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# Single-photon and two-photon absorption induced charge model calibration

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# Motivation

- ❑ Follow-up of RADLAS2013 presentation on TPA modeling

- ❑ Many use cases of the laser testing technique do not require absolute knowledge of the amount of injected charge
  - ❑ Comparing the sensitivity of different devices under test (DUT)
  - ❑ Evaluating the effect of a parameter on the DUT sensitivity (bias, temperature, frequency, load…)
  - ❑ Finding and mapping the areas of a DUT that are sensitive to a given single-event effect (SEE)
  - ❑ Pass/fail screening for single-event latchup (SEL)
  - ❑ Test set-up debugging & validation
  - ❑ …

- ❑ Some use cases require a reliable quantification of the laser-induced perturbation
  - ❑ Predicting the threshold LET for a given SEE
  - ❑ Tolerant screening for SEL (threshold prediction)
  - ❑ Event rate prediction
  - ❑ …

**WARNING**
No turn-key solution in this talk !

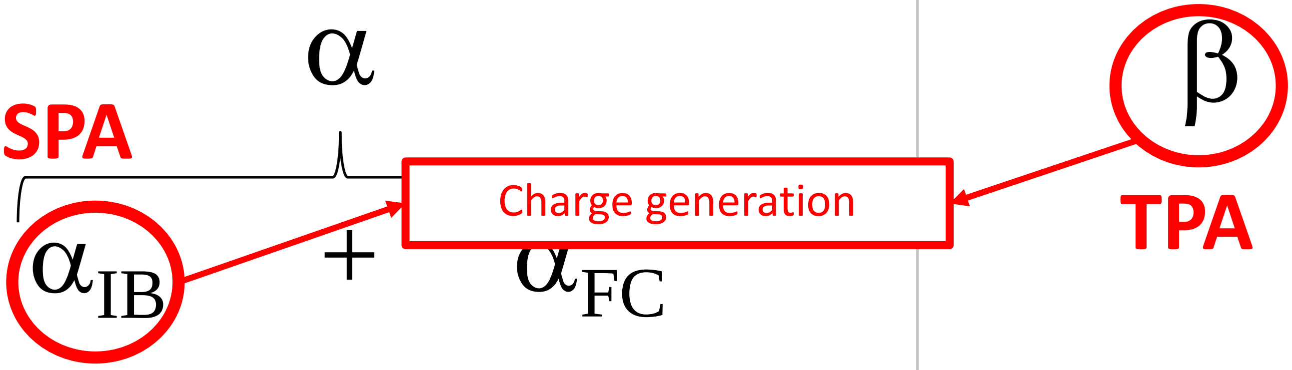
# Outline

- ☐ Reminders on Single-photon & Two-photon absorption
- ☐ Laser vs LET calibration
- ☐ Models of laser-induced charge
- ☐ Model-experiments correlation
- ☐ Conclusions

# Single- vs Two-photon absorption

Linear (single photon)
absorption

Two-photon
absorption



**SPA**

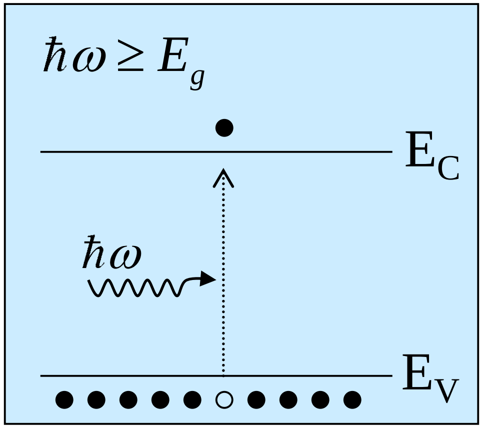
$$\overbrace{\alpha_{IB} + \alpha_{FC}}^{\alpha}$$

