Radiation effects on ITER electronics

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1. Introduction

The ITER plant systems will contain a large amount of electronic, electrical, and electromechanical (EEE) parts. Many of these parts will be, by necessity, exposed to the nuclear radiation field of the Tokamak Complex, and can be negatively affected by this environment condition [1, 2]. Nuclear radiation can damage or destroy electronic devices or sensors, corrupt signals in analogue or digital circuits, corrupt data in memories, etc. In ITER, these effects can appear progressively, due to accumulated ionization or accumulated atomic displacements, or instantaneously, due to a single neutron (the so-called Single Event Effects or SEE). Nuclear radiation can also progressively damage electrical and electromechanical equipment, mostly by accumulated ionizing dose and/or accumulated neutron fluence on the materials of their parts, causing e.g. (i) radiation induced embrittlement of organic materials, (ii) viscosity changes in oils and greases, (iii) radiation induced electrical degradation in organic electrical insulators. Additionally, nuclear radiation can progressively damage optical fibres and optical parts, mostly by accumulated ionizing dose and/or accumulated neutron fluence, causing e.g. (i) radiation-induced light absorption and/or light emission (luminescence) in transmission optical materials (e.g. lenses, windows, optical fibres), and (ii) radiation-induced erosion and impurity deposition on the surface of optical parts exposed to plasma (e.g. lenses, mirrors, windows).

2. Radiation Effects on ITER electronic devices

Radiation effects that are important to be considered for electronics fall roughly into three categories: degradation from TID, degradation from ENF, and SEE.

Degradation from TID in electronics is a cumulative, progressive degradation mechanism due to ionizing radiation – in ITER, mainly gamma from the plasma and from activated cooling water. It causes threshold shifts, leakage current and timing skews. The effect first appears as parametric degradation of the device and ultimately results in functional failure of the part containing the device. When a manufacturer advertises a device as “rad-hard”, they are almost always referring to its total ionizing dose characteristics. Rad-hard does not usually imply that the device is hard to displacement damages or single event effects caused by neutrons. In some cases, a “rad-hard” device can perform significantly worse in the ITER radiation environment if unrepresentative irradiation tests were performed by the manufacturer in the qualification process (e.g. Enhanced Low Dose Rate Sensitivity in linear bipolar devices).

Ionization induces trapped positive charges (1) in thick oxide at gate oxide extremities. These charges attract a layer of electrons (2) under the oxide. At both gate extremities, this layer of electrons constitutes a parasitic channel which allows a permanent parasitic current (3) to flow from source to drain.

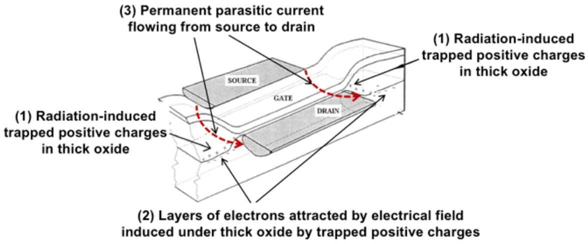


Figure 1 Leakage current induced by TID in NMOS device.

Degradation from ENF or displacement damage is cumulative, progressive non-ionizing damage due to neutrons in ITER. Neutrons produce defects mainly in optoelectronics devices such as APS, CCDs, LEDs, laser diodes, photodiodes, phototransistors and optocouplers. Displacement damage also affects the performance of linear bipolar devices. For semiconductor detectors in diagnostics, it is necessary to understand the detector technology and geometry to determine its vulnerability to the radiation environment.

SEEs result from ionization by a single charged particle as it passes through a sensitive junction of an electronic device. SEEs in ITER are caused by neutrons. Neutron induced effects result from ionized secondary particles created by nuclear reaction of the incident neutron with device’s atoms (including doping atoms, e.g. boron), or created when the incident neutron scatters off of a nucleus in the device material. Some SEEs are non-destructive, as in the case of SEU (Single-Event Upset), SET (Single-Event Transient), MCU (Multiple-Cell Upset), and SEFI (Single-Event Failure Interrupt). Single event effects can also be destructive as in the case of single event SEL (Single- Event Latch up), SEGR (Single-Event Gate Rupture), SEDR (Single Event Dielectric Rupture) and SEB (Single-Event Burnout). The severity of the effect can range from noisy data to functional failure, depending on the type of effect. The preferred method for dealing with destructive failures is to use SEE-hard semiconductor devices. When SEE-hard devices are not available, latch-up protection circuitry is sometimes used in conjunction with failure mode analysis (note: care is necessary when using SEL protection circuitry, because SEL can damage a microcircuit and reduce its reliability even when it does not cause outright failure). For non-destructive effects, mitigation takes the form of, for example, error-detection and correction codes (EDAC), and filtering circuitry.

