Chapter 6. Radiation Safety

6.1 Radiation Safety Control Policy

6.1.1 Radiation Safety Requirements

To ensure radiation safety for workers and synchrotron radiation users during the operation of the Korea 4th generation synchrotron radiation accelerator and to prevent harm to residents and the environment in the vicinity of the accelerator, an appropriate radiation safety policy must be established. The policy must be followed to ensure full compliance with the Korean Nuclear Safety Act. In addition to securing manpower and equipment, the regulation must be designed to also comply with facility requirements and handling standards. The annual effective dose limits, which are required by the Korean Nuclear Safety Act, one of the operation permit conditions, are as follows:

- **Radiation workers**: 20 mSv per year,
- **Frequent visitors**: 6 mSv per year,
- **General public (including synchrotron radiation users)**: 1 mSv per year,
- **Site boundary**: 0.25 mSv per year.

The radiation shielding and radiation safety systems of the 4th Generation Storage Ring (4GSR) should be designed to prevent the dose limits from being exceeded. Although the site boundary dose limit under the current Act applies only to nuclear reactor-related facilities, it is applied to the 4GSR due to direct radiation effects—including "skyshine"—which must be considered for large accelerator facilities like the 4GSR. In addition to the effective dose limits, the following criteria must also be satisfied:

- The concentrations of liquid and gaseous radioactive materials discharged from the facility must be lower than the discharge control limits specified in the Nuclear Safety Act.

In accordance with the “As Low As Reasonably Achievable” (ALARA) principle, the dose limit standards of the 4GSR should be set by the 4GSR operation body to consider the safety margin. It was applied when designing radiation shielding as follows:

- **Shielding criteria**
  - Normal operation (accessible area for radiation workers): 10 mSv per year
  - Normal operation (accessible area for the public, including users): 1 mSv per year

- Accidental condition: (maximum exposed dose) 1 mSv per incident

In the view of ALARA, half of the annual limit for radiation workers is applied to areas where they access regularly. Even if frequent visitors other than radiation workers enter the same area, there will be no separate shielding criteria due to the sufficiently low access time of fewer than 2,000 hours per year. Because the access time of synchrotron radiation users is also short, the dose limits of 1 mSv per year for the SR beamline experimental area, which is a regular accessible area for synchrotron radiation users, is sufficient for providing a safety margin. In the shielding criteria for accident conditions, the maximum exposure dose caused by a single accident should not exceed the annual dose limit of 1 mSv for the public.

6.1.2 Area Control and Safety Control Procedures

To ensure radiation safety, areas must be classified and managed appropriately based on dose criteria. The areas are defined as follows:

- **Restricted Area**: 0.25 mSv per year or more and less than 1 mSv per year
- **Generally-Controlled Area**: 1 mSv per year or more and less than 20 mSv per year
- **Radiologically-Controlled Area**: 20 mSv per year or more & less than 1 mSv per hour
- **High-Radiation Area:** 1 mSv per hour or more (No access zone)

The radiologically-controlled area is defined as any area that may exceed 0.4 mSv per week, as prescribed by the Nuclear Safety Act, which is equivalent to an annual dose of 20 mSv. Access to the radiologically-controlled area is permitted only for radiation workers and frequent visitors who have undergone the required training and health check-ups under the Nuclear Safety Act, and they must wear a personal dosimeter. Based on the dose rate limits, the shielding criterion is set at 5 μSv per hour following the ALARA protocol, while the generally-controlled area is limited to 0.5 μSv per hour. The high-radiation area—where human access is prohibited—refers to the interior of the accelerator tunnel during beam operation. Once beam operation ceases, the accelerator tunnel is reclassified as a radiologically-controlled area.

The SR beamline experimental area, including the experimental hutch, must be managed as a generally-controlled area. Although synchrotron radiation users in this area are classified as the general public, they must wear personal dosimeters due to the potential for exceeding the public dose limit. Furthermore, synchrotron radiation users are prohibited from entering specific areas such as the optics hutch within the experimental area. Both the experimental hutch and the optics hutch are designated as high-radiation areas during synchrotron radiation exposure, and access is strictly prohibited.

6.2 Radiation Shielding

6.2.1 Radiation Sources and Electron Beam Loss Scenarios

This section outlines key radiation sources relevant to radiation safety analysis and examines electron beam loss scenarios under both normal and abnormal operations. The FLUKA Monte Carlo code was used to determine the tunnel wall shielding and to confirm the preliminary shielding analysis performed using the SHIELD11 code.

During normal operation, the electron beam can strike components in the Linac, booster ring, or storage ring, producing high-energy bremsstrahlung photons, which in turn generate photoneutrons. In abnormal conditions, accidental beam loss also leads to high-energy radiation, necessitating proper shielding. Additional radiation sources in beamline shielding calculations include gas bremsstrahlung (GB) from electron interactions with residual gas and synchrotron radiation from bending magnets, wigglers, or undulators. All these radiations must be adequately shielded during analysis. Followings are the radiation sources in a synchrotron facility:

- Electron beam loss inside the tunnel
- High energy bremsstrahlung photons
- Photoneutrons
- Additional radiation sources for beamline shielding design:
    - GB
    - Synchrotron radiation

Beam loss scenarios under normal operation for each accelerator component, linear accelerator (Linac), booster ring, and storage ring are as follows:

(1) Linear Accelerator (Linac)

The Linac is designed to accelerate the electron beam through the accelerating columns to an energy of up to 200 MeV. During top-up operation with injection to storage ring every 2 minutes, the Linac operates at 2 Hz with a beam charge of 3 nC per pulse. The beam injection time from the Linac to the booster ring is 2.89 s/injection during the top-up operation. This results in a beam loss of 0.91 nC/2min (assuming 5% loss during extraction) at the Linac extraction point. However, during commissioning and diagnostics operations, the Linac operates at 10 Hz with a beam charge of 3 nC per pulse directed to the Linac beam dump. For shielding analysis, the following loss scenarios were considered for normal operation:

- 1% of the electron beam charge is lost at any location in the Linac (10 Hz, 3 nC/pulse, 200 MeV).

The following loss scenarios were considered for abnormal operation:

- 100% beam loss was assumed at the last accelerating column, resulting in a loss rate of 30 nC/s, equivalent to 1.88×10^{11} e/s (Linac-only mode). This is 2 orders of magnitude higher than normal operation.
- It was also assumed that the entire extracted beam from the Linac is lost at the first or second bending magnet in the LTB. The extracted beam loss amounts to 18.3 nC/2 min, equivalent to 9.53×10^{8} e/s (Linac injection mode), which is 20 times higher than the normal operation loss.

(2) Booster ring beam loss assumptions

The following loss scenarios were considered for normal operation:

- The injection efficiency from the Linac to the booster ring is assumed to be 90%, meaning 10% of the electron beam is lost:
  - 5% is lost at the Linac-to-booster injection septum.
  - 5% is uniformly distributed along the booster ring orbit.
- During acceleration from 200 MeV to 4 GeV, a 20% beam loss is assumed (1.63×10^{8} e/s). All lost electrons are considered to have the final energy of 4 GeV, making this a highly conservative assumption.
- Once the beam reaches 4 GeV, it is extracted via the extraction septum and transferred to the storage ring. A 5% beam loss is also assumed at the extraction septum (3.26×10^{7} e/s).

The following loss scenarios were considered for abnormal operation:

- In an abnormal scenario, a localized beam loss of 4 nC/2 min (2.08×10^{8} e/s) is assumed near a specific point, such as a maze door, rather than being uniformly distributed across the ring.

(3) Storage Ring Beam Loss Assumptions

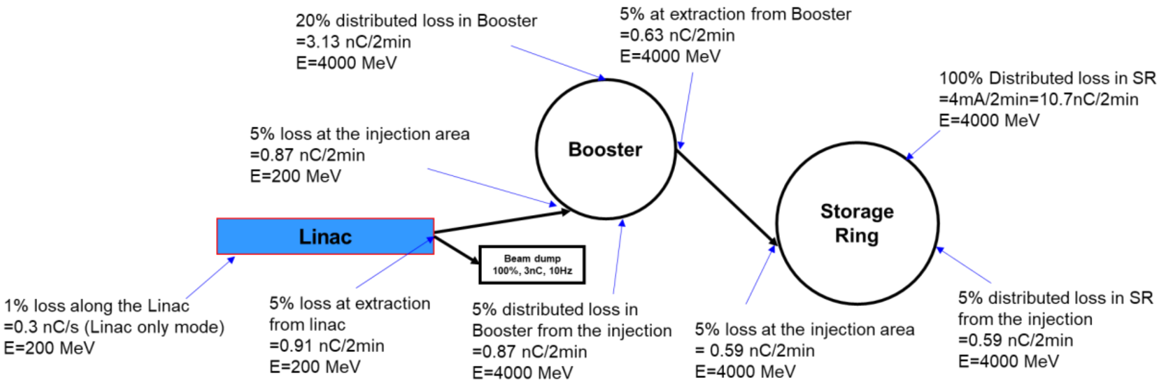
The following loss scenarios were considered for normal operation:

- The injection efficiency from the booster ring to the storage ring is assumed to be 90%, meaning 10% (6.19×10^7 e/s) of the electron beam is lost:
    - 5% is lost at the injection septum.
    - 5% is uniformly distributed along the storage ring orbit.
- The stored electron beam in the storage ring undergoes a continuous beam loss of 4 mA/2 min (10.7 nC/2 min, 5.57×10^8 e/s), which is also uniformly distributed along the ring.

The following loss scenarios were considered for abnormal operation:

- In the event of a sudden radio frequency (RF) power loss, the entire stored beam (400 mA) is assumed to be lost at a quadrupole magnet (QM) or sextupole magnet (SM), based on beam dynamics simulations.

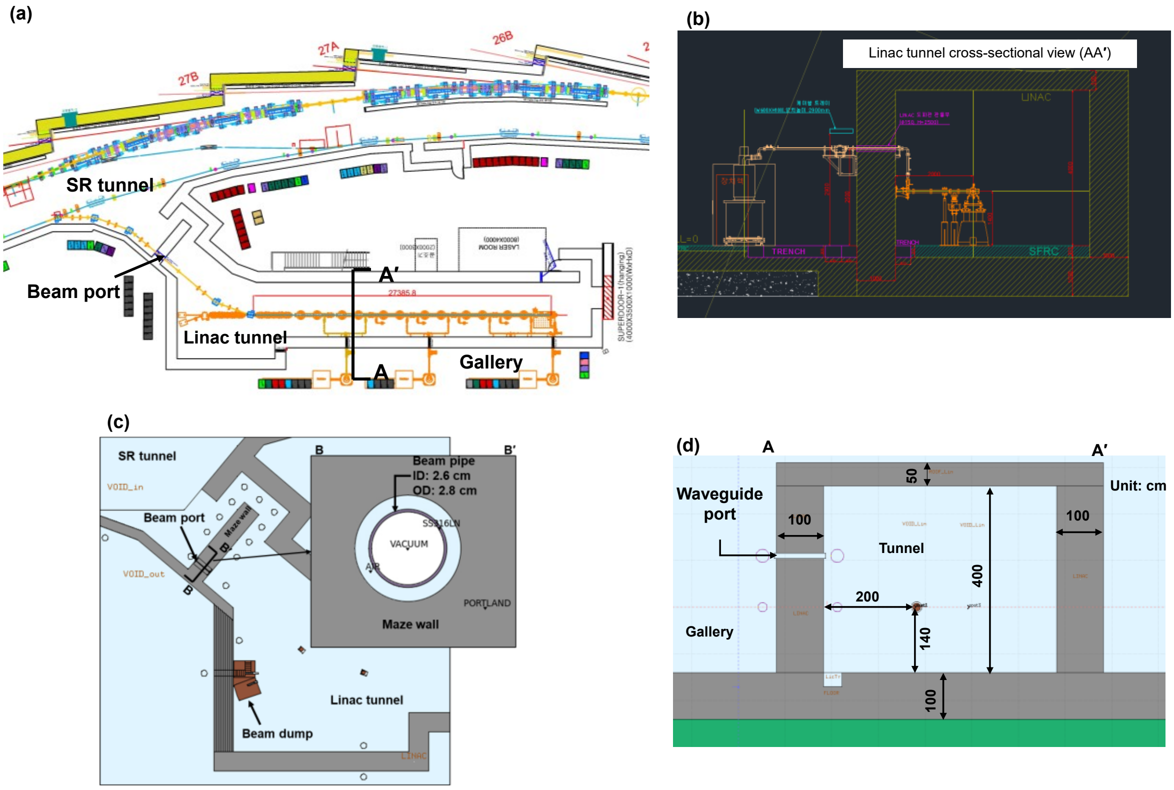
The above beam loss scenarios are summarized in <Figure 6.2.1.1 >.



<Figure 6.2.1.1> Schematic drawing of assumed beam loss scenarios for the normal operation.

6.2.2 Linac Shielding Calculations Under Normal and Abnormal Operations

<Figure 6.2.2.1 (a,b)> shows the CAD drawing of the Linac in the top view and cross-sectional views, illustrating the Linac to booster line, Linac tunnel, Linac gallery, and tunnel wall structure. The corresponding geometries modeled in FLUKA are also shown in <Figure 6.2.2.1(c,d)> in top and cross-sectional views.

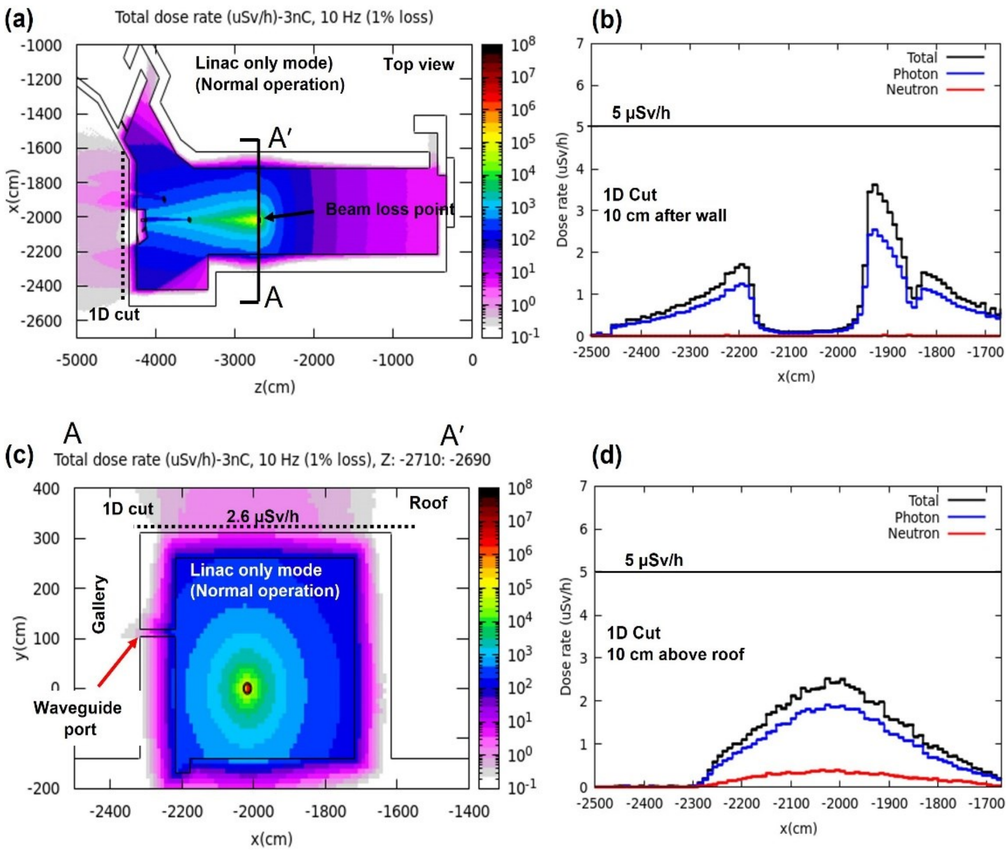


<Figure 6.2.2.1> Information of the Linac tunnel, (a) CAD drawing in the top view, (b) CAD drawing in cross-sectional view along the AA′ cut line, (c) FLUKA geometry in top view, and (d) FLUKA geometry in cross-sectional view.

The total dose rate distribution for this beam loss scenario is illustrated in <Figure 6.2.2.2 (a)> in the top view centered at the beam height. It is seen that the dose rate after the lateral walls is below 0.2 μSv/h, while the photon dose rate in the forward direction is dominant. The dose rate along the one-dimensional (1D) cut line marked in <Figure 6.2.2.2 (a)> is illustrated in <Figure 6.2.2.2 (b)>. It is seen that the total dose rate is around 4 μSv/h at 10 cm after the wall. The photon dose contributes significantly to the total dose, while the neutron dose rate is negligible. The dose rate distribution at the roof above the beam loss position and through the waveguide port is shown in the cross-sectional view in <Figure

6.2.2.2 (c)>. The total dose rate at the waveguide entrance is below 0.3 μSv/h, and the total dose rate 10 cm above the roof is 2.6 μSv/h. The contribution of photon and neutron dose rate to the total dose rate is shown in <Figure 6.2.2.2 (d)>, and as seen, the photon dose rate dominantly contributes to the total dose rate than the neutron dose rate.

In the event of an abnormal beam loss scenario, 100% of the electron beam could be lost at any location along the Linac. This means that the beam loss rate will increase by 2 orders. This abnormal condition would result in a dose rate of 400 μSv/h at 10 cm after the wall in the forward direction and 260 μSv/h at 10 cm above the roof. However, these dose rates remain below the 1000 μSv/incident threshold for an accident scenario. Additionally, the interlock system is designed to shut off the beam if the dose rate exceeds the dose limit. According to these data, the dose rate at all locations around the Linac tunnel is well below 5 μSv/h for these beam loss scenarios.

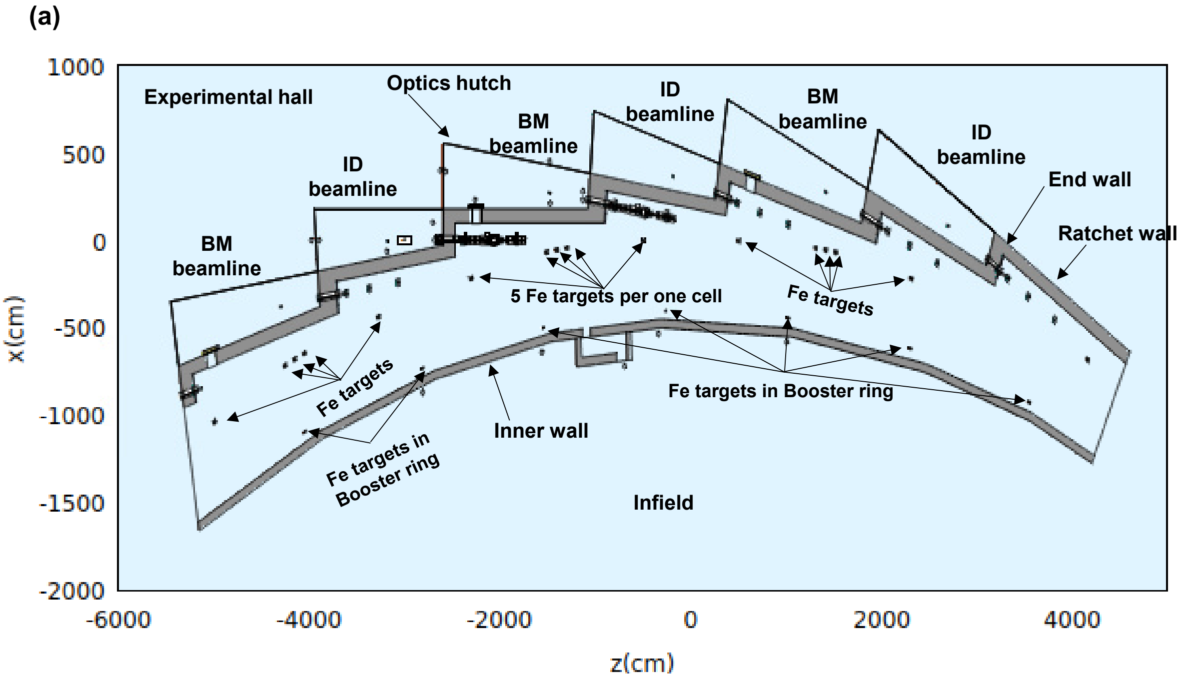


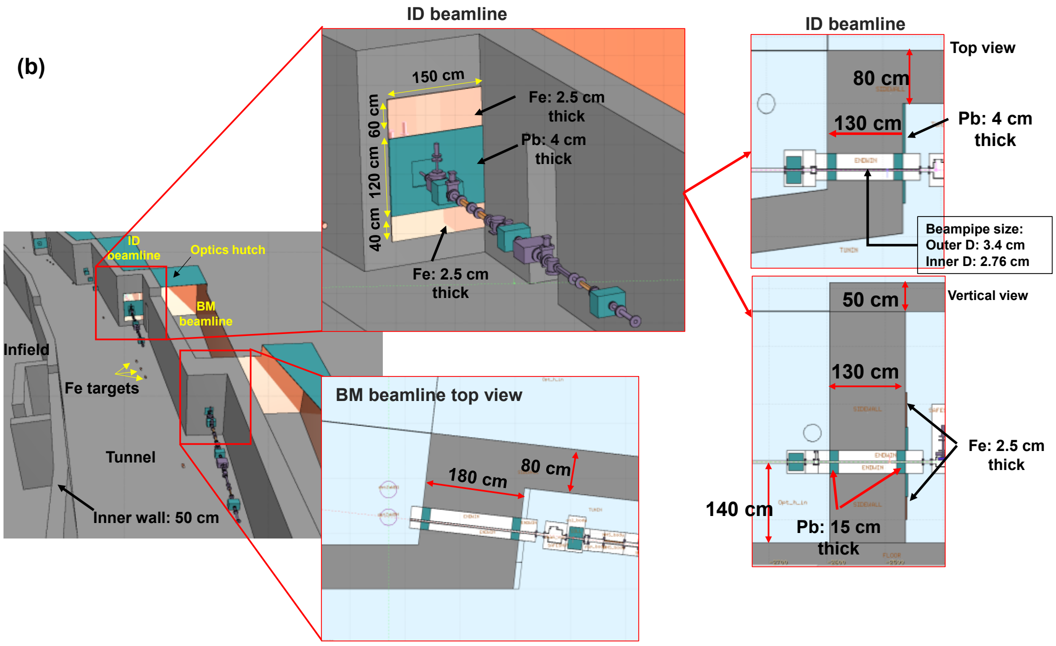
<Figure 6.2.2.2> Calculated dose rate for beam loss of 0.3 nC/s (1.88 × 10^9 e/s) under normal operation, (a) total dose rate distribution in the top view, (b) contribution of the photon and neutron dose rates to the total dose rate after the wall along the 1D cut line, (c) total dose rate distribution in cross-sectional view along the marked AA′ cut line, and (d) contribution of the photon and neutron dose rates to the total dose rate along the 1D cut line above the roof.

