Radiation Test Standards for Space

RADSAGA Training Workshop – March 2018

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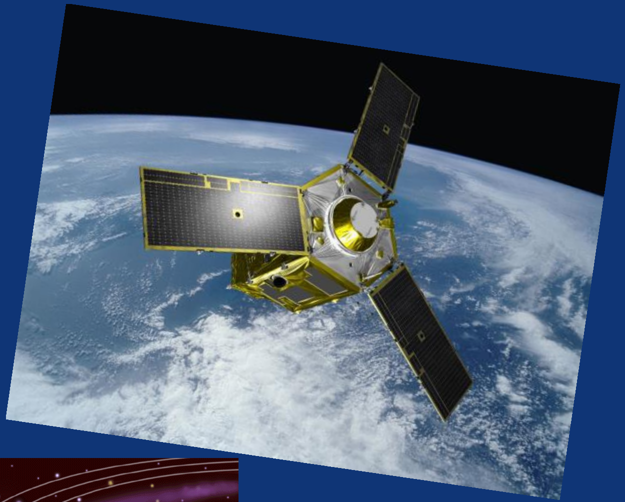

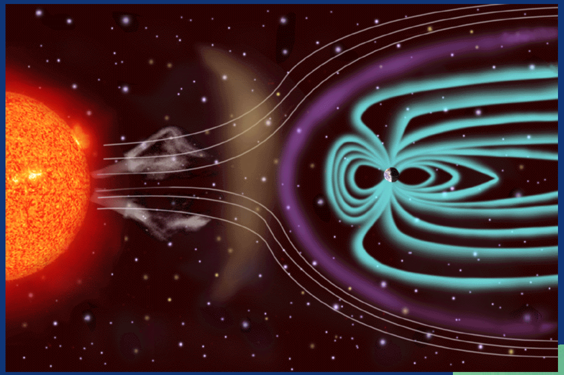

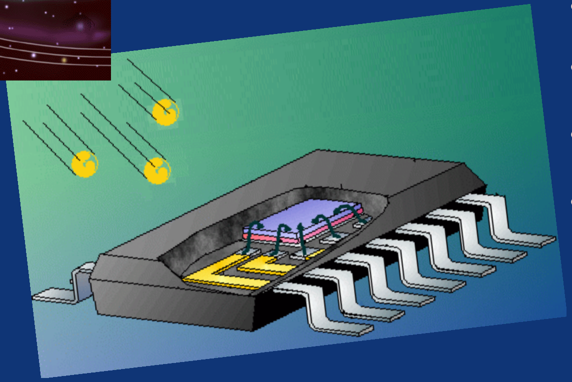

OUTLINE

Radiation Test Standards for Space

Part 1

- Radiation in Space
- Radiation effects on electronic devices
- Test Methods and standards
- Basic test plans

Part 2

- Facilities for radiation test of electronic devices
- Most common pitfalls.
- MCQ short exam
- Correction

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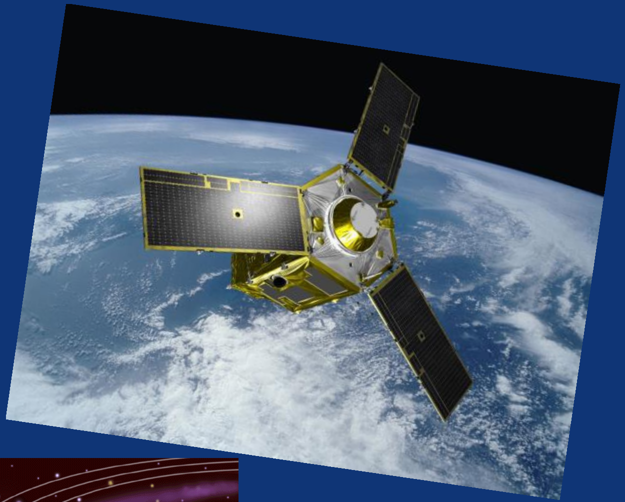

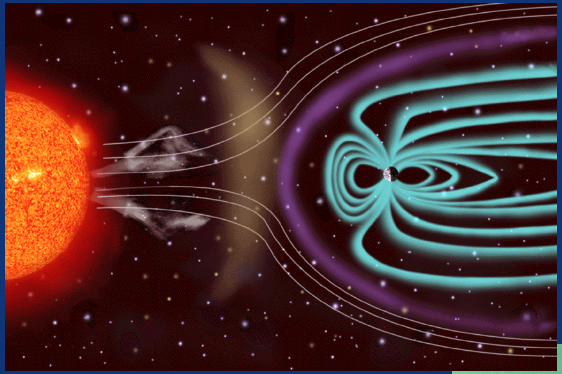

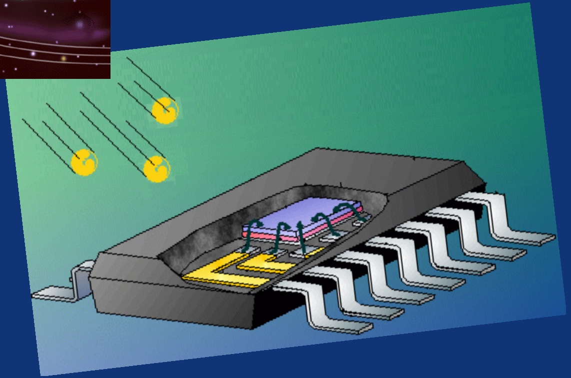

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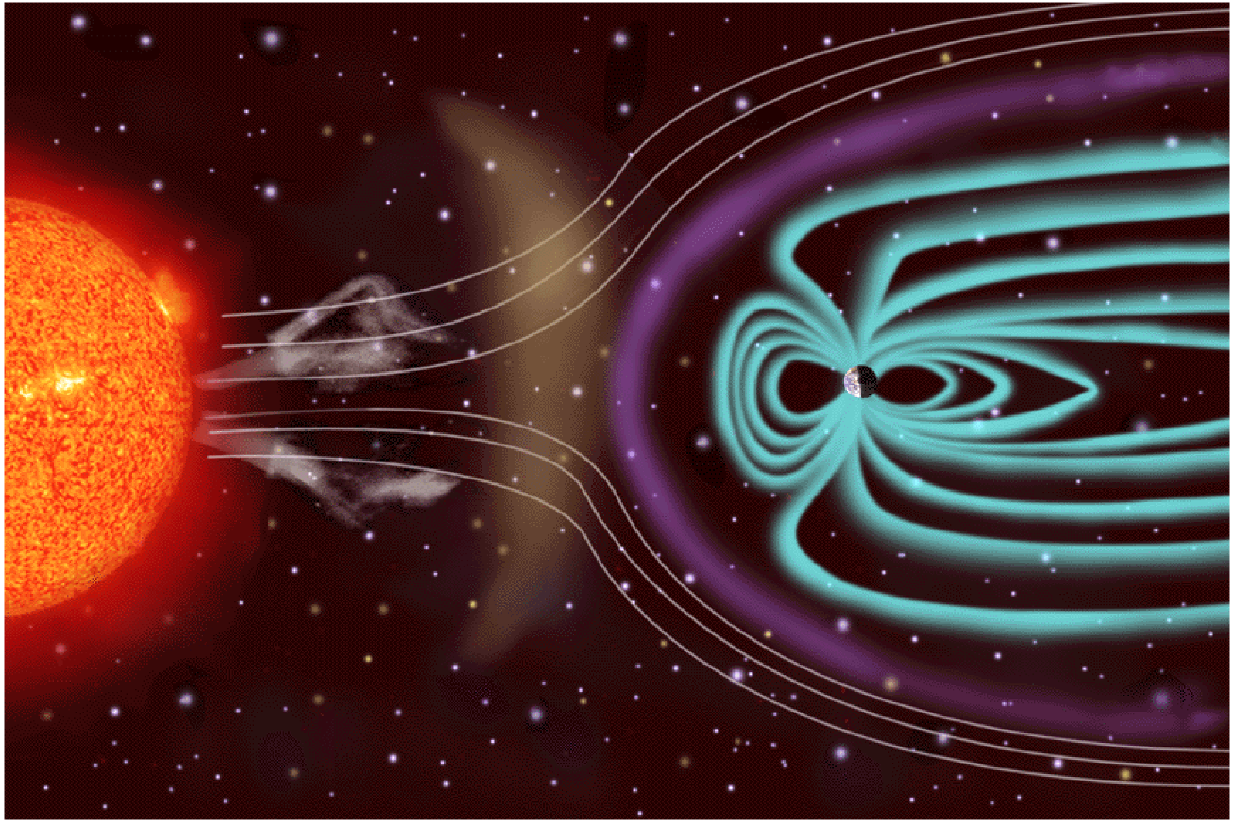
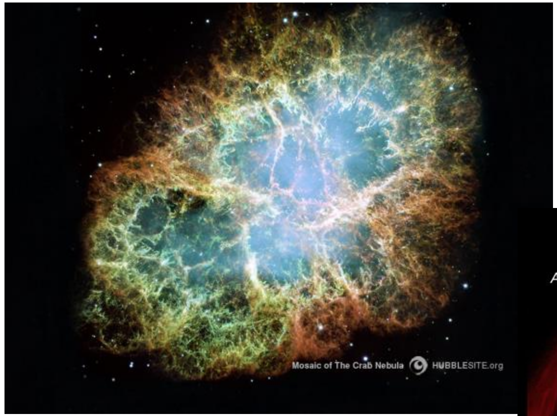
Radiation in Space:

