Single-crystal Diamond Diode X-ray Sensors

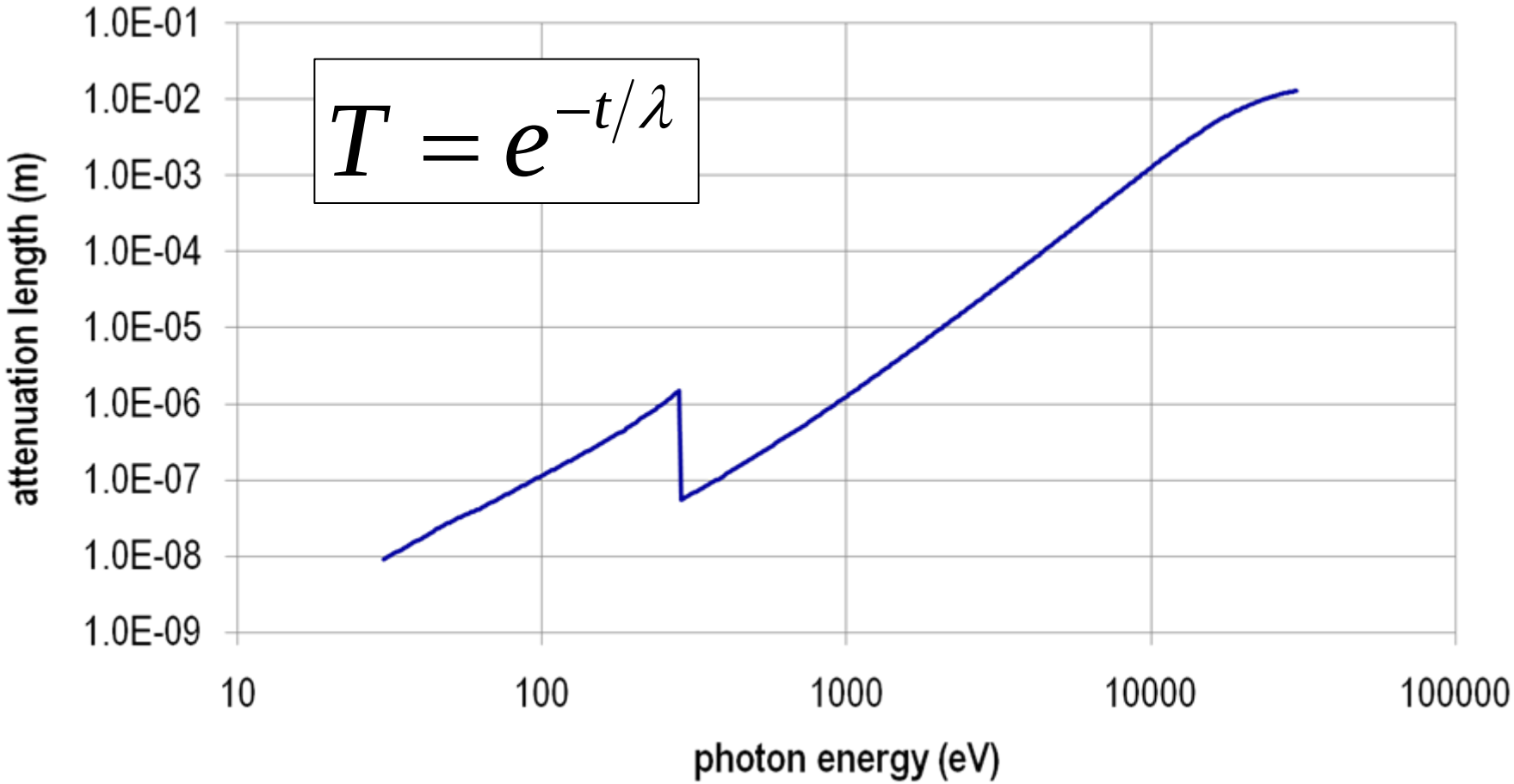
J. Keister*, J. Smedley, E. Muller, J. Bohon, Dimitre Dimitrov, Richard Busby, et al.

Commercial availability of state of the art, high-purity single-crystal synthetic diamond is allowing development of novel x-ray sensors. The low absorption and high thermal conductivity make it ideal for such application. On the other hand, charge trapping, diffusion, recombination and photoconductive gain offer challenges to realization. The underlying charge propagation dynamics are probed as such devices are developed. Successes in responsivity quantification, as well as performance at low energies, high flux and high speed are demonstrated and correlated with our developing understanding of diamond as an electronic material.

*Brookhaven National Laboratory, NSLS-II Project

DIAMP 2010 meeting @ Tech-X Corp, Boulder, CO June 14-16, 2010

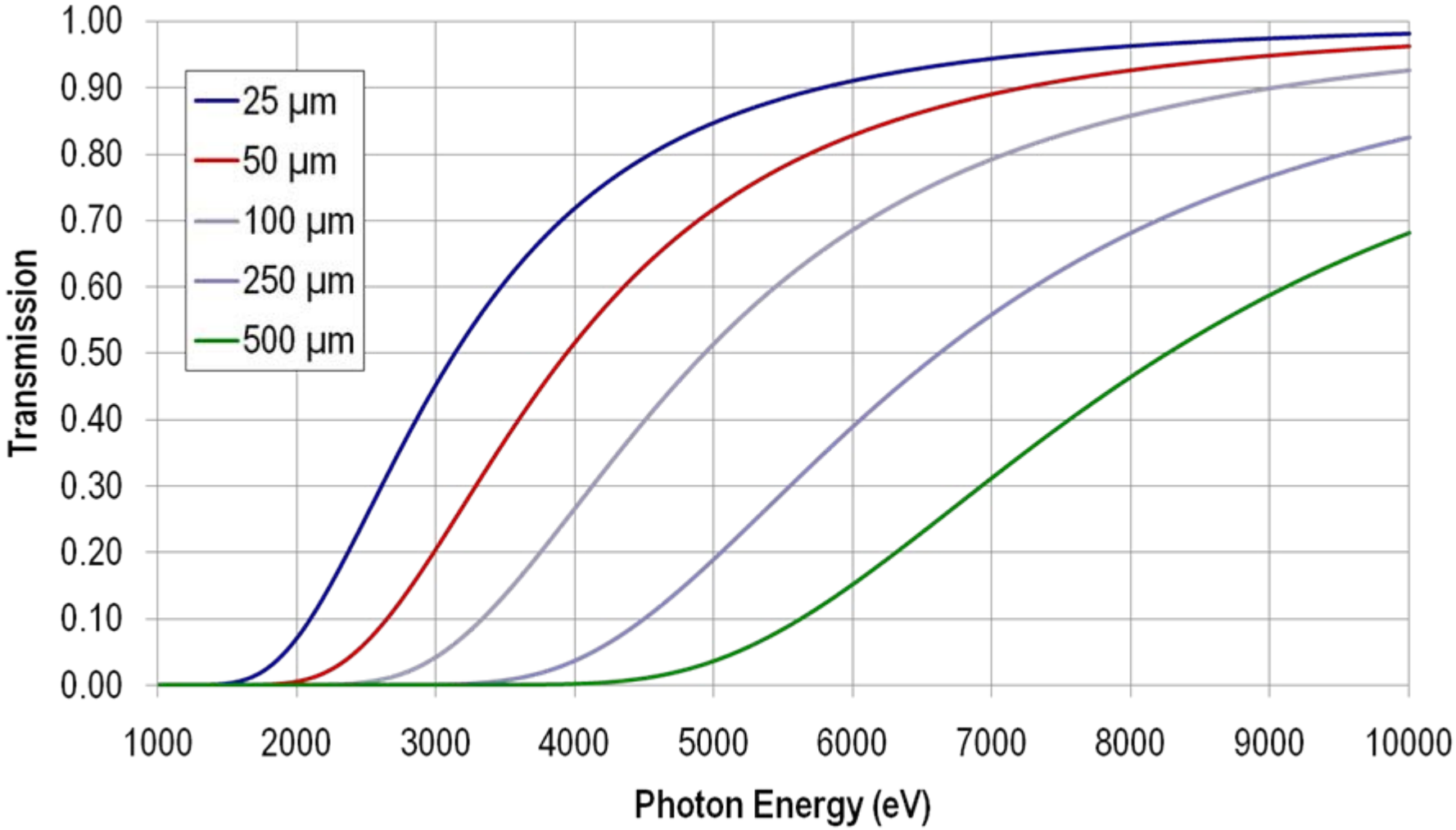
X-ray Transmission of Diamond



*Photoelectrons are “born” within the diamond and therefore lose no energy to metal contacts except by diffusion – this provides an ideal way to probe diamond bulk

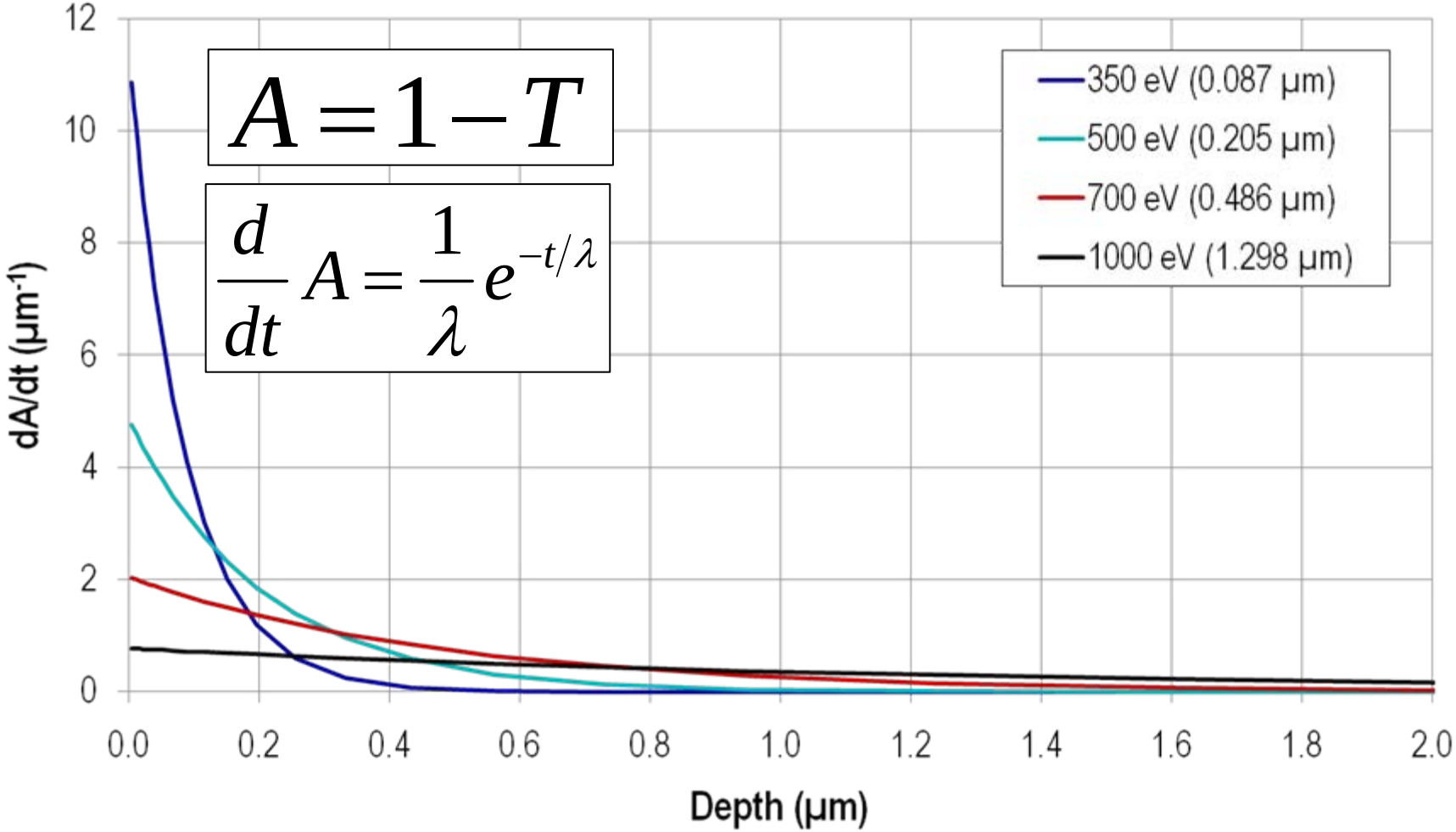
Source: http://henke.lbl.gov/optical_constants/atten2.html

