ATLAS Policy on Radiation Tolerant Electronics:

ATLAS Radiation Tolerance Criteria

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ATLAS Radiation Tolerance Criteria
for Electronic Components

(Appendix 1 of the ATLAS Policy on Radiation Tolerant Electronics revision 2)

APPENDIX 1: Radiation Tolerance Criteria for ATLAS Components

1. Simulated radiation levels

Simulated Radiation Levels ("SRL") are the radiation levels computed for the various ATLAS regions. Table 1 defines the three types of SRL that are necessary for the *ATLAS strategy for radiation tolerant or radiation-hard component procurement*.

Simulated Radiation Level	Type of Radiation Constraint	SRL Unit
SRL_{tid}	Particles producing ***TID*** (Total Ionising Dose). Example: photons.	Total Dose in 10 years: ***Gray***
SRL_{niel}	Particles producing ***NIEL*** (Non-Ionising Energy Loss). Example: neutrons.	Total Fluence in 10 years: ***1 MeV eq. neutron.cm^{-2}***
SRL_{see}	Particles producing ***SEE*** (Single Event Effects). Example: heavy fragments.	Total Fluence in 10 years: ***> 20 MeV hadron.cm^{-2}***

Table 1: Definition of the three types of simulated radiation levels

The relevance of the fluence of hadron of energy greater than 20 MeV for the estimation of *soft* SEE rates in an accelerator environment is demonstrated in reference [5]. This fluence of hadrons of energy greater than 20 MeV can also be used to estimate an upper limit of *hard* and *destructive* SEE rates. The definition of these soft, hard and destructive SEEs and the methods used to estimate their rate are given in section 2.2.

Table 2 and 3 give the values of SRL_{tid}, SRL_{niel} and SRL_{see}, computed for various ATLAS regions [6].

Remark: Table 2 and 3 give values of SRL_{tid}, SRL_{niel} and SRL_{see} up to date at the date of release of the ATLAS Policy on Radiation Policy revision 2. As mentionned in this document in section VII page 6, subsequent updated values – if any - will be made available on the "ATLAS Radiation Hard Electronics" web page[3].

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[3] The address of this web page is: http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm

