R&T PROTON DIRECT IONIZATION

Assessment of the Direct Ionization Contribution to the Proton SEU Rate

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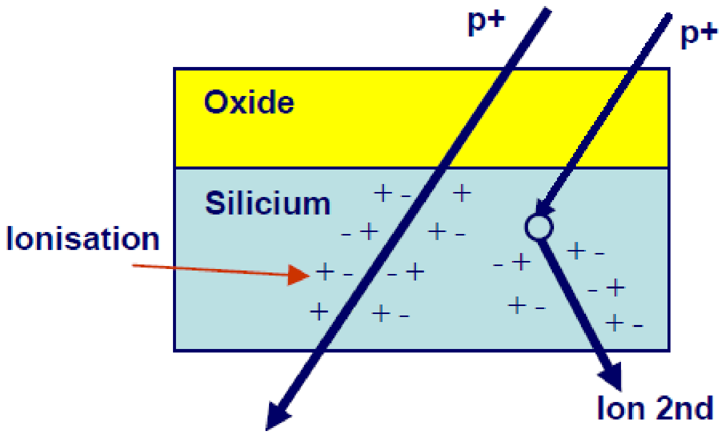
Introduction

- **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**

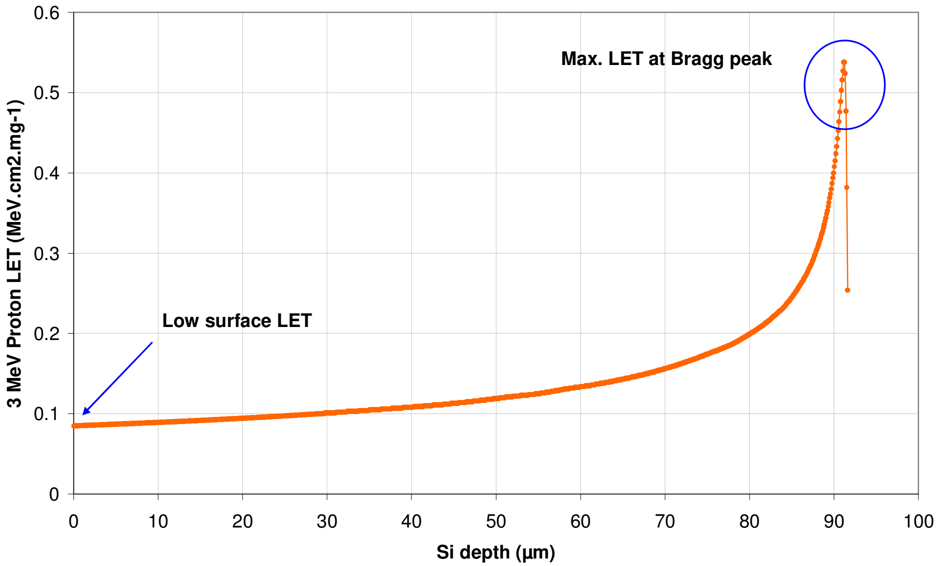


- **Proton caused SEU**
  - **Recoil atom**
    - Indirect event due to the charge generated by a secondary ion
  - **Direct ionization**
    - Charge generated by the incident proton leads to an event

- **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

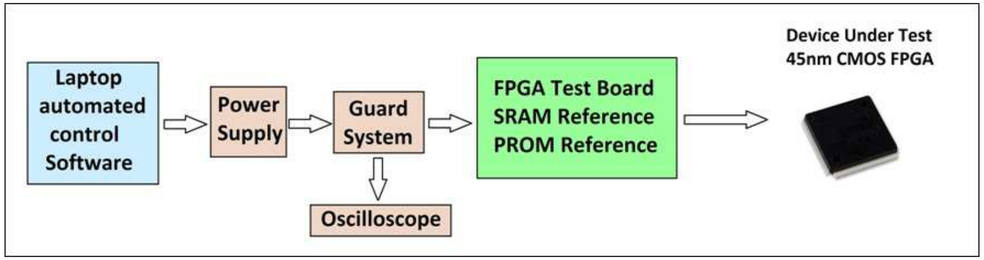
- **2012/2013 – Experimental phase preparation**
  - **Selection and procurement of potentially sensitive devices**
    - Commercially available SRAM memory cell below 65 nm tech. node
  - **Identification of an adapted test facility**
    - Proton beam at low flux under vacuum with in-situ bias and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