Single Event Gate Rupture (SEGR) induced by a single neutron happens from as follows;

A single neutron induces a nuclear reaction (e.g. on a boron doping atom in Si);

This creates a highly ionizing particle (e.g. Li^+);

This highly ionizing particle crosses the gate oxide and the N layer, where it creates a dense plasma of electron-hole pairs.

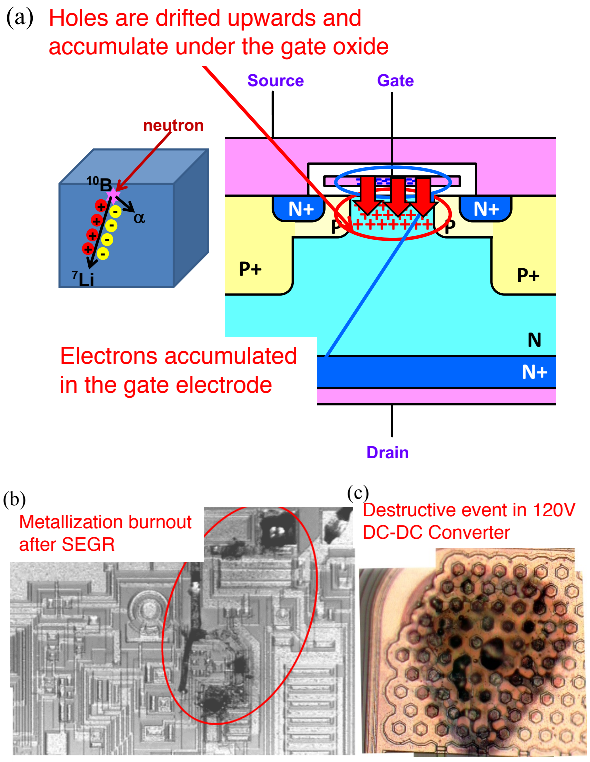
In OFF mode, the high electrical field in the N layer separates the electron-hole pairs.

Holes are drifted upwards and accumulate under the gate oxide.

These holes with their counterpart of electrons accumulated in the gate electrode,

create a high electrical field in the gate oxide, which causes the oxide breakdown.

This causes an instantaneous high current which result in the burnout of the power MOS.



Lum, et al., IEEE TNS 51 3263 (2004)

Figure 2 Single Event Burnout in power MOS.

Knowledge of devices radiation sensitivity is an essential part of the overall RHA program. For the total dose environment, the damage is caused by the ionization energy absorbed by the sensitive materials, measured in rad or in gray (1 gray = 100 rad). This implies that a number of ionization sources can be used for simulation of radiation environment. However, the total dose response is also a strong function of the dose rate. Displacement damage can be simulated for any particle by using the value of ENF. This implies that the effects of the displacement are to a first approximation, only proportional to the total energy loss through displacements and not dependant on the nature of the displacements. The neutron environment, since the SEEs result primarily from secondary particles resulting from the interaction of neutrons with device's atoms, is usually simulated with neutrons of the appropriate energy.

3. Radiation Effects on ITER electronic circuits

The radiation effects on electronic circuits (PCB) and electronic integrated circuits result from the radiation effects on their elementary constituents (transistors, diodes, ...), and depend on their design.

a) Examples of accumulated radiation effects on digital circuits are switching speed decrease, static and dynamic consumption increase, no operation induced by no switching, or by loss of precharge (dynamic logic), and so on.

b) Examples of accumulated radiation effects on analogue circuits (Δ stands for "change") are amplifiers: Δ DC bias; Δ gain; Δ GBW product; Δ offset; Δ noise; Δ slew rate; instabilities, comparators: Δ precision; Δ sensitivity; Δ speed, current mirrors: Δ precision, switches: Δ speed, Δ allowed Vin, current leakages, and so on.

c) Examples of single event effects on digital circuits are non-destructive effects such as SEU, SET, MCU and SEFI, destructive effects such as SEL, SEGR and SEB.

d) Examples of single event effects on power circuits are destructive effects such as SEGR and SEB.

e) Other examples of radiation effects on electronic circuits are recoverable or unrecoverable failures, transient or permanent errors, and so on.

4. Requirements and Architecture in ITER electronics

4.1 Identification of EEE functions

For each module, all EEE functions to be installed and/or operated in a radiation environment in ITER tokamak building, hot cell building, radwaste building, tritium building or diagnostic building are identified in the Conceptual Module's Architecture.

For electronic functions, this includes "independent" electronic functions (identified by their own functional reference in functional diagrams) as well as "dependent" electronic functions (identified in functional diagrams by the functional reference of the component where it is embedded, e.g. electronics embedded in a pump or in a valve ...).

