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Shielding Design of the PAL-XFEL Tunnel and Its Test Facilities

Pohang Accelerator Laboratory, POSTECH

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Table of contents

1 Introduction : PAL-XFEL

2 Safety policy & normal beam loss scenario

3 Tunnel shielding : Bulk shielding & entrance

4 Test facility : Injector Test Facility (ITF)

5 Test facility: Accelerating column Test Facility (ATF)

6 Conclusions

Main parameter of PAL-XFEL

Linac	Beam energy, GeV	10
	Beam charge, nC	0.2
	Slice emittance, mm-mrad	0.4 (0.6*)
	Injector gun	PC RF-gun
	Peak current at undulator, kA	3
	Repetition rate, Hz	60
	Number of bunch	Single or Two
	Linac structure	S-band
Undulator	Undulator type	Out-vacuum
	HX undulator gap (min), mm	7.2
FEL	Hard X-ray wavelength, nm Soft X-ray wavelength, nm	1 ~ 0.06 10 ~ 1.0
	FEL radiation power @ 0.1 nm wavelength and 60 fs photon beam length, GW	30
	Photon flux @ 0.1 nm, photons/pulse	> 1.0 E+12

Beam Power

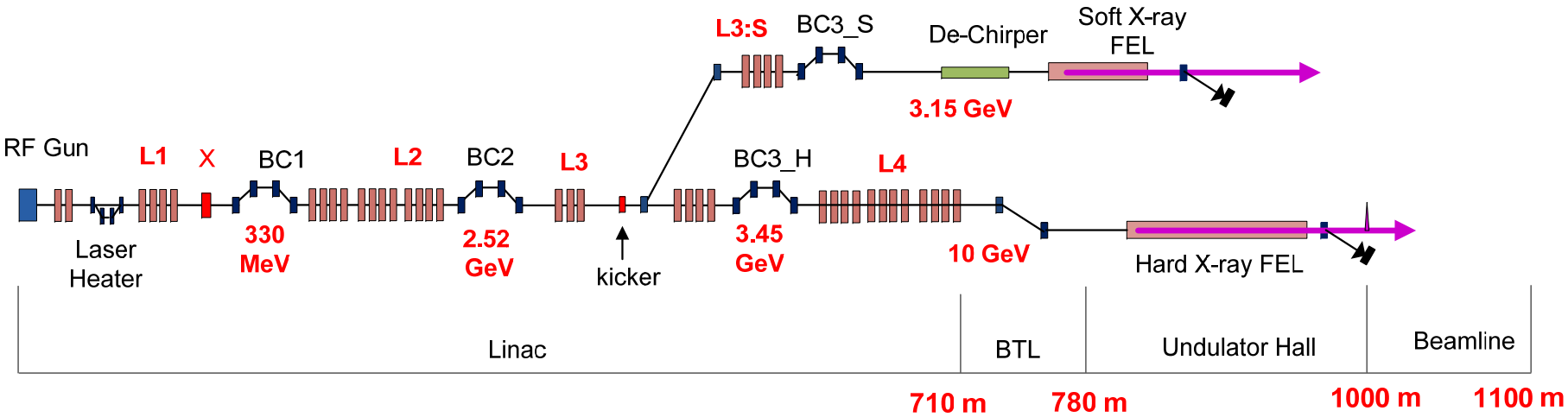
: 120 or 240 W

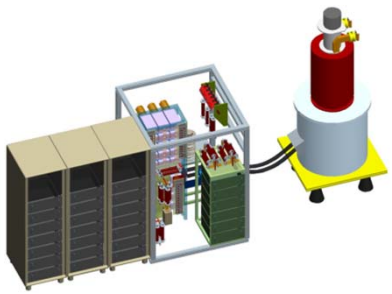
Low power,

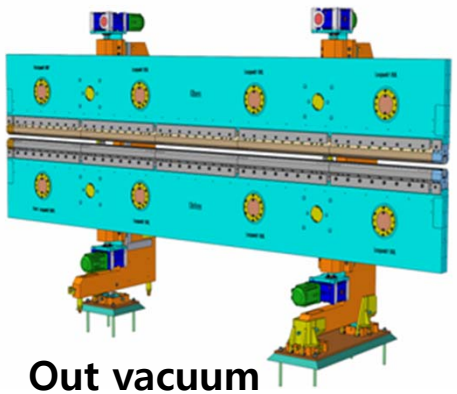
High Energy

Beam !!