Charge generation

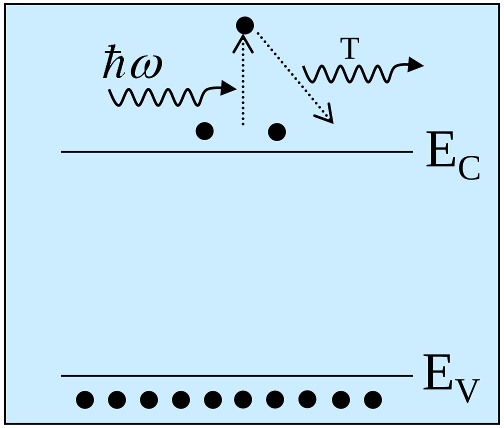
$\beta$

**TPA**

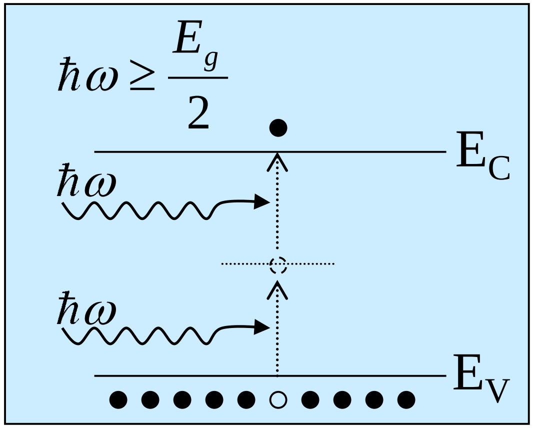
*Interband absorption*



*Free carriers absorption*



*Non-linear absorption*



# Laser-induced electron-hole pairs generation rate

- General case: $G = \frac{\alpha_{IB}}{E_\gamma} I + \frac{\beta}{2E_\gamma} I^2$

**SPA**

- $\lambda < \lambda_g \Rightarrow$ first term is dominant
- Second term usually negligible
- Induced charge $\propto$ pulse energy

**TPA**

- $\lambda_g < \lambda < 2\lambda_g \Rightarrow$ first term is null
- Second term is dominant
- Induced charge $\propto$ pulse energy$^2$
- $\beta << 1 \Rightarrow$ high intensity required
  $\Rightarrow$ femtosecond pulses

- Initial carriers distribution completely defined by modeling the laser intensity distribution