Lots of charged particles

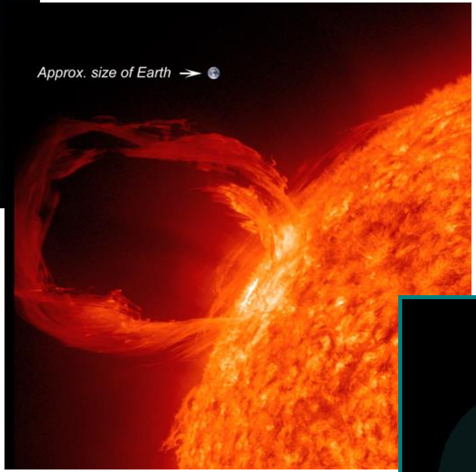


Radiation in Space:

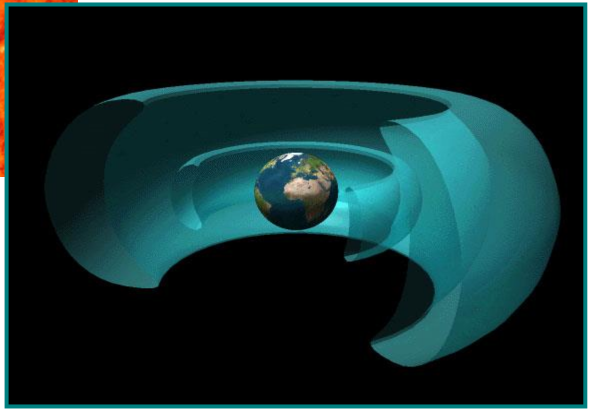
They come from:



- ❖ **Galactic Cosmic Rays**
  - Ions [-> 300MeV/n]



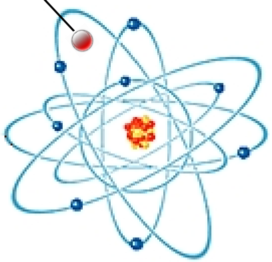
- ❖ **Sun**
  - Protons [keV - 500MeV]
  - Heavy Ions [few MeV/n - 10MeV/n]



- ❖ **Van Allen belts**
  - Protons [keV - 500MeV]
  - Electrons [eV - 10MeV]

Radiation Effects on Electronic Components:

Charged particles (ions, protons) interact either with electrons or nucleus of the target material.



Effects of radiation on electronic devices:

- Cumulative
  - Due to the collective contribution of multiple particles
  - Total dose = Ionizing dose (electrons) + Non Ionizing dose (Nucleus)

    TID: Total Ionizing Dose — **TNID or DDD: Displacement Damage Dose**

- Single
  - A unique particle is responsible of a change of state in the device.

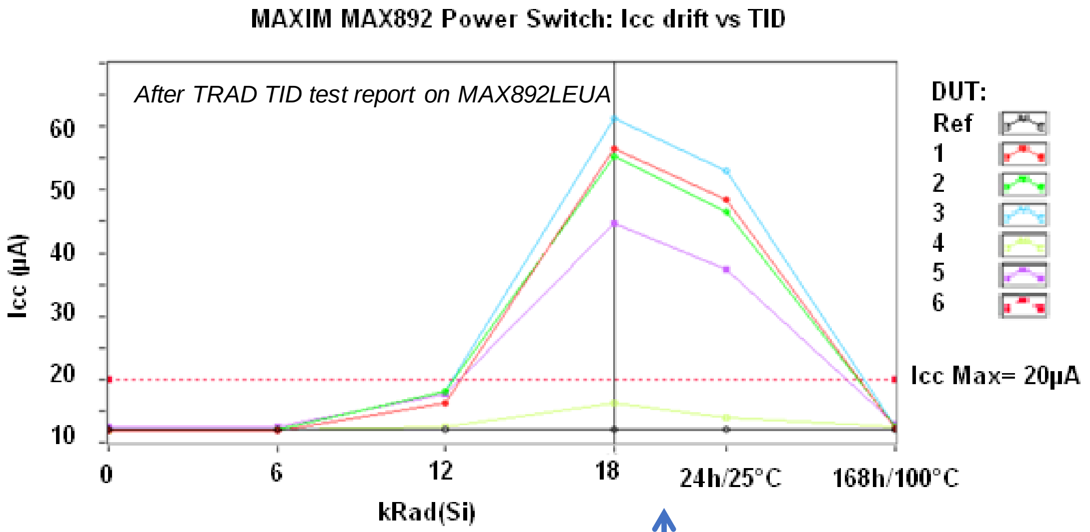
    Ionization => charge collection => SEE: Single Event Effect

Cumulative effect: Total Ionizing Dose

TID Unit: rad(Si) or Gy(Si) *(In Si)*

(1 Gy= 100rad)

- TID induces:
  - Parametric drift
  - Loss of functionality
- Key words:
  - Dose Rate: rad(Si)/s
  - Post Irradiation Annealing
  - Accelerated Annealing
  - TDE: Time Dependent Effect (trapped oxide charges and interface states)
  - TDRE: True Dose Rate Effect
  - ELDRS: Enhanced Low Dose Rate



- Type of source, biasing condition, temperature or dose rate can drastically change the test results.

Cumulative effect: Total Non Ionizing Dose

TNID Unit DDD (MeV/g) or Φ (p/cm²)

- with

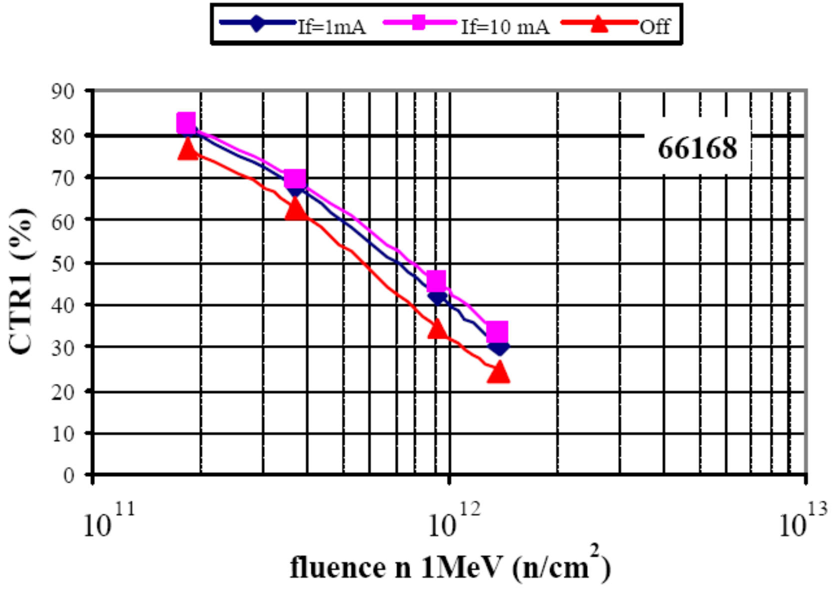
  DDD= NIEL(Si or AsGa).Φ *(In Si or AsGa)*

