Laser-Driven Proton Sources for Efficient Radiation Testing

B. D’Orsi, C. Altomare, A. Ampollini, M.D. Astorino, G. Bazzano, E. Catrix, A. Cemmi, A. Colangeli, I. Di Sarcina, D. S. Lazzaro, R. Lelièvre, S. Loreti, S. Fourmaux, J. Fuchs, P. Nenzi, G. Pagano, F. Panza, C. Ronsivalle, J. Scifo, S. Vallières and P. Antici

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Aim of the work

Electronic devices → **Irradiation** → **Study of radiation effects**

Electronic devices

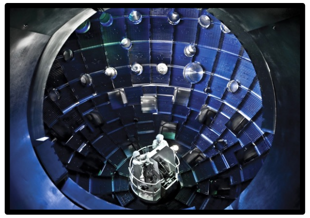
- Commercial
- Radiation tolerant
- Radiation hardened

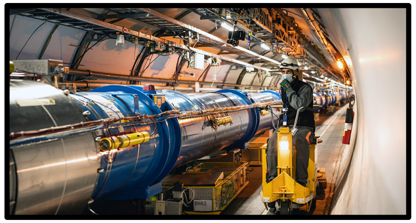
Irradiation

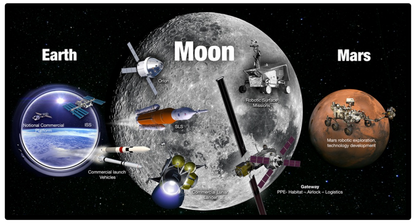
- Photons
- Protons
- Electron
- Neutrons
- Heavy ions
- Etc.

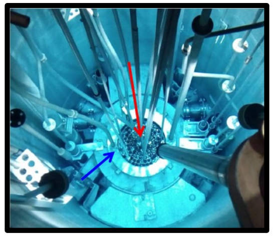
Study of radiation effects

- Electronic measurements
- Data analysis (stress testing optimization)



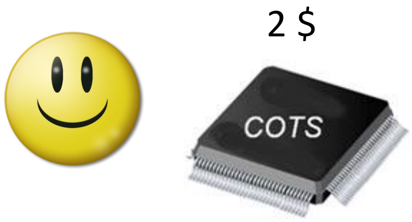




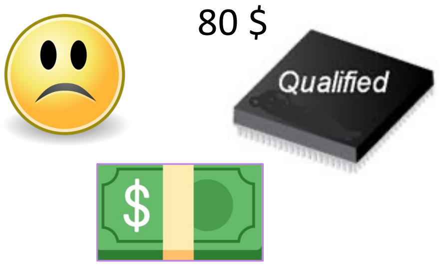


Aim of the work (2)

Electronic devices



Commercial Off-the-Shelf
(COTS)



Radiation tolerant

Irradiation

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

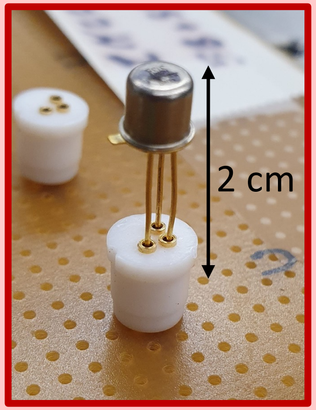
Study of radiation effects

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

Electronic components characterization before and after irradiation

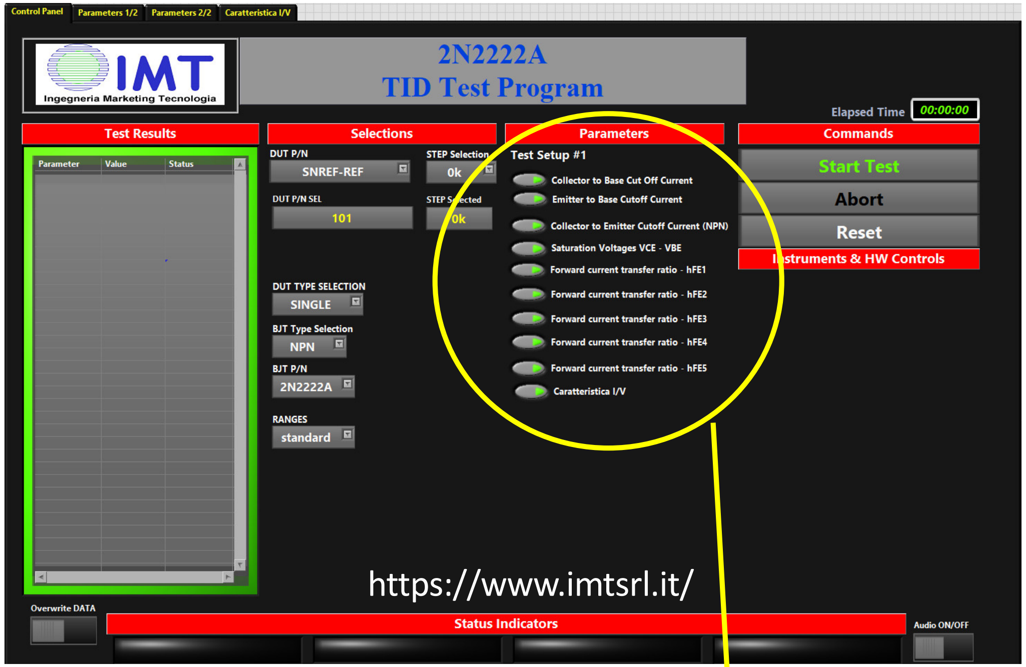
Tested components

COTS NPN and PNP Bipolar Junction Transistors (BJTs)



Radiation tolerant opto-isolator

Not reported here



Elapsed Time: 00:00:00

DUT P/N: SNREF-REF

STEP Selection: 0k

DUT P/N SEL: 101

STEP Selected: 0k

DUT TYPE SELECTION: SINGLE

BJT Type Selection: NPN

BJT P/N: 2N2222A

RANGES: standard

Test Setup #1

- Collector to Base Cut Off Current
- Emitter to Base Cutoff Current
- Collector to Emitter Cutoff Current (NPN)
- Saturation Voltages VCE - VBE
- Forward current transfer ratio - hFE1
- Forward current transfer ratio - hFE2
- Forward current transfer ratio - hFE3
- Forward current transfer ratio - hFE4
- Forward current transfer ratio - hFE5
- Caratteristica I/V

https://www.imtsrl.it/

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

Microsemi. TECHNICAL DATASHEET – 2N2222A NPN silicon switching transistor.
Microsemi. TECHNICAL DATASHEET – 2N2907A PNP small signal silicon transistor.
Skyworks. TECHNICAL DATASHEET - OLS249: Radiation-Tolerant Phototransistor Hermetic Surface-Mount Optocoupler.

