Measurements and Physics of Single Event Effects in Integrate Circuits

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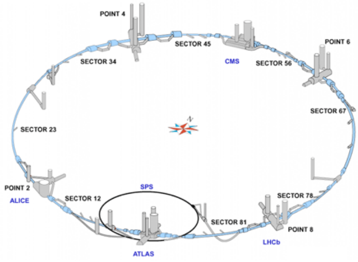
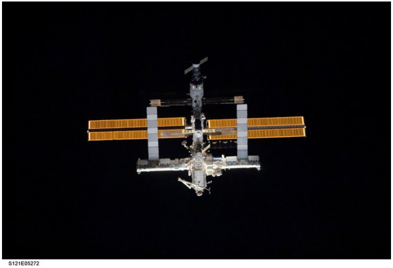
Introduction

1. Single event effects are hardware and software errors in integrated circuits (IC).
2. Applications where SEE are an issue:
    - space application where IC are subject to solar radiation, e.g protons trapped or deflected in Earth magnetic field;
    - very high energy cosmic rays and air showers might induce SEE in atmospheric balloon and low orbit experiments.
3. Accelerator application like those at LHC where radiation on electronics is extreme even by space tech standards



LHC and spectrometers (courtesy of CERN)



International Space Station (courtesy of ESA)

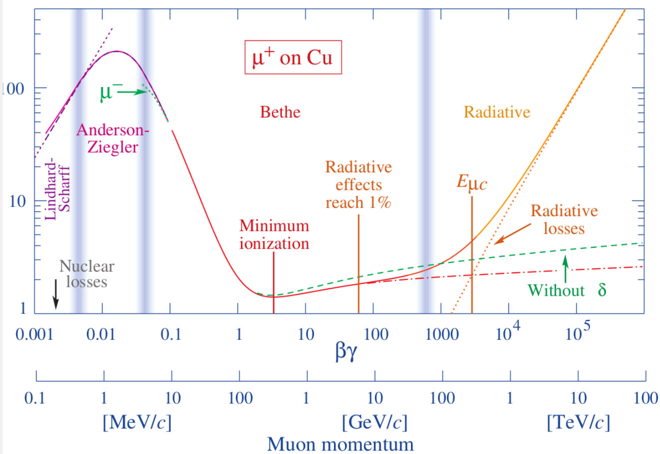
Types of radiation and their effects

1. Space and accelerator radiation are very different:
   - space: low energy protons at MeV to few hundreds MeV, also very few light ions;
   - LHC: very high energy component GeV and more, secondary nuclear interaction probable;
   - At LHC expect neutron and large-Z ions produced in secondary interactions to be important.
2. Particle energies and Z atomic number is very important for SEE production and cumulative effects.
3. Types of effects in IC (see also Vlad's and Lucian's talk next)
   - Non-permanent effects like Soft and hardware effects in IC, here single event latch-ups (SEL) are the most problematic
   - Cumulative effects due to permanent vacancies and displacements in IC active regions, these being generated by ionization and collisions with radiation

   .
4. Expect some quantitative and qualitative differences in SEE and those cumulative.

Propagation of radiation in IC active and non-active layers

1. Ionization - Mass stopping power or Liner Energy Transfer (LET) (extract from Particle Data Group's 2015 review) :



Propagation of radiation in IC active and non-active layers

1. Bethe equation:gives ionization at intermediate energy values:

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

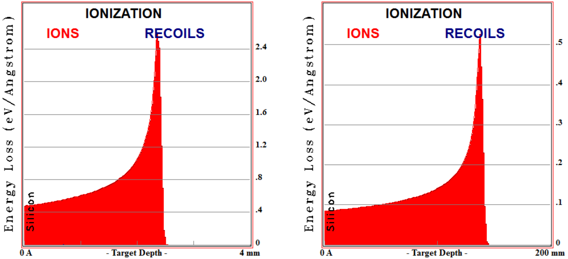
   - incident muon or ion z^2 dependence
   - target atomic number Z dependence;
   - dependence on energy ($\gamma = E/mc^2$) of charged particle, e.g ion/muon/pion.
   - dependence on inverse of atomic mass

2. non-ionizing energy loss (NIEL) or nuclear stopping power without nuclear reactions
   - ion-atom collision through nuclear Ze potential creates displacement damage

3. High energy proton or pions could induce nuclear reactions in target atom/nucleus, resulting in high-z ions or energetic Silicon from elastic collisions. ..