6.2.3 Shielding Calculations of Storage Ring Tunnel in Normal Beam Loss Scenarios

A. Shielding Calculations for the Non-Injection Area

During normal operation, the electron beam is lost uniformly over the storage ring and along the booster ring. The shielding calculations were performed for the uniformly distributed beam loss in the storage ring and uniformly distributed along the booster ring separately. Then, the results from two beam loss scenarios were added up to obtain the total dose rate. The modeled geometry of the non-injection area in the top view and in 3D are illustrated in <Figure 6.2.3.1>, showing the target positions in the storage ring and the booster ring. In the storage ring, 5 targets at each cell were assumed based on the beam dynamics simulations. The target locations in the booster ring were assumed to be at the bending magnets, where the beam loss probability is higher.





<Figure 6.2.3.1> The non-injection area of the 4GSR tunnel modeled in the FLUKA code, (a) 2D in top view, and (b) 3D view showing the details of the tunnel structure.

The ratchet end walls for ID and BM beamline have different shielding structures, as depicted in <Figure 6.2.3.1 (b)>. The information on the shielding materials and their thickness are listed in <Table 6.2.3.1>.

<Table 6.2.3.1> Required shielding materials and the thickness of the tunnel in the non-injection area

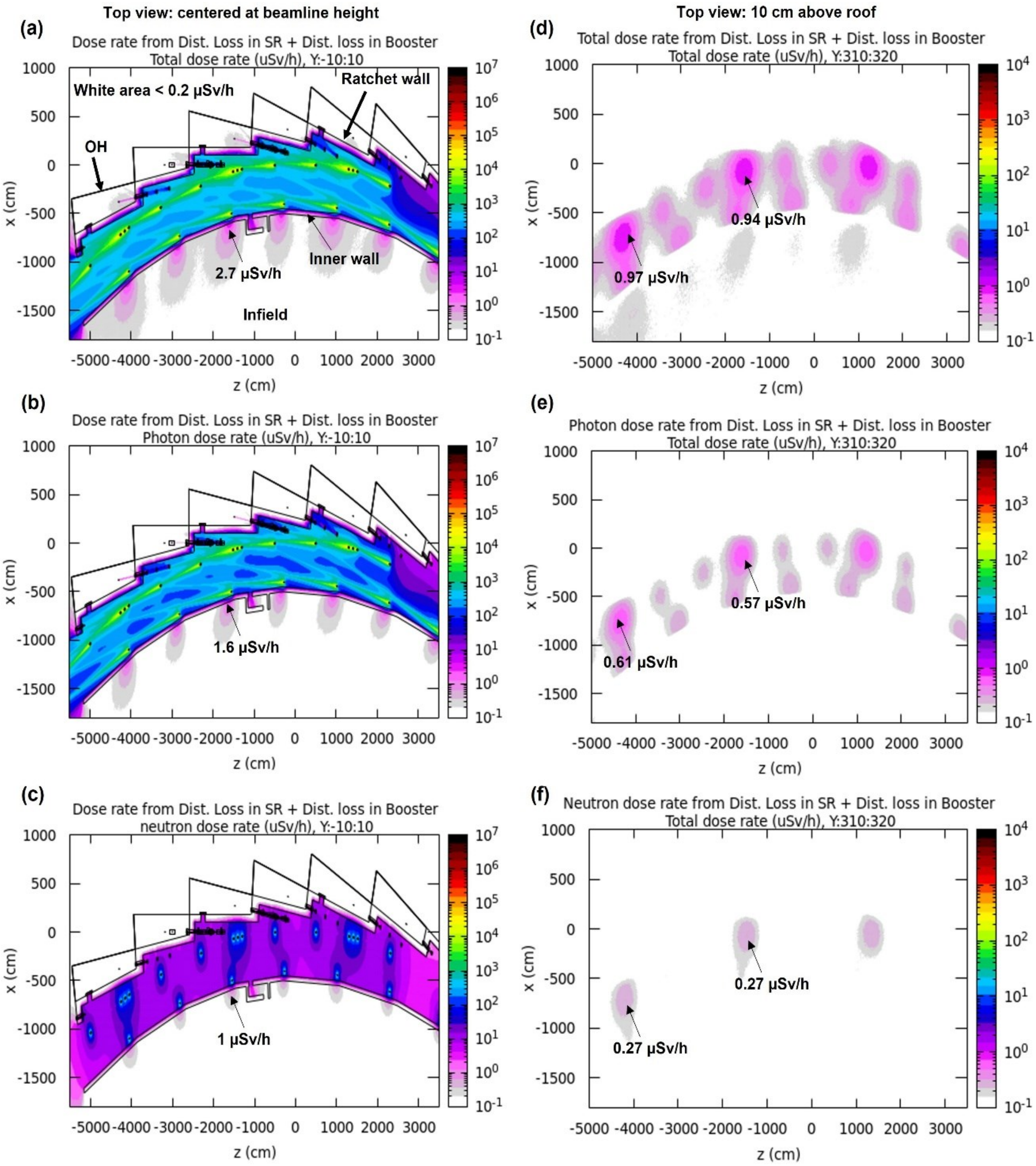
Position	Shielding material and thickness
Ratchet wall	80 cm O.C[a]
Inner wall	50 cm O.C.
End wall	ID beamline: 130 cm O.C.+ 4 cm Pb with two 2.5 cm Fe plates
	BM beamline: 180 cm O.C.
Ceiling	50 cm O.C.

[a]Ordinary concrete: ρ=2.3 g/cm^3

The calculated dose rate for two beam loss scenarios, e.g., uniformly distributed over SR and uniformly distributed over the booster ring, are shown in <Figure 6.2.3.2(a,b,c)> in the top view centered at the beamline height for the total, photon, and neutron dose rates. The total dose rate contributed by the electron beam loss in SR and booster ring is below 0.2

μSv/h in the experimental area, which is below the dose limit of 0.5 μSv/h. On the other hand, the total dose rate distribution in the infield area is contributed mainly by the electron beam loss in the booster ring. The total dose rate reaches 2.7 μSv/h after the inner wall. This is below the dose limit of 5 μSv/h defined for the radiation worker area. The photon and neutron dose rate distributions shown in <Figure 6.2.3.2(b,c)> indicate that the photon dose after the inner wall is 1.6 μSv/h and that of neutron is 1 μSv/h.

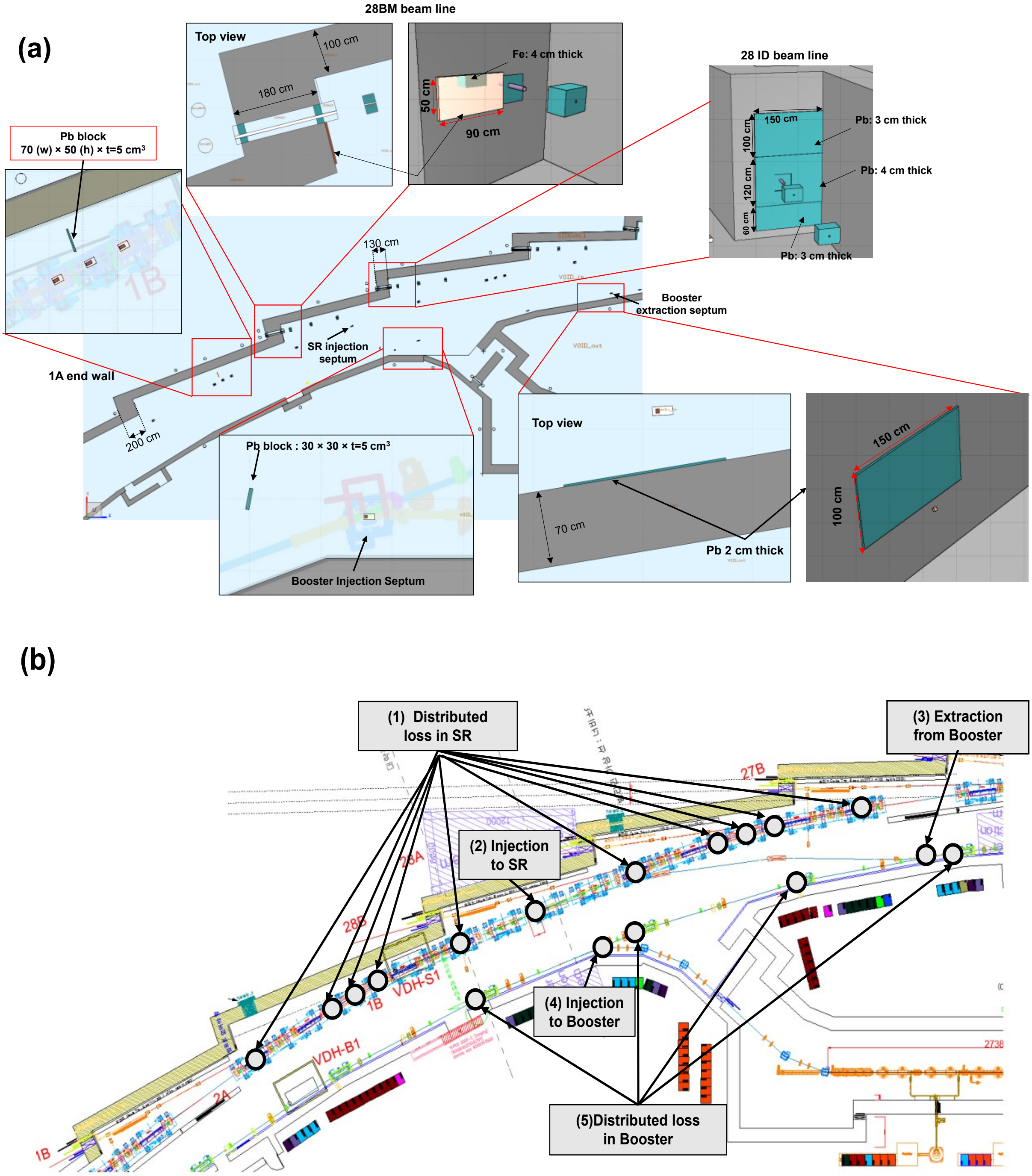
Additionally, the dose rate distributions 10 cm above the roof are shown in <Figure 6.2.3.2 (d,e,f)> for the total, photon, and neutron, respectively. The total dose rate at the roof is less than 1 μSv/h, and it is mainly contributed by the photon dose rate. The FLUKA calculations confirm that the shielding structure at the non-injection area suffices to keep the dose rate below the radiation shielding criteria.



<Figure 6.2.3.2> Dose rate distributions around the accelerator tunnel under normal operation, (a) total, (b) photon, and (c) neutron dose rate in the top view centered at the beamline height, (d) total, (e) photon, and (f) neutron dose rate at 10 cm above the roof. Uniformly distributed beam loss in SR and uniformly distributed in booster ring are added up.

B. Shielding Calculations for the Injection Area

In this section, the shielding calculations of the injection area are presented. The FLUKA geometry is shown in <Figure 6.2.3.3>, and the required shielding materials are listed in <Table 6.2.3.2>



<Figure 6.2.3.3> Injection area of 4GSR, (a) FLUKA geometry model showing the detailed shielding structure of the tunnel, and (b) beam loss positions for 5 beam loss scenarios in normal operation.

The 200 MeV-electron beam from the Linac is injected into the booster ring, and after reaching the energy of 4 GeV, it is extracted from the booster ring and then injected into the SR. During the injection process, the electron beam is lost due to misalignment of the components or magnetic field error of the septum magnets. The injection point from Linac to booster ring, the extraction point from booster ring, and the injection point to SR are close to each other. The outer wall of the storage ring-booster tunnel faces the experimental area, which is accessible to the general public, specifically users of synchrotron radiation. Since both the storage ring and the booster ring are housed in the same tunnel, the combined radiation dose from beam losses in both must not exceed 0.5 μSv/h to determine the required thickness of the outer tunnel wall.

For the infield area outside the inner wall, where public access is restricted, a shielding design limit of 5 μSv/h was applied. The shielding analysis for the injection area was performed for 5 beam loss scenarios individually. The beam loss scenarios were (1) uniformly distributed beam loss over the storage ring, (2) beam loss at the storage ring injection septum, (3) beam loss at the booster extraction septum, (4) beam loss at the booster injection septum, and (5) uniformly distributed beam loss over the booster ring. The total dose rate from all beam loss scenarios was summed up to ensure the total dose rate was below the criteria. The beam loss locations are indicated in <Figure 6.2.3.1 (b)>.

<Table. 6.2.3.2 > Required shielding materials in the injection area

Position (Injection area)	**Shielding material and thickness**
Ratchet wall	100 cm O.C.
Inner wall	- Near Booster extraction septum: 70 cm O.C + 2 cm Pb plate - Other areas: 70 cm O.C.
End wall	28 ID beamline: 130 cm O.C. + 4 cm thick Pb with 3 cm-thick Pb plates up and down
	28 BM beamline: 180 cm O.C. + 4 cm thick Fe
	1A end wall: 200 cm O.C.
Ceiling	70 cm O.C.

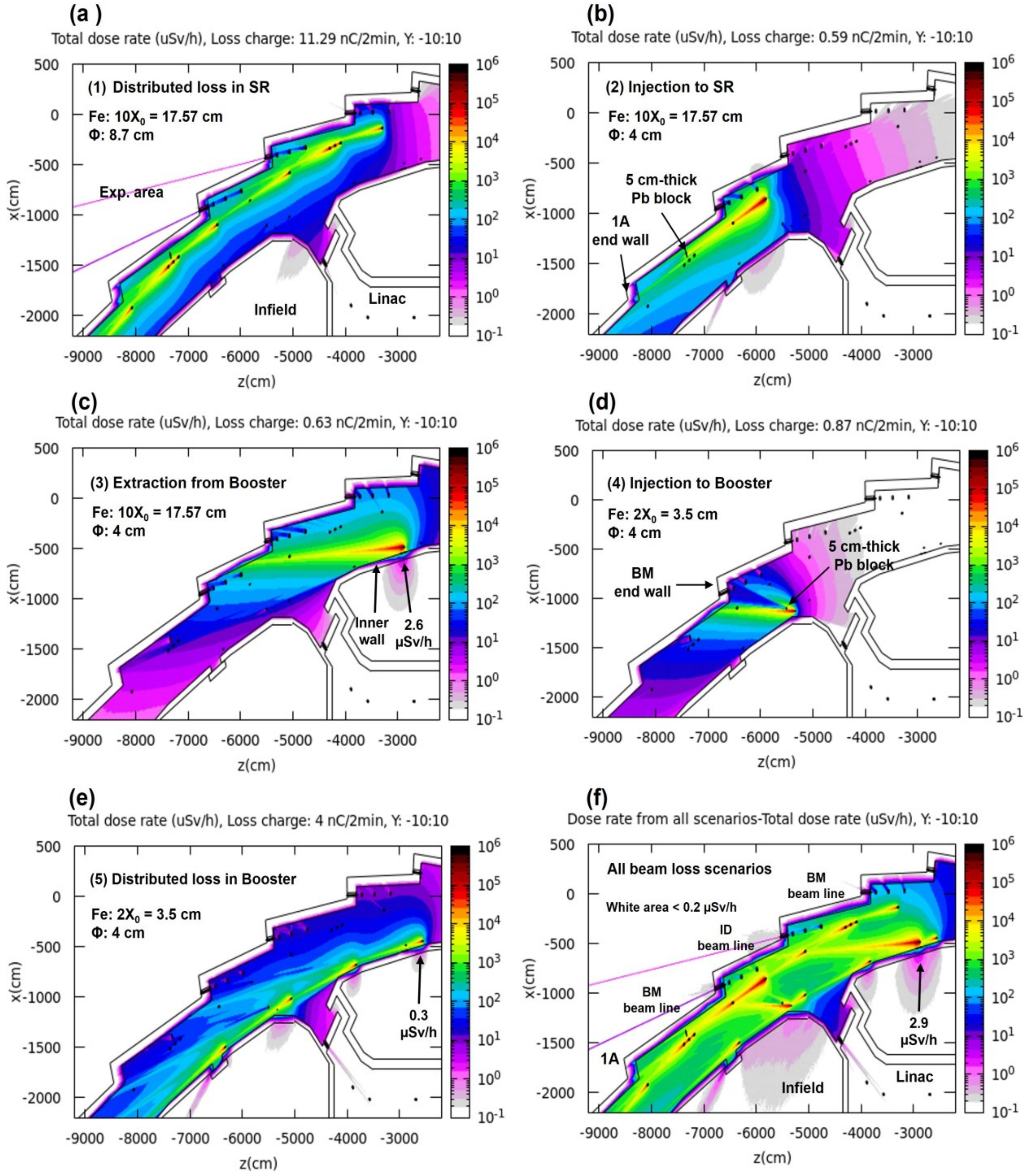
The calculated dose rate from each beam loss scenario is shown in <Figure 6.2.3.4 (a-e)>, and the total dose rate from all beam loss scenarios for the normal operation is illustrated in <Figure 6.2.3.4 (f)>. The target information for each case is indicated on each figure as well.

The distributed beam loss in the storage ring contributes to the dose rate in the experimental area rather than the infield area (<Figure 6.2.3.4 (a)>).

The beam loss at the injection point into the storage ring contributed significantly in the forward direction where the 1A end wall is located therefore, a Pb block with a thickness of 5 cm was used to suppress the forward-peaked radiation as shown in <Figure 6.2.3.4 (b)>. The dose rate results indicated in <Figure 6.2.3.4 (c)> show that the beam loss at the extraction septum of the booster contributes mainly to the dose rate after the inner wall, and that is 2.6 μSv/h. Since the beam extraction point is close to the inner wall, a Pb plate with dimensions of 150 (w) × 100 (H) × t=2 cm^3 was also attached to the wall, as shown in <Figure 6.2.3.1 (a)>.

Based on the FLUKA calculations, when the electron beam was lost at the injection point from the Linac to the booster, the generated radiation could penetrate the BM end wall, which is in the forward direction of the radiation. Therefore, a 5 cm-thick Pb block was located right after the beam loss position. It can be seen from <Figure 6.2.3.4 (d)> that the Pb block is effectively attenuating the radiation. The distributed beam loss in the booster ring contributes to the dose rate in the infield area and less to the experimental area due to its distance. <Figure 6.2.3.4 (e)> illustrates that the dose after the inner wall is 0.3 μSv/h for this beam loss scenario. It is seen from <Figure 6.2.3.4 (f)> that the total dose rate in the experimental area is below 0.2 μSv/h, considering all beam loss scenarios.

The total dose rate after the inner wall is 2.9 μSv/h as it is close to the beam extraction point from the booster. The dose rate in the experimental area and in the infield area are less than the dose limits of 0.5 and 5 μSv/h, respectively, showing the effectiveness of the tunnel shielding. Furthermore, the dose rate distributions at 10 cm above the roof were calculated. The total dose rate reached 1.7 μSv/h above the booster extraction septum, which is below the dose criteria of 5 μSv/h.



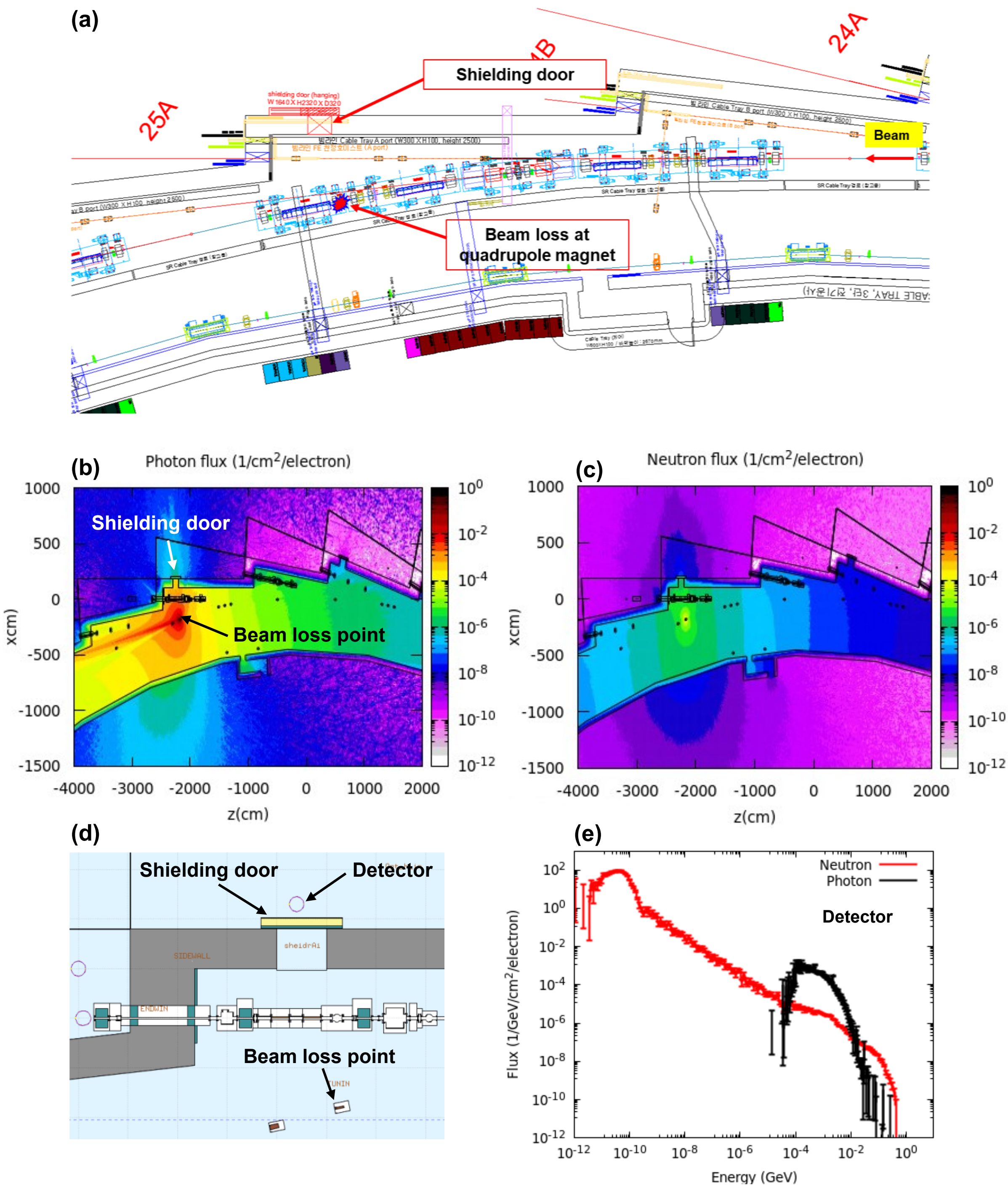
<Figure 6.2.3.4> Dose rate distributions in the top view for all 5 beam loss scenarios under normal operation in the injection area, (a) uniformly distributed beam loss over the storage ring, (b) beam loss at storage ring injection septum, and (c) beam loss at the booster extraction septum, (d) beam loss at the booster injection septum, (e) uniformly distributed beam loss over the booster ring, and (f) all beam loss scenarios.