SYSTEM	**SUB-SYSTEM**	**POSITION**				**RAW SIMULATED RADIATION LEVEL**		
		Z min (cm)	**Z max (cm)**	**R min (cm)**	**R max (cm)**	**SRL$_{tid}$ (Gy.10y^{-1})**	**SRL$_{niel}$ (1 MeV n.cm^{-2}.10y^{-1})**	**SRL$_{see}$ (>20 MeV h.cm^{-2}.10y^{-1})**
Pixel barrel	Layer 1	0	40.7	4.2	4.2	3.05E+06	1.84E+15	2.61E+15
	Layer 2	0	40.7	9.3	9.3	5.61E+05	8.59E+14	1.02E+15
	Layer 3	0	40.7	12.7	12.7	3.76E+05	5.18E+14	5.50E+14
Pixel discs	disc 1	49.1	49.1	12.1	18.2	3.36E+05	4.17E+14	4.96E+14
	disc 2	58.0	58.0	12.1	18.2	3.29E+05	4.10E+14	5.08E+14
	disc 3	65.0	65.0	12.1	18.2	3.44E+05	4.14E+14	5.23E+14
	disc 4	71.0	71.0	09.9	16.0	4.84E+05	5.61E+14	8.16E+14
	disc 5	77.0	77.0	09.9	16.0	4.89E+05	5.60E+14	8.16E+14
SCT barrel	barrel 1	0.0	75.0	30.0	30.0	1.07E+05	1.75E+14	1.43E+14
	barrel 2	0.0	75.0	37.0	37.0	7.89E+04	1.48E+14	1.12E+14
	barrel 3	0.0	75.0	45.0	45.0	5.55E+04	1.24E+14	8.25E+13
	barrel 4	0.0	75.0	52.0	52.0	4.57E+04	1.06E+14	6.25E+13
SCT disc	1-silicon	84.0	84.0	27.0	56.0	7.43E+04	1.47E+14	1.11E+14
	1-electronics	84.0	84.0	34.0	48.0	7.27E+04	1.41E+14	1.02E+14
	2-silicon	91.0	91.0	27.0	56.0	7.45E+04	1.46E+14	1.13E+14
	2-electronics	91.0	91.0	34.0	48.0	7.36E+04	1.40E+14	1.05E+14
	3-silicon	105.0	105.0	27.0	56.0	7.52E+04	1.44E+14	1.12E+14
	3-electronics	105.0	105.0	34.0	48.0	7.44E+04	1.39E+14	1.04E+14
	4-silicon	128.0	128.0	27.0	56.0	7.55E+04	1.41E+14	1.10E+14
	4-electronics	128.0	128.0	34.0	48.0	7.50E+04	1.37E+14	1.04E+14
	5-silicon	151.0	151.0	27.0	56.0	7.77E+04	1.46E+14	1.13E+14
	5-electronics	151.0	151.0	34.0	48.0	7.65E+04	1.42E+14	1.07E+14
	6-silicon	174.0	174.0	27.0	56.0	8.03E+04	1.52E++14	1.17E+14
	6-electronics	174.0	174.0	34.0	48.0	7.88E+04	1.47+E14	1.09E+14
	7-silicon	206.0	206.0	34.0	56.0	6.91E+04	1.50+E14	1.00E+14
	7-electronics	206.0	206.0	40.0	48.0	6.93E+04	1.54+E14	1.05E+14
	8-silicon	252.0	252.0	41.0	56.0	6.07E+4	1.77+E14	1.03E+14
	8-electronics	252.0	252.0	40.0	48.0	7.67E+04	1.88+E14	1.14E+14
	9-silicon	272.0	272.0	44.0	56.0	6.19E+04	1.86+E14	9.92E+13
	9-electronics	272.0	272.0	40.0	44.0	8.63E+04	2.19+E14	1.27E+14

Table 2 : SRL values computed for 10 years of operation in various ATLAS locations

