11th Radsynch, May 30 – June 2, 2023

Shielding Design and Current Status of New Compact Synchrotron Facility at PAL

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Contents

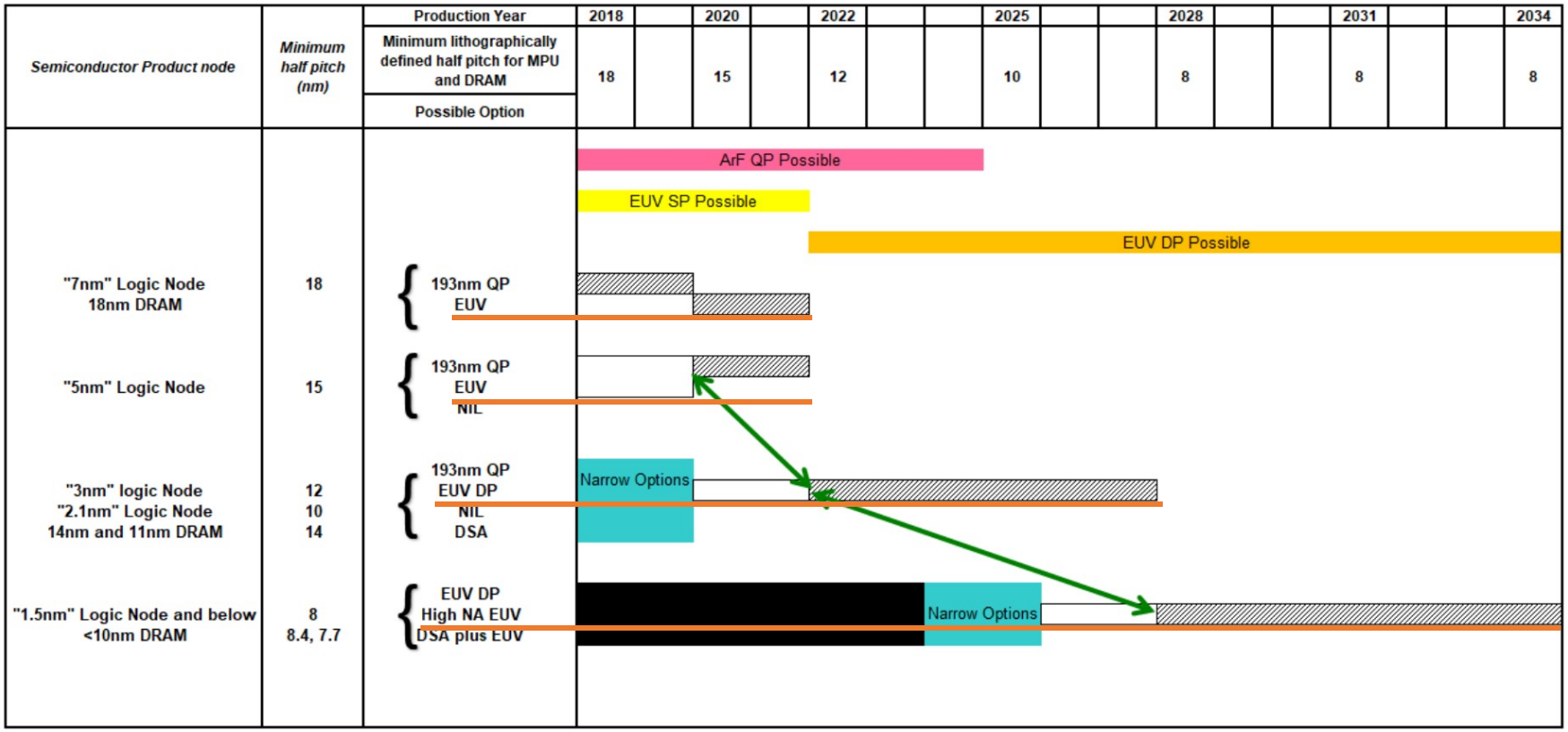
Light Sources at PAL (Project years)

1. PAL_EUV Project overview

- **PAL-EUV is a new Low Energy Synchrotron Light Source, fully funded from Korean Government**
  - **To provide diffraction-limited radiation at EUV range**
  - **Application mainly for semiconductor R&D**
  - **Construction project from March 2020 to December 2022**
  - **Project budget 29 Billion Korean Won (~21 Million US Dollar)**
    - 20 Billion Won for accelerator
    - 9 Billion Won for beamline (mask inspection)

1-1. Project Overview – EUV Lithography

- ❑ EUV Lithography is the current and future solution for semiconductor patterning technology.
- ❑ PAL-EUV is dedicated infrastructure for the EUV materials and process research.



INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS (2020 EDITION LITHOGRAPHY)

1-1. Project Overview – Building Renovation

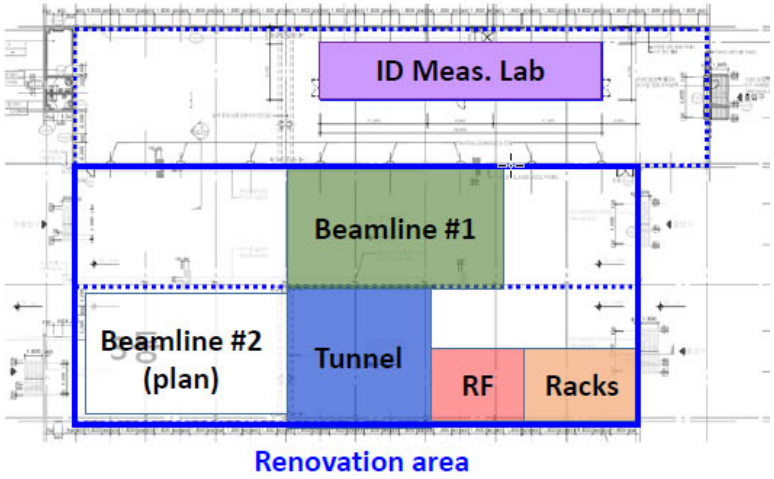
Inside Accelerator Tunnel (2023)

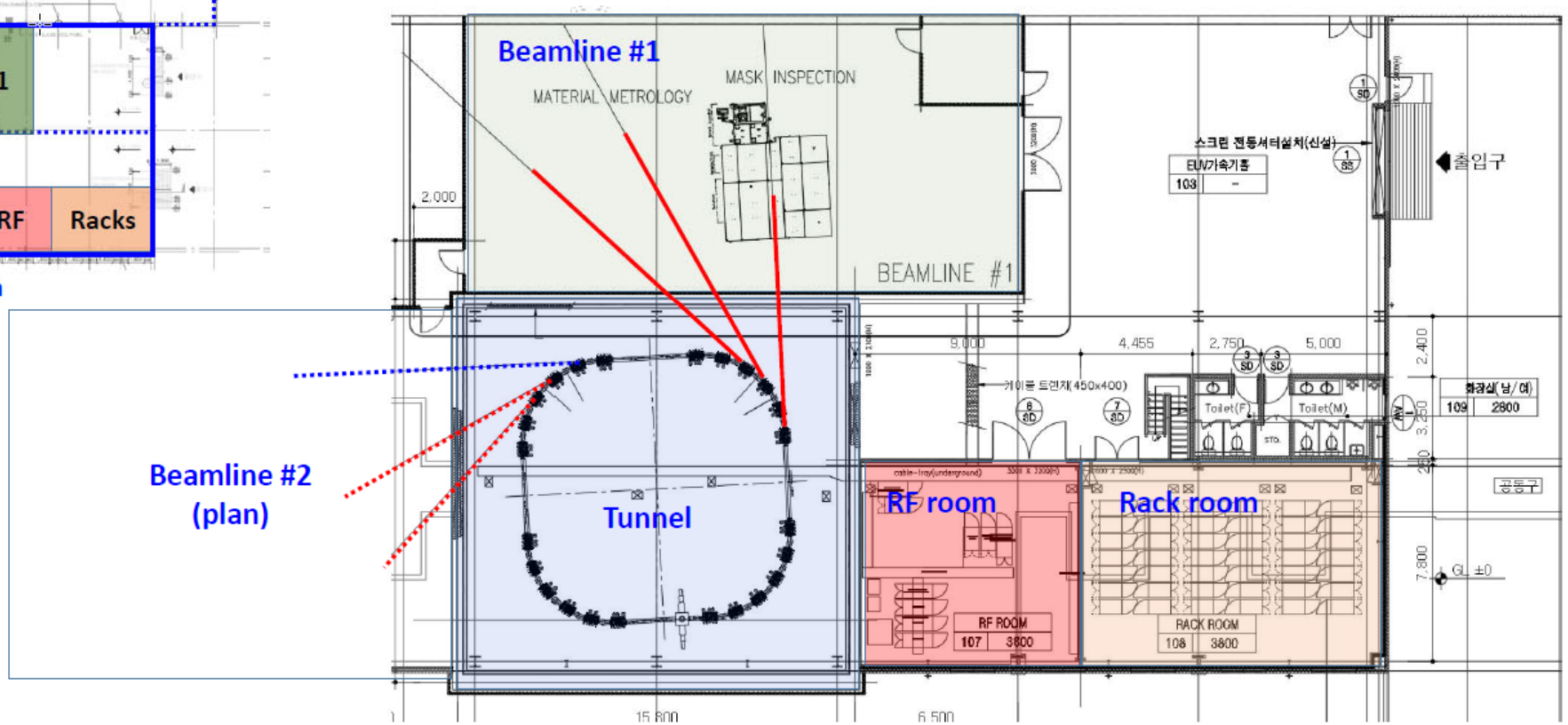
Originally "Components Storage & Assembly Building" used for PLS-II upgrade

→ PAL-EUV Building (since 2020)

Inside the Building (2020)

1-1. Project Overview – Building Layout





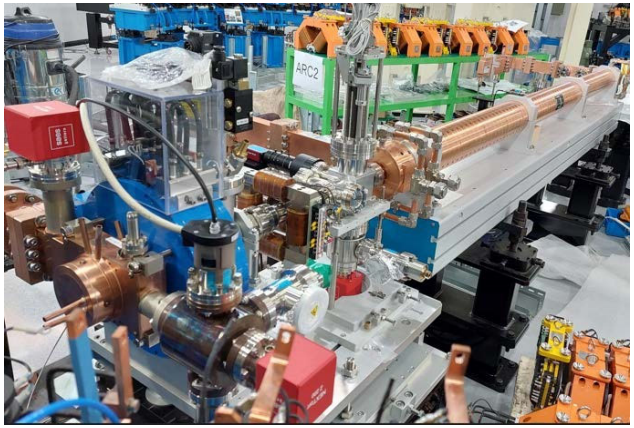
1-2. PAL-EUV Accelerators

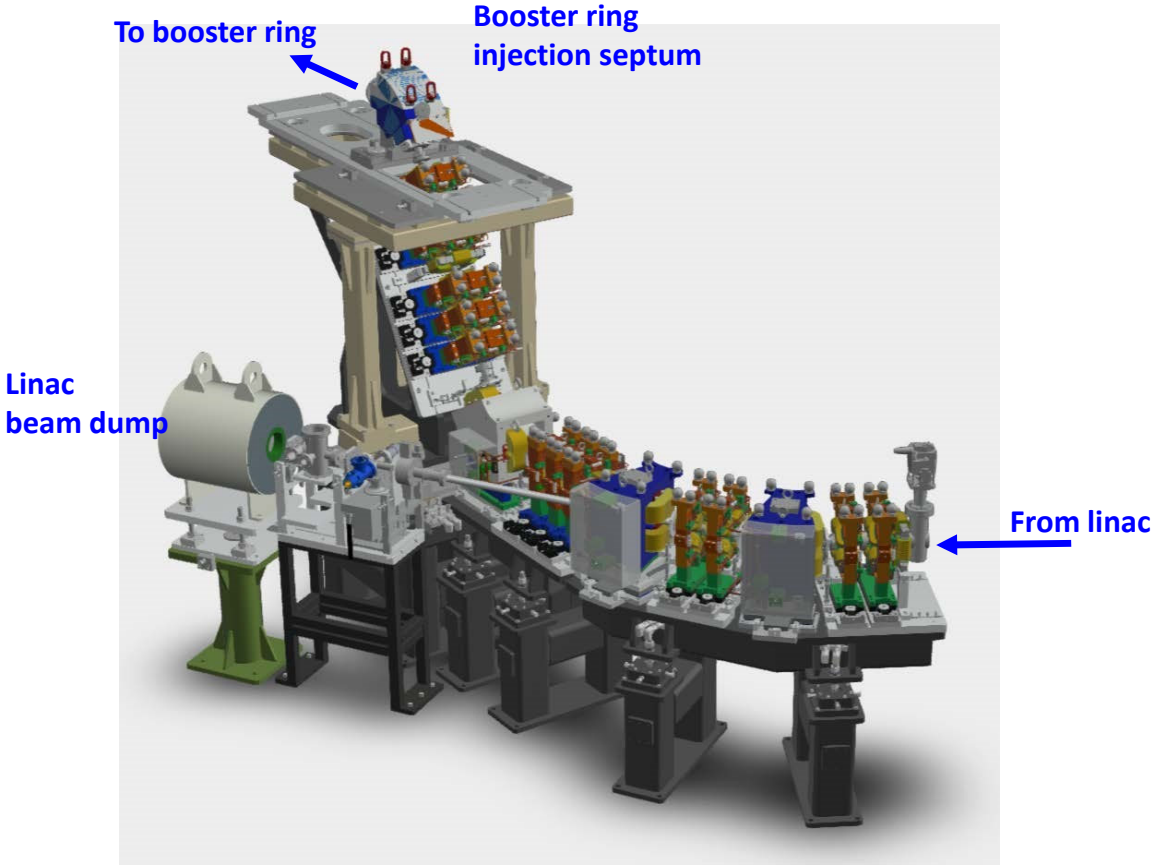
- ❑ Injector Linac (to 20 MeV)
  - Photocathode gun (in-house, 2.7 MeV) + 3 m accelerator column
  - 10 MW S-band klystron + solid state modulator
- ❑ Booster Ring(from 20 to 400 MeV)
  - 2 straights for injection/extraction
  - 500 MHz PLS cavity (reuse)
- ❑ Storage Ring(400 MeV)
  - 4 straights for injection and three IDs
  - 500 MHz RI cavity
  - 1500 MHz harmonic cavity

1-2. PAL-EUV Accelerators – Linac

❑ Electron Beam at Linac End

- Beam energy : 20 MeV
- Bunch charge : 35 ~ 300 pC
- Transverse normalized emittance : 0.5 mm mrad
- Bunch length : 2 ps rms

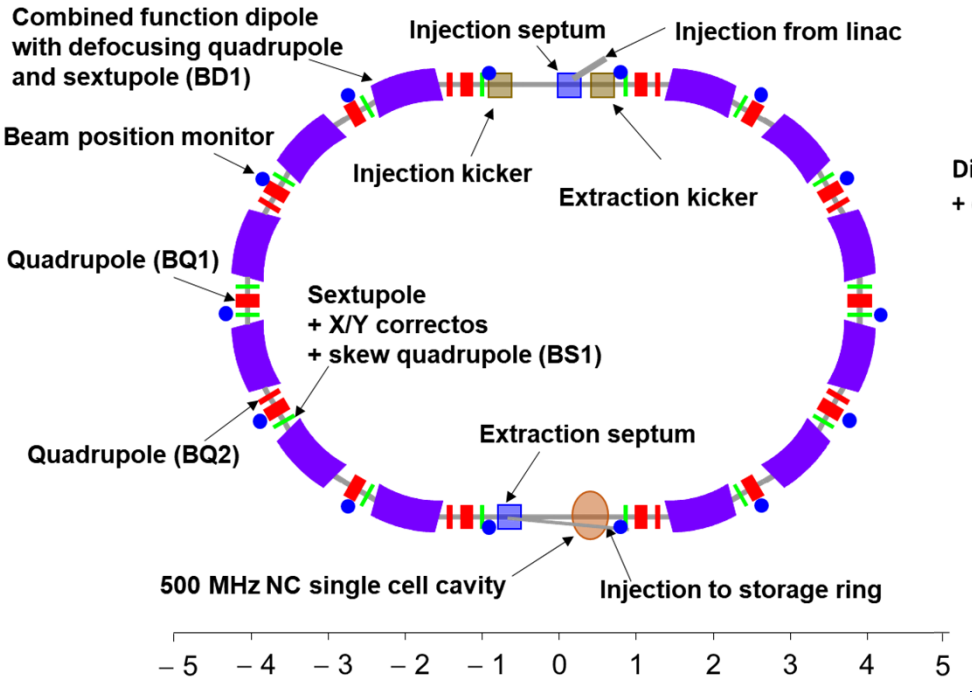




1-2. PAL-EUV Accelerators – Booster & Storage Ring

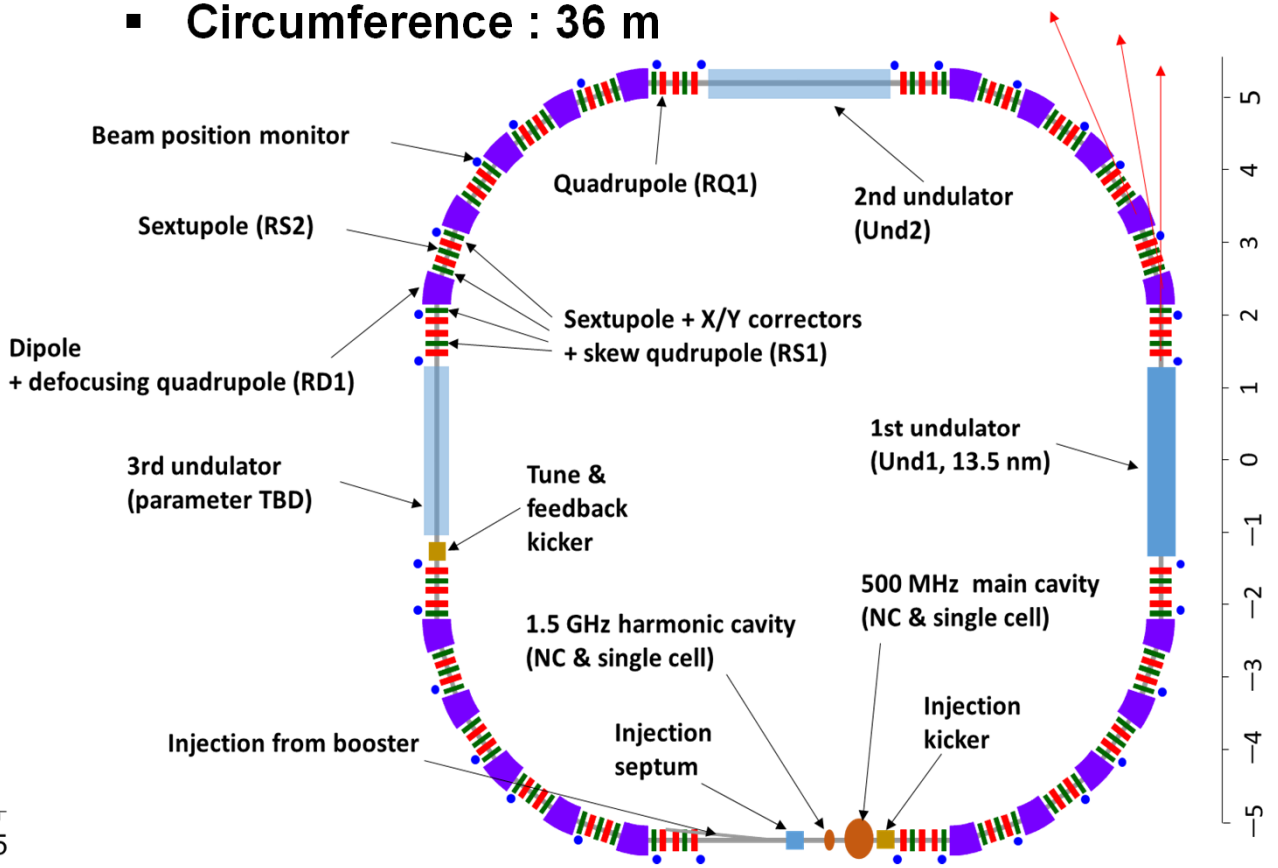
❑ Booster Synchrotron

- Beam energy : 400 MeV
- Circumference : 22.2 m
- Emittance : 4.2 nm
- Repetition rate : 0.5 Hz



