TEC-QEC

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Single-Event Effects Testing with a Laser Beam
-
Guidelines

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Motivation & scope of the work

- Laser testing: a complementary technique for in-lab SEE evaluation
  - ~30 years of literature
- Many parameters and variants of the technique
  - Need for recommendations on the method
- New users of the technique
  - Need for information for preparing and performing a laser testing campaign
- Need for practical guidelines
- IES-CNRS work under ESA Contract No 4000133635/20/NL/KML/rk
  - Writing of guidelines draft
  - Draft submitted to review by several experts
    - Comments, suggestions and corrections from: **F. Miller, D. McMorrow, G. Bascoul, A. Costantino, T. Borel, C. Poivey**
  - Writing of final guidelines document

Outline

- Document overview
- SEE laser testing: principles & parameters
- Guidelines review
- Elements for SPA equivalent LET estimation
- Summary

Guidelines document overview

- Document contents
  - Principles of SEE laser testing
  - 29 guidelines, explained
  - Some uses cases and their specificities
  - Elements for equivalent LET calculation

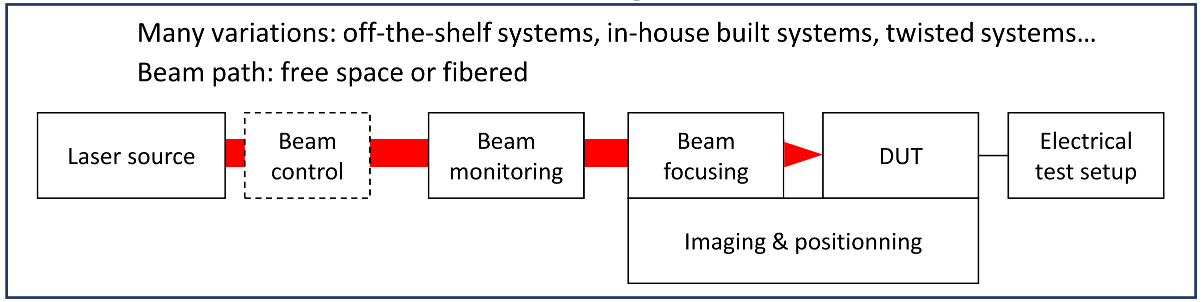
- What it is:
  - Introductive technical material
  - A set of facility-agnostic recommendations
    - to prevent rookie mistakes and save beam time
    - to provide a basis for exploitable and comparable results

- What it is not:
  - Not to define the pertinence of using laser testing (too many project-related parameters to consider)
  - Not a handbook, see scientific literature for more details
  - Not a guarantee of a successful test campaign

Principles of SEE laser testing

- Using a focused beam of short laser pulses to generate electron-hole pairs by photoelectric effect in the semiconductor volume of a device
  - Short pulses to reproduce the transient nature of an ionizing radiation interaction
  - Focused beam to reproduce the localized nature of the interaction

Laser testing beam-line



- Main advantages of laser testing
  - Spatial resolution of sensitive regions of a component
  - Convenient in-lab tool to reduce testing costs
- Main limitations
  - Requires optical access to the active semiconductor volume
  - Calibration of laser pulse energy with respect to LET has uncertainties
- No ionization of the dielectric materials ⇒ no Total Ionizing Dose
  - Laser testing not suitable if dielectric ionization may contribute to the SEE (SEGR in power devices, SEU in flash memory cells…)

Guideline #29

Laser testing in its common form is not appropriate for testing for single-events that require ionization of a dielectric layer.

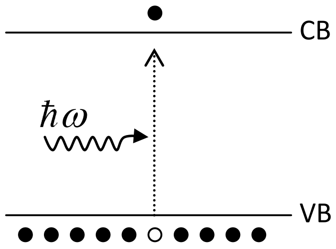
- No atomic or nuclear interaction ⇒ no Displacement Damage

Two complementary variants of the laser technique

	Single-Photon Absorption (SPA)	Two-Photon Absorption (TPA)

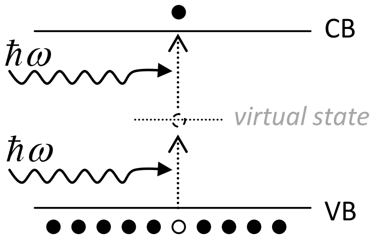
Charge generation principle

Single-Photon Absorption (SPA)



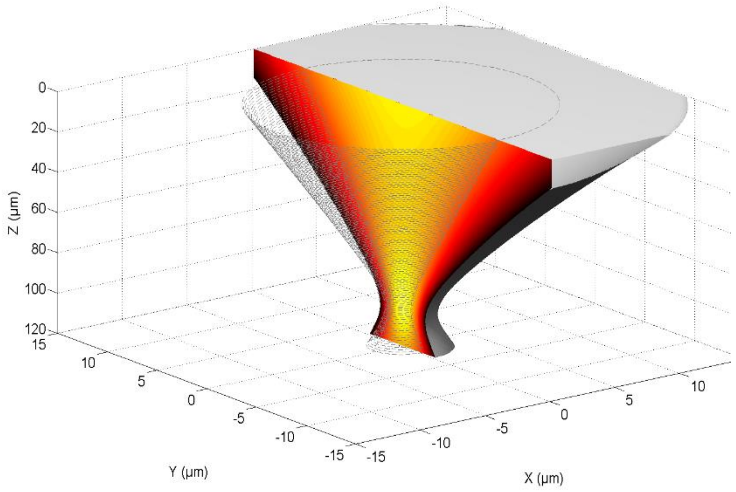
$$G = \frac{\alpha_{IB}}{\hbar\omega} I$$

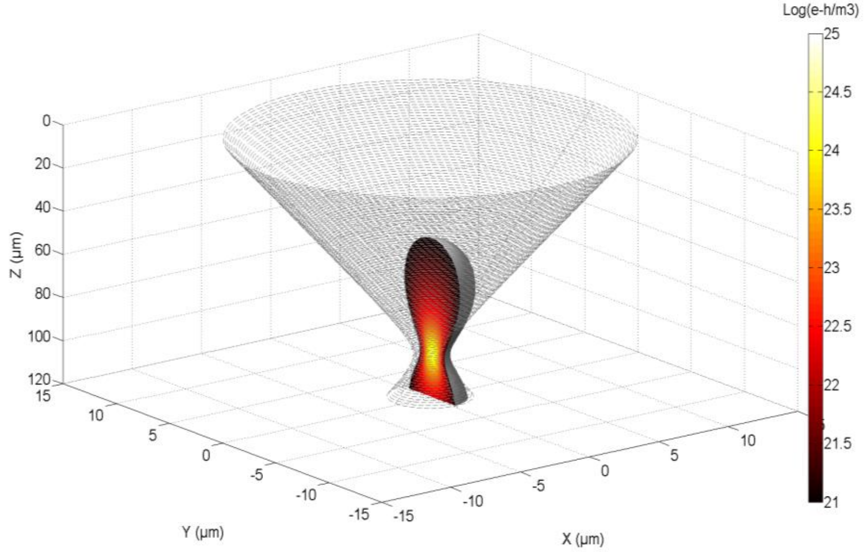
Two-Photon Absorption (TPA)



