

Measuring Pulse Energy with Solid-State Photodiodes

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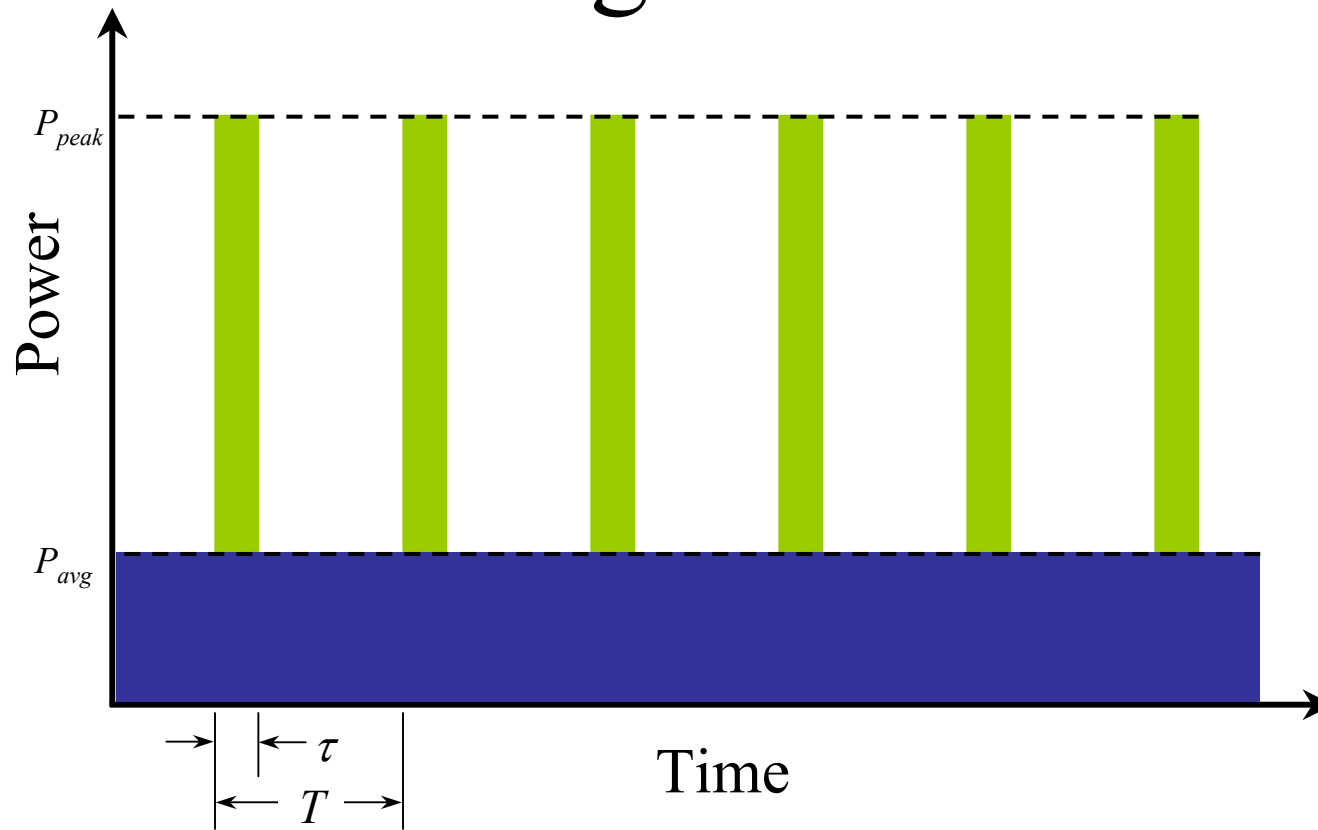
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Gaithersburg, MD, USA

Pulse Energy Measurements

Applications of pulsed radiometry include:

- synchrotron radiation (sub-ns)
- laboratory spark discharge sources (few μs)
- DUVL and excimer lasers (10 ns)
- EUVL sources:
 - laser-produced plasma (10 ns)
 - discharge produced plasma (100 ns)

Average and Peak Power



$$P_{peak} = \frac{E_p}{\tau}$$

$$P_{avg} = \frac{E_p}{T}$$

$$P_{peak} = \frac{P_{avg}}{\theta}$$

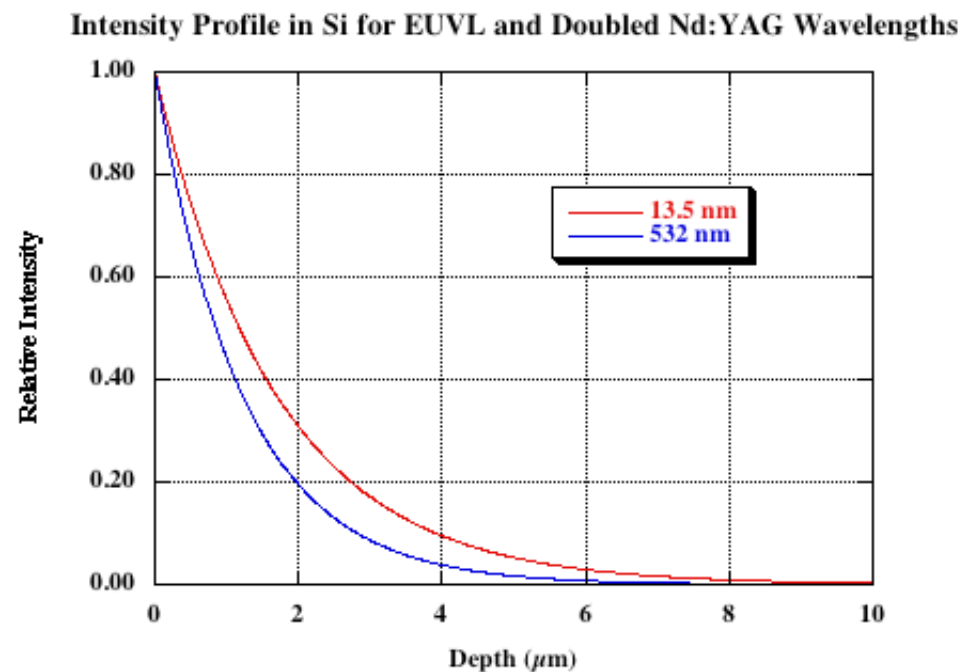
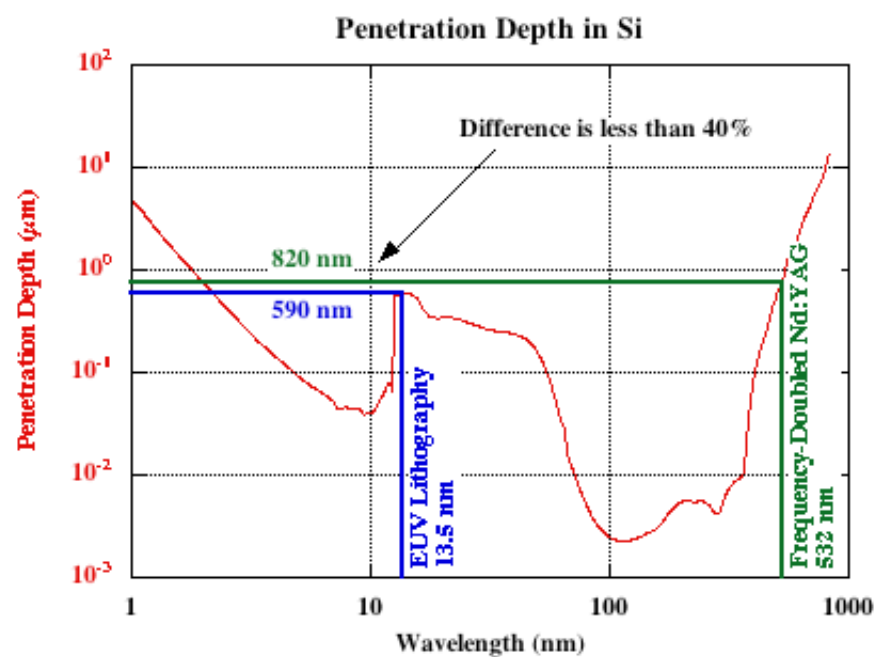
$\theta = \frac{\tau}{T}$ is the duty cycle

