Two-Photon-Absorption-Induced Carrier Generation: Calibration, Modeling, and Experimental Validation

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RADLAS 2017, 9 October 2017

Introduction/Outline

- Background
  - TPA Dosimetry
  - Modeling Carrier Generation
- Experimental Validation of NLOBPM Model
- Laser/Ion Comparison
- Challenges Moving Forward

Advantages and Applications of PLSEE

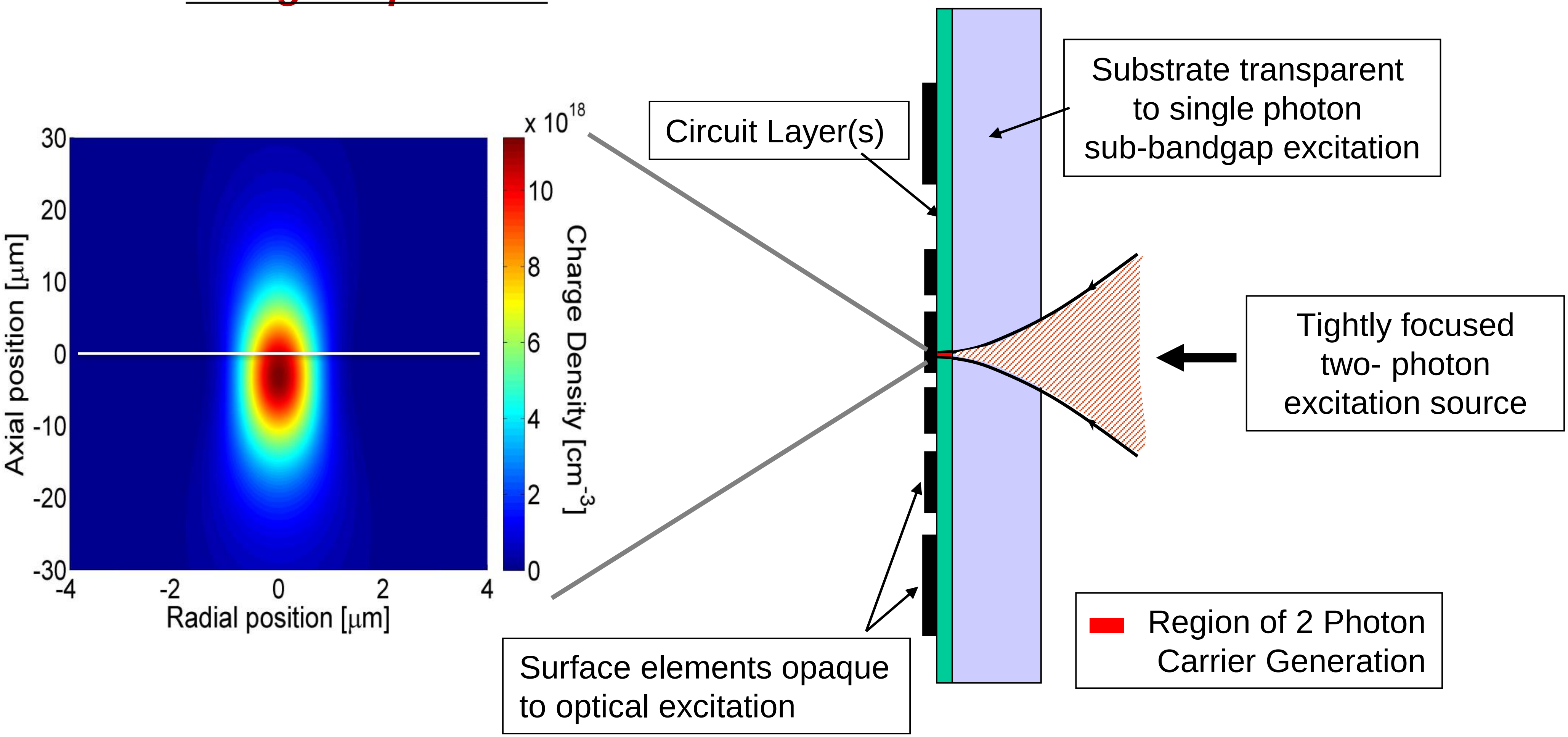
Pulsed-laser SEE is used for:

- Sensitive Node Identification/Mitigation
- SEU Mapping of sensitive areas
- Laser-Induced Latch-up Screening/Mitigation
- Single-Event Transient Characterization and Mitigation
- Single-Event Transient Screening (ASETs)
- Hardened Circuit Verification
- Dynamic SEE Testing
- Experimental Test Setup Verification
- Basic Mechanisms Studies

Recent Challenges:
Quantitative Characterization of TPA SEE

Inside the Silicon: Charge Deposition

Pulse Delivered to the Chip: TPA Dosimetry

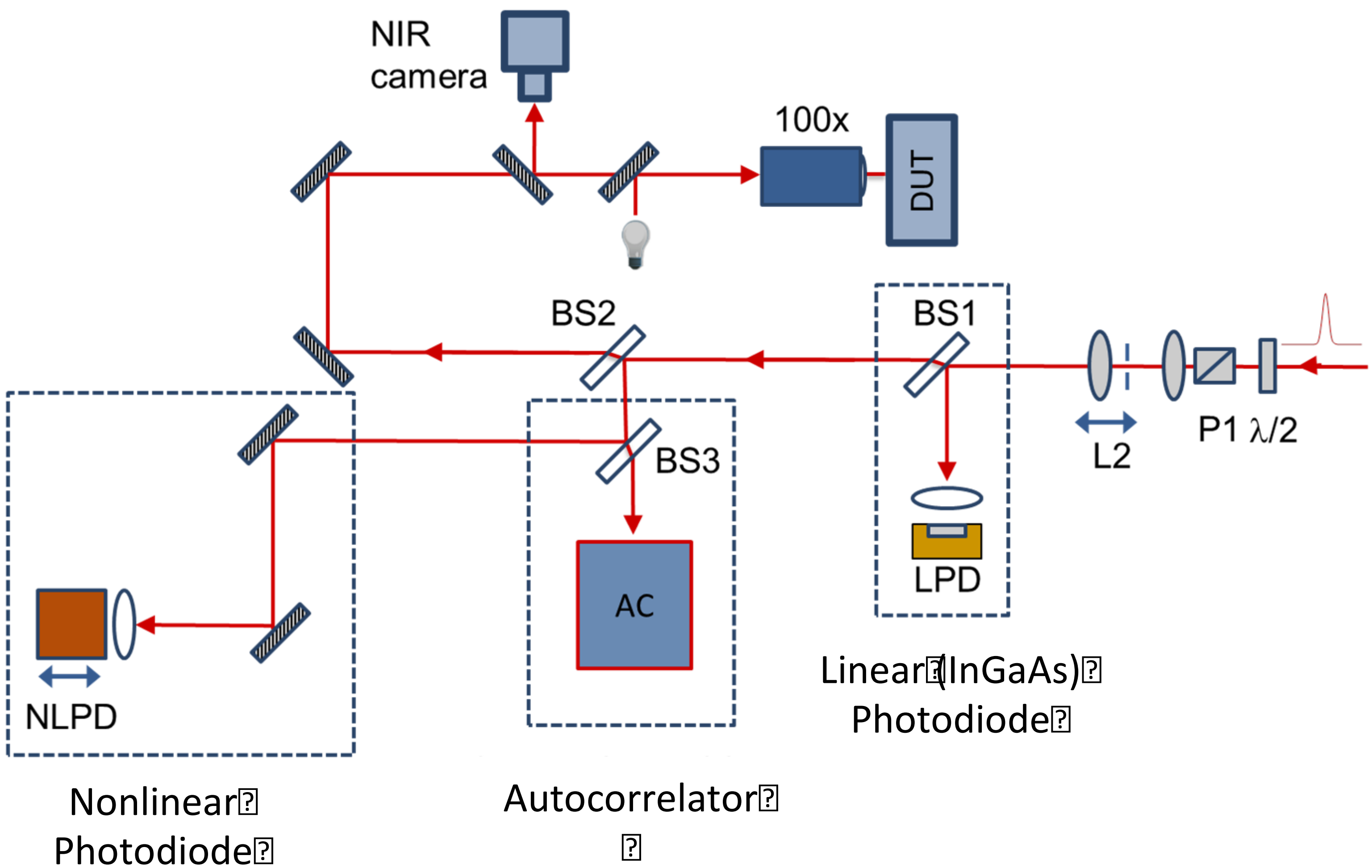


RADLAS 2017, 9 October 2017

TPA Dosimetry – Summary

- Dosimetry methodology for TPA SEE ***developed, implemented, and verified***
- Three online beam monitors
  - Laser pulse energy
  - Laser pulse width
  - Focused spot size

TPA Dosimetry



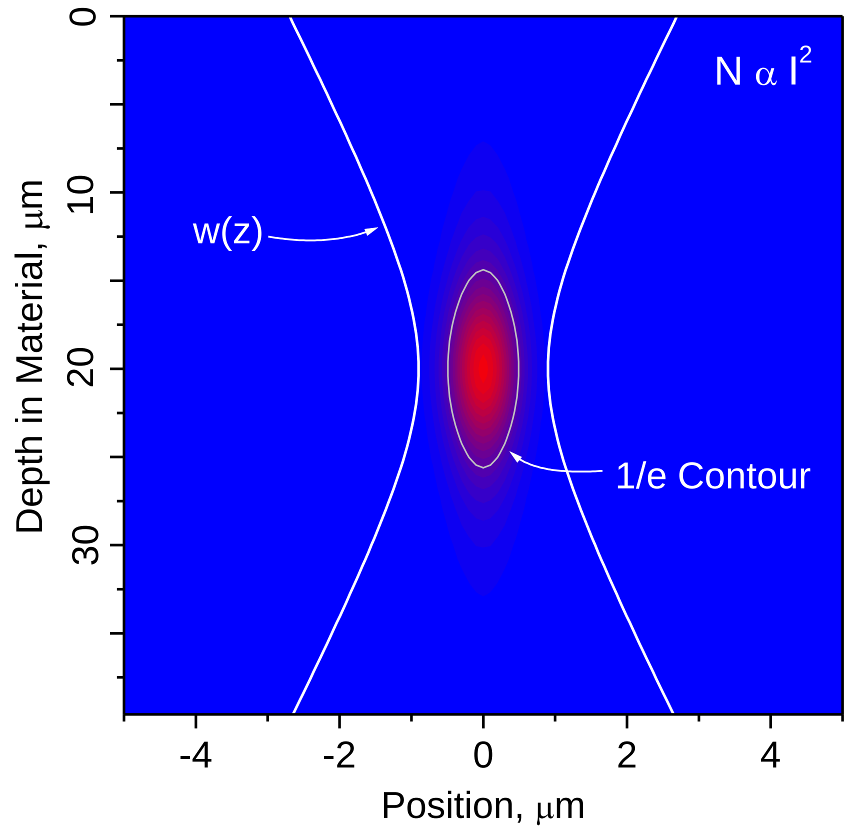
Khachatrian, *et al.*, *"A Dosimetry Method for Two-Photon Absorption Induced Single-Event Effects Measurements,"* IEEE TNS December 2014.

TPA Dosimetry – Summary

- Dosimetry methodology for TPA SEE ***developed, implemented, and verified***
- Three online beam monitors
  - Laser pulse energy
  - Laser pulse width
  - Focused spot size
- ***Capabilities:***
  - Monitor and correct fluctuations in laser system operating point
  - Set system to predefined operating point
  - Correlation of different experiments

What Happens Inside the Silicon?

- Need exists for understanding *quantitatively* the carrier density distribution in TPA SEE experiments
  - *Complicated problem*
- Community has been relying on a *"Zeroth Order"* representation
  - *Only considers carrier generation*
  - *Neglects all all other effects*
- NRL has initiated a program to address this problem



McMorrow, et. al, TNS 49, 3002 (2002).

