Perugia
INFN
Istituto Nazionale
di Fisica Nucleare

Laser System for Single Event Effects Testing and Radiation Sensitivity Mapping of ICs

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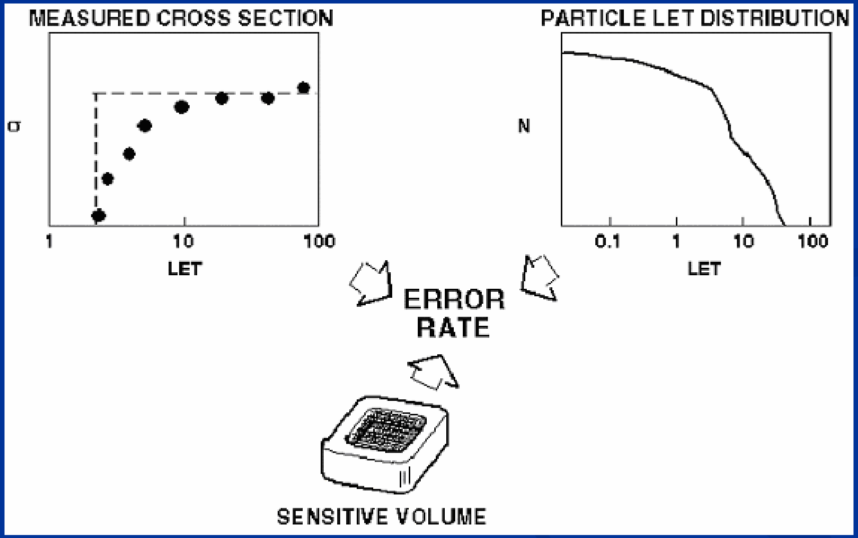
INFN Perugia

Critical Parameters for Mission Definition for Radiation Predictions

- When and how long the mission will fly
- Where the mission will fly
- What systems must operate during worst case environment conditions
- What systems are critical to mission success
- Amount of shielding surrounding devices

SEE Rate Calculations

- Involves 3 different quantities;
  - The cross section of the device, often determined empirically;
  - The distribution of particles expected in the space environment, which depends on assumptions about solar flare activity, radiation belt activity, and shielding;
  - The critical charge, sensitive area and sensitive volume associated with the SEE phenomenon of interest.



SEE Ground Testing

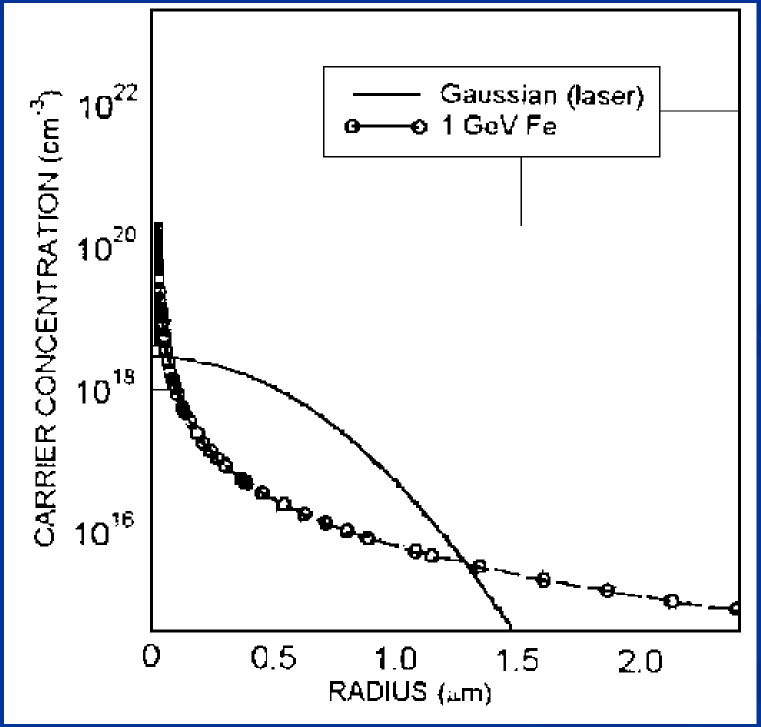
- Facilities
  - Heavy-Ion
  - Proton
  - Californium-252 source
  - Pulsed laser (developed and patented in INFN-Pg)

Understanding of Laser Technique

- Radial charge (carrier) density
- Pulse width effects
- Surface reflections
- Non-linear absorption (TPA) problem
  (Choice of optical wavelength)
- Free carrier recombination and Funnelling problems

Radial Charge Density

- Ion produce much more highly peaked radial charge distribution wrt laser. Different radial charge means different charge density, hence slightly different behaviours of DUT.



The radial charge density profile, calculated with TRKRAD, at 0.125 µm below surface.

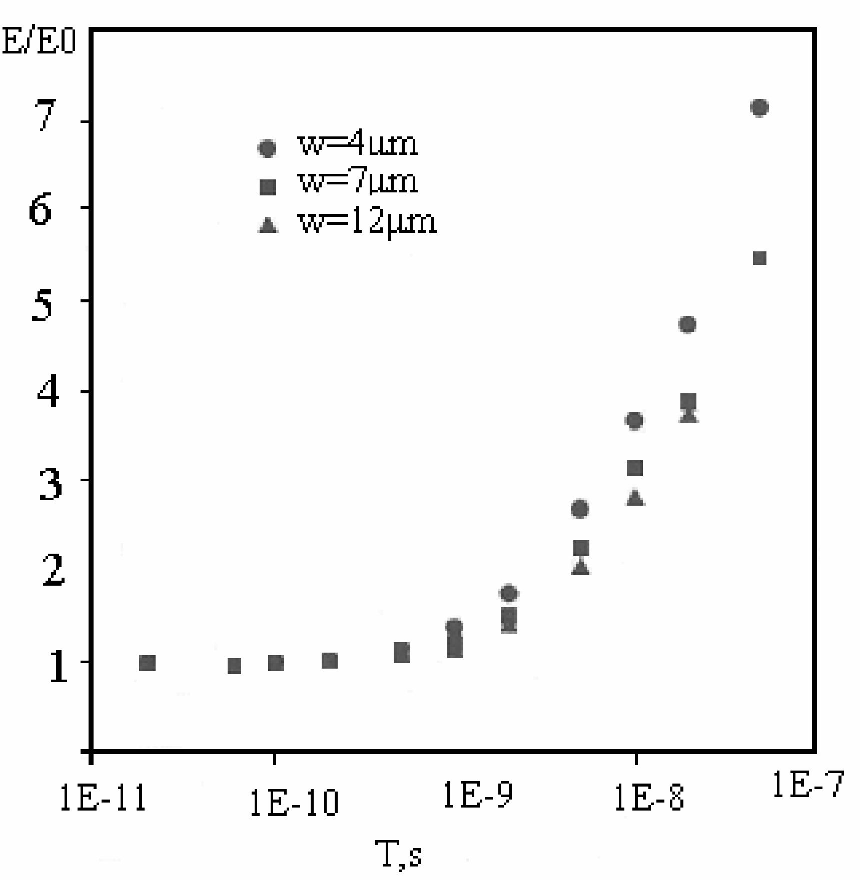
The incident LET of the ion and the laser are the same.

Reference: IEEE Trans. Nuc.Sc.V41, N6, Dec1994 (2574-2584)

Pulse Width

Relative SEL threshold laser energy vs. pulse duration. Normalized dependence is in smooth rising (E_0 corresponds to minimum pulse duration which is 10 ps in this case). For our case (15 ns) this factor is about 2.5 (E_0).

Reference: IEEE Trans. Nuc. Sc. V44, N6, Dec 1997 (2034)



Surface Reflections

- Need to know accurately the amount of light that enters the device.
  - The amount of light entering the device will depend on the nature of the device surface and on the presence of the passivation layers used for the protection of the device surface

$$I_T = I_0 \left[\frac{T^2}{1 - R^2} \right] \cdot \left[\frac{1}{1 + F \sin^2(\Delta / 2)} \right]$$

where I_t is the intensity transmitted to the silicon substrate and I_0 is the intensity incident at the passivation layer. Also

$T = t_1 t_2$ and $R = r_1 r_2$ are respectively transmittance and reflectance.

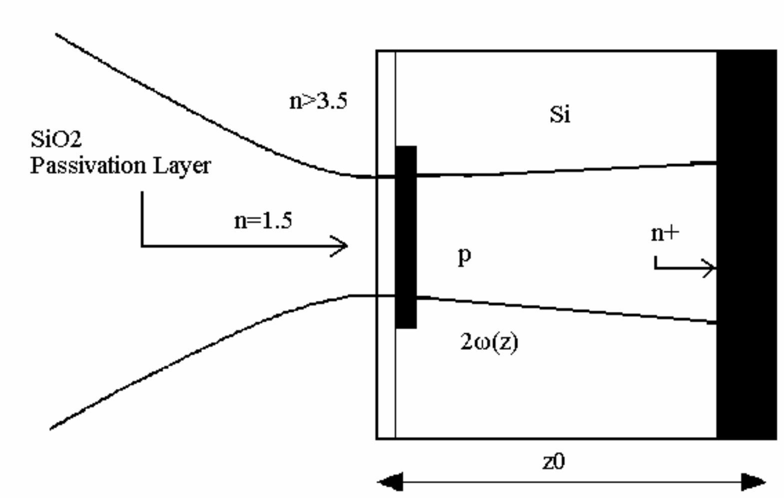
r_1 and t_1 refer to the air : $\mathrm{SiO_2}$ interface and r_2 and t_2 to $\mathrm{SiO_2}$: Si interface.

$F = \dfrac{4R}{1 - R^2}$ (Airy function) and the transmission depends on the layer thickness, d, by

$$\Delta = \frac{4\pi n d}{\lambda} \cos\Theta$$

Surface Reflections (cont'd)

- Calculating the expected surface reflections from the VA gives
  - For n(SiO_2)=1.5 and n(Si)=3.65 at Θ=0
- The relative reflection has been measured and calculated analytically.
  - Reflection measurement: we measured the reflected photons at the same solid angle first from a mirror and than from VA (obtaining relative reflection VA/mirror) . The average relative reflection is about 30%. (over 100 incident photons 30 are reflected)



TPA problem

- Two Photon Absorption: at high laser intensity it is possible that the absorption of two photons produces only one hole-electron pair.
- It's the most probable non linear effect in light absorption and is ruled by:

$$I(z) = I_0 \cdot \frac{e^{-\alpha \cdot z}}{1 + (\frac{\beta \cdot I_0}{\alpha}) \cdot (1 - e^{-\alpha \cdot z})}$$

β=two photon absorption coefficient, α=linear absorption coefficient

Note that this problem arises with high SEE LET threshold (30-50 MeV/mg/cm^2)

Use of 0.8 µm wavelength reduces this nonlinear contribution by a factor 100 wrt the use of a wavelength near bandgap (1.13 µm)

Carrier Lifetime & Funnelling

- Funnelling: when a track charge density is higher than the doping density, the junction electric field is distorted; this can determine extra charge collection.
- Carrier lifetime: hole-electron recombination rate is charge density dependent; high recombination rate lowers the charge collection.
- Both effects depends on charge density, that is different between laser and ion. That’s why we can’t completely substitute the ion-beam test with the laser method.

