Radiation Damage in Satellites, Why, What is and How to characterize at Tandar

Tandem Argentino

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Outline of this talk

- Why it happens.
  - Space Weather
- What it is.
  - Physic of Ion-solid interaction
  - Effect on semiconductor devices
- How to characterize it at Tandar.

Space the final frontier

The harsh environment of The Final Frontier

Characteristic

- Vacuum
- Residual atmosphere
- Microgravity
- Magnetic field
- Ionized particles

How affect a satellite

Ionized particles

- Low energy
  - Charge effect on insulators
    - Connected to degassing materials could originated destructive sparks.
- High energy
  - Van Allen Belts
  - Solar ejections
  - Cosmic rays

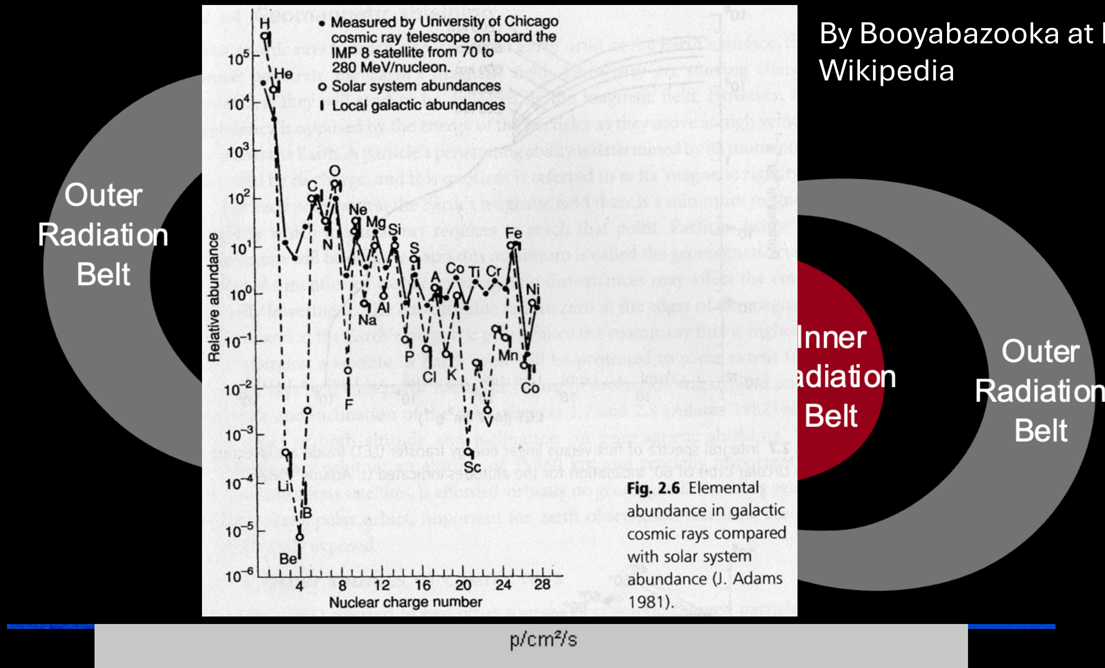


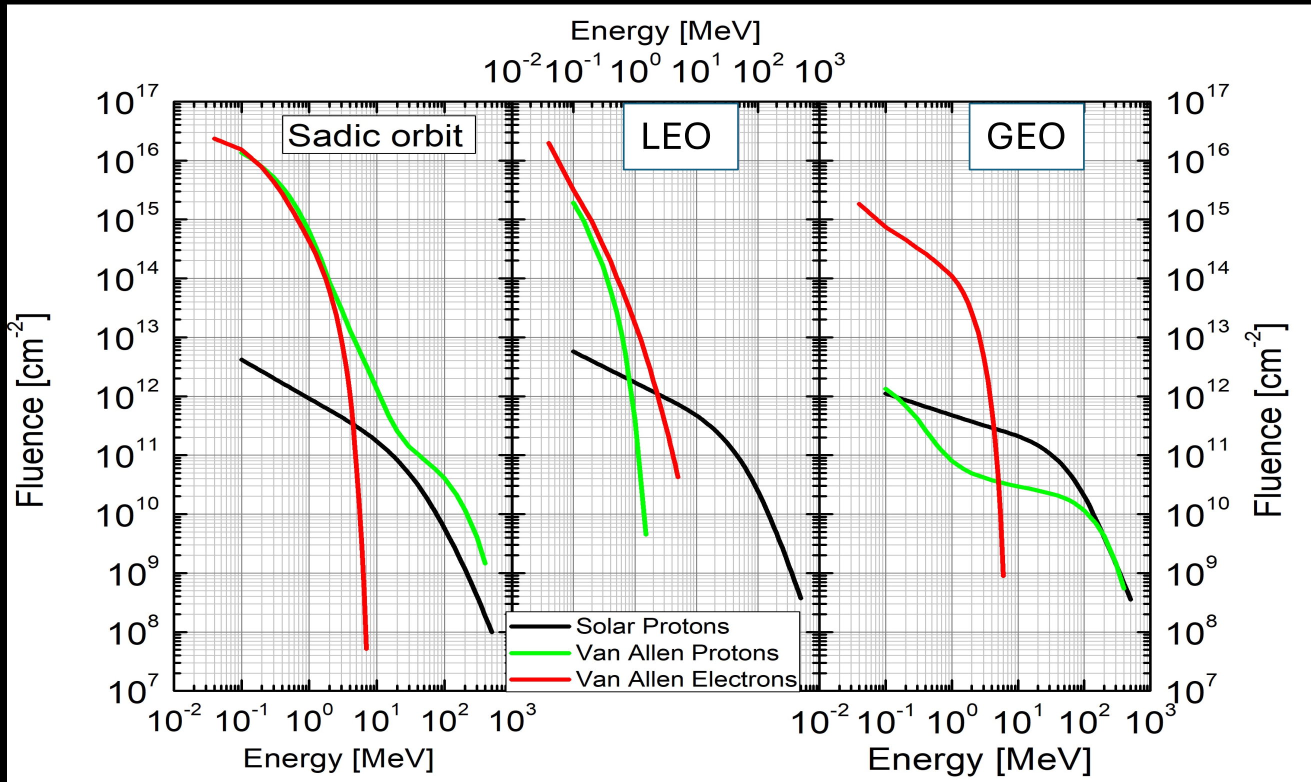
Fig. 2.6 Elemental abundance in galactic cosmic rays compared with solar system abundance (J. Adams 1981).

By Booyabazooka at English Wikipedia

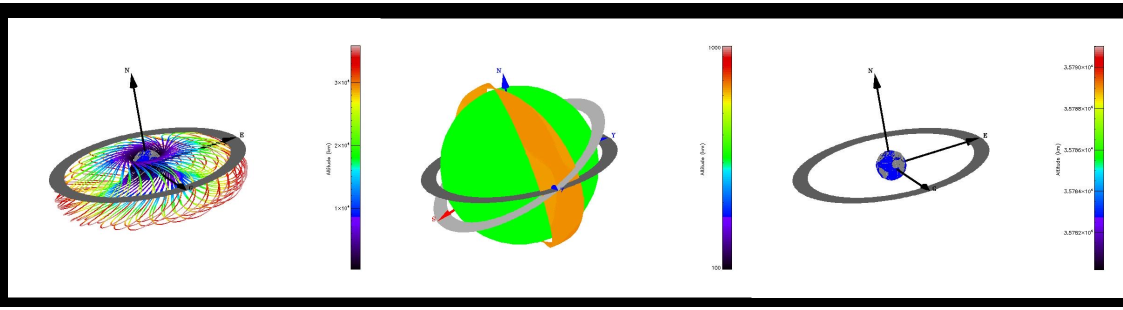
The relevance of orbits

The sadic orbit is elliptic and is designed to maximize the time in the Van Allen belts.

The other orbits are an heliosicronous (LEO) and geosincronous (GEO).



View of the orbits



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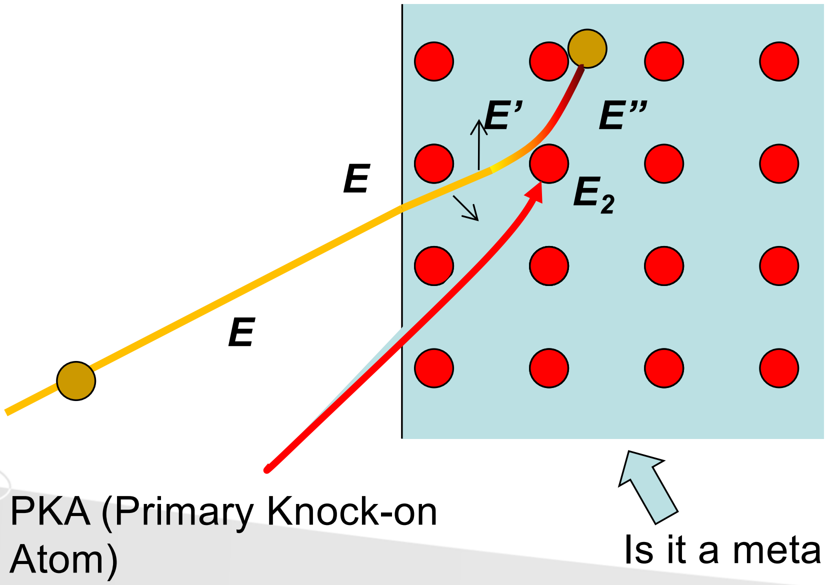
Some remarks

- Dose: Energy deposited by unit of mass.
  - Units:
    - Gray (Gy): 1Gy=1 J/kg
    - Rad (rad): 1rad=100 erg/g
    - Note: 1Gy=100 rad.
- Displacement Per Atom (DPA): Number of displacement for each atom of the target.
  - Unit: Dimensionless (expressed as a number, e.g., 0.1 DPA, 1 DPA, etc.).
- Fluence (Φ): Number of projectiles that cross a Surface perpendicular to the beam during the irradiation.
  - Unit: particles/cm^2.
- For charge particles: $\rho_1 R_1 \approx Ct.$, ρ_1 is density and is R_1 range.

Brief description of ion matter interaction



$$E_{PKA} = \frac{4M_i\ M_t}{(M_i + M_t)^2} E' \cos^2(\theta)$$

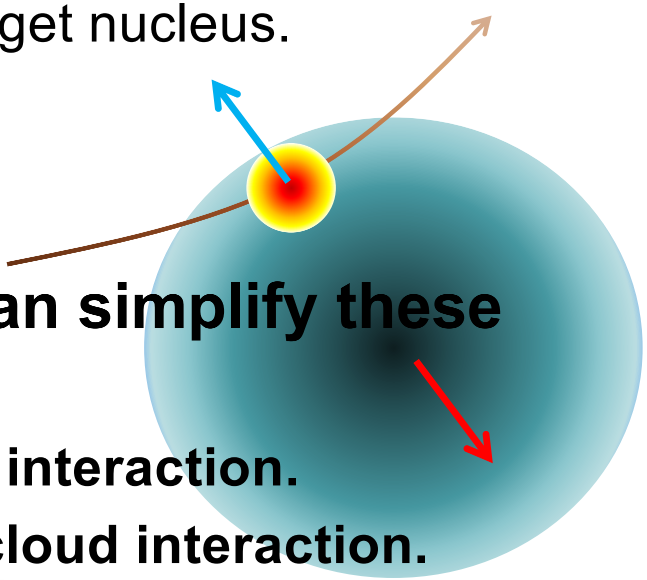
$$M_i = M_t \quad \Rightarrow \quad Máximum(E_{PKA})$$

Cross section [σ], is a measure of interaction probability.

Is it a metal or an insulator? The effect changes.

Taking a closer look

- Simultaneously the following interactions occur:
  - Electron cloud of the ion - electron cloud of the target.
  - Ion nucleus - electron cloud of the target.
  - Electron cloud of the ion - target nucleus.
  - Ion nucleus - target nucleus.



- **It is remarkable that we can simplify these interactions as:**
  - **Screened nucleus-nucleus interaction.**
  - **Incident nucleus-electron cloud interaction.**

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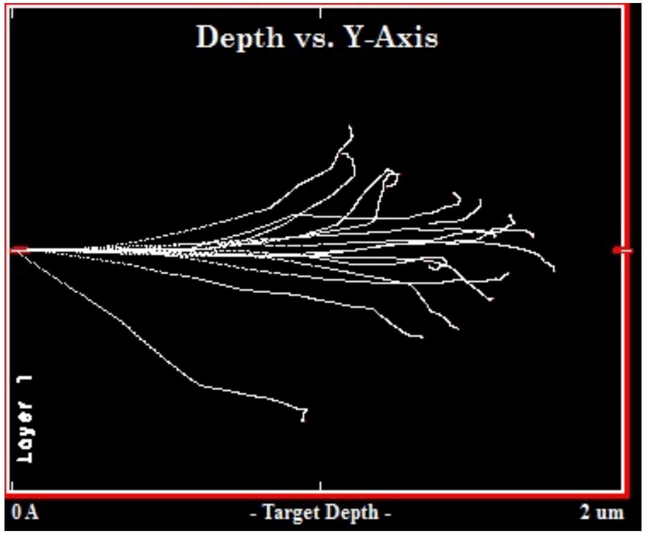
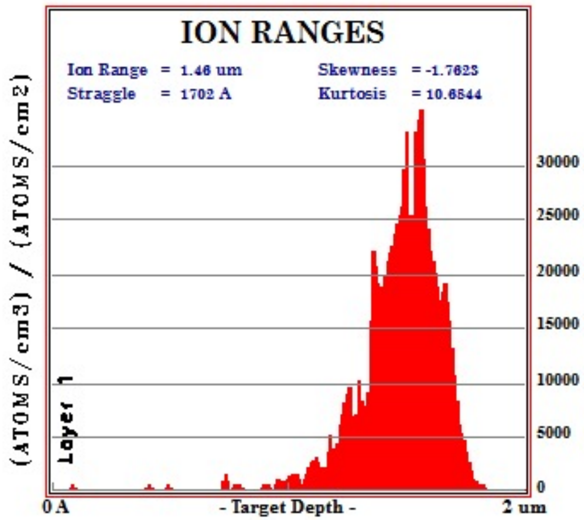
What happens to ions during irradiation?

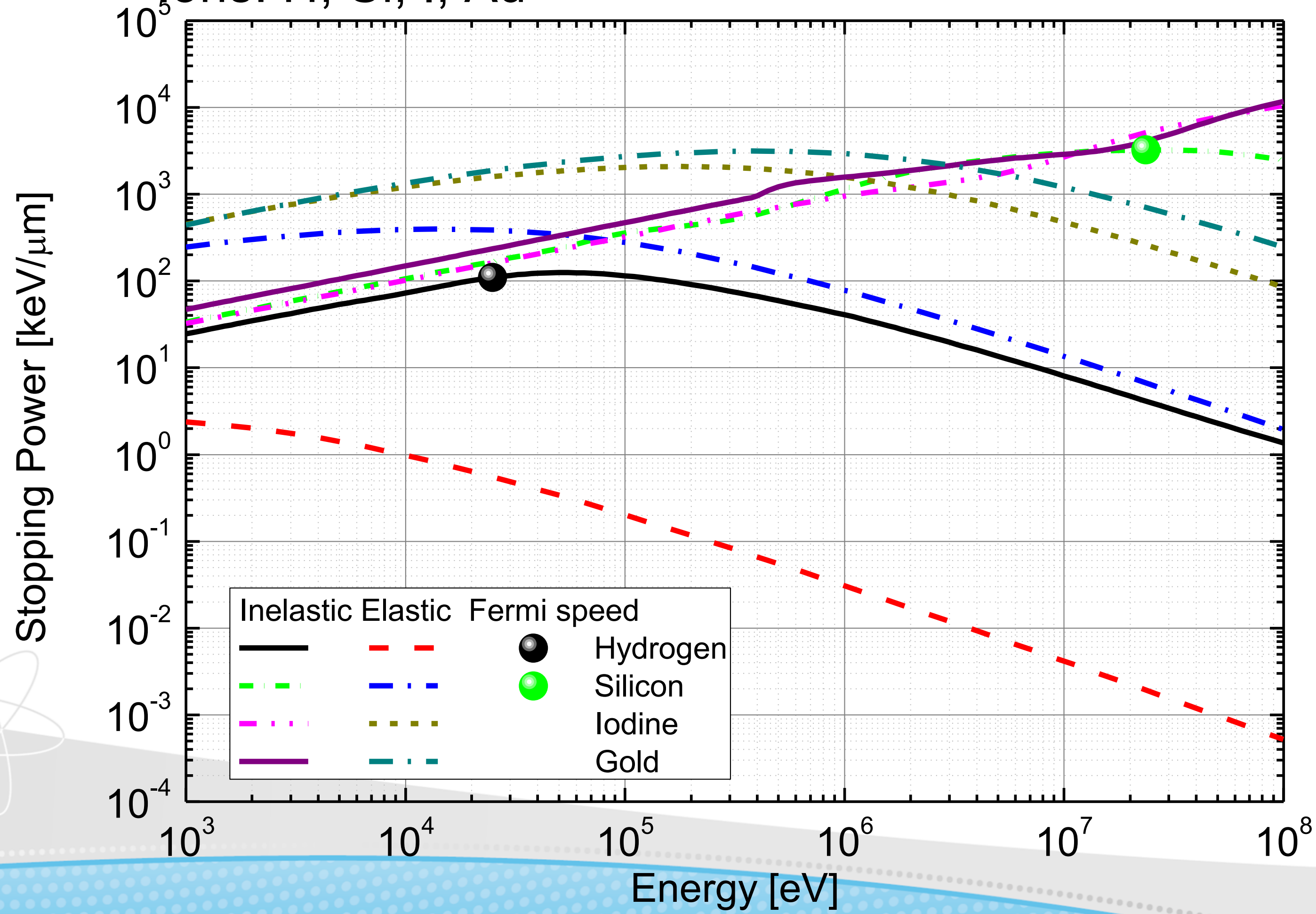
- 1000 oxygen atoms of 1 MeV in silicon.



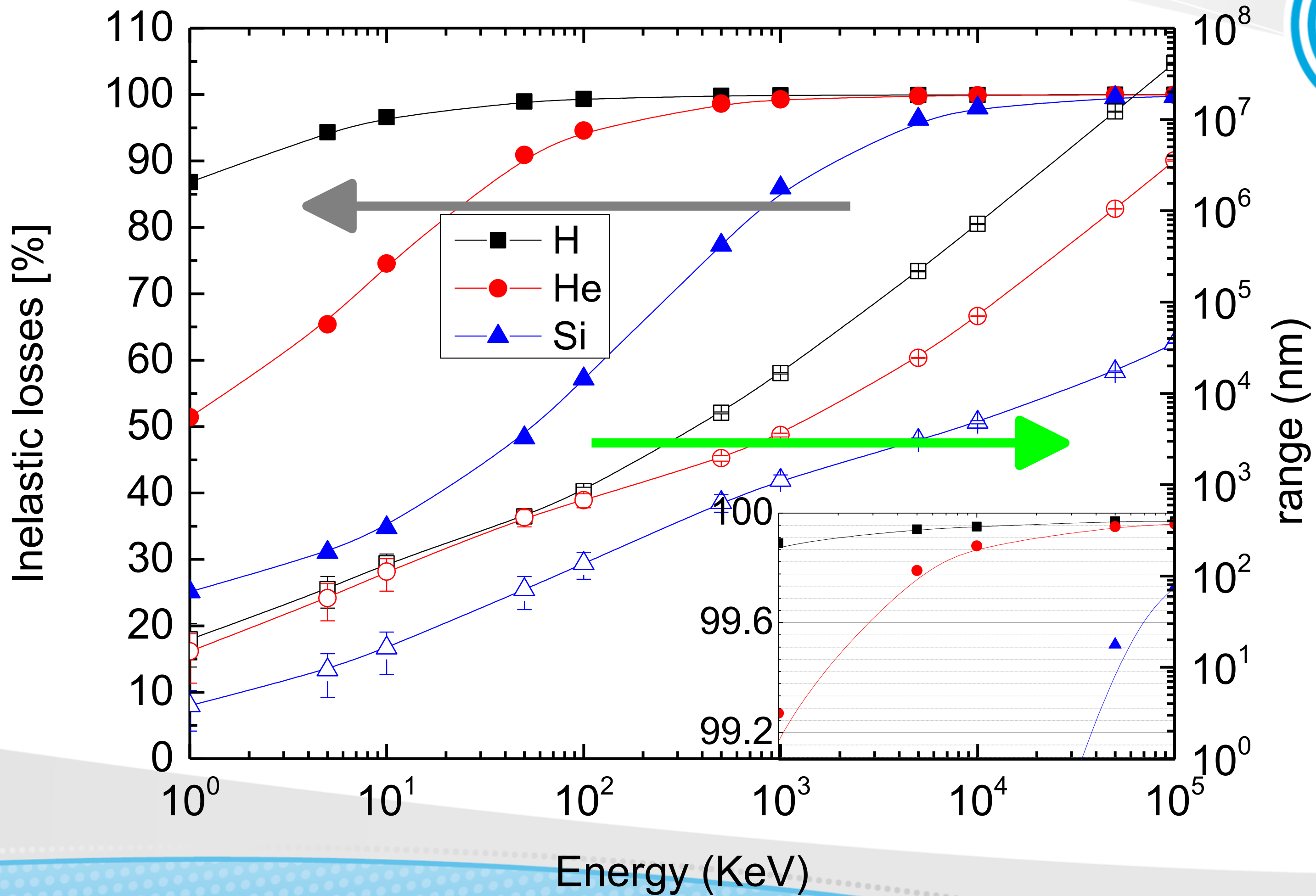


Stopping power in silicon

- Ions: H, Si, I, Au

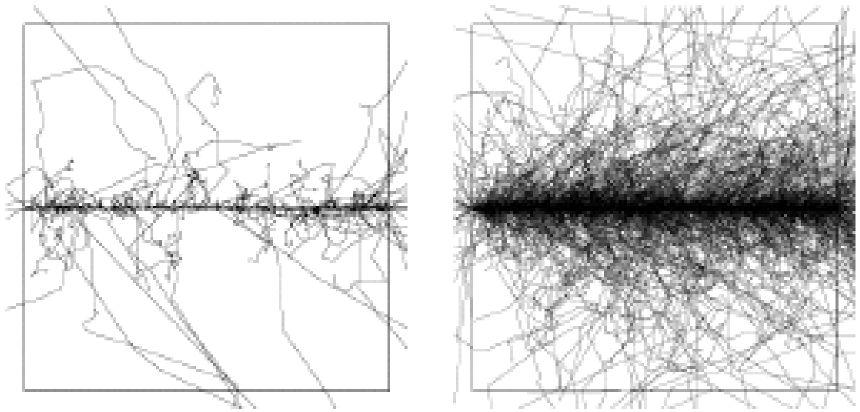


Inelastic losses in Silicon



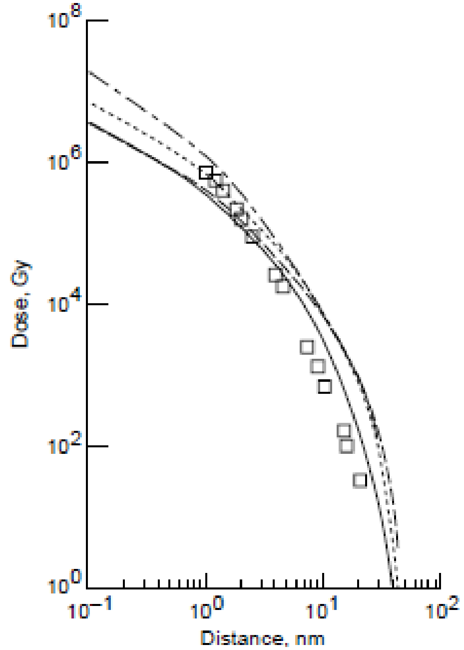
Heavy Ions dosimetry

- An important remark:
  - The damage is concentrated around its pathway.