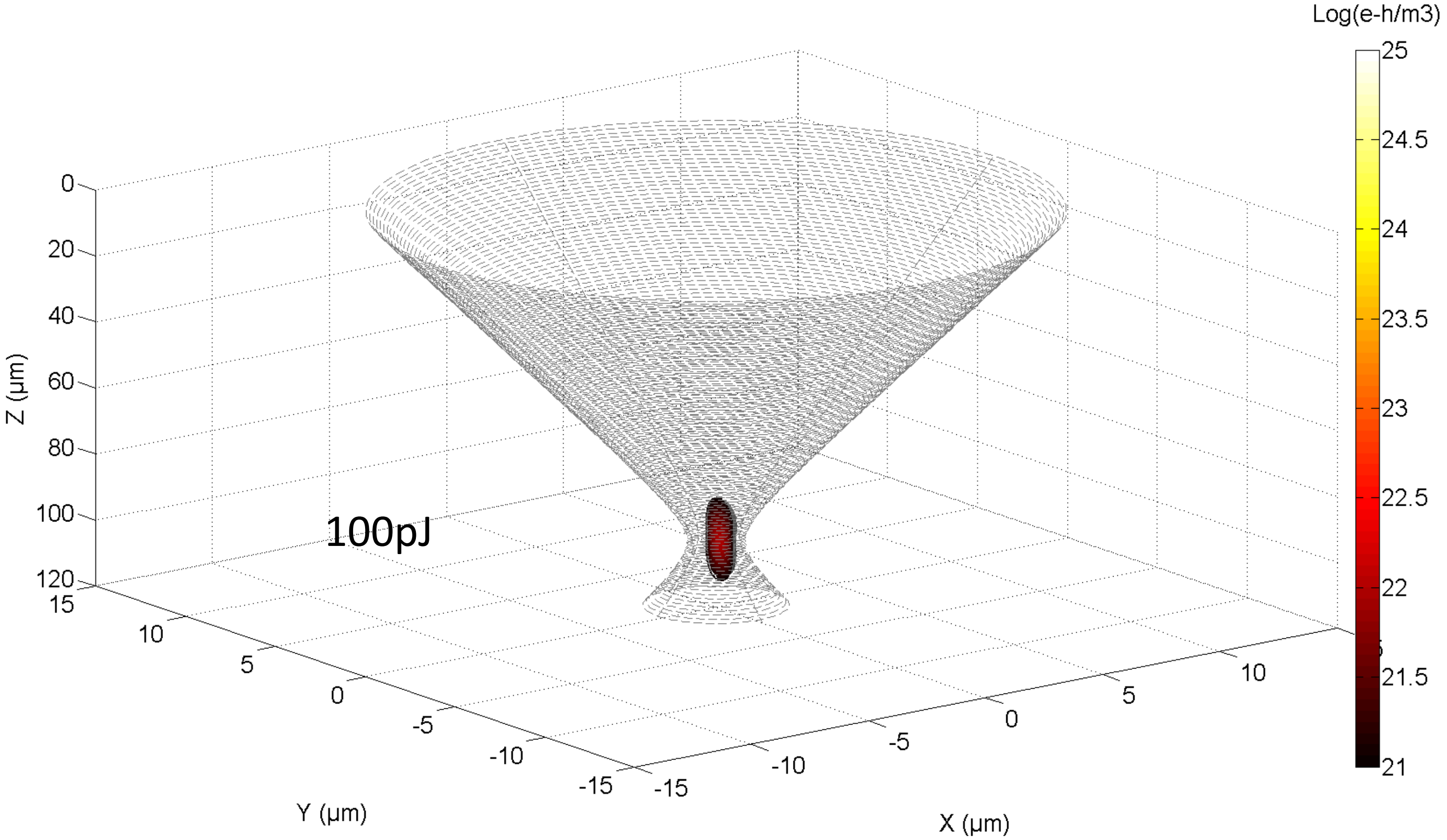
# Modeling options

- ❑ Analytic (closed form) model
    - ❑ Starting from Maxwell equations
    - ❑ No analytic solution in the general case of nonlinear propagation

- ❑ Finite Element method
    - ❑ Finite Difference in Time Domain (FDTD)
    - ❑ Maxwell equations resolved by discretizing space and time
    - ❑ Available open source and commercial tools do not always deal correctly with nonlinear propagation
    - ❑ Time and computation ressources required

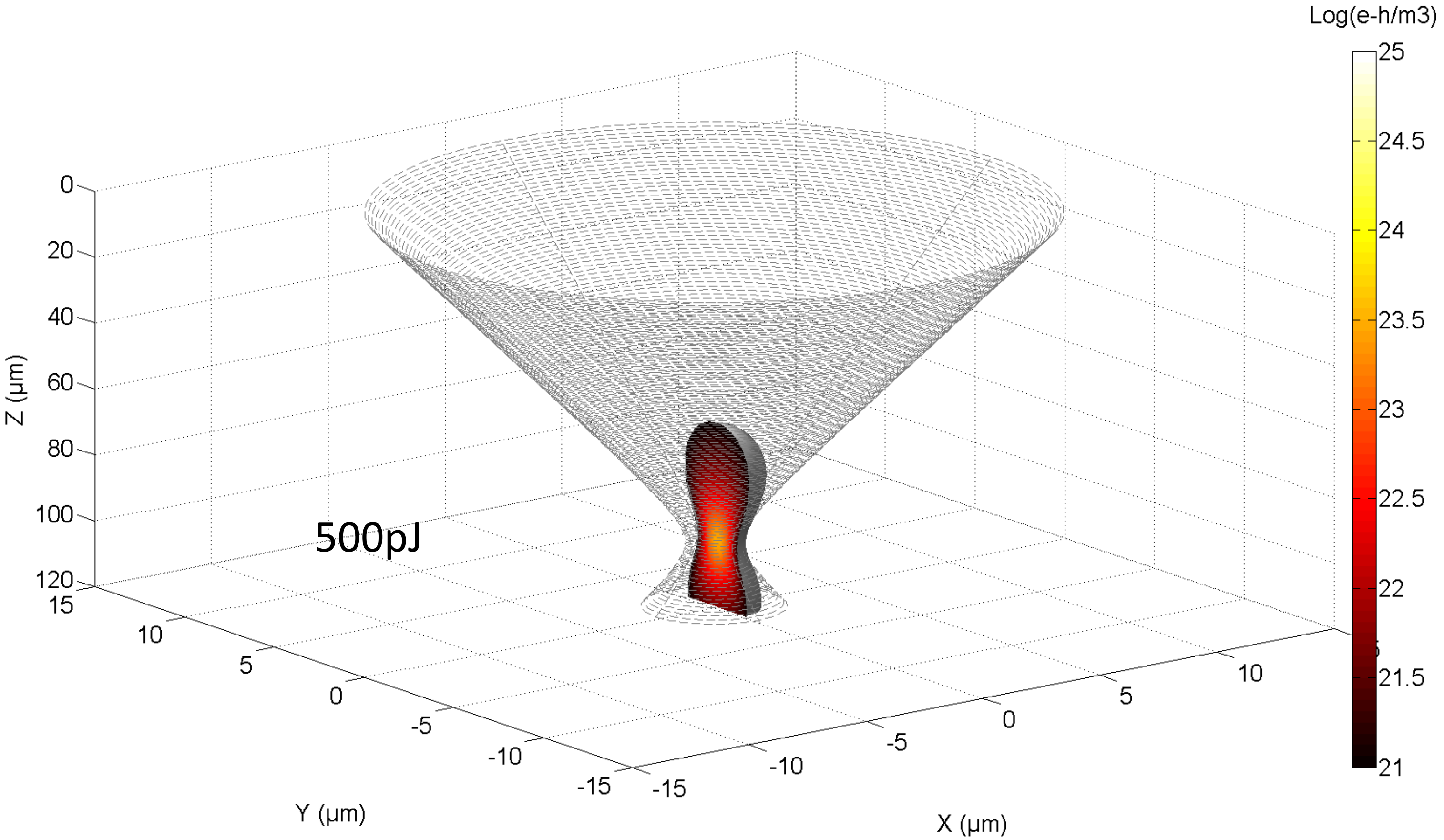
- ❑ Intermediate solution: iterative numerical model
    - ❑ Main assumption: the beam remains Gaussian
    - ❑ Discretization of space and time
    - ❑ Iterative propagation of the Gaussian enveloppe in space and time using analytic equations and complex ABCD matrices