Laser System Test Capabilities

• Cross Section vs LET measuring

We generate an array of pulsed laser ionization tracks (*Energy*) over a scanning matrix (i.e. 22x20) to simulate a SEE Ion beam test (100 pulses for each position - *IntFlx*) We count SEL event number (*NbSEL*) for each position and for a decreasing laser optical power:

$$\sigma = \frac{NbSEL}{IntFlx} \cdot \frac{SampledArea}{\cos(\theta)} = \frac{NbSEL}{1 \cdot 10^4} \cdot (R^2 \cdot \pi \cdot 10 \times 10)$$

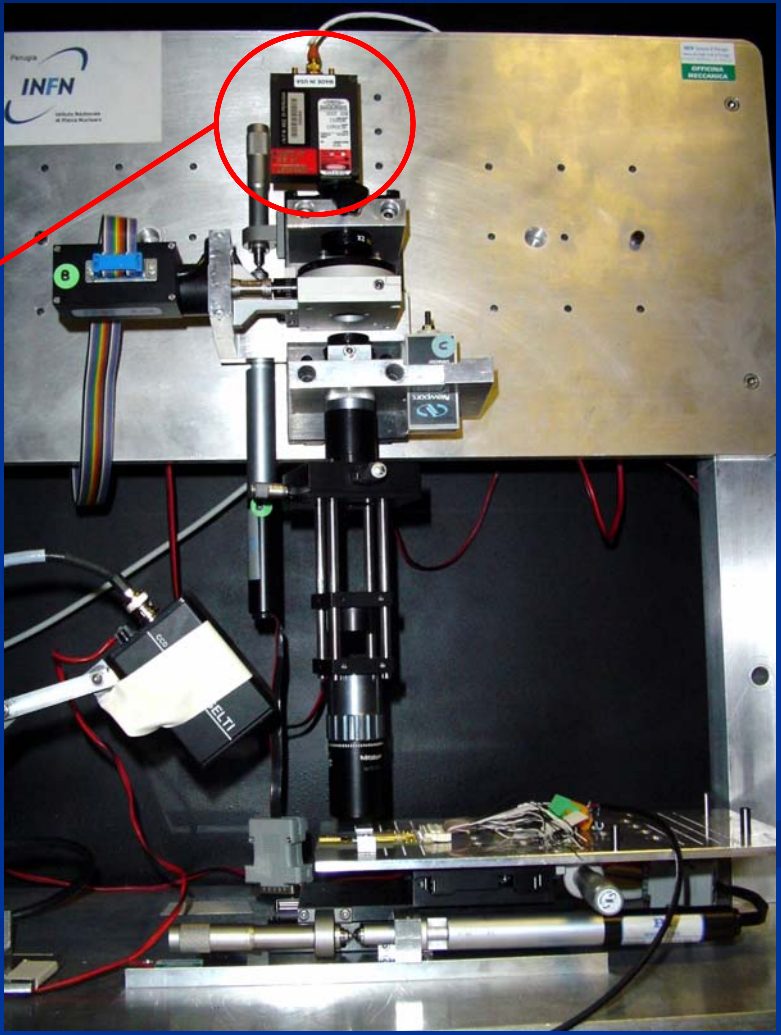
$$LET = \frac{Energy}{\rho_{Si} \cdot d_{Si}}$$

• SEL Sensitivity Mapping

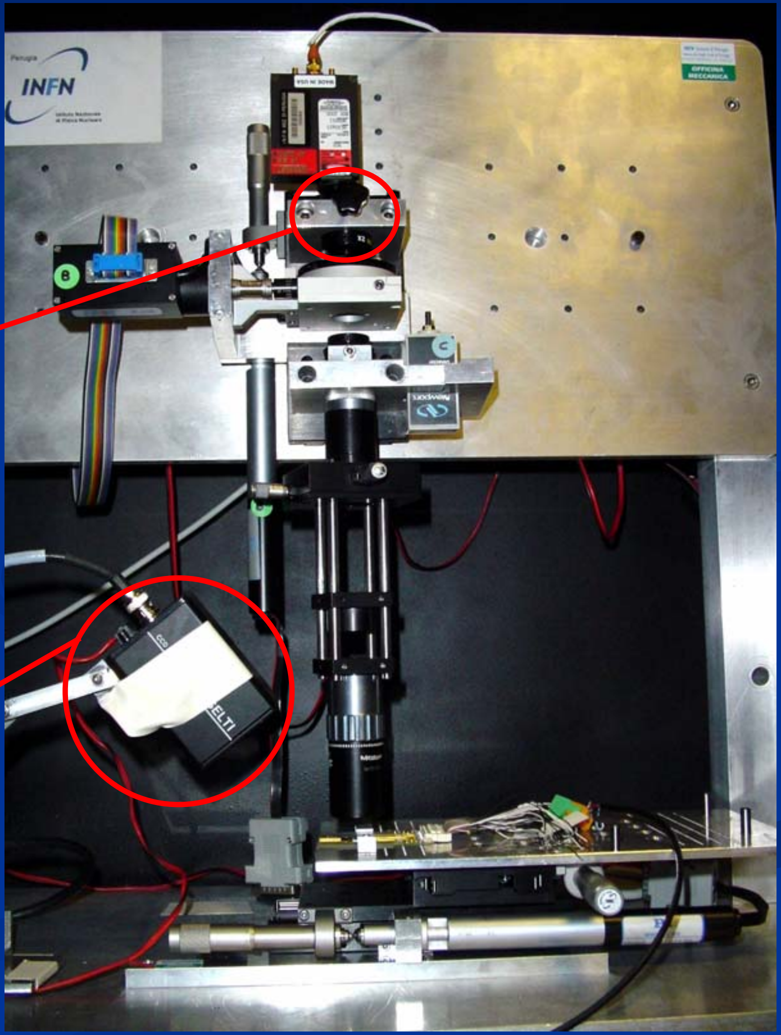
- The mapping is generated by scanning the DUT surface along a number of **rows** and stepping the DUT in the normal direction at the end of each scan (the same step of Cs vs LET procedure).
- The correlation between the Laser beam energy and the DUT response joint to accurate spatial information defines the sensitivity map of the different functional blocks of the chip → **the alignment technique is very important**.

System Setup for SEE Studies (Details and Specs)

- Pulsed Laser Diode
- 20W (@peak, 10kHz), λ=913±10nm
- 15ns pulse width
- Operating voltage range 9÷14.5V
- Repetition freq. up to 10kHz



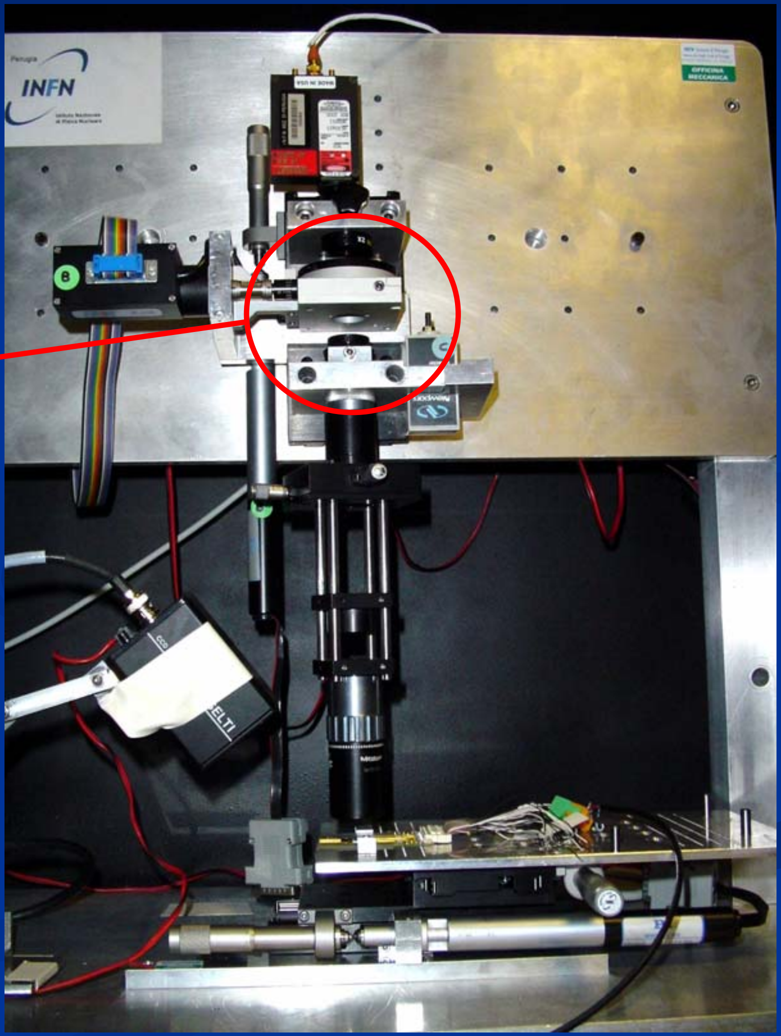
System Setup for SEE Studies (Details and Specs)



- **Astigmatism corrector** to have a quasi-circular laser spot

- PC based **IR Imaging** System

System Setup for SEE Studies (Details and Specs)



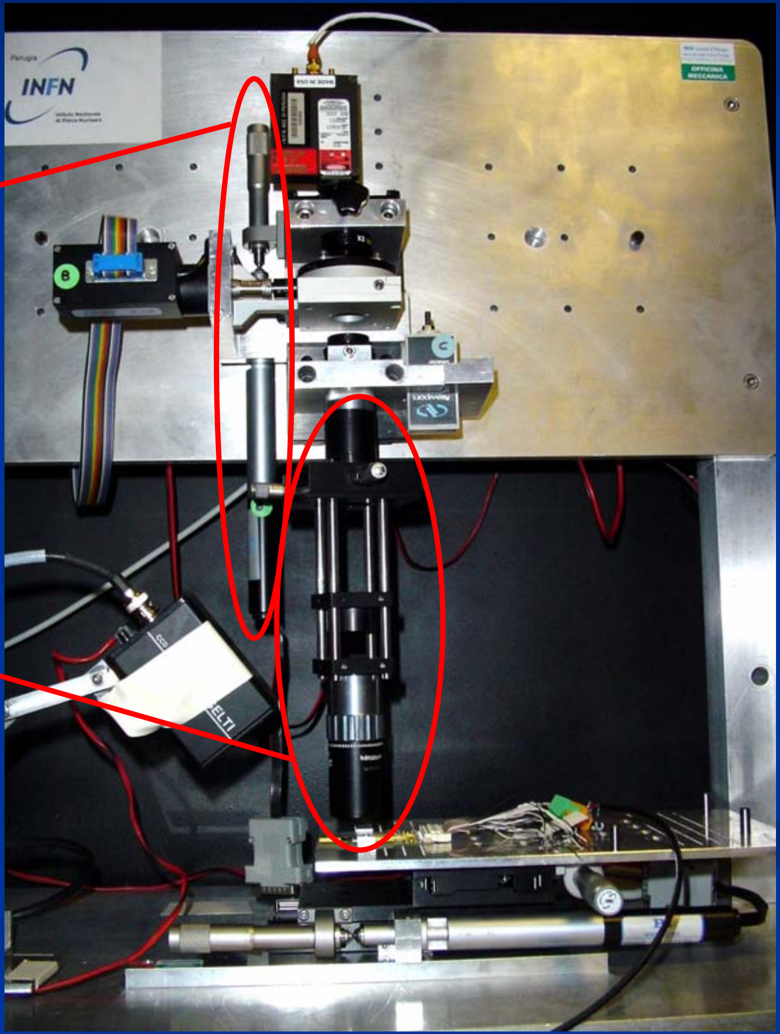
- Automatic Motorized Power Beam controller :
- Motorized Polarizer
- BeamSplitter (@50%)
- PC controlled PhotoDiode

System Setup for SEE Studies (Details and Specs)

