In vacuum ID beam line shielding commissioning and direct gas-bremsstrahlung measurements at Synchrotron SOLEIL

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Abstract

The Synchrotron SOLEIL is the new French third generation 2.75 GeV synchrotron light source in Saint-Aubin, France. SOLEIL is now operating 17 beam lines at 300 mA and top-up mode, since November 2008. This paper describes the last in-vacuum ID beam line installed on the SOLEIL storage ring and the radiation safety commissioning tests made in order to check and validate the effectiveness of the beam line shielding of the optics hutch. Results obtained at 300 mA and 400 mA are presented. At the occasion of this common radiation safety test, a direct gas-bremsstrahlung measurement assessment was realized with the collaboration of Paul Berkvens (ESRF). The display of the measurement setup is presented and the results obtained discussed.

1. Introduction

The synchrotron SOLEIL is the new French third generation synchrotron light source. It will operate 26 beam lines by the end of 2011, including 18 insertion devices and 6 bending magnet beam lines, plus 2 infra red beam lines. Fifteen beam lines (9 ID, 6 BM) plus two infra red beam lines are now operational, delivering a 300 mA synchrotron beam in top-up mode for user experimentations. Three other ID beam lines are under commissioning at the moment of this paper and one other is under construction. Before the end of 2009, 19 beam lines (including 2 infra red) will be operational at 400 mA in top-up mode.

This paper describes the radiation safety measurements performed during the first openings of the SIXS beam line front end in order to validate the effectiveness of the beam line shielding of the first optics hutch. These measurements were performed in top-up mode, at 300 mA the February 17th and at 400 mA the March 31st.

2. Presentation of the SIXS beam line

The SIXS beam line is dedicated to surface X-ray diffraction and diffusion studies for solid surfaces and interfaces structures in different and multi environment conditions. Its synchrotron light source is an in-vacuum insertion device, U20 type, set on a short straight section, with a minimum gap aperture of 5.5 mm. The beam line display in the experimental hall consist in three lead shielded hutches with one optical hutch and two separate experimental hutches housing two different experimental set-up and detectors for a multi environment diffractometer and a UHV diffractometer.

The figure 1 presents the SIXS beam line display in SOLEIL's experimental hall, showing the three lead shielded hutches.

In this paper we are focusing on the optics hutch shielding and the radiation tests performed to check and validate this shielding.

The SIXS beam line shielding has been designed by Monte Carlo calculations [2] of the scattered gas-bremsstrahlung radiations and analytical calculations of scattered synchrotron radiations produced by the U20 ondulator. For this kind of insertion device beam line, the gas-bremsstrahlung radiations largely dominate the radiation source term in order to determine the hutch shielding.

