ATLAS Policy on Radiation Tolerant Electronics:
ATLAS Standard Radiation Test Methods

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ATLAS Standard Radiation Test Methods

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

Appendix 2: ATLAS standard test methods

1. NIEL test method:

1.1. NIEL test method: 18 of 46

This test method is derived from the DOD MIL STD 883 test method 1017.2 [1], with several adaptations. It is suitable both for pre-selecting generic components and qualifying batches. The main stages of this test method are:

a / Selection of a calibrated neutron facility (1 MeV equivalent neutrons / cm^2);
b / Selection of a set of 11 good devices (for test of homogeneous[8] batch) or 22 good devices (for test of unknown[9] batch);
c / Serialisation of all devices (see appendix 2 section 1.2.);
d / Electrical measurement performed at room temperature on each device;
e / Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);
f / Irradiation of the 10 (or 20) other components up to the RTC_{niel} required for the application (see details on RTCs in appendix 1);
g / Electrical measurements performed at room temperature on each irradiated device, plus anomaly inspection after deactivation;
h / Rejection of the generic component (if the test is made to pre-select a generic component) or rejection of the batch (if the test is made to qualify a batch) if any of the 10 (or 20) components fails below $\mathrm{RTC}_{\mathrm{niel}}$;
i / Writing of test results in a standard report document (see appendix 3);
j / Feed database with test results (see section IV p.5).

1.2. Advises applicable to NIEL test method for components pre-selection or batch qualification: Preparation of the components to be tested:

- The initial set of un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[10] and manufacturer code[11] of the sample, and individual identification.

Measurement setup

- Two approaches can be used to perform irradiation and tests:
  a / Tests made using a dedicated test board: electrical measurement are made on the 11 (or 22) test components using a dedicated test board.
  b / Tests made using an entire system board: electrical measurement are made on all the components of an entire system board. In this case, the architecture of the board must enable one to check the operation of each of its individual components. The total number of test components having the same part number must be equal or larger than 11 (or 22) as recommended in 1.1.b /. If necessary, this can be obtained by performing irradiation and measurements on additional components (using a dedicated test board), or by testing several system boards.

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[8] 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.

[9] 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).

[10] Code of the date of manufacturing of the batch from which the sample is issued.

[11] Code of the production line from which the sample is issued.

- In case of on-line measurement, all the necessary precautions shall be taken to obtain an electrical measurement system which, by use of sufficient insulation, ample shielding, satisfactory grounding etc. shall yield suitably low level of interference from main power supplies and other sources of noise and leakage. The magnitude of interference from each of these items shall be sufficiently small so as not to affect any electrical measurement nor induce any damage on the device under test.
- In case of off-line measurement, all the leads of each device must be shorted together during irradiation and during transportation, either by insertion in conductive foam or by the use of an appropriate fixture.
- Only sockets that are radiation-resistant and do not exhibit any significant leakage shall be used to connect devices under test and associated circuitry to the test board. Similar precautions shall be taken with respect of cabling and switching systems. All equipment used repeatedly in radiation fields shall be checked periodically for physical and/or electrical degradation.

Irradiation:

- Two approaches can be used to perform irradiation:
  a/ If the electrical measurements are made using a dedicated test board, the irradiation of the 11 (or 22) test components shall be made on the same test board (for on line measurements) or on conductive foam or appropriate fixture(for off line measurement).
  b/ If the electrical measurements are made using an entire system board, the irradiation shall be performed simultaneously on all the components of the system board(s), or on conductive foam or appropriate fixture (off-line measurements).
- It is not necessary to apply NIEL test method on pure CMOS devices, which are naturally tolerant to displacement damage (damages produced by neutron in the semiconductor).
- Neutron fluence can be applied either in one single step or in several steps. In both cases, the cumulated neutron fluence must be equal to at least RTC_{niel}. In case of several steps, two methods can be used:
  1/ All the 10 (or 20) devices under test (DUT) are placed in the same location. Electrical measurements are performed on line during irradiation;
  2/ Several sets of 10 (or 20) DUT are placed in several locations which are chosen in order to obtain several neutron fluences ranging from a small value up to the RTC_{niel}. All the sets of components are irradiated together at the same time. Electrical measurements can be performed either on line (during irradiation) or off line (after irradiation).
- In the case of several irradiation steps, it is recommended to choose the steps in order to get an approximate linear progression of the cumulated neutron fluence in a logarithmic scale (example: 1, 3, 6, 10, 30, … ; or 1, 4, 10, 40, … ; or 1, 10, 100, …).
- During irradiation, the temperature must be under control and recorded if necessary.
- During irradiation, in case of off-line measurement, all the leads of each devices must be shorted together.
- During irradiation, in case of on-line measurement, all the leads of each devices must be properly biased in order to enable measurements. Unconnected leads are not allowed.
- The devices under test shall be exposed to a radiation constraint at least as high as RTC_{niel}.
- The total fluence of fast neutrons applied on the devices under test must be measured using activation foils such as ^{32}Sr, ^{54}Fe and ^{58}Ni placed on the devices under test during irradiation. The fluence at the DUT shall be measured to a resolution of better than 10% and the non-uniformity of the radiation field in the test area shall be a maximum of 10%. The field uniformity shall be verified if the geometry of the test setup is changed.
- Depending on the RTC_{niel}, the neutron flux shall be chosen in such a way that the errors in fluxes coming from timing errors and initial beam adjustment are kept below 5%. It shall be recorded in the standard test report document.

