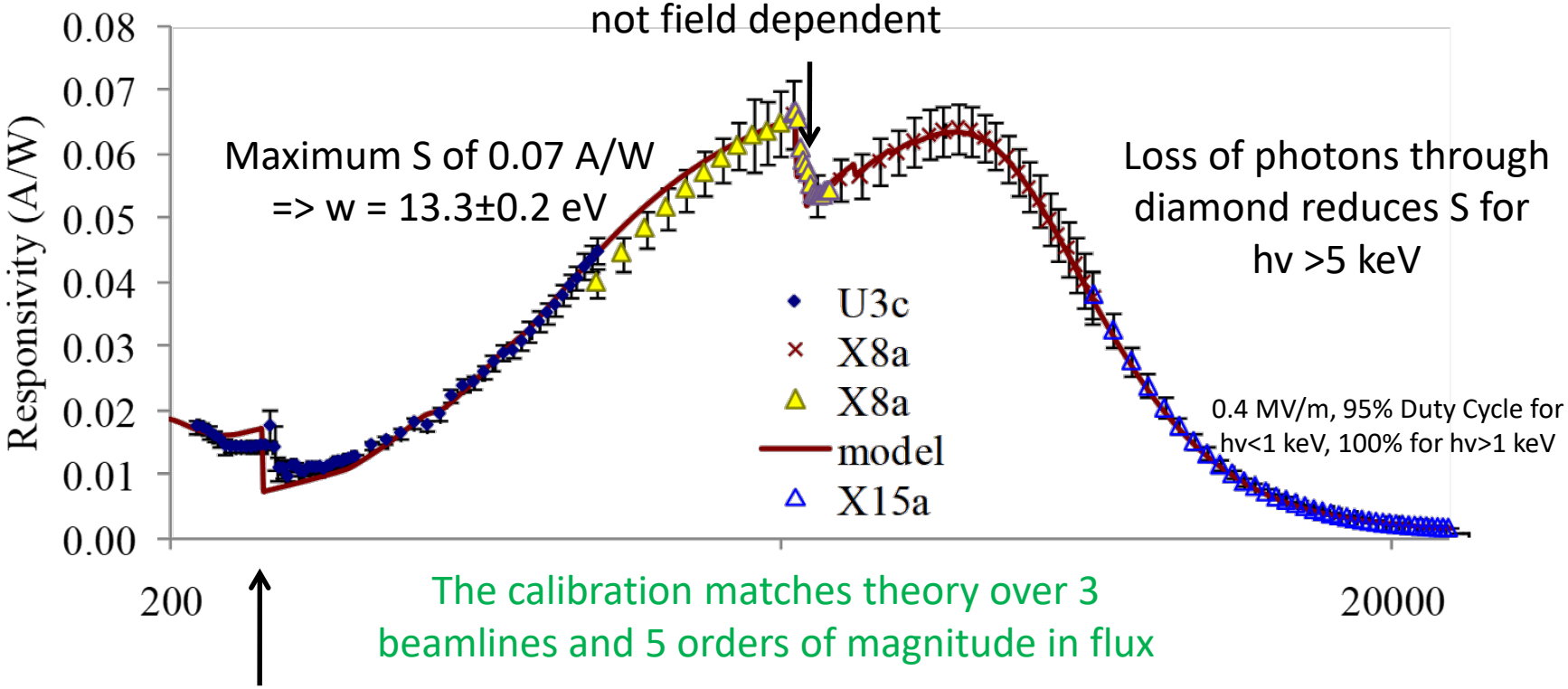


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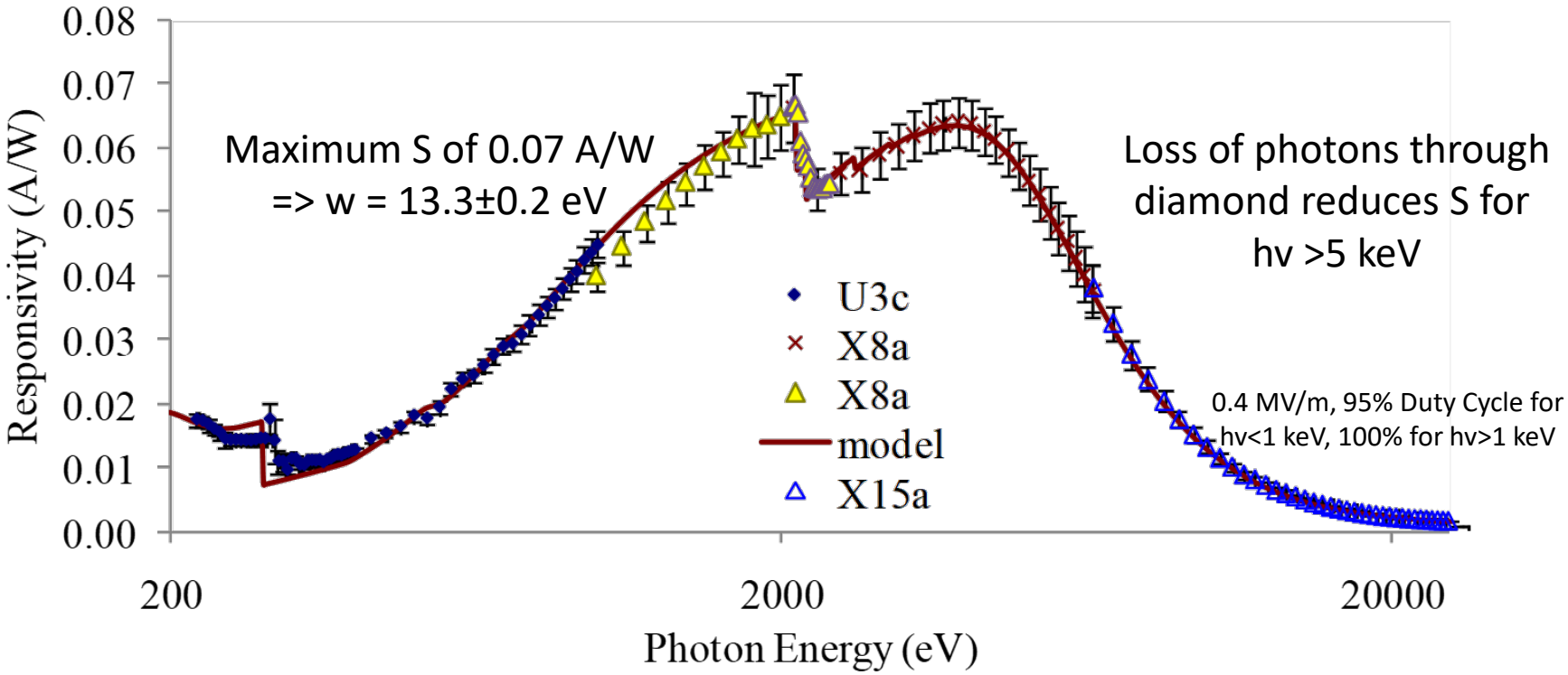
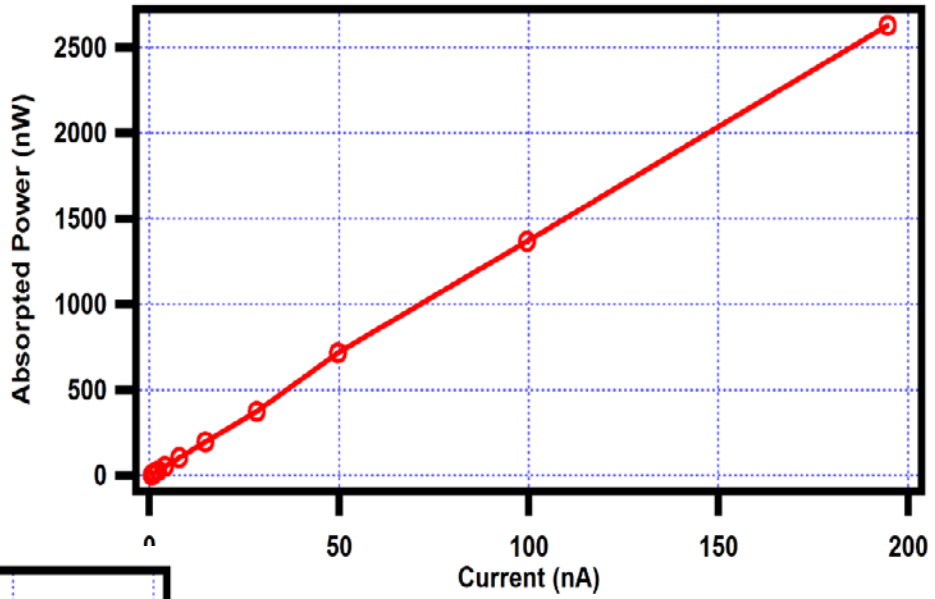
# Kinda Useless at High Energy, Right?



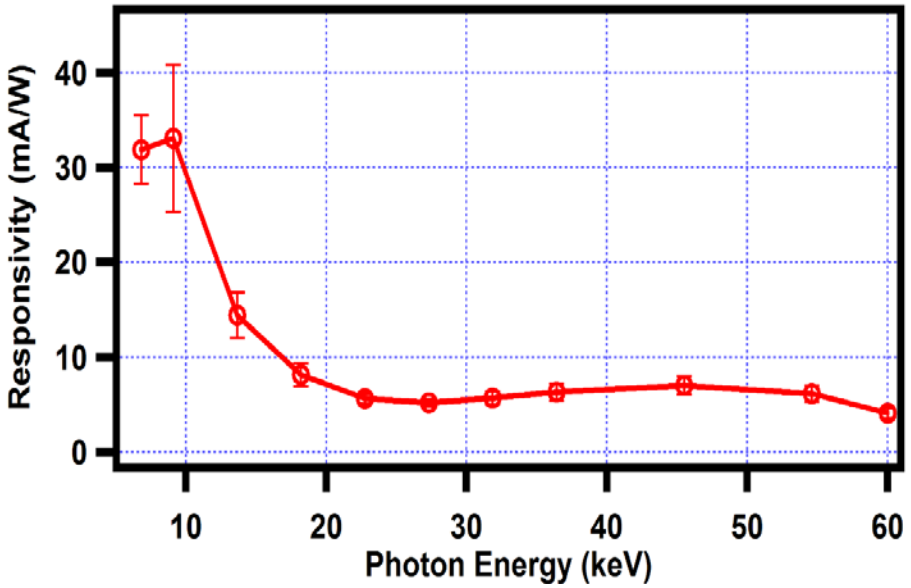
# Compton Regime

**Actually, above 20 keV, cross section is Compton dominated for carbon**

**Responsivity stabilizes (and actually rises). Compton cross section is independent of Z (though the onset of Compton dominated regime is Z dependent)**




Linearity at XPD at NSLS-II (67 keV)



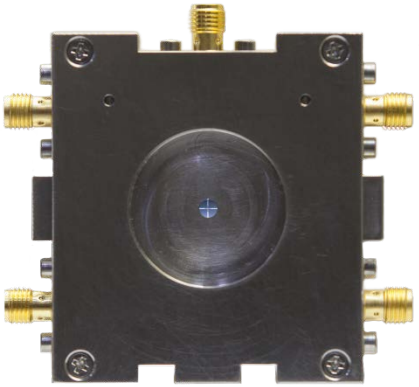

Diamond responsivity data between 6.8-60 keV @A2

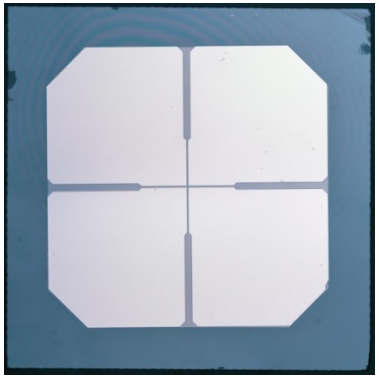
**Beam monitoring (pulse to pulse variation) should be possible**

