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Radiation tolerant integrated circuits

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Advanced Integrated Sensing
AdvISe

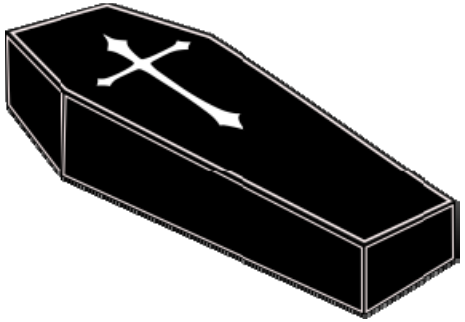
micas

CERN

Impact of radiation

Persons

- Annual base
  - 1mGy
- 50 kGy/h



For ICs

- Decreased lifetime
- Degenerated performance

- Commercial products
  - <10kGy

1Gy = J/kg

Radiation tolerant ICs

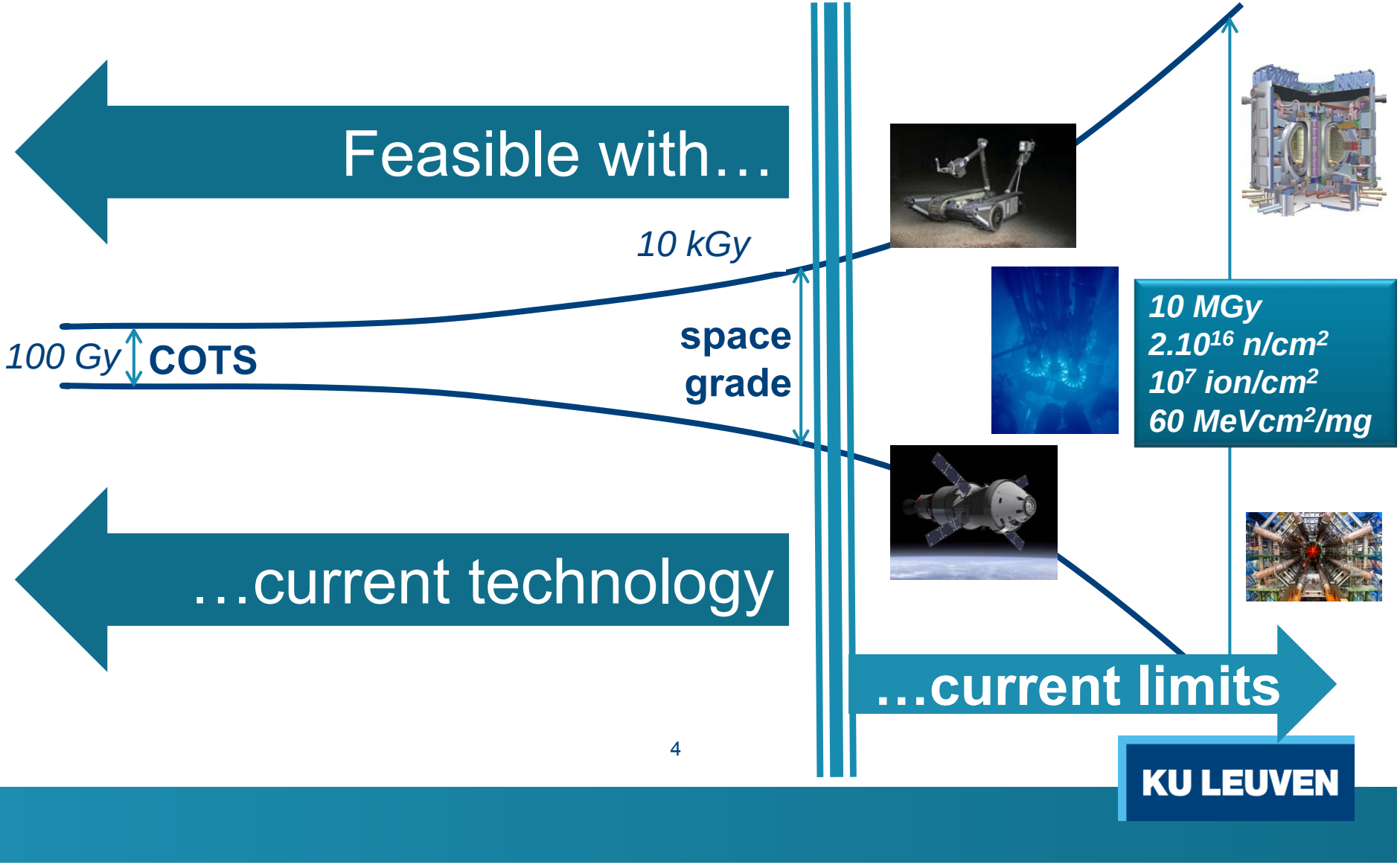
Commercial

- <10kGy
- Short space missions
- Shielding
- Outside nuclear reactor

This research

- >1MGy
- Particle physics experiments
- Deep space missions
- Nuclear reactor core
- Remote handling in nuclear incidents