NRL TPA Modeling

Goals:

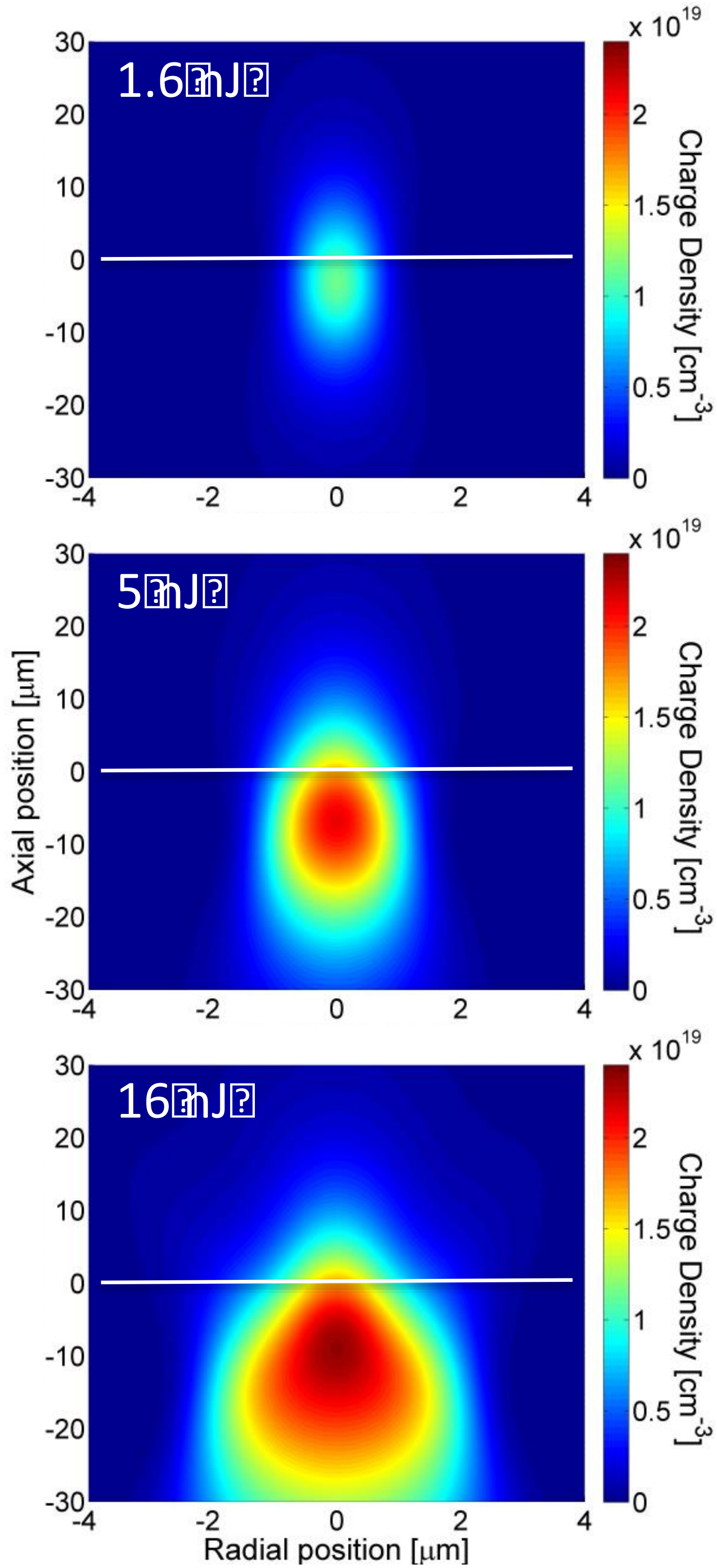
- *Produce a software program that can accurately simulate the TPA-induced carrier deposition profile in silicon for any given set of experimental conditions (Practical Goal)*
- Simulate/predict impact of various optical nonlinearities on the beam *propagation* through, and *generation of free carriers* in the medium *(Scientific Goal)*
- ***Validate results through experimental measurement***

Approach:

- Numerical modeling using existing simulation software (***NLO-BPM***) adapted for carrier generation and applied to silicon

  [Kovsh, et al., Applied Optics, 38, 1568 (1999)]

  [Hales, et al., IEEE TNS, 62, 1-8 (2015)]