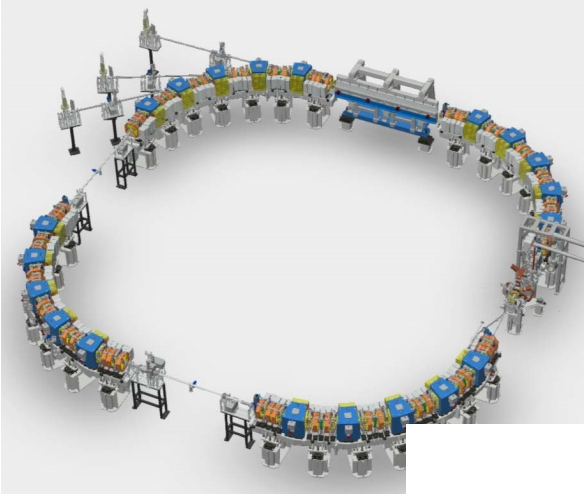
❑ Storage Ring

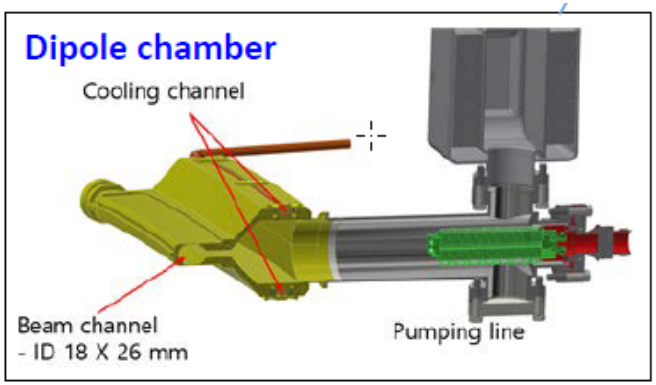
- Beam energy : 400 MeV
- Stored current : 140 mA
- Circumference : 36 m



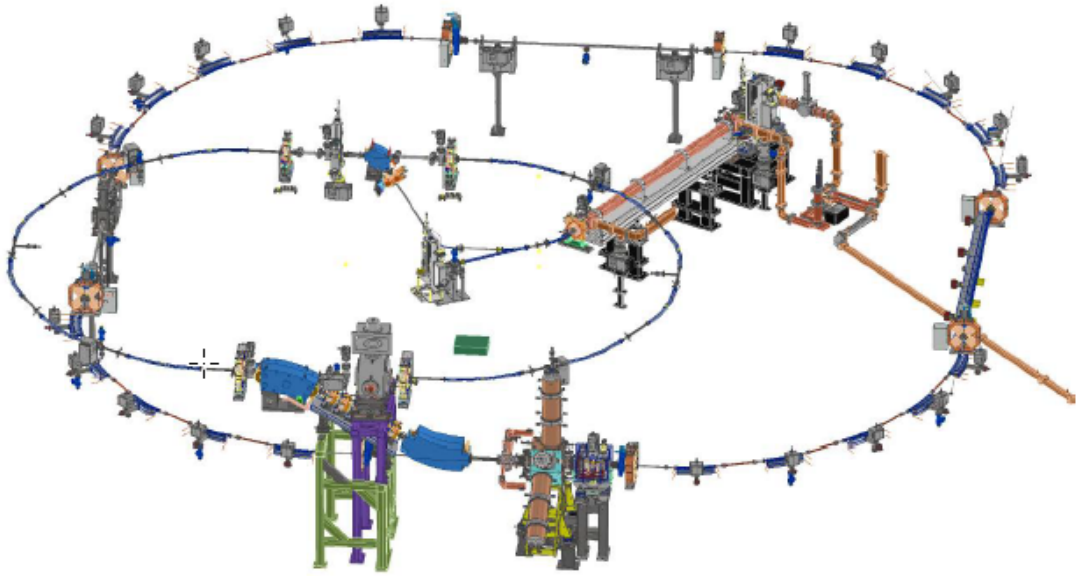
1-2. PAL-EUV Accelerators III – Booster & Storage Ring

Parameters	Values at 400 MeV
Circumference	36 m
Harmonic number	60
Beam current	140 mA
Emittance_X (nm)	1.16
Tune_X	7.153
Tune_Y	3.044
Chromaticity X, natural	-10.66
Chromaticity Y, natural	-16.71
Chromaticity X, corrected	1.0
Chromaticity Y, corrected	1.0
Alpha	0.0104
dE/turn (keV)	1.7
Energy spread (E-4)	3.82
Damping time X (ms)	30.7
Damping time Y (ms)	56.7
Damping time S (ms)	49.0





Vacuum model of PAL-EUV accelerator



2. Shieldign Design Criteria : Control Policy at PAL

- **Dose Limit (based on Korean Regulation)**
  - Radiation Workers (RW) : 20 mSv/y
  - Frequent Visitors : 6 mSv/y
  - Public (including User) : 1 mSv/y
  - Site Boundary : 0.25 mSv/y

- **Shielding Criteria**

  (Normal Operation)
  - RW accessible area : 10 mSv/y,

    (½ of dose limit based on ALARA)
  - User accessible area : 1 mSv/y

  (Abnormal Operation)

  1 mSv for single event

- **Area Classification**
  - Restricted Area : 0.25 mSv/y ≤ Dose < 1 mSv/y
  - Generally-Controlled Area : 1 mSv/y ≤ Dose < 20 mSv/y
  - Radiologically-Controlled Area : 20 mSv/y ≤ Dose < 1 mSv/h
  - High Radiation Area : Dose ≥ 1 mSv/h (No Access)

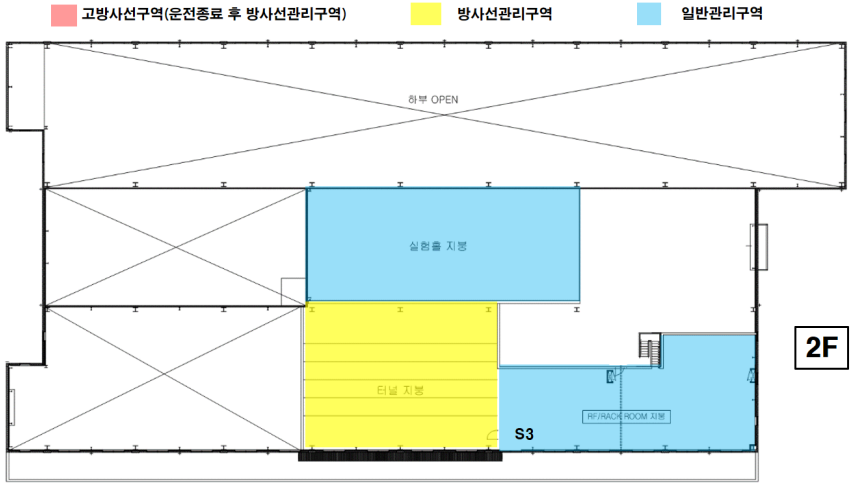
2-1. Region Classification

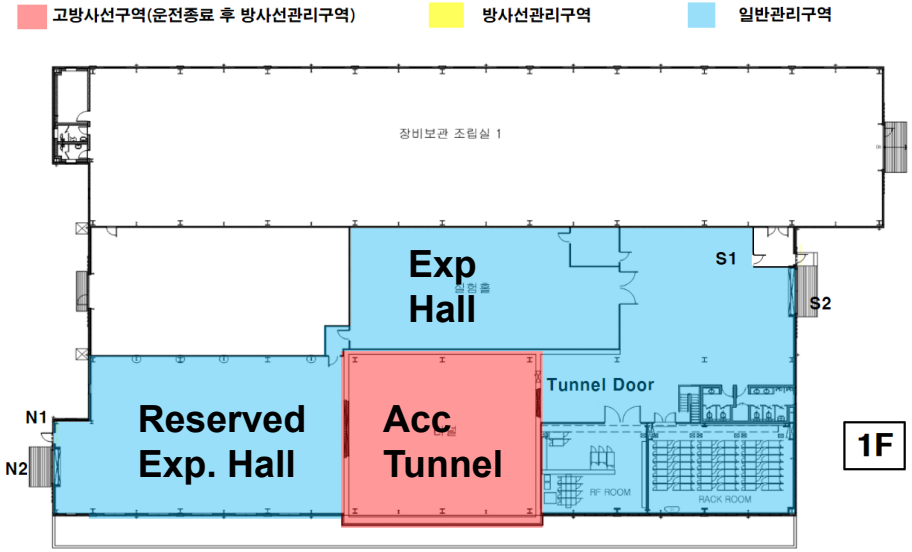
제한구역 - 부지경계내
0.25 mSv/year < Dose < 1 mSv/year
Restricted Area

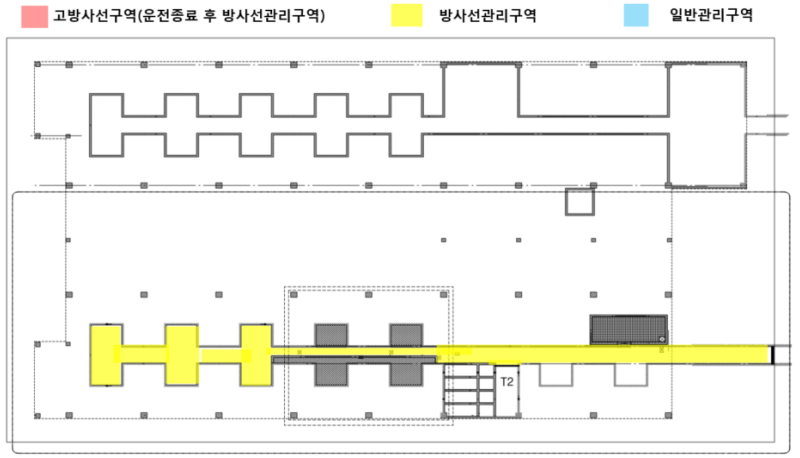
일반관리구역
1 mSv/year < Dose < 20 mSv/year
(20 mSv/year = 0.4 mSv/week = 10 μSv/hour)
Generally-controlled Area

방사선관리구역
20 mSv/year < Dose < 1 mSv /hour
또는 특별기준에 따라
Radiologically-controlled Area

고방사선구역
1 mSv/hour < Dose
High Radiation Area







3. Methods and Interesting Issues at Radiation Shielding Ana

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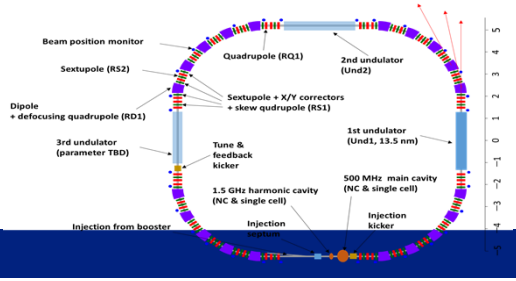
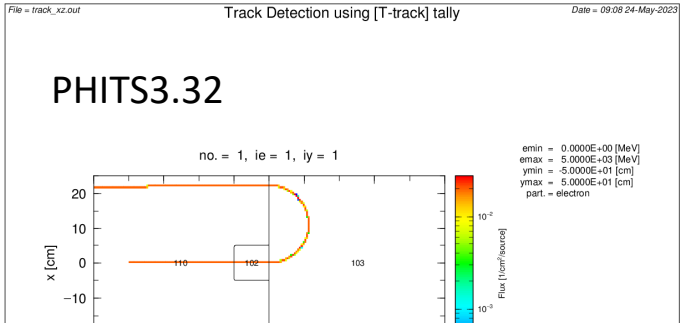
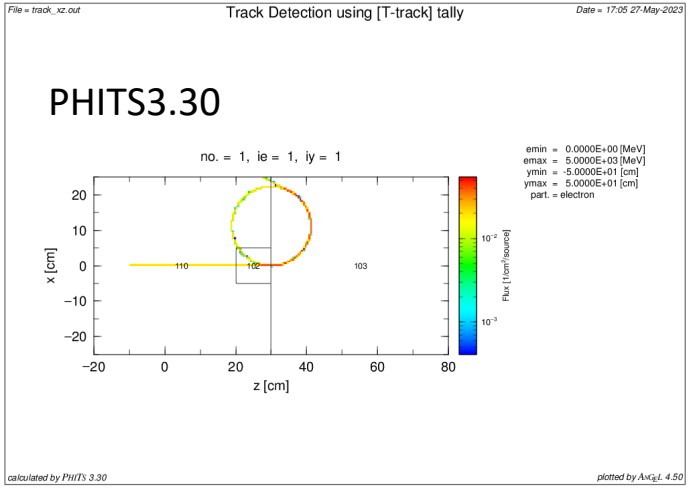
- ❑ To use SHIELD 11 to decide thickness of accelerator tunnel wall & ceiling
  - Side walls for controlled area : 40 cm Ordinary Concrete.
  - Side wall for public area : 60 cm Ordinary Concrete + Extra Pb
  - Ceiling for RC area : 10 cm Ordinary Concrete + (Extra Pb for abnormal op.)

- ❑ To use PHITS3.30 to design real shielding structure
  - Normal / Abnormal Op.
  - One shielding door equivalent to concrete wall
  - Neglecting lower energy linac in the one region
  - Safety Permanent Magnet for beam line shielding (Safety PM was not needed at PLS-I & -II)
  - Error of magnetic field simulation at old version of PHITS







3-1. Methods in Radiation Shielding Analysis

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❑ Shielding Calculation Strategy of PAL-EUV
- One wall meets out of building, public access zone.
- Shielding Criteria : 0.5 uSv/h, 5 uSv/h, 1 mSv/event
- Calculation tools : (SHIELD11), PHITS
- Beam loss scenario : Assumed from experts' experience
- 20 MeV linac is not impact machine in the view of RP

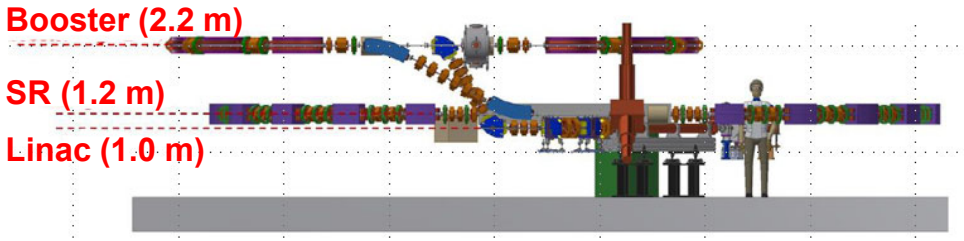
❑ Normal Beam Loss
- Beam loss at each injection process (0.5 Hz)
- Uniformly-distributed loss at Booster (400 MeV)
- Uniformly-distributed loss at SR
- Assume thick iron target (10Xo) at each dipole magnet

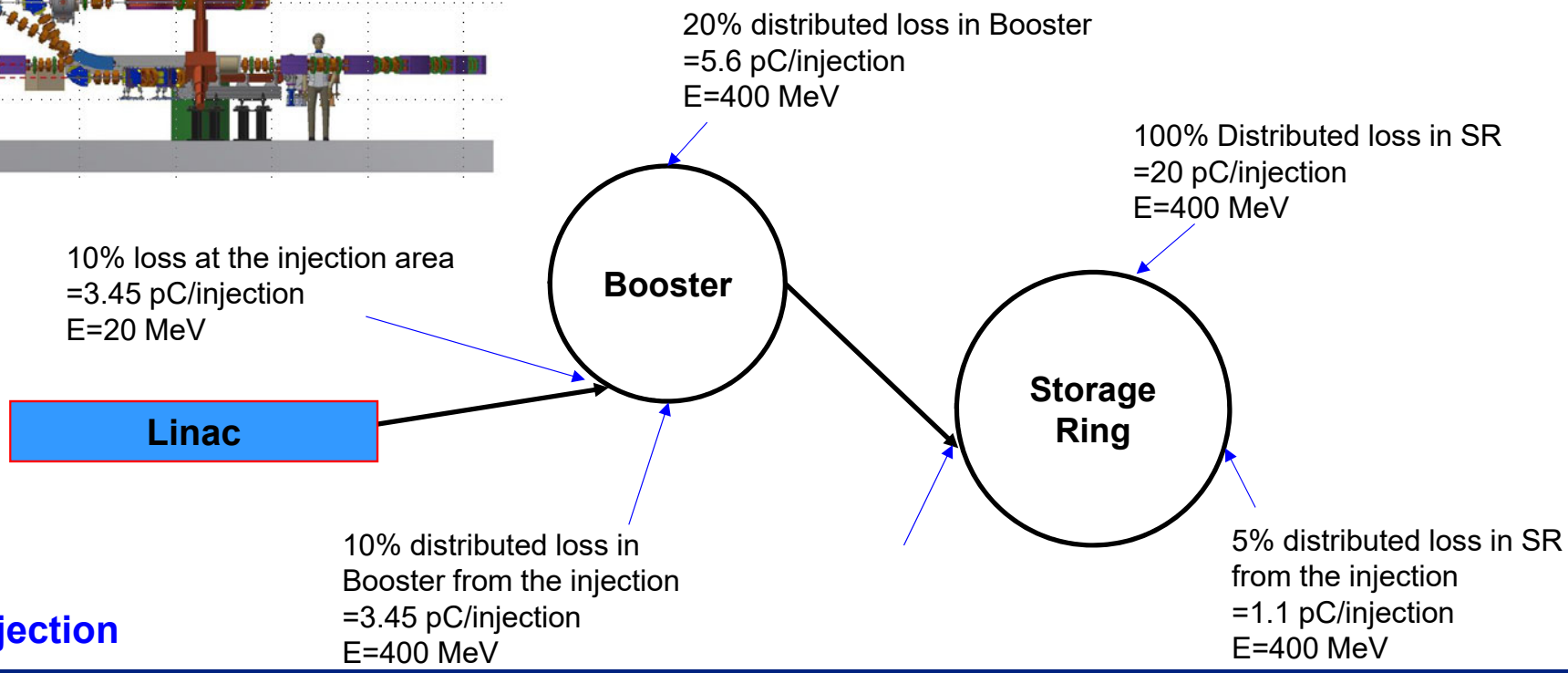
❑ Accidental Beam Loss (Abnormal Operation)
- Total loss of stored beam
- Continuous loss at one point during injection
- Beam loss by failures of magnets for injection or dipole magnets