- DDD induces:
  - Parametric drift
  - Loss of functionality

  } DDE

- Key words:
  - Flux (p/cm²/s)
  - Fluence Φ (p/cm²)
  - NIEL: (MeV/(g/cm²)) Non Ionizing Energy Loss

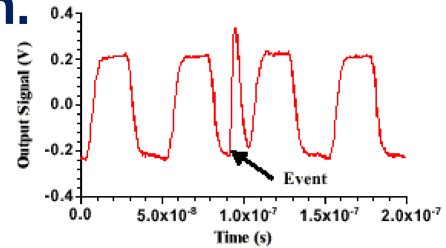
Bias effects on MICROPAC 66168 CTR drift under 1MeV neutrons



After R. Mangeret et al RADECS 2001

Single Event Effects

SEE occur when the charge collected at a node is high enough.

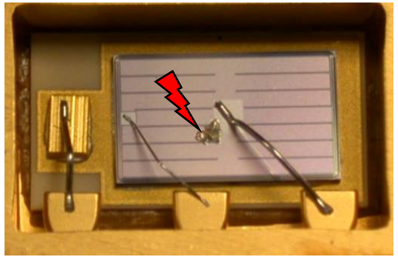


- Some are not destructive
  - SET: Single Event Transient – Analog transient change of state
  - SEU: Single Event Upset – Logical change of state on 1 bit
  - MBU: Multiple Bit Upset
  - SEFI: Single Event Functional Interrupt

- Some are potentially destructive but protection systems exist
  - SEL: Single Event Latch-up
  - SEB: Single Event Burnout

  } Parasitic conduction => Thermal destruction

- Some are destructive with no possible protection
  - SEGR: Single Event Gate Rupture
  - SEDR: Single Event Dielectric Rupture



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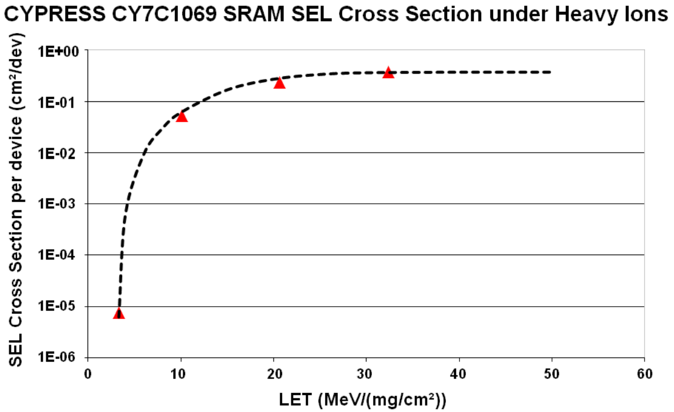
Single Event Effects

Characterization of the device response:

- For not destructive or protected SEE
  - SET, SEU, MBU, SEFI, SEL, SEB

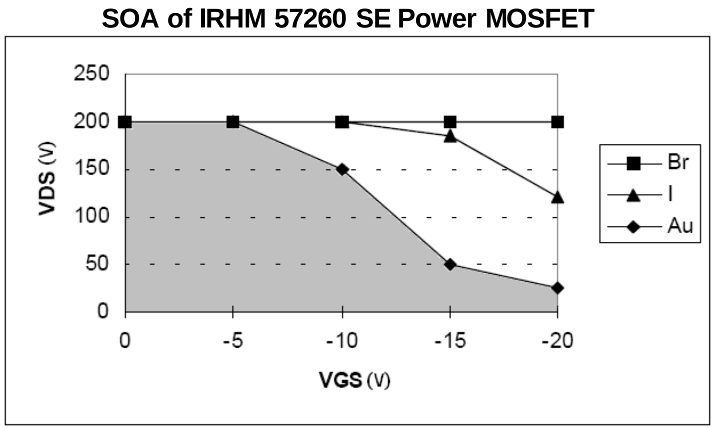
=> Cross section Curve

$$\sigma_{(LET)} = n_{event}/\Phi_{(LET)}$$



- For destructive with no possible protection SEE:
  - SEGR and SEDR

=> Safe Operating Area



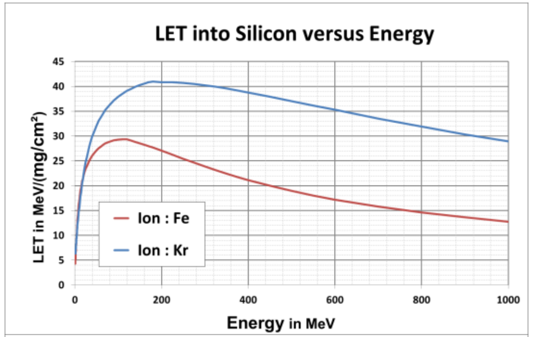
After IR datasheet

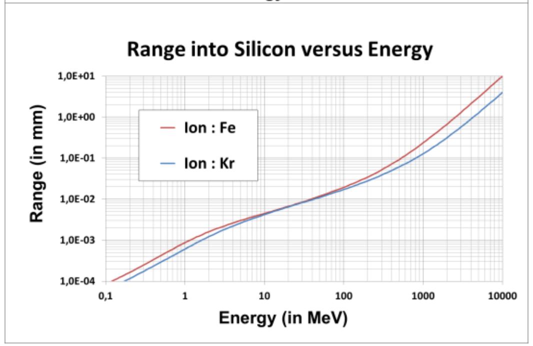
Energy, LET, Range and TID

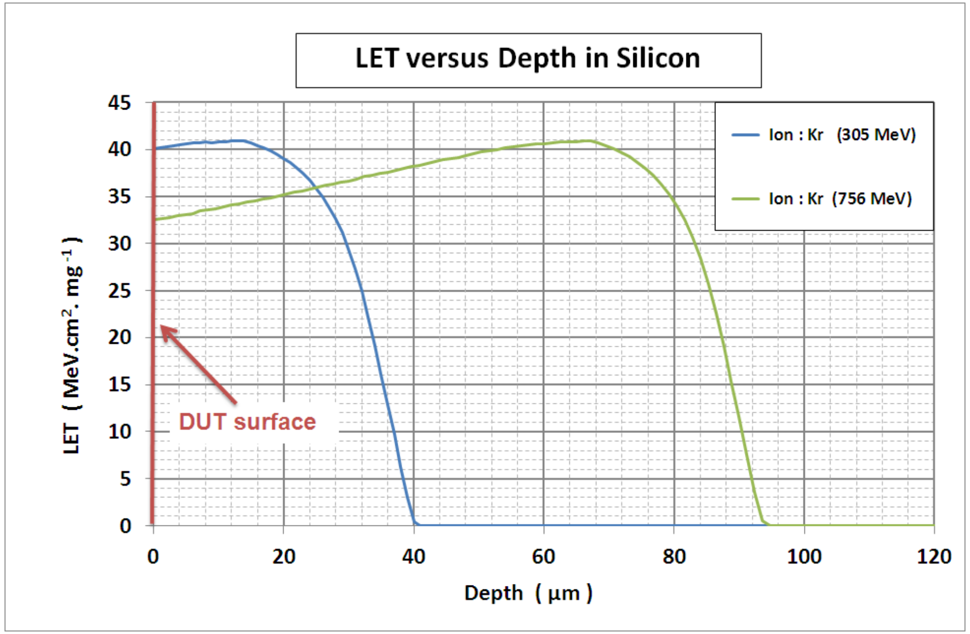
For a given charged particle and a given target material (Si):