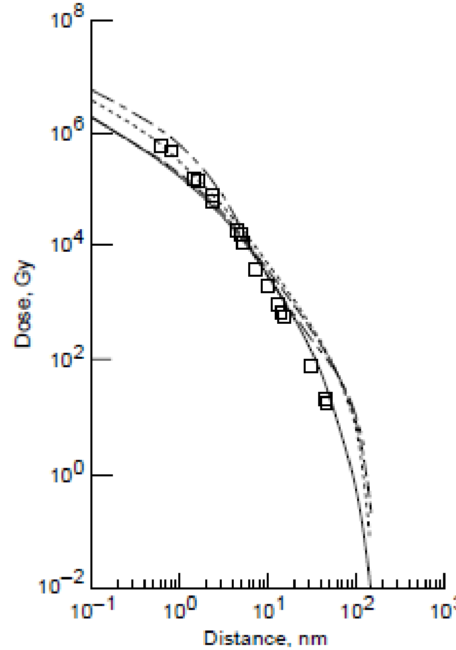


100 MeV Proton   100 MeV Alpha

Fig. 1. An example simulation 1000 events in a 6 μm silicon cube. The simulation results including all secondary particles for 100 MeV protons are depicted on the left and for 100 MeV α particles on the right. Most significant are the large number of δ electrons surrounding the track. The greater ionization of the α particles is obvious in the density of these secondary particles.



(c) For 0.25 MeV/amu ^{4}He ion.



(d) For 0.75 MeV/amu ^{4}He ion.

Heavy Ion Track-Structure Calculations for Radial Dose in Arbitrary Materials

Francis A. Cucinotta, Robert Katz, John W. Wilson, and Rajendra R. Dubey

Summarizing

- Electronic stopping power
  - From our perspective, it is responsible for the energy transfer to the electronic system. This energy can typically be converted into charge carriers.
- Nuclear Stopping power
  - It accounts for the fraction of energy transferred to the atoms in the lattice. This can result in Primary Knock-on Atoms (PKA) or secondary displaced atoms, leading to phenomena such as Wigner disease. A well-known model to describe this is the Kinchin-Pease model.

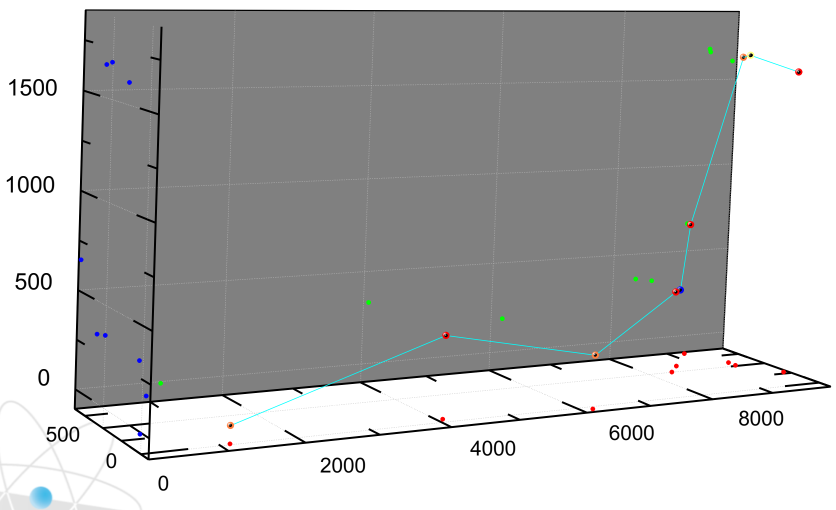
The Third field of Physics

Computer Simulations

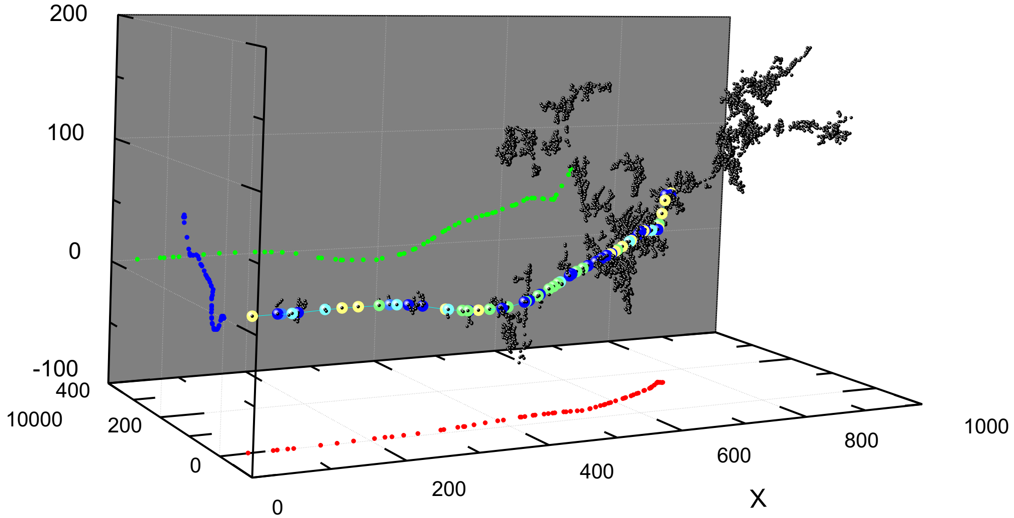
- Binary Collision Approximation
  - Computationally lightweight
  - **Only displacement cascade.**
  - Monte Carlo code
- Classical Molecular Dynamic
  - Computationally heavyweight
  - Models the entire cascade

Ions traveling through matter

H 200 KeV →Cu

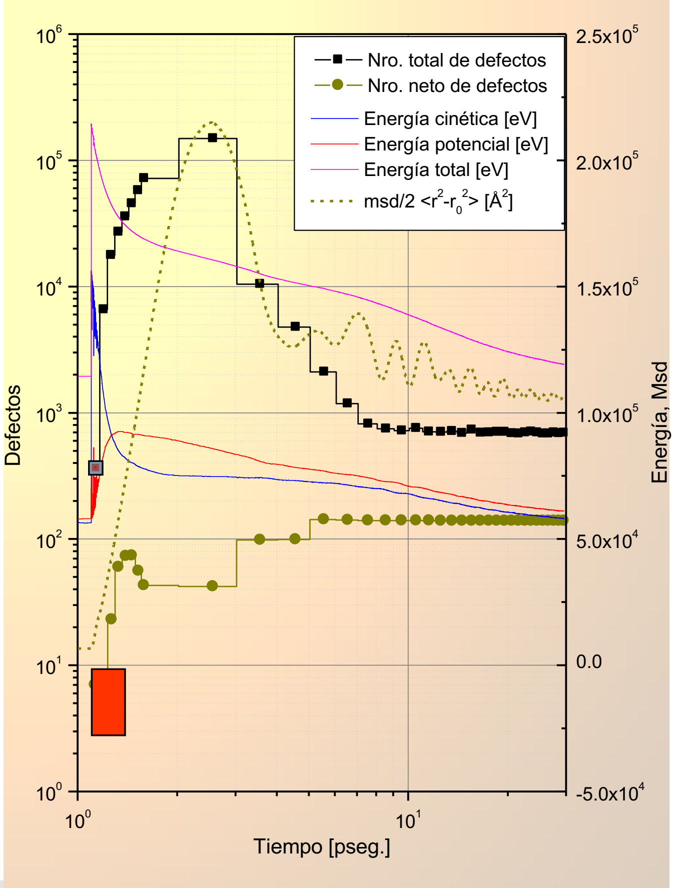


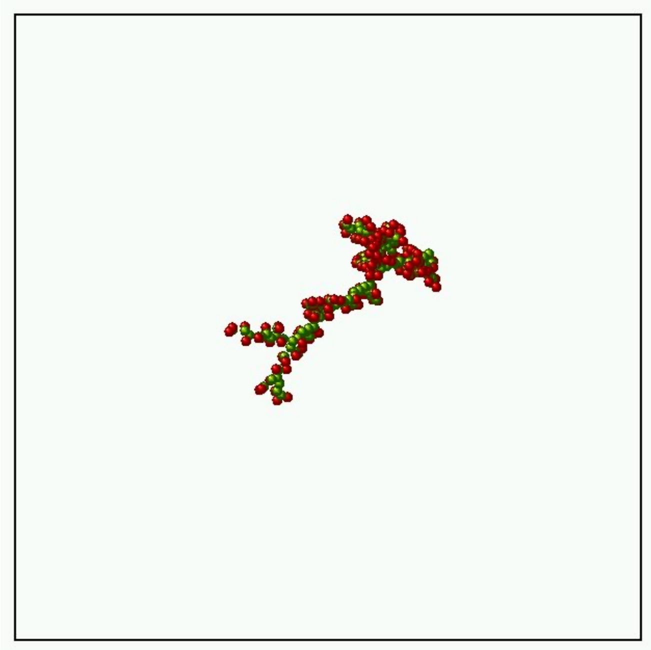
Cu 200 KeV →Cu



Binary collision Approximation

Fase Colisional





Intersticiales

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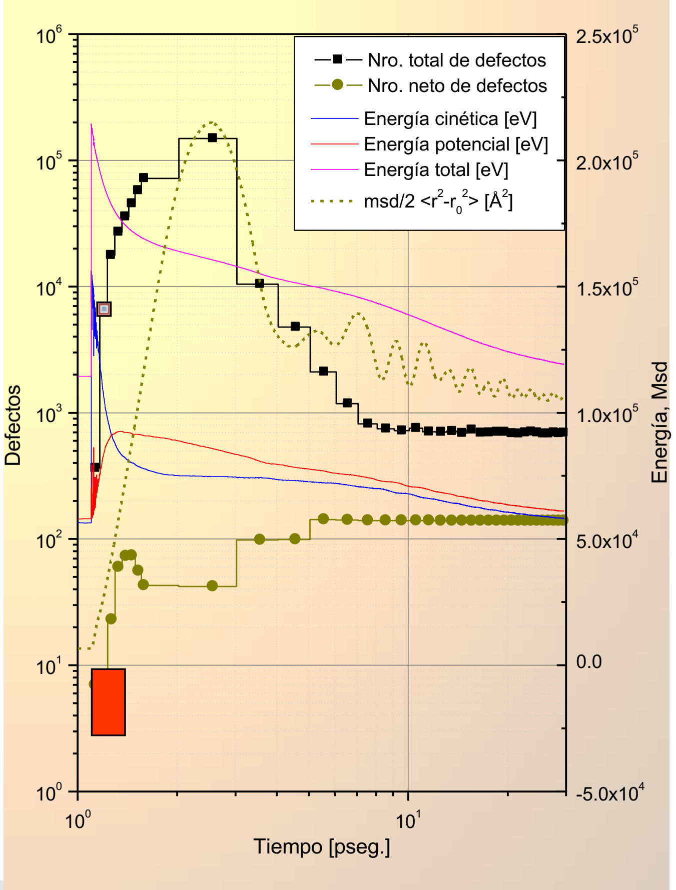
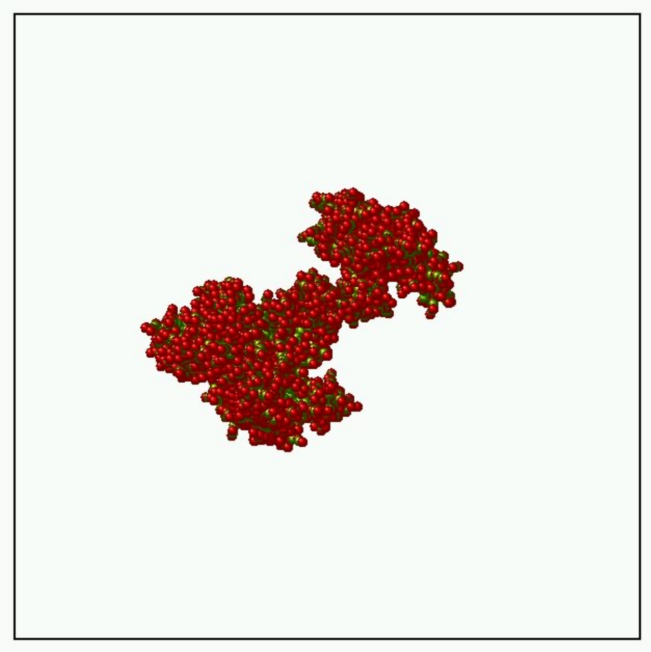
Molecular Dynamic Approximation

Fase Colisional





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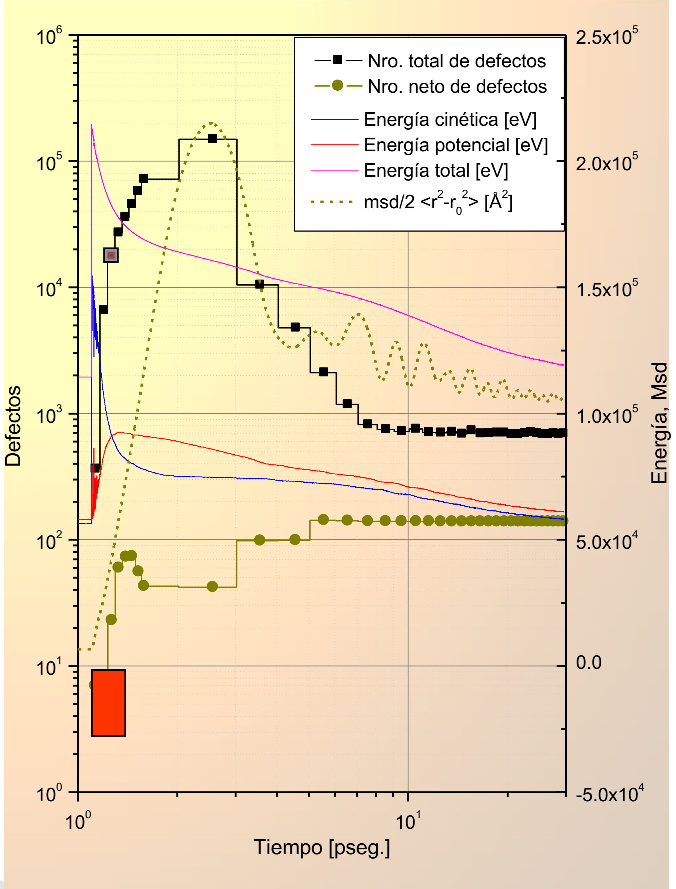

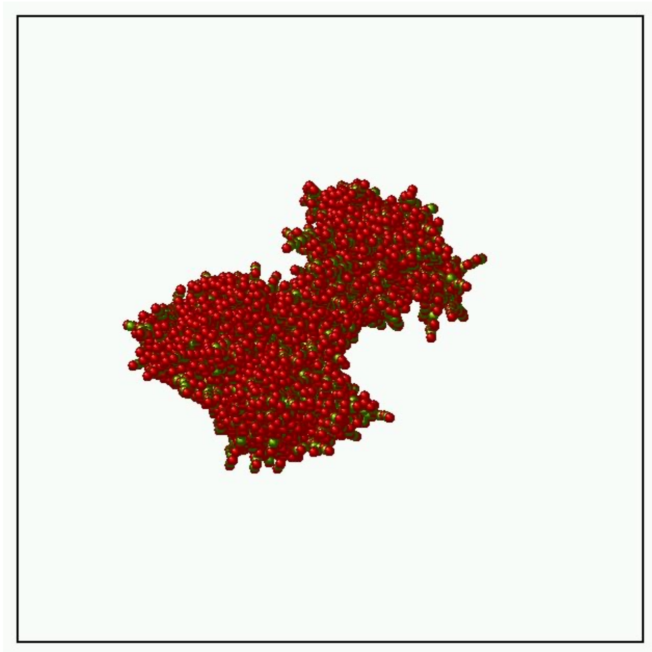

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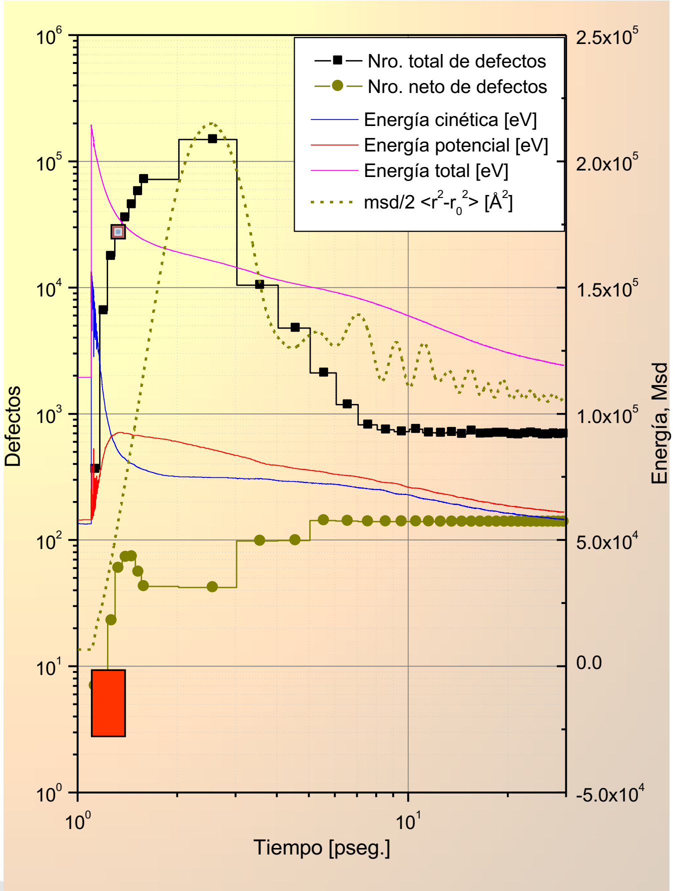

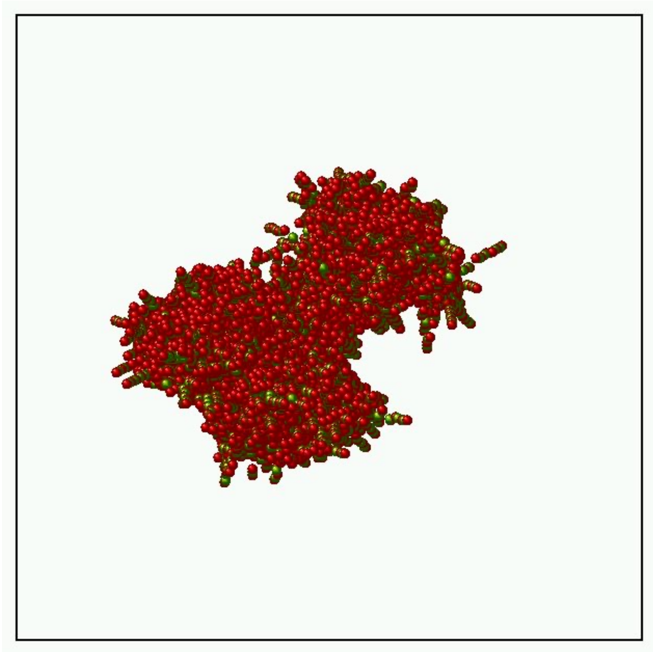

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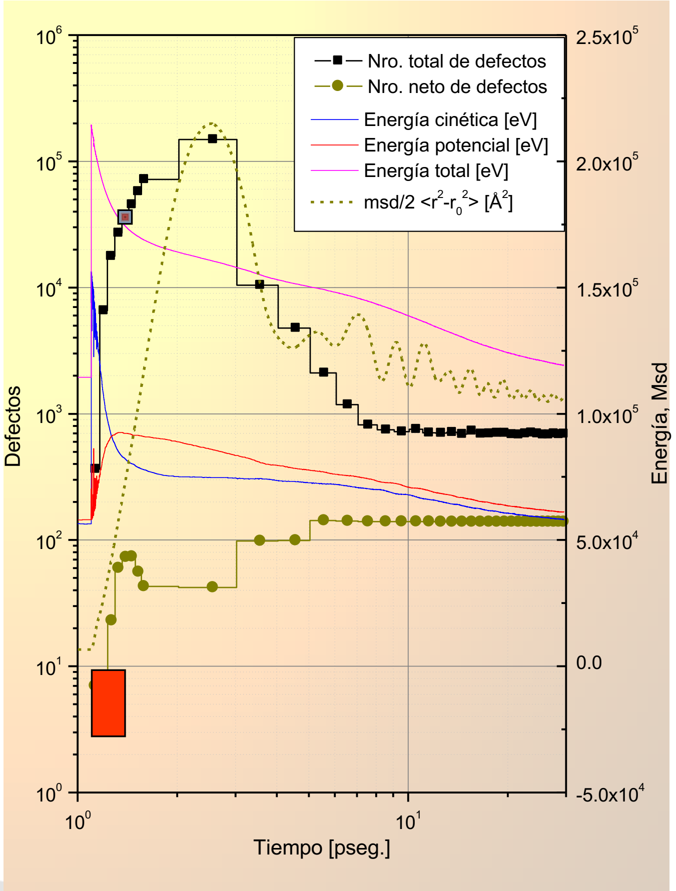