Transmission of Various Thickness Diamond



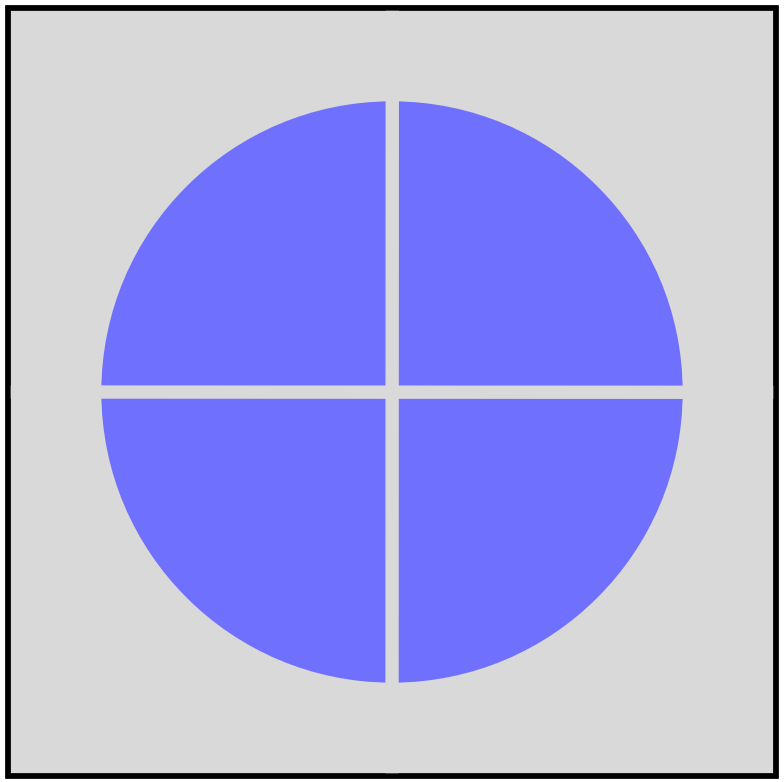
*High transmission (thin plates) desireable for low energy x-ray beamlines

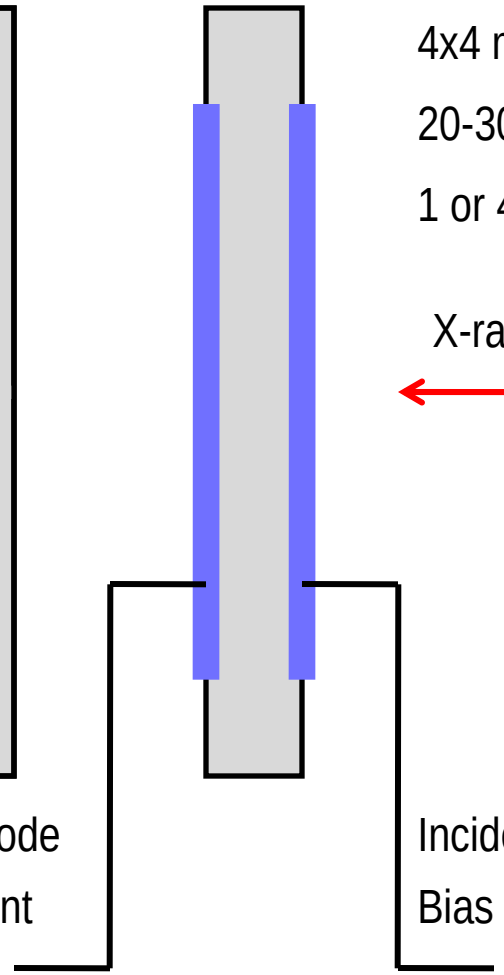
Absorption Per Unit Depth



Since soft x-ray absorption is mostly at the incident electrode, the carrier to be transmitted through the diamond plate is selected by applied bias polarity

Test Geometry





4x4 mm^2 diamond plate

20-30 nm Pt metallization

1 or 4 pads geometry

X-ray Beam Propagation

Transmission Electrode

Current measurement

Incident Electrode

Bias (+ for holes, - for electrons)

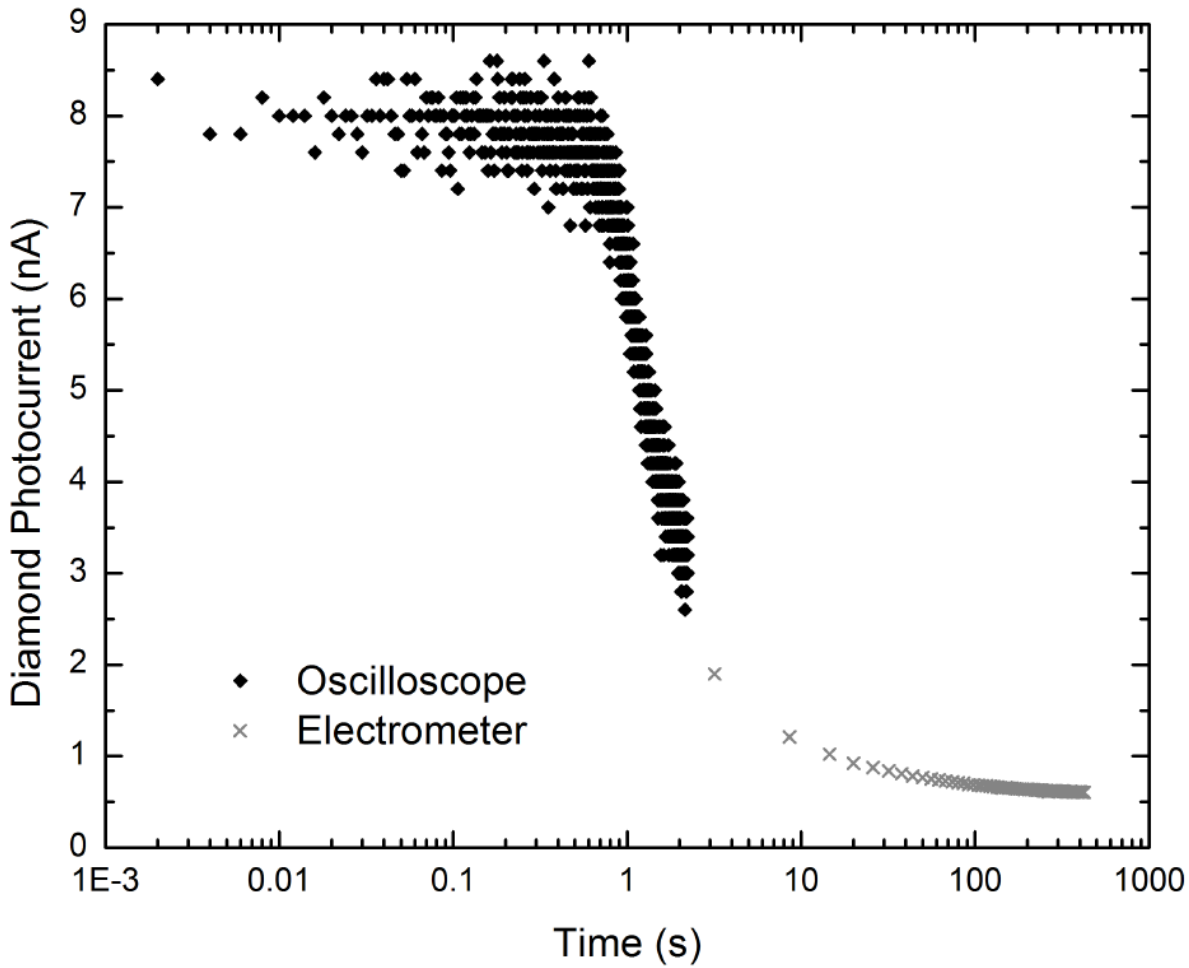
First Observations at Soft X-ray Energies

Instantaneous result for hole transmission, recovered after unbiased illumination

Data conditions:

- 1 keV x-rays
- 0.5 μW (3×10^9 phot/s) per mm^2
- 100 V bias
- Ohmic (annealed) contacts
- Oscilloscope measurements were made with 1 MΩ input impedance