SYSTEM	**SUB-SYSTEM**	**POSITION**				**RAW SIMULATED RADIATION LEVEL**		
		Z min (cm)	**Z max (cm)**	**R min (cm)**	**R max (cm)**	**SRL$_{tid}$ (Gy.10y^{-1})**	**SRL$_{niel}$ (1 MeV n.cm^{-2}.10y^{-1})**	**SRL$_{see}$ (>20 MeV h.cm^{-2}.10y^{-1})**
TRT	barrel	79.0	79.0	56.0	107.3	1.59E+04	6.68E+13	2.99E+13
	end-cap	83.0	340.0	108.0	108.0	8.14E+03	6.92E+13	1.82E+13
LAR	barrel	300.0	350.0	290.0	340.0	4.87E+01	1.56E+12	7.67E+11
	end-cap	620.0	670.0	290.0	340.0	5.67E+00	1.45E+11	2.14E+10
TILE	HV micro	210.0	210.0	400.0	400.0	6.41E–01	4.35E+10	1.76E+09
	HV opto	200.0	200.0	400.0	400.0	8.80E–01	3.28E+10	1.27E+09
	Mother	275.0	275.0	410.0	410.0	2.54E+00	2.29E+11	5.66E+10
	Integrator	210.0	210.0	410.0	410.0	5.20E–01	3.70E+10	2.80E+09
	Adder	260.0	260.0	410.0	410.0	1.22E+00	1.40E+11	2.33E+10
	Digitiser PC	275.0	275.0	410.0	410.0	2.54E+00	2.29E+11	5.66E+10
	S-link & interface	150.0	150.0	410.0	410.0	2.25E–01	1.49E+10	6.32E+08
MUON CSC	Start CSC 1	717.7	717.7	89.4	89.4	1.26E+02	5.41E+12	1.12E+12
	End CSC 1	694.1	694.1	204.7	204.7	1.47E+01	1.03+E12	1.21E+11
	Start CSC 2	735.3	735.3	89.4	89.4	1.67E+02	3.88+E12	7.50E+11
	End CSC 2	711.7	711.7	204.7	204.7	1.51E+01	1.09+E12	1.55E+11
	Start CSC 3	753.5	753.5	94.0	94.0	1.70E+02	2.96+E12	5.58E+11
	End CSC 3	730.8	730.8	204.7	204.7	2.06E+01	1.11+E12	1.95E+11
	Start CSC 4	771.1	771.1	94.0	94.0	1.91E+02	3.12+E12	4.54E+11
	End CSC 4	748.4	748.4	204.7	204.7	2.52E+01	1.19+E12	2.23E+11
MUON RPC	BMF	63.1	872.2	839.1	847.1	3.02E+00	2.49E+10	4.69E+09
	BML	15.0	966.0	750.6	758.6	3.04E+00	2.82E+10	5.65E+09
	BMS	13.5	945.5	839.1	847.1	3.03E+00	2.50E+10	4.73E+09
	BOF	60.8	1267.9	1035.5	1043.5	1.19E+00	2.14E+10	4.08E+09
	BOL	15.0	1225.2	985.3	993.3	1.33E+00	2.20E+10	4.21E+09
	BOS	1.0	1383.2	1025.8	1033.8	1.26E+00	2.10E+10	4.10E+09
MUON TGC	1	1280.0	1290.0	715.0	1180.0	2.27E+00	2.58E+10	6.54E+09
	2	1470.0	1480.0	680.0	1180.0	2.49E+00	1.42E+10	4.53E+09
MUON MDT	Barrel 1	0.0	650.0	520.0	520.0	4.69E+00	2.99E+10	5.43E+09
	Barrel 2	0.0	900.0	720.0	720.0	2.76E+00	3.01E+10	5.70E+09
	Barrel 3	0.0	1250.0	950.0	950.0	1.33E+00	2.41E+10	4.61E+09
	End-cap 1	730.0	730.0	215.0	620.0	6.38E+00	2.94E+11	4.83E+10
	End-cap 2	1350.0	1350.0	190.0	1100.0	6.22E+00	3.41E+10	8.74E+09
	End-cap 3	2230.0	2230.0	260.0	1200.0	3.26E+00	1.75E+10	2.31E+09

Table 3 : SRL values computed for 10 years of operation in various ATLAS locations (cont.)

2. Radiation tolerance criteria

ATLAS electronics components must have radiation tolerances equal to or higher than minimum values called Radiation Tolerance Criteria (RTCs). Table 4 defines the three types of RTCs that are necessary for the *ATLAS strategy for radiation tolerant or radiation hard component procurement*.

Radiation Tolerance Criterion	Type of Radiation Constraint	RTC Unit
RTC_{tid}	Particles producing ***TID*** (Total Ionising Dose)	Total Ionising Dose: ***Gray***
RTC_{niel}	Particles producing ***NIEL*** (Non-Ionising Energy Loss)	Total Fluence: ***1 MeV eq. neutron/cm²***
RTC_{see}	Particles producing ***SEE*** (Single Event Effects)	SEE rate: ***SEE/s***

Table 4: Radiation tolerance criteria

2.1. Radiation tolerance criteria RTC_{tid} and RTC_{niel}

The radiation tolerance criteria for TID and NIEL are:

- $RTC_{tid} = SRL_{tid} \times SF_{sim} \times SF_{ldr} \times SF_{lot}$ (unit : Gray)
- $RTC_{niel} = SRL_{niel} \times SF_{sim} \times SF_{ldr} \times SF_{lot}$ (unit : 1MeV eq. neutrons / cm^2)

Table 5 define the safety factors (SFs) used to compute RTCs.

Safety factor	Definition
SF_{sim}	Represents SRL inaccuracies.
SF_{ldr}	Represents low dose rate effects (LDRE).
SF_{lot}	Represents the variation of radiation tolerance from lot to lot and within a lot.

Table 5: definition of the safety factors required for RTC computations.