Current limits



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Nuclear industry

- Growing industry
- Increasing complexity

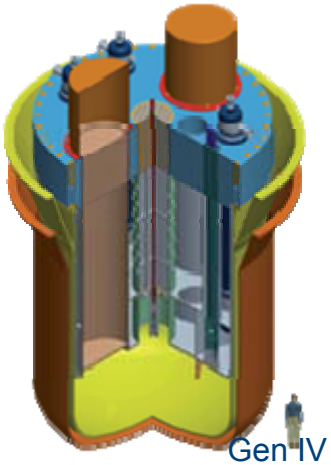
➡ Rad-Hard Technology

ICs

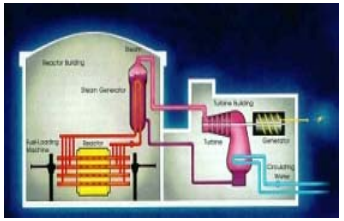
Dismantling/ Accident intervention

Swarm inspection

Remote Handling



Gen IV reactor



1st Nuclear Reactors

ITER

Time

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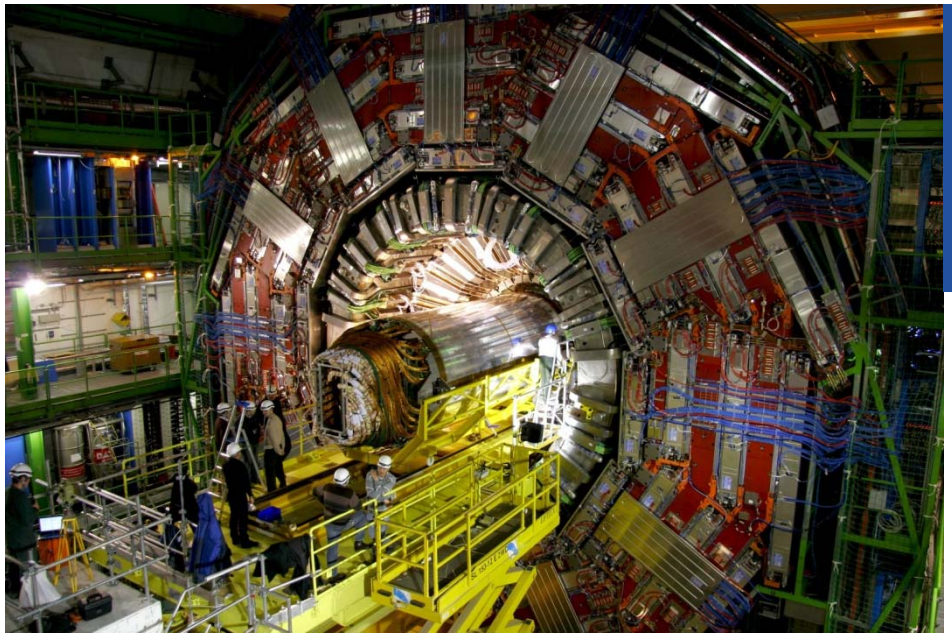
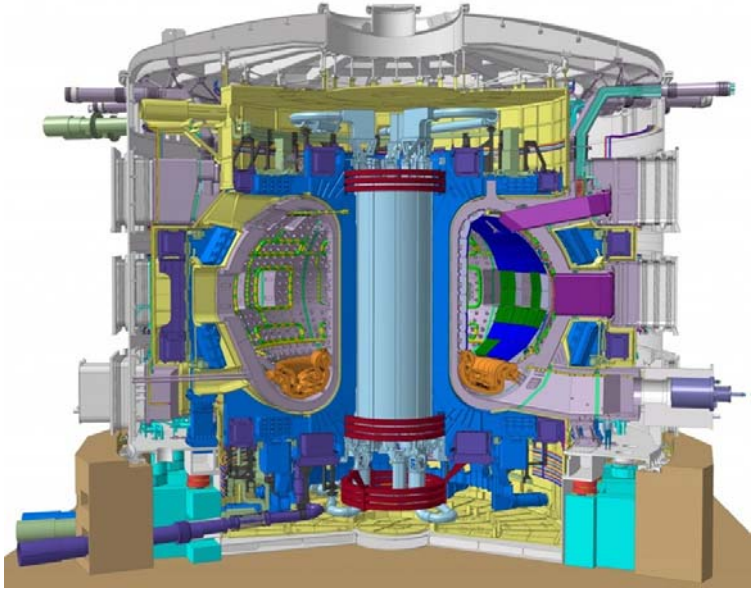
Nuclear experiments



