The shielding design of the radio frequency cavity in the storage ring of the Thailand synchrotron radiation light source

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Abstract. The radio frequency (RF) cavity provides an electric field in direction of electron beam in the synchrotron radiation machine to accelerate electron beam or compensate electron beam energy loss. Thailand synchrotron radiation machine has installed a second RF systems in the straight ring since August 2016. The RF cavity of the system can provide a maximum accelerating voltage of 300 kV at its accelerating gap. During the commissioning of the cavity in August 2016, there was a high radiation detected outside the shielding wall of the storage ring. The local shielding was installed for the safe operation of RF cavity at 185 kV. There will be a new insertion device installed in storage ring during a machine shutdown period in August 2018. This insertion device requires an operation of the RF cavity higher than 185 kV, which increases the radiation. The new design of RF cavity local shielding will also be installed. The radiation from RF cavity was investigated and the local shielding was designed using Mote Carlo simulations. This paper presents a detailed investigation and design of a local shielding together with a radiation survey results after the installation of shielding.

1. Introduction

The radio frequency (RF) cavity plays important role in the storage ring of the storage ring based synchrotron radiation light source. It provides energy to an electron beam via electric field to compensate electron beam energy loss for synchrotron radiation generation. The storage ring of the Thailand synchrotron radiation light source, which is located in the Suranaree University of Technology campus in Nakhon Ratchasima and is managed by the Synchrotron Light Research Institute (SLRI), encloses a circulating 1.2 GeV electron beam of 150 mA. This electron beam generates synchrotron radiation while it is forced to bend its trajectory by the strong magnetic field.

The RF cavity stores an electromagnetic fields energy and transfers energy to electron beam via the Lorentz force mechanism while an electron beam traverses the cavity. The RF cavity of the SLRI storage ring has the hollow cylinder shape with the disc-nose inside as shown in figure 1. Electron beam trajectory is along the center axis of the cavity. This cavity has the resonant frequency at 118 MHz and an accelerating gap length of 50 mm. The longitudinal electric field of the resonant frequency is parallel to the electron beam trajectory along an accelerating gap. Electron beam, which lose energy after generating synchrotron radiation, gains energy back to the nominal value after passing through the accelerating gap of the RF cavity. Integration of the longitudinal electric field along the accelerating gap defines an accelerating voltage or cavity voltage.
The new RF cavity of the storage ring was designed to generate the maximum cavity voltage of 300 kV. It was installed in the storage ring and commissioned in August 2016 [1]. There was a high radiation above the safety limits detected at the experimental area outside the shielding wall of the storage ring during the commissioning of the new cavity. The basic local shielding was installed at the location of the cavity inside the shielding wall of the storage ring in order to reduce the radiation from the cavity. This local shielding reduces the radiation from the cavity and makes the overall radiation dose at the experimental area becomes under the user safety operation limit of the synchrotron machine. The new insertion device was installed in the storage ring in August 2018. They require a high cavity voltage for the full operation of insertion devices in the storage ring in order to compensate a higher electron beam energy loss of the storage ring. The old local shielding of the cavity is upgraded in order to shield locally a higher radiation from the operation of the RF cavity at the higher cavity voltage.

2. Source of radiation
In the normal conducting accelerators structures like the RF cavity, the “dark current” is mainly the source of radiation. Dark currents are electrons emitted from the cavity inner surfaces and then move under the influence of a high gradient electromagnetic fields. Dark currents electrons, produced in the RF cavity by field emission, can be expressed using the Fowler-Nordheim equation [2]. The generation mechanism is mainly proportional to the surface electric field gradient at the cavity surfaces. Dark currents electrons can be further amplified by multipactoring mechanism [3] and will hit the cavity walls producing bremsstrahlung radiation. This bremsstrahlung may be of sufficient energy to cause further showering and photon production.