Motorized (1 μm repeatability)
Z-axe

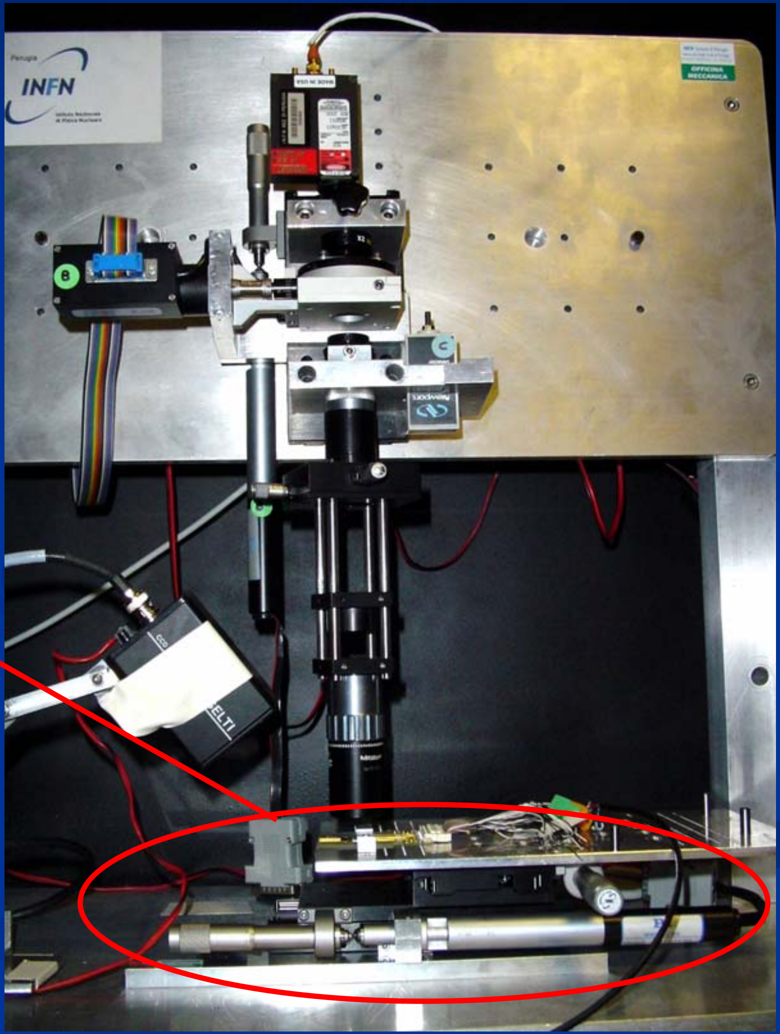
Focusing Optical Setup

Spot size (FHWM) of ~ **10 μm**

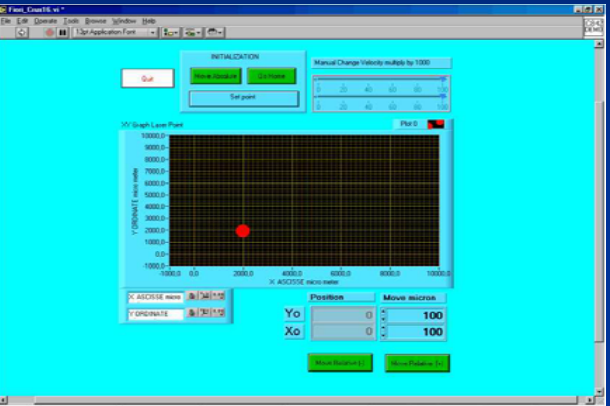


System Setup for SEE Studies (Details and Specs)

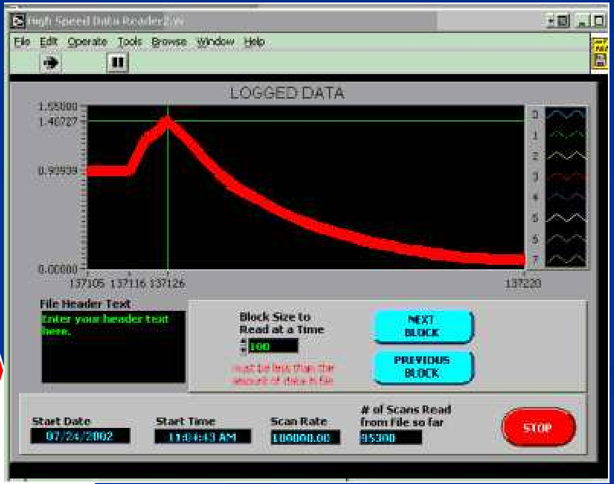
- PC controlled XY stage with a 1 μm bi-directional accuracy



System Setup for SEE Studies (Details and Specs)



Control Panel representation of the spot on the DUT surface



File Header Text: Enter your header text here.

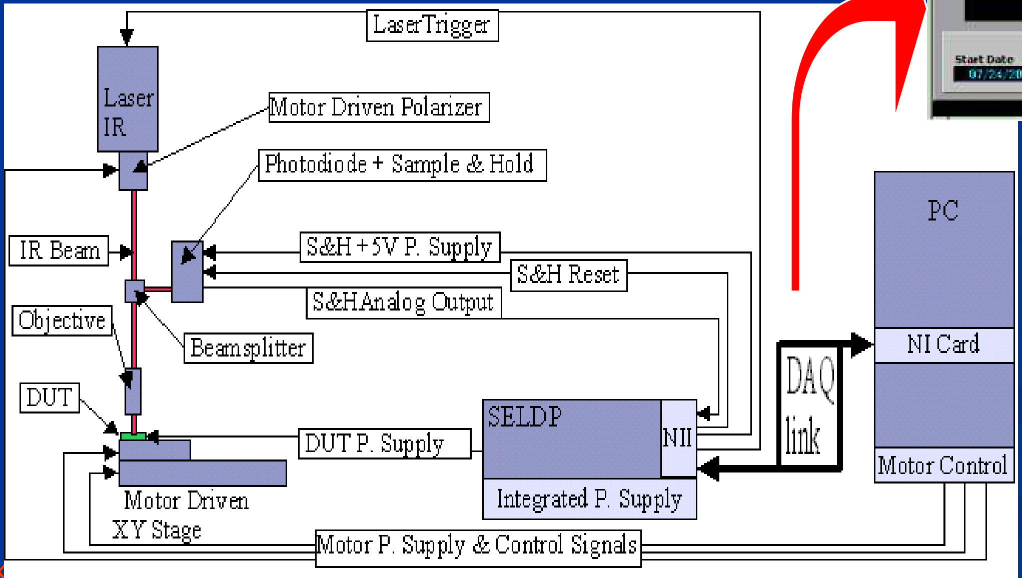
Block Size to Read at a Time: 100

Start Date: 07/24/2002

Start Time: 11:04:43 AM

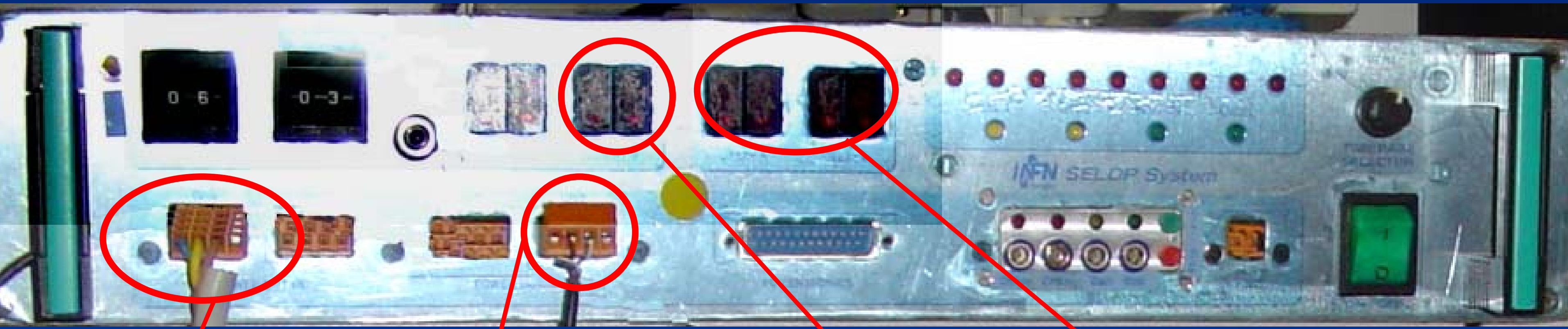
Scan Rate: 100000.00

# of Scans Read from File so far: 85300



Analog/Digital Signals Acquisition System

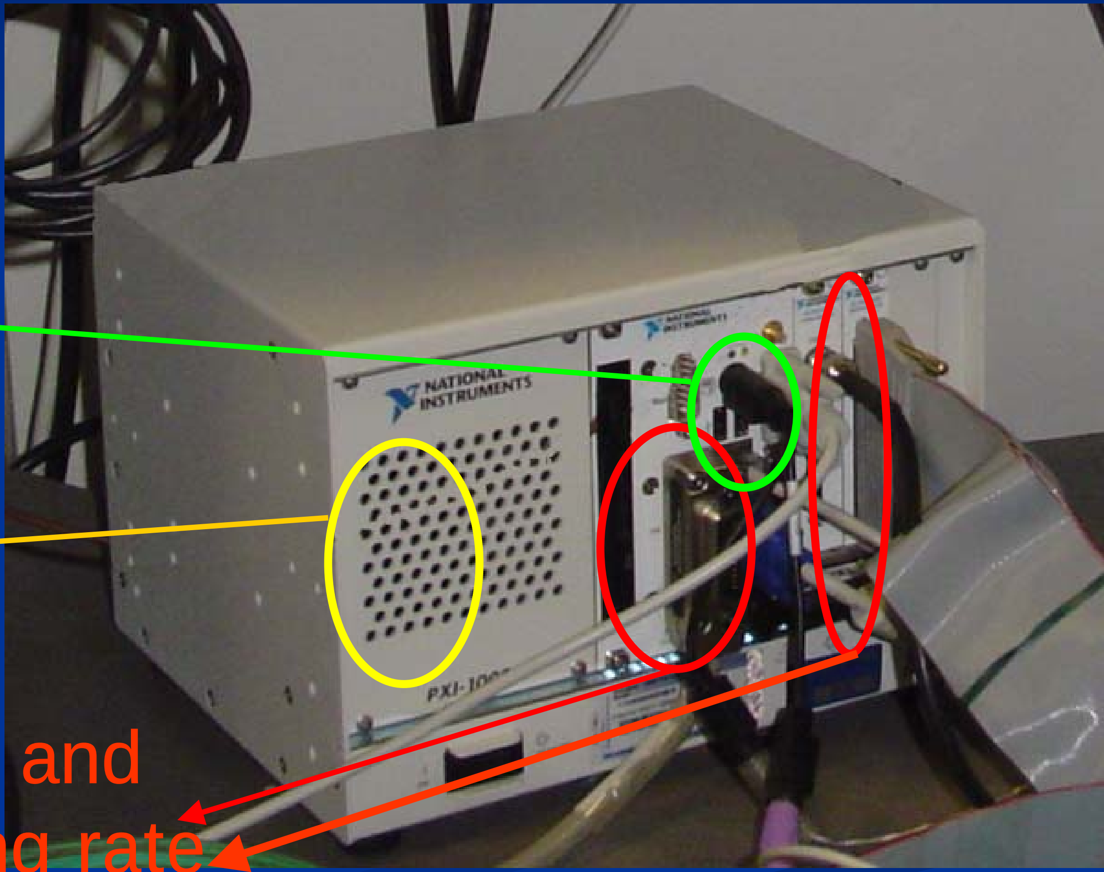
Analog/Digital Signals Acquisition System (1/2): SELDP



SELDP (Single Event Latchup Detector and Protector):

Developed at INFN sez. Perugia, it monitors the input current of DUT in an adjustable range (±12V-100mA); if a SEL is detected (SEL produces an exponential rising of the current) it suspends power supply (at a preset delay, 1 ms up to 99 s), counts the number of events.