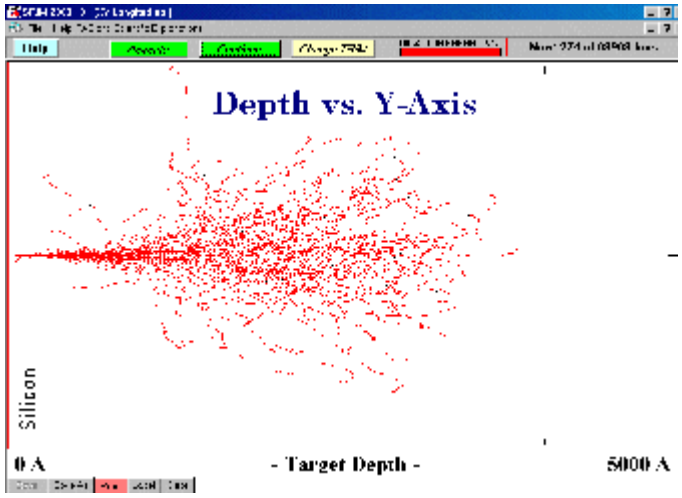


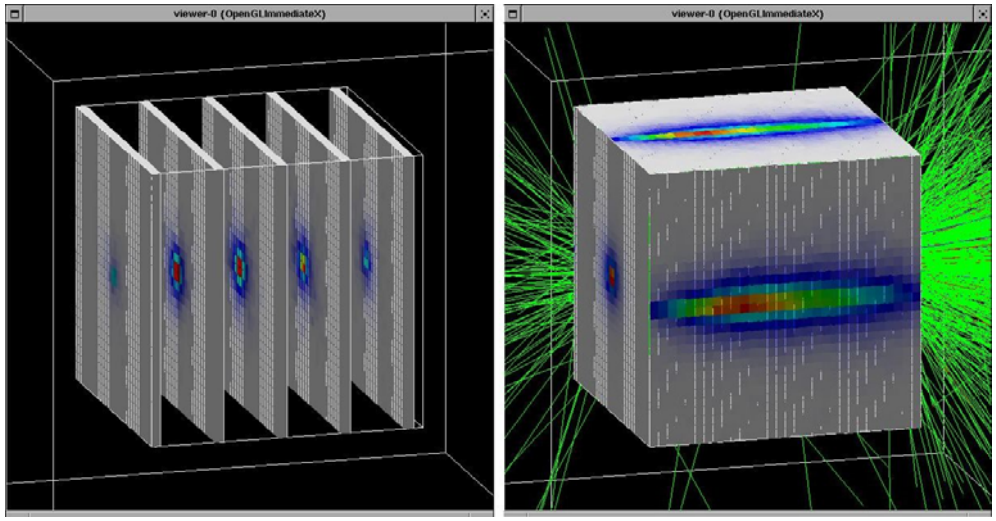
Radiation effects on CMOS Ics
Types of radiation

- Direct ionizing radiation
  - Energy deposition via electromagnetic force
    - Electronic stopping
    - Coulomb recoil (nuclei)
  - Charged particles (ions)
  - Gamma/ X -rays
  - Generates e-h pairs directly
- Indirect ionizing radiation
  - Nuclear reaction generate secondary charged particles or gamma rays
  - Inelastic collisions
  - neutrons

Radiation effects on CMOS Ics
Types of radiation

- Energy deposition per ion/particle
  - Linear energy transfer (LET)
  - dE/dx [keV/µm]
  - Use tools like SRIM or GEANT4 to simulate this





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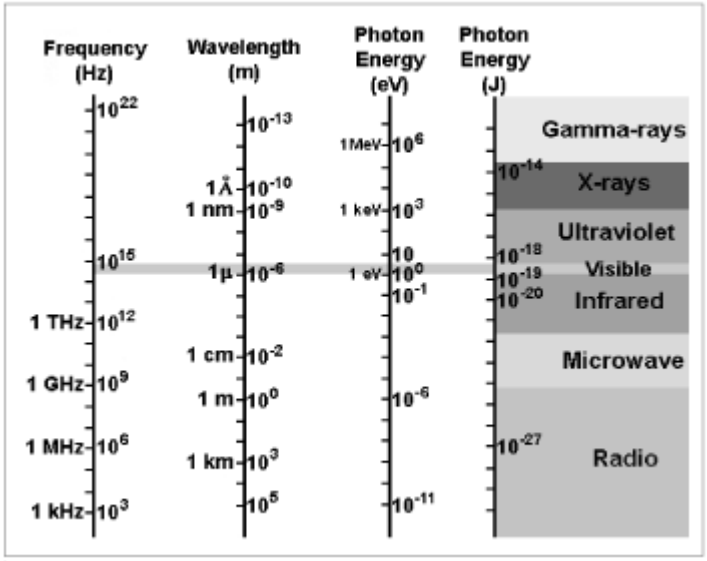
Radiation effects on CMOS Ics
Types of radiation

- Gamma rays or X-rays
  - Energy carried in photons
  - Absorption through
    - Photoelectric effect (E>BG, 1.1eV)
    - Compton scattering
    - Pair production (E> $2mc^2$ = +- 1MeV)



