Radiation Effects on Electronic Systems

Prof. dr. ir. Valentijn De Smedt

Webinar: Radiation Effects on Materials

19 June 2020

Outline

- **Introduction**
- Radiation effects in Electronic Devices
  - Total Ionizing Dose
  - Single Event Effects
- Design of Radiation Tolerant Electronics
- Conclusions

Introduction

Radiation Environments

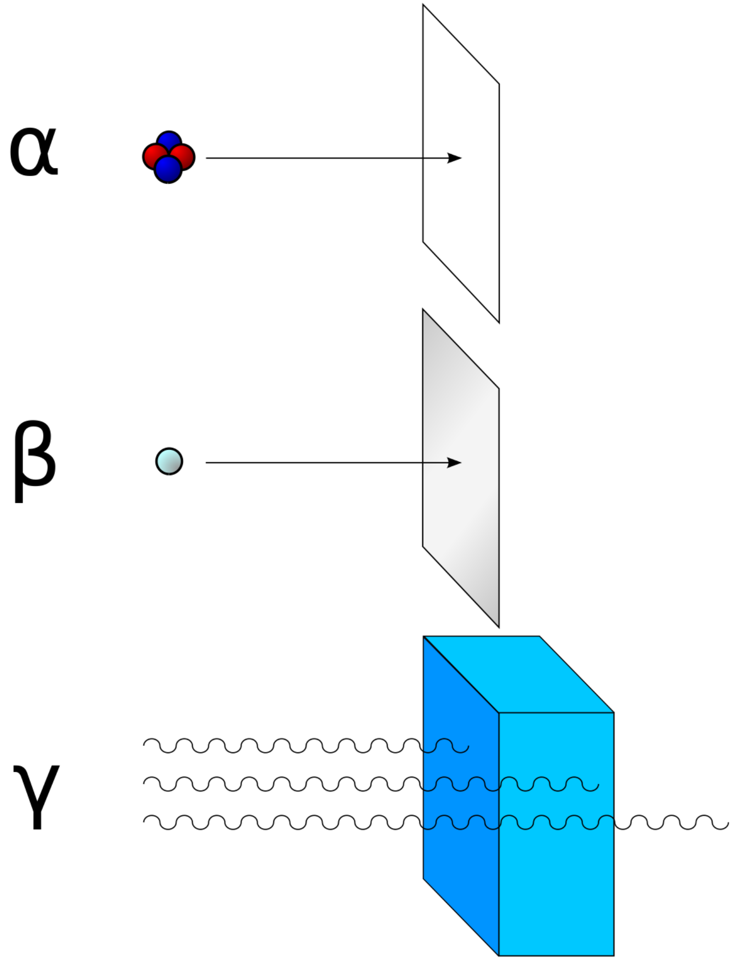
What is radiation?

Ionizing Radiation

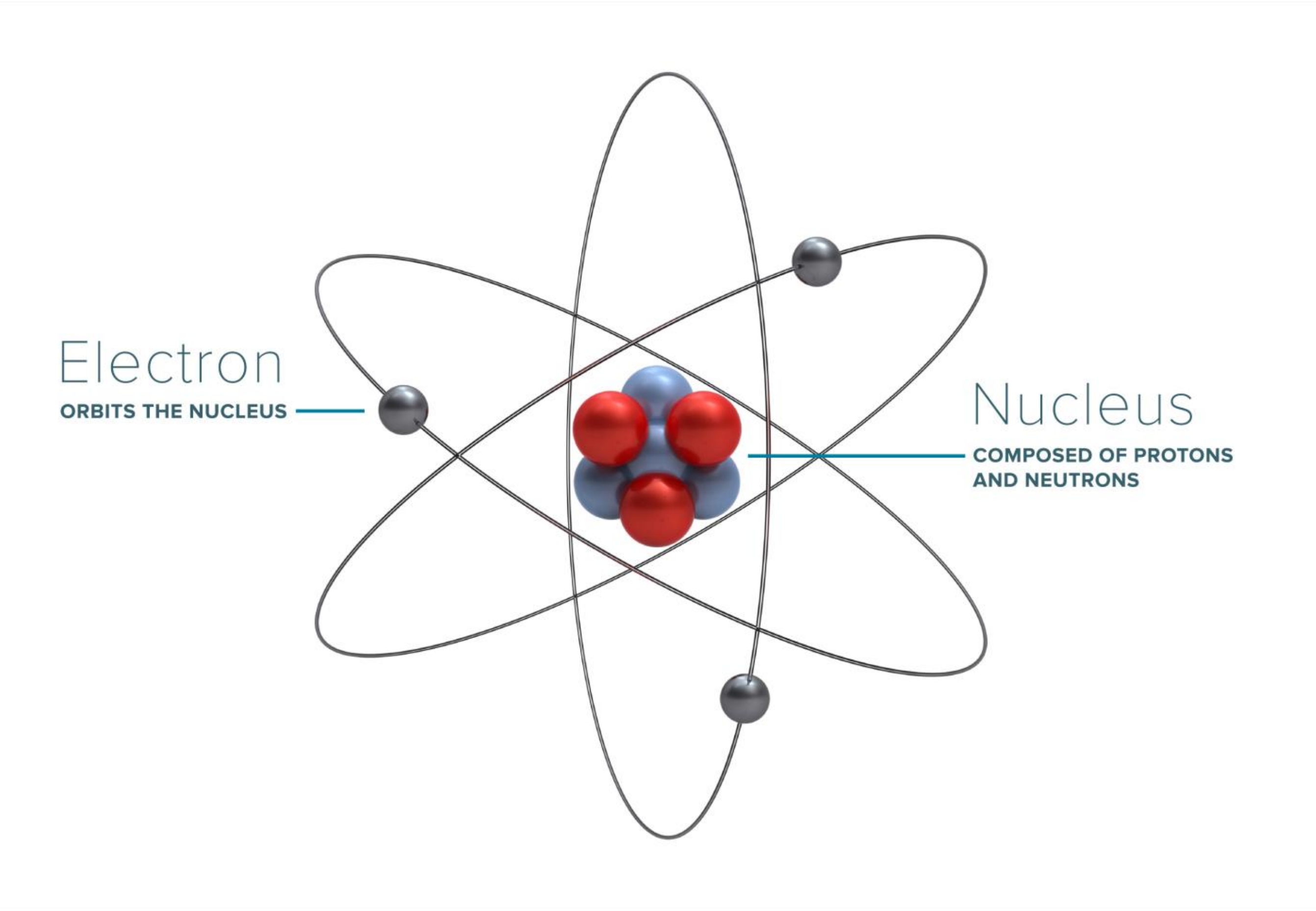
"Ionizing Radiation is radiation that carries enough energy to detach electrons from atoms or molecules"

- Subatomic particles, ions or atoms, with v > 0.01c
- Discovered by Antoine Henri Becquerel
- Impact quantified in 'Gray': $1\ Gy = 1\ \frac{J}{kg} = 1\ \frac{m^2}{s^2}$

[Wikipedia]



Atoms and their parts



Radiation Effects

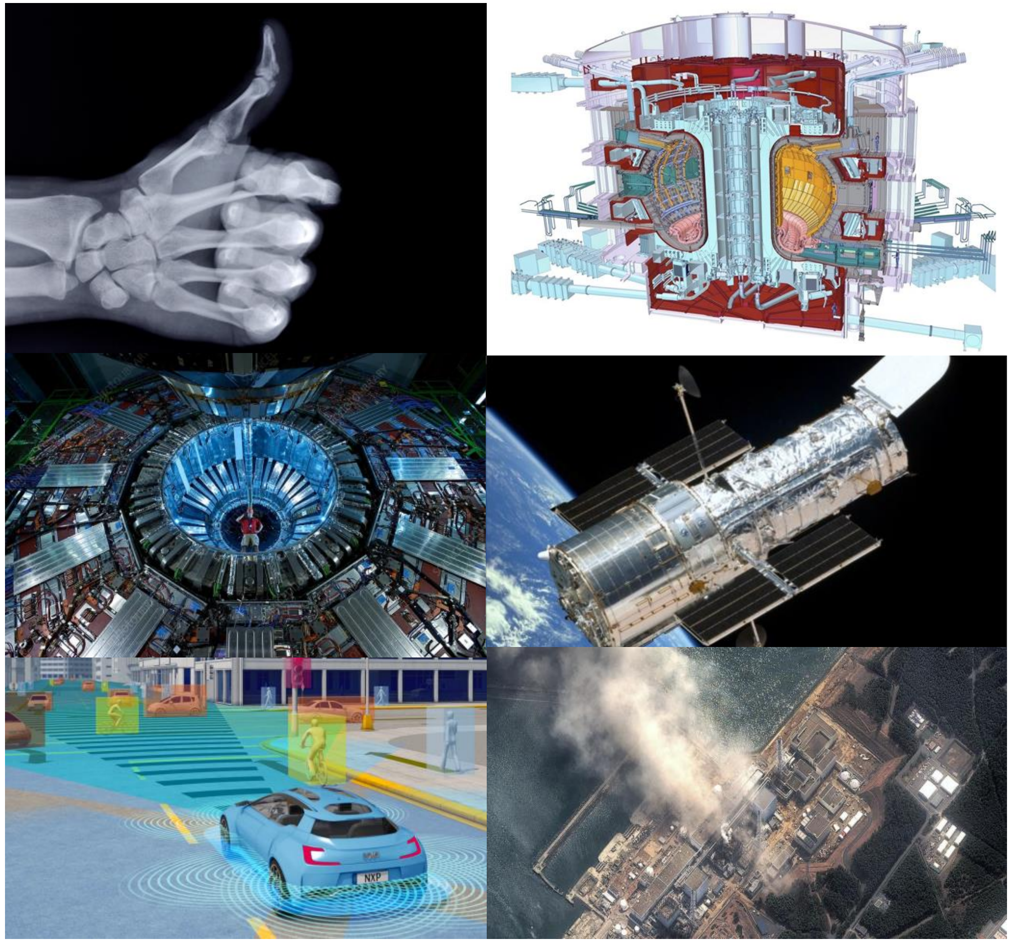
- On the human body:
  - Impacts DNA of cells:
    - Low doses (over a long period) result in mutations => Cancer, …
    - Higher doses result in malfunctioning, cells are killed

0.5 – 1.0 Gy:	Headache, infections, …	
1.0 – 2.0 Gy:	More severe symptoms	10 % killed after 30 days
3.0 – 4.0 Gy:	Internal bleadings	50 % killed after 30 days
~6.0 Gy:	Symptoms start after 30 minutes	90 % killed after 30 days
6.0 – 10.0 Gy:	Bone marrow destroyed	
>10 Gy:	Walking Ghost	100 % death in 7 days
>50 Gy:	Instantly killed (neutron bombs)	

- After first symptoms, latent phase of 3 – 12 days, new more serious symptoms

Ionizing Radiation

- Natural sources:
  - Radon in air
  - Concrete buildings
  - Minerals (Uranium, …)
  - Cosmic Radiation
- (Wo)man-made sources:
  - Nuclear power plants/waste
  - Medical (X-Ray, CT-scan, …)
  - Nuclear Weapons
  - Particle Accelerators