6.2.4 Shielding Calculations for Abnormal Beam Loss Scenarios in Storage Tunnel

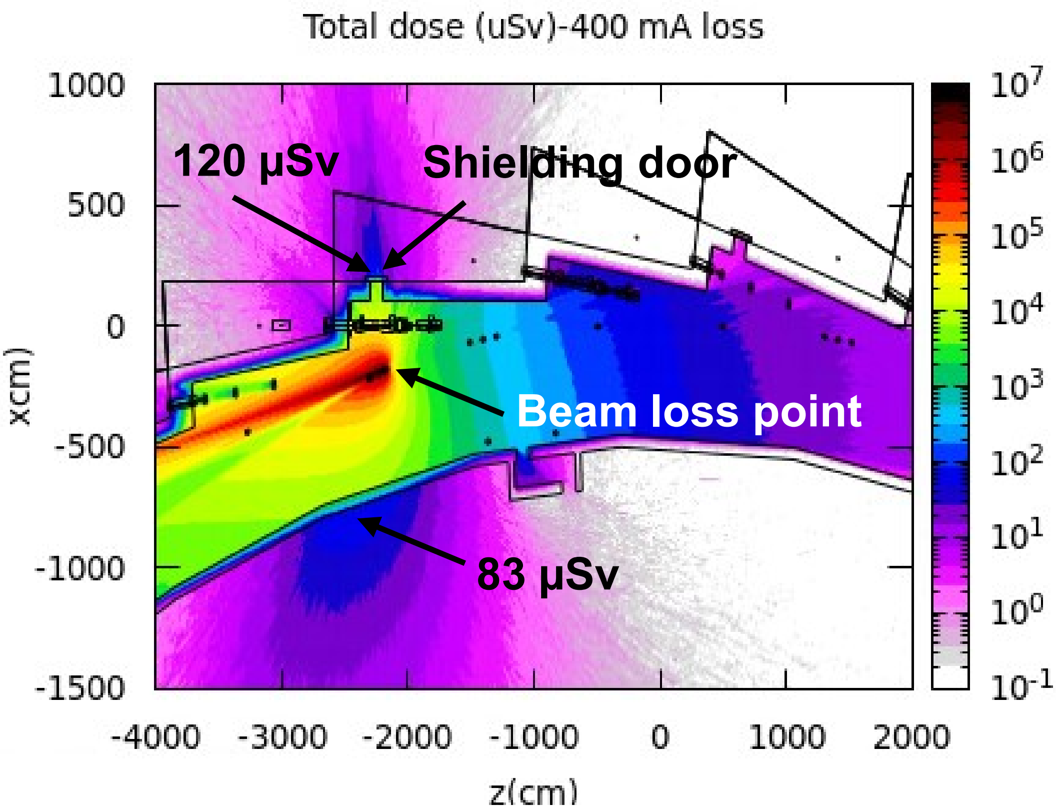
A. Accident in Storage Ring (Stored Beam Loss)

In this accidental beam loss scenario, it is assumed that the 400 mA (6.67×10^{12} e) stored beam current is lost at the quadrupole magnet of a normal cell as marked in <Figure 6.2.4.1 (a)>. The location of this beam loss was reported by the beam dynamics group as an abrupt RF power loss. The photon and neutron fluence distribution inside and outside the accelerator tunnel are presented in <Figure 6.2.4.1 (b,c)>. The photon fluence distribution is forward-peaked, while the neutron fluence distribution is quite isotropic. In addition, the photon and neutron energy spectra were also calculated after the shielding door shown in <Figure 6.2.4.1 (d)> as the door is close to the loss point, and the results are shown in <Figure 6.2.4.1 (e)>. The shielding door has a layered structure and is made of 1 cm-thick Fe + 5 cm-thick Pb + 15 cm-thick polyethylene + 1 cm-thick Fe. The figure shows that the photon fluence is higher than the neutron fluence over the energy range of 10^{-4} to 10^{-2} GeV. The neutron energies, however, expand to the lower energies of 10^{-12} GeV as they are scattered by the walls and are thermalized by the polyethylene used in the shielding door.

The total dose distribution in the top view centered at the beamline height is shown in <Figure 6.2.4.2>. The maximum dose after the shielding door is 120 μSv, which is far below the dose criteria of 1000 μSv for one event for abnormal operation. Under this beam loss condition, the shielding door and tunnel walls appear to provide sufficient shielding effectiveness.



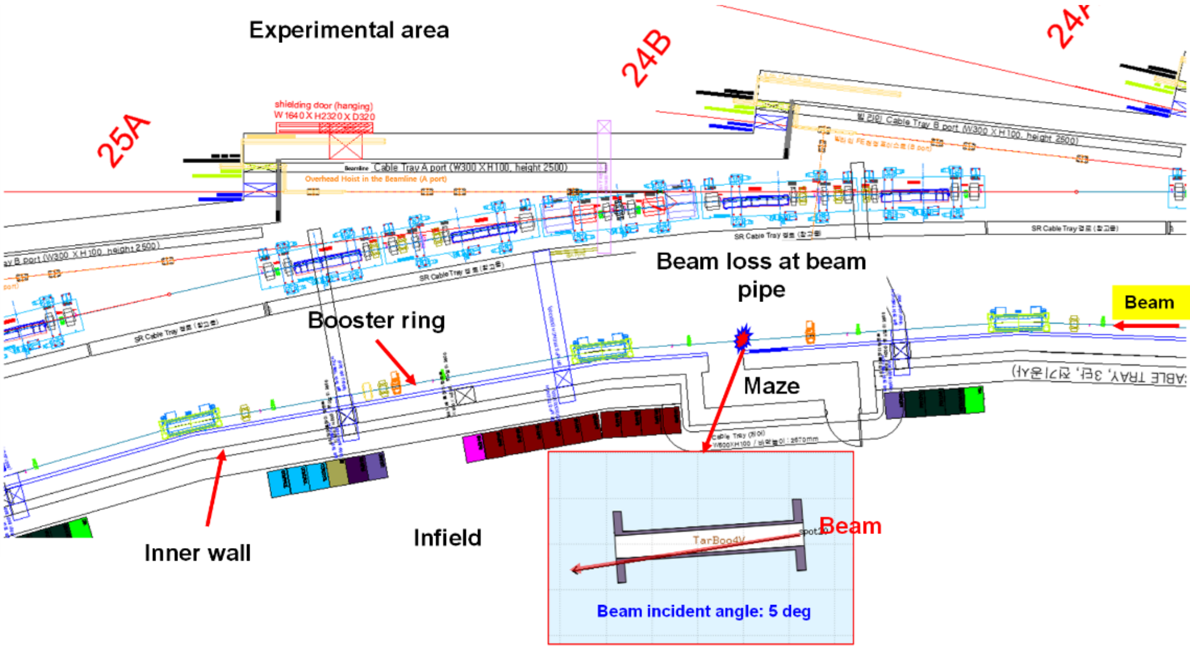
<Figure 6.2.4.1> Abnormal beam loss when a 4-GeV electron beam impact on an $10X_0$-thick Fe target, (a) beam loss location, (b) photon fluence distribution in the top view, (c) neutron fluence distribution in the top view, (d) location of detector after the shielding door, and
(e) photon and neutron energy spectra at the shown detector position.



<Figure 6.2.4.2> Total dose rate around the shielding door in top view for an accidental beam loss scenario in which 4 GeV-electron beam (400 mA) hits QM in the SR.

B. Accident in Booster Ring

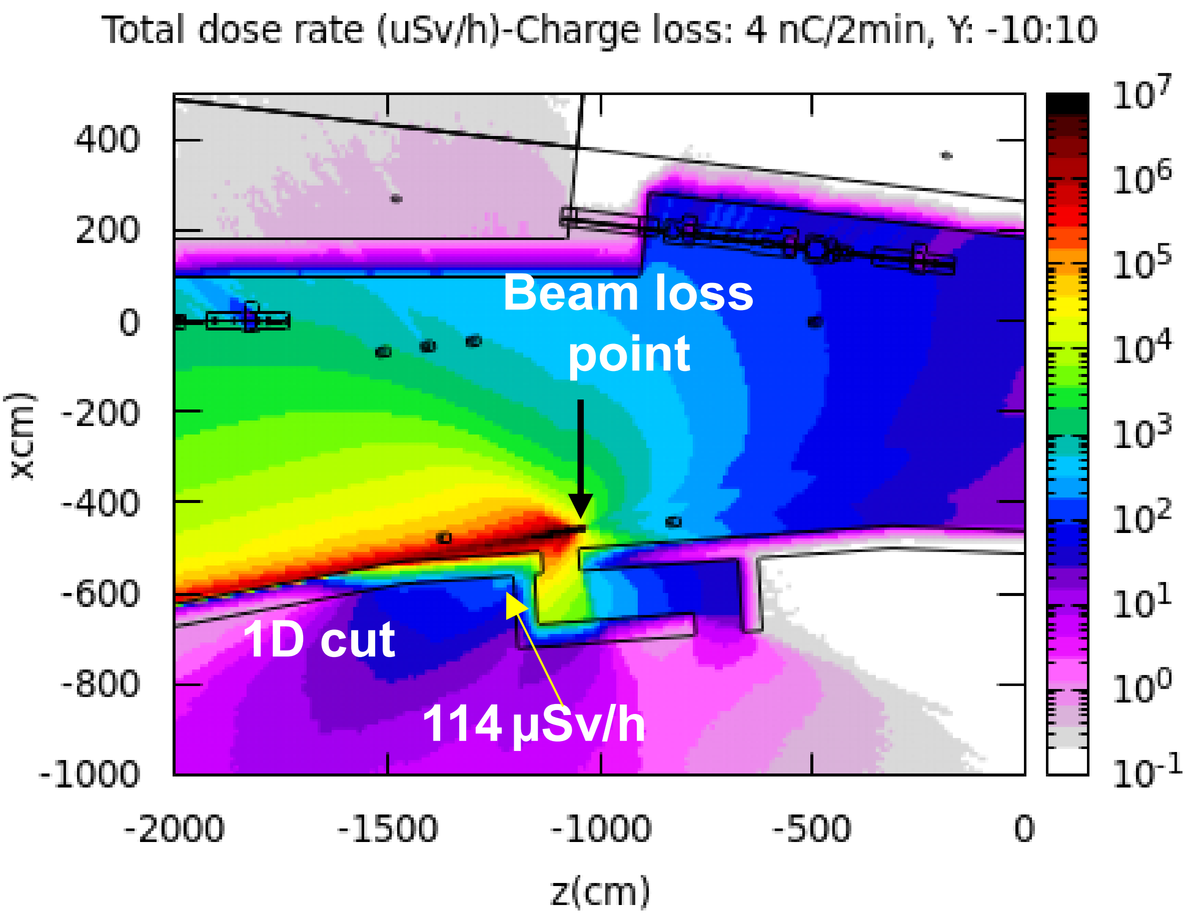
In this beam loss scenario, it is assumed that the electron beam lost in front of the maze door after hitting the beam pipe with an incident angle of 5 degrees. The beam pipe thickness is 7 mm and is made of stainless steel (SS316LN). The electron beam loss position is indicated in <Figure 6.2.4.3>. In the FLUKA calculations, the following conditions were assumed: electron beam energy: 4 GeV, beam loss rate: 4 nC/2min (2.08×10^8 e/s), target: SS316LN beam pipe (thickness= 7 mm). The electron beam hits the beam pipe with an incident angle of 5 degrees and feels an effective thickness of 80.3 mm.



<Figure 6.2.4.3> Abnormal beam loss when a 4GeV electron beam impacts on a beam pipe with an incident angle of 5 degrees in the booster ring.

The total dose rate distribution in the top view for this accidental beam loss scenario after the inner wall is depicted in <Figure 6.2.4.4>, and the total dose rate reaches the maximum of 114 μSv/h, which is below the dose limit of 1000 μSv per one event. In addition, the interlock system will shut down the beam if the dose surpasses the dose limit.

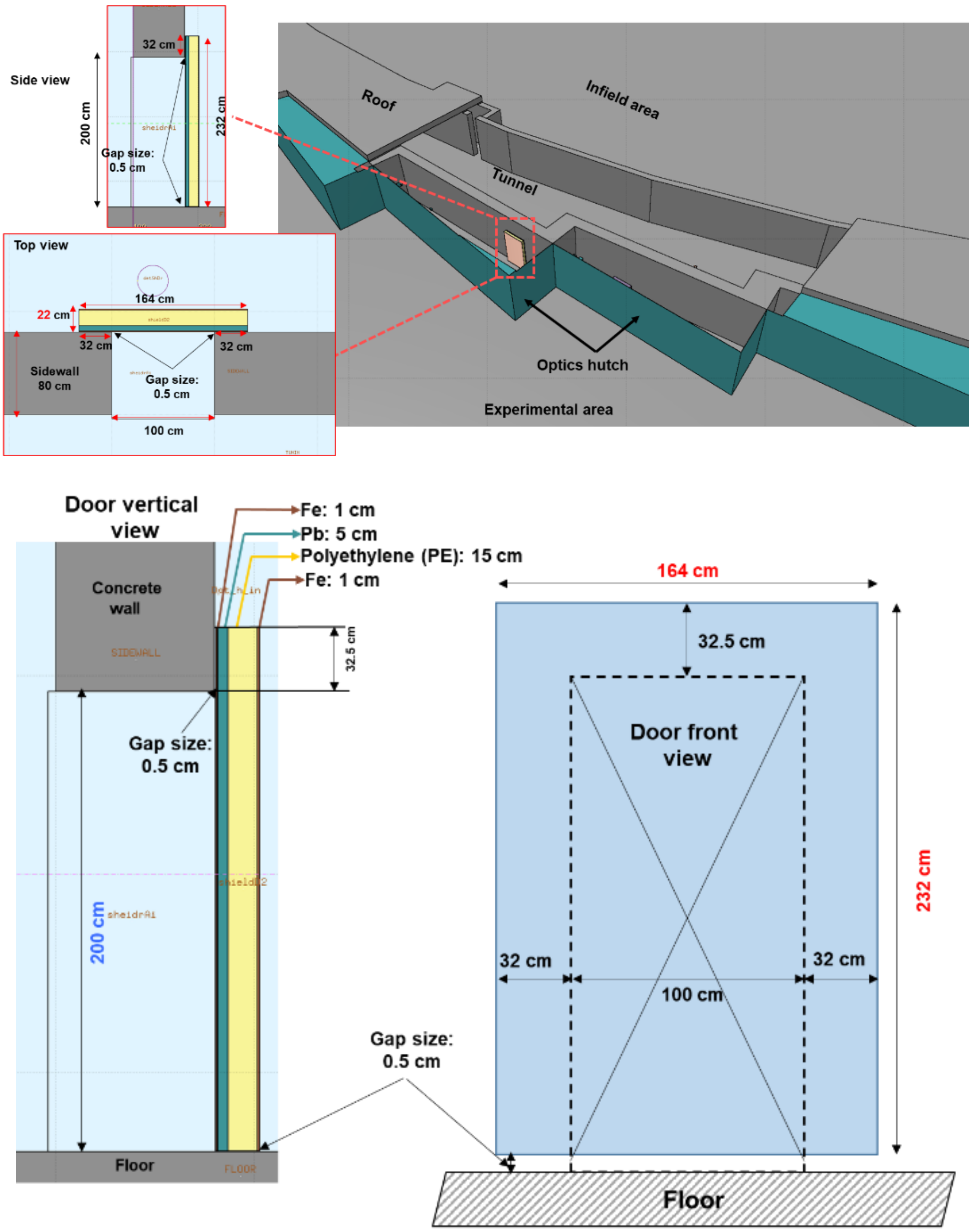
According to these calculations, under the abnormal beam loss scenarios, it can be concluded that the tunnel shielding structure and interlock system will suffice to keep the dose rate below the criteria for both normal and abnormal operations.



<Figure 6.2.4.4> Total dose rate around the maze in top view for an abnormal operation in which 4 nC/2min electron charge is lost at beam pipe in the booster ring.

6.2.5 Shielding Door Design

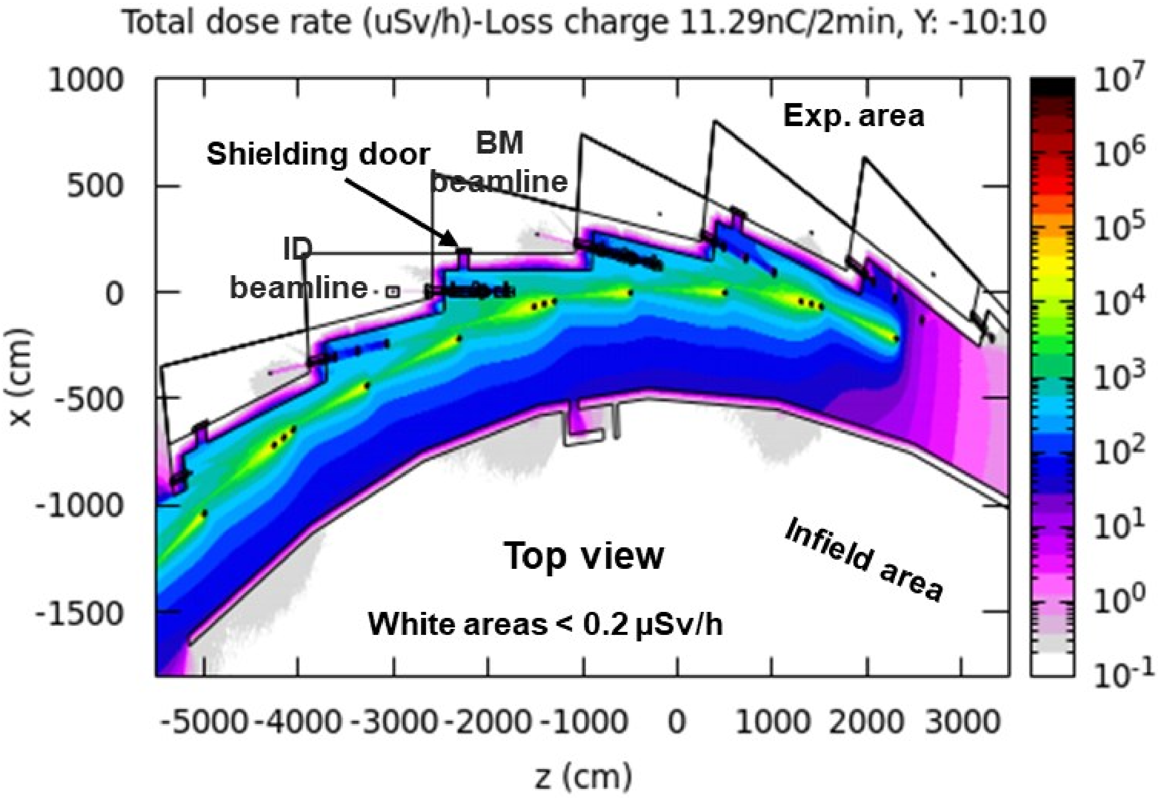
In the 4GSR tunnel, there are 10 hanging shielding doors. In this section, the design of the shielding door is presented. A multi-layered structure of iron (Fe) + lead (Pb) + polyethylene (PE) was considered for the door. <Figure 6.2.5.1> shows the modeled geometry in FLUKA, illustrating the position as well as the dimensions of the shielding door. The door dimensions are 164 cm in width and 232 cm in height, 22 cm thick, and a gap of 0.5 cm was assumed between the shielding door and the floor of the tunnel wall. The entrance dimensions were 100 cm in width and 200 cm in height, but the door was designed to provide sufficient overlap.



<Figure 6.2.5.1> FLUKA geometry showing the SR tunnel, shielding door, and its dimensions.

