RADIATION DAMAGES AND CHARACTERIZATION IN THE SOLEIL STORAGE RING

N. Hubert#, N. Béchu, P. Brunelle, L. Cassinari, C. Herbeaux, S. Hustache, J-F. Lamarre, P. Lebasque, F. Marteau, A. Nadji, L. S. Nadolski, Synchrotron SOLEIL, Gif-sur-Yvette, France

Abstract

After six years of operation, equipment located close to some vacuum chambers of the SOLEIL storage ring show unexpected damages due to radiation. It has been pointed out that, inside the so called "quadrupole" vacuum chambers, fluorescence X-rays are emitted by the materials that intercept upstream dipole synchrotron radiation. The energy of the emitted X-ray is too high to be significantly attenuated by the aluminium of which the vacuum chamber is made. Diagnostics and means used to characterize this radiation are presented, and measurements are compared to calculations.

INTRODUCTION

SOLEIL, the French 2.75 GeV third generation synchrotron light source is delivering photons to users since January 2007. 26 beamlines have been taking beam and 3 new ones are under construction [1]. Primary operation mode is 430 mA with hybrid filling pattern and top-up injection.

Premature radiation induced damages in some equipment of the storage ring that could affect the machine reliability have been detected and required investigation to understand their origin. For that purpose dedicated diagnostics have been used, and first remedies established.

EQUIPMENT DAMAGES

Description

After six years of operation, damages have been detected in some of the SOLEIL storage ring equipment. Plastics, cable insulators or glues are the most affected materials and their conditions are characteristic of radiation damages: loss of flexibility, brittle… For example, the following equipment items are affected:

- Insulator of some sextupole cables (Fig. 1)

Figure 1: Insulating layer of some sextupole magnets has become brittle due to radiation.

#nicolas.hubert@synchrotron-soleil.fr

- Insulator of some corrector cables
- Insulator of some Beam Position Monitor (BPM) cables
- Glue between some of the baking out film layers (Fig. 2)

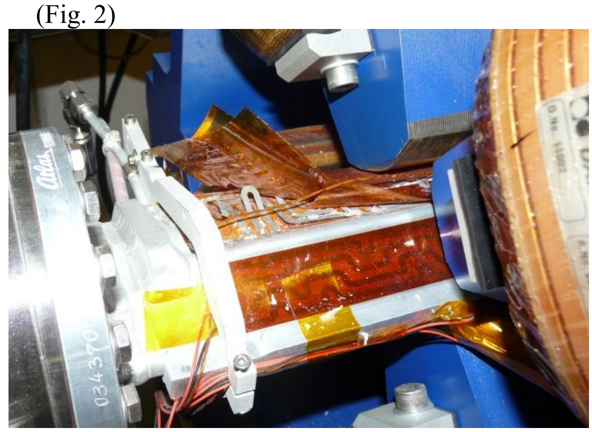

Figure 2: Glue that sticks together different kapton foils of some baking out films is damaged by radiation.

Location

All damages are located in the vicinity of given so-called "quadrupole vacuum chamber (VC)" in the arc sections of all the 16 cells of the storage ring. Moreover, damages are always located downstream a dipole magnet, each cell having 2 of them (Fig. 3). Equipment located elsewhere in the straight sections, before the first dipole magnet or even around the dipole VC (around the crotch and the longitudinal absorber), is in perfect condition.

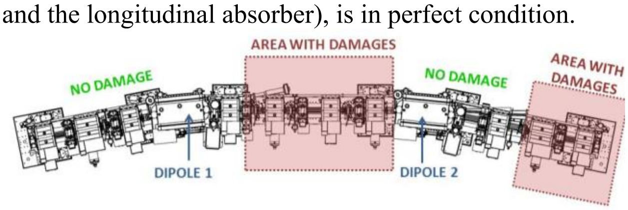

Figure 3: Example of damaged area for one cell of the SOLEIL storage ring. Damages are located around the so-called "quadrupole vacuum chambers" installed downstream dipole magnets.

