R&T PROTON DIRECT IONIZATION

Assessment of the Direct Ionization Contribution to the Proton SEU Rate

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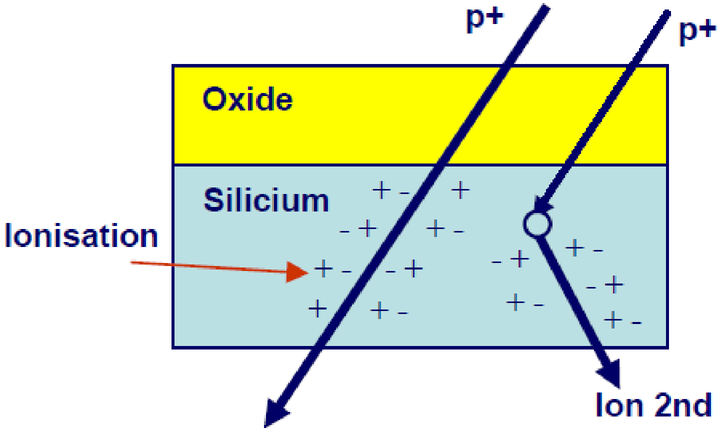
Introduction

- **Electronic device integration scale decrease → SEU sensitivity increase**

- **Technology nodes 90nm and lower (65nm, 45nm, 28nm…)**
  - **Necessary charge to upset a device low enough to be sensitive to proton direct ionization**

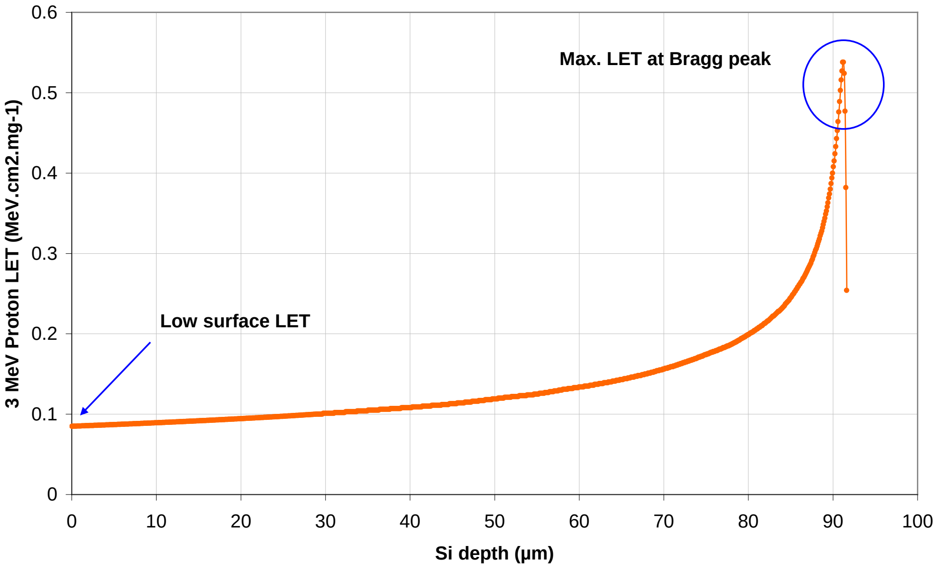
- **Proton caused SEU**
  - **Recoil atom**
    - Indirect event due to the charge generated by a secondary ion
  - **Direct ionization**
    - Charge generated by the incident proton leads to an event



- **The aim of this study is to perform experimental testing of proton direct ionization sensitivity and to propose a rate estimation method**

Introduction

- **Maximum LET at end of path**
  - **Significant deposited charge over a small distance in the last silicon microns**
- **Proton direct ionization may occur when**
  - **Maximum generated charge in the device active area**
    - Incident proton stops in the active area
  - **Device sensitive enough compared to the generated charge**
    - Low SEU critical charge



Proton ID R&T Studies Story

- **2011 – State-of-the-art establishment**
  - **Proton direct ionization methodology proposition including**
    - Experimental characterization
    - Rate computation

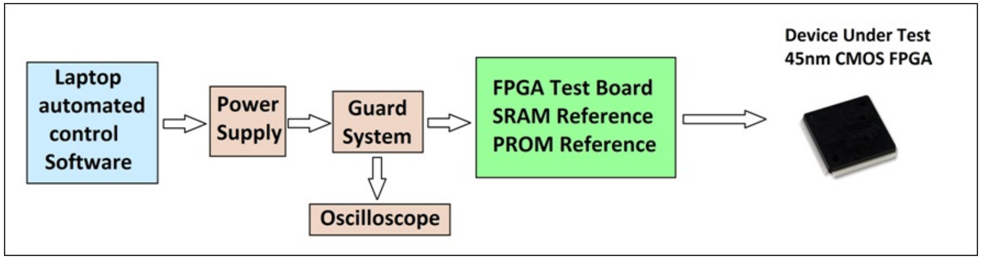
- **2012/2013 – Experimental phase preparation**
  - **Selection and procurement of potentially sensitive devices**
    - Commercially available SRAM memory cell below 65 nm tech. node
  - **Identification of an adapted test facility**
    - Proton beam at low flux under vacuum with in-situ bias and tilting possibility

- **2014 – 45nm FPGA experimental characterization**
  - **Proposed test and calculation methodology validation**
    - Direct ionization test data
    - Contribution to the SEU rate calculation
  - **Results published at NSREC**
    - NSREC 2014 Proceedings PB-5

- **2015/2016 – Proposed methodology application to existing test data**
  - **Proton direct ionization OMERE module prototype development**
  - **Proton direct ionization contribution to the rate estimation**
  - **Results submitted at Radecs 2016**