Note: buildup of gain for electron transmission vs time is also observed

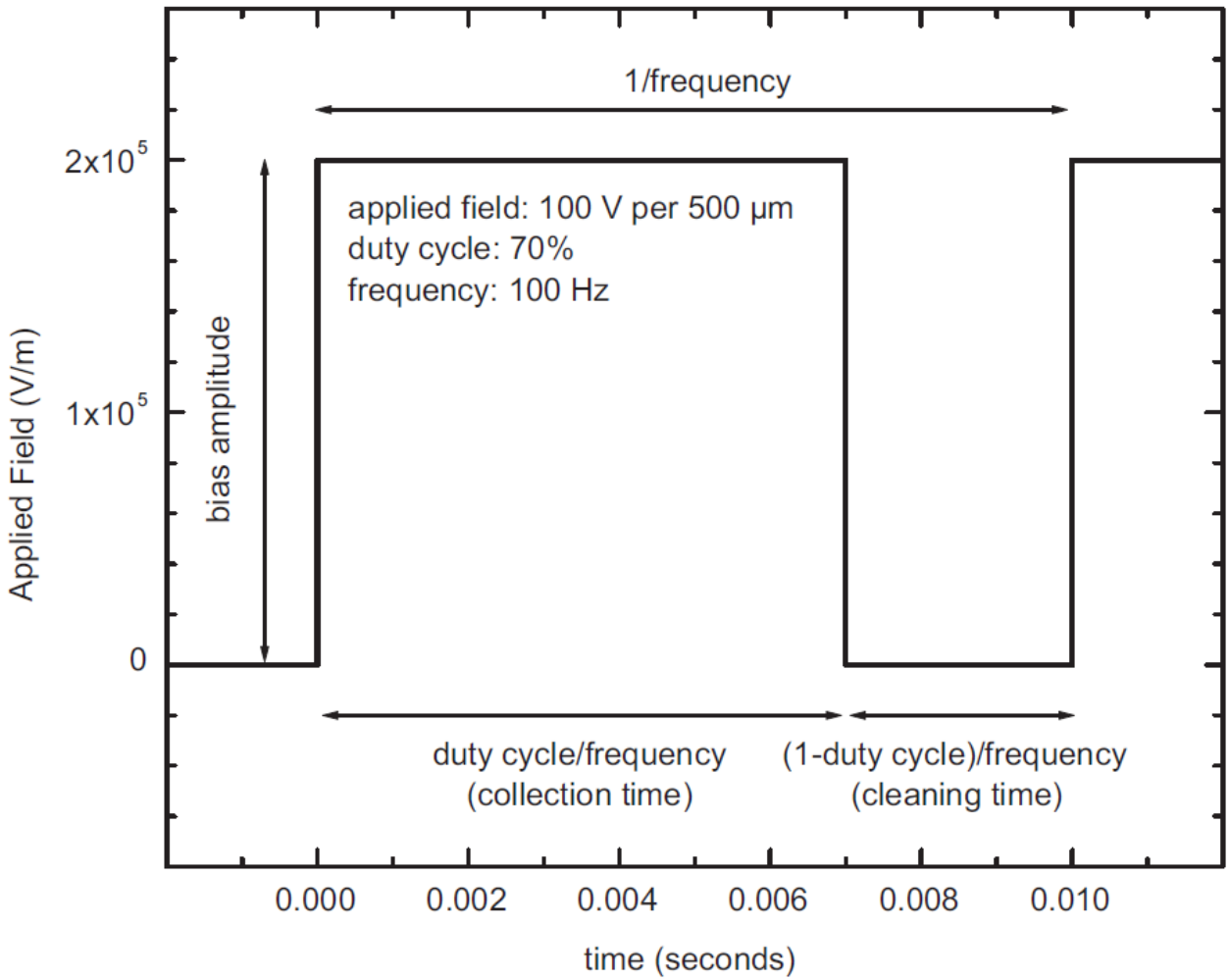


Pulsed Bias Mitigation for Charge Trapping

Biasing scheme

Reported duty cycle ("d.c.") appears in overall responsivity measurement:

$$S = \frac{1}{d.c.} \cdot \frac{I}{P}$$



"Single crystal diamond photodiode for soft X-ray radiometry"
Keister, Smedley, NIM A 606 (2009) 774–779

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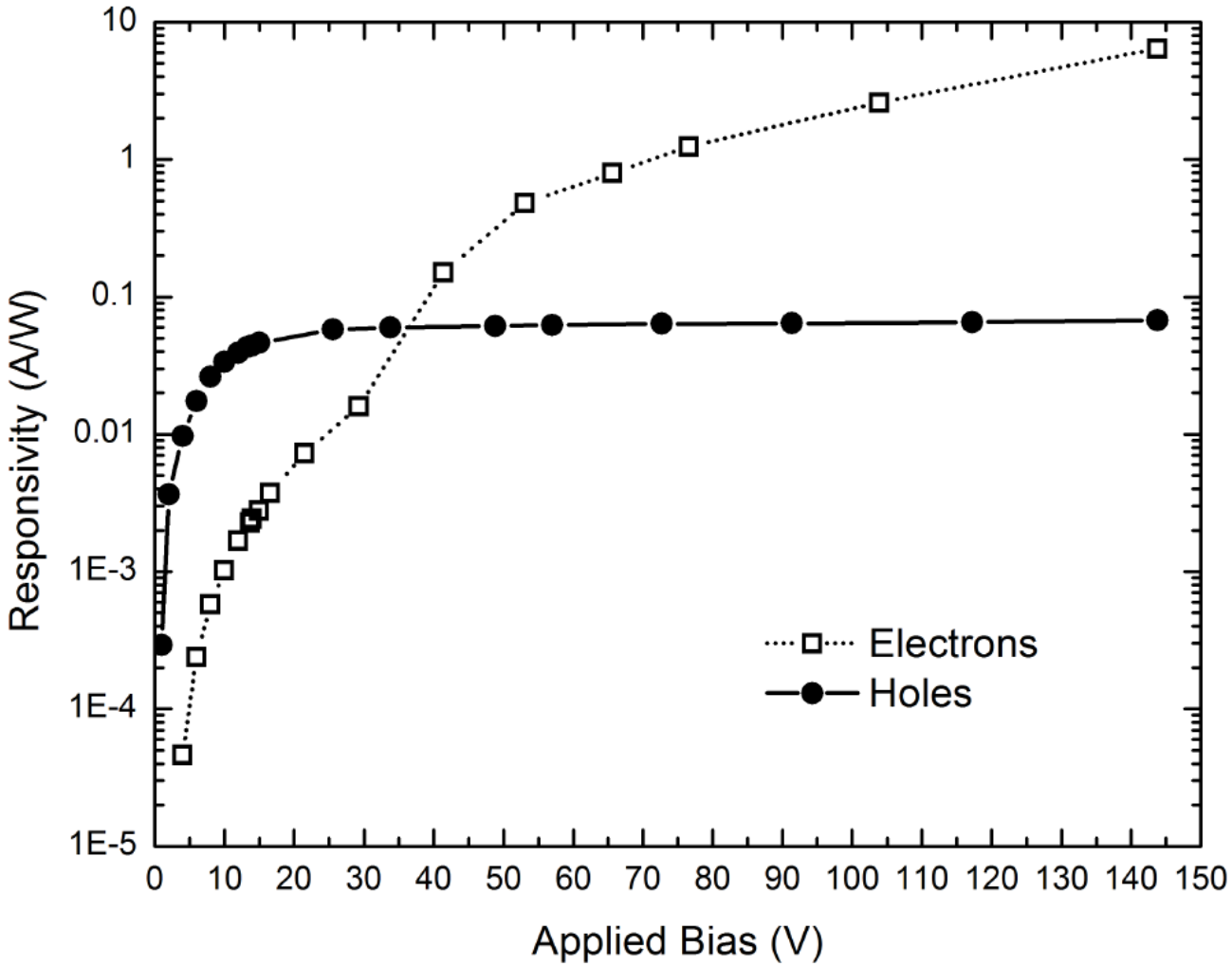
Response vs Field (e-,h+) still shows gain

Flight times are important, velocities are similar

Data conditions:

- 0.3 mm thick diamond
- ~35 nm Ti/Pt contact (annealed, ohmic)
- 1 keV photon energy
- ~60 nW beam intensity in a 0.1 mm^2 centrally illuminated area
- 50% duty cycle pulsed bias, 100 Hz

Improved diamond or blocking contacts can prevent photoconductive gain (hole injection)



"Charge Collection and Propagation in Diamond X-Ray Detectors"
Keister, Smedley, Dimitrov, Busby, to be published IEEE-TNS Aug. 2010

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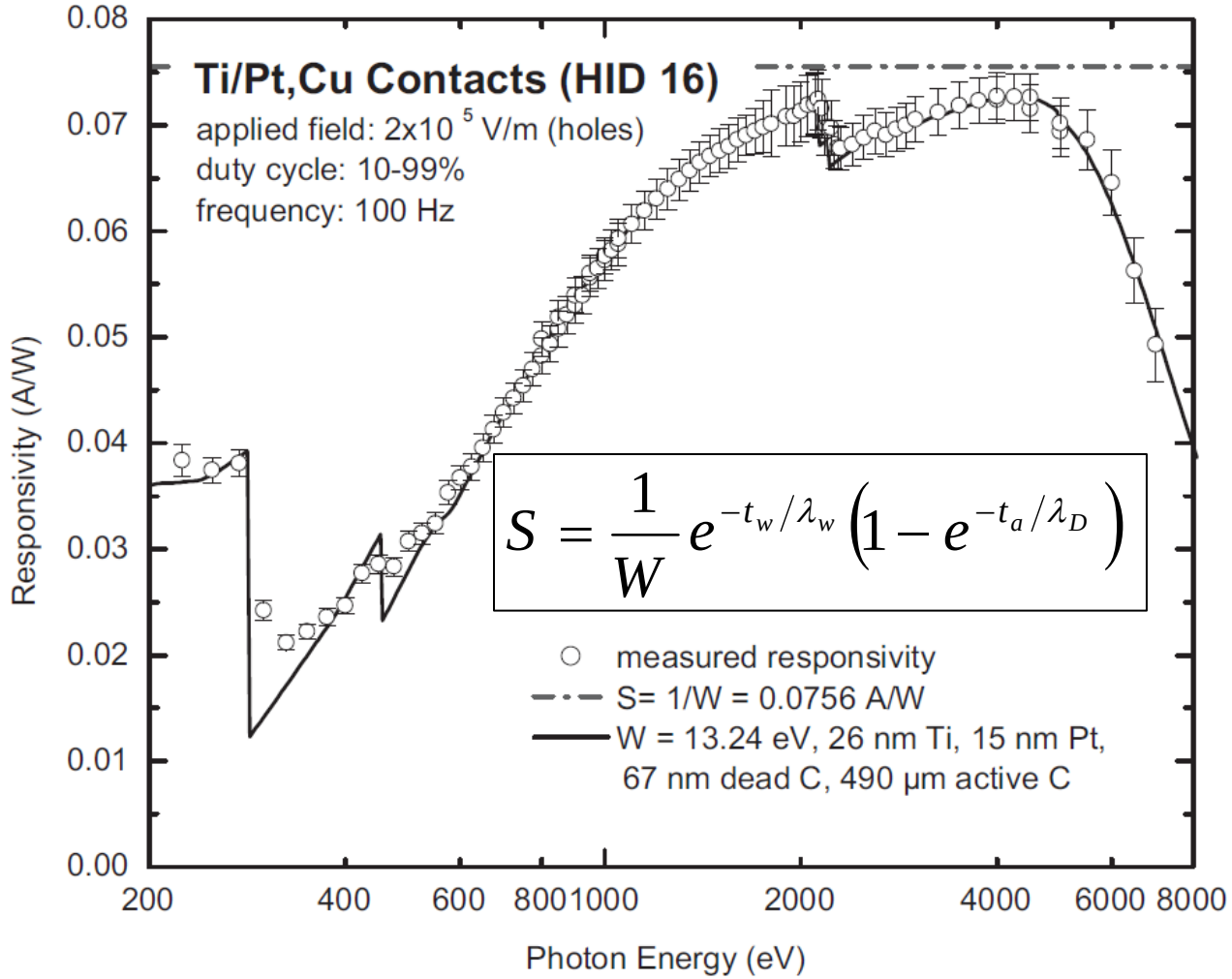
Holes, Pulsing Give Calculable Responsivity

