Study of the radiation-induced effects on COTS components

Twelfth International Conference of Radiation, Natural Sciences, Medicine, Engineering, Technology and Ecology

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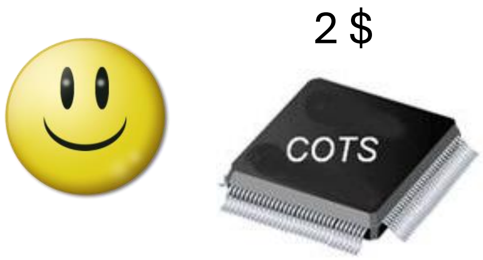
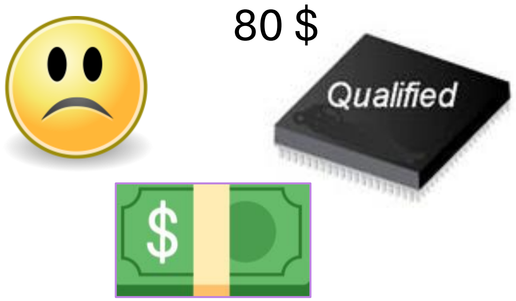
Introduction

Electronic devices



Commercial Off-the-Shelf
(COTS)



Radiation tolerant
Radiation hardened

Irradiation

- Gamma rays
- Protons (innovative and conventional sources – stress testing method validation)
- Neutrons
- Electrons

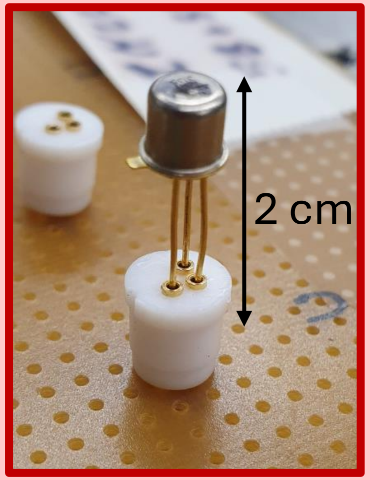
Study of radiation effects

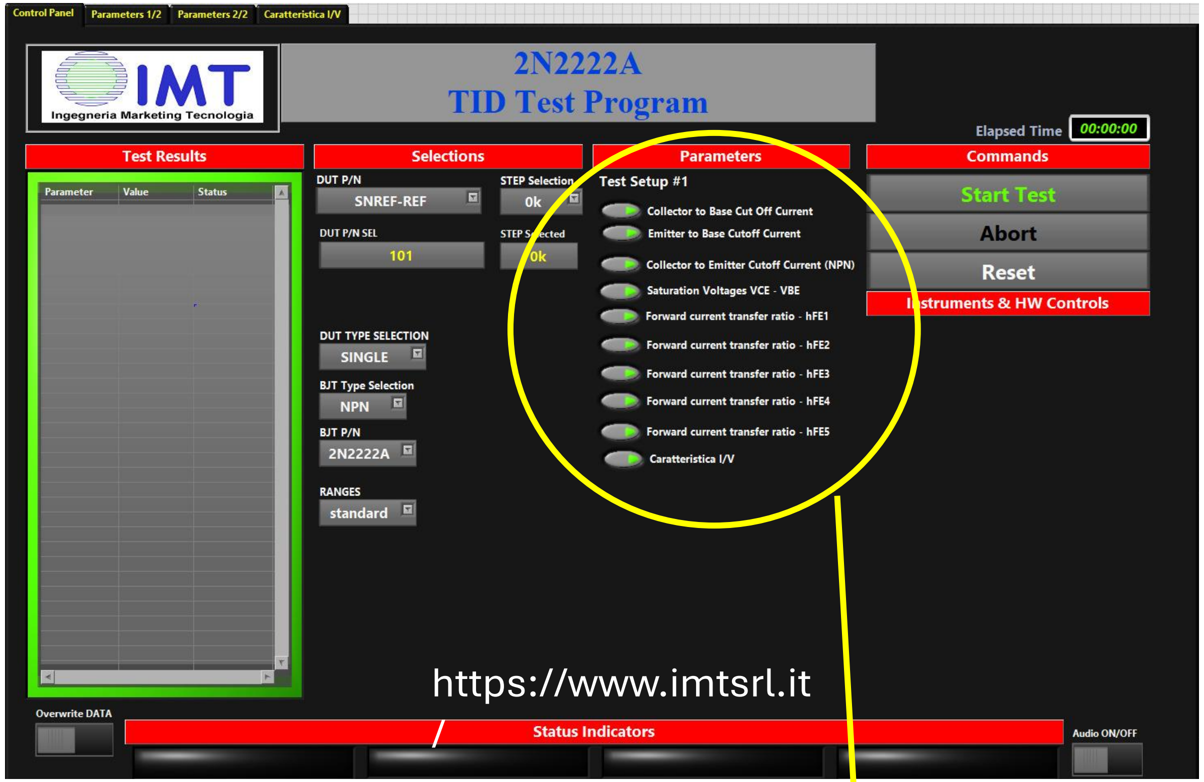
- Radiation resistance testing of specific electronic devices
- Investigate different irradiation methods for optimization of stress testing

Electronic components characterization before and after irradiation

Tested components

COTS NPN Bipolar Junction Transistors (BJTs)



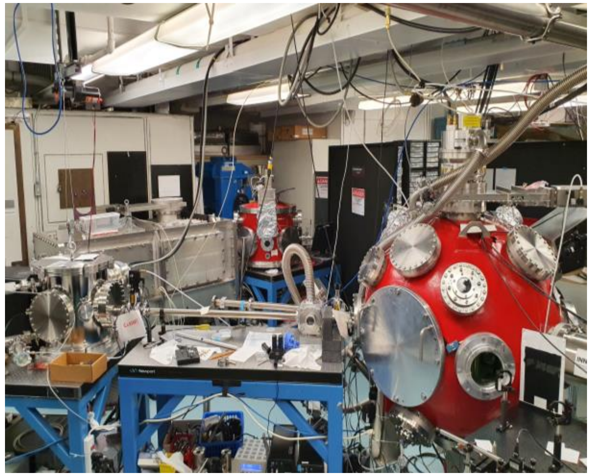


Many parameters (currents, voltages and gain) were evaluated before and after the irradiation tests.

Irradiation facilities: Canada and Italy

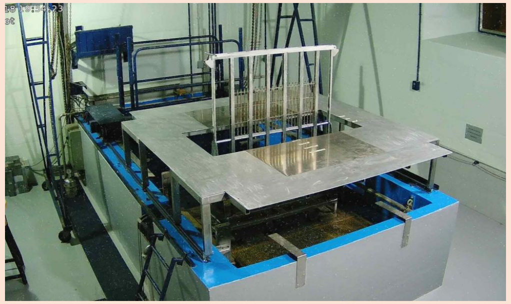
***Innovative** radiation source for stress testing*

Proton irradiation Advanced Laser Light Source (ALLS) ion beamline at INRS-EMT (Varennes, Québec, Canada)