Experimental Characterization

- **Test-bed developped by TRAD for low energy proton beam experiments**
  - SEU count
  - Stuck bit detection
  - SEFI management
  - SEL protection
- **Irradiations performed at CNA (Centro Nacional de Aceleradores, Sevilla, Spain)**
  - 3 MV Tandem accelerator
  - Incident proton energy 750keV to 6MeV
  - Tilted experiments 0° to 60°
    - Effective penetration depth variation


Laptop automated control Software

Power Supply

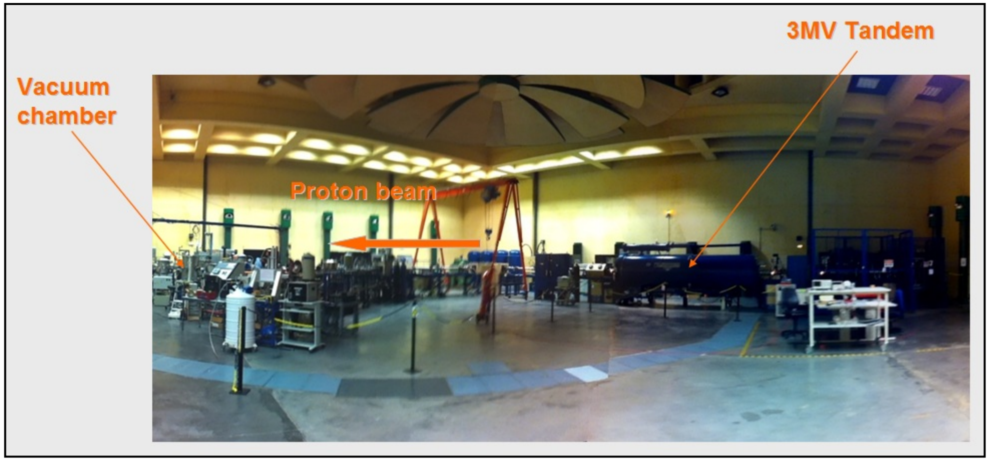
Guard System

Oscilloscope

FPGA Test Board
SRAM Reference
PROM Reference

Device Under Test
45nm CMOS FPGA

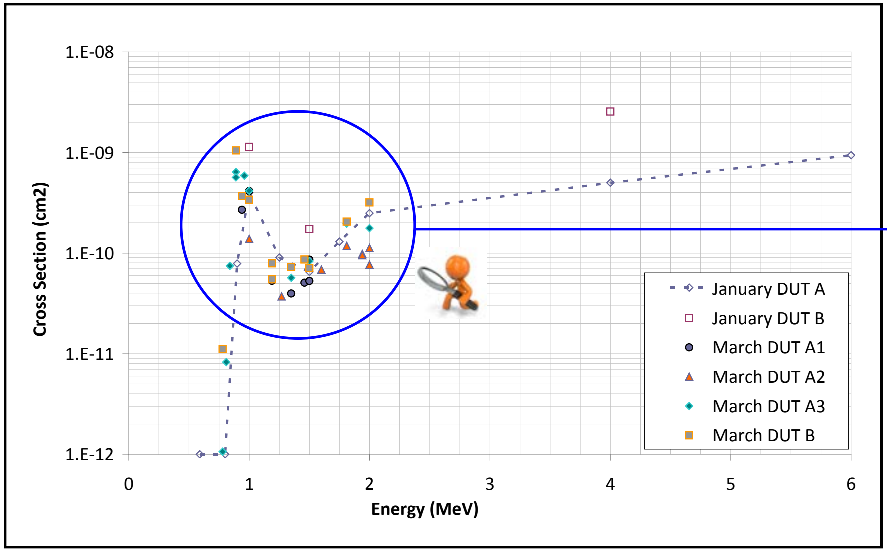
Test configuration



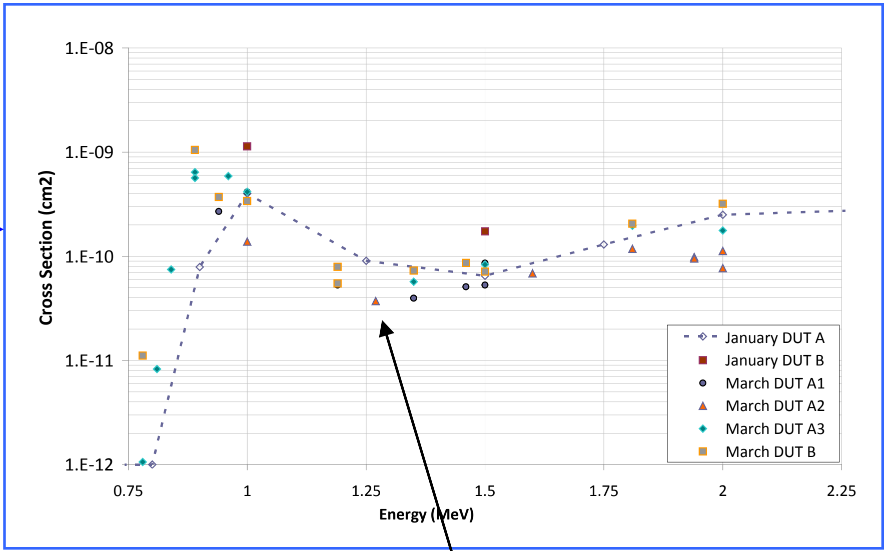
CNA proton facility

Test Results

Proton cross section σ(E)



Proton cross section σ(E) between 0.75 and 2.25 MeV



Irradiation 2MeV, 60°
displayed at 1.27MeV

- Cross section increase below 1.5MeV
  - Direct ionization sensitivity of the tested devices

- Irradiations at different energies and tilt angles
  - Tilted irradiations are plotted on the graph at the energy corresponding to the same effective range in silicon