**Also, a "Compton spectrometer" may be possible – tagging a photon in diamond and on a second detector. Measuring energy deposited in diamond and angle is sufficient to know photon energy.**

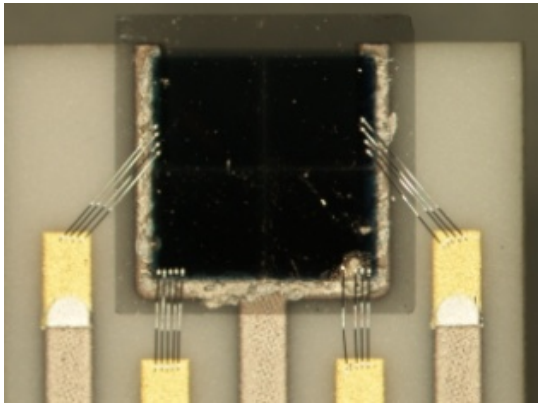
# Diamond Beam Position Monitors

Circuit Board Mounted
- Pt metallization
- wire-bonded electrodes
- SMA/LEMO connectors





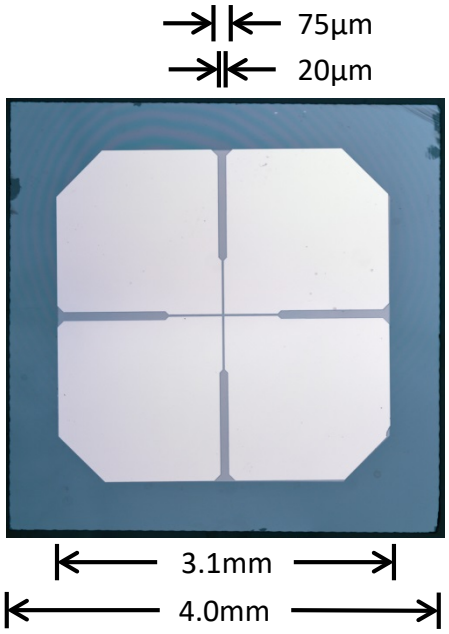
Application specific –
X-Ray fluorescence,
microEXAFS
- Ag diamond metallization
- Ceramic board
- Single channel detector designed for use with polycapillary



White BPM (X25)
- Mini-gap undulator
- ~100W incident power
- Large beam

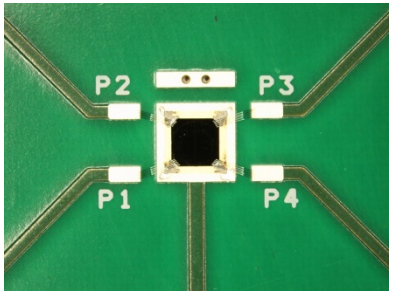
# Fabrication

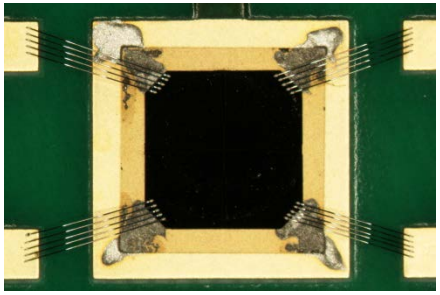
## Lithography @ CFN

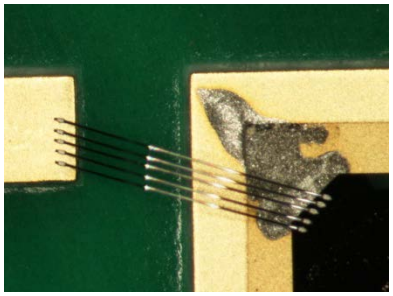



Electronic grade single crystal
(100) diamond
30-50 µm thick
20 µm street over a 1mm center region
Metalization: 25 nm Pt

## Wire Bonding - Instrumentation





25 µm aluminum wirebonds
5 bonds per pad
Conductive epoxy for backside/bias contacts

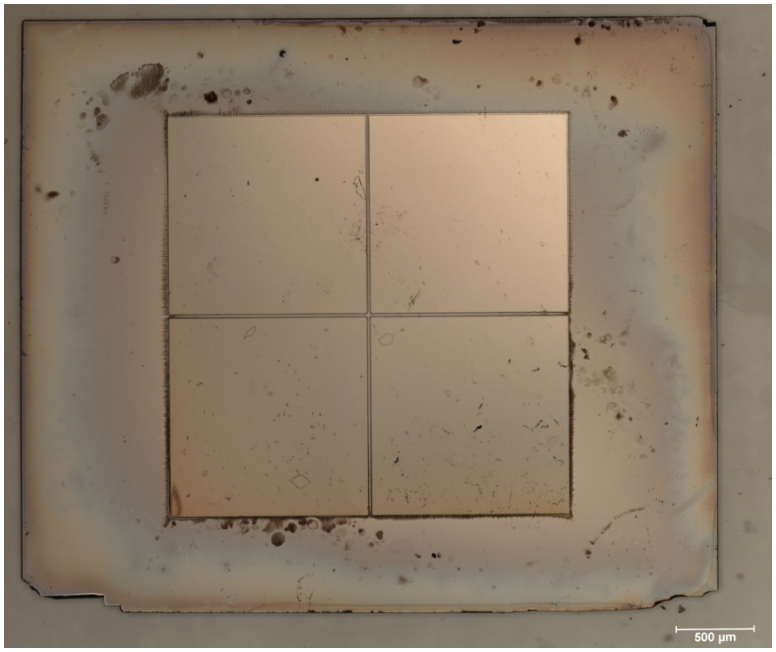
## Topography – NSLS/CHESS

White beam topography
Prior to slicing

# New Fabrication Tools

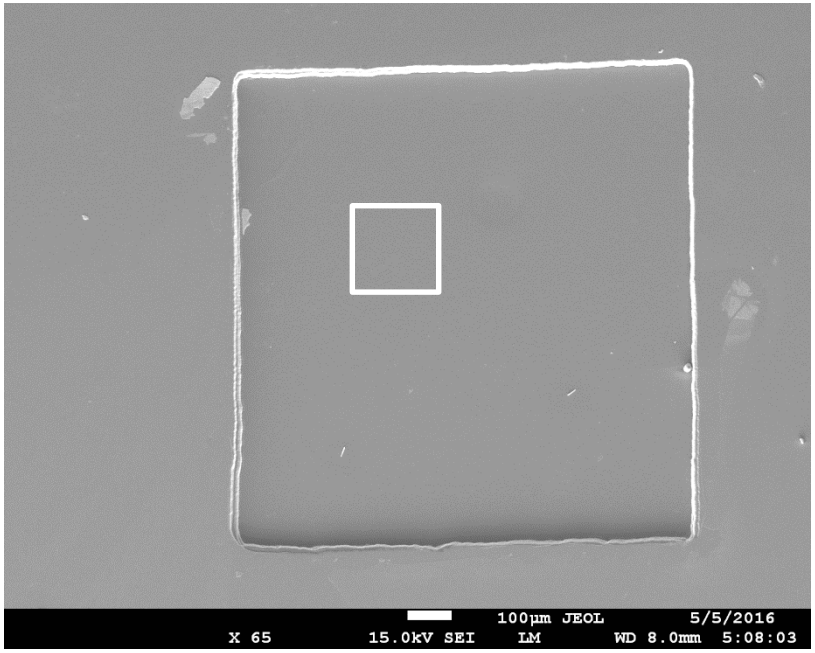
## Patterned UNCD Contacts

- Diamond Contacts – no longer the weakest link
- No fluorescent lines




## RIE ultrathin layers

- 4 µm membranes
- Transmits 2 keV photons
- Potentially much faster response
- 4 devices in use at SMI



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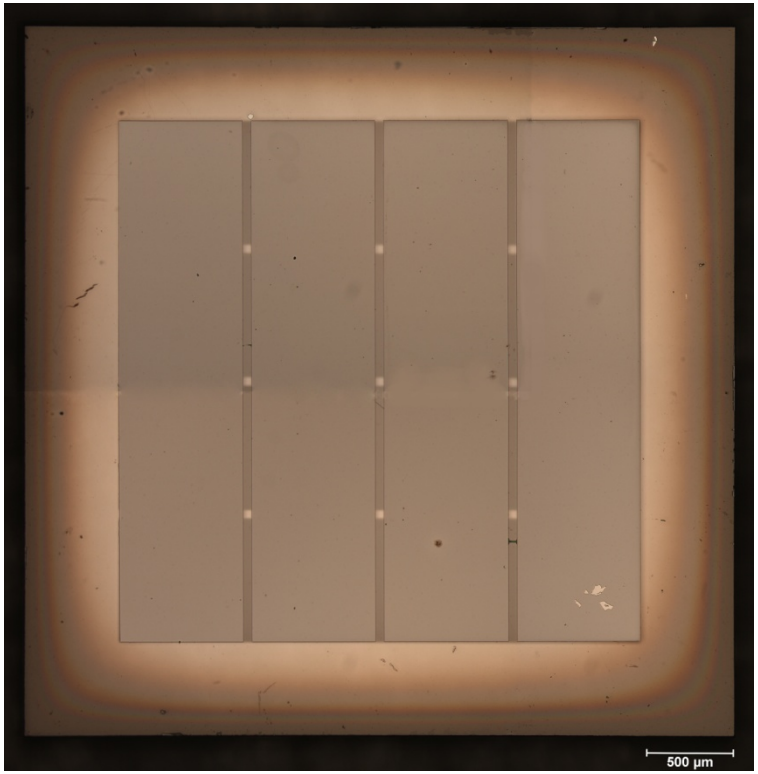


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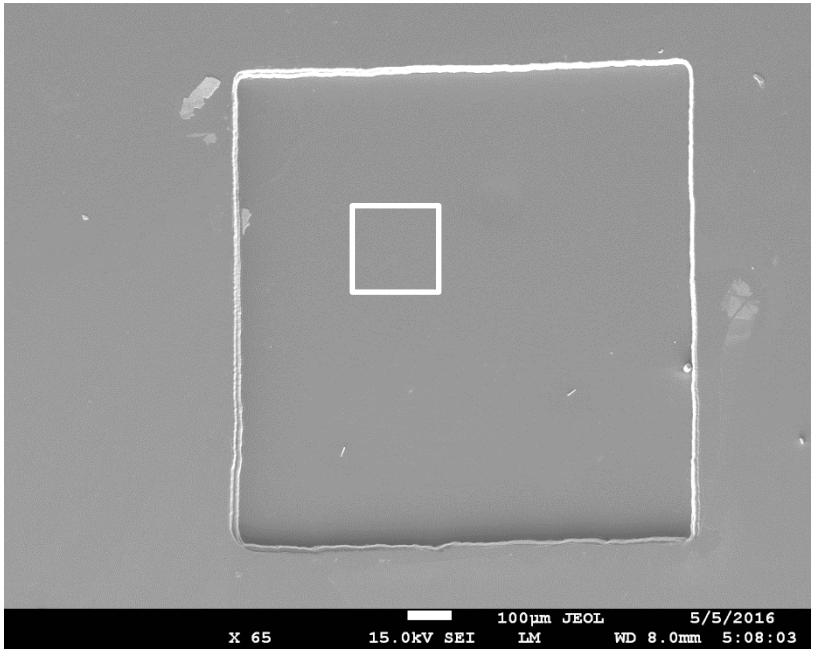