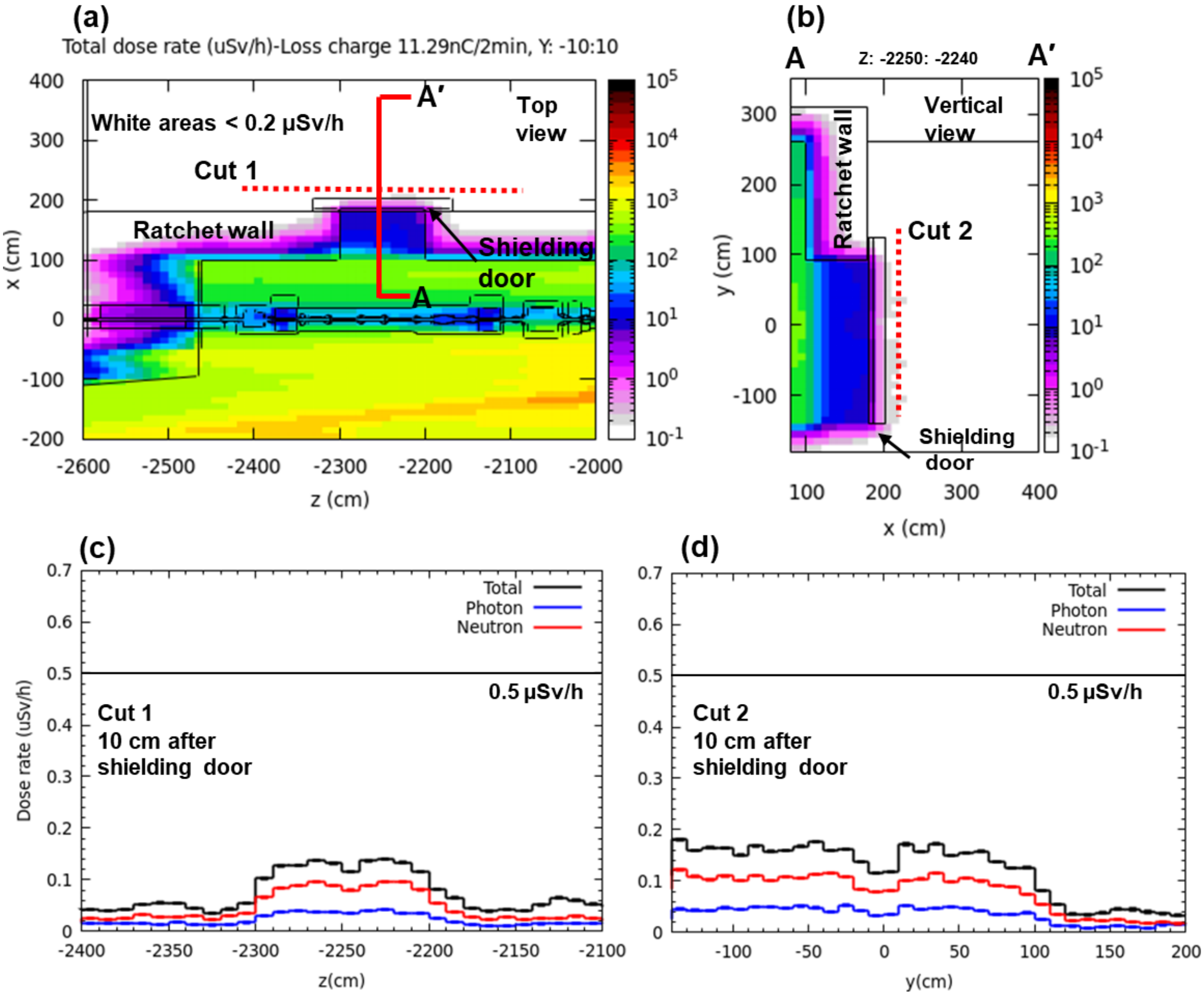
A. Evaluation of the Shielding Door Effectiveness (Beam Loss Scenario 1)

The effectiveness of the shielding door was evaluated for the uniformly distributed beam loss over the SR under normal operation. Using thick targets located at the position shown in <Figure 6.2.5.2>, with a length of 17.6 cm (10 radiation lengths) and a radius of 4 cm, the thickness and structure of the shielding door were determined to provide equivalent shielding performance to 80 cm of standard concrete when a 4 GeV electron beam strikes the target. The electron beam loss rate was 11.29 nC/2min = 6.67×10^{10} e/2min.



<Figure 6.2.5.2> Total dose rate distributions around the accelerator tunnel and shielding door for uniformly distributed beam loss in SR (normal operation) in which 4 GeV-electron (11.29 nC/2min) beam hits thick Fe targets.

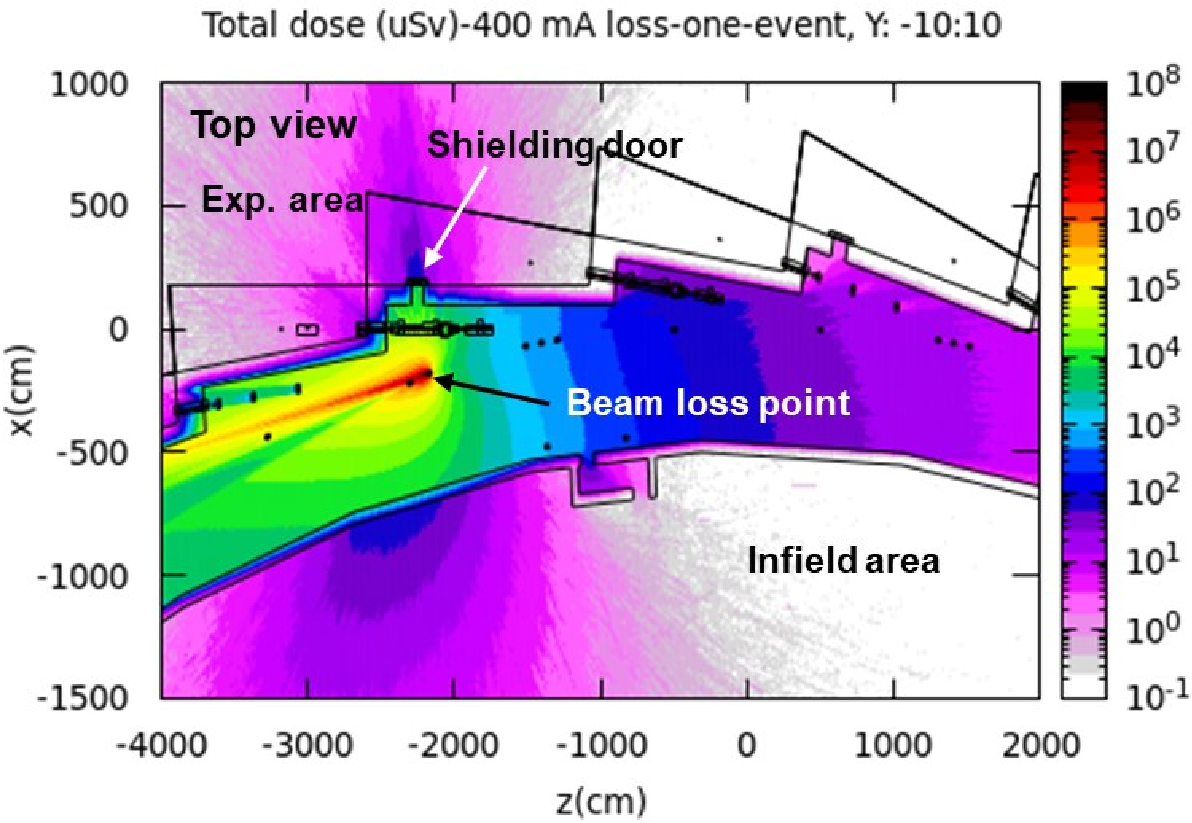
The detailed dose rate around the shielding door is also shown in <Figure 6.2.5.3> in top and its corresponding vertical views along the AA′ cut line. It is seen that dose rate after the shielding door is below 0.2 μSv/h in both top and vertical views. Additionally, the contribution of photon and neutron dose rates to the total dose rate are also shown in <Figure 6.2.5.3(c,d)> for the cut line 1 and cut line 2. The neutron dose rate is higher than the photon dose rate as can be seen in the figures. These results show that the layered structure of the shielding door appears to provide sufficient shielding effectiveness for this beam loss scenario.



<Figure 6.2.5.3> Total dose rate around the shielding door for uniformly distributed beam loss in SR (normal operation) in which 4 GeV-electron (11.29 nC/2min) beam hits thick Fe targets, (a) total dose rate distribution in top view, (b) total dose rate distribution in vertical view, (c) total, photon and neutron dose rates values along the 1D cut 1, and (d) total, photon and neutron dose rates values along the 1D cut 2.

B. Evaluation of the Shielding Door Effectiveness (Beam Loss Scenario 2)

This beam loss scenario represents an abnormal scenario that is probable to occur in SR, as discussed before. As shown in <Figure 6.2.5.4>, the shielding performance was evaluated for the case where the 400 mA (6.67×10^{12} e) of stored current is lost at the location of the quadrupole magnet, and it is close to the shielding door. The target was iron with a length of 17.6 cm ($10X_0$) and a radius of 4 cm. Under these beam loss conditions; the shielding door appears to provide sufficient shielding effectiveness.



<Figure 6.2.5.4> Total dose rate around the shielding door in top view for an accidental beam loss scenario in which 4 GeV-electron beam (400 mA) hits QM in the SR.

Based on the new 4GSR beamline front-end design, the shielding door will be shifted 185 cm upstream, with its size and structure remaining unchanged. FLUKA simulations were performed for both normal and abnormal operation scenarios to model the shifted door's performance. The results confirmed that the dose rate behind the shielding door remains below the shielding criteria.

6.2.6 Beamline Shielding Design

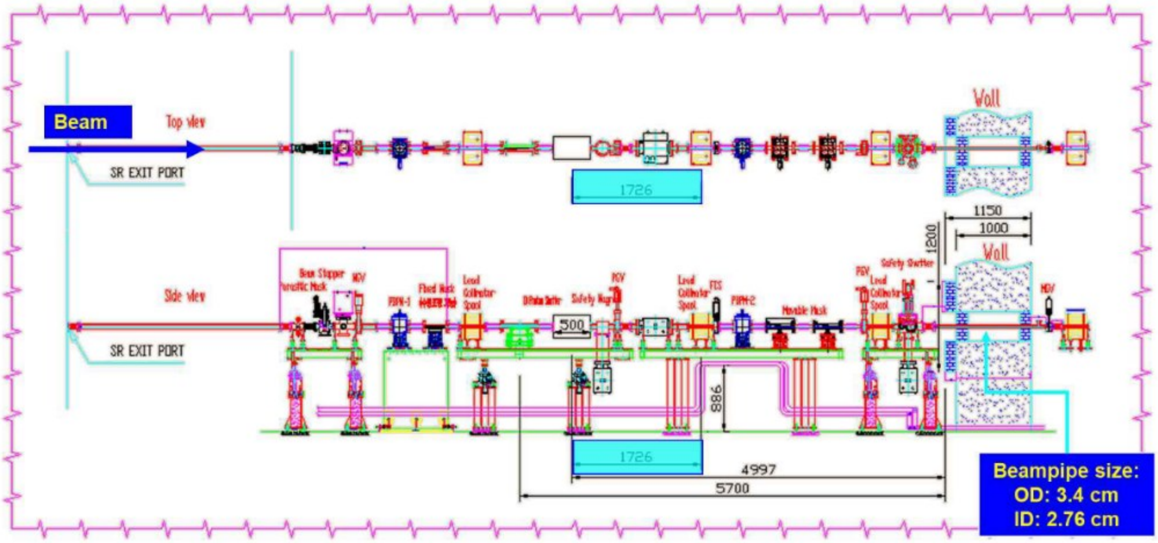
A. Safety Magnet

The dipole magnets of the 4GSR storage ring receive current from separate power supplies. If one of these power supplies fails, the electron beam can leak outside the storage ring-booster tunnel along the synchrotron beamline path. This scenario is considered the worst accident scenario. In facilities like PLS-II, where the entire dipole magnet system is powered by a single power supply, this scenario does not need to be considered. However, in the 4GSR, such a scenario is possible, and safety devices must be installed. This device is the Safety Magnet.

The safety magnet uses a 50 cm section of permanent magnet to deflect the 4 GeV electron beam downward, causing it to eventually collide with a thick lead dump installed downstream. The safety magnet specifications are as follows:

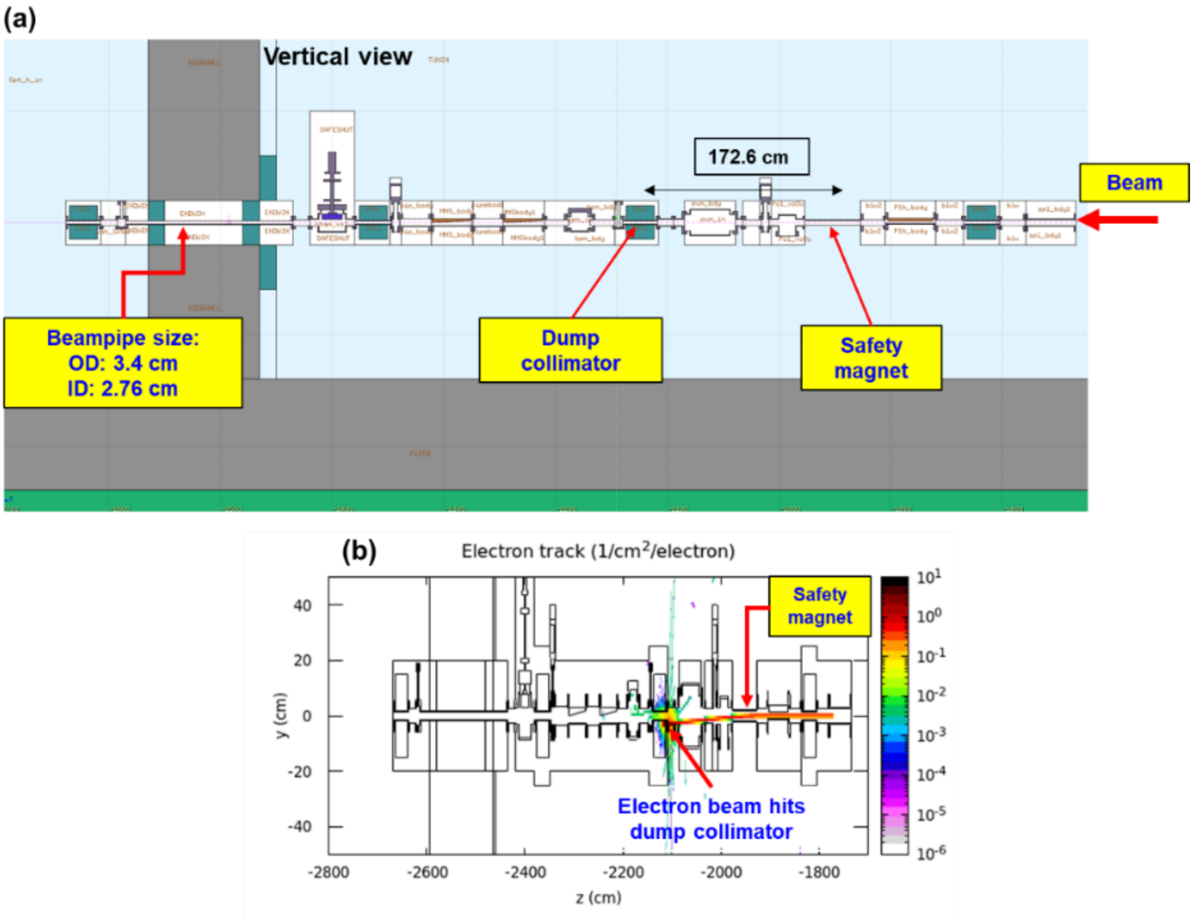
- **Length**: 50 cm
- **Magnetic field strength**: 0.5 T
- **Gap size**: 4 cm
- **Deflection angle**: 18.8 mrad

<Figure 6.2.6.1> shows the layout of the Front-End components of the synchrotron beamline and the position of the safety magnet.



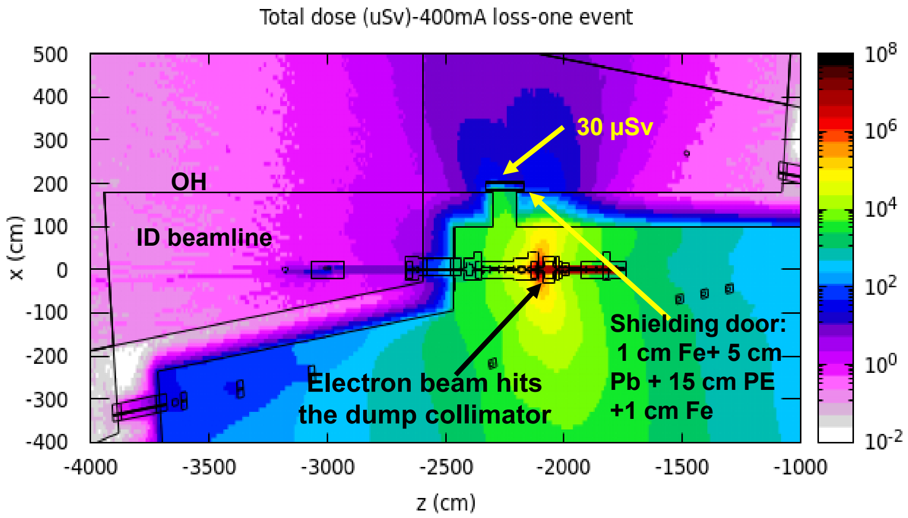
<Figure 6.2.6.1> Horizontal and vertical views of the synchrotron radiation beamline Front-End. The section marked in red indicates the distance between the safety magnet and the dumping lead collimator.

The corresponding geometry of the front end of the beamline was created in FLUKA, and the radiation dose distribution was calculated. <Figure 6.2.6.2(a)> shows the FLUKA input geometry of the front end, highlighting the safety magnet position, the distance between the safety magnet and the dump collimator, and the beam pipe size. <Figure 6.2.6.2(b)> illustrates the electron beam track passing through the safety magnet and hitting the dump collimator.



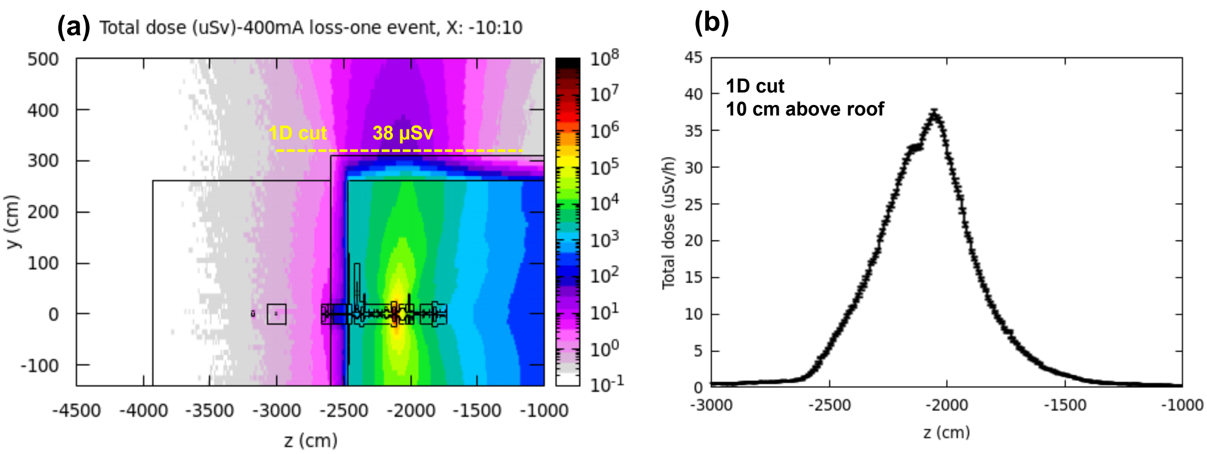
<Figure 6.2.6.2> FLUKA simulations (a) FLUKA input geometry of the beamline Front-End, (b) electron beam track after passing through the 50 cm long safety magnet and hitting Pb dump collimator.

Under abnormal operation conditions, the entire stored electron beam collides with the dump Pb collimator via the safety magnet. The evaluated radiation dose distribution in the top view is shown in <Figure 6.2.6.3> under this abnormal operation condition and when the safety shutter is open. The maximum dose was calculated to be 30 μSv/event after the shielding door and 5 μSv/event after the end wall, which is well below the accident condition limit of 1,000 μSv/event.



<Figure 6.2.6.3> Radiation dose distribution when the safety magnet entirely redirects the stored 4 GeV electron beam to collide with the lead collimator.

The evaluated radiation dose distribution in vertical view is shown in <Figure 6.2.6.4(a)>, along with the one-dimensional cut line 10 cm above the roof shown in <Figure 6.2.6.4(b)>. The maximum dose was calculated to be 38 μSv/event above the roof, which is well below the accident condition limit of 1,000 μSv/event.



<Figure 6.2.6.4> Radiation dose distribution when the safety magnet entirely redirects the stored 4 GeV electron beam to collide with the lead collimator, (a) 2-dimensional distribution in vertical view, (b) total dose rate values along the 1D cut line 10 cm above the roof.

B. Safety Shutter Design

4GSR beamlines will be equipped with a safety shutter. With the safety shutter closed, personnel can access the optics hutch interior. A safety shutter made of tungsten with dimensions of 12 (width) × 4.8 (height) × t=20 cm^3 was considered to block the GB radiation as well as high energy bremsstrahlung radiation generated from the electron beam loss in the storage ring tunnel. GB radiation is produced when stored electrons interact with the residual gas present in a vacuum chamber. The photons generated in this process, particularly at the straight sections of the accelerator, can lead to an increased dose at the beamline. Additionally, when this gas bremsstrahlung interacts with any target, it can result in the production of photoneutrons, further contributing to the radiation dose. The FLUKA code was used to determine the safety shutter dimension and its effectiveness.

It is mentioned that the dimensions of the safety shutter mentioned here are very preliminary and just a conceptual design, and might change in the future after ray tracing.

6.3 Radiological Activation and Environmental Effects

Although this synchrotron radiation accelerator uses relatively high-energy particles at approximately 4 GeV, because the type of particle is the electron, this synchrotron radiation accelerator has a lower rate of nuclear reactions and a lower generation rate of neutrons compared with accelerators with protons at energy levels of hundreds of MeV. Thus, the activation of the accelerator structure in the operation of the synchrotron radiation accelerator is significantly limited and occurs only at a specific location. It is confirmed in the operation records of many synchrotron radiation accelerators, including the PLS-II. However, after several decades of operation, if there is a process of replacing or dismantling a specific component, a solid radioactive waste may be generated. Thus, a processing infrastructure for this situation must be established.

For the same reason, since the number of radionuclides in the liquid or gaseous phase is very small, the influence on the environment is very small. However, initial and periodic verifications of the amount of production are required. On the contrary, it is necessary to calculate the radiation dose at the site boundary and check whether the safety policy has been complied with by performing an evaluation on the skyshine, in which neutrons generated during accelerator operation transmit radiation to distant areas by colliding with air molecules in the sky.