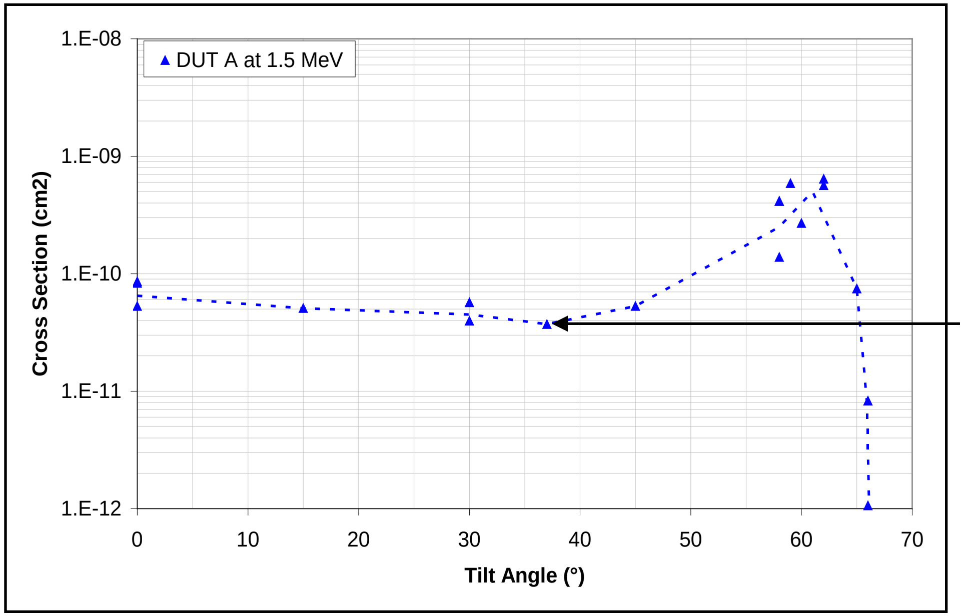
Test Results

- The experimental data is compiled in order to calculate a rate
- Reconstructed cross section curve at fixed energy as a function of the tilt angle
  - Based on the penetration depth value

R (2 MeV, 60°)
=
R (1.27 MeV, 0°)
=
R (1.5 MeV, 37°)

- At 1.5 MeV, cross section values at normal incidence are not representative of the direct ionization sensitivity

Reconstructed cross section σ(θ) at 1.5 MeV

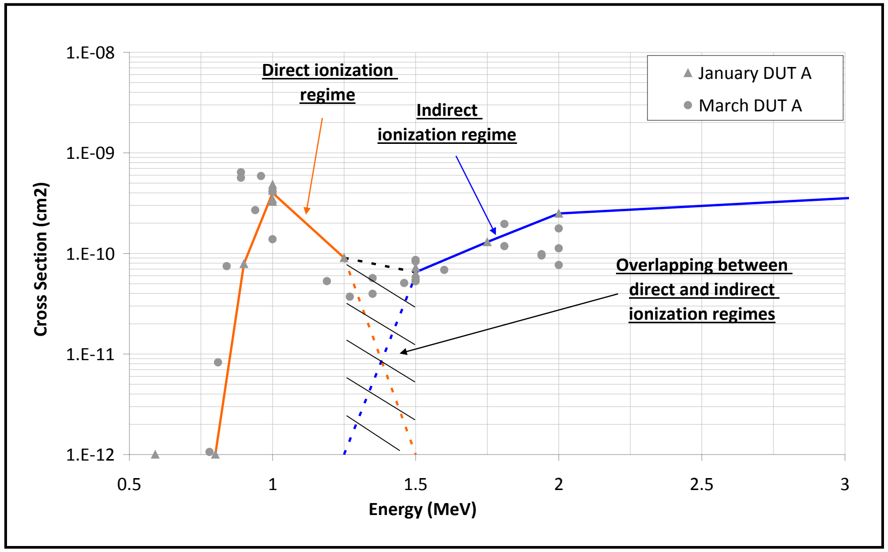


Irradiation at 2MeV, 60° displayed at 37°

Data Analysis

- **Between 1,25 and 1,5 MeV, the relative proportion of direct events decreases with respect to the indirect events increase**
  - There is an energy range in which the direct and indirect ionization regimes overlap

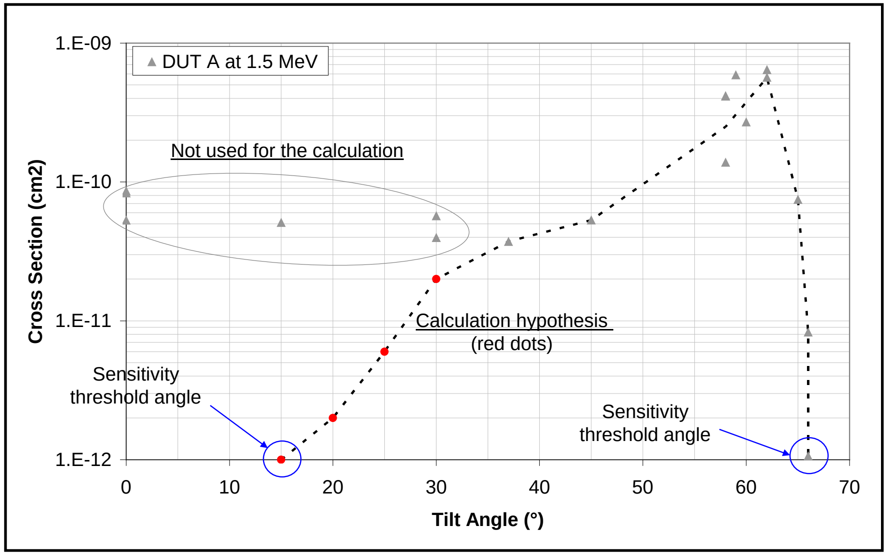
- **In order to focus on direct ionization, the test data is completed by a calculation hypothesis**
  - The two sensitivity threshold angles appearing on the graph are used to define the direct ionization sensitive layer