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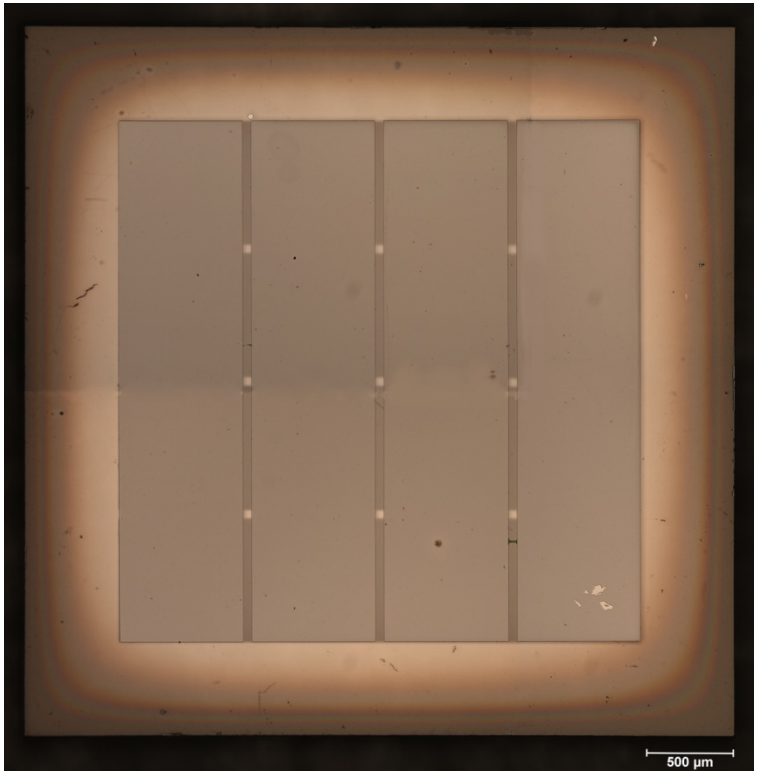


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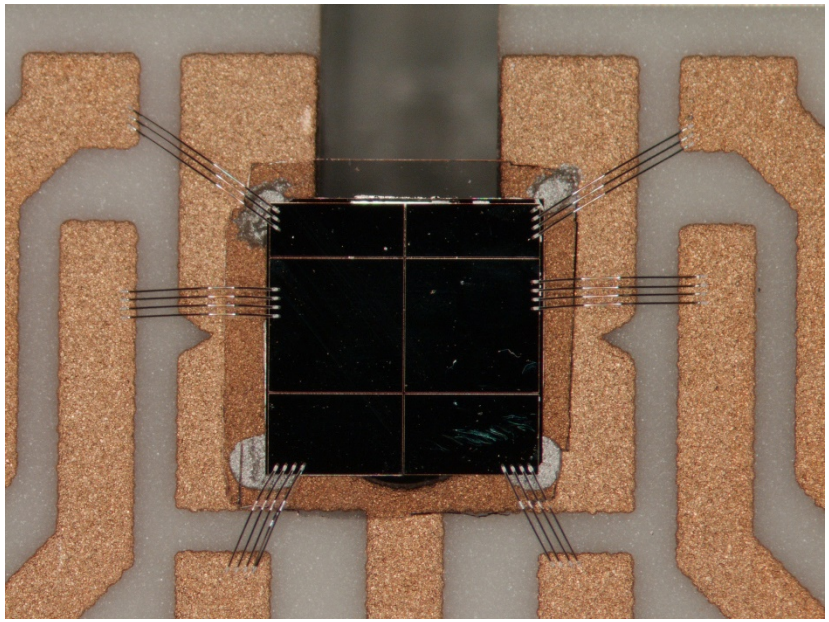

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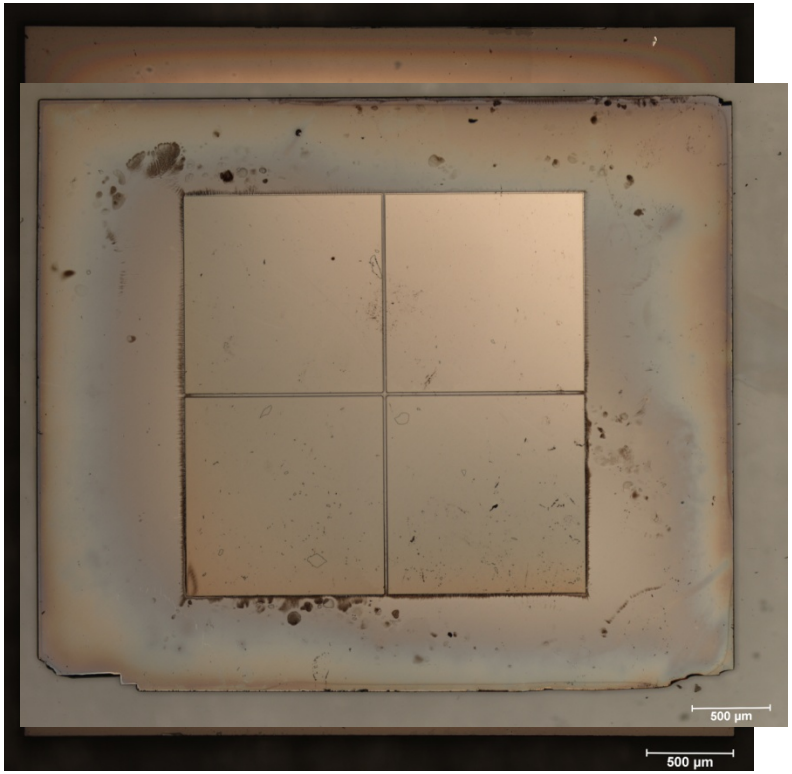


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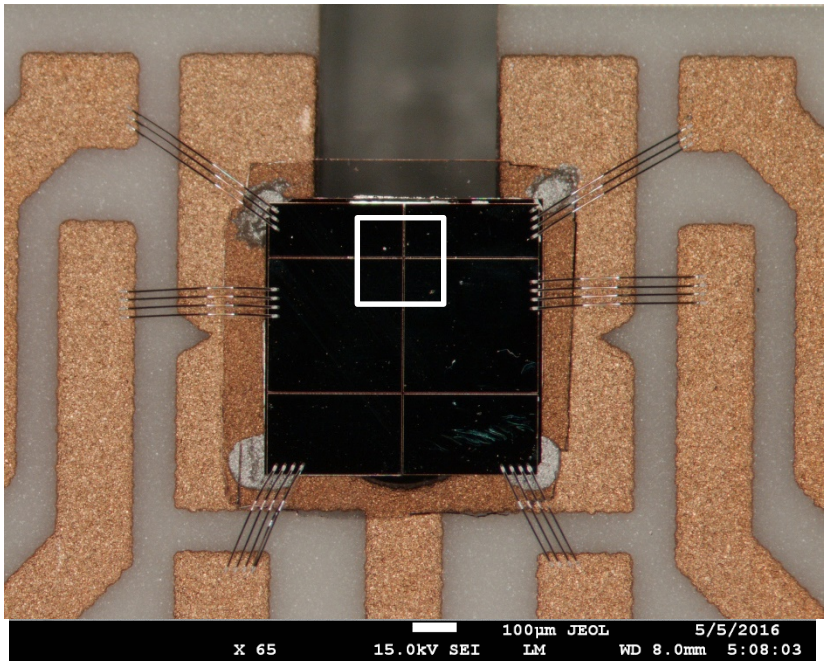
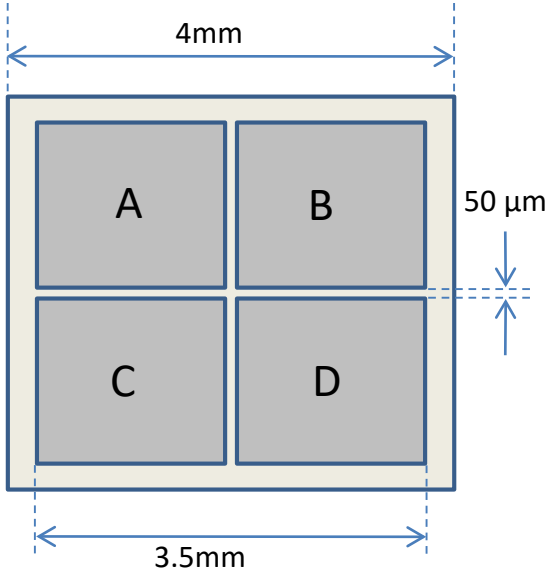
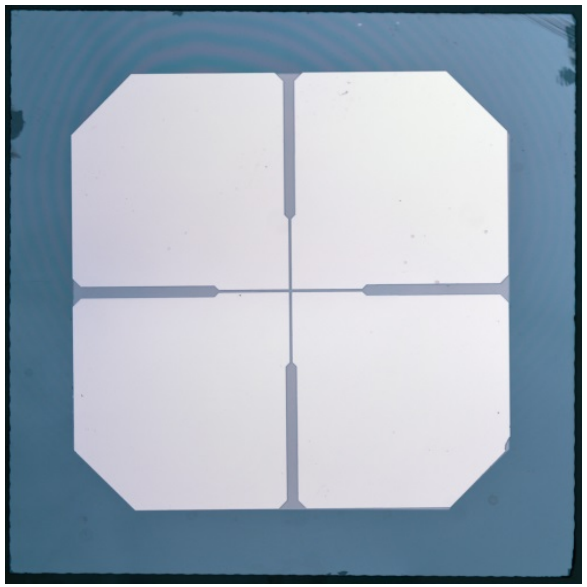
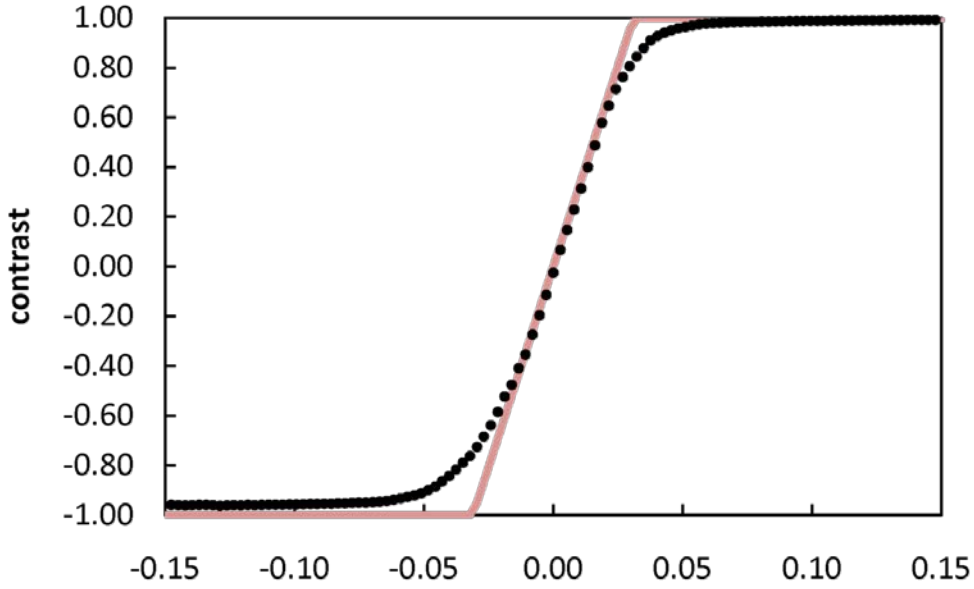