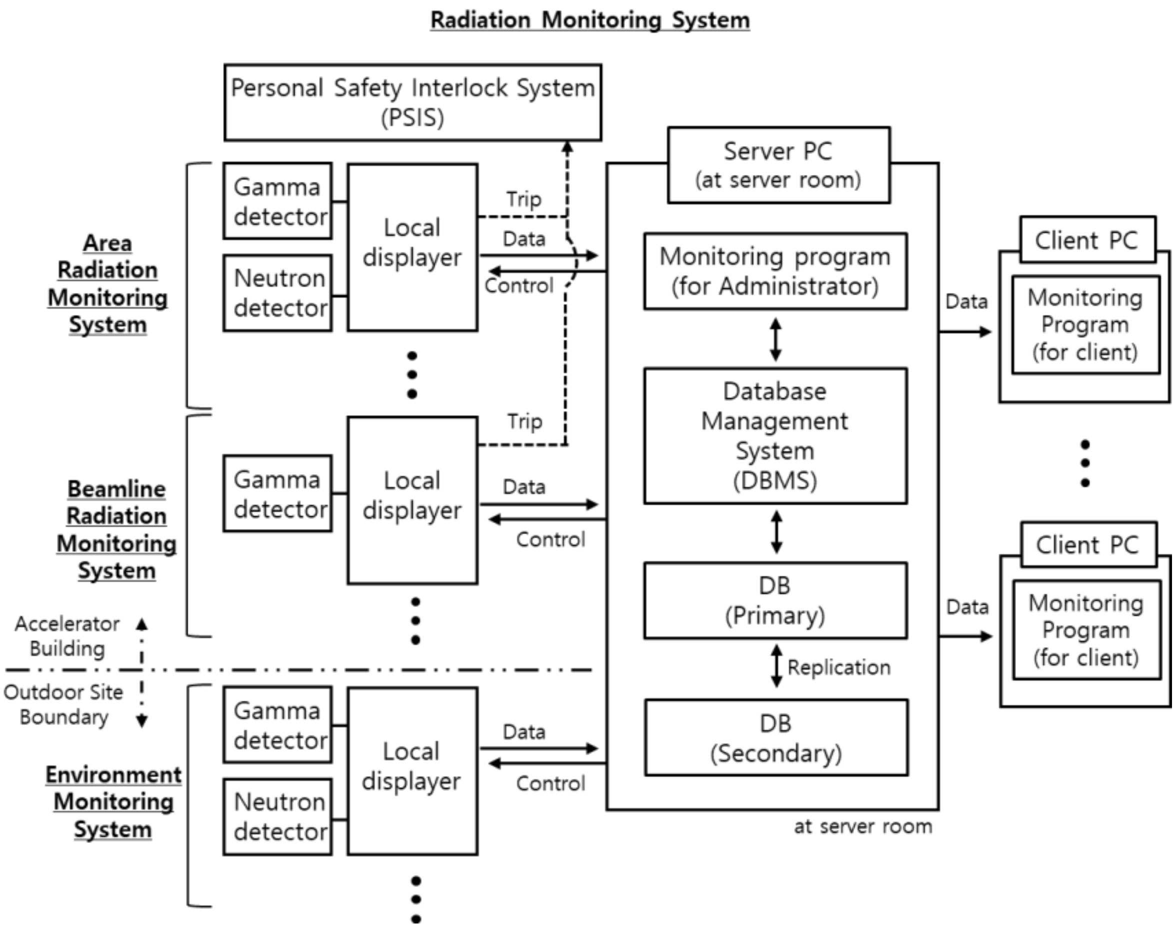
6.4 Radiation Safety System

To ensure the safe operation of a synchrotron radiation accelerator, the Radiation Monitoring System and the Personnel Safety & Interlock System (PSIS) are emphasized as essential components. The design of radiation shielding and the results of commissioning are determined during the initial planning stage, establishing the fundamental safety structure of the equipment. However, during actual operation, the safety of laboratory staff and synchrotron users is ensured by the Radiation Monitoring System and the PSIS, and their roles are highly significant.

6.4.1 Radiation Monitoring System

The Radiation Monitoring System continuously monitors both direct and induced radiation in real-time to ensure the safety of workers and users inside and outside the facility and to enable appropriate actions when necessary.

The Radiation Monitoring System is categorized into the Area Radiation Monitoring System, the Beamline Radiation Monitoring System, and the Environment Radiation Monitoring System. The Area and Beamline Radiation Monitoring Systems are responsible for continuously monitoring radiation levels within the facility. The radiation monitoring system is linked to a central server to monitor radiation in real time. It triggers an alarm when radiation levels exceed set thresholds or when there is a circuit failure, and, if necessary, it activates an interlock signal linked to the PSIS to ensure the safety of workers and users. An overview diagram illustrating this structure and functionality is provided in <Figure 6.4.1.1>.



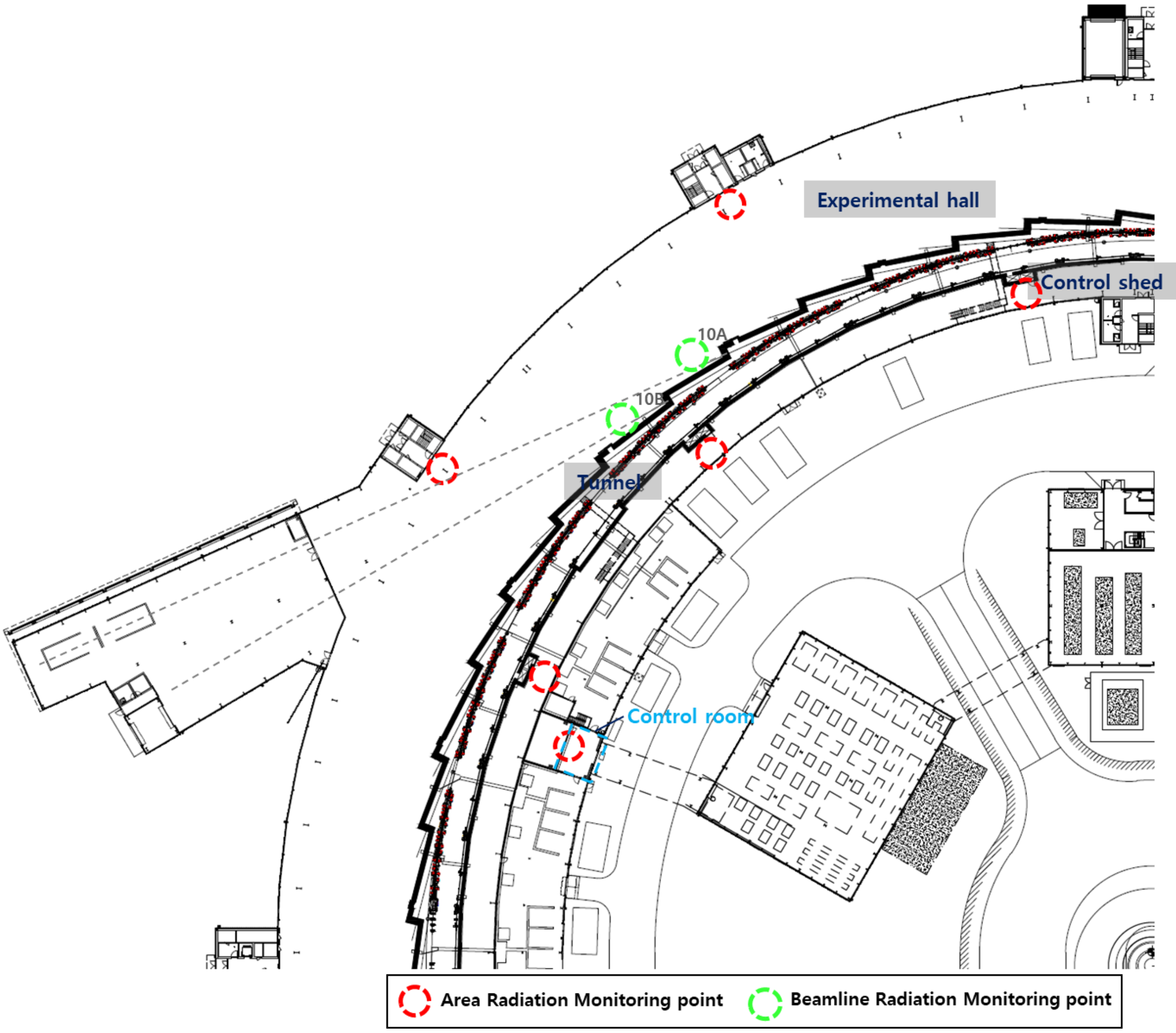
<Figure 6.4.1.1> Overview of the Radiation Monitoring System.

A. Area Radiation Monitoring System

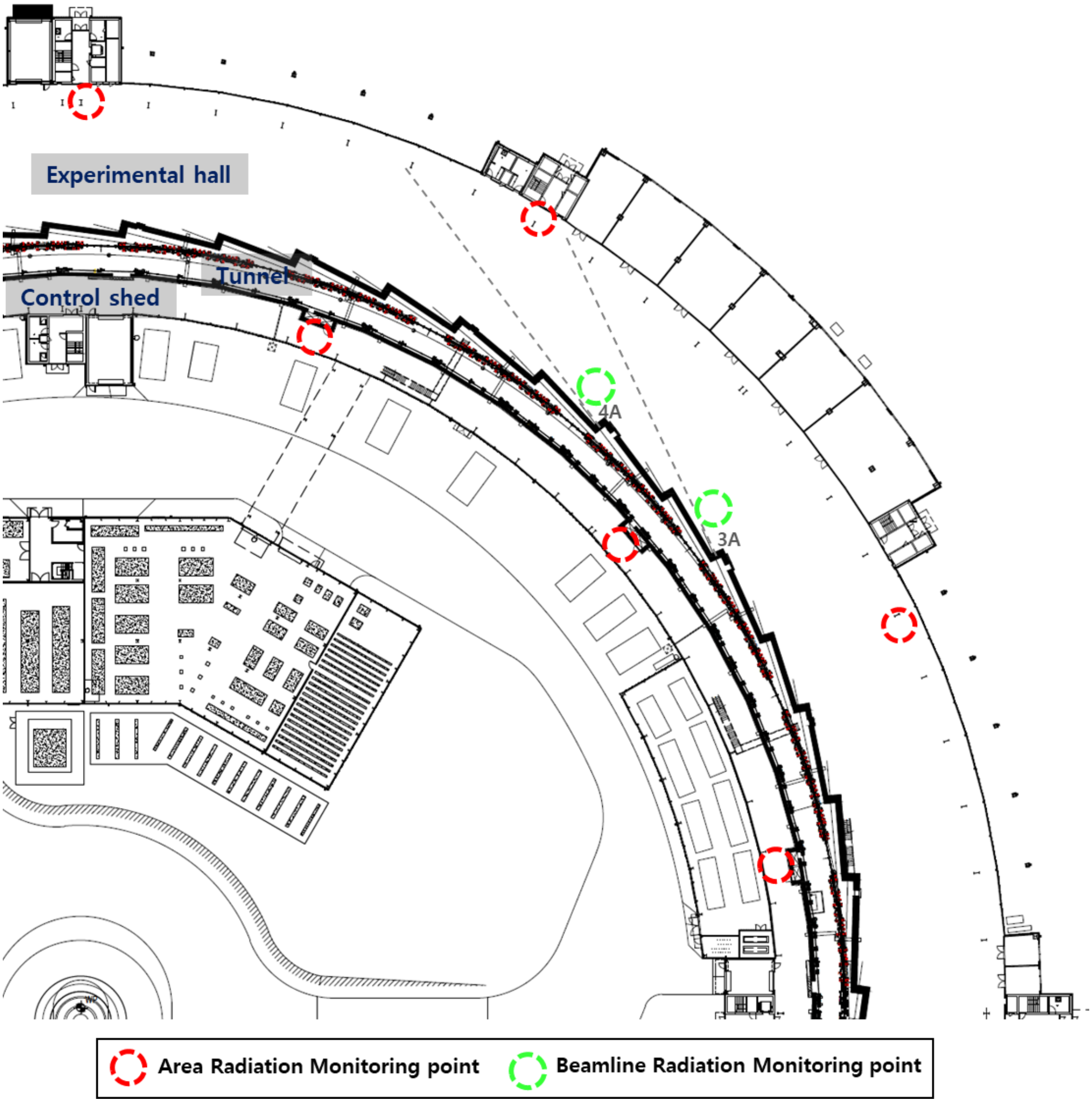
(1) Overview

The Area Radiation Monitoring System continuously monitors radiation levels within the facility. The institute strictly ensures that radiation levels outside the shielding do not exceed the legal annual dose limit of 20 mSv. Additionally, a more conservative annual limit of 10 mSv is set for the safety of workers. To comply with these standards, the Area Radiation Monitoring Systems are installed and operated in critical locations capable of detecting radiation levels exceeding the design criteria of the 4GSR. These locations include areas where beam loss frequently occurs, zones expected to have high radiation levels in the event of an accident, and areas that, despite lower radiation levels, are frequently passed through by workers and users for extended periods.

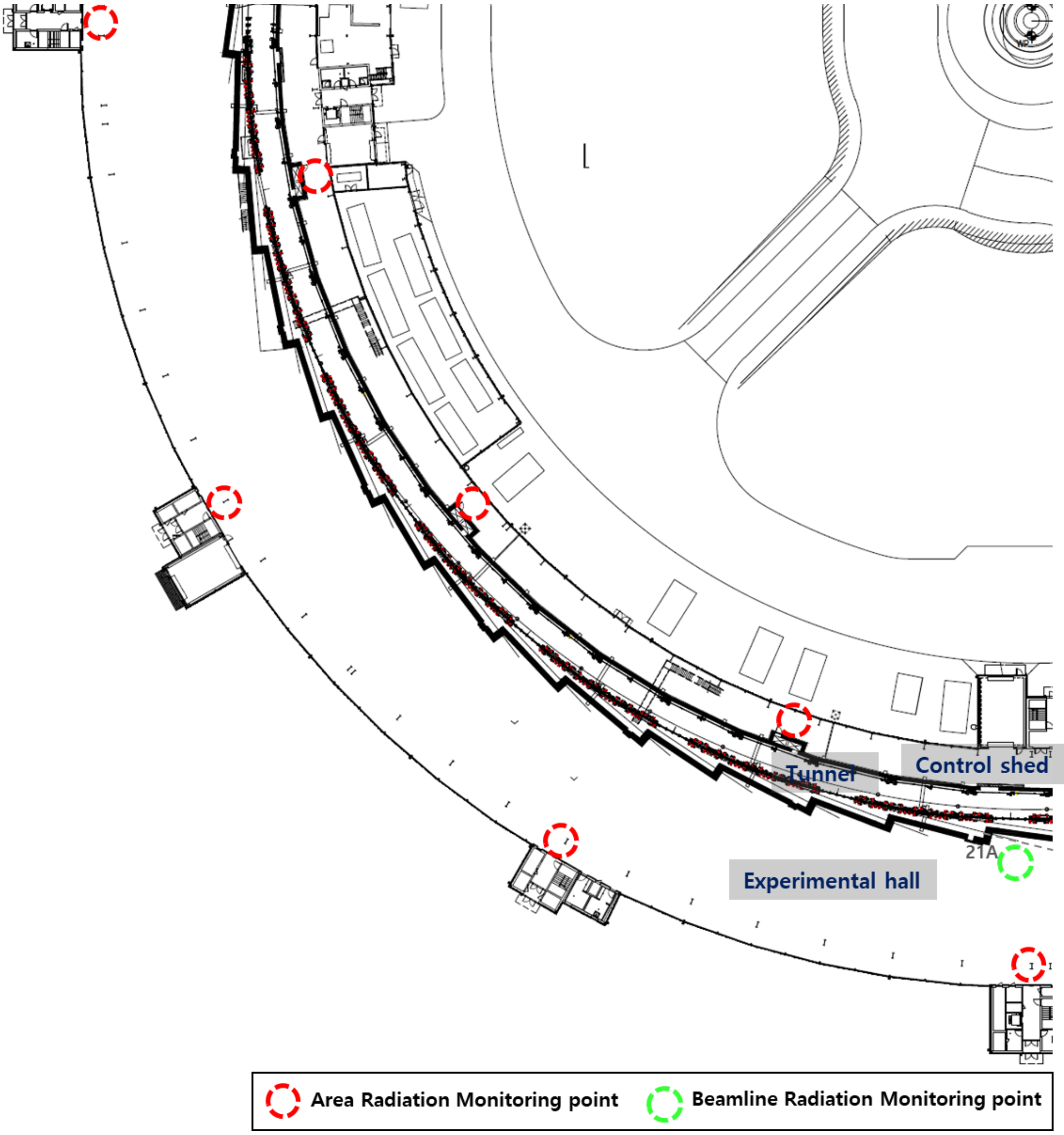
The Area Radiation Monitoring Systems are planned to be installed at a total of 30 points throughout the experimental hall and the control shed in the accelerator building, as shown in <Figure 6.4.1.2> to <Figure 6.4.1.5>. Each monitoring point will be equipped with a set of neutron and gamma-ray detectors. In the experimental hall, systems are planned to be installed at 12 points near the entry/exit located on the interior perimeter of the accelerator building and at one point in the injection area. In the control shed, the system will be installed at two points near the Linac-to-Booster (LTB) in the injection area, at one point downstream of the Linac dump, and one point in the control room, where people tend to stay for extended periods. Additionally, one system will be installed at the Klystron Gallery, where the klystron that generates X-rays is located. Furthermore, 12 monitoring points will be established near the maze doors, where high radiation doses are expected during accidental conditions. The specific number of monitoring points and their locations may be adjusted as necessary in the future.



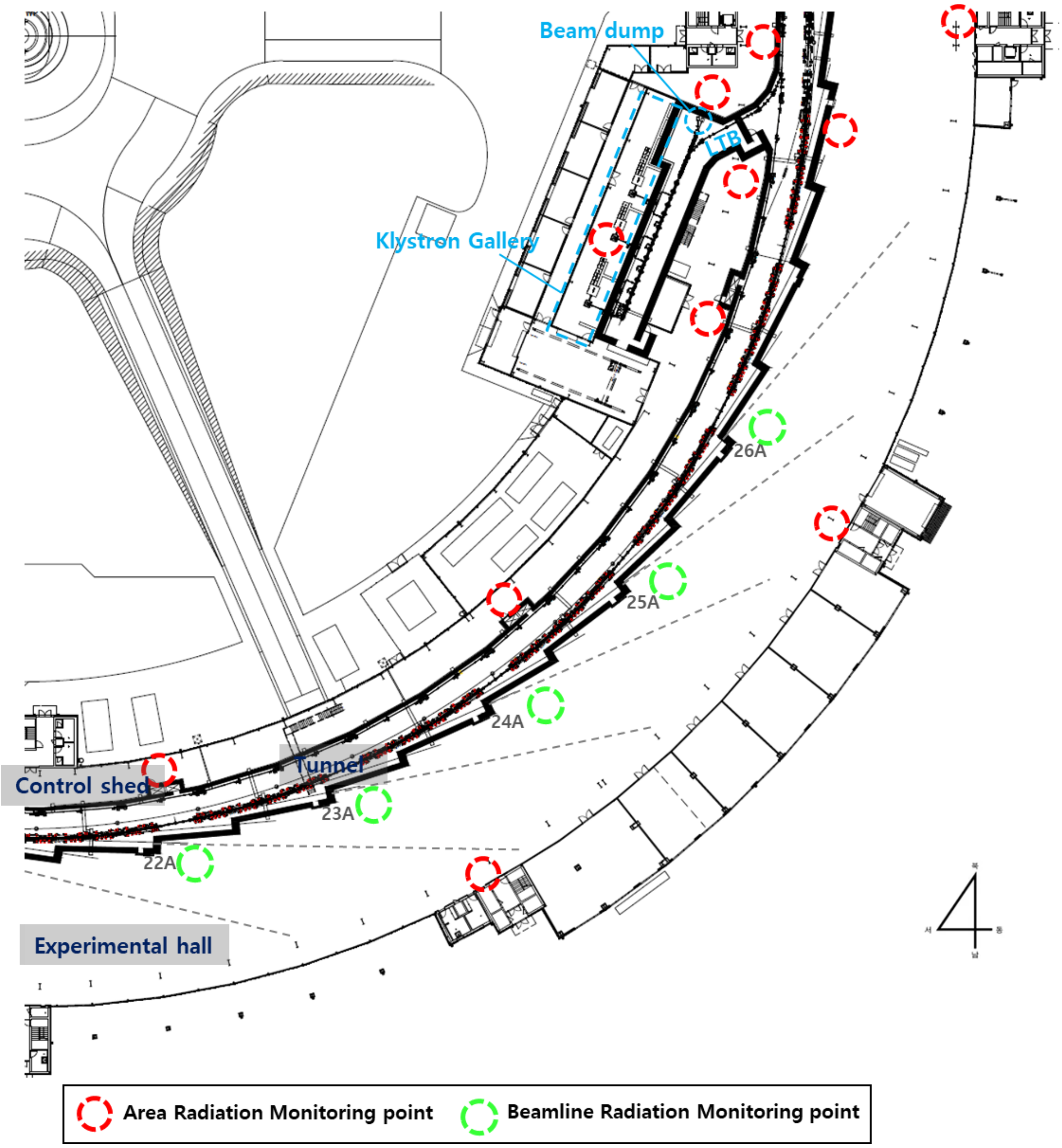
<Figure 6.4.1.2> Installation points of the Area and Beamline Radiation Monitoring System on the northwest side of the accelerator building.



<Figure 6.4.1.3> Installation locations of the Area and Beamline Radiation Monitoring System on the northeast side of the accelerator building.



<Figure 6.4.1.4> Installation locations of the Area and Beamline Radiation Monitoring System on the southwest side of the accelerator building.



<Figure 6.4.1.5> Installation locations of the Area and Beamline Radiation Monitoring System on the southeast side of the accelerator building.

(2) System Components

The Area Radiation Monitoring System primarily consists of detectors for measuring radiation, local displayer that displays and alerts the radiation levels and risk in real-time, network communication for stable signal transmission, central server that controls systems, store and manages data, and provides real-time information to users. These components and devices are designed to operate normally even during power outages by receiving power through an Uninterruptible Power Supply (UPS).

○ Detectors

To monitor radiation leakage through the shielding outer walls of the synchrotron accelerator tunnel, a pressurized ionization chamber will be used for photon detection, and an extended-range rem counter will be employed for neutron detection. The specifications for the photon and neutron detectors are as follows:

▶ **Specifications for Photon(Gamma-ray) Detector**

① **Detector Type**: Pressurized Ionization Chamber

② **Dose Rate Measurement Range**: Below 0.1 μSv/h to above 1 Sv/h

③ **Energy Measurement Range**: Below 40 keV to above 7 MeV

④ **Communication Interface**: Capable of real-time communication with the local displayer

▶ **Specifications for Neutron Detector**

① **Detector Type**: Extended-Range Rem Counter

② **Dose Rate Measurement Range**: Below 0.03 μSv/h to above 0.1 Sv/h

③ **Energy Range**: From 25 MeV (Thermal) to above 1 GeV

④ **Dead-Time Compensation**: Built-in algorithm for compensation

⑤ **Communication Interface**: Capable of real-time communication with the local displayer

○ Local Displayer

The local displayer collects signals measured by detectors, converts them into radiation units based on input variables, and provides real-time alerts on radiation levels and risks. When necessary, it activates interlocks to implement safety measures. An overview of the local displayer's structure and main functions is illustrated in Figure <6.4.1.6>. The requirements and main functions of the local displayer are as follows:

① Signal Collection, Conversion, and Output

- Collects detector signals, converts them into radiation units, and displays dose rates and accumulated dose rates for gamma-rays, neutrons, and their combinations in real time.
- Adapts built-in calculation modes to various scenarios, including normal operation and accident conditions.