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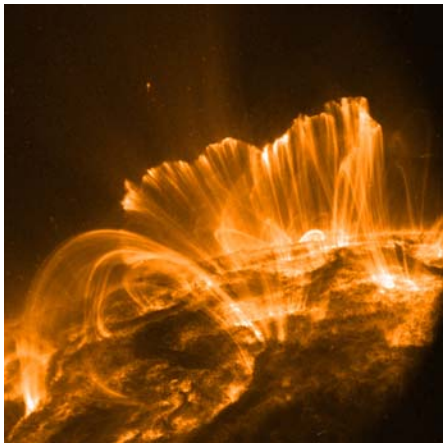
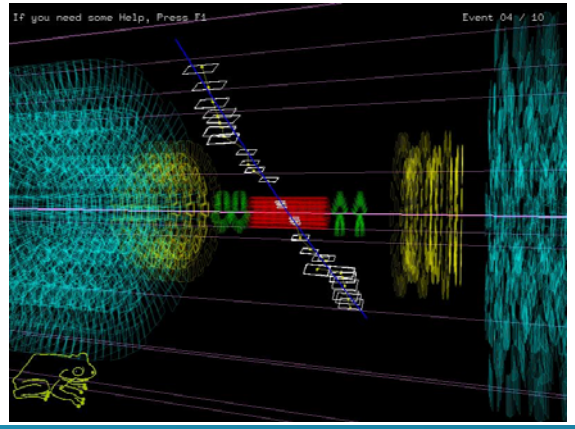
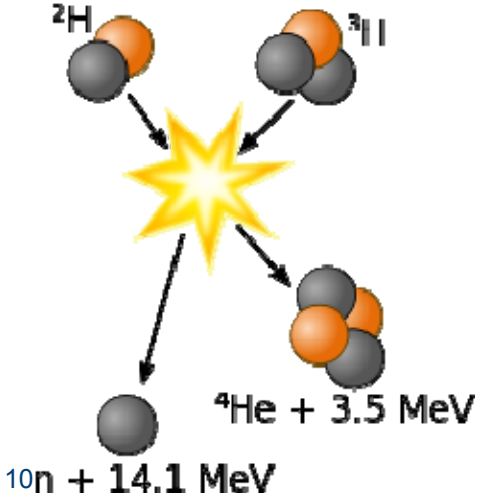
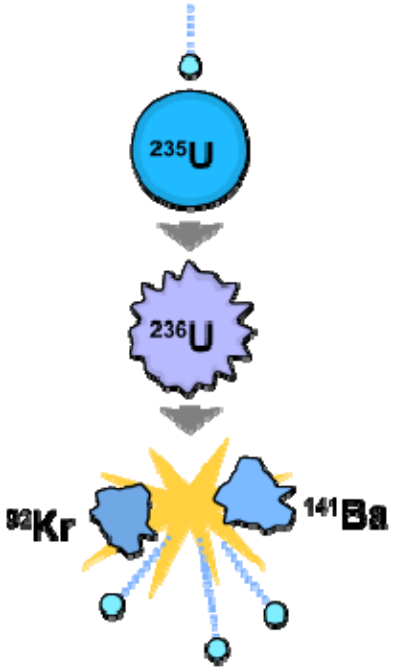
Radiation effects on CMOS Ics
Origin of radiation



- Cosmic radiation
  - Solar
  - Galactic
- Particle physics experiments
- Nuclear fission
- Nuclear fusion
- …







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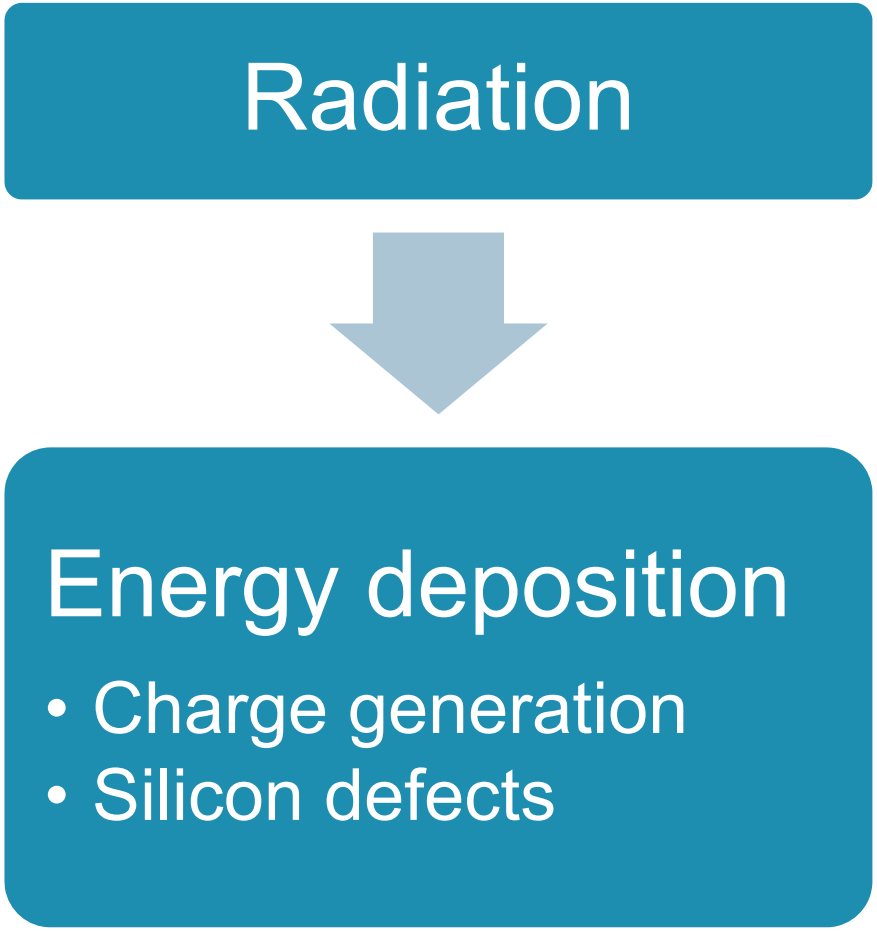
Radiation effects on CMOS Ics