- LET and Range vary with Energy

A degrader may be used to change the beam characteristics







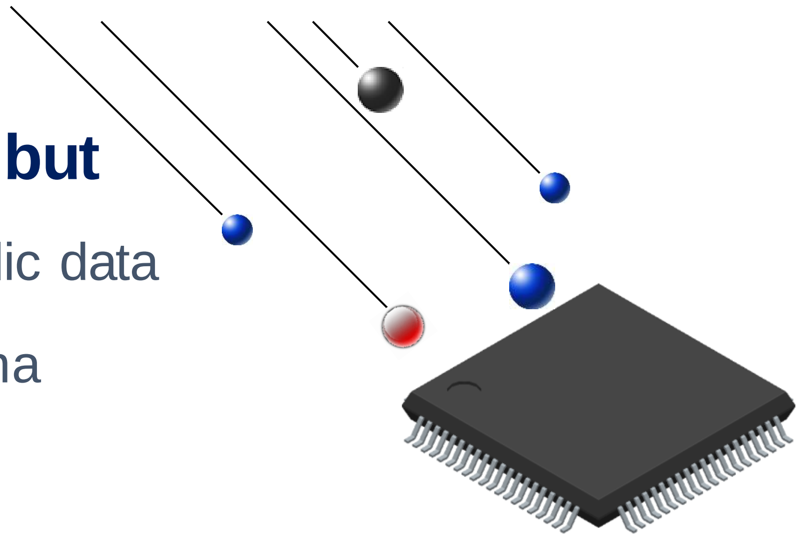
- TID deposited (in Si) by a particle fluence Φ: $TID_{(Si)} = 1.6 \times 10^{-5} . \Phi . LET_{(Si)}$

Why do we still need Radiation tests?

Radiation effects on electronic devices have been studied for years.

Prediction models have been developed but

- require a lot of parameters not available as public data
- do not cover all the radiation induced phenomena
- technologies are in permanent change



Radiation tests using ground-based facilities are often the simplest solution.

Test Methods and standards

ECSS:	European Cooperation for Space Standardization
ESCC:	European Space Component Coordination
MIL-STD:	US Military Standard
EIA-JESD:	Electronic industries Alliance / JEDEC Standard
JEDEC:	Joint Electron Device Engineering Council

Test Methods and standards: ECSS (1/2)

ECSS-Q-ST-60-15C 1 October 2012

Space Product Assurance: Radiation hardness assurance – EEE components

- §4.2. Radiation effects on components => ECSS-E-HB-10-12A
- §4.3. Evaluation of radiation effects => ECSS-Q-ST-30 (Drifts TID/TNID for Worst Case Analysis)
  => ECSS-E-ST-10-12 (Radiation Design Margins)
- §5.1. TID hardness assurance => ESCC 22900, MIL-STD 883 Method 1019, MIL-STD-750 Method 1019. } *TID Test Methods*
- §5.2. TNID hardness assurance => *"No standard method exists for TNID Testing"*
- §5.3. SEE hardness assurance => MIL-STD-750 Method 1080 (Power MOSFETs), ESCC 25100 (all other parts) EIA/JESD 57. } *SEE Test Methods*
- §5.1, 5.2 and 5.3. => ECSS-E-ST-10-04 (Mission radiation environment)
  => Lists of EEE Parts families potentially sensitive to TID, TNID, SEE

Test Methods and standards: ECSS (2/2)

Also useful but not directly concerning radiation testing.

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION

ECSS-E-ST-10-12C **15 November 2008**

Space Engineering:
Method for the calculation of radiation received and its effects, and a policy for design margins

ECSS-E-HB-10-12A **17 December 2010**

Space Engineering:
Calculation of radiation received and its effects and margin policy handbook

Test Methods and standards: ESCC

ESCC Basic Specification No. 22900 Issue 5 June 2016

Total Dose Steady-State irradiation test method

- *Testing procedures for ESCC evaluation/qualification by component manufacturer (Not covered by this course)*
- **Testing procedures for any other purpose**

ESCC Basic Specification No. 25100 Issue 2 October 2014

Single Event Effects test method and guidelines

Test Methods and standards: MIL-STD

MIL-STD 883J 7 June 2013
Test Method Standard Microcircuit

- **Method 1019.9:** **Ionizing Radiation (Total Dose) Test Procedure**

MIL-STD-750E 3 January 2012
Test Method Standard -Test Methods for Semiconductor devices

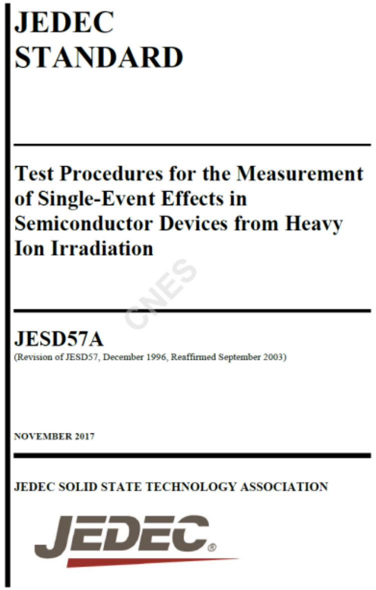
- *Method 1019.5: Steady State Total dose Irradiation procedure (Older version than 883J)*
- **Method 1080.1:** **Single Event Burnout and Single Event Gate Rupture Test**

Test Methods and standards: EIA/JEDEC

EIA/JESD 57A November 2017

Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation

This standard is not free. You shall register on the JEDEC Website.



JEDEC STANDARD

Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation

JESD57A
(Revision of JESD57, December 1996, Reaffirmed September 2003)

NOVEMBER 2017

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

Test Methods and standards: Summary

Standard	Revision date	TID	DDE	SEE
ESCC 22900-5	June 2016	X		
ESCC 25100-2	October 2014			X
MIL-STD 883J Method 1019.9	June 2013	X		
MIL-STD 750-E Method 1019.5	*January 2012*	*X*		
MIL-STD 750-E Method 1080.1	January 2012			MOSFETS Heavy ions
EIA JESD57A	November2017			Heavy ions

Test Methods and standards: TID

	ESCC22900	MIL-STD883J Method 1019.9
Source	Co60 *(or e- beam for materials)*	Co60
Dose rate calibration	≤5%	
Field Uniformity	≤10%	
Sample size	10 (ESCC Qualification or procurement) 5 per bias condition (or less) 1 control part	Not specified
Bias	Worst case condition Test Plan ±10%	Test Plan ±10%
Temperature	20°C ± 10°C (ΔT≤3°C)	Ambient: 24°C ± 6°C High or cryo: ±5°C
Radiation levels	According Test Plan ±10%	
Dose Rate	Standard rate or Low rate or other (ΔDR≤10%)	Bipolar/BiCMOS ≠ CMOS
Testing	Remote or In-Situ	
Delay between irrad. steps	2h	2h (or <20% irrad. time or dry ice)
Post irradiation annealing	Ambient / high temperature	

Test Methods and standards: TID

ESCC 22900-5:

Dose Rate (DR)

Test cond.	Dose rate	Applicability
Window 1 or Standard rate	0,36-180 kRad(Si)/h	MOS and CMOS
Window 2 or Low rate	36-360 rad(Si)/h	MOS and CMOS, Bipolar *(Including BiCMOS)* When TDE or ELDRS are suspected
Alternative DR	Agreed by ESCC executive or orderer e.g.: ≤36rad(Si)/h	As justified by application or mission or (e.g.) when ELDRS are expected

Anneal Procedure

Annealing	Condition	Applicability
Room temperature 20°C ± 10°C (ΔT≤3°C)	Same bias than irradiation one 24h may be extended to 48 and 168h	
Accelerated ageing test	Same bias than irradiation one ➢ 100°C ±5°C for 168h ➢ other temperature/duration	When TDE are suspected

Test Methods and standards: TID

MIL-STD 883J Method 1019.9:

Dose Rate (DR)

Test cond.	Dose rate	Remark	Condition
A	50-300rad(Si)/s	DR variations allowed between steps ≤10% in a step	Standard
B	≥ max application DR	Accelerated annealing test	MOS only Application DR<50rad(Si)/s
C	free	Shall be specified in test report	Low dose rate applications
D	≤10mrad(Si)/s		Low dose rate applications Bipolar, BiCMOS linear or mixed signal only
E	as previously characterized	May include irradiation at elevated temperature	Low dose rate applications Bipolar, BiCMOS linear or mixed signal only