Electrical measurements

- The main AC or DC parameters relevant for the DUT shall be measured.
- Electrical measurements shall always be done at room temperature.
- Electrical measurements can be done either on line (during irradiation) or off line (after irradiation).

Results analysis

- The failure of a component can be either the death of the component or the shift of one or more of its main relevant parameters out of the specified limits or out of the acceptable limits for the targeted application.
- For both component pre-selection and lot qualification, the basic acceptance criterion is zero failure among the entire set of tested components. However, if only one device fails, the rejection or the acceptance of a lot can be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and on the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below RTC_{niel} shall be analysed in order to determine (if possible) the failure mechanism.

Safety

- Irradiation and post-irradiation operations must be made in accordance with the Radiation Safety Rules for Material Irradiation at CERN[12].
- For safety reasons (traceability of irradiated materials, etc.), each ATLAS sub-system shall inform the responsible of radiation safety in ATLAS[13] of each campaign of neutron irradiation of material.
- After neutron irradiation, clearance must be obtained from the health physicists at the test facility before handling irradiated devices.

2. TID test methods:

These test methods are derived from the ESA SCC basic specification no 22900 [2], with several adaptations to take the specificity of ATLAS radiation environment into account. Several methods are proposed to test the tolerance of electronic components to Total Ionising Dose (TID):

TID test method for the *pre-selection*[14] of generic components

- Extended TID test method for pre-selection of CMOS devices;
- Simplified TID test method for pre-selection of CMOS devices;
- Extended TID test method for pre-selection of bipolar devices;
- Simplified TID test method for pre-selection of bipolar devices.

TID test method for the *qualification*[15] of batches

- Extended TID test method for qualification of CMOS batches;
- Simplified TID test method for qualification of CMOS batches;
- Extended TID test method for qualification of bipolar or BiCMOS batches;
- Simplified TID test method for qualification of bipolar or BiCMOS batches.

Extended test methods include experimental low dose rate effect (LDRE) tests which enable one to set $SF_{ldre} = 1$ in RTC_{tid} computations. Simplified test methods replace LDRE testing by setting $SF_{ldre} = 5$ in RTC_{tid} computations.

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[12] These rules can be found in the CERN web site: http://psschedule.web.cern.ch/PSschedule/psinfo/prp17b.pdf.

[13] Shaun Roe, phone +41 22 767 80 54, Email Shaun.Roe@cern.ch

[14] See steps 3 and 4 in sections I.1 and I.2 page 3 and 4.

[15] See steps 3 and 4 in sections I.1 and I.2 page 3 and 4.

2.1. TID test method for the *pre-selection* of generic components:

For both CMOS and bipolar devices, there are two possibilities:

(1) The *safest* solution is to set SF_{ldre} = 1 for RTC_{tid} computation and to apply the *extended* TID test methods summarised below;

(2) The *simplest* solution is to use SF_{ldre} = 5 for RTC_{tid} computation and to apply the *simplified* TID test methods summarised below.

