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DEVELOPMENT AND EVALUATION OF AN ALTERNATIVE SENSOR LIFETIME ENHANCEMENT TECHNIQUE USED WITH THE ONLINE-RADIATION-MONITORING SYSTEM (DosiMon) AT THE EUROPEAN XFEL AT DESY, HAMBURG

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Abstract

The European XFEL (E-XFEL), that started operation in September 2017 at the DESY/XFEL site in Hamburg/Germany uses a single-tunnel concept, forcing all frontend machine devices and electronics to be located inside the accelerator tunnel. Electro-magnetic showers, mainly produced by gun dark-current, RF cavity field-emission and beam-losses expose these devices to damaging irradiation. The new Online-Radiation-Monitoring-System (DosiMon) is mainly used for surveillance of radiation sensitive permanent magnet structures, diagnostic devices and rack-housed electronics. The integrated dose from Gamma- and optional future Neutron-radiation measurements can be monitored online by the DosiMon system. Safety limits ensure the correct function of monitored devices, provided by lifecycle estimations as measures for on time part exchange, to prevent significant radiation damage. A first expansion state currently enables more than 500 gamma measuring points. The development of a new sensor lifetime enhancement technique for the utilized RadFet sensors is presented together with corresponding evaluation measurements.

INTRODUCTION

The European XFEL located between the DESY campus at Hamburg and Schenefeld at Schleswig-Holstein [1,2], has been in operation since 2017, providing high duty cycle, ultra-short and extreme brilliant X-Ray beams at wavelengths about 0.5 Å. Up to 27000 pulses per second are possible due to the super conducting 17.5 GeV linac, provided by an electron beam with the corresponding time structure. The beam can be distributed into 3 undulator sections of about 200 m length, which consist of 21 to 35 undulators each. The installation of all parts including the electronics was chosen to be inside of a single tunnel system due to the overall length of the facility of about 3.4 km located in the city area of Hamburg. The environmental conditions of the single tunnel installation made it necessary, to control beam losses and radiation damage. Hence a new Embedded Radiation-Monitor-System (DosiMon) had been developed for measurement of γ-radiation at various appropriate electronics-internal and rack-external measurement points and dose levels.

The DosiMon-System uses several different sensors to ensure safe and reliable γ-radiation measurement at hundreds of measurement points, distributed along the E-XFEL. While RadFet-type solid-state radiation sensors are used for online measurement of γ-radiation [3], well-known TLD (Thermo Luminescent Detector) sensors are used to provide sporadic reference measurements of accumulated γ-dose for comparison, cross-reference and -calibration checks.

Motivation

The fingertip-sized, online-readable RadFet-type RFT-300-CC10G1 sensors from REM Oxford Ltd. [4] have been successfully used in the original version (here called pre-series version) of the DosiMon system since the first orientational measurements and have consequently been selected as appropriate γ-radiation sensors for series production [5]. The sensor principle and key parameters are described in [4,6]. After some minor manufacturing and application issues were found during the implementation phase of pre-series devices, the RadFets were redesigned in close collaboration between DESY and the supplier company REM, to form the newest RadFet series version currently in widespread use at the E-XFEL. The demanding number of E-XFEL testpoints in combination with upcoming new accelerator projects with hight demands on testpoint numbers shift a re-use of RadFets into focus. In 2016, the manufacturing company went out of business, so that further delivery of these RadFets tends to become more difficult in the future. Based on estimations and simulations for upcoming electromagnetic shower production at different testpoints along the E-XFEL, several generations of RadFet sensors have initially been purchased according to lifetime estimations.

On the other hand, the RadFet-supplier REM Oxford Ltd. recommended not to refurbish used (i. e. pre-irradiated) RadFets due to functional chip degradation, induced by the necessary heat-up process for the reduction of stored charge [7]. Early tests at the manufacturer with re-configuration temperatures around 250 °C had functionally destroyed the RadFet device.

Refurbishment

Figure 1: Climate cabinet with dose measurement setup.