$$G = \frac{\beta}{2\hbar\omega} I^2$$

Typical induced charge tracks



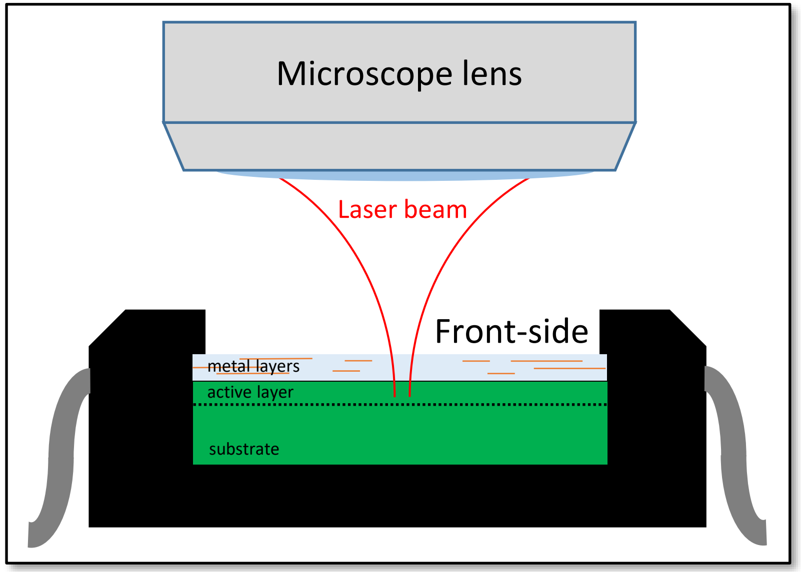


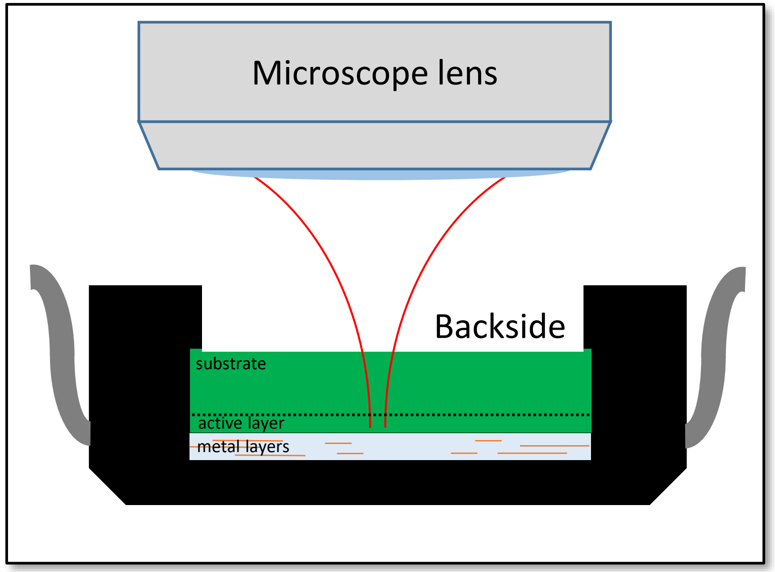
	SPA	TPA
Radial profile	Gaussian	Gaussian, $\sqrt{2}$ smaller at same λ
Longitudinal profile	Convergence + exponential attenuation	Complex, limited to focal region

Backside testing is the preferred approach

Guideline #1

The preferred approach for laser testing is the **backside** approach, in which the beam is focused through the substrate into the active layer of the device.





- Front-side testing impossible if more than 2 metal layers
- Backside testing of non-flip-chip devices requires a hole in the PCB
- Backside testing of non-flip-chip BGAs: re-packaging required

Laser wavelength

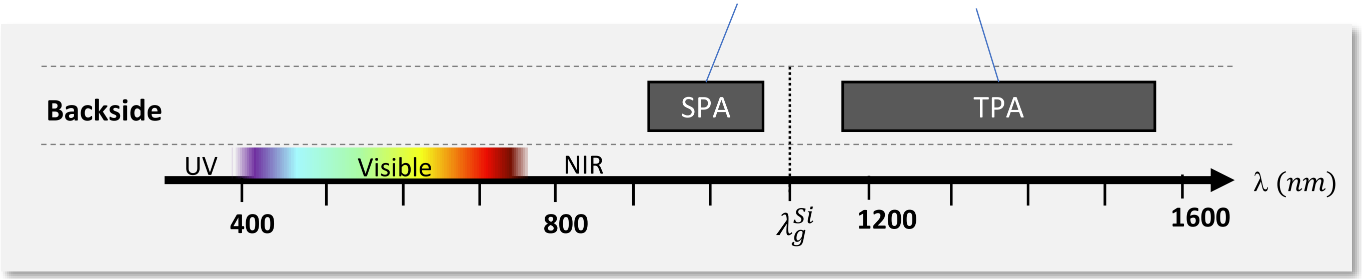
Guideline #11

For **SPA** testing of silicon devices, the recommended wavelengths are 1064 nm or 1030 nm.

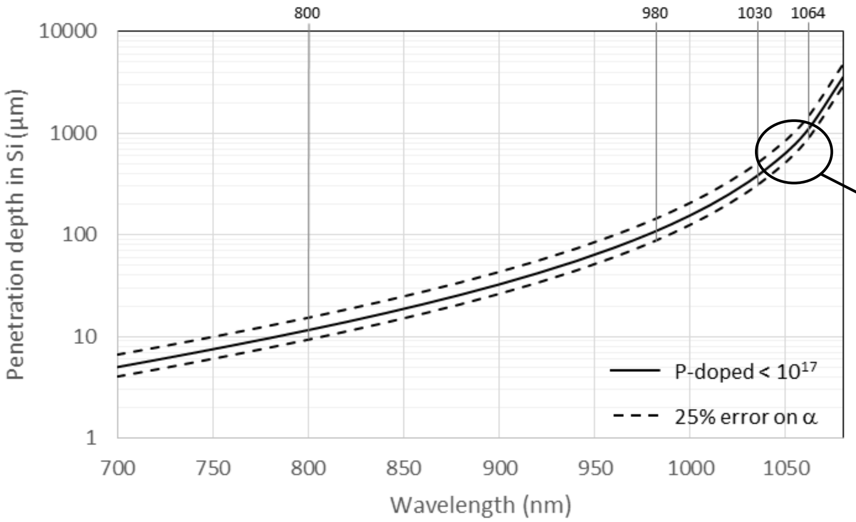
Guideline #12

For **TPA** testing of silicon devices, wavelength must be comprised between 1150 nm and 1550 nm.

