SEE laser testing using two-photon absorption:

Modeling of charge deposition

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Context & motivations

- Modeling of laser testing
  - Charge deposition profile for TCAD analysis
  - Estimation of equivalent laser LET for adjusting experimental parameters

- Single-photon absorption technique
  - Model of charge deposition: simple or advanced models available
  - Equivalent laser LET
    - Theoretical models available
    - Many empirical results available
    - Strongly dependent on optical parameters (wavelength, pulse duration…)

- Two-photon absorption
  - Model of charge deposition: only basic models available
  - Equivalent laser LET
    - A few empirical results available (Schwank et al, IEEE TNS 2011)
  - Impact of complex nonlinear effects on 3D resolution ?

⇒ **Development of a realistic model of TPA-induced charge deposition**

Contributions: P. Jaulent, PhD Thesis, Univ. Bordeaux, 2008
K. Shao, PhD Thesis, Univ. Bordeaux, 2011
A. Morisset, PhD Thesis, Univ. Bordeaux, 2012

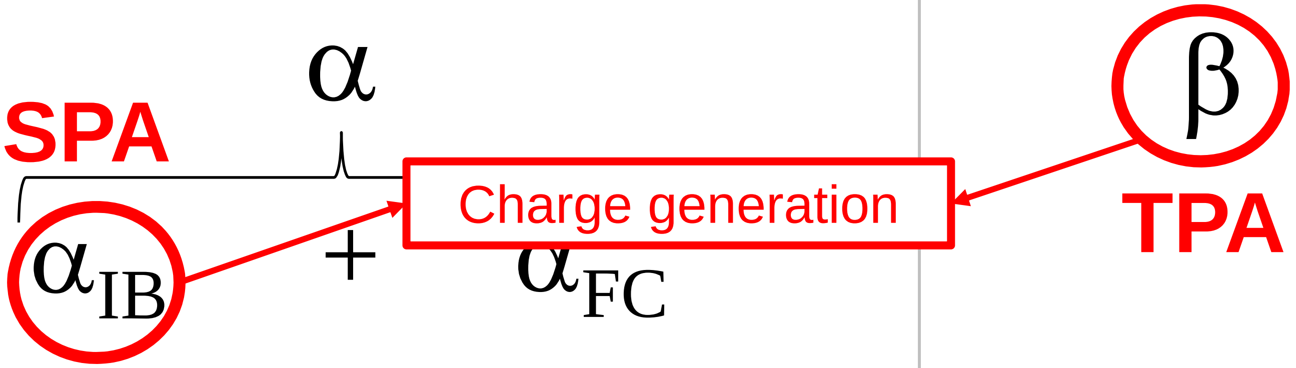
Outline

- ❑ Principles of two-photon absorption (TPA)
- ❑ Basic model of TPA-induced charge deposition
- ❑ Linear and nonlinear effects
- ❑ Advanced modeling of TPA-induced charge
  - ❑ Principles
  - ❑ Preliminary results
- ❑ Conclusions

Single- vs Two-photon absorption

Linear (single photon) absorption

Two-photon absorption



α

SPA

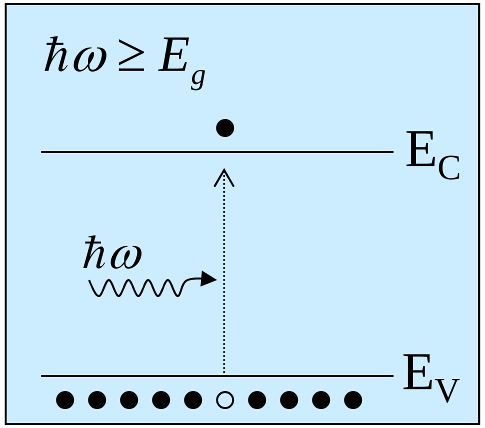
$\alpha_{IB} + \alpha_{FC}$

Charge generation

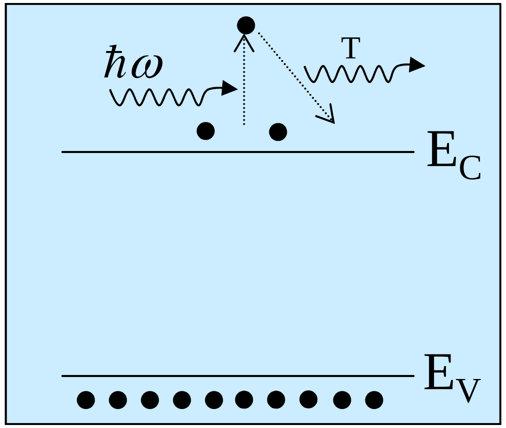
β

TPA

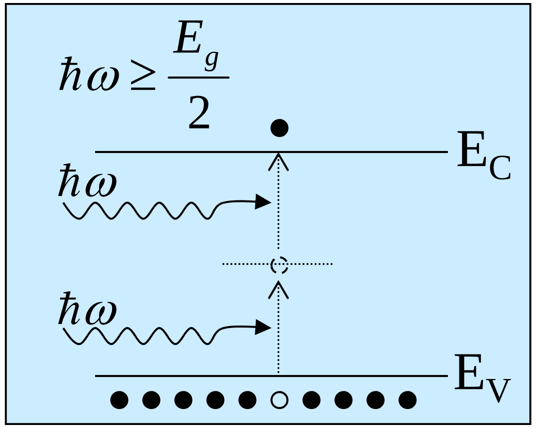
Interband absorption



Free carriers absorption



Non-linear absorption



Two-photon absorption

- Nonlinear process
  - Charge generation rate varies quadratically with laser intensity

$$G\,(\boldsymbol{r},t) \propto \beta \frac{I(\boldsymbol{r},t)^2}{2\hbar\omega}$$

- Condition on photon energy
  - Smaller than band-gap, else linear (single photon) absorption will always dominate
  - Higher than half the band-gap

- Condition on intensity
  - Low probability mechanism: $\beta \approx 1cm/GW$
  - High intensity required for significant charge generation: small spot, short pulse (fs)

TPA pros and cons

- Lateral resolution improved by $\sqrt{2}$

- Axial resolution = access to 3D resolution

- Requires femtosecond pulses
  - Laser source cost

- Quadratically sensitive to uncontrolled intensity variations
  - Energy stability
  - Spot size variations
  - Backside quality of the sample