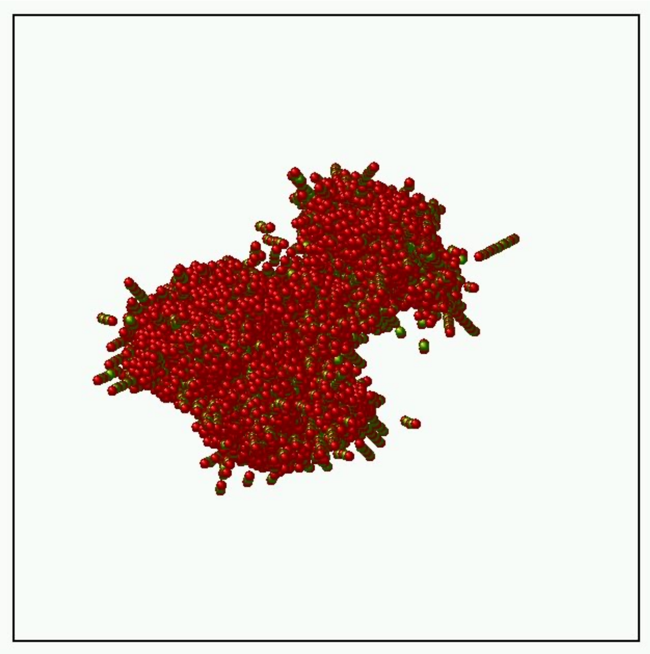

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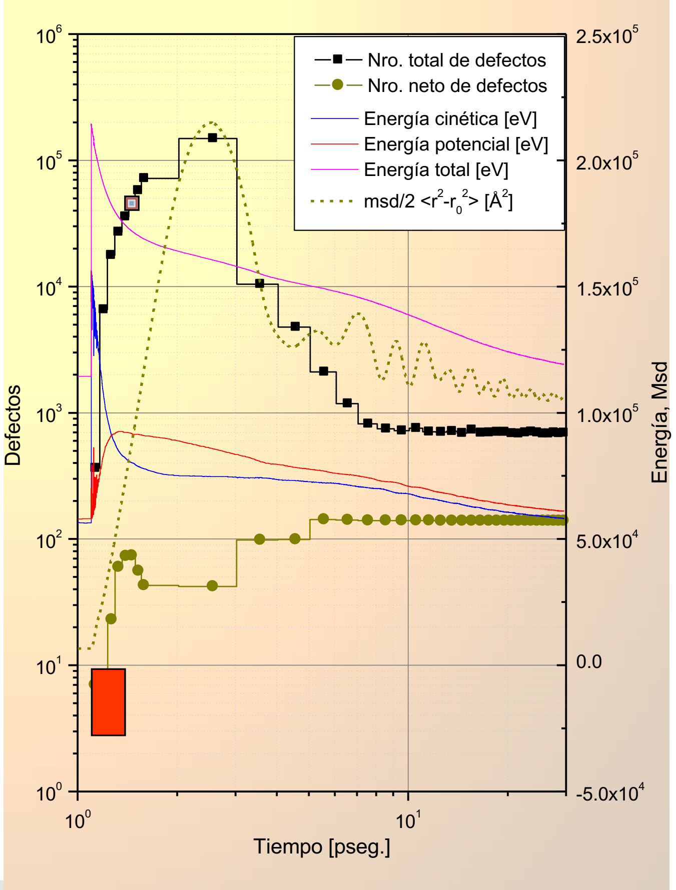

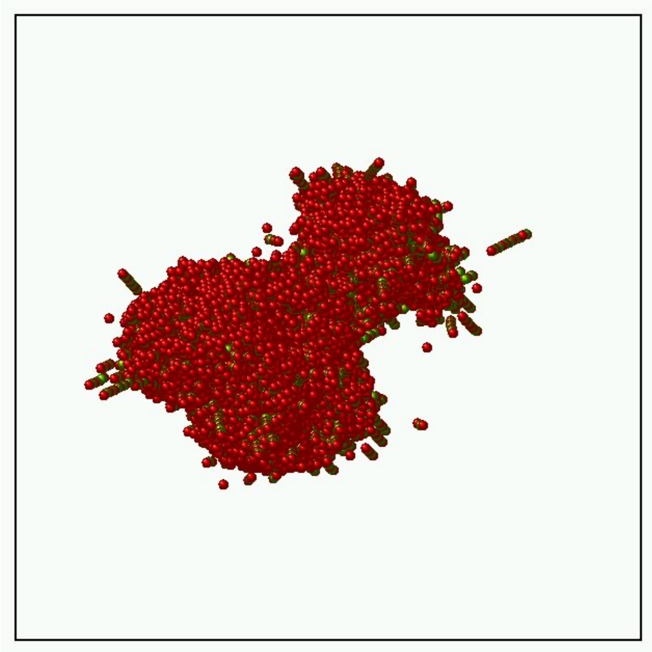

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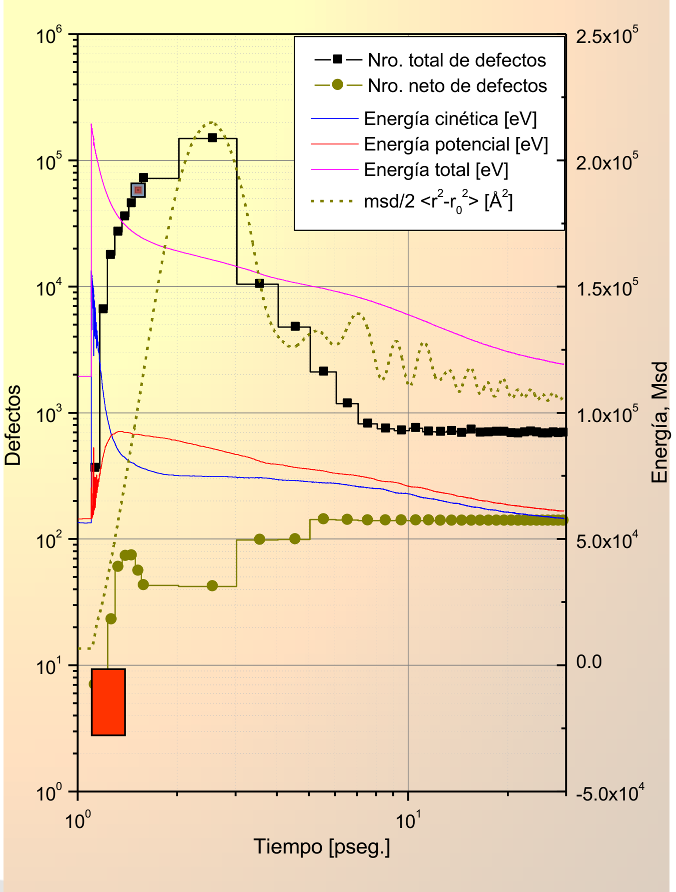

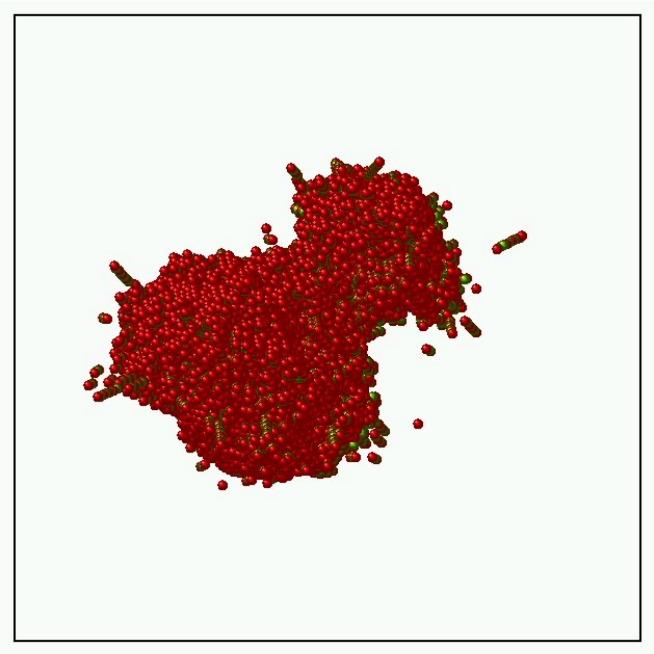

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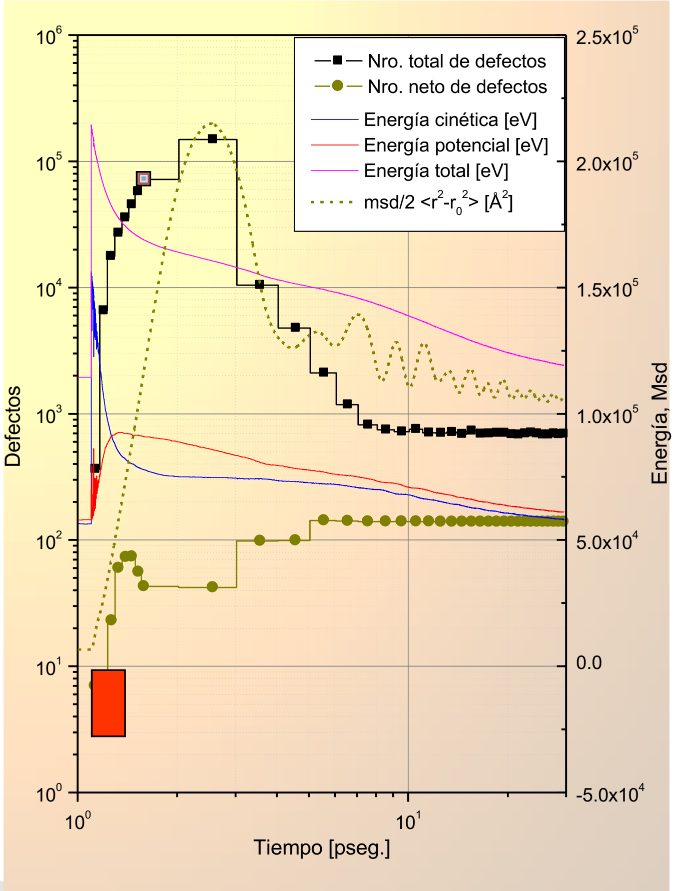

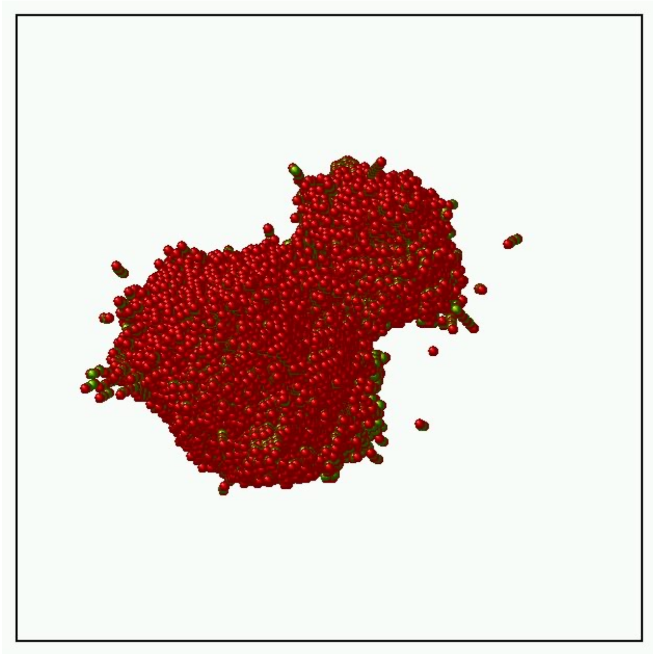

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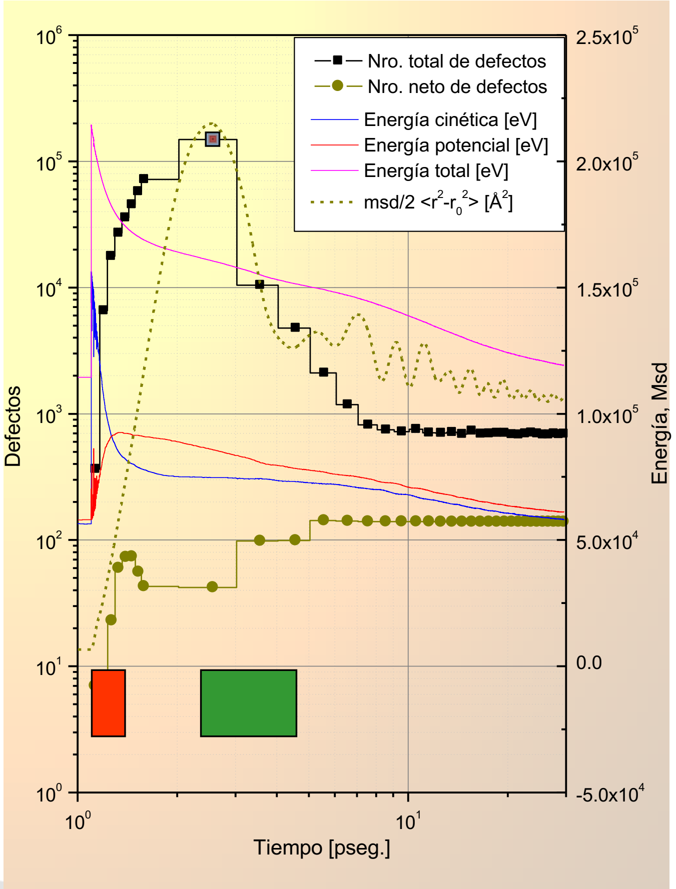
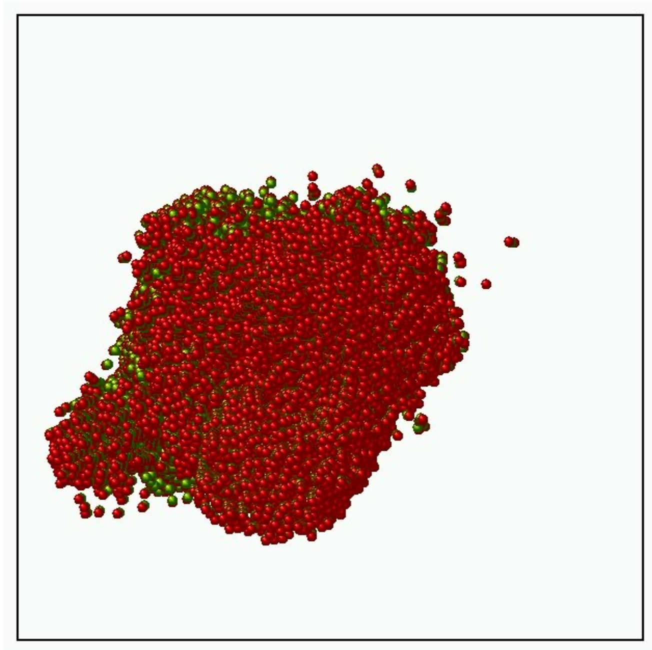
Fase de Relajación





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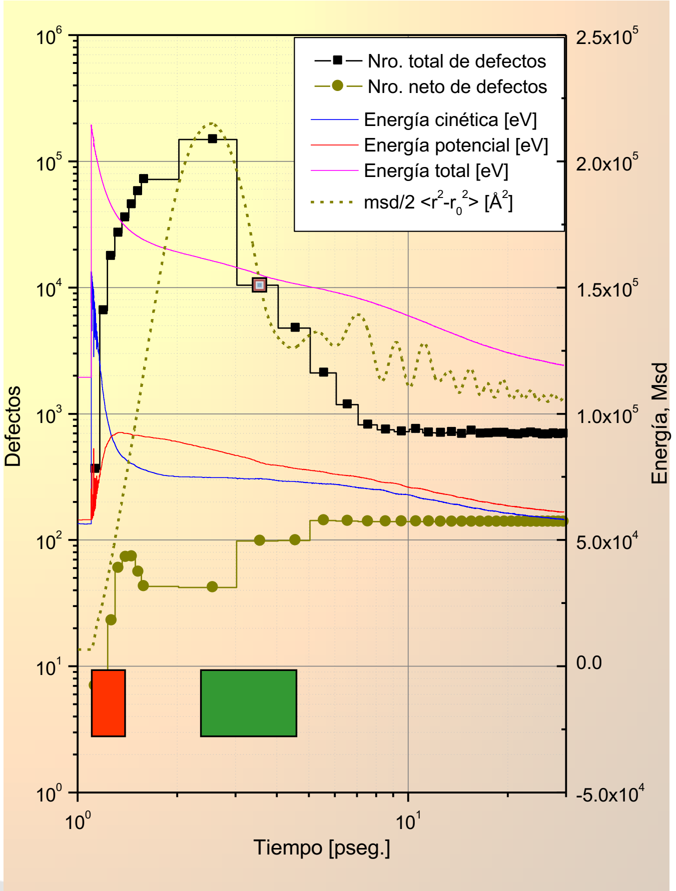

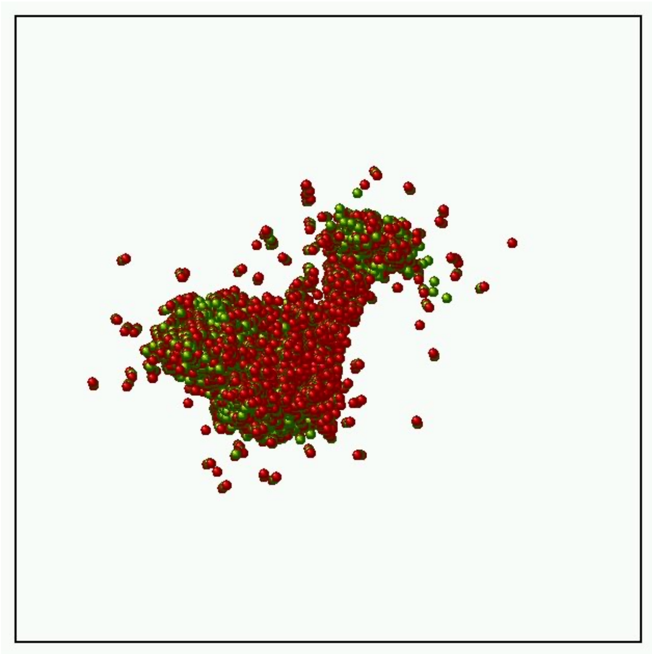

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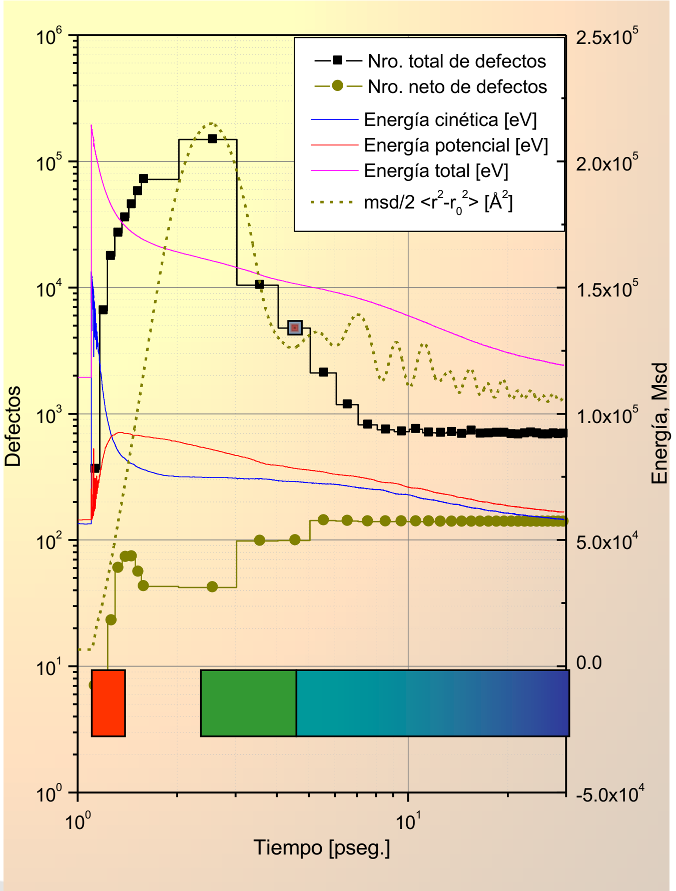
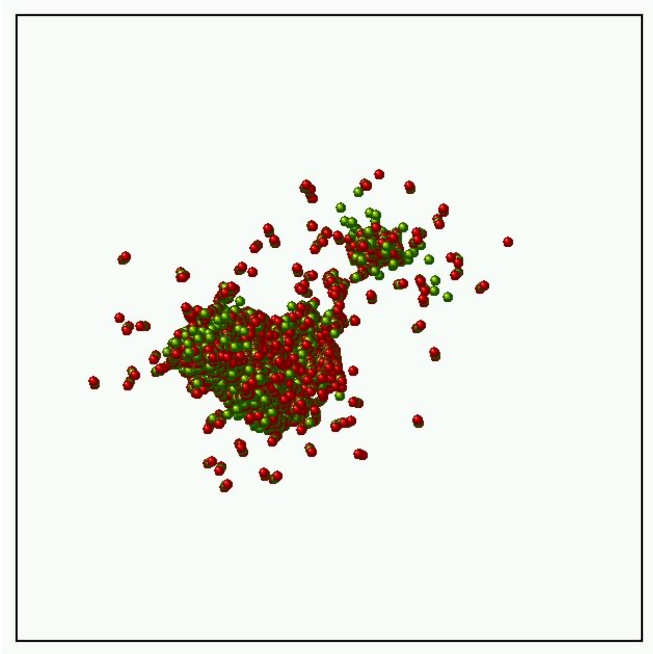
Fase de "Thermal Spike"





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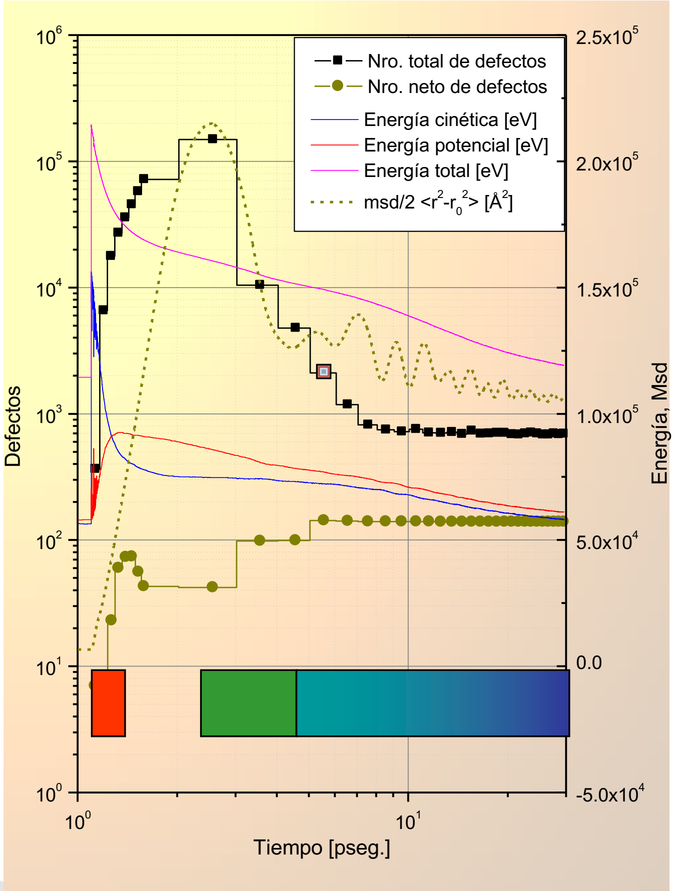