Usable wavelength range for Si devices



SPA penetration depth (attenuation by a factor *1/e)*



Substrate thinning usually NOT required for backside SPA@1064nm or TPA

Laser pulse duration

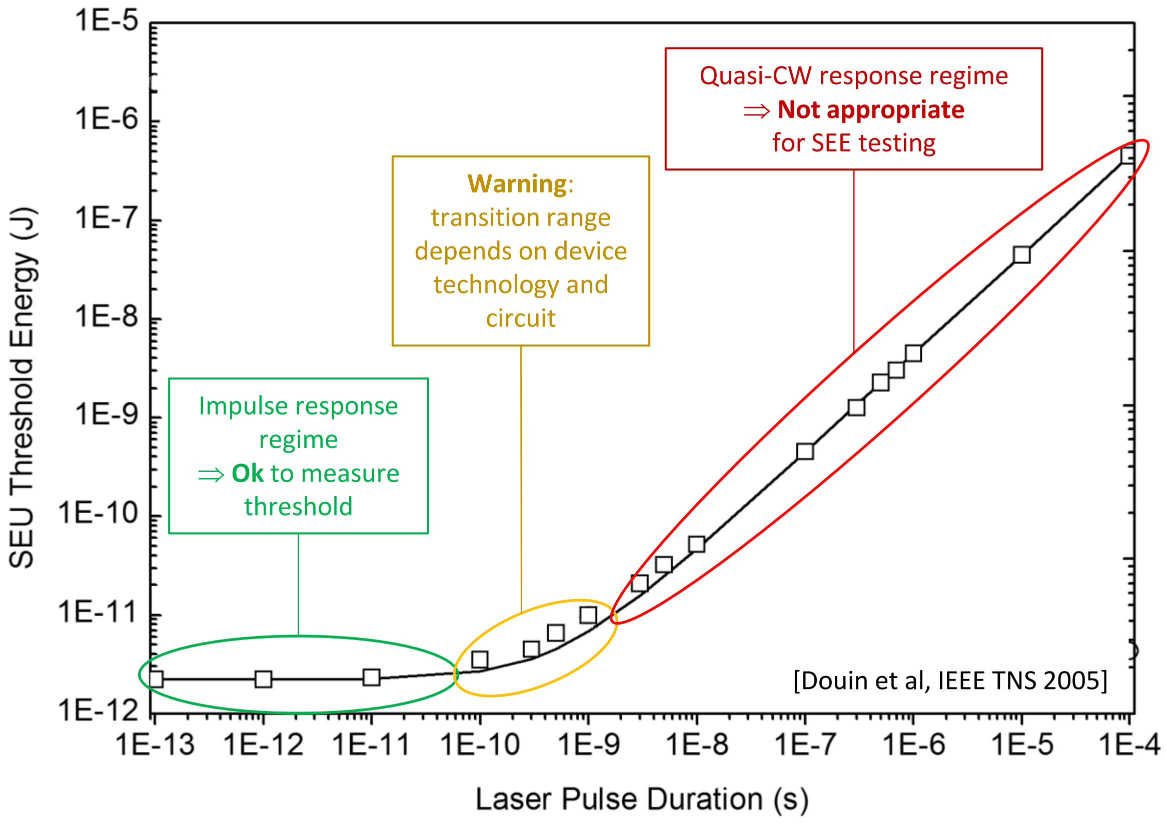
Guideline #13

For SPA testing of silicon devices, the pulse duration must be selected in the sub-nanosecond range in accordance with the DUT performances. Commonly used values are between 1 ps and 50 ps.

Guideline #14

For TPA testing of silicon devices, the pulse duration should be between 100 fs and 500 fs.

- With longer pulses:
  - ⇒ circuit response faster than charge generation
  - ⇒ results more difficult to interpret
- With shorter pulses:
  - ⇒ more non-linear effects
  - ⇒ more difficult to control & quantify the charge injection



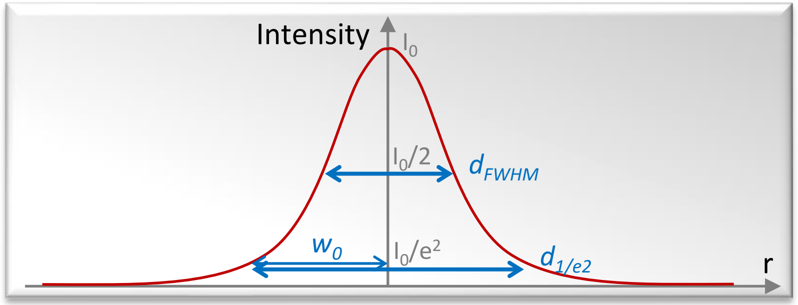
Laser spot size

Guideline #16

The laser spot size defined as the $1/e^2$ diameter of the radial intensity profile should be smaller than 1.8µm.

Guideline #17

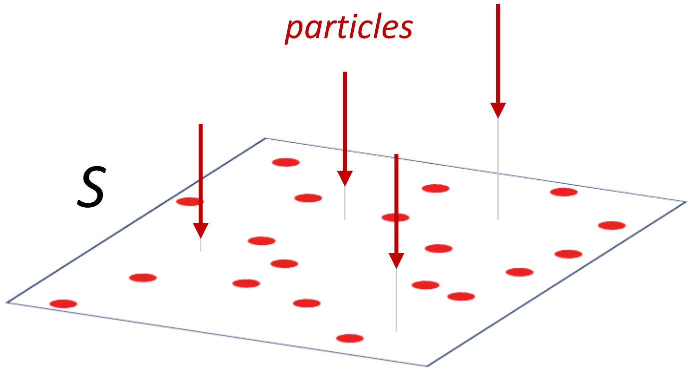
Using larger spot sizes is possible as a first approach, but it can lead to false negative or false positive results.



- The smaller, the better to mimic ion-induced charge deposition
- Minimal size is limited by diffraction
  - Always larger than an ion track, may lead to spot size effects
  - Spot size characterization close to the wavelength scale is not trivial
- Not a limiting factor for the scanning resolution nor the dimensions of testable devices
- Spot size in the active layer might be temporarily increased by:
  - Using a lower magnification objective lens
  - Defocusing the beam
- Practically, the conclusions of an SEE laser test report should rely only on results obtained with the minimal achievable spot size

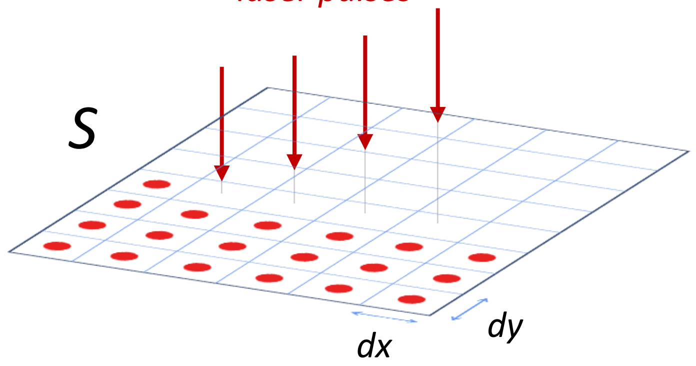
Scanning resolution ⇔ Laser pulse fluence

Particle broad-beam testing



Particle fluence: $\Phi = \frac{n_{particles}}{S}$

Laser testing



dx, dy = scanning resolution
(or steps)