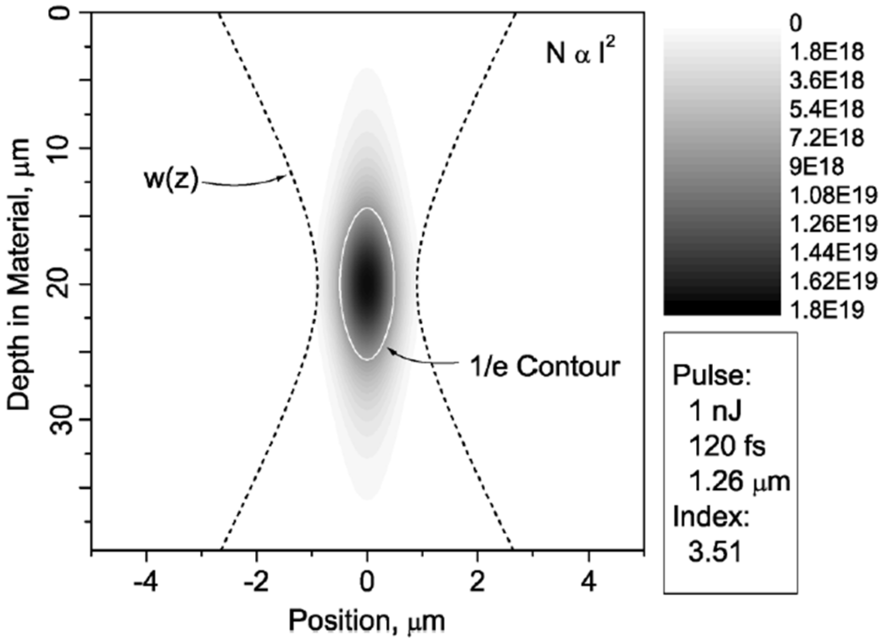
- More sensitive than SPA to focus variations
  - Not the first choice for scanning large areas

Basic models

- ❑ First order approach
  - ❑ Consider that absorption is negligible
  - ❑ Calculate intensity distribution in the absence of material interaction
  - ❑ $G(\boldsymbol{r},t) \propto \beta \frac{I(\boldsymbol{r},t)^2}{2\hbar\omega}$
- ❑ Plane wave approach

$$\frac{dI}{dz} = -\alpha I - \beta_2 I^2$$

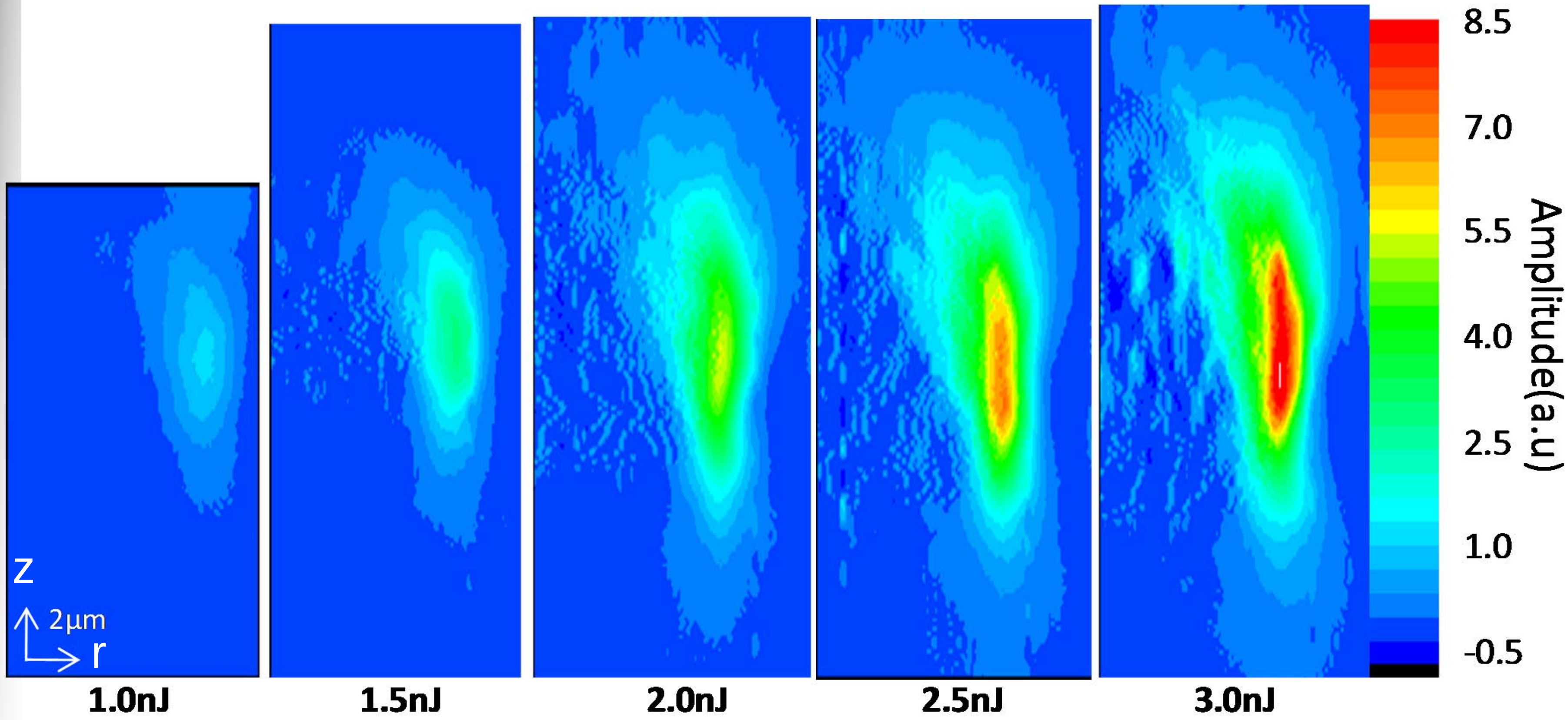
$$I(z) = I_0 \frac{e^{-\alpha z}}{1 + \frac{\beta_2 I_0}{\alpha}\left(1 - e^{-\alpha z}\right)}$$