② Alarms and Interlock System

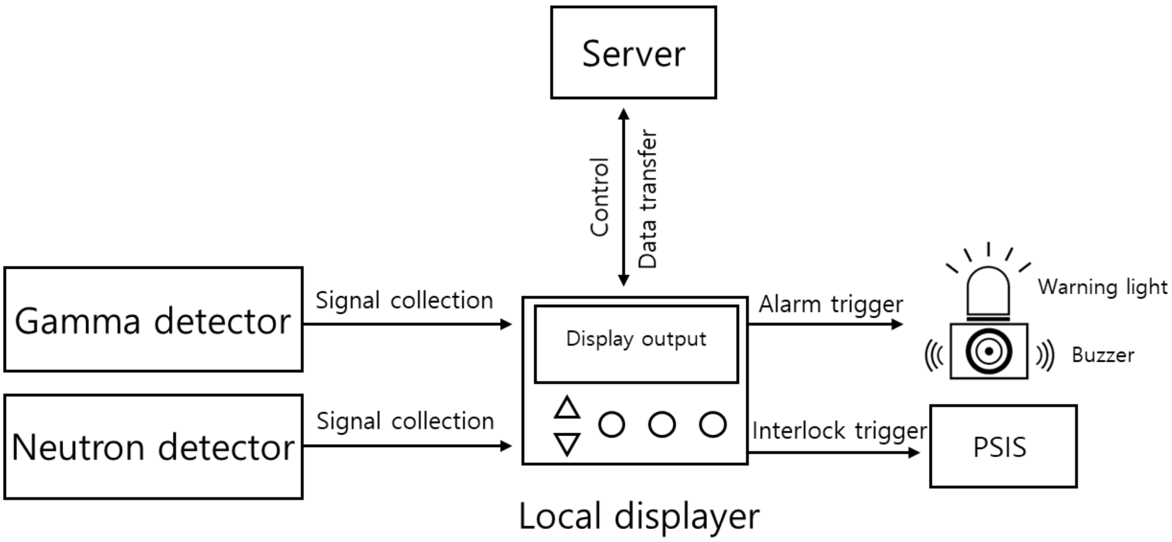
- If the instantaneous dose exceeds predefined thresholds for alert alarms and high alarms, the local displayer activates visual and auditory alarms through flashing lights and buzzers. Flashing lights use at least three colors to indicate system status:
  - **Green**: Normal operation
  - **Yellow**: Alert alarm when the instantaneous dose exceeds 3 μSv/h
  - **Red**: High alarm when the instantaneous dose exceeds 5 μSv/h
- When the cumulative dose exceeds the high alarm threshold (e.g., 5 μSv over 1 hour, configurable as needed), the internal relay triggers a beam stop interlock signal, which is sent to the PSIS to halt beam operation.

<Table 6.4.1.1> Alarm and interlock criteria for the Area Radiation Monitoring System

Criteria	Instantaneous Dose Rate	1-Hour Accumulated Dose	Action
Alert Alarm	3 μSv/h	-	Yellow light, 1-second interval warning sound.
High Alarm	5 μSv/h	-	Red light, continuous warning sound.
Safety shutter Closure (Interlock)	-	5 μSv	Interlock signal sent to PSIS.

③ Communication and Control

- Ensures compatibility with neutron and photon detectors for simultaneous signal acquisition.
- Enables real-time data transmission and reception with a central server located at a physically remote site using LAN communication, and allows the central server to remotely control local displayers.
- Allows configuration of the refresh time, determining how frequently the signals measured by the detectors are transmitted to the central server and displayed in real-time.



<Figure 6.4.1.6> Example of main features of the local displayer.

○ Network Communication

The radiation monitoring system requires highly reliable network communication between local displayers at each site and the central server. The network is capable of collecting real-time radiation signals and remotely controlling devices without traffic congestion or failures.

For the Area Radiation Monitoring System in the accelerator building (approximately 310 meters in diameter), optical fiber cables are used instead of copper wires to ensure stable and efficient communication. Optical fiber allows high-speed transmission over long distances without data loss and is immune to electromagnetic interference from RF equipment.

The physical topology of the Area Radiation Monitoring System network is configured in a ring structure, where each node is circularly connected to form a backbone. This design ensures communication continuity by rerouting data in the opposite direction if a node or link fails. To ensure network communication continuity even in the event of a failure, network transport devices such as switches and converters, equipped with recovery support protocols for ring topology, are utilized.

○ Central Server

The central server of the Radiation Monitoring System communicates with the local displayers of each system, integrating, collecting, and storing measurement data while serving as the central hub of the network. The operating program installed on the central server processes and analyzes the data, transmits it to various clients, and handles output and control functions.

▶ Operating Program Components and Roles

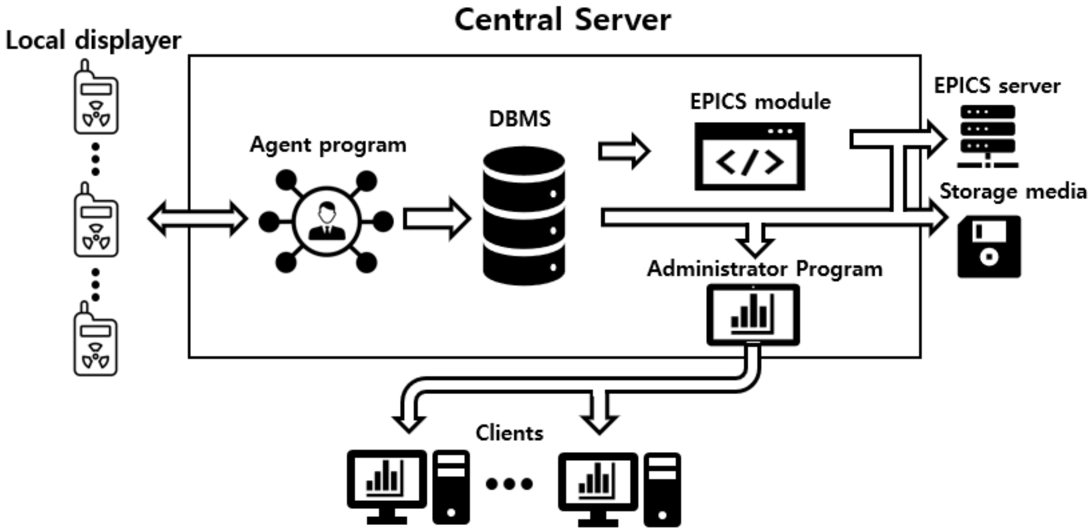
① **Agent**: Communicates with each local displayer to collect data.

② **Database Management System (DBMS)**: Safely stores and manages collected dose rates and other data.

③ **Administrator Program**: Performs real-time queries, output, control, and analysis of the stored data.

④ **EPICS Module**: Transmits the stored data to the EPICS server.

Each component of the operating program operates on an intranet TCP/IP communication protocol, ensuring stable and reliable data transmission and reception. The central server is independently powered by a UPS to prevent power loss, and to guard against data loss, it periodically saves data collected from the local displayers and processed data onto portable storage media such as CDs and DVDs. By backing up data to the EPICS server and portable storage media, past data can be safely preserved even if the central server's database encounters issues. An overview of the central server’s configuration and its operating program is illustrated in <Figure 6.4.1.7>.



<Figure 6.4.1.7> Configuration diagram of the central server and operating program for the Radiation Monitoring System.

The administrator program is divided into a server program and a client program. The server program, installed on the central server, is responsible for controlling the local displayers and analyzing the collected data. It can perform various device control tasks, such as managing calibration variables, alarms, beam stop signals, and interlock settings. The client program, installed not only on the central server but also on the client, enables real-time monitoring of data stored in the database. The detailed features of the server and client programs of the administrator program are as follows:

▶ **Server Program Features**

① **Data Collection and Transmission**: Collecting local displayer data, building the database, and real-time transmission to the EPICS server through the EPICS module.

② **Local Displayer Control**: BKG, calibration parameters, operation mode, alarms, interlock settings.

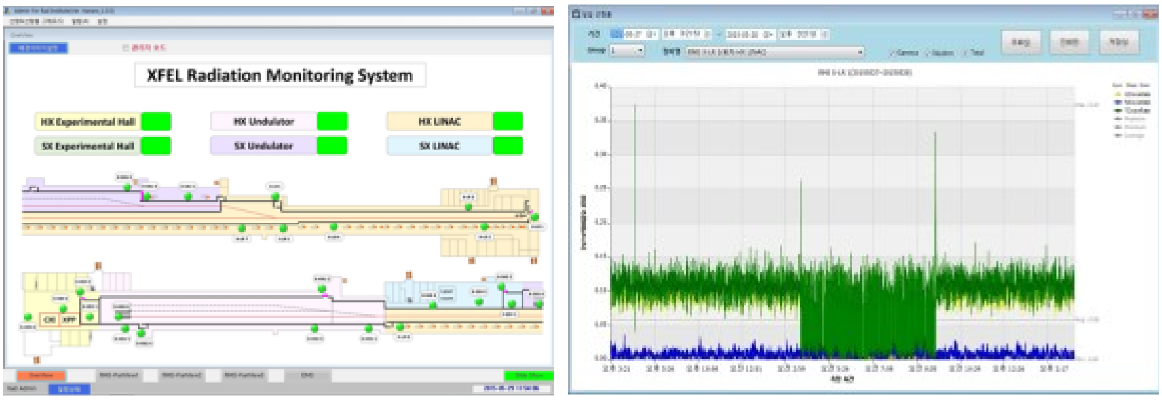
③ **Monitoring Function**: Real-time monitoring of each local displayer's data, dose rate graphs, and operational status.

④ **Data Query and Report Output**: Accessing past dose rate data, alarms, and abnormal data and outputting reports.

▶ **Client Program Features**

① **Monitoring Function**: Real-time monitoring of each local displayer's data, dose rate graphs, and operational status.

Examples of the interface screens for the administrator program are shown in <Figure 6.4.1.8>. As illustrated in the screen examples, the administrator program allows real-time monitoring of dose variations by region at a glance, facilitating radiation information tracking and enabling quick responses in case of emergencies.



(a) (b)

<Figure 6.4.1.8> Examples of (a) real-time radiation monitoring and (b) dose rate history in administrator program (Reference: *PAL-XFEL monitoring screen of administrator program*).

B. Beamline Radiation Monitoring System

(1) Overview

During Top-Up operation, bremsstrahlung from electron collisions with Front-End components and air particles can be scattered by optical components, potentially leaking around the Photon Transfer Line (PTL). To prevent this, optics hutches are installed around the PTL to restrict personnel access. To ensure that the radiation dose outside the optics hutch in the experimental area, where personnel may reside, does not exceed the dose limit of 10 mSv per year, the Beamline Radiation Monitoring System is configured and operated to continuously monitor radiation levels.

For the initial 10 beamlines, the Beamline Radiation Monitoring System equipped with one gamma-ray detector each will be installed and operated near the optics hutch of each beamline in the accelerator building, with the 10 monitoring points shown in <Figure 6.4.1.2> to <Figure 6.4.1.5>.

(2) System Components

○ Detectors

The gamma-ray detectors of the Beamline Radiation Monitoring System, which detect bremsstrahlung radiation leaking near the PTL, have a fast response time to promptly activate alarms or interlocks, ensuring the safety of workers and users around the optics hutch.

▶ **Specifications for Photon(Gamma-ray) Detector**

① **Detector Type: Pressurized Ionization Chamber**

② **Dose Rate Measurement Range**: Below 0.1 μSv/h to above 1 Sv/h

③ **Energy Measurement Range**: Below 40 keV to above 7 MeV

④ **Communication Interface**: Capable of real-time communication with the local displayer

⑤ **Response Time**: Within 5 seconds (BKG to 5 μSv/h)

○ Local Displayer

① **Signal Collection, Conversion, and Output**

- Collects detector signals, converts them into radiation units, and displays dose rates and accumulated dose rates for gamma-rays (photons)in real time.
- Adapts built-in calculation modes to various scenarios, including normal operation and accident conditions.

② **Alarms and Interlock System**

The alarm and warning criteria and operating mechanism for instantaneous dose values in the Beamline Radiation Monitoring system are identical to those of the Area Radiation Monitoring System. When the cumulative dose exceeds the high alarm threshold, the internal relay is activated to send a safety shutter closure interlock signal to the PSIS, closing the safety shutter.

<Table 6.4.1.2> Alarm and interlock criteria for the Beamline Radiation Monitoring System

Criteria	Instantaneous Dose Rate	1-Hour Accumulated Dose	Action
Alert Alarm	3 μSv/h	-	Yellow light, 1-second interval warning sound.
High Alarm	5 μSv/h	-	Red light, continuous warning sound.
Safety shutter Closure (Interlock)	-	5 μSv	Interlock signal sent to PSIS.

③ **Communication and Control**

- Ensures reliable signal acquisition from photon detectors.
- Enables real-time data exchange with a remote server and allows remote control via LAN
- Allows refresh time configuration for real-time signal updates.

○ Network Communication

To ensure efficient communication between the Beamline Radiation Monitoring System, which is widely distributed throughout the accelerator building, and the central server, a ring topology using optical fiber cables and network transport devices equipped with fault recovery support protocols will be employed, similar to the Area Radiation Monitoring System.

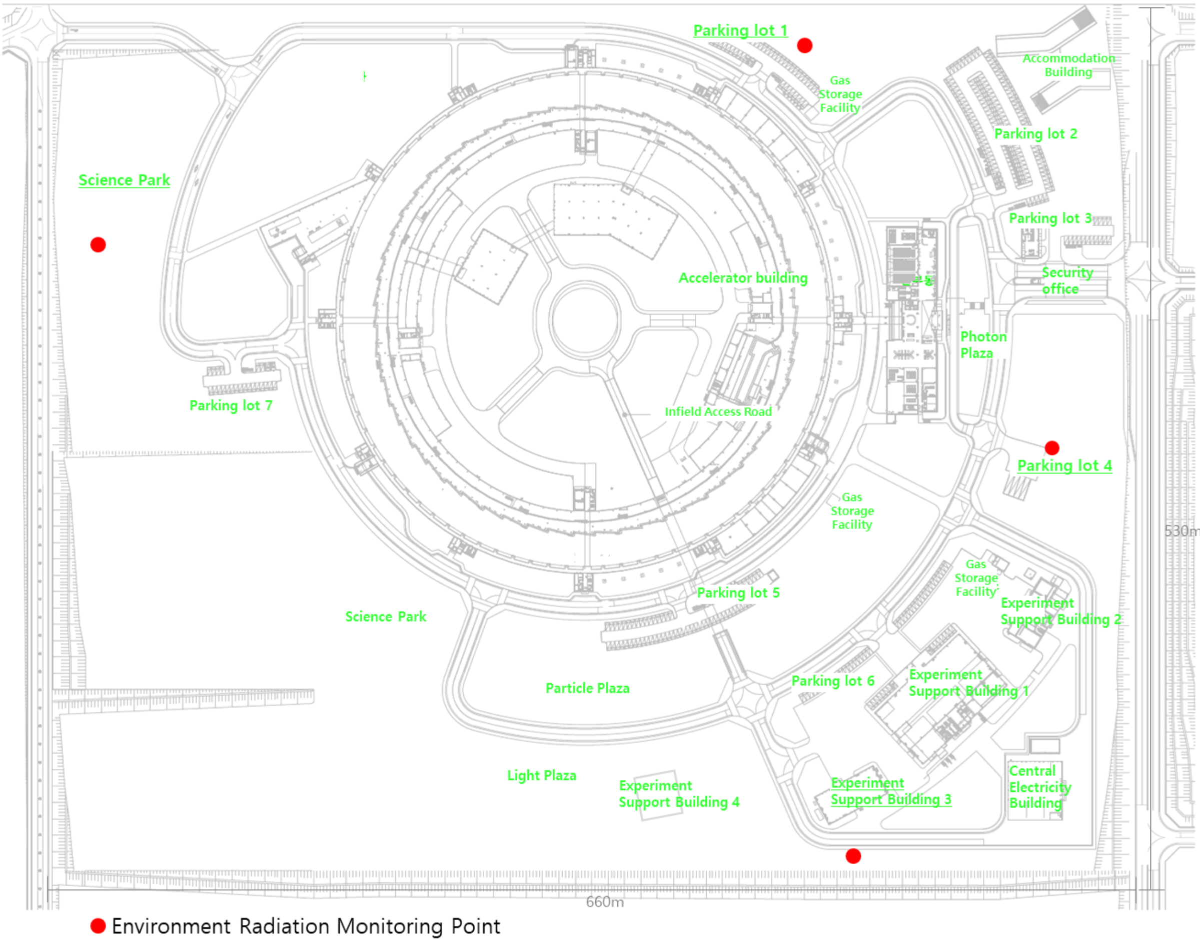
○ Central Server

The three systems − Area, Beamline and Environment − are all operated using the same central server, and the details are identical to those described earlier for the central server of the Area Radiation Monitoring System.

C. Environment Radiation Monitoring System

(1) Overview

The Environment Radiation Monitoring System will be installed at four points near the outer site boundary of the accelerator facility, adjacent to residential areas. This ensures that radiation levels in the environment remain below the facility's internal management standard of 0.25 mSv per year, enabling continuous monitoring and management of environmental radiation levels. The planned installation points are as follows: one near Parking Lot 1 on the northern boundary, one near Parking Lot 4 on the eastern boundary, one near the Science Park on the western boundary, and one near Experiment Support Building 3 on the southern boundary. The installation points of the Environment Radiation Monitoring System are illustrated in <Figure 6.4.1.9>.



<Figure 6.4.1.9> Installation points of the Environment Radiation Monitoring System.

(2) System Components

○ Detectors

The detectors used in the Environment Radiation Monitoring System will be the same as those used in the Area Radiation Monitoring System. Pressurized ionization chambers will be used for photon detection, and extended-range rem counters will be used for neutron detection. However, the detectors in the Environment Radiation Monitoring System is designed with resistance to external environmental conditions and signal stability.

▶ **Specifications for Photon(Gamma-ray) Detector**

① **Detector Type**: Pressurized Ionization Chamber

② **Dose Rate Measurement Range**: Below 0.1 μSv/h to above 1 Sv/h

③ **Energy Measurement Range**: Below 40 keV to above 7 MeV

④ **Communication Interface**: Capable of real-time communication with the local displayer

⑤ **Operating Temperature**: Below -20℃ to above 50℃

⑥ **Operating Humidity**: Above 90%

▶ **Specifications for Neutron Detector**

① **Detector Type**: Extended-Range Rem Counter

② **Dose Rate Measurement Range**: Below 0.03 μSv/h to above 0.1 Sv/h

③ **Energy Range**: From 25 MeV (Thermal) to above 1 GeV

④ **Dead-Time Compensation**: Built-in algorithm for compensation

⑤ **Communication Interface**: Capable of real-time communication with the local displayer

⑥ **Operating Temperature**: Below -20℃ to above 50℃

⑦ **Operating Humidity**: Above 90%

○ Local Displayer

The local displayer of the Environment Radiation Monitoring System does not consider interlock or alarm signaling, unlike the local displayer of the Area Radiation Monitoring System.

① **Signal Collection, Conversion, and Output**

- Collects detector signals, converts them into radiation units, and displays dose rates and accumulated dose rates for gamma-rays, neutrons, and their combinations in real time.

② **Communication and Control**

- Ensures compatibility with neutron and photon detectors for simultaneous signal acquisition.
- Enables real-time data exchange with a remote server and allows remote control via LAN
- Allows refresh time configuration for real-time signal updates.

○ Network Communication

The Environment Radiation Monitoring System is distributed more widely across the external environment of the outdoor site boundary compared to the Area Radiation Monitoring System. To transmit data quickly and efficiently over such long distances without data loss, a star-shaped physical topology using optical fiber cables will be implemented. With only four installation points and nodes for the system, the star topology is advantageous in terms of setup time, cable cost, and data transmission efficiency.

○ Central Server

The three systems – Area, Beamline and Environment – are all operated using the same central server, and the details are identical to those described earlier for the central server of the Area Radiation Monitoring System.

○ Instrument Shelter

The Environment Radiation Monitoring System is operated in the external environment near the site boundary. To minimize the impact of external factors such as sunlight, rain, and wind, 4 instrument shelters are installed to house the system components. Each instrument contains key elements of the system, including detectors, local displayers, and network devices. They are designed to be waterproof, dustproof, and insulated, with capabilities for automatic heating and cooling. Maintaining a stable internal temperature without significant fluctuations is especially important as detector signals are sensitive to temperature changes.

D. Calibration and Adjustment

Detectors of the Radiation Monitoring System will be calibrated internally. The calibration frequency will follow the schedule recommended by the manufacturer. Most detectors will be calibrated during 4GSR's regular maintenance periods, and any detectors not calibrated during this time will be calibrated while the accelerator is in operation. To prepare for such situations, spare detectors will be purchased and kept ready to ensure that no radiation monitoring points are left unmonitored during accelerator operation.

E. Radioactivity and Sample Analysis System

To measure the activation of various accelerator components or radioactive contamination in air or low-conductivity water used for cooling the accelerator, an HPGe detector measurement system will be operated. This system identifies radionuclides and measures their specific activities to perform quantitative and qualitative contamination analysis. For samples that are easy to collect in small quantities, a fixed HPGe detector system will be used to measure contamination. For accelerator metal components, such as vacuum vessels or electromagnets, which are difficult to sample or involve contamination over a wide area, an *in-situ* measurement method using a mobile HPGe detector system will be employed. The HPGe detector measurement system consists of an HPGe detector, preamplifier, amplifier, ADC, and MCA.

F. Mobile Radiation Measuring Devices

Portable radiation detectors will be used for on-site radiation measurements. A portable ionization chamber will measure spatial gamma radiation, while a portable REM counter will measure spatial neutron radiation. For residual radioactivity (activation) measurements, a GM counter and proportional counter detectors supporting various probes for multipurpose use will be utilized. Additionally, electronic dosimeters will be employed as supplementary devices for radiation workers entering high-radiation zones or for temporary visitors requiring radiation monitoring.