Minimum Interacting particle and Bragg peaks

1. Physics of SEE is dominated by maximally ionization particles like ions at Bragg peak when the ionization and nuclear stopping power is maximum;



Bragg peaks for incident proton on Silicon for 20 MeV and 200 MeV energy, respectively. The penetration depth is significantly different

2. protons could induce nuclear reaction with production of ions in this class;
3. Minimum interacting particles like muons with momenta close to GeV/c have generally LET below SEL and SEU threshold.

Ions at international testing facilities

Cocktail No 1: ***High LET***

M/Q	Ion	DUT energy [MeV]	Range [μm Si]	LET [MeV/mg/cm²]
5	$^{40}Ar^{8+}$	151	40	15.9
5	$^{20}Ne^{4+}$	78	45	6.4
5	$^{15}N^{3+}$	60	59	3.3
4.96	$^{124}Xe^{25+}$	420	37	67.7
4.94	$^{84}Kr^{17+}$	305	39	40.4

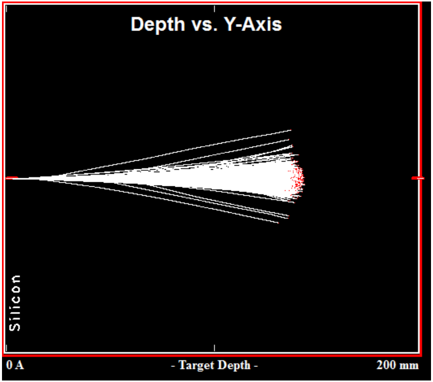
Cocktail No 2: ***High penetration***

M/Q	Ion	DUT energy [MeV]	Range [μm Si]	LET [MeV/mg/cm²]
3.25	$^{13}C^{4+}$	131	292	1.1
3.14	$^{22}Ne^{7+}$	235	216	3
3.33	$^{40}Ar^{12+}$	372	117	10.2
3.22	$^{58}Ni^{18+}$	567	100	20.4
3.32	$^{83}Kr^{25+}$	756	92	32.6

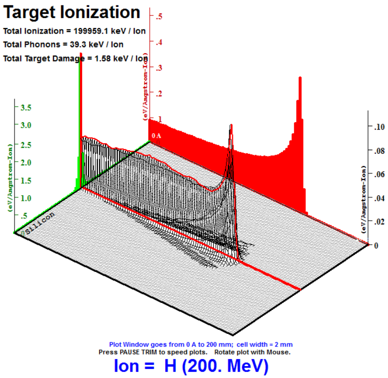
UCL Louvain ion beams and their energies and penetration depth in Silicon

Ions and protons in IC material - no nuclear interactions

1. Working in Silicon-only approximation for active and dice layers
2. Computing simulation SRIM-/TRIM "Stopping and Range of Ions in Matter" or "TRansport of Ions in Matter" http://www.srim.org/

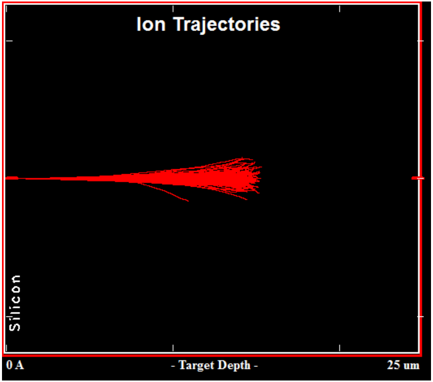


penetration depth and range in Silicon for incident proton of 200 MeV

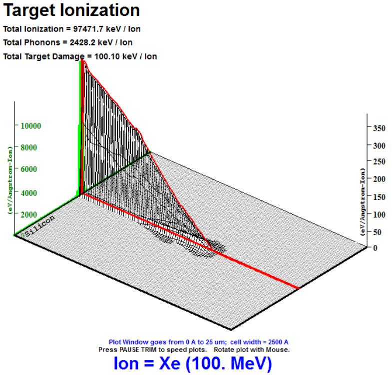


Ionization straggling and relative ionization versus phonons and nuclear stopping power

Ions and protons in IC material - no nuclear interactions



penetration depth and range in Silicon for incident Xenon ion of 100 MeV



Ionization straggling and relative ionization versus phonons and nuclear stopping power

1. For 100 MeV Xenon in Silicon the Bragg peak is partially visible, as the maximum LET is at energy value bellow 100 MeV.