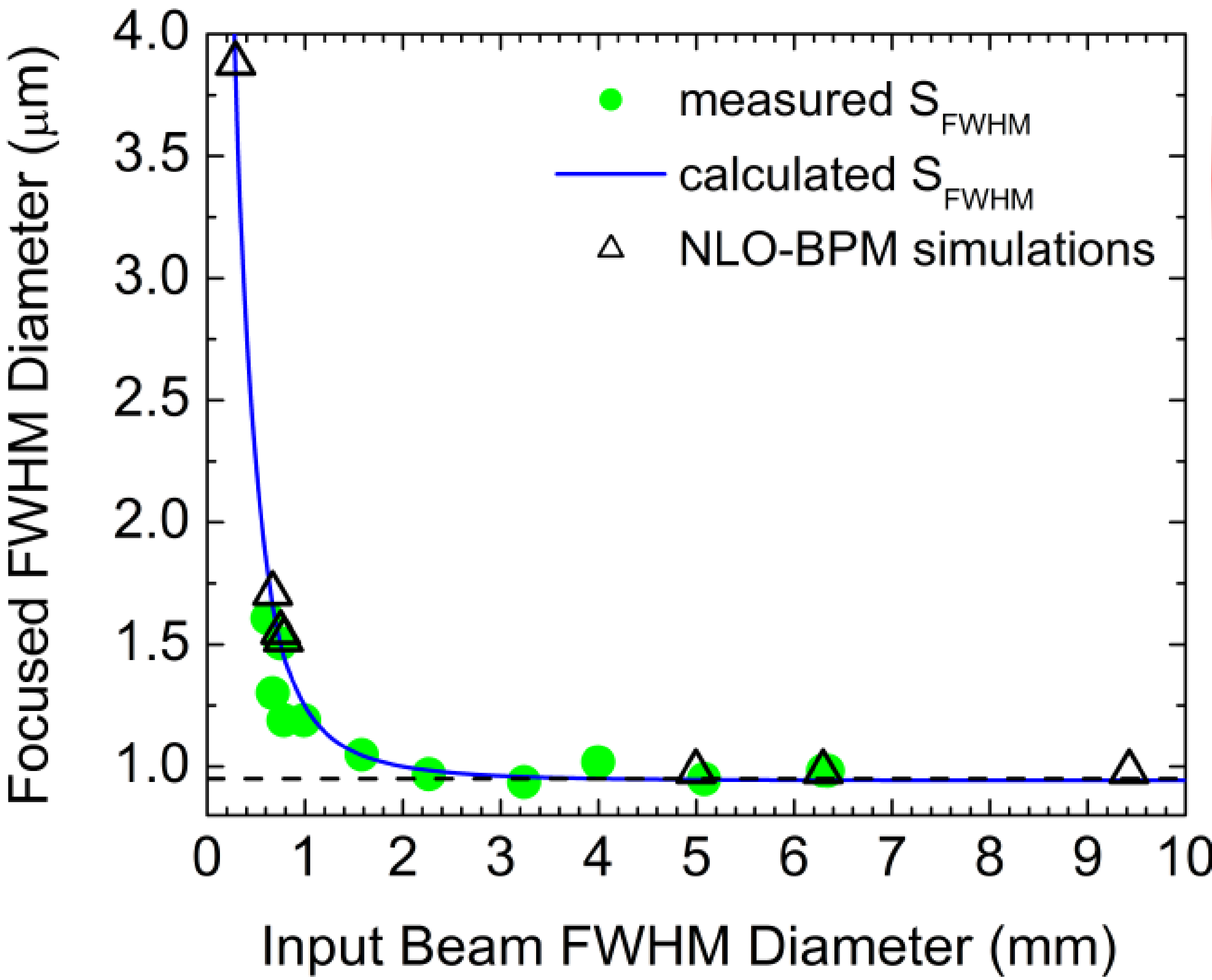
1.6 nJ

5 nJ

16 nJ

Hales, et al., TNS 2015

Experimental Validation



$$S_{FWHM} = K_{FWHM}\, \lambda\, f\#$$

$$K_{FWHM} = 1.036$$

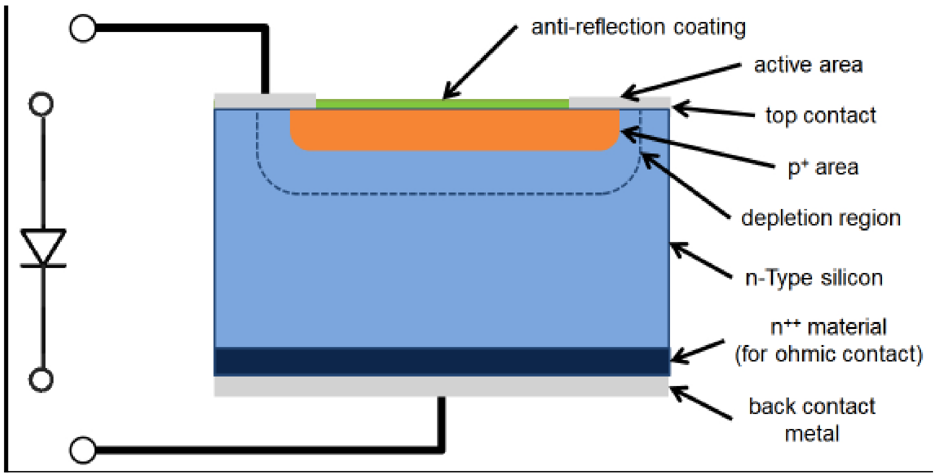
$$- 0.058T_r - 0.156/T_r^2$$

**H. Urey, Applied Optics, vol. 43, pp. 620-625, 2004.*

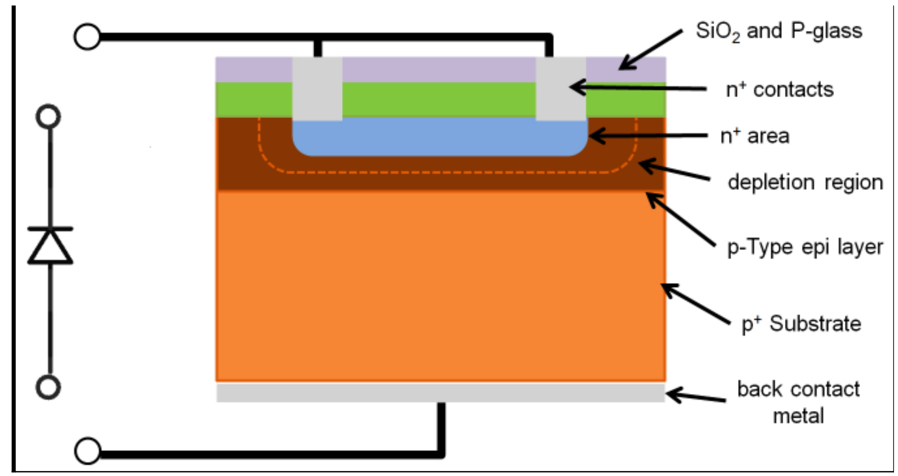
Hales, et al., TNS 2015

Experimental Validation of NLOBPM

Silicon Bulk Diode



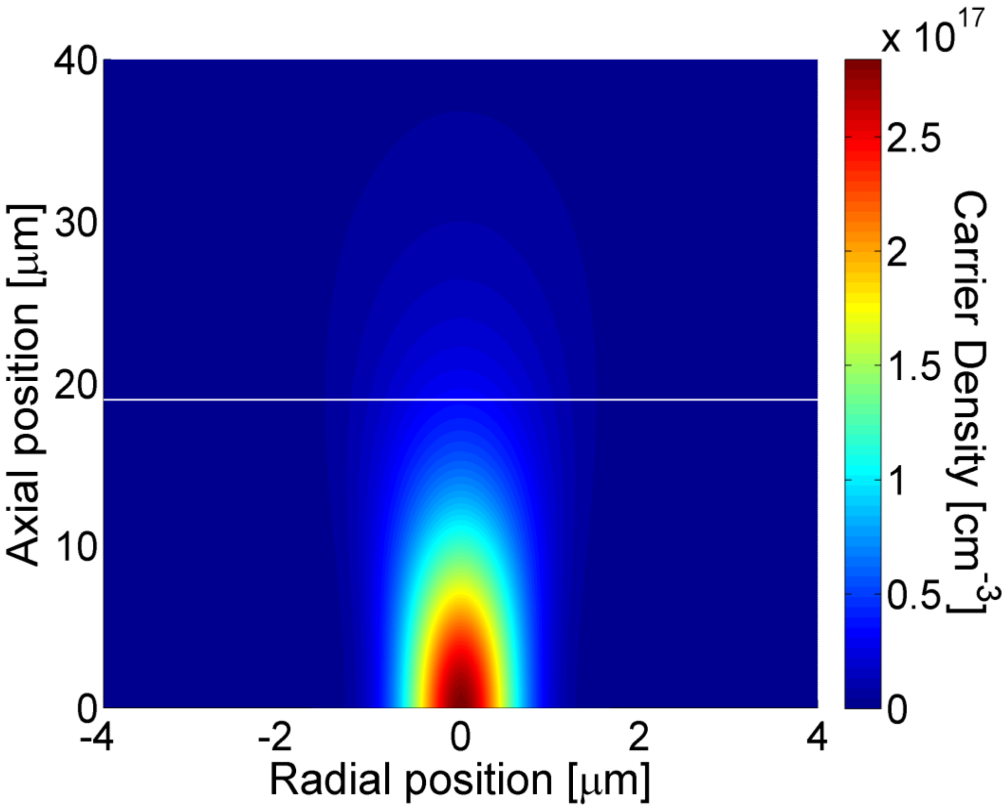
Silicon EPI Diode

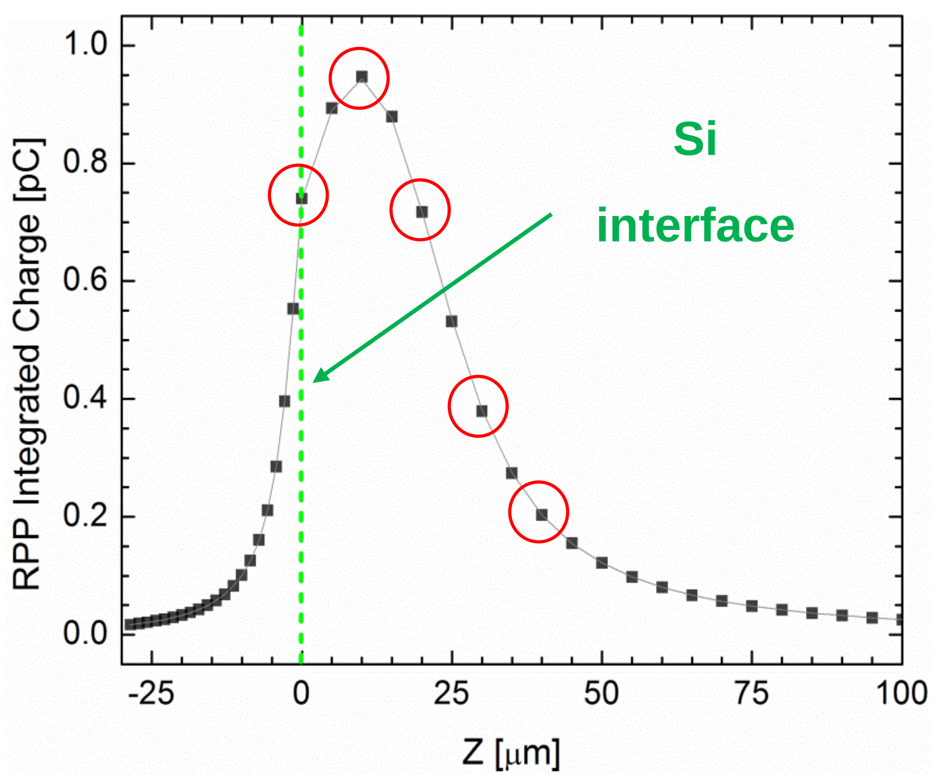


Observable: Charge-collection transient

- "Z" Dependence of collected charge

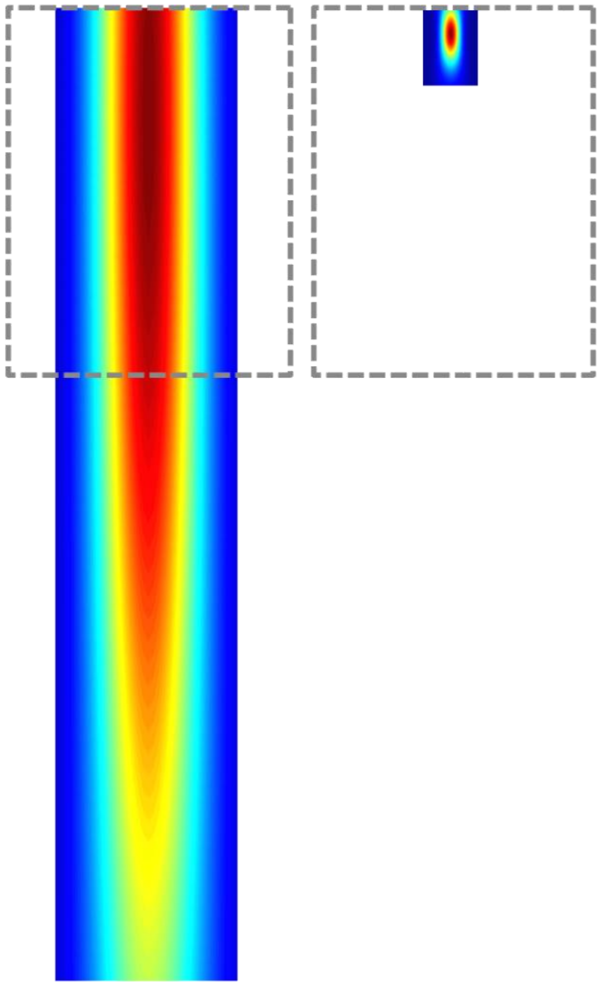
RPP and Depth Profiles





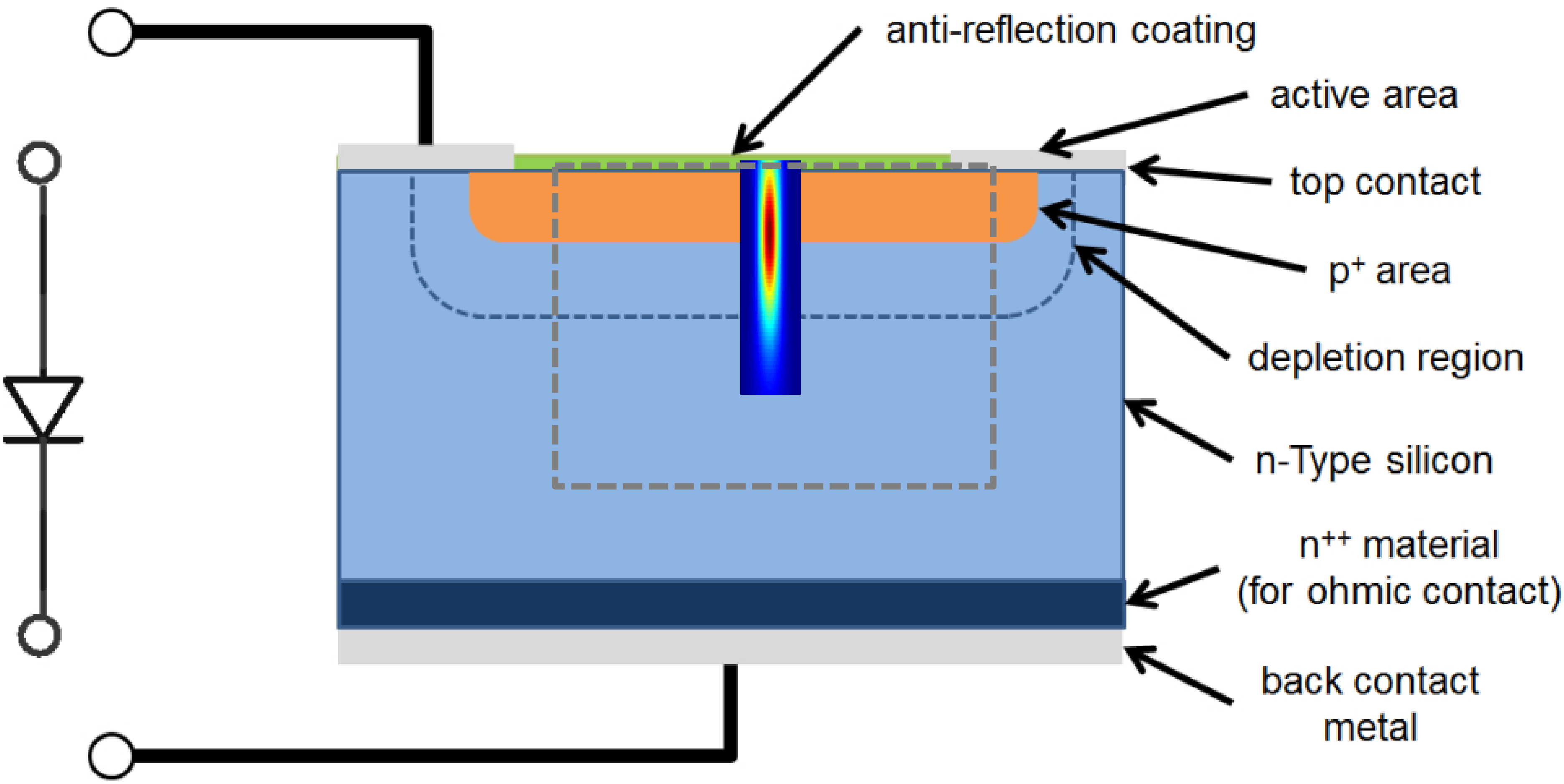
- ***RPP model*** used to estimate collected charge
  - *Preliminary collaborative TCAD analysis with Robust Chip Inc. shows good correlation with RPP model for bulk diode*
- ***"CC z-scans"*** – depth profiles of integrated/collected charge as a function of axial or "z" position of focus – can be generated