6.4.2 Personnel Safety & Interlock System

The Personnel Safety & Interlock System (PSIS) installed at 4th Generation Storage Ring(4GSR) facility is one of the key safety systems for its operation. It is designed to protect the lives of laboratory personnel and researchers from abnormal operations and unexpected accidents. Since the system for machine protection is implemented according to the unique characteristics of each device, it is handled by the department in charge of the device. Here, we describe the PSIS that is installed for the protection of human from the radiation.

A. Basic Requirements

(1) Reliability

Reliability refers to the probability that equipment will perform its intended function in a given environment for an intended period without failure. In other words, reliability refers to a value obtained by probabilistically calculating the failure number of the equipment during the given time, and is generally called as a failure rate and represented by "λp". The PSIS is based on 10^4 hours.

$$\lambda p = \frac{\text{Number of Failures}}{10{,}000\ (\text{hours})} \qquad \text{(Eq. 6.4.2.1)}$$

(2) Fail-safe

The fail-safe requirement refers to the reversion of a system into a predetermined safe state at the time of defect or failure occurrence. In this case, the safe state should be designed to be the state in which the sensor is shorted due to power interruption or cable connection shorting.

(3) Redundancy

The redundancy means to prepare for failure and increase reliability by redundantly using the equipment that performs the same function.

(4) Self-test

A self-diagnostic function that enables the operation of equipment and lines to be tested is required.

(5) Simplicity

To prevent malfunction, the structure should be simplified and installed separately from other control cables. Cables are arranged by area, as well as maintenance and testing.

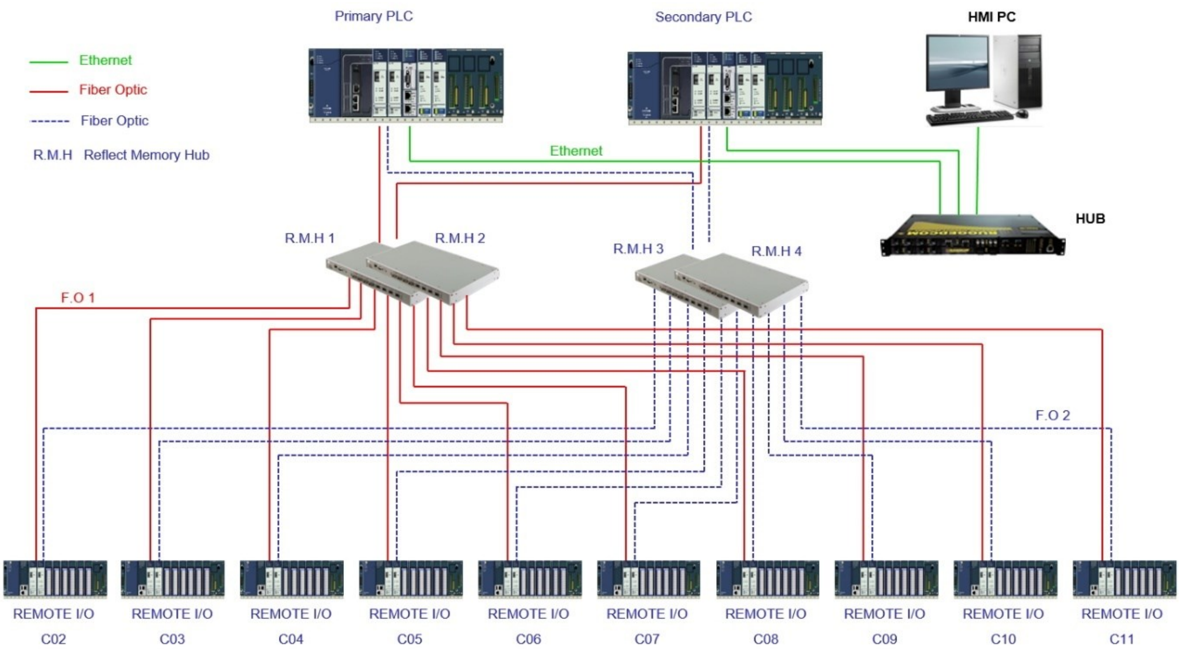
(6) Cable Protection

Separate cable ducts are used to prevent deterioration of function due to cable damage, disconnection, and cable cuts due to unintentional mistakes by workers.

B. Configuration and functions

(1) Main Sequence System

The main sequence system refers to the main management system of a redundant PSIS based on a programmable logic controller (PLC), as shown in <Figure 6.4.2.1>. This system stores all operation scenarios of the PSIS, and outputs a signal to operate the subsystems according to the specified operation scenario when a signal is input from the subsystems.



<Figure 6.4.2.1> Configuration example of Main Sequence System.

The configuration of the Main Sequence System, as illustrated in Figure 6.4.2.1, consists of a PLC CPU, Memory Sync, Data Link, and Remote Input/Output (I/O) modules. Each PLC rack includes a CPU, Memory Sync, and Data Link, and to ensure redundancy, two

PLC racks are installed in parallel using a hot standby mode. In the 4GSR facility, a total of 10 Remote I/O racks are distributed across different locations due to the large circumference of the 4GSR storage ring and the scattered control elements for input and output. The CPU rack and Remote I/O Rack #1 are installed in the server room, while the remaining nine Remote I/O racks are located in the Linac and SR Control Shed. Communication between the PLC CPU rack and the Remote I/O racks is facilitated through a Memory Xchange module connected to the PLC CPU, using fiber optic cables. The Reflect Memory Hub and Remote I/Os are structured in a Star configuration to maximize network reliability. The configuration and components of the Main Sequence System are described as follows.

○ PSI PLC CPU Hot Standby Mode

The Hot Standby mode refers to the simultaneous operation of an active system and an identical standby system. If a fault occurs in the active system, the standby system immediately takes over, ensuring continuous operation without interruption. Data between the two systems is synchronized in real-time through mirroring, enabling seamless switchover to the standby system without data loss or value discrepancies during operation.

○ Basic Requirements of the PSI PLC CPU Hot Standby Mode

- Standby System identical to the Active System must be implemented.

- Real-time memory synchronization between the Active System and Standby System must be ensured.

- Immediate data exchange with Remote I/O during switchover must be achieved.

- No data loss or memory value changes should occur during the switchover process.

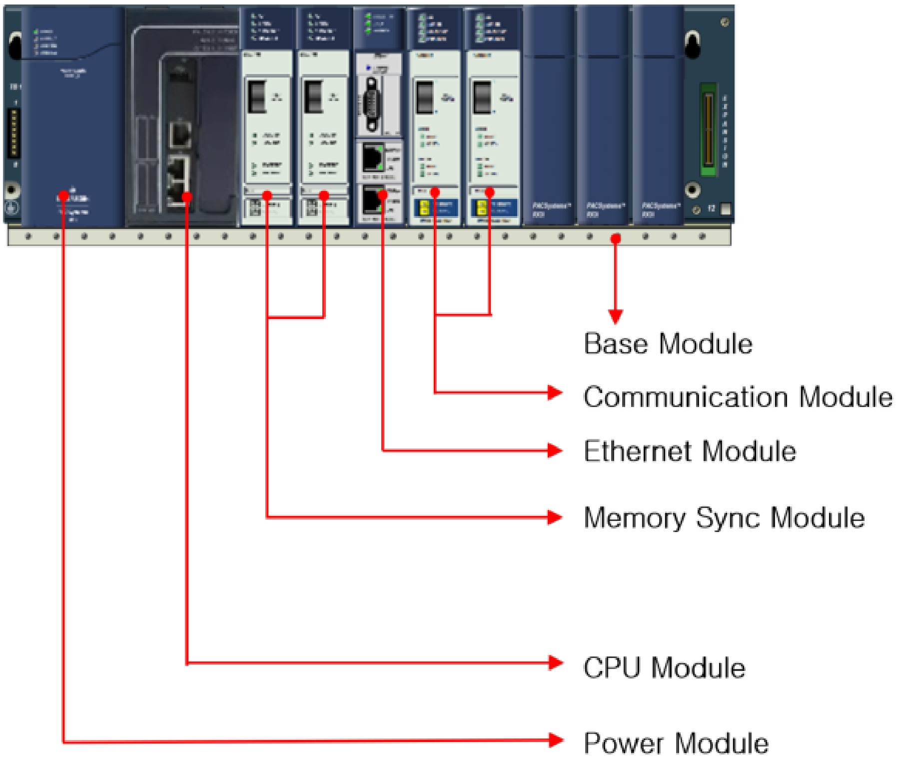
○ Advantages of the PSI PLC CPU Hot Standby System

- Enhanced System Reliability and Stability: The Hot Standby mode allows for uninterrupted continuous operation of the PSI system, significantly improving its reliability and stability.

- Risk Reduction: The Hot Standby mode protects equipment and facilities from unexpected hardware failures, reducing exposure to potential risks.

○ Components of the Main PSI PLC CPU Rack (C01)

The Main PSI PLC CPU system utilizes highly reliable CPUs installed in parallel to form a redundant CPU setup. To enable real-time switchover using the Hot Standby mode, the system requires the following components:



<Figure 6.4.2.2> Configuration example of Main PSIS PLC CPU Rack (C01).

① Power Module

② CPU Module

③ Memory Sync Module

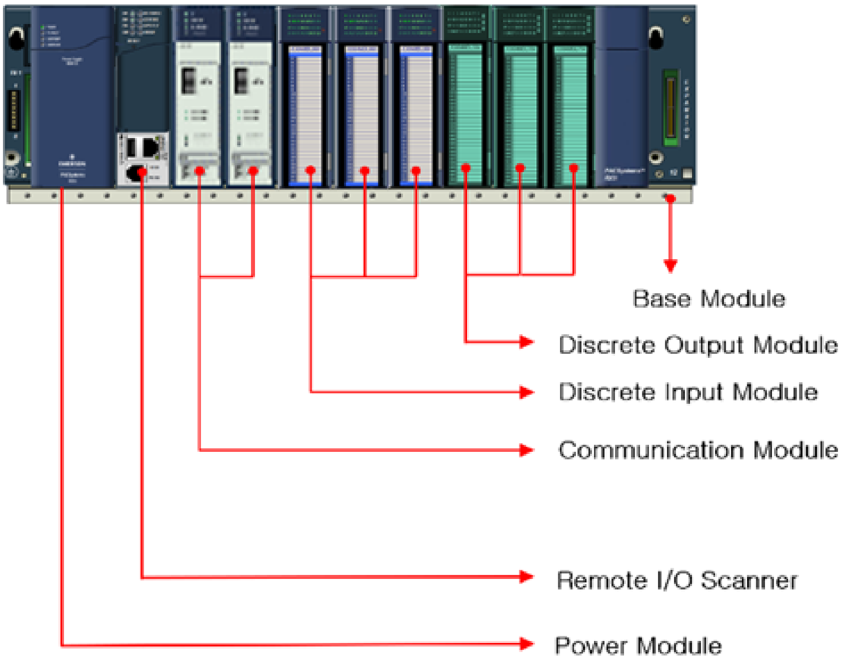
④ Communication Module

⑤ Ethernet Module

⑥ Base Module

⑦ R.F.M (Reflect Memory) Hub

○ **Components of Local Remote I/O Rack (C02 to C011)**



<Figure 6.4.2.3> Configuration example of Local Remote I/O Rack.

① Power Module

② Remote I/O Scanner

③ Communication Module

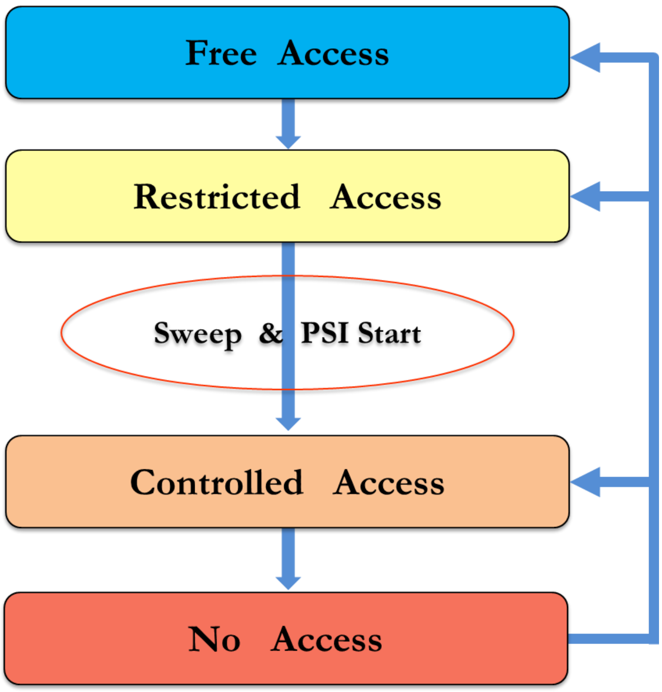
④ Discrete Input Module

⑤ Discrete Output Module

⑥ Base Module

(2) Access Control System

The system for managing access to radiologically-controlled areas comprises sensors and actuators. The components of the Access Control System include Limit Switches, ID Card Readers, Key Banks, Mechanical Door Locks, Electric Door Locks, Emergency Exit/Entrance Boxes, and Video Surveillance (CCTV). The access control system is divided into four levels: Free Access, Restricted Access, Controlled Access, and No Access (<Figure 6.4.2.4>).



<Figure 6.4.2.4> Access Control System workflow.

○ Free Access

All workers are granted access to the areas such as the accelerator tunnel when the region is fully open.

○ Restricted Access

The access level can be adjusted according to the region. In cases where there is no risk of radiation, such as during maintenance, access needs to be restricted for other reasons like equipment protection, entry records are logged in the Access Control System.

○ Controlled Access

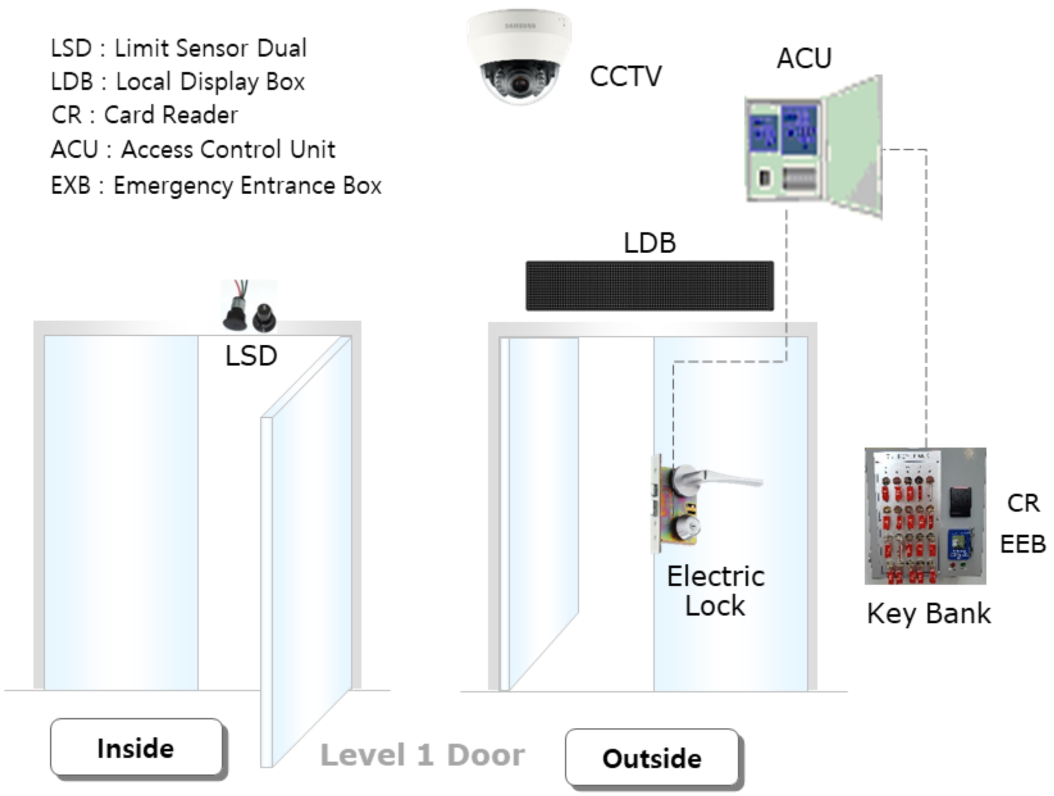
When the beam operation is in preparation, access to the region is restricted. Only authorized workers are allowed to enter using an ID Card, and all entry activities are continuously recorded. Access to the accelerator tunnel requires the use of both an ID Card and the Key Bank system. When entering the accelerator tunnel, each individual must carry one Personal Key, and during this time, beam operation is not permitted by the PSIS.

○ No Access

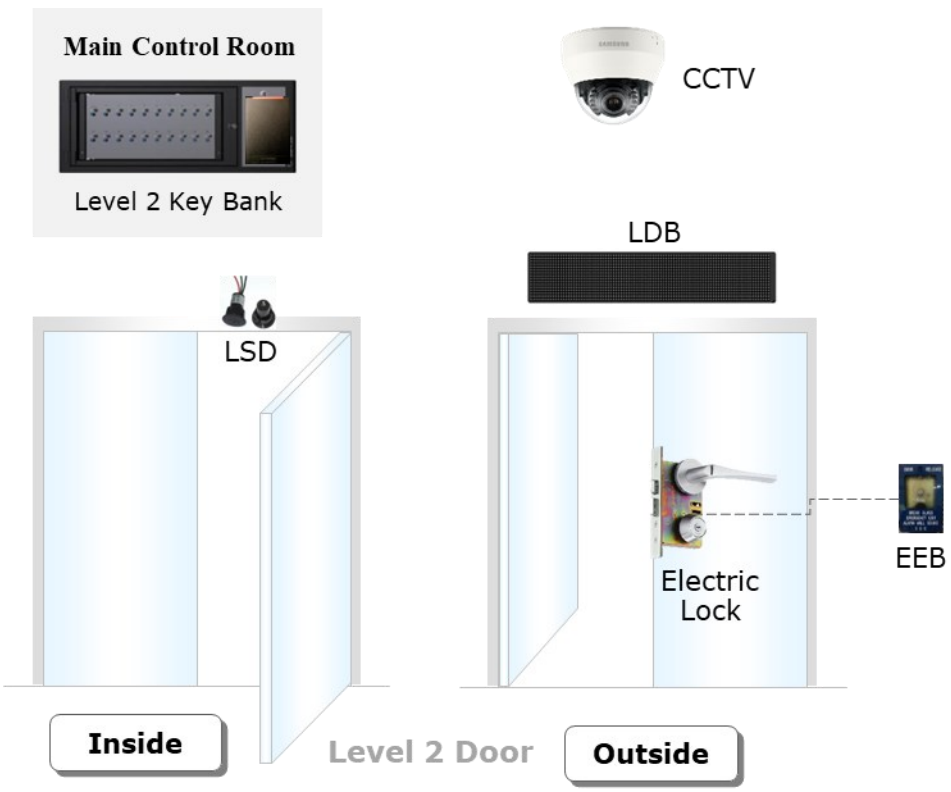
When the beam is in operation or residual radiation is present, no one is allowed to enter. The doors in the 4GSR facility are classified by purpose into personnel access doors and goods handling doors for the transport of equipment and materials. All doors are categorized into the following four levels, as summarized in <Table 6.4.2.1> and illustrated in <Figure 6.4.2.5> to <Figure 6.4.2.7>.

<Table 6.4.2.1> Classification of 4GSR Door Levels

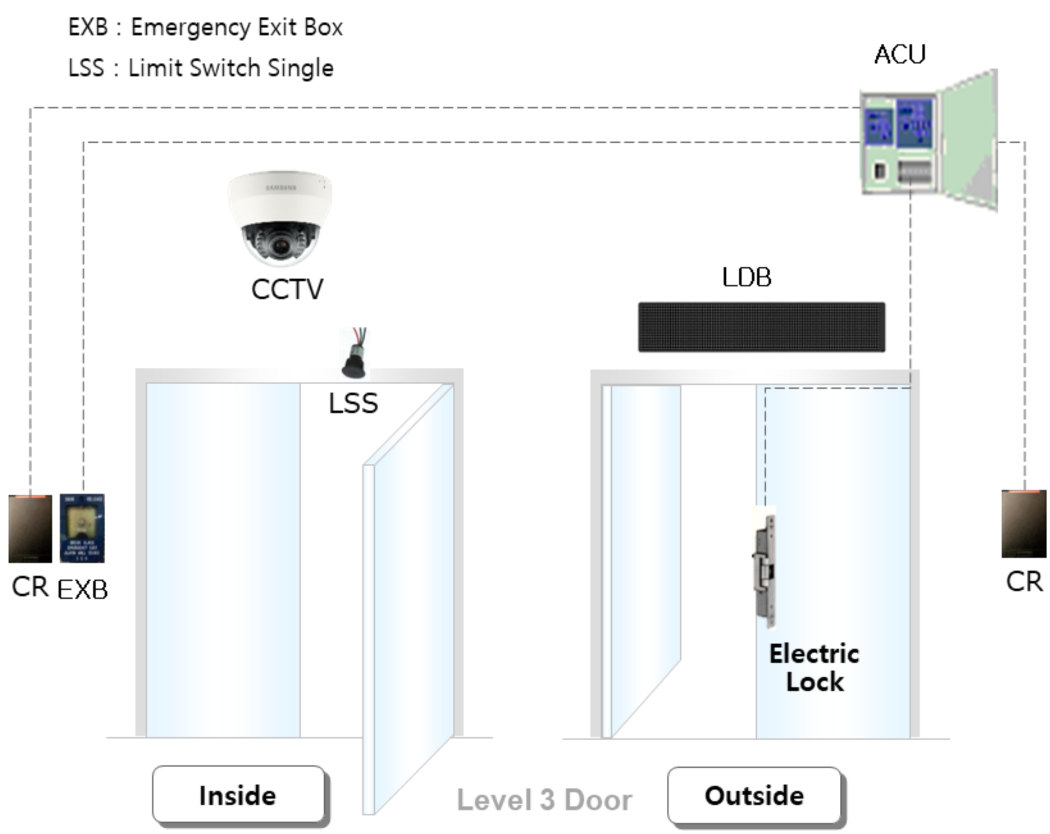
Level	Card Key	PSIS
Level 1	O	Connected
Level 2	O	Connected
Level 3	O	Connected
Level 4	O	No Connection



<Figure 6.4.2.5> Configuration of Level 1 Door.



<Figure 6.4.2.6> Configuration of Level 2 Door.



<Figure 6.4.2.7> Configuration of Level 3 Door.