***Conventional** radiation sources for stress testing*

ENEA
ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

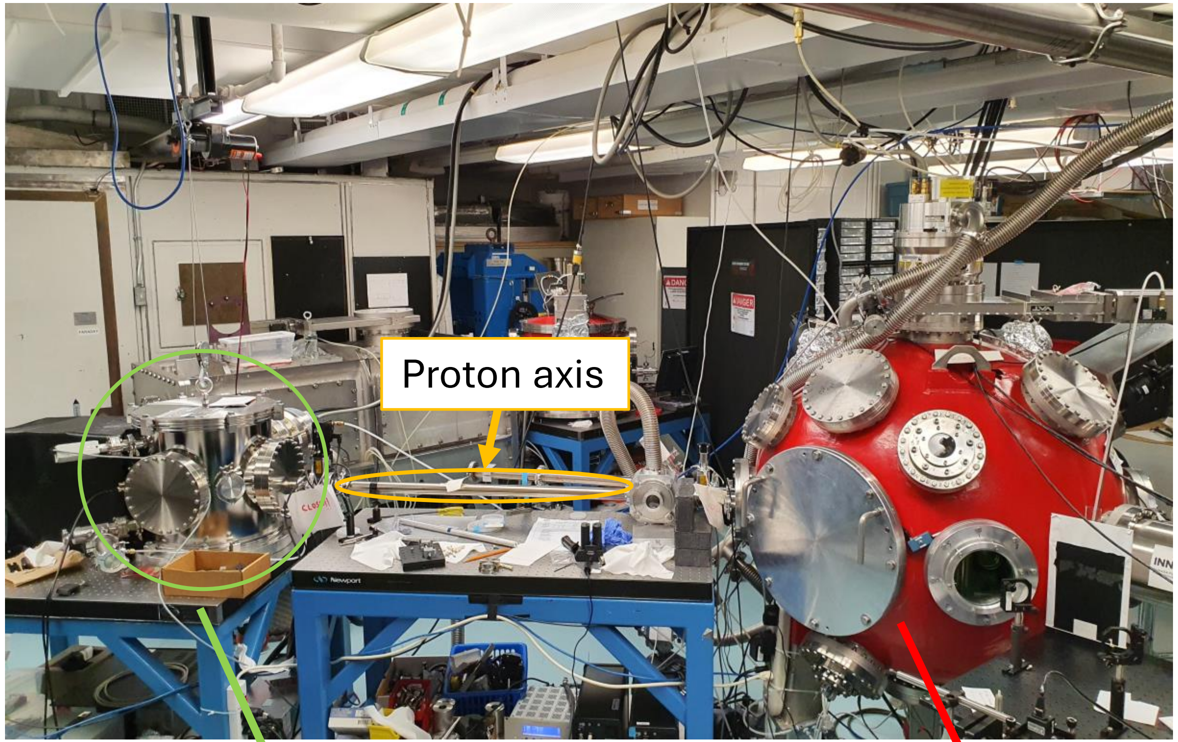


Gamma irradiation
Calliope facility at ENEA Casaccia R.C. (Rome, Italy)

Neutron irradiation Frascati Neutron Generator at ENEA Frascati R.C. (Frascati, Italy)

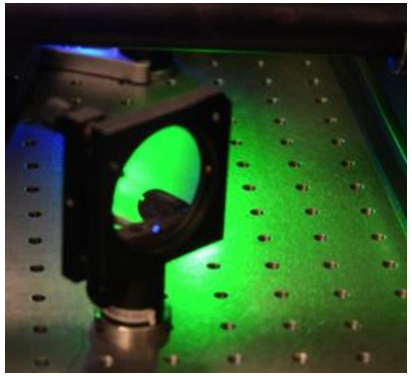
ALLS facility at INRS-EMT (Varennes, Québec, Canada)

At the **Institut National de la Recherche Scientifique** in Québec (Canada), laser-accelerated protons with a broad energy spectrum are available at the **ALLS** (Advanced Laser Light Source) **laboratory**.



Titanium-Sapphire laser

The most powerful available in Canada **!**



Thomson Parabola with a MicroChannel Plate (allows high repetition-rate shots) as ion detector.

Boule rouge: multiple target holder (800 targets that can be shot automatically), proton source, optics, samples

Laser beam peak power	750 TW
Central wavelength	800 nm
Pulse repetition rate	2.5 Hz (5 shots each 2 seconds)
Energy per pulse	Up to 13 J
Pulse duration	17 fs
Beam diameter	170 mm
Picosecond contrast	$1x10^{-12}$

https://alls.inrs.ca/beamlines-endstations

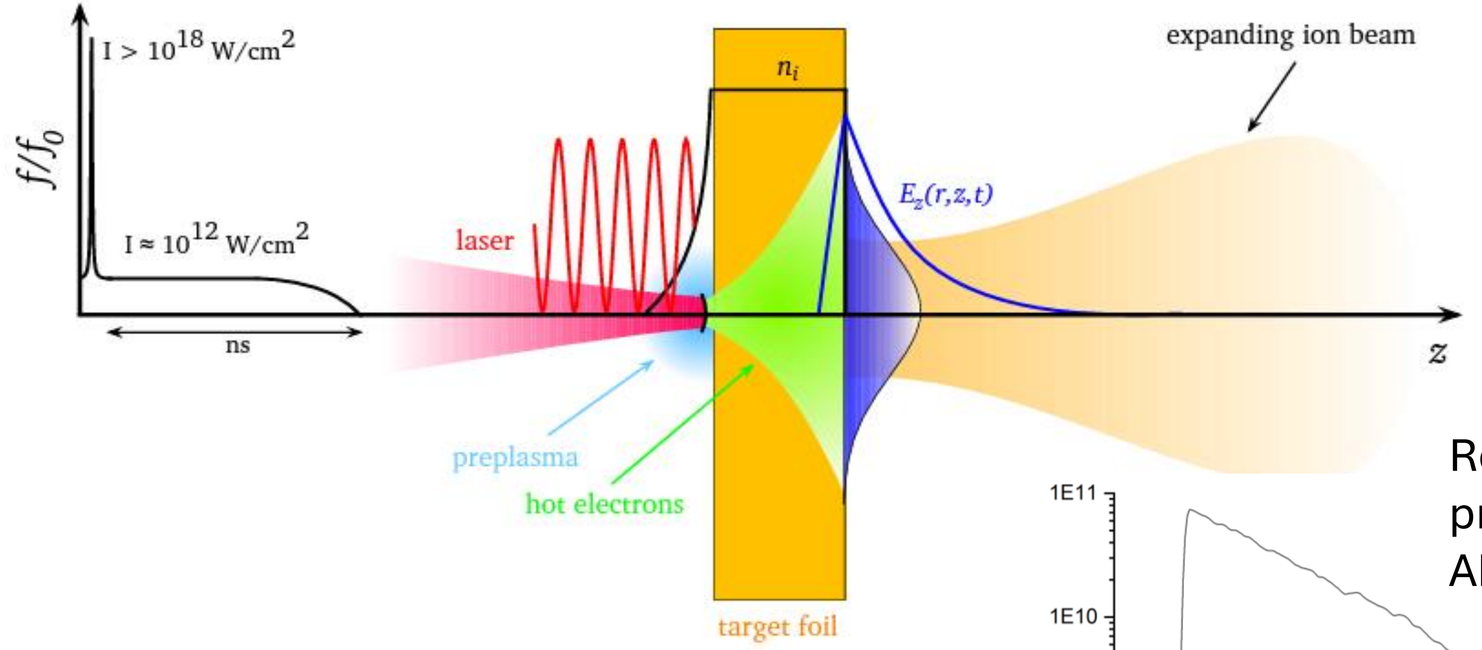
ALLS facility at INRS-EMT : TNSA mechanism and proton spectrum

Laser beam is **focused** down to an **intensity of 1.3x10^{20} W/cm^2**

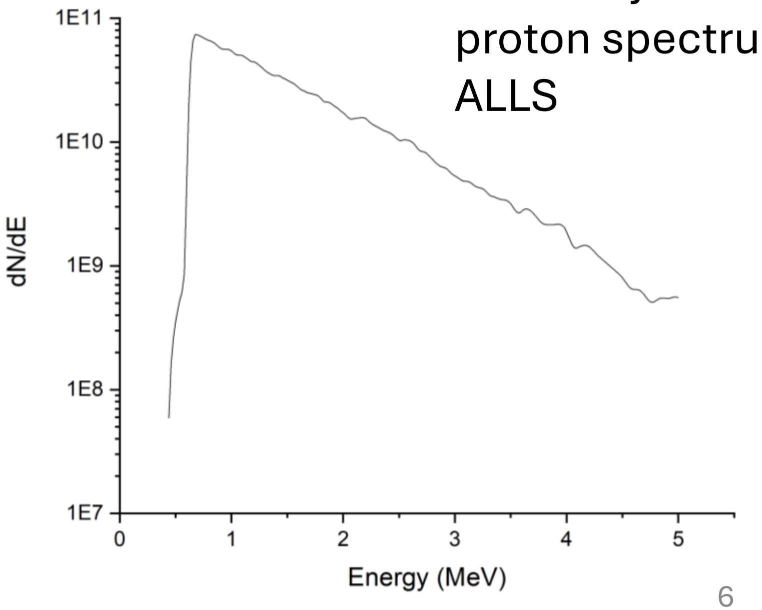
Target Normal Sheath Acceleration (TNSA) mechanism

Ion acceleration

Thin target irradiation by an intense laser pulse:



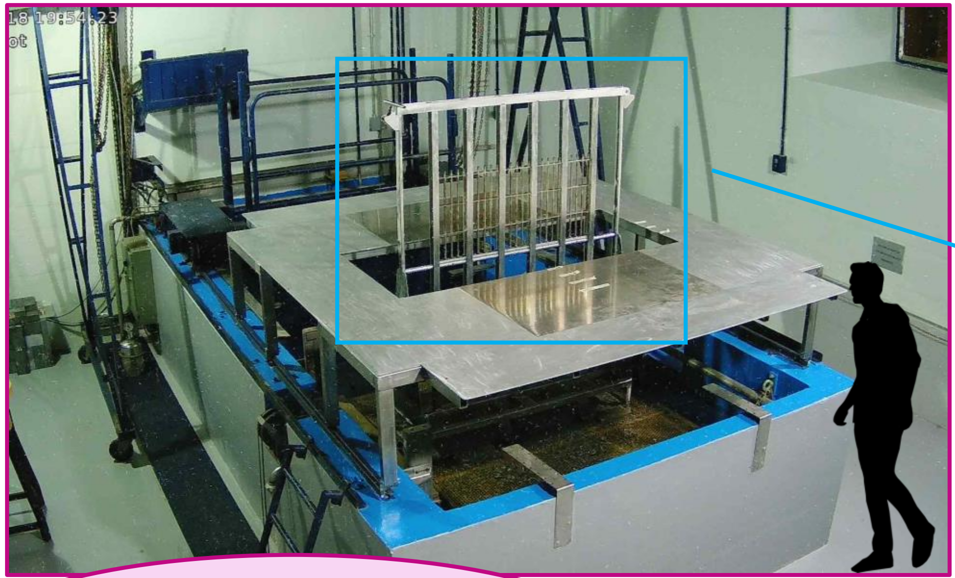
Routinely available proton spectrum at ALLS



- Preplasma creation at the front side of the target
- Main high-intensity laser pulse interaction with the plasma
- Hot electrons acceleration and propagation through the target
- Dense sheath generation at the rear side of the target
- Electric field creation
- Ionization of target rear surface and ions acceleration

M. Roth and M. Schollmeier. IonAcceleration – Target Normal Sheath Acceleration. In CAS - CERN Accelerator School: Plasma Wake Acceleration, pages 231–271, Geneva, 2016.CERN.

Calliope gamma irradiation facility at the ENEA Casaccia R.C. (Rome, Italy)

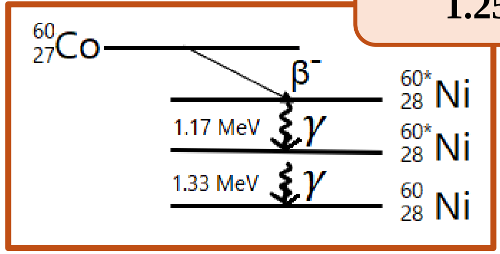


Maximum available **dose rate** (May 2024): **6.2 kGy/h**

Maximum allowed activity: **3.7×10^{15} Bq (100 kCi)**

Pool-type irradiation facility equipped with a **^{60}Co gamma** source in a large volume (7×6×3.9 m^3) shielded cell.
Dosimetric and **characterization** laboratories are available.

Cherenkov effect around the 25 source rods in the plane rack (activity of around 70 kCi)



Mean energy: **1.25 MeV**

- **Irradiation tests at different dose rates, atmospheric and temperature conditions and under bias.**
- **Simulation of the gamma field by Fluka/MCNP code (irradiation cell and irradiated samples).**
- **Online tests and remote acquisition.**
- **ISO 9001 – ISO 17025 (by 2024)**

Activities (research & qualification):
Space, Nuclear, High Energy Physics, environment, radiobiology, Cultural Heritage, agrifood, medicine…

https://www.enea.it/it/seguici/pubblicazioni/pdf-opuscoli/calliope.pdf

Frascati Neutron Generator at the ENEA Frascati R.C. (Frascati, Italy)

The Frascati Neutron Generator (FNG) is a medium intensity neutron source housed in a large shielded cell (11.5×12×9 m^3).

It consists of a linear electrostatic accelerator of D+ ions up to 270 keV and 1 mA.

Research activities:

Benchmark experiments, detector calibration, detector development, Space, Nuclear, Biology, High Energy Physics, environment…

Target	Neutron energy	Maximum neutron flux
Tritiated	**14 MeV** ($T(d,n)^4He$)	$5 \cdot 10^9$ n/cm^2/s
Deuterated	**2.45 MeV** ($D(d,n)^3He$)	$5 \cdot 10^7$ n/cm^2/s

- **Simulation of the neutronic field by MCNP code**
- **Test with high flux, on bias and online data acquisition from the Control Room**

M. Martone, M. Angelone, M. Pillon, The 14 MeV Frascati Neutron Generator (FNG), Journal of nuclear materials, Volume 212-215 Part II, pp. 1661-1664 (1994)

Possible radiation effects on electronics

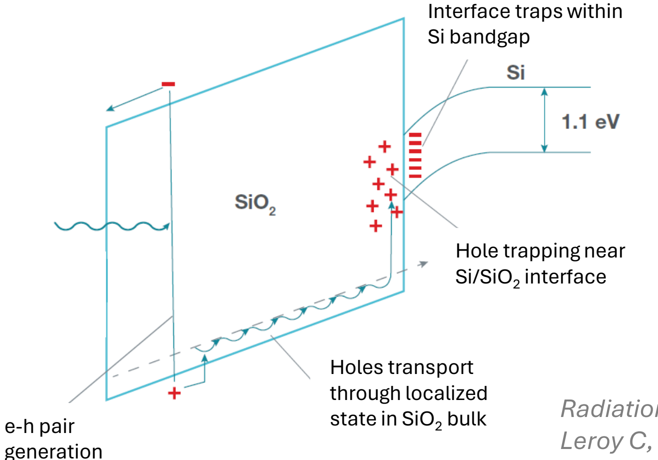
The active material of electronic devices is often made of **silicon.**

Energy loss by ionization: interactions of atomic particle which result in the *excitation* or *emission* of atomic electrons

Gamma radiation

Total Ionizing Dose (TID) damage

Surface damage



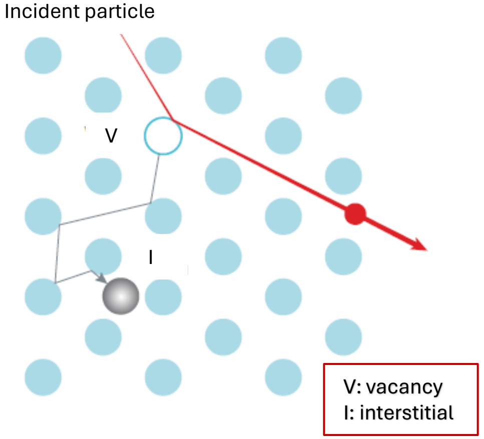
Non Ionizing Energy Loss (NIEL) processes: interactions in which the energy imparted by the incoming particle result in *atomic displacement*.

Protons neutrons

Displacement Damage (DD) dose

Bulk damage

Cumulative effects



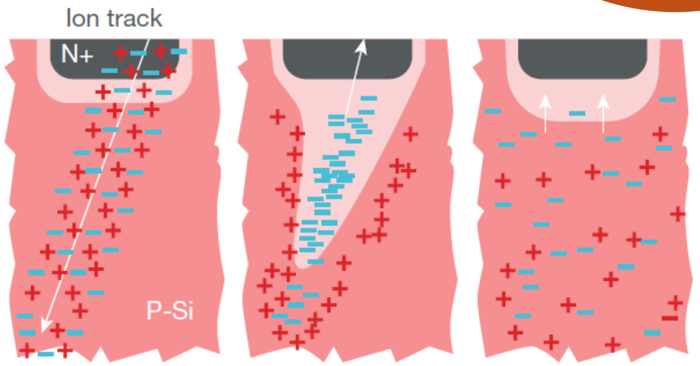
Single event effect (SEE): related to single individual interactions:

→ **single event upset (SEU)**: bit flips in memory circuits;

→ **single event latchup (SEL)**: locally deposited charge.