Anneal Procedure

Annealing		
Extended room temperature 24°C ± 6°C	Same bias than irradiation one No longer than the real application	MOS or Bipolar Only Parametric failure
MOS accelerated annealing test	• Overtest (0,5 x appllication dose) • Accelerated Annealing ➢ 100°C ±5°C for 168h ±12 h ➢ other temperature/duration	MOS Low DR Application Reveals TDE Application dose > 5krad(Si)
Others	• Application DR • Low DR + Overtest • Elevated temperature irradiation	Bipolar or BiCMOS Application DR<50rad(Si)/s Reveals ELDRS

Test Methods and standards: TID

ESCC22900-4:

	Window	Dose rate in krad(Si)/h	Dose rate in Gy(Si)/h	Dose rate in Gy(Si)/s
	Standard Dose Rate	0.36 to 180	3.6 to 1800	10^{-3} to 0.5
If TDE	Low Dose Rate	0.036 to 0.360	0.36 to 3.6	10^{-4} to 10^{-3}

MIL STD883J Method 1019.9:

	Window	Dose rate in rad(Si)/s	Dose rate in Gy(Si)/s
MOS	Standard Dose Rate	50 to 300	0,5 to 3
Bipolar, BiCMOS, Linear or mixed signal	Low Dose Rate	$<10^{-2}$	$<10^{-4}$

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Test Methods and standards: SEE

	ESCC 25100-2	JESD57A
Source	Particle accelerator	Van de Graaff or cyclotron accelerator*
Particle type	Heavy ions and protons	Heavy ions only
Field Uniformity	±10% (fluence & energie)	±10% (fluence) and <1% impurity
Range (heavy ions)	40µm (60µm for linear & thick SV devices/SEE)	Adequate
Flux	Few 10 to 10^5 ions/cm²/s and 10^5 to 10^8 p/cm²/s	10^3 to 10^5 ions/cm²/s
Energy (protons)	20 to 200MeV	NA
Dosimetry	Continuous monitoring (accuracy ±10%)	
Testing	Vacuum chamber (delidded components) / in air	Delidded/Decapsulated or thinned devices
Max fluence	10^7 ions/cm² or up to 10^{11} p/cm²	10^7 ions/cm² 10^6 ions/cm² or 100 errors 5.10^5 ions/cm² (large discrete devices)
Temperature	Monitored and recorded	
Sample Size	3 (2 as a minimum) for non destructive SEE 3 per bias condition for destructive SEE	Qualification: 4 Non qualification: see MIL-HDBK-814

** Synchrotron pulsed beam may interfere*

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Test Methods and standards: SEE

Recommended test conditions

SEE	ESCC 25100-2	JESD57A
SEU	Min Vcc and max clock frequency	
SET	Worst case or application equivalent	Worst case to be determined experimentally
SEL	Max Vcc and max operating temperature	
SEB	Low operating temperature MIL-STD-750 Method 1080	Max reverse Bias and Low operating temperature
SEGR		Max gate bias. Power MOSFETs: Max VDS & Max Vgs (Off)

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Test Methods and standards: SEB &SEGR

MIL-STD-750E Method 1080.1:

Heavy ion irradiation of planar vertical power MOSFETs

May be extended to protons or other MOSFETs or MOS capacitors

Source	Van de Graaff or cyclotron
Particle type	Heavy ions
Field Uniformity	±15% (fluence)
Range (heavy ions)	Sufficient No tilted beam
Flux	Adjusted (<100 SEB/s and measurable time to SEGR)
Dosimetry	Continuous monitoring
Testing	Vacuum chamber (delidded components)
Max fluence	10^5 to 10^7 ions/cm²
Temperature	Monitored (low temperature is worst case for SEB)
Sample Size	Sufficient (e.g. 3 per bias)

Test plan: TID or TNID

This document fixes the radiation test method. It gives enough information to reproduce the test.

Concerning TID, the following information are mandatory:

- **Device description/identification**
- **Facility**
- **Radiation levels**
- **Radiation Dose Rate**
- **Bias condition to be applied during irradiation or for in-situ measurements.**
- **List of the required electrical measurements**
- **Number of tested devices per bias condition.**
- **Test sequence if special requirements are needed (e.g. additional delay to perform measurements between irradiation steps).**
- **Anneal and accelerated ageing tests conditions.**

ESCC TID Test Plan form is available on ESCIES Web site (ESCC Forms section)

(escies.org, Our activities/ESCC Specifications/ ESCC Forms section)

This TID test plan can also be used for DDD.

Test plan: SEE

Concerning SEE, the following information are mandatory:

- Device description/identification
- Irradiation Type (Heavy ions, Protons)
- SEE test type (SEL, SEU, SEB, Other…)
- Selected facility and particles characteristics (ion, LET, range in the case of ions)
- Electrical conditions including bias conditions, test patterns and test system.
- Number of tested devices per bias or test condition

ESCC SEE Test Plan form is available on ESCIES Web site
(escies.org, Our activities/ESCC Specifications/ ESCC Forms section)

ESCIES
European Space Components Information Exchange System

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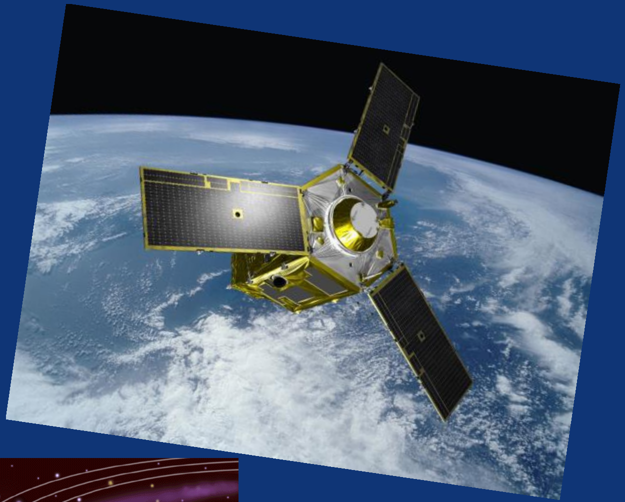

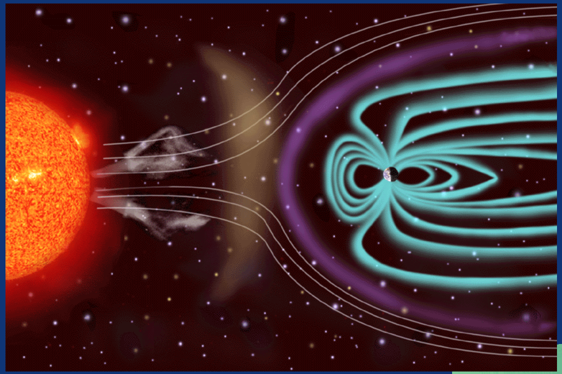

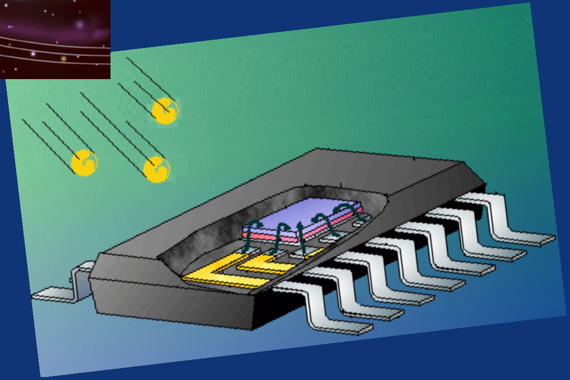

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- Most common pitfalls.
- MCQ short exam
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Facility for TID test of electronic devices:

Cobalt 60 source is agreed by both standards for the test of electronic devices.