Storage Ring Parameters for PAL EUV	
Beam energy [MeV]	400
Beam current [mA]	140
Beam life time [min]	30 (1800 s)
Circumference [m]	36
Stored charge [nC]	16.8
Stored electron	1.05×10^{11}
Stored energy [J]	42
Beam loss (pC/s)	16.8/(1800) = 9.33
Beam loss (e/s)	5.83×10^{7}

3-2. Methods – Normal Beam Loss

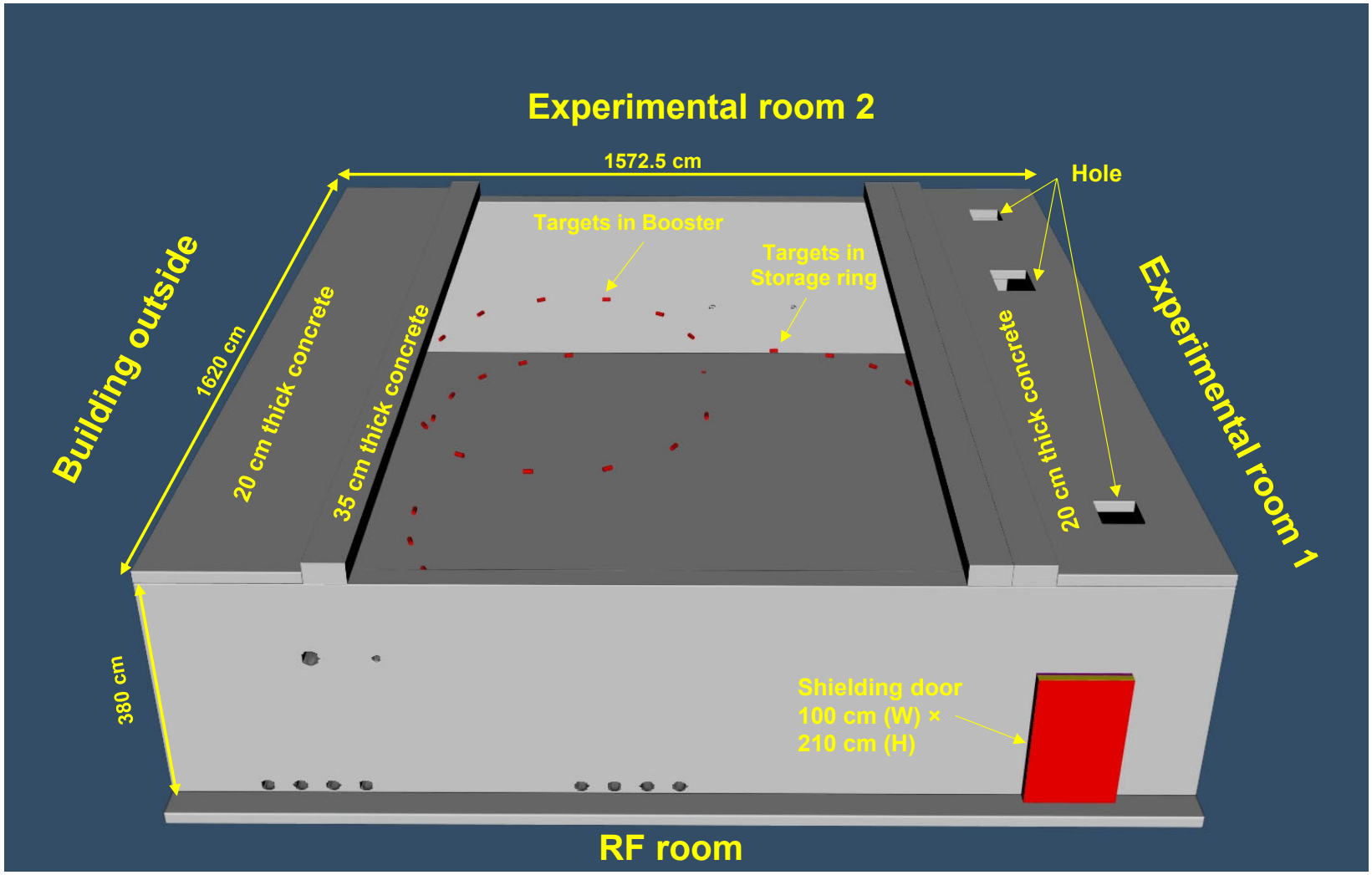
1. Dose rate from distributed loss of stored beam in storage ring → [20pC/injection is lost during 2 seconds]
2. Dose rate during the injection from booster to storage ring→ [5% loss locally+ 5% distributed loss in SR]
3. Dose rate from distributed beam loss during boosting → [20% distributed loss]
4. Dose rate during the injection from linac to booster → [10% loss locally+10% distributed in Booster]

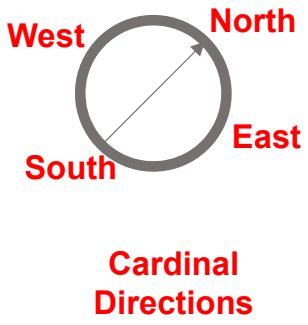




Every 2 second: 1 injection

3-3. Objects of Radiation Shielding Analysis (except beam line)





4. Radiation Shielding Analysis using PHITS code

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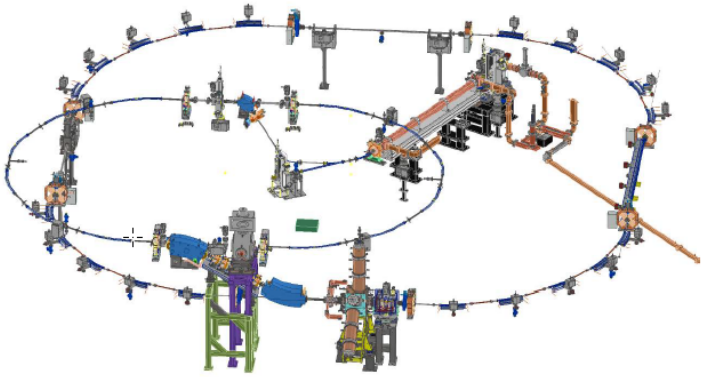
❑ Accelerator Conditions

- Good injection efficiency (90% B to SR)
- Mild loss during boosting (20% loss but 400 MeV)
- Relatively low beam power (140 mA, 1.05 x 10^{11} e-, 0.5 Hz injection rate)

❑ What is beam loss condition with no detail information from Accelerator group

- All bending magnets is normal beam loss point for distributed loss
  ➔ Loss at thick target (Φ8 cm x 17.6 cm Iron)
  Beam direction is the same to normal beam direction
- Any bending magnet failure is assumed for abnormal op.
  ➔ Thinner target (2 cm-thick Iron) for beam line shielding
- Injection failure is also assumed as failure of first bending magnet after injection
- The most accidental case – 400 MeV electrons go to beam line, experimental hall.

Vacuum model of PAL-EUV accelerator



4-1. Final Results of Main Radiation Shielding Structure

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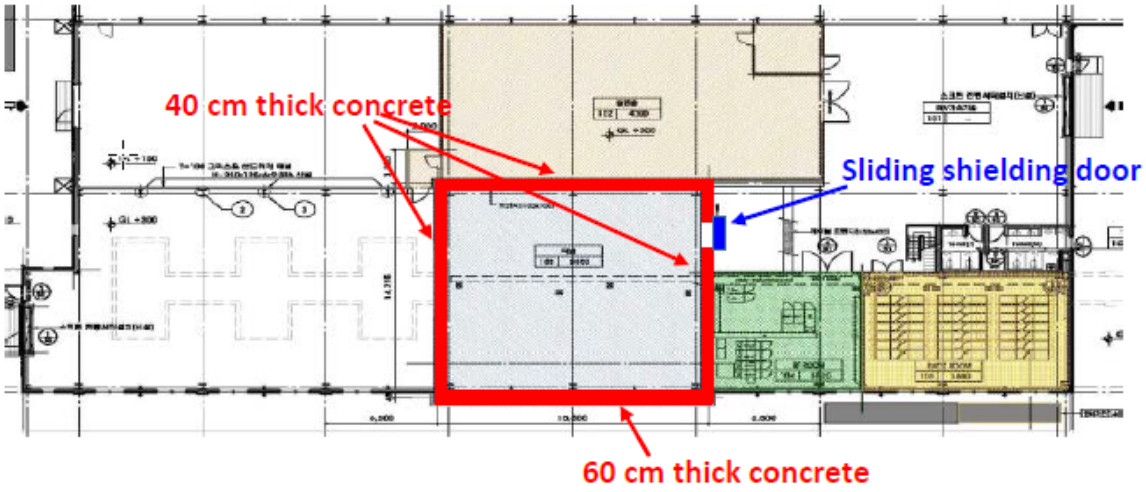
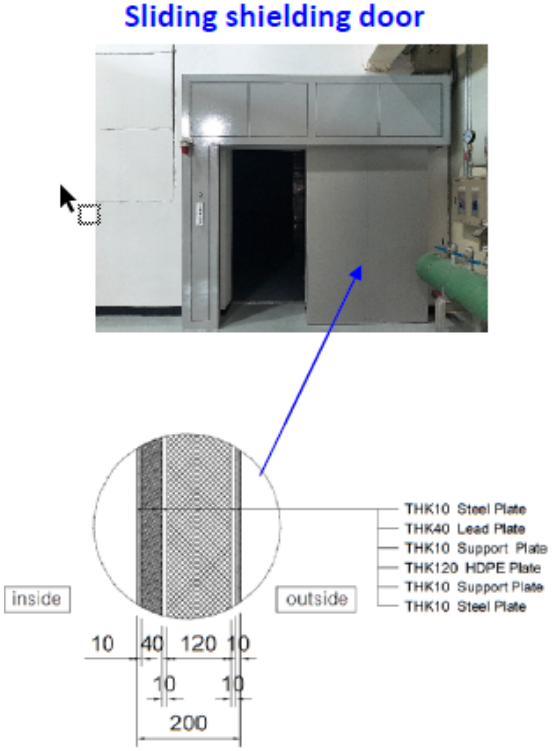
❑ Main Shielding Structure

- Side wall : 40 cm O.C. or 60 cm O.C.
- Ceiling : 35 cm thick O.C. removable panels
  (Structural requirement, a few cm Fe is sufficient for area control)
- Shielding Door : Pb (40 mm)+ HPDE (120 mm) + Steel 4.2 mm
- Additional shielding for public zone



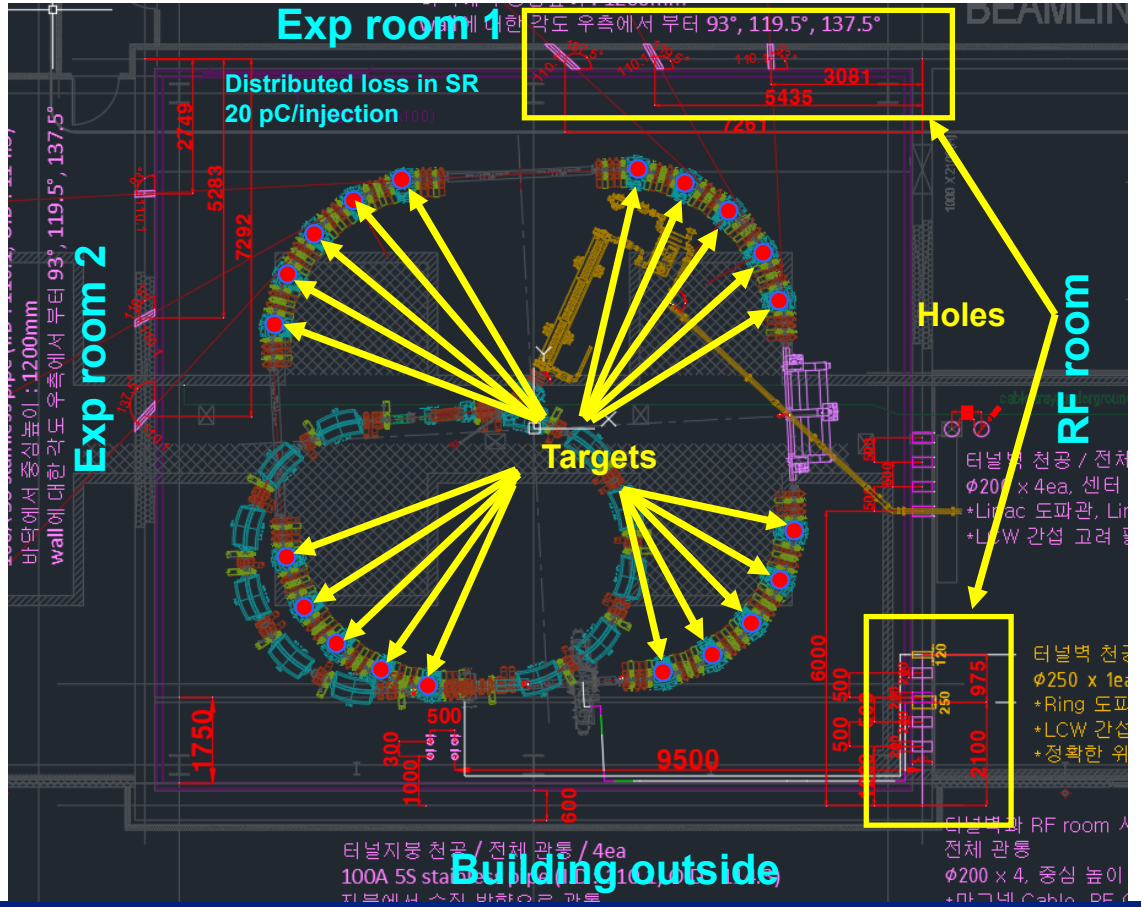


4-1 Case 1: To Design Main Tunnel Structure

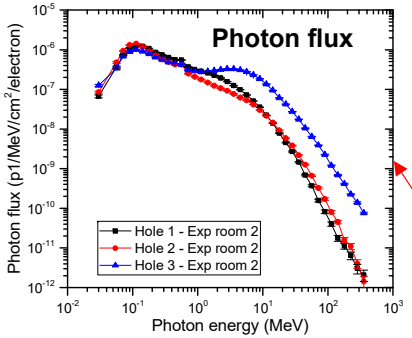
A. Distributed loss of stored beam in storage ring (1/5)

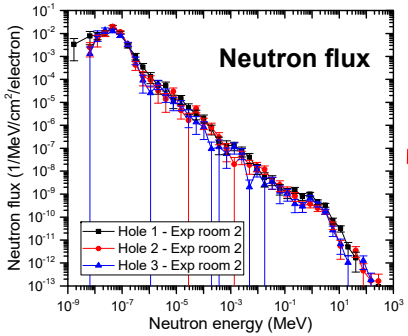
Adding 20 targets to the geometry (at dipole magnets of storage ring)

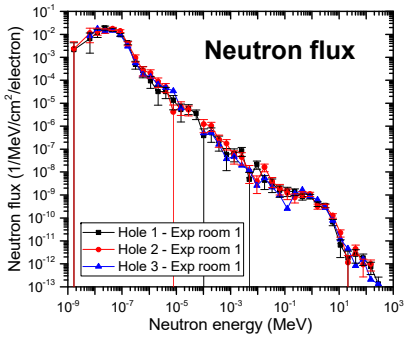
- Target : 20 Fe (cylindrical)
- Thickness : 10 X_0 (17.6 cm)
- Radius : 3 X_m (4 cm)
- Beam loss : 20 pC/injection=10 pC/s
- Electron energy: 400 MeV

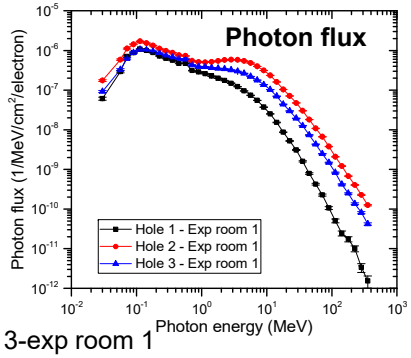


Distributed loss of stored beam in storage ring (2/5)-Flux

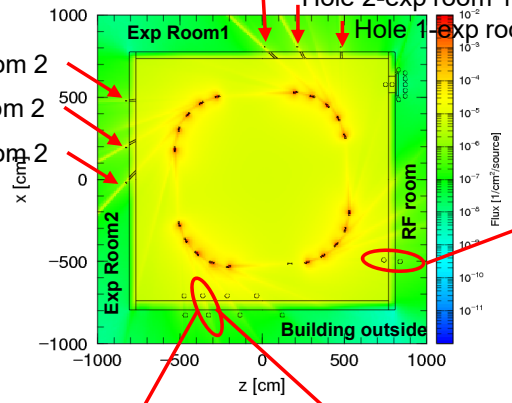


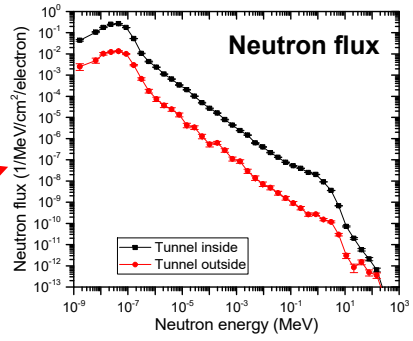


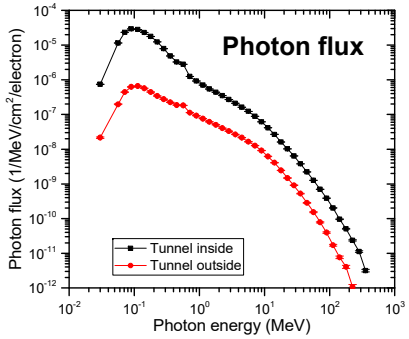


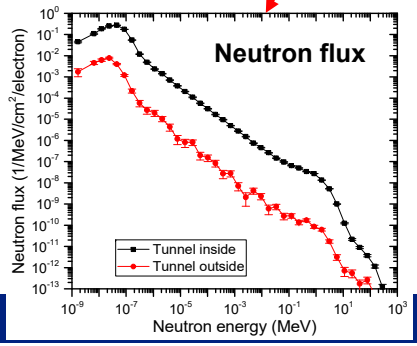


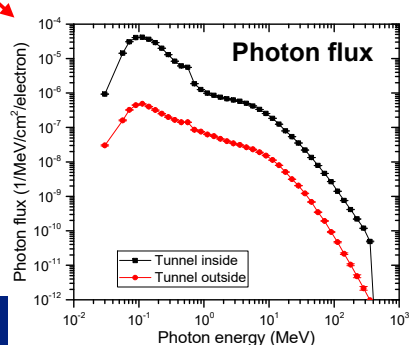
Hole 3-exp room 1
Hole 2-exp room 1
Hole 1-exp room 1
Hole 1-exp room 2
Hole 2-exp room 2
Hole 3-exp room 2











