Diamond Devices
Amplifier to Detector

John Smedley

Instrumentation Division Seminar

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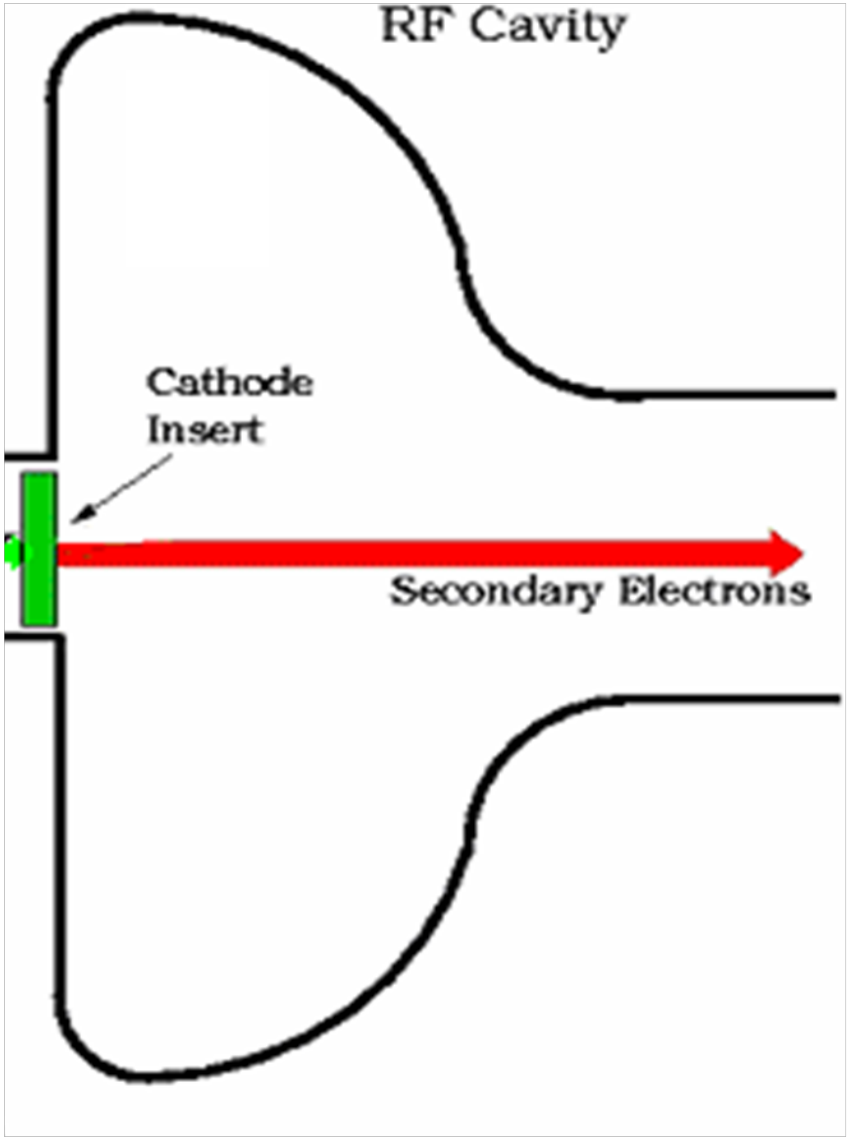
Overview

- Diamond as a secondary emission “amplifier”
- Amplifier results using electrons
- Diamond x-ray detectors
- High-flux detector results at x28c

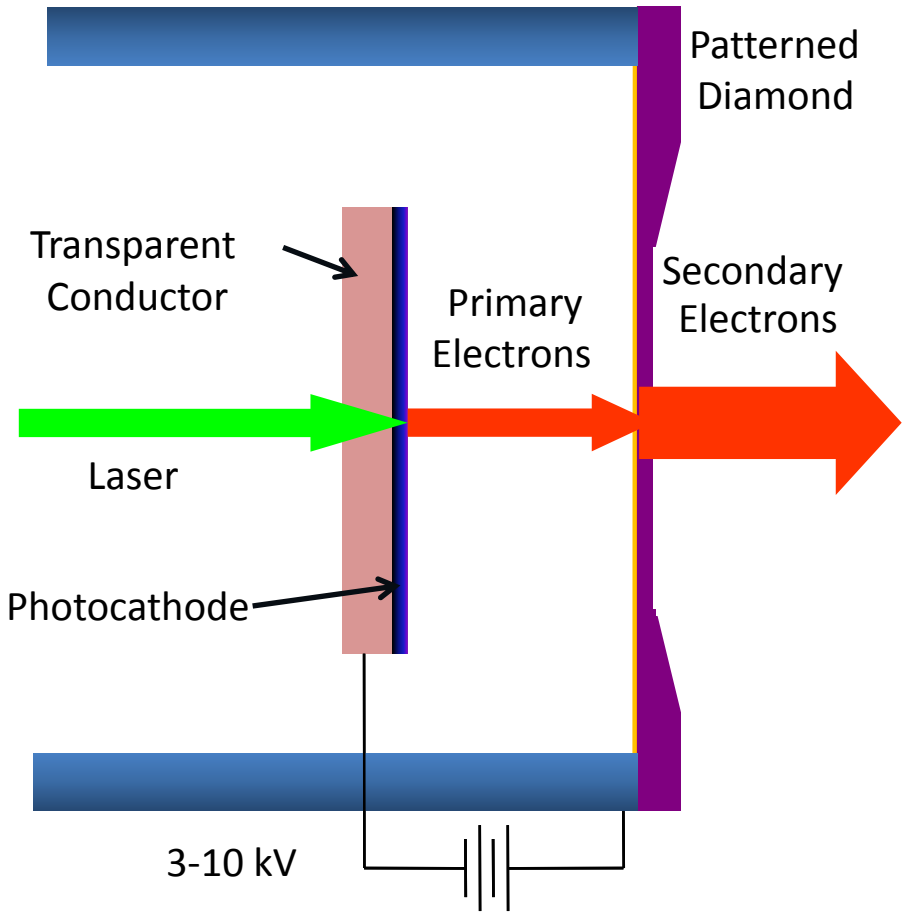
Diamond Amplifier Concept

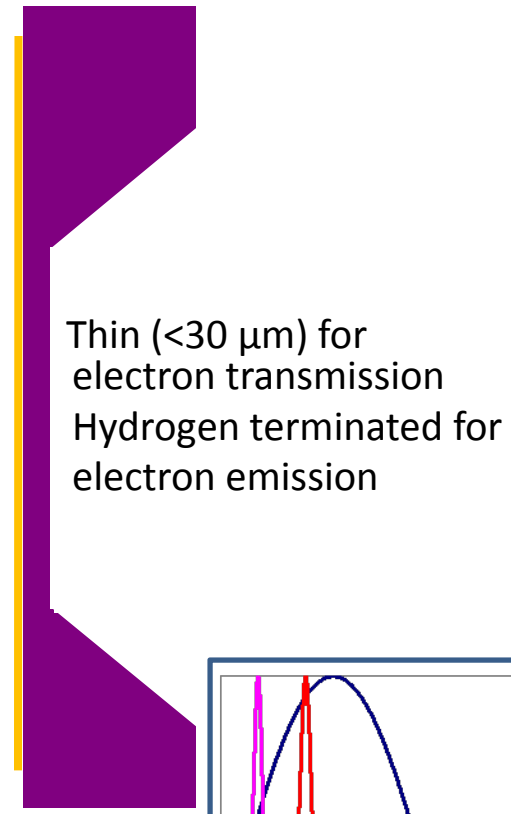
Advantages

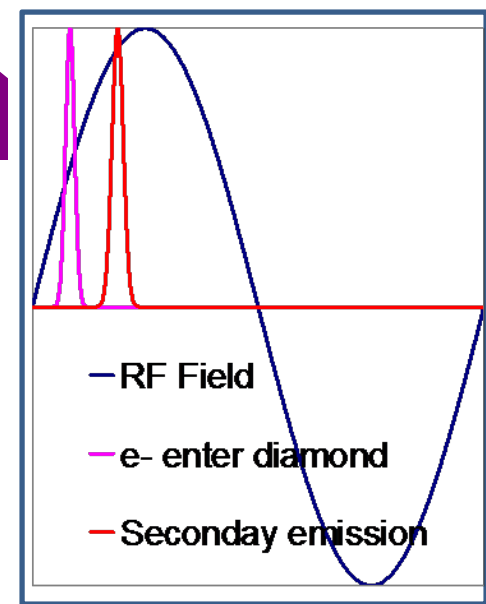
- Secondary current can be >300x primary current
  - Lower laser power
  - Higher average currents
- Diamond acts as vacuum barrier
  - Protects cathode from cavity vacuum and ion bombardment
  - Protects cavity from cathode (prevents Cs migration)
  - Should improve cathode lifetime
- e^- thermalize to near conduction-band minimum
  - Minimize thermal emittance



Diamond Amplifier Concept







Electron saturation velocity in Diamond is ~.2 µm/ps
Takes 150 ps to go 30 µm = 40 degrees of RF
Electrons must exit diamond in time to escape injector
Irregularity of surface will cause bunch spreading

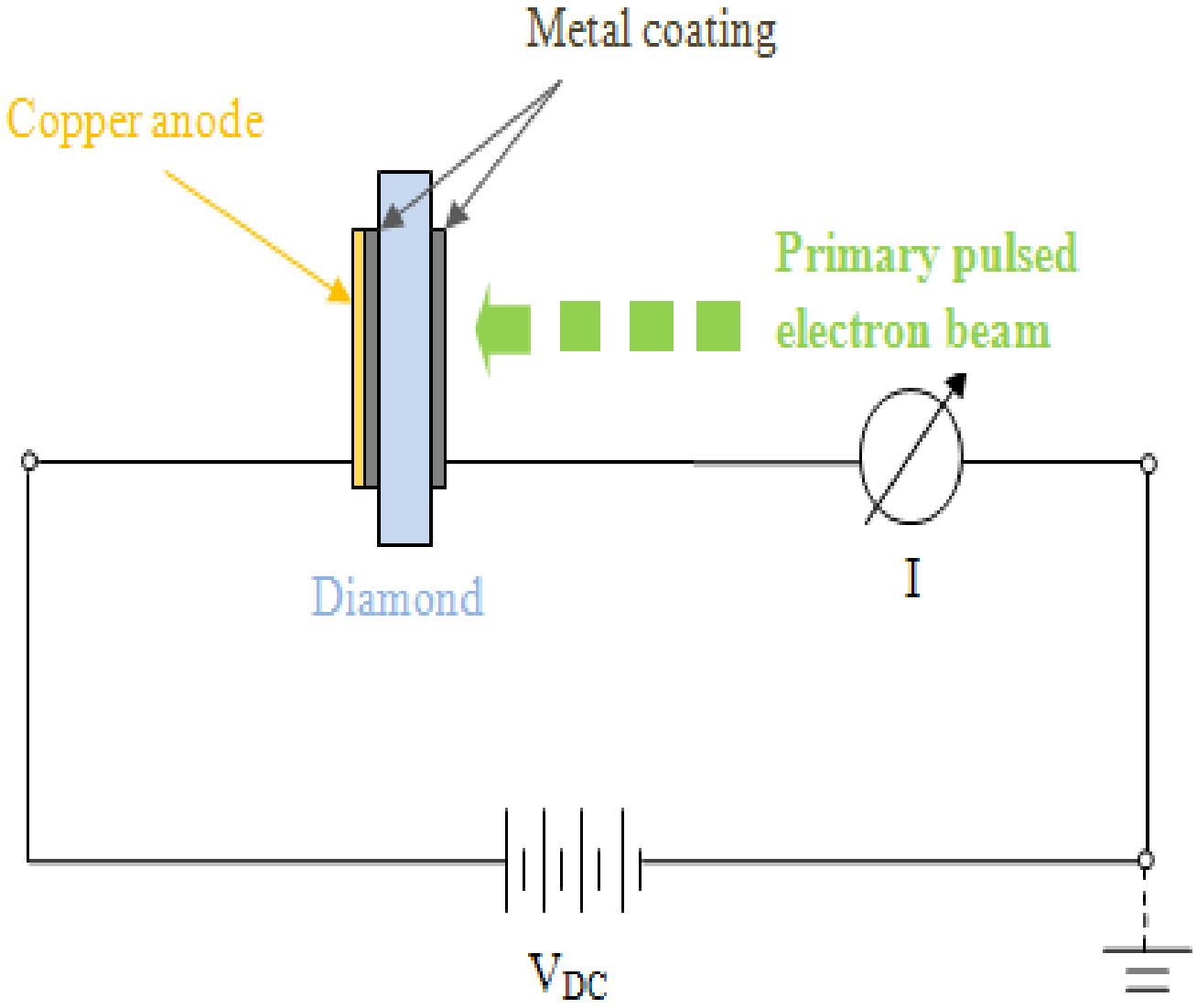
Responsivity and "Gain"

- In the detector business, the term gain is generally reserved for amplification mechanisms which add energy to the signal in the conversion mechanism (avalanche in a gas detector, for example)
- For the electron "amplifier", this is not the case – the incident electron is losing it's energy, and this energy is converted into carriers, much like an ionization mode gas detector.
- Similarly, in a photodetector, the energetic electron produced via absorption of an x-ray photon will produce many carriers
- The "responsivity" of a photodetector (in A/W) is given by:

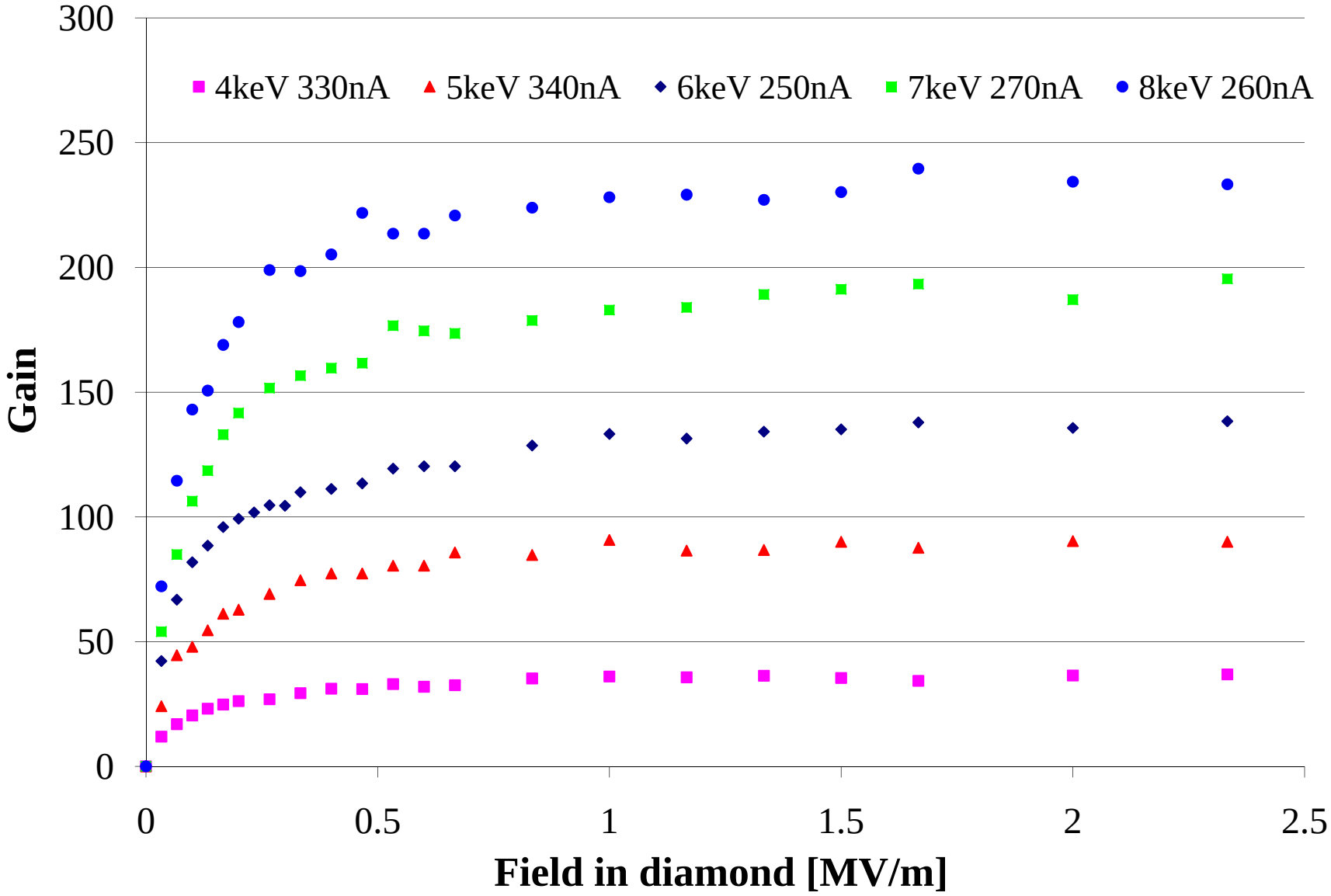
$$S = \frac{1}{W} e^{-t_{window}/\lambda_{window}} \left(1 - e^{-L_{active}/\lambda_{active}}\right)$$

W: mean ionization energy – energy required to create an e-h pair

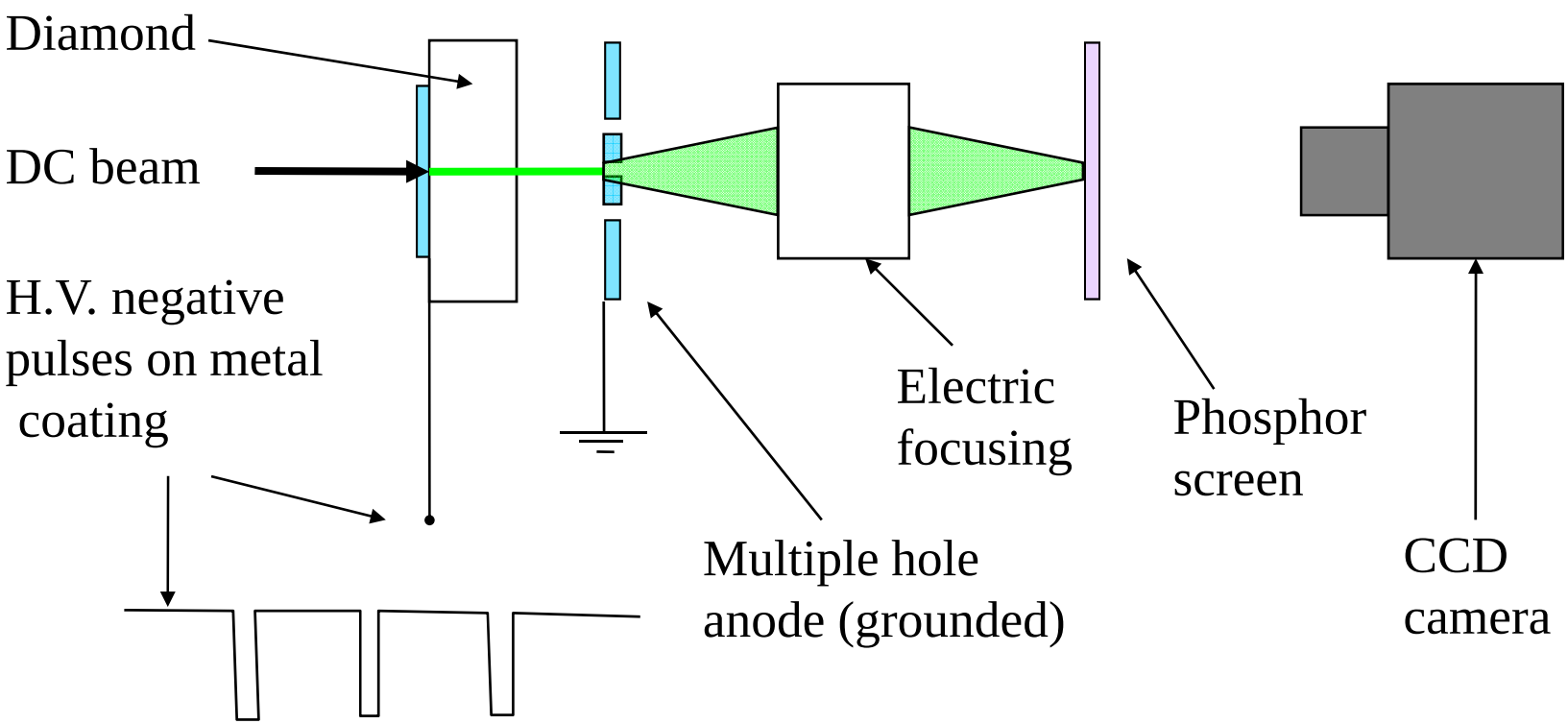
Transmission Mode Measurement



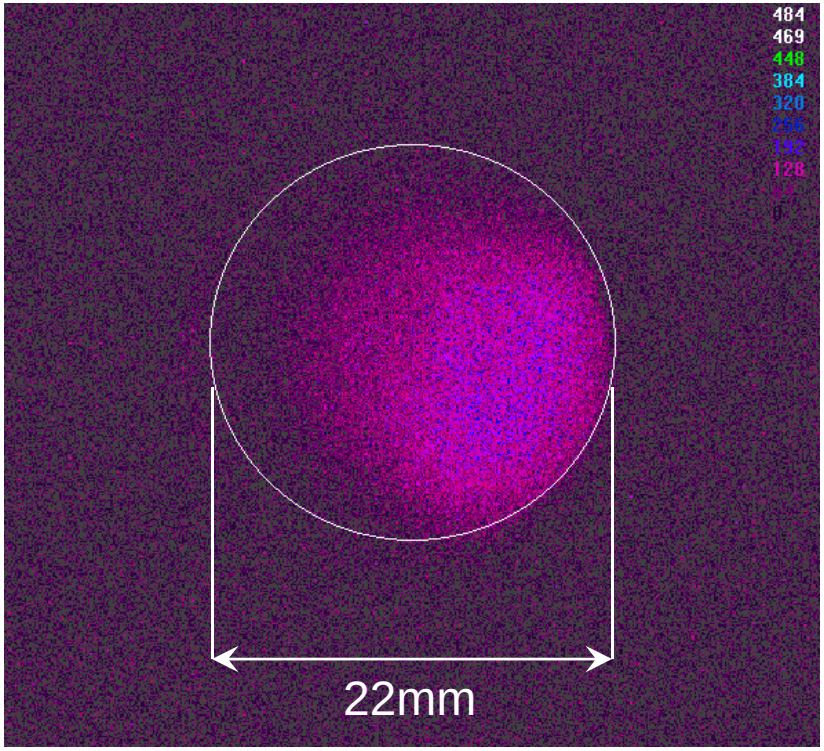
Transmission Mode Gain



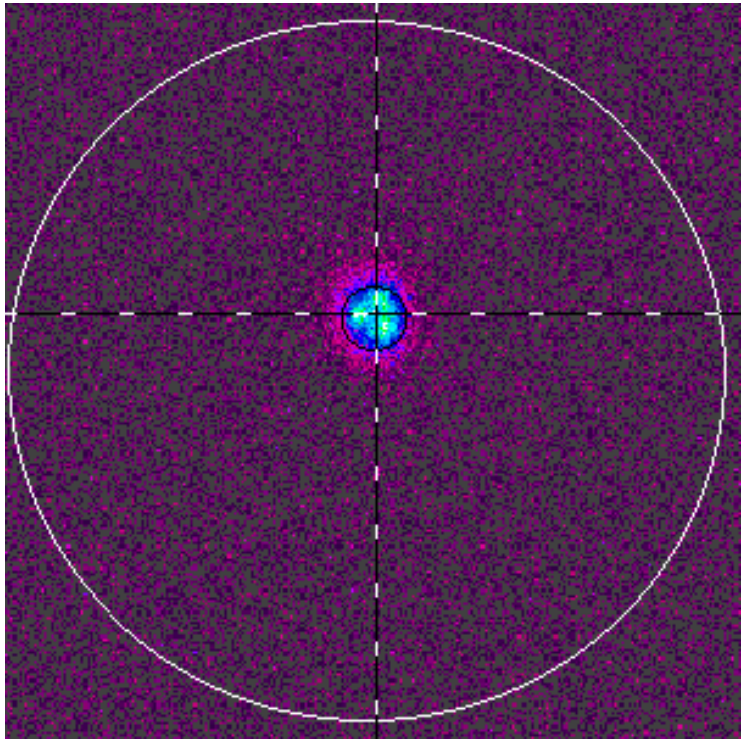
Emission test diagram



First observed beam from diamond amplified cathode



Without focusing



With focusing and reduced primary current

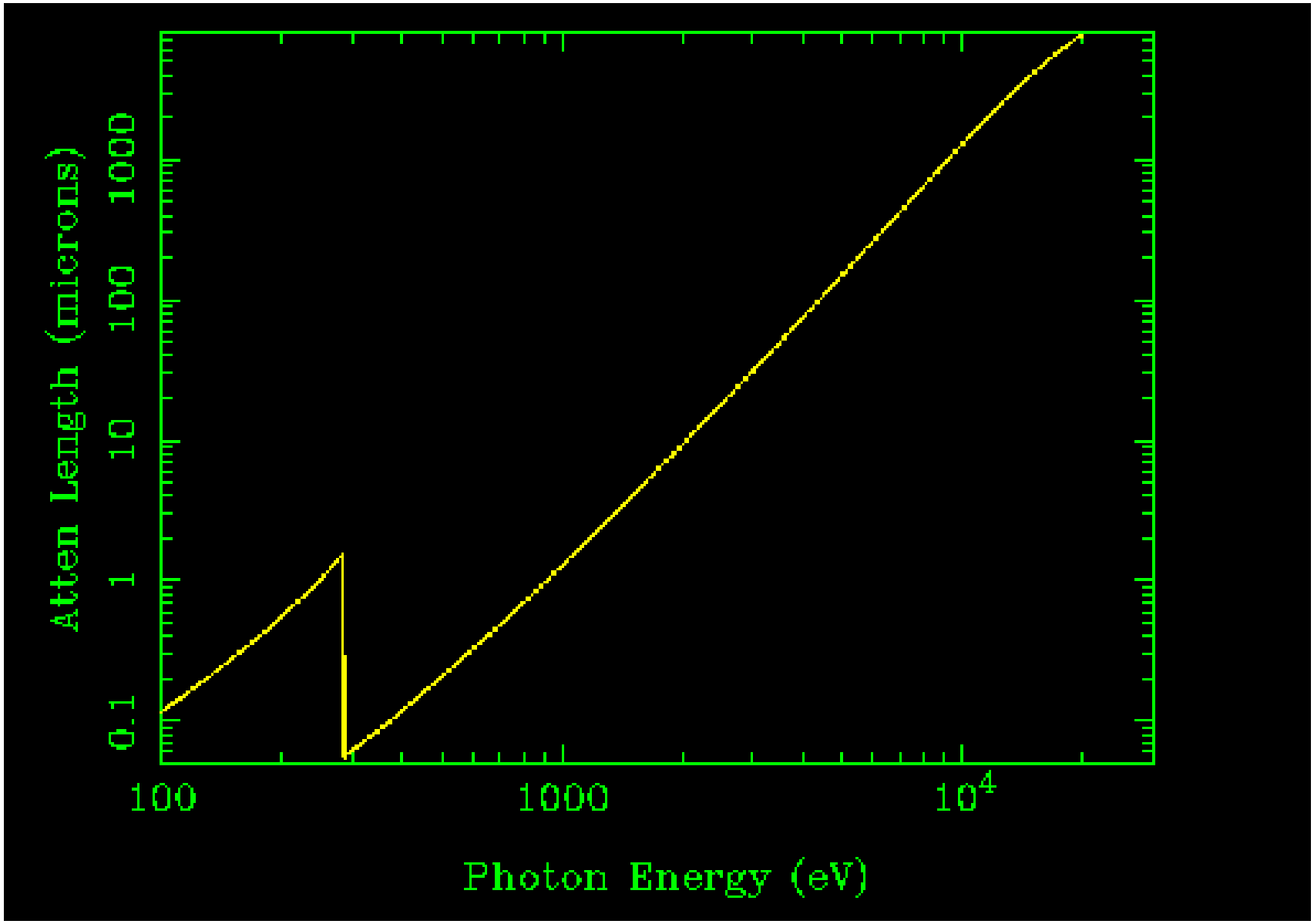
IPri=300nA. HV: 3kV (1.7MV/m in diamond).
Freq. = 1kHz, Duty cycle = 0.001

Gain of 40 was measured in our current test conditions.