- Co60 decays in Ni60 while emitting β and γ rays

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^{-} + \overline{\upsilon}_{e} + 2\gamma$$

- These γ rays (1,1732 & 1,3325MeV) have a high power of ionization and range
- Dose rate varies with the distance to the source. DR(d)= f(1/d²)
- Half-life period is 5,27 years.
- This radioelement is highly radiotoxic (doubly encapsulated sources).
- Co60 sources may be panoramic or confined in an irradiator.

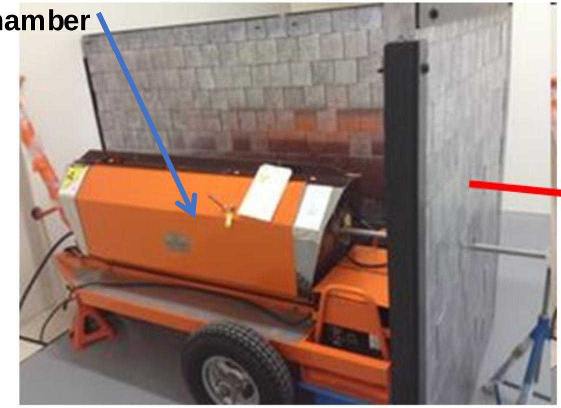
=> Example of panoramic source: GAMRAY facility, TRAD, Toulouse, France

Example of Co60 facility for TID testing

GAMRAY is based on a CEGELEC panoramic irradiator.

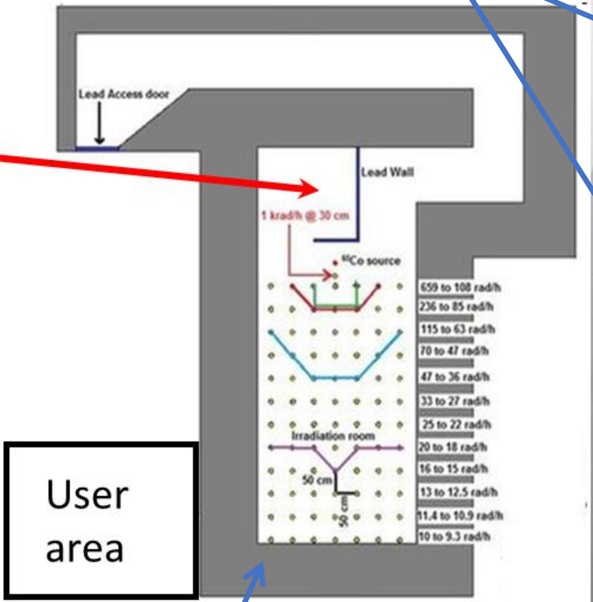
Source Activity: 400Cu (07/2016), Dose Rate: 1rad(Si)/h to 2krad(Si)/h without shielding.

Depleted U shielded storage chamber



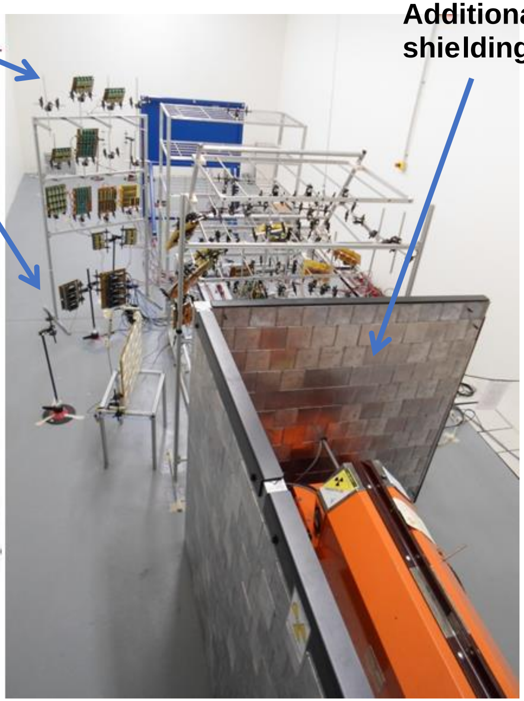
Source guide

Various samples under exposure



Concrete wall >1m

Additional Lead shielding wall



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Facilities for SEE test of electronic devices:

Heavy ions and protons are used for the SEE test of electronic devices.

- **Heavy ions:**
  - **High energy heavy Ions (>10MeV/n)** — *=> Example: GANIL, Caen, France*
    - In air
    - Devices in their original package
  - **Limited energy heavy ions (<10MeV/n)** — *=> Example: UCL-HIF, Louvain la Neuve, Belgium*
    - In vacuum
    - Delidded, decapsulated or thinned devices
- **Protons:** *(20-200MeV)*
    - In air
    - Devices in their original package
    - *Also used for TNID tests (30-60MeV)*

=> Examples: UCL-LIF, Louvain la Neuve, Belgium
KVI-CART, Groningen, The Netherlands

High energy beams *(E>10MeV/n)*

=> Beam propagates in air.

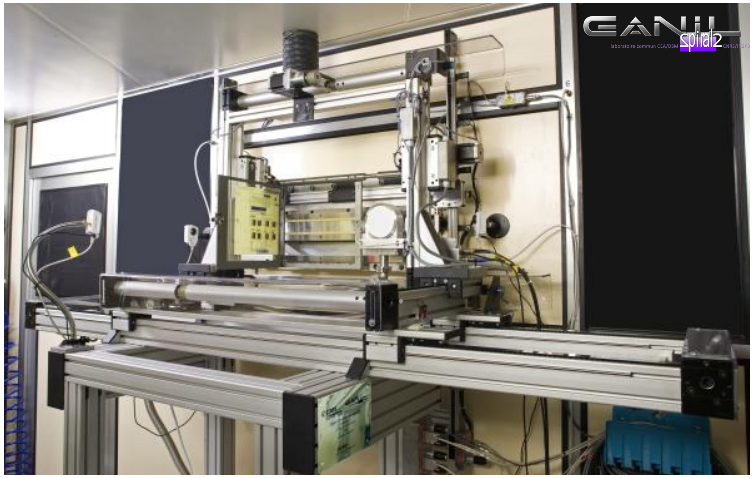
DUT can be tested in its package.

Secondary energetic particles

Activation of the beam line elements and DUT.

Heavy ions:
GANIL, TAMU, RADEF

Protons:
KVI, PSI, UCL, RADEF, TRIUMF…



©GANIL

Example of high energy beams: Heavy ions at GANIL

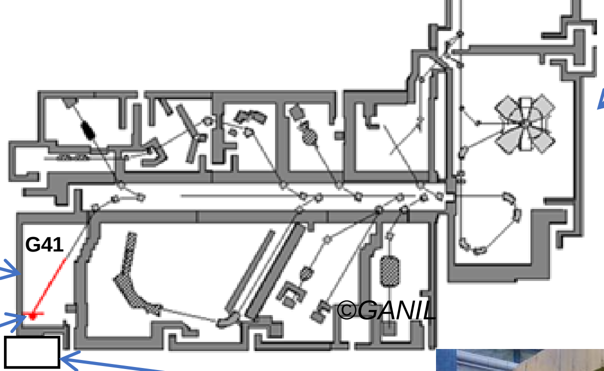
Grand Accelerateur National d'Ions Lourds, Caen, France.