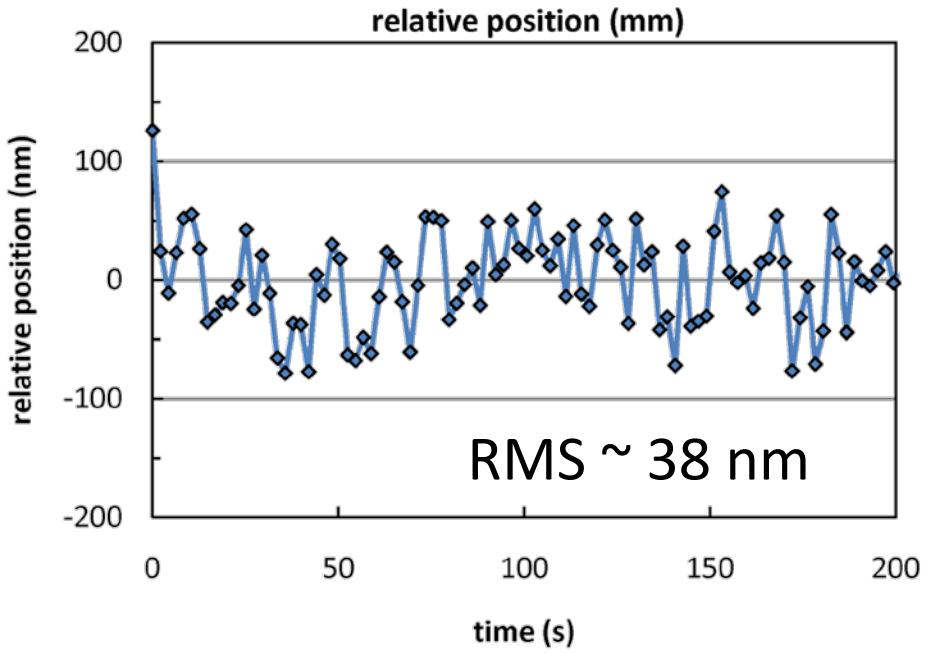
# Beam Position Monitors



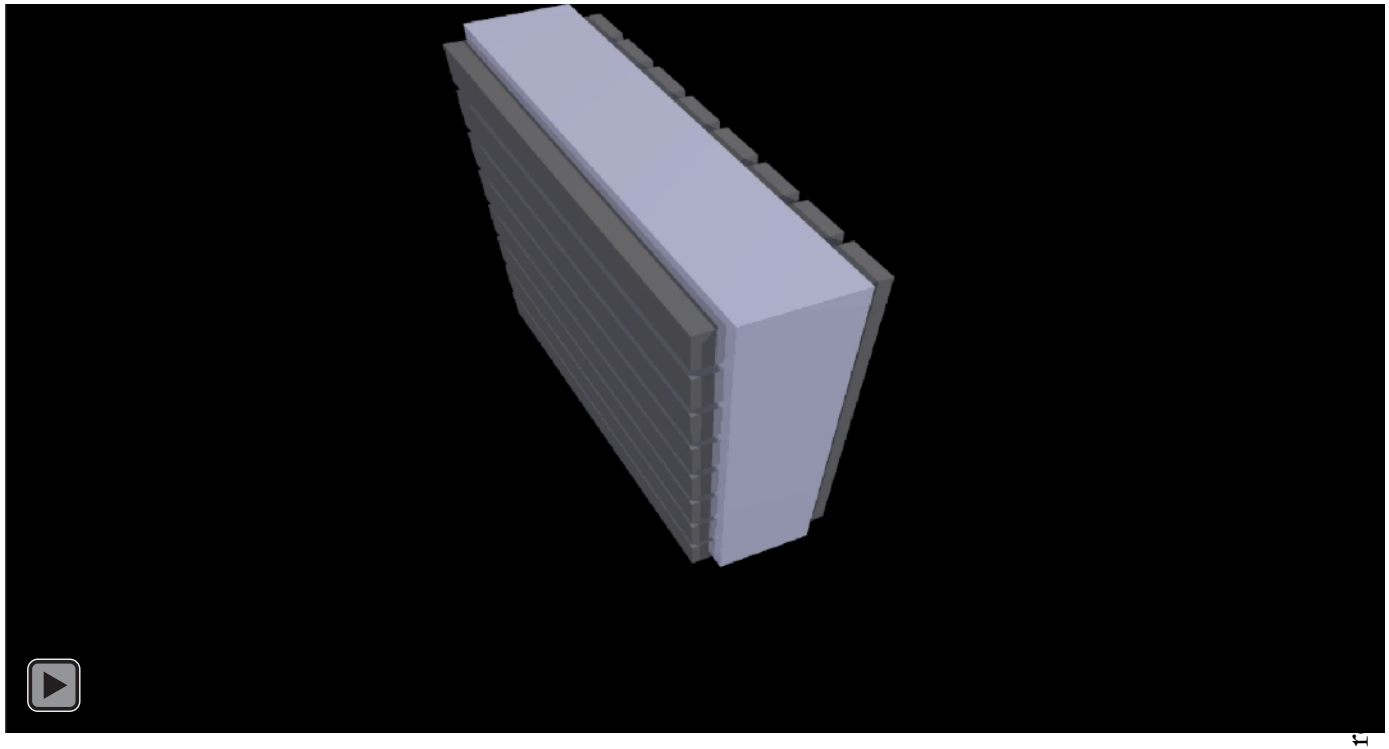

$$X = G_x \frac{(I_B + I_D) - (I_A + I_C)}{I_A + I_B + I_C + I_D}$$





# Pixelated Diamond Window



Pixels are created by metalizing one side of the diamond with horizontal stripes and the other with vertical stripes. As the x-rays pass through the diamond, the induced current is collected in each vertical stripe, while the bias is applied to individual stripes on the other side. This bias is cycled, allowing readout of one line of “pixels” at a time.

**Image Readout**

- 32 x 32 stripes, yielding 1024 pixels
- Only one row is active at a time minimizing ohmic heat generation.
- Project goal of real time imaging at 1 Hz, currently at 32 Hz
- Up to ~10mA per pixel
- **FPGA controlled, versatile operating modes**

**Window Fabrication**

- The diamond sensor will be brazed to a stainless steel vacuum flange.
- The diamond and electronic interconnects will be protected by a metal mask.
- Heat dissipation provided by water cooling.

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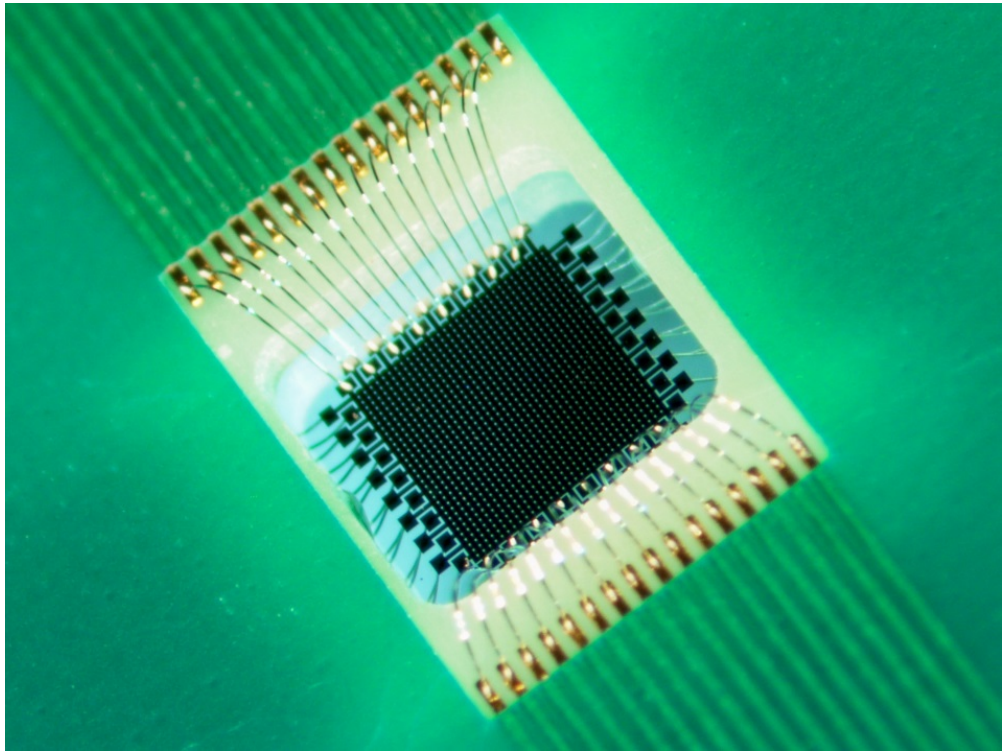

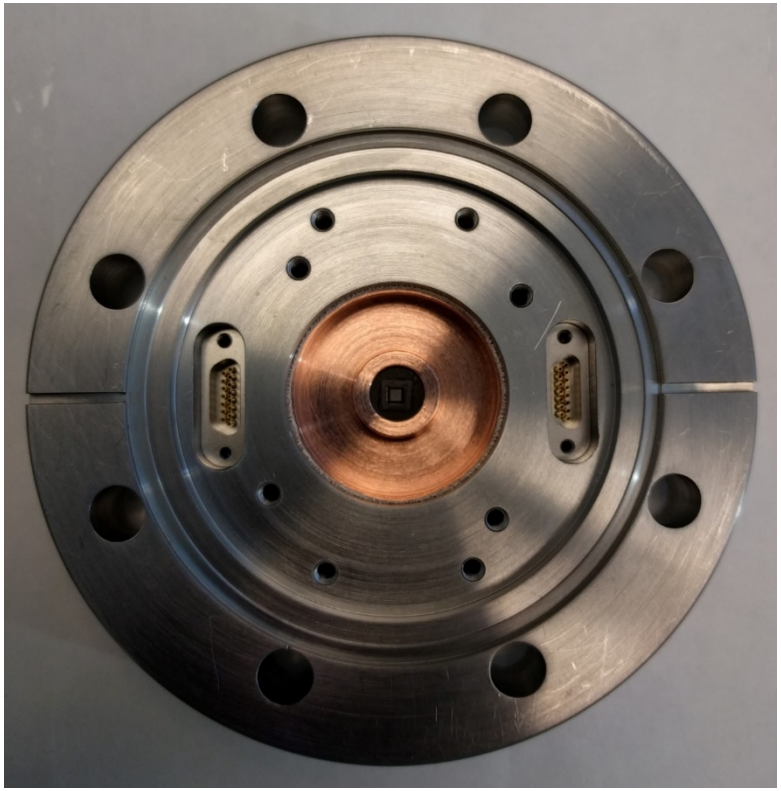

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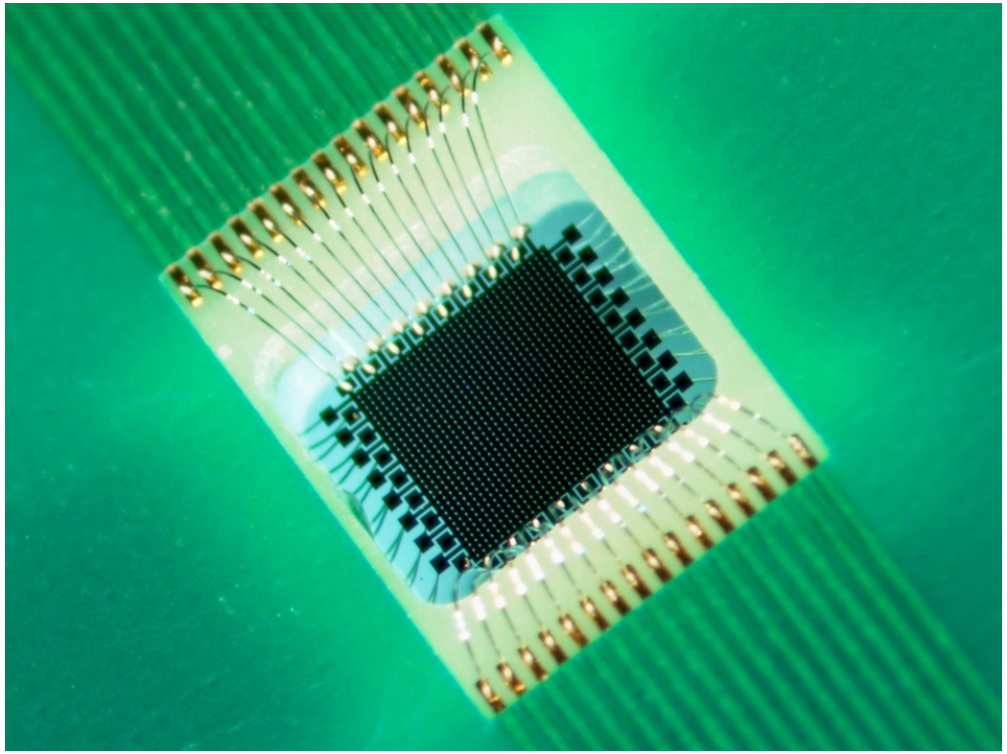