Heavy ions

Single interaction



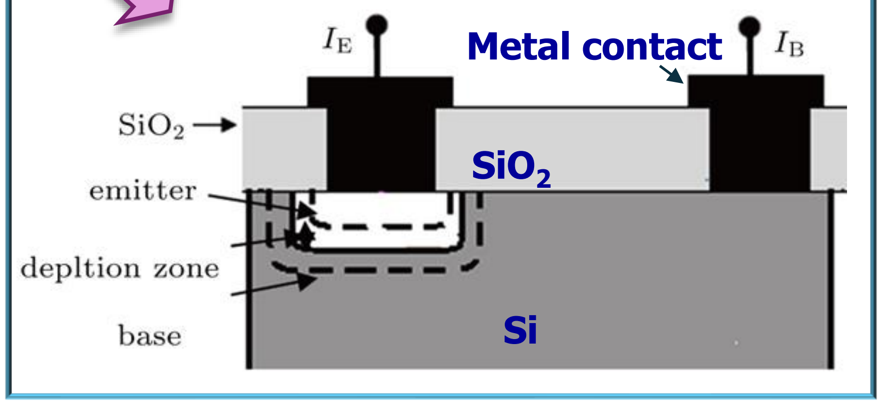
Radiation Handbook for electronics, Texas Instruments (2018) www.ti.com/radbook

Leroy C, Rancoita PG. Particle interaction and displacement damage in silicon devices operated in radiation environments. Reports Prog Phys. 2007;70(4):493–625

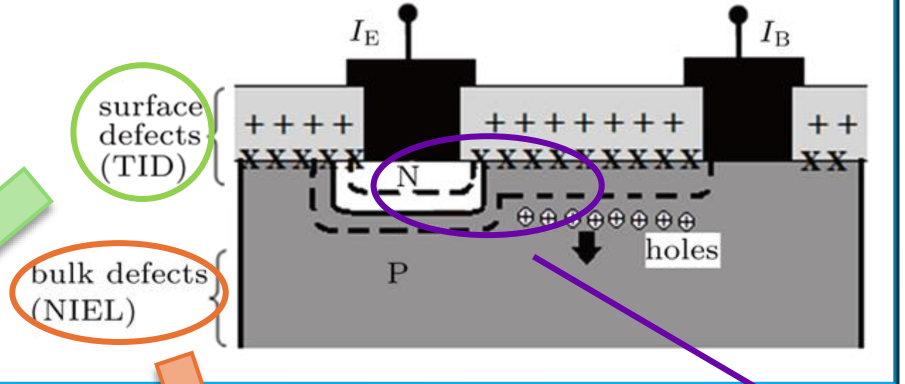
Typical radiation effects on BJTs

Base Emitter (BE) junction of NPN BJTs

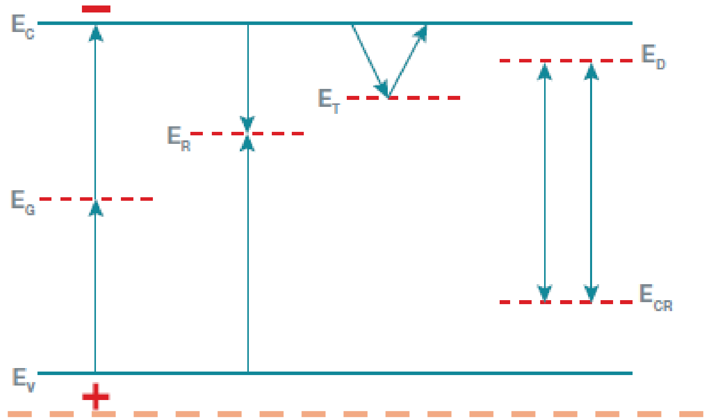
BEFORE IRRADIATION



AFTER IRRADIATION



Interstitials-vacancies creation



Spreading of BE depletion region (increased recombination, increased base current)

Reduction of minority carriers lifetime (increased recombination)

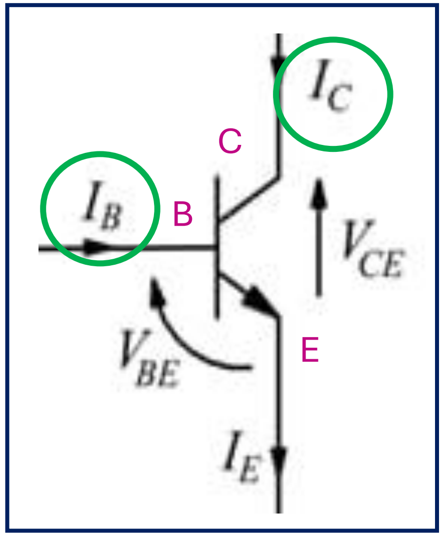
These effects translate in BJTs current gain degradation

e^--h creation and separation
→ e^- drift outside the oxide
→ h migration and trapping in the Si-SiO_2 interface

J Assaf 2018 Chinese Phys. B 27 016103
Radiation Handbook for electronics, Texas Instruments (2018) www.ti.com/radbook

COTS BJTs:
Radiation damage evaluation

To evaluate the radiation effect, the **β parameter**, corresponding to the transistor **current gain**, the **leakage currents** and **saturation voltages** were measured.



$$I_c = \beta I_B$$

I_C: collector current
I_B: base current
I_E: emitter current
V_{CE}: collector to emitter voltage
V_{CE}: emitter to base voltage

Gain:

$\rightarrow \beta_1$ measured for $I_c = 0.1\ mA$

$\rightarrow \beta_2$ measured for $I_c = 1\ mA$

$$\Delta\left(\frac{1}{\beta}\right) = \frac{1}{\beta^{irr}} - \frac{1}{\beta^{0}}$$

Other measured parameters:

Leakage currents

I_{CBO} (collector base cutoff current)
I_{EBO} (emitter base cutoff current)
I_{CEO} (collector emitter cutoff current)

Current that flows when the device is in off state

Saturation voltages

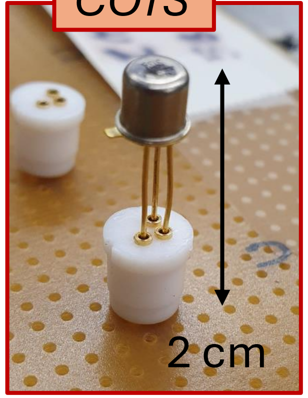
$V_{CE(SAT)}$ collector to emitter saturation voltage
$V_{BE(SAT)}$ base to emitter saturation voltage

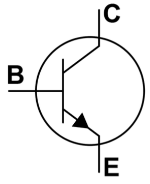
Voltage beyond which the collector current remains constant as the base current increases.

COTS BJTs:
gamma irradiation steps and measurements - 1

^{60}Co gamma radiation

COTS



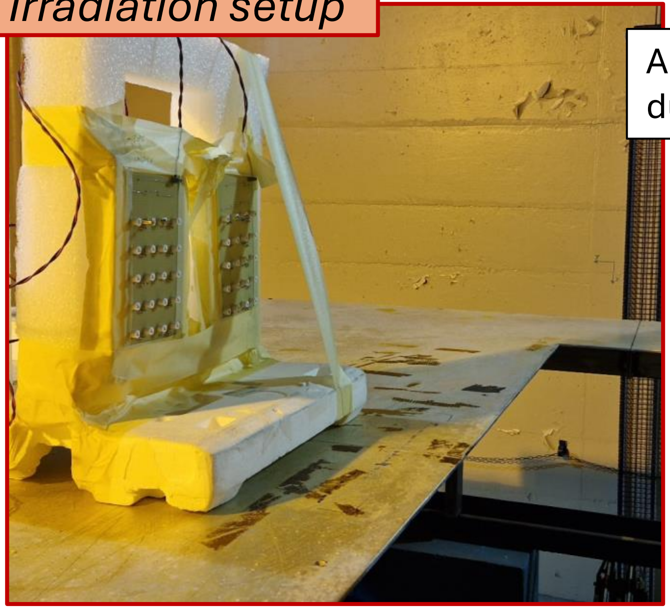


NPN

- **Eighteen samples** (NPN bipolar transistors 2N2222A) two for each irradiation condition
- Irradiation at different absorbed doses
- Dose rate = ~ **1 kGy(Si)/h**

Irradiation test	Total absorbed dose (kGy)
1	~1
2	~2.2
3	~26
4	~70
5	~120
6	~240
7	~320
8	~420
9	~520

Irradiation setup



All samples were biased during irradiation (+30 V).