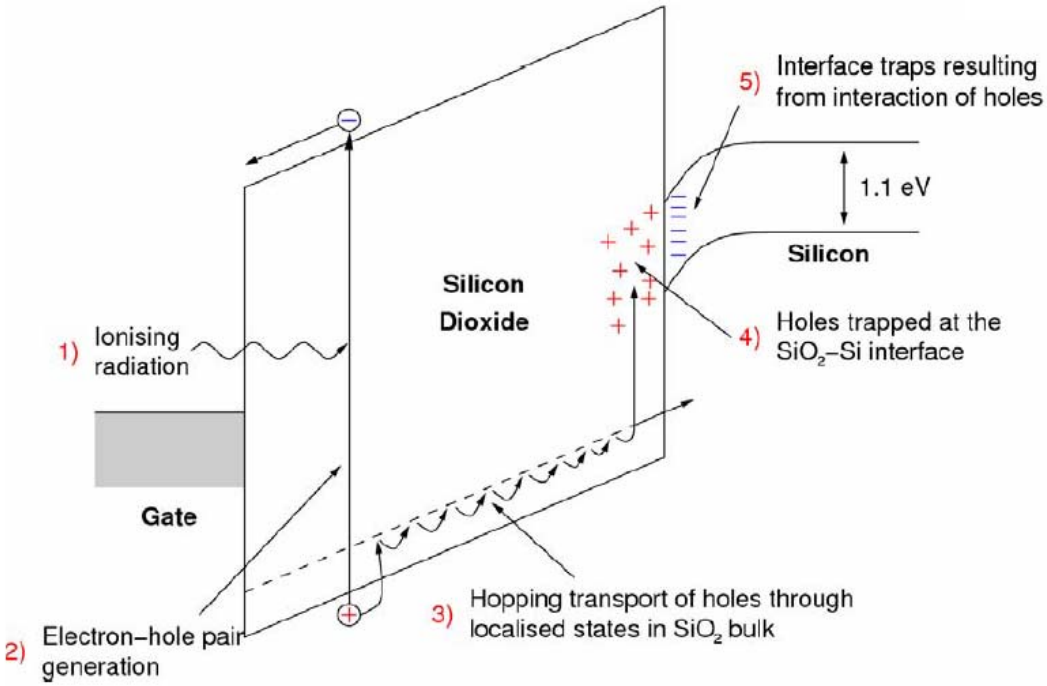
Radiation effects on CMOS Ics
CMOS effects

- Long term effects
  - Change of transistor behavior
  - Accumulating effect
  - Time: days, months, years

- Single events
  - Injection of charge
  - time: ns

Radiation effects on CMOS Ics
Long term effects

- Radiation generates e-h pairs in oxide
- Trapped charges in oxides accumulate
- Positive charges get trapped
- Vt decreases
- NMOS
  - |Vt| drops
  - Shows an increase at high dose rates
- PMOS
  - |Vt| increases



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Radiation effects on CMOS Ics
Long term effects

- Shrinking CMOS technology
  - Less charge collected
  - Cox increases
  - Sensitivity ~ t_{ox}^2

$$\Delta V_T = \frac{\Delta Q_{ox}\left[\mathrm{C/m^2}\right]}{C_{ox}\left[\mathrm{F/m^2}\right]} = \frac{\Delta \rho_{ox}\left[\mathrm{C/m^3}\right].t_{ox}^2\left[\mathrm{m^2}\right]}{\varepsilon_{ox}\left[\mathrm{F/m}\right]}$$