Why use X-rays?

- Penetration depth is a strong function of energy -> Can differentiate between surface and bulk effects
- Electron energy from photoabsorption is well defined – can accurately measure mean ionization energy W
- Absorption edges allow differentiation of attenuation from metal vs loss of carriers to diffusion into surface
- Distinguish between electron and hole effects
- Shorter pulses and higher flux available
- Calibrated diagnostic beamlines available at NSLS

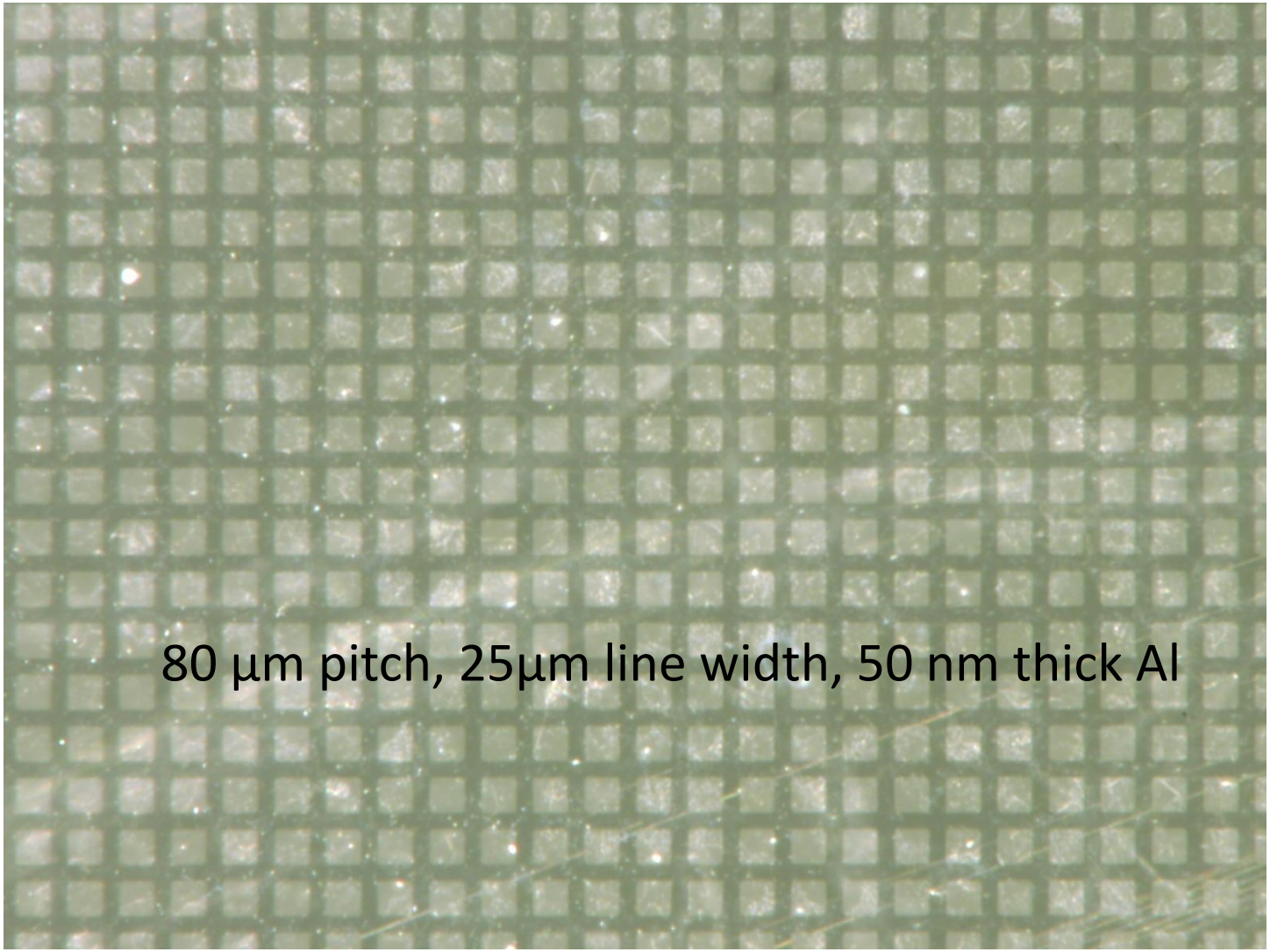
Photon Absorption Length



Metal-Diamond Interface

- We will consider two types of contacts:
  - Contacts which allow charge carriers to pass with sufficient ease to require the diamond to remain charge neutral on average. These contacts allow photoconductive gain, and we'll call them injecting.
  - Contacts which restrict the flow of charge to an extent sufficient to allow the diamond to charge. We'll call these contacts blocking.
- For diamond with oxygen surface termination, all metal contacts tested (Ti/Pt, Pt, Al, Cu, Nb, & Mo) have been blocking
- Oxygen can be removed by thermal annealing, causing contacts to become injecting (remember this – it will come up later)
- For Moly, thermal annealing has been used to create injecting Mo_2C contacts

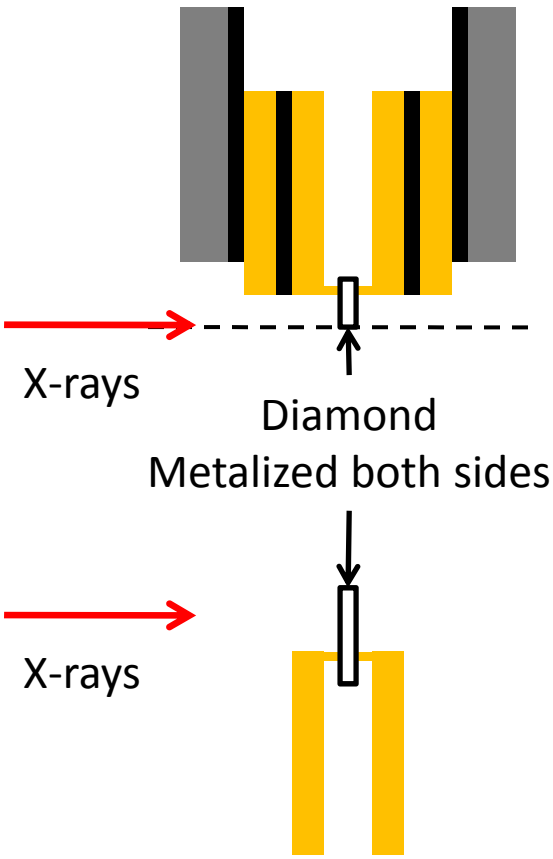
Lithographic Pattering of Contacts



Diamond as a Detector

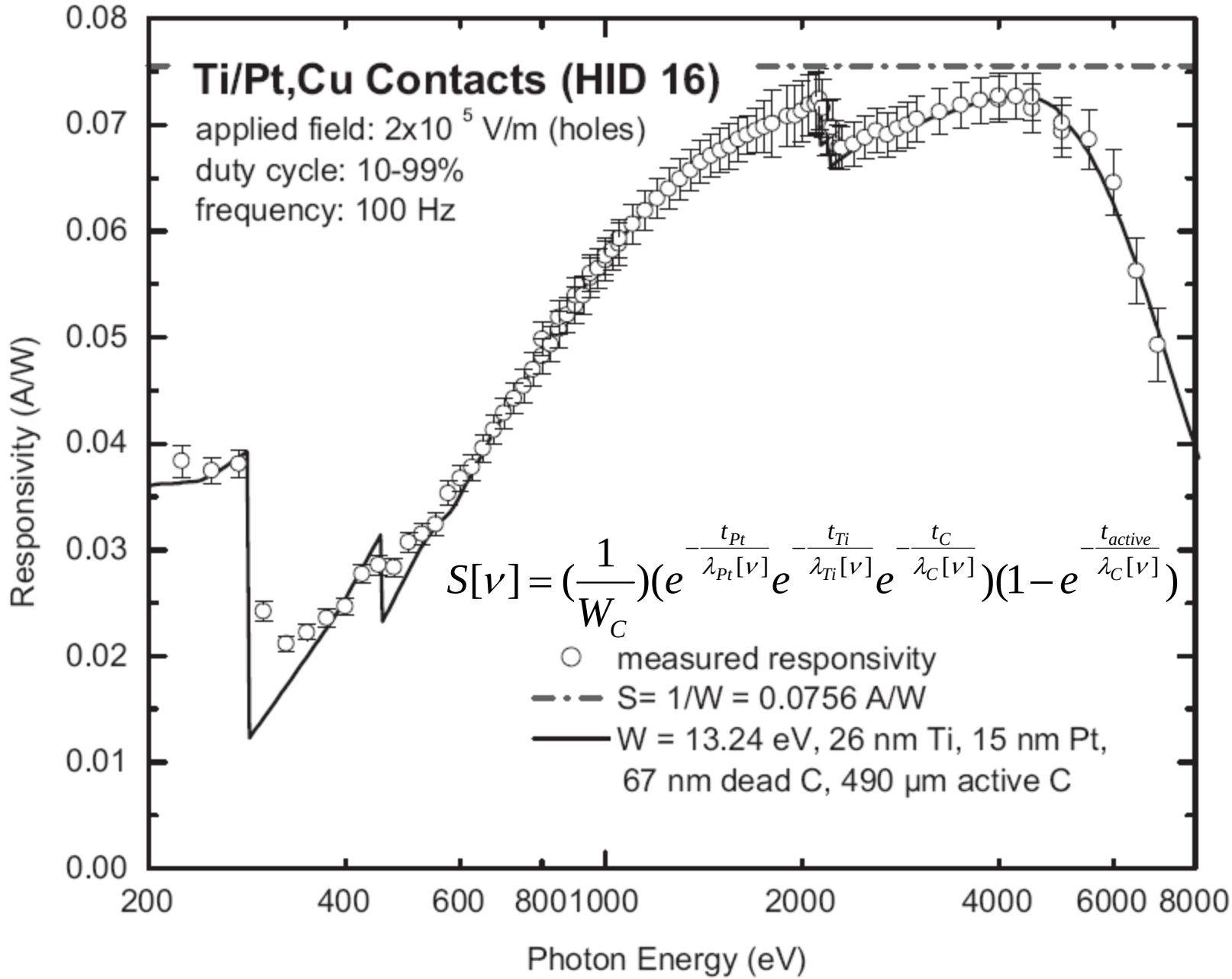
- Initial oxygen termination achieved by acid etch or ozone exposure
- Diamond metalized on both surfaces with 3mm diameter electrodes
- X-rays generate carriers (stand in for the energetic e^- in the amplifier)
- Soft x-rays generate carriers near incident surface (similar to e^- case), allowing electron and hole motion to be separated by biasing
- Harder x-rays go all the way through, creating a column of charge
- Leakage is <1 pA for oxygen terminated diamonds, even for 1kV bias

Two detector geometries

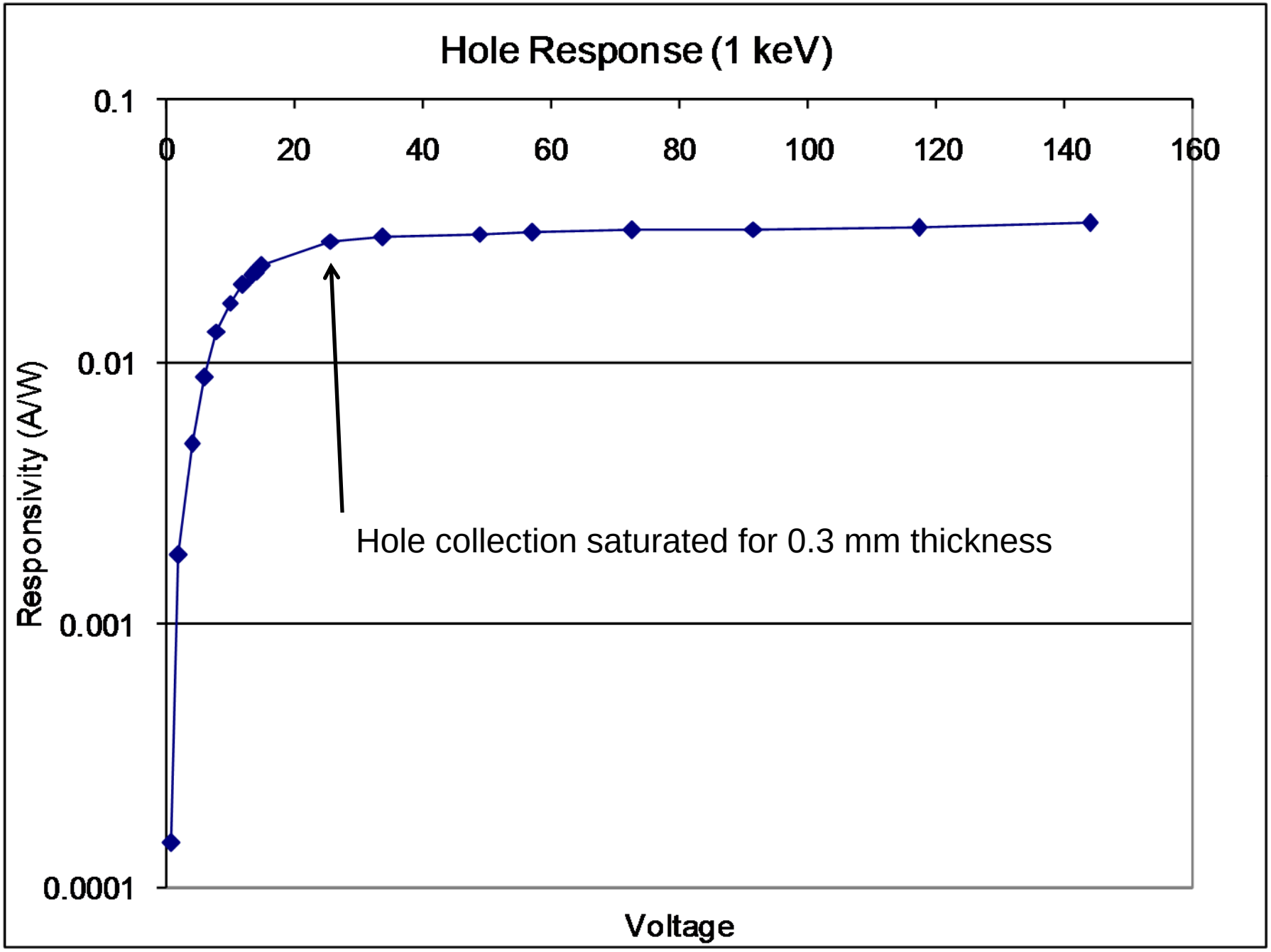


Trapping and Pulsed Bias

- Initially, DC bias was used on detector
  - For soft x-rays, hole response was much lower than expected, and non-linear with flux
- By pulsing the bias on the detector (using an amplified square wave for bias)
  - Hole response matched the model prediction for bias field greater than 0.1 MV/m -> nearly all charge collected
  - Works for wide range of frequencies (1 Hz to >10kHz) and duty cycles (up to 99%)
  - During off cycle, x-ray illumination generates carriers which drift toward and neutralize trapped charge