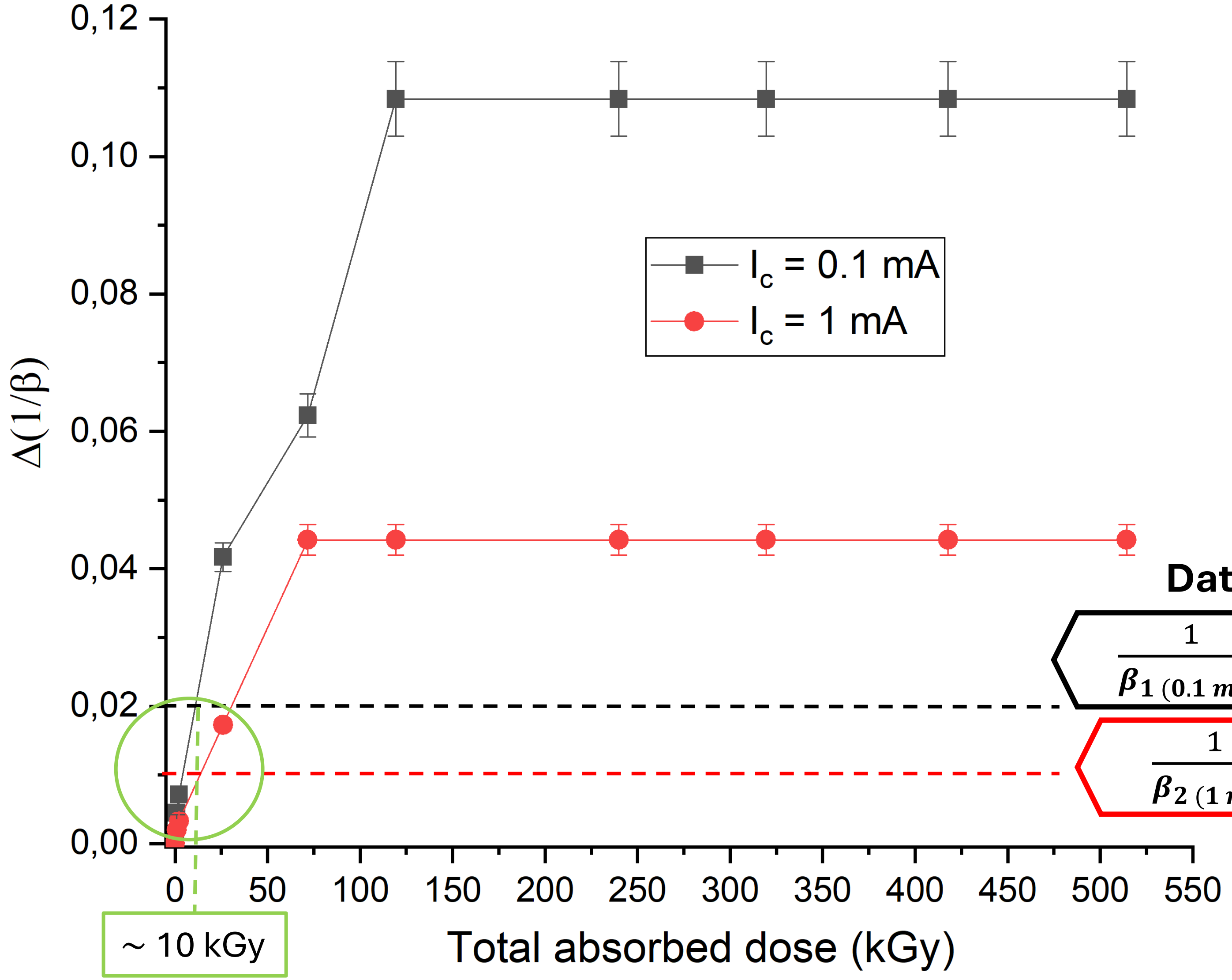
Irradiation tests:

Irradiation at room temperature and parametric tests after irradiation

Annealing followed by parametric tests**:**
-24 hours at room temperature
-168 hours at 100 °C

COTS BJTs:
gamma irradiation steps and measurements - 2

^{60}Co gamma radiation



$$\Delta\left(\frac{1}{\beta_i}\right) = \frac{1}{\beta_i^{irr}} - \frac{1}{\beta_i^{0}}$$

$\frac{1}{\beta_1^0} \sim 0.004$

→ $\beta_1$measured for $I_c = 0.1\ mA$

$\frac{1}{\beta_2^0} \sim 0.004$

→ $\beta_2$measured for $I_c = 1\ mA$

Datasheet

$\frac{1}{\beta_{1\,(0.1\,mA)}} < 0.02$

$\frac{1}{\beta_{2\,(1\,mA)}} < 0.01$

HEAVILY damaged

after irradiation at absorbed dose values > ~10 kGy(Si)

COTS BJTs: *gamma irradiation steps and measurements - 3*

^{60}Co gamma radiation

Annealing tests

ACS Discovery DM340C climatic chamber

After irradiation, two annealing tests were performed in order to evaluate the **recovery** of the parameters.

Slight recovery of the samples irradiated up to 2.2 kGy(Si) after the annealing tests

No recovery of the heavily damaged samples after the annealing tests

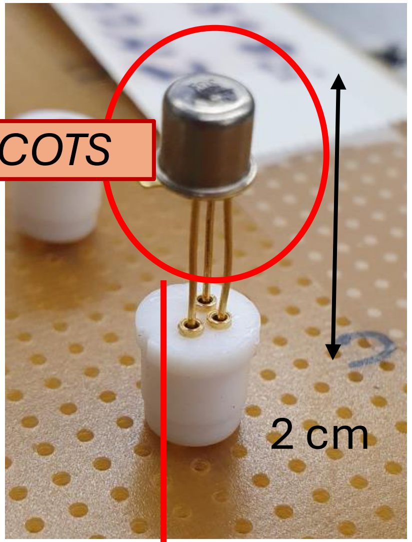
End of irradiation
↓
Annealing step: 25 °C for 24 hours.
↓
Parametric test
↓
Annealing step: 100 °C for 168 hours.
↓
Parametric test
↓
End of test

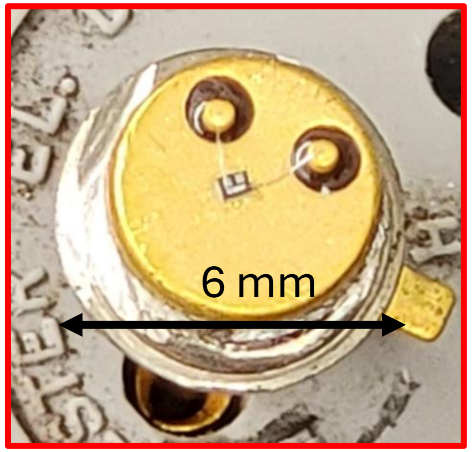
COTS BJTs: proton irradiation tests (ALLS) and measurements - 1

Laser-driven Protons

- **Six decapped samples** (NPN bipolar transistors 2N2222A)
- Irradiation at different absorbed dose

Dose ~ 3.5 *Gy* per each shot





The lid was removed

All samples were unbiased during irradiation.

MATLAB

Irradiation test	Number of shots	Absorbed dose (Gy)
1	1	3.5
2	5	17.5
3	50	175
4	100	350
5	250	875
6	400	1400

Irradiation tests:

Irradiation at room temperature and parametric test after irradiation

Annealing followed by parametric tests**:**
-24 hours at room temperature
-168 hours at 100 °C