  - Better radiation performance
- IO devices vs core devices

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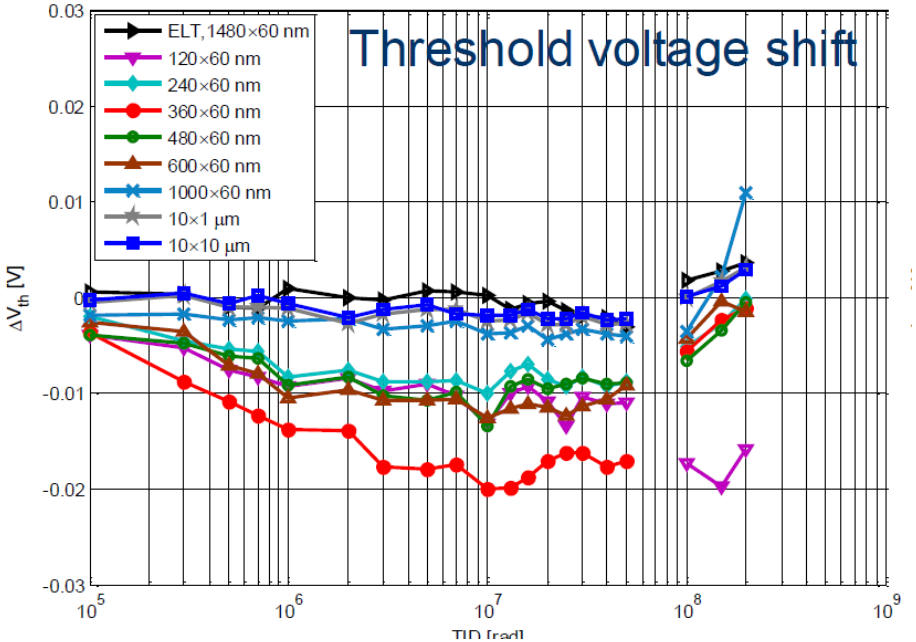
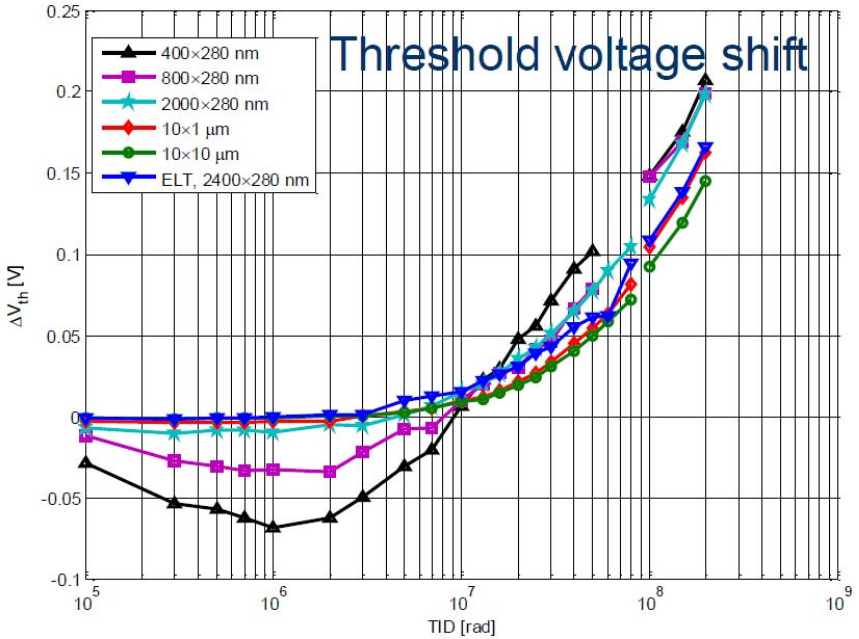
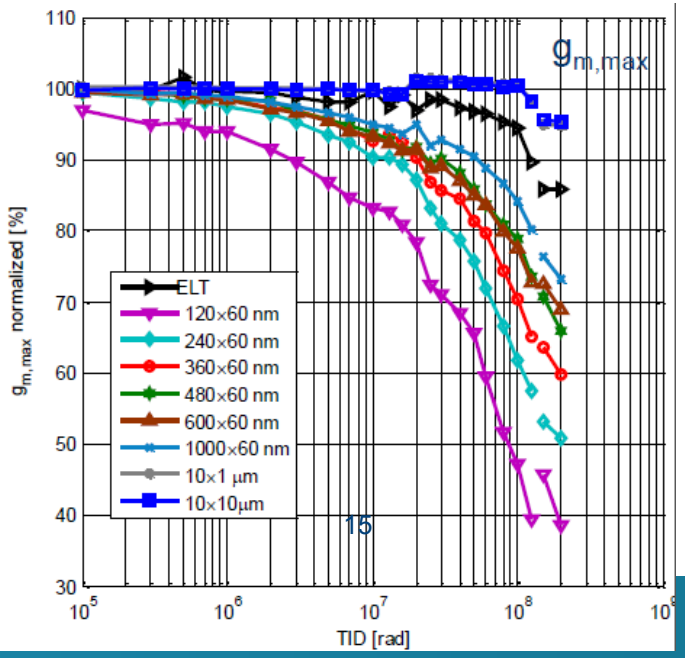
Core nmos 65nm



IO nmos 65nm





[S. Bonacini , Cern]