2.1.1. Extended TID test method for the pre-selection of CMOS devices:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for test made on components from homogeneous[16] lot) or 22 good devices (for test made on components from unknown[16] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 1 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step (TID = RTC_{tid}), annealing under bias (168 hours at room temperature) plus electrical measurements (room temperature) at 24 hours and 168 hours; rejection of the generic component if one of the 10 (or 20) components fails;
i/ Accelerated ageing under bias (168 hours at 100 °C);
j/ Electrical measurements at room temperature; rejection of the generic component if one of the 10 (or 20) components fails;
k/ Writing of test results in a standard report document (see appendix 3);
l/ Feed database with test results (see section IV p.5).

2.1.2. Simplified TID test method for the pre-selection of CMOS devices:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for test made on components from homogeneous[16] lot) or 22 good devices (for test made on components from unknown[16] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurement at room temperature on each device;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 5 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step (TID = RTC_{tid}), annealing under bias (168 hours at room temperature) plus electrical measurements (room temperature) at 24 hours and 168 hours; rejection of the *generic component* if one of the 10 (or 20) components fails;
i/ Writing of test results in a standard report document (see appendix 3);
j/ Feed database with test results (see section IV p.5).

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[16] See footnote (8) and (9) in page 18.

2.1.3. Extended TID test method for the pre-selection of bipolar devices:

The main stages of this test method are:

2.1.3.1. Preparation of the test:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of (11+2n) good devices (for test made on components from homogeneous[17] batch) or (22+4n) good devices (for test made on components from unknown[17] batch). The 2n (or 4n) components will be used to determine the worst case temperature which will be set during the final radiation test in order to experimentally represent low dose rate effects (LDRE). The value of n shall be chosen in order to allow an estimation of the worst case temperature with a reasonable accuracy (chose at least n>3).
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurement performed at room temperature on each device;
e/ Random selection of 1 component among the set of (11+2n) devices (or 2 components among the set of (22+4n) devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);

2.1.3.2. Determination of the worse case temperature:

f/ Random selection of 2 devices (for test made on components from homogeneous[17] batch) or 4 devices (for test made on components from unknown[17] batch) among the set of remaining devices;
g/ Irradiation under bias at room temperature of the 2 (or 4) selected devices by steps up to the RTC_{tid} required for the application (use $SF_{ldre} = 1$ to compute RTC_{tid});
h/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*;
i/ Redo (n-1) times the steps e/, f/ and g/, each time with 2 (or 4) new devices heated during irradiation at (n-1) different temperatures comprised between 20°C and 90°C. After each of these e/ + f/ + g/ steps, perform electrical measurements at room temperature on each 2 (or 4) devices. Determine the irradiation temperature that produces the worst radiation damage;

2.1.3.3. Final radiation test:

j/ Irradiation under bias at the worst case temperature (determined in stage i/) of the 10 (or 20) remaining components, in one or several step(s) up to the RTC_{tid} required for the application (set $SF_{ldre} = 1$ to compute RTC_{tid});
k/ Electrical measurements on each irradiated component, at room temperature *within 1 hour after the end of each dose step* . Rejection of the *generic component* if one of the 10 (or 20) components fails;
l/ Writing of test results in a standard report document (see appendix 3);
m/ Feed database with test results (see section IV p.5).

2.1.4. Simplified TID test method for the pre-selection of bipolar devices:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for test made on components from homogeneous[17] batch) or 22 good devices (for test made on components from unknown[17] batch).
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurement performed at room temperature on each device;

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[17] See footnote (8) and (9) in page 18.

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 5 to compute RTC_{tid});
g/ Electrical measurements on each irradiated component, at room temperature *within 1 hour after the end of each dose step* . Rejection of the *generic component* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

2.2. TID test method for the *qualification* of batches:

Here also, for both CMOS and bipolar devices, there are two possibilities:
(1) The *safest* solution is to set SF_{ldre} = 1 for RTC_{tid} computation and to apply the *extended* TID test methods summarised below;
(2) The *simplest* solution is to use SF_{ldre} = 5 for RTC_{tid} computation and to apply the *simplified* TID test methods summarised below.

2.2.1. Extended TID test method for the qualification of CMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[18] lot) or 22 good devices (for qualification of unknown[18] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 1 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step (TID = RTC_{tid}), annealing under bias (24 hours at room temperature);
i/ Accelerated ageing under bias (168 hours at 100 °C);
j/ Electrical measurements at room temperature; rejection *of the lot* if one of the 10 (or 20) components fails;
k/ Writing of test results in a standard report document (see appendix 3);
l/ Feed database with test results (see section IV p.5).