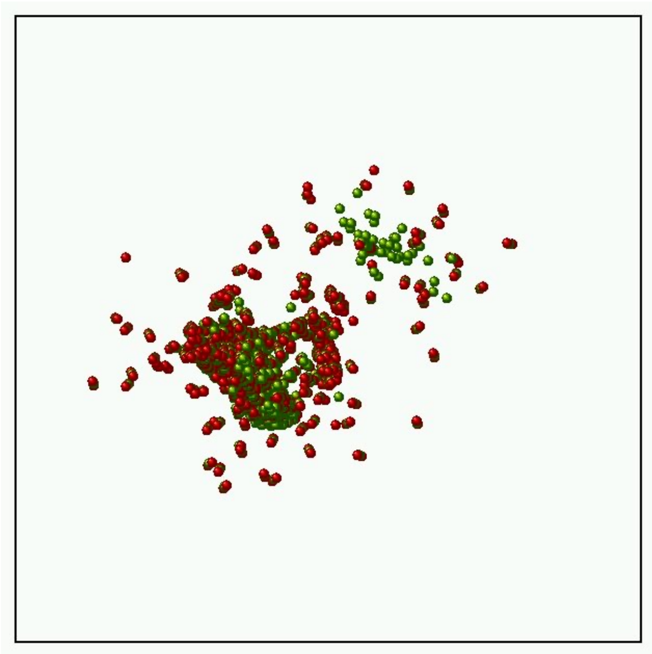

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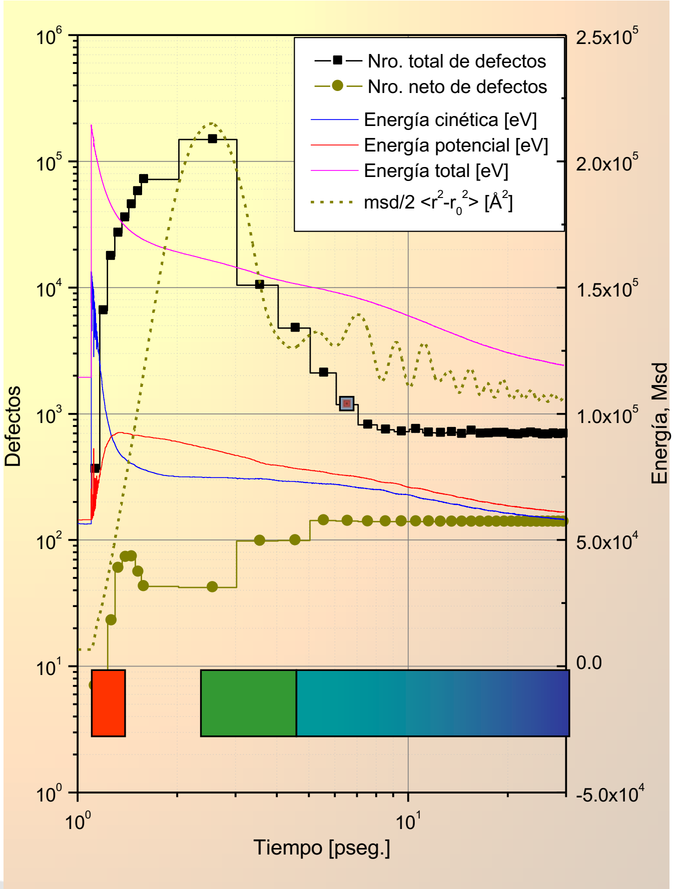

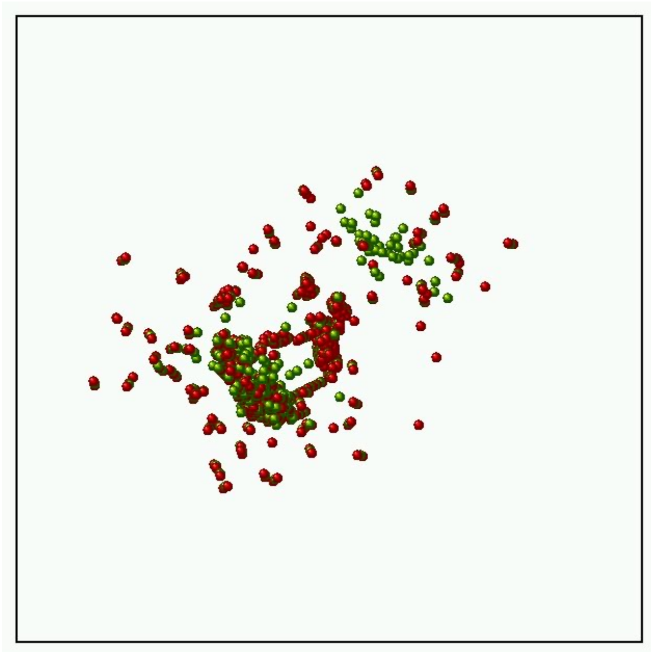

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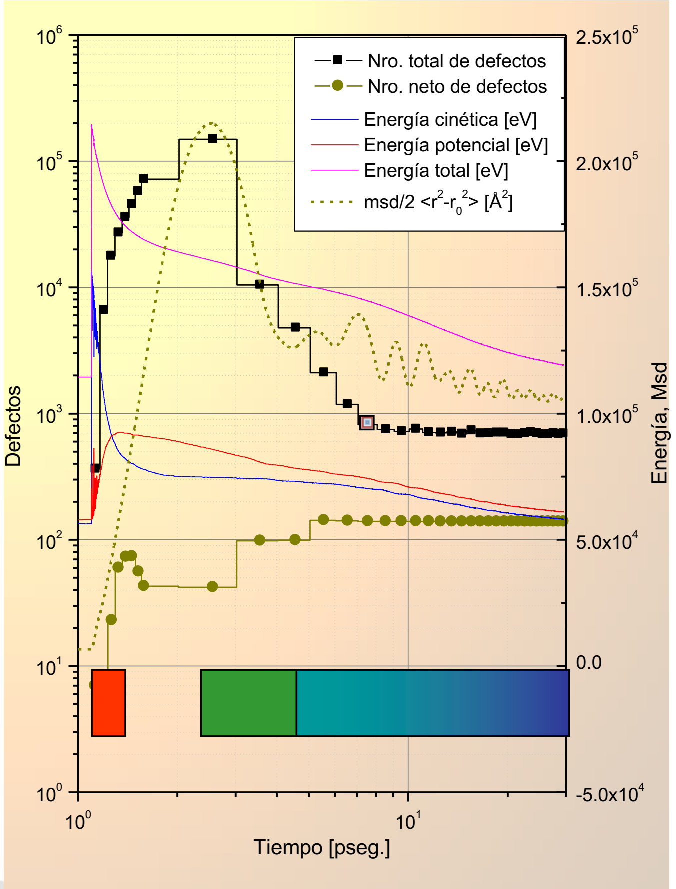

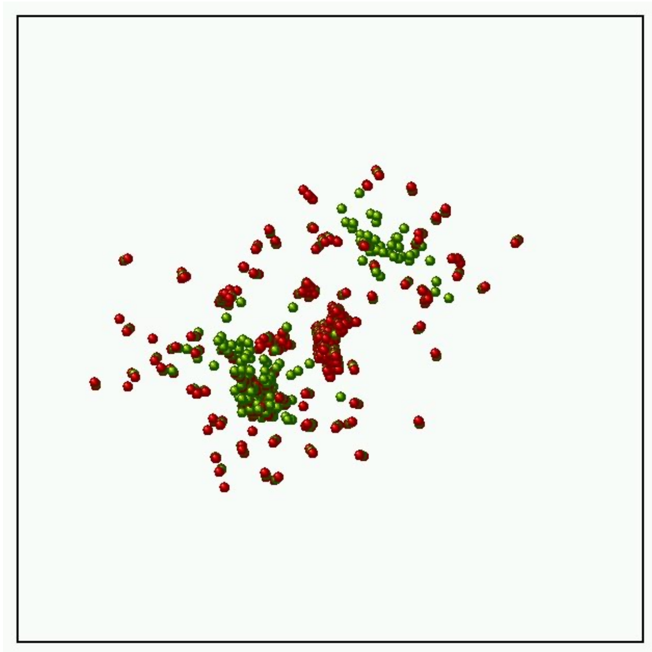

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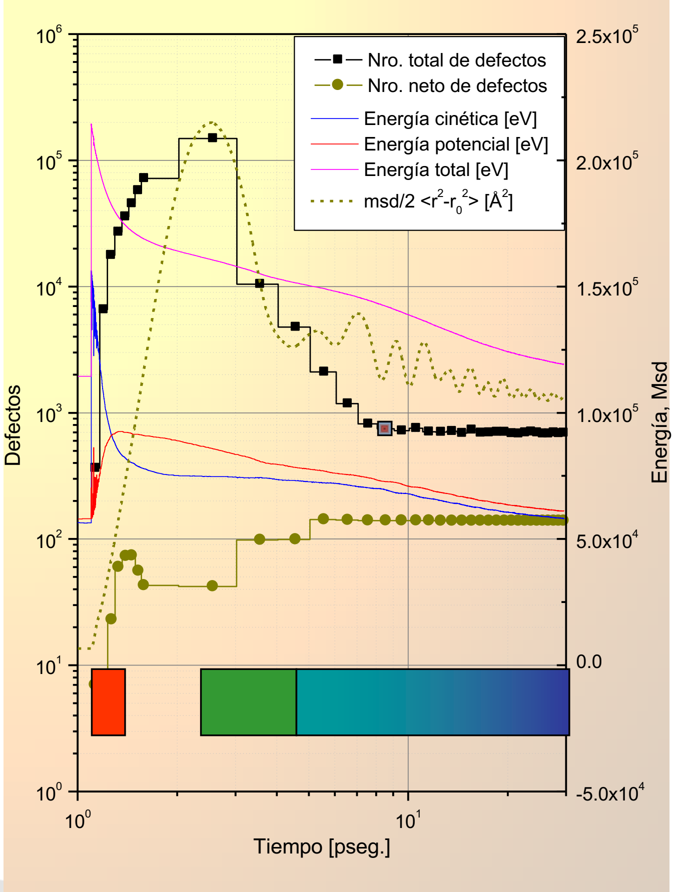

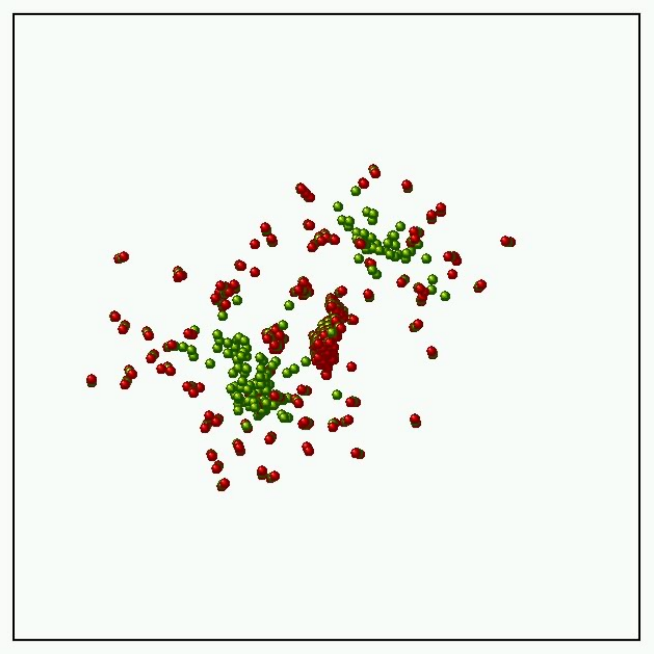

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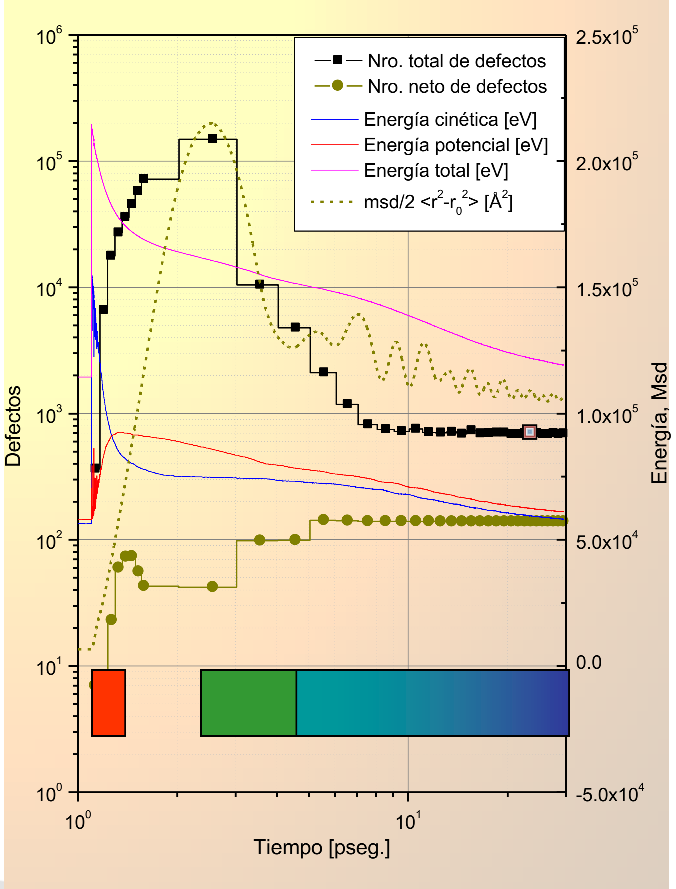

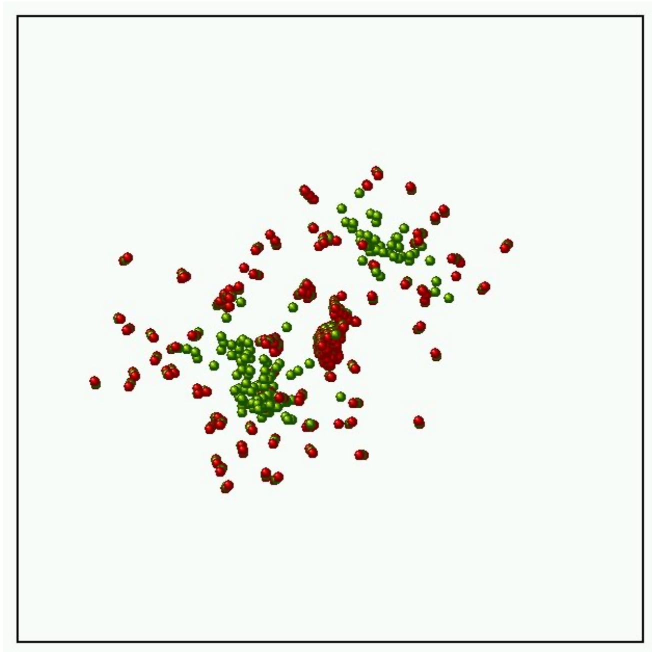

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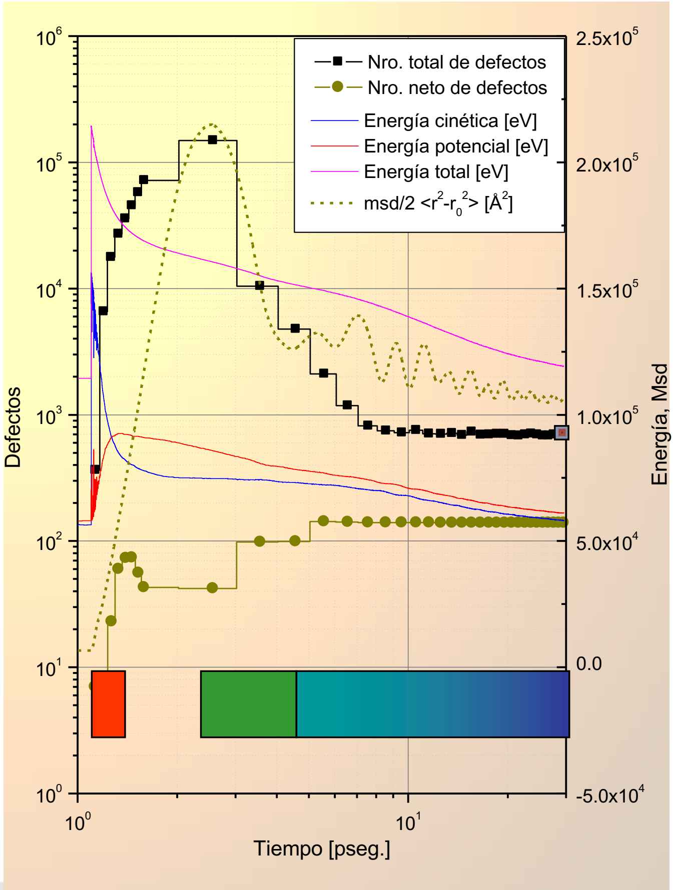
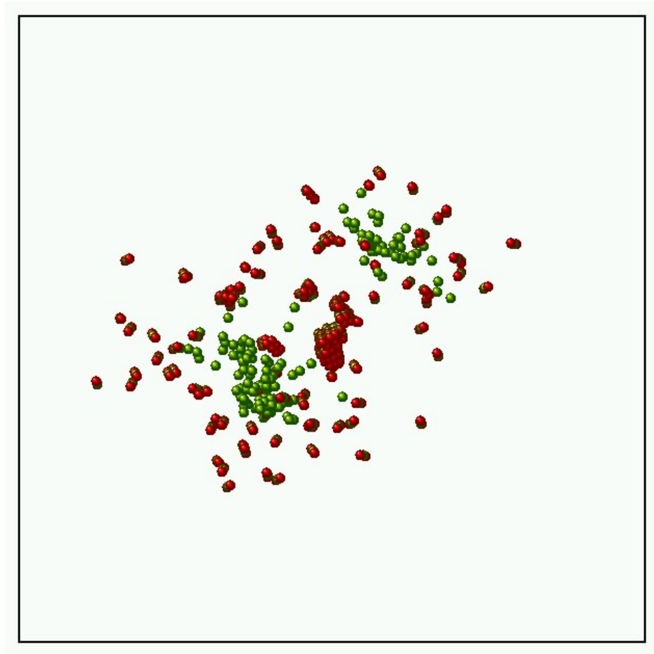
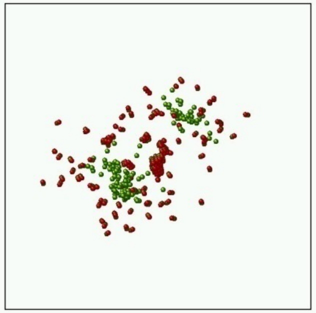




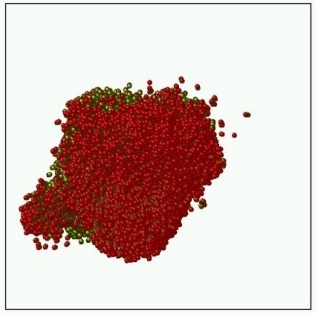
Intersticiales

Vacancias

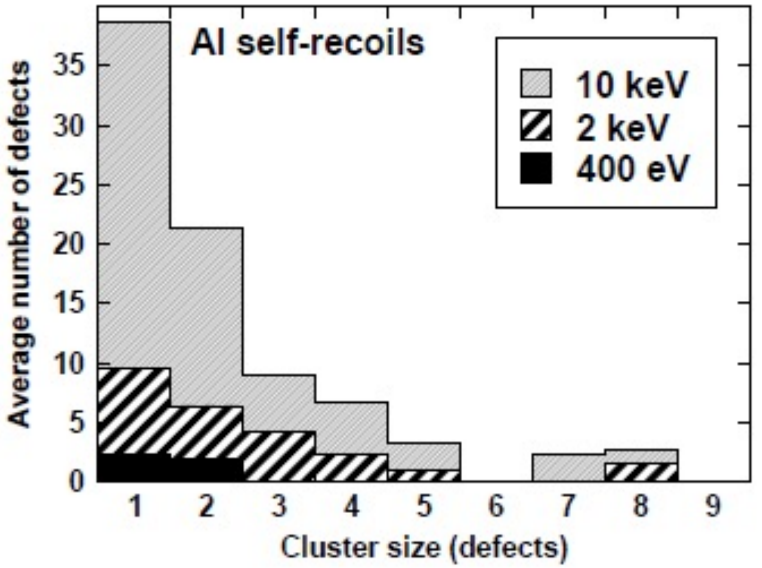
Molecular Dynamic Approximation

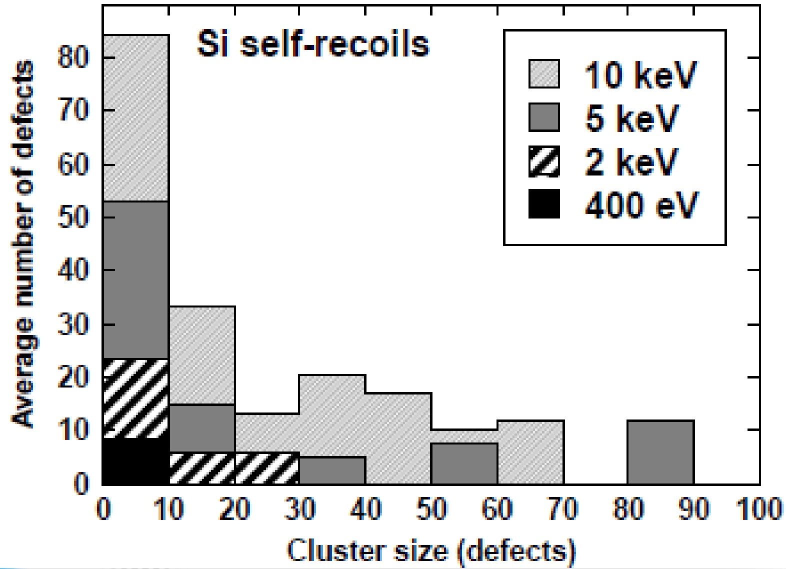


The exception: silicon



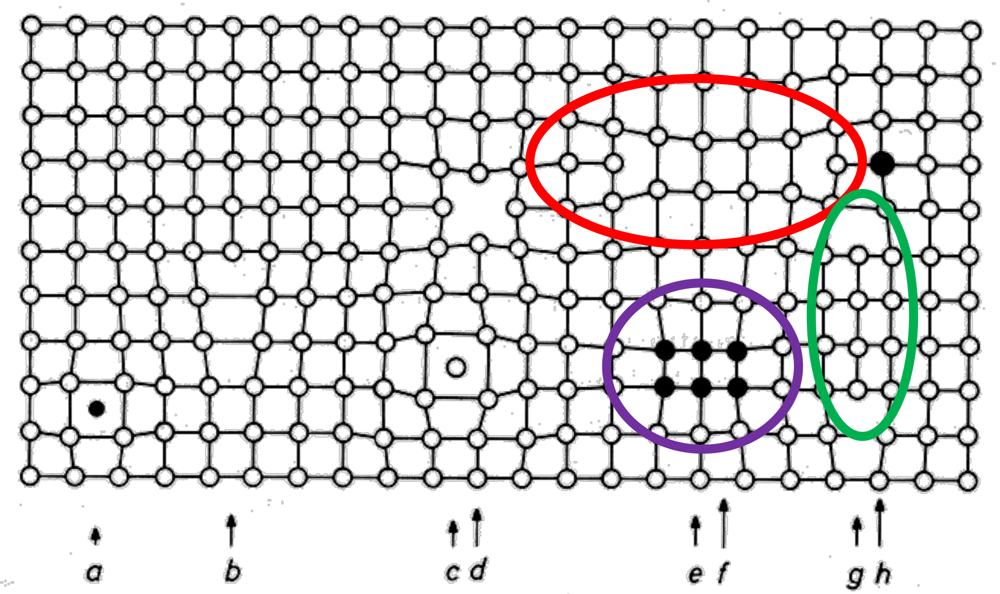
- Size distribution of defects clusters for Al and Si (From M.J. Caturla).