Simple responsivity model

All absorbed photon energy ultimately produces charge via Auger relaxation and secondary electron generation; deviations from bulk responsivity are determined by absorption and recombination

W measurement with low uncertainty: W = 13.3 ± 0.3 eV (compare to 3.66 eV for silicon, 34 eV for air)

(1/eV = A/W)



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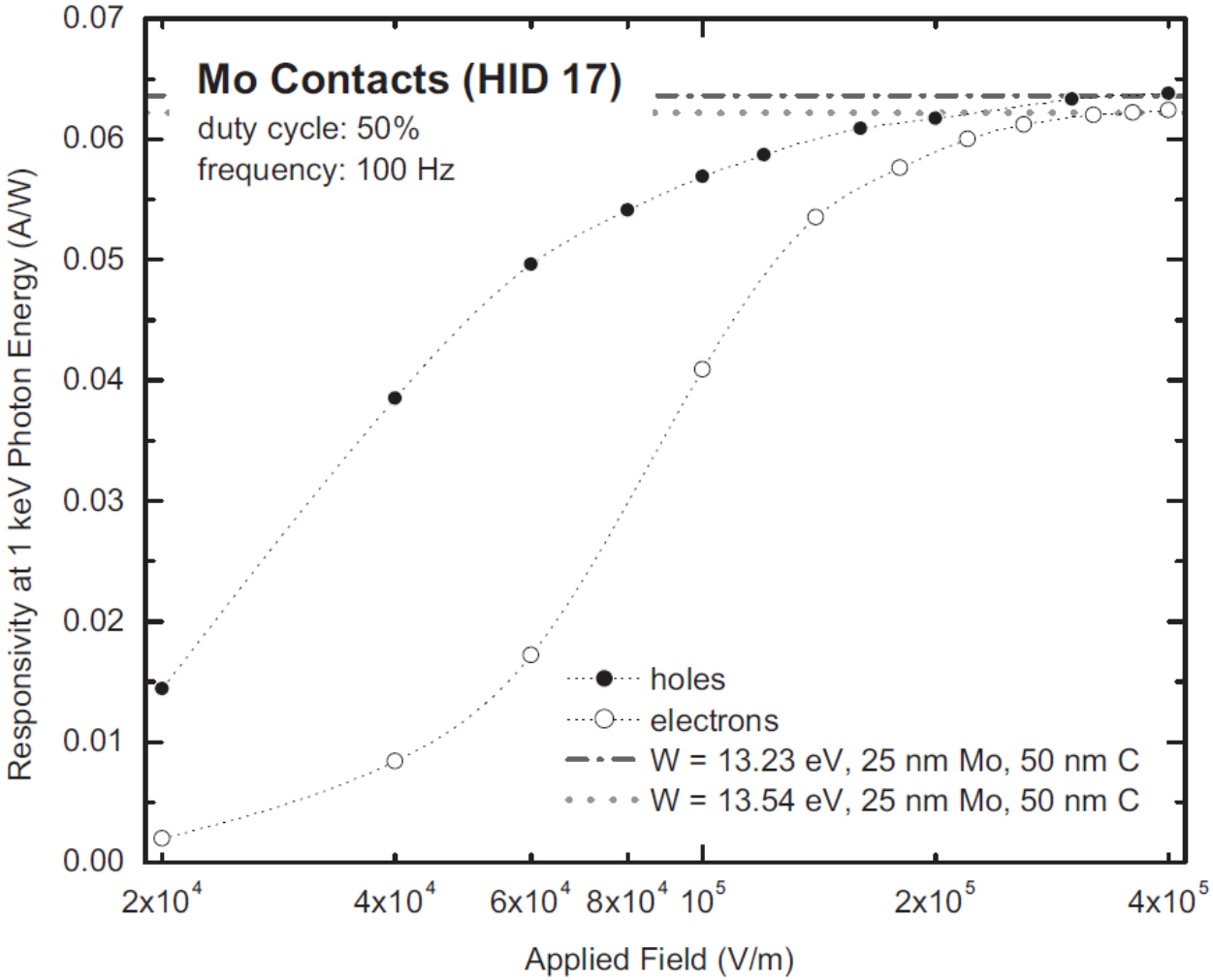
Blocking Contacts, Pulsing: e^- vs h^+

Unannealed Molybdenum contacts

Soft x-rays, bias polarity determine carrier which must cross the diamond bulk

Hole collection is more efficient (electrons are trapped)



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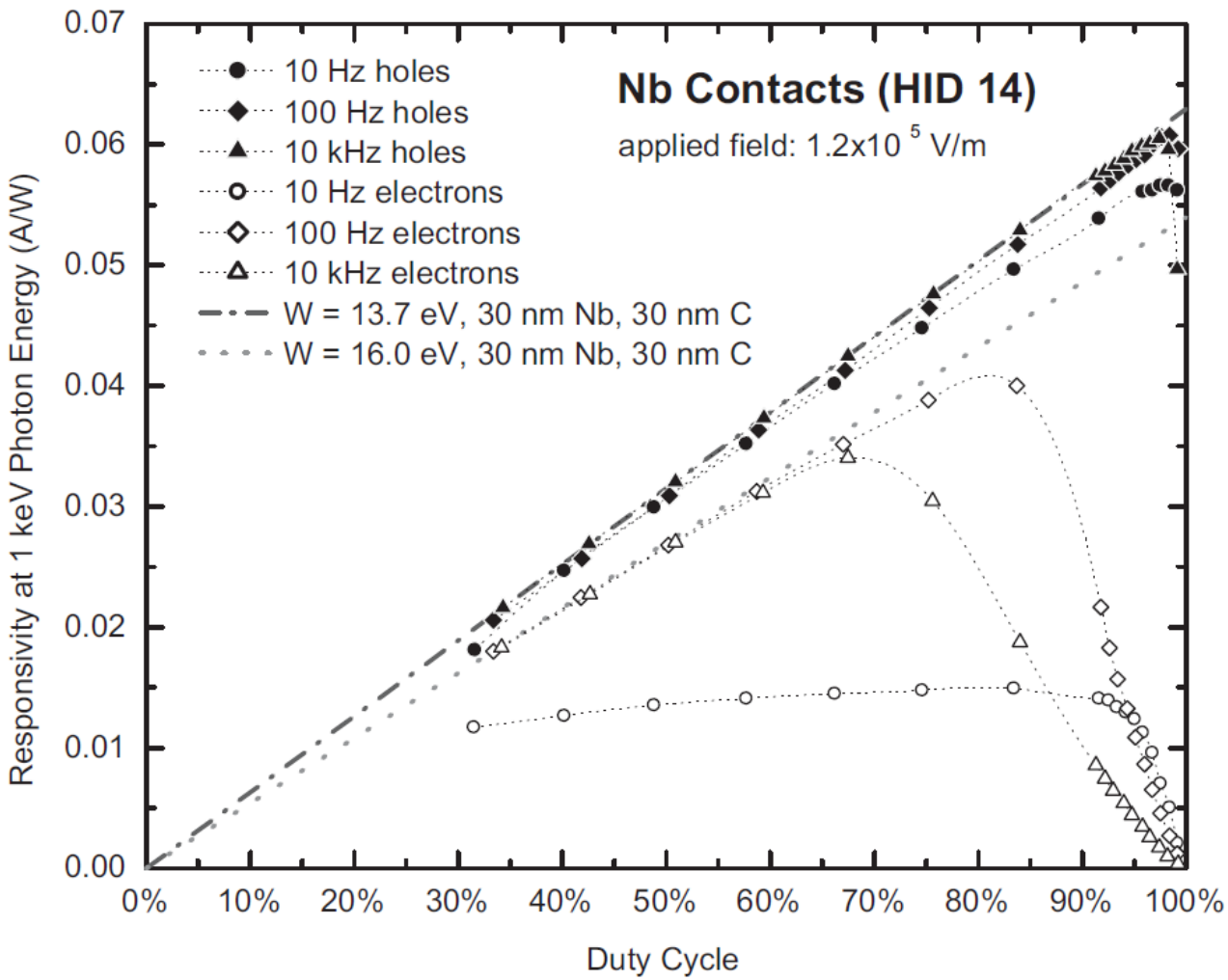
Duty Cycle and Charge Cleaning: e^- vs h^+

Responsivity here is not corrected for duty cycle (to show effect of changing it)
True linearity is 100% extrapolated value
Linear dependence on duty cycle indicates "safe" operating range

Holes have higher bulk responsivity and can be collected at higher duty cycle (>90%); where charge is trapped (mostly electrons), lower d.c. is required (60% or less)