Remedies

Deterioration of cable insulators poses of course a risk to the machine reliability (short circuits) and they have been quickly repaired either by replacing the insulator itself (sextupoles) or the cables (correctors). BPM cable insulators have not been damaged enough to have any consequences on the position measurement quality. To avoid additional damage requiring an expensive replacement, disposable pigtails have been inserted between original cables and BPMs (Fig. 4).

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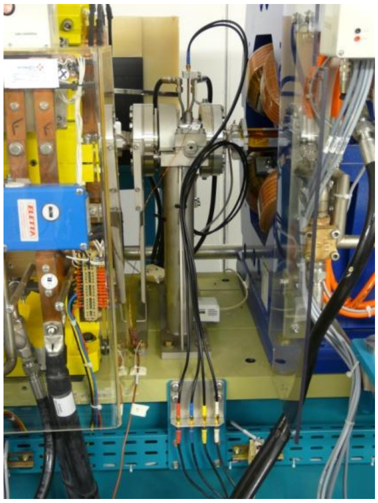

Figure 4: Insertion of disposable pigtails between BPM and its cables to avoid damages of the long and expensive cables.

Nevertheless the most concerning issue is the damage of the baking out films. All the SOLEIL quadrupole VCs are coated with Non Evaporable Getter (NEG) to reduce photon stimulated desorption rate [2]. This NEG layer needs to be activated at 180°C. To perform this baking out, thin films made of resistors stick between kapton foils have been glued on those VCs. In that way, baking out can be done in-situ without opening and removing quadrupole and sextupole yokes installed around the chambers.

Thereby replacing damaged and unusable films is a tedious and very time demanding task that will be done only if necessary. Moreover with nominal operation at 430 mA, new films are damaged rather quickly (less than 2 years), so preventive replacement is not an option.

A study is on-going to find new glue material more radiation hardened than the present one.

DOSE MEASUREMENTS

Dose Spatial Distribution

To characterize the origin of the radiation, a measurement of the dose distribution has been done on cells C08 and C10 of the storage ring. Gafchromic XR-RV3 [3] radiology films have been used for that purpose. Those films are usually used in the medical field for surface peak skin dose measurement. They are big enough (14"x17") to cover a large area around the VC. Their dose range is 0.01 Gy to 30 Gy. Those films do not need any processing and can be directly scanned (Epson perfection V700 Photo) after exposition.

A preliminary calibration has been done to determine the Red, Green and Blue (RGB) response to radiation. Calibration has been done at the Meditest Company [4] with a 40 keV X-ray tube for the source and a solid state dose sensor for absolute measurement (Radcal DDX6 [5]).

Calibration curves show a good sensibility to radiation for the red (low dose) and the green (high dose) colours, while the blue cannot be used (Fig. 5).

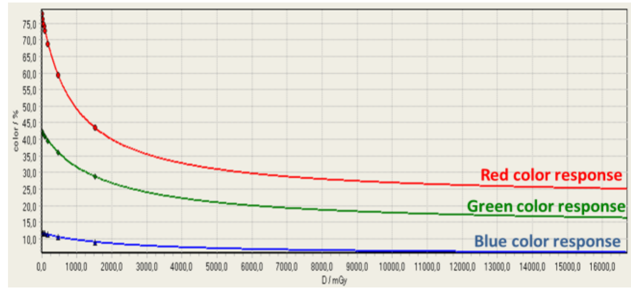

Figure 5: Calibration curves: amplitudes of the red, green and blue colours in function of the dose. For their better sensitivity only red and green can be used for dose measurement.

Films have been installed longitudinally on all the surface of the VC and also transversally on the upstream and downstream faces of quadrupole and sextupole magnets (Fig. 6).