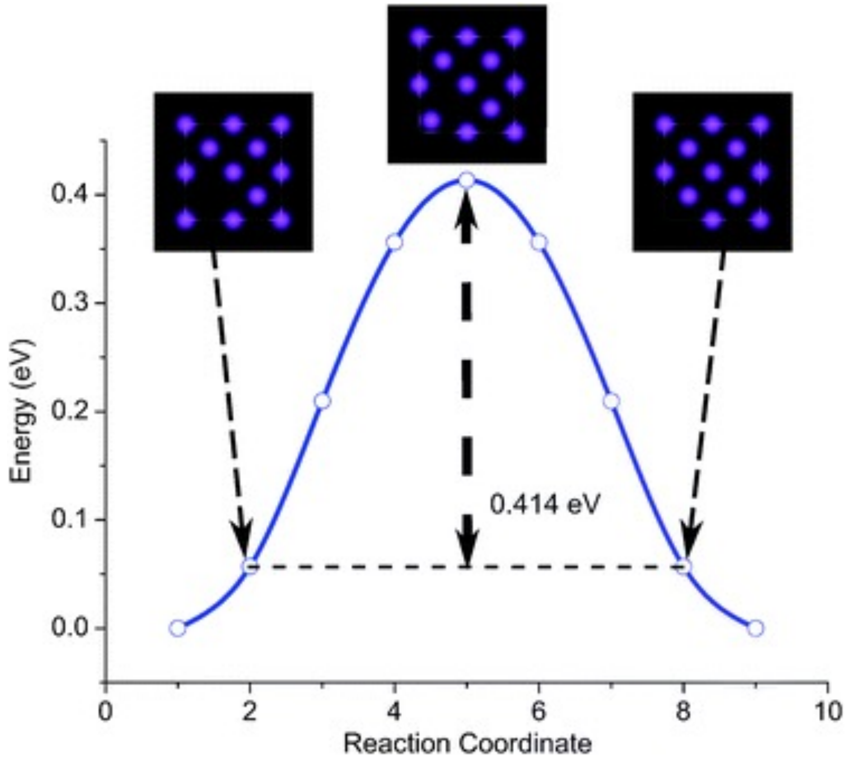
Defects

- Defect review
  a. Interstitial impurity
  b. Edge dislocation
  c. Interstitial
  d. Vacancy
  e. Vacancy Loop
  f. Precipitate
  g. Loop de intersticiales
  h. Substitutional impurity

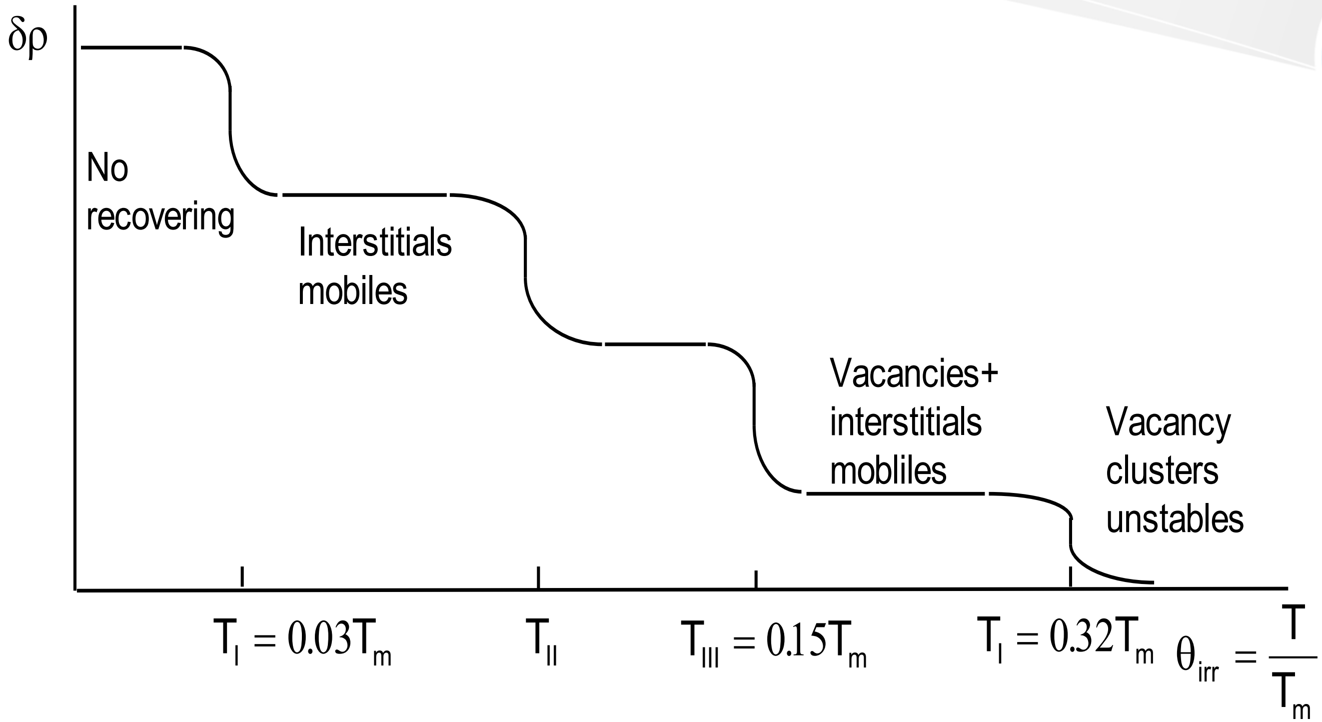


About defect movement (I)

- A simulation of a vacancy movement in Al.
- Observe the atom in the lower left corner.
- The highest point is the "saddle point".
- The energy required for atomic jumps is typically provided by thermal vibrations.



The secret life of defects



Isochronal Annealing: This process shows the different recovery stages of a typical material.


MAMBA
because it's going to happen to you.

Thank you
Questions?

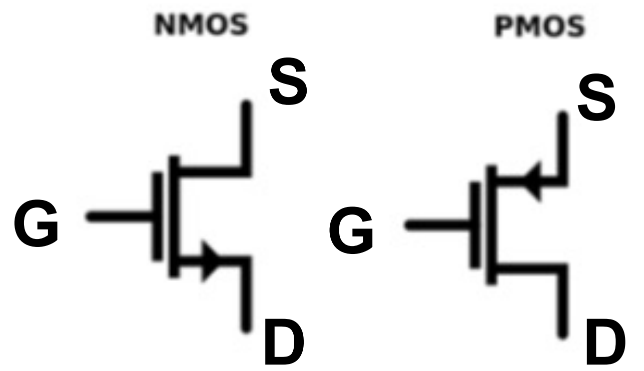
How is the effect on the devices?

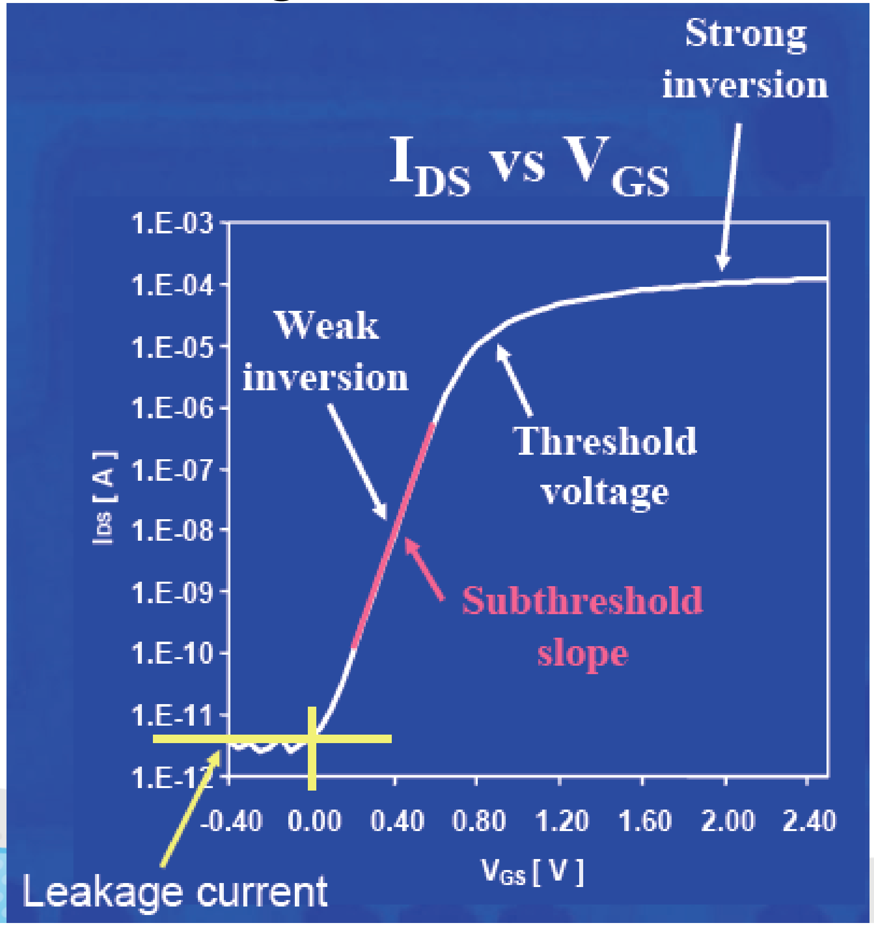
- **Advertisement**: This description is necessarily incomplete; new devices, geometries and materials emerge every day challenging our understanding of their effects.

Summarizing ion-solid interaction

- There are two effects on semiconductors devices produced by energetic ions
  - The Electronic stopping power
    - Charge accumulation at insulators. → **T**otal **I**onizing **D**ose (**TID**)
    - Charge injection in the device. → **S**ingle **E**vent **P**henomena (**SEP**)
  - The Nuclear Stopping power
    - Displacement cascades and consequent defect production. → **T**otal **N**on **I**onizing **D**ose (**TNID**)

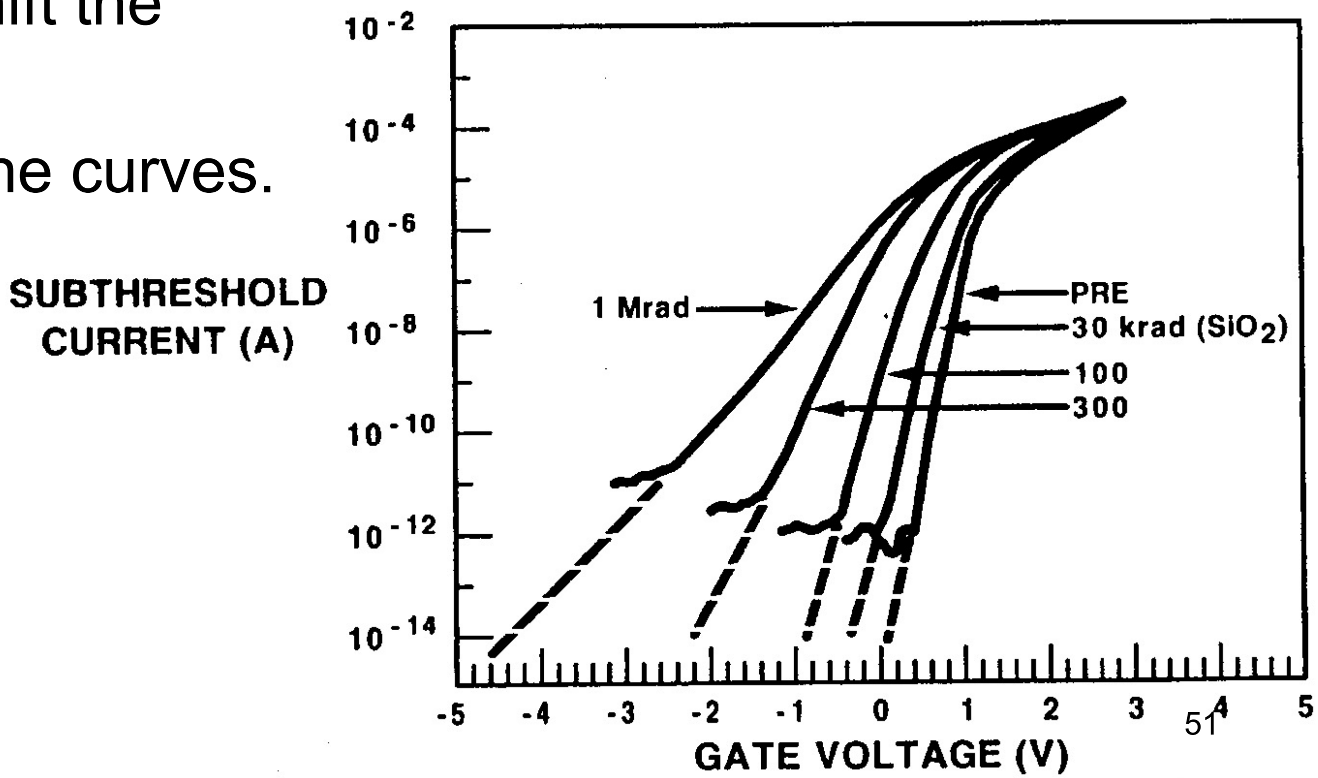
TID in MOS devices
What does I_{ds} vs. V_{gs} curve means?





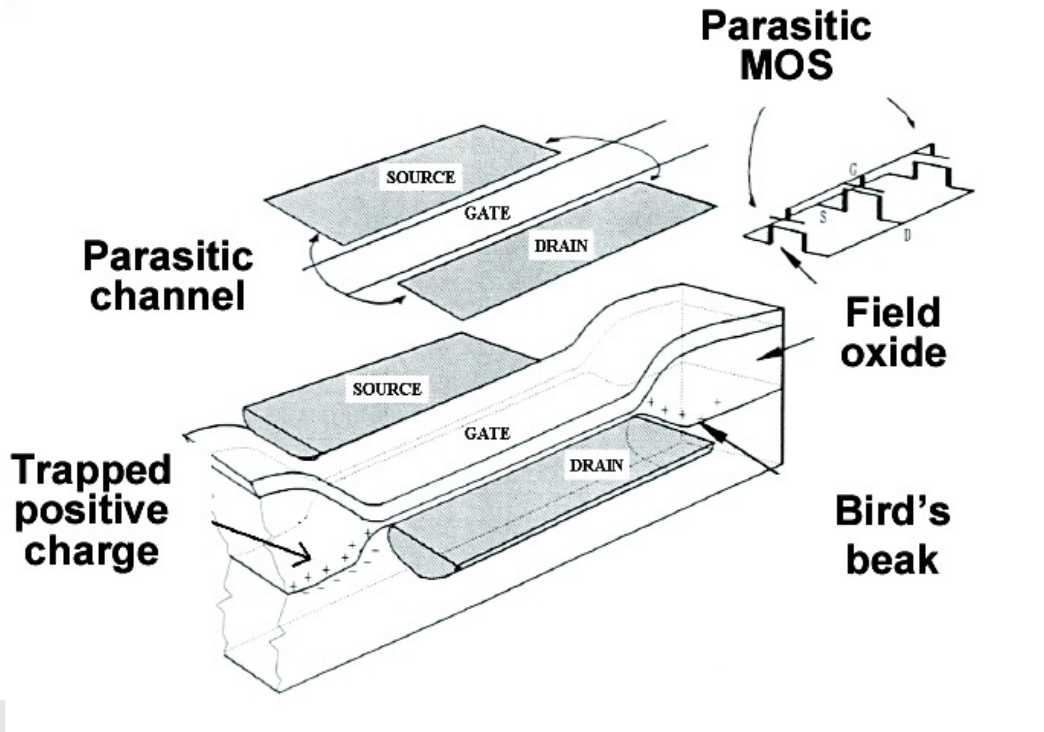
TID in MOS devices

- Features in the current-voltage graph
  - Charges in the Oxide shift the curves.
  - Interface traps deform the curves.



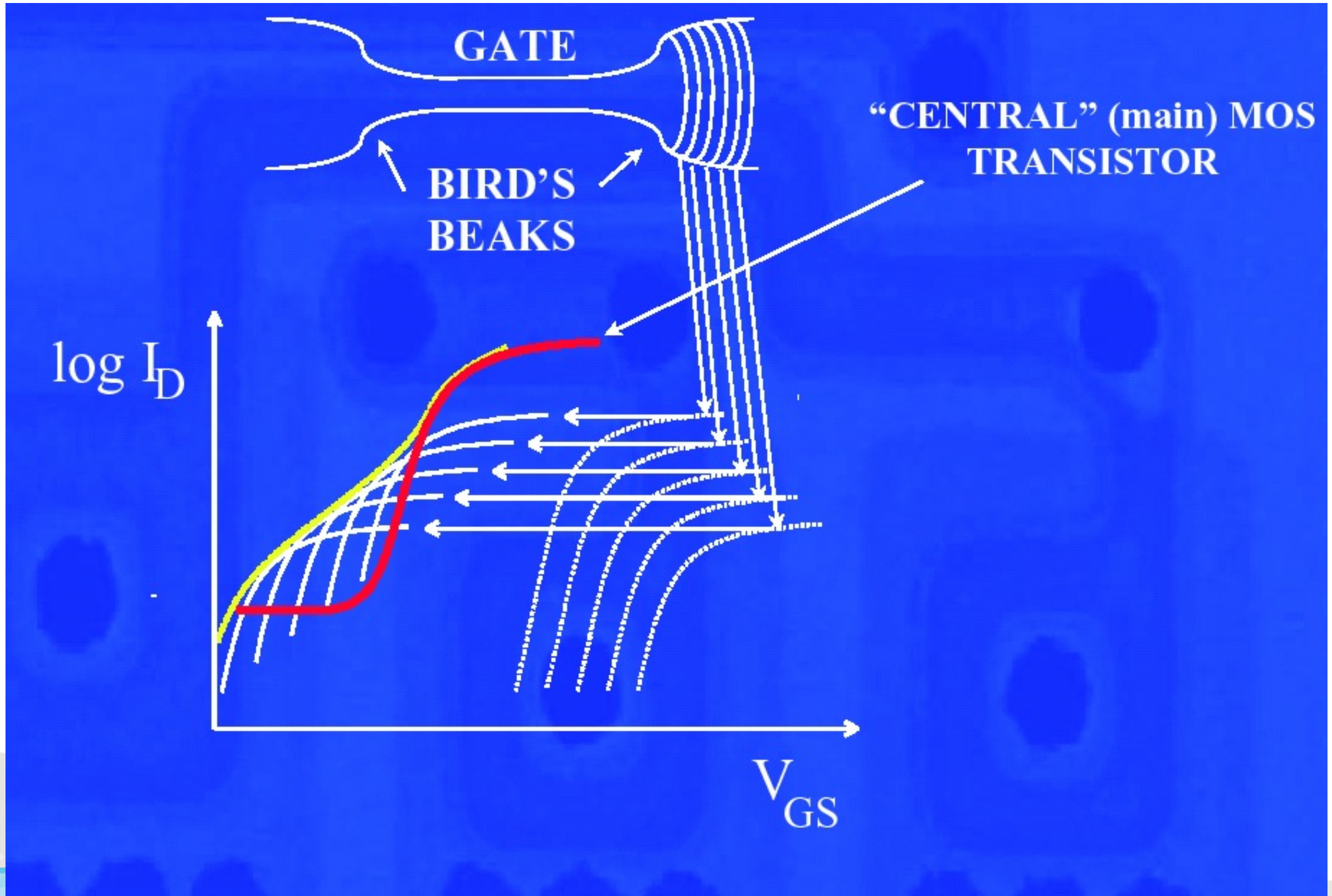
TID in MOS

Leakage curren t⇒ ∃ Parasitic MOS **(1)**

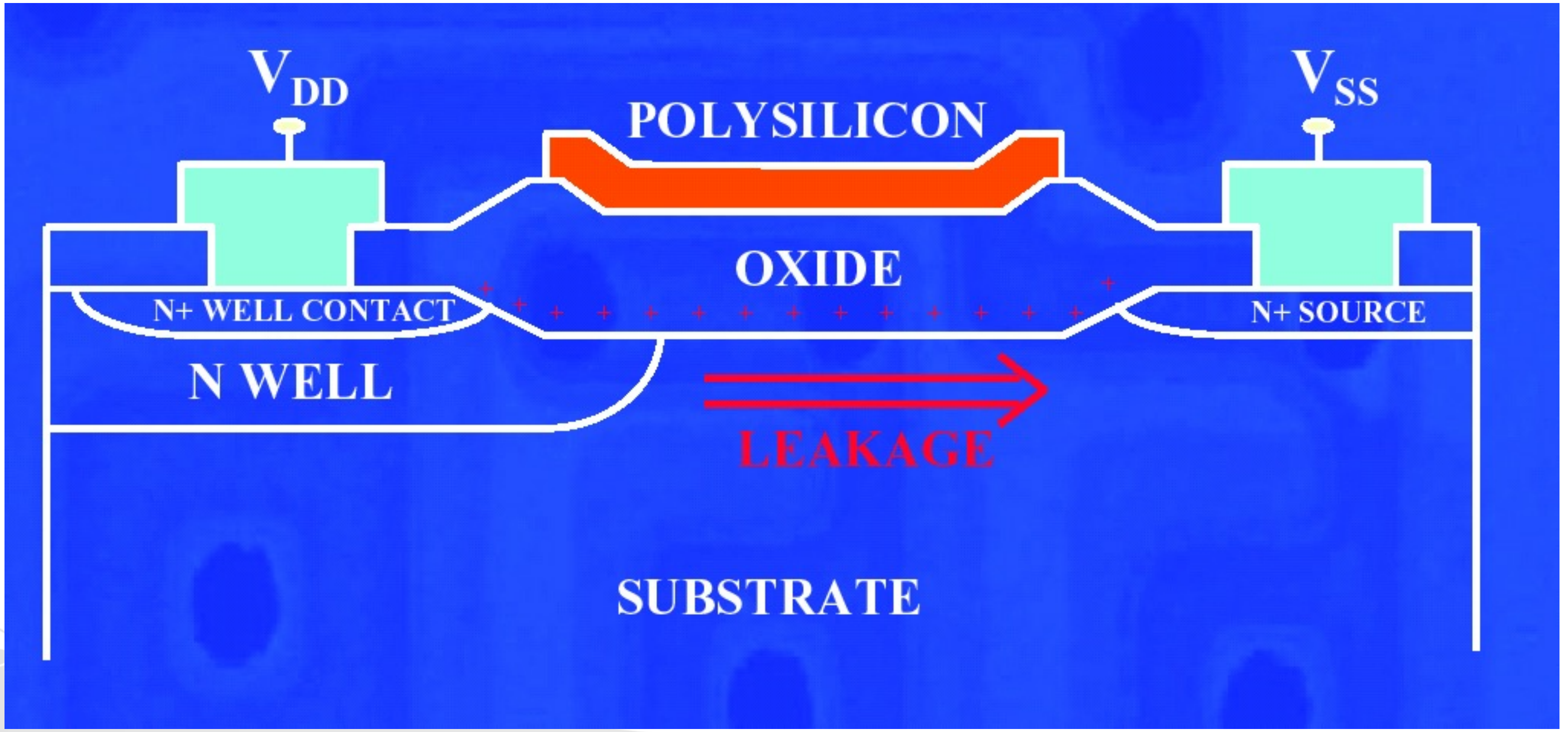


TID in MOS

Leakage curren t⇒ ∃ Parasitic MOS **(2)**



Leakage current between transistors



Summarizing ion-solid interaction

- There are two effects on semiconductors devices produced by energetic ions
  - The Electronic stopping power
    - Charge accumulation at insulators. → **T**otal **I**onizing **D**ose (**TID**)
    - Charge injection in the device. → **S**ingle **E**vent **P**henomena (**SEP**)
  - The Nuclear Stopping power
    - Displacement cascades and consequent defect production. → **T**otal **N**on **I**onizing **D**ose (**TNID**)

SEP (Single Event Phenomena)

Electrical disturbance induced by highly ionizing particles (heavy ions, protons, neutrons)

Results in effects: non-destructive / destructive

Data corruption

Transient disturbance

High current conditions / Electric field

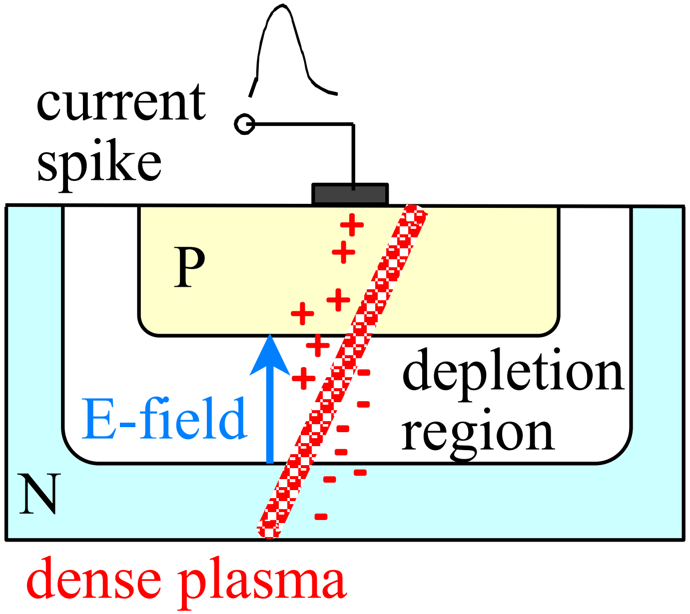
Affects different types of devices and technologies, impacting system performance.