McMorrow et al, IEEE TNS 49, 6, 2002

- ❑ Both approaches can not account for real laser-silicon interaction processes

Experimental Characterization of TPA spot in Si



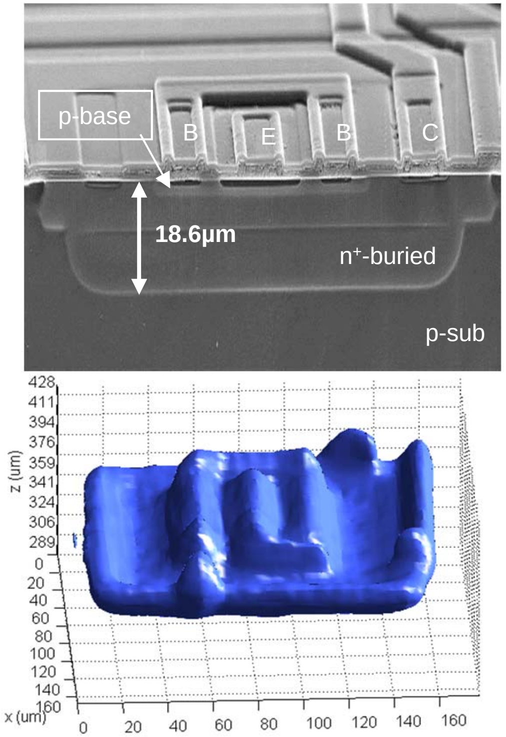
Shao et al, Optics express, 2011

Applications of TPA laser testing

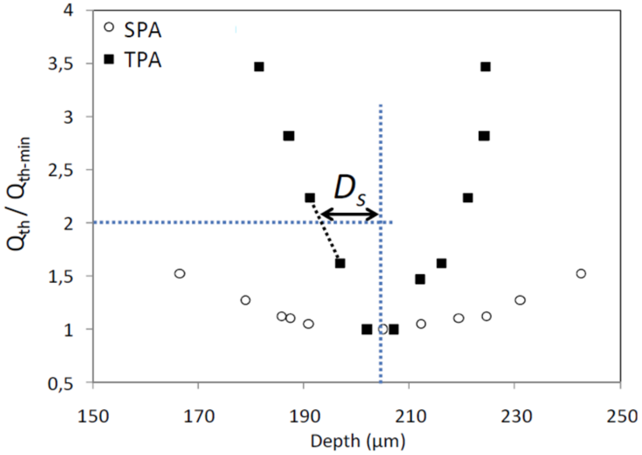
- ❑ Same applications as SPA

  \+

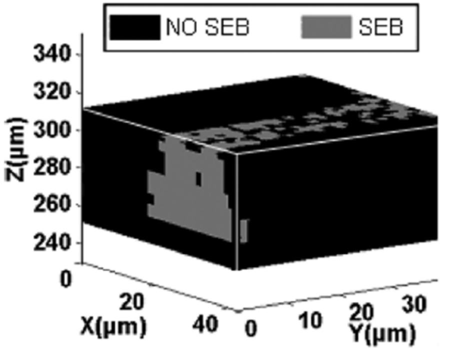
- ❑ 3D « sensitive volume » characterization
  - ❑ SET in LM324 op amp
  - ❑ SEB in Power MOSFETs
  - ❑ SEL in 130nm SRAM



Jaulent et al, NSREC 2008



Faraud et al, IEEE TNS 2011



Darracq et al, IEEE TNS 2012

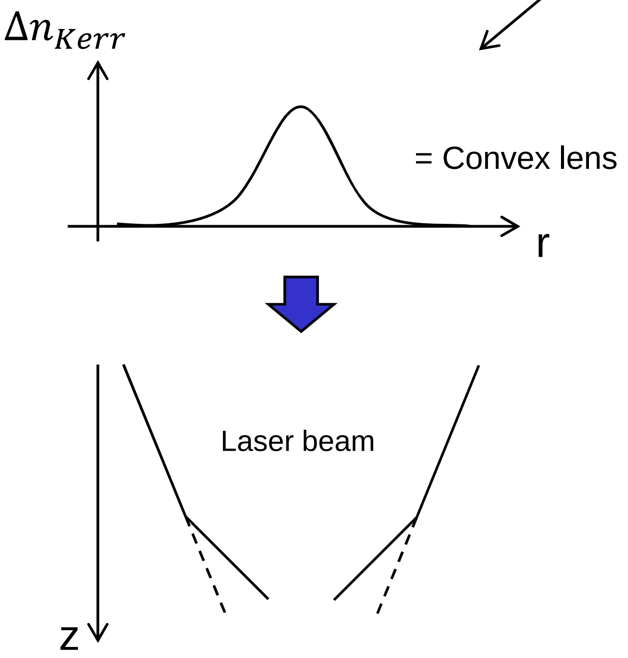
Optical propagation mechanisms to consider

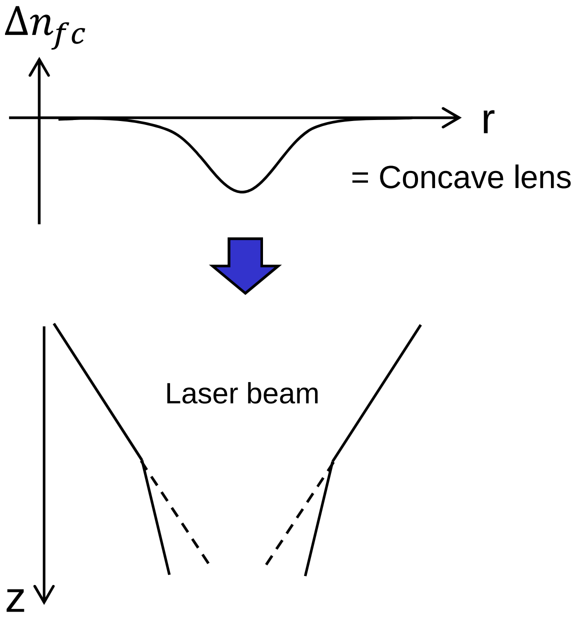
- Static free carriers absorption
  - Beam attenuation through the bulk
- Depletion
  - Beam attenuation around the focus if significant two-photon absorption
- Kerr effect
  - Refraction index variation with intensity
  - Radial profile of intensity can lead to self focusing, filamentation, destruction…
  - Time profile of intensity can lead to phase modulation
- Plasma effect
  - Carriers generated by the front of the pulse can affect both the refractive index and the absorption coefficient

- These effects may have an impact on:
  - Radial profile: spot size, lateral resolution
  - Axial profile: axial spot extension, axial resolution
  - Time profile (assumed to be negigible)
  - Amount of generated charge

Kerr and Plasma effects on focusing

Refractive index: $$n = n_{Si} + \underbrace{\Delta n_{Kerr}(I)} + \underbrace{\Delta n_{fc}(N)}$$





- ❑ Which effect is predominant ? Do they compensate each other ?
- ❑ Is there a threshold energy at which those effects become non negligible ?

Modeling options

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

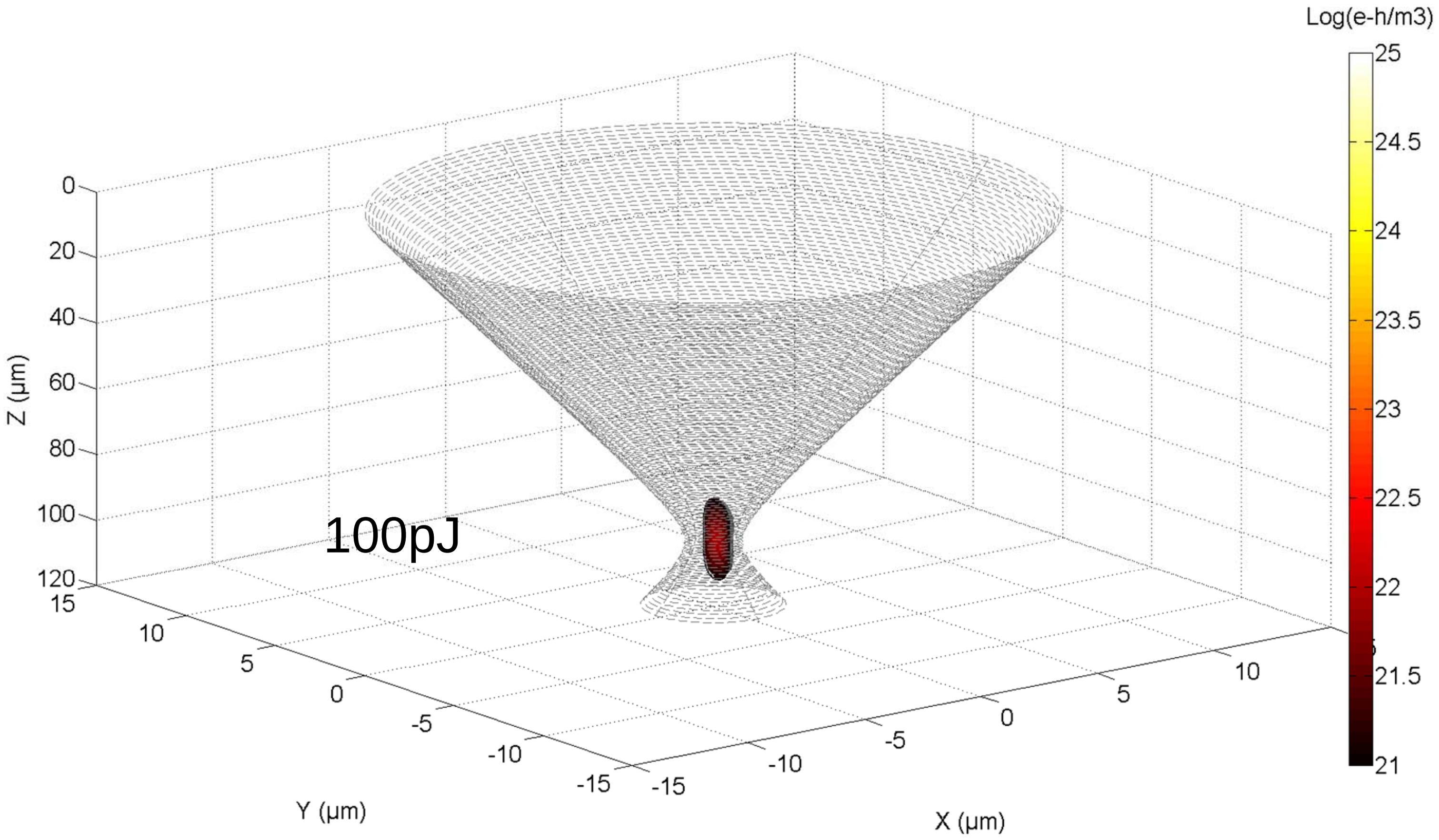
- Finite Element method
  - Finite Difference in Time Domain (FDTD)
  - Maxwell equations resolved by discretizing space and time
  - To date: available open source and commercial tools do not deal correctly with nonlinear propagation
  - Some results with proprietary two-temperature FDTD model (Bogatyrev et al, J. Appl. Phys., 2011)
  - 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