Direct ionization regime

Indirect ionization regime

Overlapping between direct and indirect ionization regimes



Not used for the calculation

Calculation hypothesis (red dots)

Sensitivity threshold angle

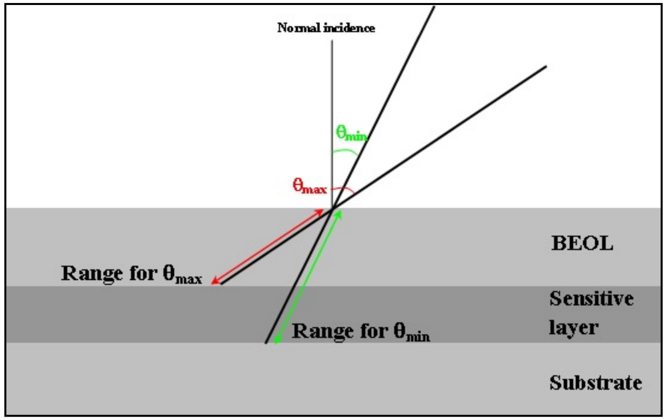
Sensitivity threshold angle

Data Analysis

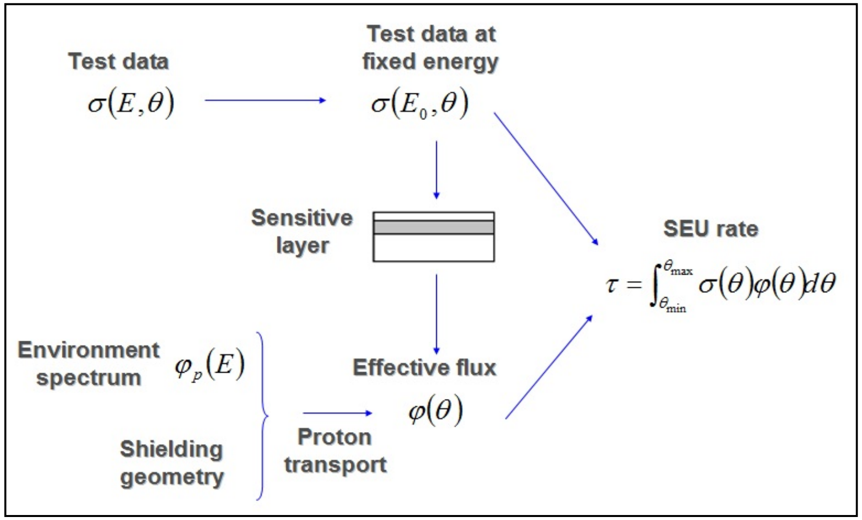
- **Sensitive layer depth and thickness calculated with respect to the threshold angles**
  - 15° and 66° in the example of DUT A at 1.5MeV

- **It is assumed that an incident proton has to stop in the sensitive layer in order to be likely to create an event by direct ionization**
  - Effective flux φ(θ) to take into account at each angle
  - φ(θ) is the proportion of protons from the environment spectrum with a path ending in the sensitive layer

- **At a tilt θ, over all the incident protons stopping in the sensitive layer, the ratio of particles leading to an event is given by the measured cross section σ(θ)**
  - Simplification : $\sigma(\theta) = \sigma_{max}$



Sensitive layer calculation

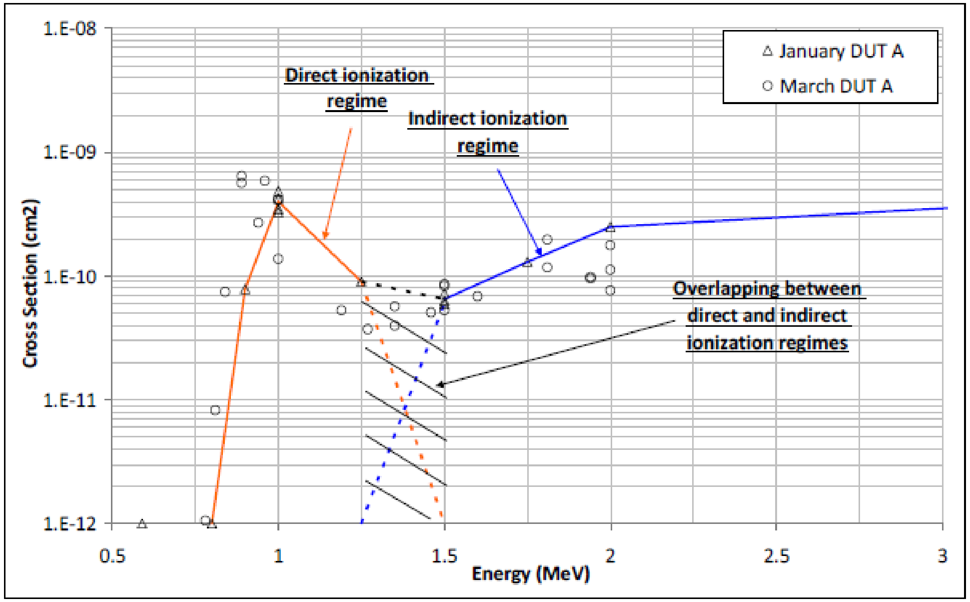


Calculation methodology

Direct Ionization Rate Calculation

- **A worst-case hypothesis is considered for the calculation**

$$\tau = \int_{\theta_{\min}}^{\theta_{\max}} \sigma(\theta)\varphi(\theta)d\theta \longrightarrow \tau = \boxed{\sigma_{peak}} \int_{\theta} \varphi(\theta)d\theta$$