Irradiation facilities: Italy and Canada

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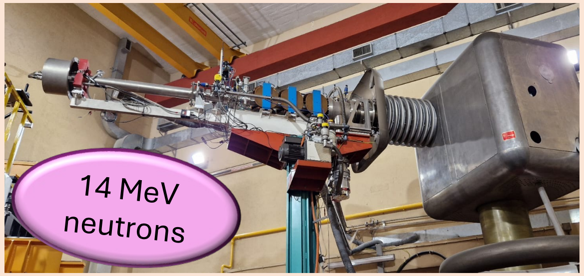
***Conventional** radiation sources for stress testing*

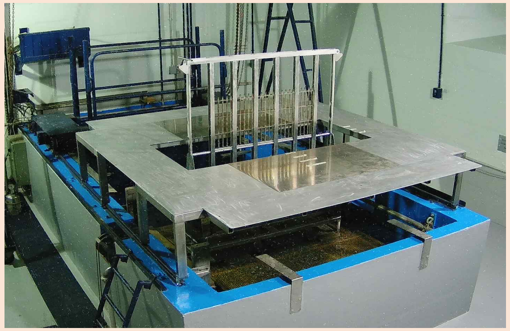
ENEA



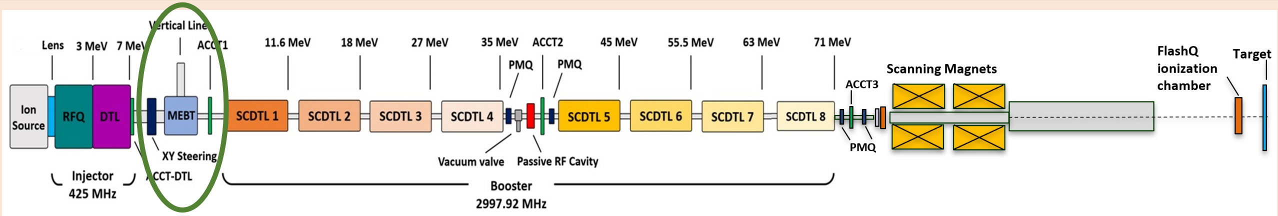
Neutron irradiation Frascati Neutron Generator at ENEA Frascati R.C. (Frascati, Italy)

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

^{60}Co gamma photons (mean energy 1.25 MeV)



Dosimetric laboratory available



2.8 MeV protons

Proton irradiation TOP IMPLART at ENEA Frascati R.C. (Frascati, Italy)

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

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

INRS

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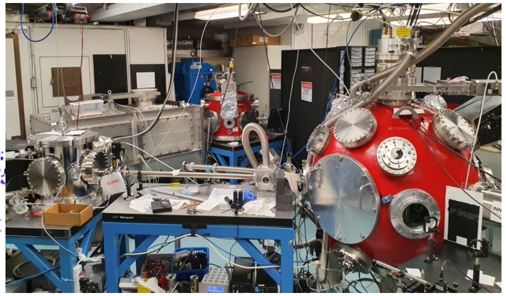
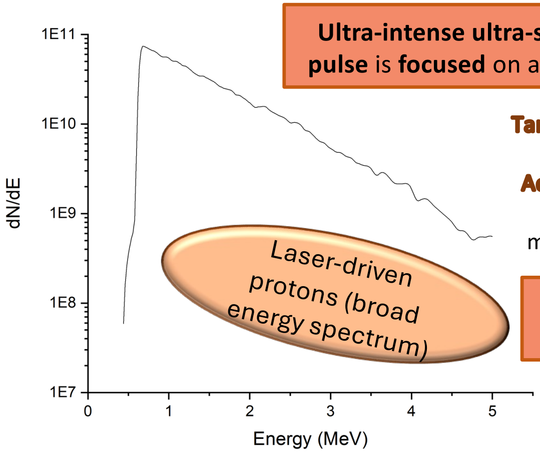




Ultra-intense ultra-short laser pulse is focused on a thin target

Target Normal Sheath Acceleration (TNSA) mechanism

Proton acceleration

Possible radiation effects on electronics

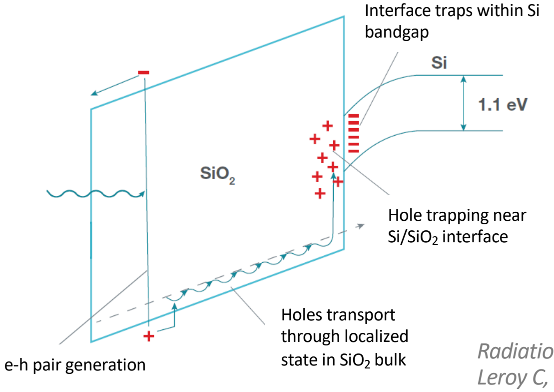
The active material of electronic devices is often made of **silicon.**

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



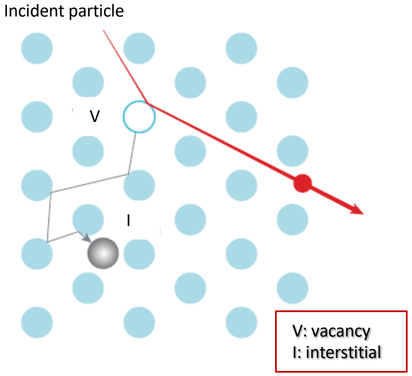
Non Ionizing Energy Loss (NIEL) processes: interactions in which the energy imparted by the incoming particle result in *atomic displacement.*

Protons neutrons

Displacement Damage (DD) dose

Bulk damage

Cumulative effects



Not applicable in this study

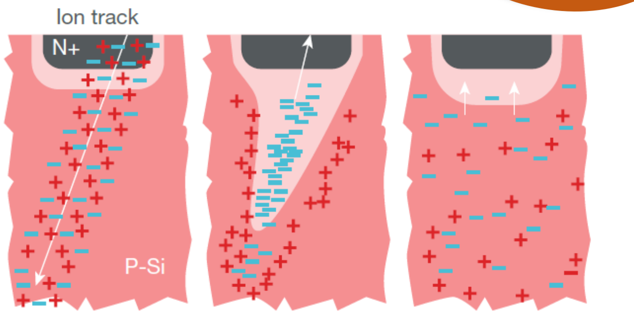
Single event effect (SEE): related to single individual interactions:

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

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

Single interaction

Heavy ions



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 (as easiest semiconductor component)

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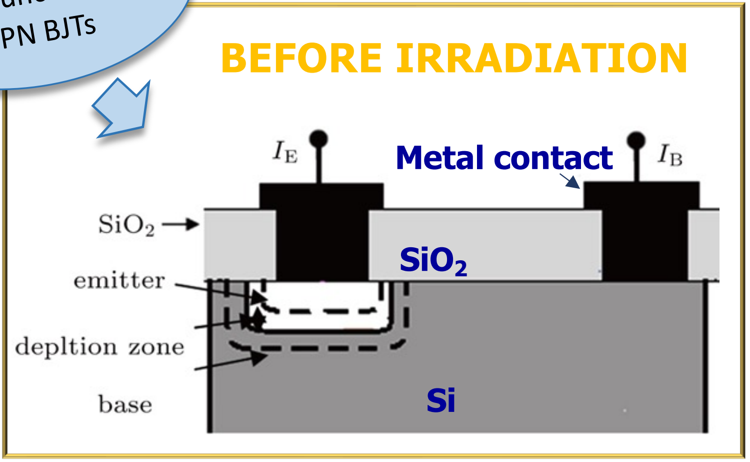
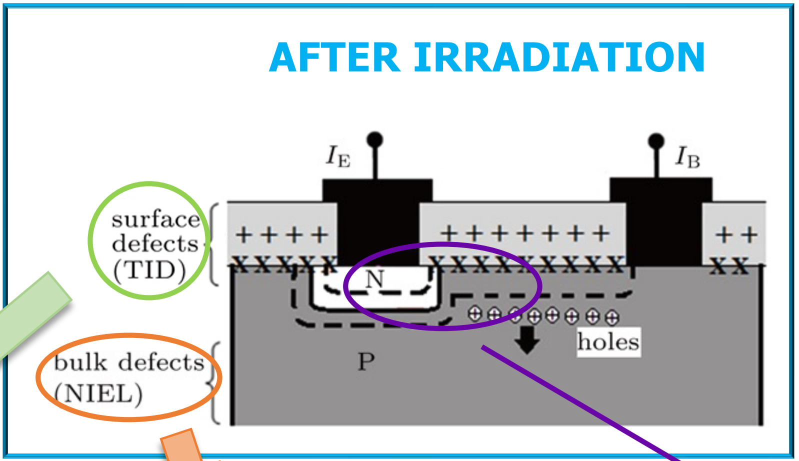
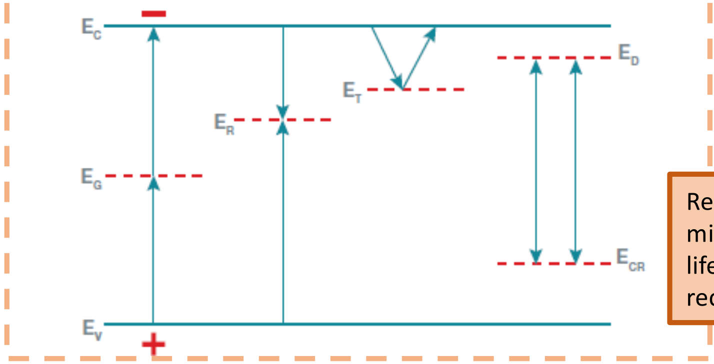
Base Emitter (BE) junction of NPN BJTs