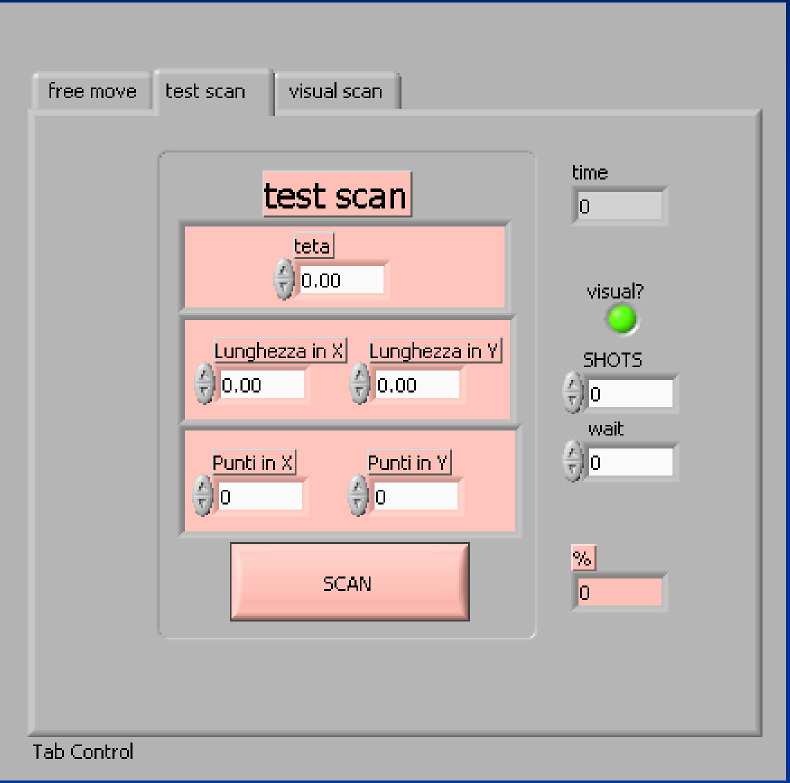
Analog/Digital Signals Acquisition System (2/2): PXI



Compact Stand alone System:

- Serial interface to control the motorized axes
- Pentium 3 1GHz CPU based computer
- GPIB interface and 20kHz Sampling rate DAQ card to SELDP

Alignment Laser IR Setup (1/2)



free move | test scan | visual scan

test scan

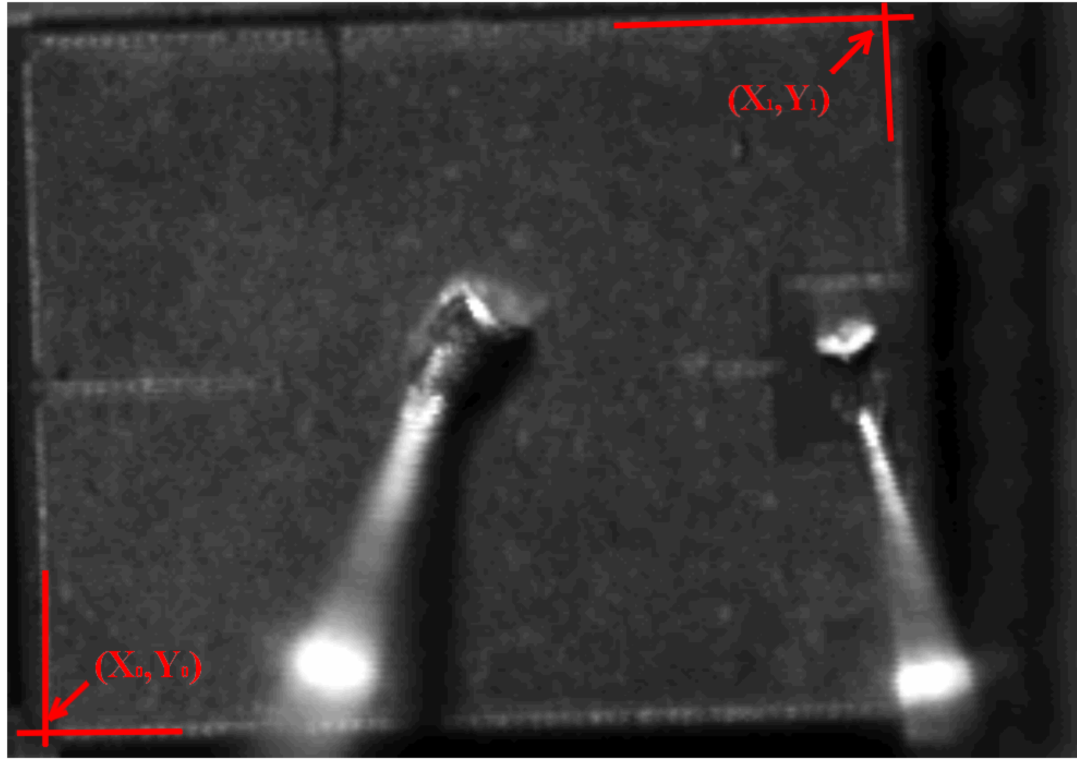
teta: 0.00

Lunghezza in X: 0.00
Lunghezza in Y: 0.00

Punti in X: 0
Punti in Y: 0

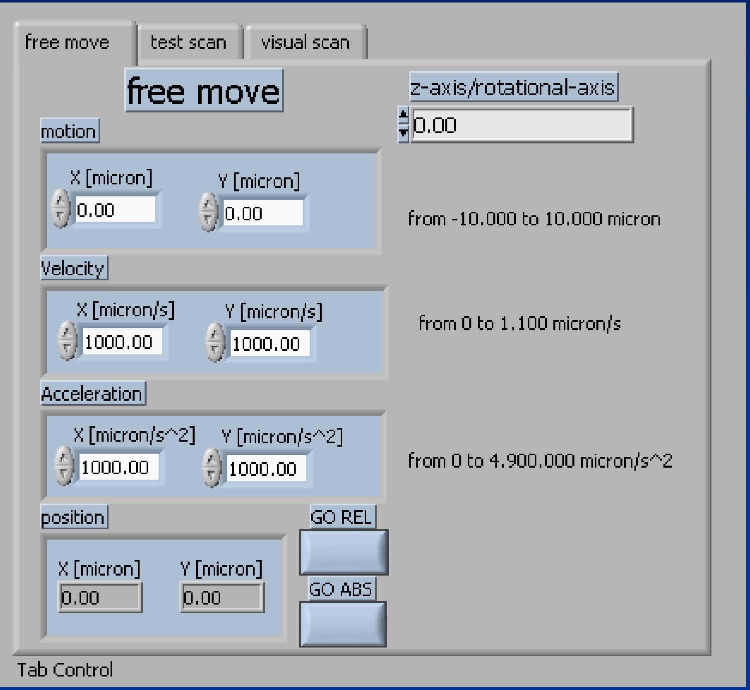
time: 0
visual? ●
SHOTS: 0
wait: 0
%: 0

LabView Panel Control for a Preliminary laser scanning of chip surface to acquire an image, and find alignment points (pointing geometric details of the chip layout).



An example of laser imaging (300x200 pixels - 10µm grid spaced): a Power MosFET chip with a 3000x2100 µm active area

Alignment Laser IR Setup (2/2)



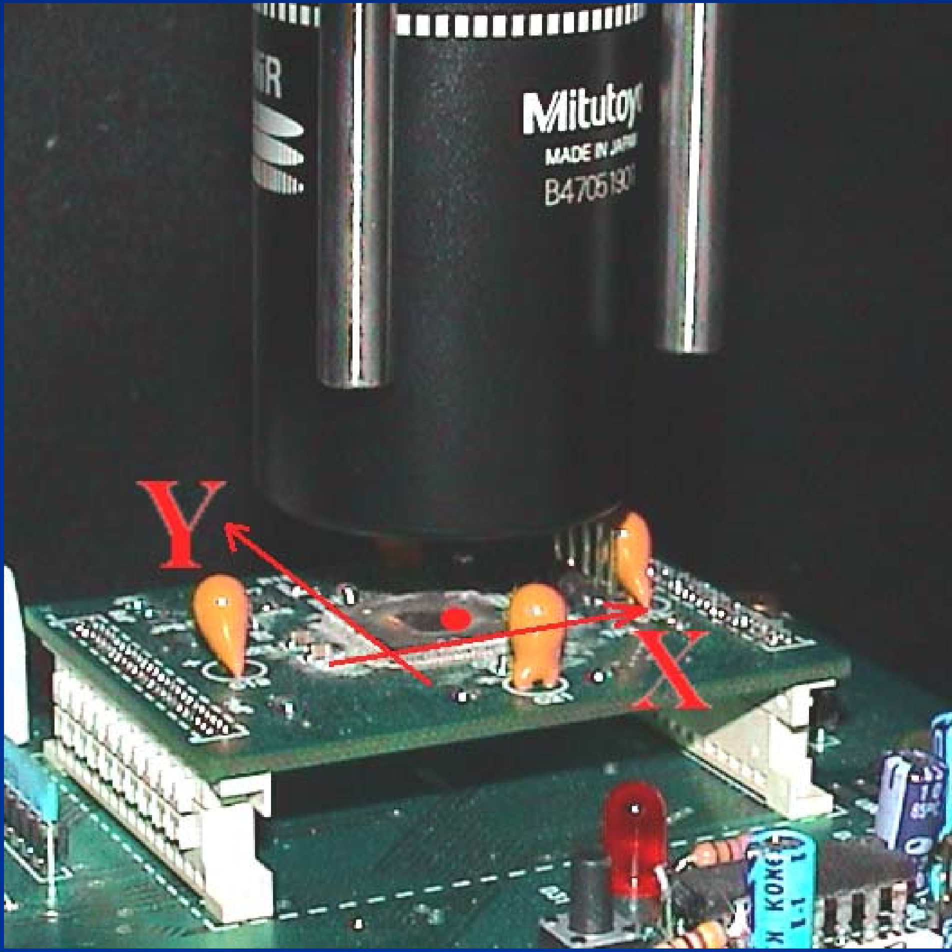
z-axis/rotational-axis: 0.00

motion
X [micron]: 0.00
Y [micron]: 0.00
from -10.000 to 10.000 micron

Velocity
X [micron/s]: 1000.00
Y [micron/s]: 1000.00
from 0 to 1.100 micron/s

Acceleration
X [micron/s^2]: 1000.00
Y [micron/s^2]: 1000.00
from 0 to 4.900.000 micron/s^2

position
X [micron]: 0.00
Y [micron]: 0.00



LabView Control Panel to select free moving mode or predefined matrix automatic scanning mode.

Comparison with Ion Data

- Linear Energy Transfer Calculations have been performed using SRIM/TRIM simulation software package. Analysing the ionisation output file, we achieved the energy value, which gives LET using the following conversion:

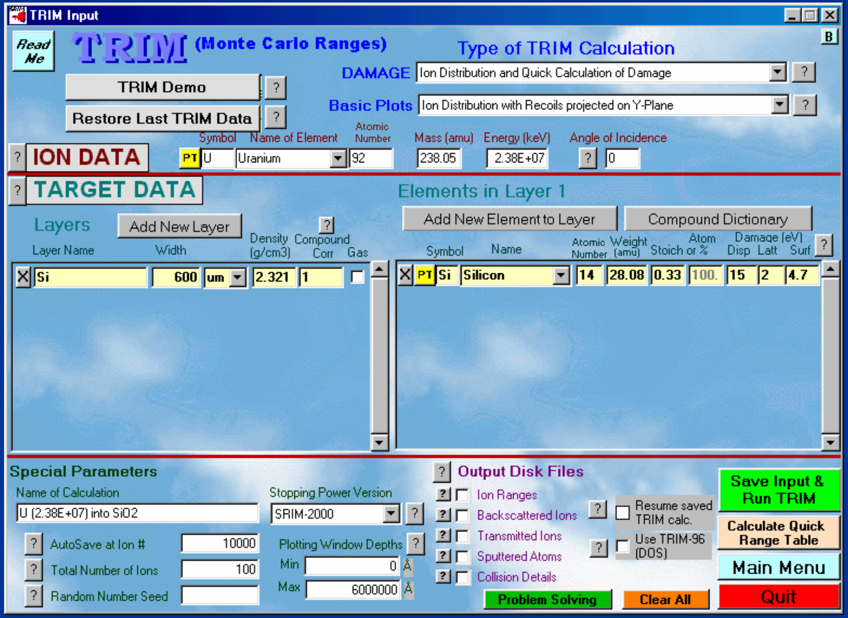
$$LET = \frac{Ionization(eV/Ion/Ang)}{23.211} = MeV/(cm^2/mg)$$

Cross-sections have been calculated using the following formula:

$$\sigma = \frac{NbSEL}{IntFlx} \cdot \frac{Area}{\cos(\theta)}$$

(the beam area is considered 4 cm^2), and IntFlx is the fluence)

LET Calculation with Ion Data using TRIM



Type of TRIM Calculation

DAMAGE: Ion Distribution and Quick Calculation of Damage

Basic Plots: Ion Distribution with Recoils projected on Y-Plane

ION DATA

Symbol	Name of Element	Atomic Number	Mass (amu)	Energy (keV)	Angle of Incidence
U	Uranium	92	238.05	2.38E+07	0

TARGET DATA – Layers

Layer Name	Width		Density (g/cm3)	Compound Corr	Gas
Si	600	um	2.321	1	☐

Elements in Layer 1

Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich or %		Damage (eV) Disp	Latt	Surf
Si	Silicon	14	28.08	0.33	100.	15	2	4.7