Distributed loss of stored beam in storage ring (3/5)- Dose

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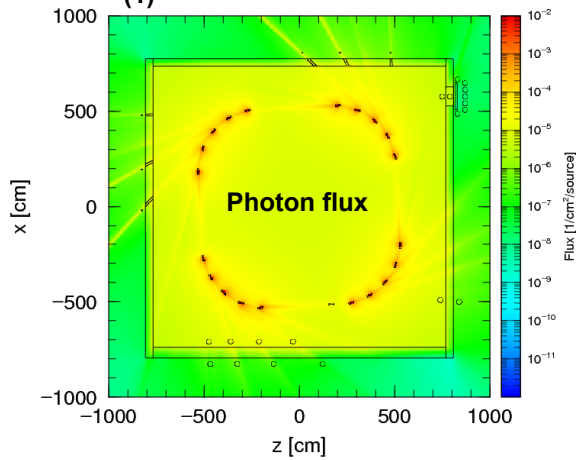
North East West South

Top view
Height: 120 cm

Beam loss:
20 pC is lost
during 2 seconds

(1)



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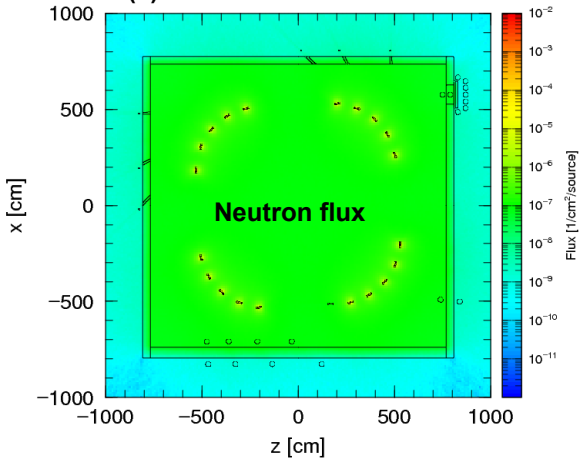

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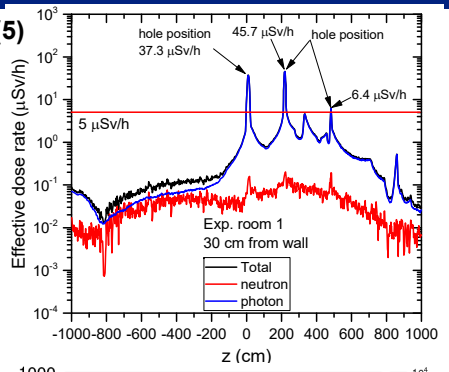

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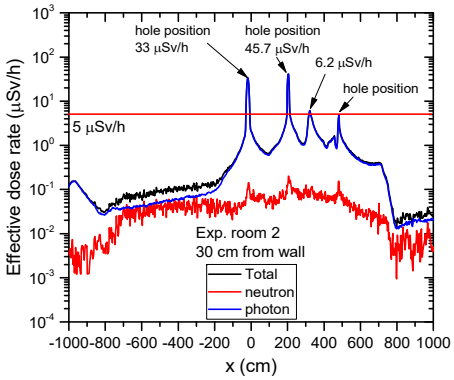

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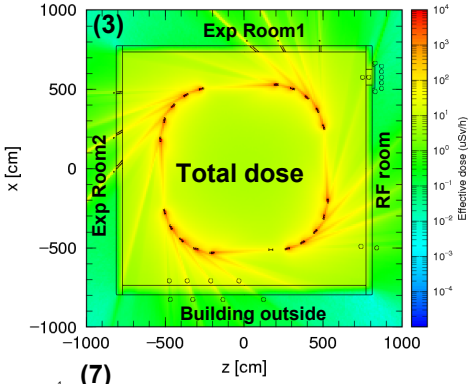

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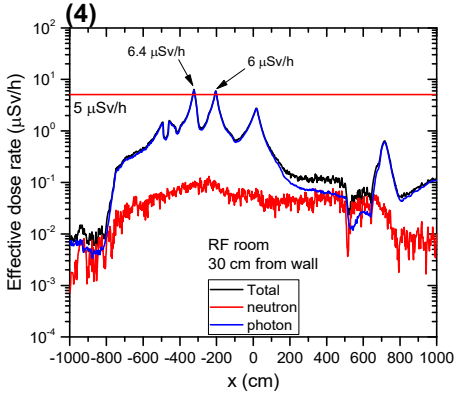

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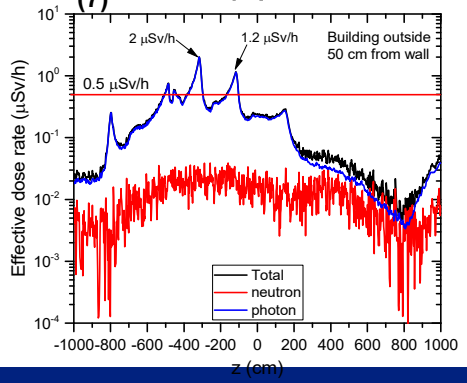
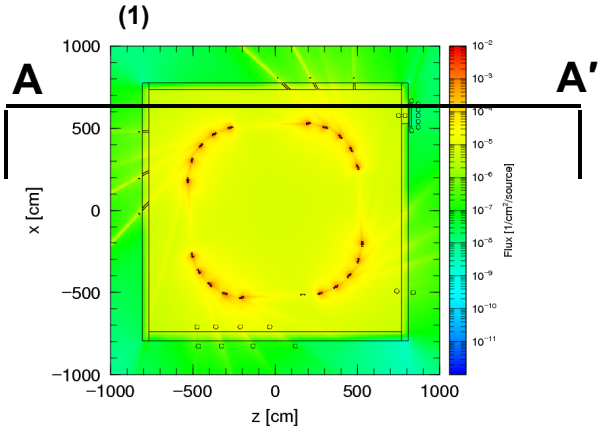
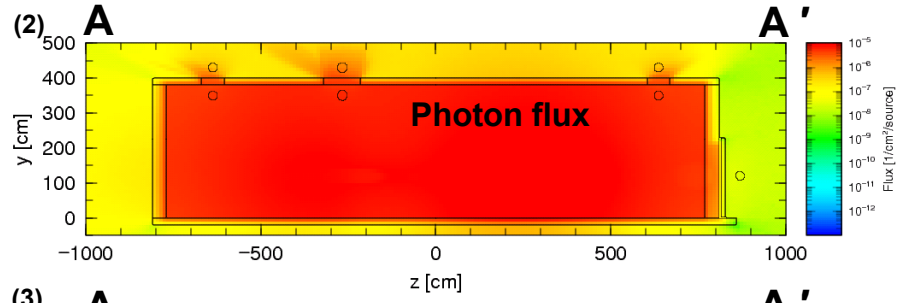
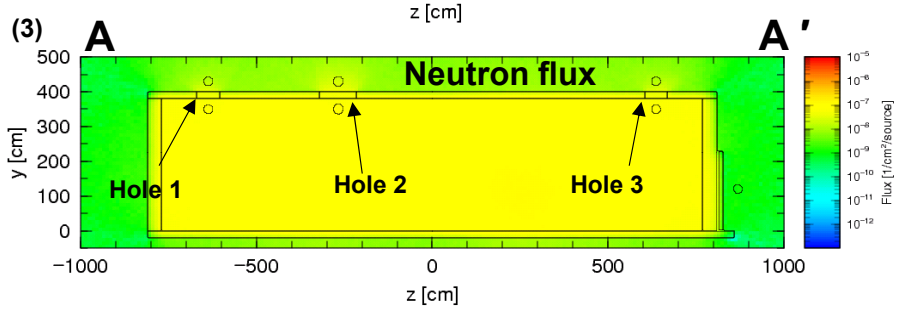
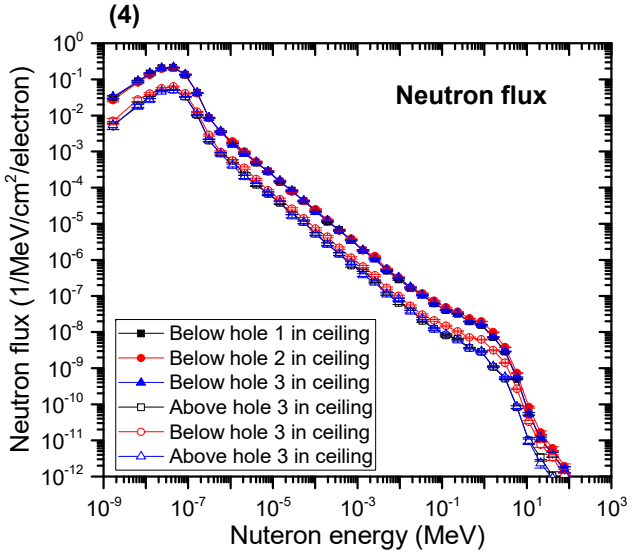


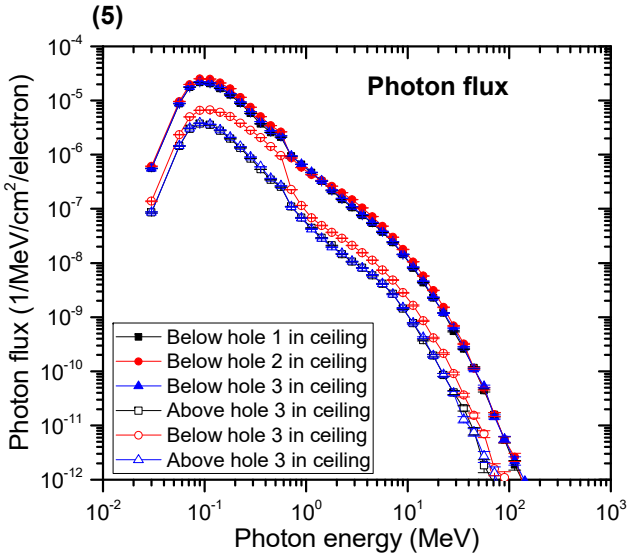
Distributed loss of stored beam in storage ring (4/5)- Flux



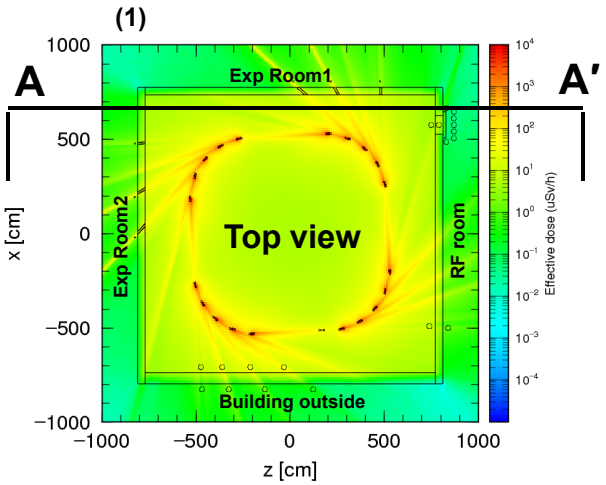


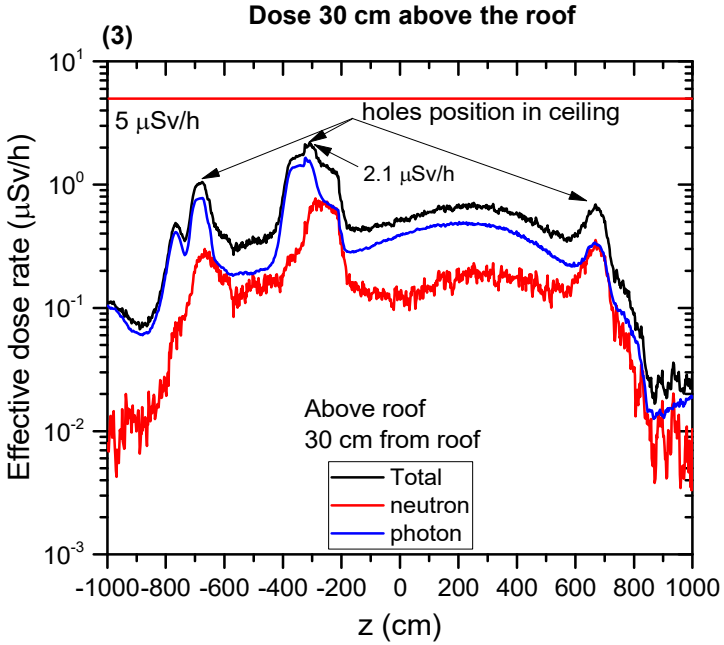


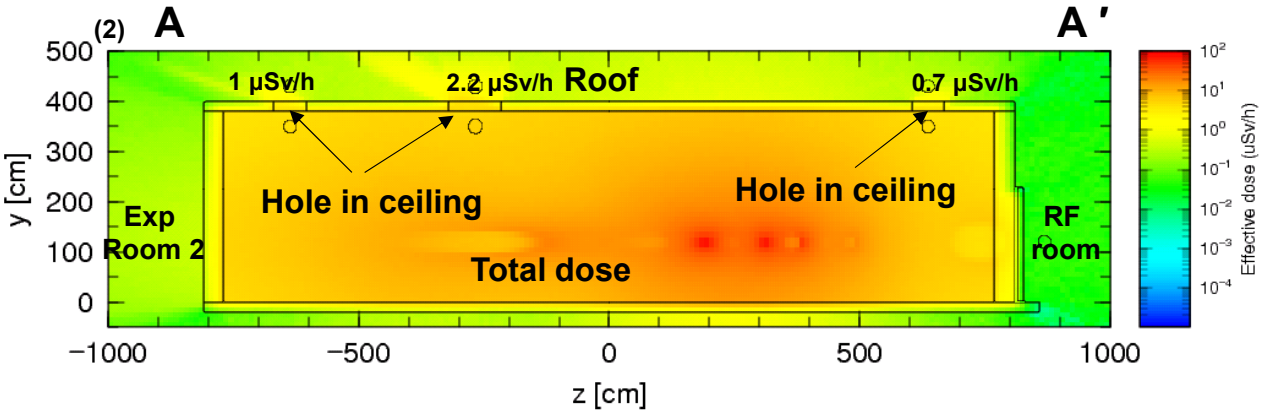




Distributed loss of stored beam in storage ring (5/5)- Dose





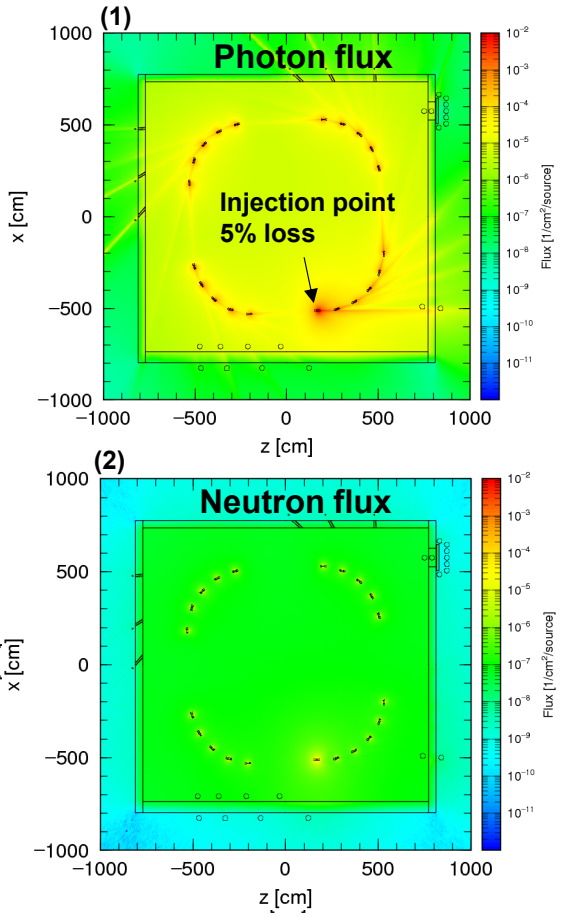


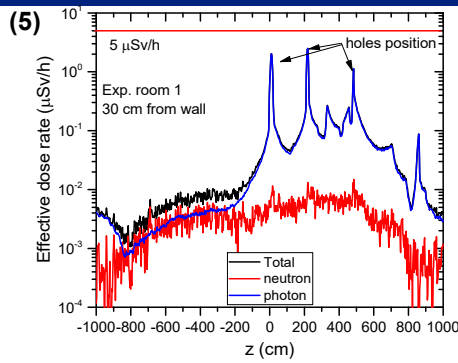
Vertical view

B. Beam loss during injection from Booster to SR (2/7)- Dose

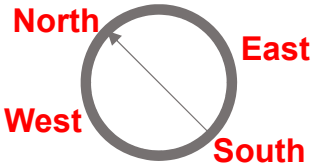
Beam loss: 2.2 pC/injection
[5% loss at injection point]
[5% loss distributed]