In the case of the SLRI storage ring RF cavity, the maximum surface electric field are localized around the disc-shape of the nose section of the cavity as illustrated in figure 2. This surface electric field is proportional to the RF power delivered to the cavity in order to generate an accelerating voltage. The 30 kW RF power is needed to generate 300 kV cavity voltage across the accelerating gap inside this cavity. The surface electric fields amplitude can be maximum at 10 MV/m near the edge of the disc-shape from the input power of 30 kW. If the assumption of dark currents electrons has zero energy when emit from the surface, the maximum energy gain of dark current electrons under this 10 MV/m surface electric field is the multiply of charge of electron (e), the field amplitude, and the gap length, which is equal to 10 MV/m*0.05 m*e = 0.5 MeV or 500 keV. This is the maximum energy gain of the dark current electron travelling through the accelerating gap. The 500 keV value will be set as the maximum energy case of the dark current electrons energy.
Figure 2. Electric fields lines from simulation of the SLRI storage ring RF cavity. Size of the arrow indicates the field amplitude. The maximum electric field locates around the disc-shape of the nose.

In another case, it can be assumed that dark current electrons can be accelerated by an accelerating voltage across the gap. The maximum energy gain is the multiply of electron charge and the accelerating voltage for example if the cavity is operated at 200 kV accelerating voltage the dark current electrons will have maximum energy gain of 200 keV over the accelerating gap. In other possibility is that the maximum energy of produced photon, from bremsstrahlung, inside the cavity is estimated the same as the dark current electron energy, hence the 300 kV accelerating voltage will generate 300 keV dark current electrons and these dark electrons will produce 300 keV photons. The three cases of radiation source are explored in the Monte Carlo simulations using the Monte Carlo Particle and Heavy-Ion Transport code System (PHITS) [4] for estimating the local RF cavity shielding efficiency.

3. Geometry model

The RF cavity body is made from the oxygen free high thermal conductivity (OFHC) copper, in order to have a uniform thermal expansion when applying the RF power. For the SLRI new RF cavity, the thickness of cavity walls is in range from 30 - 60 mm as illustrated in figure 3. The cavity shape has been simplified in the simulation by using combinations of cylinder and a hollow cylinder to represent a cavity-like shape with the same physical dimension of the actual cavity. The local shielding has been installed at the RF cavity inside the storage ring shielding wall, which is the 500 mm concrete wall. The local shielding was installed to reduce the radiation from the cavity, so the loss of injection beam during the injection and the stored electron energy is omitted from the local shielding design as it was already included in the storage ring shielding wall design.

The local shielding is not completely the box with the cavity inside. It is partially shield with some open areas for cable trays, connecting wires, and RF input power coupler. It also has the open space for servicing the RF cavity. The sketch of the local shielding is illustrated in figure 4. There is no lead sheet at the ground floor and the inner ring side of the cavity. The local shielding has three layers with the lead sheet in the middle layer. The lead sheet is sandwiched between the 3 mm metal plates. Thickness of the lead sheet is 3 mm for the top and the outer ring side of the cavity. The 5 mm lead sheet is used for the upstream and downstream side. These upstream and downstream sides were upgraded in September 2018 from the old configuration, which has only the 6 mm metal plates shielding. This configuration of lead and metal shielding is modelled in the simulation and used for all simulation cases.
4. Simulation results

Simulations were done on seven cases for the upgraded shielding, the 500 keV electron source, the three accelerating gap voltages energy of both electron and photon sources (200 keV, 250 keV, and 300 keV). For the old shielding cases, simulations were done only at the 300 keV sources energy. The source is modelled as the disc-shape source located at the surface of the disc-shape nose of the cavity with the inner radius of 55 mm and the outer radius of 140 mm. Direction of the source is moving toward the cavity wall in -z direction (upstream side of the cavity), which is in the opposite direction of the electron beam trajectory as shown in figure 3. The source is set to be a Gaussian energy distribution with the center energy of distribution setting at the maximum energy of each cases and the FWHM of distribution is 10% of the maximum energy. Simulations were aimed to measure the efficiency of the shielding in each energy cases, so the number of particles (photon and electron) were tracked crossing from cell to cell starting from the inside of the cavity to the outside of the shielding. The total number of particles...
crossing out the outer wall surface of the shielding is compared to the total number of particles crossing the inner wall surface of the shielding for calculating the leakage of the particles. These total number of particles crossing out the shielding wall surfaces can be separated between the shielded areas and unshielded areas to investigate the effectiveness of the shielding.