Experimental Geometries - TPA



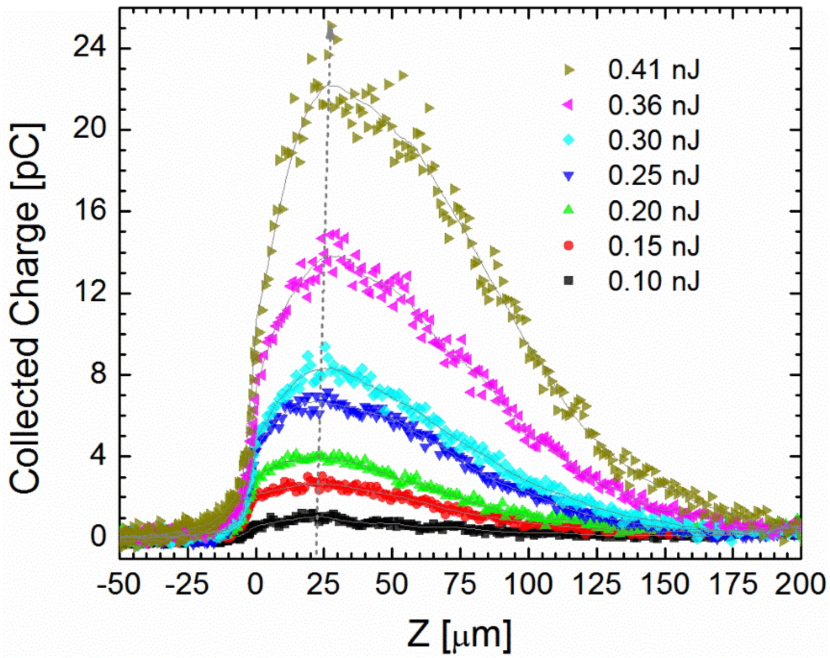
Dosimeter　　*DUT: 100x*

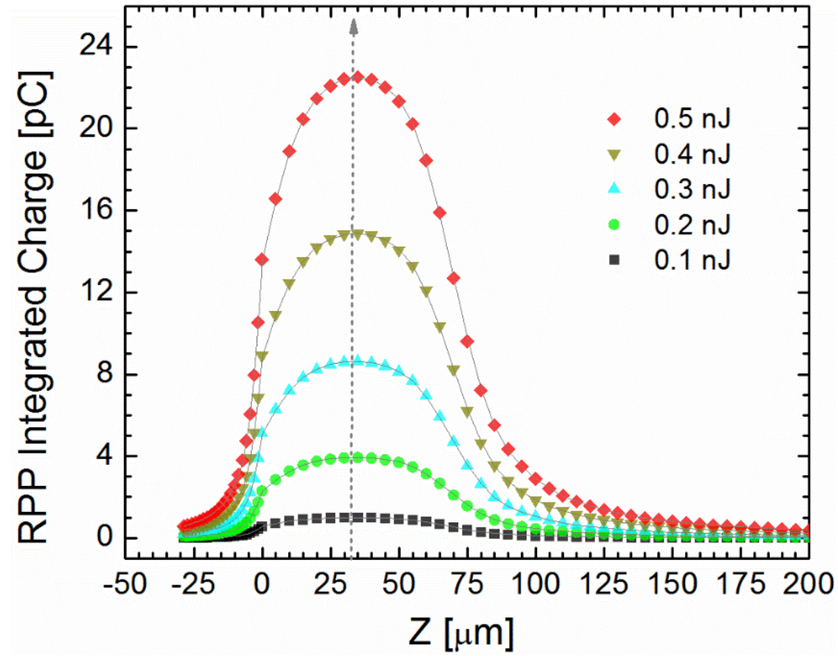
Centronic Bulk Si Diode



RPP depth of 66 μm >> charge profile size

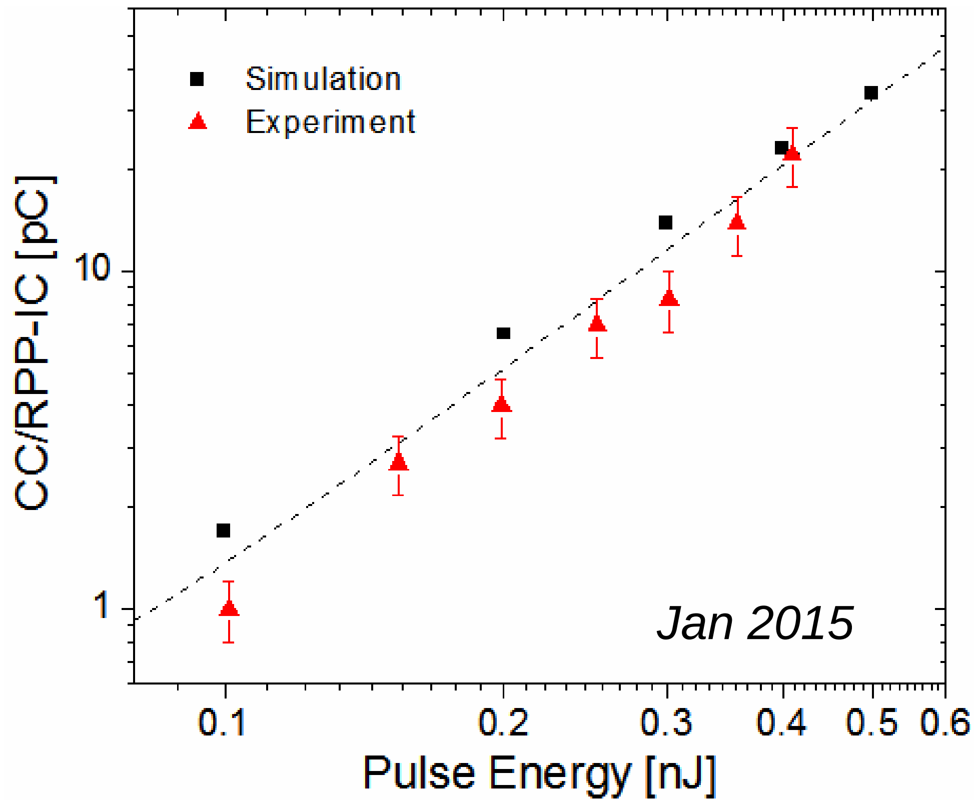
Centronic Bulk Si Diode

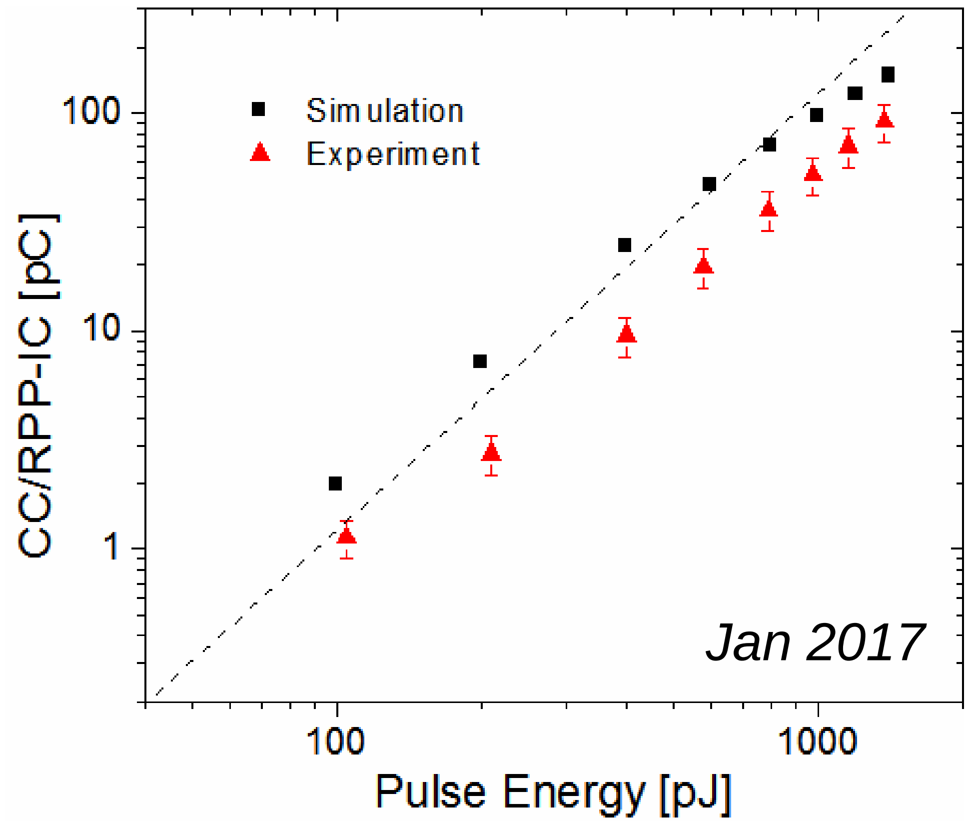




- Diode studied extensively via both TPA and SPA; detector used for dosimeter
- Magnitudes, positions, trends of z-scans show good agreement
- Simulations narrower/more symmetric than experimental data; oversimplification of RPP?