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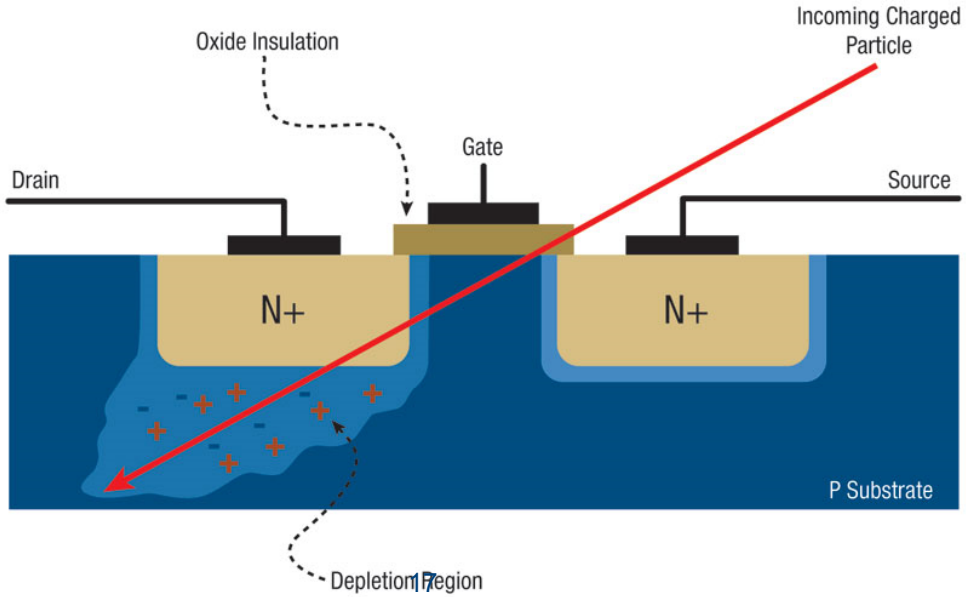
Radiation effects on CMOS Ics
Short term effects

- Single events
  - SET : Single event transients
    - Goes away after some time
  - SEU : Single event upsets
    - Remains
    - Registers
  - SEL: Single event latchup
- Charge generated by a single particle

Radiation effects on CMOS Ics
Short term effects

- Single particle generates e-h pairs
- Electric field in depleted regions cause high drift current
- Remaining charge is transported via diffusion
- Direct ionization or secondary charged particles by nuclear reactions



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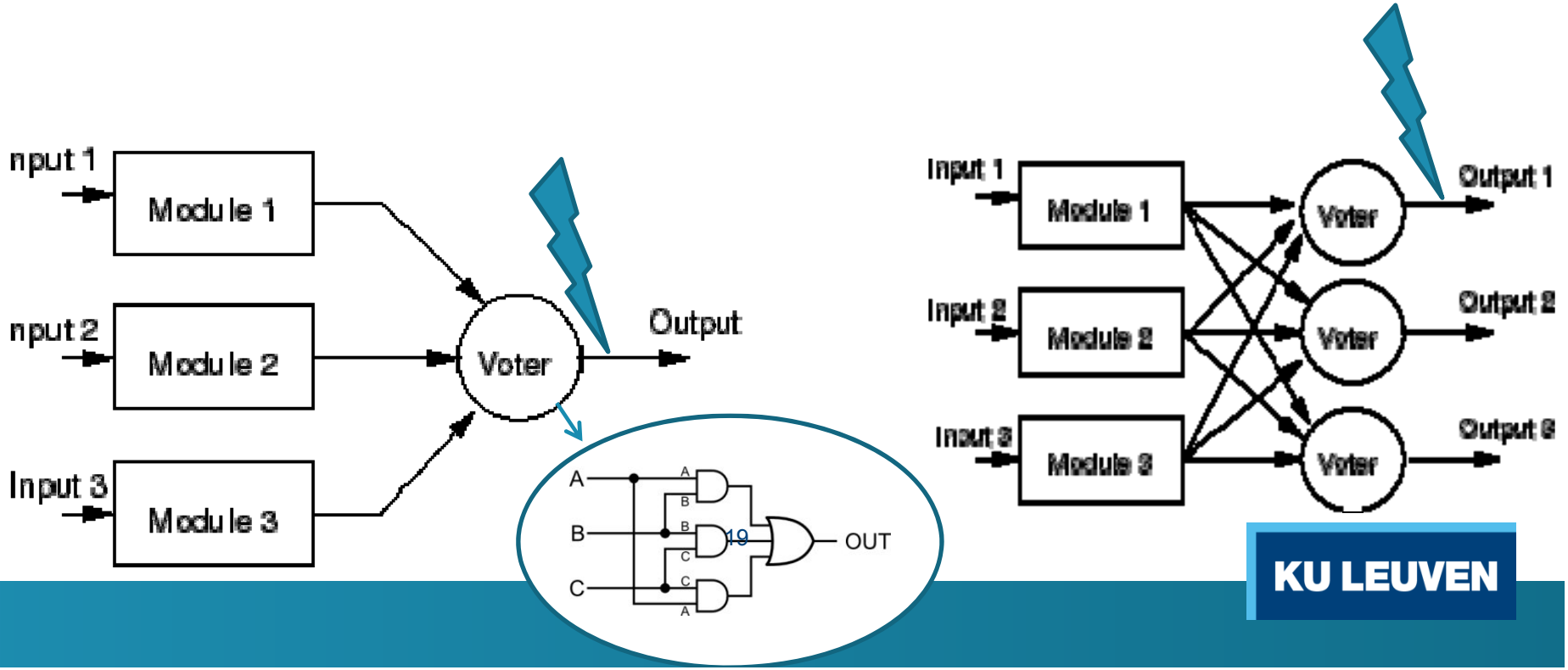
Radiation effects on CMOS Ics
Single events – Digital Circuit effects