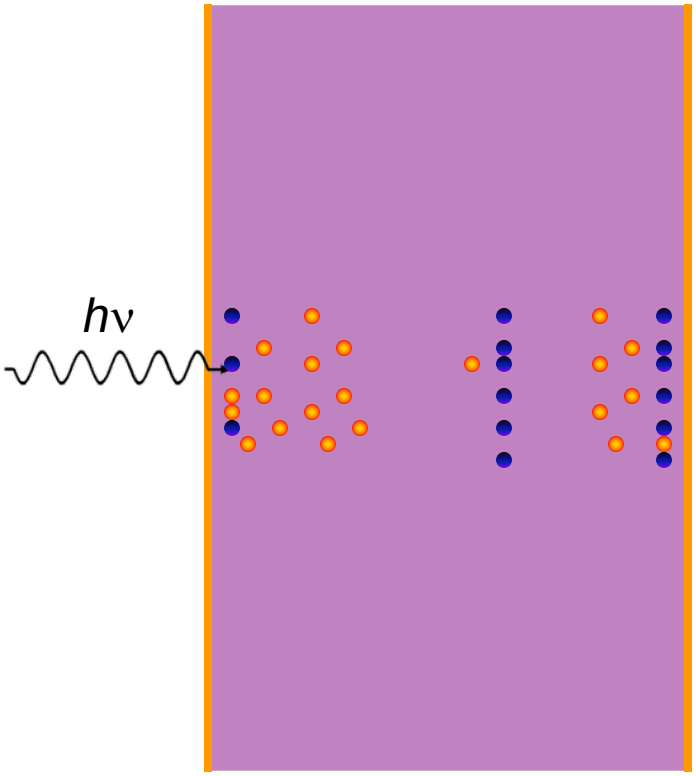
J. Keister & J. Smedley, NIM, accepted


Hole Response (1 keV)
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
140
160
Responsivity (A/W)
Voltage
Hole collection saturated for 0.3 mm thickness

What about electrons?

- Electron response depends strongly on type of electrical contacts
- For blocking contacts, electrons exhibit significantly more trapping than holes
  - Lower duty cycle of pulsed bias to avoid signal loss
  - Never collect all electrons
- For injecting contacts, photoconductive gain is observed
  - Trapped electrons act as effective “doping” of material
  - Holes are injected from opposite electrode

Photoconductive Gain



Photons produce initial carriers
Electrons drift through diamond
Some electrons are trapped in material
Act as effective p-type doping as long they are trapped

On average, one hole is injected into diamond for each trapped electron, keeping material charge neutral

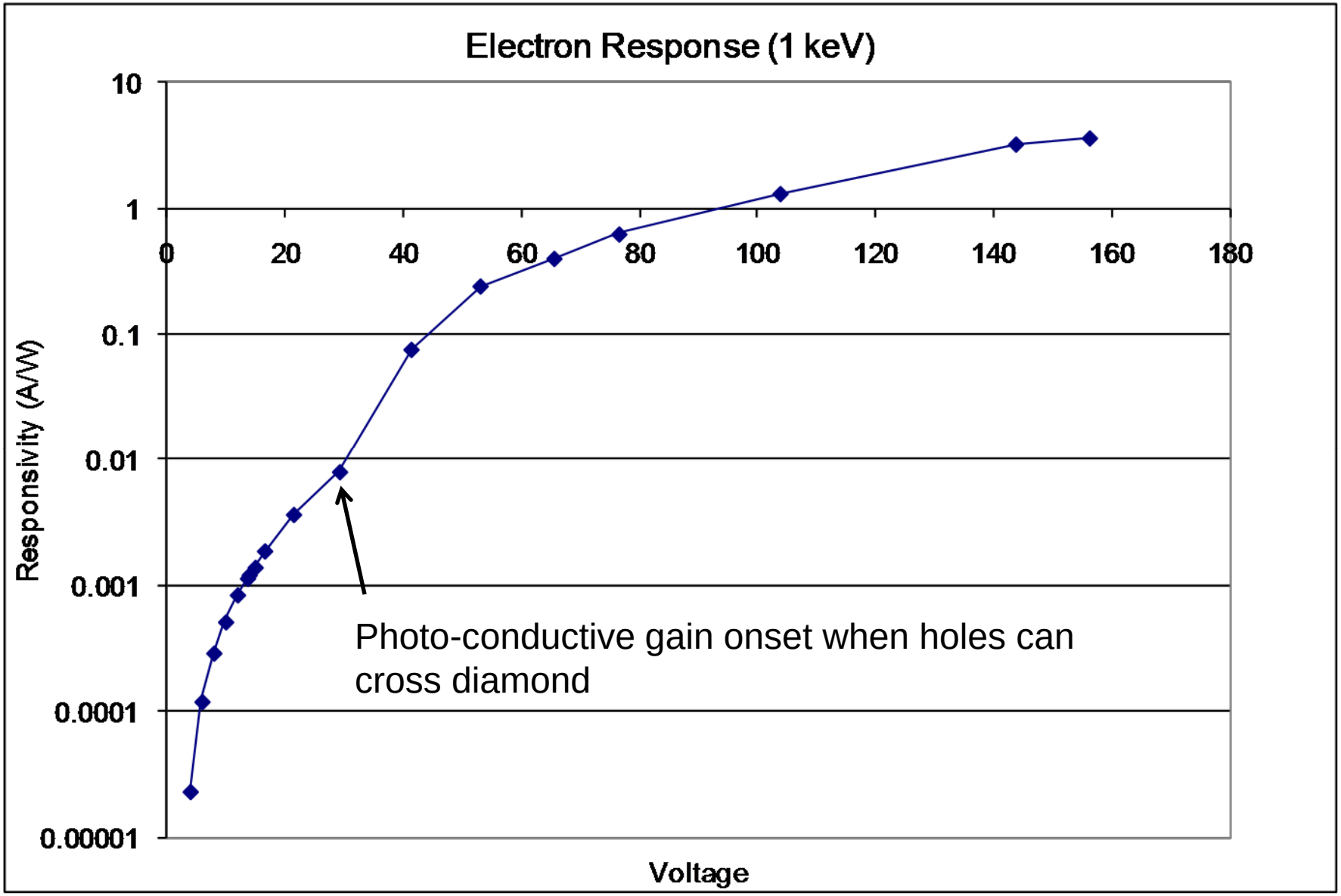
Holes drift through diamond
New holes enter, each time adding current

Process continues until the hole is trapped in the material or the trapped electron is neutralized

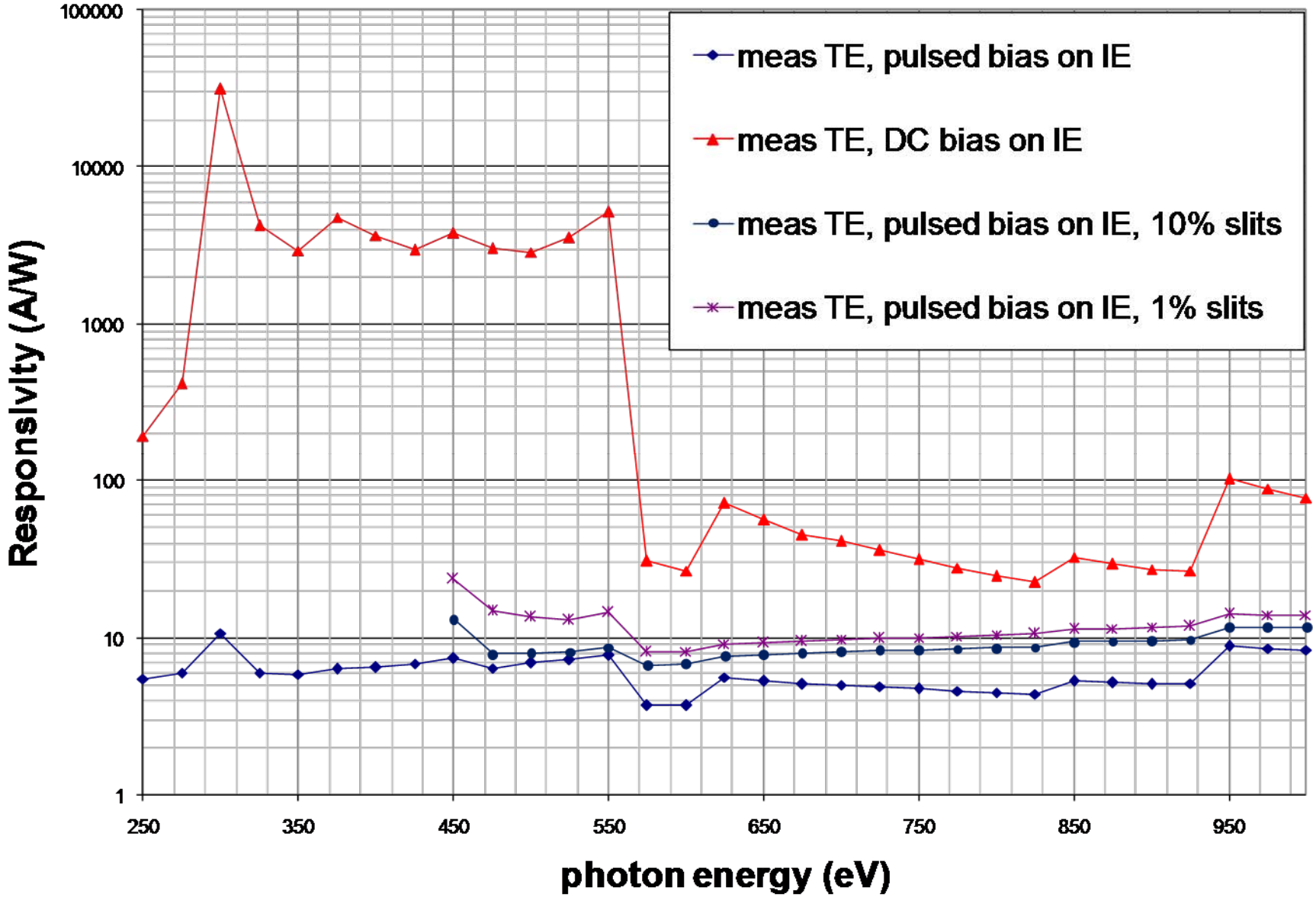
$$Gain = \frac{\tau_{holes}}{t_{holes}}$$

Hole lifetime

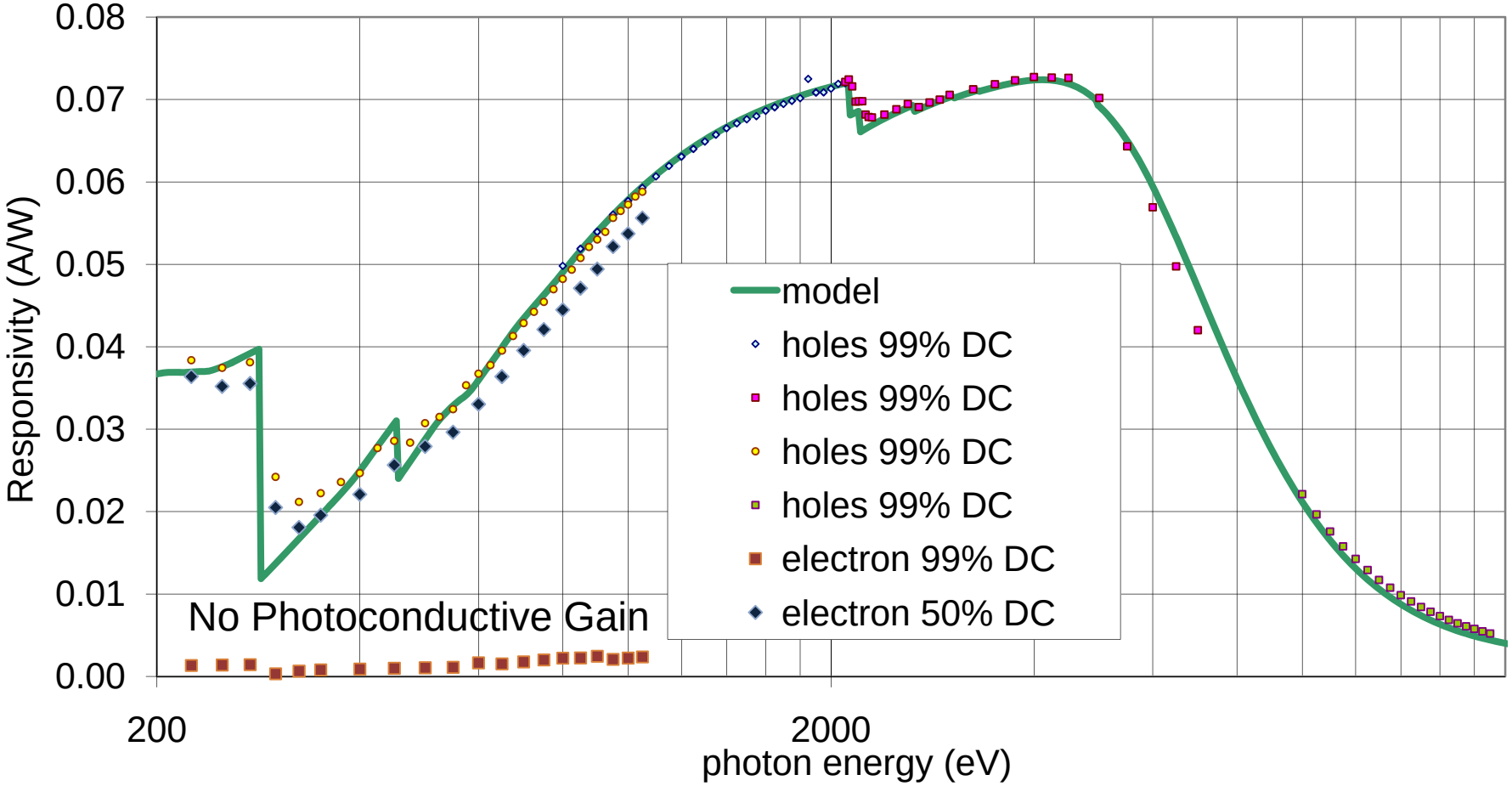
Hole transit time


Electron Response (1 keV)
10
1
0.1
0.01
0.001
0.0001
0.00001
0
20
40
60
80
100
120
140
160
180
Responsivity (A/W)
Voltage
Photo-conductive gain onset when holes can cross diamond