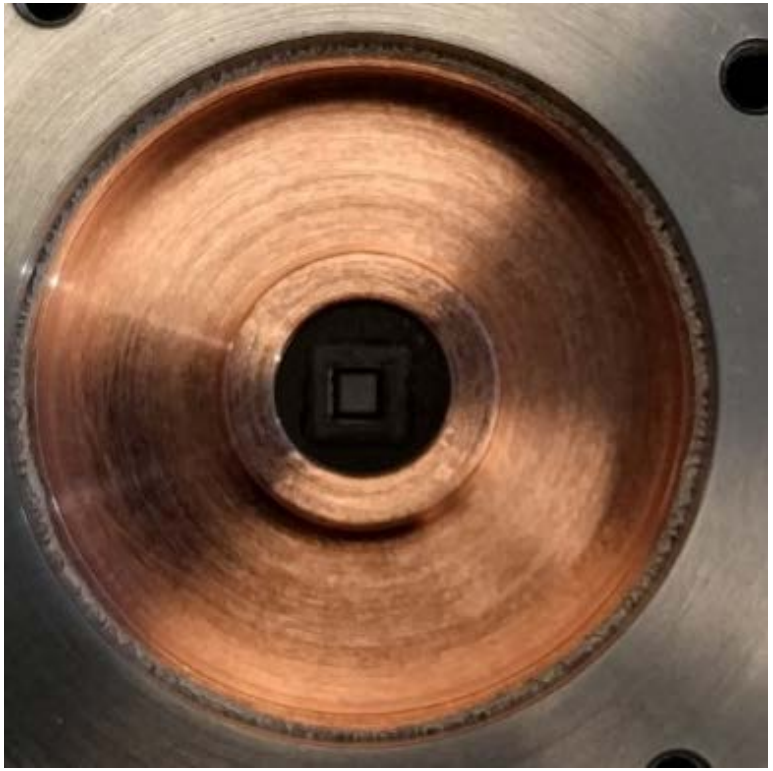

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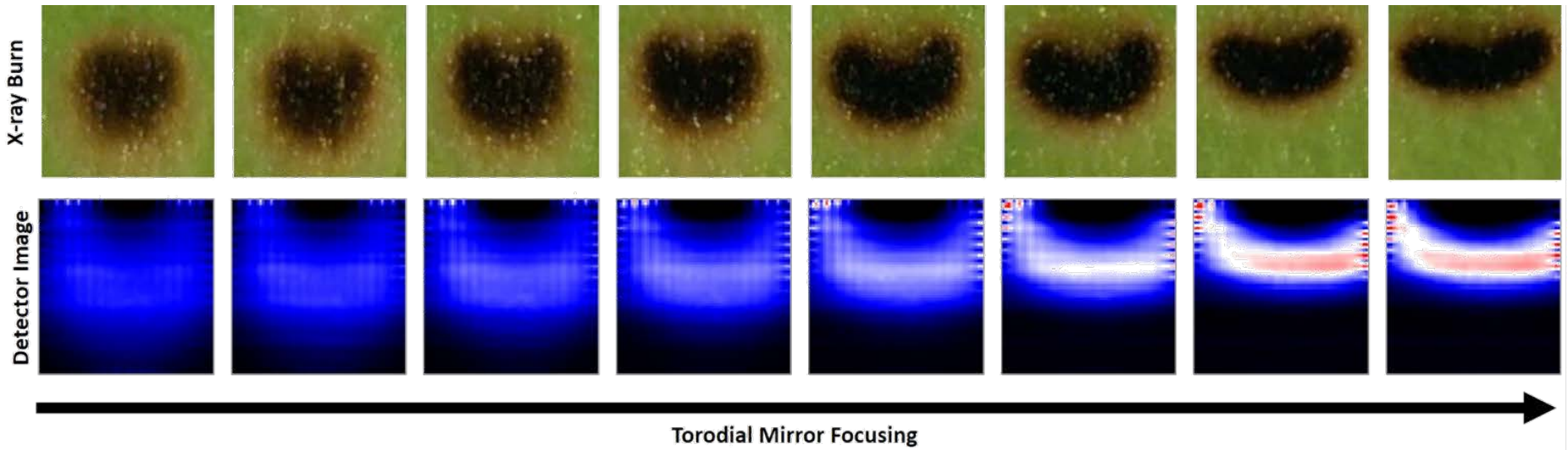
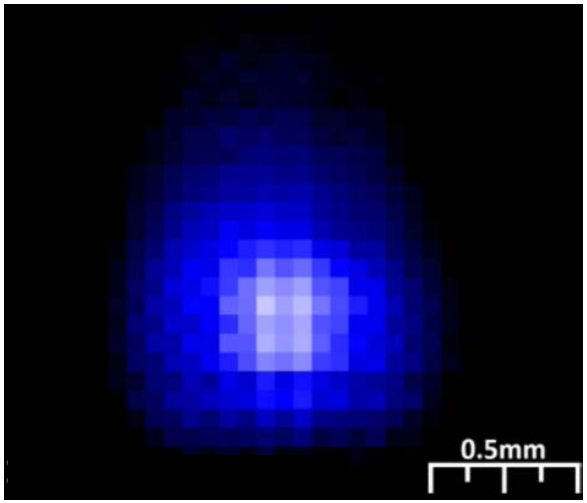
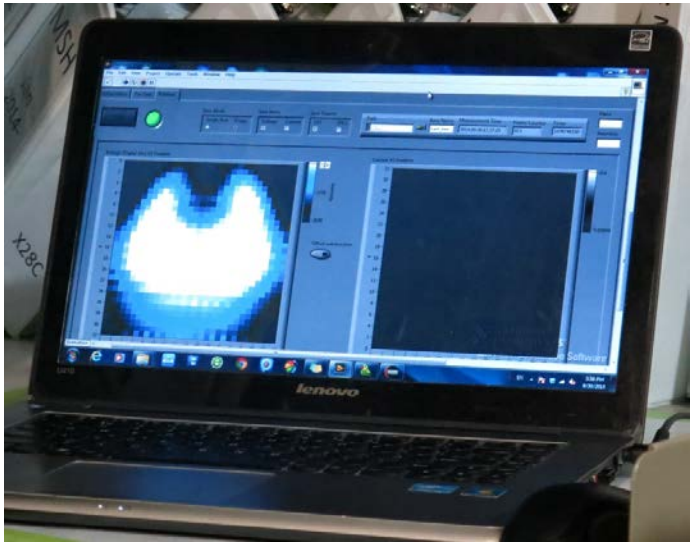
# Beam Imaging