100 Hz or greater frequency is recommended



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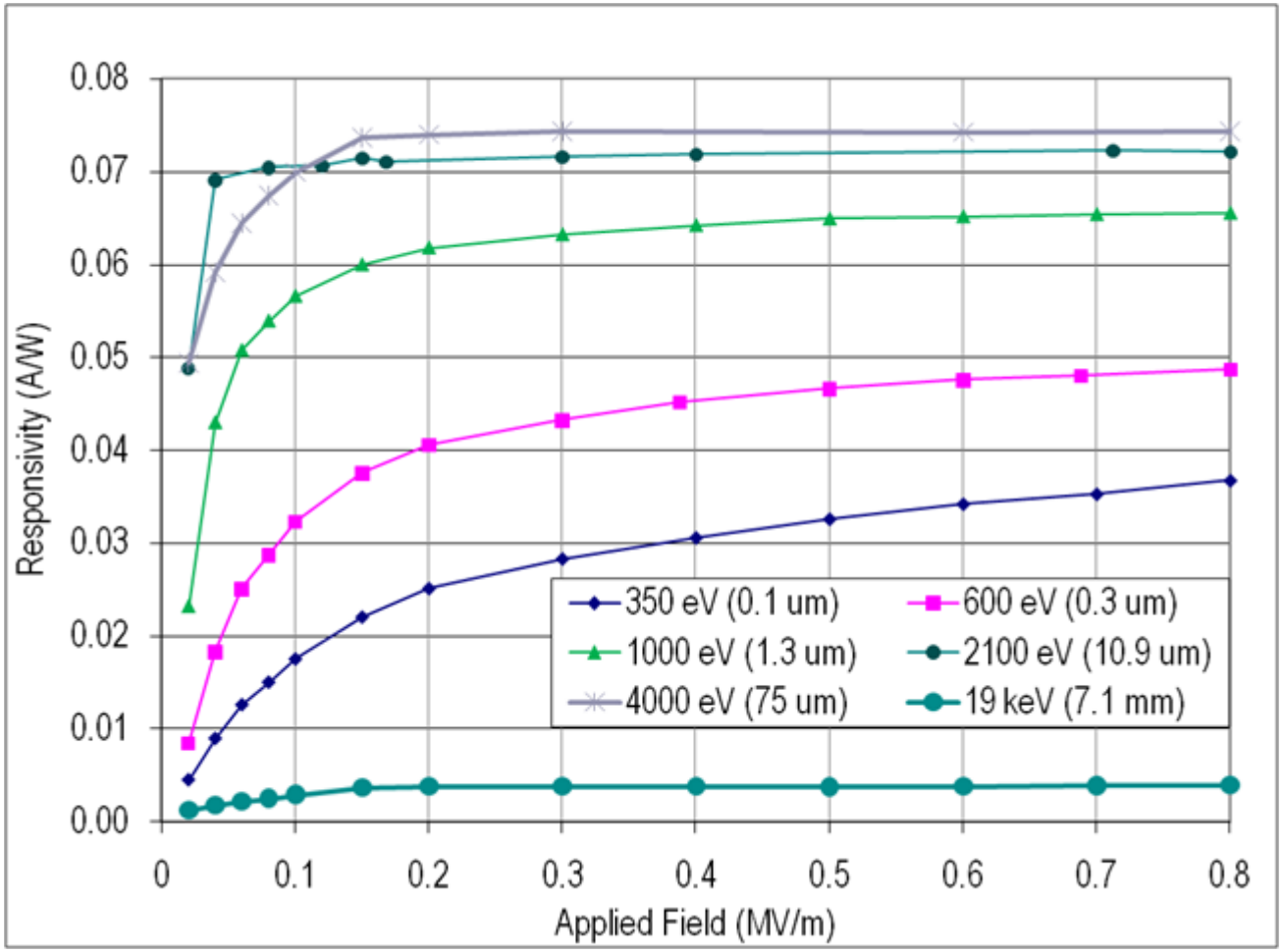
Photon Energy and Field Dependece

As energy is increased, two effects are observed:

1. Attenuation length is increased (charge is initially deposited further into the bulk, away from contacts where diffusion / recombination can cause losses)

2. Selection of a primary carrier becomes less importance (both carriers drift from the bulk); lower-mobility electrons begin to participate even under “hole” bias

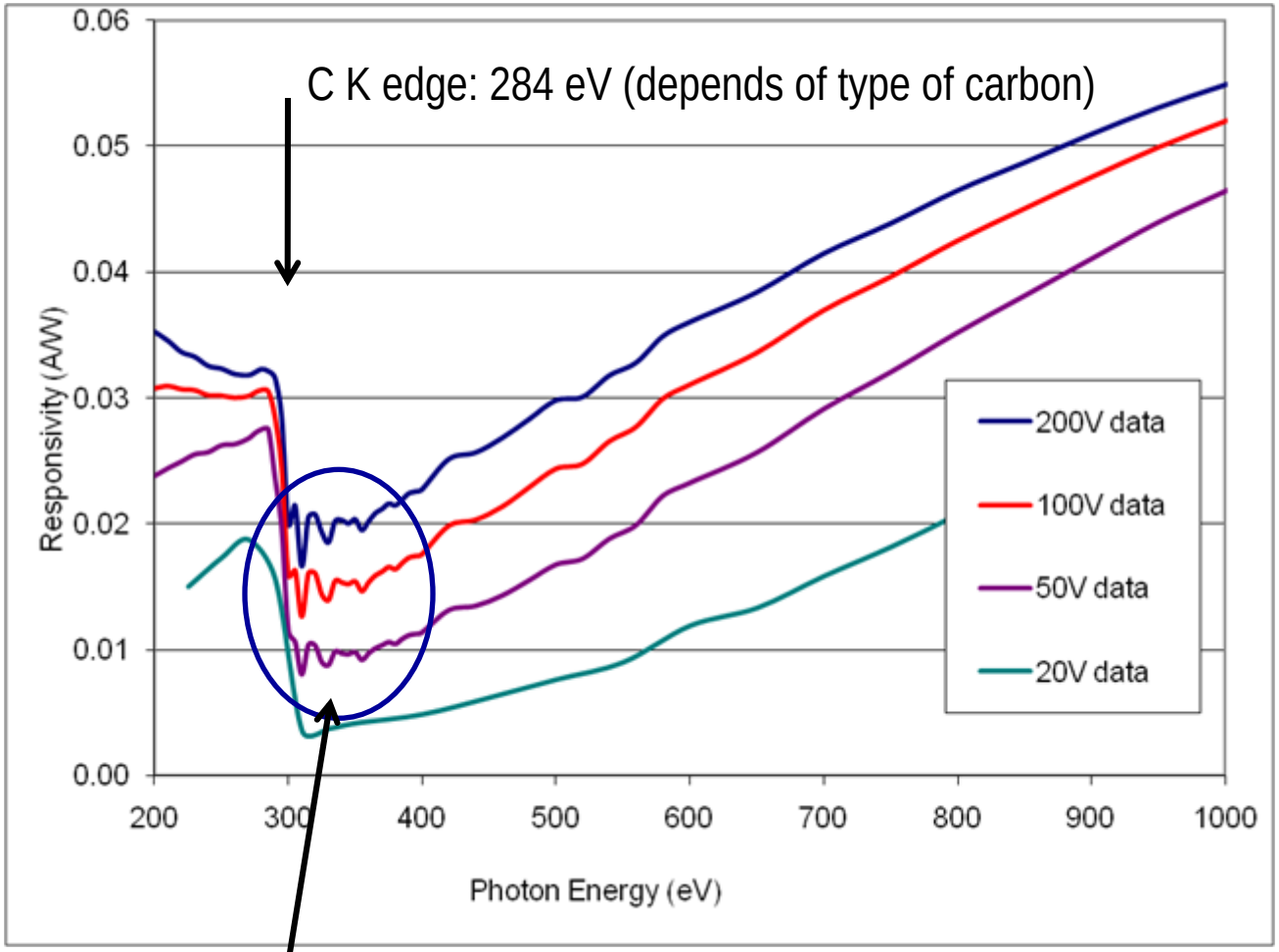


Field Dependence at Low Energy

Diffusion into window contact limits responsivity at low energies, where attenuation length is short

At low field, recombination from carbon absorption is signal-limiting

At high field, diffusion loss is less important, and metal contact features dominate (e.g. below 300 eV)



Spectroscopic features characteristic of diamond (not graphite)

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Diffusion/Recombination at Entrance Window

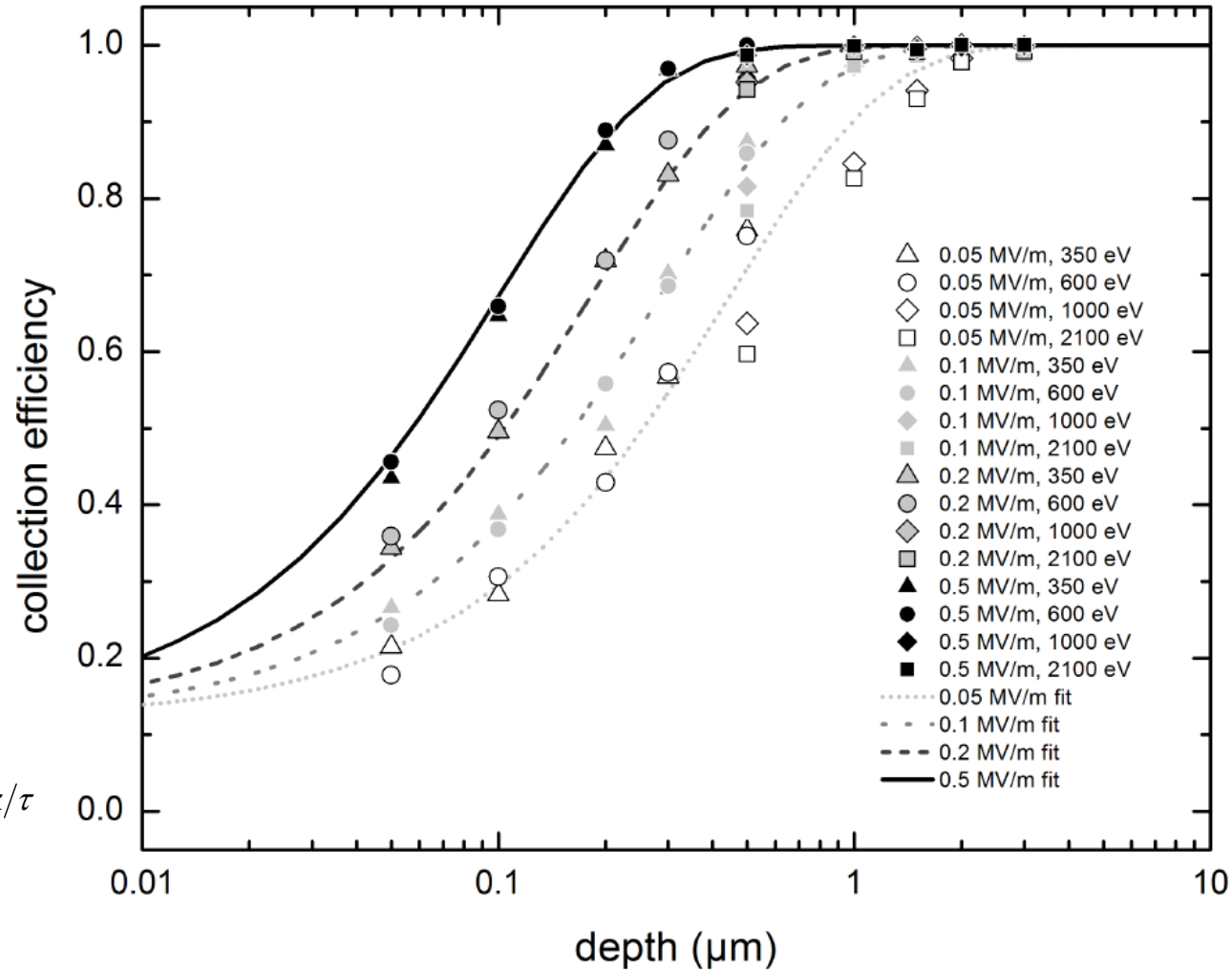
VORPAL simulations:

Escape of energetic electrons from metal contact into active diamond not considered

Field dependence strong, energy dependence weak.