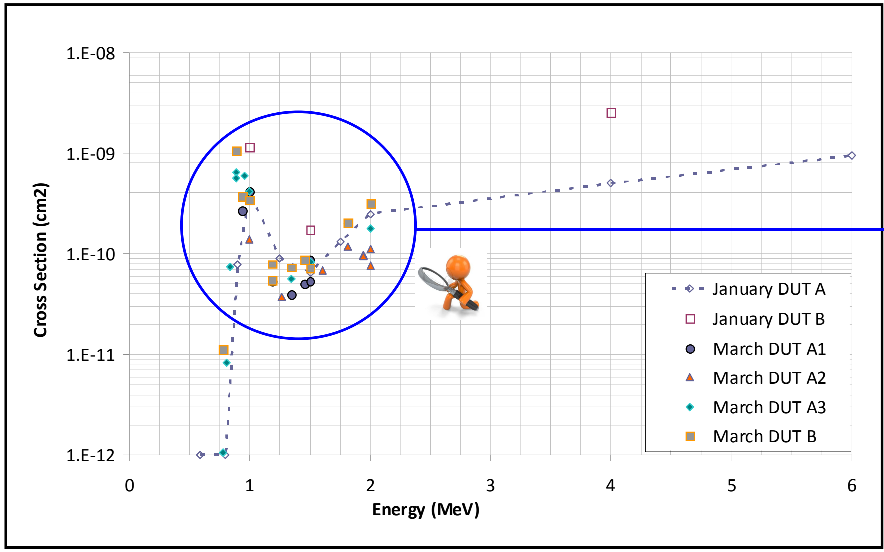


Test configuration

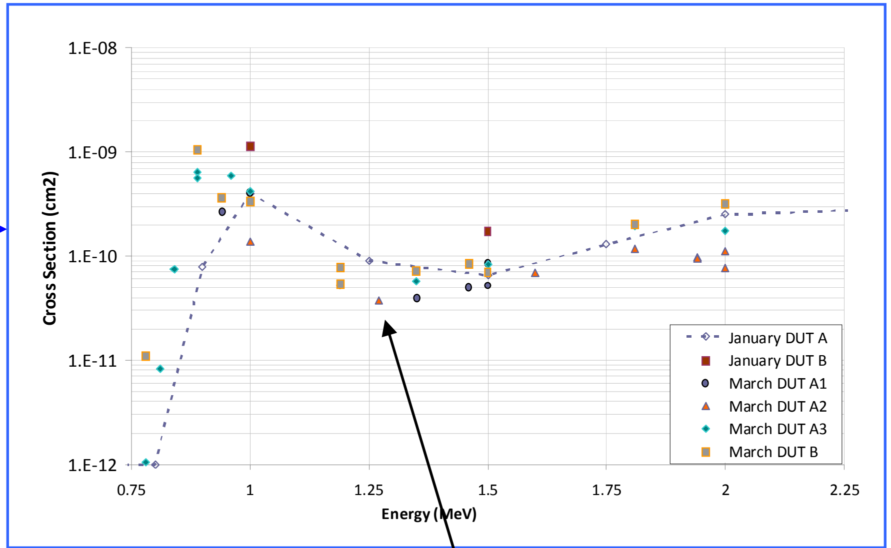
CNA proton facility

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

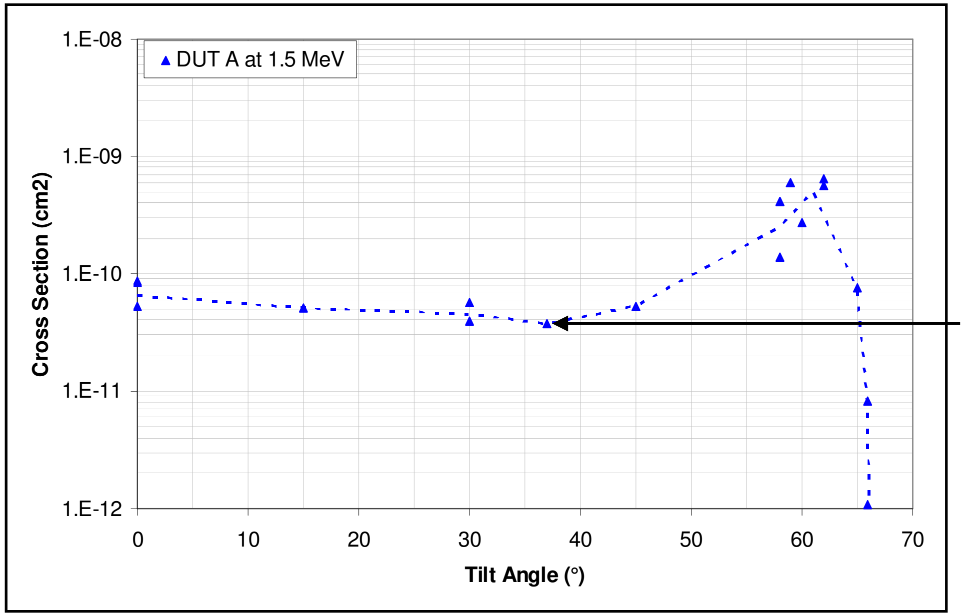
- **The experimental data is compiled in order to calculate a rate**

- **Reconstructed cross section curve at fixed energy as a function of the tilt angle**
  - Based on the <u>penetration depth</u> 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