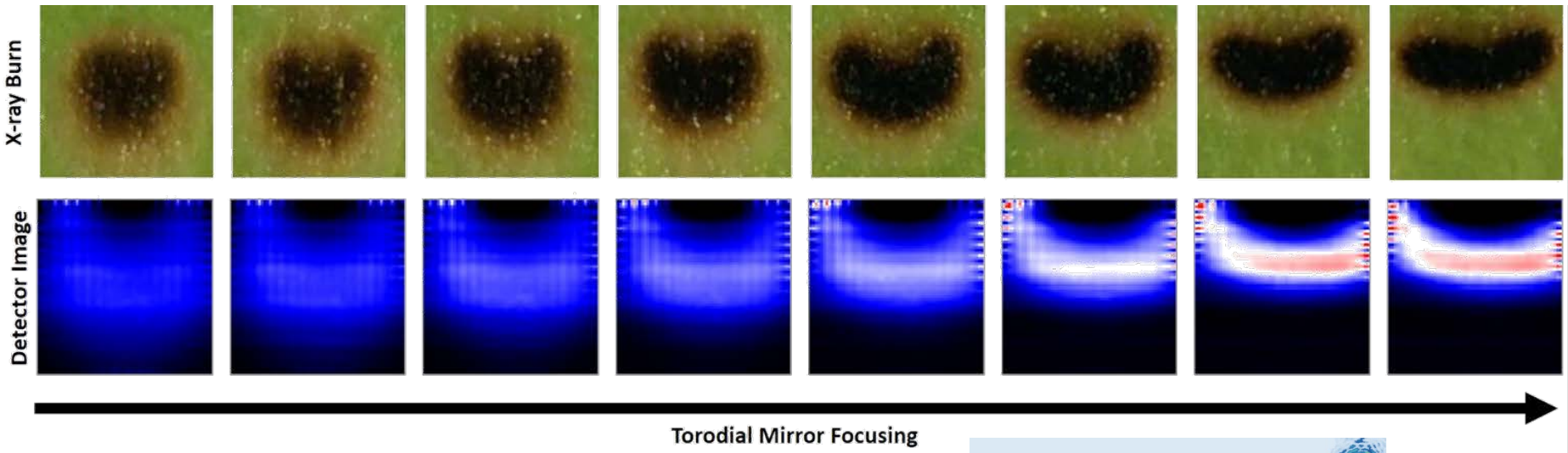




CHESS G3 Beam



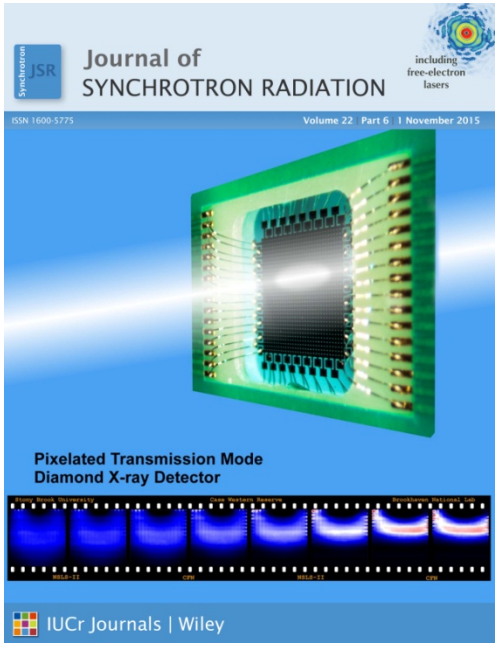

NSLS X28C Beam

# Beam Imaging





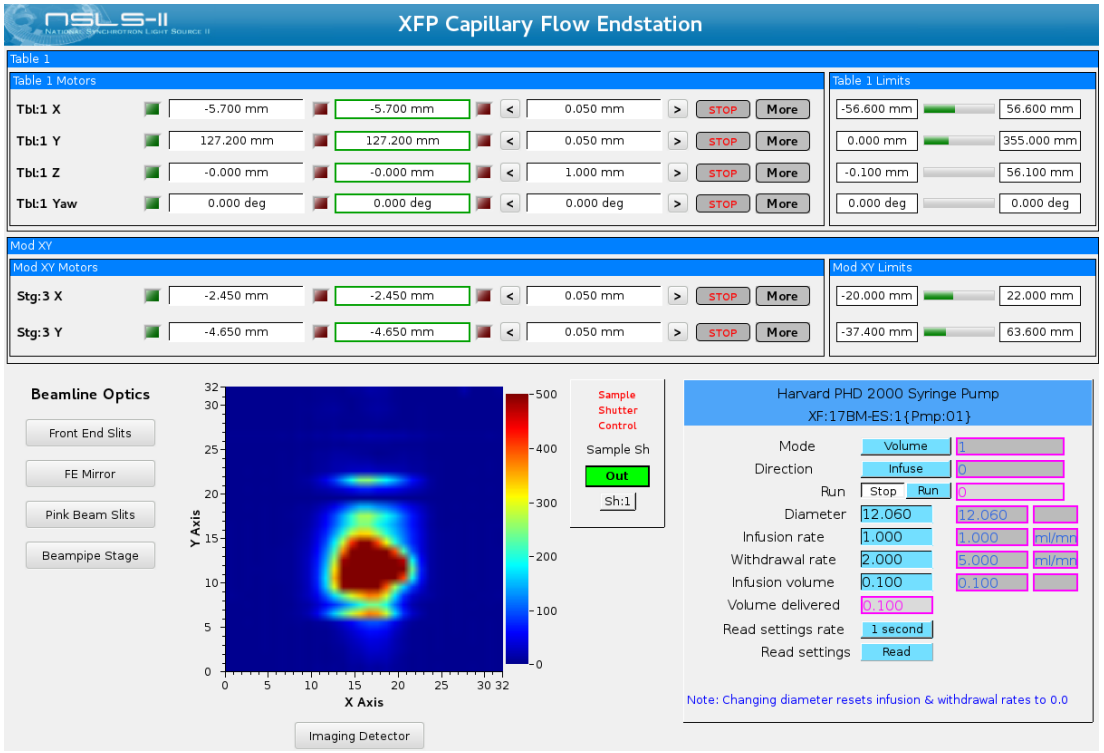
**R&D100 2016 Finalist**



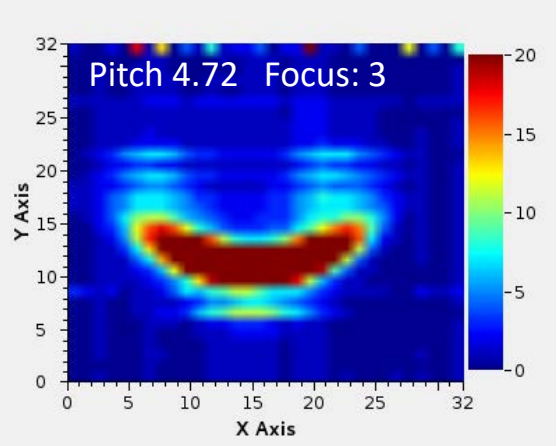

**Zhou et al. (2015) JSR 22 :1396 (cover article)**

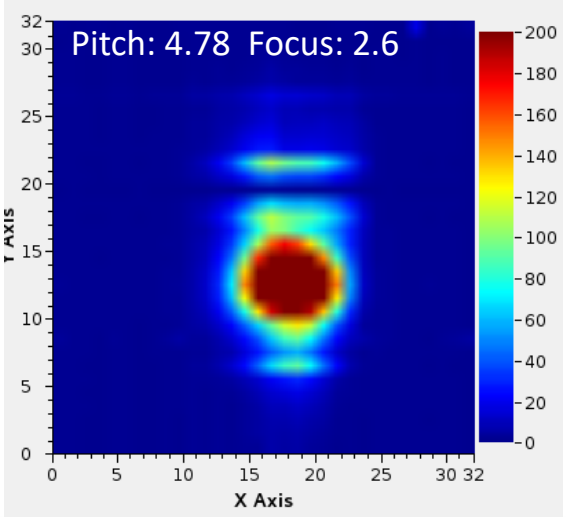
# Imaging Detector at NSLS-II XFP

- **Integrated into XFP Beamline Controls System (EPICS/CSS)**
- **Used to align XFP toroidal focusing mirror (beamline commissioning)**

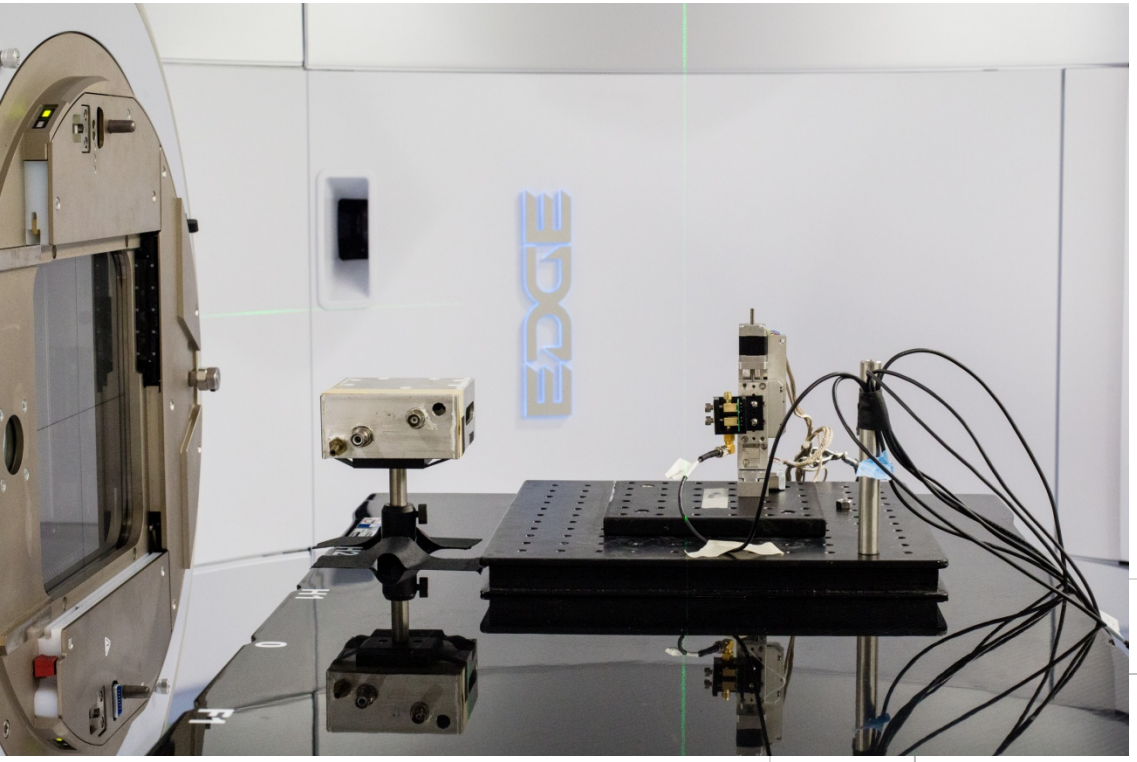


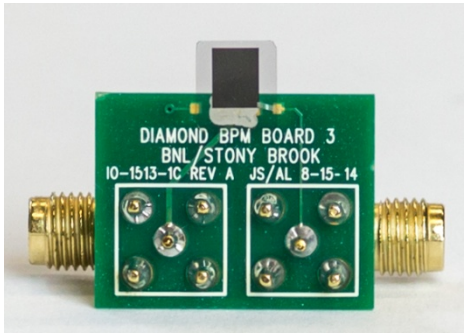

## Beam Images at Different Mirror Settings



# Gamma Ray Therapy

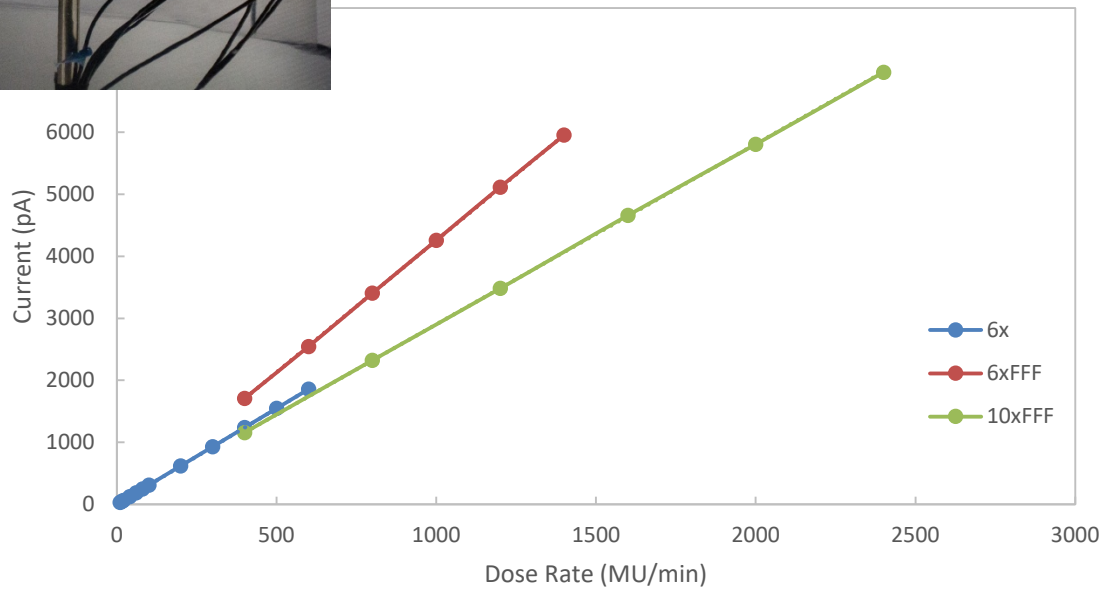


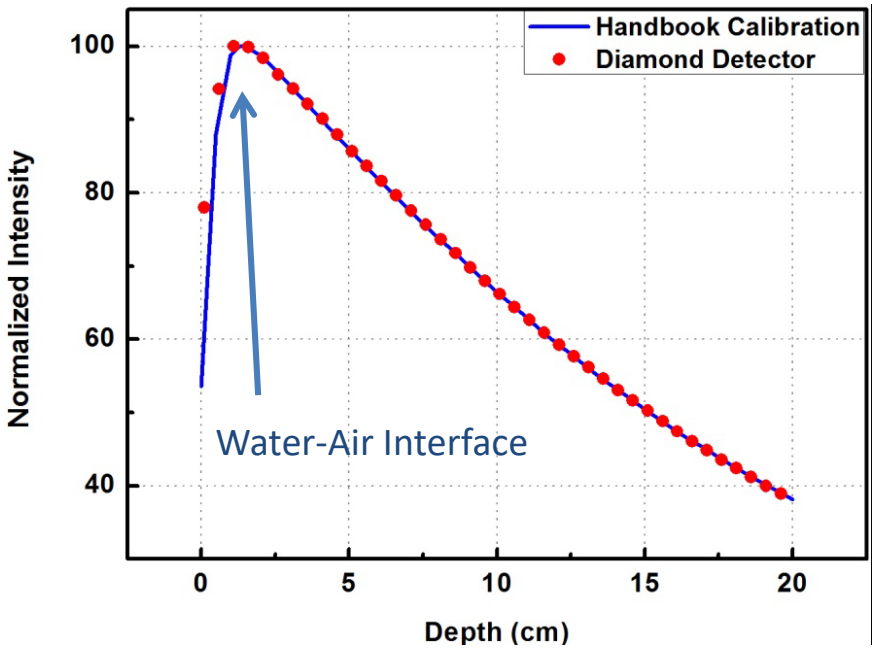

**50 µm diamond shows less variation than "standard" ion chambers for machine calibration. Will also improve characterization of radiation field profile used for treatment.**