① Level 1

Level 1 doors are authorized for access to the tunnel interior during restricted access conditions. These doors are connected to the PSIS, which prohibits beam operation if the door is opened or a Personal Key is removed from the Key Bank. The configuration of Level 1 doors is shown in <Figure 6.4.2.5>, and there is a total of five locations: one in the Linac building and four in the Storage Ring building.

② Level 2

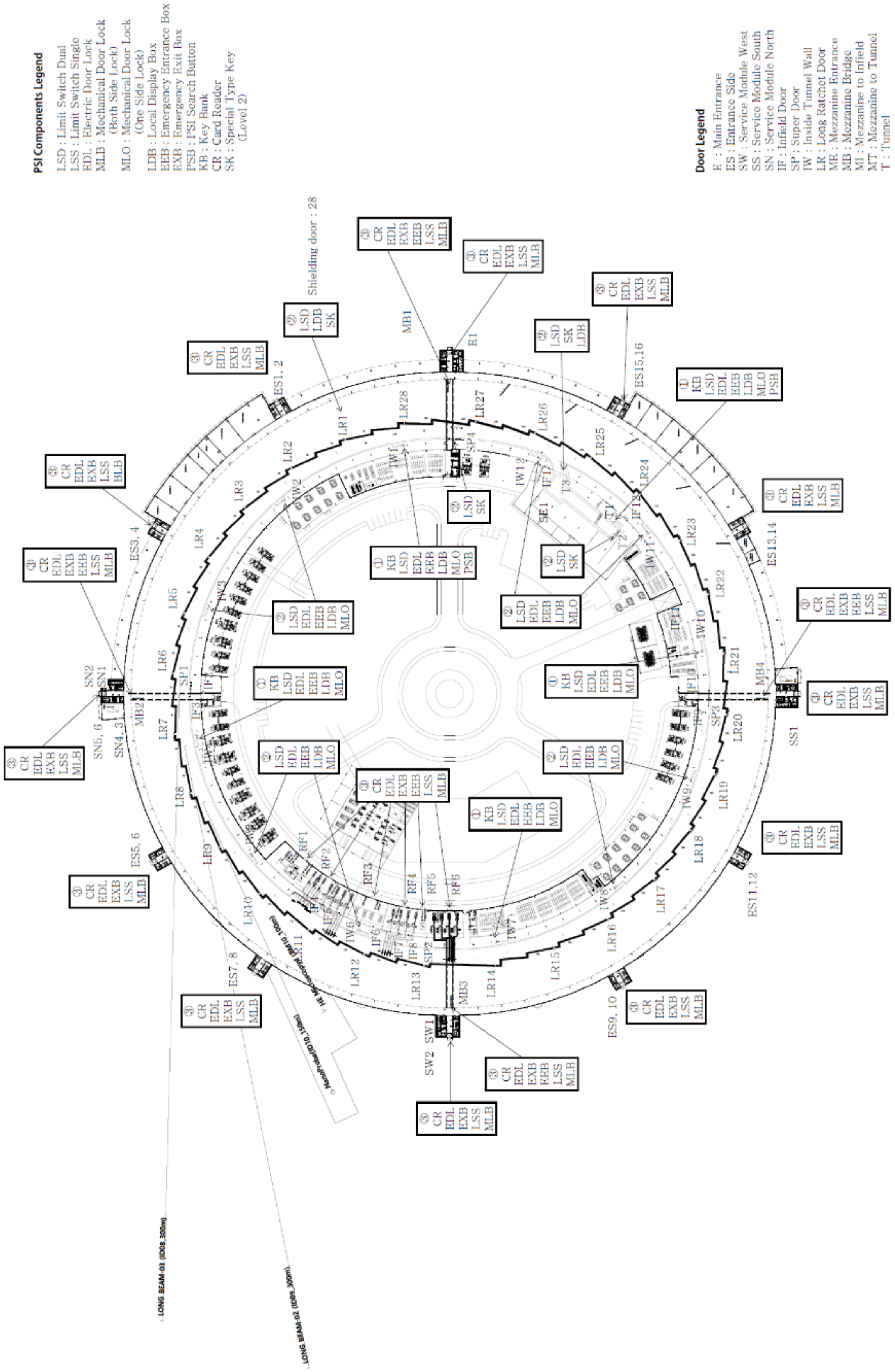
The functionality of Level 2 doors is identical to that of Level 1 doors, such that beam operation is stopped by the PSIS if a door is opened or a Key is removed from the Key Bank. However, to enhance safety and management efficiency, Level 2 doors are used only during maintenance periods or for equipment transportation when their use is essential. Regularly used doors are designated as Level 1. The configuration of Level 2 doors is shown in <Figure 6.4.2.6>, and there is a total of 45 locations: two in the Linac building and 43 in the Storage Ring building.

③ Level 3

Unlike Level 1 and Level 2 doors, which prohibit access to the tunnel interior, Level 3 doors restrict access to the controlled areas of the 4GSR facility. These doors are equipped with PSI devices but are not interlocked with beam operation. Level 3 doors can be accessed using an ID card or a Key from the Level 3 Key Bank located in the control room. For frequently accessed doors, ID Card Readers are installed both inside and outside the door to log and verify user information against the access control server. There is a total of 52 Level 3 doors.

④ Level 4

Level 4 doors are not managed in relation to radiation safety and are not controlled by the PSIS. These include personal office doors within the building as well as doors equipped with ID Card Readers for building security management. Doors managed by ID Card Readers leave an access record.



<Figure 6.4.2.8> Configuration of Access Control System at accelerator building.

(3) Machine Interface System

The Machine Interface System is a system designed to isolate risk factors in the event of a PSIS trip or equipment failure. This system essentially manages beam operation by establishing a relationship between the Main Sequence System, which acts as the core of PSIS during operation, and the operator based on signals received from individual PSIS equipment. The purpose of this system is to create an organic connection between the PSIS and the operation of the multi-purpose synchrotron radiation accelerator, enabling appropriate control for each operational situation of the accelerator.

The functionality of the Machine Interface System connects to the PLC Remote I/O input and output modules of the PSIS. The input module reads the operational status of equipment through contact signals, while the output module uses DC 24 V to drive relays that enable equipment operation. In the event of a trip, the relay output is interrupted, halting the operation of the equipment. This configuration enhances system stability by adhering to the Normal Close method, where the system defaults to a closed state when no signal is given or during a power outage.

<Table 6.4.2.2> summarizes the key equipment of the 4GSR accelerator connected via the Remote I/O module of the PSIS.

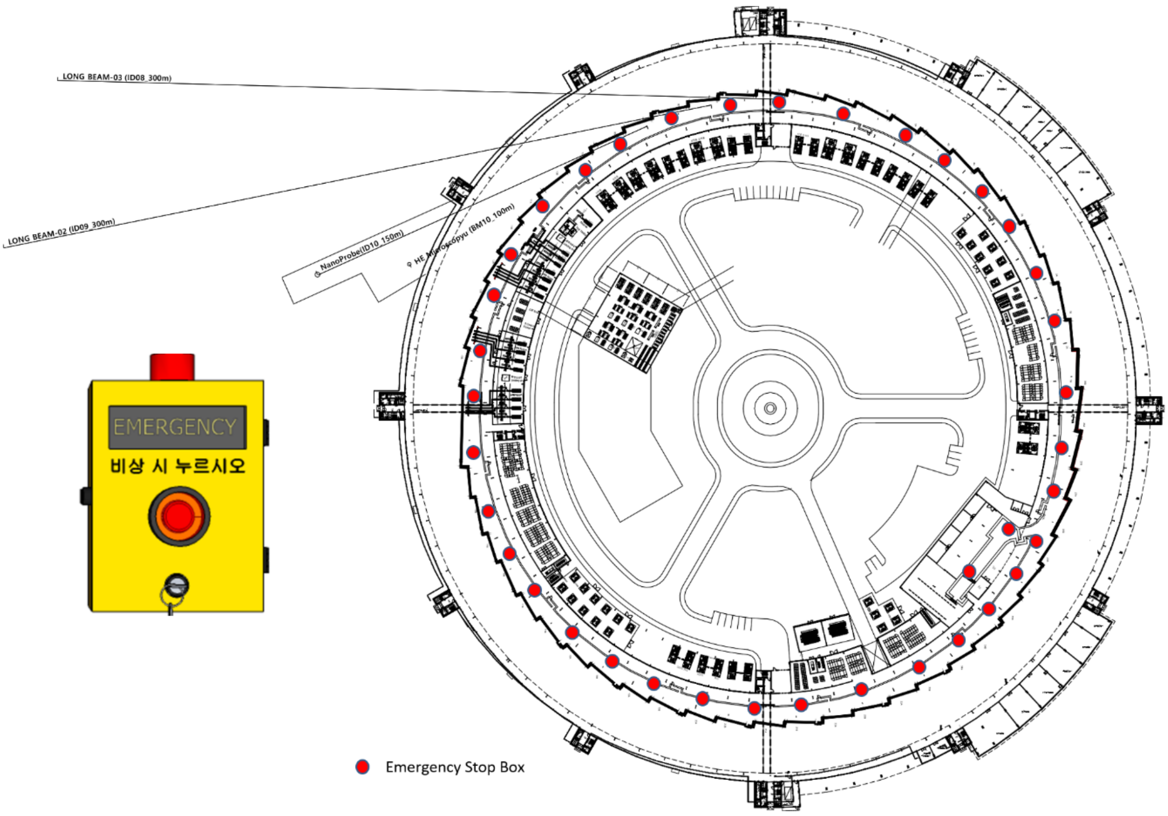
<Table 6.4.2.2> Key Devices Connected to the PSIS in the 4GSR Accelerator

Key Device	PLC I/O	Meaning	Description
Electron Gun Laser Shutter	Input:	Beam ON	Monitors the status of the electron gun laser shutter.
	Output:	Beam OFF	Stops the operation of the electron gun, preventing electron emission from the electron gun.
Linac Gate Valve	Input:	Beam ON	Monitors the operational status of the gate valve.
	Output:	Beam OFF	Closes the gate valve, blocking the electron beam transmission.
Linac RF LLRF	Input:	RF ON	Monitors the operational status of the Linac LLRF.
	Output:	RF OFF	Stops the operation of the Linac LLRF, halting electron beam acceleration.
Linac RF Od. H.V P/S	Input:	RF ON	Monitors the operational status of the accelerator tube; Linac RF ON signal.
	Output:	RF OFF	Stops the operation of the accelerator tube, halting electron beam acceleration.
BTL E-Beam FCS	Input:	Top-up ON	Monitors operational status in Top-up mode.
	Output:	Top-up OFF	Stops the electron beam in Top-up mode.
BTL Safety Shutter	Input:	Top-up ON	Monitors operational status in Top-up mode.
	Output:	Top-up OFF	Stops the electron beam in Top-up mode.
SR RF LLRF	Input:	RF ON	Monitors the operational status of the SR LLRF.
	Output:	RF OFF	Stops the SR LLRF operation, halting the electron beam or dark current.
SR RF H.V	Input:	RF ON	Monitors the operational status of the accelerator tube; SR RF ON signal.
	Output:	RF OFF	Stops the operation of the accelerator tube, halting electron beam acceleration.
SR Beam Stopper	Input:	Beam ON	Monitors the operational status of the SR accelerator tube.
	Output:	Beam OFF	Stops the operation of the SR accelerator tube, blocking electron beam transmission.
SR Booster Ring LLRF	Input:	RF ON	Monitors the operational status of the booster ring LLRF.
	Output:	RF OFF	Stops the operation of the booster ring LLRF, halting electron beam acceleration.
Beamline Safety Shutter	Input:	Safety Shutter Open	Monitors the open/close status of the beamline safety shutter.
	Output:	Safety Shutter Closed	Blocks synchrotron radiation or accidental radiation in the beamline.

(4) Emergency Stop System

The Emergency Stop System is designed to detect emergency situations. The actual beam shutdown is managed by the Machine Interface System. Emergency stop boxes inside the tunnel are planned to be installed at approximately 30 m intervals, with 36 units in the storage ring tunnel and 2 units in the linear accelerator, as shown in <Figure 6.4.2.9>.

The Emergency Stop Box is composed of a reset key switch, an emergency stop button, and a lamp. The boxes are installed in highly visible yellow and red colors. The reset function is exclusively used as an input for the Main Sequence System, while the lamp operates only through the output of the Main Sequence System. Pressing the emergency stop button triggers the Main Sequence System to blink the lamp on the respective emergency stop box and the LED on the control room status panel, simultaneously halting beam operations.



<Figure 6.4.2.9> Configuration of Emergency Stop Box.

(5) Display & Alarm System

The Display System can be divided into Local Display Boxes and the PSI Status Board. Local Display Boxes are located within the controlled area and indicate whether the door is accessible or not. The display options for the Local Display Boxes at tunnel entry doors are "No Entry," "Restricted Access," and "Authorized Access." The installation of Local Display Boxes will be arranged at doors leading directly into the tunnel, experimental areas, and the main entrances of buildings.

The Alarm System notifies users of emergency stops due to PSI trips, operation start, and PSI operation mode change. It consists of a warning light and a buzzer. A total of 16 sets will be installed at 100 m intervals inside the tunnel, and additional sets will be installed at 200 m intervals in the experimental areas.

○ Warning Light

- Red: Indicates the start of a "No Entry" mode or an emergency state.

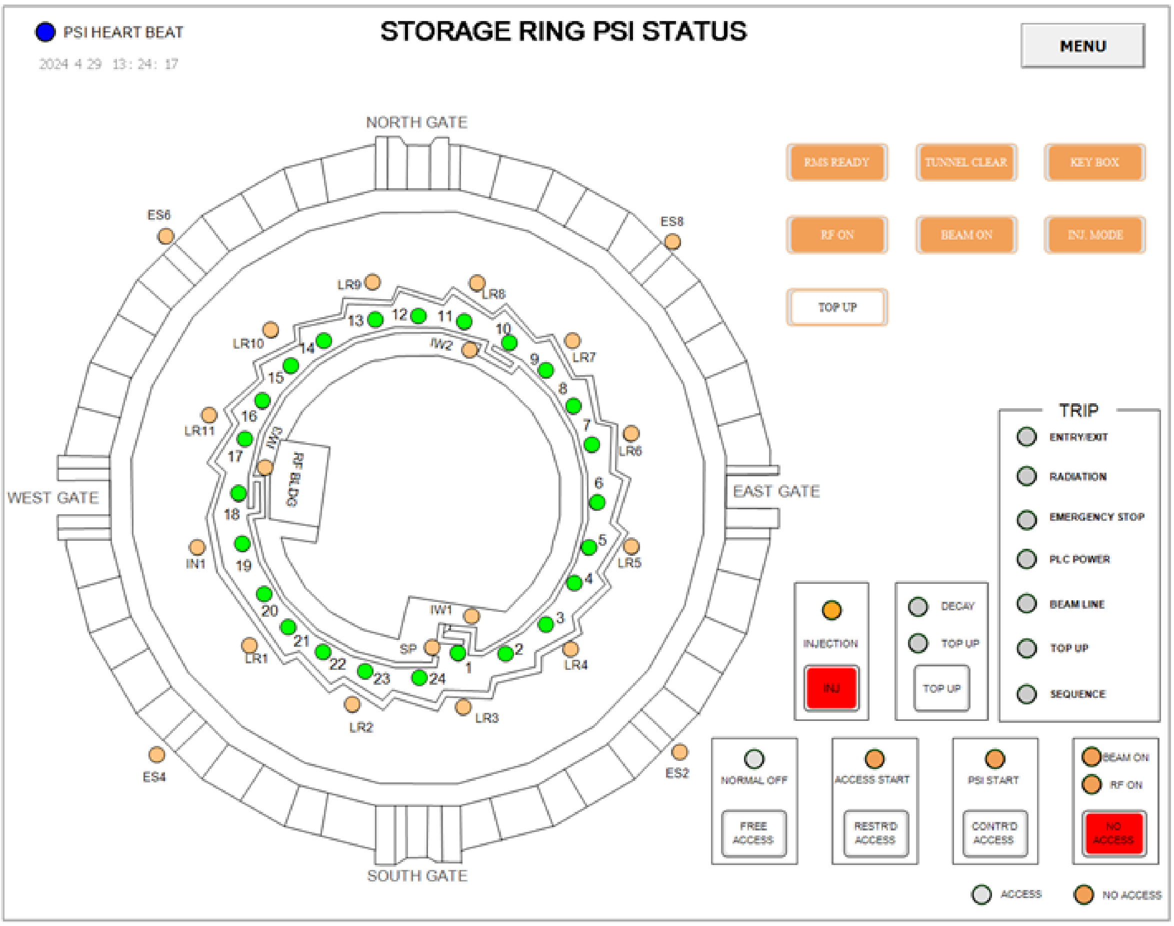
- Yellow: Indicates the start of a "Restricted Access" mode.

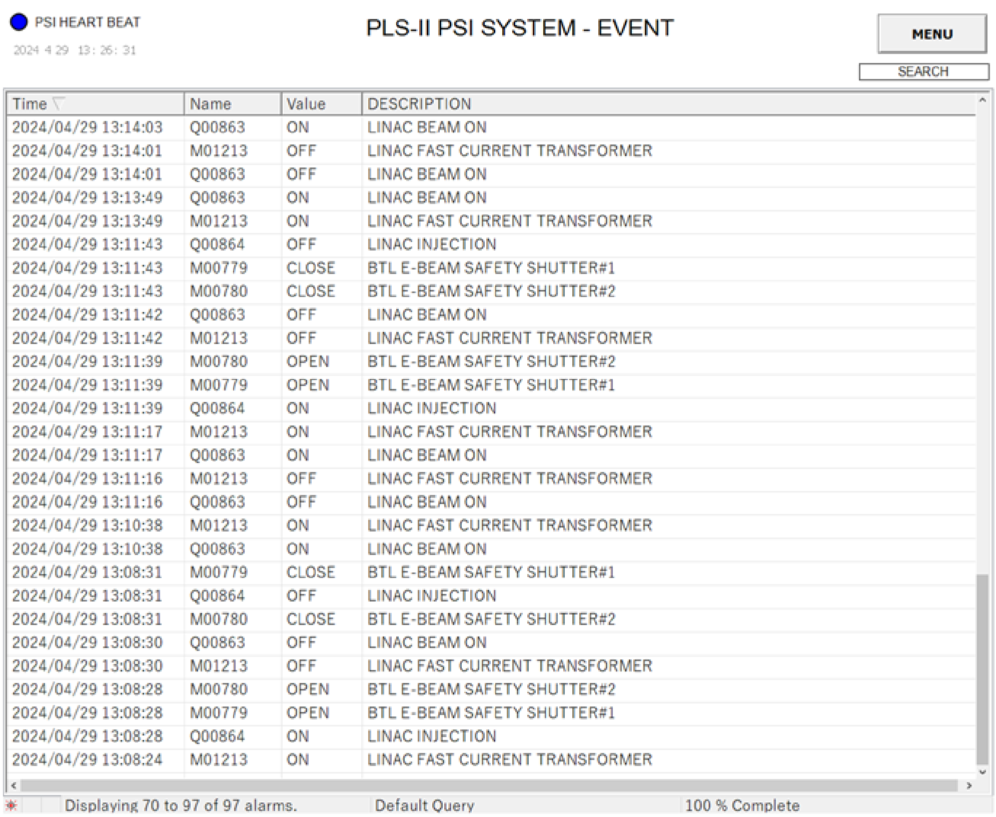
○ Buzzer

- Indicate the start of a "No Entry" mode or an emergency state.

(6) Human Machine Interface (HMI) System

The human machine interface (HMI) system monitors various equipment in the site from the main sequence system (PLC) in real-time in a computer environment and expresses the conditions and situations of the sites to allow the operator to monitor them in the form of pictures or values, as exemplified in <Figure 6.4.2.10>. The HMI function is only related to monitoring, and the main sequence system cannot be controlled using the HMI system. The HMI system has various functions, including a function that shows the site status as a picture, an alarm status function that processes real-time or history data, and a notification function for the operator when an abnormal situation occurs at the site so that the operator can act against any abnormal situation.





Time	Name	Value	DESCRIPTION
2024/04/29 13:14:03	Q00863	ON	LINAC BEAM ON
2024/04/29 13:14:01	M01213	OFF	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:14:01	Q00863	OFF	LINAC BEAM ON
2024/04/29 13:13:49	Q00863	ON	LINAC BEAM ON
2024/04/29 13:13:49	M01213	ON	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:11:43	Q00864	OFF	LINAC INJECTION
2024/04/29 13:11:43	M00779	CLOSE	BTL E-BEAM SAFETY SHUTTER#1
2024/04/29 13:11:43	M00780	CLOSE	BTL E-BEAM SAFETY SHUTTER#2
2024/04/29 13:11:42	Q00863	OFF	LINAC BEAM ON
2024/04/29 13:11:42	M01213	OFF	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:11:39	M00780	OPEN	BTL E-BEAM SAFETY SHUTTER#2
2024/04/29 13:11:39	M00779	OPEN	BTL E-BEAM SAFETY SHUTTER#1
2024/04/29 13:11:39	Q00864	ON	LINAC INJECTION
2024/04/29 13:11:17	M01213	ON	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:11:17	Q00863	ON	LINAC BEAM ON
2024/04/29 13:11:16	M01213	OFF	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:11:16	Q00863	OFF	LINAC BEAM ON
2024/04/29 13:10:38	M01213	ON	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:10:38	Q00863	ON	LINAC BEAM ON
2024/04/29 13:08:31	M00779	CLOSE	BTL E-BEAM SAFETY SHUTTER#1
2024/04/29 13:08:31	Q00864	OFF	LINAC INJECTION
2024/04/29 13:08:31	M00780	CLOSE	BTL E-BEAM SAFETY SHUTTER#2
2024/04/29 13:08:30	Q00863	OFF	LINAC BEAM ON
2024/04/29 13:08:30	M01213	OFF	LINAC FAST CURRENT TRANSFORMER
2024/04/29 13:08:28	M00780	OPEN	BTL E-BEAM SAFETY SHUTTER#2
2024/04/29 13:08:28	M00779	OPEN	BTL E-BEAM SAFETY SHUTTER#1
2024/04/29 13:08:28	Q00864	ON	LINAC INJECTION
2024/04/29 13:08:24	M01213	ON	LINAC FAST CURRENT TRANSFORMER

Displaying 70 to 97 of 97 alarms. Default Query 100 % Complete

<Figure 6.4.2.10> Configuration example of Human Machine Interface (HMI) System.