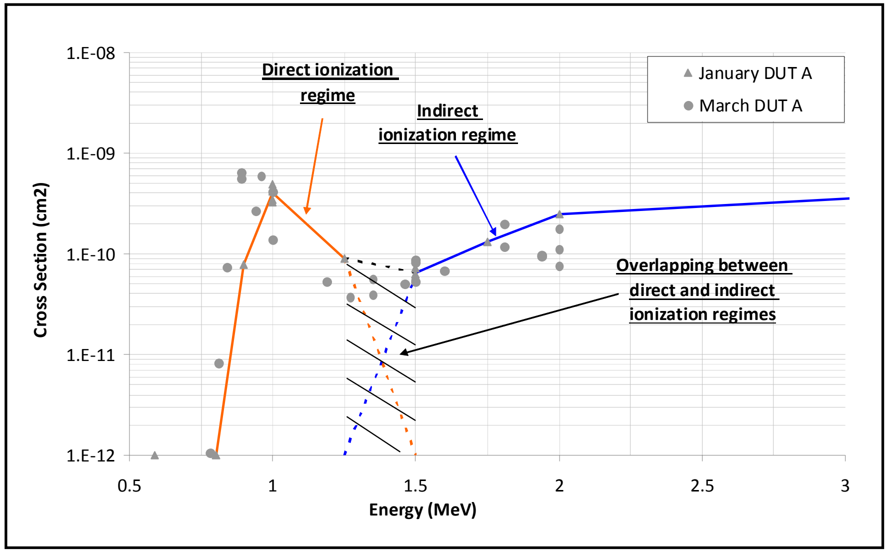


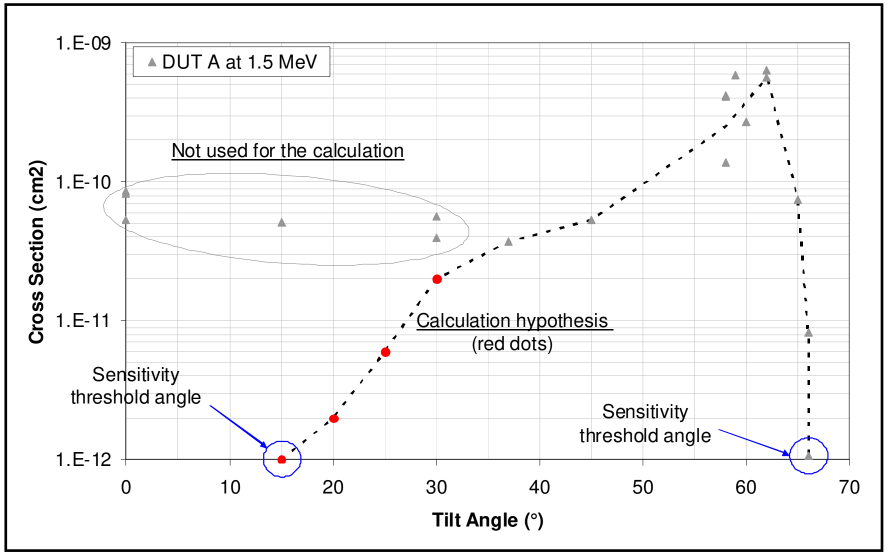
Irradiation at 2MeV, 60° displayed at 37°

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



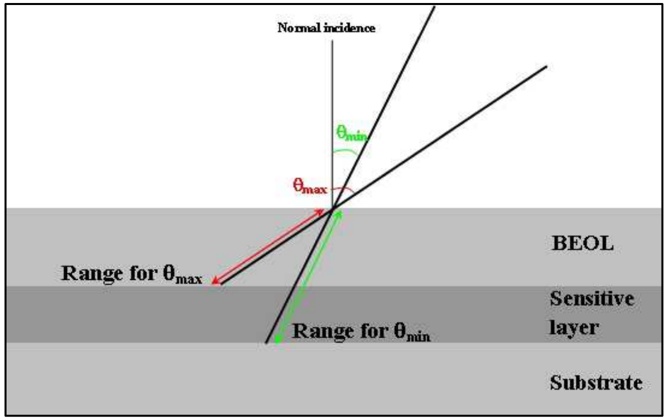