Ionizing Radiation

- Natural sources:
  - Radon in air
  - Concrete buildings
  - Minerals (Uranium, …)
  - **Cosmic Radiation**
- (Wo)man-made sources:
  - **Nuclear power plants/waste**
  - **Medical (X-Ray, CT-scan, …)**
  - Nuclear Weapons
  - **Particle Accelerators**

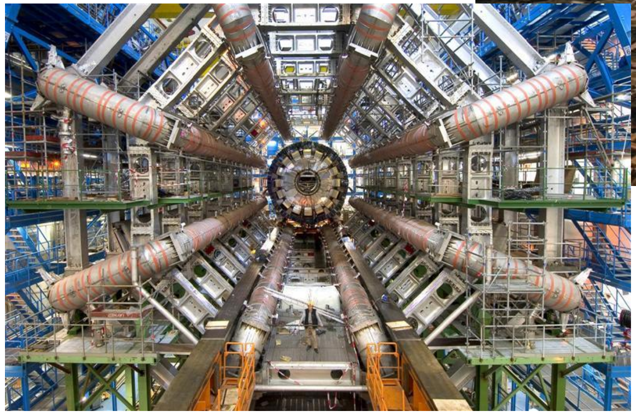
[Wikipedia], [www.CERN.ch], [www.justscience.in]

Some radiation sources

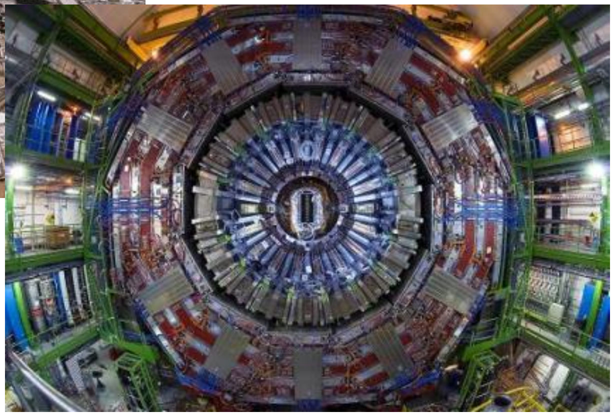
- **Cosmic rays:** 85% protons, 14% alpha particles, and 1% heavy ions, x-ray and gamma-ray radiation. The atmosphere filters most of these, so they are primarily a concern for spacecraft and high-altitude aircraft, but can also affect ordinary computers on the surface.
- **Solar particle events** come from the direction of the sun and consist of a large flux of high-energy (several GeV) protons and heavy ions, again accompanied by x-ray radiation.
- **Van Allen radiation belts** contain electrons (up to about 10 MeV) and protons (up to 100s MeV) trapped in the geomagnetic field. Secondary particles result from interaction of other kinds of radiation with structures around the electronic devices.
- **Nuclear reactors:** gamma and neutron radiation can affect sensor and control circuits in nuclear power plants.
- **Particle accelerators** produce high energy protons and electrons, and the secondary particles produced by their interactions produce significant radiation damage on sensitive control and particle detector components.
- **Nuclear explosions** produce a short and extremely intense surge through a wide spectrum of electromagnetic radiation, an electromagnetic pulse (EMP), neutron radiation, and charged particles.
- **Chip packaging materials** were an insidious source of radiation that was found to be causing soft errors in new DRAM chips in the 1970s.