Laser pulse fluence: $\Phi = \frac{n_{pulses}}{S} = \frac{1}{d_x d_y}$

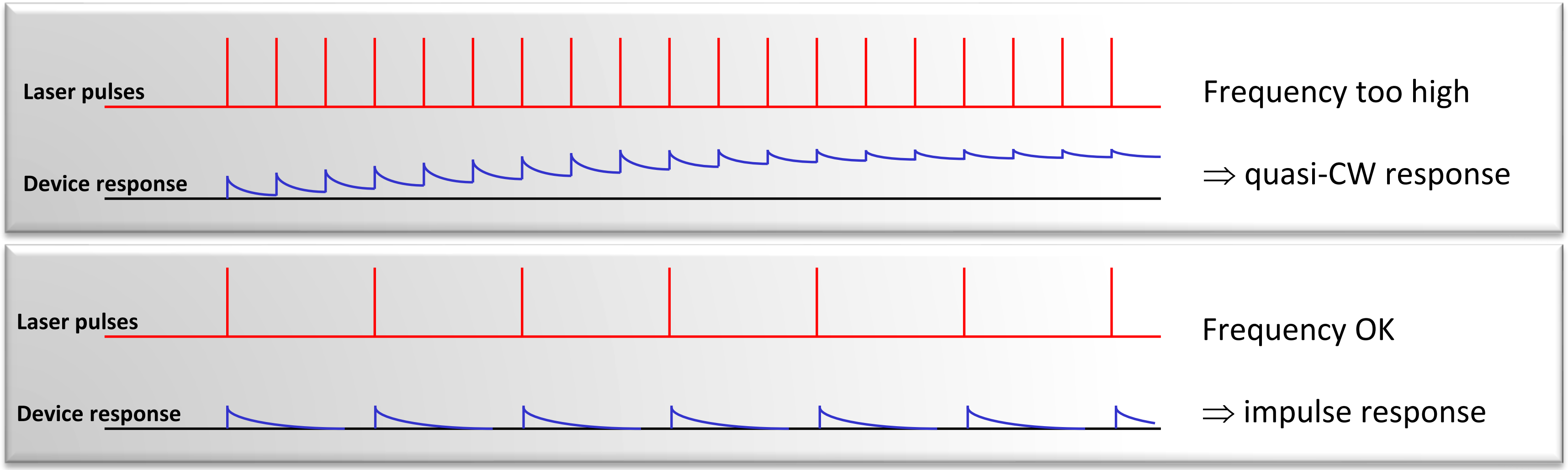
Resolution (dx=dy)	**Fluence**
1 µm	10^8 cm^{-2}
3 µm	10^7 cm^{-2}
10 µm	10^6 cm^{-2}
31 µm	10^5 cm^{-2}

The choice of the scanning steps can be done to achieve either a target fluence or a given mapping precision, independently of any consideration on the laser spot size.

Laser pulse frequency

Guideline #15

Except for special circumstances, the laser pulse frequency should not exceed 1kHz and should be adjusted with respect to the scanning speed and the test loop frequency.



- Using a high pulse frequency is tempting to rapidly achieve a target laser pulse fluence and reduce scanning time

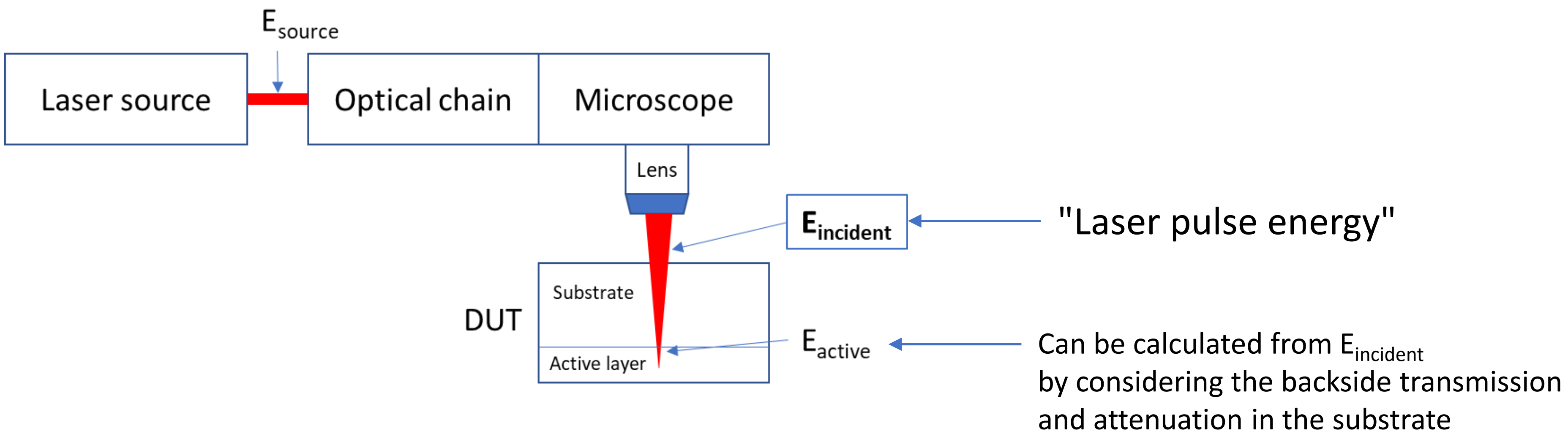
  BUT

- Pulse period should be long enough to enable the device to return to a steady state (including charge transport + circuit effect + **local temperature**) between two consecutive pulses
  - Note that consecutive pulses are usually delivered on the DUT close to each other (one step distance)

Laser pulse energy

Guideline #18

When defining or mentioning the laser pulse energy, it should be understood that it refers to the pulse energy incident on the beam entrance surface of the DUT.



- The pulse energy ($\propto$ number of photons per pulse) is the main variable parameter during an experiment
  - Controls the amount of generated charge
  - Can be varied almost continuously and rapidly
  - Useful range: from fJ to 10s of nJ depending on wavelength, DUT substrate…