Data Analysis

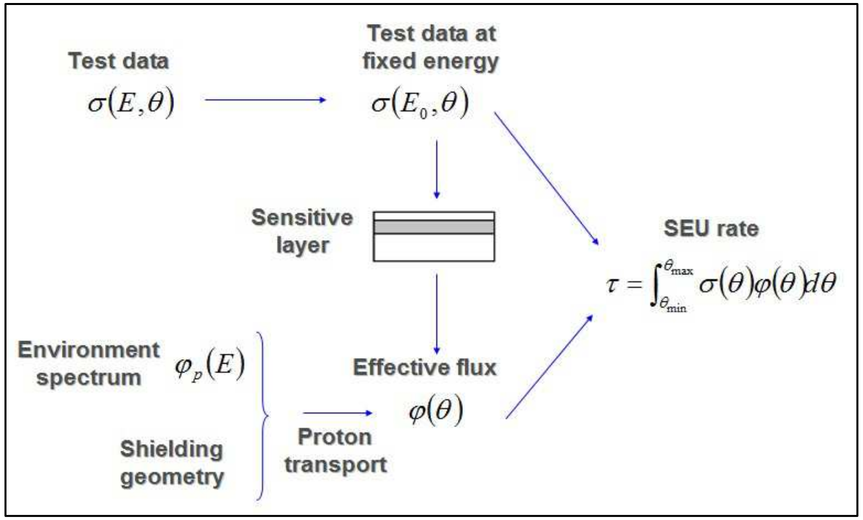
- **Sensitive layer depth and thickness calculated with respect to the threshold angles**
  - 15° and 66° in the example of DUT A at 1.5MeV