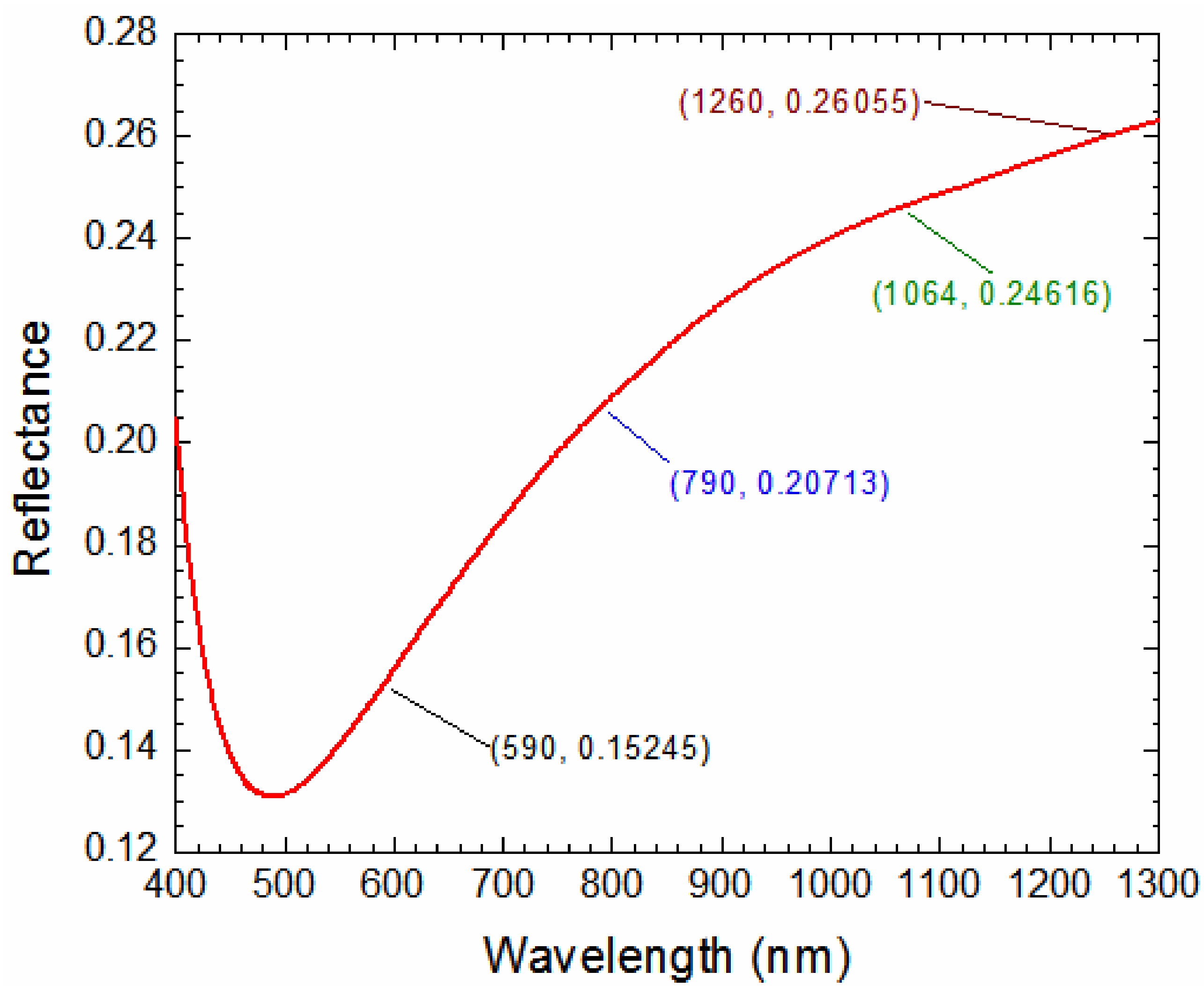
Correlation Study: Centronic Bulk Diode





Simulation consistently overestimates CC

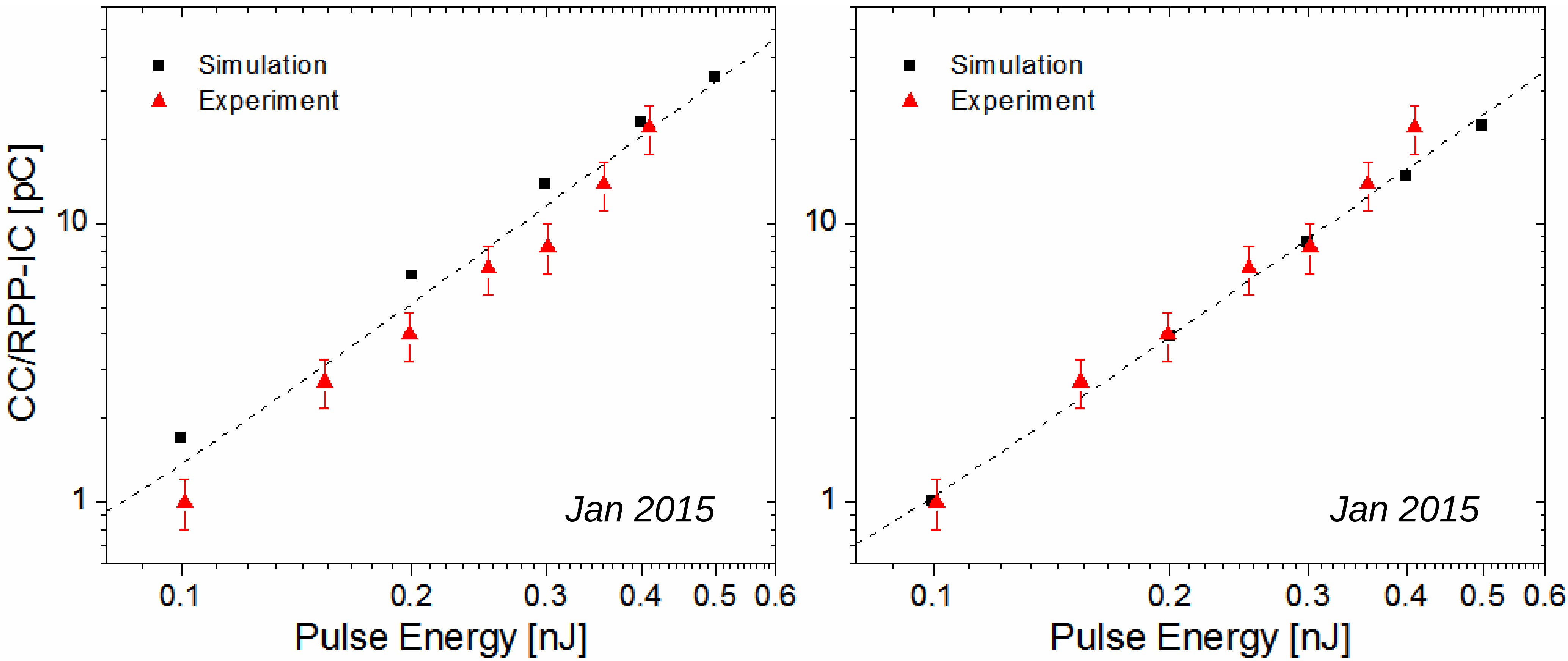
Impact of Surface Reflections



- Sims consistently overestimate CC
- Previously assumed perfect AR coating (R=0%)
- Communication with Centronic yielded specific information on SiO_2 AR coating and then calculated dispersion of reflectance
- *Significant reflectance found at all wavelengths*