Laser testing campaign

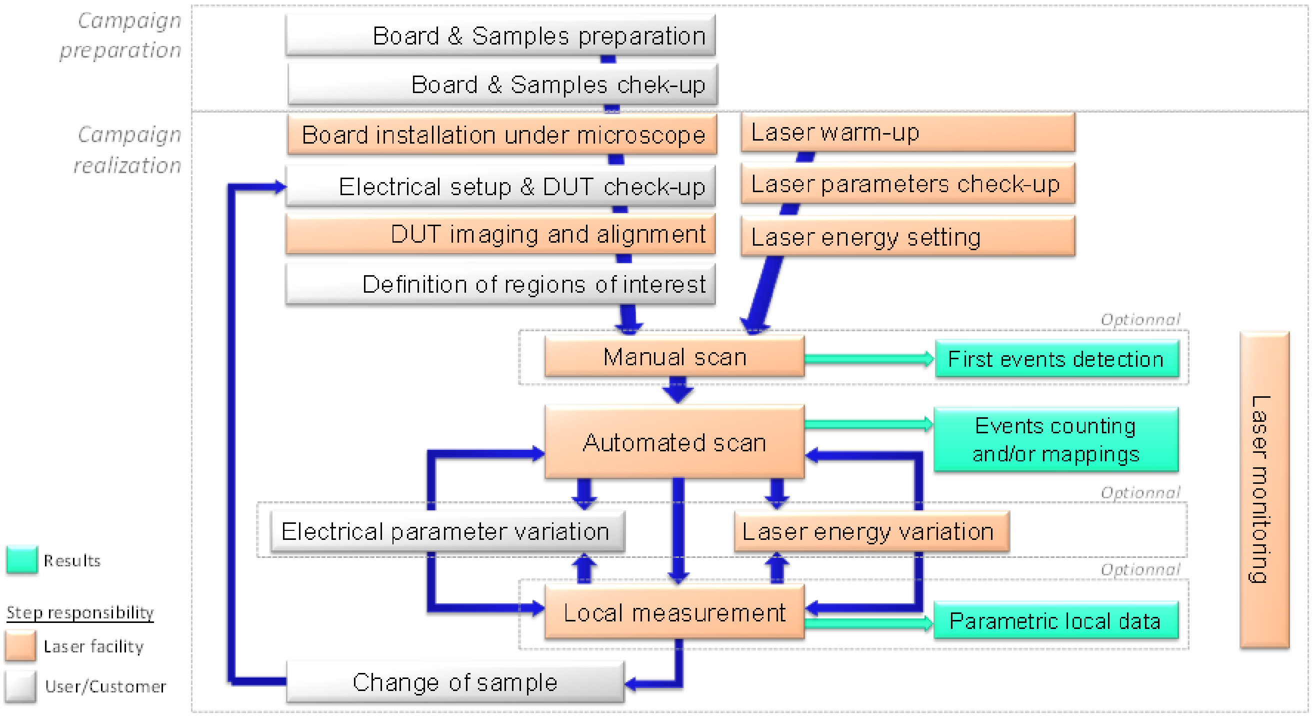
Guideline #2

When testing at an external facility, the responsibility of each step should be clearly attributed prior to the campaign to either the facility operator or the external user.

Guideline #25

Users must follow the laser safety regulations of the facility.

- Typical steps:

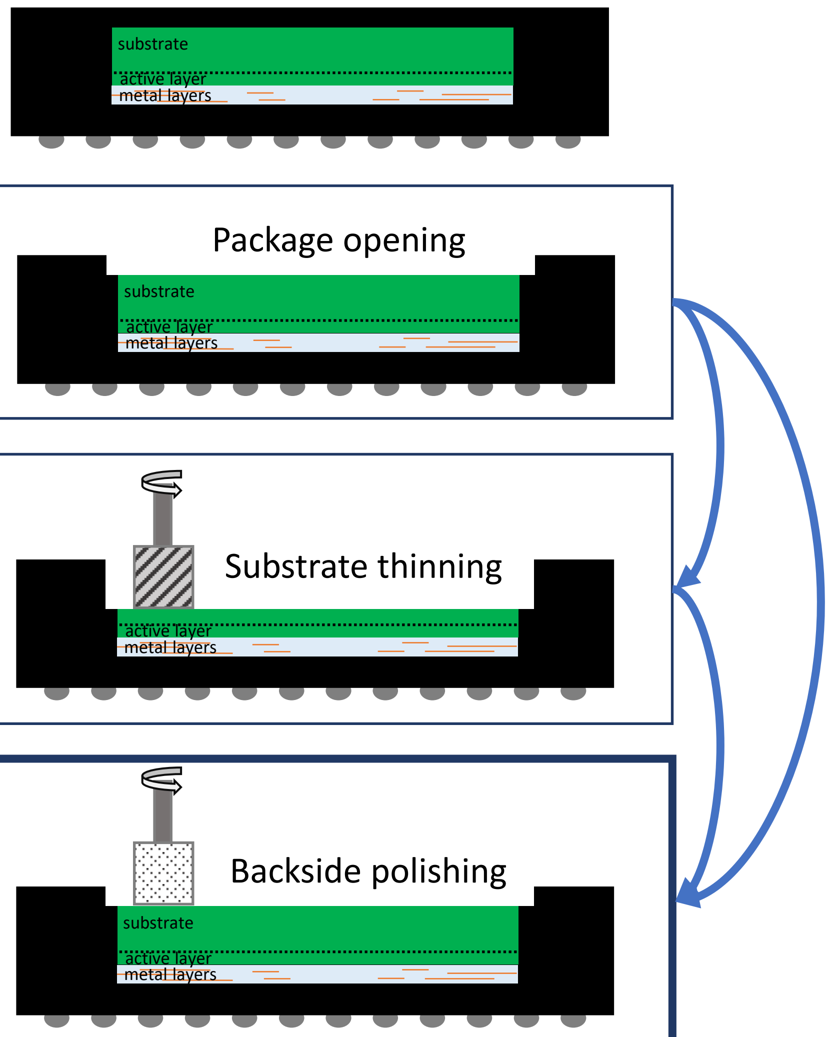


Sample preparation steps

Guideline #21

Sample preparation for backside laser testing must include the optical polishing of the backside surface.

Example: flip-chip BGA



Required: optical access to the backside of the die

- In the presence of a backside electrode (eg: drain of Power MOSFETs), a local aperture in the electrode is required

Optional: substrate thinning

- Required only for non-standard thick and heavily doped substrates
- Remaining thickness homogeneity within a few µm is crucial

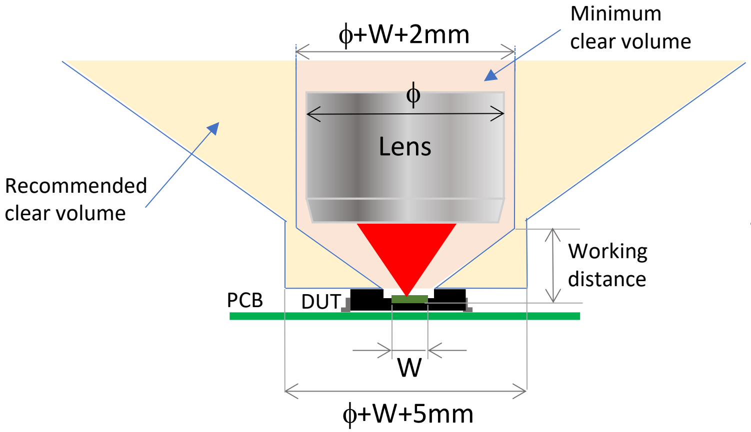
Required: <u>mirror-like</u> polishing of the backside surface

- Additional step compared to a preparation for heavy-ion testing
- <u>Requires inspection with optical microscope</u>
- No residual scratch or deposition should be visible

Test board design considerations

Guideline #22

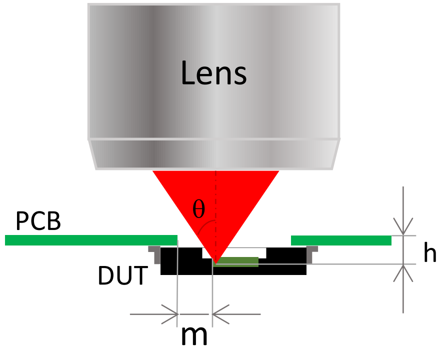
The test board must have a volume clear of any element around the DUT to enable the approach of the microscope objective lens.