Series refurbishment of REM RadFets needs a specified tempering procedure, to carefully and safely remove the stored charge from an irradiated RadFet, obtaining a fresh device afterwards without any stored dose information or other irreversible structural or functional changes (Figure 1).

While changes by mechanical or electrical influences (e. g. handling, ESD) is covered by normal operational risk, specific damages of a pre-irradiated RadFet through tempering can in principle be comprised from any combination of the following points, which were specifically considered during the development of the refurbishment process:

1. De-calibration or damage at any of the two dose source channels A or B by the tempering process (heat).
2. De-calibration or damage of the diode-channel by irradiation and/or
3. Mechanical damage at any material inside the RadFet (RadFet-chip, covering material (glob), electrical connections (weldings, bonding-wires), PCB) and/or material connections.

The main goal of an appropriate refurbishment process is to achieve, that all formerly pre-irradiated REM RadFets behave after tempering like a typical new, un-irradiated RadFet and show the following initial functionality as needed by the E-XFEL, depending on their mode of operation:

- high-bias (18V) mode: linear sensitivity approx. 5,639 Gy/V, initial resolution approx. 25 mGy, dynamic upper dose limit > 120 Gy, source channel integrated linearity < 4% and an initial un-irradiated on-chip diode,
- zero-bias mode (0V) mode: non-linear initial corrected resolution of approx. 100 mGy and corrected dynamic upper dose limit of > 4 kGy and an initial un-irradiated on-chip diode.

Several items provisions have to be considered to enable refurbishment of a pre-irradiated RadFet for E-XFEL use:

- refurbished RadFets underlie the functional specifications shown above,
- refurbished RadFets must retain their properties at least for an operational lifespan as specified for a new RadFet,
- refurbished RadFets must not show any visual mechanical damage or disorder due to thermal stress over their typical operational lifetime,
- an appropriate refurbishing procedure for a RadFet must be as gentle as possible to ensure proper functionality as specified above, at minimum time and cost without rejects.

In a first investigation phase, highly pre-irradiated zero-bias RadFets have undergone a simple single-phase 150°C tempering procedure without online-readout control, before they were long-term irradiated again together with other reference sensors in a special test setup at the FLASH linear accelerator at DESY, Hamburg.

In a second investigation phase, six other, differently pre-irradiated RadFets from the E-XFEL SASE sections were chosen for stress tests. Five of them were tempered by a common versatile procedure with online-readout control, being stopped after different, RadFet-specific times each, to gain pre-irradiation-related tempering intervals at maximum thermal stress to the RadFet material.

A third investigation phase was introduced to implement and test a resulting single-phase, medium-time pre-series tempering-procedure using online-readout control. A resulting series tempering procedure will be defined in this paper for mass-refurbishment of REM RadFets, resulting in an implementation phase 4. All these phases will be described together with evaluation measurements in detail in the following chapters.

PHASE 1

In phase 1, two RadFets (RF23, RF24) have been irradiated in zero-bias mode to high accumulated dose levels near the upper dynamic dose limit (RF23: 3.3 kGy, RF24: 4.8 kGy), using the 450 MeV radiation shower produced by the e+/e- tungsten target at the LINAC II pre-accelerator at DESY in 2011. These pre-irradiated RadFets have been stored for fade-out over 4 years, before they were tempered in a climate cabinet over 75 hours at 150 °C (rel. humidity < 5 %) in August 2015. The tempered RadFets have been applied directly afterwards to an accelerator-based long-term measurement setup at FLASH [5], together with two new RadFets and corresponding TLD-100 reference sensors each, completed by an online-readable Pandora radiation sensor [8] (see Figure 2). One of the RadFets (RF23) is located upon the roof of the RF-GUN rack, below the ACC1 acceleration cryo-module, while the other (RF24) is located downstream behind the RF-GUN rack near the Pandora location. Initial measurements in 2012 had shown comparable results between these RadFets and the Pandora [5].