2.2.2. Simplified TID test method for the qualification of CMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[18] lot) or 22 good devices (for qualification of unknown[18] lot);
c Serialisation of all devices (see appendix 2 section 2.3.);
d Electrical measurements on each device at room temperature;

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[18] See footnote (8) and (9) in page 18.

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 5 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step (TID = RTC), annealing under bias (24 hours at room temperature);
i/ Electrical measurements at room temperature; rejection *of the lot* if one of the 10 (or 20) components fails;
j/ Writing of test results in a standard report document (see appendix 3);
k/ Feed database with test results (see section IV p.5).

2.2.3. Extended TID test method for the qualification of bipolar or BiCMOS batches:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[19] lot) or 22 good devices (for qualification of unknown[19] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components *at worst case temperature* (determined during pre-selection tests, see section 2.1.3.) under bias in one or several step(s) up to the RTC_{tid} required for the application (set SF_{ldre} = 1 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection *of the lot* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

2.2.4. Simplified TID test method for the qualification of bipolar or BiCMOS batches:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[19] lot) or 22 good devices (for qualification of unknown[19] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components *at room temperature* under bias in one or several step(s) up to the RTC required for the application (set SF_{ldre} = 5 to compute RTC_{tid});
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection *of the lot* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

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[19] See footnote (8) and (9) in page 18.

2.3. Advice applicable to each TID test methods for components pre-selection or lot qualification:

Preparation of the components to be tested:

- The initial sets of un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[20] and manufacturer code[21] of the sample, and individual identification.

Measurement setup

- Two approaches can be used to perform irradiation and tests:
  a/ Tests made using a dedicated test board: electrical measurement are made on the 11 (or 22) test components using a dedicated test board.
  b/ Tests made using an entire system board: electrical measurement are made on all the components of an entire system board. In this case, the architecture of the board must enable one to check the operation of each of its individual components. The total number of test components having the same part number must be equal or larger than 11 (or 22) as recommended in 1.1.b/. If necessary, this can be obtained by performing irradiation and measurements on additional components (using a dedicated test board), or by testing several system boards.
- In case of on-line measurement, all the necessary precautions shall be taken to obtain an electrical measurement system which, by use of sufficient insulation, ample shielding, satisfactory grounding, etc., shall yield suitably low level of interference from main power supplies and other sources of noise and leakage. The magnitude of interference from each of these items shall be sufficiently small so as not to affect any electrical measurement nor induce any damage on the device under test.
- Only sockets which are radiation-resistant and do not exhibit any significant leakage shall be used to connect devices under test and associated circuitry to the test board. Similar precautions shall be taken with respect of cabling and switching systems. All equipment used repeatedly in radiation fields shall be checked periodically for physical and/or electrical degradation.

Irradiation:

- Two approaches can be used to perform irradiation:
  a/ If the electrical measurements are made using a dedicated test board, the irradiation of the 11 (or 22) test components shall be made on the same test board.
  b/ If the electrical measurements are made using an entire system board, the irradiation shall be performed simultaneously on all the components of the same system board(s).
- TID can be applied either in one or several irradiation steps. In the case of several irradiation steps, it is recommended to chose radiation steps in order to get an approximate linear progression of the cumulated ionising dose in a logarithmic scale (example: 1, 3, 6, 10 , 30, … ; or 1, 4, 10, 40, … ; or 1, 10, 100, …).
- In the case of several irradiation steps, the time interval from the completion of an exposure (i) to the start of the next exposure (i+1) shall be a maximum of 3 hours. If this cannot be achieved, devices shall be irradiated in one step.
- During irradiation, devices must be AC + DC biased using conditions representatives of their regular operation.

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[20] Code of the date of manufacturing of the batch from which the sample is issued.
[21] Code of the manufacturing line from which the sample is issued.