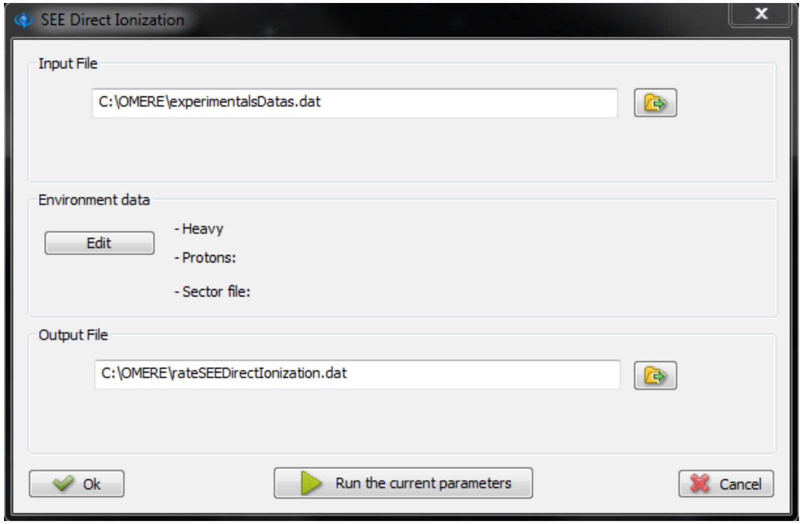


Consideration of a step function

→ worst-case, takes into account the uncertainty on σ_{peak}

Direct Ionization Rate Calculation

- **Development of a direct ionization rate calculation module in OMERE 5.0**
  - Specific format for input test data
  - Energy – Angle – Cross-section



SEE Direct Ionization

Input File

C:\OMERE\experimentalsDatas.dat

Environment data

- Heavy
- Protons:
- Sector file:

Output File

C:\OMERE\rateSEEDirectIonization.dat

- **Documentary research for available proton test data**
  - **[RD1]** Low Energy Proton Single-Event-Upset Test Results on 65 nm SOI SRAM, David F. Heidel, IEEE TNS VOL. 55, NO. 6, DECEMBER 2008
  - **[RD2]** Heavy Ion, High-Energy, and Low-Energy Proton SEE Sensitivity of 90-nm RHBD SRAMs, E. H. Cannon, IEEE TNS VOL. 57, NO. 6, DECEMBER 2010
  - **[RD3]** The contribution of low-energy protons to the total on-orbit SEU rate, N. A. Dodds, IEEE TNS DECEMBER 2015
  - **[RD4]** Single-Event Upsets and Multiple-Bit Upsets on a 45 nm SOI SRAM, David F. Heidel, IEEE TNS VOL. 56, NO. 6, DECEMBER 2009
  - **[RD5]** Low-Energy Proton Testing Using the Boeing Radiation Effects Laboratory 2.2 MeV Dynamitron, Jerry Wert, February 2012

Direct Ionization Rate Calculation

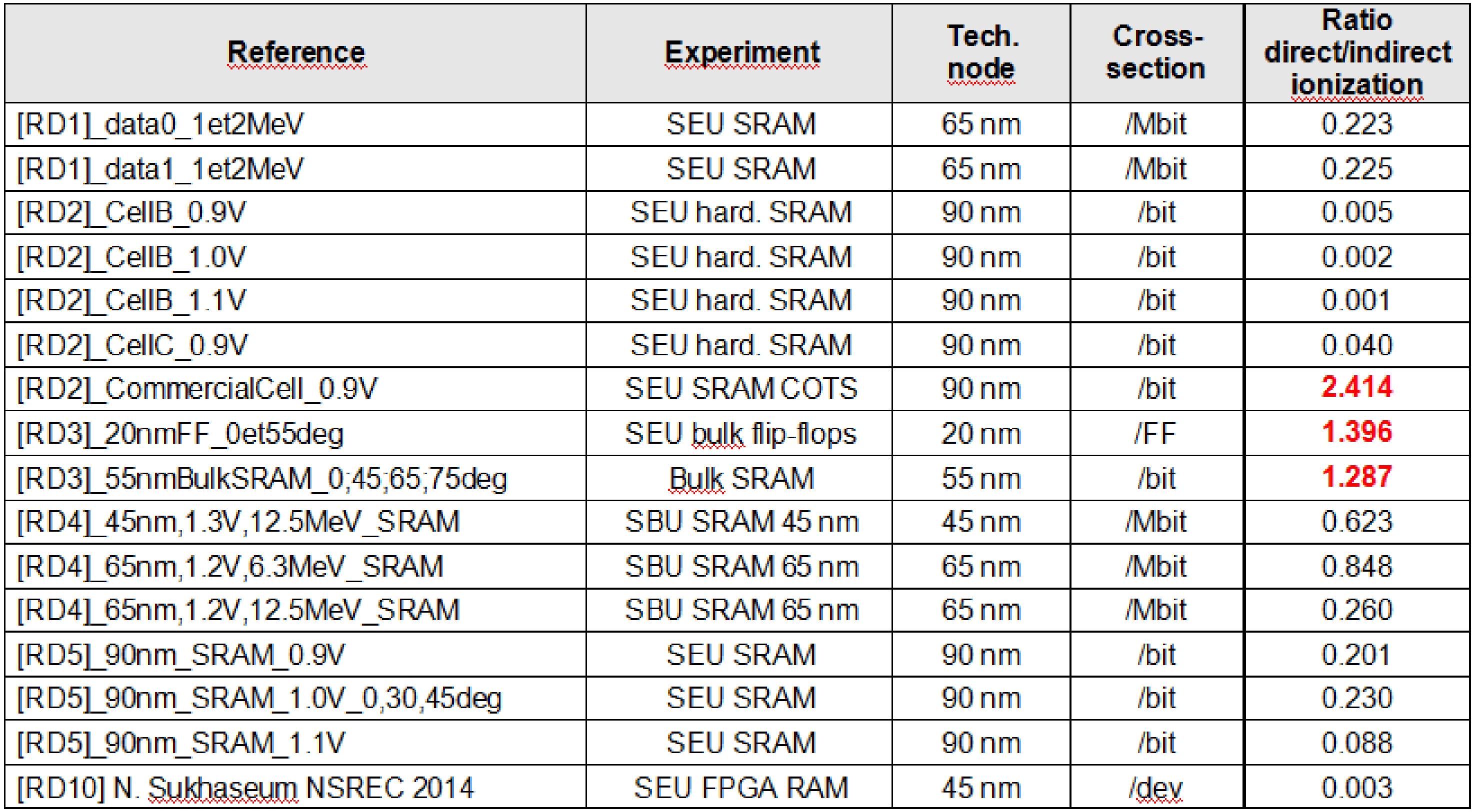
- **Rate calculation for a typical orbit**
  - **LEO 800 km (1 g.cm^{-2})**
    - Direct ionization event rate (per dev. or per bit, per day)