Table 1. The photon leakage out of shielding wall for various scenarios.

| Scenarios                          | Total leakage (%) | Leakage at shielded areas (%) | Leakage at unshielded areas (%) |
|-----------------------------------|-------------------|-------------------------------|---------------------------------|
| **Upgraded shielding cases**      |                   |                               |                                 |
| - Case 1: 200 keV electron source | 16.75             | 0.00                          | 16.75                           |
| - Case 2: 250 keV electron source | 17.19             | 0.00                          | 17.19                           |
| - Case 3: 300 keV electron source | 18.11             | 0.00                          | 18.11                           |
| - Case 4: 500 keV electron source | 16.76             | 0.02                          | 16.74                           |
| - Case 5: 200 keV photon source   | 32.61             | 0.01                          | 32.59                           |
| - Case 6: 250 keV photon source   | 32.16             | 0.01                          | 32.15                           |
| - Case 7: 300 keV photon source   | 25.93             | 0.02                          | 25.91                           |
| **Old shielding cases**           |                   |                               |                                 |
| - Case 8: 300 keV electron source | 17.93             | 0.09                          | 17.83                           |
| - Case 9: 300 keV photon source   | 25.90             | 0.09                          | 25.81                           |

The photon leakage out of the shielding from seven cases are listed in table 1 together with the results of the previous shielding. For the upgraded shielding, it reduces the photon leakage to 16 % - 32 % in any case of the sources. Most of photon is leaked at the areas that have no shield. Simulations at 300 keV sources of before and after adding lead sheets shown that there is not much improvement of the radiation shield by adding only the lead sheets at the upstream and downstream. This is because there are several areas at the upstream and downstream that have no lead shields as the sketch shown in figure 4. The upstream area is also the high radiation area suggested from simulation results in figure 5. The upstream side is in close proximity to the accelerating gap of the RF cavity, which is where the radiation occurs, and the source direction is also moving toward the upstream side. This makes the photon leakage at the upstream side is higher than the downstream side in all cases.

The simulations suggest that the leakage is in the unshielded areas and has a high leakage at the upstream side of the cavity. The configuration of the shieldings is sufficient to shield the radiation from the cavity. The new local shielding, which is movable or easy to dismantle for servicing the cavity, should be added at the unshielded areas at both upstream and downstream side to further reduce the total leakage of particles.

5. Measurement data

After upgrading the upstream and downstream shielding by adding the total 5 mm lead sheet, 5-stacks of 1 mm lead sheet, the survey of radiation inside and outside the local shielding were performed. These measurements were done with and without the stored electron beam inside the storage ring. Electron beam was stored at 150 mA for the measurement with beam cases. The operation of the RF cavity was set at 200 kV and 250 kV. The optically stimulated luminescence (OSL) dosimeter was used in the measurement for the total accumulated dose. The OSL is capable of measuring radiation doses received from beta particle in the energy range of 150 keV to 10 MeV, photon in the energy range of 5 keV to 20 MeV, and neutron in the energy rage of 40 keV to 5 MeV. It has a digital display, which can show either the current measuring dose rate or the accumulated dose. The accumulated dose measurement mode was used during the measurement. The accumulated dose was acquired from each dosimeter by recording the dose value difference between the beginning and the end of each recording period. The accumulated dose was collected over one hour for each case. Form these dose measurements, the dose rate can be calculated in unit of mSv/h. The OSL dosimeters were placed at all directions on both inside
and outside the local shielding to measure the efficiency of the shields. The locations of these dosimeters are depicted in figure 6.

Figure 5. Photon tracking results with the (a) 300 keV electron source, (b) 500 keV electron source, and (c) 300 keV photon source.

Figure 6. Sketch of OSL dosimeters location (green rectangle) during the measurement. Insets are pictures of the upstream and the downstream OSL positions during the measurement.

There are four cases of measurements. Case 1, operating the RF cavity at 200 kV and store beam at 150 mA for one hour. Case 2, operating the RF cavity at 250 kV and store beam at 150 mA for one hour. Case 3, operating the RF cavity at 200 kV with no beam stored for one hour. Case 4, operating the RF cavity at 250 kV with no beam stored for one hour. The measurement results are shown in table 2. It shown that the shielding can reduce the gamma dose rate 50-70 %. Comparing with the simulation results in table 1 for the case of the source energy of 200 keV and 250 keV (case 1, case 2, case 5, and
case 6 in table 1), it is found that the simulations results with a photon source (case 5 and case 6) are in good agreement with the measurement results. The simulations predicted the leakage ~32 % while the measurements show the maximum shielding efficiency of 70 %.