- **Heavy ions**

2x compact cyclotrons C0

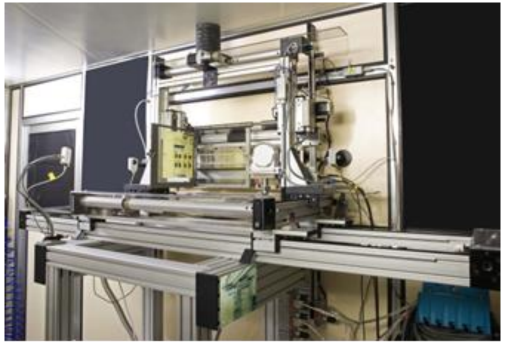
2x 4 sectors cyclotrons CSS

Beam Transport



laboratoire commun CEA/DSM CNRS/IN2P3

DUT Holder



Control room

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Example of high energy beams: Heavy ions at GANIL

One ion available per campaign

- Example $^{136}Xe^{48+}$, E = 49.6 MeV/u = 6745.6 MeV, Flux: 10^2 -10^5 ions/cm²/s
  - Characteristics in Si:

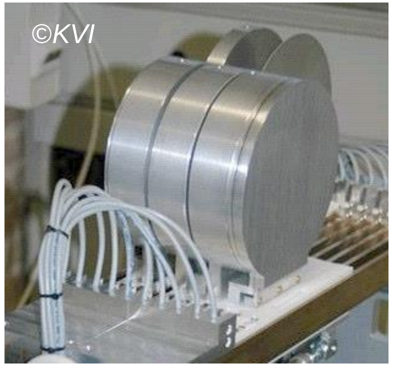
Air (mm)	Al (µm)	E (MeV/n)	LET (MeV/(mg/cm²))	Range (µm)
53	0	46.89	26.63	707.65
100	100	40.25	29.17	568.16
100	400	20.69	41.54	233.44
100	500	11.93	51.95	122.53
150	500	9.27	55.35	93.58

After J.C. Foy, GANIL

Example of high energy beams: Protons at KVI-CART

AGOR cyclotron

KVI



or

KVI Beam energy degrader

CNES/TRAD Automatic beam energy degrader for “in-orbit-like” proton spectrum reconstruction.

DUT holder

Possible close-to-DUT test system location

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Example of high energy beams: Protons at KVI-CART

Proton Beam characteristics:

- Primary beam energy: 40-190MeV
- Energy at DUT level (using degraders): 10-184MeV
- Flux: 10^8 to 10^9 p/cm²/s
- Flux diameter at DUT level versus homogeneity:
  - Standard: 70 mm , 3%
  - Wider: 110mm, 10%
- Distance between DUT and Test system placed at:
  - Control room: 40 m
  - B-Lab: 15m
  - Close-to DUT location: 1m

Lower energy beams *(E<10MeV/n)*

=> Beam cannot propagate in air

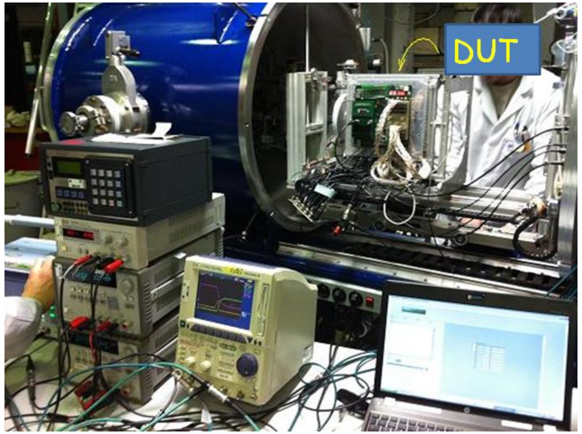
Heavy ions:
UCL, BNL,…

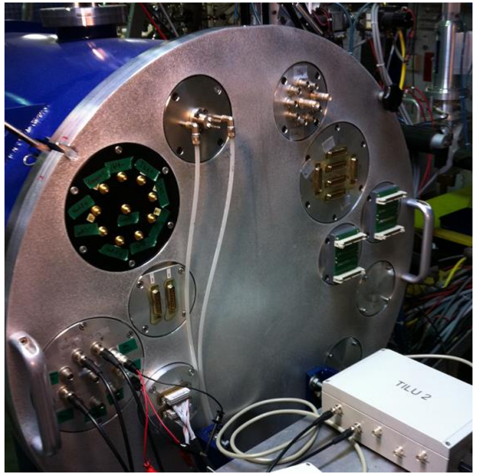
Vacuum test chamber is mandatory.

DUT cannot be tested without package opening.

No Activation of the beam line elements or DUT.

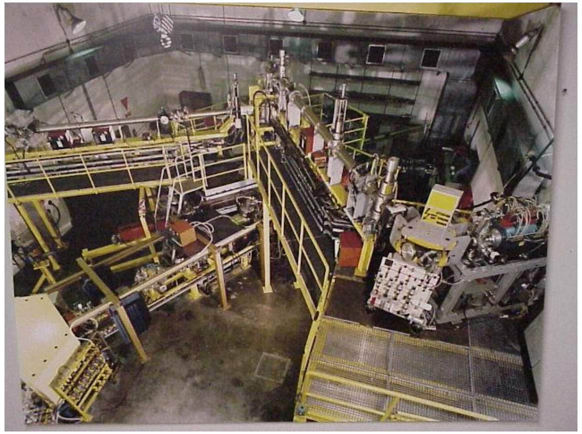
No significant Radiation level Close to the test Chamber.





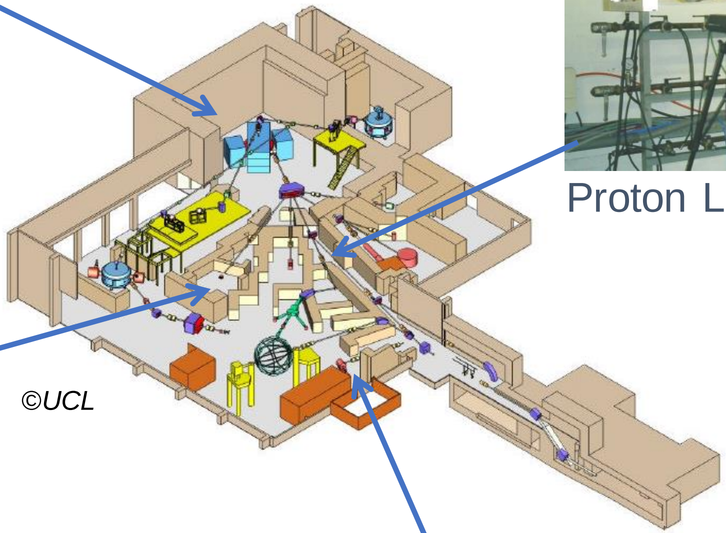
©UCL

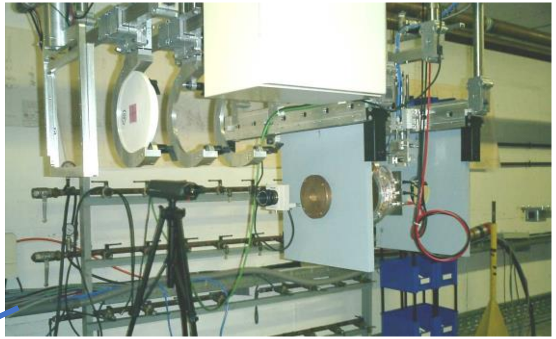
Example of Lower energy beams: Heavy ions at UCL



Cyclone 110 cyclotron

UCL





Proton Line (LIF)

Mono Energetic
Neutron line (NIF)

Heavy ions line (HIF)

Example of Lower energy beams: Heavy ions at UCL

Heavy ion Campaign (HIF)

- HIF ion cocktail: Typical fluxes few particles/cm²/s to 1,5 10^4 ions/cm²/s, beam diameter: 2.5 cm (10% homogeneity)

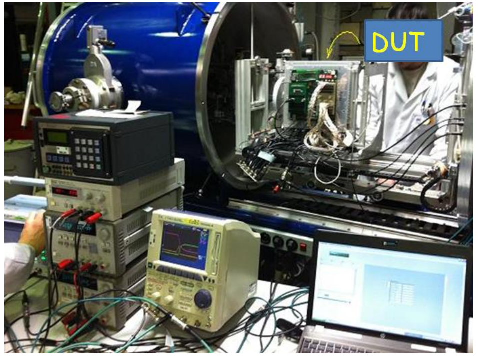
Ion	M/Q	Energy on device	Range on device	LET on device
		[MeV]	[µm]	[MeV/(mg/cm²)]
$^{13}C^{4+}$	3,25	131	269,3	1,3
$^{22}Ne^{7+}$	3,14	238	202	3,3
$^{27}Al^{8+}$	3,37	250	131,2	5,7
$^{40}Ar^{12+}$	3,33	379	120,5	10,0
$^{53}Cr^{16+}$	3,31	513	107,6	16,0
$^{58}Ni^{18+}$	3,22	582	100,5	20,4
$^{84}Kr^{25+}$	3,35	769	94,2	32,4
$^{103}Rh^{31+}$	3,32	972	88,7	45,8
$^{124}Xe^{35+}$	3,54	995	73,1	62,5