Reference	Experiment	Tech. node	Cross-section	Direct ionization	
				Rate	Rate /bit
[RD1]_data0_1et2MeV	SEU SRAM	65 nm	/Mbit	9.43E-01	9.43E-07
[RD1]_data1_1et2MeV	SEU SRAM	65 nm	/Mbit	9.48E-01	9.48E-07
[RD2]_CellB_0.9V	SEU hard. SRAM	90 nm	/bit	4.51E-09	4.51E-09
[RD2]_CellB_1.0V	SEU hard. SRAM	90 nm	/bit	1.91E-09	1.91E-09
[RD2]_CellB_1.1V	SEU hard. SRAM	90 nm	/bit	1.24E-09	1.24E-09
[RD2]_CellC_0.9V	SEU hard. SRAM	90 nm	/bit	1.32E-08	1.32E-08
[RD2]_CommercialCell_0.9V	SEU SRAM COTS	90 nm	/bit	2.04E-06	2.04E-06
[RD3]_20nmFF_0et55deg	SEU bulk flip-flops	20 nm	/FF	1.28E-07	1.28E-07
[RD3]_55nmBulkSRAM_0;45;65;75deg	Bulk SRAM	55 nm	/bit	2.02E-07	2.02E-07
[RD4]_45nm,1.3V,12.5MeV_SRAM	SBU SRAM 45 nm	45 nm	/Mbit	2.61E-02	2.61E-08
[RD4]_65nm,1.2V,6.3MeV_SRAM	SBU SRAM 65 nm	65 nm	/Mbit	3.58E-02	3.58E-08
[RD4]_65nm,1.2V,12.5MeV_SRAM	SBU SRAM 65 nm	65 nm	/Mbit	2.18E-02	2.18E-08
[RD5]_90nm_SRAM_0.9V	SEU SRAM	90 nm	/bit	1.70E-06	1.70E-06
[RD5]_90nm_SRAM_1.0V_0,30,45deg	SEU SRAM	90 nm	/bit	1.94E-06	1.94E-06
[RD5]_90nm_SRAM_1.1V	SEU SRAM	90 nm	/bit	7.47E-07	7.47E-07
[RD10] N. Sukhaseum NSREC 2014	SEU FPGA RAM	45 nm	/dev	2.49E-05	2.49E-05

Direct Ionization Rate Calculation

Comparison with the « indirect » ionization rate

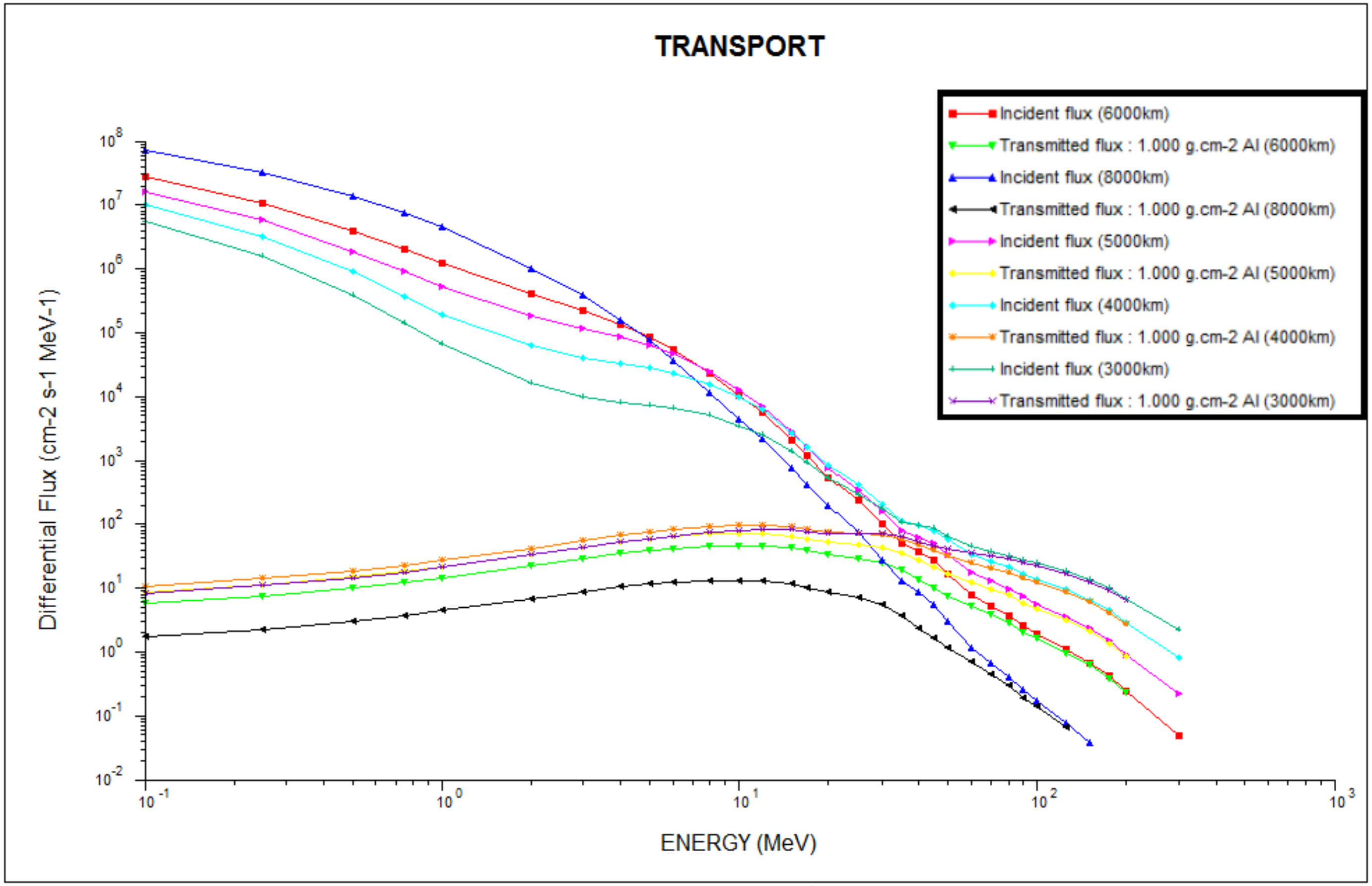
- **LEO 800 km (1 g.cm^{-2})**
  - Rate ratio (direct ionization divided by indirect ionization)