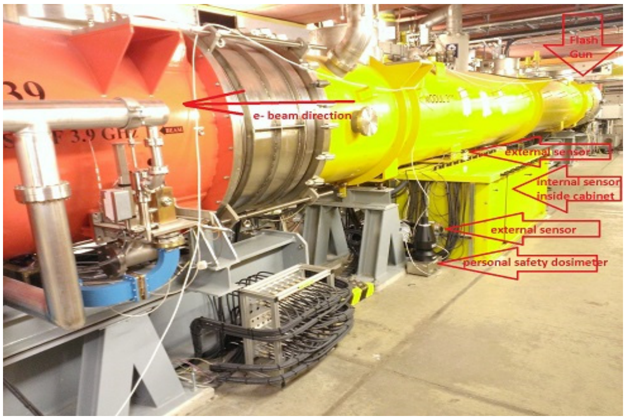

Figure 2: Flash RF-gun rack DosiMon system setup [5].

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Both tempered RadFets (RF23, RF24) have shown good dose measurement functionality over the last 4 years (still ongoing) at the 18 V high-bias measurement setups, while the on-chip diodes showed degradation due to the high pre-irradiation levels. The tempered RadFets delivered reasonable initial offset voltages, reasonable sensitivity deviation of approx. +/- 4% between tempered and corresponding new RadFet, as well as between both source channels at the tempered and the new RadFets each. High-bias setups have been selected to maximize the sensitivity of the measurements for RadFet parameter deviations compared to the specified properties (see above). Progress of accumulated γ-dose over the last two years show good correlation between the new RadFets and the corresponding tempered ones at both locations (RF23: -3.79% see Figure 3, RF24: +5,21% not shown).

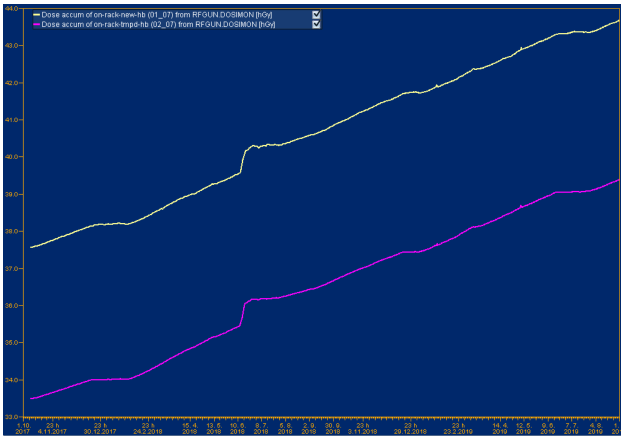

Figure 3: Synchronism of accumulated dose between tempered (RF23, magenta) and new RadFet (yellow) over two years, (offset unadjusted; dose in [Gy]).

PHASE 2 (RUN 1 – 5)

Six further RadFets have been selected for phases 2 and 3, all pre-irradiated in zero-bias mode at the E-XFEL diagnostic undulators at all SASE sections to high accumulated dose levels over a wide dose range up to the dose upper dynamic limit. Accumulated dose levels spanned a range from approximately 100 Gy to 4.5 kGy in zero-bias mode. Five of them were tempered in phase 2 at corresponding run numbers 1-5 in a common versatile procedure with online-readout control, as shown in Figure 4.

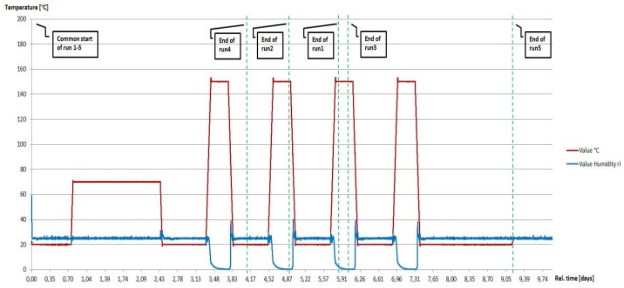

Figure 4: Common refurbishment climate profile of phase 2/runs 1-5 with run-end markers, (temperature = red, rel. humidity = blue, run-end markers = green).