Its importance is increasing due to:

reduced size and greater integration (lower noise margin).

Greater complexity (multiple modes of operation).

Use of non-hardened components (COTS).



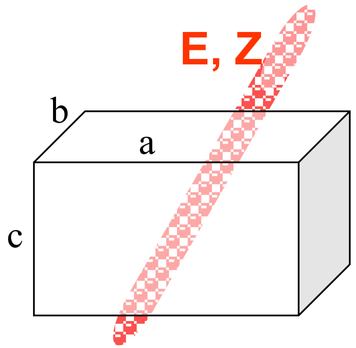
SEP basic (1)

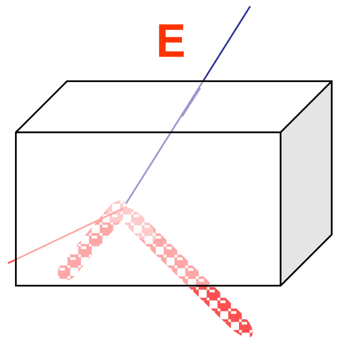
Physical mechanism

Deposition of a charge greater than or equal to threshold charge (Q_T) in or near the sensitive volume (SV).

The charge collected at the sensitive node results in SEP

The node or SV is modeled as a Parallelepiped





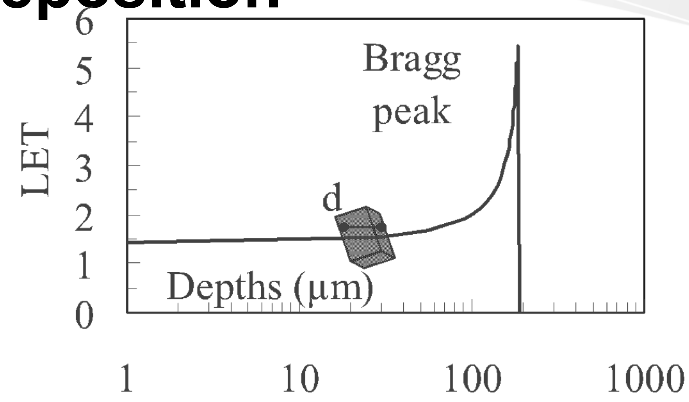
Energetic Heavy Ion
Direct mechanism

Energetic protons or neutrons
Indirect mechanism (nuclear spallation reactions)

SEP basic (2)
Charge Deposition

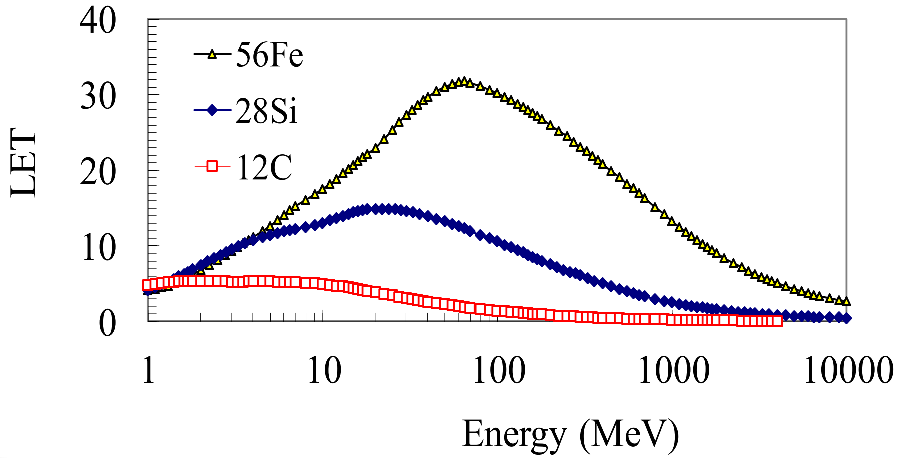
Linear Energy Transfer (*LET*)
[MeV .cm² /mg]

$$\begin{cases} LET(x) = \frac{1}{\rho}\frac{dE}{dx}(x) & 0 \le x \le r \\ LET(x) = 0 & Otherwise \end{cases}$$

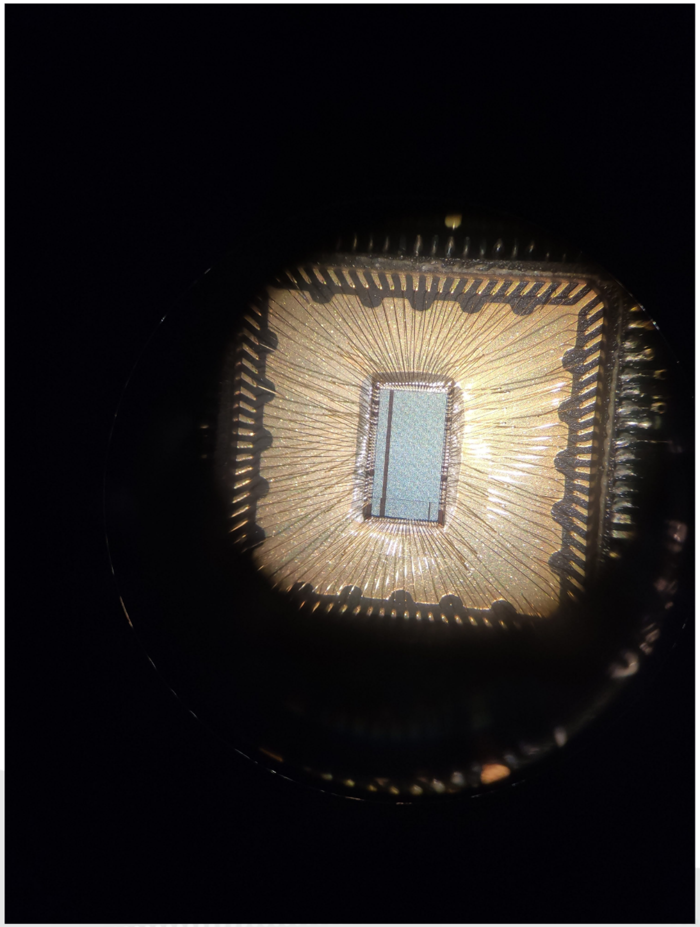


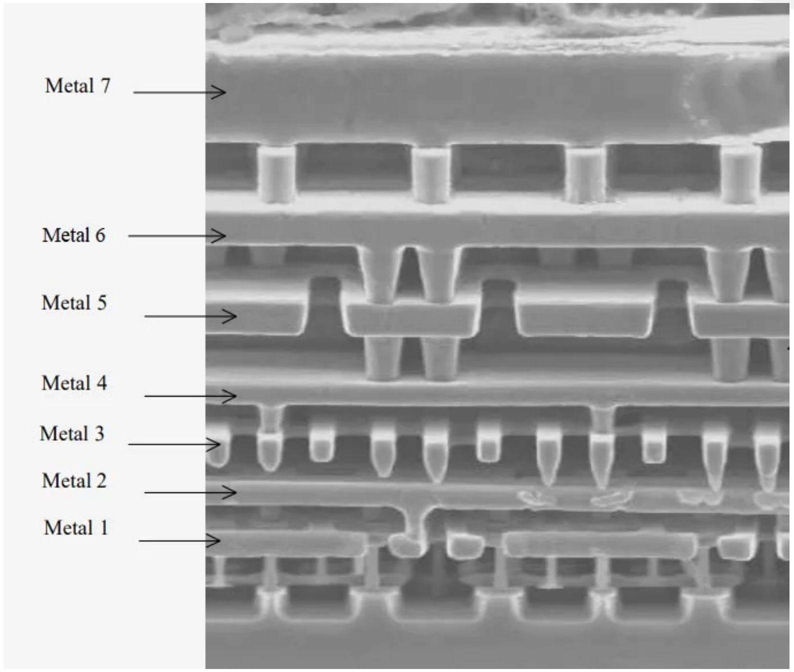
E_{dep} proportional to the path within the sensitive volume.

$$E_{dep} \approx LET \times d \times \rho$$



The semiconductor device (Chip)





All this layers are measure as silicon thikness equivalent.

Cross section of a chip, at bottom silicon, the rest are layers of silicon dioxide and metal contacts.
At right a picture of a decapsulate device.

The SEP ZOO (1)

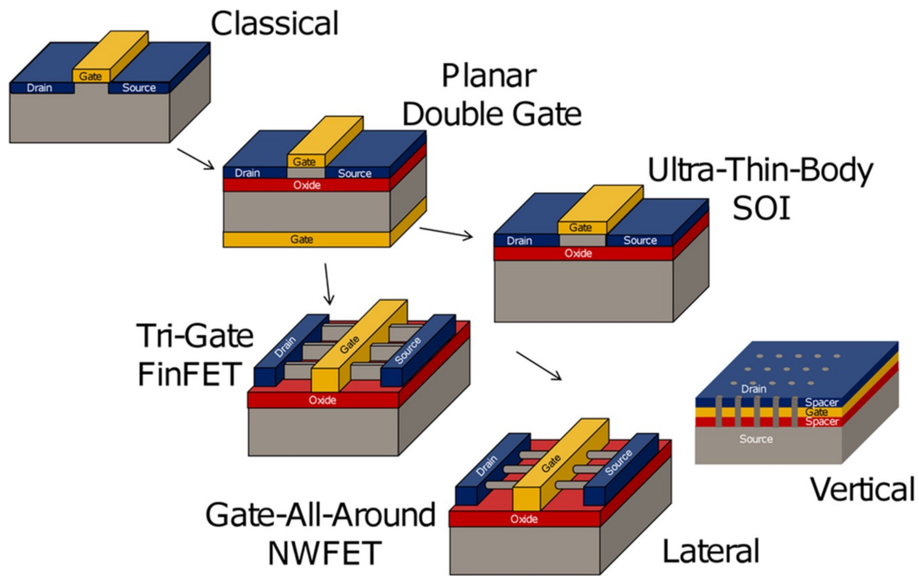
Single Event ....

Upset - SEU	corruption of information stored in a memory element	Memories, latches in logical devices
Multiple Bit Upset - MBU	Multiple memory elements corrupted on a single hit	Idem ⇑
Functional Interrupt -SEFI	Loss of normal operation	Complex devices with control and/or storage sections
Transient - SET	Impulsive response of a certain amplitude and duration	Analog circuits, processors, mixed signal, photonics, etc.
Disturb - SED	Momentary corruption of information stored in a bit	Combinational logic circuits, latches in logic devices
Hard Error - SHE	Unalterable change of state in a memory element	Memories, latches in logical devices

Latchup - SEL	High current conditions	CMOS, BiCMOS devices
Snapback - SESB	High current conditions	Mosfet de canal N, disk. SOI
Burnout - SEB	Destructive burning	BJT, N-channel Power MOSFET
Gate Rupture - SEGR	dielectric breakdown of the gate	Power MOSFETs
Dielectric Rupture - SEDR	dielectric breakdown	Non-volatile NMOS struct., FPGA, linear devices...

Last word on SEP
New technologies bring new challenges

- **Smaller Size Implications:** Cross-section reduction, but also critical charge reduction. So, which effect dominates?
- New geometries and materials.
- New technologies, such as spintronic, optoelectronic, memristors, qubits and more.



Summarizing ion-solid interaction

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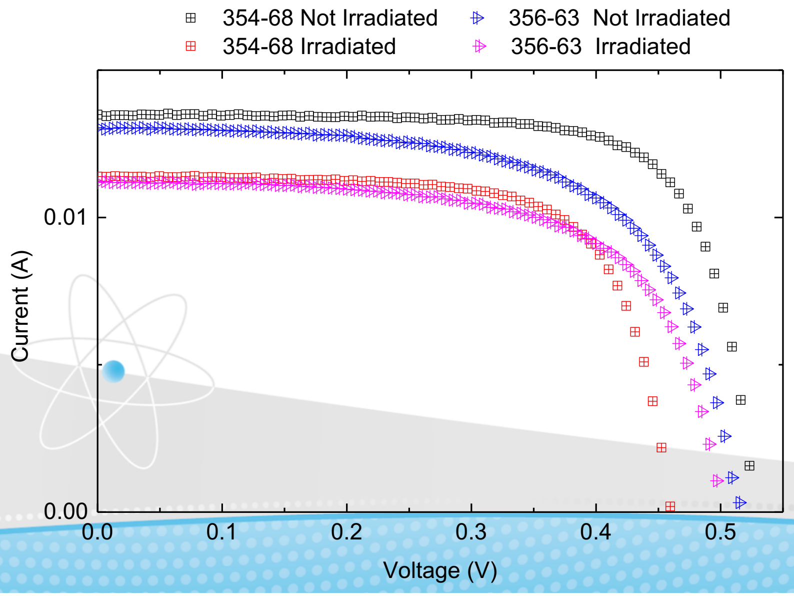
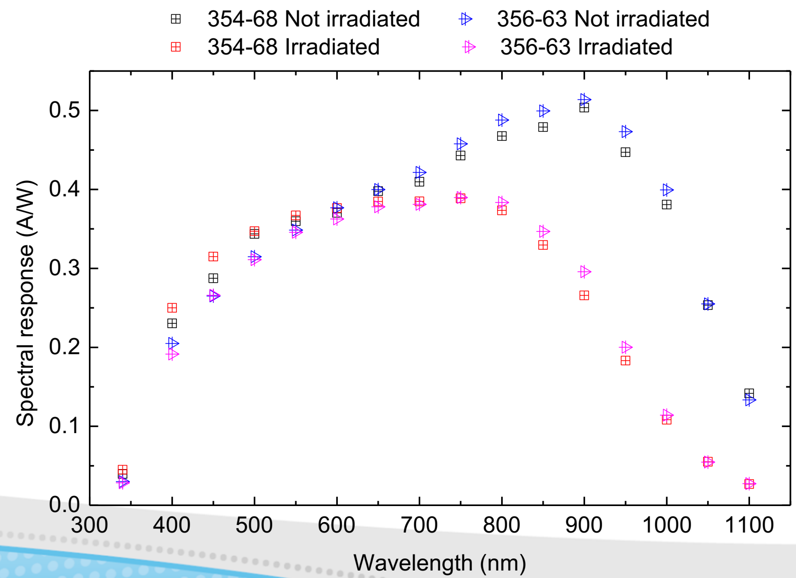
    - Displacement cascades and consequent defect production. → **T**otal **N**on **I**onizing **D**ose (**TNID**)

TNID Basic (I)

- It primarily affects devices located outside the satellite, such as solar cells, optical sensors, and others.
- The displacement cascades produce charge traps, which degrade performance. For example, in a raw solar sensor.





Going back to the ground

- How can we study the effects on devices?
- Roughly speaking, a description of the irradiation could be:
  - Continuous carrier production due electronic stopping power.
  - **Along its path**, the impinging ion could transfer energy to the lattice through collisions that eventually produce displacement cascades.
  - **There is a lapse between two ions producing displacements close enough for defects to interact**.

How to characterize Radiation effects on Earth (0)

- Choosing the right radiation source (e.g., photons, electrons, neutrons, or heavy ions).
- Matching the energy deposition (dose) to space conditions.
- Analyzing the impact on materials and devices, such as:
  - Charge carrier production.
  - Displacement damage.
  - Performance degradation.

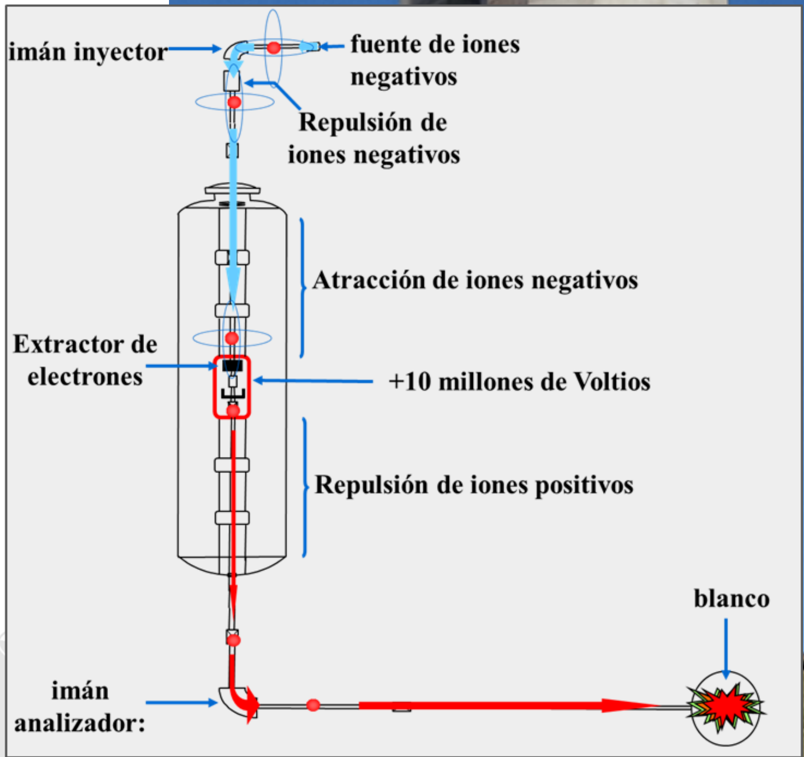
How to characterize Radiation effects on Earth (1)

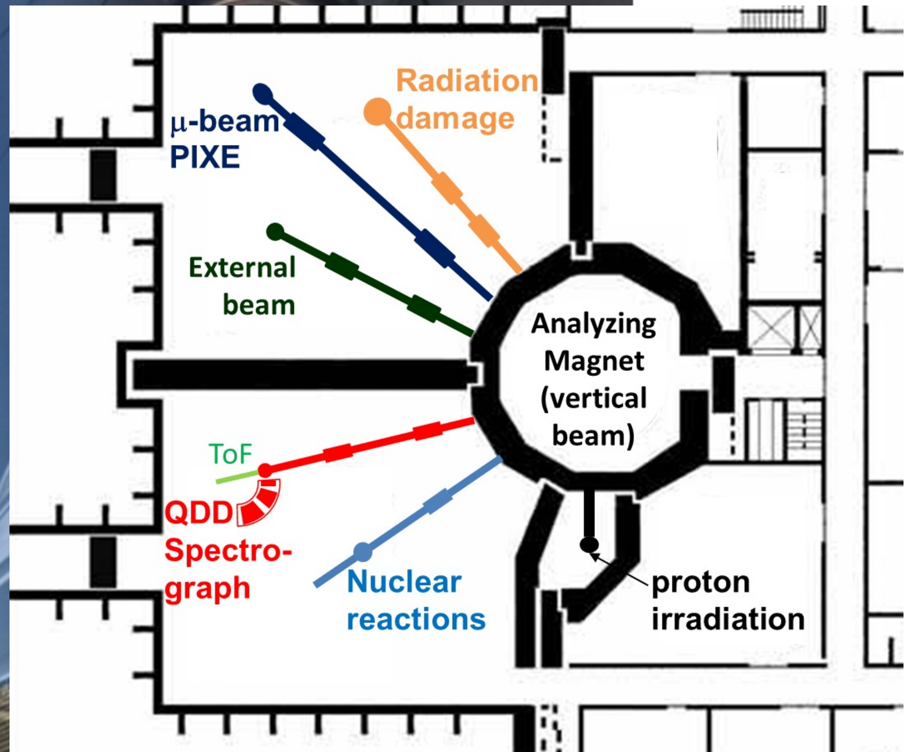
- Irradiating with (Less expensive options):
  - Photons:
    - It is the cheapest
    - Compare to space through the energy deposited by mass unit (Dose).
    - TID and SEP (using Laser beams)
  - Electrons
    - Most abundant in Low Earth Orbit (LEO).
    - Very inefficient to cause damage.
    - Requires an accelerator, it is the standard for testing solar cells.
    - TID, TNID
  - Neutrons
    - Not naturally present in space
    - Only feasible if you have free access to a reactor.
    - TNID, SEP (Through spallation nuclear reaction)

How to characterize Radiation effects on Earth (2)

- Irradiating with (More expensive Options):
  - Protons
    - Second most abundant ion in space
    - Efficient to produce damage
    - Wide energy range and then depth inside of satellite
    - Requires an accelerator
    - May require device decapsulation
    - TID, TNID, SEP (Through spallation nuclear reaction)
  - Heavy Ions
    - Very useful to characterize Single Event Phenomena (SEP).
    - Requires an accelerator
    - Needs device decapsulation.
    - SEP

TANDAR


imán inyector
fuente de iones negativos
Repulsión de iones negativos
Atracción de iones negativos
Extractor de electrones
+10 millones de Voltios
Repulsión de iones positivos
blanco
imán analizador:

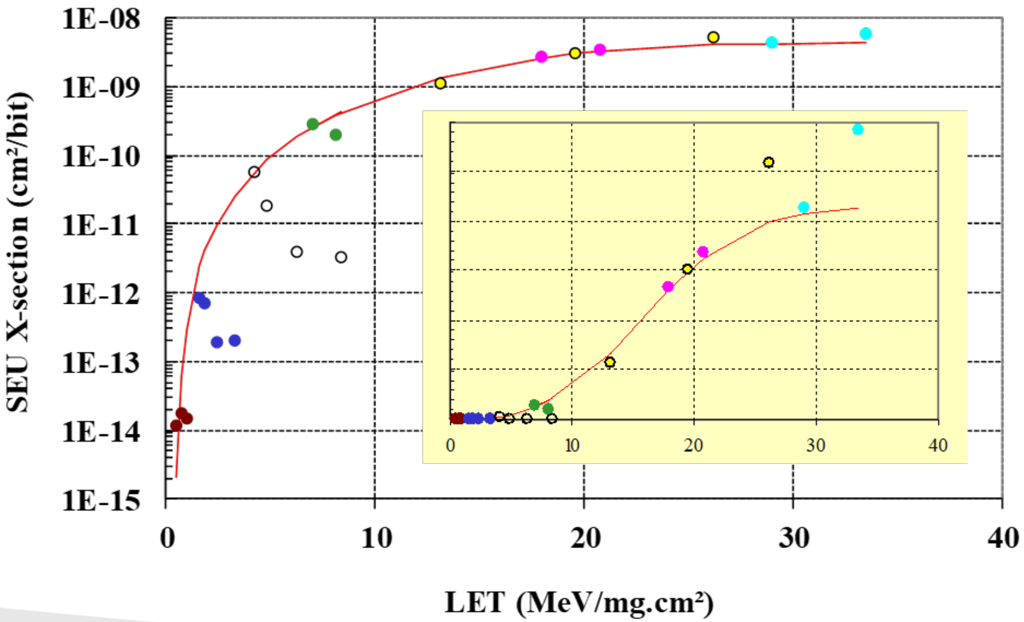

μ-beam PIXE
Radiation damage
External beam
Analyzing Magnet (vertical beam)
ToF
QDD Spectro-graph
Nuclear reactions
proton irradiation

SEP Measurement

Cross section (CS or σ): It is the probability of a SEP occurrence. The number of events produced per unit of particle fluence is measured experimentally.