Electron Response, injecting



Electron and hole response, blocking

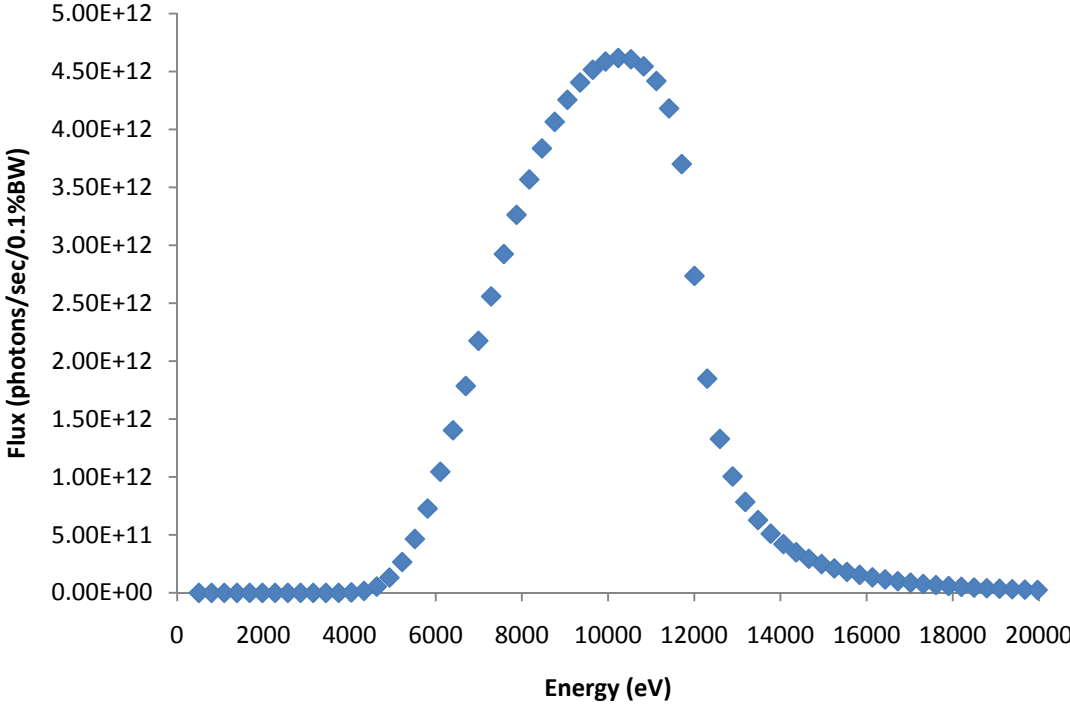


Responsivity Conclusions

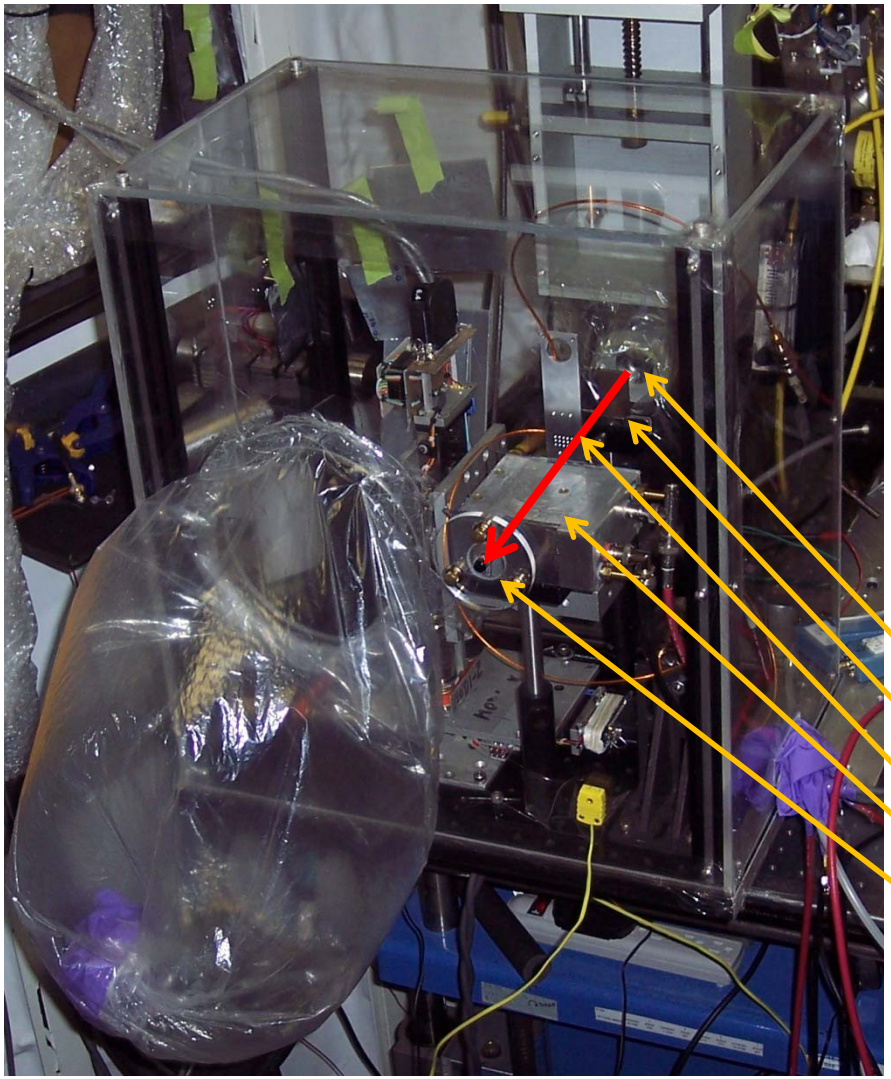
- Holes have larger CCD than electrons in these synthetic diamonds (due to ultra low N content)
- Charge collection for holes is limited only by diffusion of carriers if field is low – for E>0.1 MV/m, all holes collected
- Simple model of Responsivity yields a pair creation energy of 13.3 +/- .25 eV
- Electron trapping occurs in bulk diamond; cannot collect all electrons – leads to PC gain w/ injecting contacts
- Can sweep trapped charge by irradiating diamond w/o bias

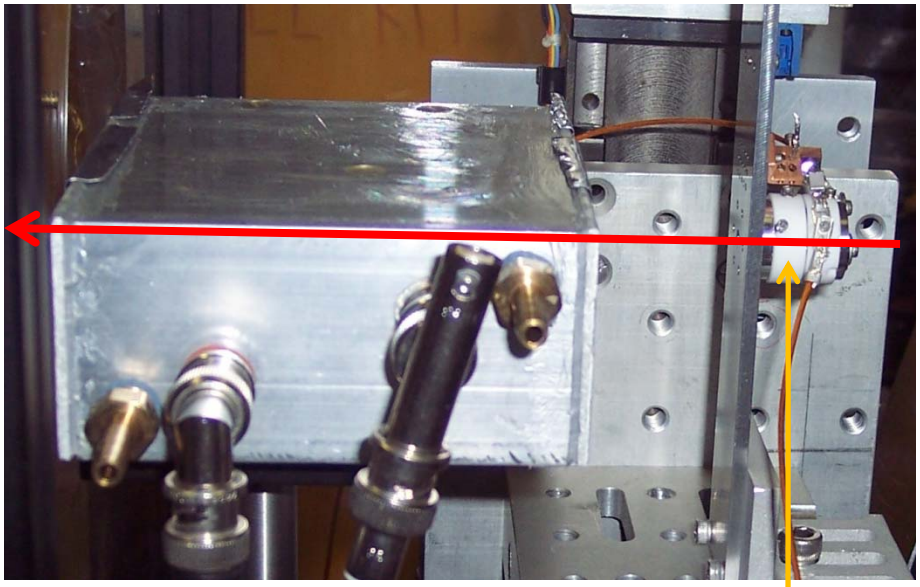
White Beam Test

- Diamond detector used on beam at X28C, with 17W of X-ray power, ranging from 6 keV to 15 keV
- Intercepted ~3% of beam
- Ion chamber used for low power calibration, copper calorimeter for higher power
- Generated 40 mA of current in a 2mm^2 area
- **2 A/cm^2**
- Can see NSLS ring repetition frequency on detector