EUVL requires $P_{avg} = 120$ W at IF plane, $f = 10$ kHz ($T = 100$ μ s)

LPP ($\tau = 10$ ns) $\theta = 1 \times 10^{-4}$ $P_{peak} = 1.2$ MW

DPP ($\tau = 100$ ns) $\theta = 1 \times 10^{-3}$ $P_{peak} = 120$ kW

Green Light as Proxy for EUV

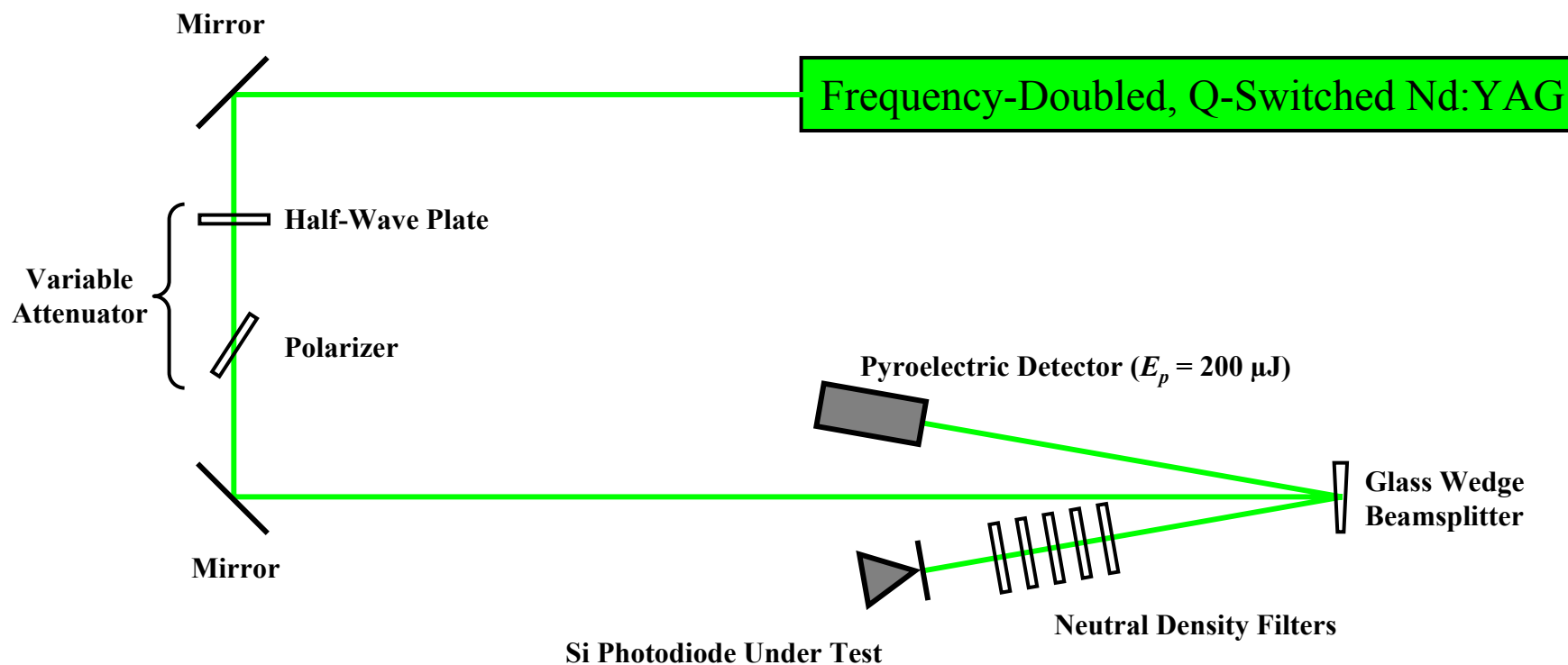


Saturation is an electronic, not an optical, effect.

13.5 nm and 532 nm radiation generate similar charge carrier distributions in Si.