Particle accelerators and colliders
e.g. Large Hadron Collider @ CERN

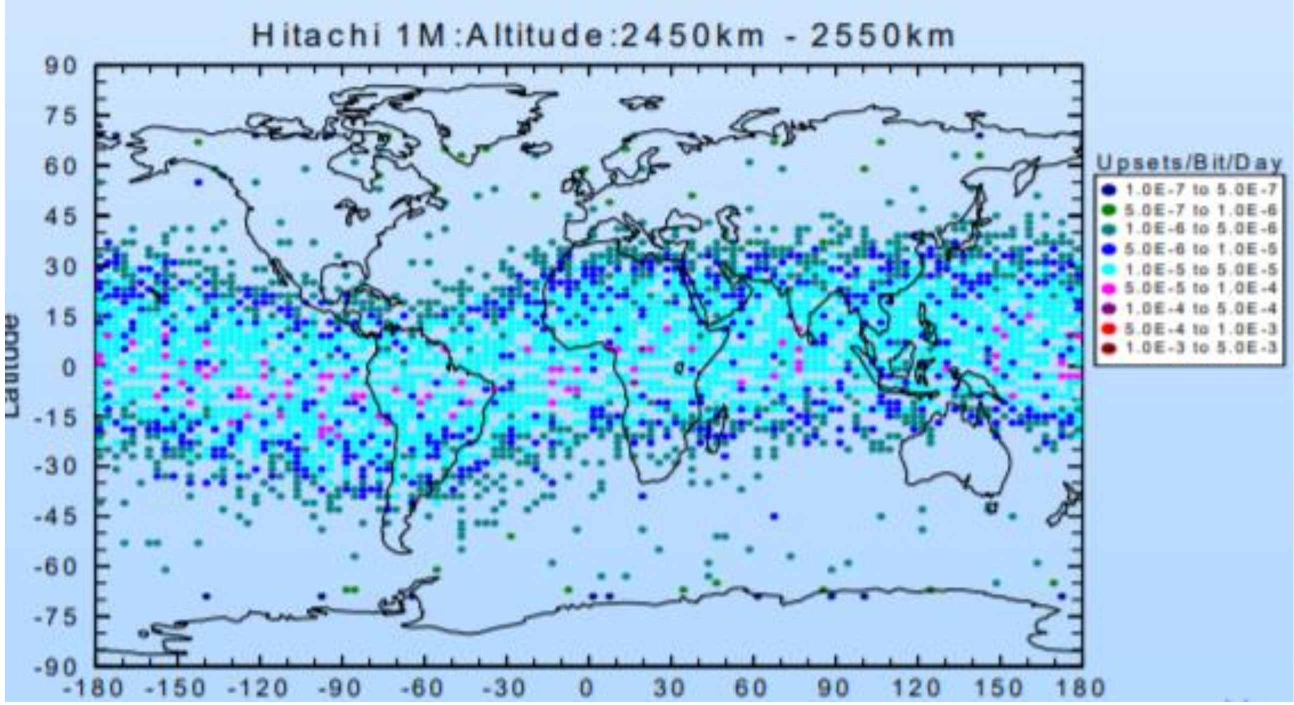
ATLAS

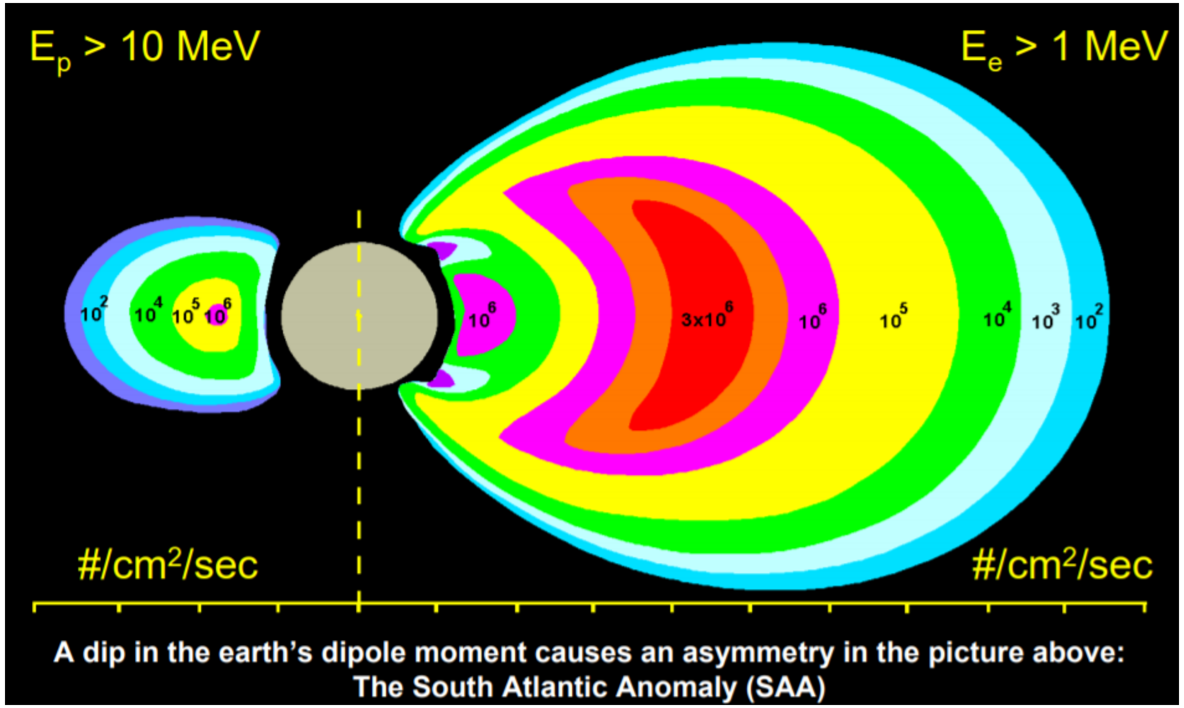


CMS



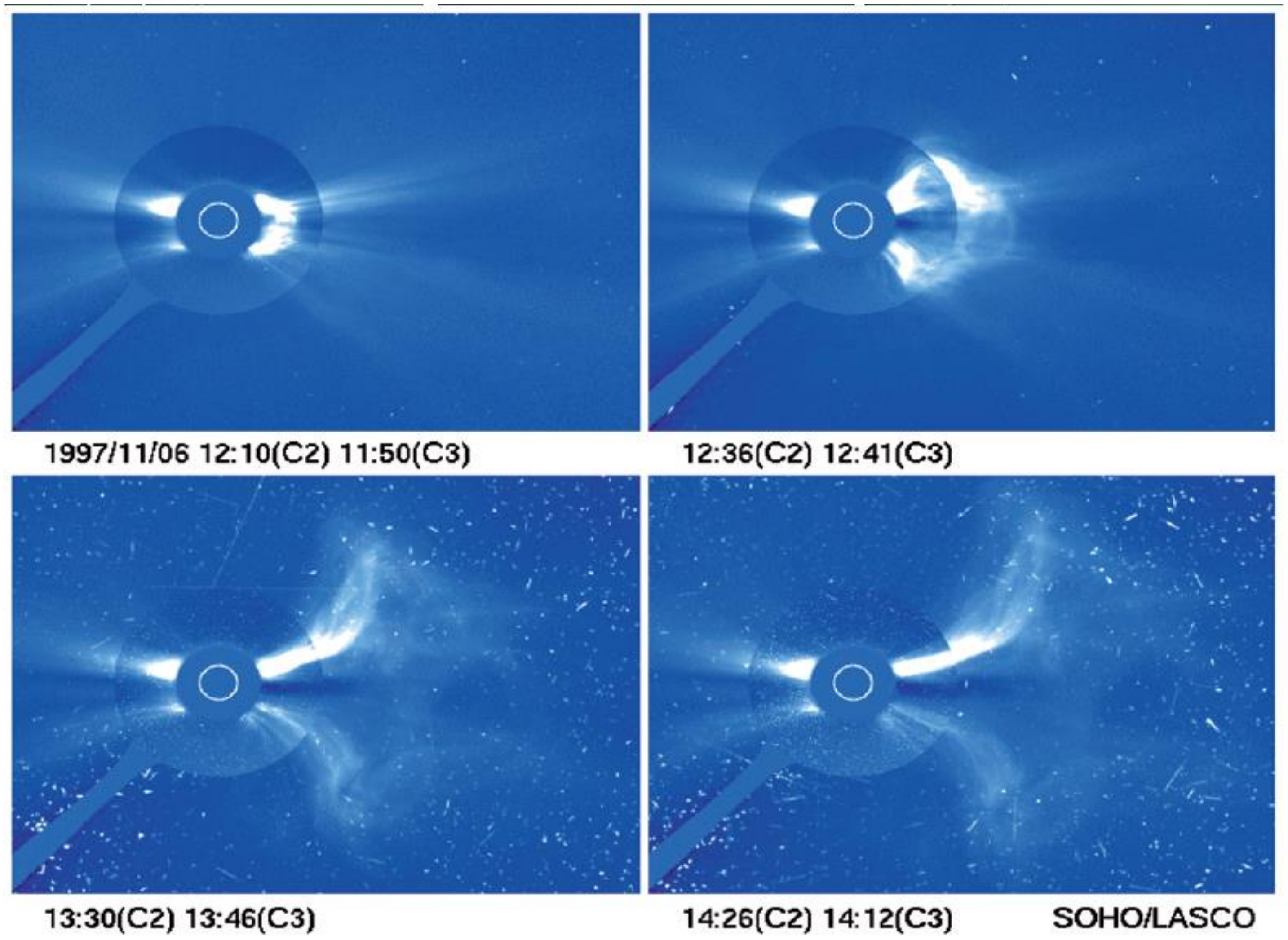
Van Allen belt trapped particles





[NASA]

Significant failures



[ESA]


:(
Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.
0% complete
For more information about this issue and possible fixes, visit https://www.windows.com/stopcode
If you call a support person, give them this info:
Stop code: MANUALLY INITIATED CRASH

Significant failures

- 2003 – Belgium – 4096 extra votes during elections for a candidate. This was spotted only because politician had more votes than possible
- Quantus airliner Singapore-Perth (Australia) plunged through the sky for 23 seconds. SEU in the avionics and autopilot caused plane to drop
- Smartphone and computer crashes

RAM	Vendor/ RAM Type (D or S)	Measr'd WNR SEU X-Sct'n, cm ^{2}/bit	Gr'nd level SEU Rate, Up/bit-hr, WNR-Scaled	Calculated Ground SEU Rate, Up/bit-hr, BGR Method
TC514400	Toshiba/D	1.2E-13	2.3E-12	2.1E-12*
MSM514400	Oki/D	2.2E-14	4.3E-13	N/A
TMS44100	TI/D	9.3E-14	1.8E-12	2.3E-12
IDT71256	IDT/S	6.5E-14	1.3E-12	2.3E-12
HM65656	Matra/S	1.9E-13	3.7E-12	1.2E-12
MCM6206	Motorola/S	1.4E-13	2.7E-12	7E-13*
MCM6246	Motorola/S	1.3E-14	2.4E-13	3.4E-13
Average (7 RAMs)		1.9E-13	1.8E-12	2.5E-12

Upsers/bit/hr

16 GB memory

2.3e-12 x 16 x 8e9 = **0.23 upsets/hour**

1 each 4-5 hours!

[Boeing]

Reliability is a problem even for ground applications!

Outline

- Introduction
- **Radiation effects in Electronic Devices**
  - Total Ionizing Dose
  - Single Event Effects
- Design of Radiation Tolerant Electronics
- Conclusions

Radiation effects on electronics

What happens with electronics impacted by radiation?

- Tsjernobyl 1986
- “Joker” robot sent to clean the roof

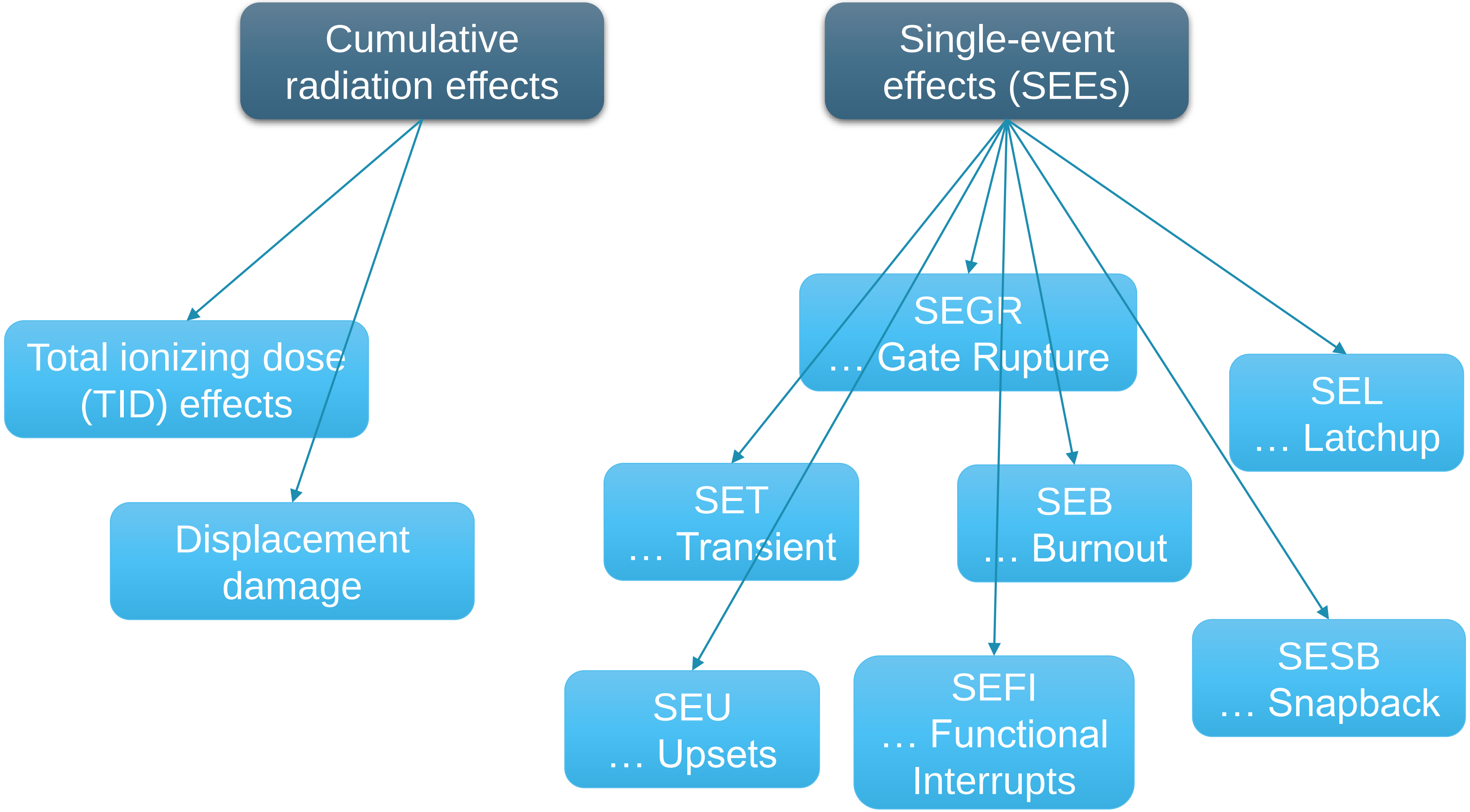
“Exposure to radiation is cumulative, and it doesn’t go away”

Radiation effects on electronics

"The Soviets used about 60 remote-controlled robots, most of them manufactured domestically within the U.S.S.R. Although several designs were eventually able to contribute to the cleanup, most of the robots quickly succumbed to the effects of high levels of radiation on delicate electronics."

[The Scientist]

Radiation effects in electronics

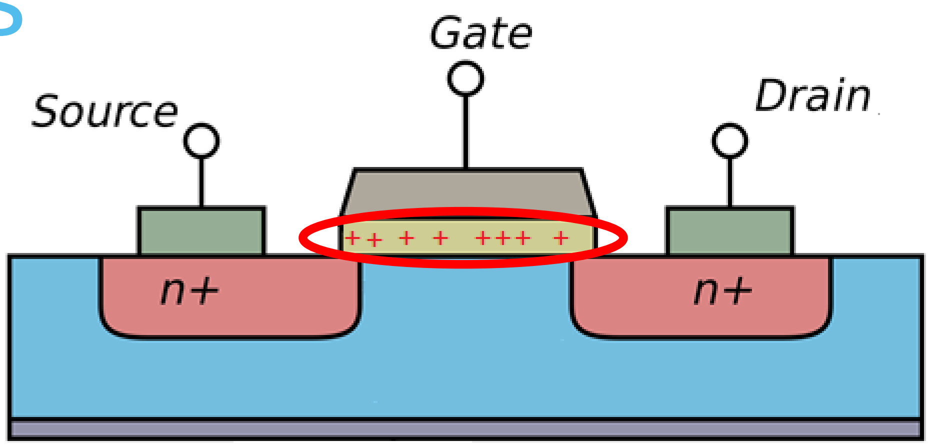


Radiation effects on electronics

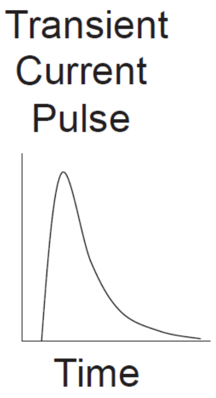
- **Total Dose effects (TD):**
  - **Cumulative and long term**
  - Accumulation of trapped charges in devices (Si/SiO2 interface)
  - defects in the bulk (displacement damage)
  - Device degradation

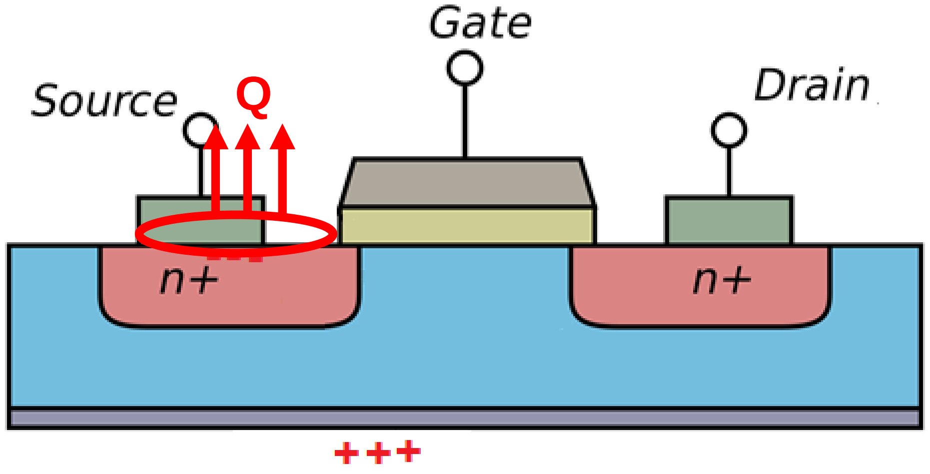
- **Single event effects (SEE):**
  - **Stochastic effect**
  - Charge deposition by a single particle
  - Soft or hard errors
  - Charge Q injected into circuit