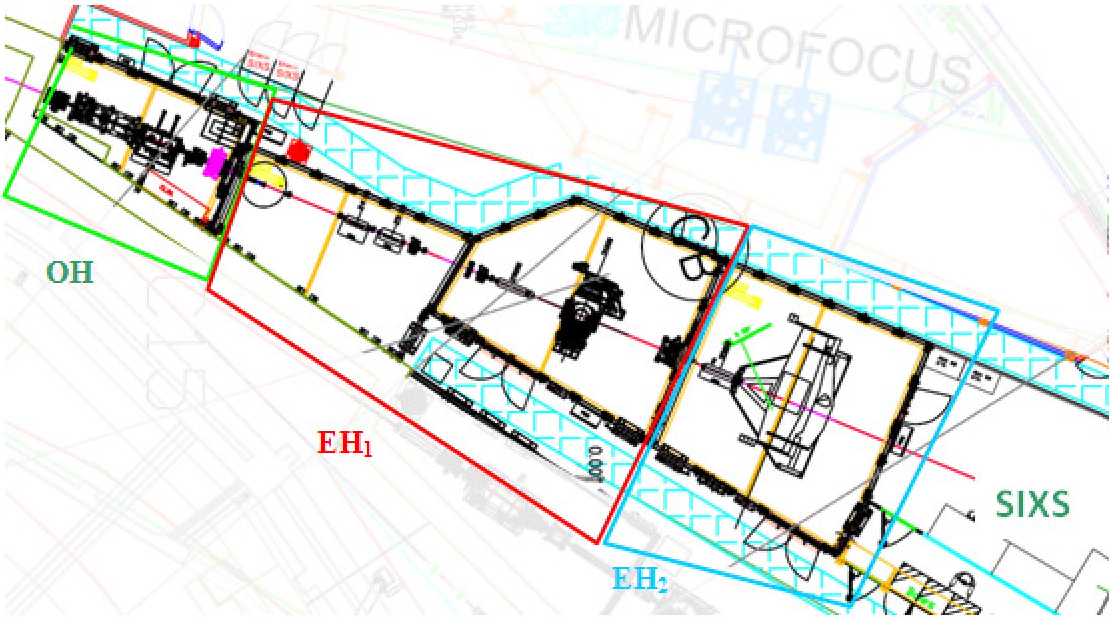

Fig.1 - Layout of the SIXS beam line in the experimental hall of synchrotron SOLEIL.

The table 1 below gives the parameters and residual gas composition in the straight section vacuum pipes and ondulator vessel used for the shielding calculations. We assumed an average vacuum pressure of 2.10^{-9} mbar along the straight section at 500 mA and a residual gas composition based on the typical RGA results at ESRF similar ID section.

Electron beam energy	2.75 GeV
Stored beam current	500 mA
Straight section length	7.74 m
Average vacuum pressure	$2.\ 10^{-9}$ mbar
Front end aperture	$2 \times 2\ \text{mm}^2$
U20 type minimum gap	5.5 mm
Maximum vertical magnetic field	1.03 T
Vacuum residual gas composition	
H_2	80 %
CO	10 %
CO_2	5 %
CH_4	3 %
H_2O	2 %

Table 1 - Parameters used for MC calculations to define lead shielding thicknesses of the SIXS optics hutch.

These parameters and MC calculations performed by P. Berkvens with the “Beamlines”[2] code lead to panel lead shielding thicknesses of 15 mm for the side wall, 80 mm for the back wall and 10 mm for the roof[3], assuming that roof access is strictly forbidden during operation.

3. Radiation safety protocol to test beam line shielding efficiency

Before allowing the beam line to take synchrotron beam in the hutch, it is mandatory by French regulation Authority to test and verify the shielding efficiency and the tightness of the shielding panels of the hutch.

3.1. Beam line hutch set up

For this purpose, a radiation safety test is scheduled by the radiation safety group, the beam line team and the vacuum group as soon as the beam line is ready to take the maximum beam load of stored beam current achievable with the ID at its minimum gap. In order to perform such a test, the ID has to be ready in the storage ring, the front end must be complete and operational and the first optics hutch has to be fully equipped with all the utilities and the personal safety system (PSS) already tested and operational.

For such radiation tests, the optics hutch is almost empty with only the end of the front end vacuum system. After the ending valve of the front end, a filters chamber is mounted in order to protect a water cooled beryllium window from the high power of the SR beam. An additional nitrogen circulation is installed behind the beryllium window in order to protect it from the ozone produced by the SR beam in the air of the hutch. The scattering of both gas-bremsstrahlung and SR beam is realized by the use of copper water cooled scatterer that will be set in different positions along the beam axis during the test. Figure 2 presents photography of the mounting with the filters chamber, the beryllium window and the copper scatterer.

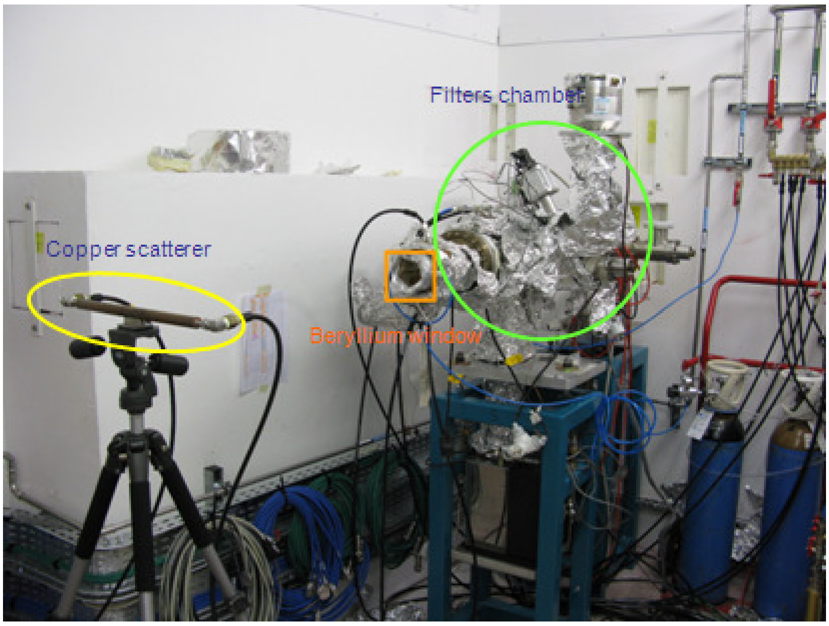

Fig.2 - Mounting for the radiation safety test of the optics hutch.