Top view
Height: 120 cm

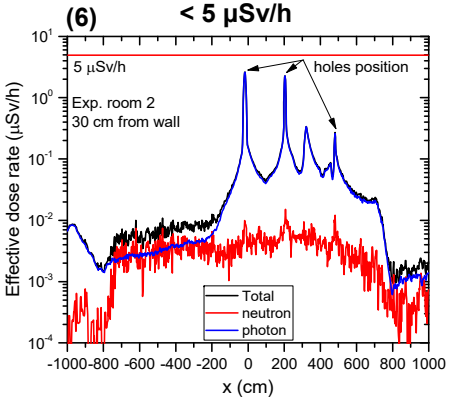


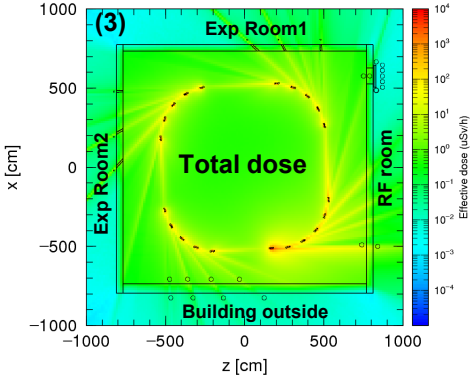


Dose in Exp. Room
< 5 μSv/h

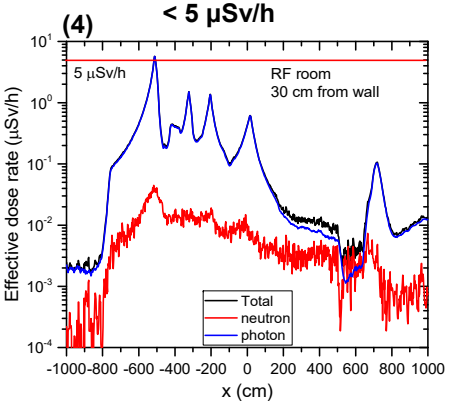


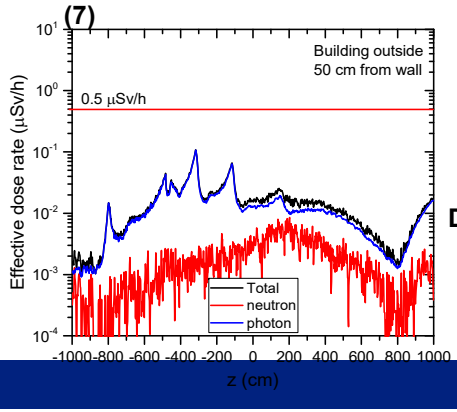
Dose in Exp. Room
< 5 μSv/h





Dose in RF room
< 5 μSv/h





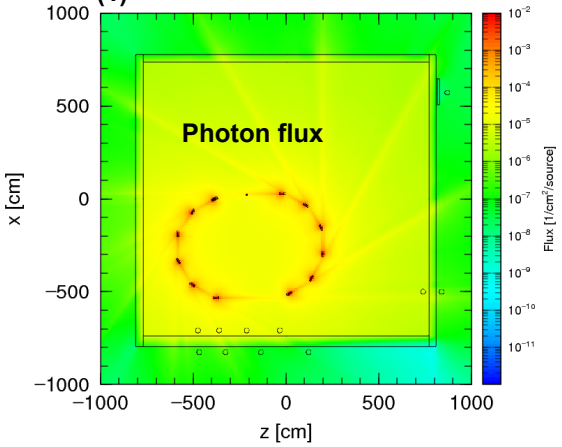
Dose outside of building < 0.5 μSv/h

C. Distributed beam loss during boosting (2/4)- Dose

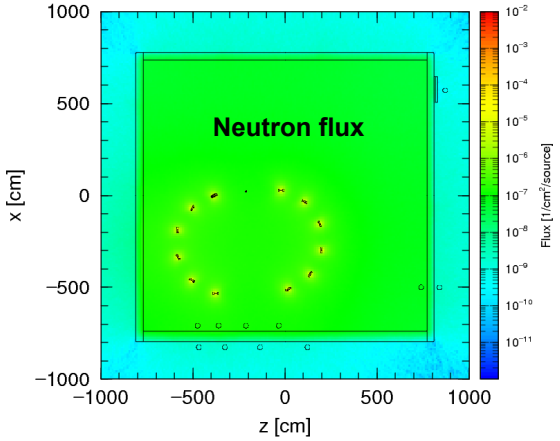
Beam loss: 5.6 pC/injetion
[20% distributed loss]

Top view
Height: 220 cm

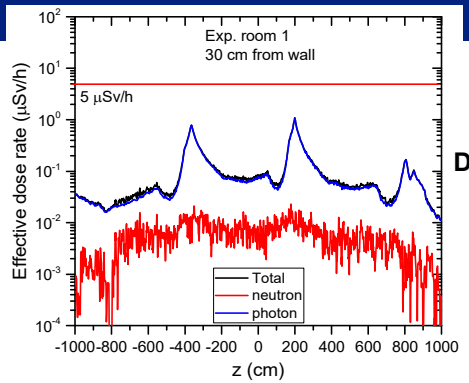
(1)



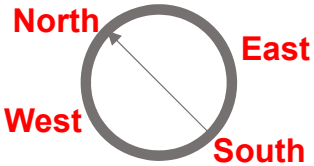
(2)



(5)

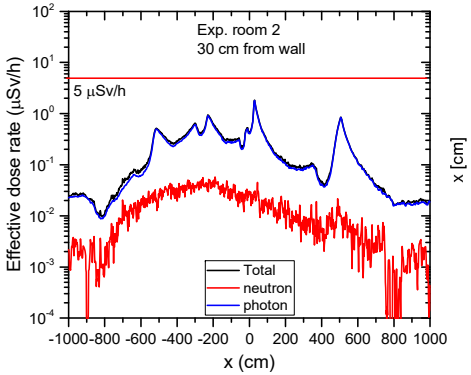


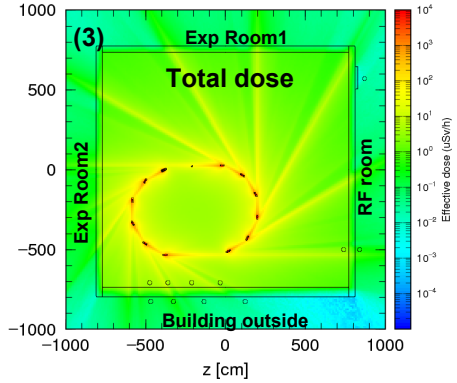
Dose in Exp. Room
< 5 μSv/h



Dose in Exp. Room
< 5 μSv/h

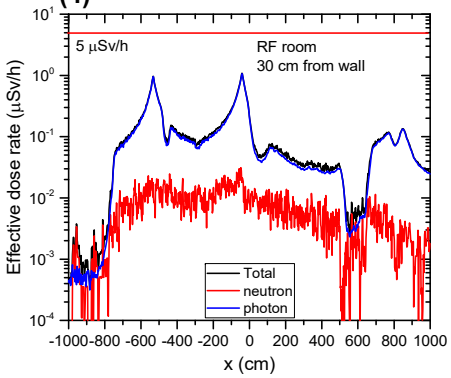
(6)



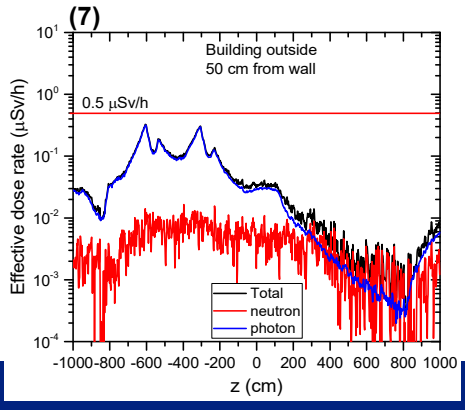


Dose in RF room
< 5 μSv/h

(4)



(7)



Dose outside of building < 0.5 μSv/h

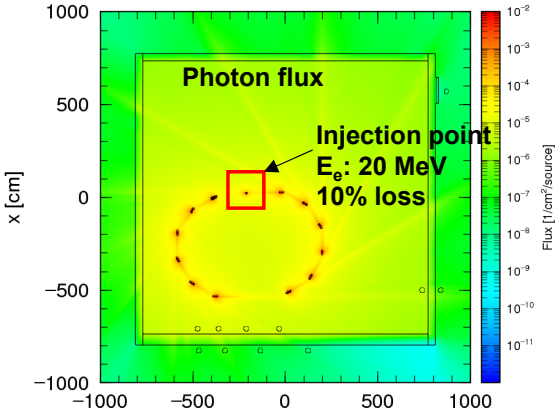
D. Beam loss during injection from linac to Booster (2/4)- Dose

Beam loss: 6.9 pC/injection
[10% loss at injection point]
[10% loss distributed]

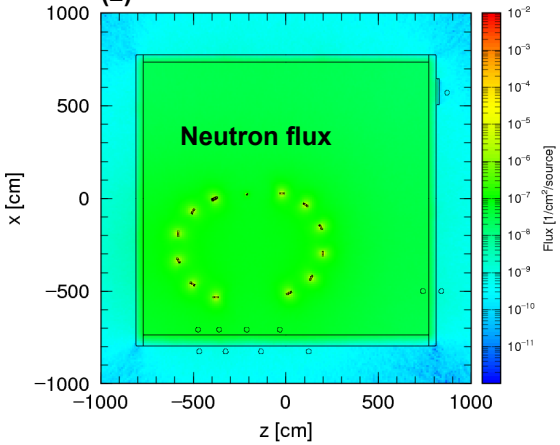
Top view
Height: 220 cm

North
East
West
South

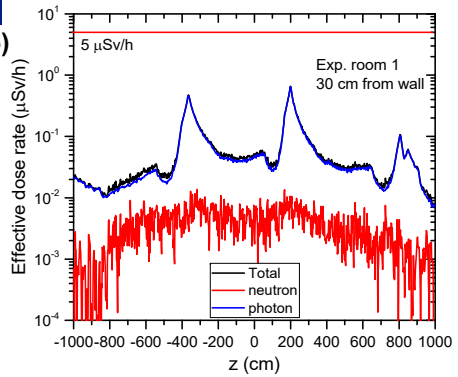
(1)



(2)



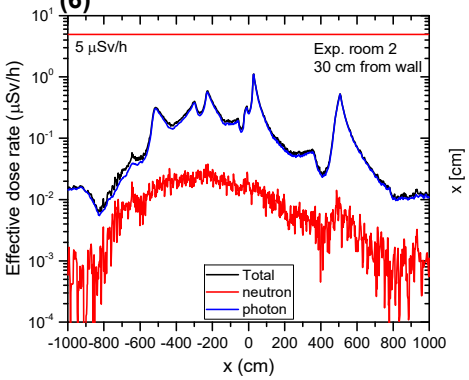
(5)



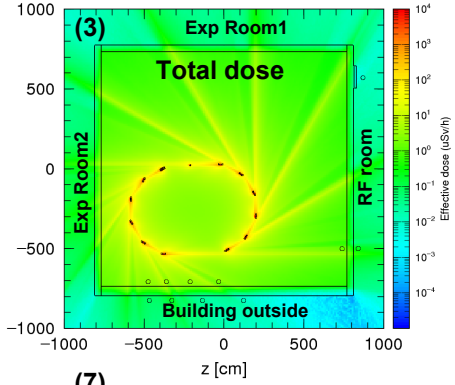
Dose in Exp. Room
< 5 μSv/h

Dose in Exp. Room
< 5 μSv/h

(6)

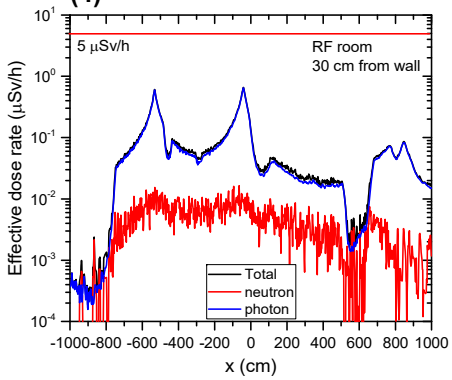


(3)

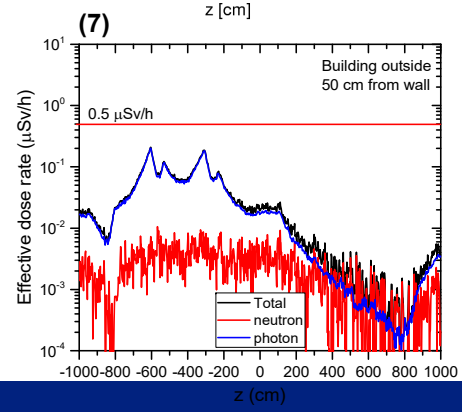


Dose in RF room
< 5 μSv/h

(4)



(7)



Dose outside of building < 0.5 μSv/h

Total dose rate top view (Height: 120 cm)-unit: μSv/h

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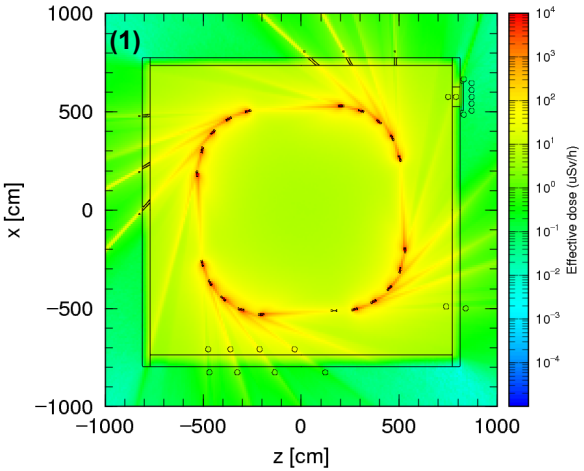
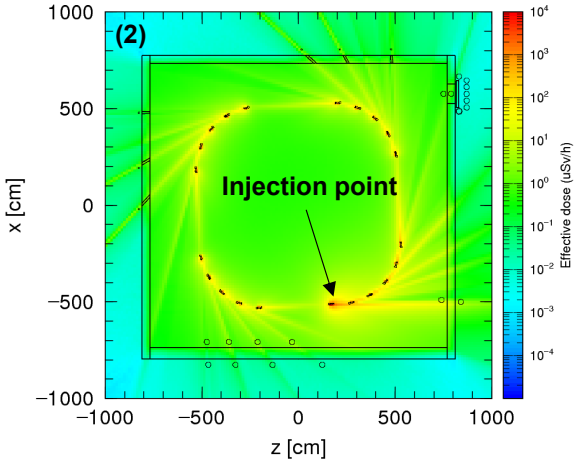
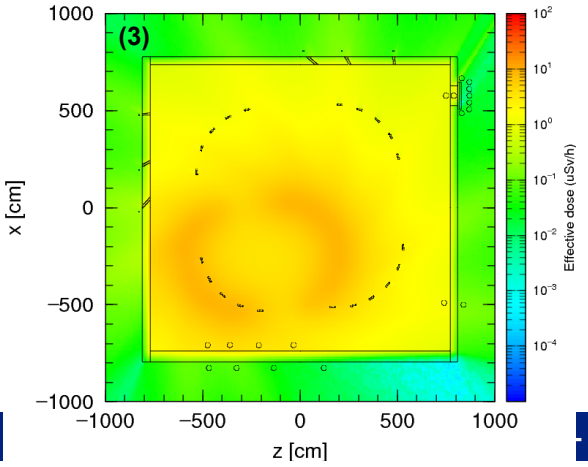
1) Distributed loss of stored beam in storage ring
- **Beam loss: 20 pC/injection [10 pC/s]**



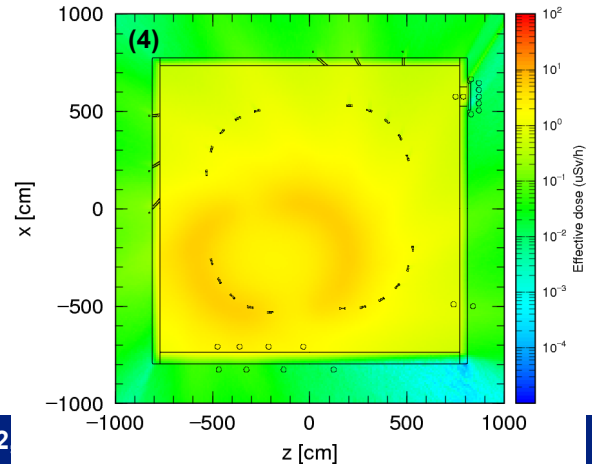
2) Dose rate during injection from Booster to SR
- **10% beam loss**
- **Beam charge loss: 2.2 pC/injection and 1800 injections during 1 hour**



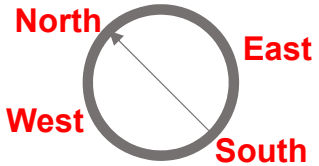
3) Distributed beam loss during boosting
- **20% Beam loss**
- **Beam charge loss: 5.6 pC/injectoin**



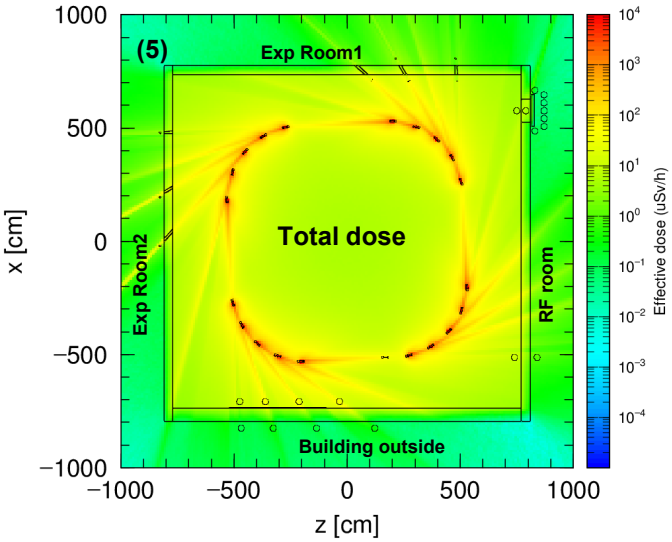
4) Beam loss during injection from linac to Booster
- **20% beam loss**
- **Beam charge loss: 6.9 pC/injection,**