**Table 2.** Dose rate (mSv/h) measurement at the shielding wall.

| Locations                      | Case 1 | Case 2 | Case 3 | Case 4 |
|-------------------------------|--------|--------|--------|--------|
| Up-stream side                 |        |        |        |        |
| Top of chamber                 |        |        |        |        |
| - Inside shielded wall         | 7.25   | 68.64  | 3.88   | 49.33  |
| - Outside shielded wall        | 8.55   | 39.70  | 1.18   | 27.10  |
| Inner ring side of chamber     |        |        |        |        |
| - Inside shielded wall         | 27.82  | 47.98  | 2.12   | 29.58  |
| - Outside shielded wall        | 8.07   | 30.36  | 1.31   | 23.02  |
| Outer ring side of chamber     |        |        |        |        |
| - Inside shielded wall         | 11.61  | 29.61  | 0.84   | 18.49  |
| - Outside shielded wall        | 1.31   | 12.63  | 0.25   | 9.19   |
| Down-stream side               |        |        |        |        |
| Top of chamber                 |        |        |        |        |
| - Inside shielded wall         | 1.08   | 7.36   | 0.21   | 5.12   |
| - Outside shielded wall        | 2.52   | 14.75  | 0.00   | 9.09   |
| Inner ring side of chamber     |        |        |        |        |
| - Inside shielded wall         | 0.64   | 5.51   | 0.09   | 3.66   |
| - Outside shielded wall        | 0.56   | 5.20   | 0.12   | 3.79   |
| Outer ring side of chamber     |        |        |        |        |
| - Inside shielded wall         | 0.98   | 6.69   | 0.20   | 4.55   |
| - Outside shielded wall        | 0.56   | 5.84   | 0.12   | 4.30   |
| Top side                       |        |        |        |        |
| - Inside shielded wall         | 0.32   | 190.48 | 0.10   | 15.80  |
| - Outside shielded wall        | 0.00   | 0.02   | 0.00   | 0.02   |
| STR wall side                  |        |        |        |        |
| - Inside shielded wall         | 0.32   | 7.92   | 0.06   | 6.07   |
| - Outside shielded wall        | 0.00   | 0.02   | 0.00   | 0.01   |

There is also a high radiation during the operation of the RF cavity at 250 kV. This may come from a high dark current electrons from the inner surface of the RF cavity. During the measurement, the dose rate monitor around the experimental area, which is outside the storage ring shielding wall, were also recorded. These data are plotted and shown in figure 7. These dose rate dosimeters also detected a high radiation during a 250 kV operation of the RF cavity. These dose rate monitoring data of the with and without beam cases suggest that the main contribution of the radiation can be the dark current electrons inside the cavity as the dose rates are not significant different between both cases. Dose rate outside the storage ring shielding wall is approximately 1 µSv/h during the 250 kV operation. This dose rate is below the safety dose rate limit of 10 µSv/h, which is equivalent to 20 mSv/year, and is also less than the controlled dose rate (5 µSv/h) of the experimental area. So it is safe for users to perform their experiments, but they need to evacuate the area during the injection period.
6. Conclusions
The shielding of the new RF cavity has been upgraded by adding a 5 mm lead sheet at the upstream and downstream side of the cavity. This will allow a high cavity voltage up to 300 kV operation to serve the full insertion devices operation of the storage ring. Simulation with PHITS shown that the shielding can reduce the photon to 16-32 % in all cases of the sources. The locations where the leakage of photon occurring are mainly the unshielded areas. The measurement dose rate was measurement inside and outside the local shielding. It shown that the shielding can reduce the gamma dose rate 50-70 % which are in good agreement with the simulation of the photon source cases. The upgraded local shielding of the cavity has helped reducing the experimental area dose rate while operating the cavity at 200 kV and 250kV.

The experiments and measurements results also suggest that the main source of radiation at the RF cavity is the dark current electrons emitted from the inner surface of the cavity. These dark current electrons can be measured using the faraday cups attached to both end of the cavity, but this requires taking the cavity out of the storage ring. In order to treat the dark current electrons, the cavity should be continuing conditioned with the RF power at a high cavity voltage for long period of time (more than 24 hours) or operating the cavity at a high cavity voltage for long period (more than two months). These will decrease the dark current electrons as the inner surface of the cavity will be cleaner and smoother. Further activities will be the addition of the new local shielding at the unshielded areas at the upstream side, which is the highest radiation area suggested by simulations and measurements.

References
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