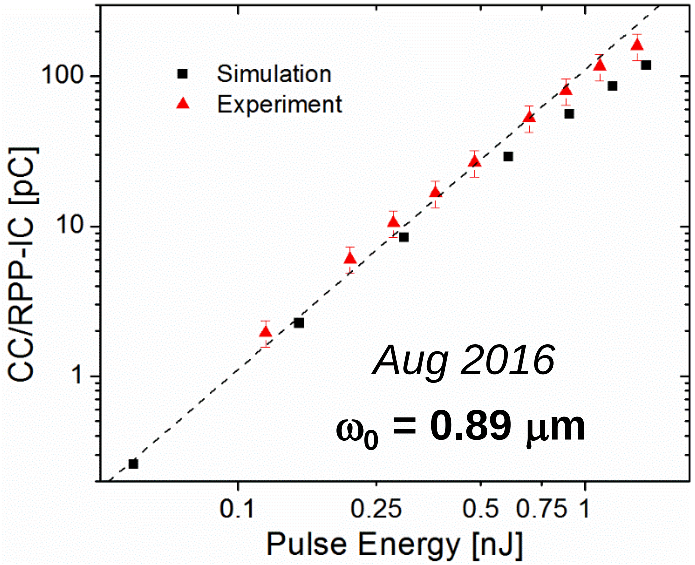
Impact of Surface Reflections

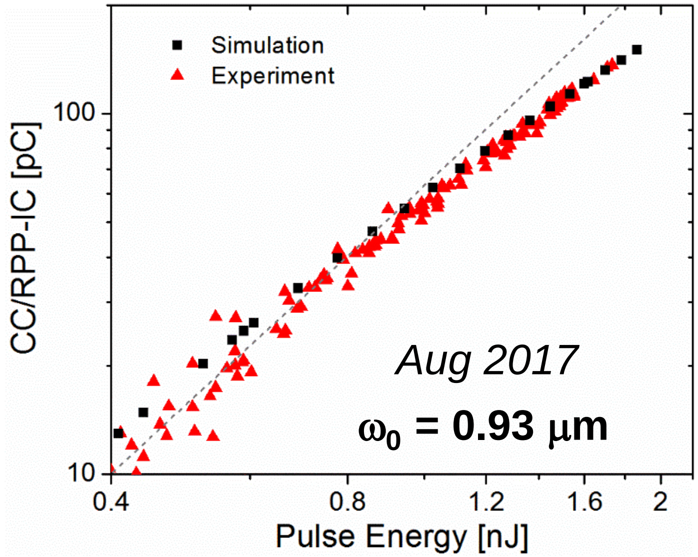
January 2015 Data

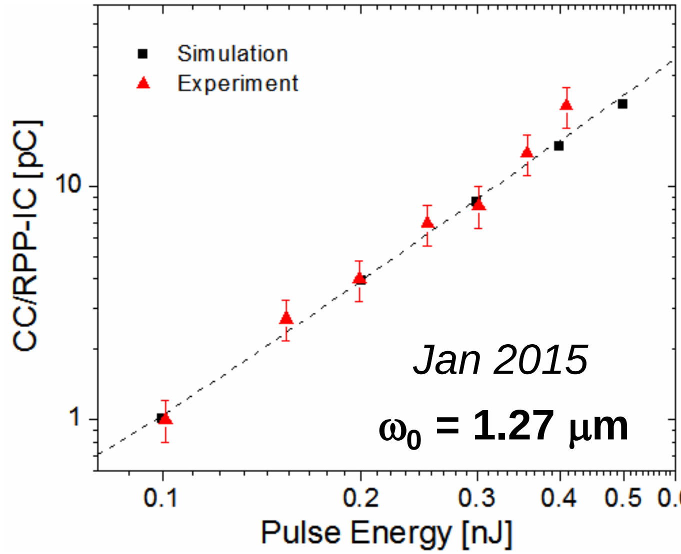


Correlation Study: Centronic Bulk Diode

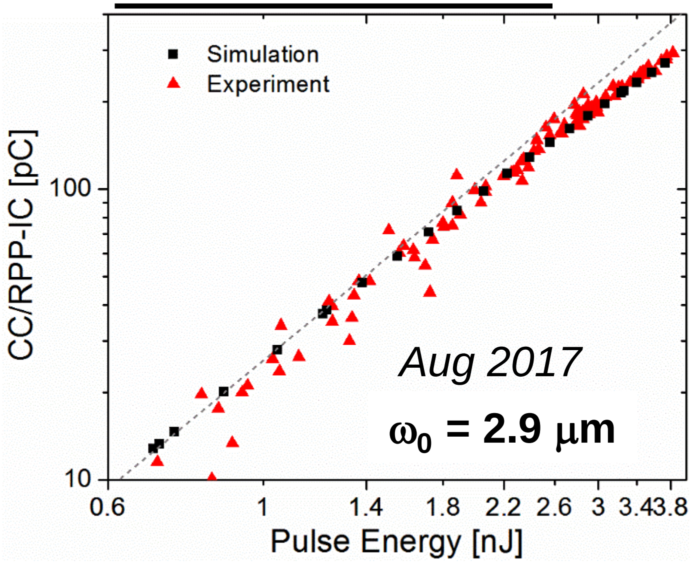
DUT Position

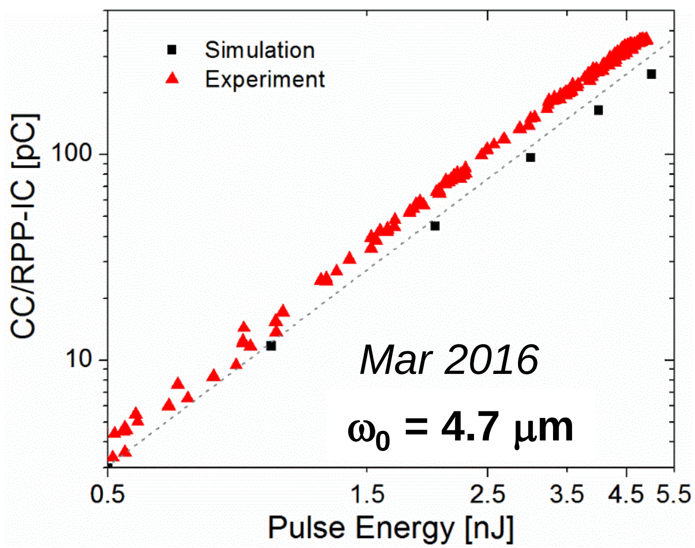


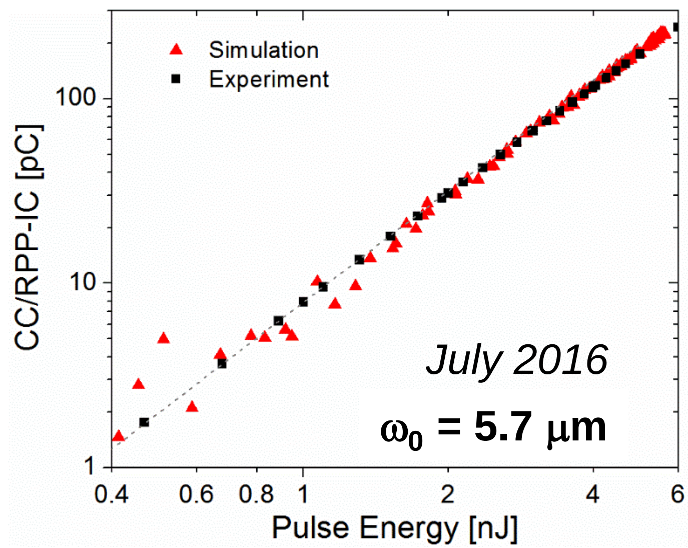




Dosimeter Position

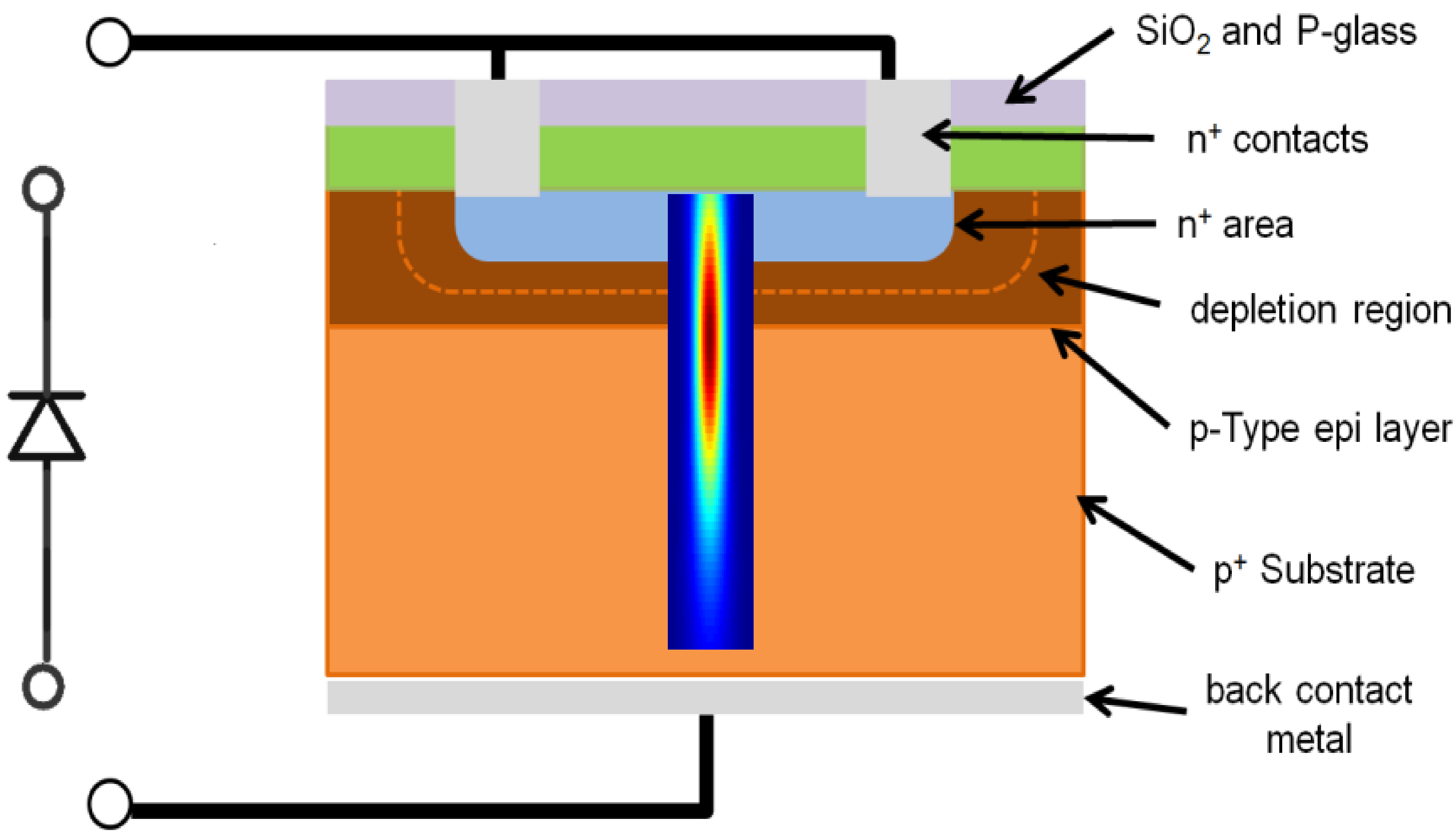






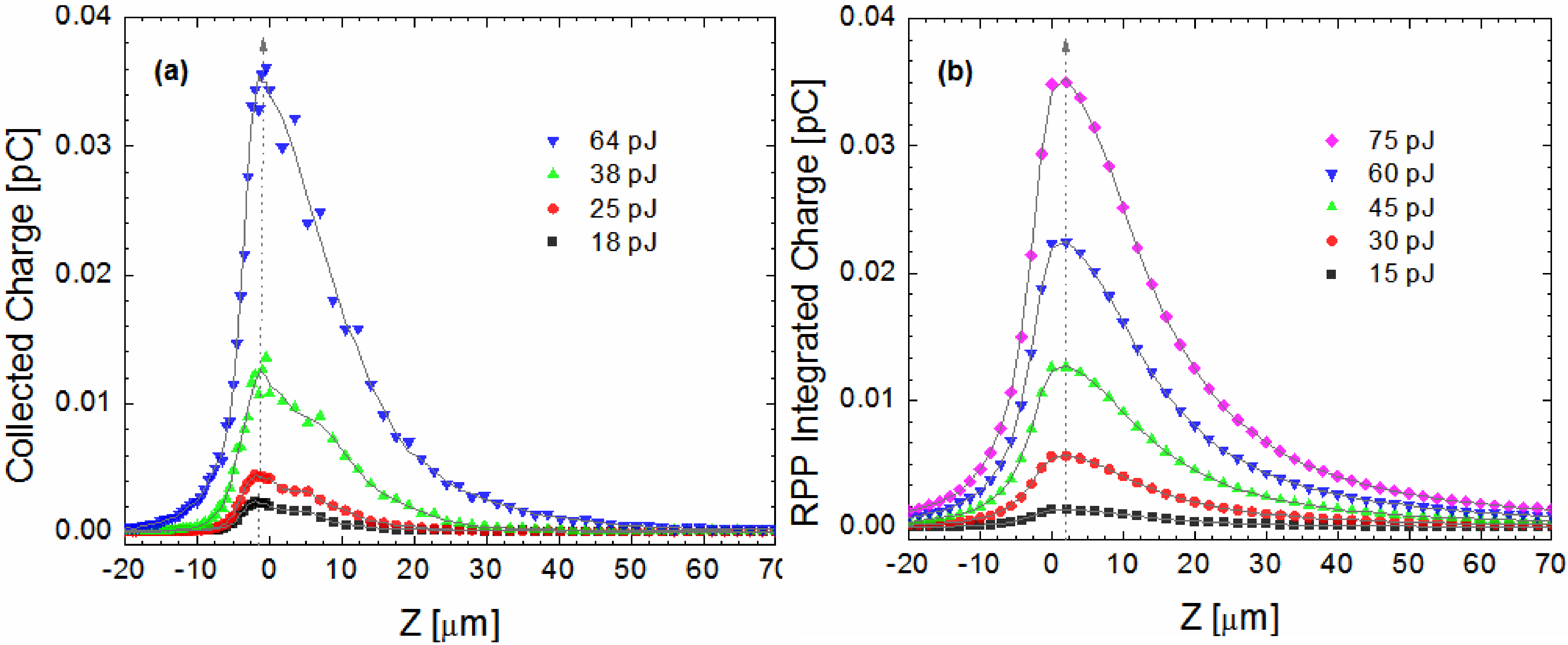
Measurements taken over 2.5 year time frame using multiple focusing configurations

Correlation Study:
Sandia n+/p/p+ Epitaxial Diode



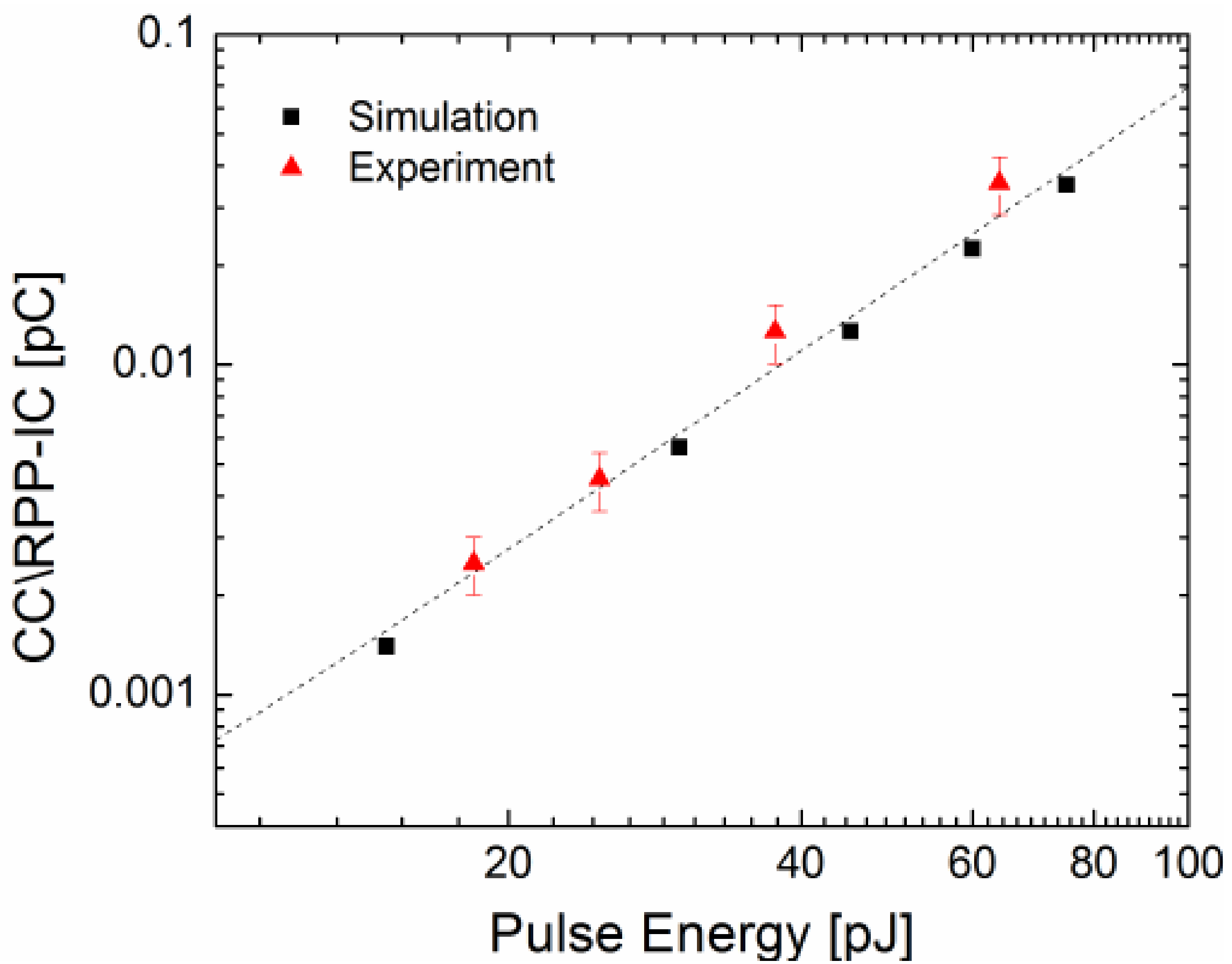
RPP depth of 2.3 μm << charge profile size