Iterative numerical model

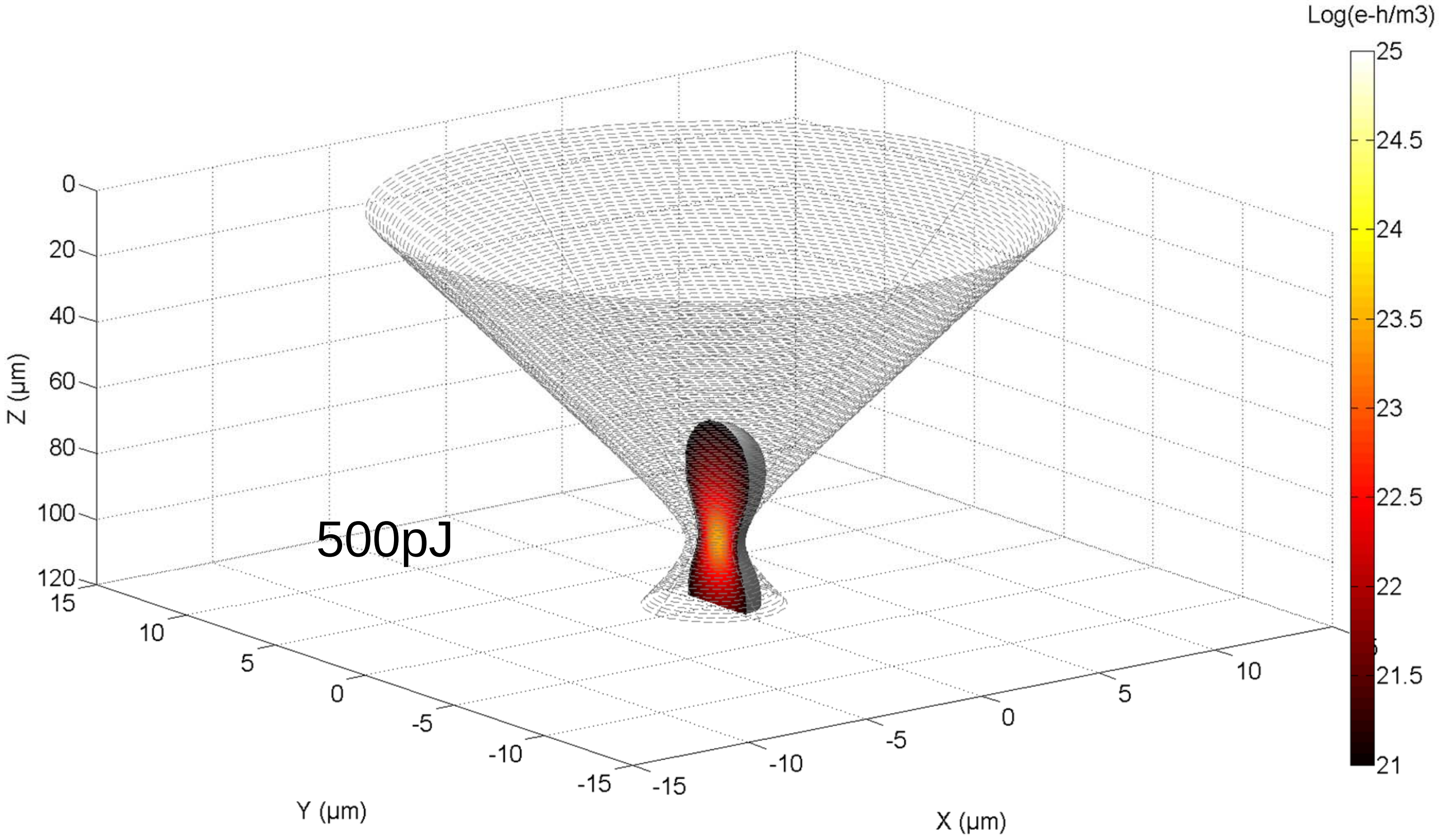
- Principles
    - Time and optical axis (substrate thickness) discretized into slices
    - Each time slice of the Gaussian pulse is propagated through all the substrate slices, calculating charge generation
    - Gaussian radial profile calculated in each substrate slice using complex ABCD transport matrices, taking into account charge generated at previous times
- Included effects
    - Static free carrier absorption
    - Depletion
    - Kerr effect on radial profile
    - Plasma effect
- Phase modulation not included in the model
- Material optical properties and laws taken from the literature
- Provides intensity and charge distribution vs space and time
- Implemented in C++ and Matlab
- First sets of results, refinements in progress