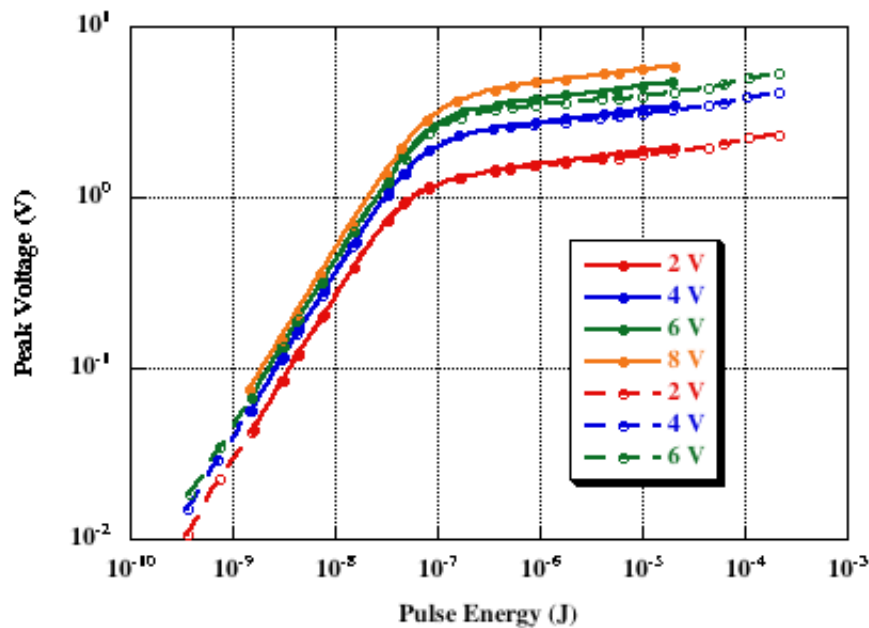
Saturation behavior at 13.5 should be similar to behavior at 532 nm.

Basic Saturation Measurement

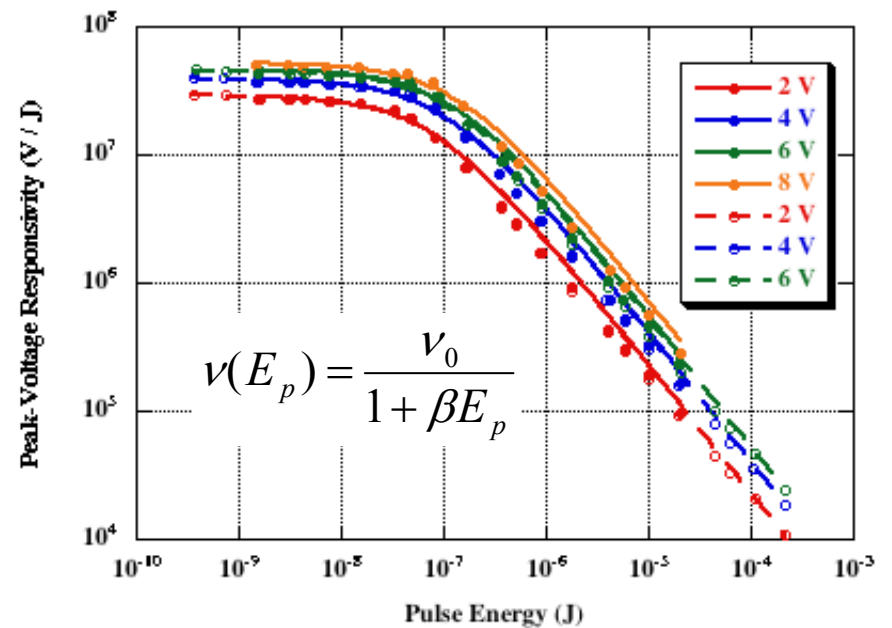


Voltage Responsivity

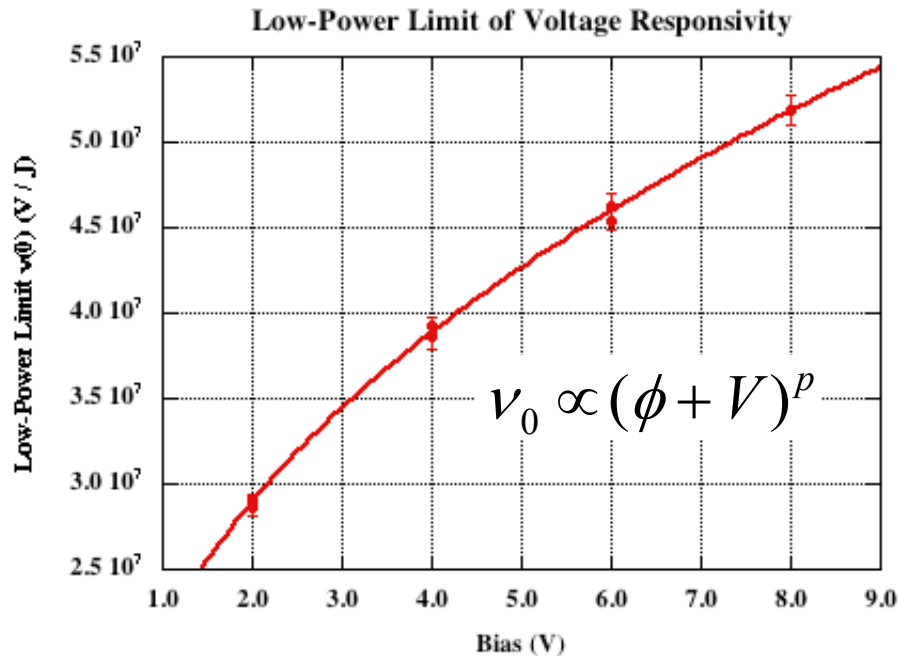
Peak-Voltage Signal with Various Reverse Bias Voltages



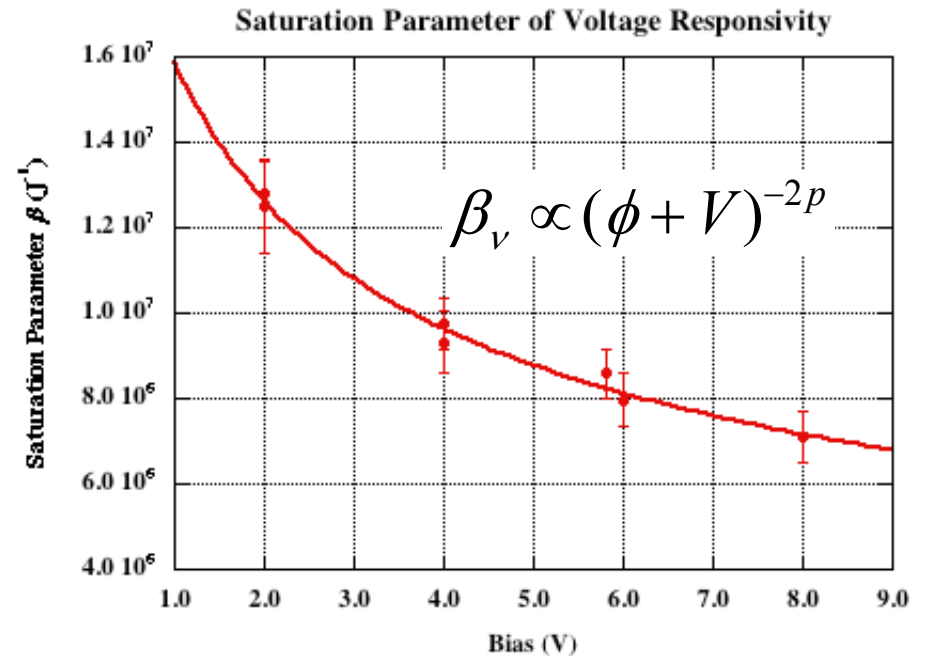
Peak-Voltage Responsivity with Various Reverse Bias Voltages