COTS BJTs: proton irradiation tests (ALLS) and measurements - 2

Laser-driven Protons

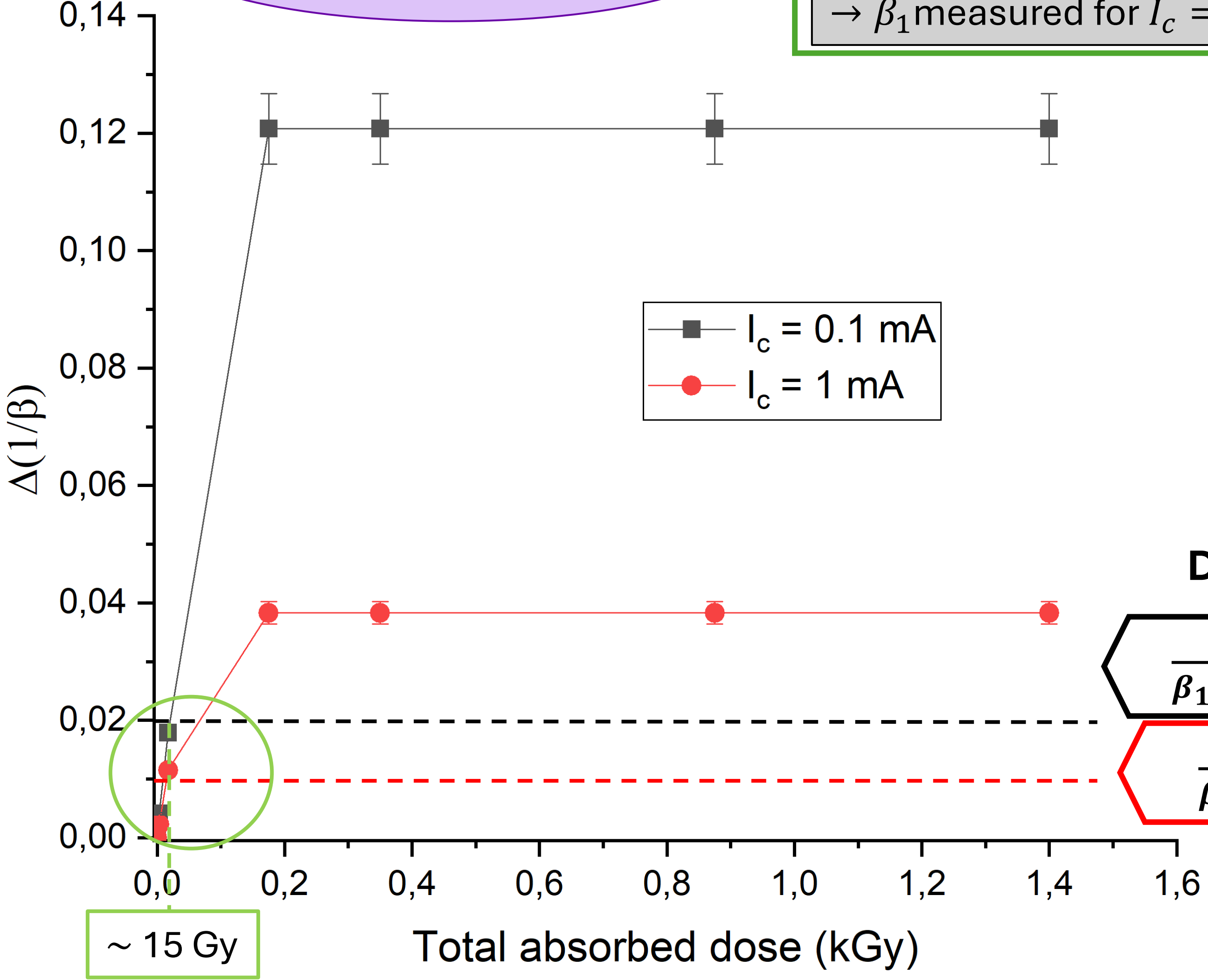
Each sample was irradiated with a given number of shots (1, 5, 50, 100, 250, 400)

$$\Delta\left(\frac{1}{\beta_i}\right) = \frac{1}{\beta_i^{irr}} - \frac{1}{\beta_i^{0}}$$

$\frac{1}{\beta_1^0} \sim 0.004$ $\quad$ $\frac{1}{\beta_2^0} \sim 0.004$

$\rightarrow \beta_1$ measured for $I_c = 0.1\ mA$

$\rightarrow \beta_2$ measured for $I_c = 1\ mA$



Datasheet

$\frac{1}{\beta_{1\,(0.1\,mA)}} < 0.02$

$\frac{1}{\beta_{2\,(1\,mA)}} < 0.01$

HEAVILY damaged

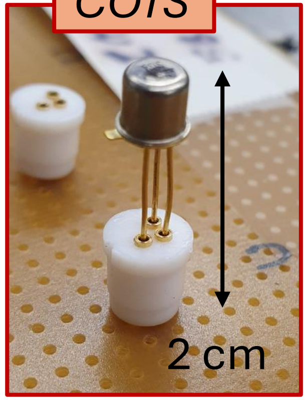
after irradiation with a number of shots > ~4 (~15 Gy)

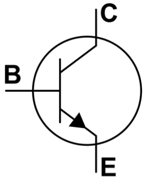
No recovery after the annealing tests

COTS BJTs: neutron irradiation tests and measurements - 1

14 MeV Neutrons

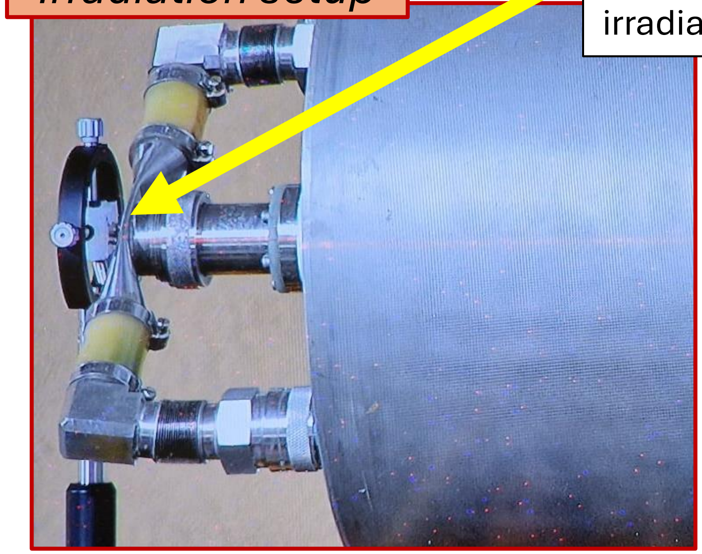
COTS





- **Ten samples** (NPN bipolar transistors 2N2222A) two for each irradiation condition
- Irradiation up to different neutron fluences (14 MeV neutrons)

Irradiation setup



All samples were unbiased during irradiation.

$\mathrm{SR} - NIEL\ Calculator\ (ASTM\ E722 - 19)$

Irradiation test	Neutron fluence	NIEL absorbed dose (Gy)
1	$2 \cdot 10^{9}$ n/cm^2	$1.2 \cdot 10^{-3}$
2	$2 \cdot 10^{11}$ n/cm^2	$1.2 \cdot 10^{-1}$
3	$2 \cdot 10^{12}$ n/cm^2	1.2
4	$1 \cdot 10^{13}$ n/cm^2	$0.6 \cdot 10^{1}$
5	$2 \cdot 10^{13}$ n/cm^2	$1.2 \cdot 10^{1}$

Irradiation tests:

Irradiation at room temperature and parametric test after irradiation

Annealing followed by parametric tests**:**
-24 hours at room temperature
-168 hours at 100 °C

ASTM E722-19: Standard Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics
https://www.sr-niel.org/index.php/sr-niel-web-calculators/niel-calculator-for-neutrons-using-astm-standards/neutrons-niel-calculator