Typical working distance: 10mm

Guideline #23

The laser light cone must not be clipped by the DUT package, socket or test board.



$\theta > 40°$

or

$m \approx h \frac{NA}{\sqrt{1-NA^2}} + 1\text{mm}$

Guideline #24

The test board should not embed any source of continuous or episodic vibrations.

DUT board installation and positionning under microscope

Guideline #3

Nothing should make contact with the microscope lenses, either during the test board installation or during the scanning of the DUT.

Guideline #4

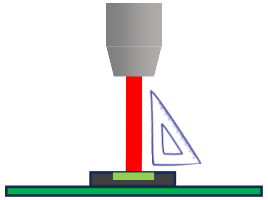
The DUT and its test setup should be checked after installation on the beam line for signal integrity issues.

Guideline #5

Large pieces of dust that are visible in the microscope image using a large field of view should be removed from the DUT surface.

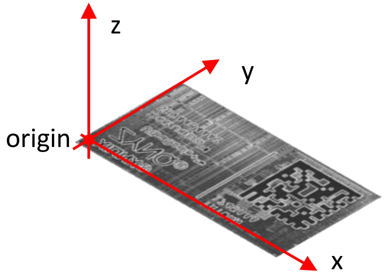
Guideline #6

The orthogonality of the DUT surface with respect to the optical axis of the microscope should be adjusted, typically by tilting the test board.



Guideline #7

The origin and orientation of the XYZ system of coordinates of the scanning system should be defined for each sample in a reproducible manner and visually verified using the imaging system. The position of the origin with respect to the DUT should be checked periodically during a campaign to detect and correct any mechanical drift.



Methodology: define regions and runs

- If DUT area > a few mm^2
  - Scanning the whole die with the finest resolution is neither needed nor realistic (too long)

- Divide the DUT area into regions of interest (ROI)
  - Using symetries and repetitions in the floorplan wisely
  - Using random sampling
  - Trade-off between:
    - Desired coverage of the die
    - Required resolution or target fluence for each ROI
    - Available beam time

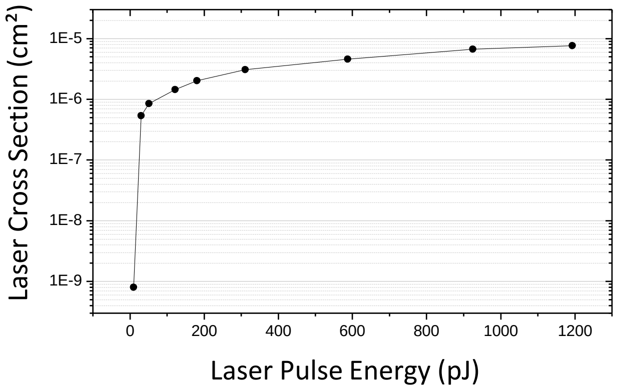
- Each ROI may require multiple runs (i.e. scans), with different:
  - Energies
  - Electrical parameters

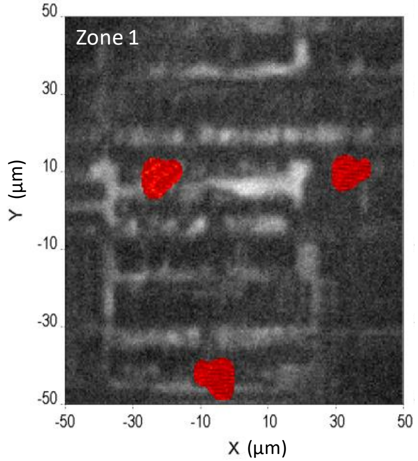
Methodology: define test goals

Guideline #8

The goal of each run must be clearly defined between events screening, counting or mapping.

Goal S	Goal C	Goal M
Events **S**creening	Events **C**ounting	Events **M**apping





M ⊂ C ⊂ S, but M slower than C slower than S

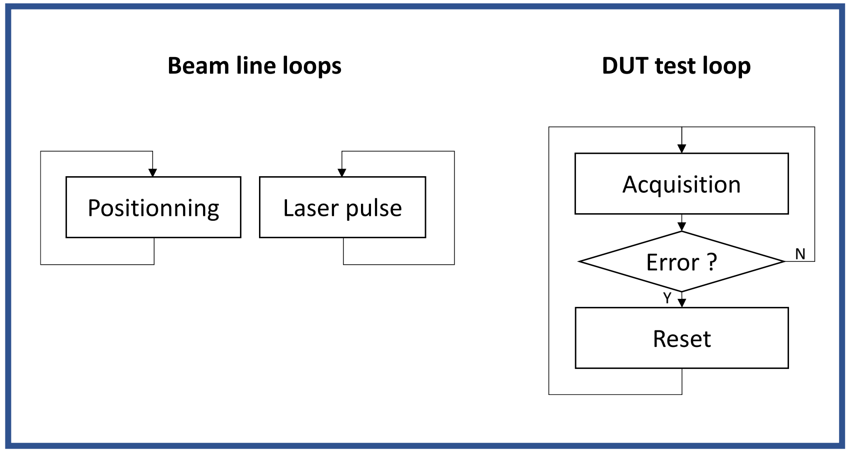
Compatible scan modes	A, **B**, C, D	**B**, C, D	B, **C**, D

Methodology: scan (& test synchronization) mode

Guideline #9

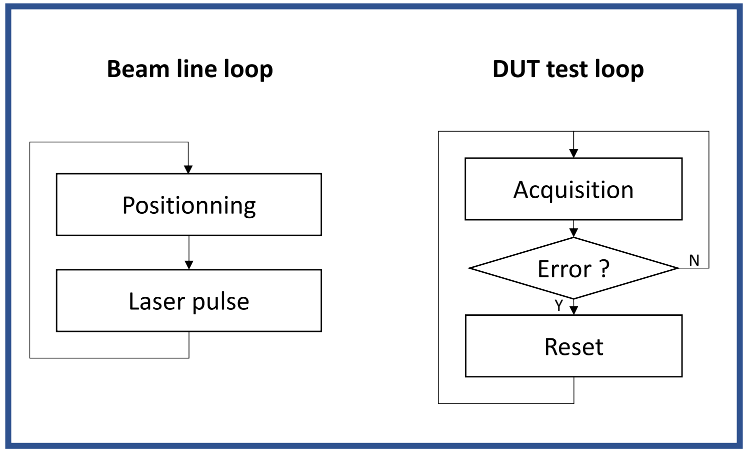
The scan mode must be defined in accordance with the test goal