Schematic drawing of PAL-XFEL



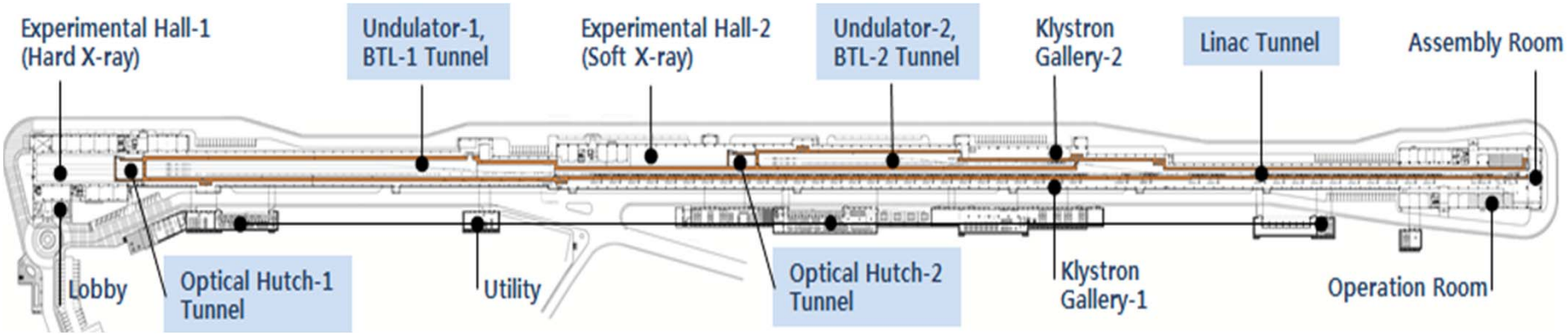




Out vacuum Undulator

(EURO-XFEL undulator design)

PAL-XFEL building



Safety policy of PAL

☐ Radiation Control Policy based on Korean Regulation

- Annual dose limit for radiation worker: 20 mSv/year
- Annual dose limit for publics: 1 mSv/year
- Environmental limit (Site boundary): 0.25 mSv/year
- 6 mSv/year for frequent visitors, 10 μSv during 1 hour for temporary visitors

☐ Shielding Criteria based on ALARA

- **10 mSv/year on Surface (2000 h -> 5 μSv/hour)**
- **1 mSv during 1 hour for accidental event**
- **Area requirements (e.g. 0.4 mSv/week)**

☐ Area Classification

- Restricted Area: 0.25 mSv/y < Dose < 1 mSv/y
- Generally-Controlled Area: 1 mSv/y < Dose < 20 mSv/y
  (a dosimeter is required)
- Radiologically-Controlled Area: 20 mSv/y < Dose < 1 mSv/h
- High Radiation Area: 1 mSv/h < Dose
  (No Access)

Normal beam loss scenario

□ **Normal beam loss of the PAL-XFEL**

1) Full power beam loss at main beam dump

: 120 or 240 W (10 GeV, 0.2 nC, 60 Hz, 1 or 2 bunch)

2) Low power beam loss at linac and undulator section

- ~~**One beam pulse loss is allowed every second.**~~
  ~~**120 W /60 pps = 2 W, 1.67% (4 W for 2 bunches)**~~

➡
- **Linac : 1.2 W, 1% (2.4 W for 2 bunches)**
- **Undulator : 0.12 W, 0.1% (0.24 W for 2 bunches)**

3) Low power beam loss at several dumps

(tune-up dump, spectroscopy dumps) : 2 or 4 W

□ **Interlock system :** to control the loss rate based on integrated loss during a preset time

Methods for shielding design

□ Bulk tunnel shielding

: using fundamental semi-empirical formula, SHIELD11 (SLAC)

□ Analyzing for detailed geometries like entrance and duct at the tunnel

: using Monte Carlo code, FLUKA

- Tunnel entrance at the tunnel

  : 1 hinged, 4 sliding doors

  : 5 maze entrance

Methods for shielding design

□ SHIELD11_PAL.xls, 12 Dec. 2012, Edited by J.H. Oh and H.S. Lee

SHIELD11_PAL_ver0.

Ref. 1. Radiation protection at high energy electron accelerators, Rad. Prot. Dosim. Vol. 96, No 4, pp. 333-343 (2001)
Ref. 2. The SHIELD11 Computer Code, SLAC-R-737/UC-414 (2005)
Edited at 12.Dec.2012, Joo-Hee Oh, Hee-Seock Lee

$$H_p\left[\frac{Sv.m^2}{h.kW}\right] = (E\times 10^{-11})\times\left[\frac{(\cos(\alpha-\theta))}{\alpha+d}\right]^2\times\left[\left(1.06\times 10^6 E\times e^{-0.959\sqrt{\theta}}\times e^{-\frac{L\rho}{\lambda}}+683\times e^{-\frac{\theta}{72.2}}\times e^{-\frac{R\rho}{\lambda}}\right)\times e^{-\frac{\mu_p d}{\cos(\alpha-\theta)}}+0.267HEN\right], (2005)$$

$$H_n\left[\frac{Sv.m^2}{h.kW}\right] = (E\times 10^{-11})\times\left[\frac{(\cos(\alpha-\theta)}{\alpha+d}\right]^2\times\left[\left(\frac{13.7\times e^{-\frac{d\rho}{\lambda_1\cos(\alpha-\theta)}}}{A^{0.65}(1-0.72\cos\theta)^2}\right)+\left(\frac{43.9\times e^{-\frac{d\rho}{\lambda_2\cos(\alpha-\theta)}}}{A^{0.37}(1-0.75\cos\theta)}\right)+\left(4.93Z^{0.662}\times e^{-\frac{d\rho}{\lambda_3\cos(\alpha-\theta)}}\right)\right]$$