Protons and nuclear interactions in IC material

Work in progress

Past tests and SEE cross-sections

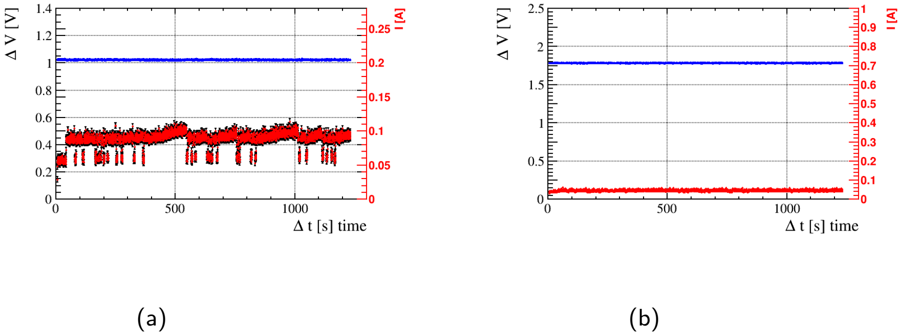


Figure: (a) Core and BRAM supply current and voltage, measurement during irradiation with Ne beam, LET similar to Legnaro test, the low current values correspond to the reprogramming of device during a blind scrubbing; (b) 1.8 V I/O rail current and voltage

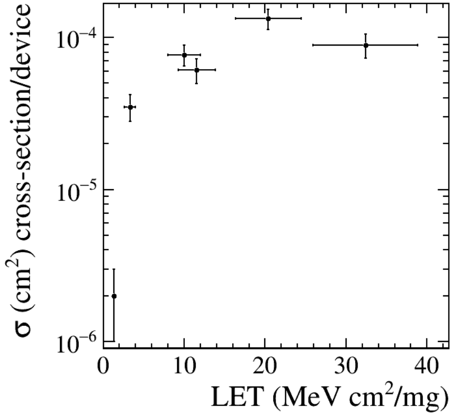


Figure: SEU which crashes the user logic the synchronization being lost - Louvain measurements

FPGA micro-latch-ups rate and cross-section

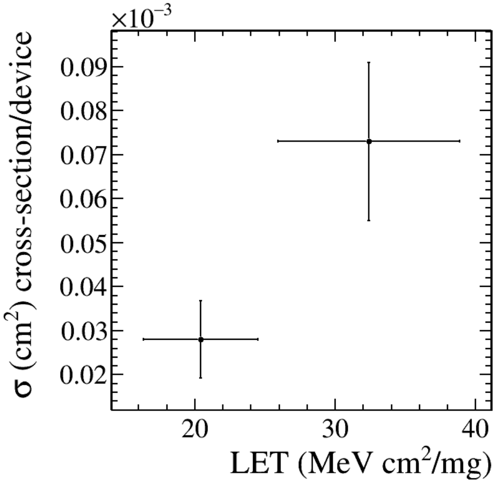


Figure: SEL or the micro-latch-ups that literature claims are harmless - Louvain measurements

Conclusions and plans

1. Work is ongoing to finish the 2 ion and one proton irradiation;
2. An extrapolation of results to LHC radiation environment is expected to be done
3. Need to build a realistic radiation environment model: ions, pions, protons.
4. Simulations are done to obtain an estimate of ion flux for each Z especially for those above Silicon atomic number at LHC,
5. besides the SEE, the cumulative Total Ionization Dose and Displacement effects are investigated
6. So far one FPGA chip and 2 ASICs were tested
7. Radiation testing campaign 2 runs in 2016 and 2 runs approve for next year..