Radiation measurements are realized with both portable radiation monitors and passive thermo luminescent dosimeters (TLD) displayed all around the hutch on each panel and with specific attention at joints between panels and at doors panels and frame which are weak points of the hutch shielding tightness. An additional fixed radiation monitoring is performed by the ionization chamber installed along the side wall panel and connected to the PSS. This monitor is dedicated in normal operations to interlock the front end during top-up operation if the integrated dose gets higher dose than the accepted dose threshold of 2 µSv within four hours of integration.

3.2. Sequence of the radiation safety test measurements

First of all, the front end is open with low current stored. Then, the ID is slowly closed, step by step, up to the minimum gap value of the ID. This allows the correct alignment of the synchrotron source and the front end to be checked before going further with a beam imaging monitor place a bit downstream of the beryllium window. Then, a first radiation survey is performed around the hutch in order to search any important leakage in the shielding. Usually, the stored beam current is about 30 or 50 mA for this first step.

Then after, the maximum current available is injected into the storage ring and maintain by top-up mode. Few amount of current being regularly injected with opened front end to keep the stored current at a given value. A complete radiation survey is realized for each position of the copper scatterer in the optics hutch.

Figure 3 presents the three positions of the copper scatterer used during the radiation safety test of SIXS first optics hutch.

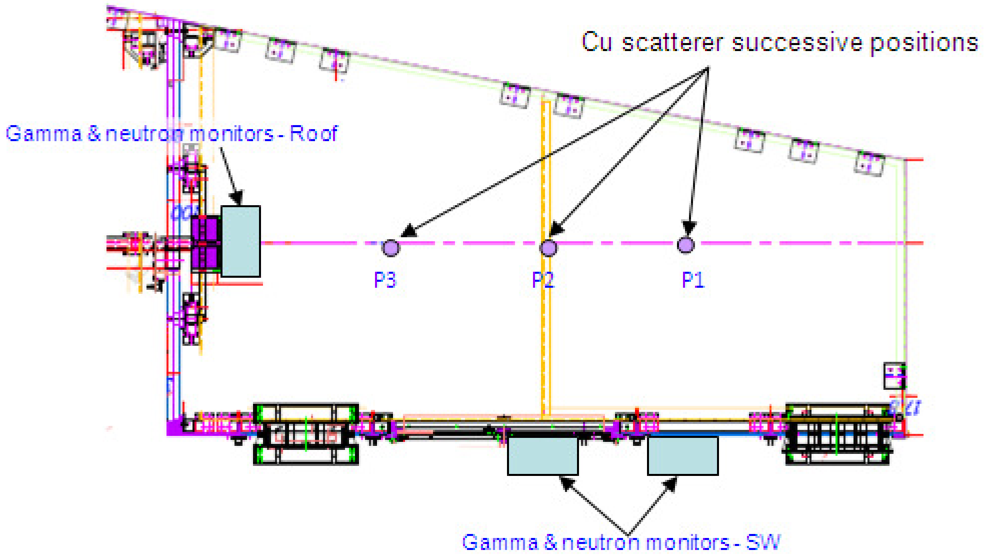

Fig.3 - Successive scatterer positions within the radiation measurements around the SIXS optics hutch.

Figure 4 presents two beam views taken during the radiation tests. The first one showing the synchrotron beam on a X-ray beam imager in order to verify that it is not even partly cut by a misalignment of the different front end absorbers or diaphragms with the ID. The second picture shows the visible synchrotron light beam crossing the beryllium window and hitting the copper scatterer.