Model results: charge track profile

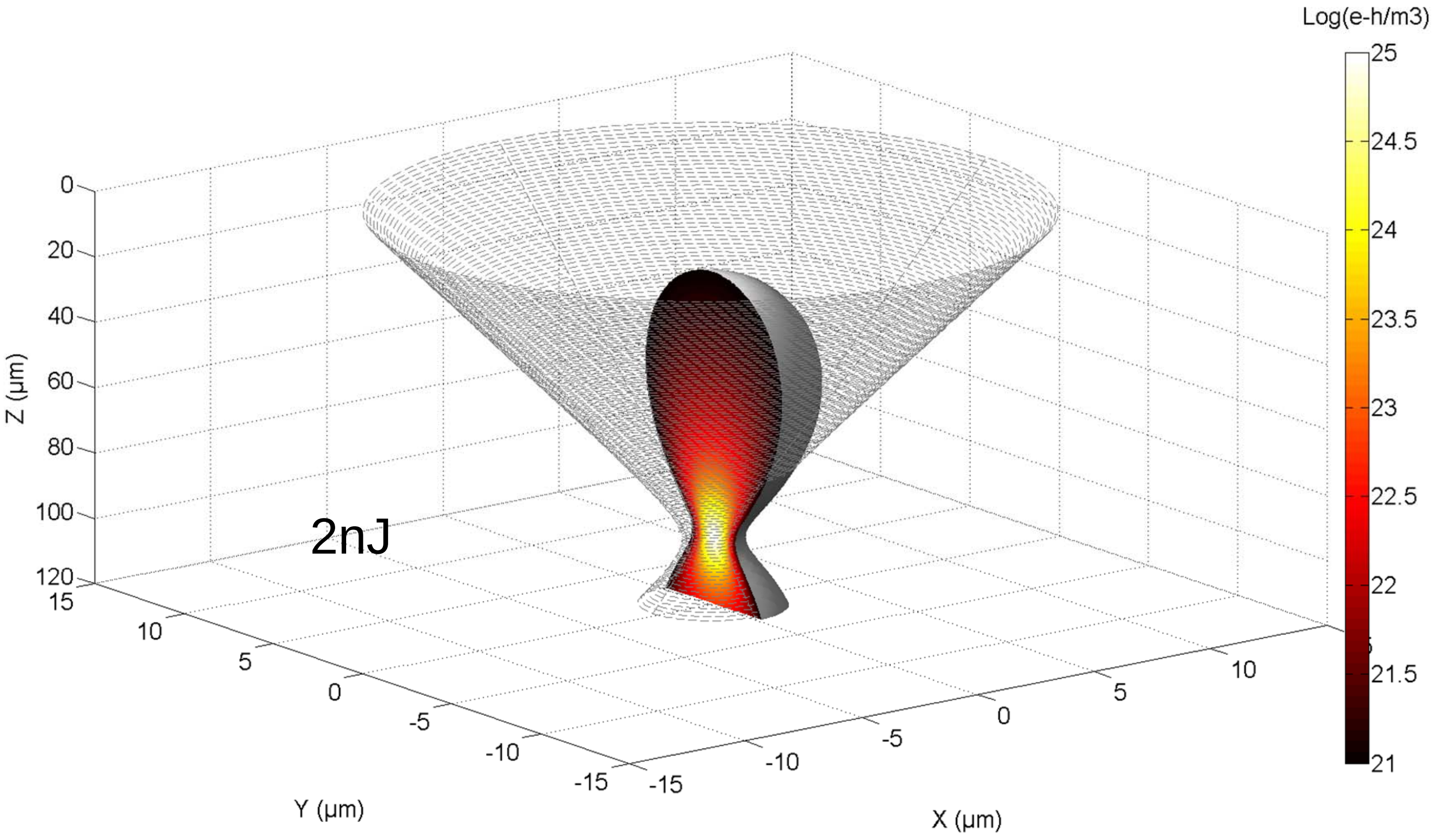


- Wavelength: 1.3µm
- Pulse duration: 100fs
- Substrate doping: 10^{18} cm^{-3}

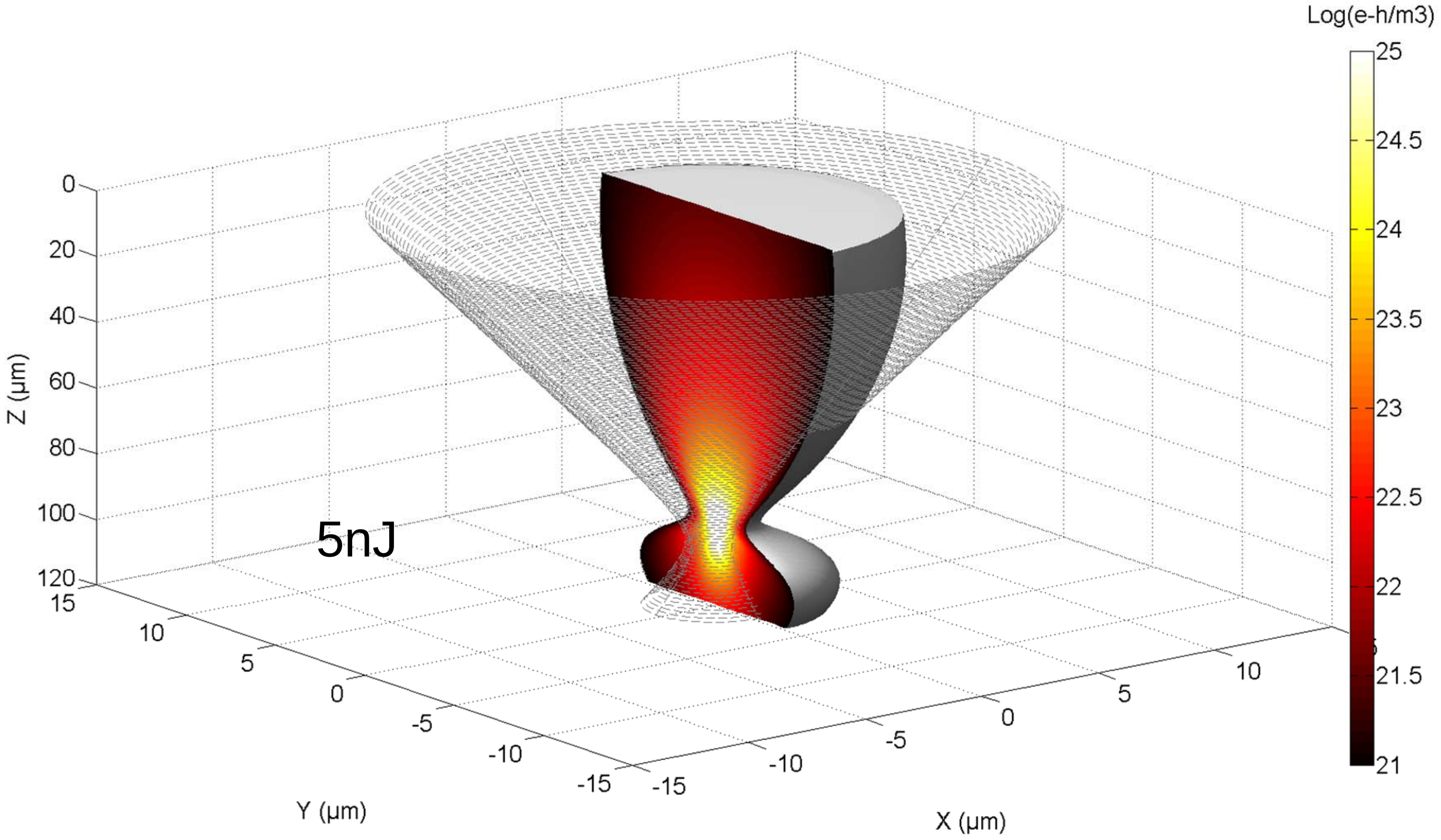
Model results: charge track profile



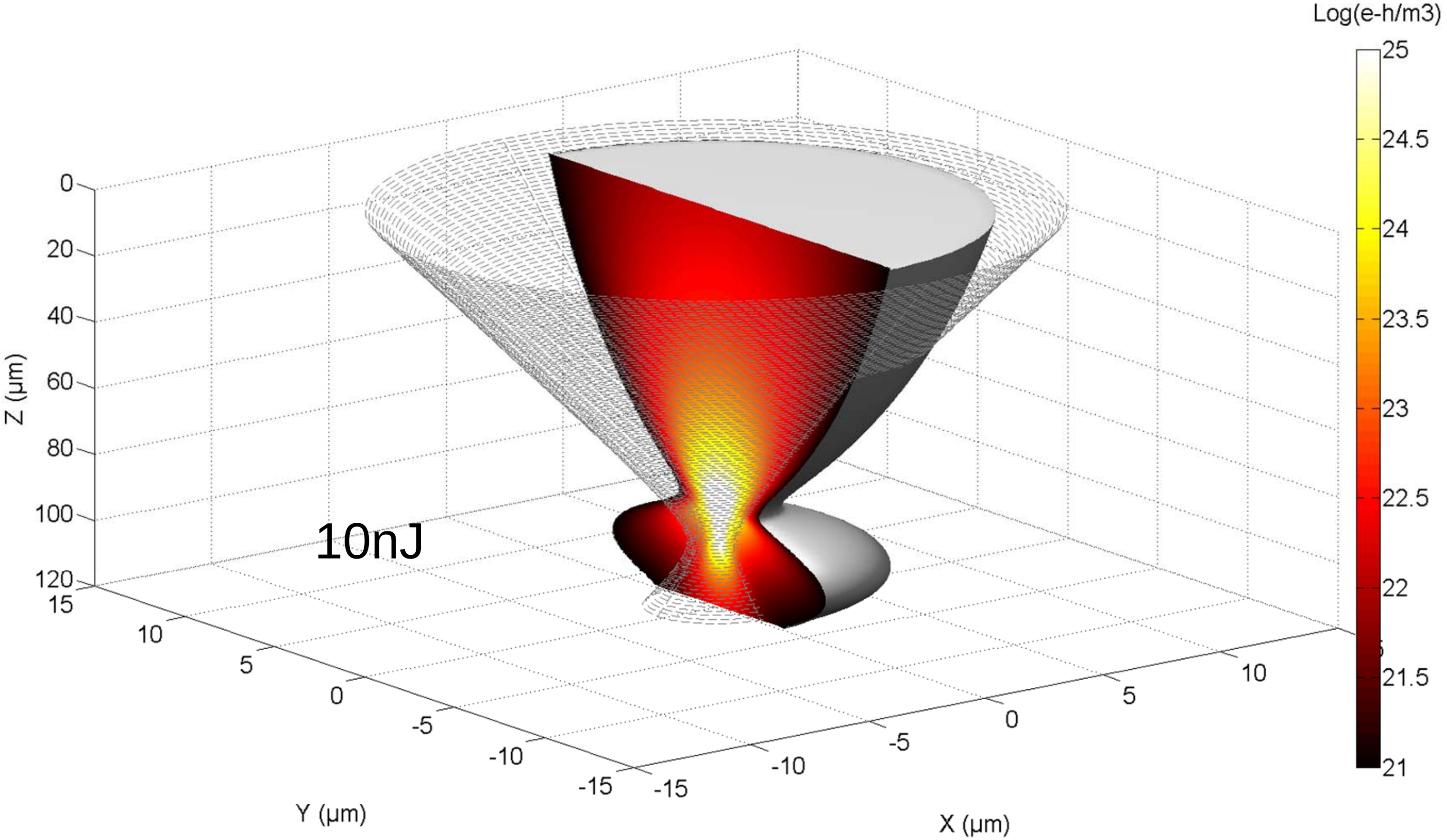
Model results: charge track profile



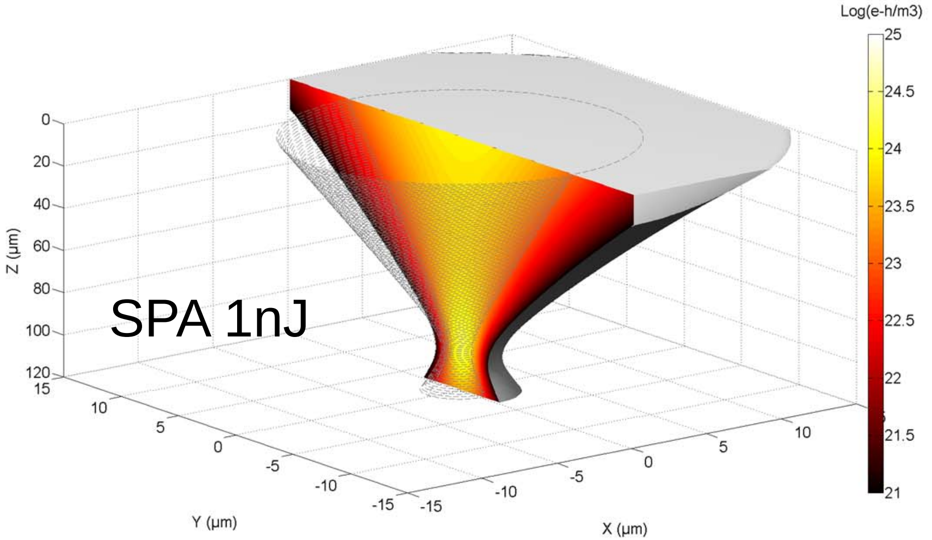
Model results: charge track profile



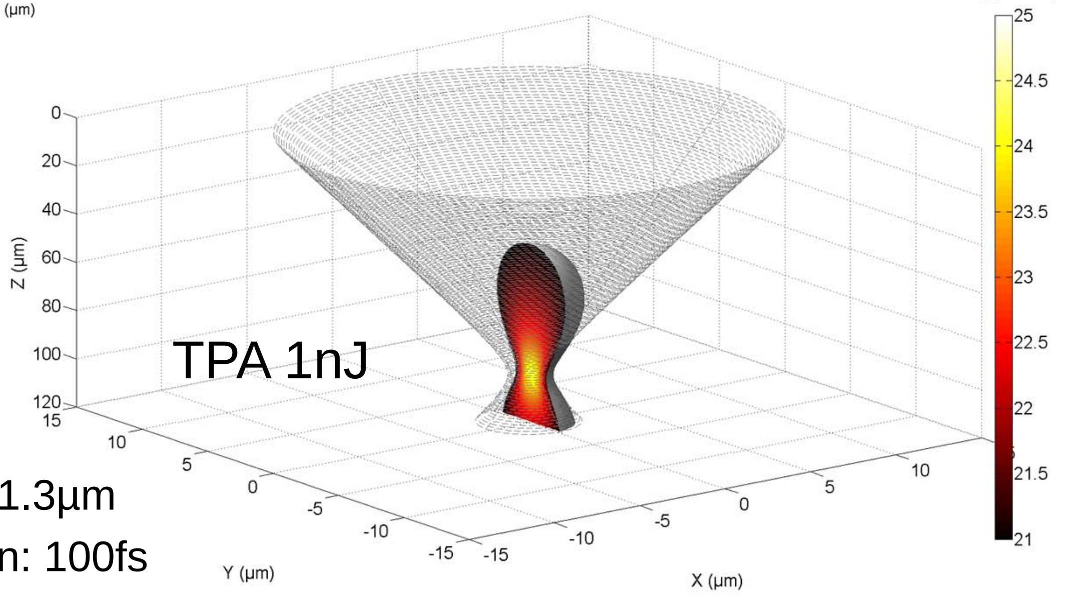
Model results: charge track profile



SPA vs TPA