COTS BJTs: neutron irradiation tests and measurements - 2

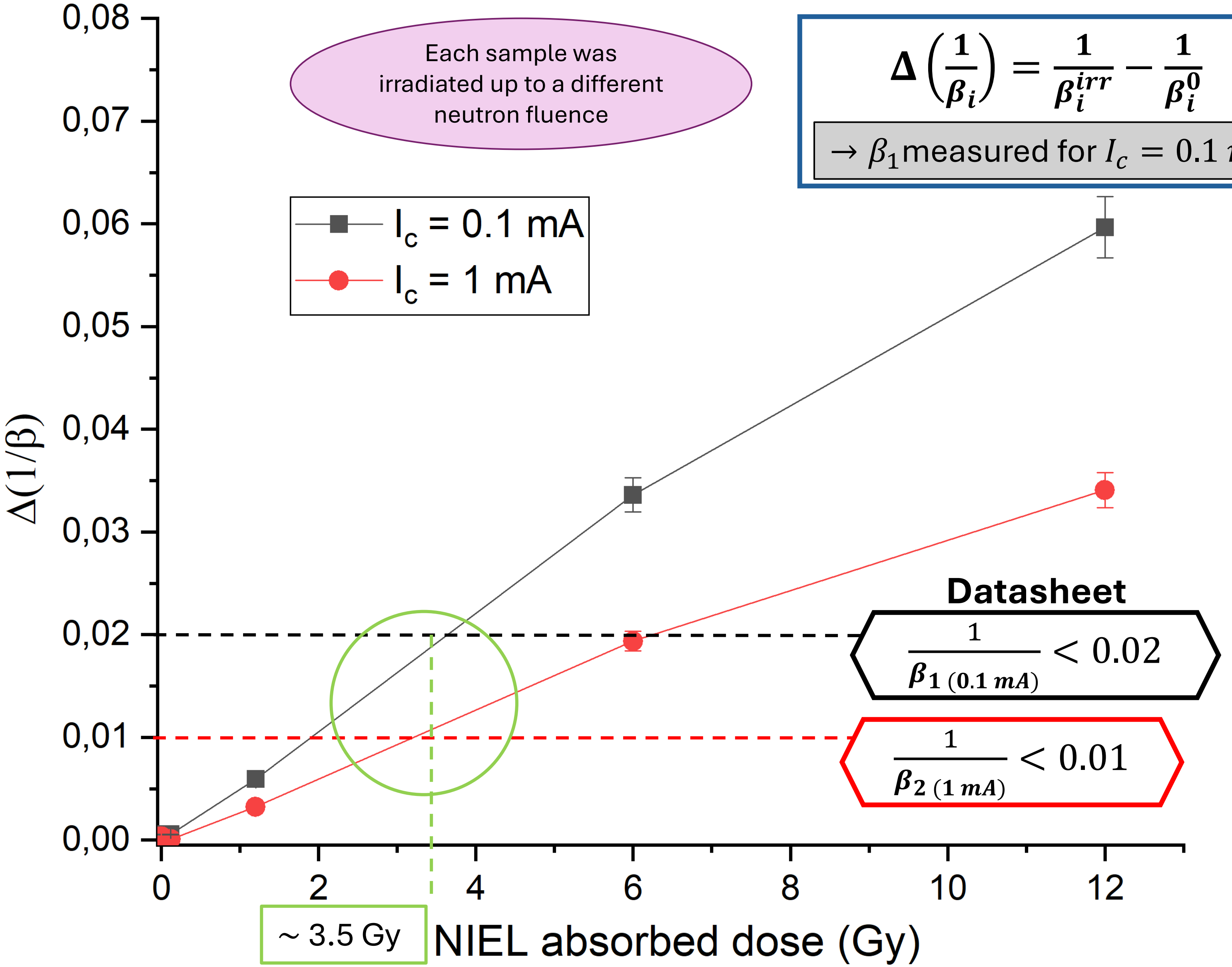
14 MeV Neutrons

$$\Delta\left(\frac{1}{\beta_i}\right) = \frac{1}{\beta_i^{irr}} - \frac{1}{\beta_i^{0}}$$

$\frac{1}{\beta_1^0} \sim 0.004$ $\frac{1}{\beta_2^0} \sim 0.004$

$\rightarrow \beta_1$ measured for $I_c = 0.1\ mA$

$\rightarrow \beta_2$ measured for $I_c = 1\ mA$



HEAVILY damaged

after irradiation with neutron fluence $> \sim 6 \cdot 10^{12}$ n/cm^2 ($D_{NIEL} \sim 3.5$ Gy)

Ongoing annealing tests

NIEL dose deposition study – 1

Non Ionizing Energy Loss (NIEL) processes are mainly related to bulk damage (Frenkel pairs creation, DD)

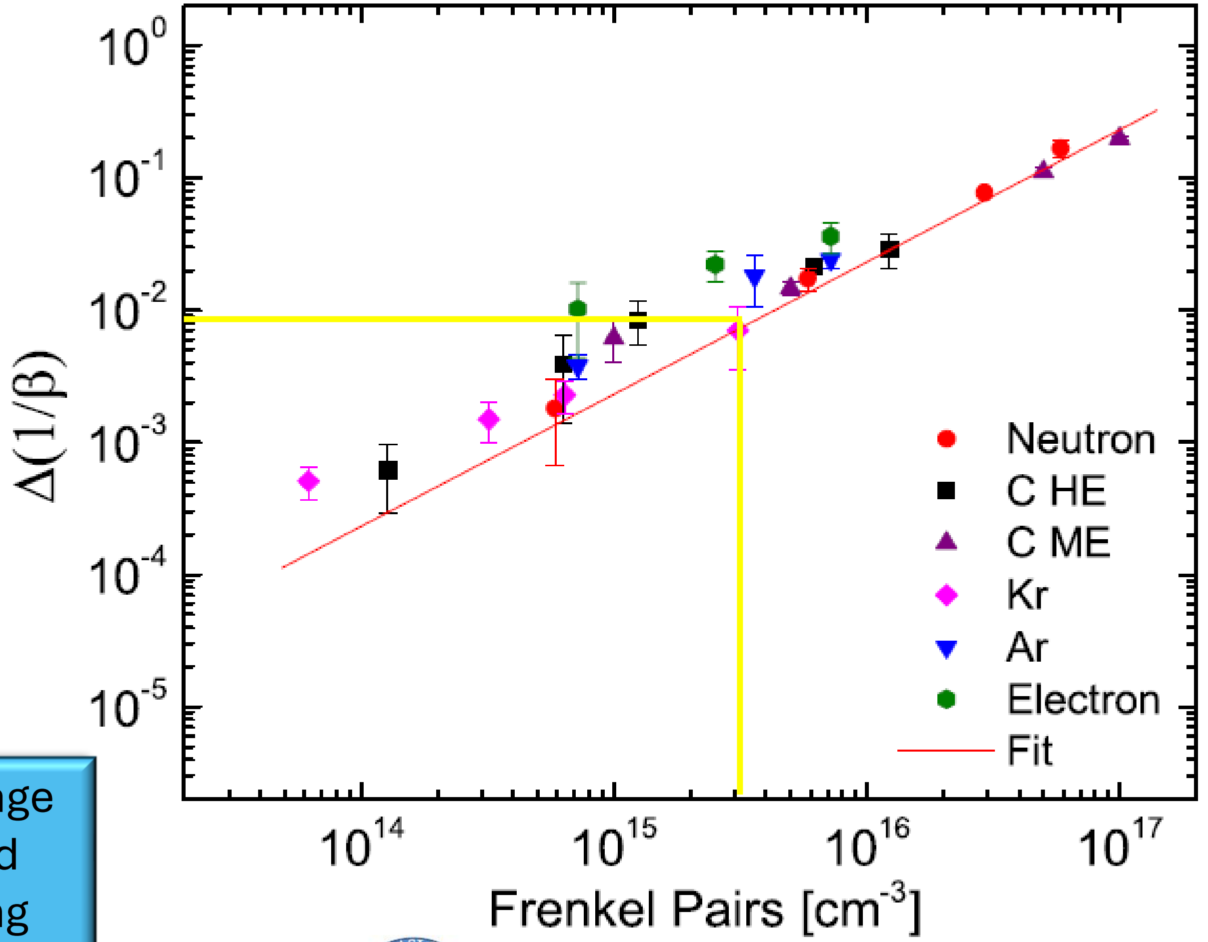
$$\text{Total Dose} = \text{Dose}_{\text{TID}} + \text{Dose}_{\text{NIEL}}$$

TID: Surface damage

NIEL: Bulk damage

TID depends on radiation type and irradiation conditions

NIEL dose allows to predict the damage (proportional to the number of created defects) that cause the malfunctioning **independently of the radiation type**



http://www.asif.asi.it/

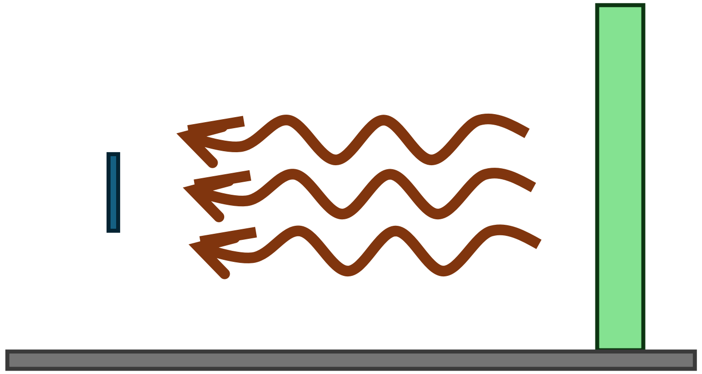
Milano Bicocca University (Physics Dept.)