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

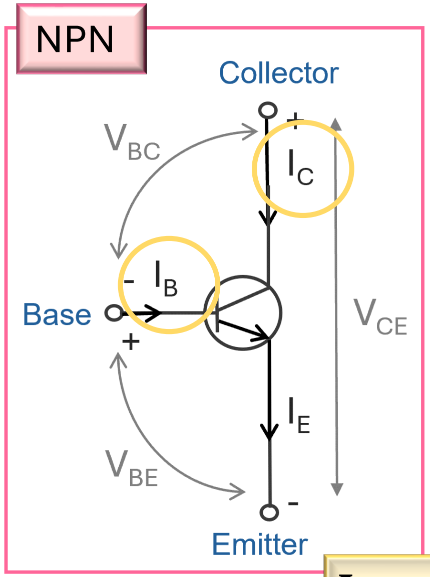
e^--h creation and separation
→ e^- drift outside the oxide
→ h migration and trapping in the Si-SiO_2 interface

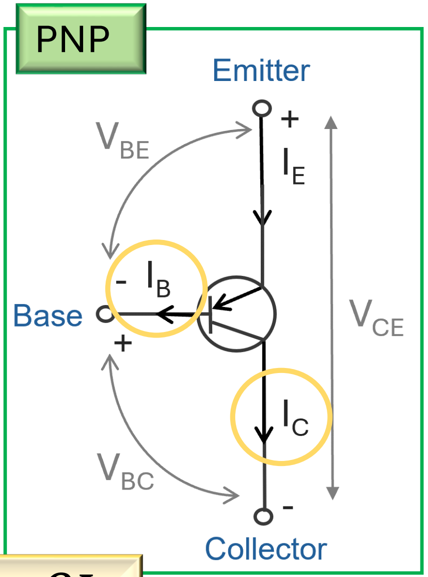
J Assaf 2018 Chinese Phys. B 27 016103
Radiation Handbook for electronics, Texas Instruments (2018) www.ti.com/radbook

COTS BJTs:
Radiation effects evaluation

Innovative Particle Acceleration Technologies
Lasers • Applications • Beamlines

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_{BE}: base to emitter voltage
V_{BC}: base to collector voltage

Microsemi. TECHNICAL DATASHEET – 2N2222A NPN silicon switching transistor.
Microsemi. TECHNICAL DATASHEET – 2N2907A PNP small signal silicon transistor.

β_1 measured for $I_c = 0.1\ mA$
β_2 measured for $I_c = 1\ mA$
β_3 measured for $I_c = 10\ mA$
β_4 measured for $I_c = 150\ mA$
β_5 measured for $I_c = 500\ mA$

Gain

Other measured parameters

Saturation voltages

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

Voltage beyond which the I_C remains constant as the I_B increases.

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

I_C-V_{CE} characteristic curves

Collector current versus the collector to emitter voltage at a fixed I_B (50 μa)

COTS BJTs:
Summary of performed irradiation tests

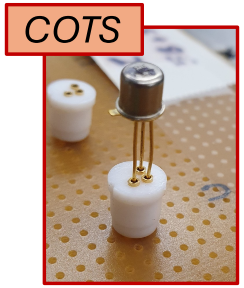
The components were characterized **before** and **after** irradiation.

	COTS **NPN bipolar transistor (2N2222A)**	**COTS** **PNP bipolar transistor (2N2907A)**
Gamma irradiation (Calliope)	✓	✓
Neutron (FNG)	✓	✓
Protons (TOP IMPLART)	✓	✓
Proton irradiation (ALLS)	✓	Next step

COTS BJTs: gamma irradiation tests and measurements - 1

^{60}Co gamma radiation

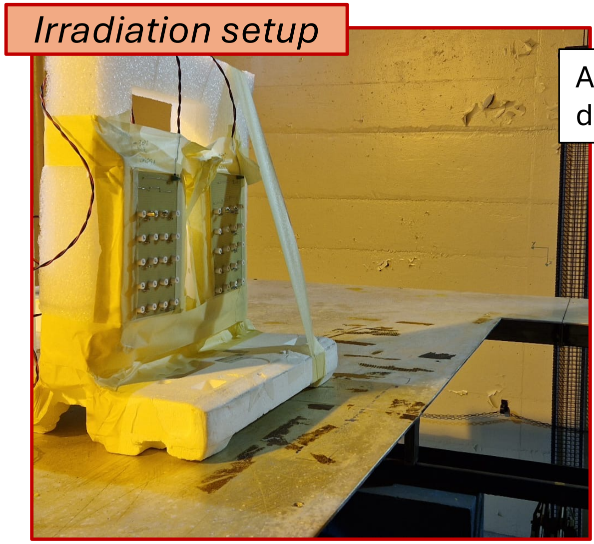
COTS



- **36 samples** (18 NPN and 18 PNP BJTs) 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

1 kGy(Si): 1 kGy absorbed dose in silicon. All reported doses are referred to silicon.

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

^{60}Co gamma radiation

NPN

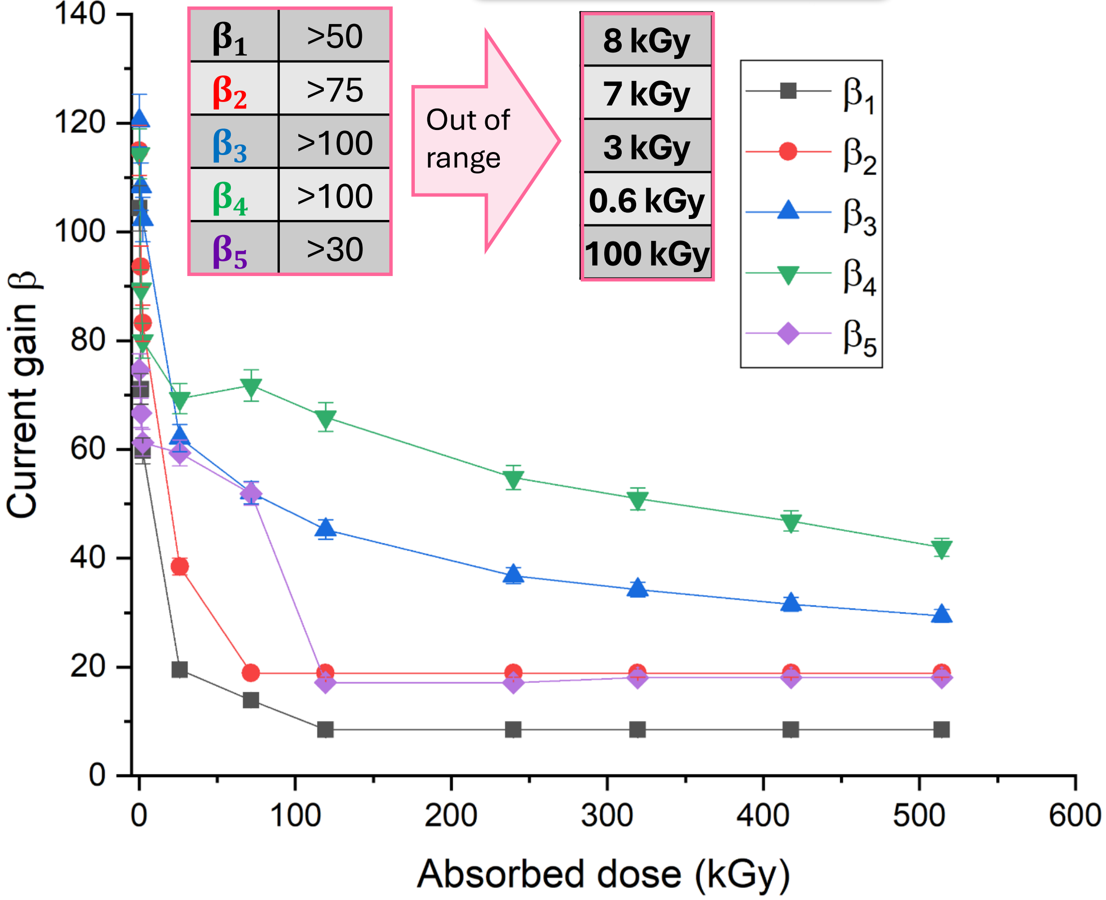
Datasheet allowed values

β_1	>50
β_2	>75
β_3	>100
β_4	>100
β_5	>30

Out of range

HEAVILY damaged after:

8 kGy
7 kGy
3 kGy
0.6 kGy
100 kGy



PNP

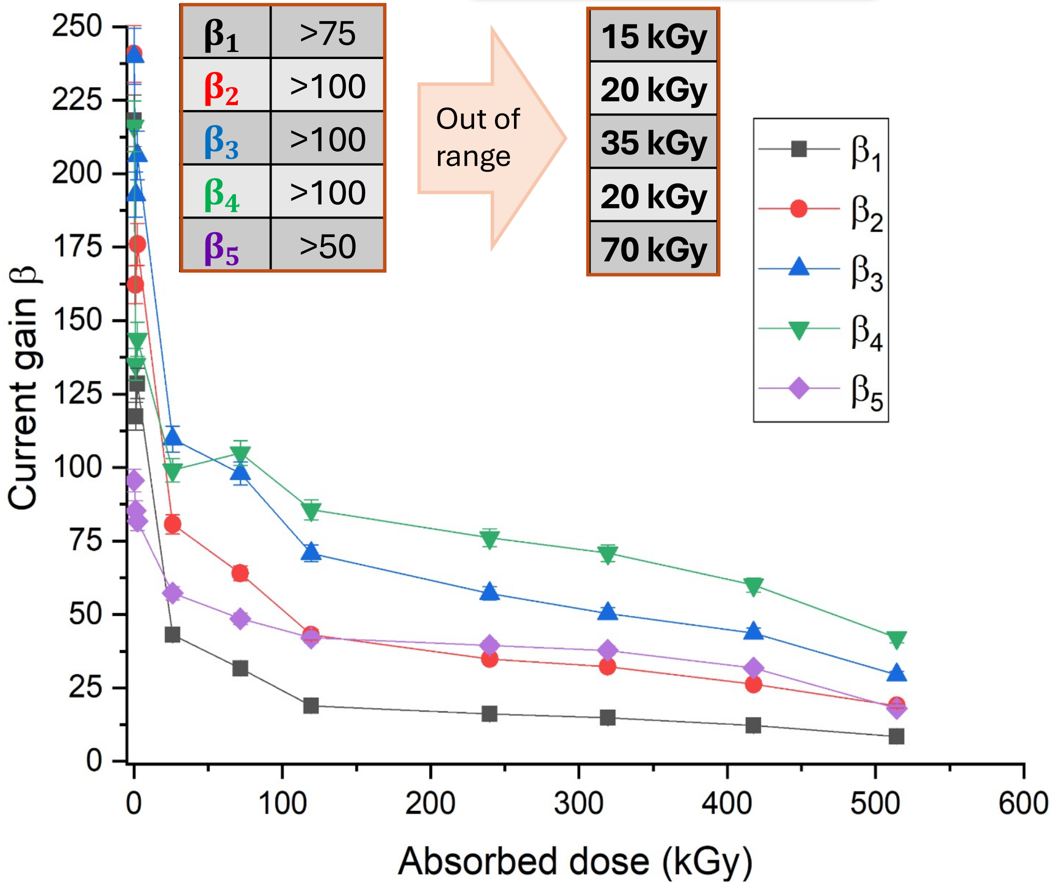
Datasheet allowed values

β_1	>75
β_2	>100
β_3	>100
β_4	>100
β_5	>50

Out of range

HEAVILY damaged after:

15 kGy
20 kGy
35 kGy
20 kGy
70 kGy



COTS BJTs:
annealing tests and measurements - 4

^{60}Co gamma radiation

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

End of irradiation

Annealing step:
25 °C for 24 hours.

Parametric test

Annealing step:
100 °C for 168 hours.

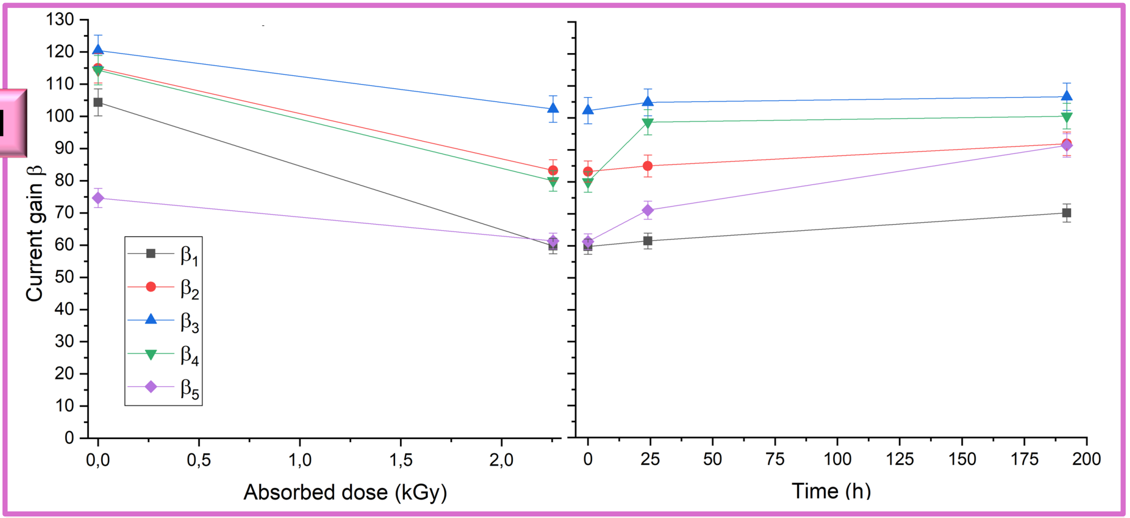
Parametric test

End of test

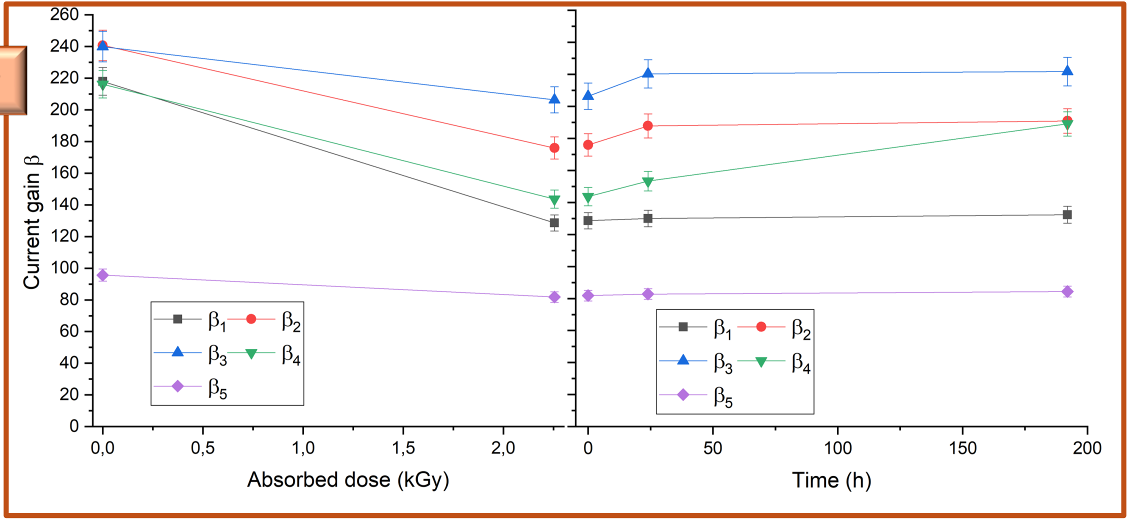
No recovery of the heavily damaged samples after the annealing tests