# Model results: charge track profile

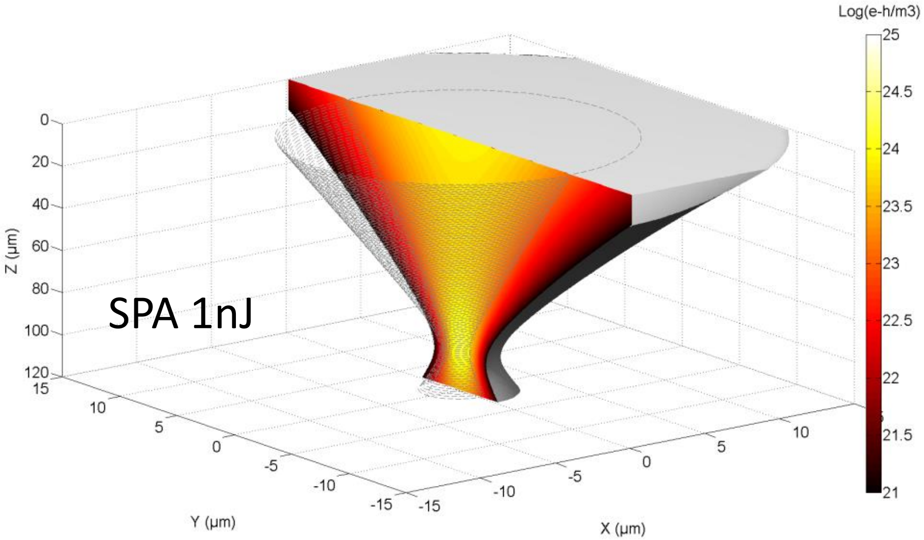


- ☐ Wavelength: 1.3µm
- ☐ Pulse duration: 100fs
- ☐ Substrate doping: $10^{18}$ cm$^{-3}$

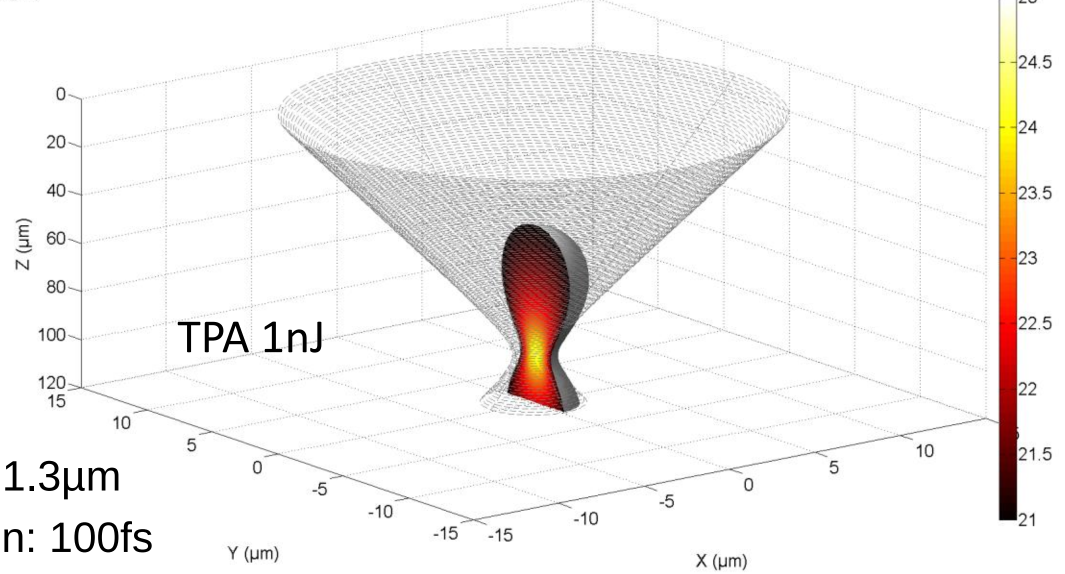
# Model results: charge track profile



# SPA vs TPA



- Wavelength: 1.064µm
- Pulse duration: 30ps



- Wavelength: 1.3µm
- Pulse duration: 100fs

# The question of calibration

- ❑ Laser-induced charge can be calculated with good accuracy as a function of:
  - ❑ Laser parameters (energy, wavelength, pulse duration…)
  - ❑ IC parameters: substrate doping
  - ❑ IC preparation parameters: substrate thickness, backside surface quality (transmission)