4.2 Determination of the individual unmitigated radiation conditions

During the ITER life cycle, each physical item will have one or several successive locations in ITER (e.g. operation location, shutdown location, storage location, maintenance location ...).

For each individual EEE function, the ITER reference radiation data (ref. [3]) must be used to define a set of individual unmitigated radiation conditions (see below), taking into account the future locations and duration of radiation exposure of the physical item assigned to the function, at each phase of the ITER life cycle:

- Individual unmitigated radiation conditions relevant for all EEE functions:

a. Integrated individual unmitigated Total Ionizing Dose (in Gray) accumulated during all periods where the physical item assigned to the EEE function will be exposed to radiation (powered and not powered) during its full life cycle;

b. Integrated individual unmitigated Equivalent Neutron Fluence (in 1 MeV Si-equivalent neutron.cm^{-2}) accumulated during all periods where the physical item assigned to the EEE function will be exposed to neutron flux (powered and not powered) during the full ITER life cycle.

- Individual unmitigated radiation condition relevant for electronic items only:

c. Instantaneous individual unmitigated Total Neutron Flux (in neutron·cm^{-2}·s^{-1}) to which the physical item assigned to the electronic function will be exposed when powered during its full life cycle. This must be the worst case unmitigated total neutron flux to which the physical item will be exposed when powered during its full life cycle.

4.3 Determination of the collective unmitigated radiation conditions

Groups of EEE functions having similar functional requirements must be identified.

Sub-groups of EEE functions having both similar functional requirements and similar radiation and temperature environmental conditions must be identified.

To prevent duplication of efforts and to reduce procurement costs, whenever possible and appropriate, EEE functions should be standardized. Therefore, within each sub-group of EEE functions:

1) all sets of individual functional requirements must be replaced by a unique set of collective functional requirements applicable to all the EEE functions of the sub-group;

2) all individual temperature requirements must be replaced by a unique set of collective temperature requirements applicable to all the EEE functions of the sub-group.

3) all sets of individual unmitigated radiation conditions must be replaced by a unique set of collective unmitigated radiation conditions based on the worst case individual unmitigated radiation conditions of the EEE functions of the sub-group (see below):

- Collective unmitigated radiation conditions relevant for all EEE items:

a. Integrated collective unmitigated Total Ionizing Dose (in Gray) = worst case among all the integrated individual unmitigated Total Ionizing Doses of all the EEE functions of the sub-group;

b. Integrated collective unmitigated Equivalent Neutron Fluence (in 1 MeV Si-equivalent neutron·cm^{-2}) = worst case among all the integrated individual unmitigated equivalent neutron fluences of all the EEE functions of the sub- group;

- Collective unmitigated radiation condition relevant for electronic items only:

c. Instantaneous collective unmitigated Total Neutron Flux (in neutron·cm^{-2}·s^{-1}) = worst case among all the instantaneous individual unmitigated total neutron flux of all the electronic functions of the sub-group.

4.4 Alert thresholds on radiation environment for ITER EEE items

4.4.1 Alert thresholds on radiation environment for Electronic items

Table 1 below gives the ITER alert thresholds on nuclear radiation conditions for electronics. Countermeasures are required when one (or several) collective unmitigated radiation condition(s) is(are) above these alert thresholds. TNF alert threshold is justified in ref. [4].

Table 1 Alert thresholds on radiation environment for electronics.

Function	**TID:** **Total Ionizing Dos (Gray Si)**	**EFE (Si):** **Equiv. Neutron Fluence (1 MeV Si eq·n·cm-^{2})**	**TNF:** **Total Neutron Flux (n·cm^{-2}·S^{-1})**
Critical electronic function	1	1E18	1E-2
Non-critical electronic function	10	1E10	1E2

4.4.2 Alert thresholds on radiation environment for optical fibres

Table 2 gives the ITER alert thresholds on nuclear radiation conditions for optical fibres which may be associated with EEE. The scope of this table is limited to radiation-induced attenuation (RIA) only, for optical fibres used for digital data transfer at the following Telecom wavelengths: 1310 nm and 1550 nm.

Table 2 alert thresholds on nuclear radiation conditions for optical fibres.

Part	**TID:** **Total Ionizing Dos (Gray Si)**	**EFE (Si):** **Equiv. Neutron Fluence (1 MeV Si eq·n·cm-^{2})**	**TNF:** **Total Neutron Flux (n·cm^{-2}·S^{-1})**
Radiation hardened pure-silica core or F-doped core optical fiber for critical electronic data transmission function	100	1E13 (eq dose < 1Gy@1MeV)	N.A.