Table 6 and 7 give SF values for various ATLAS locations [6]. In these tables, columns (a) to (f) correspond to the following cases:

(a) Applies on SRL_{tid} only, for COTS only, except if TID tests are made with accelerated ageing at elevated temperature (in this case, $SF_{ldr} = 1$);
(b) Applies on SRL_{tid} only, for radiation-hard ASICs only, except if TID tests are made with accelerated ageing at elevated temperature (in this case, $SF_{ldr} = 1$);
(c) Applies on all SRL for the *pre-selection* of COTS issued from unknown[4] batches *if their qualification is to be done on unknown COTS batches*;
(d) Applies on all SRL for the *qualification* of unknown COTS batches;
(e) Applies on all SRL for *pre-selecting* COTS or ASICs issued from homogeneous[5] batches or from unknown batches, *only if their qualification is to be done on homogeneous batches*;
(f) Applies on all SRL for the *qualification* of homogeneous COTS or ASICs batches;

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[4] An unknown batch is a batch of components provided by a vendor without information on the production line, on the batch number, etc. (these components may be issued from different batches or different production lines).

[5] A homogeneous batch (or diffusion batch) is a batch of components issued from wafers manufactured together at the same time on a known production line.

SYSTEM	**SUB-SYSTEM**	**SF_{sim}**			**SF_{ldr}**				**SF_{lot}**		
SF applies on:		**SRL_{tid}**	**SRL_{niel}**	**SRL_{see}**	**SRL_{tid} (a)**	**SRL_{tid} (b)**	**SRL_{niel}**	**SRL_{see}**	**All SRL (c), (d)**	**All SRL (e)**	**All SRL (f)**
Pixel barrel	Layer 1	3.5	5	5	5	1.5	1	1	4	2	1
	Layer 2	3.5	5	5	5	1.5	1	1	4	2	1
	Layer 3	3.5	5	5	5	1.5	1	1	4	2	1
Pixel discs	Disc 1	3.5	5	5	5	1.5	1	1	4	2	1
	Disc 2	3.5	5	5	5	1.5	1	1	4	2	1
	Disc 3	3.5	5	5	5	1.5	1	1	4	2	1
	Disc 4	3.5	5	5	5	1.5	1	1	4	2	1
	Disc 5	3.5	5	5	5	1.5	1	1	4	2	1
SCT barrel	Barrel 1	3.5	5	5	5	1.5	1	1	4	2	1
	Barrel 2	3.5	5	5	5	1.5	1	1	4	2	1
	Barrel 3	3.5	5	5	5	1.5	1	1	4	2	1
	Barrel 4	3.5	5	5	5	1.5	1	1	4	2	1
SCT disc	1-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	1-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	2-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	2-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	3-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	3-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	4-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	4-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	5-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	5-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	6-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	6-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	7-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	7-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	8-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	8-electronics	3.5	5	5	5	1.5	1	1	4	2	1
	9-silicon	3.5	5	5	5	1.5	1	1	4	2	1
	9-electronics	3.5	5	5	5	1.5	1	1	4	2	1

Table 6: SF values for various ATLAS locations.