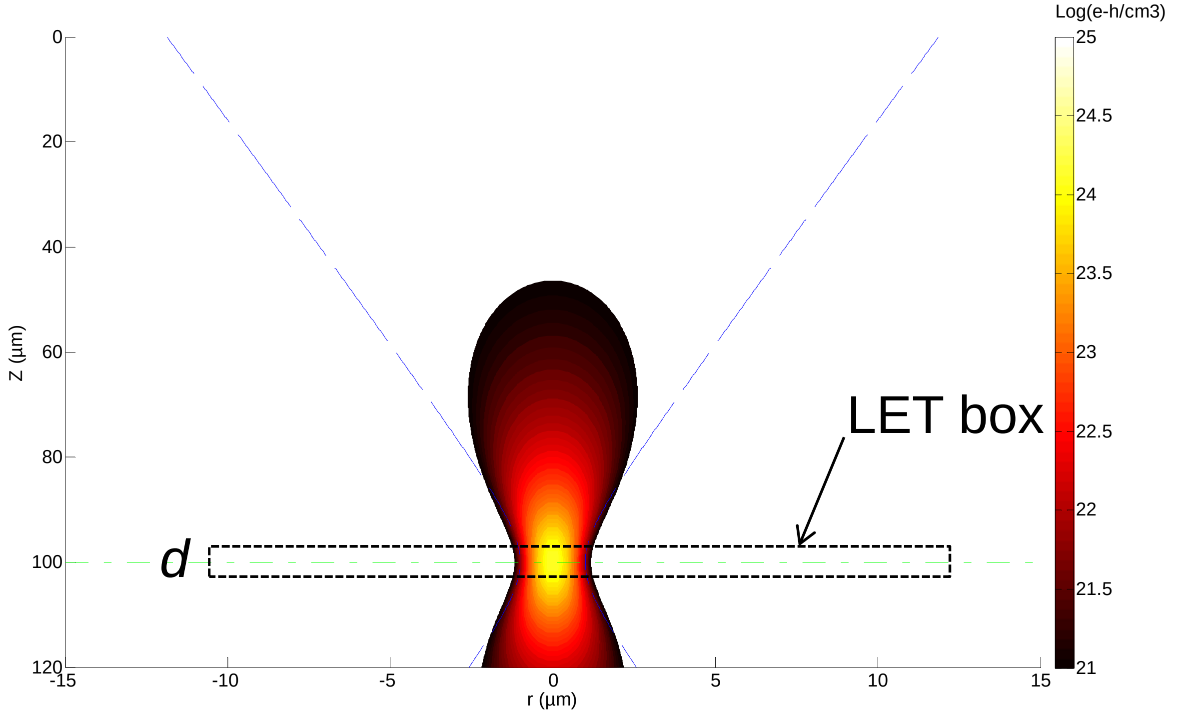


- ❑ Wavelength: 1.064µm
- ❑ Pulse duration: 30ps



- ❑ Wavelength: 1.3µm
- ❑ Pulse duration: 100fs

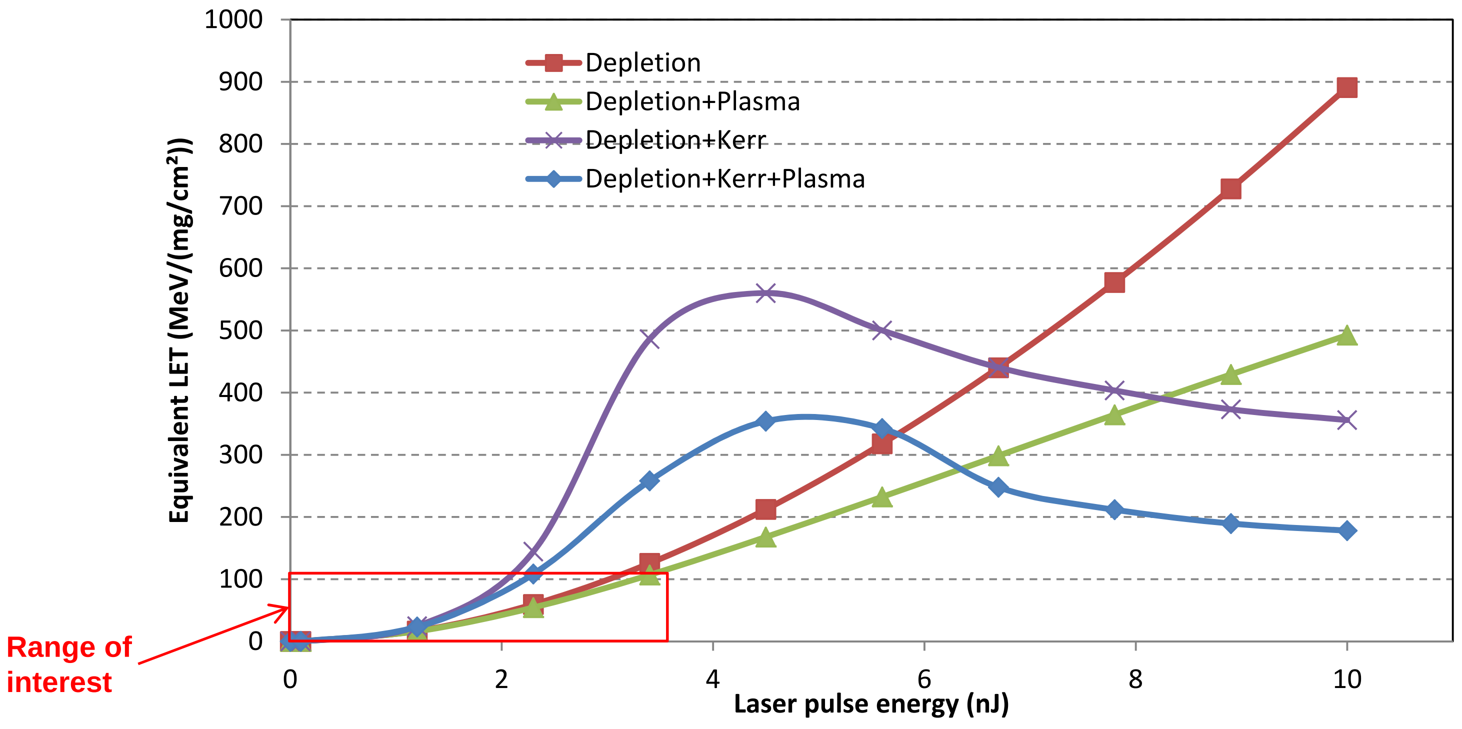
Equivalent LET



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

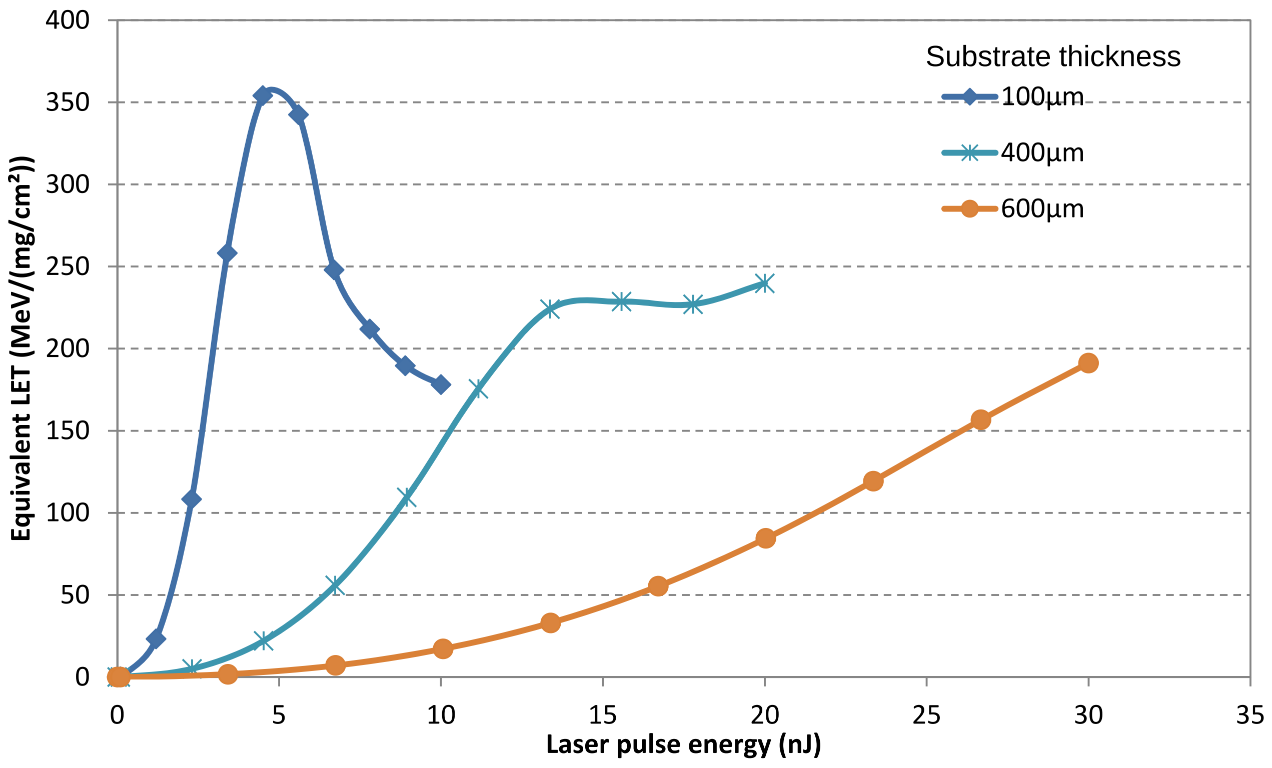
- ☐ Not to be taken as an absolute value, but it provides a practical way of quantifying the influence of experimental parameters on charge deposition

Equivalent LET vs Energy