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

NPN



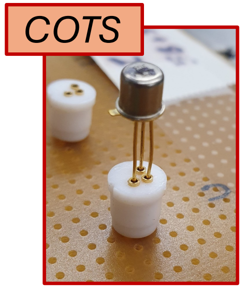
PNP



COTS BJTs:
neutron irradiation tests and measurements - 1

14 MeV neutrons

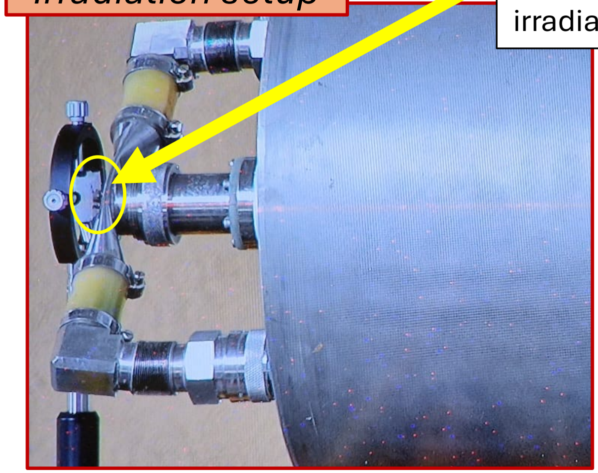
COTS



- **20 samples** (10 NPN and 10 PNP BJTs) two for each irradiation condition
- Irradiation up to different neutron fluences (14 MeV neutrons)

Irradiation test	Neutron fluence
1	$2 \odot 10^{9}$ n/cm^{2}
2	$2 \odot 10^{11}$ n/cm^{2}
3	$2 \odot 10^{12}$ n/cm^{2}
4	$1 \odot 10^{13}$ n/cm^{2}
5	$2 \odot 10^{13}$ n/cm^{2}

Irradiation setup



All samples were unbiased during irradiation.

Irradiation tests:

Irradiation at room temperature and parametric test after irradiation

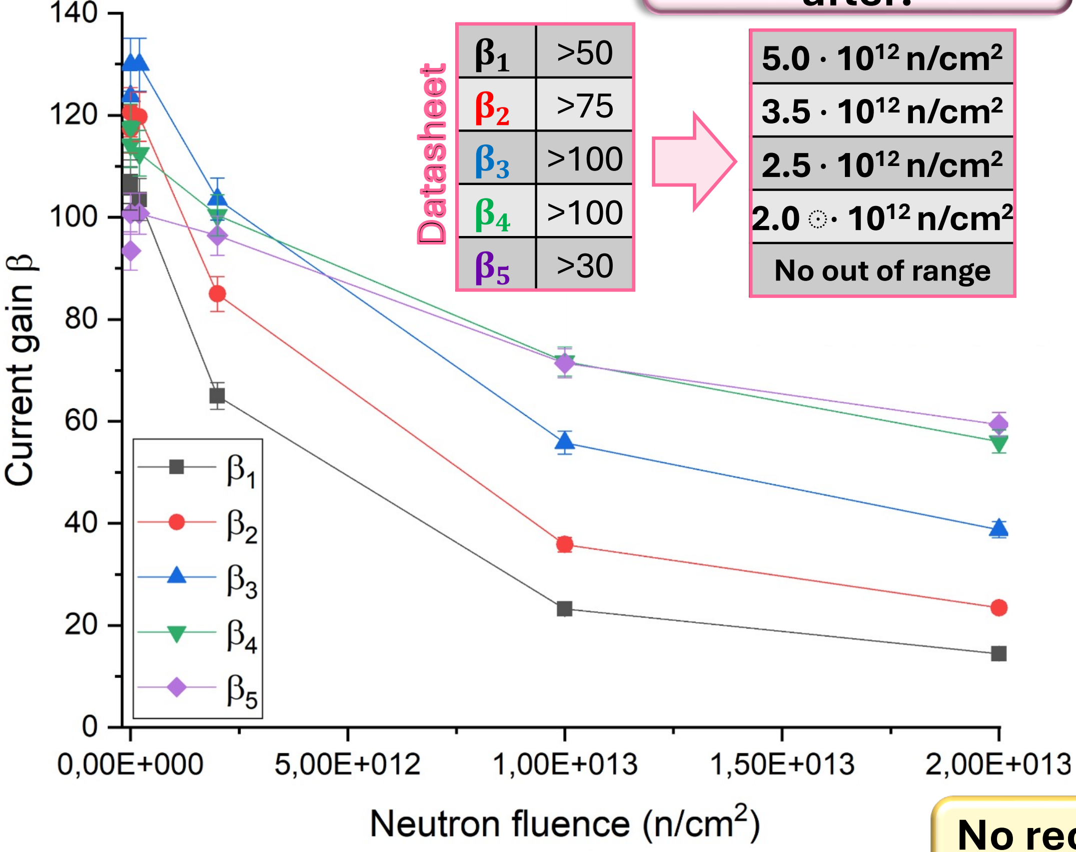
Annealing followed by parametric tests**:**
-24 hours at room temperature
-168 hours at 100 °C