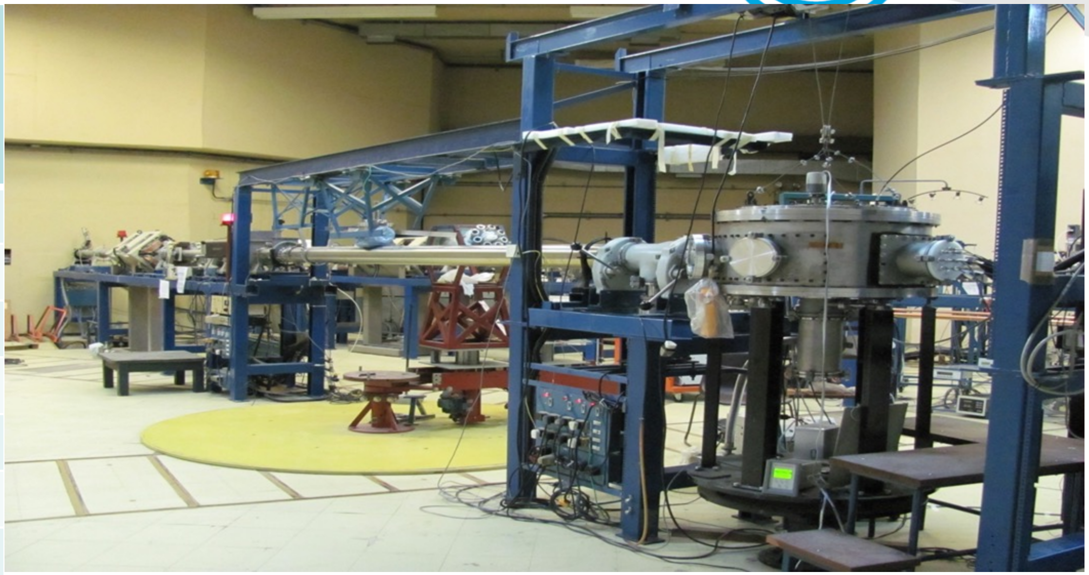
The CS curve measures the LET-dependent of the sensitive area of the chip.

$$\sigma(LET) = \frac{Number\ of\ events}{Fluence}\ [cm^2]$$



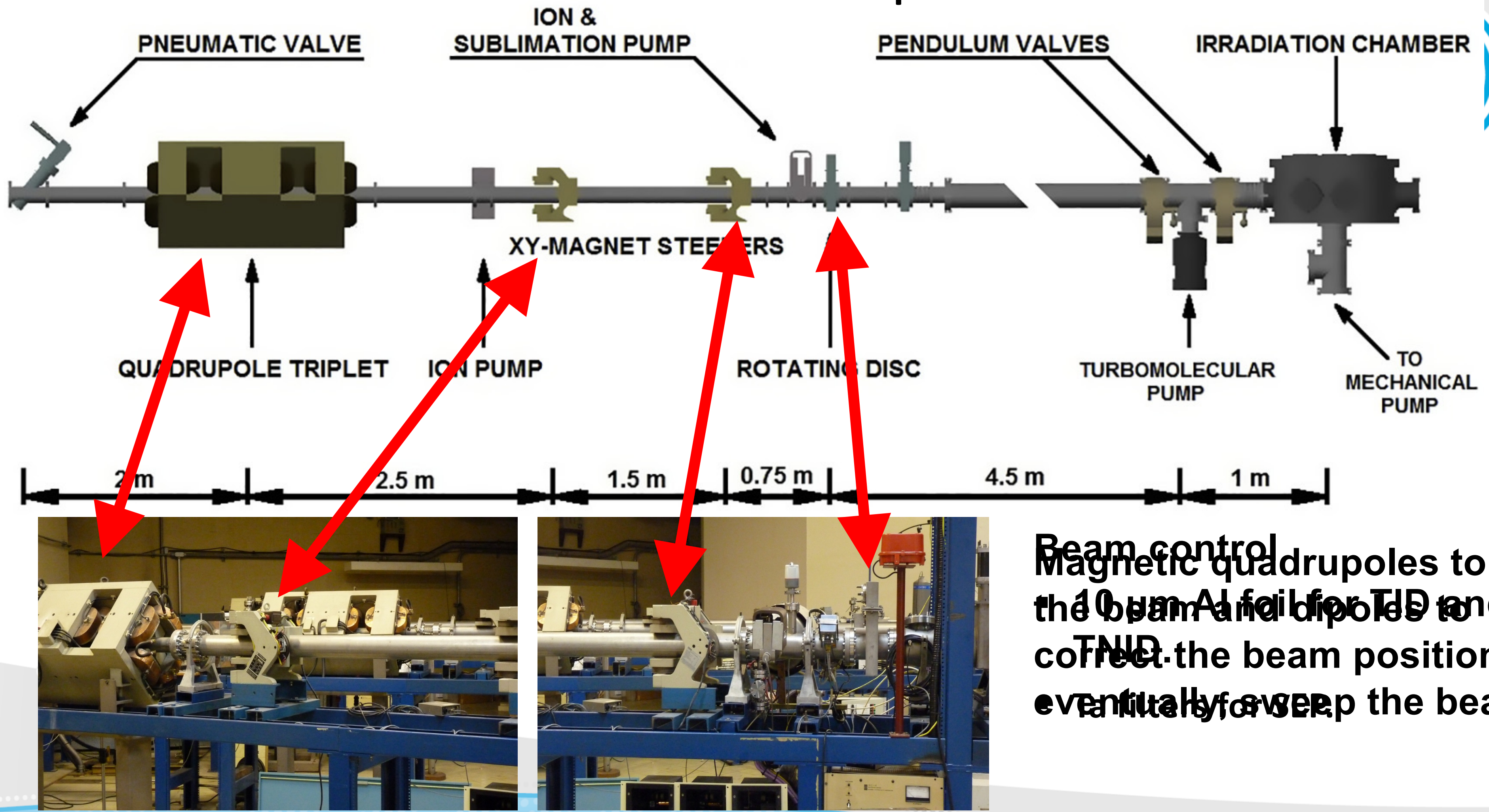
EDRA beam line

Ion	Energy beam (MeV)	Range in Si (µm)	LET in Si (MeV cm^2 mg^{-1})
$^{12}C_6$	25	25.6	3.5
$^{16}O_8$	30	21	5.7
$^{19}F_9$	35	21	6.8
$^{35}Cl_{17}$	75	21	16.5
$^{48}Ti_{22}$	90	20	24.2
$^{58}Ni_{28}$	120	23	31.4
$^{79}Br_{35}$	140	22.2	40.8
$^{127}I_{53}$	150	20.5	53.6
$^{197}Au_{79}$	170	20	65.8



Ions and energy available at EDRA facility for SEP measurements.

How to simulate the space environment



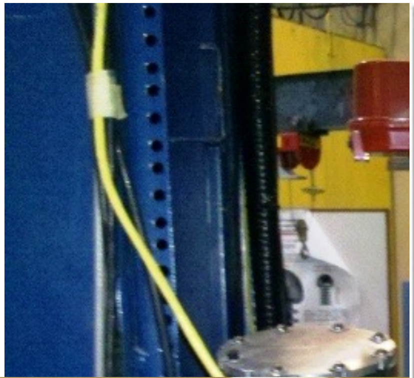
Beam control

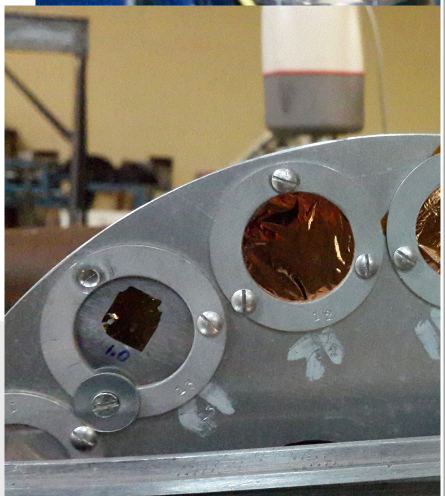
Magnetic quadrupoles to focus the beam and dipoles to correct the beam position and, eventually, sweep the beam.

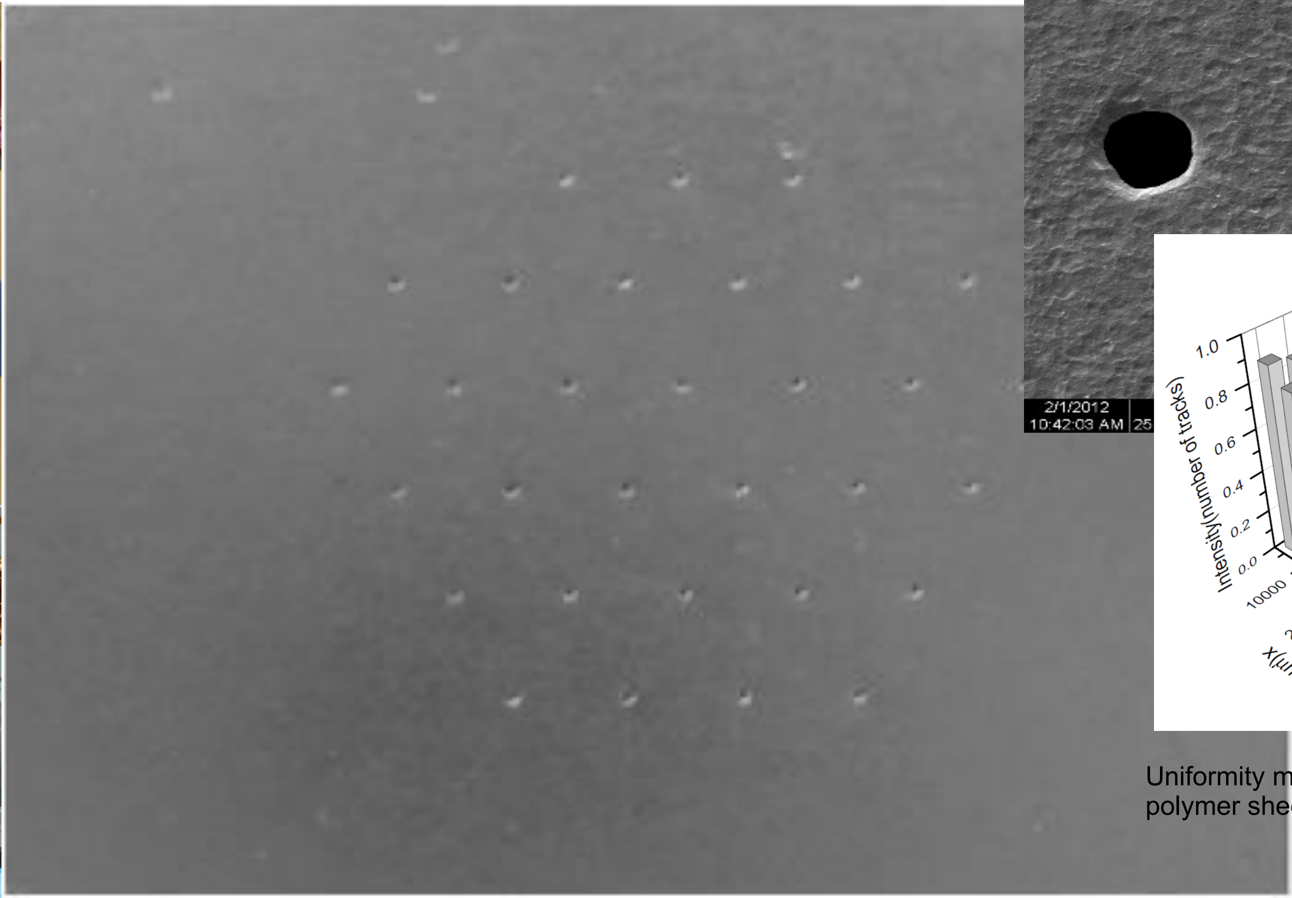
- **10 um Al foil for TID and TNID.**
- **Ta filters for SEE.**

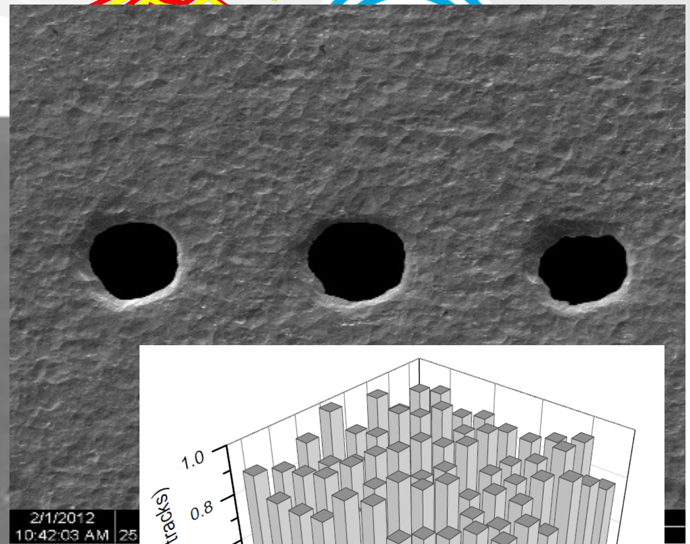
How to simulate the space environment

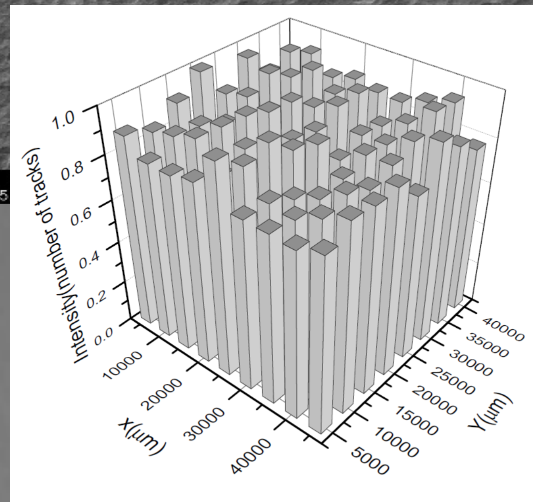
Tantalum filter for SEP





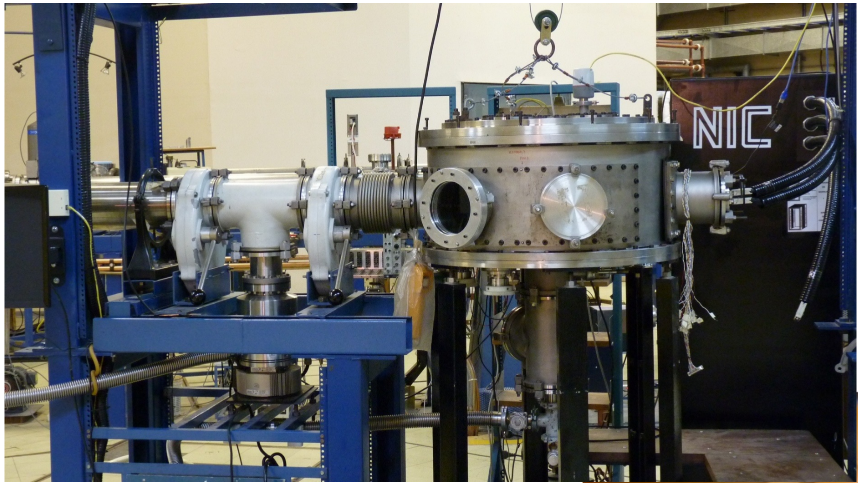






Uniformity measurement observed in a 5x5 cm^2 polymer sheet irradiated with tantalum filter

The Irradiation chamber



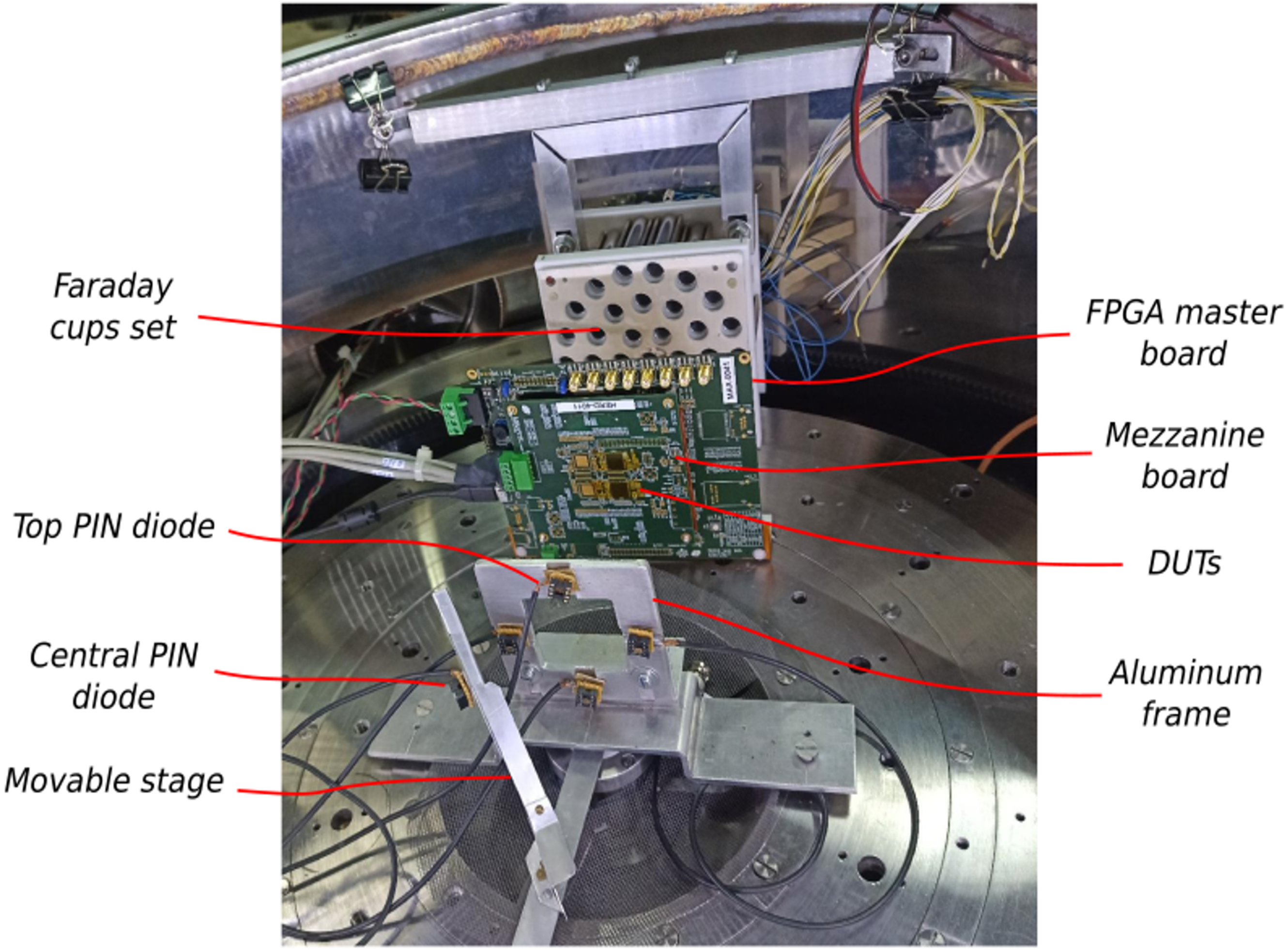
In-situ experiments

- High vacuum conditions
- Controlled temperature -120 ºC to 150ºC
- Three rotatable ring to move the sample holder
- Window for allow a solar simulator to *in situ* irradiations

Flux beam measure *in-situ*

- Faraday Cup and an electrometer (TID and TNID)
- PIN diodes and NIM electronic modules

The SEP irradiation

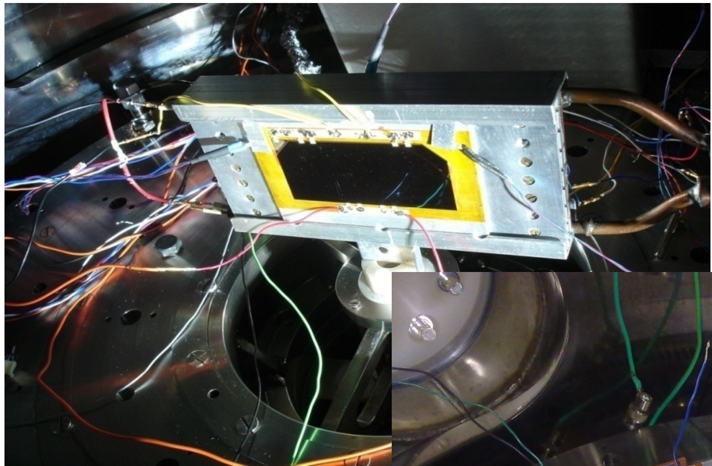


SEP Experiment

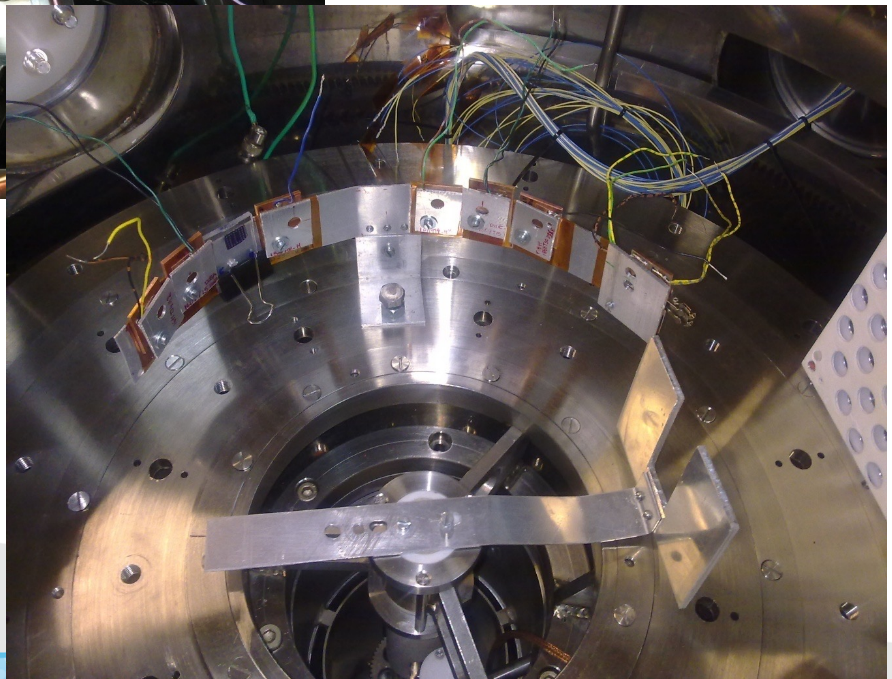
Webcam irradiation with 8 MeV proton

TID and TNID measurements at Tandar

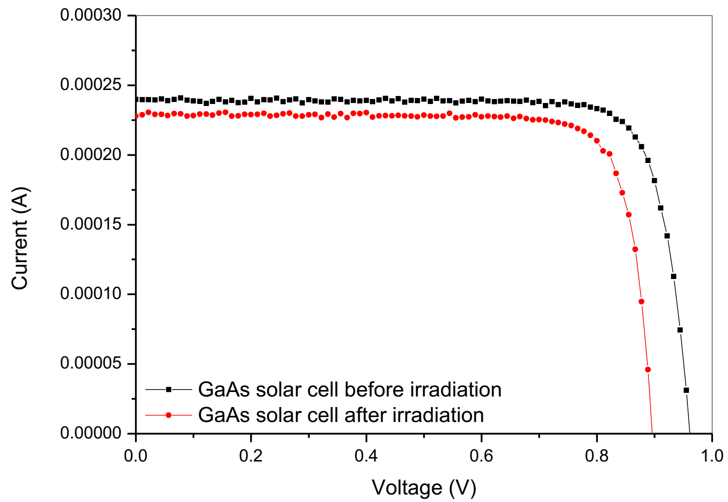
10 MeV protons



Advance space solar cell



Top view of the irradiation chamber



Homo junction, double junction and triple junction of III-V semiconductors

Radiation Damage Test Conditions for Solar Cells

- **Some standards that include radiation damage from solar cells**
  - Space systems — Space solar cells — Electron and proton irradiation test methods, ISO 23038 (2006).
  - Space engineering, Photovoltaic assemblies and components, ECSS-E-ST-20-08C (2008).
  - Qualification and Quality Requirements for Space Solar Cells, AIAA S-111-2005.