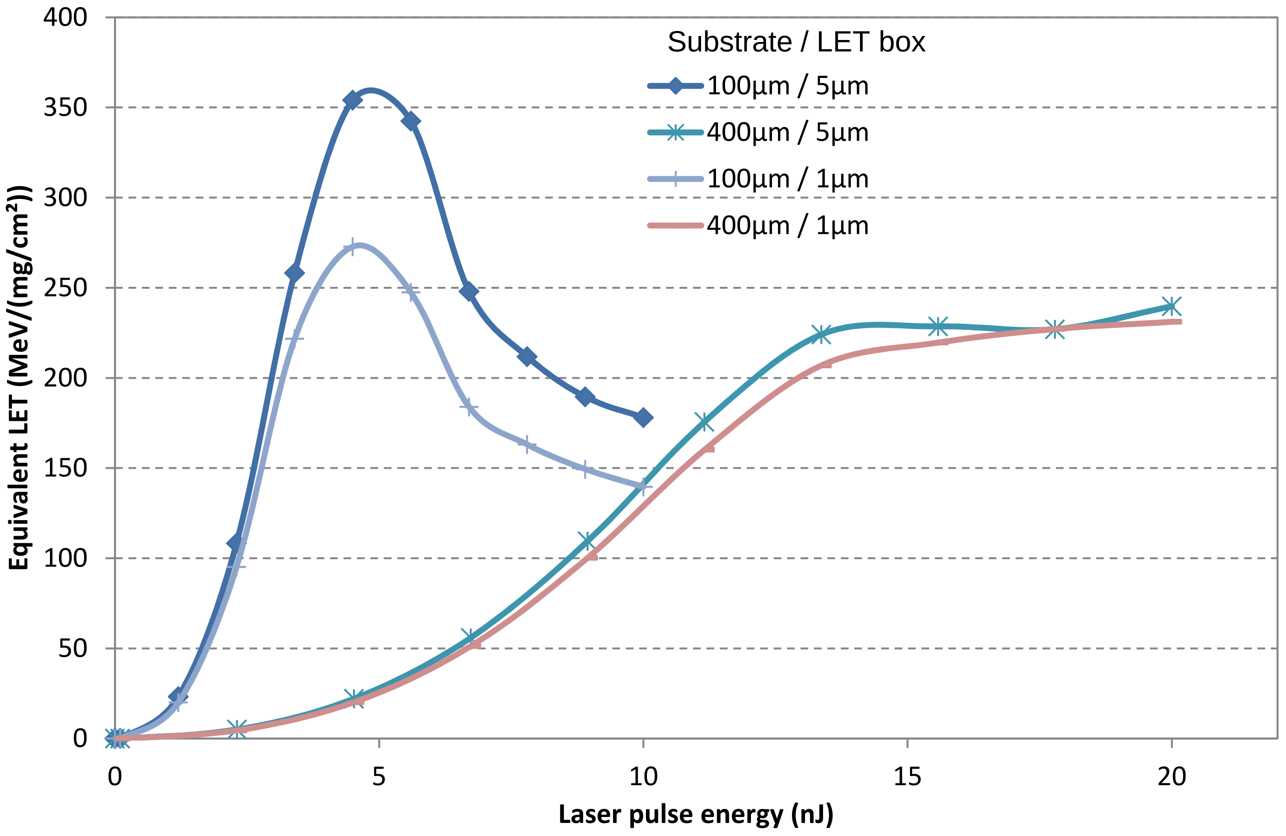
- ❑ Propagation mechanisms competition in range of interest
- ❑ Kerr effect limits the accessible range of very high LET that are commonly achieved with SPA

Effect of substrate thickness



- ☐ Significant contribution of plasma effect in thick substrates reduces the equivalent LET

Effect of LET box thickness



- ☐ Effect induced by rapid axial variations of the charge profile in the focus region
- ☐ Effect more important for thin substrate because mainly related Kerr effect
- ☐ Charge deposition almost homogeneous along 5µm within the LET range of interest

Conclusions

- A new numerical model of charge deposition by TPA laser testing
- Some progress towards a better quantification of charge injection with the TPA technique
- Several propagation mechanisms compete within the energy range of interest for TPA testing
- The model allows quantifying axial spot displacement vs energy
- Model refinements and optimization in progress