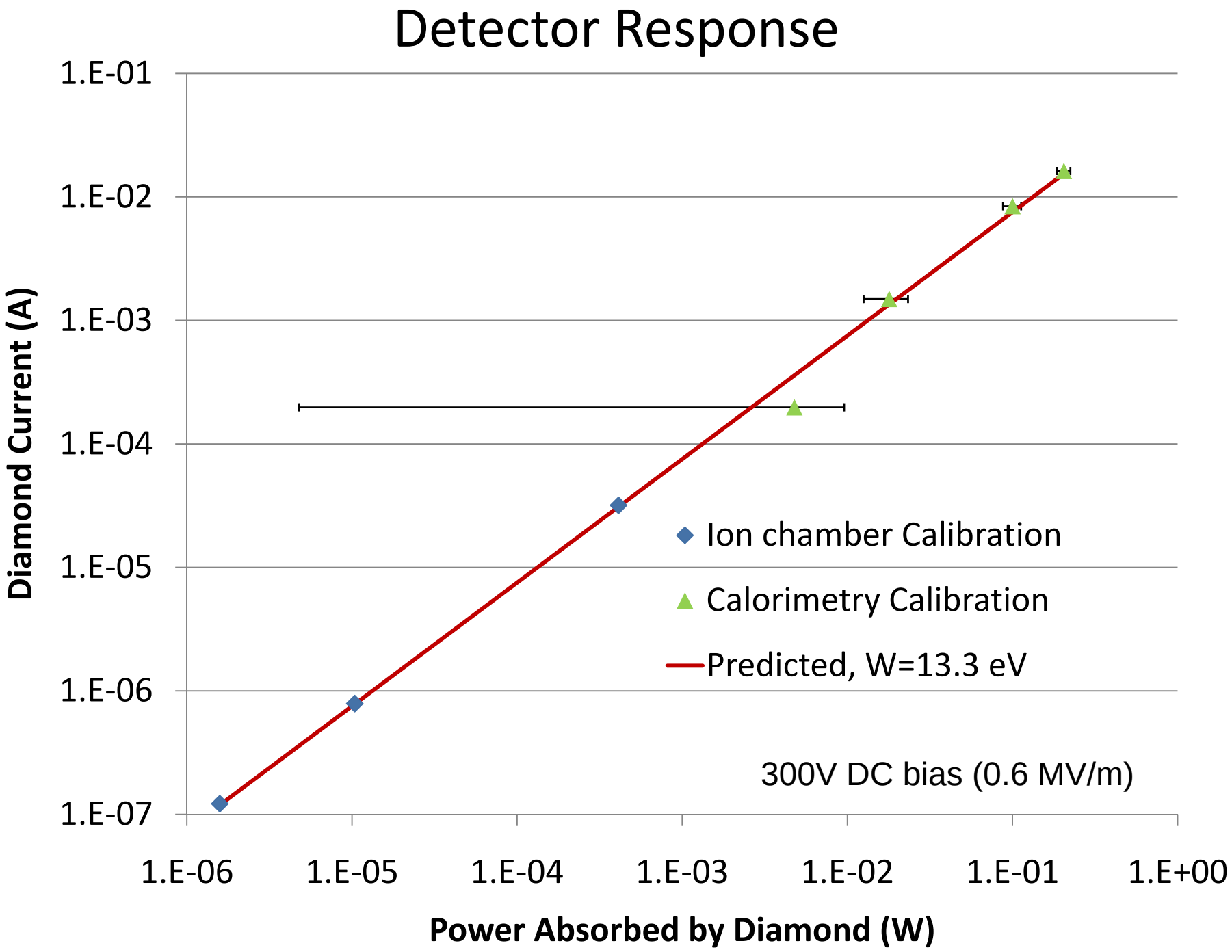


X28c Setup

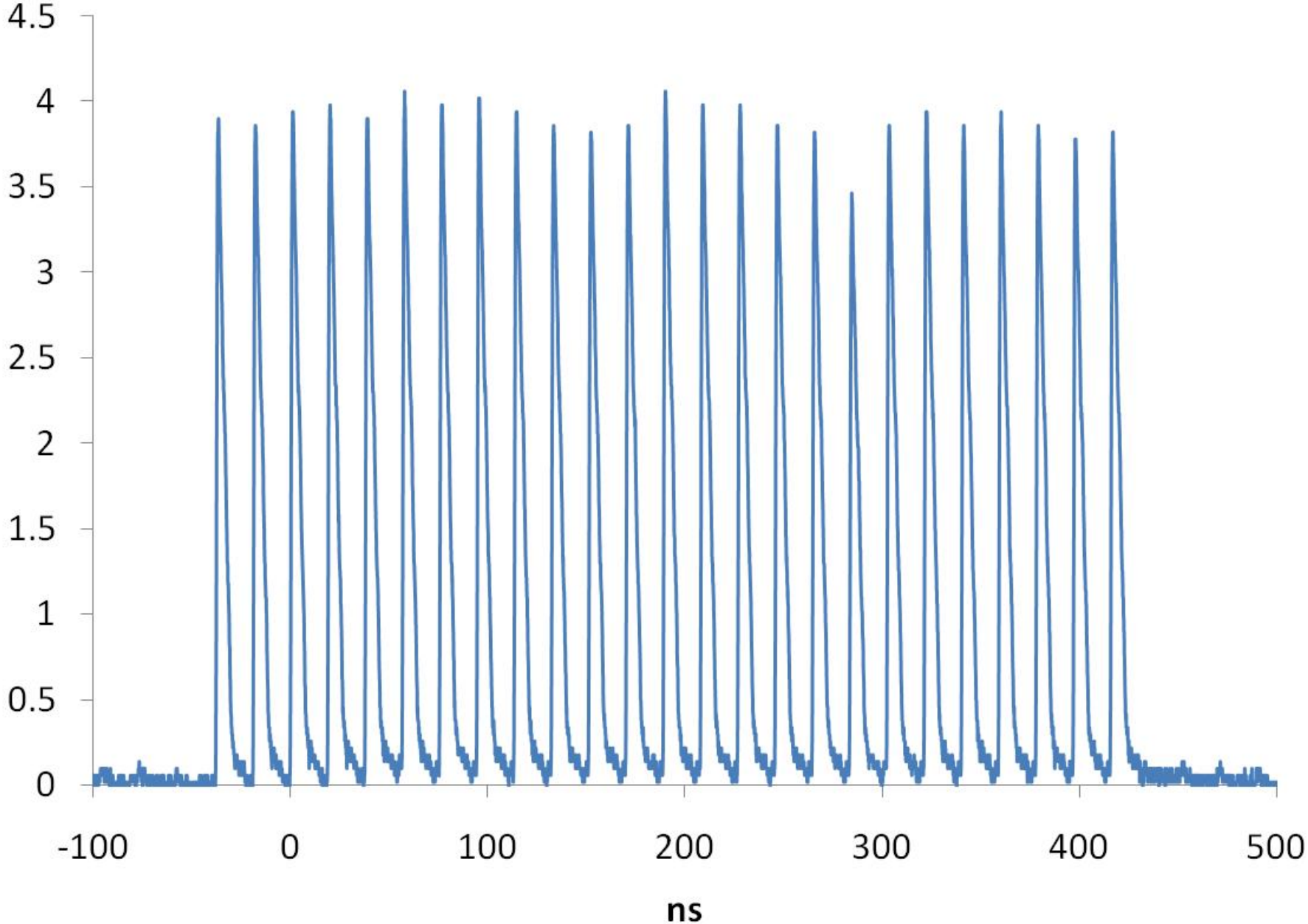




X-ray port
Beam defining aperture
Diamond Detector
Ion Chamber
Calorimeter

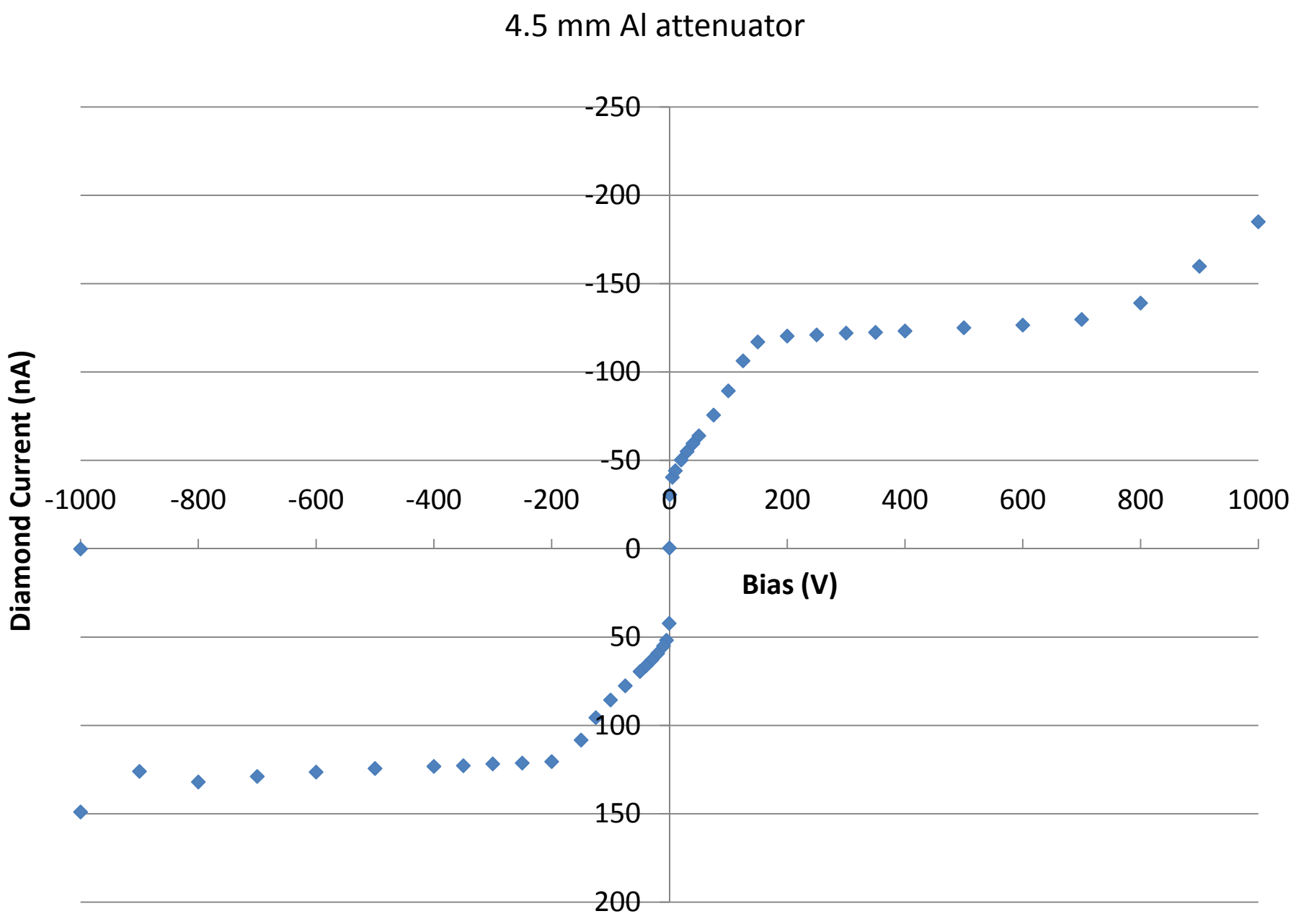

Detector Response
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
Diamond Current (A)
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
Power Absorbed by Diamond (W)
Ion chamber Calibration
Calorimetry Calibration
Predicted, W=13.3 eV
300V DC bias (0.6 MV/m)

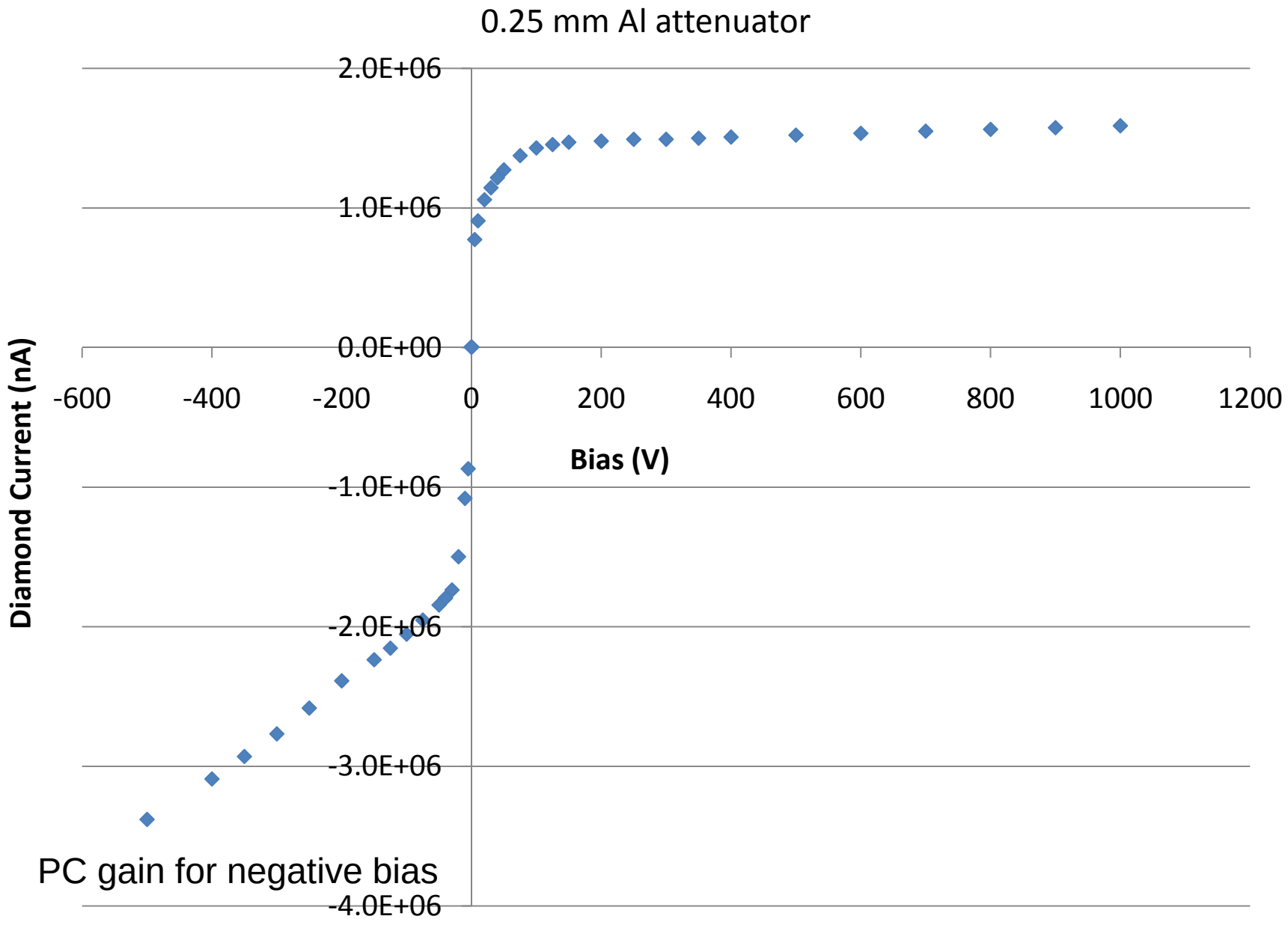
Pulse response, 2 MV/m



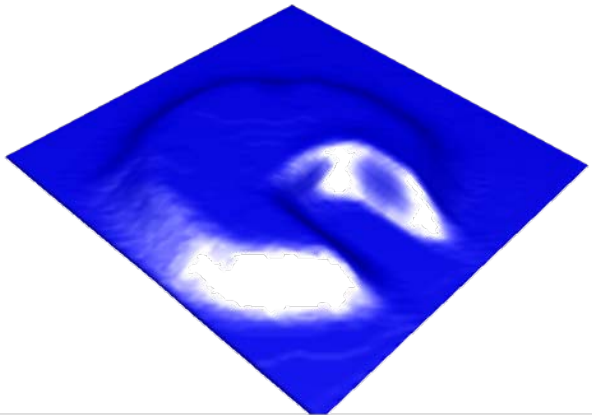
Radiation Hard?

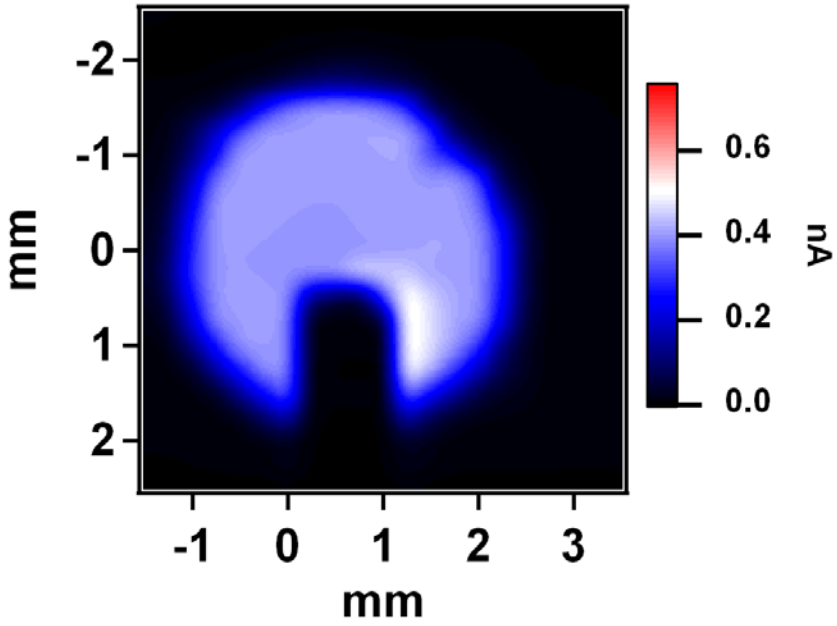
- The diamond was not obviously harmed by absorption of 10^8 rads of x-rays
- However, continuously driving 16+ mA of current at up to 1 kV bias (16 W of electrical power) caused significant heating of device
- This lead to a change in the nature of the response
  - Initially, diamond was a diode, with blocking contacts
  - During high flux measurement, photoconduction was observed for negative bias
  - This change in the contact was permanent – loss of oxygen?
- Subsequent response maps showed that photoconductive region is tiny (~200 microns across), and that a region of PC gain for opposite polarity is present in the unirritated area


4.5 mm Al attenuator
Diamond Current (nA)
Bias (V)
-250
-200
-150
-100
-50
0
50
100
150
200
-1000
-800
-600
-400
-200
0
200
400
600
800
1000