- **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 $\varphi(\theta)$ to take into account at each angle
  - $\varphi(\theta)$ 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 $\sigma(\theta)$**
  - Simplification : $\sigma(\theta) = \sigma_{max}$



Sensitive layer calculation

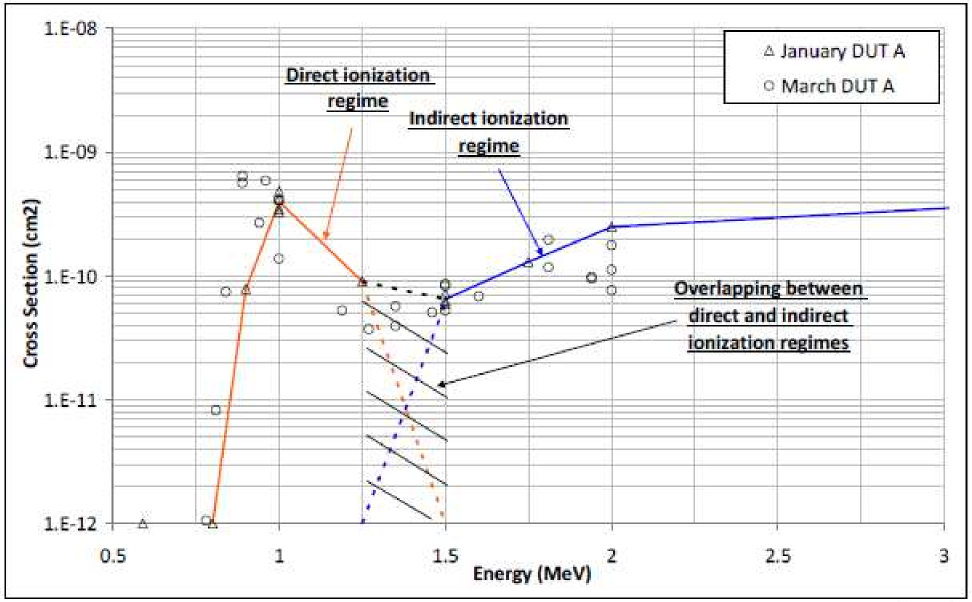


Calculation methodology

Direct Ionization Rate Calculation

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