1+2+3+4



Dose rate from all beam loss scenarios
- **Beam charge loss: 34.7 pC/injection**



Top view
Height: 120 cm

- June2

Total dose rate top view (Height: 120 cm) dose rate unit: μSv/h

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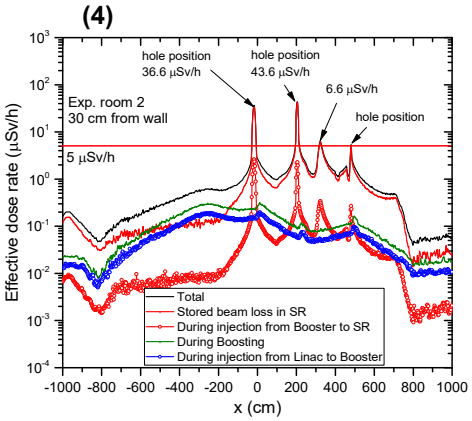
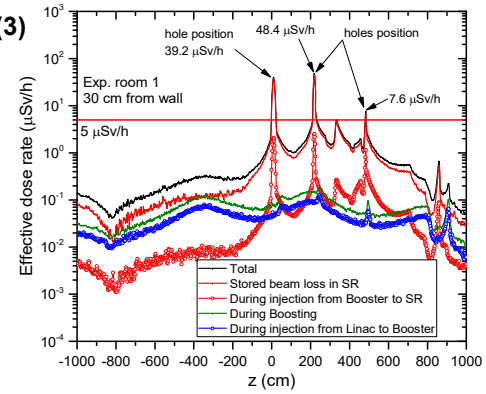
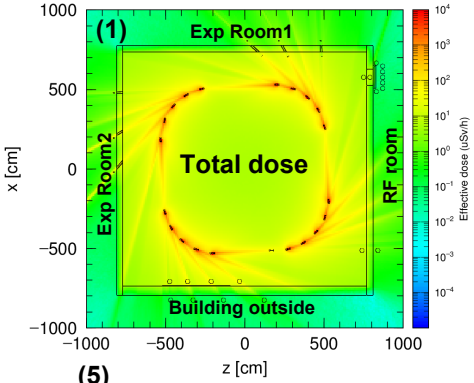
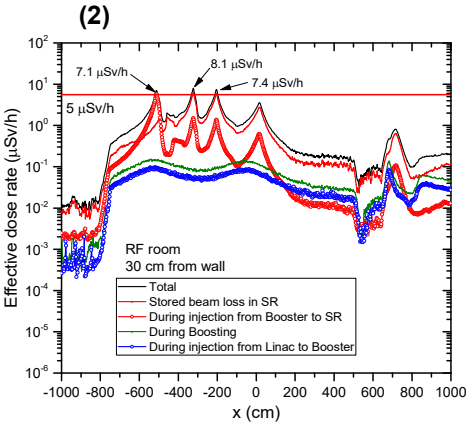
North East West South

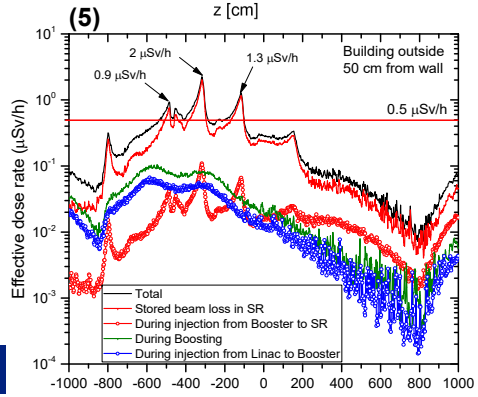
Dose from each beam loss scenario



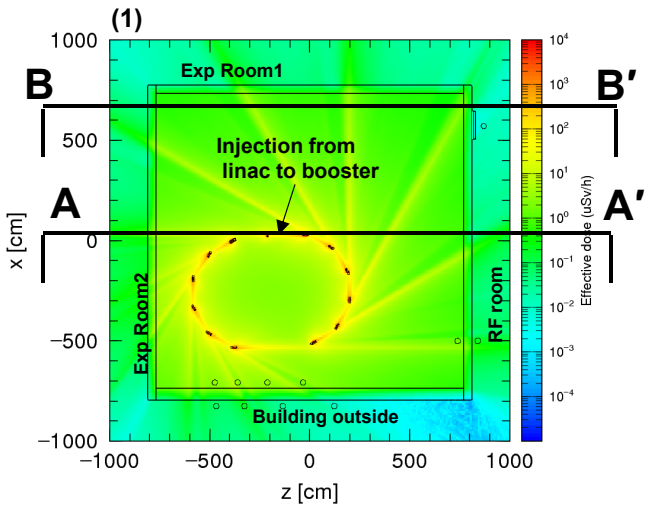






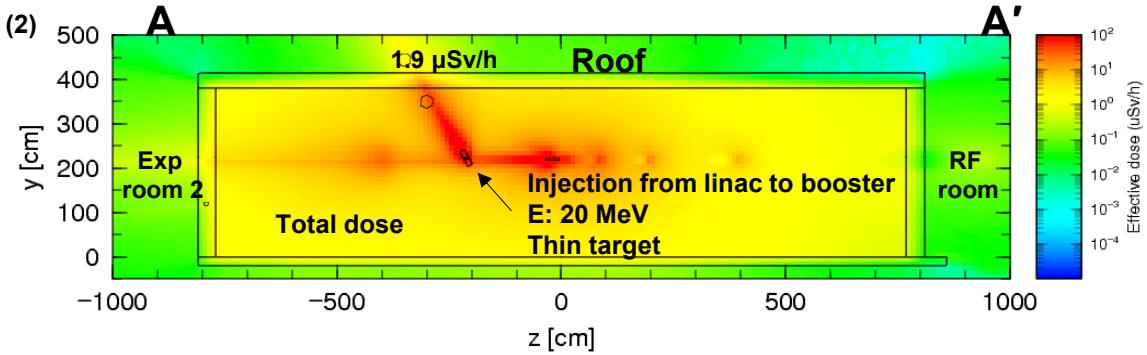


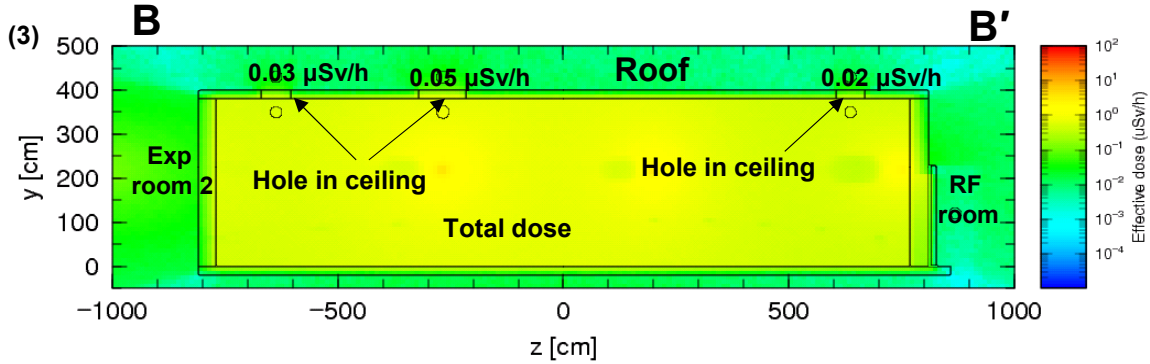
Why considering linac ? – for Ceiling
Beam loss during injection from linac to Booster (4/4)- Dose



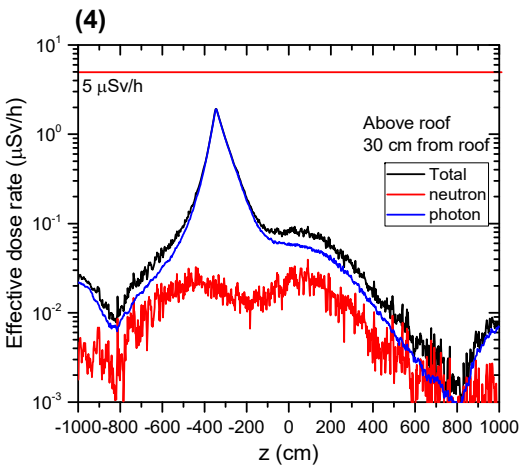
Top view
Height: 220 cm

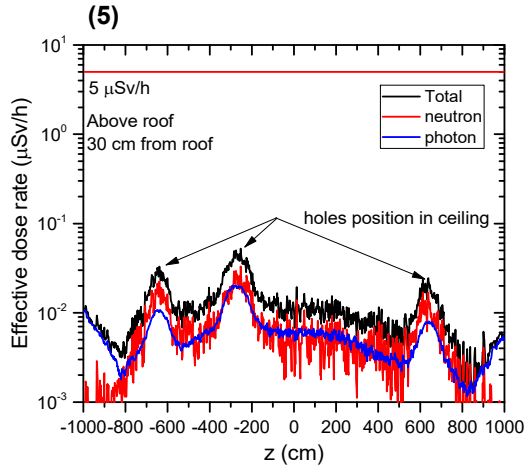
Vertical view



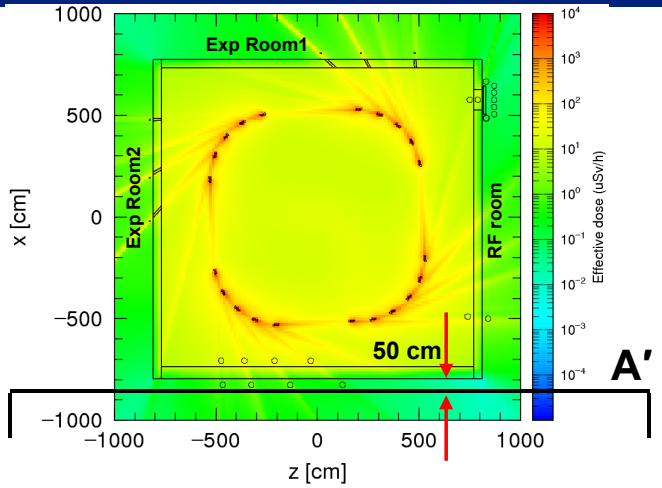


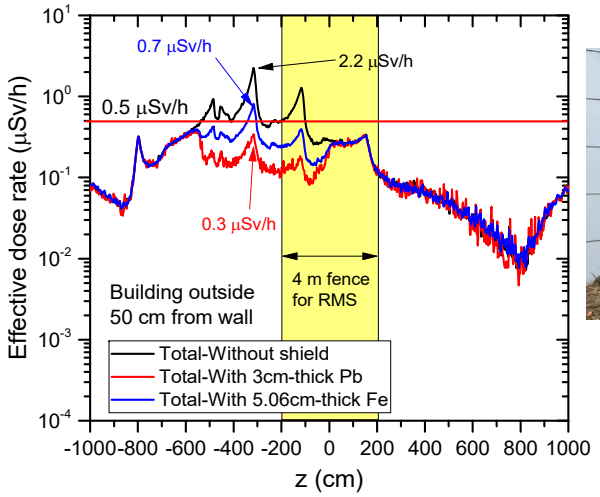
Dose 30 cm above the roof



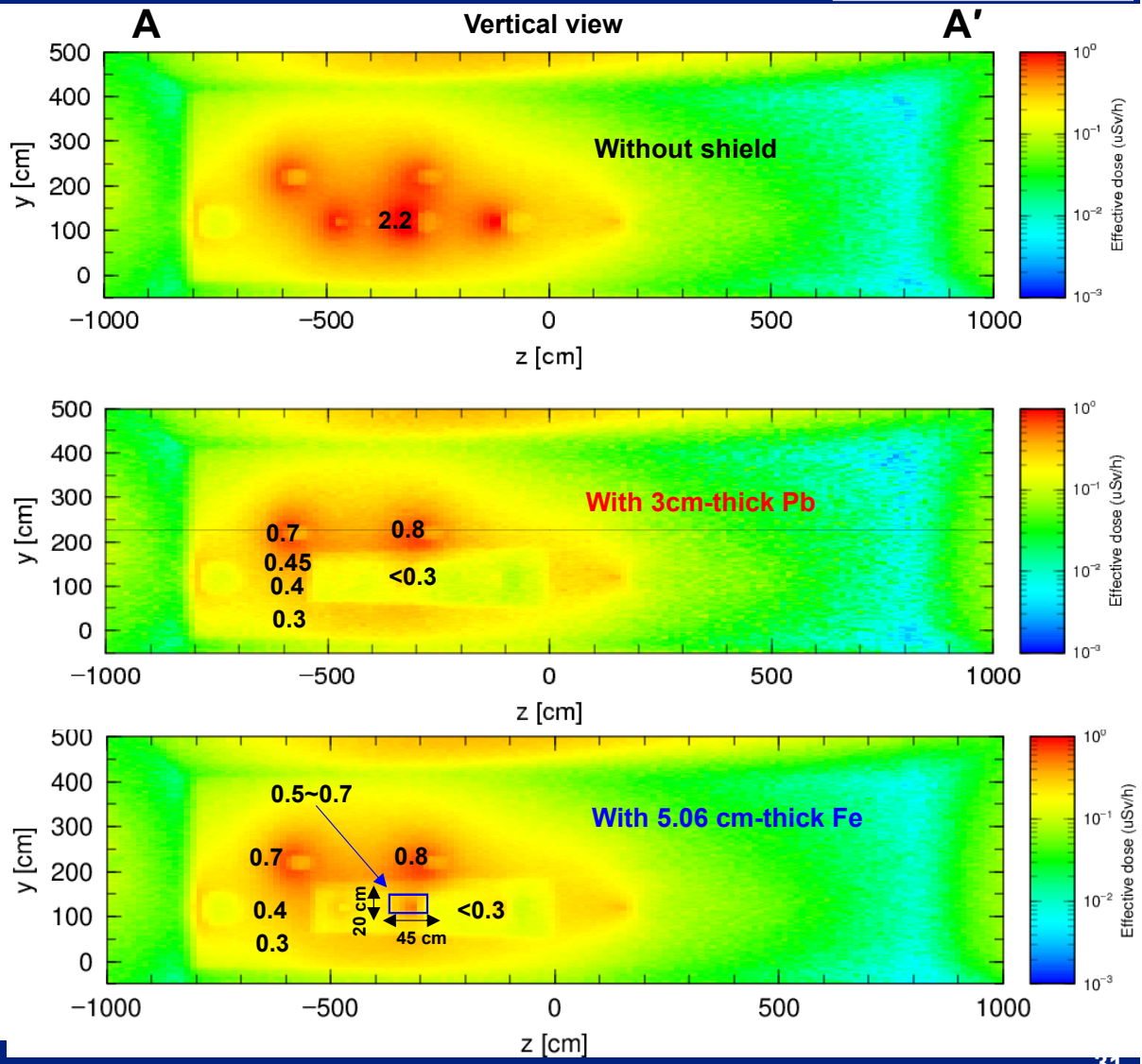


Additional Pb or Fe Shield for Public Area



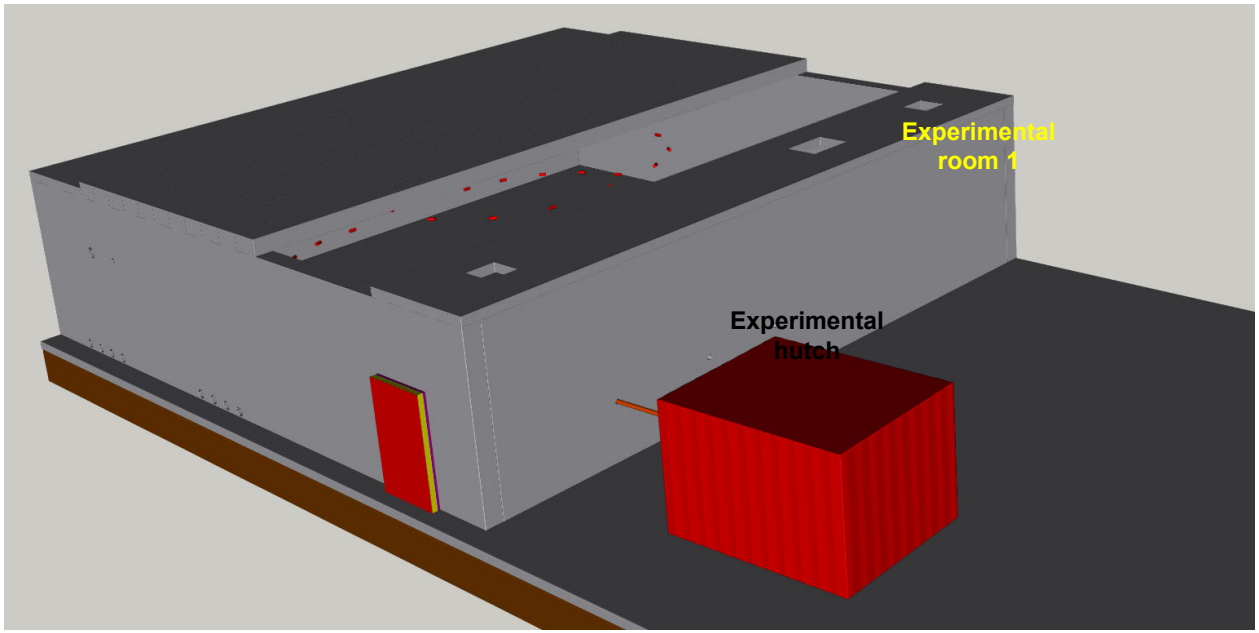


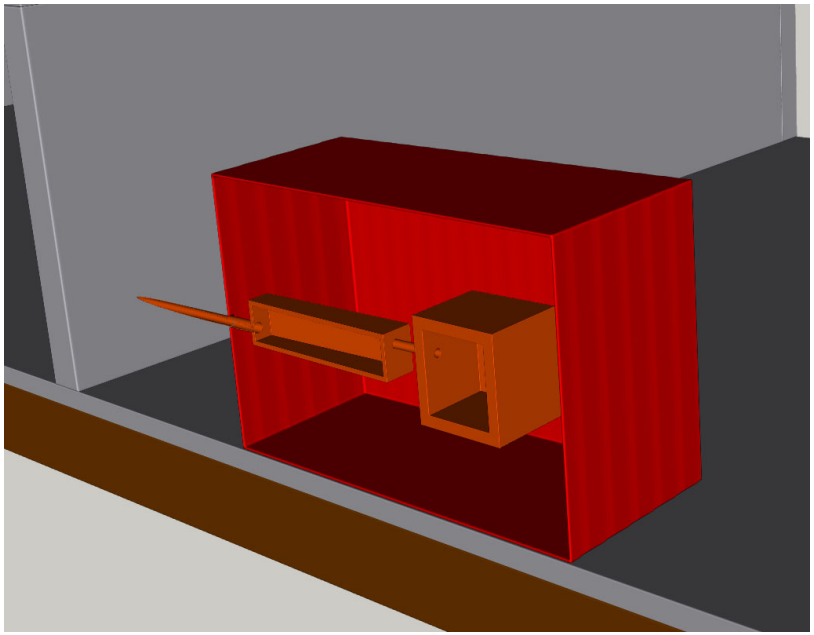
Unit: μSv/h



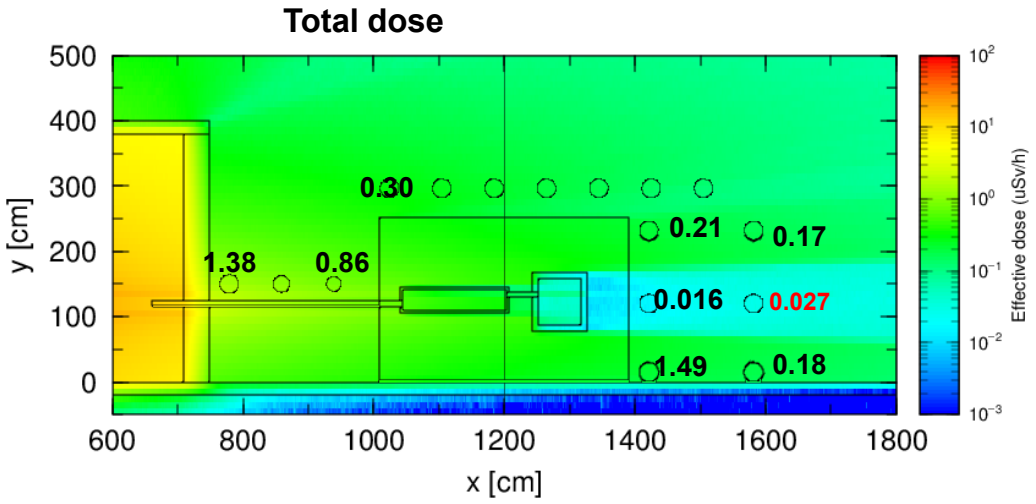
4-2 Beamline Shielding Analysis: 3D view of the Experimental Hutch