- ❑ SPA
  - ❑ Accurate analytical and numerical models available

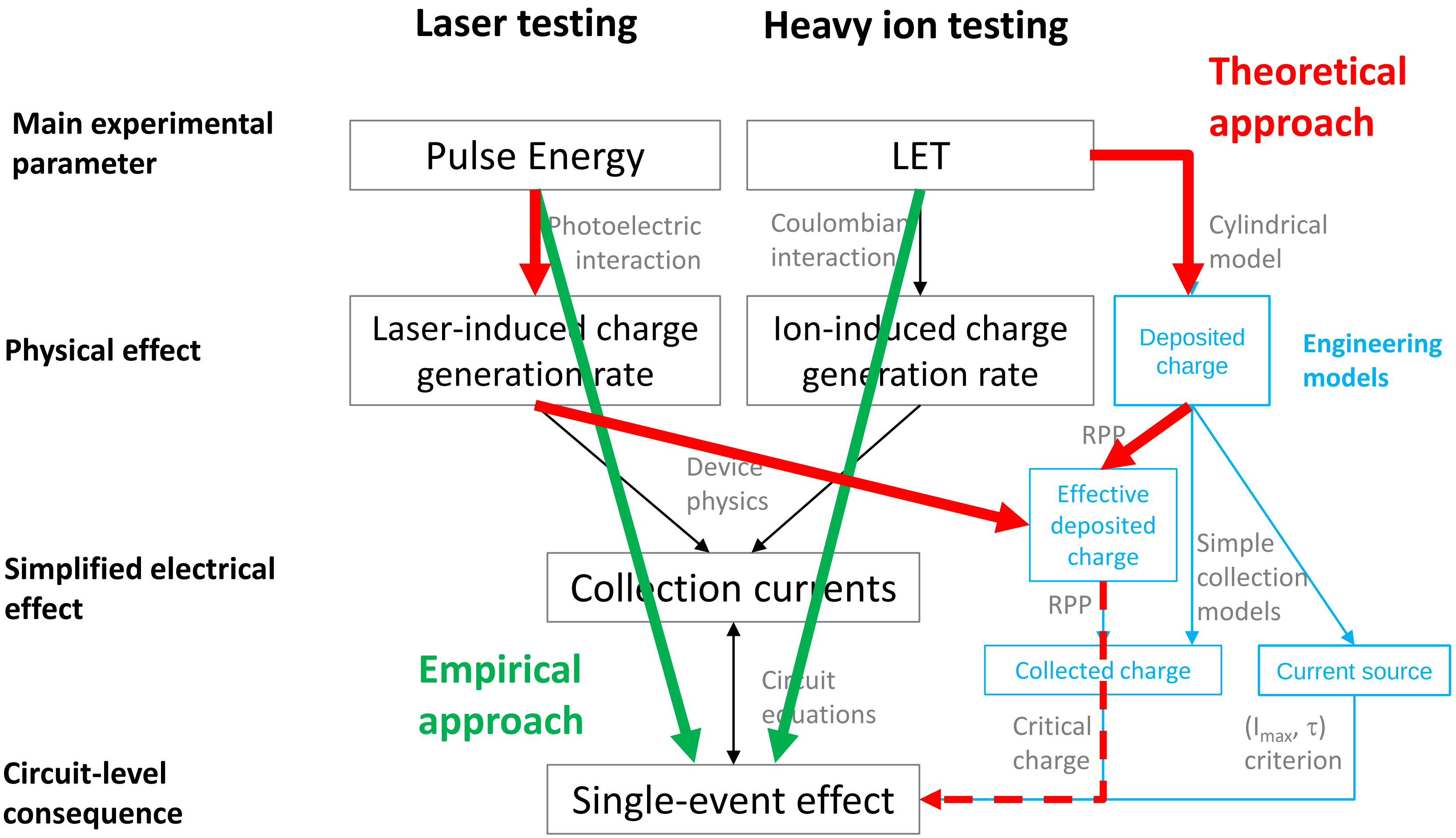
- ❑ TPA
  - ❑ Good-enough numerical models available (still not including all the non-linear optics phenomena)