SYSTEM	**SUB-SYSTEM**	**SF_{sim}**			**SF_{ldr}**				**SF_{lot}**		
SF applies on:		**SRL_{tid}**	**SRL_{niel}**	**SRL_{see}**	**SRL_{tid} (a)**	**SRL_{tid} (b)**	**SRL_{niel}**	**SRL_{see}**	**All SRL (c), (d)**	**All SRL (e)**	**All SRL (f)**
TRT	barrel	3.5	5	5	5	1.5	1	1	4	2	1
	end-cap	3.5	5	5	5	1.5	1	1	4	2	1
LAR	barrel	3.5	5	5	5	1.5	1	1	4	2	1
	end-cap	3.5	5	5	5	1.5	1	1	4	2	1
TILE	HV micro	3.5	5	5	5	1.5	1	1	4	2	1
	HV opto	3.5	5	5	5	1.5	1	1	4	2	1
	Mother	3.5	5	5	5	1.5	1	1	4	2	1
	Integrator	3.5	5	5	5	1.5	1	1	4	2	1
	Adder	3.5	5	5	5	1.5	1	1	4	2	1
	Digitiser PC	3.5	5	5	5	1.5	1	1	4	2	1
	-link & interface	3.5	5	5	5	1.5	1	1	4	2	1
MUON CSC	Start CSC 1	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 1	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 2	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 2	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 3	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 3	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 4	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 4	3.5	5	5	5	1.5	1	1	4	2	1
MUON RPC	BMF	3.5	5	5	5	1.5	1	1	4	2	1
	BML	3.5	5	5	5	1.5	1	1	4	2	1
	BMS	3.5	5	5	5	1.5	1	1	4	2	1
	BOF	3.5	5	5	5	1.5	1	1	4	2	1
	BOL	3.5	5	5	5	1.5	1	1	4	2	1
	BOS	3.5	5	5	5	1.5	1	1	4	2	1
MUON TGC	1	3.5	5	5	5	1.5	1	1	4	2	1
	2	3.5	5	5	5	1.5	1	1	4	2	1
MUON MDT	Barrel 1	3.5	5	5	5	1.5	1	1	4	2	1
	Barrel 2	3.5	5	5	5	1.5	1	1	4	2	1
	Barrel 3	3.5	5	5	5	1.5	1	1	4	2	1
	End-cap 1	3.5	5	5	5	1.5	1	1	4	2	1
	End-cap 2	3.5	5	5	5	1.5	1	1	4	2	1
	End-cap 3	3.5	5	5	5	1.5	1	1	4	2	1

Table 7: SF values for various ATLAS locations (cont.).

Remark 1: the location (Rmin, Rmax, Zmin, Zmax) of the electronics of the sub-systems mentioned in tables 6 and 7 is given in tables 2 and 3.

Remark 2: Table 6 and 7 give values of SF_{sim}, Sf_{ldr} and SF_{lot} up to date at the date of release of the ATLAS Policy on Radiation Policy revision 2. As mentioned in this document in section VII page 6, subsequent updated values – if any - will be made available on the “ATLAS Radiation Hard Electronics” web page[6], together with the updated values of SRL_{tid}, SRL_{niel} and SRL_{see}.

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[6] The address of this web page is: http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm

2.2. Radiation tolerance criterion RTC_{see}

2.2.1. Definition of the three RTC_{see}:

The generic acronym SEE (Single Event Effect) represents at once SEU (Single Event Upsets), SEL (Single Event Latch-up), SEGR (Single Event Gate rupture) and SEB (Single Event Burnout). These various SEEs can be distributed in three categories:

- *Soft SEEs* (also called soft SEUs) are radiation induced bit flips that corrupt data or system configurations. They are *not permanent effects* (they are cancelled by resetting the system or rewriting data in a memory). Example: a “1” changed into a “0” in a combinatorial logic circuit, or in a register, or in a memory.
- *Hard SEEs* (also called hard SEUs) are radiation induced bit flip that corrupts data or system configurations. They are *permanent effects* (they are not cancelled by resetting the system or rewriting data in a memory). Example: a bit stuck to “1” in a memory cell.
- *Destructive SEEs* (SELs, SEBs, SEGRs) produce permanent short circuits. SELs are destructive SEEs, unless a robust architectural solution protects the circuit against thermal destruction resulting from latch-up. SEBs and SEGRs are always destructive SEEs.

The radiation tolerance criteria for soft, hard and destructive SEEs are defined in table 8:

Radiation Tolerance Criterion	**Category of SEE**	**RTC Unit**
$RTC_{see.s}$	soft SEE	Soft SEE rate: ***soft SEE / s***
$RTC_{see.h}$	hard SEE	Hard SEE rate: ***hard SEE / s***
$RTC_{see.d}$	destructive SEE	Destructive SEE rate: ***destructive SEE / s***

Table 8: Radiation tolerance criteria RTC_{see}

The values of these RTCs must be defined by each ATLAS Sub-system for each electronic function. They are the maximum rates acceptable for soft SEUs, for hard SEUs and for destructive SEEs.

Remark: destructive SEEs can induce fire in electronics systems. In ATLAS electronics systems, for safety reasons, components sensitive to destructive SEEs are not allowed unless a proven robust architectural solution protects the system against SEE induced fire.