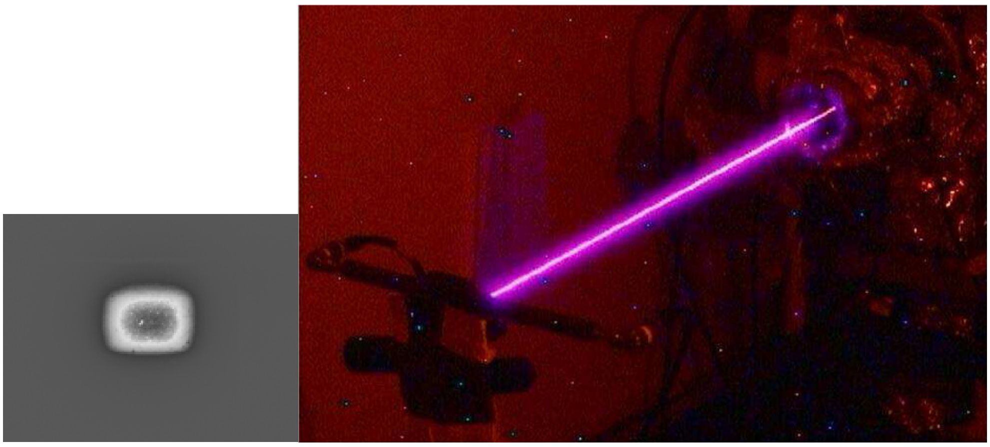

Fig.4 - Synchrotron light beam alignment check with front end aperture (left) and lightning of the synchrotron beam in the air of the optics hutch (right).

4. Radiation measurements

4.1. First attempt by February 17th 2009

The first radiation safety test of the optics hutch of SIXS beam line was performed during the night of Tuesday February 17th.

4.1.1. Direct gas-bremsstrahlung measurements

Prior to the radiation safety measurements, we take the opportunity of this radiation test to have some measurements of direct gas-bremsstrahlung produced in the straight section of this in vacuum ID beam line. This campaign was made possible by the help of Paul Berkvens, head of ESRF safety group, who came at SOLEIL with the specific detectors used for these measurements within the framework of collaboration with SOLEIL safety group. These measurements were performed by exposing a small Farmer type ionization chamber (PTW 31002) into the direct gas-bremsstrahlung beam. The ionization chamber was connected to a PTW Unidos dosimeter system outside of the optics hutch. The ionization chamber was placed on the copper scatterer support behind 13 mm of lead in order to avoid the synchrotron radiations coming from the upstream and downstream bending magnets of the straight section. The U20 ID was set fully open (30 mm) in order to cut the synchrotron radiation production of the ID. Dose rate measurements were performed for different stored current values from 50 mA to 450 mA witch was the maximum stored beam achievable at that time.

The goal of these measurements was to verify that the gas-bremsstrahlung power produced by the electrons in the straight section is actually proportional to the square electron beam intensity stored in the synchrotron ring of SOLEIL.

As usually admitted, the gas-bremsstrahlung power could be described by equation (1) below:

$$P = C \times \frac{dE}{dx}(E_e) \times p \times I \times L \qquad (1)$$

where p refers to the vacuum pressure in the straight, I to the electron beam intensity, L to the length of the straight section, and

$$\frac{dE}{dx}(E_e)\text{: to the electron stopping power } (\propto E_e)$$

Then, p being proportional to the beam intensity and to the energy of electrons, one can describe the gas-bremsstrahlung intensity proportional to the square of the electron beam energy and to the square of the beam intensity stored in the ring as described in formula (2) presented below.