Correlation Study:
Sandia n+/p/p+ Epitaxial Diode



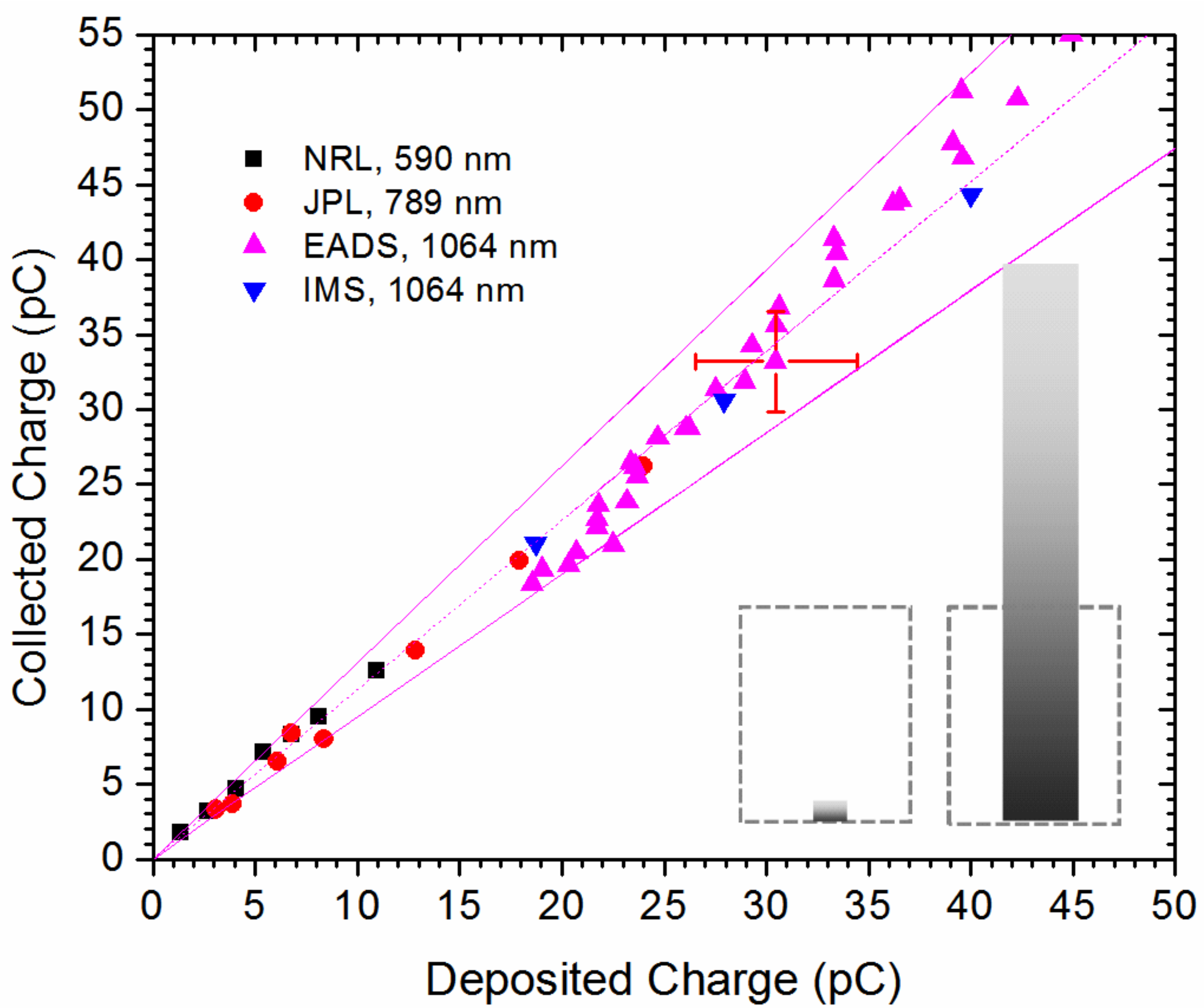
- Well-defined charge collection depth
- Overall magnitudes, positions, trends of z-scans show good agreement
- Narrower scans peaked closer to z = 0 are reproduced by simulations

Correlation Study:
Sandia n+/p/p+ Epitaxial Diode



Error Analysis: SPA Measurements

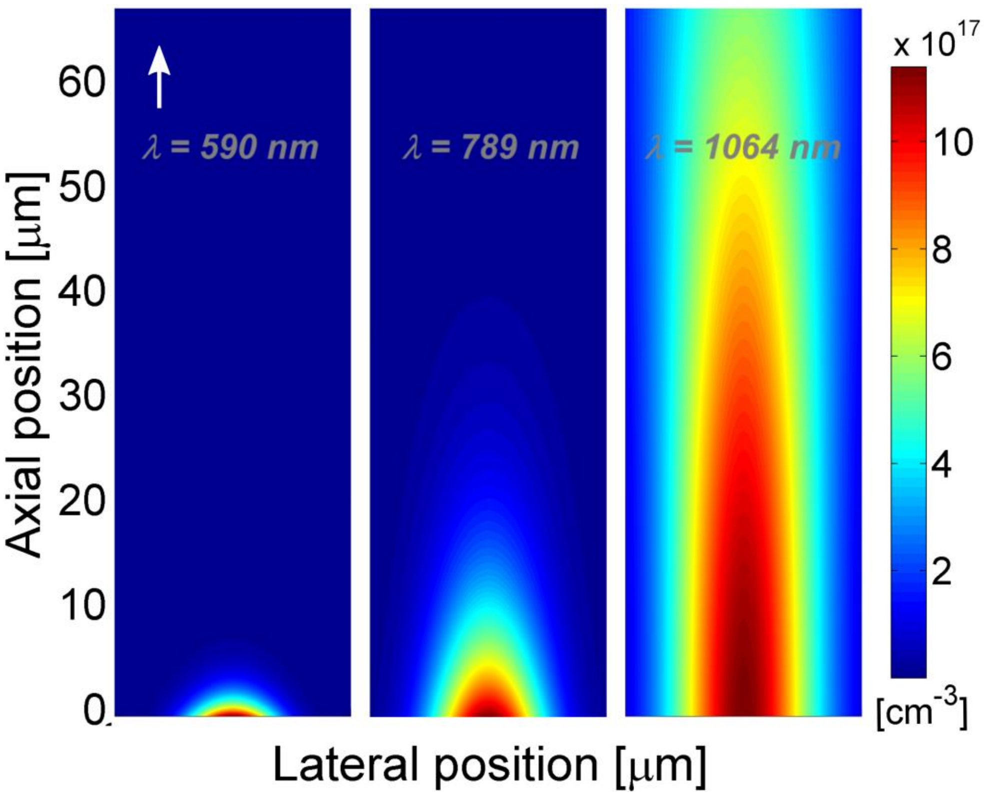
$$Q_{\max}^{(1)} = q\frac{E\lambda}{hc} \qquad Q_z^{(1)} = Q_{\max}^{(1)}\left(1 - \exp\left[-\alpha z_{RPP}\right]\right)$$

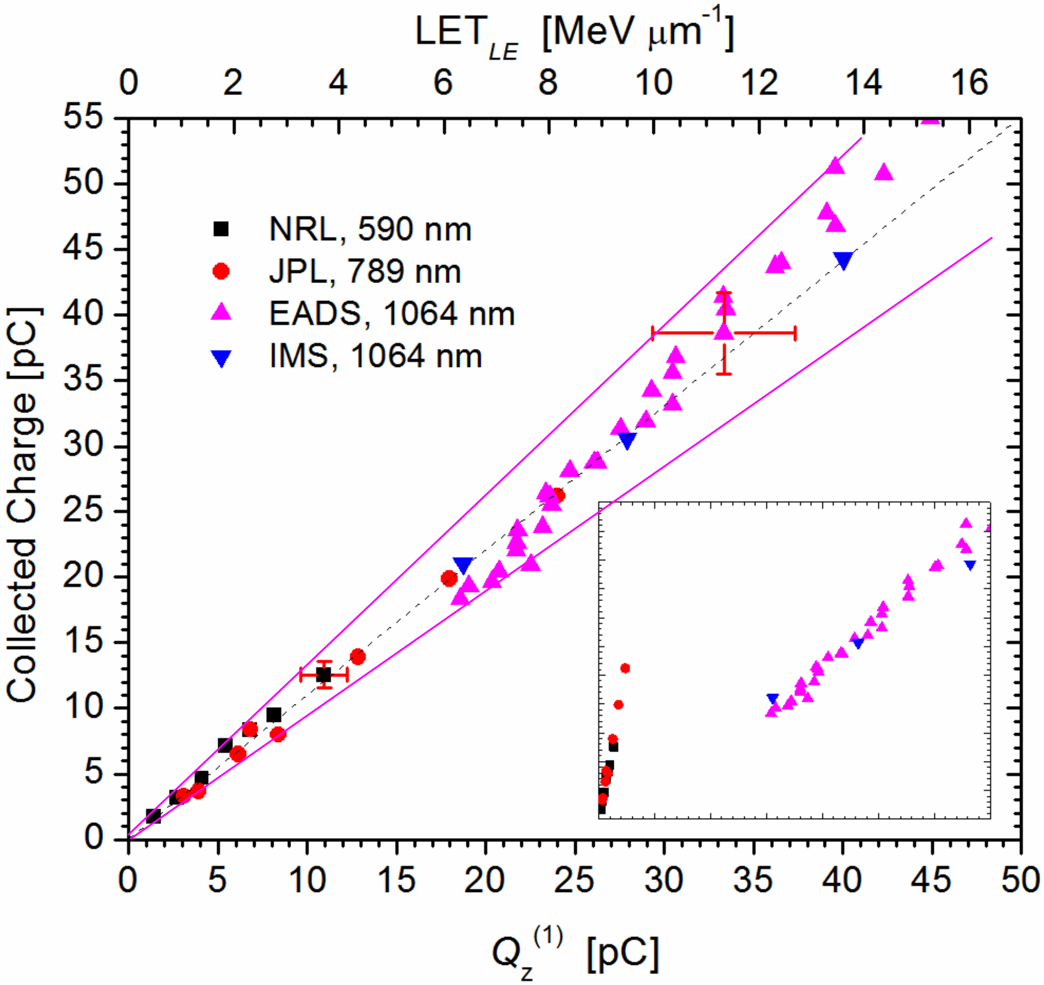


- Simple analytic equations for SPA charge deposition allow for error analysis
- Horizontal error bars show systematic error in Q_z (13%), vertical error bars show random error in *CC* values (10%)
- Total error (± 16%, red lines) encompasses both
- Measurements from different sites with different charge distributions all lie within confidence intervals given by the total error

SPA Data from: Buchner, IEEE TNS, 59, 988 (2012)