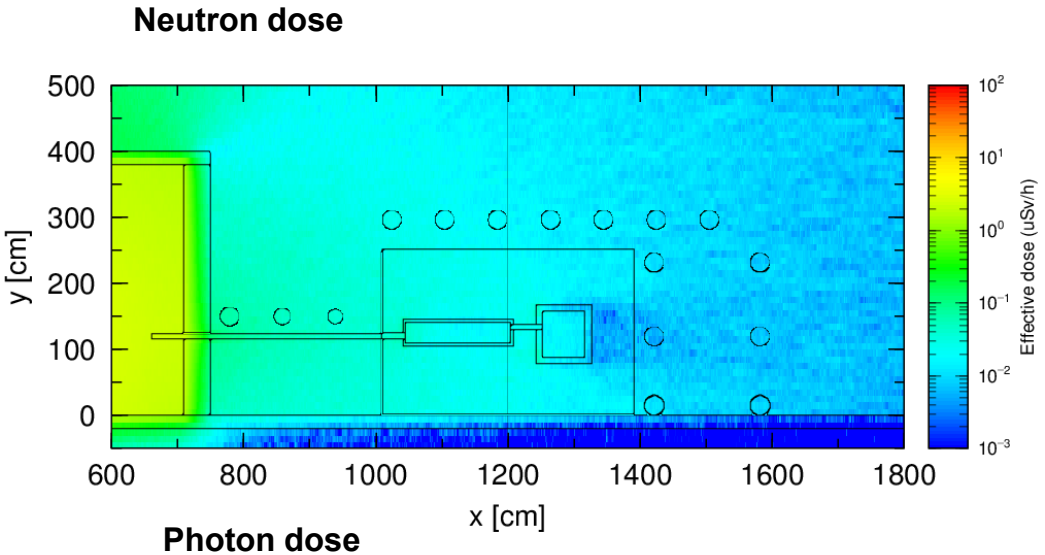
* 1 Air
* 2 Concrete
* 3 Iron
* 4 Lead
* 5 PE
* 6 STS304
* 7 soil

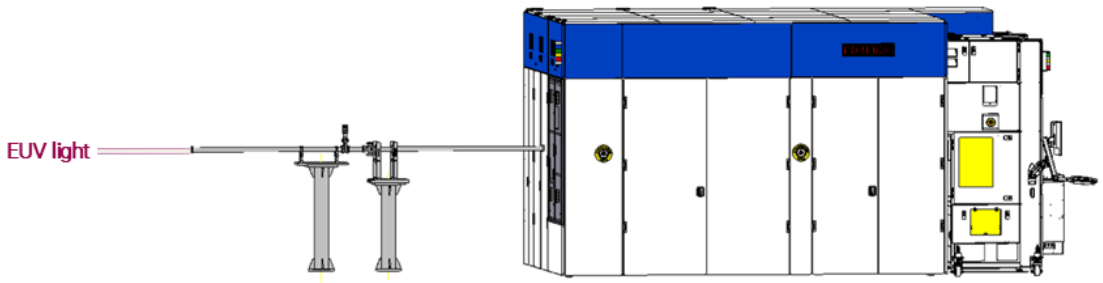


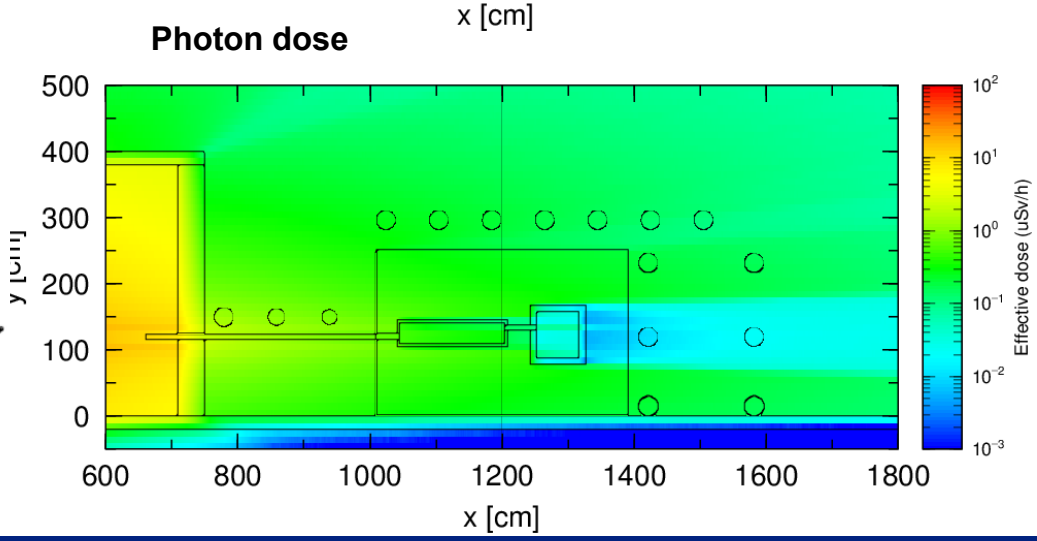


Beam line: Normal operation-Dose-Vertical view-YX

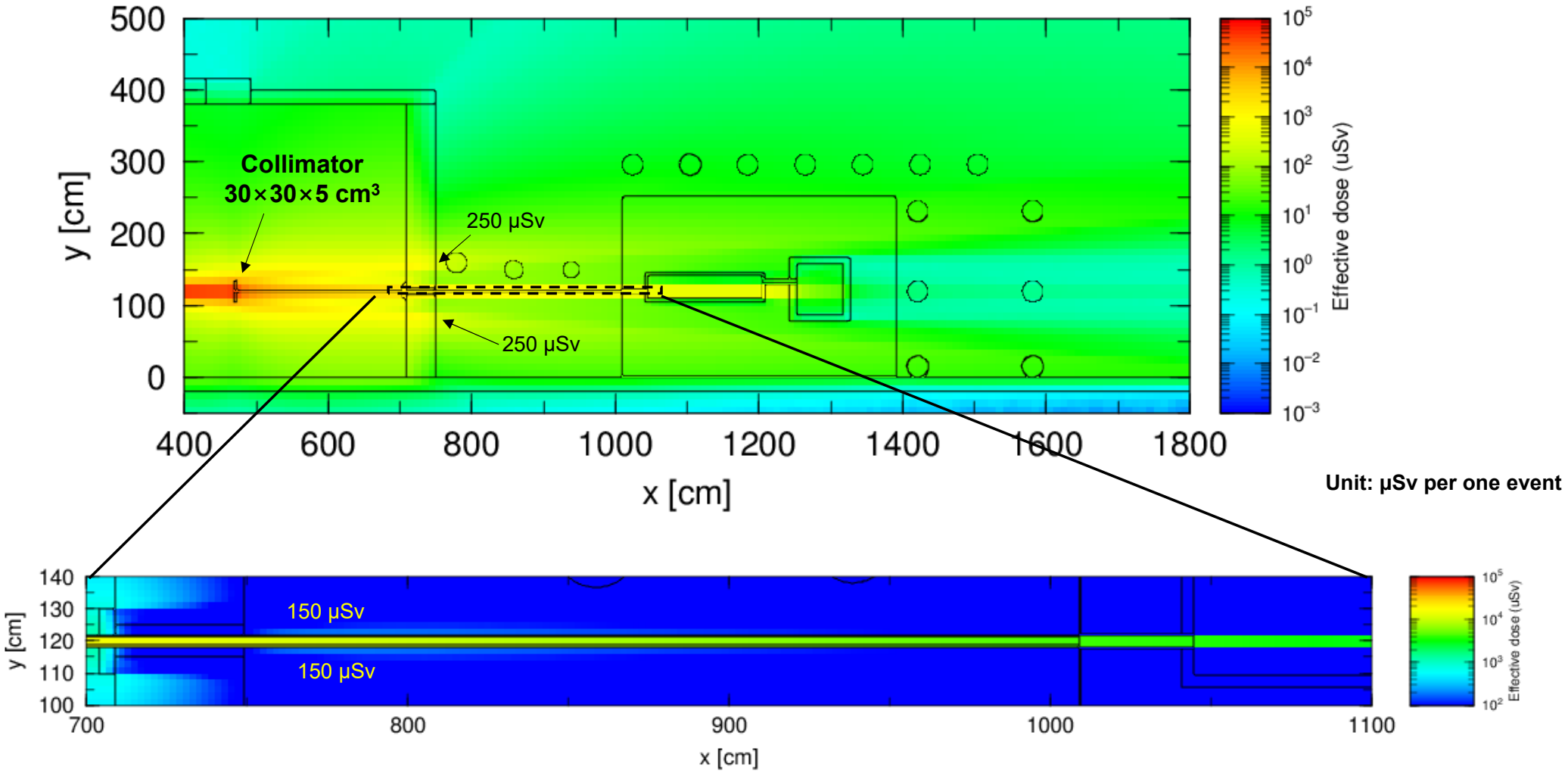








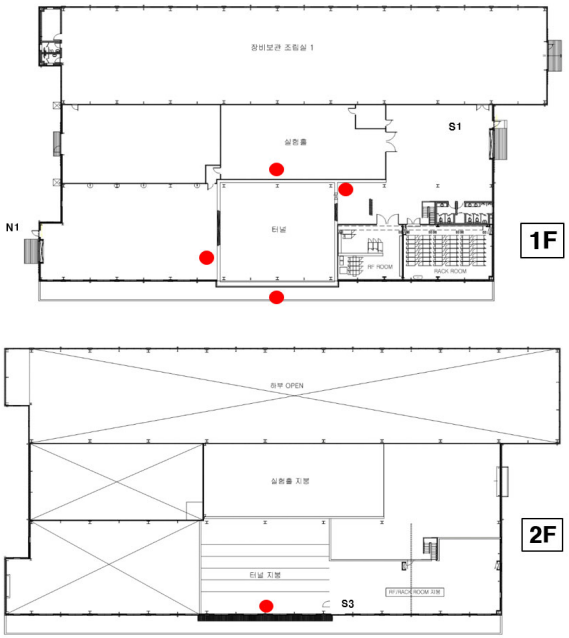
Beam line : Accident in storage ring (Stored beam loss)- Dose-vertical view