Special Parameters

Name of Calculation: U (2.38E+07) into SiO2

Stopping Power Version: SRIM-2000

AutoSave at Ion #: 10000

Total Number of Ions: 100

Random Number Seed:

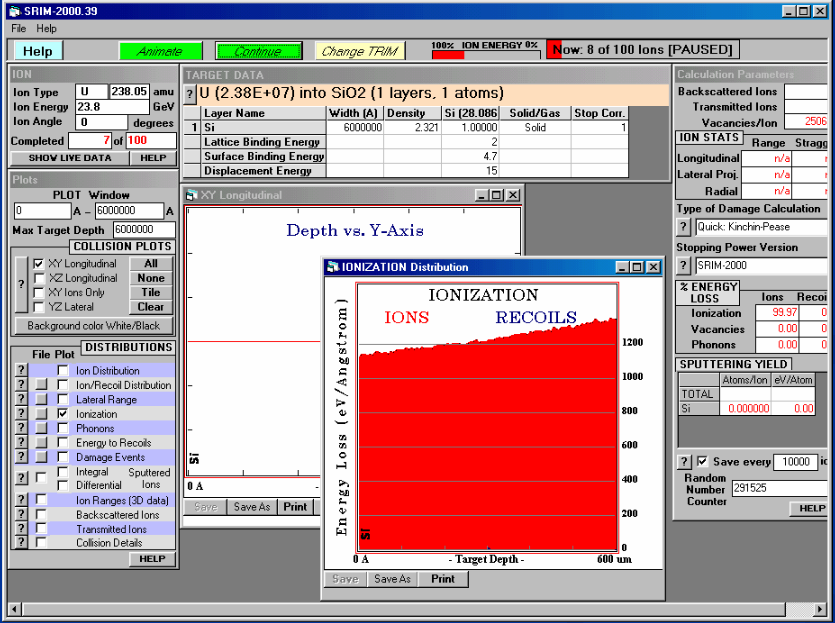
Plotting Window Depths: Min 0 Å, Max 6000000 Å

Output Disk Files

- ☐ Ion Ranges
- ☐ Backscattered Ions
- ☐ Transmitted Ions
- ☐ Sputtered Atoms
- ☐ Collision Details

☐ Resume saved TRIM calc.

☐ Use TRIM-96 (DOS)



Now: 8 of 100 Ions [PAUSED]

ION

Ion Type: U 238.05 amu

Ion Energy: 23.8 GeV

Ion Angle: 0 degrees

Completed 7 of 100

PLOT Window: 0 A – 6000000 A

Max Target Depth: 6000000

COLLISION PLOTS

- ☑ XY Longitudinal
- ☐ XZ Longitudinal
- ☐ XY Ions Only
- ☐ YZ Lateral

DISTRIBUTIONS (File, Plot)

- ☐ Ion Distribution
- ☐ Ion/Recoil Distribution
- ☐ Lateral Range
- ☑ Ionization
- ☐ Phonons
- ☐ Energy to Recoils
- ☐ Damage Events
- ☐ Integral / ☐ Differential Sputtered Ions
- ☐ Ion Ranges (3D data)
- ☐ Backscattered Ions
- ☐ Transmitted Ions
- ☐ Collision Details

TARGET DATA

U (2.38E+07) into SiO2 (1 layers, 1 atoms)

	Layer Name	Width (A)	Density	Si (28.086	Solid/Gas	Stop Corr.
1	Si	6000000	2.321	1.00000	Solid	1
	Lattice Binding Energy			2		
	Surface Binding Energy			4.7		
	Displacement Energy			15		

Calculation Parameters

Backscattered Ions:

Transmitted Ions:

Vacancies/Ion: 2506

ION STATS	Range	Stragg
Longitudinal	n/a	
Lateral Proj.	n/a	
Radial	n/a	

Type of Damage Calculation: Quick: Kinchin-Pease

Stopping Power Version: SRIM-2000

% ENERGY LOSS	Ions	Recoi
Ionization	99.97	0
Vacancies	0.00	0
Phonons	0.00	0

SPUTTERING YIELD

	Atoms/Ion	eV/Atom
TOTAL		
Si	0.000000	0.00

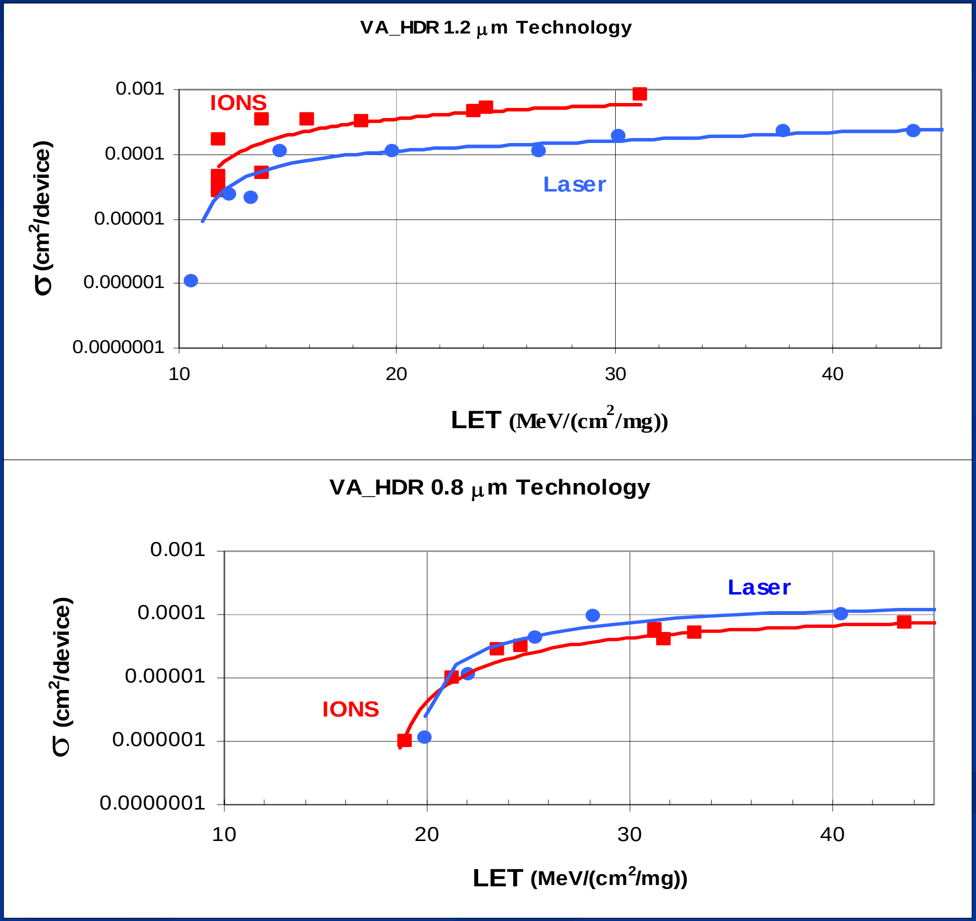
☑ Save every 10000

Random Number Counter: 291525

Cross Section vs LET measurment and Ion Beam Test comparison

Here are shown the results of our **Laser test** after corrections (circles) in comparison with those obtained using Xe^{129}, Au^{197} and U^{238} **ion beams** (squares) in the energy range 200-800 eV/nucleon.

Let thr MeV/mg/cm^2	IONS	Laser
1.2 µm	11.8	10.6
0.8 µm	18.9	19.9

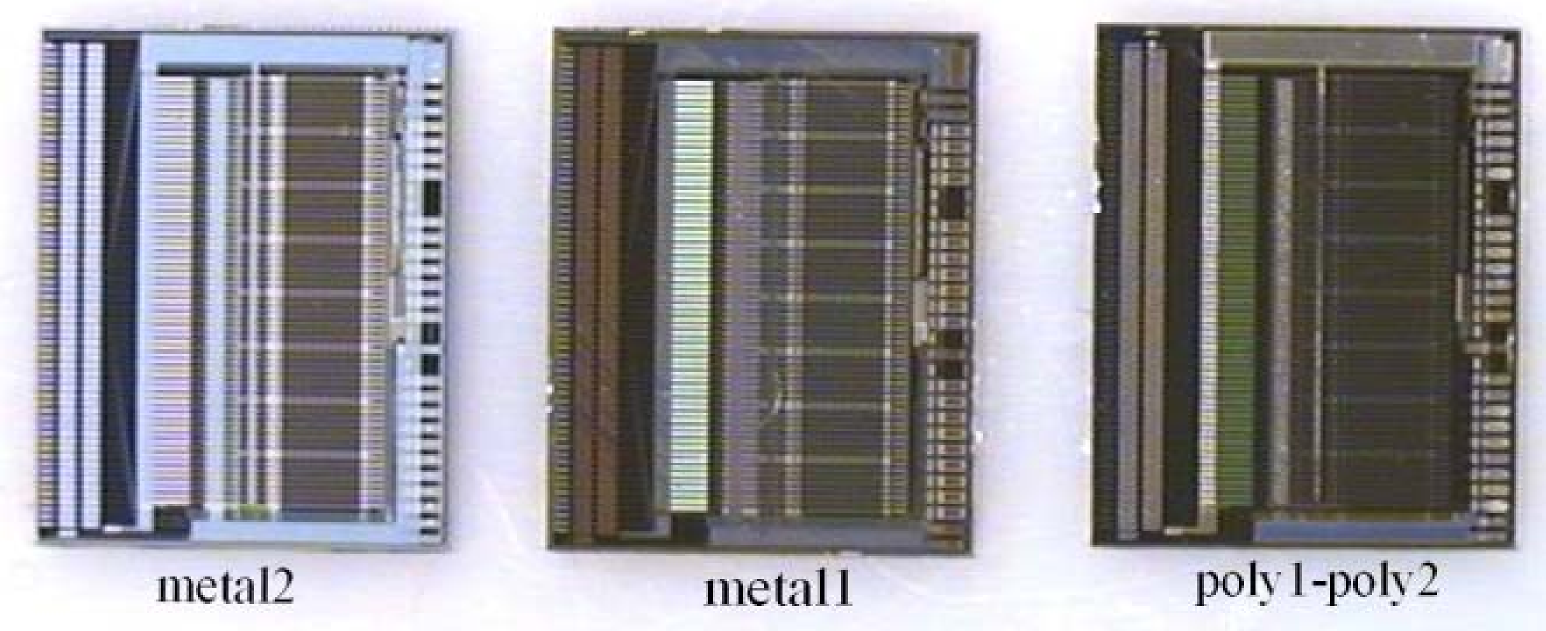


Comparison of two Measurement Techniques

	Cross Section		LET	
	ION BEAM	**LASER**	**ION BEAM**	**LASER**
σ Plateau, LET thrs.	0.8μm: cm^2 1.2μm:	0.8μm: cm^2 1.2μm:	0.8μm: 18.9 $MeVcm^2/mg$ 1.2μm: 11.8	0.8μm: 19.9 $MeVcm^2/mg$ 1.2μm: 10.6
Limitations	No precise info available on uniformity of the ion beam over DUT surface.	Dimensions of matrix and number of pulses used per point are limited .	Limited knowledge on the interior structure of VA.	The overall detection efficiency is about 33%.
Errors	22%	21%	5%	24%including errors(%) on efficiencies: 3% on 95%, 3% on 83%, 10% on 60%, 5% on70%.
Prospective	Better knowldege on ion beam distribution over the DUT surface.	Higher matrix definition and higher number of pulses.	Better knowledge on the interior structure (technolgy used) of DUT.	Reducing inefficiencies by optimizing parameters related to the setup: spot size – beam energy loss – pulse width

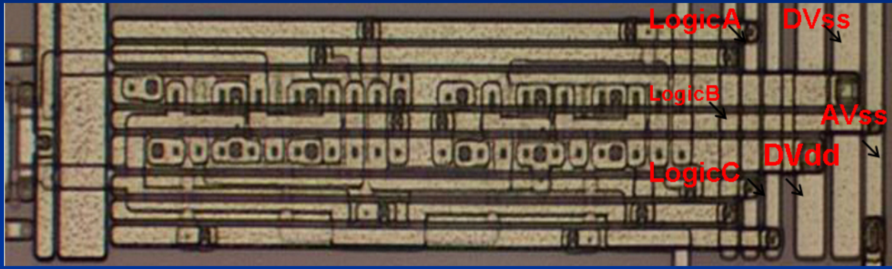
VA64_HDR9a architecture analysis by Reverse Engineering techniques (1/3)