Reference	Experiment	Tech. node	Cross-section	Ratio direct/indirect ionization
[RD1]_data0_1et2MeV	SEU SRAM	65 nm	/Mbit	0.223
[RD1]_data1_1et2MeV	SEU SRAM	65 nm	/Mbit	0.225
[RD2]_CellB_0.9V	SEU hard. SRAM	90 nm	/bit	0.005
[RD2]_CellB_1.0V	SEU hard. SRAM	90 nm	/bit	0.002
[RD2]_CellB_1.1V	SEU hard. SRAM	90 nm	/bit	0.001
[RD2]_CellC_0.9V	SEU hard. SRAM	90 nm	/bit	0.040
[RD2]_CommercialCell_0.9V	SEU SRAM COTS	90 nm	/bit	**2.414**
[RD3]_20nmFF_0et55deg	SEU bulk flip-flops	20 nm	/FF	**1.396**
[RD3]_55nmBulkSRAM_0;45;65;75deg	Bulk SRAM	55 nm	/bit	**1.287**
[RD4]_45nm,1.3V,12.5MeV_SRAM	SBU SRAM 45 nm	45 nm	/Mbit	0.623
[RD4]_65nm,1.2V,6.3MeV_SRAM	SBU SRAM 65 nm	65 nm	/Mbit	0.848
[RD4]_65nm,1.2V,12.5MeV_SRAM	SBU SRAM 65 nm	65 nm	/Mbit	0.260
[RD5]_90nm_SRAM_0.9V	SEU SRAM	90 nm	/bit	0.201
[RD5]_90nm_SRAM_1.0V_0,30,45deg	SEU SRAM	90 nm	/bit	0.230
[RD5]_90nm_SRAM_1.1V	SEU SRAM	90 nm	/bit	0.088
[RD10] N. Sukhaseum NSREC 2014	SEU FPGA RAM	45 nm	/dev	0.003