Radiation effects on electronics



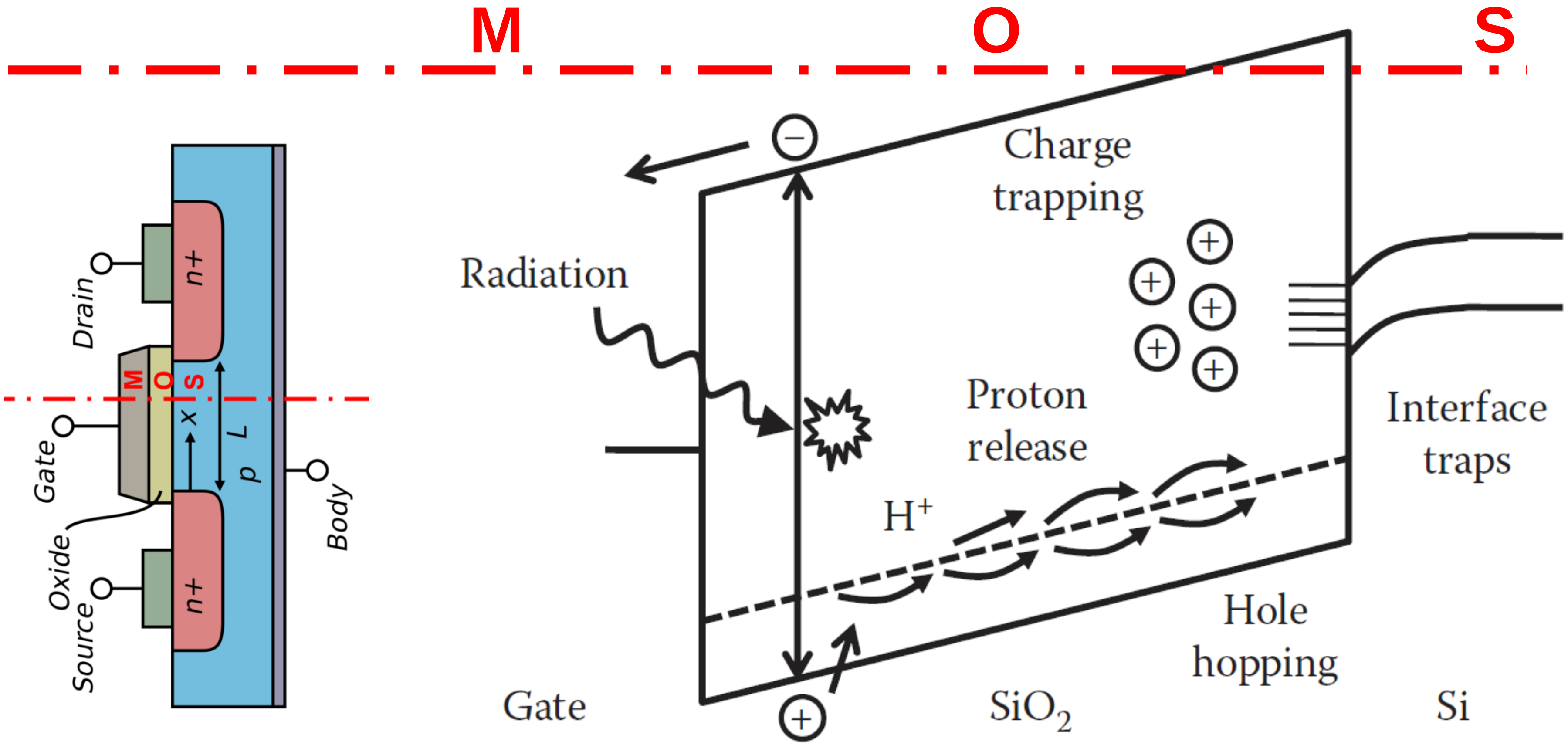
- **Total Dose effects (TD):**
  - **Cumulative and long term**
  - Accumulation of <u>trapped charges</u> in devices (Si/SiO2 interface)
  - defects in the bulk (displacement damage)
  - Device degradation
  - Total Dose: [Gray] (J/kg)





- **Single event effects (SEE):**
  - **Stochastic effect**
  - Charge deposition by a <u>single particle</u>
  - Soft or hard errors
  - Charge Q injected into circuit [C]

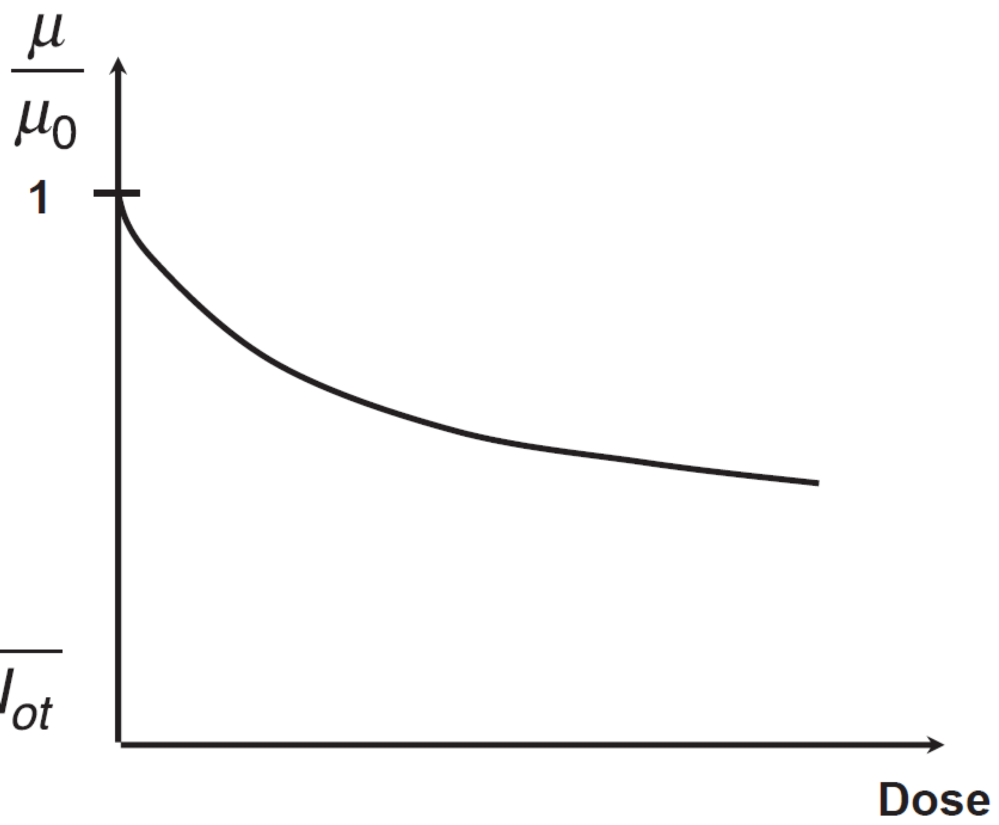
Radiation effects in MOS devices



Energy band diagram of a MOS system on a p-substrate, biased at a positive voltage. (Adapted from O. Flament, J. Baggio, S. Bazzoli, S. Girard, J. Raimbourg, J. E. Sauvestre, and J. L. Leray, *Advancements in Nuclear Instrumentation Measurement Methods and their Applications [ANIMMA]*, 2009, p. 1.)

Radiation effects in MOS devices
Mobility degradation

- Mobility decreases due to scattering from radiation-induced charges near the interface



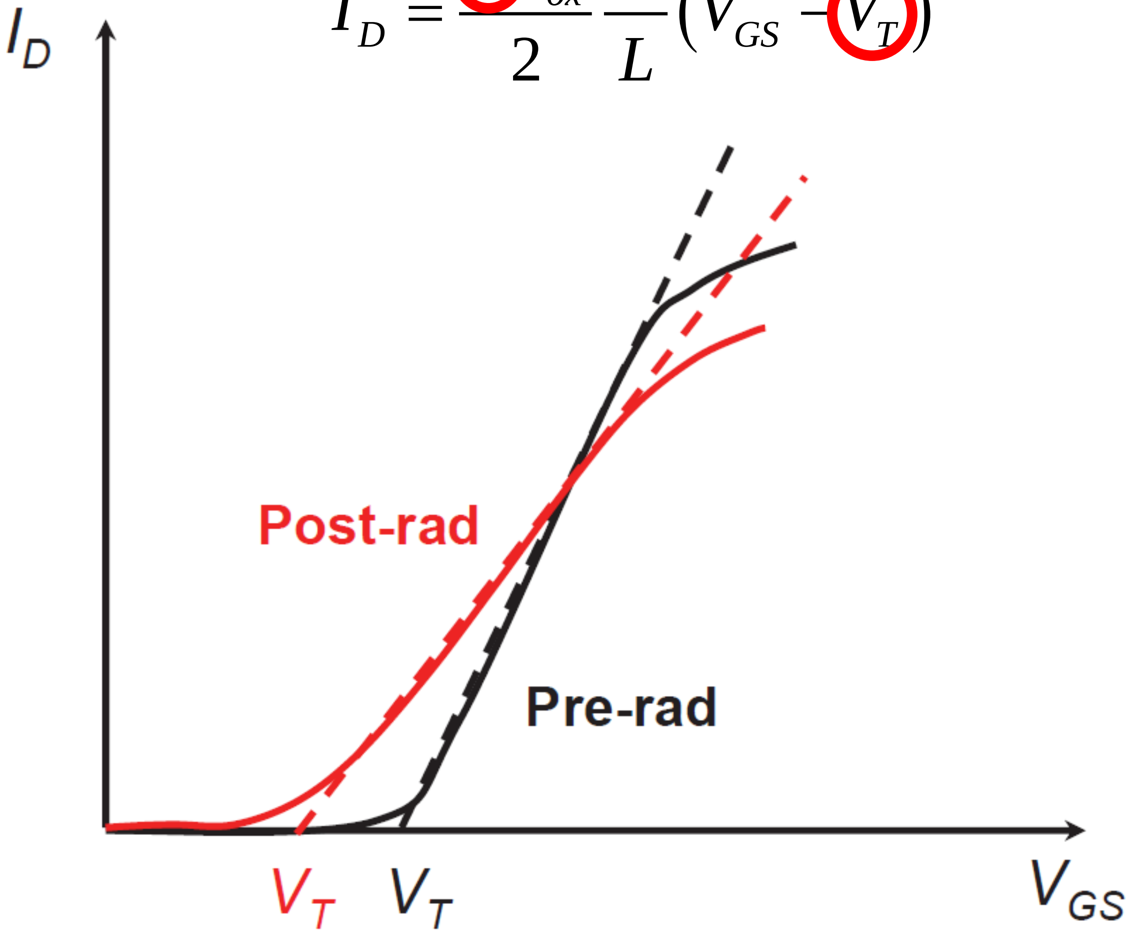
$$\mu = \frac{\mu_0}{1 + \alpha_{it}\Delta N_{it} + \alpha_{ot}\Delta N_{ot}}$$