- **Some observations on ISO 23038**
  - Electrons (1 MeV)
    - Vacuum: Preferential
    - Temperature < 40ºC
    - Spatial Uniformity < 10%
    - Flux: 10^9 to 10^{12} e cm^{-2} sec^{-1}
  - Protons (10 MeV)
    - Vacuum < 10^{-3} Pa
    - Temperature < 40ºC
    - Spatial Uniformity < 10%
    - Flux: 10^9 to 10^{12} p cm^{-2} sec^{-1}
  - Annealing may be important in some cases.
  - Number of samples: 5 to 12 for each fluence and energy.

Radiation Damage Testing Conditions for Electronic Devices

- **Some standards that include radiation damage from solar cells**
  - TOTAL DOSE STEADY-STATE IRRADIATION TEST METHOD, ESCC Basic Specification No. 22900 (2010).
  - Space product assurance - Electrical, electronic and electromechanical (EEE) components, ECSS-Q-ST-60C Rev.2 (2013).
  - Space engineering - Methods for the calculation of radiation received and its effects, and a policy for design margins, ECSS-E-ST-10-12C (2008).
  - IONIZING RADIATION (TOTAL DOSE) TEST PROCEDURE, METHOD 1019.7, MIL-STD-883G (2006).

- **Some observations on the rules**
  - TID y TNID
    - Electrons
    - Protons
    - Gamma (^{60}Co)
      - Flux 0.5 a 3 Gry srg^{-1}
  - Annealing may be important in some cases.
  - Number of samples: 5 to 12 for each fluence and energy.
  - SEP
    - Protons
      - E> 100 MeV
    - Heavy Ions
      - Flux< 10^5 p cm^{-2} seg^{-1}
  - Spatial Uniformity < 10%

The CAC method for TNID (I)

In this method we aim to emulate the spatial PKA spectra in terms of energy and depth.

It is a cheap method that uses a minimum of devices under test it.

- Requirements
  - Two free packages:
    - SRIM (www.srim.org) MonteCarlo binary collision approximation code for transport of ions in matter.
    - SPENVIS (www.spenvis.oma.be) a WWW interface to models of the space environment and its effects; including galactic cosmic rays.
  - An electrostatic heavy ion accelerator to test the device.

The CAC method for TNID (II)

- Strengths
  - Unlike other methods for characterizing damage, this approach has a strong foundation in physics.
- Weakness
  - It is not always possible to find the right irradiation conditions.
  - It does not solve the so-called acceleration factor problem.
  - A separate irradiation is required for each device and spatial condition.

The CAC method

Applied to study a Carrington-type event

1. Applied to study a coarse solar sensor (CSS) in a Carrington-type event.
2. Carrington Event (1859):
   - Largest solar storm ever recorded
   - Caused forest fire
   - Led to telegraph line failures
   - Produce northern lights in Rome, Cuba and Hawaii
   - Left traces of nitrates in polar ice.

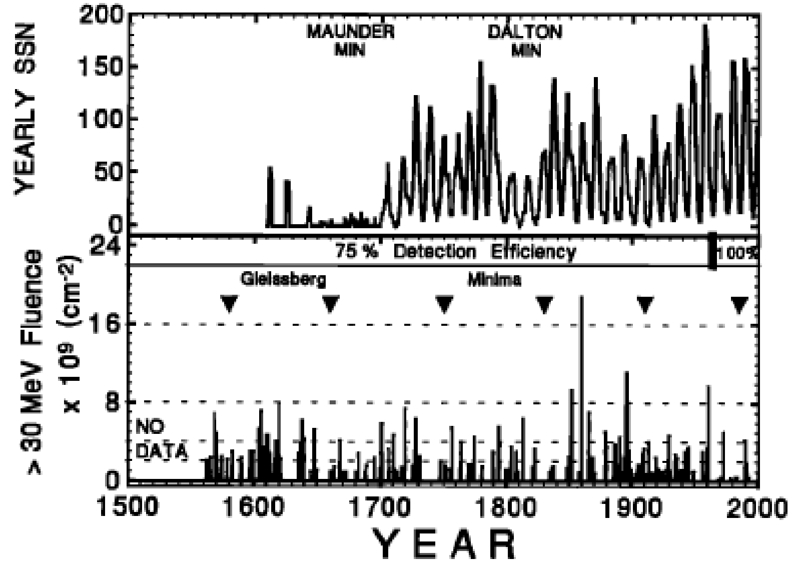
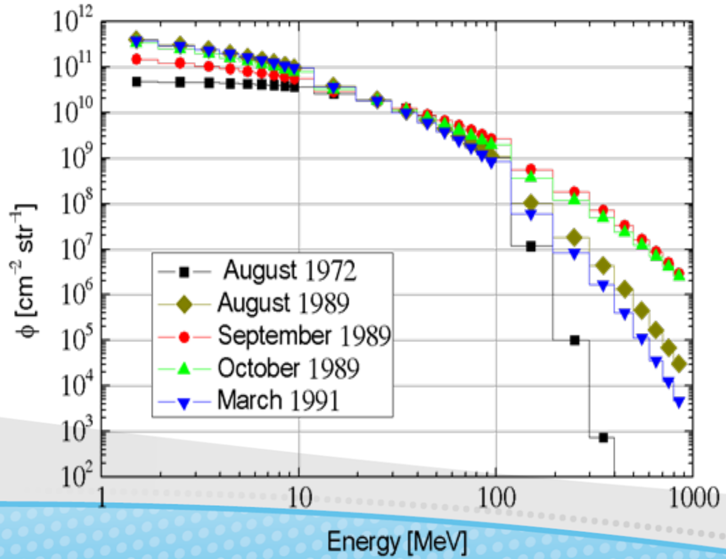


Figure 1. The times of occurrence of >30 MeV solar proton events with fluence exceeding 1.0×10^9 cm^{-2} as derived from the nitrate data (1561–1950) and from ionospheric and satellite data since 1950. The times assigned to the minima of the Gleissberg cycle are shown by the triangular markers. The annual international sunspot numbers are given in the top panel.

The CAC method
How make a Carrington type event

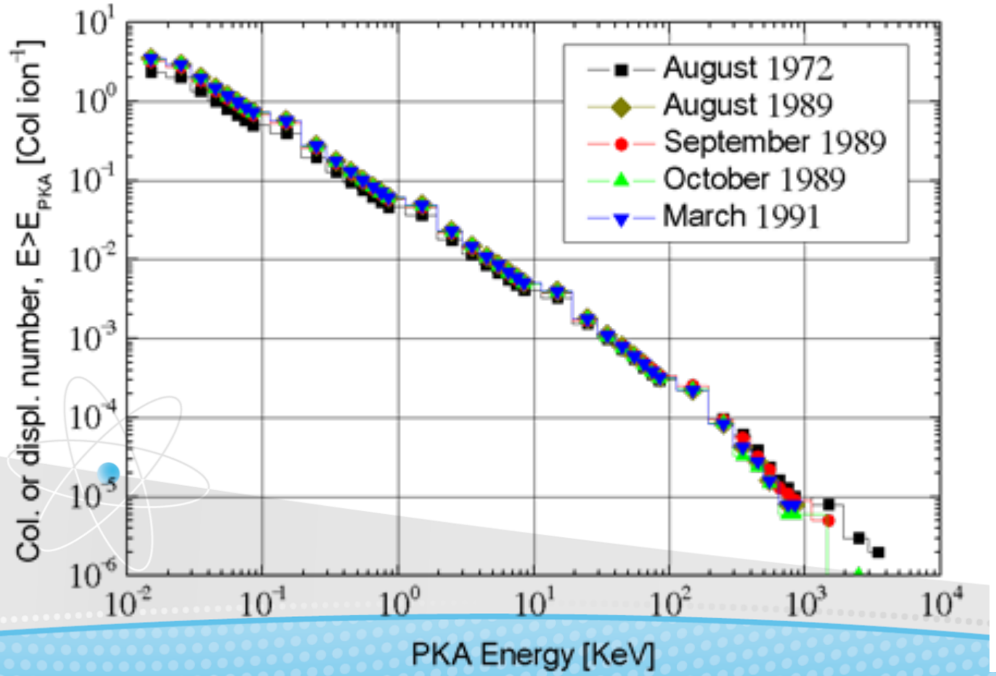
1. Xapsos et al.[1] demonstrated that a solar event could be reasonable fitted with: $\Phi = \Phi_0 \exp(-kE^{\alpha})$
2. Fluence of protons with E>30 MeV are in ice-cores [2].
3. Take the fit parameters of few Solar flares, and scales to $\Phi(E > 30\ MeV)$ corresponds to obtained from the ice-cores.

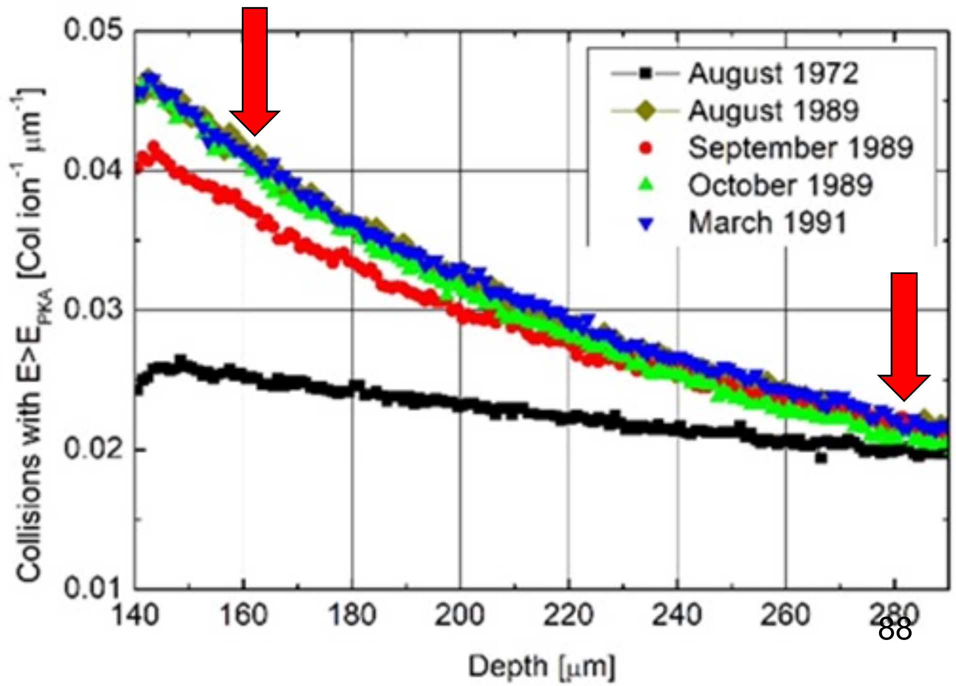


[1] M. A. Xapsos et al., "Characterizing solar proton energy spectra for radiation effects applications", IEEE Transactions on Nuclear Science, vol. 47, no. 6, pp. 2218-2223, Dec. 2000, doi: 10.1109/23.903756.
[2] K. G. McCracken, G. A. M. Dreschhoff, E. J. Zeller, D. F. Smart and M. A. Shea, "Solar cosmic ray events for the period 1561–1994: 1. Identification in polar ice, 1561–1950", J. Geophys. Res., vol. 106, pp. 21 585–21 598, 2001.

The CAC method
Now applying the CAC method (I)

1. Starting from the “Carrington fluences” we run the TRIM code and process the output COLLISON.TXT to generate PKA spectra and the corresponding dependency in depth.

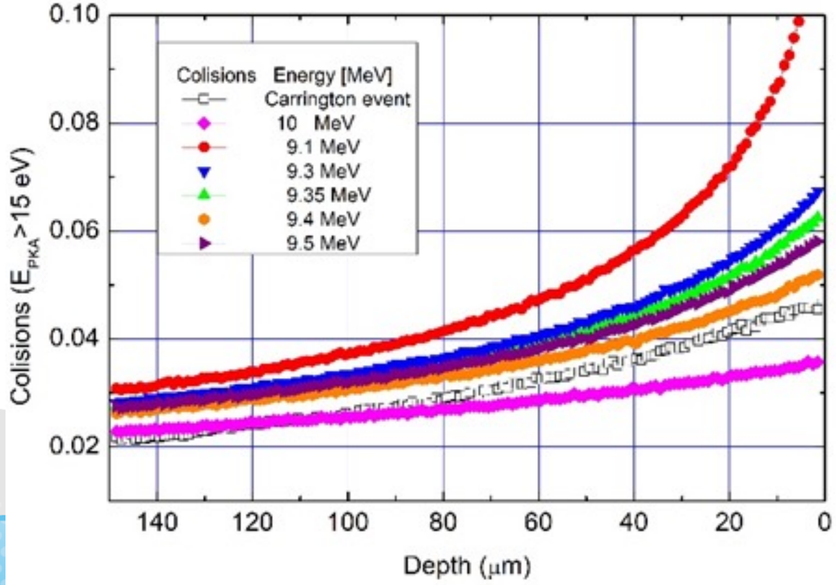


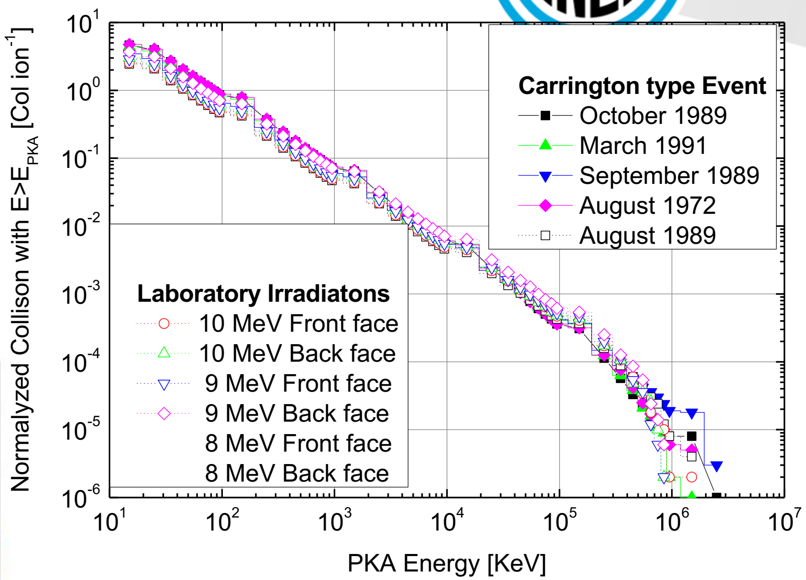


The CAC method

Now applying the CAC method (II)

- Now compare the PKA spectra for monoenergetics simulation with Carrington simulation.
  - Their look very similar, in energy distribution.
  - However, in laboratory irradiation, the results will differ as follows:



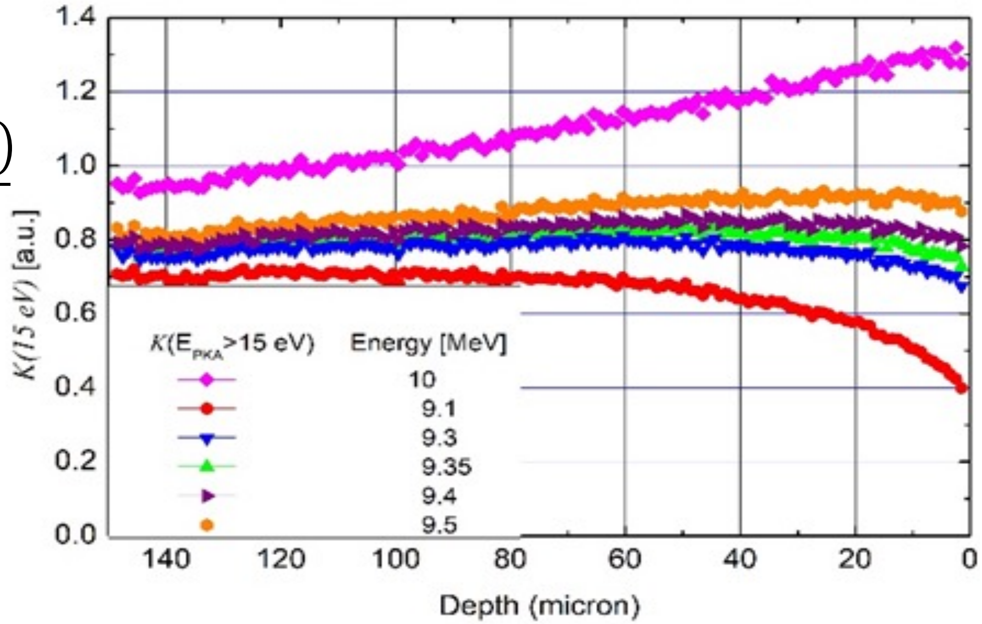


The CAC method
Now applying the CAC method (III)

- To define an irradiation that produces a PKA spectrum in both energy and depth, we establish the following:

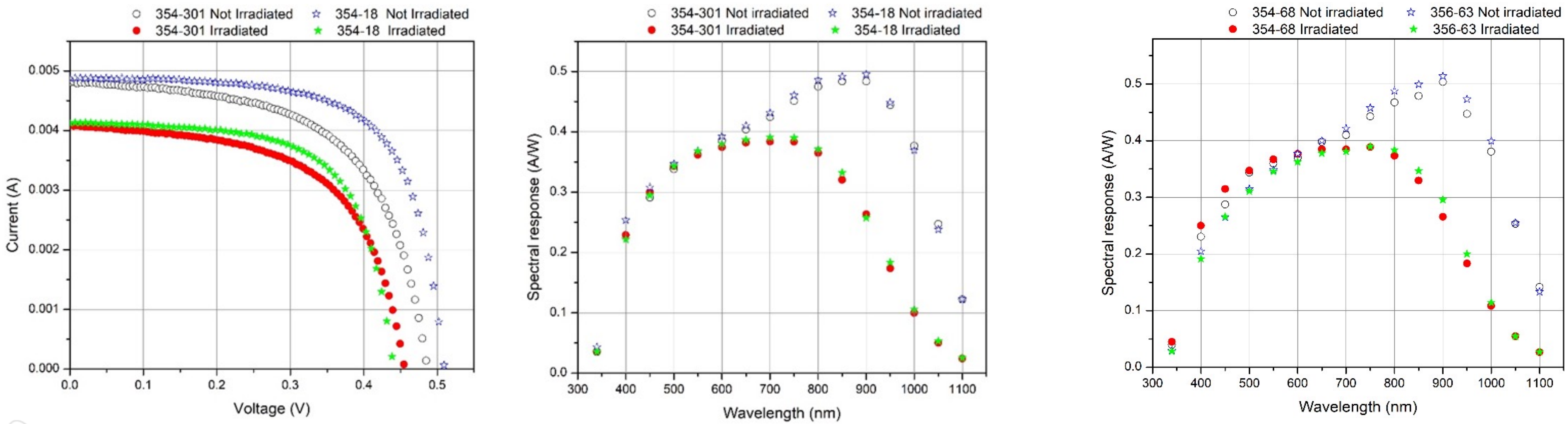
$$\Phi_{Lab,i} = \Phi_{Space,i} K_i\left(E_{ref}\right) \quad \text{and} \quad K_i\left(E_{ref}\right) = \frac{n_{Space,i}\left(E_{ref}\right)}{n_{Lab,i}\left(E_{ref}\right)}$$

- If we can find a $K_i\left(E_{ref}\right)$ approximately constant, we have an irradiation setup that will produce a damage similar that in space.
- Back-face irradiation at 9.4 MeV is considered the most effective approach.



The CAC method
Now applying the CAC method (IV)

- The results of irradiation are:



- **Remark**: In this case the event duration could be two or three days, the irradiation is between one and three hours. The acceleration factor is Ok. But for a total mission fluence in something as five years we must be conscious of acceleration factor and assume that is our best possibility.

Thank you
Questions?