$$P \propto E_e^2 \times I^2 \times L \qquad (2)$$

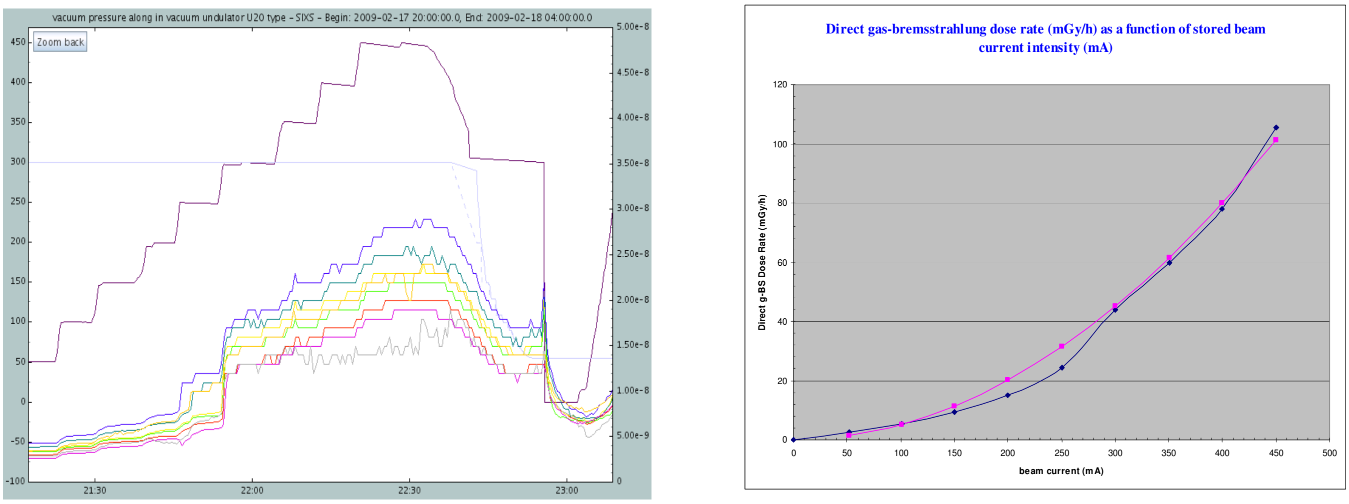

Fig.5 - Left : Electron intensity in the storage ring and different measured vacuum pressures in the straight section of SIXS (I14-C). Highest values of pressure refer to the in vacuum ID vessel gauges. Right: Direct gas-bremsstrahlung dose rates measured for current intensity from 50 mA to 450 mA (blue curve). Quadratic fit of the intensity of the electron stored beam (pink curve)

Taking into account the natural background, one can see that, on the right of Figure 5, we obtain a slightly good agreement with a quadratic current response of the direct gas-bremsstrahlung dose rates measured into the beam axis.

4.1.2. Radiation safety controls

Because of a problem on the RF system of the storage ring that happened just after the end of the gas-bremsstrahlung measurements, the radiation safety test was performed at only 300 mA instead of 400 mA as initially scheduled. In top-up operations at 300 mA and with the U20 ID gap closed at 5.5 mm, the average vacuum pressure in the straight was about 1.5 10^{-8} mbar. Radiation measurements pointed out the fact that in front of the doors of the hutch and on the roof dose rates are a bit higher than expected and with repeated pics over 1 µSv/h where shielding has been designed to have less than 0.5 µSv/h at 500 mA. We also experienced a few total beam trips during the measurement session which lead to integrated dose of 1.5 µSv and 2.3 µSv per beam loss behind the doors and on the roof respectively. These dose levels were very high and mean that in case of a total beam trip, the beam line will be interlocked by the PSS. It was also established that almost the entire beam was lost in the SDC14 straight section (SIXS beam line one). Because of these beam trips, the passive dose dosimeters spread all around the optics hutch were blinded by these large amounts of equivalent dose.

So, in these conditions and with such radiation measurements results it was not possible to validate the efficiency of the SIXS optics hutch and a second radiation test session was scheduled.

4.2. Second attempt by March 31st 2009

In order to be able to status on the quality of the hutch shielding as far as possible independently of any unforeseen event, this second radiation test was split into two parts. First to minimize the risk, radiation surveys were performed in decay mode of operation at 400 mA. Refills were done with closed front end. No radiation leakage was detected and all the dose rates measured were slightly lower than 0.4 µSv/h all around the hutch. Then, the second part of the test was performed in top-up mode at 400 mA almost in the same conditions than the first time. Dose rates measured were found again higher than the goal limit of 0.5 µSv/h, with particular points like door panels at 0.8 µSv/h with occasional peaks at 1.2 µSv/h. This time we did not encounter total beam trips so it was necessary to force total beam losses by tripping the storage ring RF system. These forced beam trips were mainly concentrated in SDC14 and lead again to high integrated doses of about 0.85 µSv behind the doors and almost 1.5 µSv on the roof. Because the beam trips were forced at demand, dose rates could have been measured by portable ionization chambers and the corresponding results (probably underestimated) were 2.3 mSv/h behind the doors and 38 mSv/h on the roof.