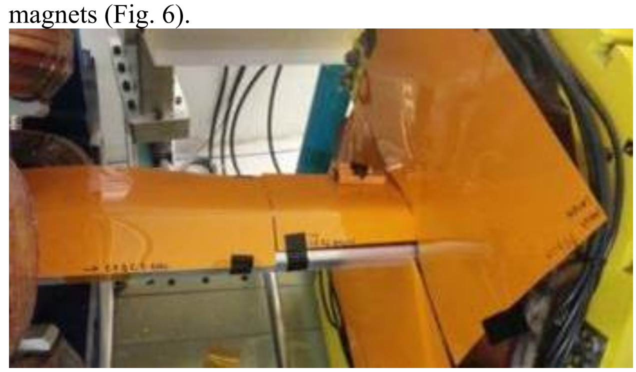

Figure 6: Gafchromic films installed on the VC and against a sextupole magnet in cell C08 (before exposition).

Films have been exposed during 12 minutes with a 16.4 mA current stored in the machine (equivalent to a 3.2 mA.h integrated current). Measurements confirmed that radiations are localized only around quadrupole VC installed downstream a dipole magnet. There, dose distribution read on the films is not uniform but shows a source that is localized in the quadrupole VCs and distributed all along their length (Fig 7).

Doses measured in the straight sections, before the first dipole or even around the dipole VC (around the crotchs and the longitudinal absorbers) are negligible.

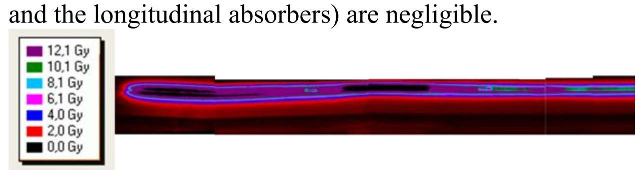

Figure 7: Dose distribution measured longitudinally on the surface of one of the quadrupole VC. Scanned image has been converted in dose scale.

The dose measured on films installed transversally confirms that the radiation source is located in the quadrupole VC.

Absolute Dose Measurements

The highest doses are on contact with the VC and decay quickly with the distance. Absolute dose measurement has been done at the location of the

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equipment that is damaged by radiation. By normalizing with the integrated current during the exposition time, dose rate and the total dose received since the commissioning of the machine have been estimated (Table 1). Baking out films are the equipment receiving the highest dose rate (31 kGy/Ah) as they are in direct contact with the VC. Estimated total dose received by this type of equipment since the start of the machine is extremely high: 300 MGy.

Table 1: Absolute Dose Measurement at the Location of Equipment Damages. Doses Have Been Measured for an Integrated Current of 3.2 mA.h. Normalization by this Value Gives a Dose Rate (in Gy/Ah) and Total Dose Received Since the Start of the Machine (9800 A.h Integrated Current)

Equipment	Distance to VC (cm)	Meas. dose (Gy)	Dose Rate (Gy/Ah)	Total Dose (Gy)
Corrector Cables	20	0.5	156	$1.5\ 10^{6}$
Sextupole Insulators	25	0.3	94	$0.9\ 10^{6}$
BPM Cables	25	0.3	94	$0.9\ 10^{6}$
Baking out Film	contact	100	31250	$300\ 10^{6}$

RADIATION SOURCE

Machine Design

When going through each of the 32 dipole magnets, the electron trajectory is bent by an angle of 196 mrad; therefore photons are produced within that angle in the horizontal plane. A large part of those photons is absorbed by three different elements: the crotch absorber (first 102 mrad, 7.6 kW at 500 mA), the longitudinal absorber (following 69 mrad, 5.1 kW) and by the quadrupole VCs (Fig. 8) installed downstream the dipole (last 25 mrad, 1.8 kW).

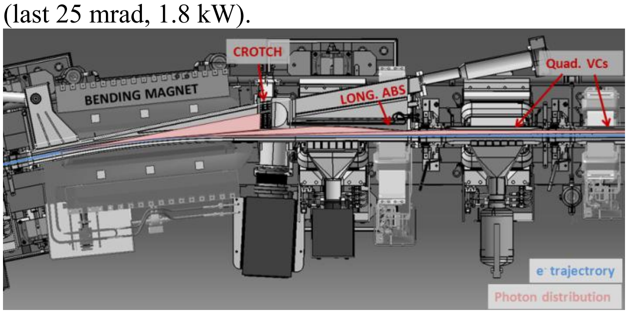

Figure 8: Photons produced in the dipole magnets are absorbed by one of the following elements depending on their emission angle: crotch, longitudinal absorber or quadrupole VC (top view).