- During irradiation, the temperature must be under control and recorded.
- The devices under test shall be exposed to a radiation constraint at least as high as RTC_{tid}.
- The Total Ionising Dose (TID) applied on the devices under test must be measured using appropriate dosimeters. The dose at the devices under test shall be measured to a resolution of better than 10% and the non-uniformity of the radiation field in the test area shall be a maximum of 10%. The field uniformity shall be verified if the geometry of the test set-up is changed.
- Depending on the RTC_{tid}, the dose rate shall be chosen in such a way that the errors in dose coming from timing errors and initial beam adjustment are kept below 5%. It shall be recorded in the standard test report document.
- The radiation beam shall be perpendicular to the top face of the device under test.

Electrical measurements

- The main AC or DC relevant parameters for the DUT shall be measured.
- Electrical measurements shall always be done at room temperature.
- Electrical measurements can be done either on line (during irradiation) or off line (after irradiation).
- If devices have to be removed from their exposure sockets, then, during transport, the leads must be shorted together, either by insertion in conductive foam or by the use of an appropriate fixture.
- The time interval from the completion of an exposure to the end of the measurement of electrical parameters shall be a maximum of 1 hour.

Results analysis

- The failure of a component can be either the death of the component or the shift of one or more of its main relevant parameters out of the specified limits or out of the acceptable limits for the targeted application.
- For both component pre-selection and lot qualification, the basic acceptance criterion is zero failure among the entire set of tested components. However, if only one device fails, the rejection or the acceptance of a lot can be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and of the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below RTC shall be analysed in order to determine (if possible) the failure mechanism.

3. **Single event effects (SEE) test method:**

In HEP detectors, SEE will be produced by secondary particles resulting of interactions of hadrons with the material constituting the integrated circuits (i.e. the semiconductor chip and the package). These secondary particles have a small range; they are produced inside the semiconductor or inside the package of the integrated circuits in which they will perhaps induce SEEs. SEE tests made using proton or neutron beam involve these mechanisms based on secondary particles; thus they are more representative of actual HEP detectors conditions than SEE tests made using heavy ion beam. Moreover, the only existing models suitable to estimate SEE rate in an accelerator environment are based on SEE tests made with a proton beam [5] or on SEE tests made with a neutron beam [9]. For these reasons, the test methods proposed below to estimate SEE rates in a given ATLAS environment are based on the use of proton beam or of neutron beam.

3.1. Single event effects (SEE) test method based on proton beam for the pre-selection of ICs:

Soft[22] SEE tests can be done with protons having energy equal or higher than 60 MeV. However, as discussed in appendix 1 section 2.2.3, 60 MeV protons are not energetic enough to trig hard[22] or destructive[22] SEEs. Global SEE tests (including soft, hard and destructive SEEs) requires energy ≥ 500 MeV. The test method proposed below is suitable to estimate soft, hard and destructive SEE rates in a given ATLAS environment, depending on the energy of the proton beam. For the estimation of soft SEE rates, the choice of the test beam (60 MeV) and the method for estimating SEE rates are based on advice from [5]. For the estimation of hard or for destructive SEE rates, the choice of the test beam (≥ 500 MeV) and the method for estimating SEE rates are based on the analysis given in appendix 2 section 2.2.3 and on advice from [7].

The main steps of this proton-based SEE test method are:

a/ Selection of a calibrated proton facility suitable to provide a proton beam with a constant energy (60 MeV < E < 200 MeV for soft SEE tests only, 500 MeV < E < 1 GeV for global SEE test including soft, hard and destructive SEEs).
b/ Selection of a set of 4 good devices issued from *several* homogeneous[23] lots, or issued from *one or more* unknown[23] lot;
c/ Serialisation of all devices (see appendix 2 section 3.3.);
d/ Electrical measurements on each device at room temperature;
e/ Irradiation of each Device Under Test (DUT) at a controlled temperature, with a constant proton flux, up to a total fluence large enough to produce a total number of SEEs large enough for relevant statistics.
f/ During irradiation: on line electrical operation and measurement on the 4 devices; on line record of the measurement results;
g/ After irradiation and deactivation: post-irradiation inspection;
h/ Using recorded test results, computation of the soft, hard and destructive SEE rates expected in the targeted application. Comparison of these rates with the RTC_{see} using the relations (1), (2) and (3) given in appendix 1 sections 2.2.2. and 2.2.3. Rejection of the generic component if one or more of the tested components does not satisfy these relations.
i/ Writing of test results in a standard report document (see appendix 3);
j/ Feed database with test results (see section IV p.5).