- Selective delayering of three different samples:

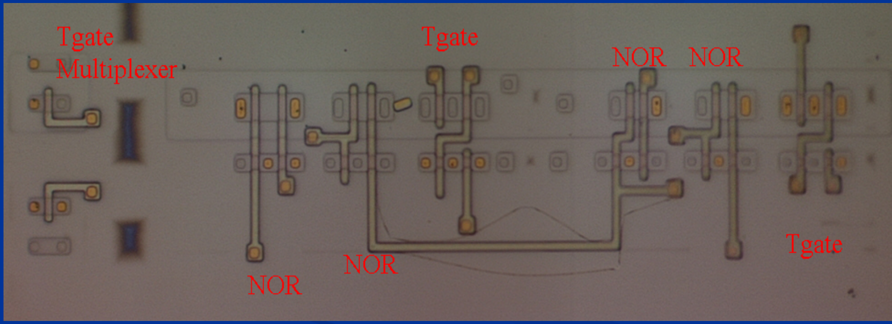


RIE(SF_6+O_2) **WET etching(HF – 55 sec.)**

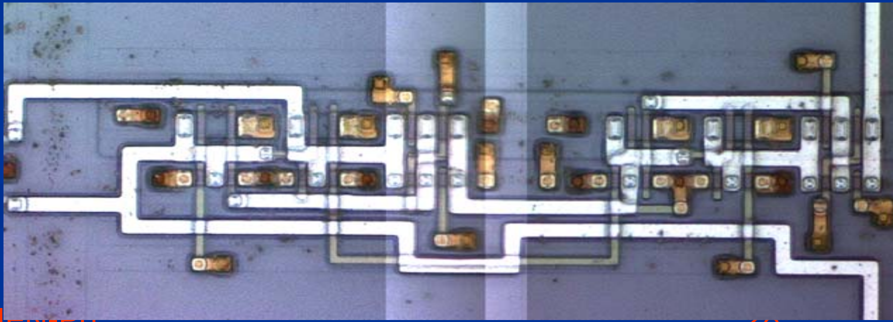
VA64_HDR9a architecture analysis by Reverse Engineering techniques (2/3)



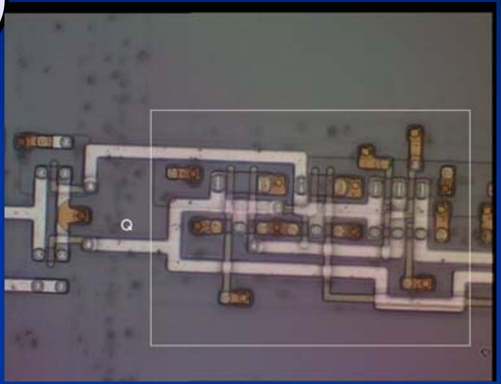
- Metal2 layout:
  - I/O contacts recognition LogicA=Ckb; LogicB=Ck; LogicC=DReset
- Poly1/2 layout:
  - Gate recognition
- Vista metal1:
  - Gate to gate connections recognition



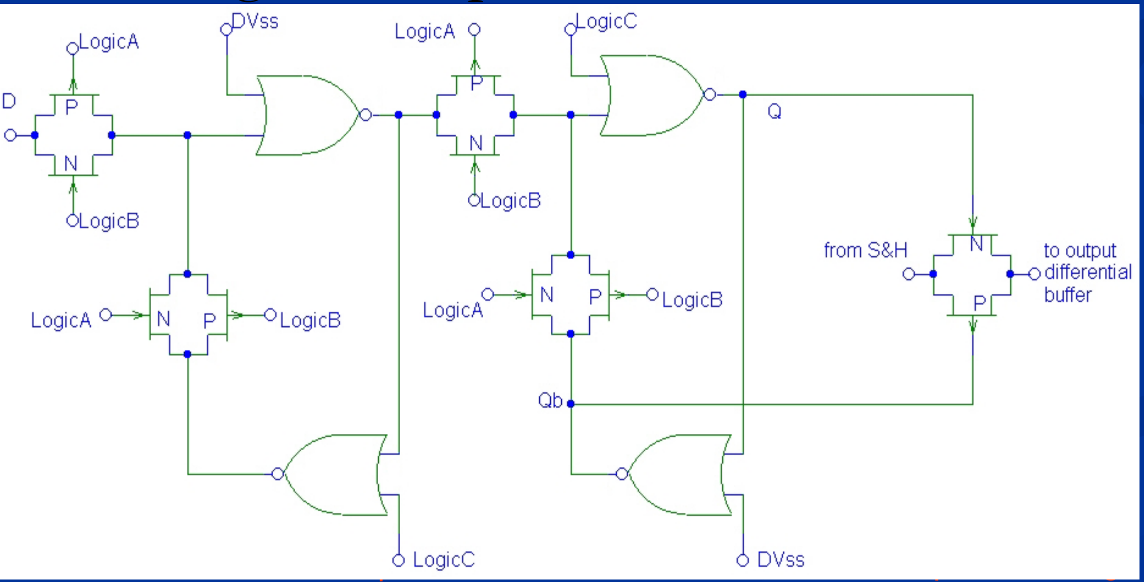
Circuit layout and logic, or analogic, functions reconstruction

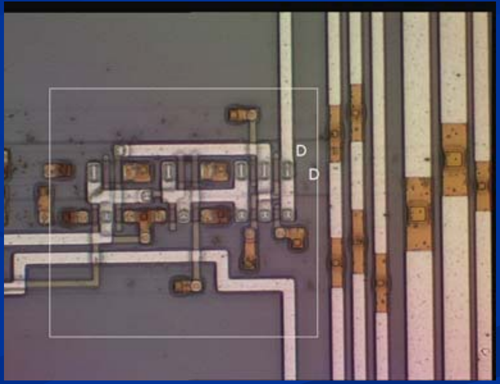


VA64_HDR9a architecture analysis by Reverse Engineering techniques (3/3)

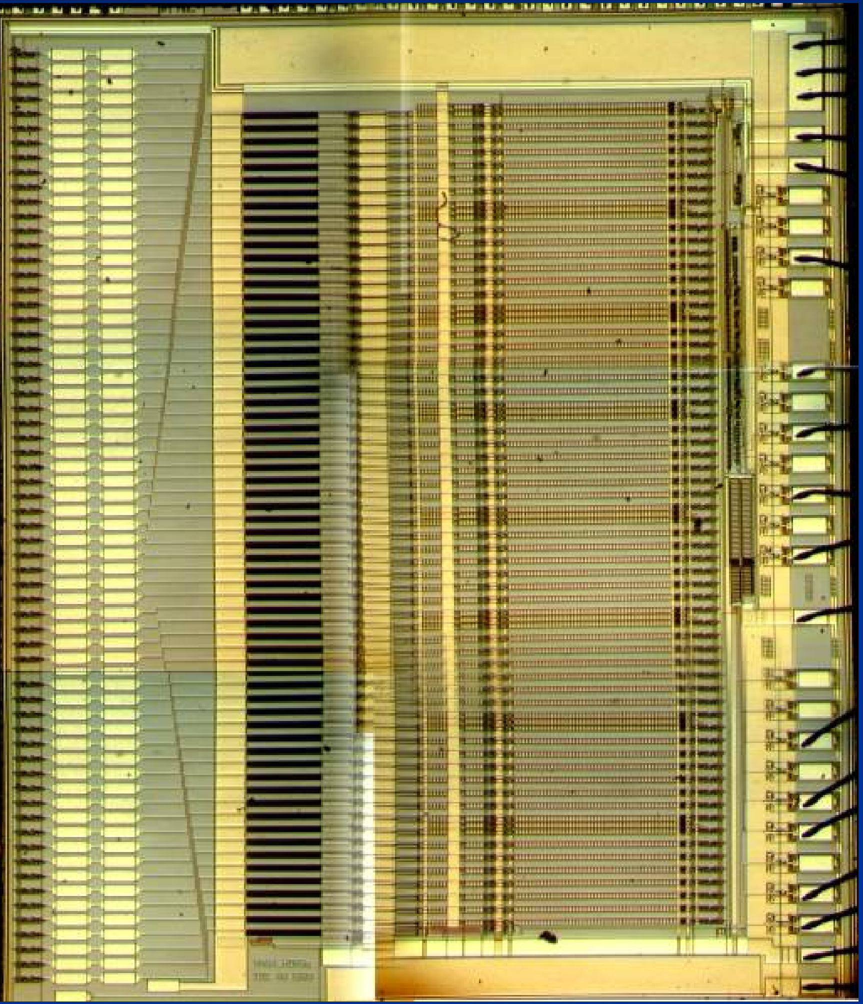


- D Flip-Flop master-slave.
- 64 bit Shift Register
- Analogic Multiplexer (Tgate) command by the Q e Qb single cell register output.





Device Under Test: VA64_HDR9a

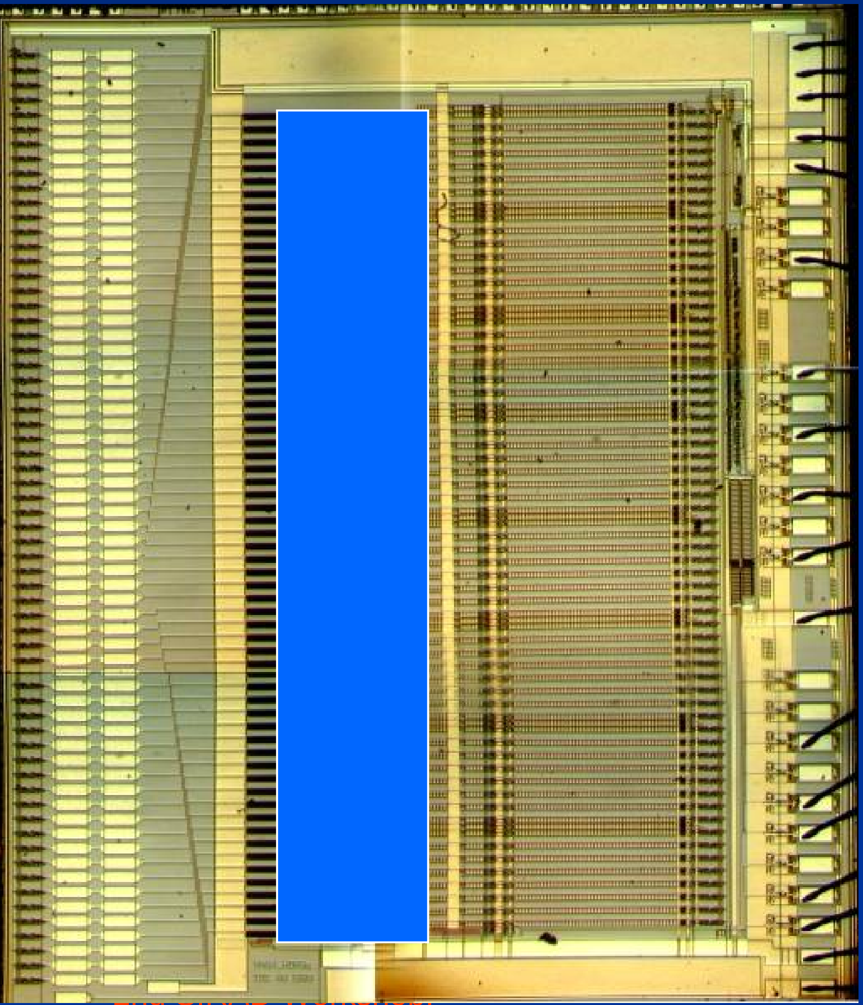


The VA-HDR has 64 channels low noise CMOS charge preamplifier, CR-RC semi-gaussian shaper, Sample&Hold and analog multiplexer.