Reverse Bias Effect on Voltage



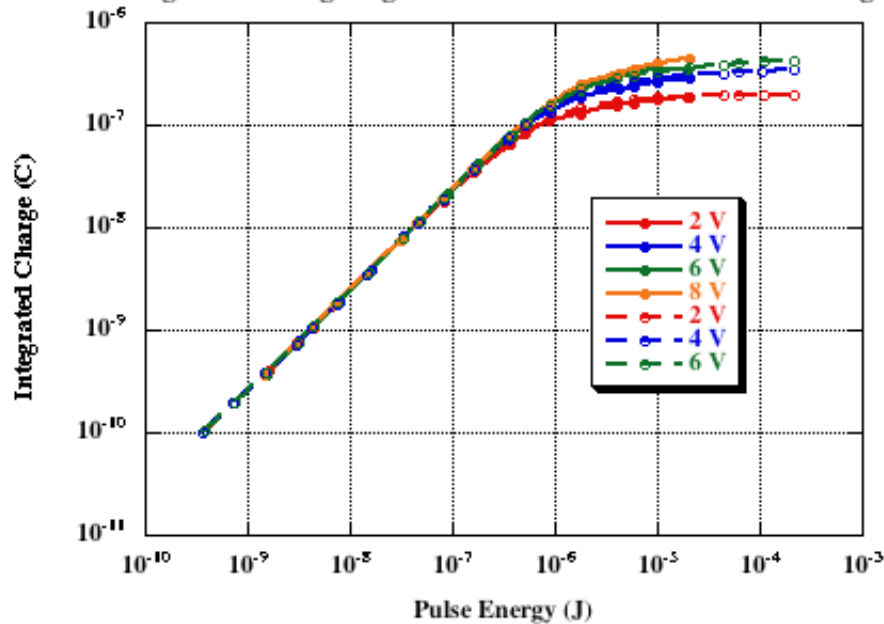
The low power limit of responsivity is a function of bias as the change in depletion region width changes the device capacitance.



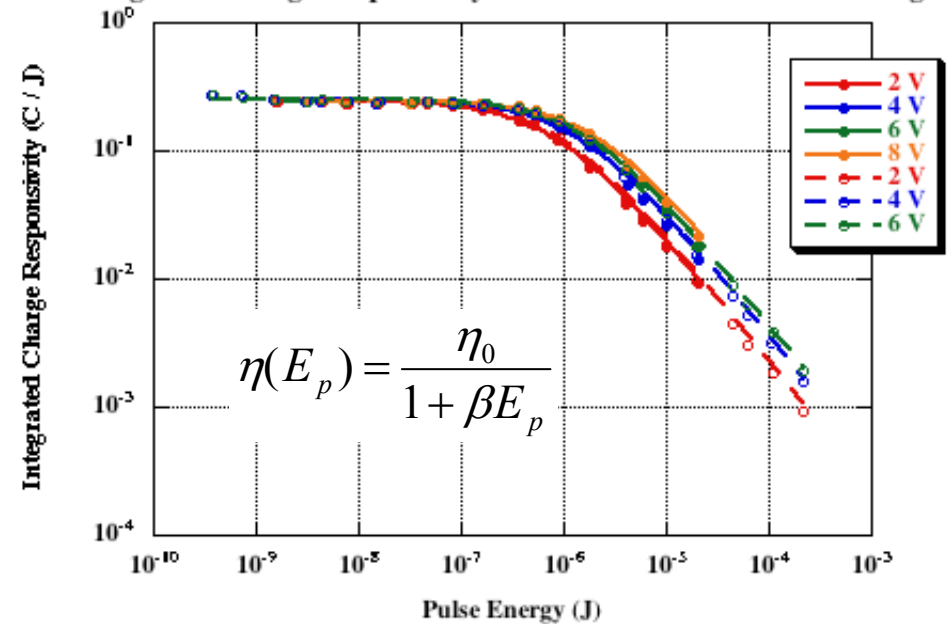
The saturation parameter is a function of bias as one over the square of the depletion region width.