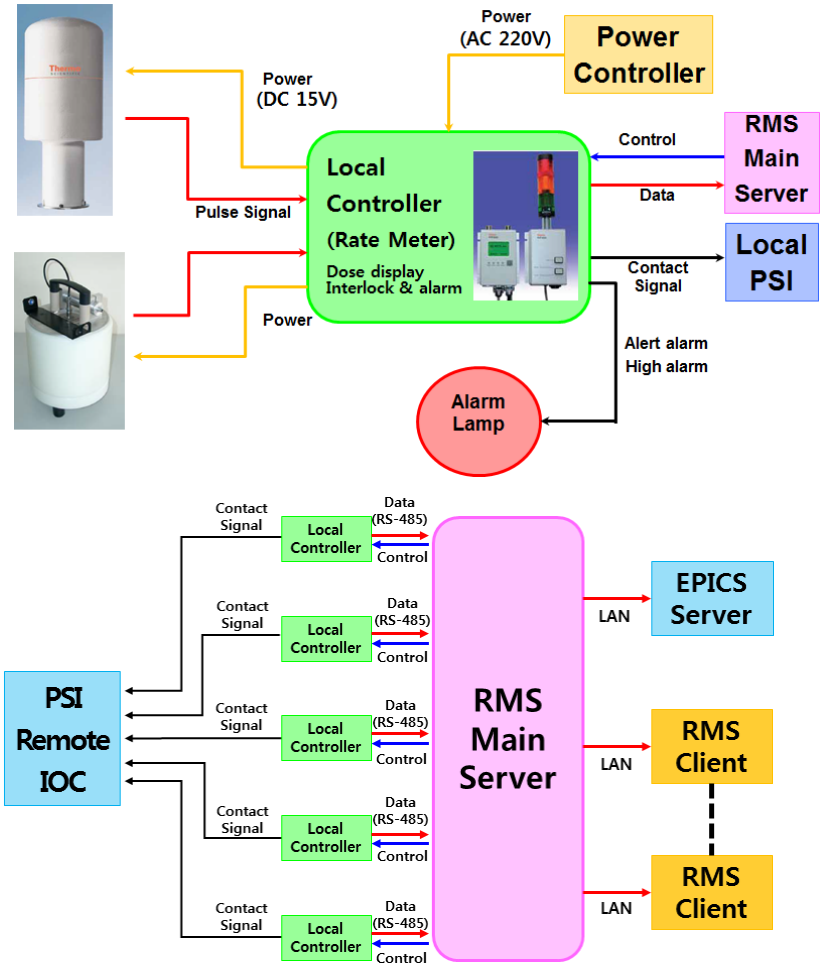
Unit: μSv per one event

5. Radiation Safety System – Area Monitoring System

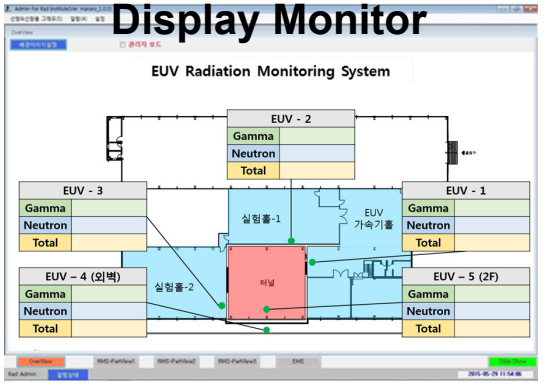
Locations

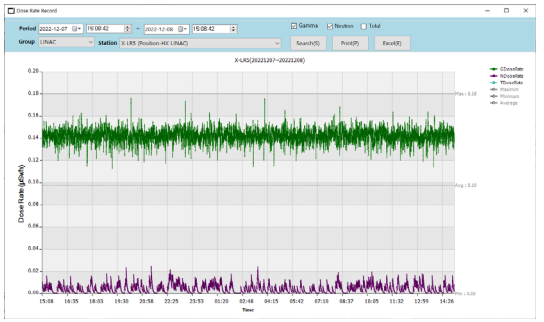


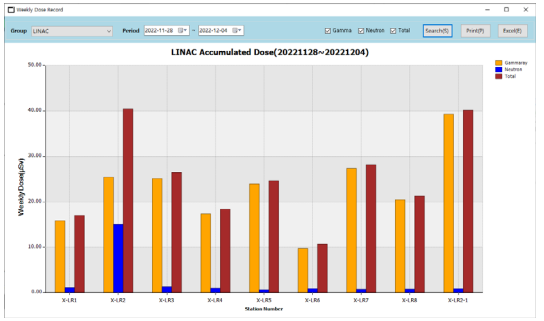
System Configuration



Display Monitor

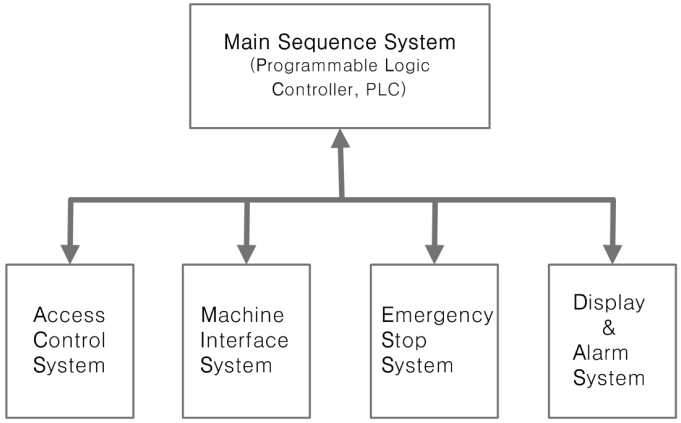




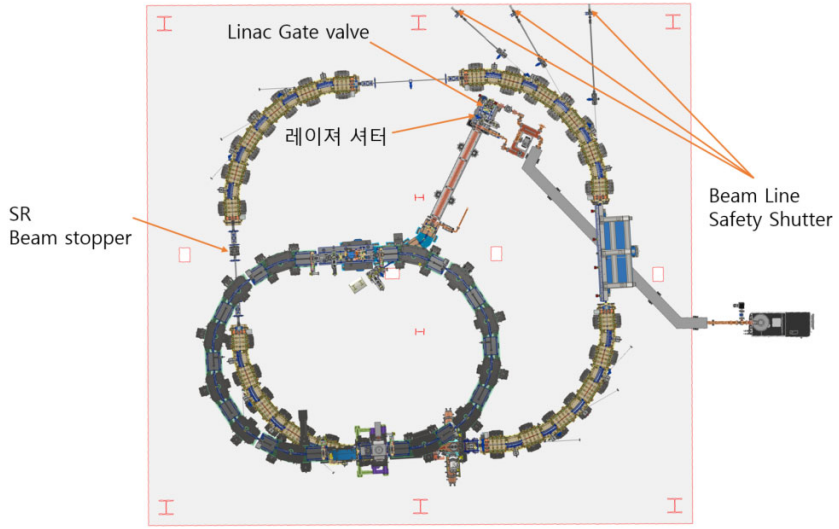


5. Radiation Safety System – Personnel Safety & Interlock Sy

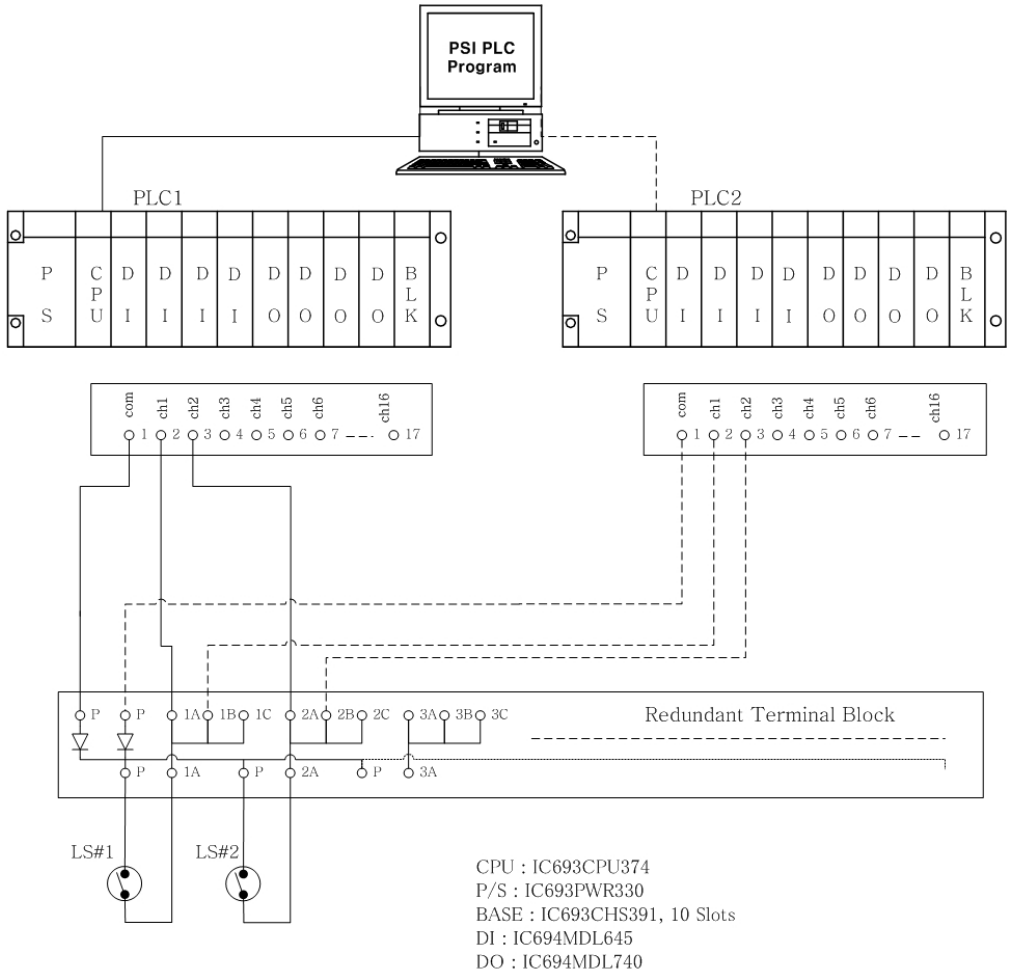
PSIS Configuration



Example of Machine Interface System



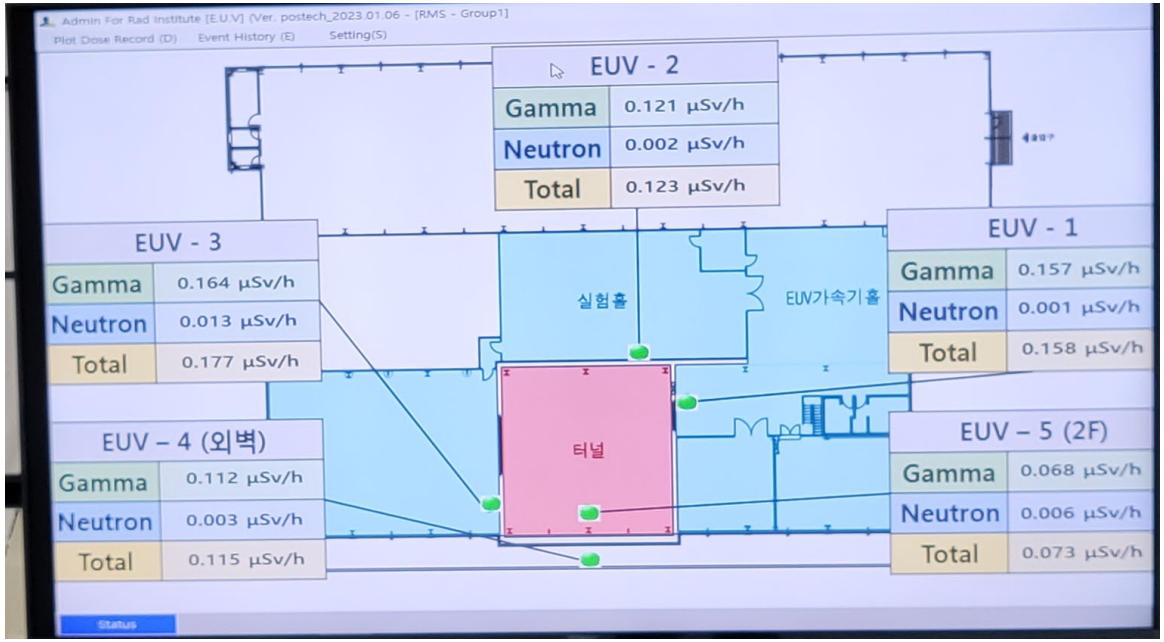
Main Sequence System (PLC-based)



6. Commissioning & Radiation Control

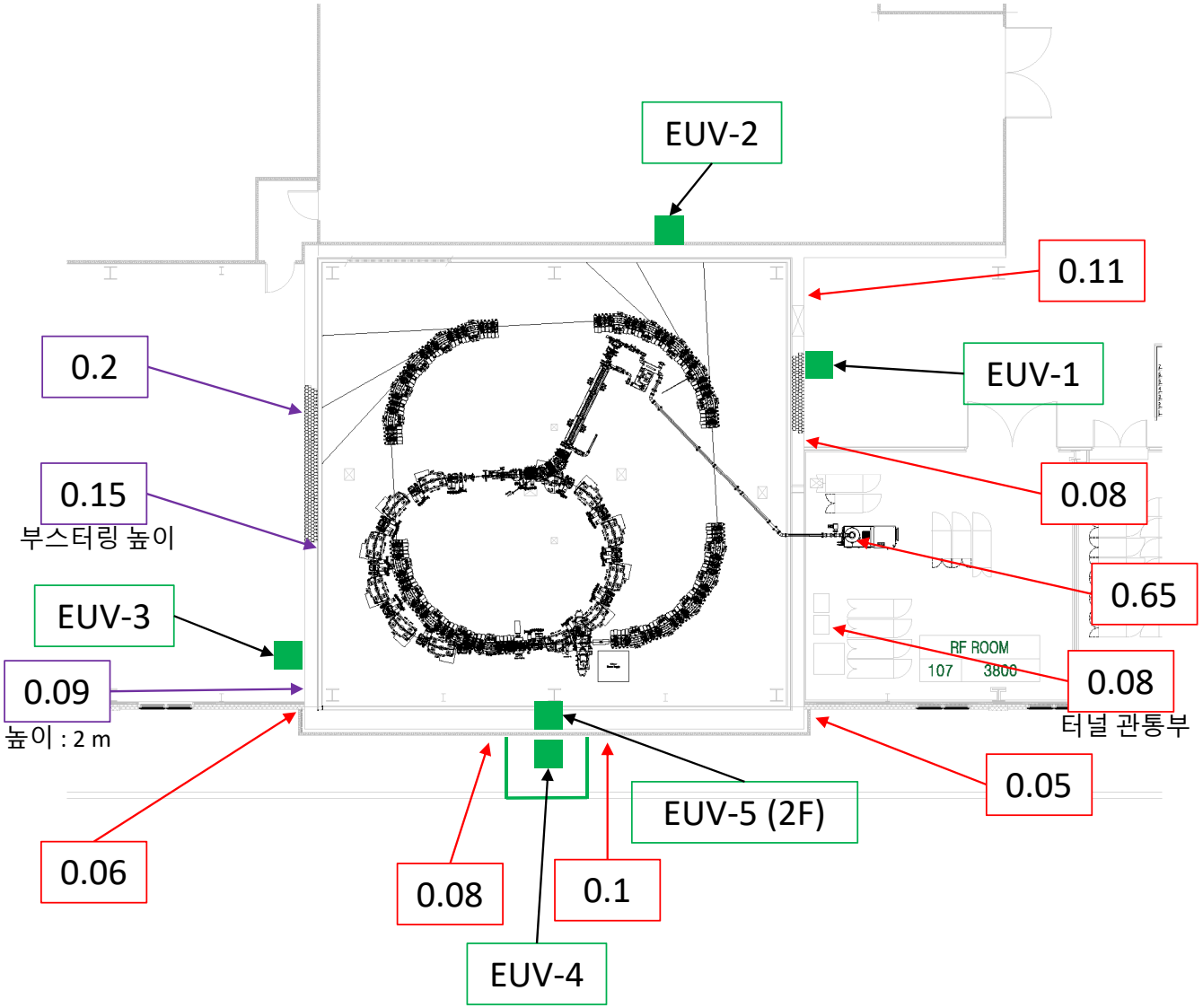
PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

- At present, Commissioning of Booster Synchrotron
  - Linac commissioning started at Feb. 1st.
  - 280 MeV is achieved at May 15th.
  - Commissioning will be finished before August.
  - User service is planned to start at late 2023.



Radiation Control Example

EUV 1F



Unit : µSv/h

RMS location

Operation Condition

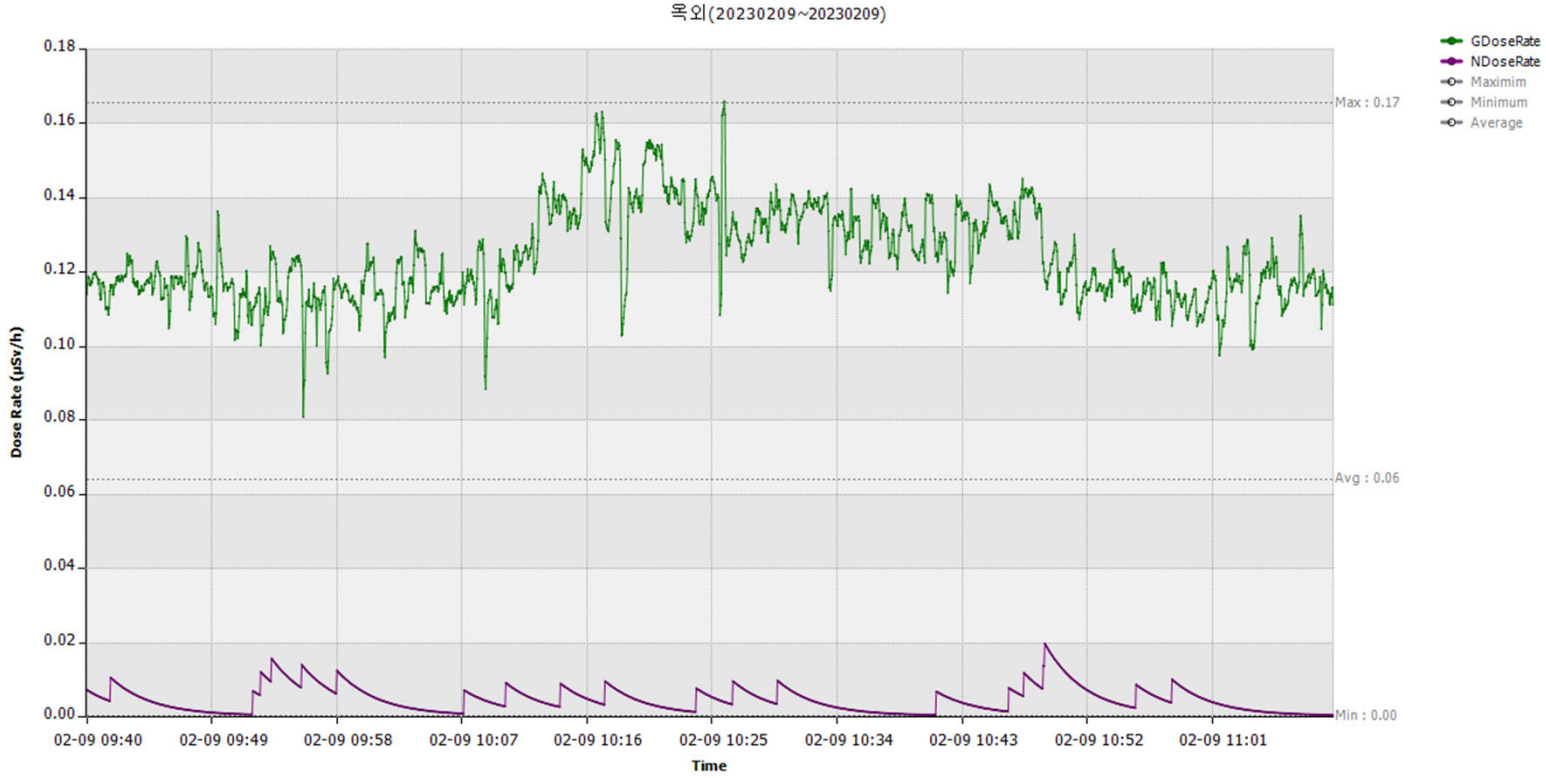
End Point : Booster Ring
Beam Energy : 280 MeV
Beam Charge : < 10 pC
Repetition Rate : 0.5 Hz

측정 일시
2023. 05. 23

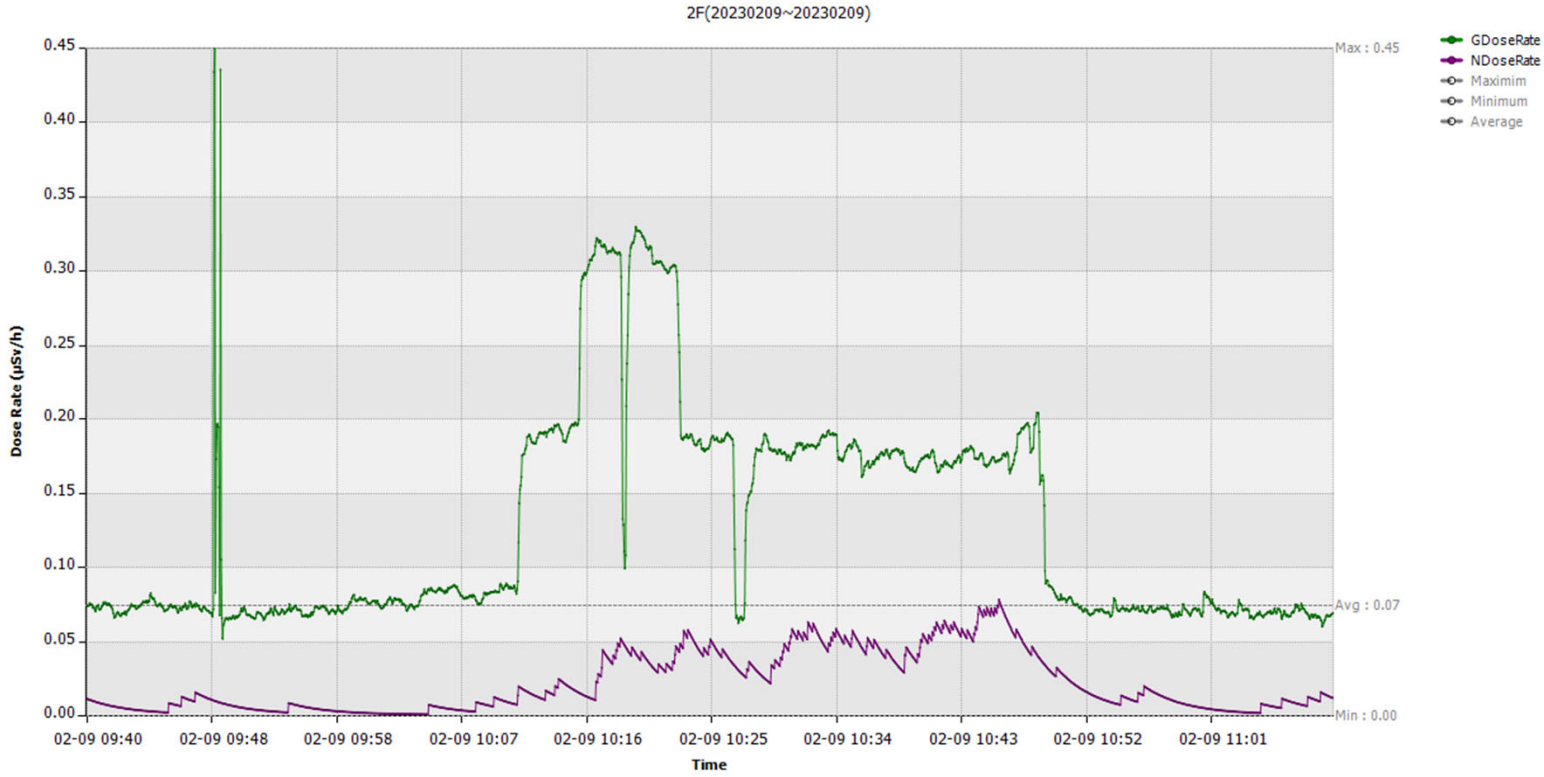
측정자 : 이욱제, 배오륜

검출기
Model : 451P
S/N : 4481
C.F : 1.112
BKG : 0.2 µSv/h 이하

EUV-4 (outdoor, public zone) Dose level

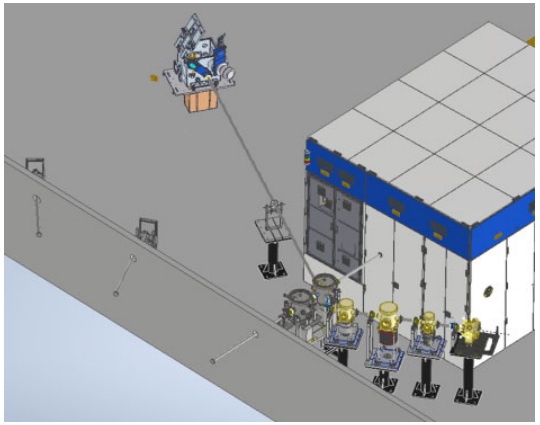


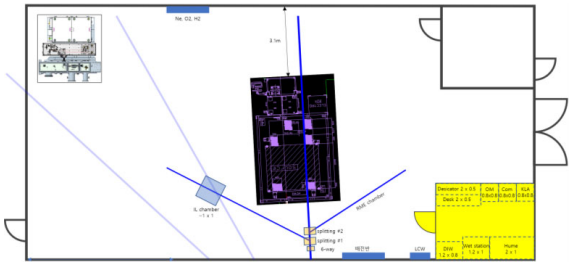
EUV-5 (2F) Dose level



7. Summary

- ❑ New compact synchrotron radiation facility (PAL-EUV) was launched for EUV industrial application
- ❑ Radiation Shielding Analysis was carried out by PHITS3.30.
- ❑ After getting operation permit, the commissioning is in process.
- ❑ The analysis results will be confirmed in the commissioning period.
- ❑ Upcoming issues
  - Installing Safety Permanent Magnet for beam line shielding (after updating PHITS version)
  - Radiation level control at 400 MeV for Booster & Storage Ring
  - New beam line structure (Modified & Additional branch lines)





Thank You for Your Attention!