The crotch and the longitudinal absorber, made out of copper are inside or just behind the dipole stainless steel VC. Quadrupole VCs are made out of extruded aluminium and NEG coated for vacuum improvement.

Fluorescence

Under the effect of the incident photon beam produced by the upstream dipole, materials of the VC and the NEG coating fluoresce and emit X-rays isotropically (Fig. 9). Depending on their energy, those X-rays are then possibly absorbed by the material (VC, air…) encountered during their diffusion.

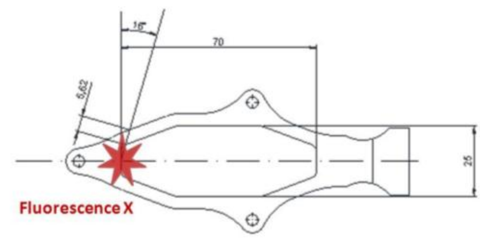

Figure 9: Cross section of a quadrupole VC. Minimum thickness is 3 mm. Upstream dipole synchrotron radiation is intercepted by the chamber inducing X-ray fluorescence of its materials.

Dose distribution measured with Gafchromic films in the transversal plane shows lobes with very high dose (~ 12 Gy) and area with low dose (<0.1 Gy) even at the contact of the VC. Fluorescence X-rays go through a thickness of aluminium determined by their angle of emission. Transmission coefficient calculation, depending on the emission angle (and thus the crossed Al thickness) is perfectly correlated to the dose distribution that has been measured in the transverse plane (Fig. 10)

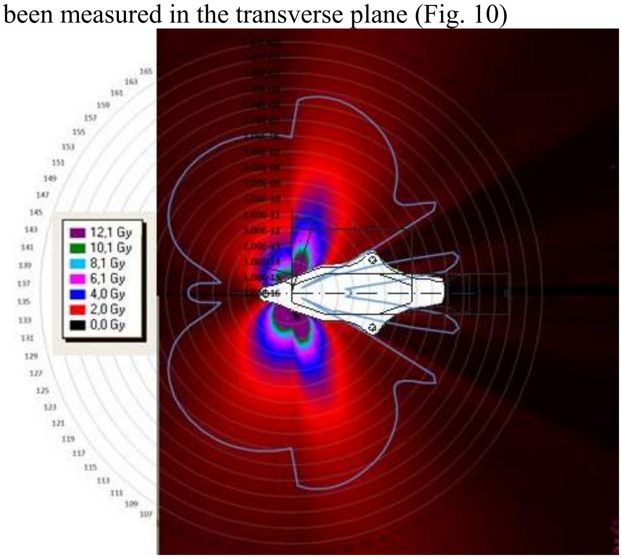

Figure 10: Correlation between the dose distribution measured with Gafchromic films and the calculation of 15 keV X-ray transmission factor (blue curve) as a function of the crossed Al thickness (transversal plane).

Photon Energy Measurement

To determine the materials that fluoresce, X-ray energy measurement has been carried out with a Röntec Silicon Drift Detector (SDD) installed in the storage ring tunnel. X-rays entering such a detector ionise the silicon and the electron cloud created is drifted to an anode. The charge of each electron cloud is proportional to the energy deposited by the incoming X-ray. Measured energy spectra exhibit characteristic fluorescence lines coming from material entering in the composition of VC or the NEG coating (Fig. 11):

- Fe (0.7%), Cu (0.15-0.4%) and Zn (0.25%) are impurities in the aluminium VC. Their spectrum lines are respectively at 6.4 keV (Kα) and 7.06 keV (Kβ), 8.05 keV (Kα) and 8.64 keV (Kα).
- Zr is one of the three NEG coating components (Zr, Ti, V), with fluorescence lines at 15.78 keV (Kα) and 17.67 keV (Kβ).

Detected Kr fluorescence lines may be residuals from NEG coating process (done under Kr atmosphere). The origin of Sn spectrum lines is not yet understood.