Charge Responsivity

Integrated Charge Signal with Various Reverse Bias Voltages

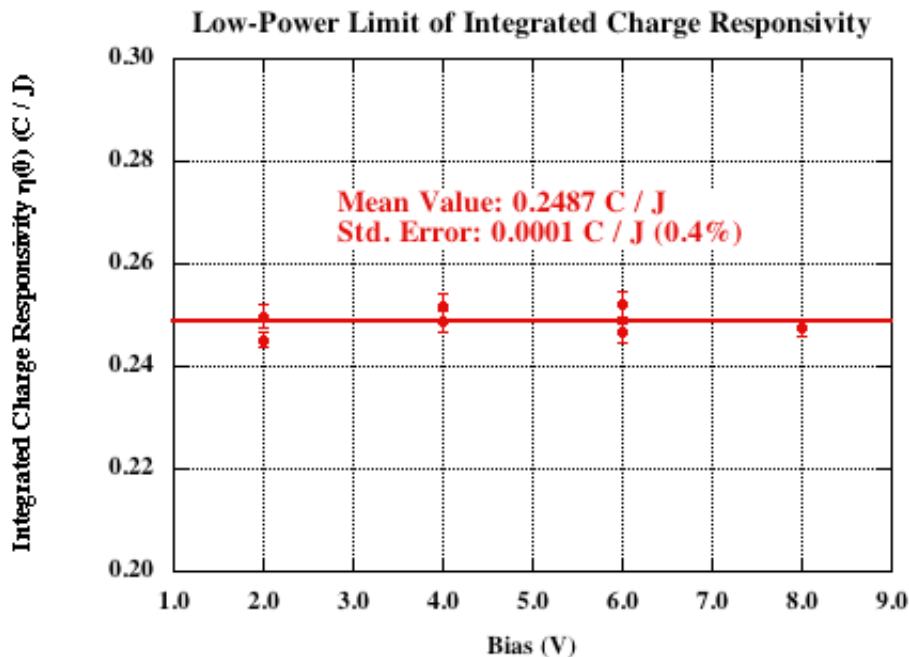


Integrated Charge Responsivity with Various Reverse Bias Voltages

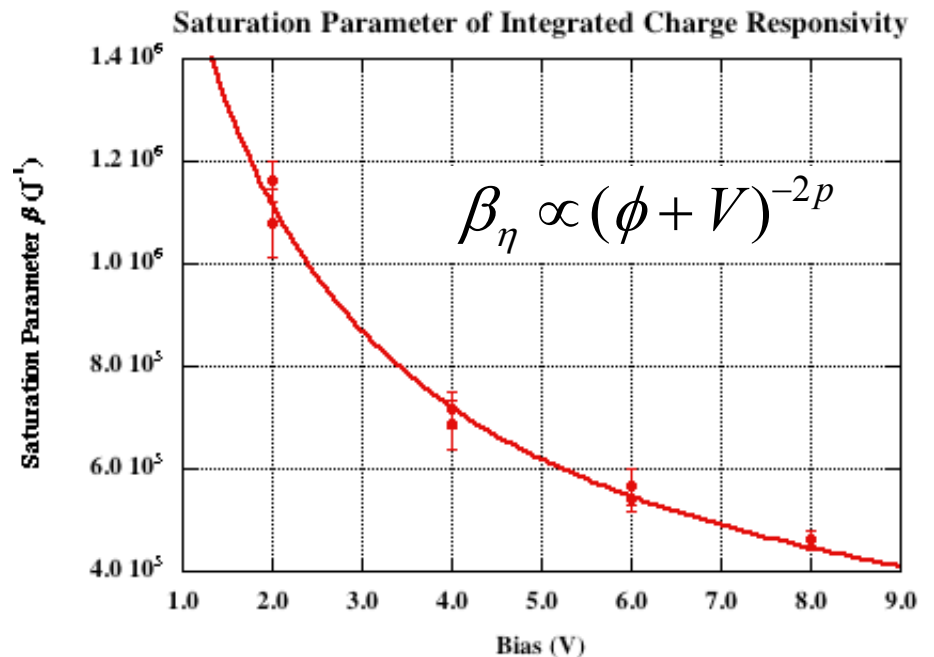


$$Q = \int I(t) dt = \frac{1}{R} \int V(t) dt$$

Reverse Bias Effect on Charge



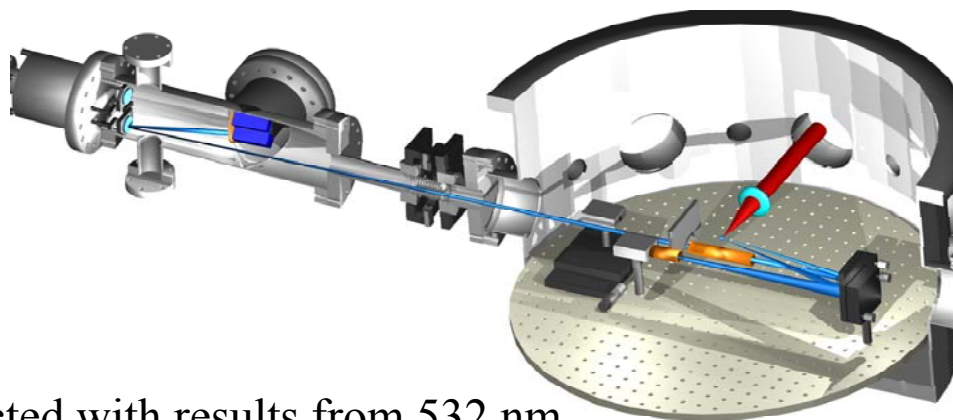
The low power limit of responsivity is not a function of bias and is in good agreement with a low-power cw calibration.



Saturation parameter is a function of bias as one over the square of the depletion region width.

Validation of Green Proxy

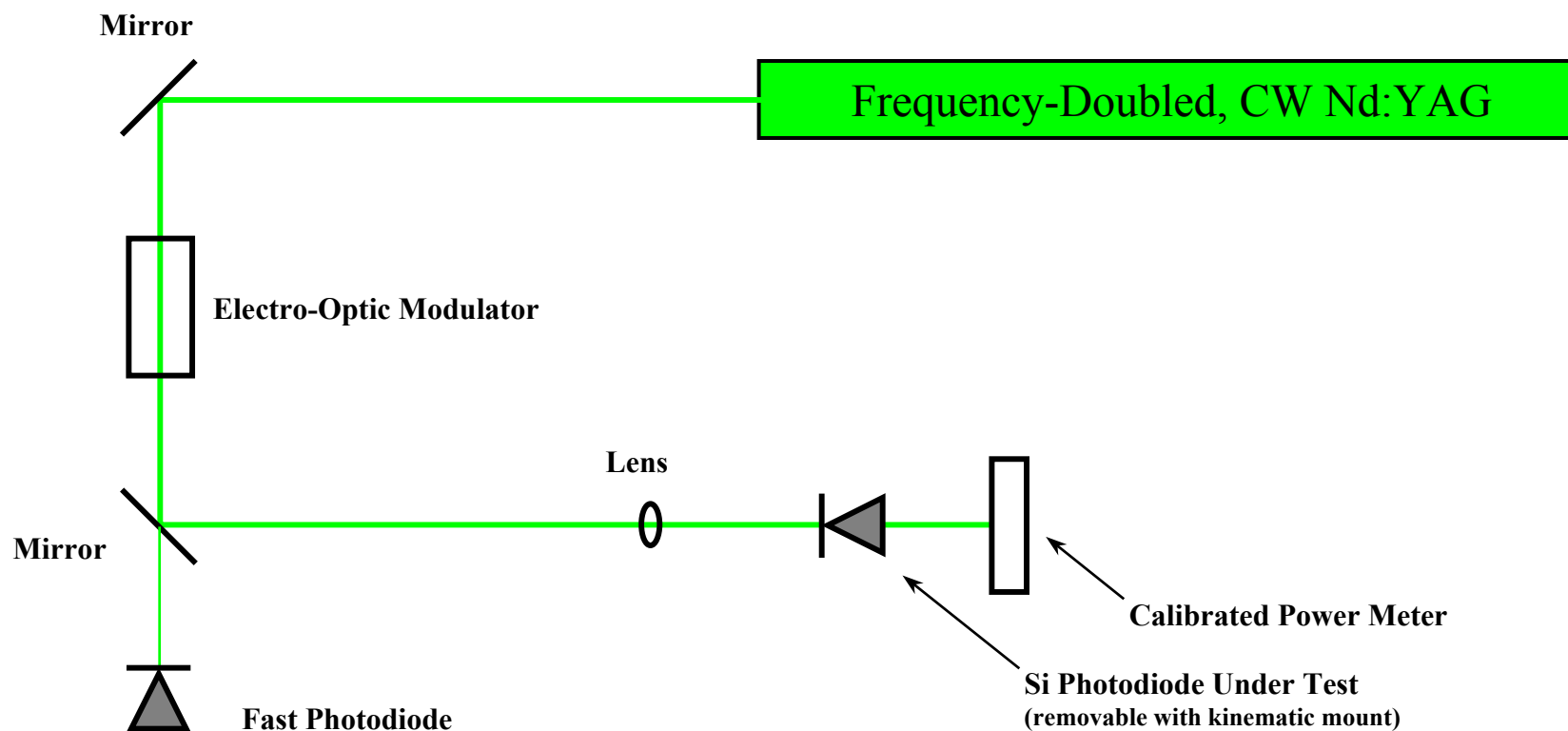
A 13.5 nm dosimeter was calibrated on a laser-produced plasma and the individual components (filters, mirror, and photodiode) were calibrated at the synchrotron.