COTS Telecom-grade (phosphorus-free) optical fibre for critical electronic data transmission function	10	1E13 (eq dose < 1Gy@1MeV)	N.A.
Radiation hardened pure-silica core or F-doped core optical fibre for non-critical electronic data transmission function	1000	1E13 (eq dose < 1Gy@1MeV)	N.A.
COTS Telecom-grade (phosphorus free) optical fibre for non-critical electronic data transmission function	100	1E13 (eq dose < 1Gy@1MeV)	N.A.

The thresholds provided in this table are the radiation conditions above which there is a risk of radiation-induced attenuation RIA ≥ 3 dB per 100 meters of optical fibre.

These thresholds must be used to determine if the global attenuation A of the optical link complies with the maximum attenuation $Amax$ allowed for the optical link, i.e. if the following condition on the optical link global attenuation is satisfied:

$$A(dB) = \sum_i IL_i(dB) + \sum_j \left[\left(\frac{TID_j}{TID_{th}}\right) + \left(\frac{ENF_j}{ENF_{th}}\right)\right] \times 0.03dB \leq A_{max}(dB)$$

Where
$A(dB)$ is the global attenuation of the optical link;
$A_{max}(dB)$ is the maximum attenuation allowed for the optical link;
i is an index which identifies the optical connectors installed on the optical link.
j is an index which identifies the segments of the optical fibre: each segment j is a 1- meter long portion of the fibre, starting at distance j meters from the fibre extremity identified as origin (coordinate = 0);
$IL_i(dB)$ is the insertion loss of the optical connector i;
TID_j is the worst case TID to which the segment j of the fibre is exposed;
TID_{th} is the alert threshold on TID specified in table 2;
ENF_j is the worst case ENF to which the segment j of the fibre is exposed;
ENF_{th} is the alert threshold on ENF specified in table 2.

Countermeasures are required when the above condition on the optical link global attenuation is not satisfied.

Deeper vulnerability analysis is required for profile of use outside the scope of this table, such as fibre-based diagnostics or fibre-based sensing (punctual or distributed sensors). For such applications, fibres containing phosphorus in their core and/or cladding are forbidden.

4.4.3 Alert thresholds on radiation environment for Electronic items

Table 3 gives the ITER alert thresholds on nuclear radiation conditions for optical lenses and windows which may be associated with EEE.

Table 3 Alert thresholds on nuclear radiation conditions for optical lenses and windows.

Part	**TID:** Total Ionizing Dose (Gray Si) to risk 3 dB RIA over 1cm thickness (500-800nm)	**ENF (Si):** Equiv. Neutron Fluence (1 MeV Si eq· n·cm^{-2})	**TNF:** Total Neutron Flux (n·cm^{-2}·s^{-1})
COTS radiation hard optical glass for critical EEE function	1 kGy	1E12	N.A.
COTS standard optical glass for critical EEE function	0.1 Gy	1E9	N.A.
COTS radiation hard optical glass for non-critical EEE function	10 kGy	1E13	N.A.
COTS standard optical glass for non-critical EEE function	1 Gy	1E10	N.A.

4.4.4 Alert thresholds on radiation environment for E&E items

Table 4 below gives the ITER alert thresholds on nuclear radiation conditions for E&E items without electronics and without optical parts, installed outside B11 bioshield.

Table 4 Alert thresholds on nuclear radiation conditions for E&E items without semiconductors.

Function	Material embedded in the function	TID[a]: Total Ionizing Dose (Gray)	Neutron fluence	Neutron flux
Critical E&E function without semi-conductor	Metal	N.A.	N.A.[b]	N.A.
	Mineral oil lubricants	1E5	N.A.[b]	N.A.
	Organic material other than optical material	1E2	N.A.[b]	N.A.
	Non-organic electrical insulator	N.A.	N.A.[b]	N.A.
	Any material other than the above and other than optical material	1E5	N.A.[b]	N.A.
Non- critical E&E function without semi-conductor	Metal	N.A.	N.A.[b]	N.A.
	Mineral oil lubricants	1E6	N.A.[b]	N.A.
	Organic material other than optical material	2E2	N.A.[b]	N.A.
	Non-organic electrical insulator	N.A.	N.A.[b]	N.A.
	Any material other than the above and other than optical material	1E6	N.A.[b]	N.A.

(a) TID includes ionizing dose from gamma and from neutrons.
(b) Neutron-induced displacement damages effects outside the bioshield area are negligible, and neutron induced ionization effects are included in TID.

5. Conclusions

The purpose of this paper is to manage the risks of degradation and failure of systems induced by nuclear radiation effects on their EEE constituents, by ensuring their Nuclear Radiation Compatibility (NRC). Therefore, define the overall workflow and main tasks to performed to ensure EEE NRC, and identifies their main inputs and outputs. We also define EEE NRC rules, requirements and applicable standards, specifies the phasing of EEE NRC tasks and summarized the EEE NRC.

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