Mode A
Asynchronous scan and test



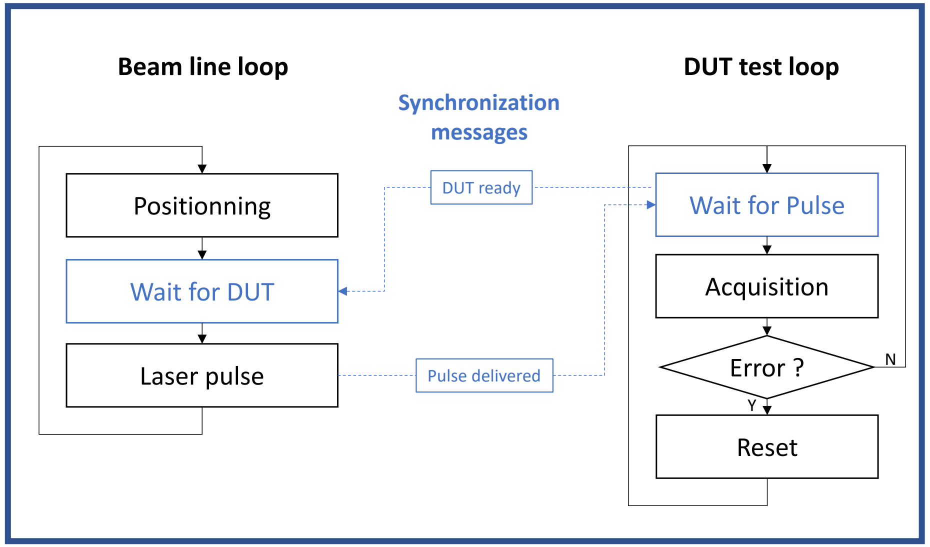
Fastest mode, impact positions not strictly controlled

Mode B
Asynchronous test



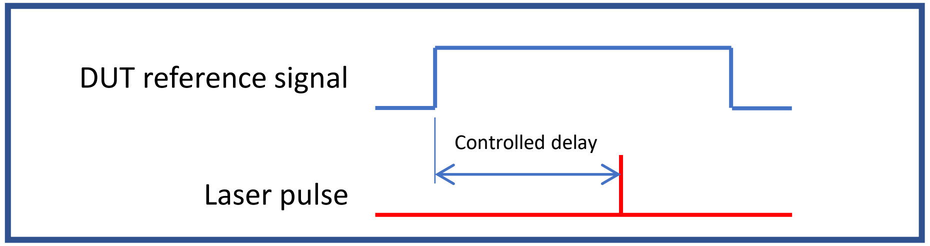
Fast, one acquisition per pulse not guaranteed

Mode C
Synchronous test



One acquisition per pulse is guaranteed

Mode D
Time-resolved test

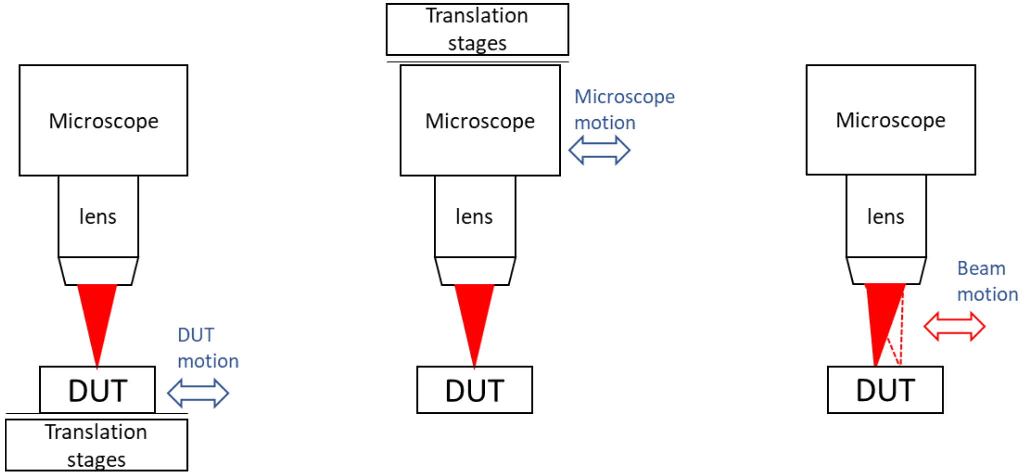


- A & B: same test setup as for broadbeam testing
- C & D: test setup adaptation required

Scanning motion & pattern

Guideline #10

The scan motion must be compatible with the selected laser technique and the DUT electrical interface.



	DUT motion*	Microscope motion	Beam motion
SPA	✓	✓	✓
TPA	✓	✓	✗
Compatible with micro-probing	✗	✓	✓

*Most common approach

- Scanning pattern
  - Rectangular grid, random walk…

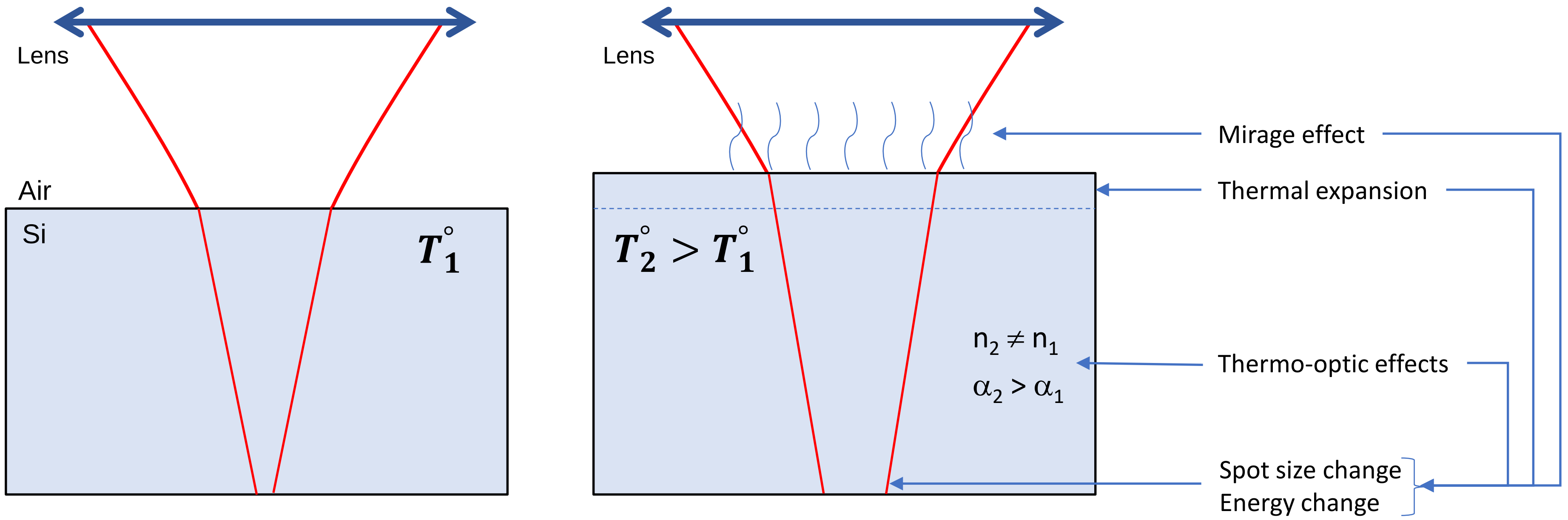
Temperature

Guideline #19

The temperature of the beam-line room should be actively stabilized.