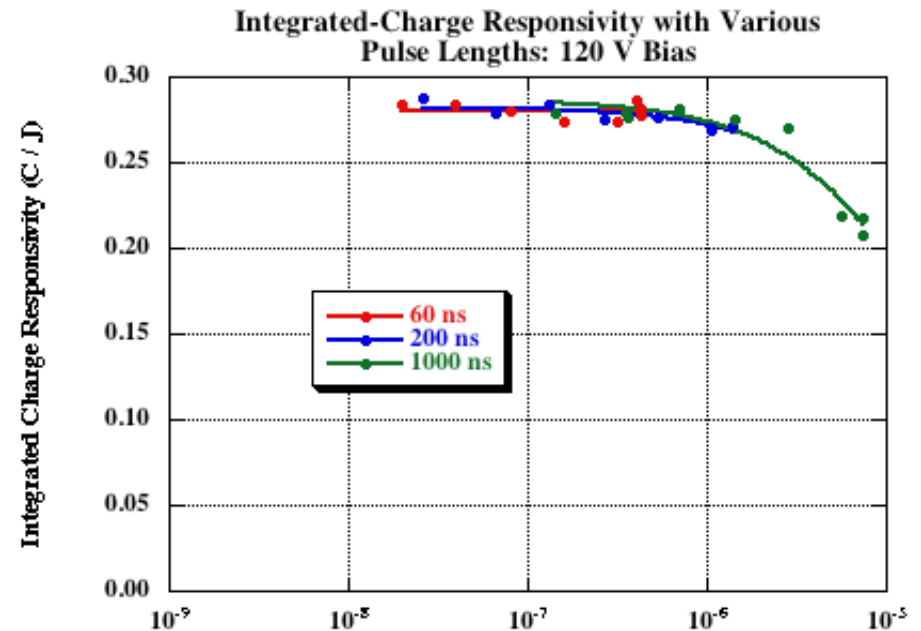
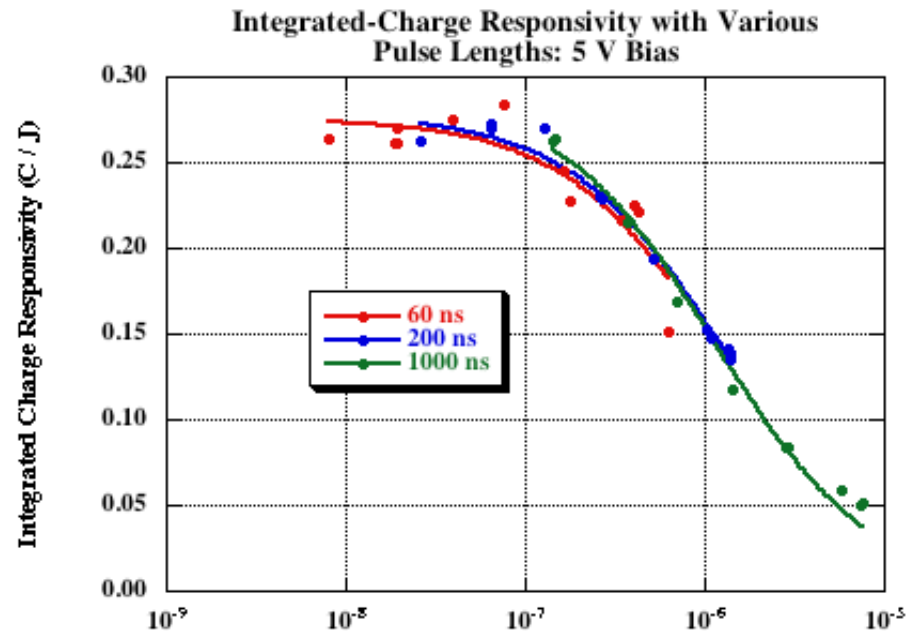
Data from 13.5 nm were successfully corrected with results from 532 nm

<u>Condition</u>	<u>Charge (nC)</u>	<u>E_p Error</u>	<u>Uncompensated</u>	<u>Compensated</u>	<u>Uncertainty</u>
1 (biased)	1.24	-0.3%	+2.0%	-2.2%	2.9%
2 (biased)	0.17	0.0%	+4.2%	-0.2%	3.1%
3 (biased)	0.17	0.0%	+6.4%	+2.1%	5.4%
4	1.21	-2.2%	-1.0%	-3.3%	3.4%
5	0.28	-0.5%	+5.9%	+2.0%	3.2%
6	0.17	-0.3%	+3.6%	-0.6%	3.4%
7	0.17	-0.3%	+5.7%	+1.6%	3.2%
Standard	2.47	-4.4%	—	—	—