Leroy C, Rancoita PG. Principles of Radiation Interaction in Matter and Detection. WORLD SCIENTIFIC (2016).
Consolandi C. et al,. (2006). Systematic investigation of monolithic bipolar transistors irradiated with neutrons, heavy ions and electrons for space applications. NUCL INSTRUM METH PHYS RES B. (2006)

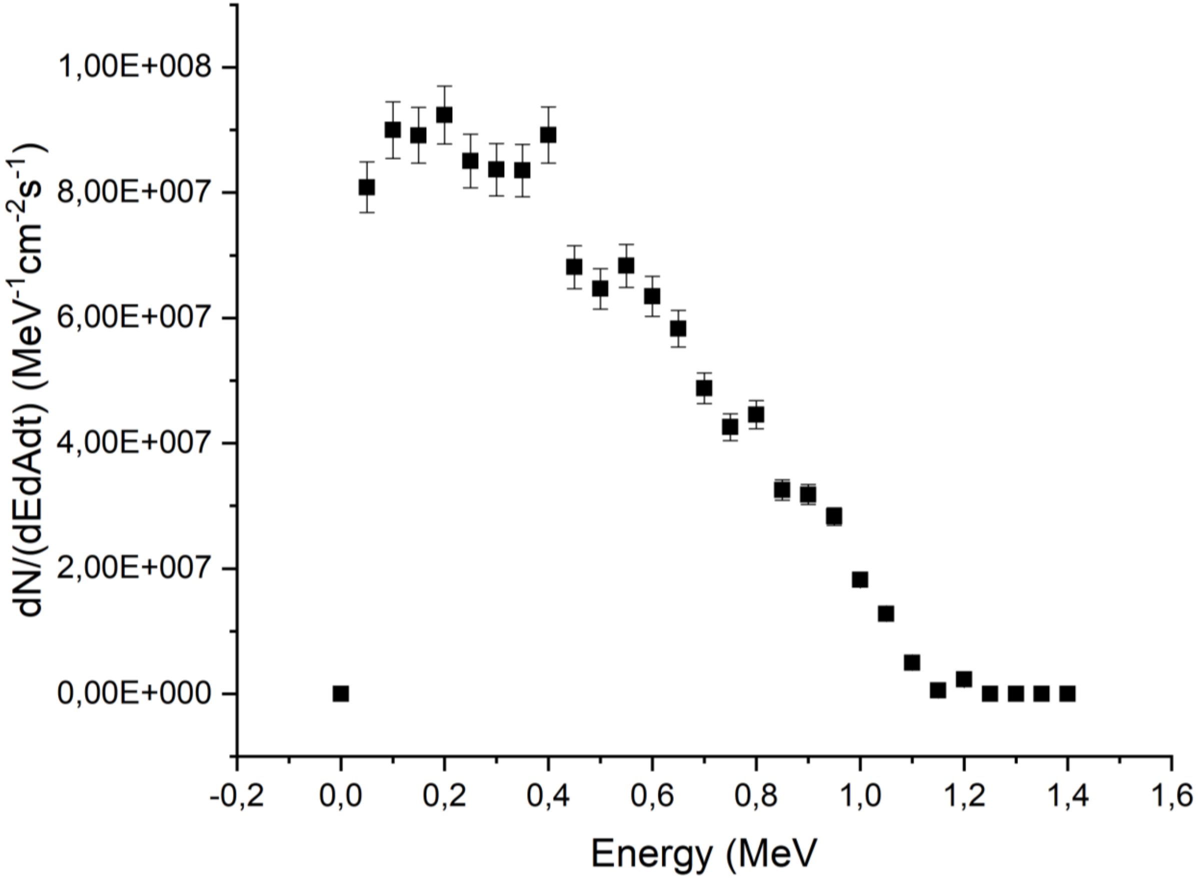
NIEL dose deposition study – 2

^{60}**Co photons** directly induce only TID damage but can create **Compton electrons** responsible of **DD**.

- Sample geometry
- Sample position inside the irradiation cell
- Irradiation conditions (dose and dose rate)



MCNP simulation

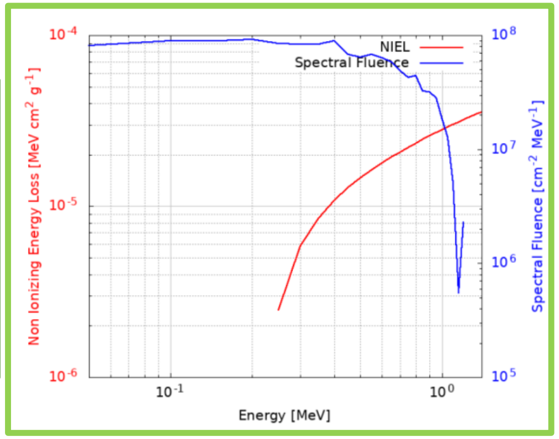


The **electron flux** for gamma irradiation at ~1 kGy(Si)/h

NIEL dose deposition study – 3

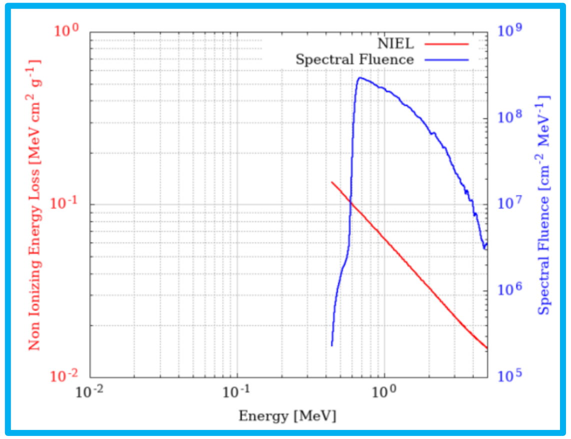
NIEL dose evaluation → ASI sr-niel calculators

Electrons



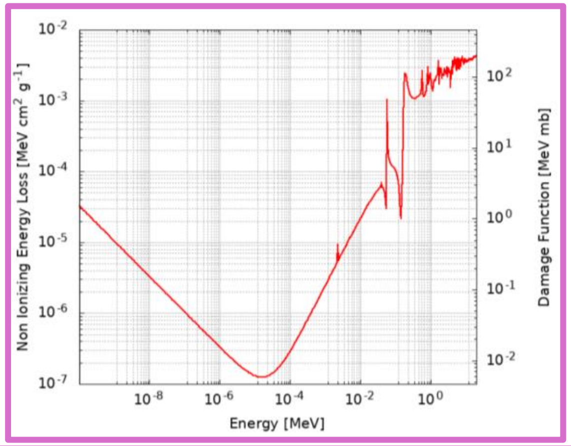
$\text{Dose}_{\text{NIEL}}$ corresponding to fixed irradiation conditions

Protons



$\text{Dose}_{\text{NIEL}}^{\text{shot}} = 2.3 \cdot 10^{-3}$ Gy

Neutrons



$\text{Dose}_{\text{NIEL}}$ for a given 14 MeV neutron fluence

Dose at which the component functioning is compromised

Dose	Sample irradiated with gamma radiation	Sample irradiated with protons	Sample irradiated with neutrons
Total	~10 kGy	~ 15 Gy	Ongoing
TID	~10 kGy	~14.99 Gy	
NIEL	~ 0.01 Gy	~0.01 Gy	

Total Dose $= \text{Dose}_{\text{TID}} + \text{Dose}_{\text{NIEL}}$

https://www.sr-niel.org/index.php/sr-niel-web-calculators

Conclusion

Radiation effects

- Acceptable current gain decrease of biased ***COTS transistors*** *after:*

- Gamma irradiation up to ~10 kGy(Si);
- Laser-accelerated protons irradiation up to ~4 laser shots (~ 15 Gy);
- Neutron irradiation up to a neutron fluence of $6 \cdot 10^{12}$ n/cm^2.

- **Heavily damaged** samples did **not recover** after the annealing tests.

NIEL study

- NIEL dose study allows to evaluate the bulk damage independently of the radiation source.

- Same NIEL absorbed dose (gamma and protons) causes same damage;
- Same total absorbed dose (gamma and protons) causes different damages.

- Ongoing analysis of data obtained after neutron irradiation;
- Ongoing irradiation tests with conventional proton sources and electrons.

Thank you for your attention!

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