Design and realized in 0.8 µm **AMS BiCMOS Epi (16 µm thick)** RAD-HARD **technology**

Optical view of the chip (5000x5600 μm^2)

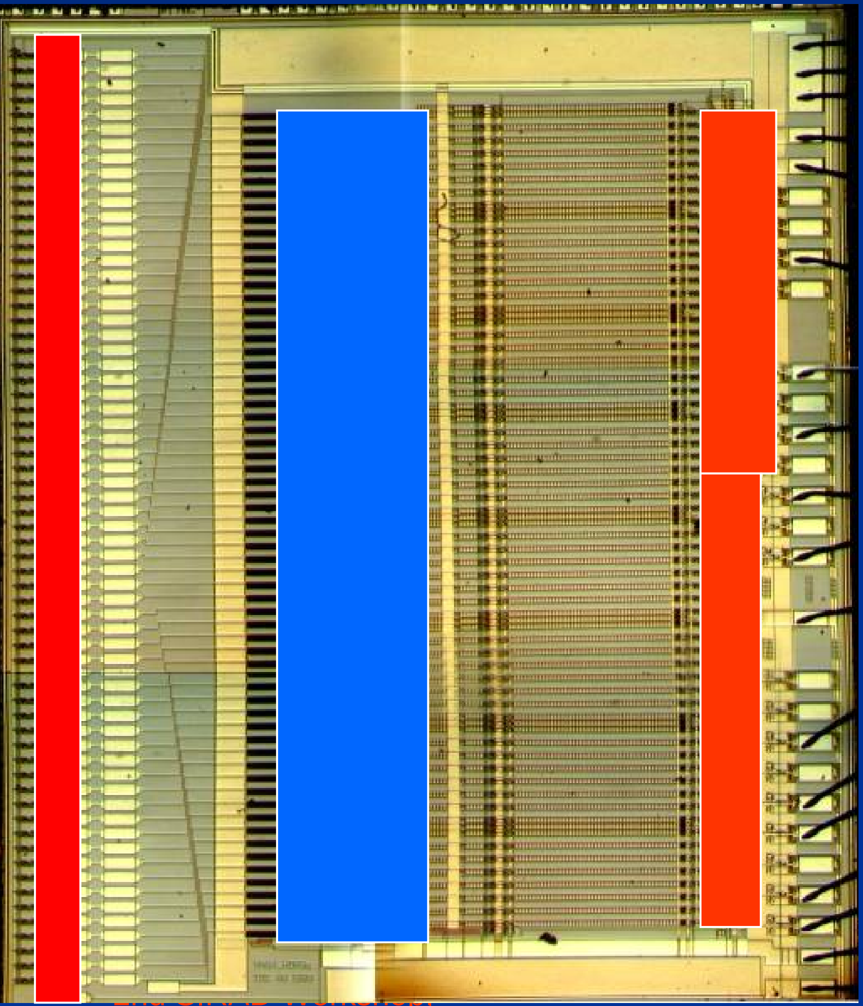
Device Under Test: VA64_HDR9a



- 64 channels Preamplifier

Optical view
of the chip

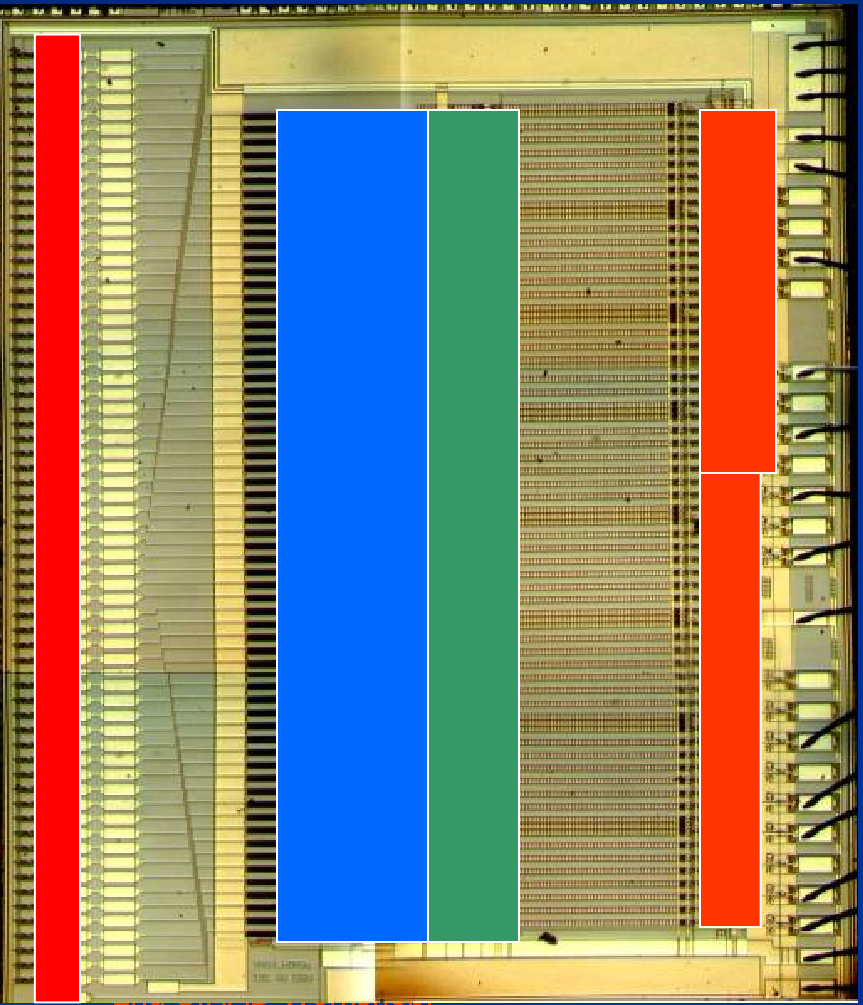
Device Under Test: VA64_HDR9a



- 64 channels Preamplifier
- Digital Controls and Multiplexers

Optical view
of the chip

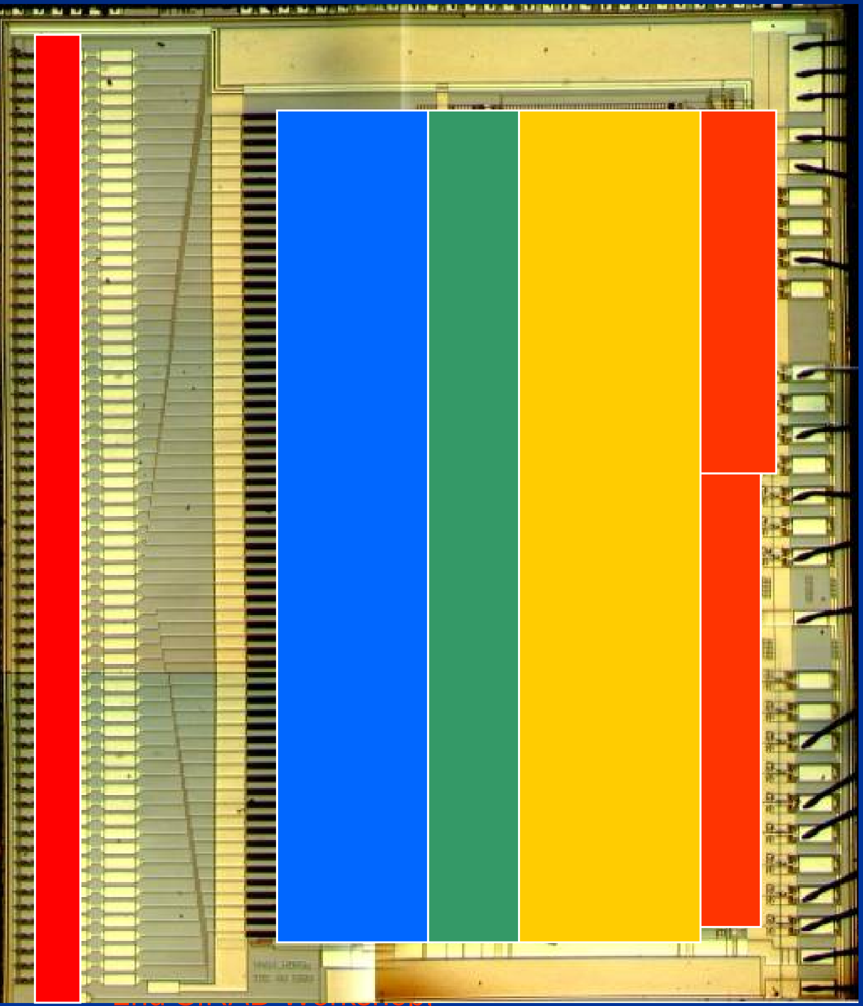
Device Under Test:
VA64_HDR9a



- 64 channels Preamplifier
- Digital Controls and Multiplexers
- 64 Channels Shaper

Optical view
of the chip

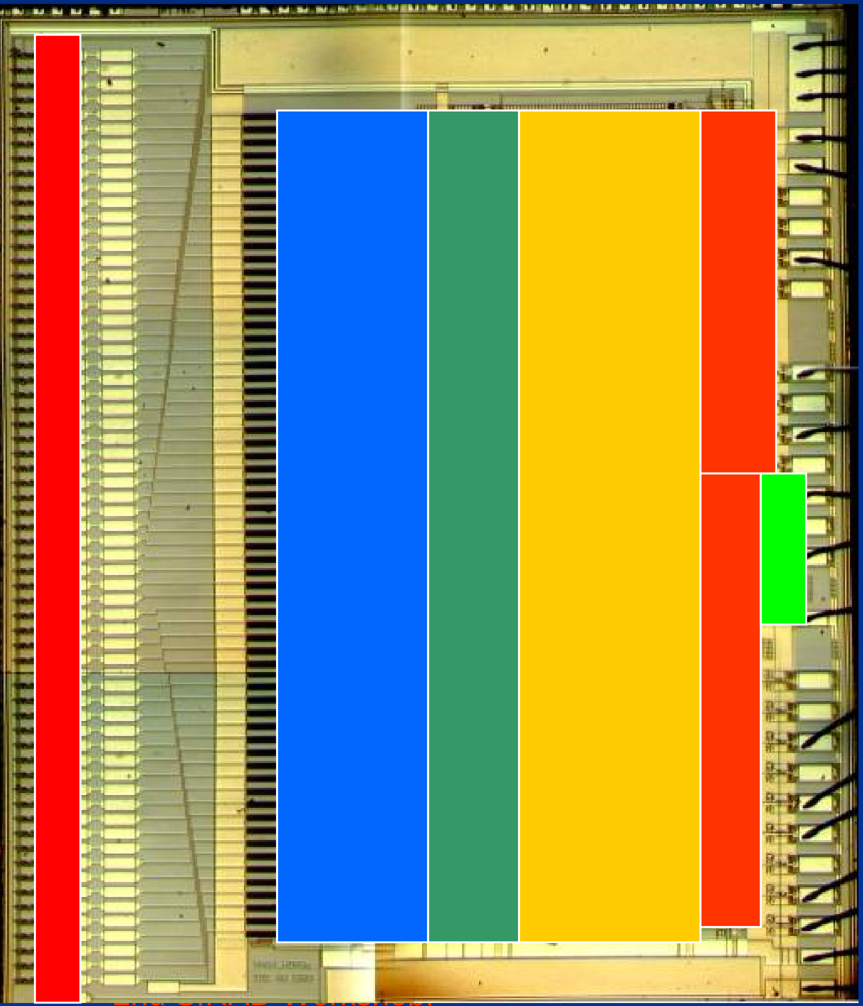
Device Under Test: VA64_HDR9a



- 64 channels Preamplifier
- Digital Controls and Multiplexers
- 64 Channels Shaper
- 64 Channels Sample&Hold

Optical view
of the chip

Device Under Test: VA64_HDR9a



- 64 channels Preamplifier
- Digital Controls and Multiplexers
- 64 Channels Shaper
- 64 Channels Sample&Hold
- Output Buffer