Laser-Ion Correlation - SPA

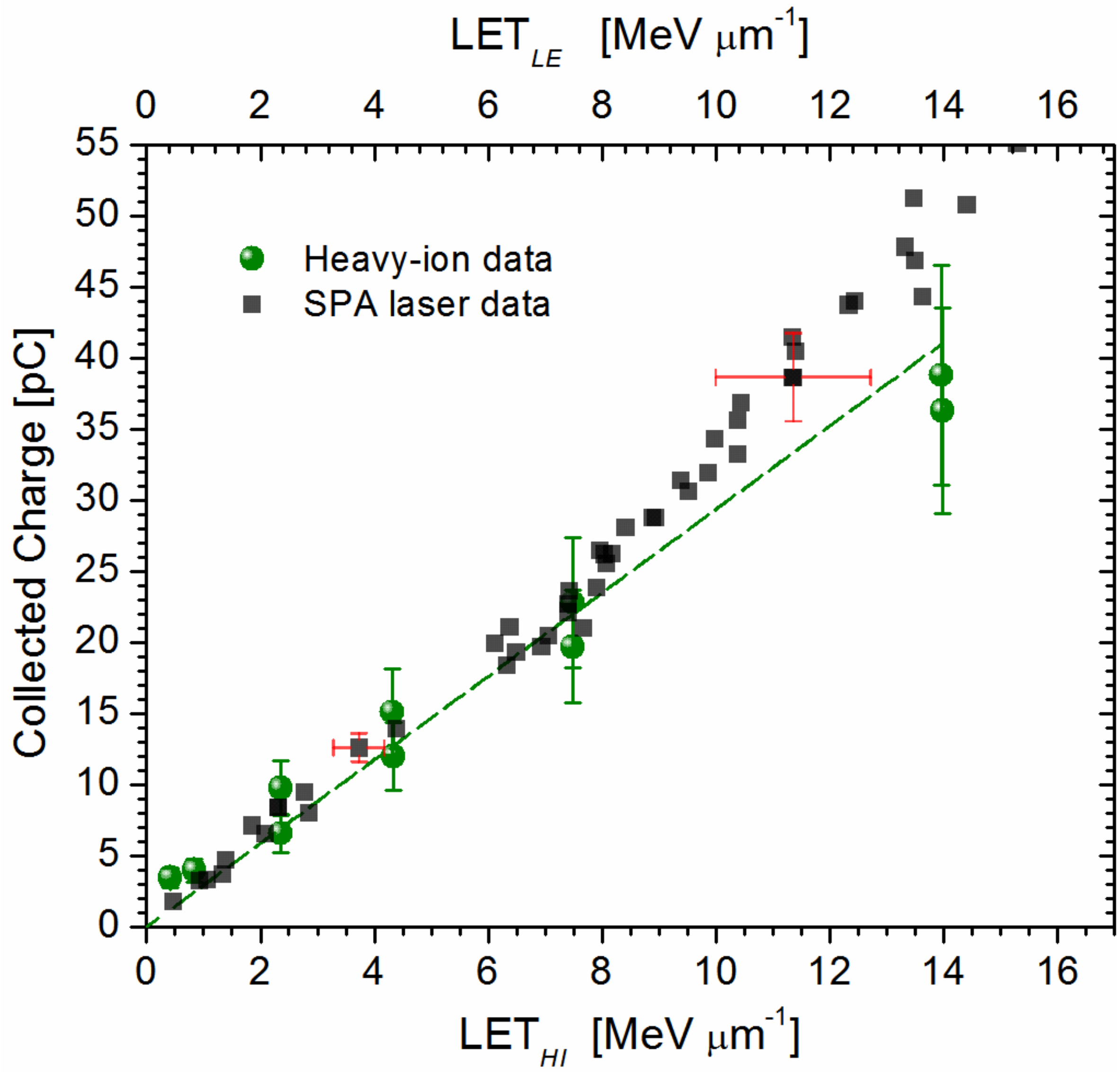




Laser Equivalent LET = $Q_z^{(1)}/z$

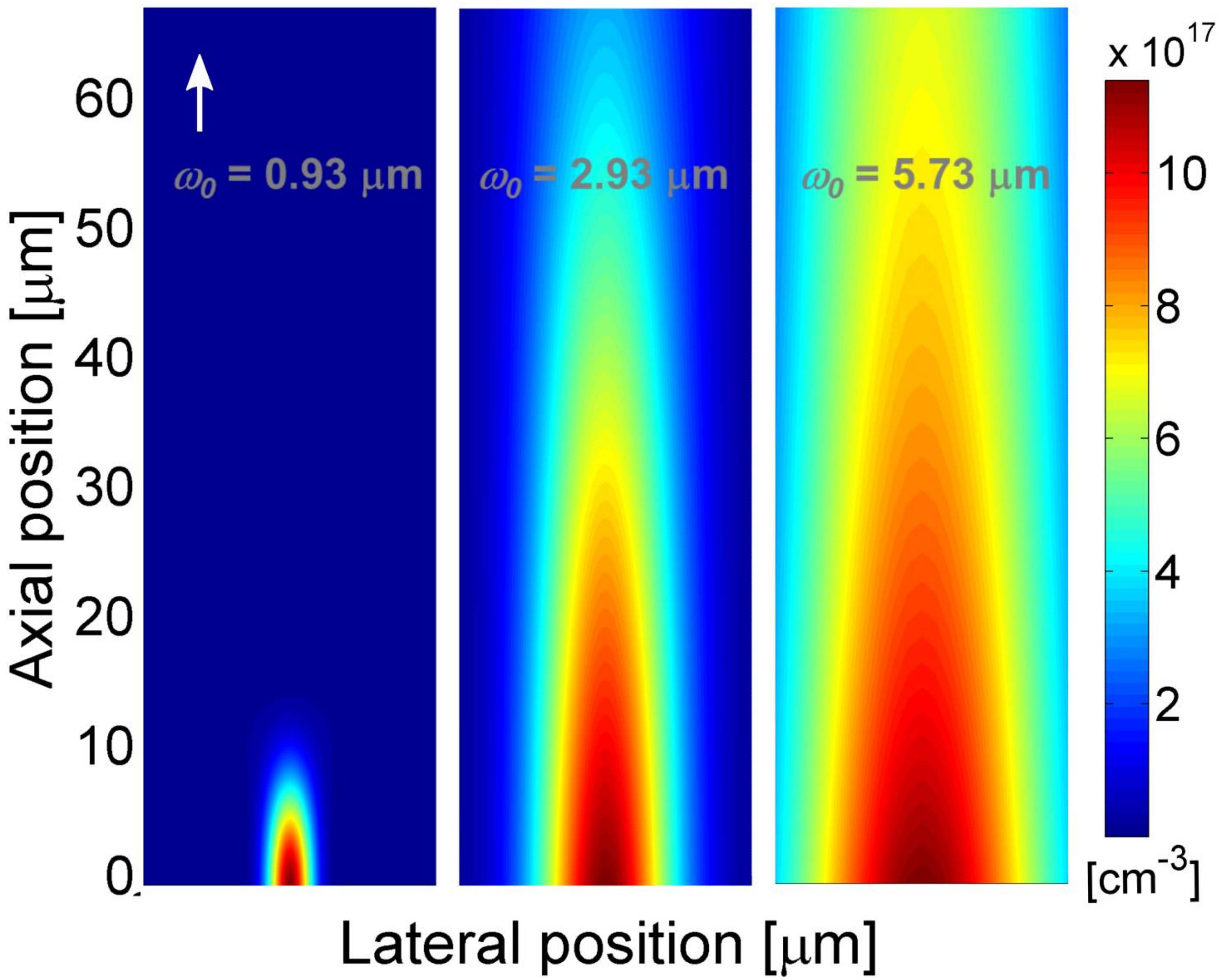
SPA Data from: Buchner, IEEE TNS, 59, 988 (2012)

Laser-Ion Correlation - SPA

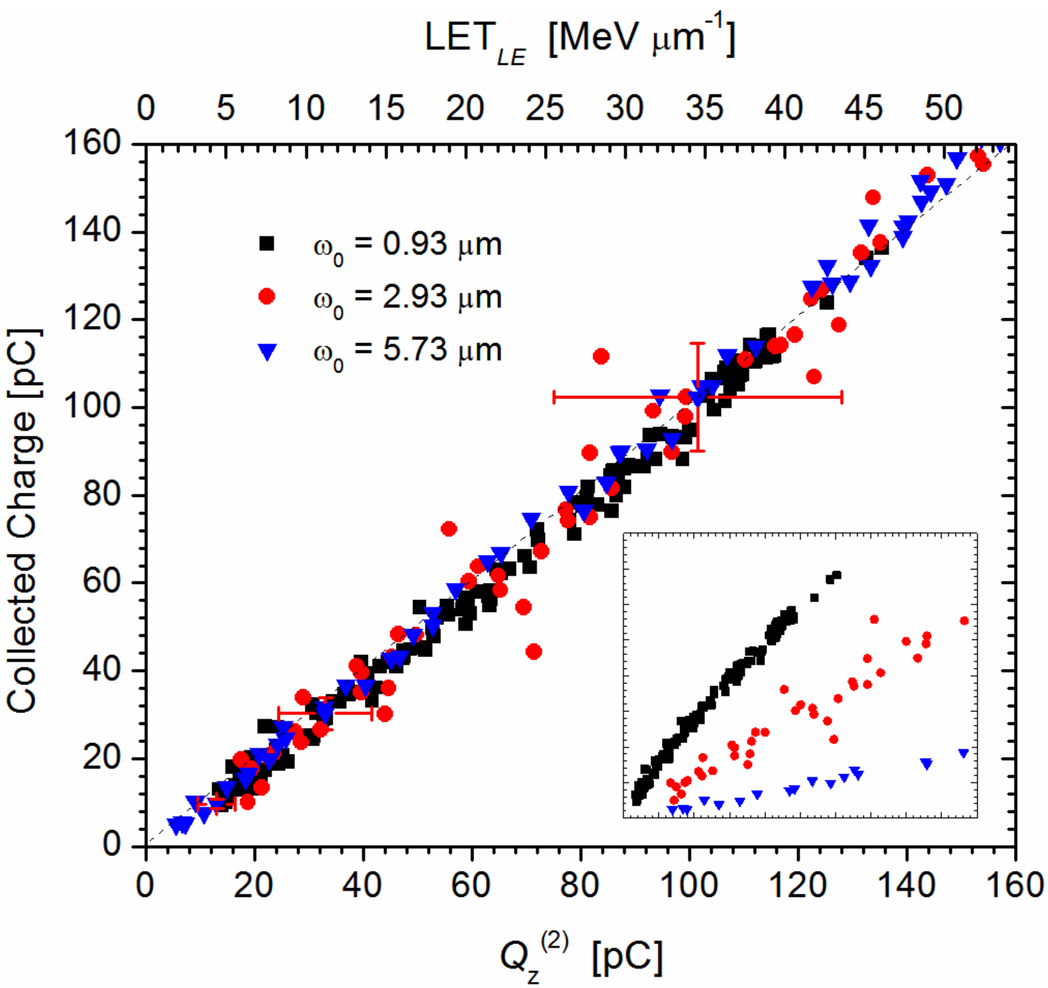


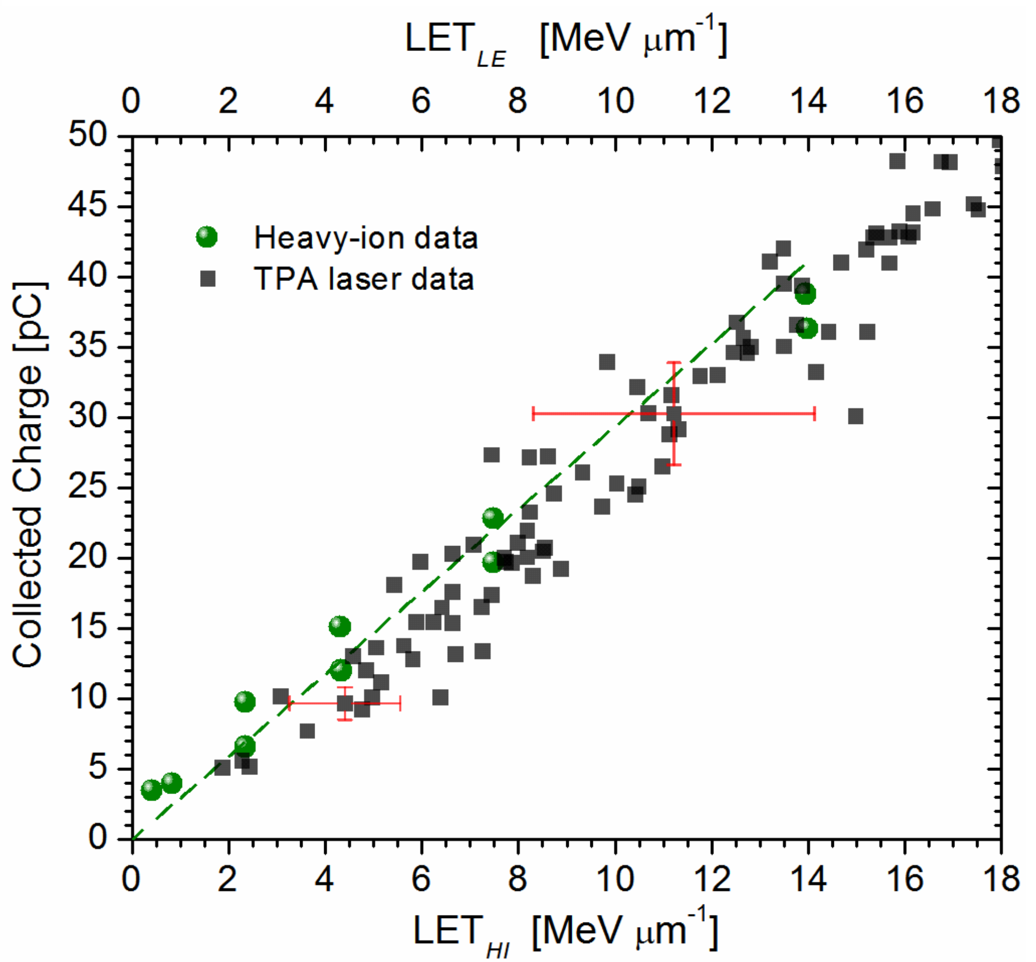
Data from: Buchner, IEEE TNS, 59, 988 (2012)

Laser-Ion Correlation - TPA



Laser-Ion Correlation - TPA





Hales, et al., Presented at RADECS 2017

Conclusions/Summary

- Validation of NLOBPM with experimental data continues
  - ***Quantitative agreement with experimental observables***
  - ***NLOBPM code is performing as hoped***
- Current Challenges/In Progress
  - Integration with device simulators (TCAD)
  - Application to more complex device structures
- Laser/Ion comparison is progressing
- Recent results (not presented)
  - GaAs Diode
  - GaN Diode
  - SiGe Diode
  - SiGe HBT
  - GF 32 nm PD SOI NFET
  - Analytical equations for integral CC (TPA and SPA)