3.2. Single event effects (SEE) test method based on neutron beam for the pre-selection of ICs:

The test method proposed below is suitable to estimate the rates of *soft* SEE in a given ATLAS environment. It is based on advises from [9]. It requires neutrons having energy tuneable from 5 MeV to at least 25 MeV. However, 25 MeV neutrons are not energetic enough to trig hard[17] or destructive[17] SEEs. Global SEE tests (including soft, hard and destructive SEEs) would require neutrons having an energy ≥ 500 MeV.

The main steps of this neutron-based SEE test method are:

a/ Selection of a calibrated neutron source suitable to provide a neutron beam with a constant energy tuneable from E_{min} = 5 MeV to E_{max} = 25 MeV. This neutron source can be a cyclotron with a proton or a deuteron beam impinging on a Beryllium target and producing neutrons via stripping reactions.

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[22] See definition in appendix 1 section 2.2.1.
[23] See footnote (8) and (9) in page 18.

b/ Selection of a set of 4 good devices issued from *several* homogeneous[24] lots, or issued from *one or more* unknown[24] lot;

c/ Serialisation of all devices (see appendix 2 section 3.3.);

d/ Electrical measurements on each device at room temperature;

e/ Irradiation by steps of each Device Under Test (DUT) at a controlled temperature, with a constant neutron flux having an energy set to E_{test}.
The total number of energy steps (n) must be chosen in order to obtain the required accuracy. For step i, $E_{test} = E_{min} + i \times (E_{max} - E_{min})/n$, with $1 \leq i \leq n$. For each step, the total neutron fluence must be large enough to produce a total number of SEEs large enough for relevant statistics.

f/ During each irradiation step: on line electrical operation and measurement on the 4 devices; on line record of the measurement results;

g/ After the last irradiation step and after deactivation: post-irradiation inspection;

h/ Using test results recorded during each step of neutron irradiation (energy E_{test}), computation of the soft SEE rates expected in the targeted ATLAS application:

- Comparison of the SEE rates measured at each neutron energy E_{test} with the value of the integral I_{BGR} given below, where the $BGR(E_n, E_r)$ curves can be found in [9] and references therein together with differential neutron energy spectrum dN/dEn (for each neutron energy E_{test}).

  $$I_{BGR} = \int_{E_n} BGR(E_{n,} E_r) \times \frac{dN}{dE_n} dE_n$$

  For this comparison, a χ^2 dependence of the recoil energy E_r, in the linear fit of the measured SEE rate versus I_{BGR}, is to be done. The optimal value $E_{r.opt}$ corresponds to the minimum value χ^2_{min}. This optimal value $E_{r.opt}$ gives the optimal integral $I_{BGR.opt}$ that enables one to derive a constant C = measured SEE rate / $I_{BGR.opt}$.
- Computation of the integral $I_{BGR(ATLAS)}$ corresponding to a given location in ATLAS, using the differential neutron energy spectrum expected at this location.
- Computation of the rate of soft SEE expected in the targeted ATLAS application:

  $$\text{Soft } SEU_f = C \times I_{BGR(ATLAS)}$$

i/ Rejection of the generic component if one or more of the tested components does not satisfy the relation (1) prescript in appendix 1 section 2.2.2.

j/ Writing of test results in a standard report document (see appendix 3);

k/ Feed database with test results (see section IV p.5).

3.3. Advice for the SEE test method:

- SEE test method given in 3.1. applies only to the pre-selection of generic components.
- SEE tests are *not required for the qualification of lots* because results of pre-selection SEE tests are supposed to be enough reproducible to make qualification SEE tests unnecessary.

Preparation of the components to be tested:

- The initial sets of 4 un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Deluding of the devices under test (DUT) is not required for SEE tests made with *protons* or *neutrons*. Deluding of the DUTs is mandatory for ion-based SEE tests.

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[24] See footnote (8) and (9) in page 18.

- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[25] and manufacturer code[26] of the sample, and individual identification.

Measurement setup

- Irradiation and measurement shall be made with components on board, either using an actual ATLAS system board, or using a dedicated test board.
- If irradiation and measurements are made using an actual ATLAS system board, the architecture of the system board must enable to run and to measure the DUT.