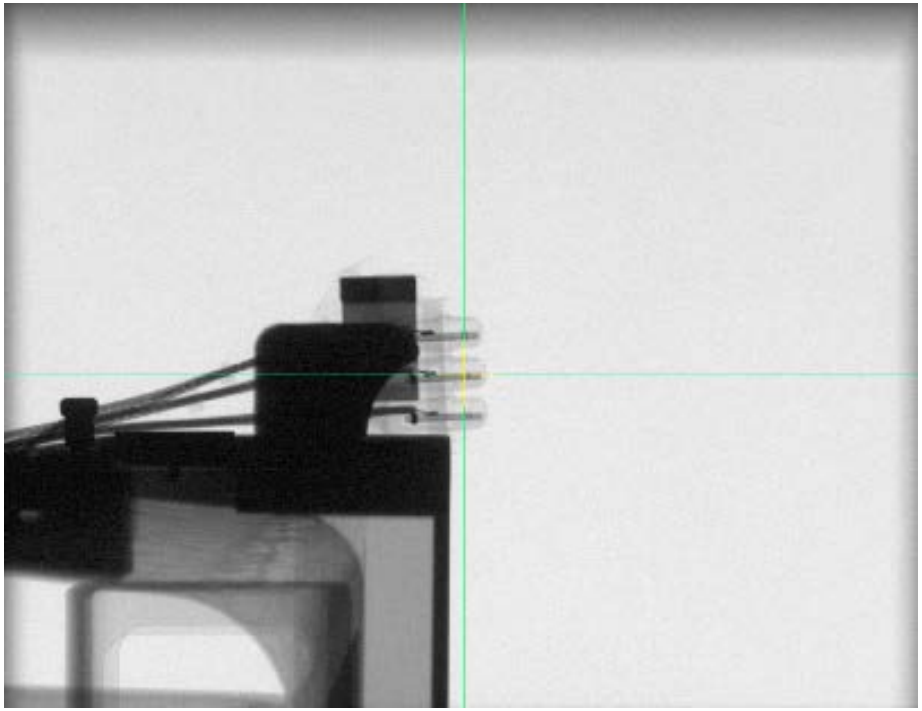
Stony Brook University

Diamond Detector Linearity



# Intensity vs. Depth

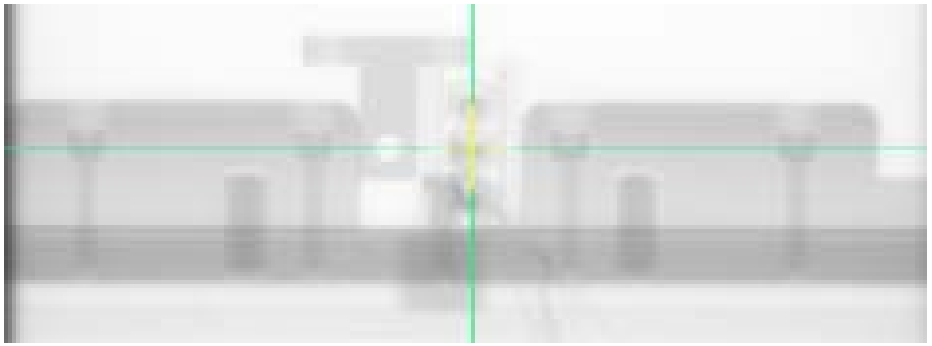


$$I = I_o \cdot e^{-\mu \cdot d} \xrightarrow{water} I_o \cdot e^{-\mu \cdot \rho t}$$

- t (cm) is depth of water
- ρ (g/cm3) is density of water;

The mass absorption coefficient μ can be fitted as 0.0372 $cm^2/g$ in water
=> Gamma ray energy is **~3.5MeV**

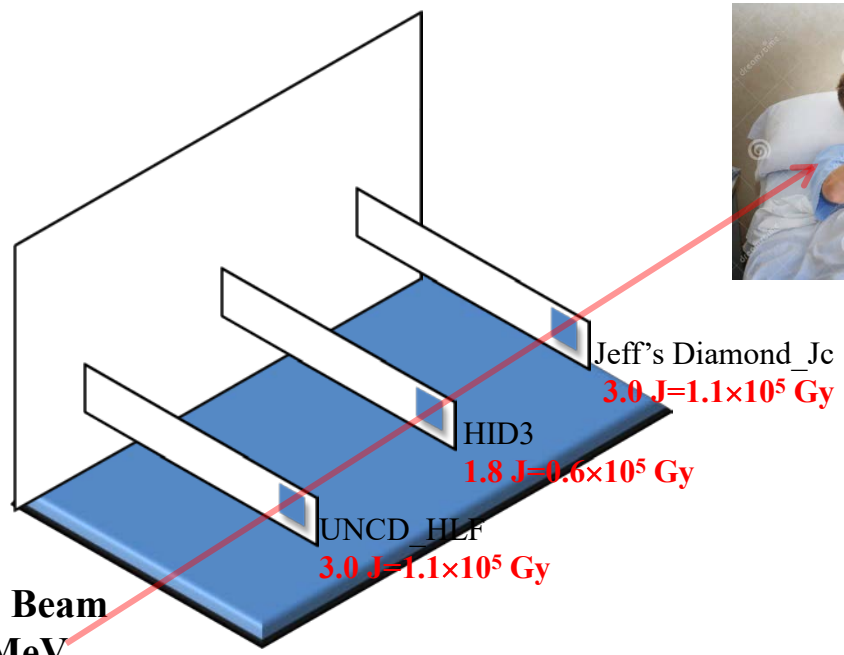


# Proton Therapy – Radiation Damage

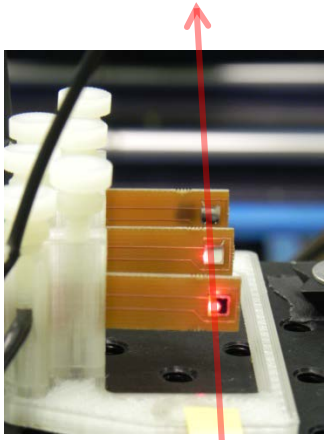
In principle, detector operation for protons is no different than for x-rays

Main difference – protons have sufficient momentum to damage the diamond lattice

=> Need to quantify radiation damage!




**Patient**
**800MeV**
**4.5 kJ=2.8×10⁶ Gy**



- Diamond Detector Power Absorption: 0.067%
- 10-years dose for medical use:

10 yrs × 350days/yr × 8hrs/day × 3patients/hr × 2shift/patient × (1~2 Gys) = (1.68~3.36) ×10⁵ Gy

- Corresponding diamond detector absorption radiation for 10-years medical dose:

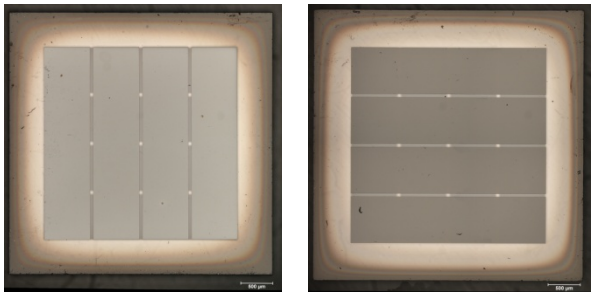
(1.68~3.36) ×10⁵ Gy × 0.067% = (6.34~12.68) ×10³ Gy

=> Delivered Dose is 100 yrs of normal operation!

# LANL Radiation Set-up

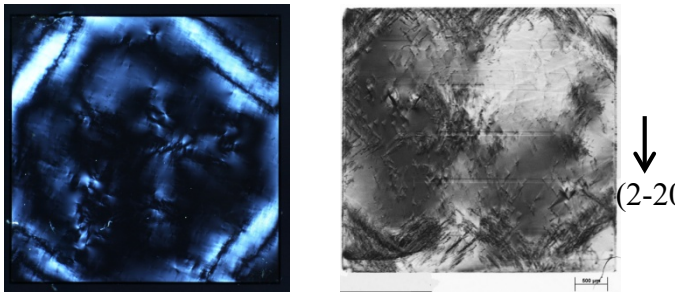
# Proton Therapy – Radiation Damage

## Optical Images



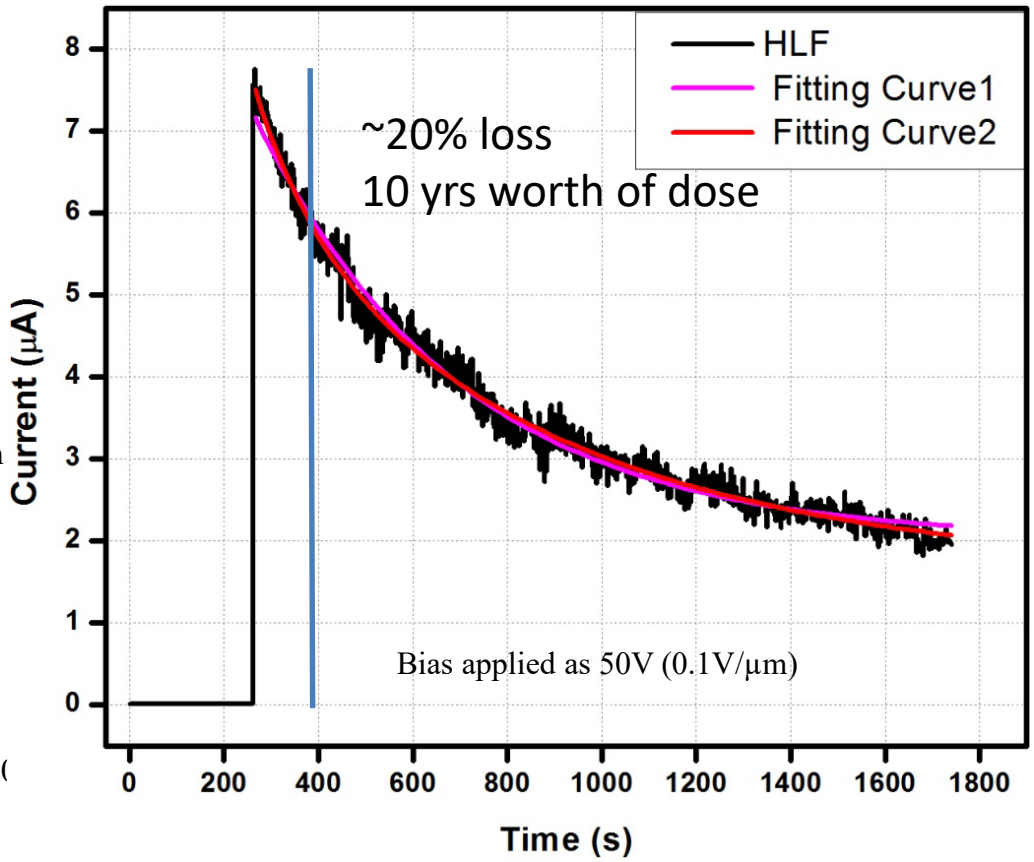
- Diamond thickness: ~500µm;
- Diamond Size: 4.11mm × 4.10mm;
- Active Area: 2.95mm × 2.95mm;
- Pattern Size: strip width=0.7mm; street=50µm

## Birefringence & Topography Image



- Birefringence image displays some slip band at corners;
- Topography displays low density dislocations in the active area;

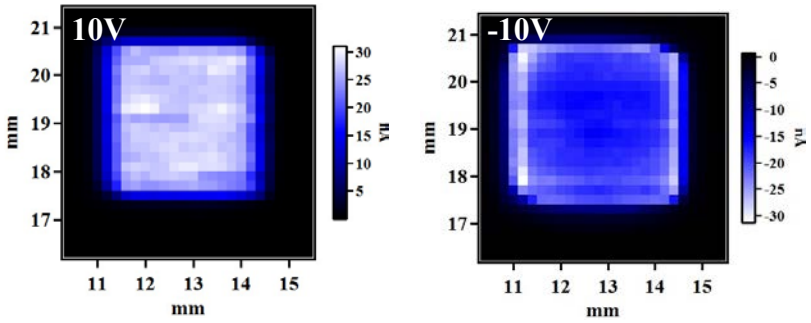
## During Proton Radiation



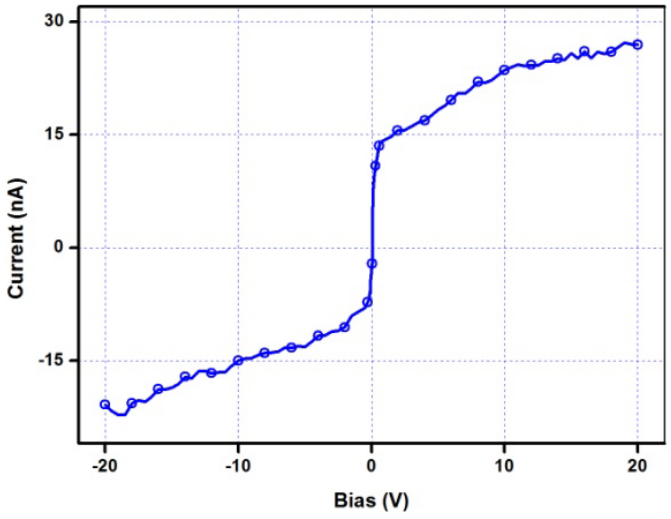

Radiation does not cause visible change, nor large scale structural change
However, the charge collection in the material does change, likely due to new trap centers