Empirical expression – assumes effects of oxide charges on mobility are projected to interface (fall off strongly with distance of charge into the oxide)

Radiation effects in MOS devices

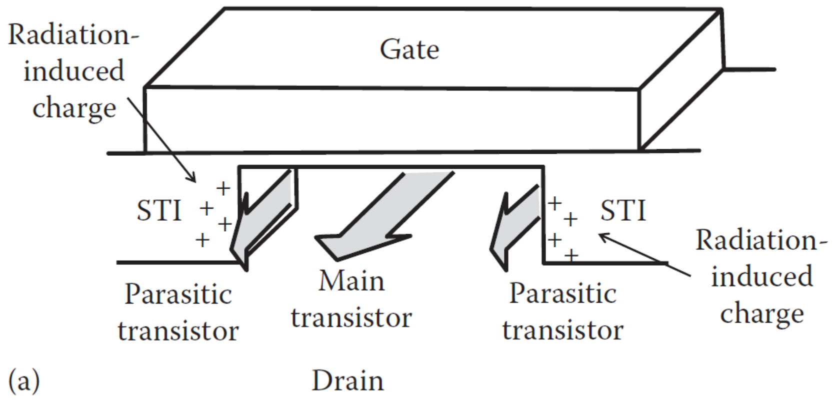
- Radiation-induced charges
  - Translate curve (threshold shift)
  - Stretchout from interface traps
  - Mobility degradation

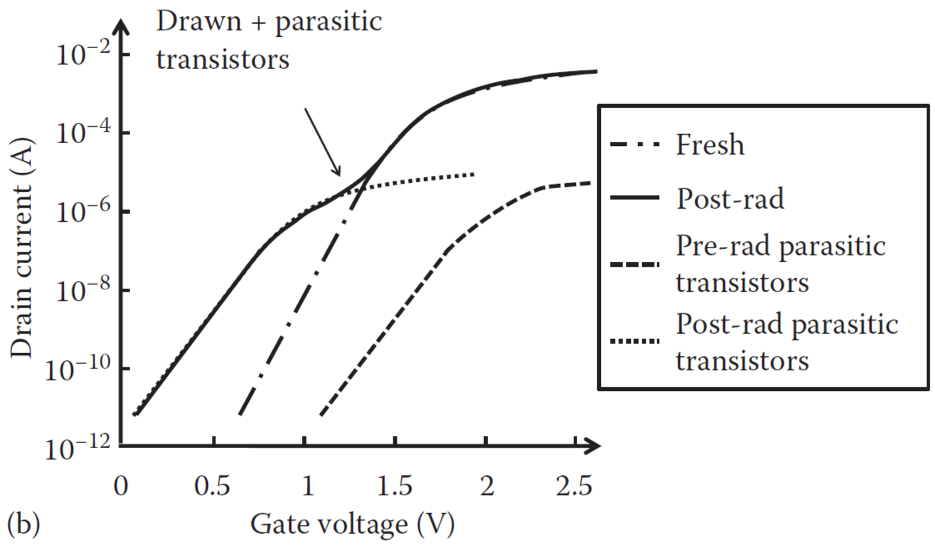
$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2$$



KU LEUVEN

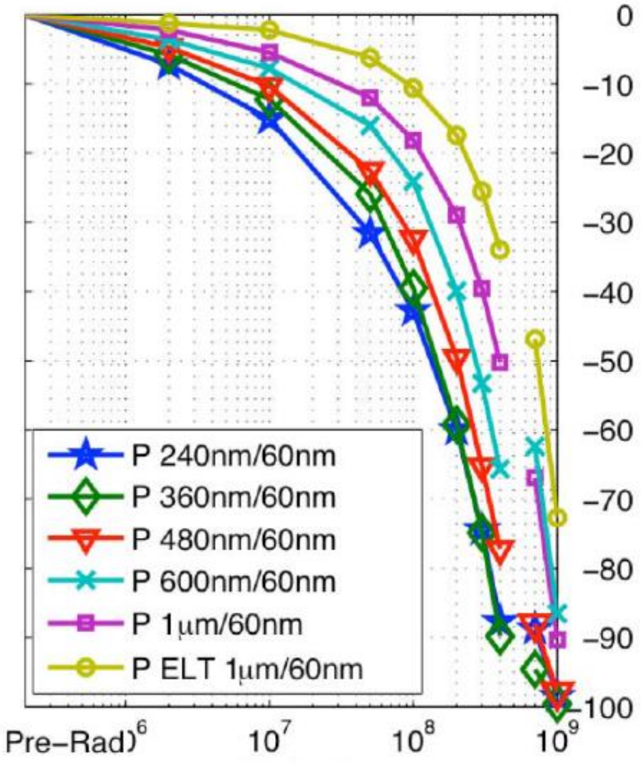
Radiation effects in MOS devices leakage current



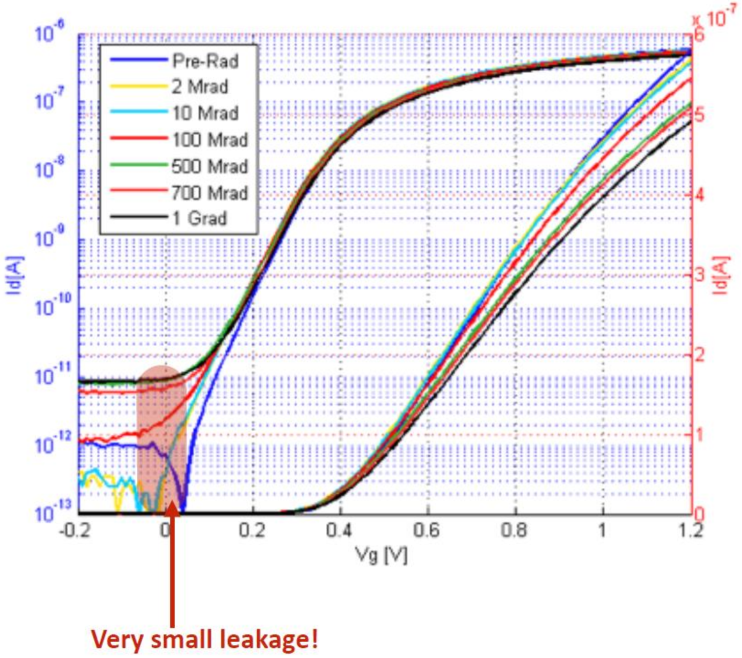


65 nm transistor

%I PMOS



NMOS



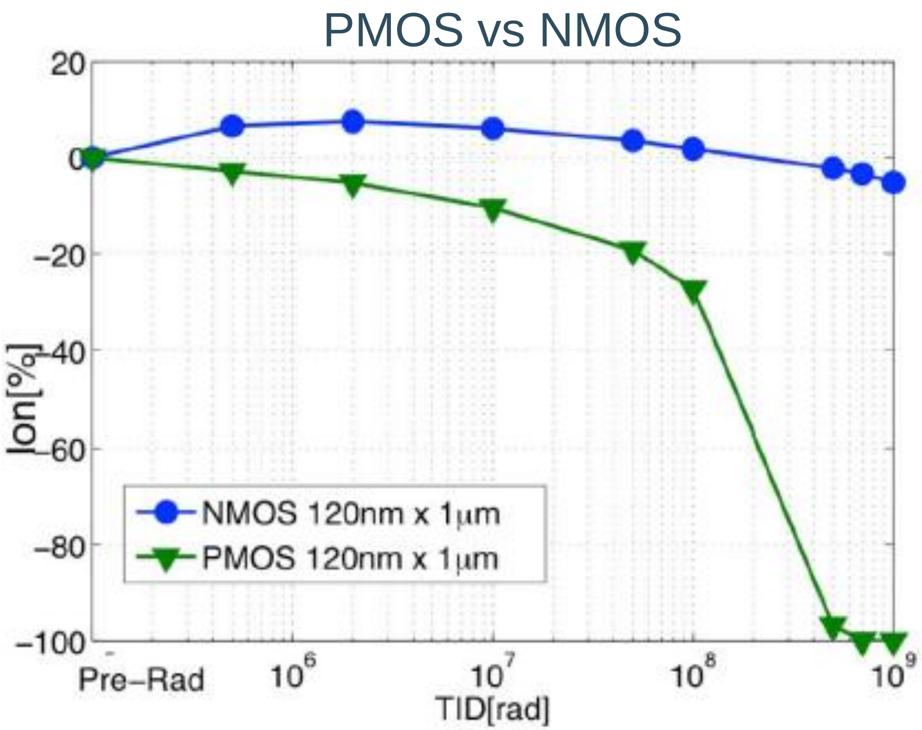
Transistors' size: W=120nm, L=1um
Irradiation conditions:
T = 25C
Bias: |Vgs|=|Vds|=1.2V