Variable-Pulse Length Saturation Measurement



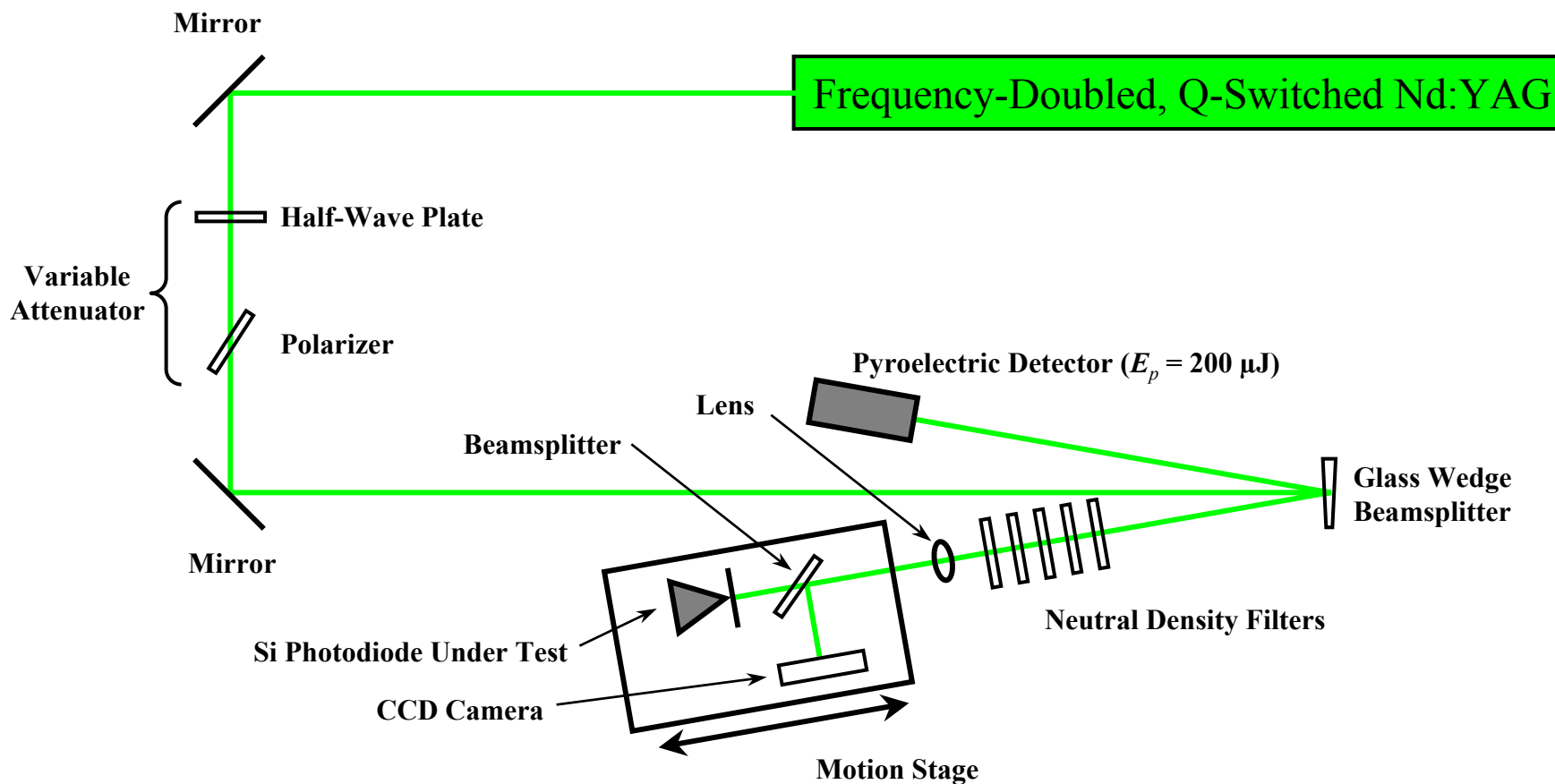
Dependence on Pulse Length



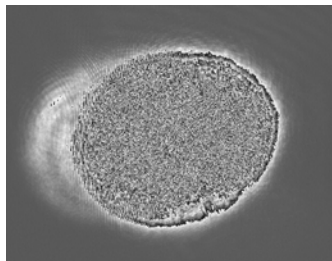
From 60 ns to 1 μ s, there is no apparent dependence on the pulse length, only pulse energy.

This is consistent with all optical pulse lengths much less than the photodiode impulse response time of several μ s.

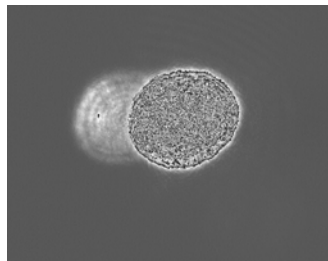
Variable-Area Saturation Measurement



Dependence on Spot Size



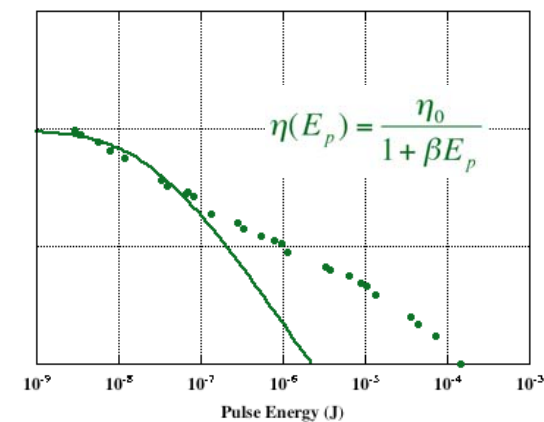
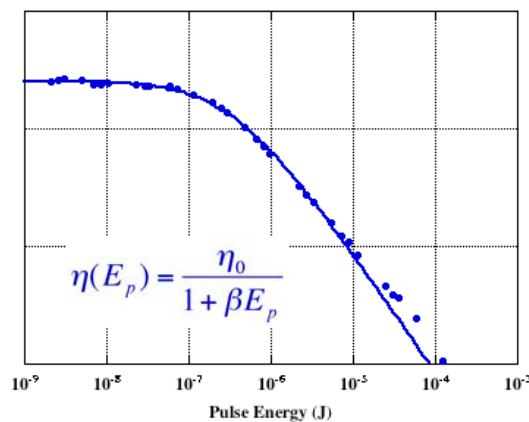
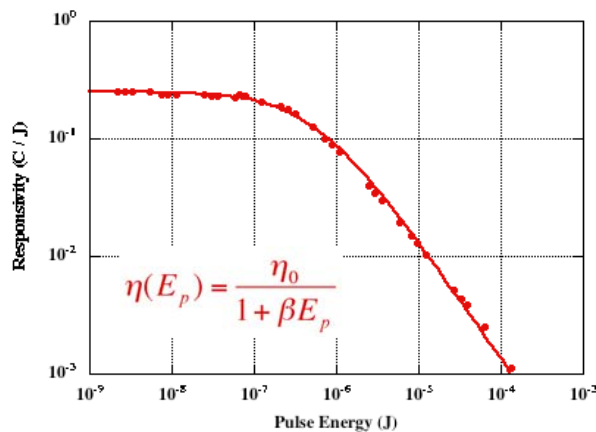
2.0 mm²