- ❑ However, calculating the deposited charge is not sufficient for calibration

- ❑ For laser SEE testing, calibration usually means:
  - ❑ Finding a relationship between the main experimental parameters: laser energy and ion LET
  - ❑ Defining the “equivalent” LET of a given laser energy

- ❑ Typical calibration approaches
  - ❑ Based on the calculation of equal <u>effective</u> deposited charge
  - ❑ Based on SEE threshold experimental measurements

# Calibration approaches



**Laser testing**

**Heavy ion testing**

**Theoretical approach**

**Main experimental parameter**

Pulse Energy

LET

Photoelectric interaction

Coulombian interaction

Cylindrical model

**Physical effect**

Laser-induced charge generation rate

Ion-induced charge generation rate

Deposited charge

**Engineering models**

RPP

Device physics

Effective deposited charge

**Simplified electrical effect**

Collection currents

RPP

Simple collection models

Collected charge

Current source

**Empirical approach**

Circuit equations

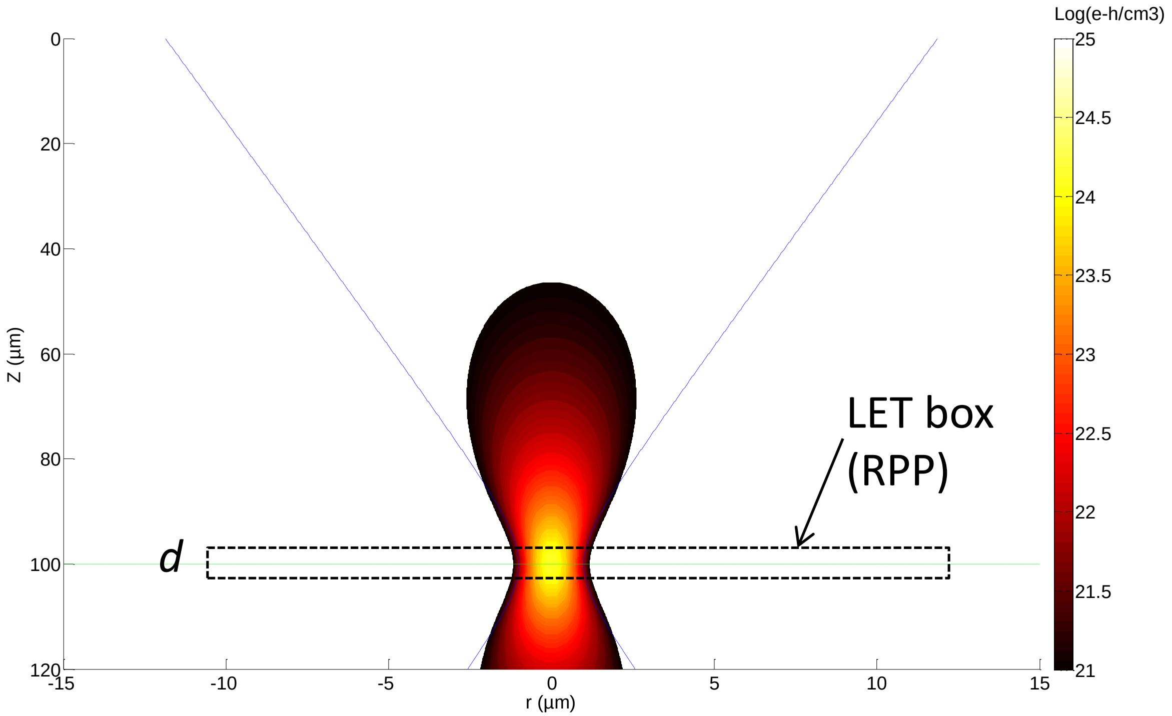
Critical charge

$(I_{max}, \tau)$ criterion

**Circuit-level consequence**

Single-event effect

# Equivalent Laser LET



$$LET_{TPA} = \frac{1}{d} \iiint_{LET\ box} N_{TPA}(\boldsymbol{r})d\boldsymbol{r}$$