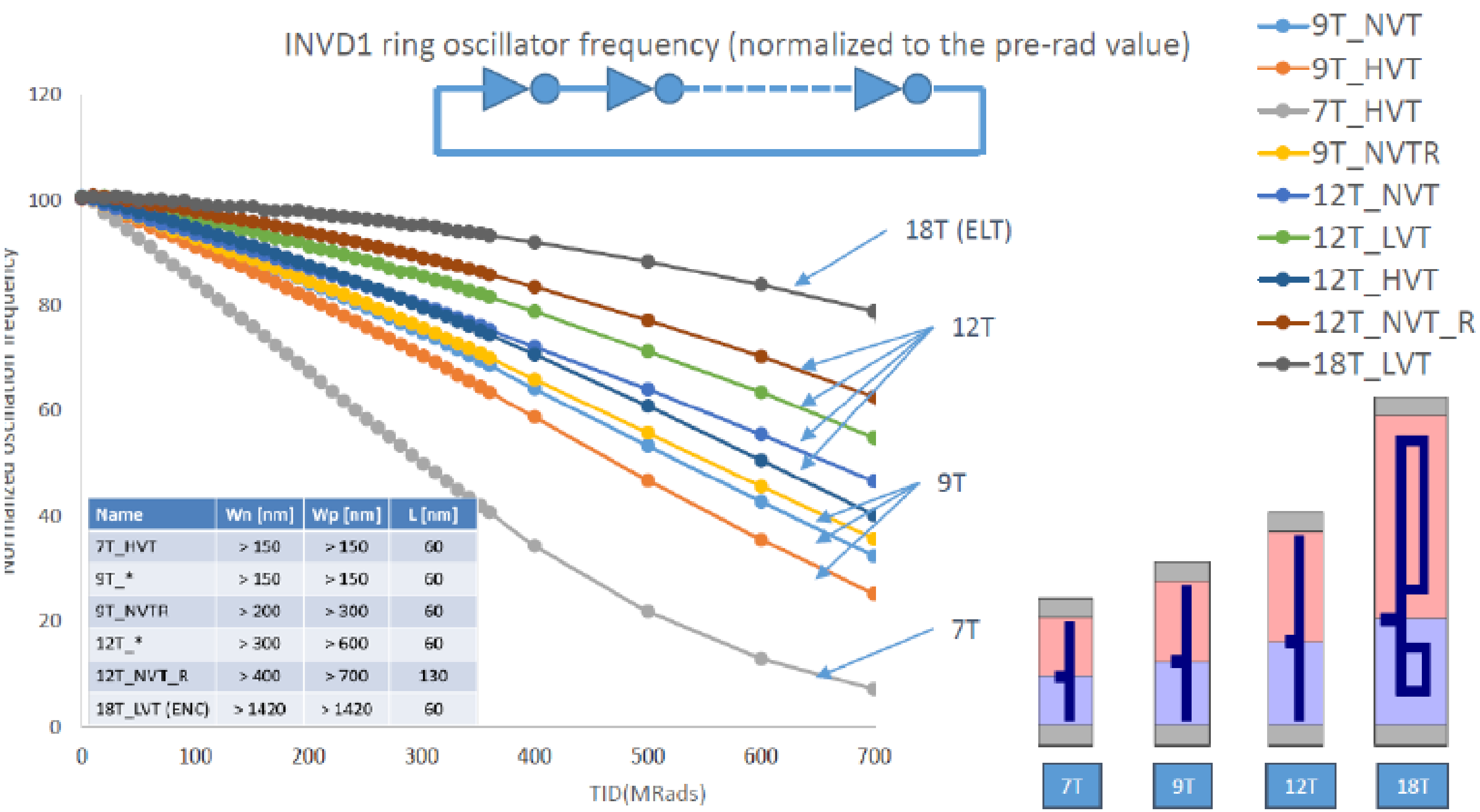
KU LEUVEN

Outline

- Introduction
- Radiation effects in Electronic Devices
  - Total Ionizing Dose
  - Single Event Effects
- **Design of Radiation Tolerant Electronics**
- Conclusions

Radiation effects in MOS devices



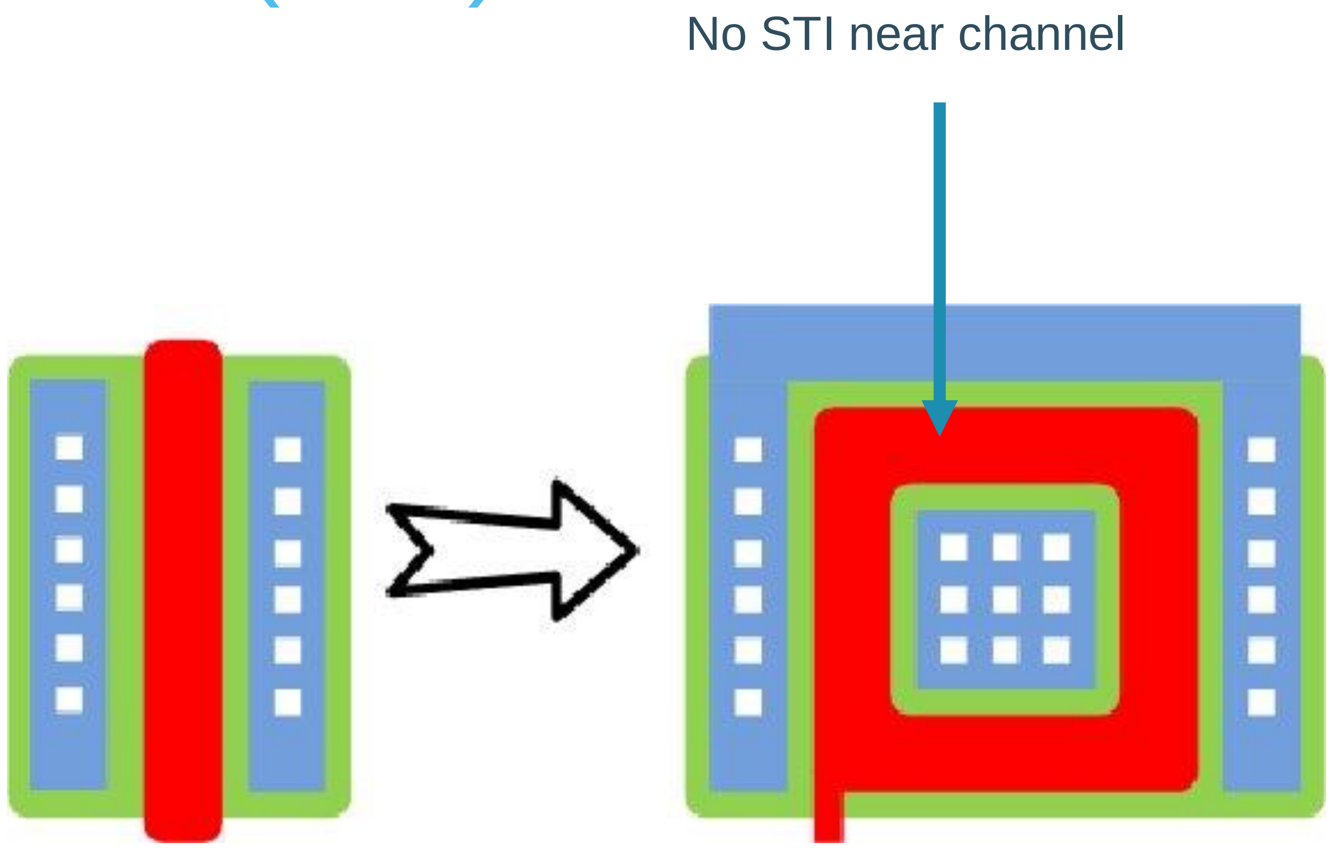


Name	Wn [nm]	Wp [nm]	L [nm]
7T_HVT	> 150	> 150	60
9T_*	> 150	> 150	60
9T_NVTR	> 200	> 300	60
12T_*	> 300	> 600	60
12T_NVT_R	> 400	> 700	130
18T_LVT (ENC)	> 1420	> 1420	60

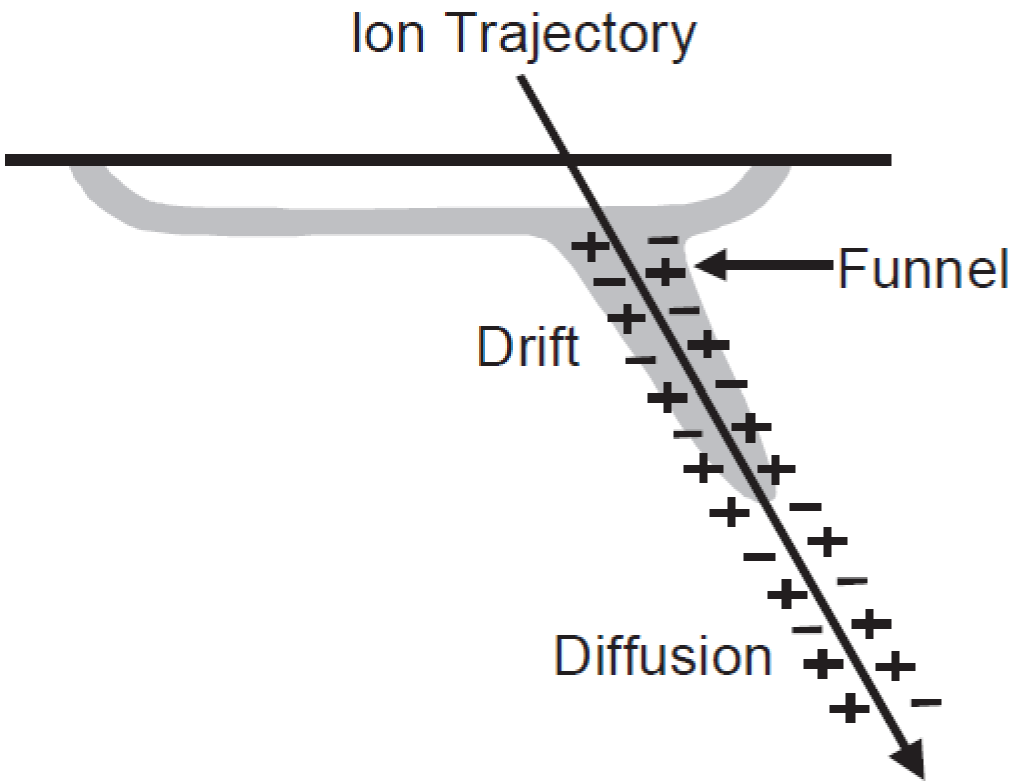
Enclosed Layout Transistor (ELT)

Gate all around transistor

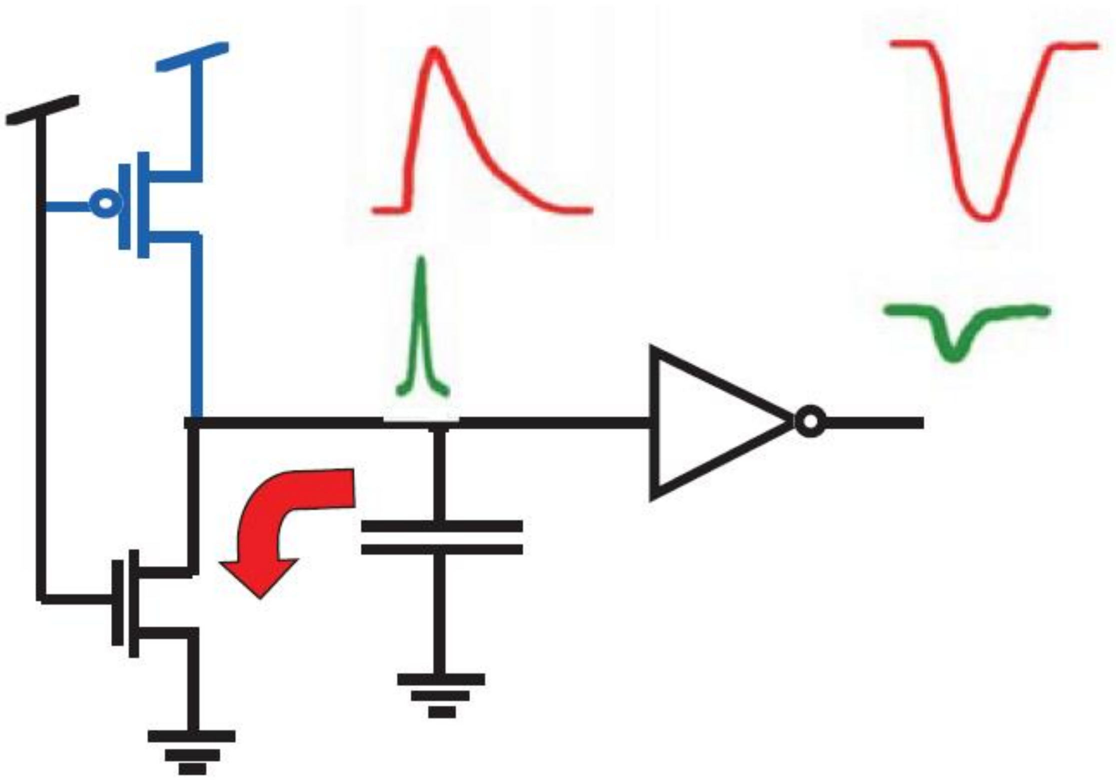
- Advantages
  - Avoids STI oxide near channel
  - “Best” TID performance
  - Improved digital speed (smaller junction capacitance)
- Disadvantages
  - Difficult DRC rules (corners)
  - Sub 45nm: X and Y poly rules different
  - Minimum drain area (minimum W)
    - High power consumption for digital
  - Matching not very good
  - Effective W not precisely known (2D current profile)
  - Special LVS and PEX rules required – PCELL development