Guideline #20

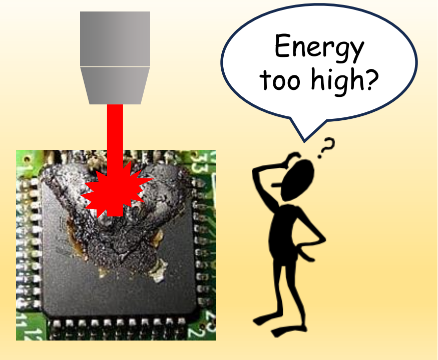
The temperature of the DUT die should be stabilized before each run to prevent uncontrolled variations in the laser propagation and charge generation mechanisms.



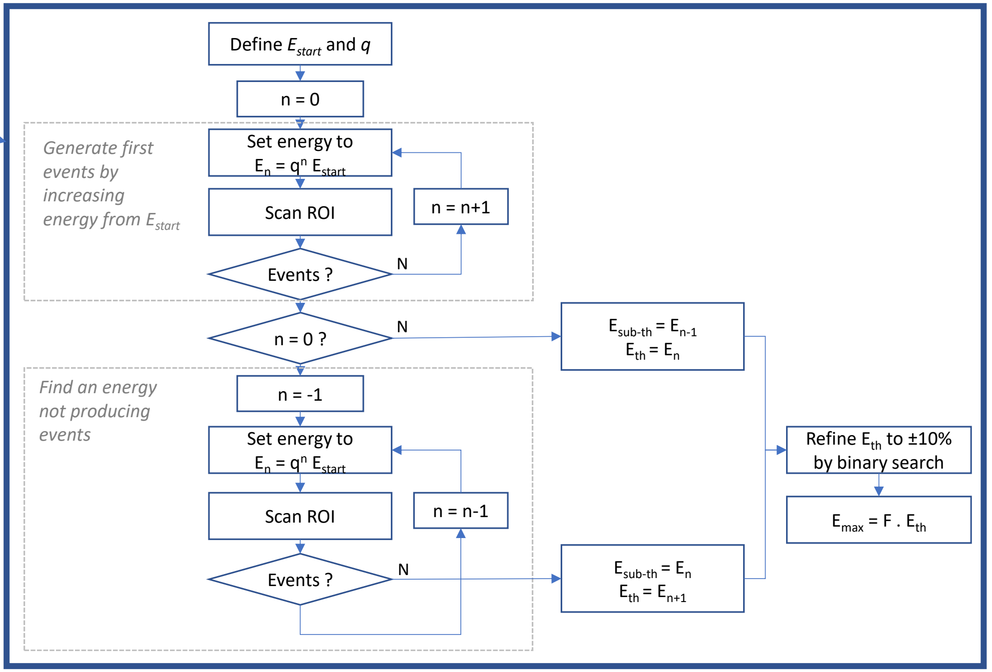
<u>Rule of thumb</u>: keep $T°_{DUT}$ variations below 10°C during a run

Methodology: defining the useful energy range

- Risk of degradation/destruction by a single laser pulse if pulse energy is too high
  - Damage energy threshold depends on DUT technology and laser parameters



- Start with low energy: E_{start}
- Search for events threshold energy: E_{th}
  - Using geometric scaling of E_{start}
- Define maximum energy: $E_{max} = F \times E_{th}$



DUT technology	E_{start} (pJ)	q	F
Deep sub-micron CMOS	1	3	50
Older CMOS	10	2	100
Linear or power device	20	2	200

Parameters monitoring

Laser pulse energy:

Guideline #26

The laser pulse energy should be periodically monitored and recorded.

Spot size:

Guideline #27

The focused laser spot size of a **free-space optical setup** should be periodically monitored and recorded.

Focus position:

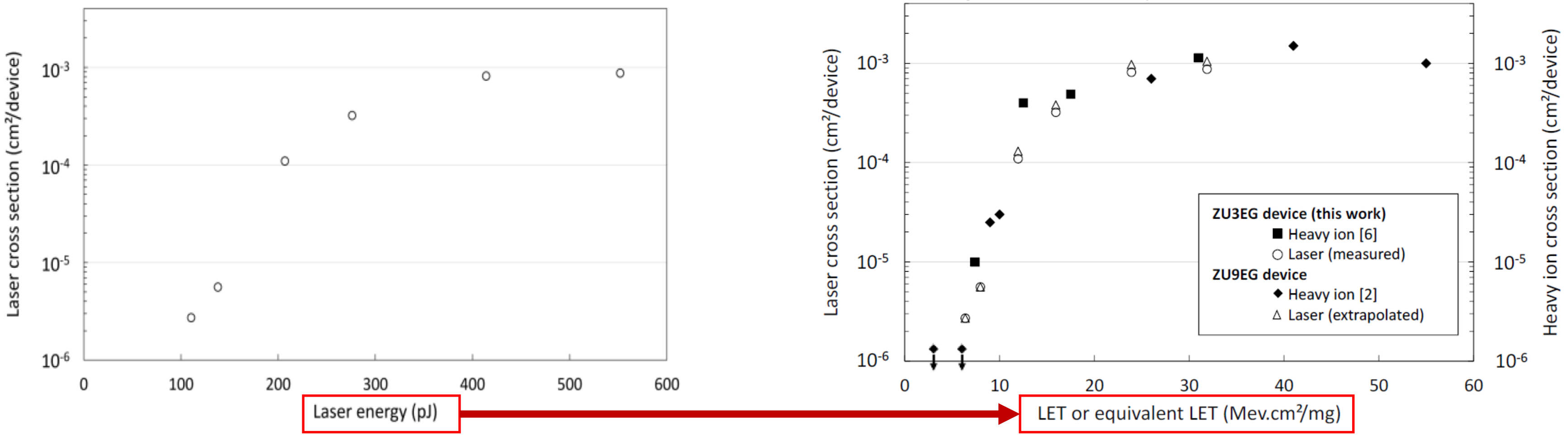
Guideline #28

The position of the beam-waist along the microscope axis with respect to the DUT should be maintained in the active layer of the DUT during the scans, with a tolerance that should be defined as a function of the test goal and parameters.

Particularly critical for TPA

Elements for equivalent LET calculation

[Fongral et al, to be presented @ RADECS 2023]



Equivalence of charge deposition in sensitive volume V: $LET_{laser} = \frac{E_p}{d_V} \iiint_V N_{las}(\boldsymbol{r})\, d\boldsymbol{r}$

For SPA: $LET_{laser} = K_{SPA} E$ [J/m]

with, in first approximation: $K_{SPA} = \alpha_{IB} T_b e^{-\alpha d_s} T_{box} \frac{E_p}{E_\gamma}$

LET_{laser}: equivalent LET
N_{las}: generated charge distribution
E: incident laser pulse energy
E_p: energy for pair creation (3.6eV in Si)
E_γ: photon energy
V: sensitive volume
d_V: thickness of sensitive volume
d_S: substrate thickness
α_{IB}: Si interband absorption coefficient
α: Si total absorption coefficient
T_b: backside surface transmission
T_{box}: burried oxide transmission (=1 for bulk)

This provides a good order of magnitude in most cases, many refinements are possible

Summary

- Practical guidelines for laser SEE testing
- First steps towards homogenization of the technique
- Similar effort in progress in the US by NASA, JPL, NRL, DTRA
  - Document to be released soon
- Readers & users feedback is welcome