2.2.2. Use of $RTC_{see.s}$ for the selection or the qualification of electronics components

a / Soft SEE rate foreseen in ATLAS sub-systems:

The study of SEU rates published in reference [5] shows that the probability of soft SEU production is almost identical for all hadron above 20 MeV, and that the contribution to soft SEE rate of hadrons below 20 MeV is much smaller than that of hadrons above 20 MeV. This enables one to extrapolate the soft SEE (or soft SEU) rate measured with 60 – 200 MeV proton to that produced by all the hadrons of energy greater than 20 MeV foreseen in a given ATLAS location, and so to predict the soft SEU rate in this location.

The prediction of soft SEU rate in a given ATLAS location by extrapolation of measurements made with 60 – 200 MeV protons can be done as follow:

$$\text{Soft SEU}_f = (\text{soft SEU}_m / \text{ARL}) \times (\text{SRL}_{see} / 10^8\text{s}) \times \text{SF}_{sim}$$

Where:

- "Soft SEU_f" is the *foreseen rate of soft SEU* in a given ATLAS location (soft SEU / s);
- "Soft SEU_m" is the total *number of soft SEU measured* during the total duration of proton beam tests (use the worst case value measured among the 4 DUT);
- "ARL" is the *Applied Radiation Level* (total fluence of 60 – 200 MeV proton applied during SEE measurement, in hadron / cm^2);
- "SRL_{see}" is the *Simulated Radiation Level* (total fluence of hadrons of energy greater than 20 MeV foreseen in 10 years in the ATLAS location, in hadron / cm^2);
- 10^8s represents the integrated beam time (in seconds) expected in 10 years of LHC operation.
- "SF_{sim}" is the safety factor explained and given in section 2.1.

b / Interpretation of SEE tests:

Soft SEE (or soft SEU) rates foreseen for each ATLAS electronics components in a given ATLAS location must be lower than the corresponding radiation tolerance criterion:

$$(1) \quad \text{Soft SEU}_f < \text{RTC}_{see.s}$$

The pre-selection of a generic component requires that all the tested components satisfy this relation.

2.2.3. Use of $\text{RTC}_{see.h}$ and $\text{RTC}_{see.d}$ for the selection of electronics components

a / Hard SEE rate and destructive SEE rate foreseen in ATLAS sub-systems:

The equivalence of the probability of producing SEE for all the hadrons of energy greater than 20 MeV, established in [5], concerns *soft* SEUs only. Up to now, no study has been done to estimate the rates of *hard SEUs or destructive* SEEs in an *accelerator environment*. Without such a study, it is very difficult to predict accurately the rates of hard or destructive SEE for ATLAS. However, it is possible to make an approximate estimation of an upper limit for these rates.

The production of hard SEUs or destructive SEEs requires a high local instantaneous energy deposition (higher than that required for producing soft SEUs). The deposition of this high energy requires particles having a high LET (Linear Energy Transfer, or dE / dX). In HEP experiments like ATLAS, particles with a high LET are produced by fission reactions induced by energetic hadrons on elements heavier than 170-180 AMU [7]. The range of these particles in silicon or in the material from the integrated circuit package is typically less than 10 µm, which means that only secondary particles from fission reactions occurring *in silicon* or *in the material from the package* can produce hard or destructive SEEs. The main elements constituting silicon integrated circuits (ICs) and their packages are listed in table 9. Among these elements, only five of them have an atomic number higher than 170. These elements are tungsten, tantalum, gold, lead and platinum. Tungsten is used in a relatively thin layer to build an inter-metal barrier in “via” (vertical link between two metal layers). Tantalum is (very rarely) used to build a conductive layer on the top of the CMOS gate oxides. Lead could be used to make SnPb ball bumps in some hybrid systems like Pixel Detectors[7]. Gold constitutes the wire bonds of most of the ICs. Platinum is (very rarely) used in a thin layer to build inter-metal barriers in “via”. Among these five elements, tantalum and platinum are very rarely used, so the most probable contributors to fission reactions are tungsten, gold and lead. The cross sections of fission reactions induced by protons in these elements increase with the proton energy up to saturated values, which occur at about 300 MeV for lead, 500 MeV for gold, and more than 800 MeV for tungsten [8]. However, the fission cross section of tungsten bombarded with protons is much smaller than that of gold and lead, so we can neglect the increase of this cross section between 500 MeV and the saturation energy. It can be estimated that most of the fission reactions can be triggered by 500 MeV protons.