Single-event effects



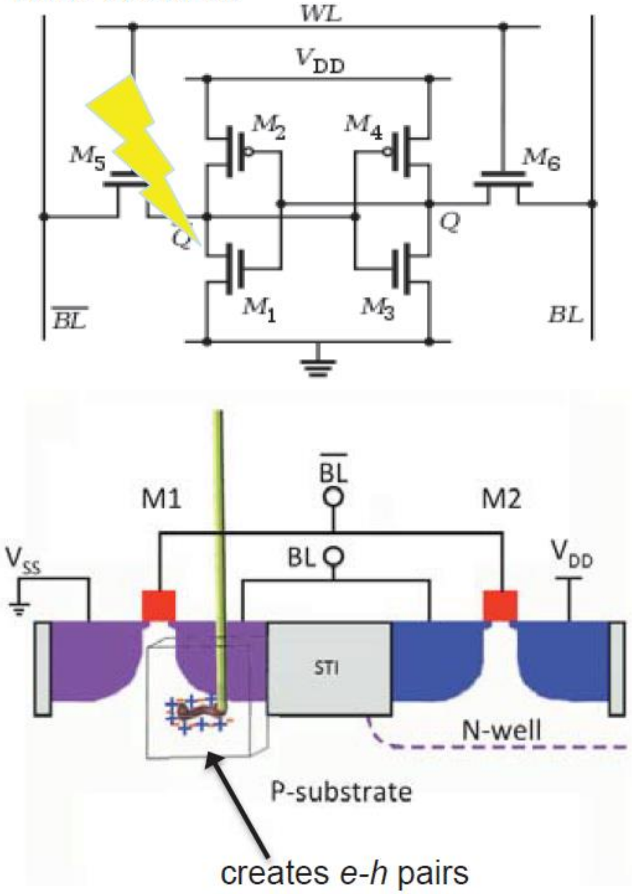
Single-event transients



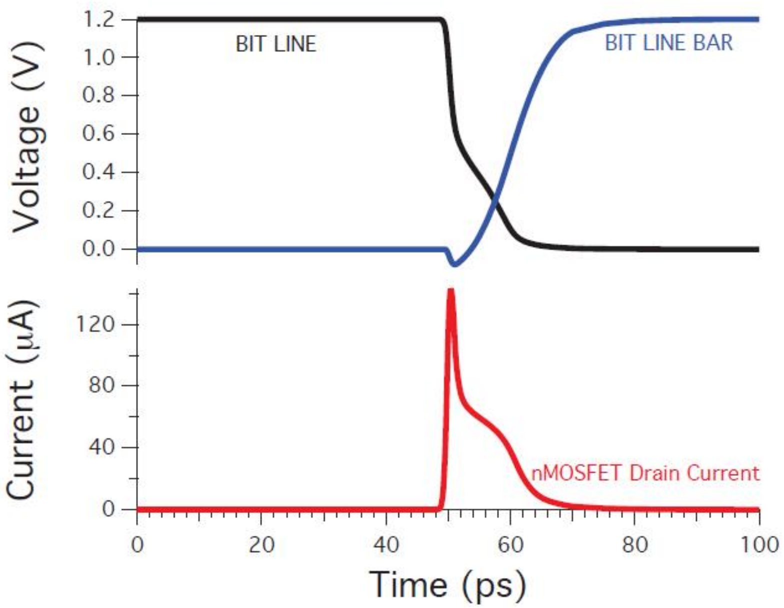
S.P. Buchner, NSREC SC 2001

Single-event effects
SEU in SRAM

Particle Strikes Sensitive Node of SRAM



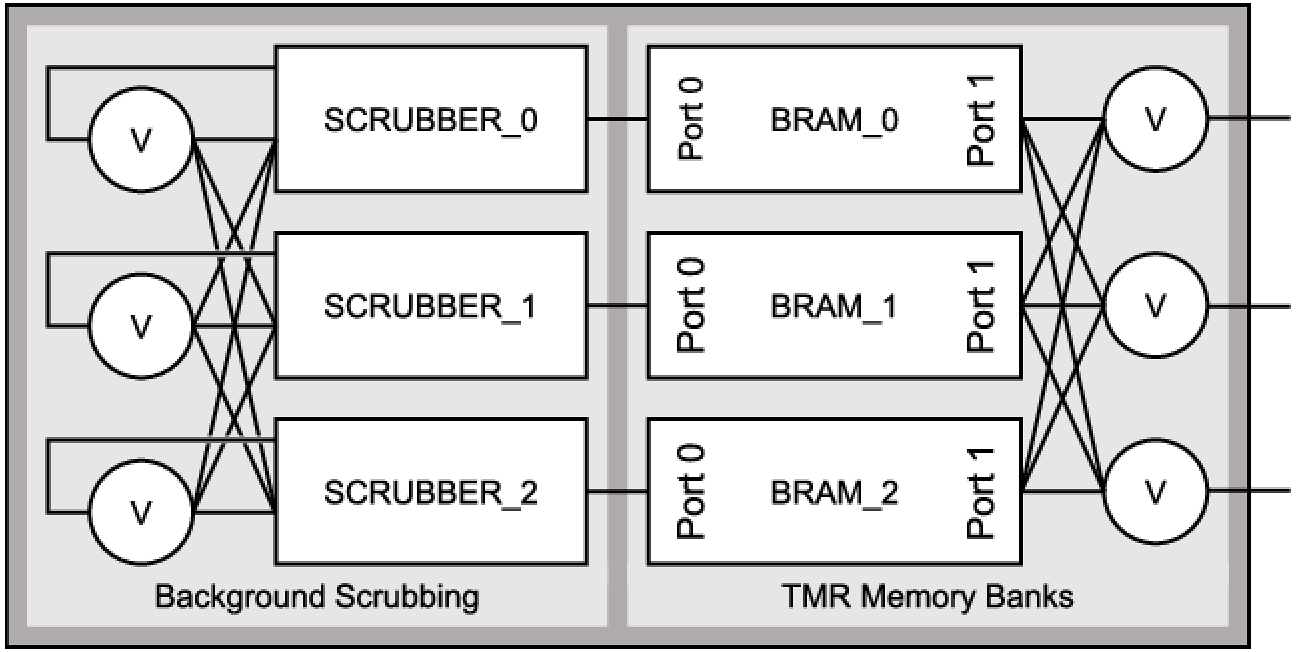
Circuit Transient Response
Results in Error

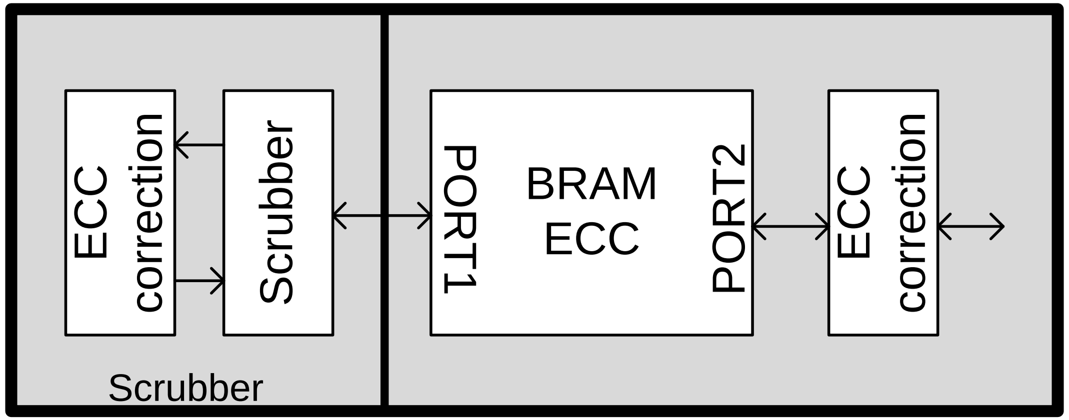


SRAM memories

- Error Detection and correction (EDAC)
- TMR: corrects any number of bits if RAMs are separated sufficiently – large overhead
- Parity: Single error detection
- CRC code: Detects errors in a block
- Hamming code: Single error correction, double bit detection
- RS code: corrects consecutive and multiple bytes

[Keller, 2017]



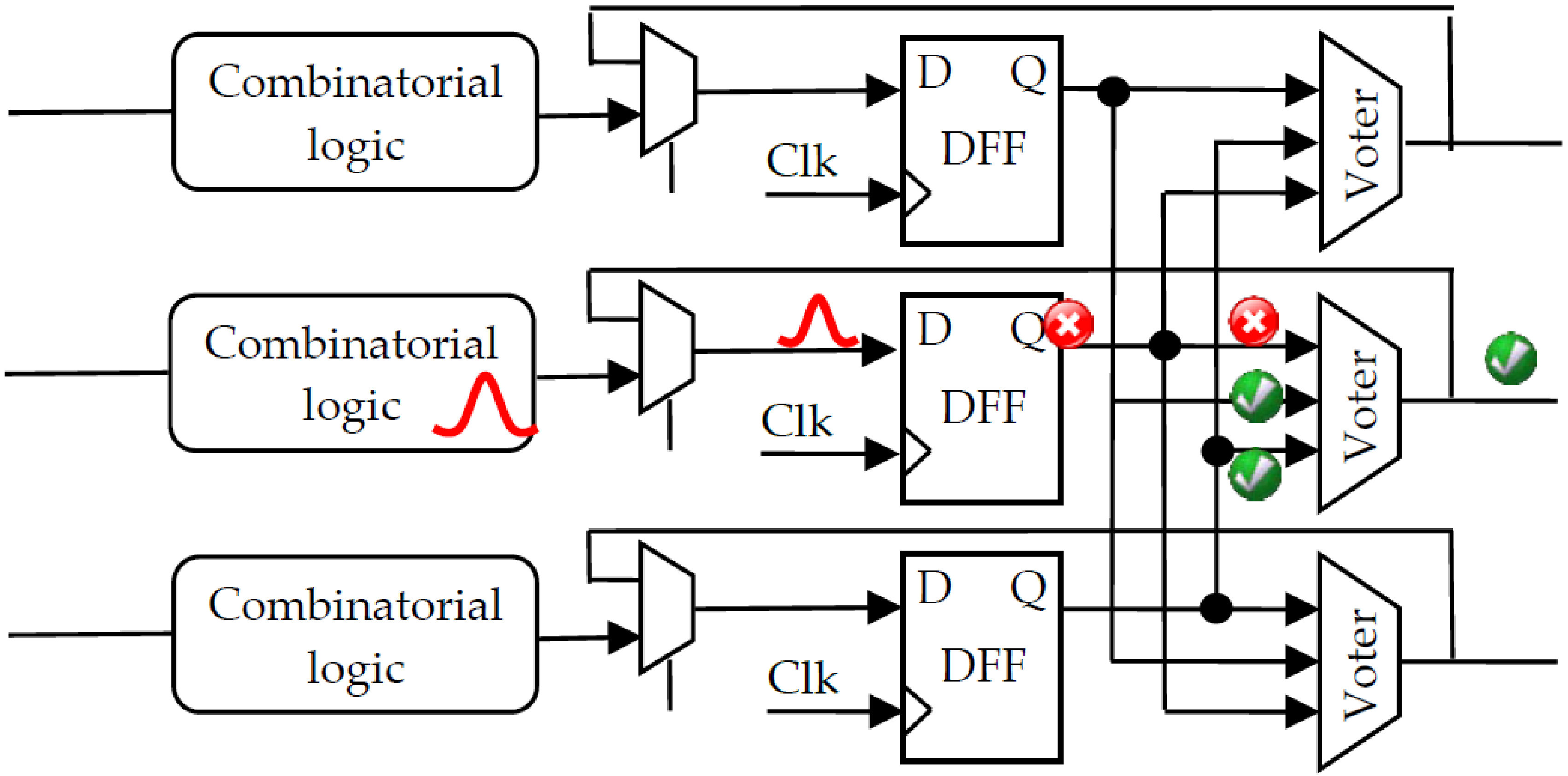


Radiation hardened digital circuits
Triple Modular Redundancy (TMR)