Fluorescence from other main components such as Al (VC, 96%), Ti and V (NEG-coating) have not been detected. Indeed their fluorescence lines are at lower energy: respectively 1.49 keV, 4.51 keV and 4.95 keV, and probably attenuated by the VC (see next paragraph).

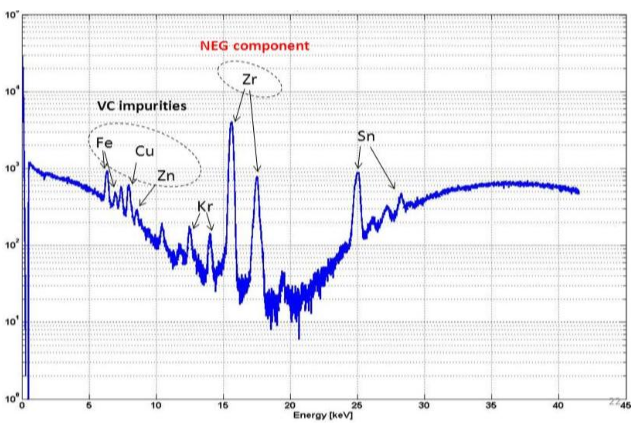

Figure 11: X-ray spectrum analysis acquired with a silicon drift detector. Measurement confirms the fluorescence of NEG coating material (Zr) and of some impurities in the Aluminium of the VC (Fe, Cu and Zn).

VACUUM CHAMBER MATERIAL

Shielding Effect

As the fluorescence occurs inside the VC, the first 'obstacle' seen by the produced X-rays is the VC itself. Depending on the thickness and the type of material crossed, X-ray intensity is attenuated following the formulae given in equation 1:

$$\mathrm{I}(x) = I_0 \times \mathrm{e}^{-\mu x}, \qquad (1)$$

where I_0 is the radiation intensity at the entrance of the material, x is the thickness of the material and μ is the linear attenuation coefficient of the material (building-up factor included).

A comparison with other materials as Cu or Stainless Steel (SS) usually used for the VC manufacturing shows that Al is the one with the poorest "shielding effect". In particular X-rays in the 10 to 30 keV energy range are well attenuated by 3mm of Cu or SS whereas they are not by 3 mm of Al (Fig. 12). Typically Zr (NEG coating) fluorescence X-rays at 15 keV are attenuated by a factor 3.10^2 with 3 mm thick Al VC (to be compared with an attenuation factor of 6.10^{53} for the same thickness of SS).

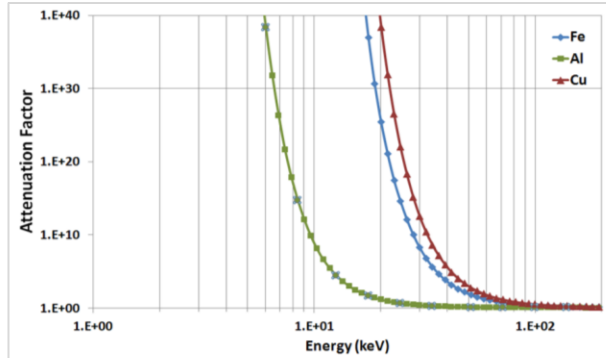

Figure 12: Attenuation factor applied to X-rays crossing 3 mm of Al (green), Fe (blue) or Cu (red) depending on their energy.

CONCLUSION

Origin of the radiation that damages some of the equipment in the storage ring is understood and characterized: fluorescence X-rays are emitted when the NEG coated quadrupole vacuum chamber is hit by synchrotron radiation issued from the upstream dipole. Those X-rays are mainly emitted by the zirconium from the NEG. Their energy (15 keV) is too high to be efficiently attenuated by the 3 mm aluminium thickness of the vacuum chamber.

SOLEIL experience shows that NEG coated aluminium vacuum chamber is not a relevant solution in case this one has to intercept part of the upstream synchrotron radiation. The use of stainless steel or copper with NEG coating is probably a more appropriate combination to limit fluorescence radiations and damages on equipment. Such quadrupole vacuum chambers will be tested in the next months as a dedicated experiment on the machine.

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