# XBIC evaluation before and after Protons

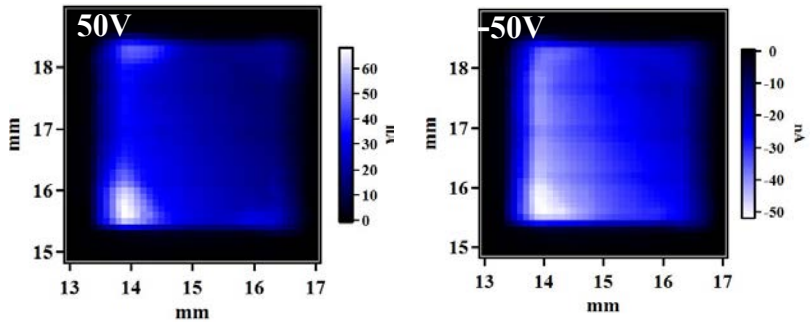
Performance Before Radiation @CHESS G2



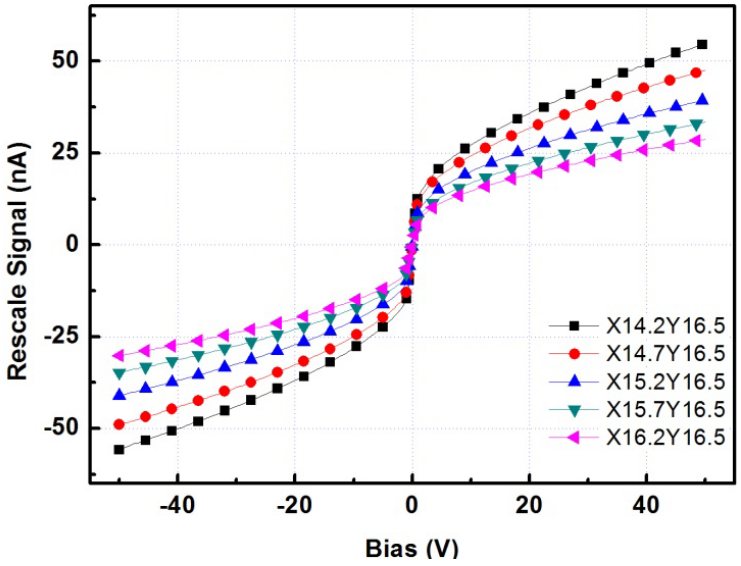

Initially uniform, even at low bias




Performance After Radiation @CHESS G2




Proton beam gradient imprinted in device response post irradiation

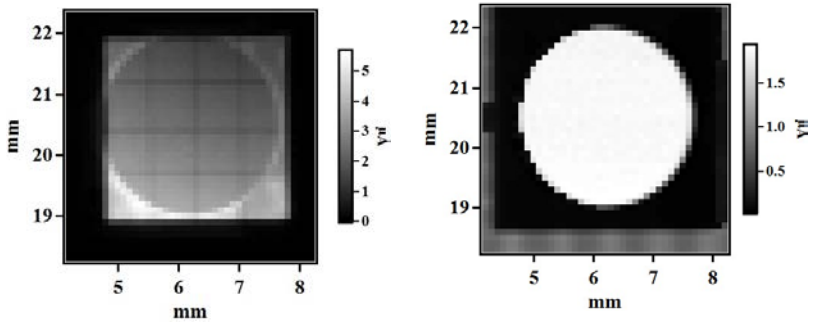



Post irradiation, still unsaturated at 50V
22% to 45% of full collection

# More performance tests after radiation @XFP (NSLS-II)

## ➢ Response Map @50V

Monitor @20V



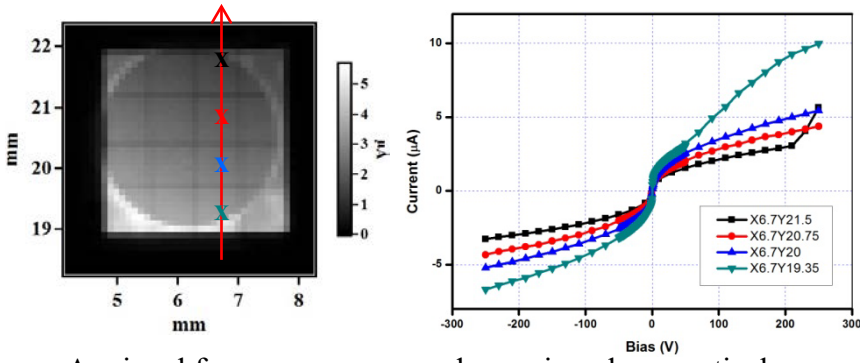

- Response map from monitor displays good uniformity

⇒The varying signals in detector is from detector itself;

- From monitor's signal *(~1.87μA)*, detector's saturate signal should be ~11.7μA *(actual signal is 1.6-4.7μA)* ;

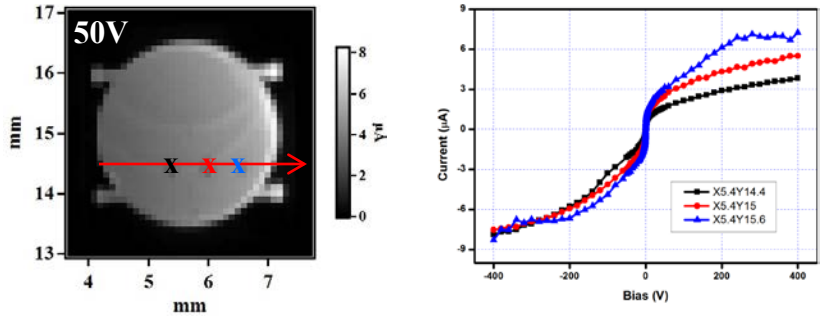
⇒The decay ratio is 13.7%-40.2%.

## ➢ Bias Scan (Along vertical direction)




- As signal from response map decreasing along vertical direction, bias scan curve flattens in the same direction.

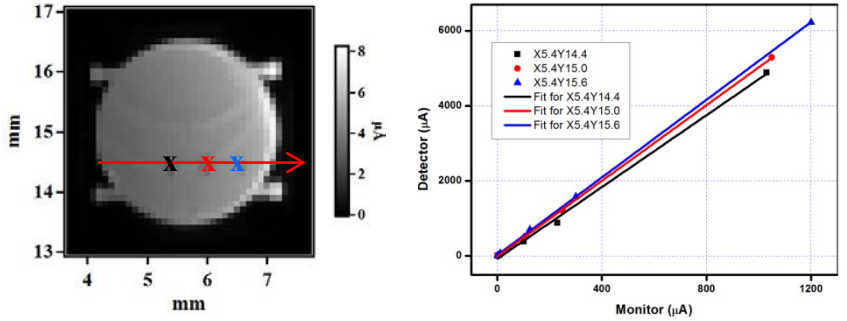
## ➢ Bias Scan (Along gradient direction)




- Bias scan curves are asymmetric under positive and negative bias;
- Signals under positive bias reflects gradient radiation on diamond;
- Detector's saturate signal should be ~11.6μA

⇒The decay ratio is 25.9%-48.3%

## ➢ Flux Calibration (Along gradient direction)



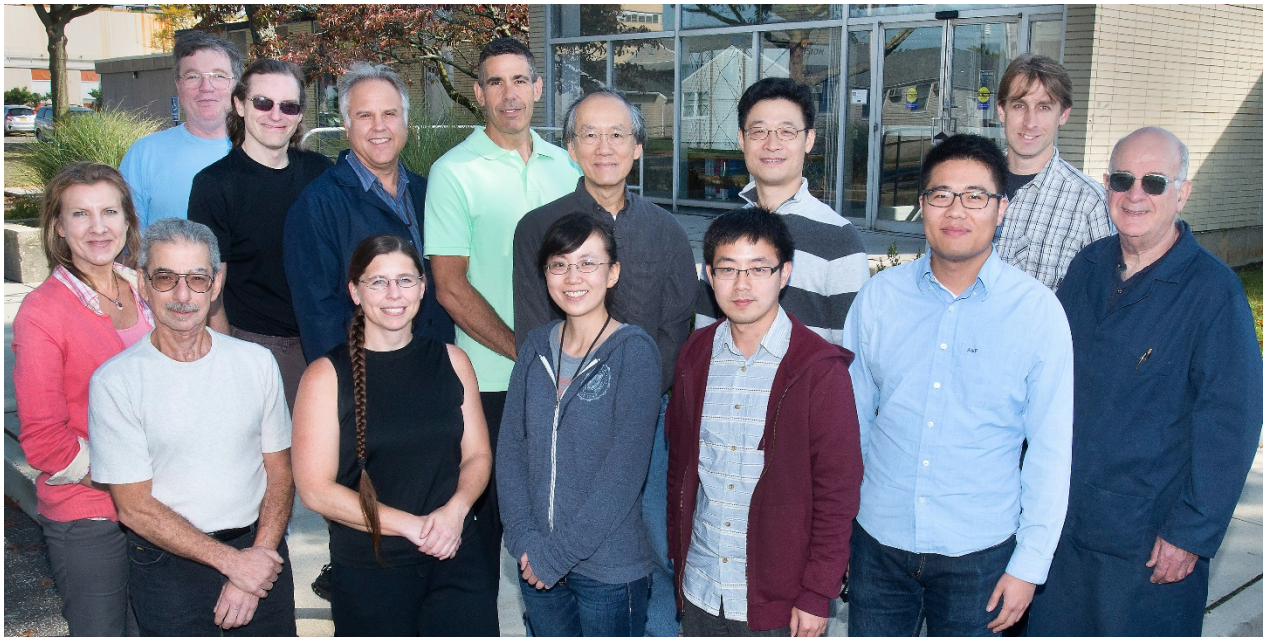

- Flux and response remain linear relationship, but the slopes change slightly according to radiation damage;

# Conclusions

- Flux linearity demonstrated over ***11 orders of magnitude***
- X-ray BPMs monitors for monochromatic and white beam
- Commercialized by Sydor Instruments
  - 30+ devices at NSLS-II
  - Devices delivered to Diamond, APS, CHESS
- Position resolution of better than 50nm, and single bunch flux and position have been achieved
- 1k pixel transparent beam imager developed
- Proton and C-Ion imagers being tested
  - Radiation damage is observable but likely acceptable
  - Devices maintain flux linearity but lose spatial uniformity
  - Source is trapping sites within material, not gross structural changes

**Thank you!**

# Acknowledgements



*Stony Brook:* **Erik Muller, Tianyi Zhou, Mengnan Zou, Owen Ding,** Sam Ryu, James Han, Jinkoo Kim

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*CFN*: Ming Lu

**Bold** = Diamond Group

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*Cornell/CHESS*: Arthur Woll, Howard Joress, Jacob Ruff

*Applied Diamond*: Joe Tabeling

Stony Brook University

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