Simulations results well-approximated by a simple form (useful for further analysis):

$$CE = 1 - (1 - CE_0)e^{-x/\tau}$$



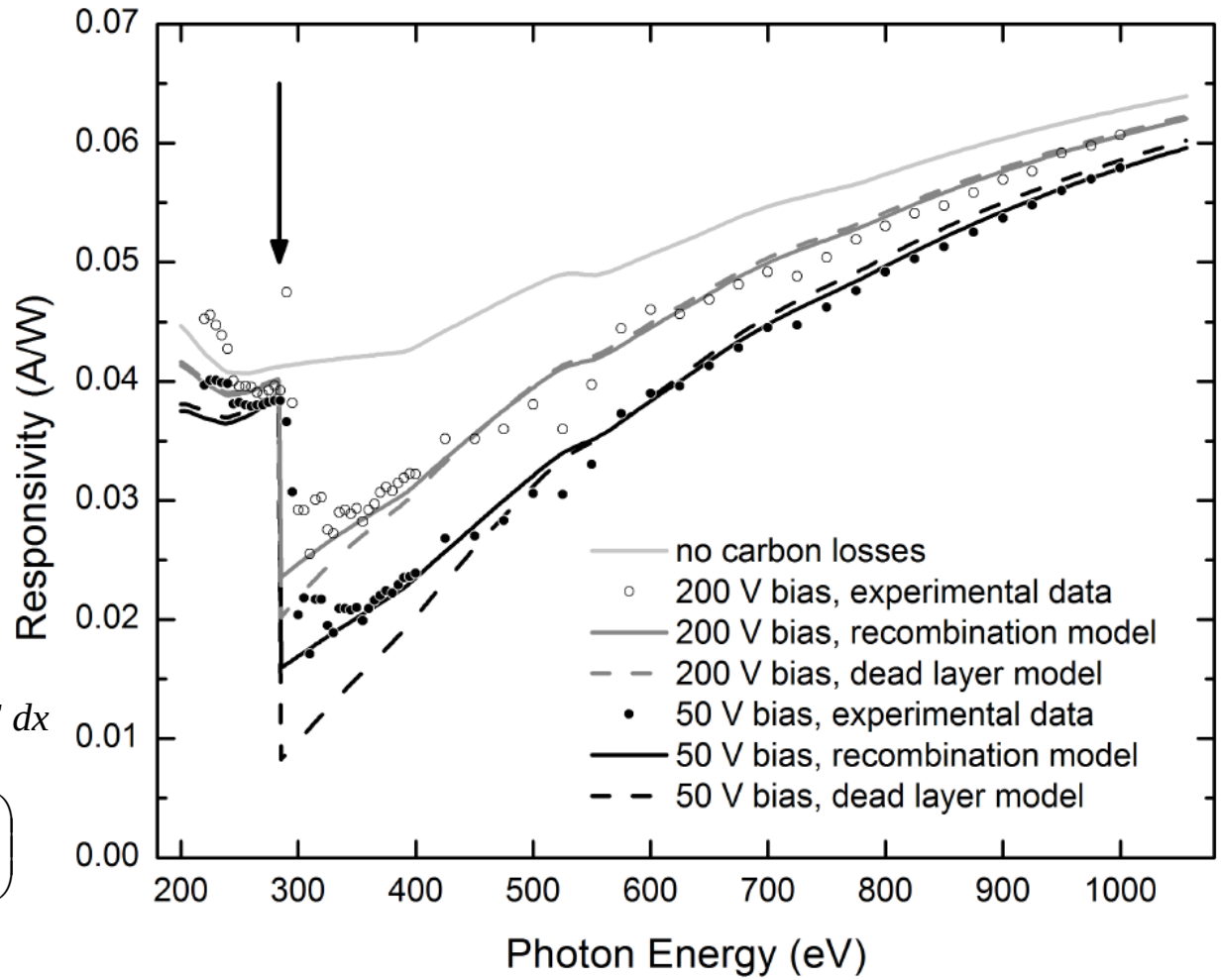
Combined model (diffusion & recombination)

Experimental data for responsivity, and fitting models:

- Simple carbon deadlayer
- Recombination (folding collection efficiency vs. depth data into photon energy scan data):

$$S = \frac{1}{W} e^{-t_M/\lambda_M}\left(1 - e^{-t_a/\lambda_D}\right)\int_0^\infty \frac{1}{\lambda_D} e^{-x/\lambda_D} CE\, dx$$

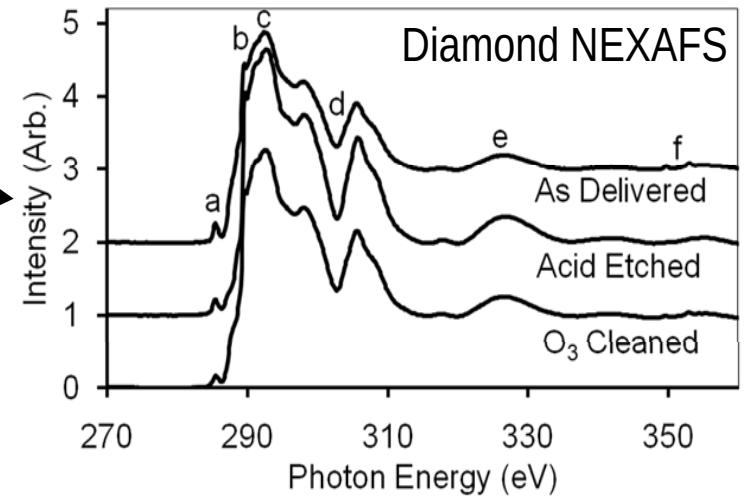
$$= \frac{1}{W} e^{-t_M/\lambda_M}\left(1 - e^{-t_a/\lambda_D}\right)\left(1 - \frac{1 - CE_0}{1 + \lambda_D/\tau}\right)$$



Carbon / Diamond K Absorption Spectra

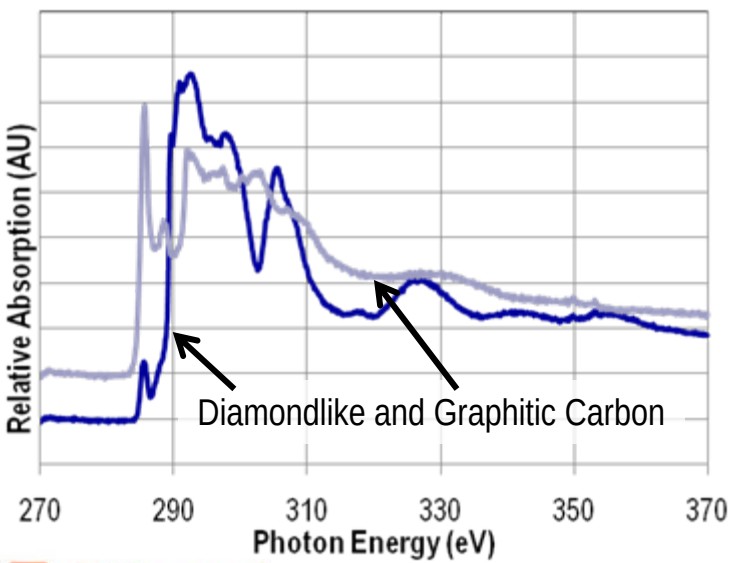
Characteristic features:

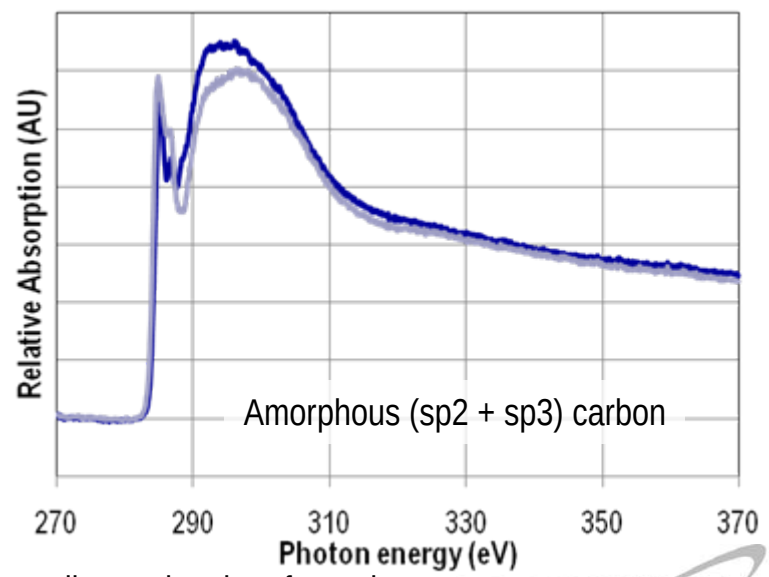
a. sp^2 (surface)
b. Onset of sp^3 (diamond) bulk signal
c.-f. Additional signature features of diamond



Nominal Carbon (K) Absorption Edge:

- Amorphous or graphitic carbon: 284 eV
- Diamondlike absorption edge: ~ *290* eV





"Laser patterning of diamond. Part II. Surface nondiamond carbon formation and its removal", Smedley, et al., J. Appl. Phys. 105, 123108 (2009)