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

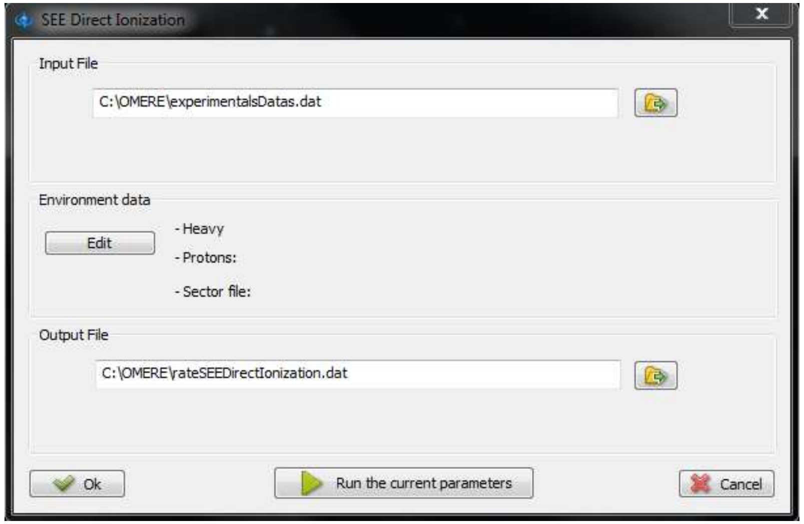


Consideration of a step function

→ 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



- **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

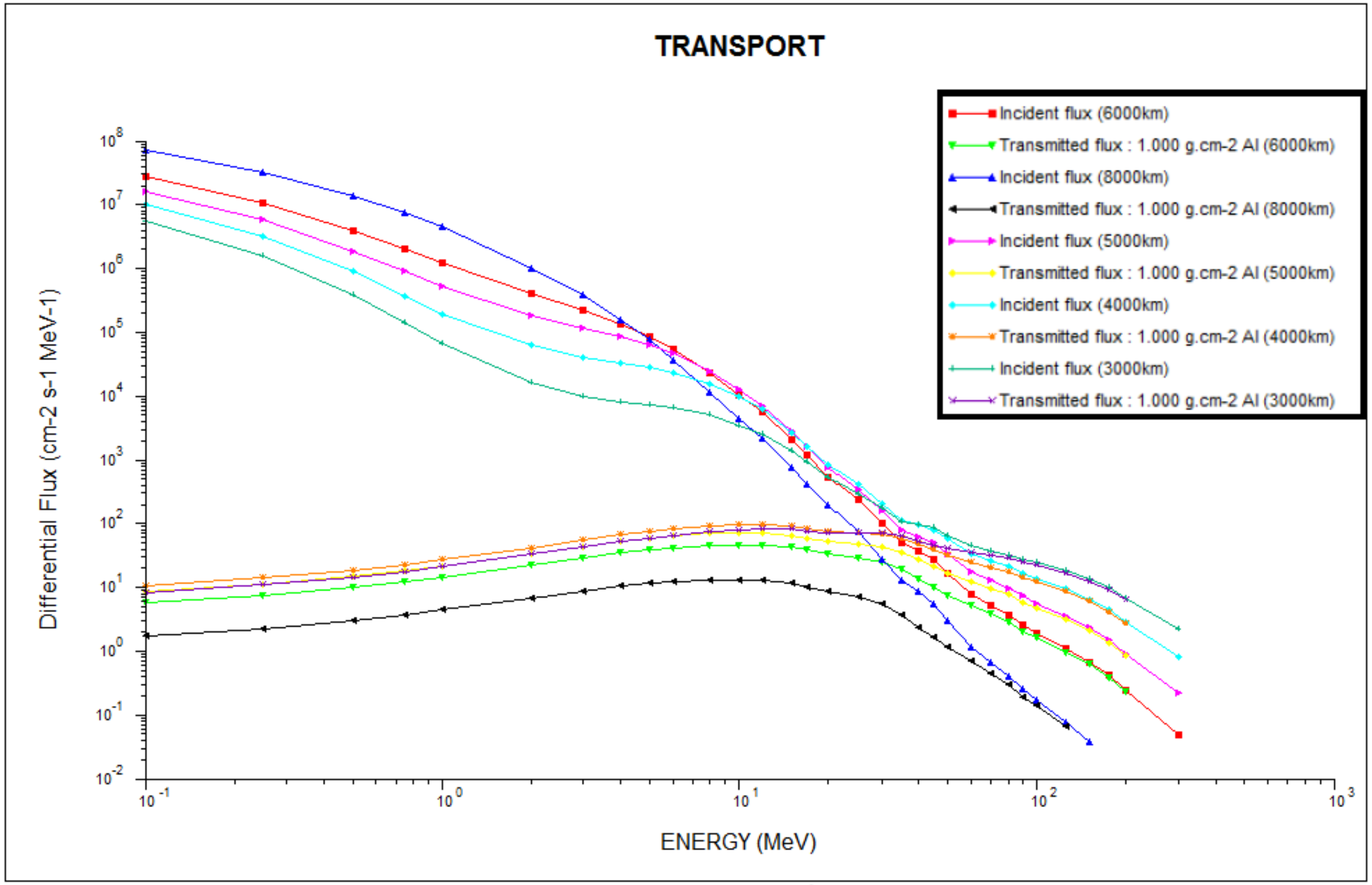
Direct Ionization Rate Calculation

▪ 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

- **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