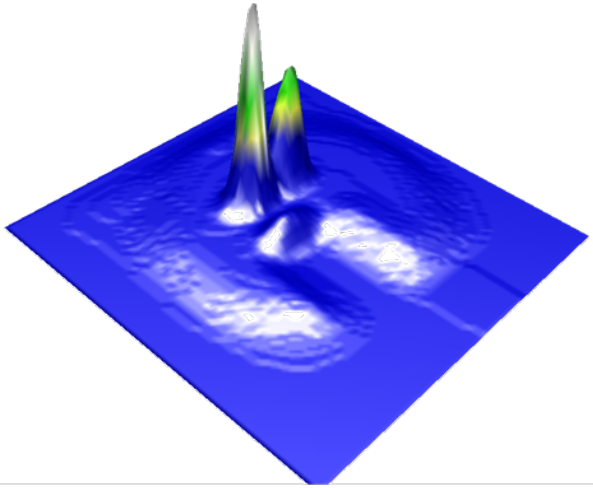

0.25 mm Al attenuator
2.0E+06
1.0E+06
0.0E+00
-1.0E+06
-2.0E+06
-3.0E+06
-4.0E+06
-600
-400
-200
0
200
400
600
800
1000
1200
Bias (V)
Diamond Current (nA)
PC gain for negative bias

HID14 in X15
(80%, 100V, 1kHz, 19keV)

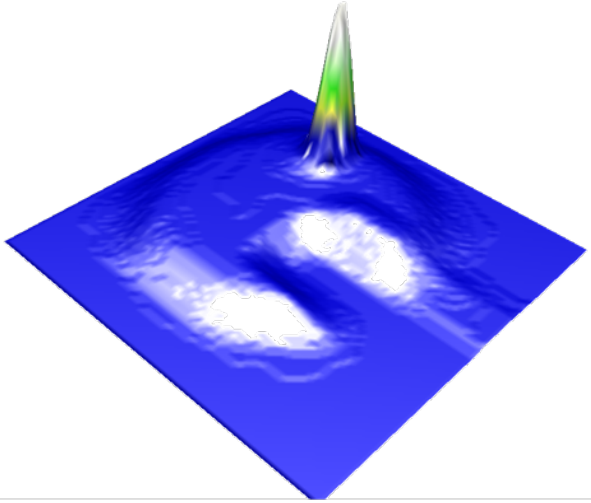




HID18 in X6B
(80% ,-100V, 1kHz, 19keV)

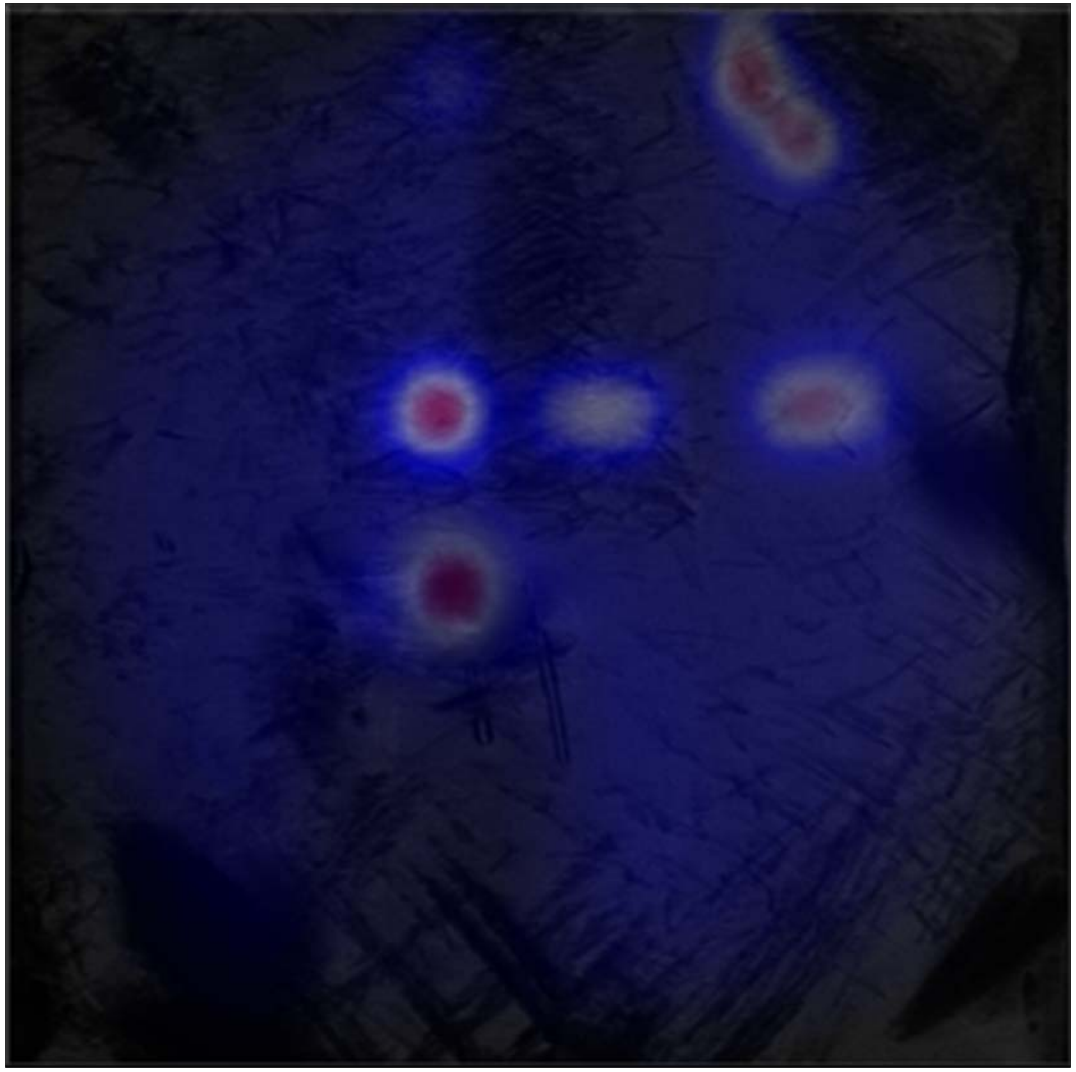


HID18 in X6B
(80% ,+100V, 1kHz, 19keV)



Localized charge trapping causing localized gain

Related to defects/inclusions?



Conclusions & Thoughts

- Diamond detector response is linear from 100pW – 1W incident x-ray power, and predictable for photon energies from 0.2-28 keV
- For soft x-rays, pulsed bias allows clearing of trapped charge to achieve (nearly) full charge collection
- Above 4keV, DC bias is adequate, even at high flux
  - Pulsed bias is still useful to prevent PC gain, and limit current
- Temporal response of detector is consistent with carrier velocity and thickness
- Up to 40 mA (2 A/cm^2) passed through diamond
- For amplifier, demonstrated emission "gain" of 40
- Due to it's mechanical and thermal properties, diamond is already a candidate to replace beryllium for x-ray windows for some NSLS II beamlines – can we instrument these windows?

Thank you for your attention!

- Thanks to Jen Bohon, Wei Chen, Elaine DiMasi, Jim Distel, Bin Dong, Dan Fischer, Joe Harder, Abdel Isakovic, Cherno Jaye, Jeff Keister, Zhenxian Liu, Erik Muller, Balaji Raghothamachar, Triveni Rao, Bill Smith, Jean Jordan-Sweet, John Walsh
- Special thanks to Pavel & Veljko for helping me understand photoconduction!
- C-AD Diamond Team: Ilan Ben-Zvi, Andrew Burrill, Xiangyun Chang, David Pate, Erdong Wang, Qiong Wu
- Simulations: Richard Busby, Dimitre Dimitrov
- Beamlines: U2A, U2B, U3C, U7A, X3B, X6B, X8A, X16C, X19C, X20A&C, X28C

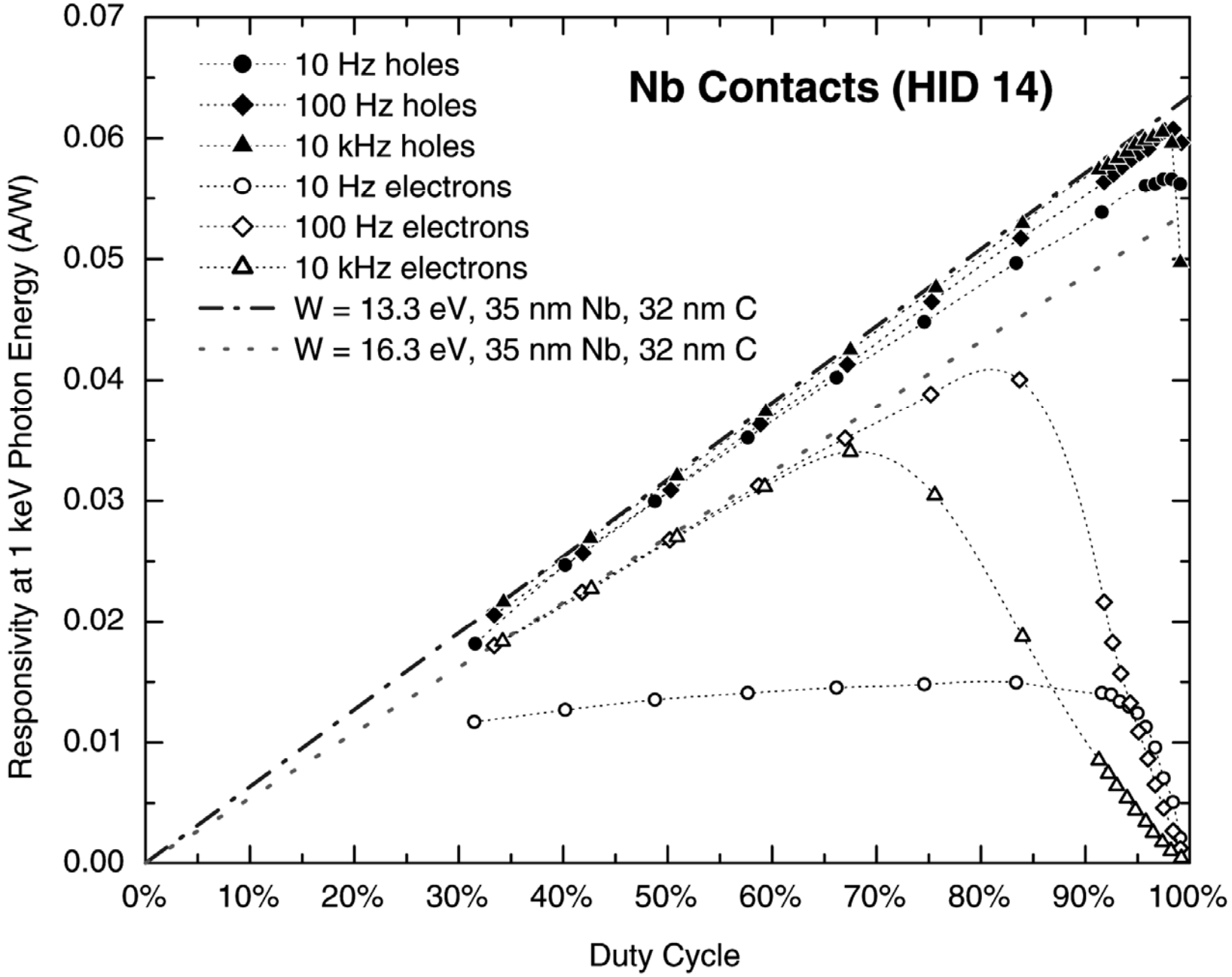
Why Diamond?

Electron Amplifier

- Radiation hard
- Fast (high mobility)
- High thermal conductivity
- Robust ohmic contacts
- Negative electron affinity
  - Easy (Hydrogen)
  - Robust (Covalent Bond)
  - Controllable?