0.60 mm²

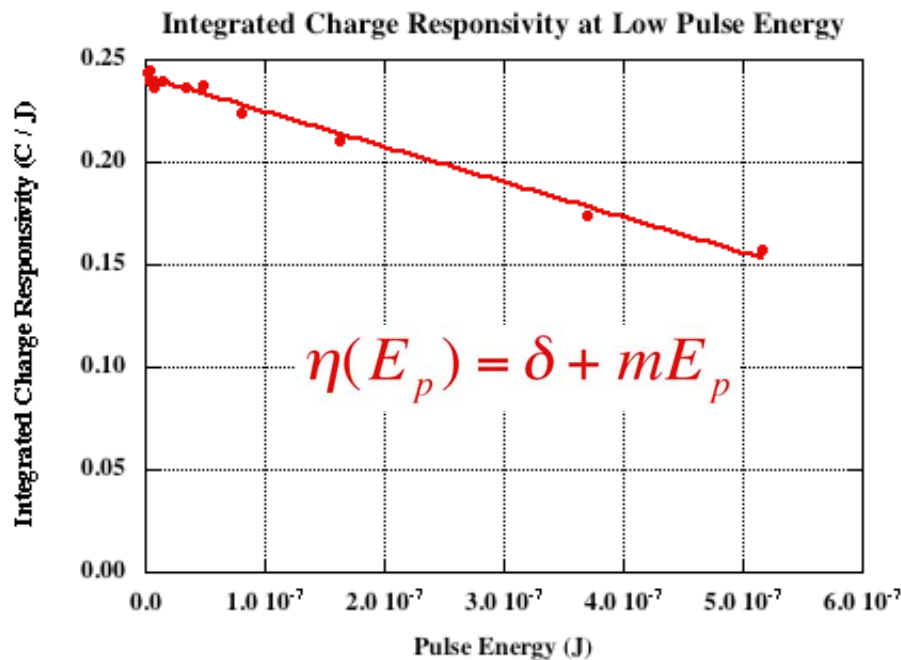


0.005 mm²



The saturation of the photodiode is quenched with high power density.

Implications for Radiometry



$$\eta(E_p) = \frac{\eta_0}{1 + \beta E_p}$$

Expand as MacLaurin Series:

$$\eta(E_p) \approx \eta_0 - \eta_0 \beta E_p$$

Calculate both parameters
from low-power data:

$$\eta_0 = \delta \quad \beta = \frac{-m}{\delta}$$

Even at low pulse energies, there is saturation.

Implications for Radiometry

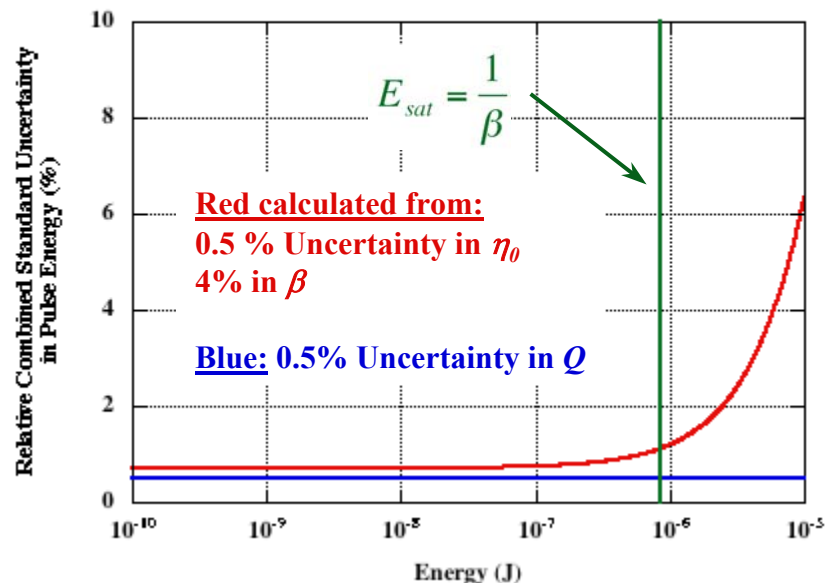
Let Q be the measured charge.

Pulse energy is given by:

$$E_p = \frac{Q}{\eta_0 - \beta Q}$$

The relative standard uncertainty in E_p is:

$$\frac{u_c^2(E_p)}{E_p^2} = \left(1 + \beta E_p\right)^2 \frac{u_c^2(Q)}{Q^2} + \left(1 - \frac{\beta Q}{\eta_0}\right)^{-2} \frac{u_c^2(\eta_0)}{\eta_0^2} + E_p^2 u_c^2(\beta)$$



E_{sat} is where the responsivity is one half the low-power limit and the measured charge is:

$$Q_{sat} = \frac{\eta_0}{2\beta}$$

Implications for Radiometry

δ = acceptable error in pulse energy measurement assuming a linear detector, i.e. $E_p = Q / \eta_0$.

This defines a limiting responsivity, and corresponding energy E_{lim} and measured charge Q_{lim} .

$$\eta(E_{lim}) = (1 - \delta) \eta_0 \qquad E_{lim} = \frac{\delta}{(1 - \delta)\beta} \qquad Q_{lim} = \delta \frac{\eta_0}{\beta}$$

Typical Biased Values: $\eta_0 \approx 0.25 \text{ C / J}$
 $\beta \approx 5 \times 10^5 \text{ J}^{-1}$
 $\delta \approx 0.01$ } $E_{lim} \approx 20 \text{ nJ}$
 $Q_{lim} \approx 5 \text{ nC}$

EUVL Intermediate Focus: $E_p \approx 10 \text{ mJ}$

Future Work

- Additional experiments to validate the use of 532 nm green light as a proxy for 13.5 nm EUV
- Improve model to describe quenching of saturation at high power density, possibly due to lateral diffusion current
- Establish calibration service for pulsed response of photodiodes and other instruments