- Registers
  - Upsets
  - Metastability
- Analog Circuits
  - Transients
  - Phase jumps
- Latchup trigger

Radiation hardening techniques
Single events – Digital Circuit Solutions

- Triplication of all registers and logic
- Voters to select correct result
- Always need 3 voters!
- 3 inputs, 3 outputs, 3 modules, 3 voters



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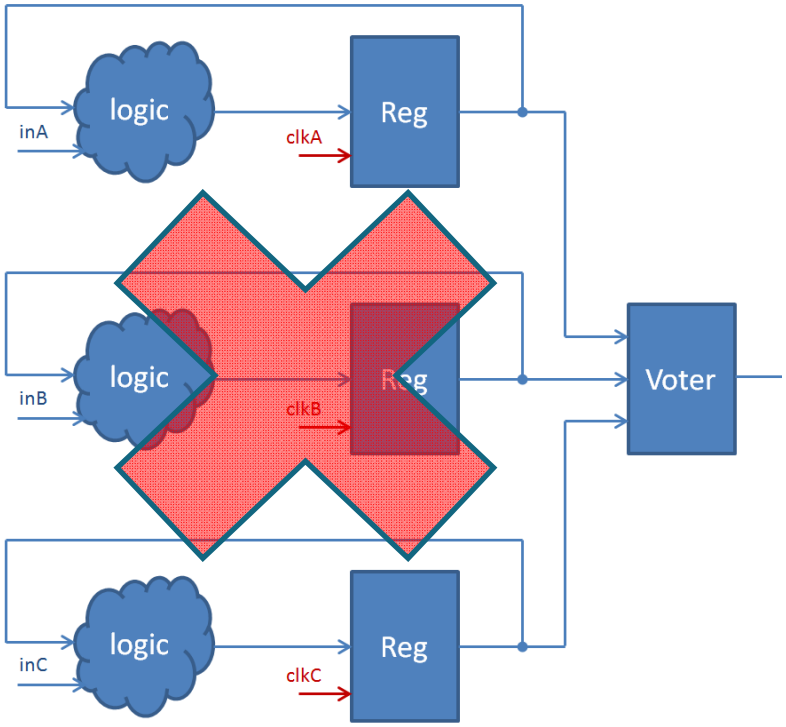
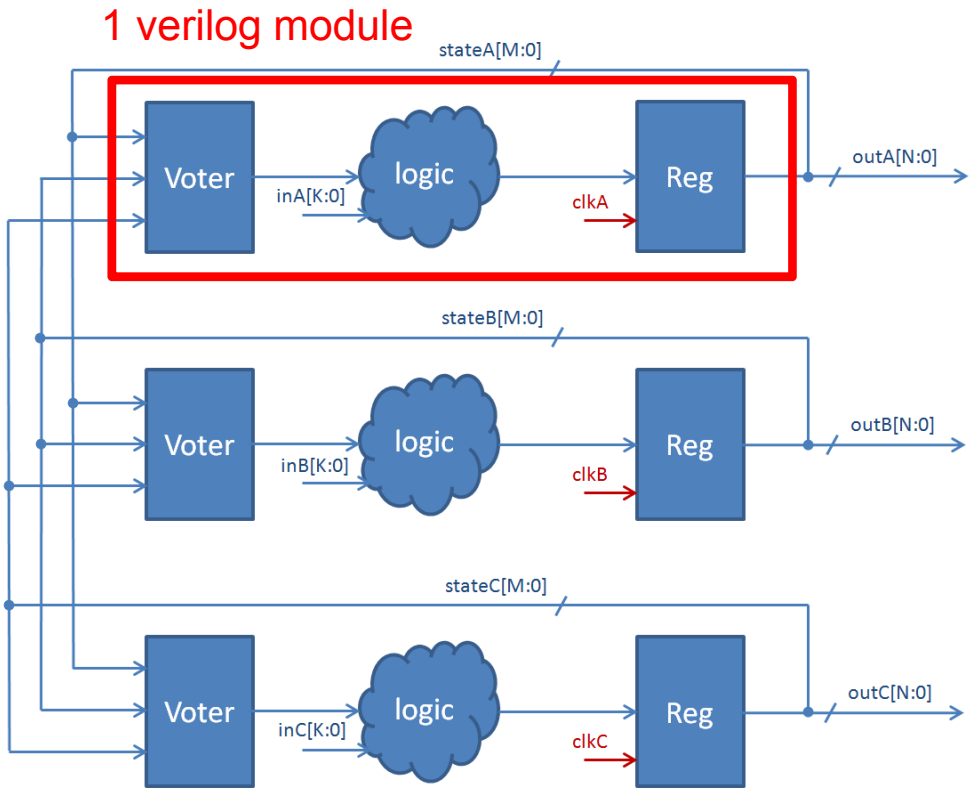
Radiation hardening techniques
Single events – Digital Circuit Solutions





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Summary

- Nuclear industry is growing
- Radiation tolerant circuits needed
- Long term and short term events
- CMOS scaling helps
- Digital circuits can be easily hardened using TMR
- Analog circuits can use feedback and online calibration

Thank you

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