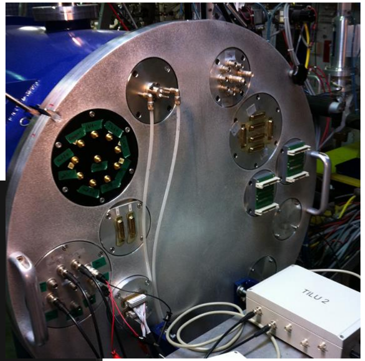
Most common pitfalls

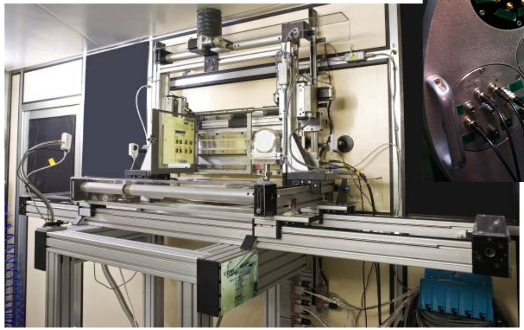
Beam time is expensive and rare. A serious preparation is necessary to avoid last minute problems that can make impossible the test or invalid the data collected.

Most common pitfalls

Compatibility of test system with test chamber/ DUT holder



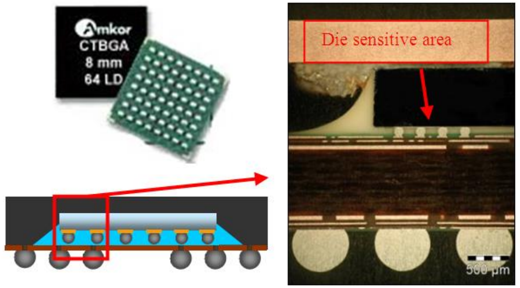




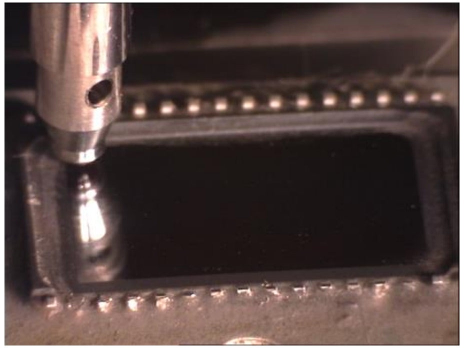
- In Vacuum:
  - Test chamber size
  - Feed through connector
- In air (high energy accelerators and Co60 source)
  - Distance to the control room (continuous monitoring)
  - Additional shielding if test system cannot be deported
- The DUT alignment system is fragile
  - Limited weight
  - Sufficient cable length
- SEE test under protons or TID:
  - Do not place any active component close to the DUT (even backside).
  - This is not a problem under medium energy heavy ions.

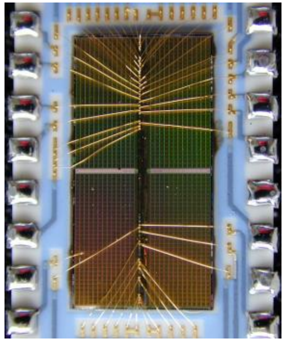
Sample preparation (SEE in Vacuum)

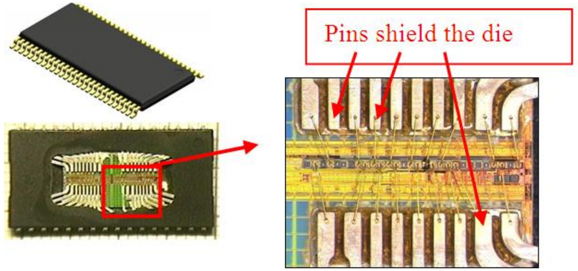
- Some packages cannot be opened while keeping the DUT functional
  - Flip chip assembled packages
  - Lead frame on top of the die



=> Backside irradiation after thinning or re-bonding







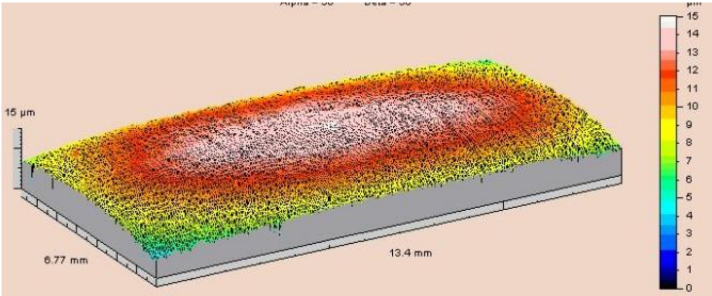
After F. Courtade & al., RADECS 2005.

=> Sample preparation Yields may be very low

Most common pitfalls

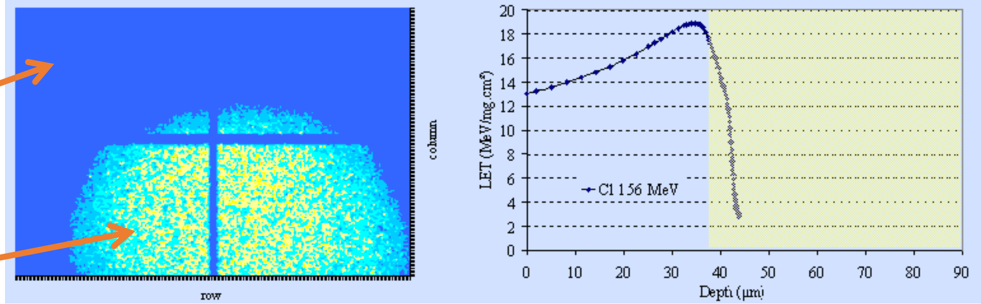
Energy limitation (heavy ions)

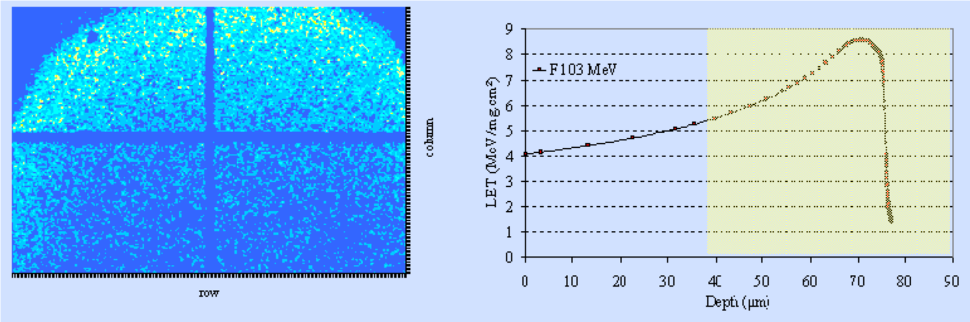
- LET at SV level shall be estimated:
  - Is it different from the surface?
  - Is it constant?



No SEU

SEU





Observation of sample thickness inhomogeneity with backside irradiation

After S. Duzellier & al, RADECS 2002

Most common pitfalls

Temperature monitoring

Some opened devices are sensitive to light

Total dose shall be calculated (heavy ions and protons)

Scheduling is sometimes difficult (TID)

Radiation Safety rules shall be respected

- Before entering the facility (previous information)
- During the test campaign and after irradiation when DUT become active due to high energies and fluences

Dosimetry concerns

Whatever the facility (accelerator or source), the user may insure that complete set of dosimetry data is provided in terms of intensity and homogeneity and that the quality of the irradiation is checked all along the test campaign.

Thank you for your attention.

It's time for a short exam.

25 Multiple Choice Questions

Only one answer by question

30 minutes.

MCQ correction & questions

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie-Sklodowska-Curie grant agreement number 721624.