Optical view
of the chip

SEL Sensitivity Mapping of VA64_HDR9a

Pulse Energy at the minimum

Number of Events per point

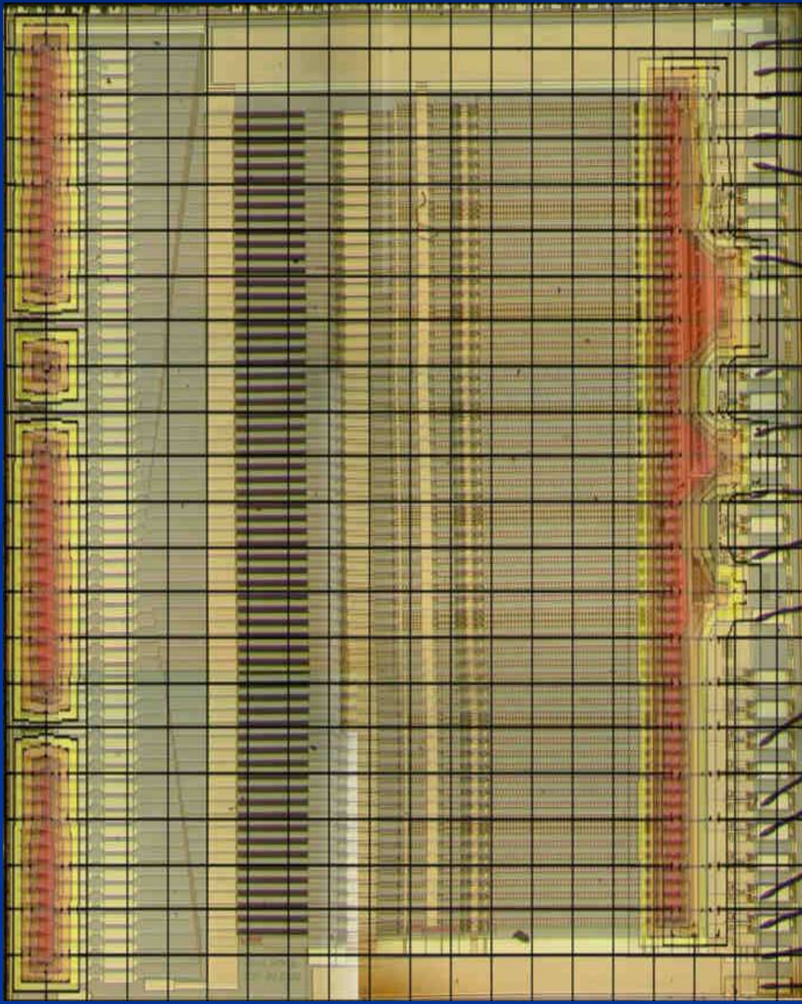
🟥 80-100

🟫 60-80

🟧 40-60

🟨 20-40

⬜ 0-20



SEL Sensitivity Mapping of VA64_HDR9a

Pulse Energy at the maximum

Number of Events per point

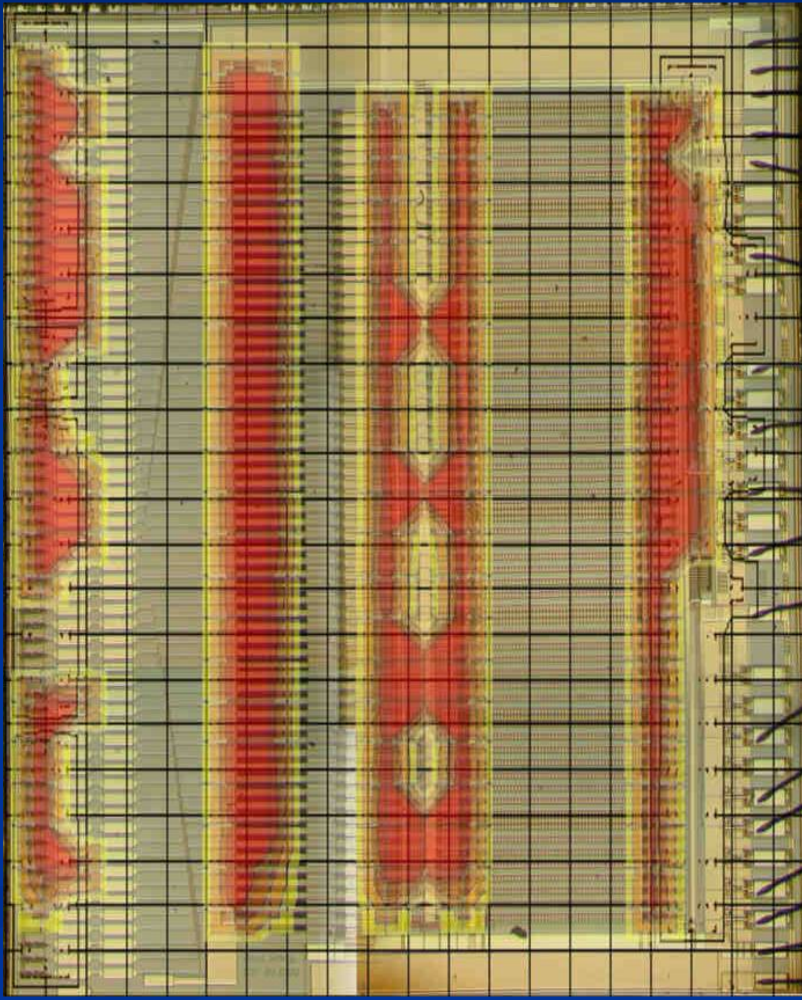
🟥 80-100

🟫 60-80

🟧 40-60

🟨 20-40

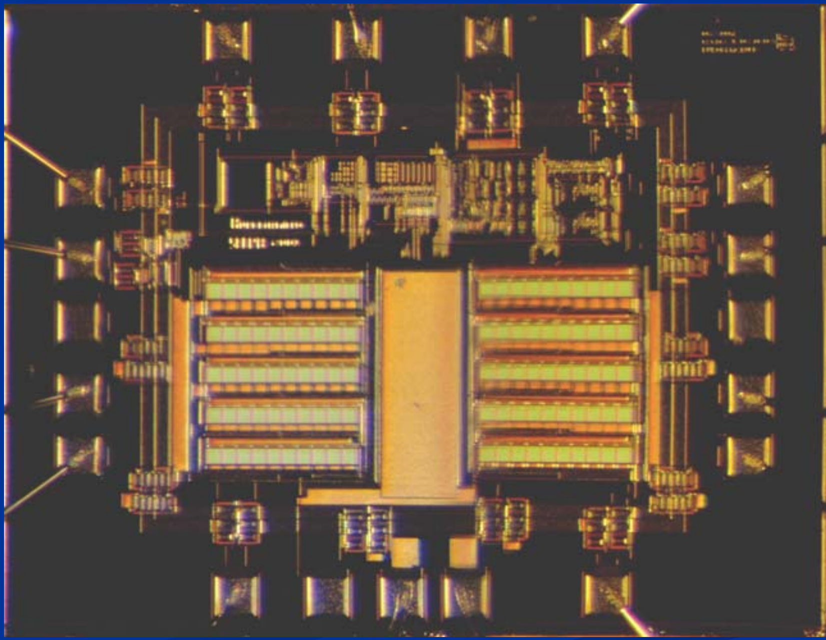
☐ 0-20



Device Under Test: SELP - CAEN

- Die dimensions: 1700x2400 μm^2
- Chip designed and realized by Aurelia Microelettronica-CAEN in 0.8 μm **DMILL**, a mixed analog/digital technology hardened to tolerate a combination of 10Mrad and 1014 neutrons/cm^2
- At the **Ion beam test** at Darmstadt:

Beam Energy **U^{92}** [MeV/nucl.]	100
LET [Mev/mg/cm2]	58



In the LET range up to 58 (MeV/mg/cm^2)

NO SEE was detected

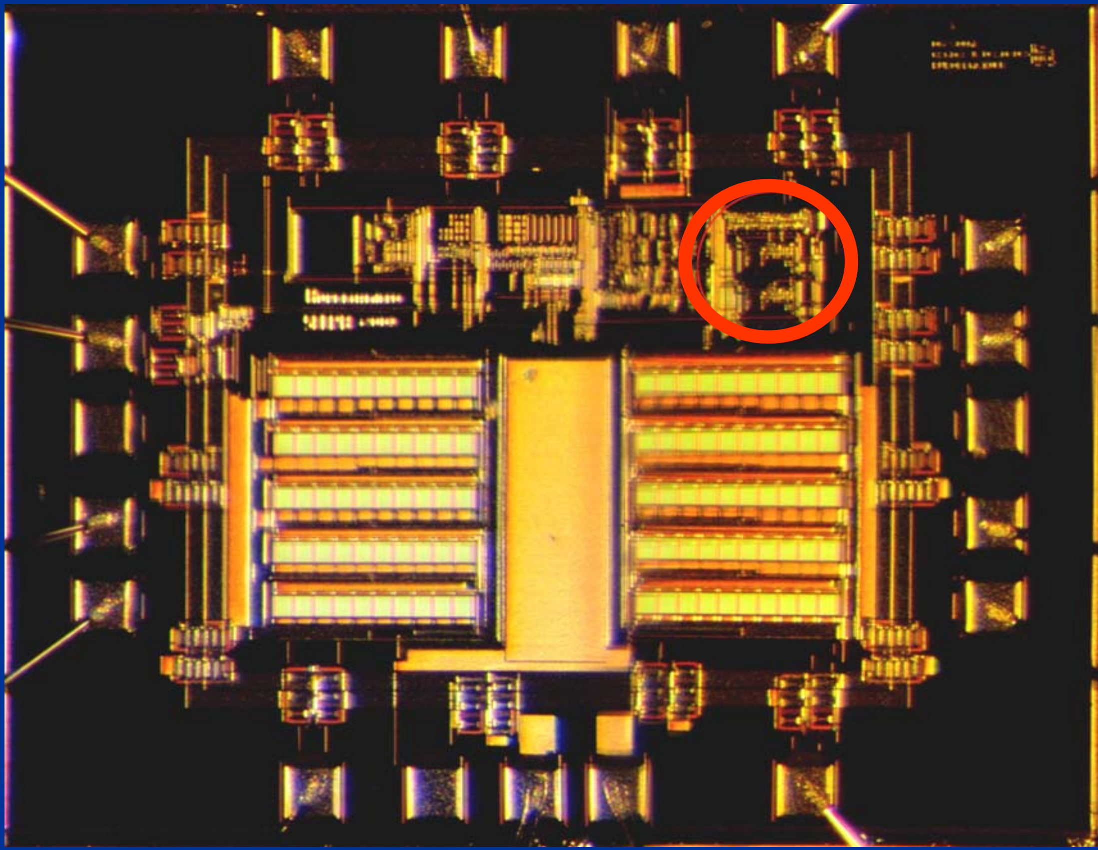
Device Under Test: SELP - CAEN

- At the coordinates [um]: $(X_0,Y_0)=(600,400-500)$ with a tollerance of ±50um,

Using our Laser Test System, **we discovered an area in which some flip-flops, stimulated by the laser have changed their logical state, causing a SEU.**

↓

SEE is detected



Advantages and Limitations of Laser Technique

- Advantages of pulsed laser system
  - **Spatial information**
  - Non-destructive
  - Temporal information
    - **Synchronization** to the circuit clocks hence SEE can be measured as a function of timing (logic circuits are sensitive to the arrival of laser pulse during circuit clock rising and falling edges)
  - Fast test for radiation hardness assurance (it is ok even if laser and HI do NOT give the same LET thresholds)
  - **Convenience**
    - Cost
    - Time

- Limitations of laser technique
  - **No absolute measure** of SEE threshold
  - No direct measure of the Asymptotic Cross-Section
  - **Inability of light to penetrate metal**

Progresses (2001-2004)

- Patent published (num. ITRM20020382 on 16/01/2004),
- Presented on the stand of INFN in COPIT (Comitato Parlamentare Technologie Innovative), Roma, May 2003,
- ASI-Universita'-Aurelia Microelettronica contract in the **"Programma di Trasferimento Tecnologico dal / nel settore spaziale" WP3.2, is successfully completed.**

Conclusions and Future Plans

- Extension of the system for use of laser sources with different wavelengths (performance test of detector systems),
- Backside testing (DUT back-side trimming) in collaboration with Thales,France,
- Complete the Labview package for a user friendly utilization of setup both for SEE sensitivity mapping and cross-section testing,
- Industrialization of the system