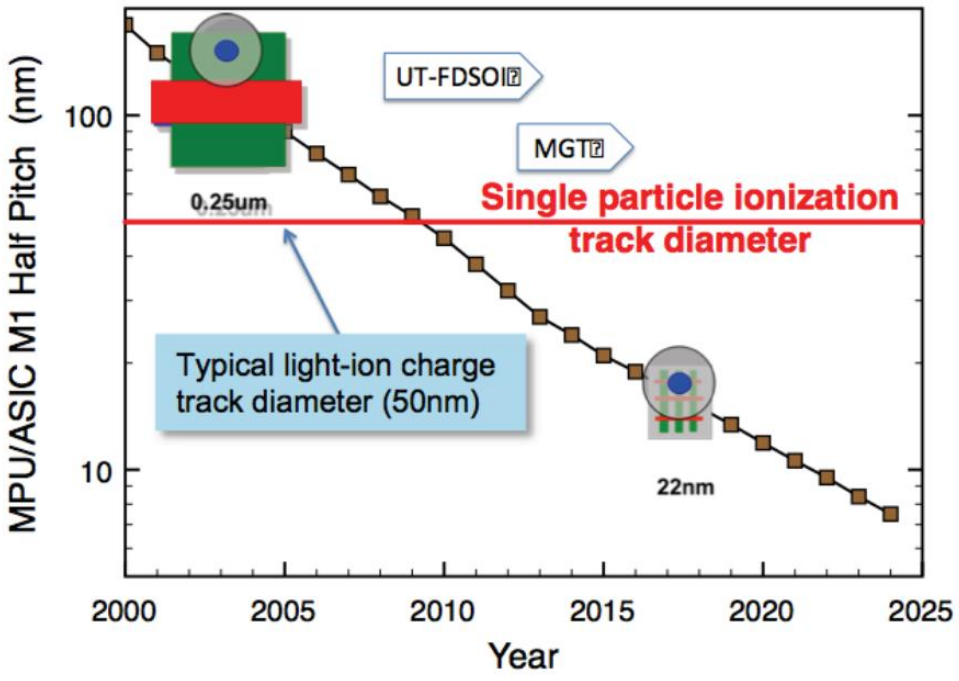
- 3 logic paths
- 3 clock trees
- 3 Voters

- Full TMR has more than 3x overhead (power; area)
- Timing overhead due to voters
- MBU important in new technologies

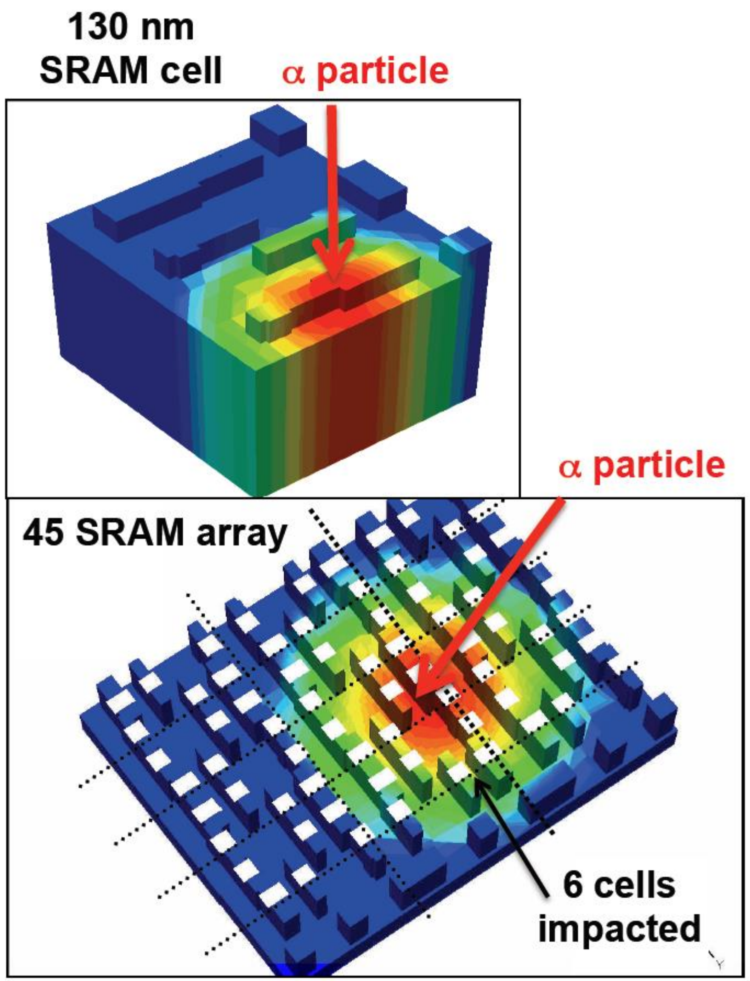
- “Weak” TMR also possible
    - (1 CK-tree ; 1 combo)



Radiation effects and IC technology scaling



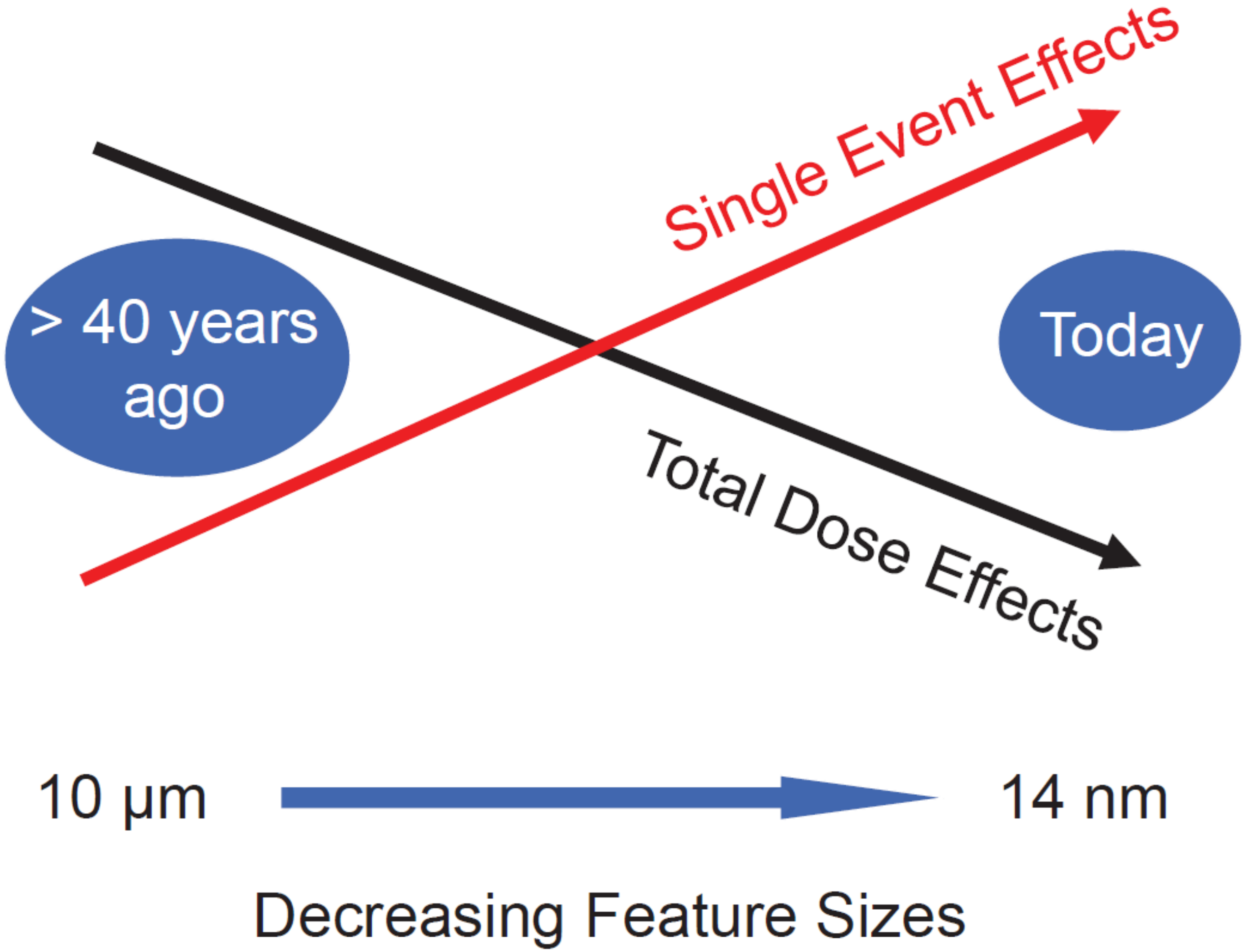
Adapted from L.W. Massengill (IRPS 2012)



After P. Roche (Year-In-Review on SER, IRPS 2006)

Radiation effects and IC technology scaling

- Thinner oxides and better oxide/silicon interfaces have reduced total dose effects.
- Smaller devices at lower voltages with less charge movement have resulted in increased single event effects.



Outline

- Introduction
- Radiation effects in Electronic Devices
  - Total Ionizing Dose
  - Single Event Effects
- Design of Radiation Tolerant Electronics
- **Conclusions**

Conclusion

- Radiation has many origins
- Radiation damage:
  - Cumulative damage (TID): Device become slow and noisy
  - Instant damage (SEE): Spikes in the circuit, possibly destructive!
- Increasing number of applications
  - Smaller chip technology
  - Increasing number of computer-driven applications
- Careful design and test strategy needed

Questions?

Advanced Integrated Sensing

ADVISE

Prof. Dr. Ir. Valentijn De Smedt

KU Leuven – ADVISE (Campus Geel)

Kleinhoefstraat 4

2440 Geel

valentijn.desmedt@kuleuven.be

www.kuleuven.be/advise