4.3. Discussion

This was the first time that such bad results were obtained at SOLEIL for beam line hutch radiation safety tests because it was not possible to authorize the beam line staff to start the commissioning of the beam line with SR beam just after the tests. So what was wrong with this particular beam line?

First, instead of the three first in vacuum ID beam lines, the SIXS U20 ID was not installed before the starting of the storage ring operations but just a couple of months before the tests. So the vacuum pressure was quite poor during the tests (1.5 10^{-8} mbar instead of 2. 10^{-9} mbar for the value retained for shielding calculations) and probably responsible of the higher amount of gas-bremsstrahlung entering the optics hutch.

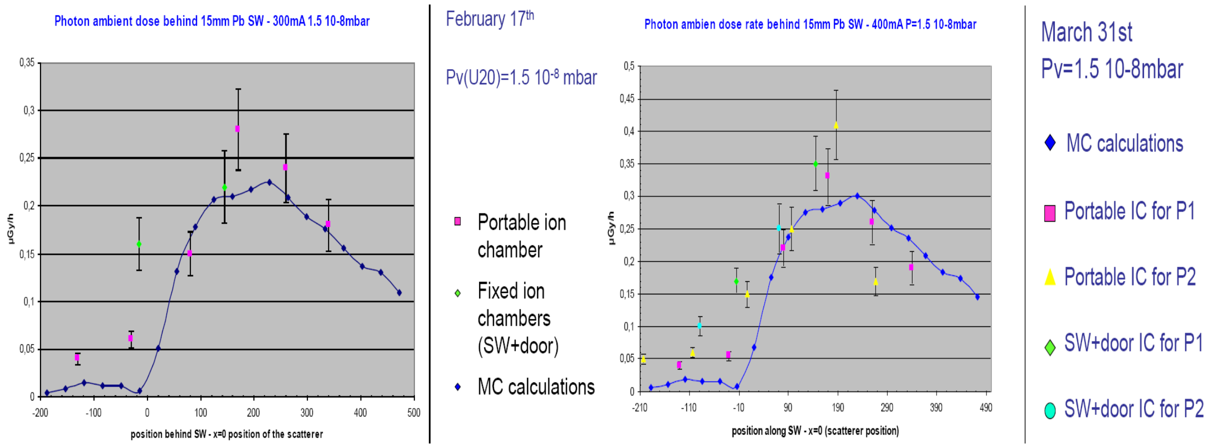

Fig.6 - Comparison of dose rate measurements performed both dates and Monte Carlo calculations done by P. Berkvens with "Beamlines" MC code [2].

Paul Berkvens made some calculations in the same way as the ones performed for the design of the shielding but with the current and the vacuum pressure encountered during the two tests. On Figure 6, one can see that agreement is not so bad between the simulations and the averaged dose rates recorded during both tests but measurements are always higher and this is not enough to explain the pulsed high dose rates observed.

Two additional crucial points have to be presented. First, the effective aperture of the front end is quite smaller than the one used for the shielding calculations (0.6x1.8 mm^2 instead of 2x2 mm^2) but it means that dose rates should be lower than values expected from calculations. Second, the actual residual gas composition is more effective in gas-bremsstrahlung production because of the presence of high Z species as shown in table 2.

Vacuum residual gas composition	
H_2	42 %
CO	30.4 %
CO_2	5.6 %
CH_4	3 %
H_2O	9 %
CF_4	10 %

Table 2 - Residual gas composition in SIXS ID in vacuum vessel given by RGA measurement (to compare with Table 1 composition)

The effects of these two parameters are evaluated in Figure 7 which presents the gas-bremsstrahlung spectrum produced in the different cases. The blue curve refers to the gas-bremsstrahlung produced by a 500 mA electron beam in the straight with a gas composition as described in table 1 and with the front end aperture of 4 mm^2. The red curve is almost the same but with the residual gas composition as presented in table 2. The orange curve is the same than the red one but taking into account the reduced aperture of the front end of 0.6x1.8 mm^2. And the green one, supposed to be more realistic, is almost the same than de orange one but mixing table 1 and table 2 residual gas compositions with respect to in vacuum ID vessel length (2 m with table 2 composition) and complement straight length (~5.7 m with table 1 composition).