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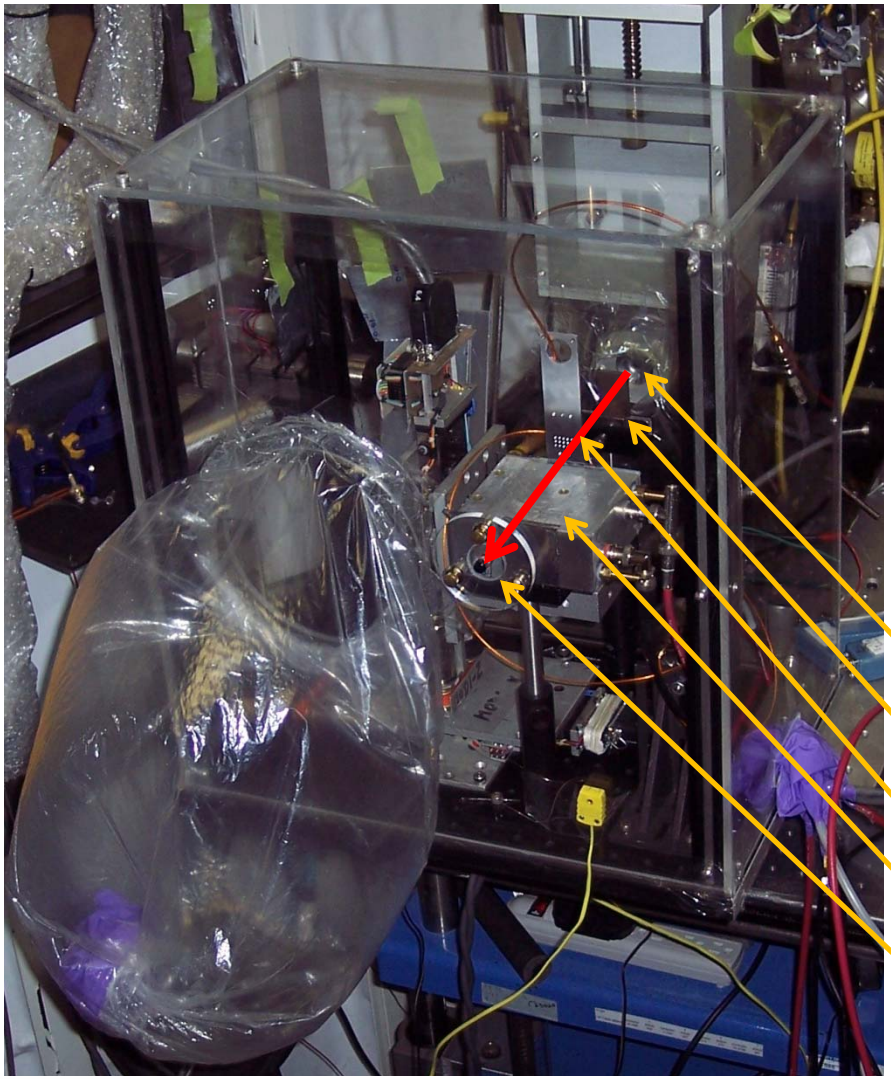
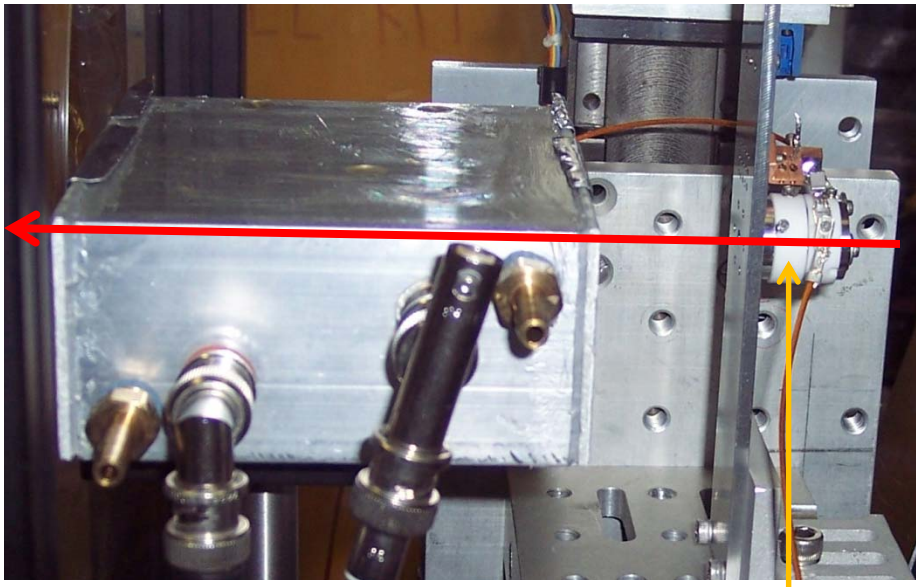
White/Pink Beam Setup at NSLS-X28c





X-ray port

Beam defining aperture

Diamond Detector

Ion Chamber

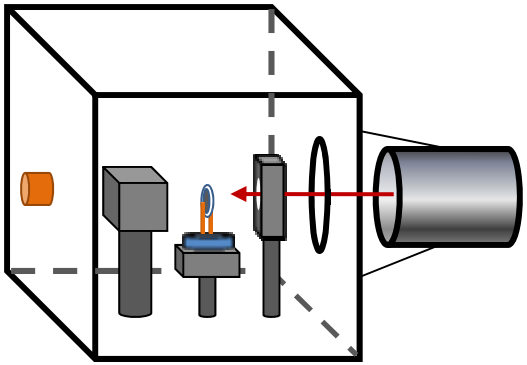
Calorimeter

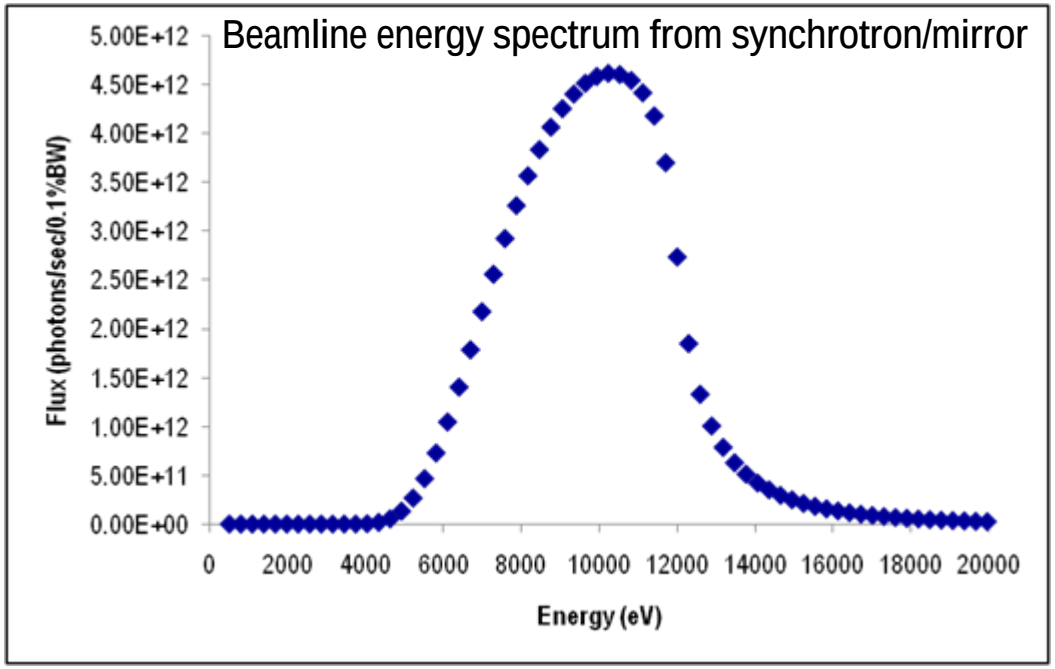
White Beam Test

Flux Linearity and Current Limit Test

- X-ray focused/unfocused white beam used to generate carriers
- Up to 11-17 W of x-ray power, with energies ranging from 6-15 keV
- 2mm^2 area intercepts ~ 3% of the beam (unfocused), full beam (focused to 1.1x0.6 mm^2)
- Diamond absorbs ~10%
- 85 mA current: 13 A/cm^2 (focused)
  40 mA current: 2 A/cm^2 (unfocused)
- Ion chamber used for low power calibration, copper calorimeter for higher power
- Response is linear over *11 orders of magnitude*

*White beam flux / positioning diagnostics presently sought by several synchrotrons





"Development of diamond-based x-ray detection for high flux beamline diagnostics", Bohon, Muller, Smedley in preparation.

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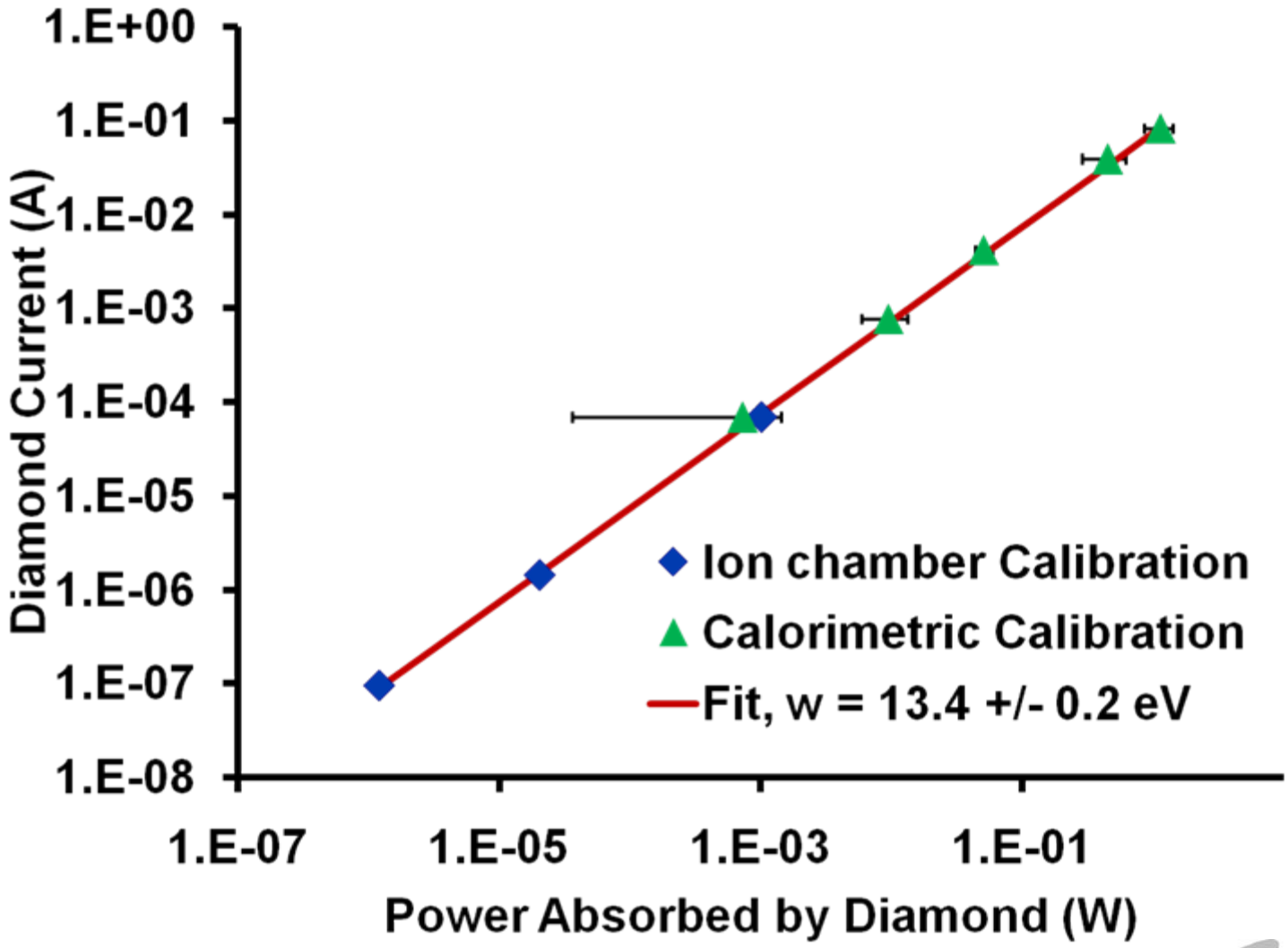
Flux Linearity

Fit parameters:
- Mirror angle (affects spectrum)
- W parameter (matches monochromatic measurements!)

Note:
85 mA ~ 13 A/cm^2 (10x the amplifier need)!