Element	**Relative abundance in silicon integrated circuits**	**Use**	**Atomic weight**
Silicon	Large	Main semiconductor	28
Boron	Small (< 1E-3%)	Doping	11
Arsenic	Small (< 1E-3%)	Doping	*75*
Phosphor	Small (< 1E-3%)	Doping	31
Aluminium	Large (few μm thick)	Interconnection metal (AlCu) in ≥ 0.25 μm processes	27
Copper	Large (> 6000 Å)	Interconnection metal (Cu) in advanced processes	64
Tungsten	Small (~ 1000 Å)	Inter-metal barrier in via	**184**
Titanium	Small (few 100 Å)	Inter-metal barrier; Gate conductive layer	48
Tantalum	Small (~ 1000 Å)	Gate conductive layer (very rarely)	**181**
Oxygen	Large (SiO_2)	Gate oxides, field oxides	16
Nitrogen	Possibly large (Si_3N_4)	Passivation nitrides	14
Gold	Large	Bonding wires	**197**
Lead	Possibly large	Bumping balls	**207**
Tin	Possibly large	Bumping balls	118
Indium	Possibly large	Bumping balls	115
Platinum	Small (few 100 Å)	Inter-metal barrier in via (very rarely).	**195**

Table 9: Main elements constituting ICs and their package.

Now an approximate upper limit for the rates of hard SEUs and destructive SEE can be estimated, by assigning the maximum SEE production probability to all the hadrons having an energy higher than a minimum value below which neither hard SEUs nor destructive SEEs occur. As discussed above, the maximum SEE production probability is approximately that measured on ICs irradiated with *500 MeV* protons. For convenience, the minimum value under which neither hard SEUs nor destructive SEEs occur could be set at 20 MeV, which corresponds to the energy threshold used to estimate soft SEU rates.

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[7] For this reason, it is recommended to use indium bumps instead of SnPb bumps, whenever it is possible.

The estimation of the rates of hard SEUs and destructive SEEs in a given ATLAS location by extrapolation of measurements made with 500 MeV protons can be done as follow:

$$\text{Hard or destructive SEE}_f = (\text{hard or destructive SEU}_m / \text{ARL}) \text{ x } (\text{SRL}_{see} / 10^8\text{s}) \text{ x } \text{SF}_{sim}$$

Where:

- "Hard or destructive SEU_f" is the *foreseen* *rate of hard or destructive SEU* in a given ATLAS location (hard or destructive SEU / s);
- "Hard or destructive SEU_m" is the total *number of hard or destructive SEU measured* during the total duration of proton beam tests (use the worst case value measured among the 4 DUT);
- "ARL" is the *Applied Radiation Level* (total fluence of 500 MeV proton applied during SEE measurement, in hadron / cm^2);
- "SRL_{see}" is the *Simulated Radiation Level* (total fluence of hadrons of energy greater than 20 MeV foreseen in 10 years in the ATLAS location, in hadron / cm^2);
- 10^8s represents the integrated beam time (in seconds) expected in 10 years of LHC operation.
- "SF_{sim}" is the safety factor explained and given in section 2.1.

b / Interpretation of SEE tests:

The rates of hard SEUs or destructive SEEs foreseen for each ATLAS electronic component in a given ATLAS location must be lower than the corresponding radiation tolerance criterion:

$$\text{Hard SEU}_f < \text{RTC}_{see.h} \quad (2)$$

$$\text{Destructive SEU}_f < \text{RTC}_{see.d} \quad (3)$$

The pre-selection of a generic component requires that all the tested components fulfill this relation.