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

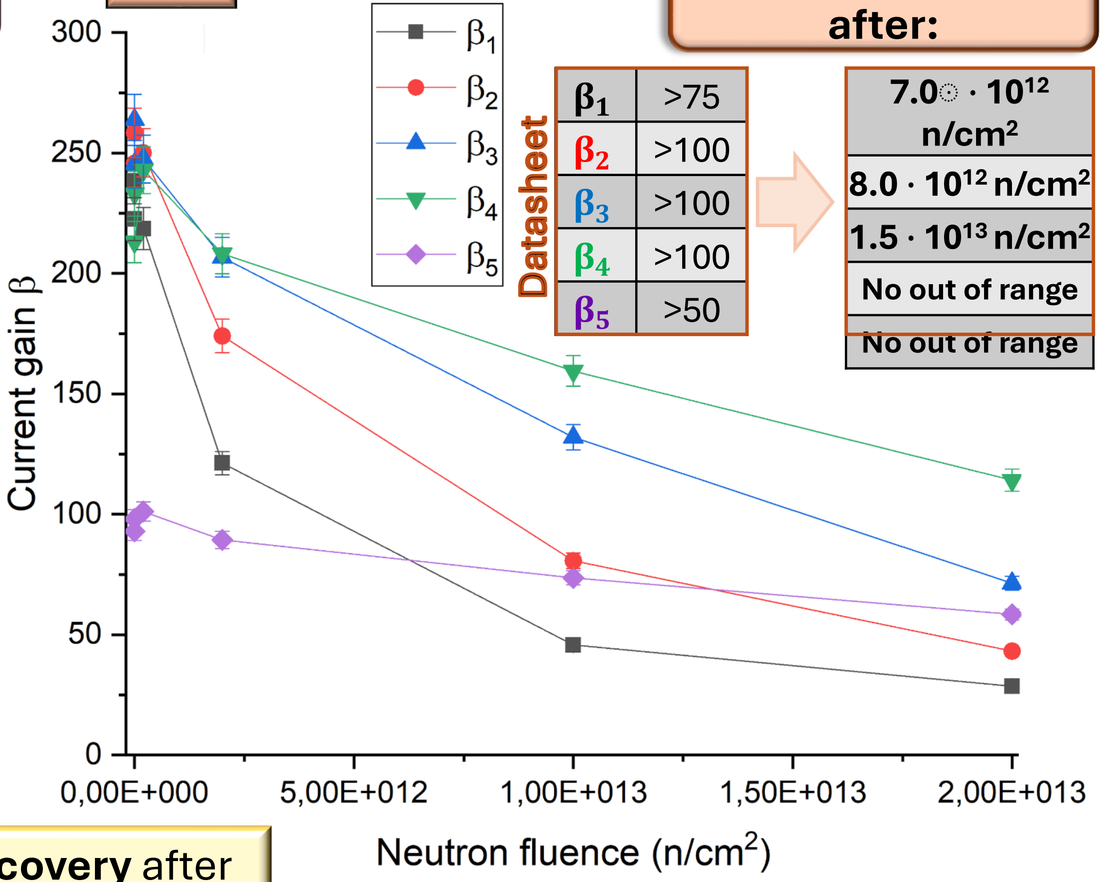
14 MeV neutrons

NPN



	Datasheet	HEAVILY damaged after:
β_1	>50	$5.0 \cdot 10^{12}$ n/cm²
β_2	>75	$3.5 \cdot 10^{12}$ n/cm²
β_3	>100	$2.5 \cdot 10^{12}$ n/cm²
β_4	>100	$2.0 \cdot 10^{12}$ n/cm²
β_5	>30	No out of range

PNP

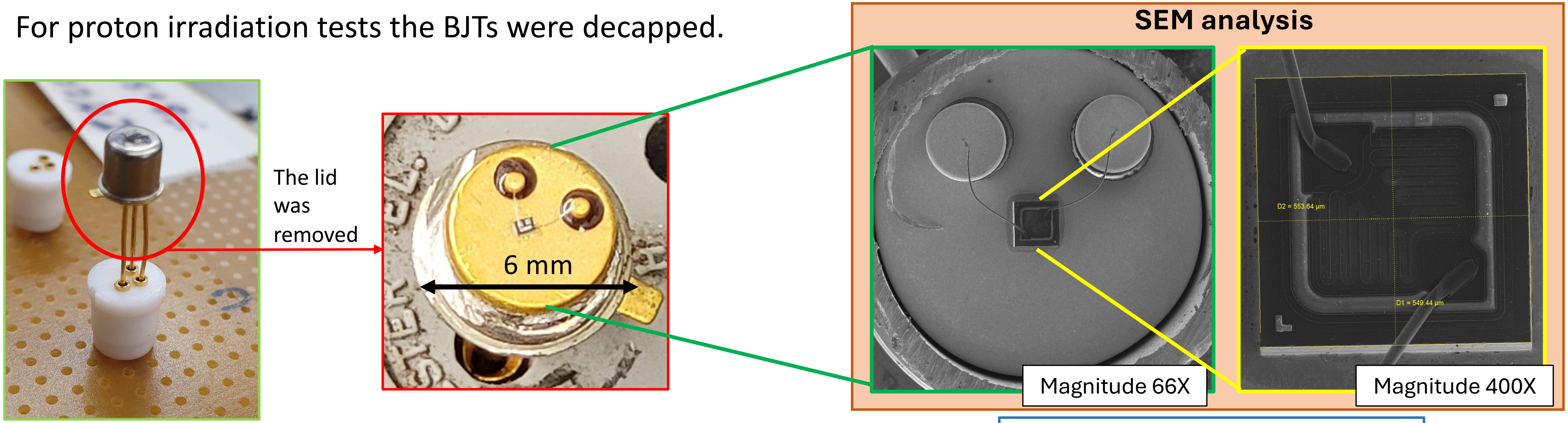


	Datasheet	HEAVILY damaged after:
β_1	>75	$7.0 \cdot 10^{12}$ n/cm²
β_2	>100	$8.0 \cdot 10^{12}$ n/cm²
β_3	>100	$1.5 \cdot 10^{13}$ n/cm²
β_4	>100	No out of range
β_5	>50	No out of range

No recovery after annealing tests

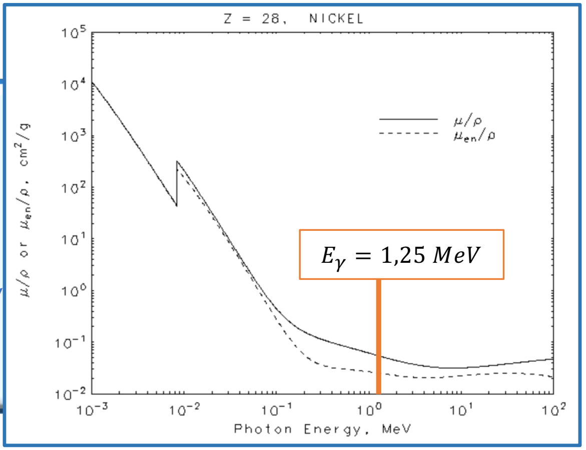
COTS BJTs: samples preparation for proton irradiation (TOP IMPLART and ALLS)

For proton irradiation tests the BJTs were decapped.



The lid thickness was about 300 µm.

- Projected range of 5 MeV protons in Nickel → 73 µm
- Gamma radiation attenuation coefficient: 1.00016 (*not attenuated*)



COTS BJTs:
proton irradiation (TOP IMPLART) and measurements - 1

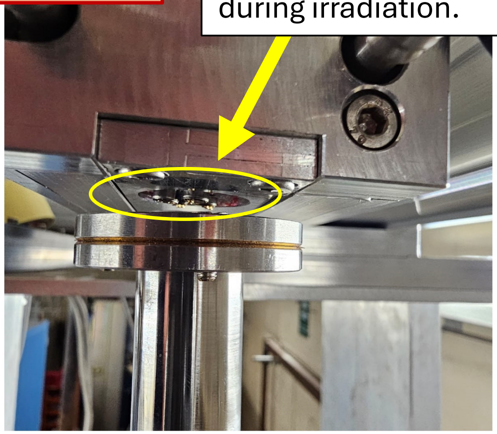
Conventional protons

COTS

- **12 decapped samples** (6 NPN and 6 PNP BJTs) two for each irradiation condition
- Irradiation up to different proton fluences (2.8 MeV protons)

Irradiation test	Proton fluence
1	$3.38 \odot 10^{9}$ p/cm^{2}
2	$3.38 \odot 10^{10}$ p/cm^{2}
3	$2.5 \odot 10^{11}$ p/cm^{2}

Irradiation setup



All samples were unbiased during irradiation.

Irradiation tests:

Irradiation at room temperature and parametric test after irradiation

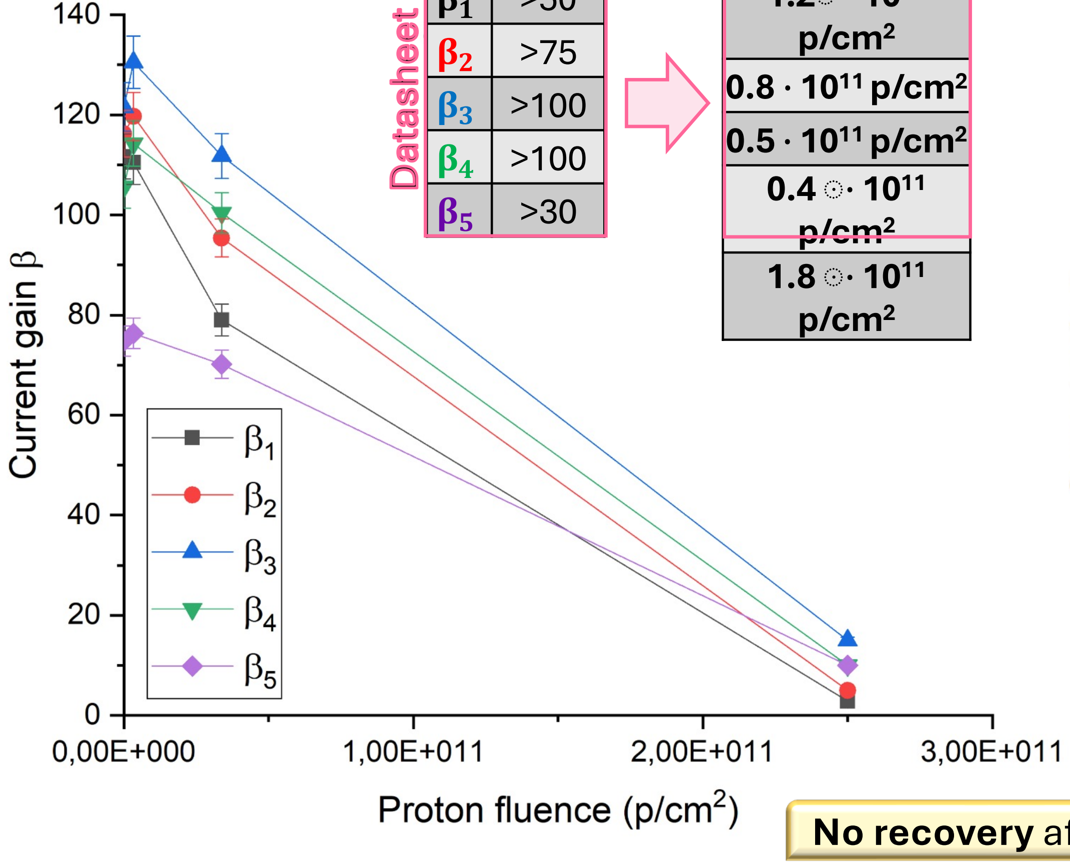
Annealing followed by parametric tests**:**
-24 hours at room temperature
-168 hours at 100 °C

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:
proton irradiation (TOP IMPLART) and measurements - 2

Conventional protons

NPN



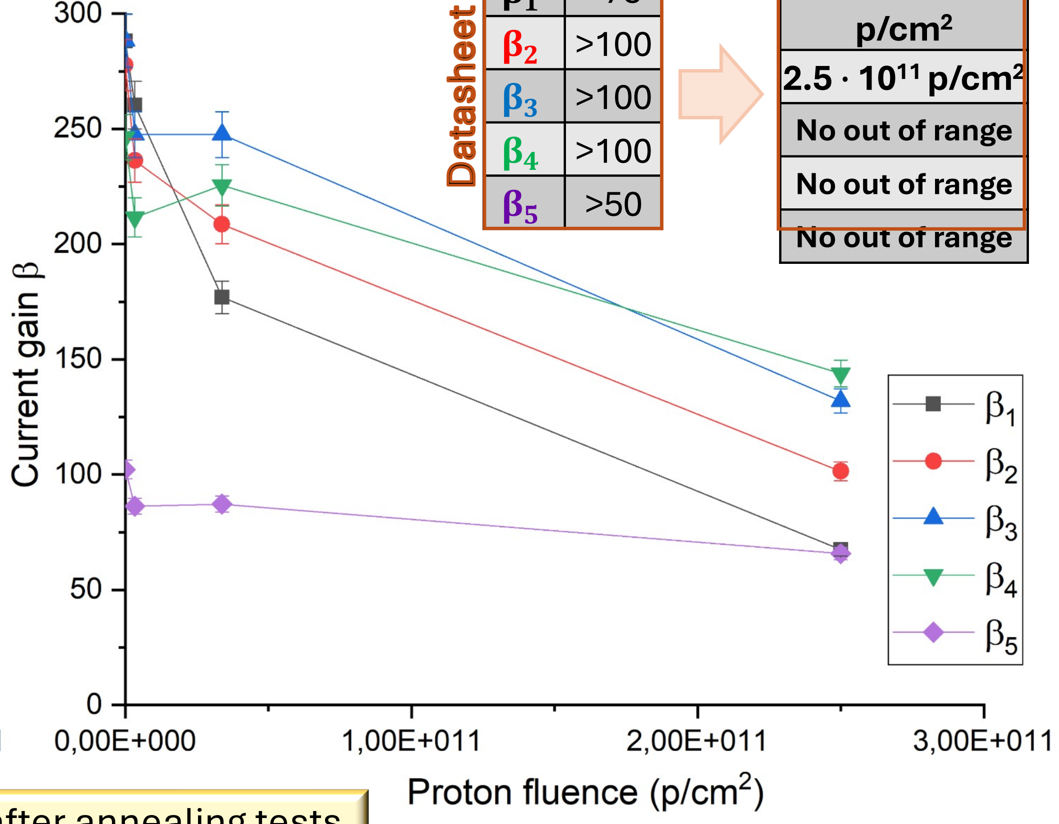
Datasheet

β_1	>50
β_2	>75
β_3	>100
β_4	>100
β_5	>30

HEAVILY damaged after:

1.2◌ · 10^{11} p/cm^2
0.8 · 10^{11} p/cm^2
0.5 · 10^{11} p/cm^2
0.4 ◌· 10^{11} p/cm^2
1.8 ◌· 10^{11} p/cm^2

PNP



Datasheet

β_1	>75
β_2	>100
β_3	>100
β_4	>100
β_5	>50

HEAVILY damaged after:

2.1◌ · 10^{11} p/cm^2
2.5 · 10^{11} p/cm^2
No out of range
No out of range
No out of range

No recovery after annealing tests

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

Laser-driven protons

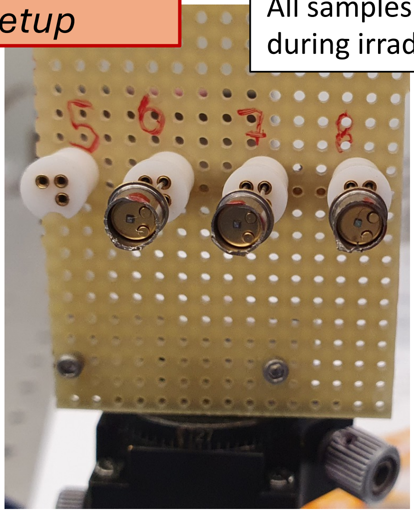
COTS

- **6 decapped samples** (NPN BJTs)
- Irradiation at different absorbed doses

Irradiation test	Number of shots
1	1
2	5
3	50
4	100
5	250
6	400

Irradiation setup

All samples were unbiased during irradiation.



Irradiation tests:

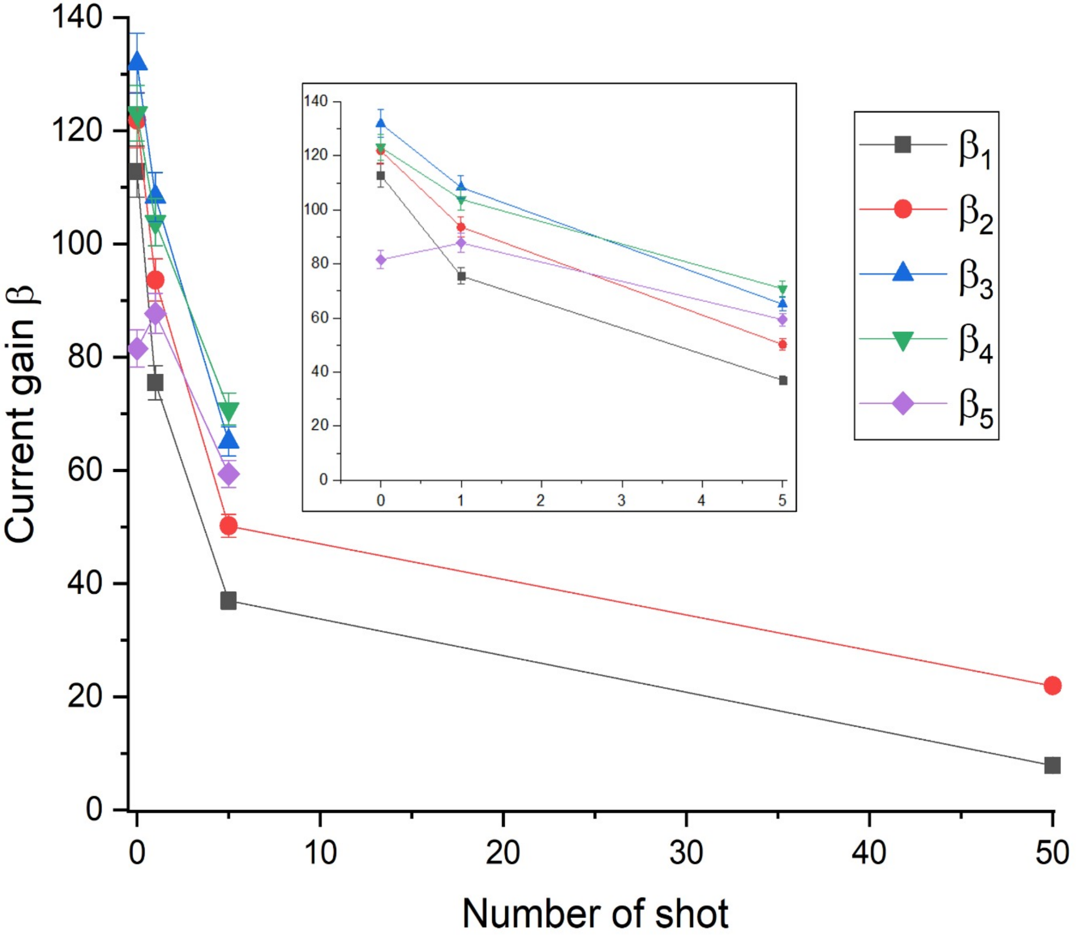
Irradiation at room temperature and parametric test after irradiation

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

NPN



HEAVILY damaged after:

	Datasheet	HEAVILY damaged after:
β_1	>50	**4 shots**
β_2	>75	**3 shots**
β_3	>100	**2 shots**
β_4	>100	**2 shots**
β_5	>30	**No out of range**

No recovery after the annealing tests

Dose deposition study

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

TID:
Surface
damage

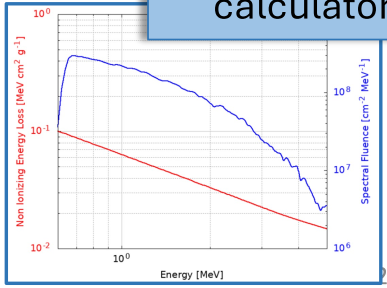
NIEL:
Bulk
damage

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**

For each radiation source $\text{Dose}_{\text{NIEL}}$ contribution to $\text{Dose}_{\text{TOTAL}}$ was evaluated

ASI sr-niel calculator



Leroy C, Rancoita PG. Principles of Radiation Interaction in Matter and Detection. WORLD SCIENTIFIC (2016).

Results summary

The results obtained after irradiation of BJTs and the results of the dose deposition study were merged.

Doses/fluences causing gain to exit allowed ranges

NPN

	Gamma	Neutrons	Conventional protons	Laser-driven protons
β_1	8 kGy	$5.0 \cdot 10^{12}$ n/cm^2	1.2◌ $\cdot 10^{11}$ p/cm^2	4 shots
β_2	7 kGy	$3.5 \cdot 10^{12}$ n/cm^2	$0.8 \cdot 10^{11}$ p/cm^2	3 shots
β_3	3 kGy	$2.5 \cdot 10^{12}$ n/cm^2	$0.5 \cdot 10^{11}$ p/cm^2	2 shots
β_4	600 Gy	2.0 ◌$\cdot 10^{12}$ n/cm^2	0.4 ◌$\cdot 10^{11}$ p/cm^2	2 shots
β_5	100 kGy	/	1.8 ◌$\cdot 10^{11}$ p/cm^2	/

PNP

	Gamma	Neutrons	Conventional protons
β_1	15 kGy	7.0◌ $\cdot 10^{12}$ n/cm^2	2.1◌ $\cdot 10^{11}$ p/cm^2
β_2	20 kGy	$8.0 \cdot 10^{12}$ n/cm^2	$2.5 \cdot 10^{11}$ p/cm^2
β_3	35 kGy	$1.5 \cdot 10^{13}$ n/cm^2	/
β_4	20 kGy	/	/
β_5	70 kGy	/	/

All the values were transformed into absorbed doses

NPN

		Gamma	Neutrons	Conventional protons	Laser-driven protons
β_1	Dose$_{TOTAL}$	8 kGy	62.5 Gy	2.05 kGy	13.6 Gy
	Dose$_{NIEL}$	0.06 Gy	3.0 Gy	0.46 Gy	0.01 Gy
β_2	Dose$_{TOTAL}$	7 kGy	43.8 Gy	1.37 kGy	10.2 Gy
	Dose$_{NIEL}$	0.06 Gy	2.1 Gy	0.31 Gy	0.01 Gy
β_3	Dose$_{TOTAL}$	3 kGy	31.3 Gy	856 Gy	6.8 Gy
	Dose$_{NIEL}$	0.02 Gy	1.5 Gy	0.24 Gy	$5.0 \cdot 10^{-3}$ Gy
β_4	Dose$_{TOTAL}$	600 Gy	25 Gy	685 Gy	6.8 Gy
	Dose$_{NIEL}$	$5.0 \cdot 10^{-3}$ Gy	1.2 Gy	0.14 Gy	$5.0 \cdot 10^{-3}$ Gy

PNP

		Gamma	Neutrons	Conventional protons
β_1	Dose$_{TOTAL}$	15 kGy	87.5 Gy	3.02 kGy
	Dose$_{NIEL}$	$1.2 \cdot 10^{-1}$ Gy	4.3 Gy	0.83 Gy
β_2	Dose$_{TOTAL}$	20 kGy	100 Gy	3.6 kGy
	Dose$_{NIEL}$	$1.6 \cdot 10^{-1}$ Gy	5 Gy	1 Gy

Dose irradiation effects by different sources

NPN		Gamma	Neutrons	Conventional protons	Laser-driven protons
β_1	$\text{Dose}_{\text{TOTAL}}$	8 kGy	62.5 Gy	2.05 kGy	13.6 Gy
β_2	$\text{Dose}_{\text{TOTAL}}$	7 kGy	43.8 Gy	1.37 kGy	10.2 Gy
β_3	$\text{Dose}_{\text{TOTAL}}$	3 kGy	31.3 Gy	856 Gy	6.8 Gy
β_4	$\text{Dose}_{\text{TOTAL}}$	600 Gy	25 Gy	685 Gy	6.8 Gy

- **Gamma radiation** highest required absorbed dose
- **Laser-driven protons** lowest required dose

- **Two orders of magnitude difference** in total absorbed dose for **conventional protons** and **laser-driven protons**
- Approximately the same amount of protons
- A significant distinction lies in the **total irradiation time** and **pulse length** between proton bunches:
  Conventional: pulse length 400 s to deliver 10^{11} protons
  Laser-driven: pulse length 13 ns to deliver 0.2 ◌10^{11} protons and 6 seconds to deliver 10^{11} protons.
  Therefore laser-driven protons require two order of magnitude less time to deliver the same amount of protons.

→ Laser-driven protons can reproduce intense mechanical and thermal damage within a very short timeframe, preventing material recovery.

B. D‘Orsi et al., in review at Sci. Rep.

Conclusion

Laser-acceleration ions can be used for testing electronic components/systems that require radiation hardening

Similar to Radiobiological effectiveness (RBE) in biological applications, these particles can be more efficient than other conventional stress testing methods

The efficiency comes from the very short and intense dose delivery, that does not allow the materials to relax and makes the dose "more efficient" (equivalent to FLASH therapy in cancer treatment)