Different run lengths had been selected during the temper operation to be able to cope with any RadFet, that might have been damaged throughout the tempering evaluation process, according to different pre-irradiation levels. The different run-end markers show the end of each specific tempering run in the diagram, producing different tempering intervals at maximum thermal stress to the RadFet material as desired for tempering validation. Figure 5 demonstrates the RadFet source channel progress at phase2, run 5. The on-chip diode channel on the bottom shows the relation to the process temperature in inverse and scaled representation. Strong fading is clearly visible in the high temperature sections.

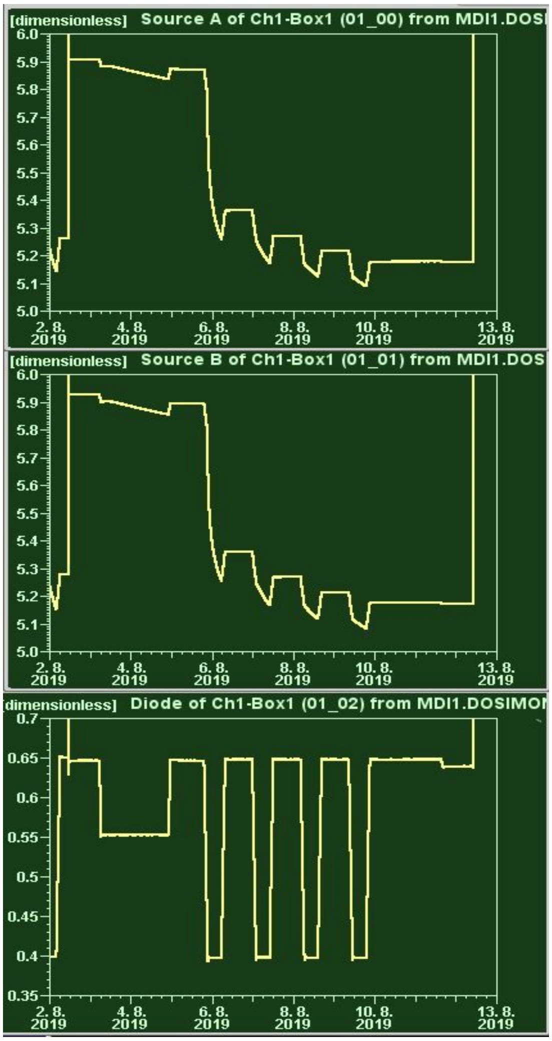

Figure 5: RadFet source channels A & B progress at phase 2, run5 versa on-chip diode voltage [V] (~ x-T[K]).

PHASE 3 (RUN 6)

A third phase was introduced to implement and test a resulting single-phase, medium-length tempering-procedure using online-readout control. The following Figure 6 shows the typical common tempering diagram used at phase 1, phase 3 (run 6) and phase 4.

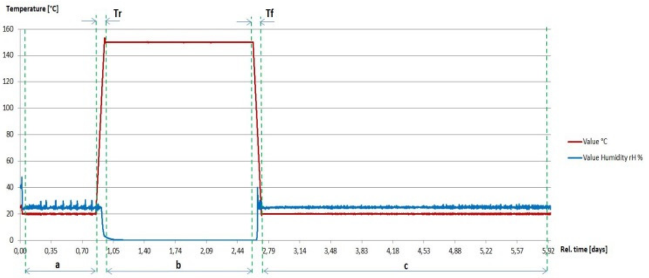

Figure 6: Common refurbishment climate profile of phase 1, phase 3 (run 6) and phase 4 (temperature = red, rel. humidity = blue, section markers = green).

Sections a (20 h) and c (48 h) were intentionally long, to ease recognition of potential residual fading at the environmental temperature range (20°C) before and after the tempering. No fading was detected though on the newly measured offset voltage level at the end of the tempering process as depicted in Figure 7.