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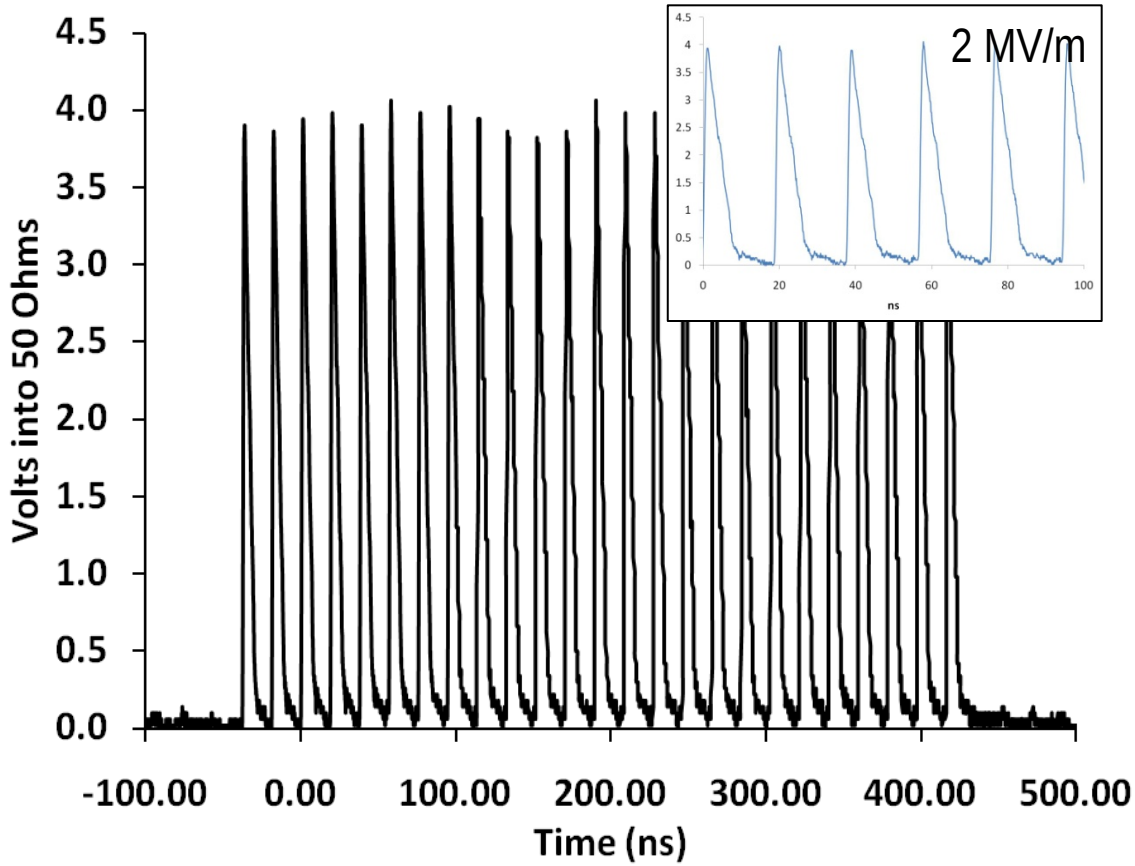
High Speed Performance

High bias, blocking contacts, high quality diamond allows observation of synchrotron bunches with <5 ns response time (X28c pink beam)

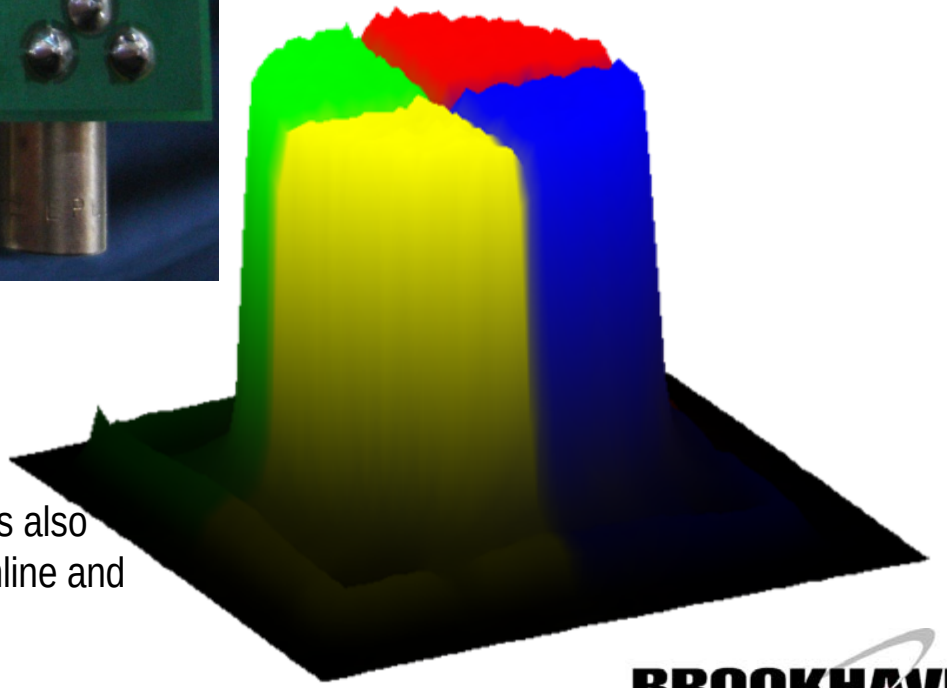
NSLS-XRAY ring structure (25 of 30 bunches filled) clearly seen, with low background (minimal photoconductive "persistent" current)

(details addressed by J. Smedley)



Quad Beam Position Monitor

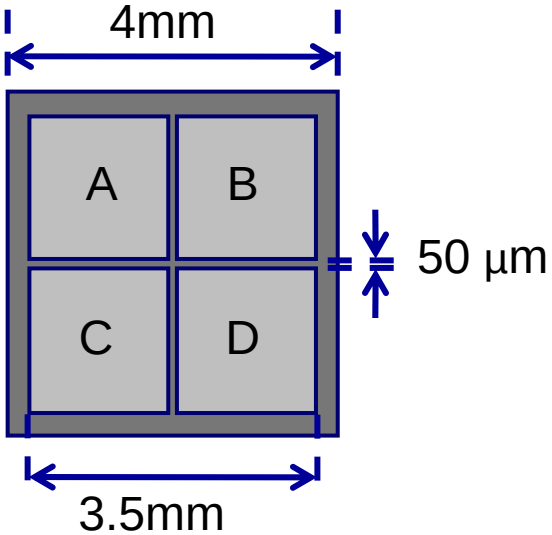
- PCB-mount version for monochromatic (low intensity) beam
- Wirebonds to LEMO connectors (may also use clips)
- 50 µm “street” between quadrant pads
- Ultra-slim design to reach tight spaces



High sensitivity, response uniformity across each of 4 pads

*Monochromatic beam flux / positioning diagnostics also presently sought by several synchrotrons for beamline and accelerator diagnostics (also white beam)

Quad Diode Position Monitor



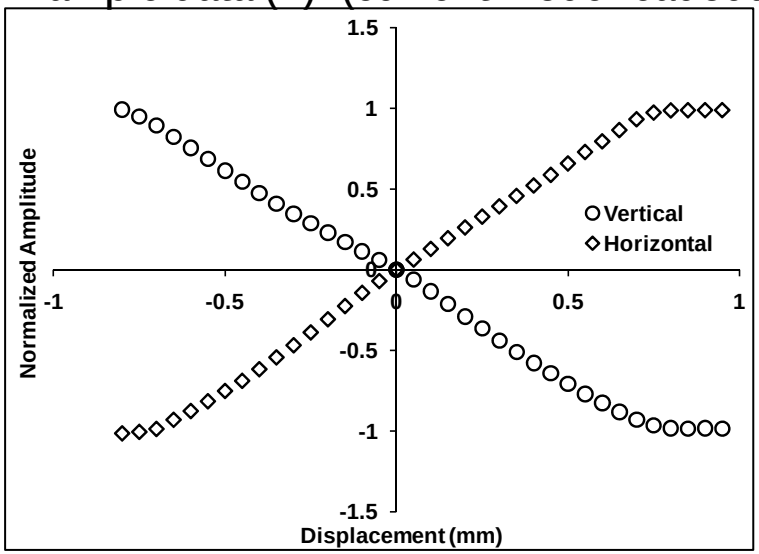
Quadrant Beam Position Monitor

One side metalized with quadrant geometry (30nm Pt),
Opposite side is a solid electrode
Beam position is determined by

$$X = G_x \frac{(B+D)-(A+C)}{A+B+C+D} \qquad Y = G_y \frac{(A+B)-(C+D)}{A+B+C+D}$$

G_x and G_y depend on beam size and shape and must be calibrated

Example data (Y): (current mode readout)



Quadrant detector measurement: Positional resolution of a single crystal quad detector measured with white beam.

"position noise" is a combination of actual beam wander, motor position noise, and detector noise (ultimate spatial resolution down to 0.1 um possible), here ~6 um (beam dominated).

~300 um thickness; tested at NSLS beamline X28c

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Keys to Sensor Success

3 ways to make the diode non-photoconductive (fast and quantitative):

1. Make sure it has no relevant defects (nano inclusions?) – topography
2. Use blocking contacts (and prevent annealing) – Pt, Al?
3. Use pulsed bias (reduced duty cycle)

Furthermore, *high field* helps with

- Diffusion/recombination loss mitigation
- Device speed (also thinner plates help)
- Spatial resolution (also thinner plates help)

Lingering Questions about Diamond

- Trapping: Charge becoming “trapped” builds up polarization field for subsequent charge to propagate through (both carriers)
  - Time evolution of charge-up, cleaning given flux of photons of given energy (pulsed bias, single bunch)
  - Relate observed time behavior to material defectivity/purity
  - Differences in responsivity, CCD between carriers
- Diffusion-limited resolution and quad design optimization (both carriers)
- Boundary effects
  - Charge from metal contact
  - Conductivity along bare diamond surface
  - Blocking contacts, hole injection

Acknowledgments

- BNL-NSLS, many beamlines (L. Berman, M. Allaire, B. Dong, Z. Zhong, E. Dimasi, J. Sweet)
- CWRU-CBS (J. Bohon, M. Sullivan)
- LANL (J. Distel, D. Casperson)
- Tech-X (D. Dimitrov. R. Busby)
- U. Stony Brook (E. Muller, B. Raghothamachar, M Dudley, M. Gaowei)
- BNL-IO (J. Smedley, D. Pinelli, G. DeGeronimo, J. Walsh, J. Triola)
- BNL-CAD (I. Ben-Zvi, X. Chang, Q. Wu)
- APS (K. Attenkofer)
- BNL-PXRR (A. Heroux, J. Skinner, D. Schneider, R. Sweet)