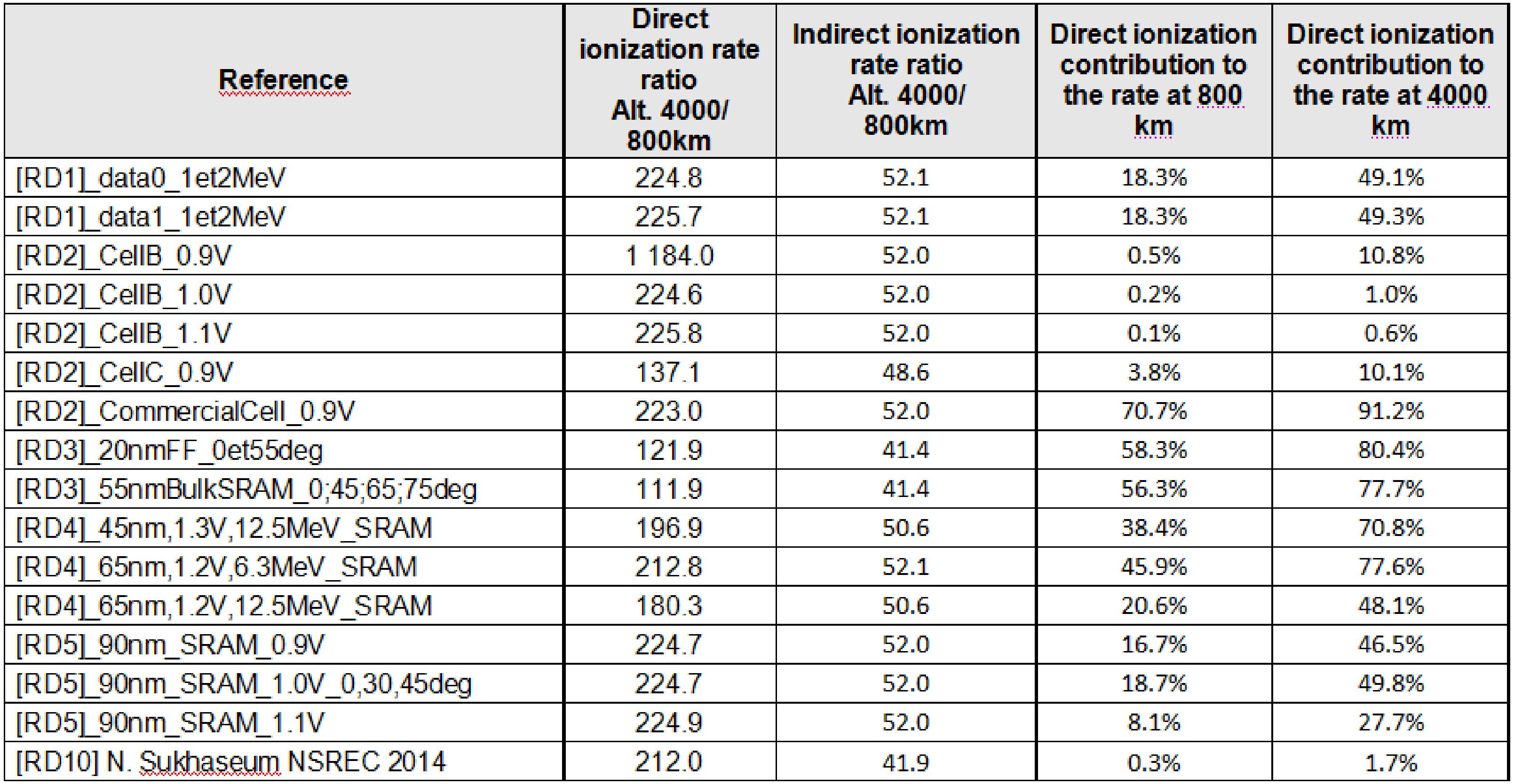
Proton Environment Impact

- **Trapped proton flux at different altitudes**
  - External and transported flux (behind 1 g.cm^{-2})
  - Worst-case at 4000 km alt.



Proton Environment Impact

- **The contribution of proton direct ionization to the SEU rate depends on the mission**



Reference	Direct ionization rate ratio Alt. 4000/ 800km	Indirect ionization rate ratio Alt. 4000/ 800km	Direct ionization contribution to the rate at 800 km	Direct ionization contribution to the rate at 4000 km
[RD1]_data0_1et2MeV	224.8	52.1	18.3%	49.1%
[RD1]_data1_1et2MeV	225.7	52.1	18.3%	49.3%
[RD2]_CellB_0.9V	1 184.0	52.0	0.5%	10.8%
[RD2]_CellB_1.0V	224.6	52.0	0.2%	1.0%
[RD2]_CellB_1.1V	225.8	52.0	0.1%	0.6%
[RD2]_CellC_0.9V	137.1	48.6	3.8%	10.1%
[RD2]_CommercialCell_0.9V	223.0	52.0	70.7%	91.2%
[RD3]_20nmFF_0et55deg	121.9	41.4	58.3%	80.4%
[RD3]_55nmBulkSRAM_0;45;65;75deg	111.9	41.4	56.3%	77.7%
[RD4]_45nm,1.3V,12.5MeV_SRAM	196.9	50.6	38.4%	70.8%
[RD4]_65nm,1.2V,6.3MeV_SRAM	212.8	52.1	45.9%	77.6%
[RD4]_65nm,1.2V,12.5MeV_SRAM	180.3	50.6	20.6%	48.1%
[RD5]_90nm_SRAM_0.9V	224.7	52.0	16.7%	46.5%
[RD5]_90nm_SRAM_1.0V_0,30,45deg	224.7	52.0	18.7%	49.8%
[RD5]_90nm_SRAM_1.1V	224.9	52.0	8.1%	27.7%
[RD10] N. Sukhaseum NSREC 2014	212.0	41.9	0.3%	1.7%

Criticality Assessment

- **16 test data sets from the literature**
  - Typical LEO orbit : limited impact observed
  - Only one device with more than factor 5 in the worst-case environment

Reference	Experiment	Tech. node	Rate ratio direct/indirect ionization (LEO 4000 km)	Rate ratio direct/indirect ionization (LEO 800 km)
[RD1]_data0_1et2MeV	SEU SRAM	65 nm	0.964	0.223
[RD1]_data1_1et2MeV	SEU SRAM	65 nm	0.973	0.225
[RD2]_CellB_0.9V	SEU hard. SRAM	90 nm	0.122	0.005
[RD2]_CellB_1.0V	SEU hard. SRAM	90 nm	0.010	0.002
[RD2]_CellB_1.1V	SEU hard. SRAM	90 nm	0.006	0.001
[RD2]_CellC_0.9V	SEU hard. SRAM	90 nm	0.112	0.040
[RD2]_CommercialCell_0.9V	SEU SRAM COTS	90 nm	**10.364**	**2.414**
[RD3]_20nmFF_0et55deg	SEU bulk flip-flops	20 nm	**4.105**	**1.396**
[RD3]_55nmBulkSRAM_0;45;65;75deg	Bulk SRAM	55 nm	**3.477**	**1.287**
[RD4]_45nm,1.3V,12.5MeV_SRAM	SBU SRAM 45 nm	45 nm	**2.425**	0.623
[RD4]_65nm,1.2V,6.3MeV_SRAM	SBU SRAM 65 nm	65 nm	**3.464**	0.848
[RD4]_65nm,1.2V,12.5MeV_SRAM	SBU SRAM 65 nm	65 nm	0.927	0.260
[RD5]_90nm_SRAM_0.9V	SEU SRAM	90 nm	0.870	0.201
[RD5]_90nm_SRAM_1.0V_0,30,45deg	SEU SRAM	90 nm	0.993	0.230
[RD5]_90nm_SRAM_1.1V	SEU SRAM	90 nm	0.383	0.088
[RD10] N. Sukhaseum NSREC 2014	SEU FPGA RAM	45 nm	0.017	0.003

Conclusion

- **Over the panel of selected devices for this analysis**
  - **Critical impact of proton direct ionization observed only on few cases**
  - **In extreme cases (very sensitive device in worst-case environment) the proton direct ionization contribution can reach 90% of the trapped proton SEU rate**

- **The work on this topic is going on in 2017…**
  - **Software development**
    - Calculation accuracy improvement by taking into account the cross section curve shape in the rate estimation (not only the σ_{peak})
  - **Environment contribution**
    - Study the cases of solar and cosmic protons in order to asses the proton direct ionization rate criticality for such space environments