Irradiation

- A global proton-based SEE test (including soft, hard and destructive SEEs) requires protons with an energy ≥ 500 MeV. However, protons with too high energy (>> 1GeV) could produce a lot of *small fragments* which will have a smaller LET than that of the few bigger fragments produced by 500 MeV – 1 GeV protons. For this reason, it is recommended to perform global SEE tests with protons having an energy comprised between 500 MeV and 1 GeV. Proton beams with an energy higher than 1 GeV can be used for SEE tests, however they must be calibrated before being used. The calibration must be done by comparing the rates of SEE (including destructive SEEs) produced by the proton beam under calibration to the rates of SEE (including destructive SEEs) produced by a proton beam with an energy selected in the range 500 MeV – 1 GeV.
- For the time being, there is no model that allows to estimate SEE rates *in HEP experiments* on the basis of SEE tests made using *heavy ions*. For this reason, it is recommended to use heavy ion tests *only* to identify and then *to reject* generic components which are sensitive to SEE. In this case, the threshold of sensitivity (threshold LET) below which generic components will be rejected must be determined by the ATLAS Sub-systems.
- The proton flux used for SEE tests must be high enough to allow a reasonable duration of the experiment, and low enough to allow an accurate identification of individual SEEs.
- Only the DUT must be irradiated. The other components must be protected from radiation using appropriate shielding.
- If the test is made using an actual ATLAS system board, during irradiation, all the board must be biased and operated in order to run and measure the DUT.
- If irradiation and measurement are made using dedicated test boards, then two methods can be used to operate and measure DUTs during irradiation:
  1/ Sequential operation and measurement of each DUT, one by one, using a dedicated test board. In this case, the other DUTs and the components from the board other than the DUTs (for instance MUXs, etc.) must be protected from radiation using shield or by placing them out of the beam;
  2/ Simultaneous operation and measurement of all the DUTs together using a dedicated test board. In this case, components from the board other than the DUTs must be protected from irradiation using a shield or by placing them out of the beam.
- During irradiation, temperature must be set and maintained at a value close to that foreseen in actual ATLAS operating conditions, and must be recorded.
- During irradiation, DUTs must be AC + DC biased using conditions representatives of those of their regular operation. All the necessary precautions must be taken in order to avoid any damage that could be produced by the measurement system (parasitic electrical pulses).

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[25] Code of the date of manufacturing of the batch from which the sample is issued.
[26] Code of the manufacturing line from which the sample is issued.

- During irradiation, DUTs that die[27] before the targeted total fluence is reached must be replaced by new good devices, then the irradiation must be pursued up to the targeted total fluence.
- If no SEE occurs with a total fluence equal to SRL_{see}, or if the total number of SEEs measured with a total fluence equal to SRL_{see} is too small to provide relevant statistics, then the irradiation must be pursued up to two times SRL_{see}.

Electrical measurements

- During irradiation, digital circuits must be automatically and periodically written and read (search for temporary or permanent bit errors); analogue circuits must be automatically and continuously read (search for parasitic transient pulses), and power consumption must be automatically and continuously measured on both analogue and digital circuits (search for SEL, SEGR or SEB);
- During irradiation, all measurements must be automatically recorded on line.

Results analysis

- The failure of a component can be either the death of the component (destructive SEE) or a rate of soft or hard SEEs higher than the acceptable limits (RTC_{see}) for the targeted application.
- The basic acceptance criterion is zero failure among the set of 4 tested components. However, if only one device fails, the rejection or the acceptance of a generic component shall be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and of the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below RTC_{see} must be analysed in order to determine (if possible) the failure mechanism.
- Components that are sensitive to *destructive* SEEs shall not be used in ATLAS unless a proven robust architectural solution protects the system against thermal destruction.

Safety

- Irradiation and post-irradiation operations must be made in accordance with the Radiation Safety Rules for Material Irradiation at CERN[28].
- For safety reasons (traceability of irradiated materials, etc.), each ATLAS sub-system shall inform the responsible of radiation safety in ATLAS[29] of each campaign of irradiation of material.
- After irradiation, clearance must be obtained from the health physicists at the test facility before handling irradiated devices.

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[27] The death of these devices could result from the TID, from the NIEL, from destructive SEEs or from parasitic electrical pulses.

[28] These rules can be found in the CERN web site: http://psschedule.web.cern.ch/PSschedule/psinfo/prp17b.pdf.

[29] Shaun Roe, phone +41 22 767 80 54, Email Shaun.Roe@cern.ch