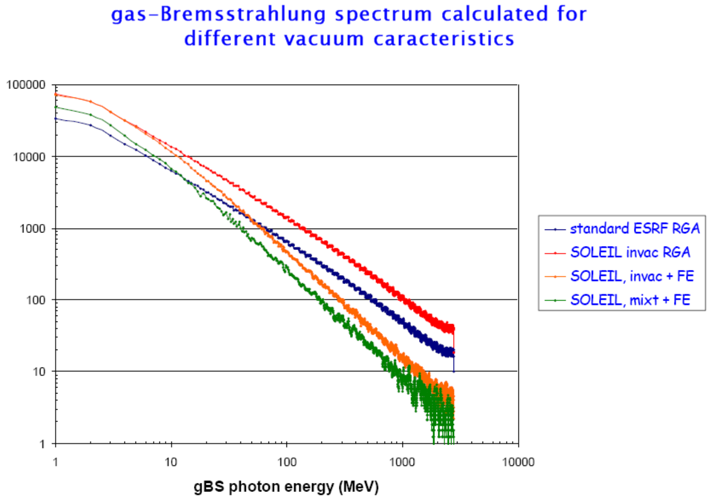

Fig.7 - Comparison of gas-bremsstrahlung spectrum produced by a 500 mA electron beam @ 2. 10^{-9} mbar for different residual gas compositions and front end apertures. Calculations made by P. Berkvens with "Beamlines" MC code [2].

This could explain partly the results of the dose rate measurements performed, particularly if you take into account that the average pressure was 7.5 times higher than the one used to obtain the green curve, but not completely. The last explanation was given at the occasion of the next shutdown when the ID vacuum vessel was opened to be checked. As it is shown on the pictures of Figure 8, the two sides of the copper liner that protects the permanent magnets of the ID present some sort of a wave clearly visible on the left picture, and even a small hole is quite clearly visible on the right view. This last point could explain the reason why the beam losses are concentrated in that particular straight section and probably why the dose rates measured around the optics hutch where so high with the combination of the other facts pointed out above.

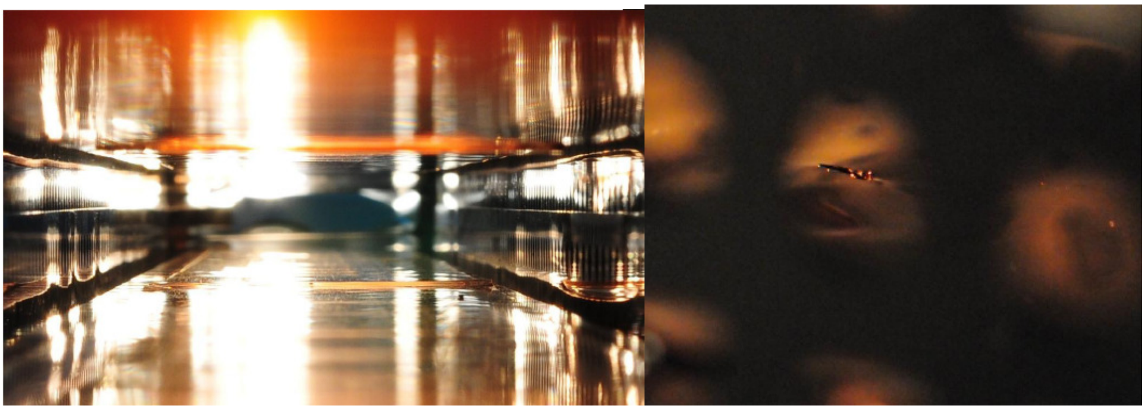

Fig.8 - Damages visible on both side of the protection liner of the magnets of the U20 in vacuum ID of beam line SIXS. On the left view, the bumps up and down sides; on the right view the hole.

5. Conclusion and additional notes

These measurements and results point out the fact of how the vacuum conditions are critical with respect to gas-bremsstrahlung production and radiation protection around the ID beam line in synchrotron facilities. So a great care has to be taken during the shielding design to take into consideration the vacuum issue and its consequence in terms of shielding and operational constraints.

During the weeks that followed the Radsynch Conference, the in vacuum ID of the SIXS beam line was replaced during the next shutdown and it was observed during the following run that the beam losses do not concentrate anymore in the SDC14 straight section. Unfortunately, the beam line was still not ready to take beam for an additional radiation test at the moment of this paper was written.

6. Acknowledgements

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References

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