- ☐ Not to be taken as an absolute value, but may provides orders of magnitude

# Equivalent Laser LET

$$\boxed{LET = K_{SPA}E}$$

$$\boxed{LET = K_{TPA}E^2}$$

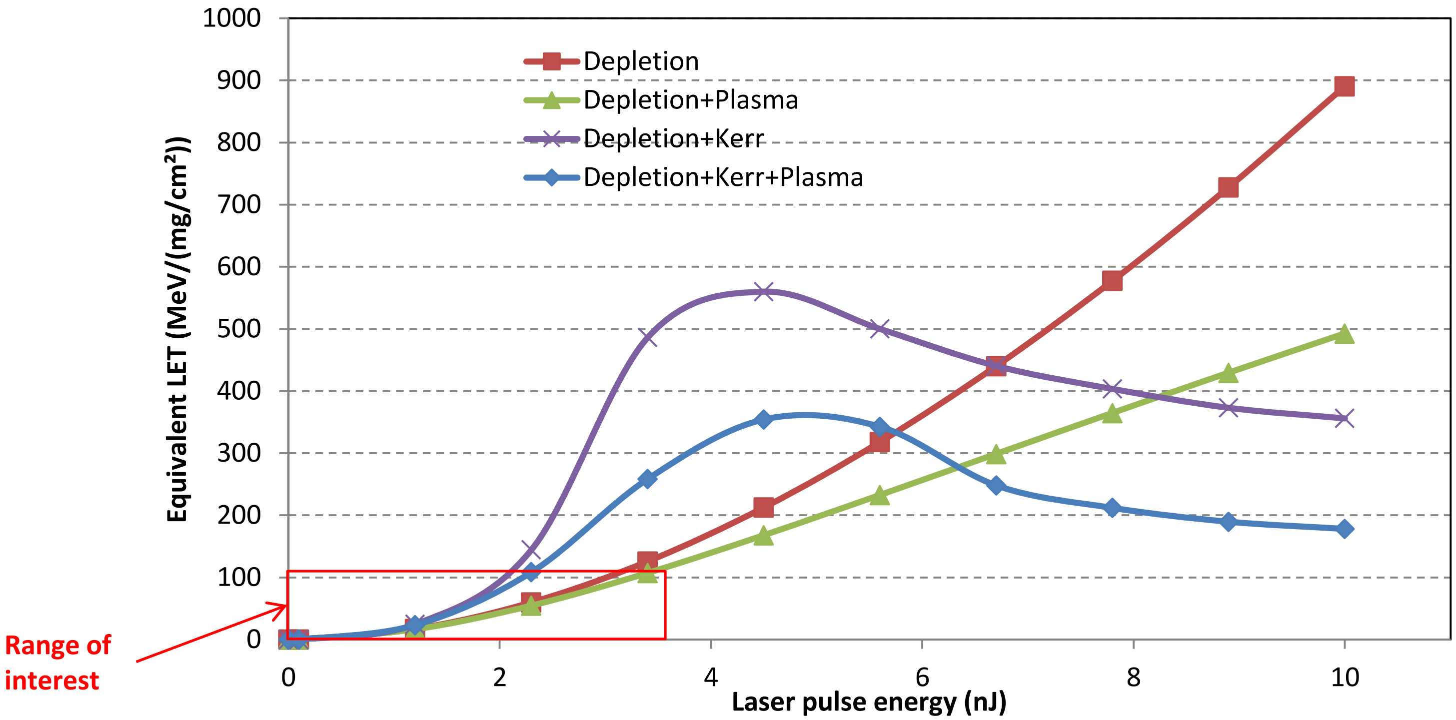
*E* = laser pulse energy in the active thickness of the DUT

- *K* coefficients estimated by calculation (based on RPP model) or experimental calibration (based on heavy ion data)
- Calibration coefficients are specific to a laser facility (laser parameters)
- Calibration can be seriously affected by optical setup variations
- Calibration is expected to be reliable for different devices **with the same technology <u>and</u> design density**

- **Calculated *K* coefficients may require an additionnal calibration step in order to:**
  - Adjust for unknown parameters: substrate doping, metal density
  - Adapt for charge collection mechanisms differences related to process details and laser spot size effects

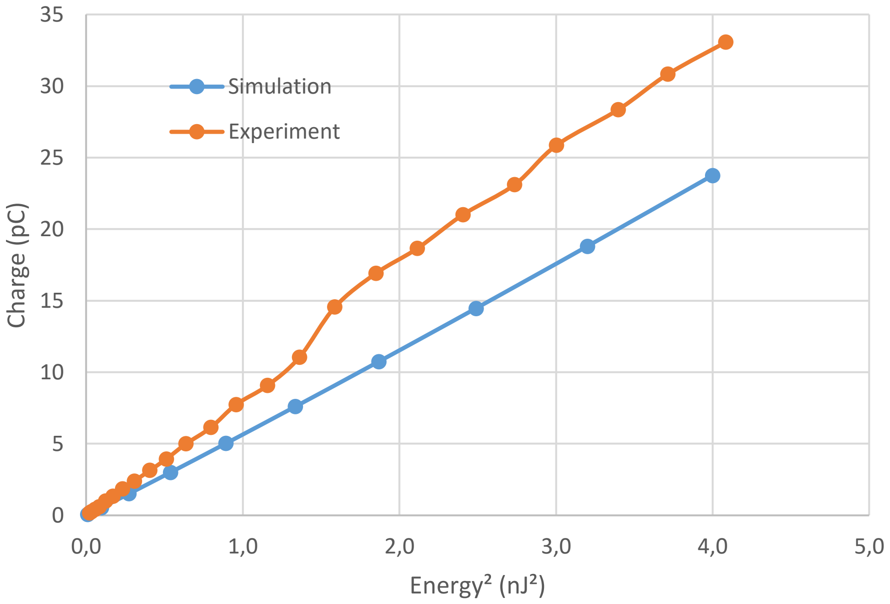
- Introduction of a correction factor: $k_C = K_{exp}/K_{sim}$