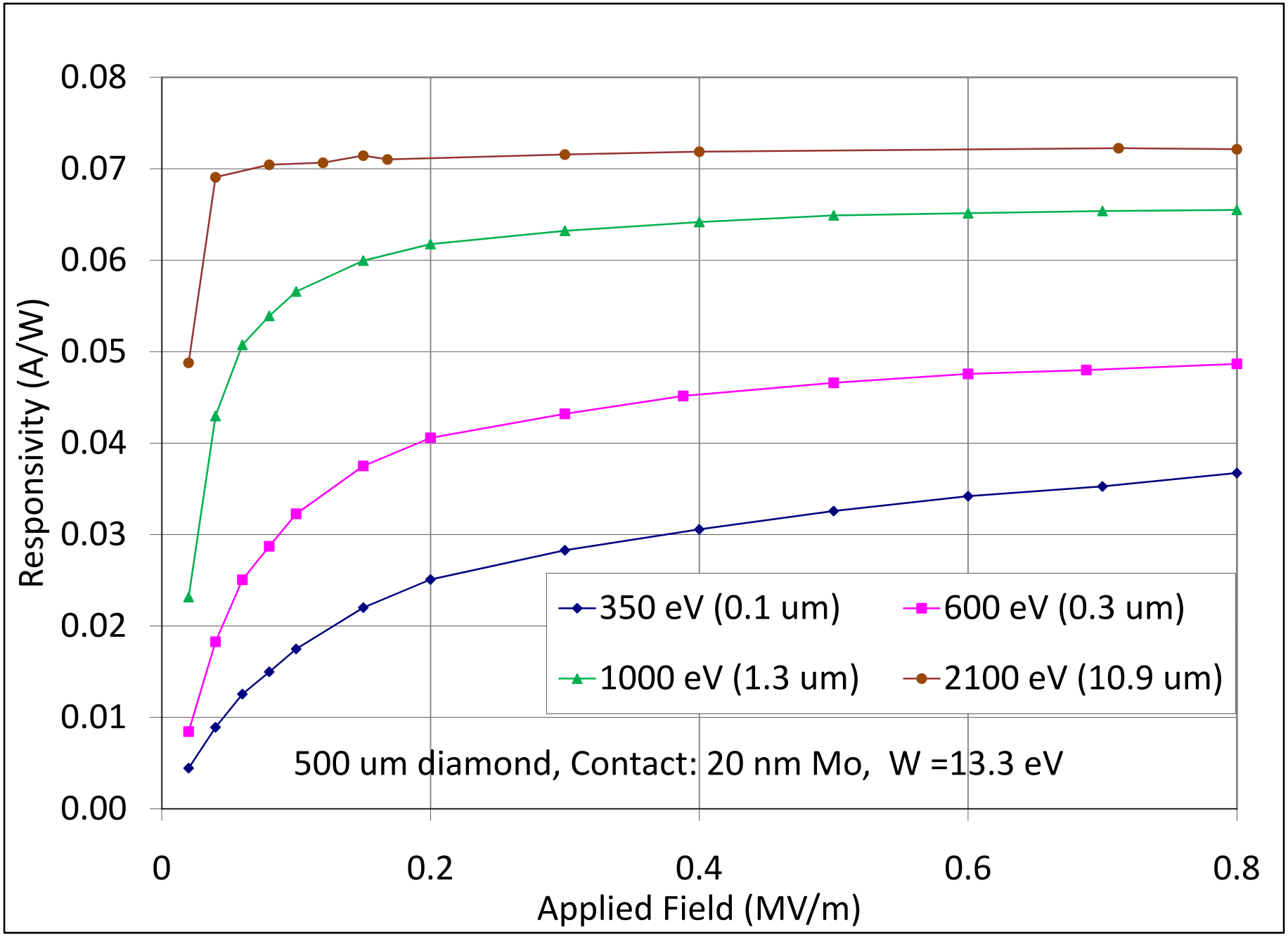
Detector

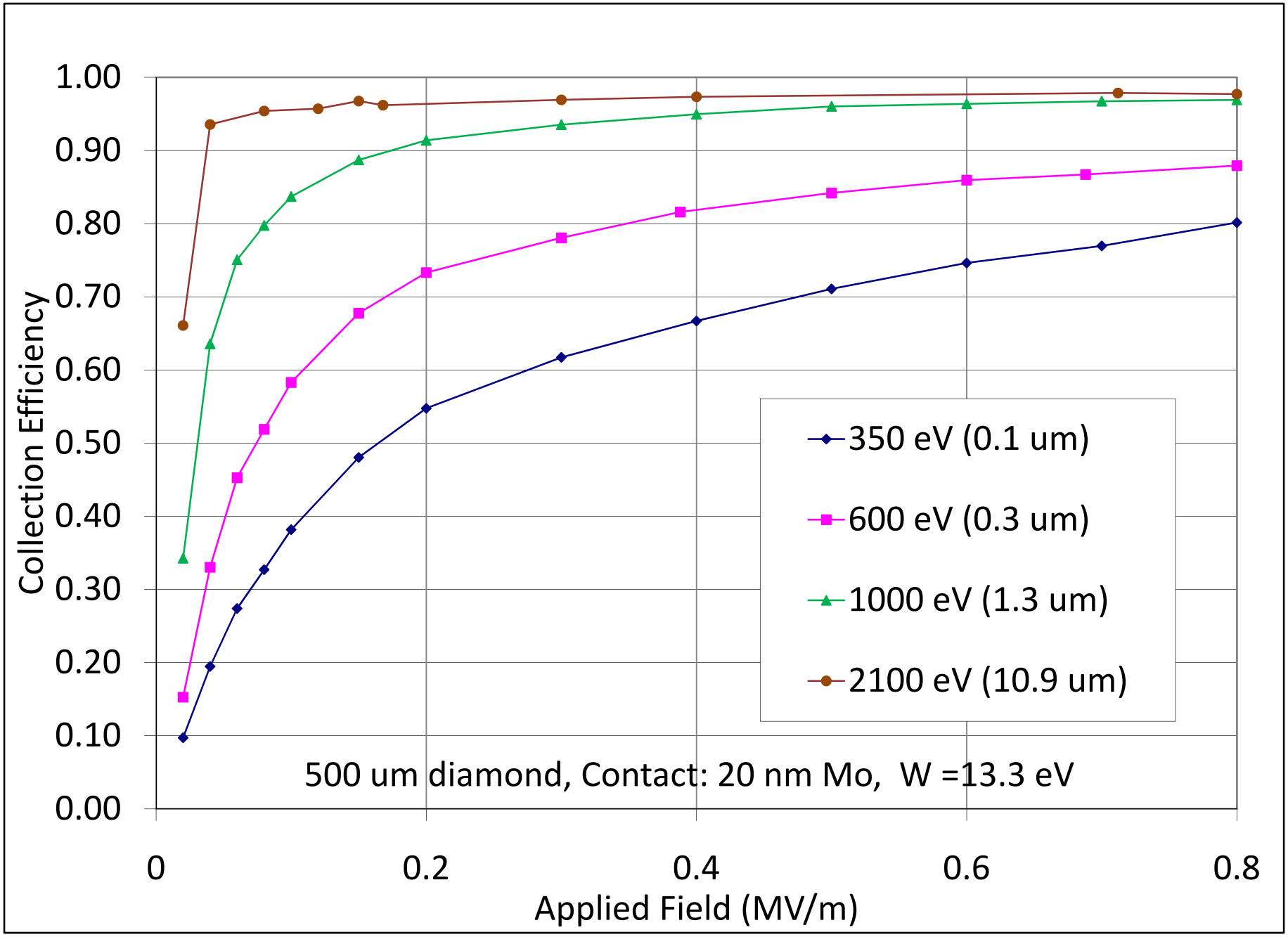
- Radiation hard
- Fast
- High thermal conductivity
- Robust ohmic contacts
- Solar blind
- Low leakage
- Low absorption
  - Transmission devices (beam monitors)

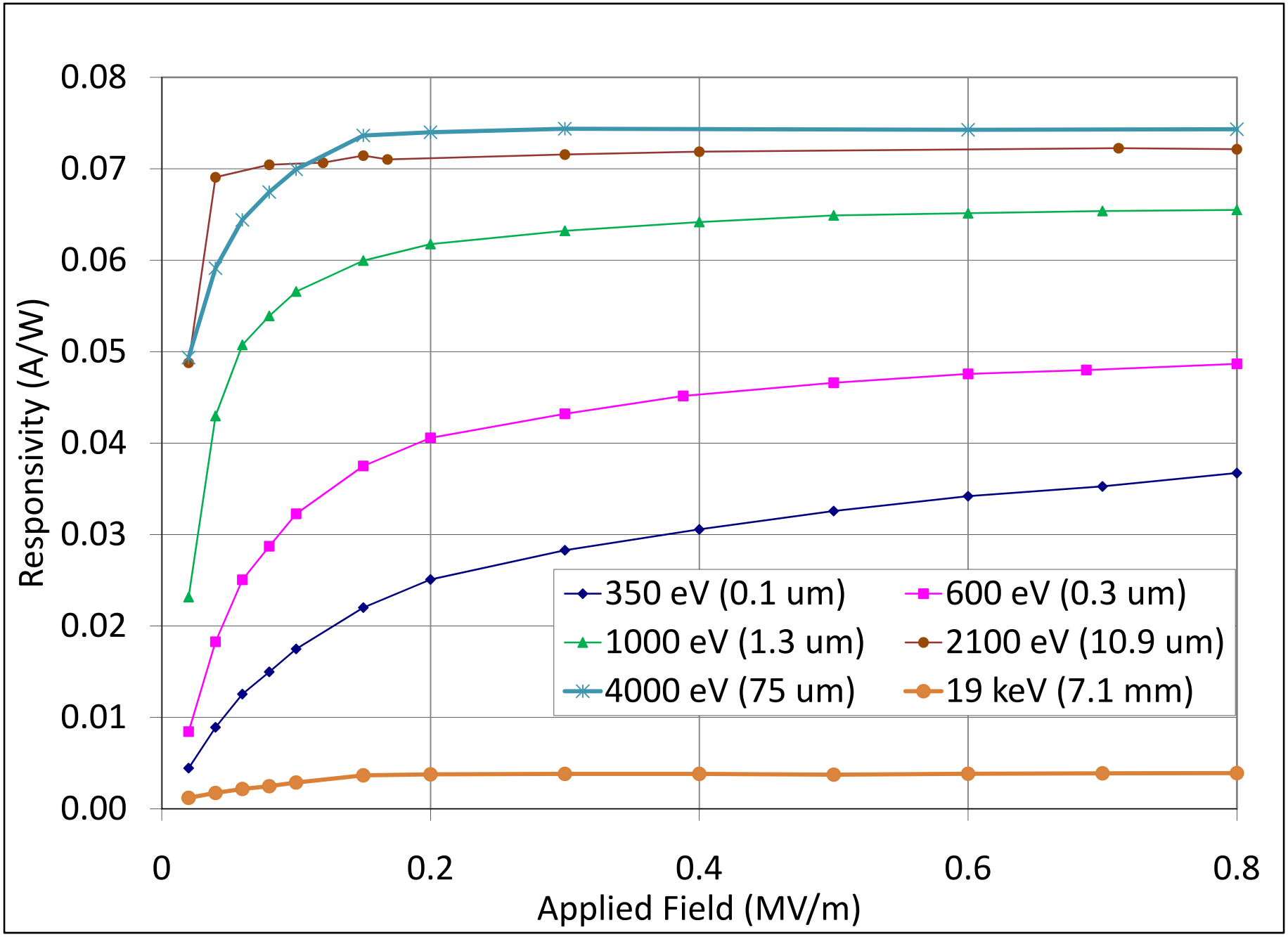
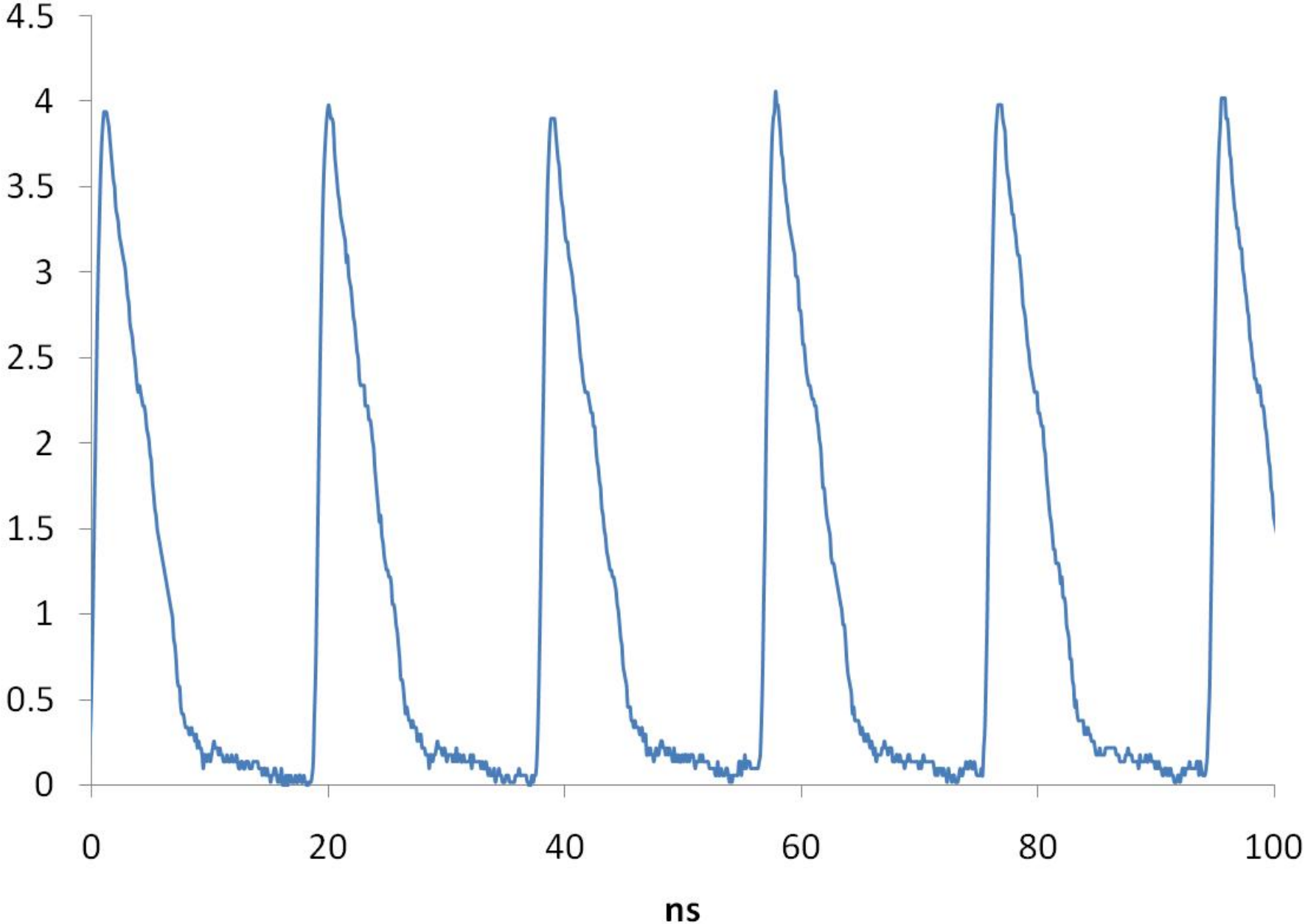

Nb Contacts (HID 14)
10 Hz holes
100 Hz holes
10 kHz holes
10 Hz electrons
100 Hz electrons
10 kHz electrons
W = 13.3 eV, 35 nm Nb, 32 nm C
W = 16.3 eV, 35 nm Nb, 32 nm C
Responsivity at 1 keV Photon Energy (A/W)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Duty Cycle

Interface Layer Recombination

- Carbon edge feature in responsivity is largely due to short absorption length (<100 nm)
- Carriers produced near electrode may diffuse into metal and recombine, leading to loss of charge
- This process is field dependent, leading to a charge collection efficiency which depends on the field
- Electron trapping in the diamond can reduce the field dear the electrode, leading to increased recombination
- For photon energies below 2 keV, when biasing for holes, the field required to saturate the collection reduces as photon energy increases, due to increased penetration depth
- For photon energies above 4keV, the photons are being absorbed in the bulk of the diamond, making it impossible to differentiate electron motion from hole motion


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Responsivity (A/W)
0
0.2
0.4
0.6
0.8
Applied Field (MV/m)
350 eV (0.1 um)
600 eV (0.3 um)
1000 eV (1.3 um)
2100 eV (10.9 um)
500 um diamond, Contact: 20 nm Mo, W =13.3 eV


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Collection Efficiency
0
0.2
0.4
0.6
0.8
Applied Field (MV/m)
350 eV (0.1 um)
600 eV (0.3 um)
1000 eV (1.3 um)
2100 eV (10.9 um)
500 um diamond, Contact: 20 nm Mo, W =13.3 eV


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Responsivity (A/W)
0
0.2
0.4
0.6
0.8
Applied Field (MV/m)
350 eV (0.1 um)
600 eV (0.3 um)
1000 eV (1.3 um)
2100 eV (10.9 um)
4000 eV (75 um)
19 keV (7.1 mm)

Pulse response, 2 MV/m