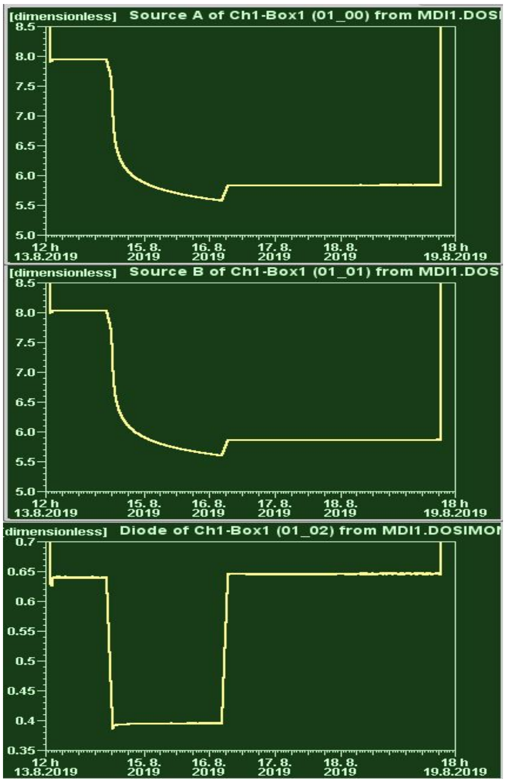

Figure 7: RadFet source channels A & B progress at phase 3, run6 versa on-chip diode voltage [V] (~ x-T[K]).

The mechanical integrity of each tempered RadFet has been investigated visually using a digital microscope (Keyence 'VH-Z20UR', objective magnification factor: 20). The phase 1 RadFets could not yet be investigated due to ongoing operation at FLASH. No suspicious mechanical fissures, scars or surface deformations could be found at any of the 6 tempered RadFets from phase 2 and 3. Only a slight color change had been observed at all PCB surfaces as shown in Figure 8, without any mechanical or structural damage potential.

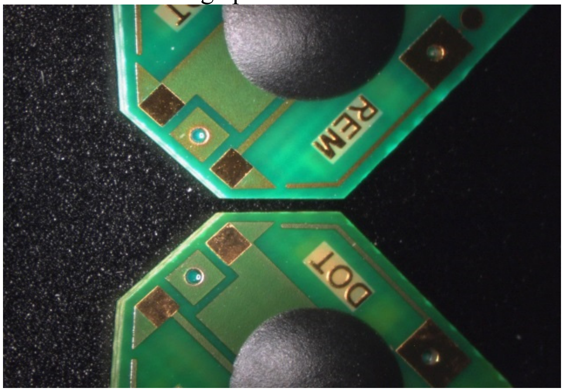

Figure 8: comparison between new (upper) and tempered (run 5; lower) RadFets (detail view).

PHASE 4 (RECOMMENDATION)

As a result of the tests and measurements described above, a series tempering procedure has been defined as a recommendation for mass-refurbishment of REM RadFets for the E-XFEL. Figure 6 shows the principle tempering procedure of phase 4 with a = 1 h, b = 75 h and c = 1 h. In difference to phase 4, the rudimentary phase 1 did not define any fadeout sections (a = 0 h, c = 0 h) before and after the heating section b (75 h). Online readout has not been done in phase 1 and is also not foreseen in phase 4 to speed up the series refurbishment and save thermal-sensitive material (cables, sensor holders), as phase 2, run 1-6 measurements have proven minimum residual RadFet charge after the tempering phase.

CONCLUSION

The prerequisites and conditions for mass refurbishment of XFEL RadFets (REM) have been defined. Different tempering procedures and corresponding measurements have been set up, to enable validation of the RadFet properties after a tempering process. Long-term measurements were conducted at the FLASH accelerator at DESY for successful validation of the correct functionality of refurbished RadFets. As shown by visual inspection, the RadFets do not suffer thermo-mechanically by the temper process. A series refurbishment procedure was specified, to enable mass RadFet refurbishment with minimum effort (setup, material, cost, time) and high throughput. The RadFet on-chip diodes were found to suffer irreversible from strong irradiation even after tempering. As only RadFets with high pre-irradiation dose levels near the upper dynamic limit will typically be refurbished, it is recommended, that tempered zero-bias RadFets should only be used in the same mode as before the tempering process, to inhibit precision temperature-correction by degraded on-chip diodes in a high-bias measurement. Reusing a high-bias RadFet after tempering is not restricted to any specific operation mode.

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