# Equivalent LET vs Energy



# Model/experiment correlation: case 1

- ☐ PIN photodiode
- ☐ 20µm depletion depth
- ☐ TPA experiment
- ☐ Charge collection measurement



Possible deviation sources:

- Spot size error
- β error
- Energy measurement errors
- Charge collection efficiency
- Charge integration (noise)

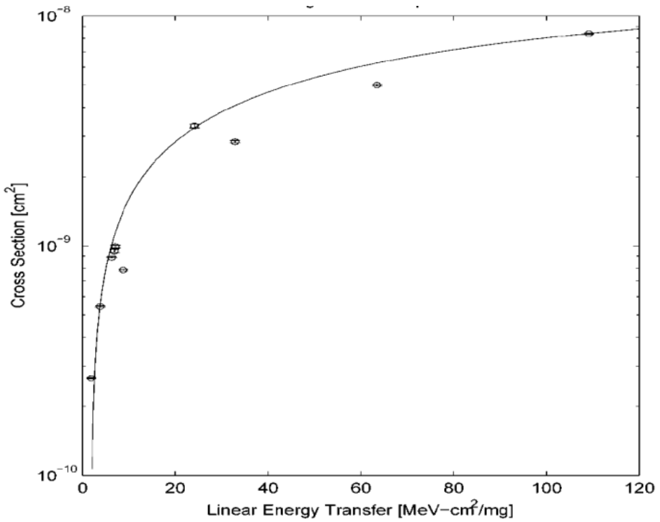
Correction factor:

$k_C = K_{exp}/K_{sim} = 1.4$
due to model limitations
& measurement errors

# Model/experiment correlation: case 2

- 28nm Bulk CMOS SRAM
- 700µm thick substrate
- TPA experiment

- Experimental calibration
  - Energy threshold for SEU: 67pJ±5pJ
  - Using heavy ion data from Lee et al, IEEE REDW, 2014
    - LET threshold for SEU (Weibull fit): 1.9 MeV/(mg/cm²)
  - LET = K E²
    - ⇒ K = 4.2 $10^{-4}$ MeV/mg/cm²/pJ²



- Model calibration
  - Using energy threshold and an RPP depth of 1µm
    - Calculated equivalent LET = 0.24 MeV/(mg/cm²)
    - ⇒ K = 5.3 $10^{-5}$ MeV/mg/cm²/pJ²
    - ⇒ Correction factor: $k_C = K_{exp}/K_{sim}$ = 7.9 (bad experimental calibration)

  - Device possibly sensitive to proton direct ionization ⇒ LET threshold extracted from Weibull fit of heavy ion data not reliable for laser experimental calibration

# Lessons learned

- Experimental (empirical) calibration
  - should not be based on events with low $LET_{th}$
  - should be based on SEL data when possible
  - should be confronted to state-of-the-art model-based calibration

- Correction factor $k_C$
  - Provides a measurement of experiment/model correlation
  - May be used for both SPA and TPA
  - Rule of thumb: $k_C<0.5$ or $k_C>2$ reveals incomplete modeling (spot size effect, collection mechanism, electrical effect…) or bad data (threshold measurement error, surface quality…)

- On recent COTS, accurate threshold measurement & calibration not the first priority for non-destructive event rate prediction
  - Measuring the saturation cross section probably more useful

# Conclusions

- Laser SEE testing sometimes (i.e. not always) require calibration of the laser energy with respect to the standard LET metric

- In the last ten years, significant progresses have been done in modeling laser-induced charge (SPA or TPA)
  - Mostly proprietary models
  - Link between deposited charge and SEE still often based on RPP or simple diffusion models

- Experimental calibration vs model-based calibration
  - Experimental calibration still preferred by end-users for RHA
  - When possible, both approaches should be confronted
  - Correction factor proposed as a metric of calibration quality (reliability?)

- Possible ways to move forward
  - Open source model or freeware tool
  - RADLAS database of laser testing results with sufficient information for model-based calibration