[For target]
Z : atomic number
A : atomic mass
μ_p : linear attenuation factor
X_0 : radiation length ,
X_m : moliere radius

[For shielding materials]
$$X_0 = \frac{716A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$
ρ : material density
μ_p : photon mass attenuation facto...
λ_i : mean free-path factors(mass attenuation factor for neutron)

[For Geometry]
α : angle of primary shield relative to beam direction, deg
θ : angle of first detector, deg
a : distance from target to shielding material, cm
d : thickness of shielding material, cm

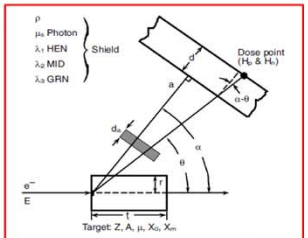
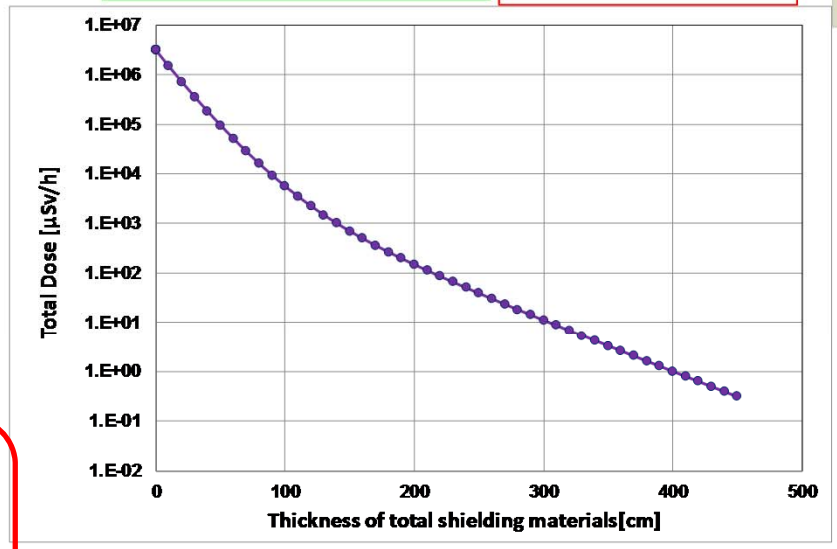


Figure 9. Geometry representation used in the SHIELD11 code: Photon and neutron dose equivalent is calculated at a point behind a primary slab shield. Additional 'local' shielding of different material, situated between the target and the point of interest, can be taken into account. See text for the meaning of parameters describing properties of the target and shielding.

• Critic
0.01 r.
17.3 r.
2 inch
3.74 M
• Stand
Length
Radius
• λi : m
• μ : li

MATERIAL INFORMATION

		Target	Primary Shield	Add Shield 1	Add Shield 2	(APS_LS_293[1997])
		Fe	OrdinaryConc	None	None	
MatID		FE	CONC	None	None	
Z (Zmat)		26.000	13.000	0.000	0.000	
A (Amat)		55.850	26.980	0.000	0.000	
Density (RHOm	g/cm3	7.870	2.350	0.000	0.000	
r.l. (RLmat), X_0	g/cm2	13.840	26.700	0.000	0.000	
	cm	1.759	11.362	0.000	0.000	
Moliere Length	g/cm2	10.700	11.100	0.000	0.000	
(XMUmat)	cm	1.360	4.723	0.000	0.000	
MFP (Xmfp)	g/cm2	47.000	30.000	1.000	1.000	GRNs(λ1)
	/cm	0.167	0.078	0.000	0.000	
	g/cm2	145.000	55.000	1.000	1.000	MIDs(λ2)
	/cm	0.054	0.043	0.000	0.000	
	g/cm2	145.000	120.000	1.000	1.000	HENs(λ3)
	/cm	0.054	0.020	0.000	0.000	
	g/cm2	33.600	42.000	1.000	1.000	GamD(μ)
	/cm	0.234	0.056	0.000	0.000	
	g/cm2	145.000	120.000	1.000	1.000	Gaml
	/cm	0.054	0.020	0.000	0.000	



 # Change Values in ' BLUE '

Target Material : FE

Primary Shield Material: CONC

Added Shielding Material : Add shield 1: None; Add shield 2: None

INPUT		target to shield	target length	target radius		
α (deg)	θ (deg)	a (cm)	t (cm)	r (cm)	Beam Power (kW)	Beam Energy (GeV)
90	78	150	25.4	5.08	0.24	10

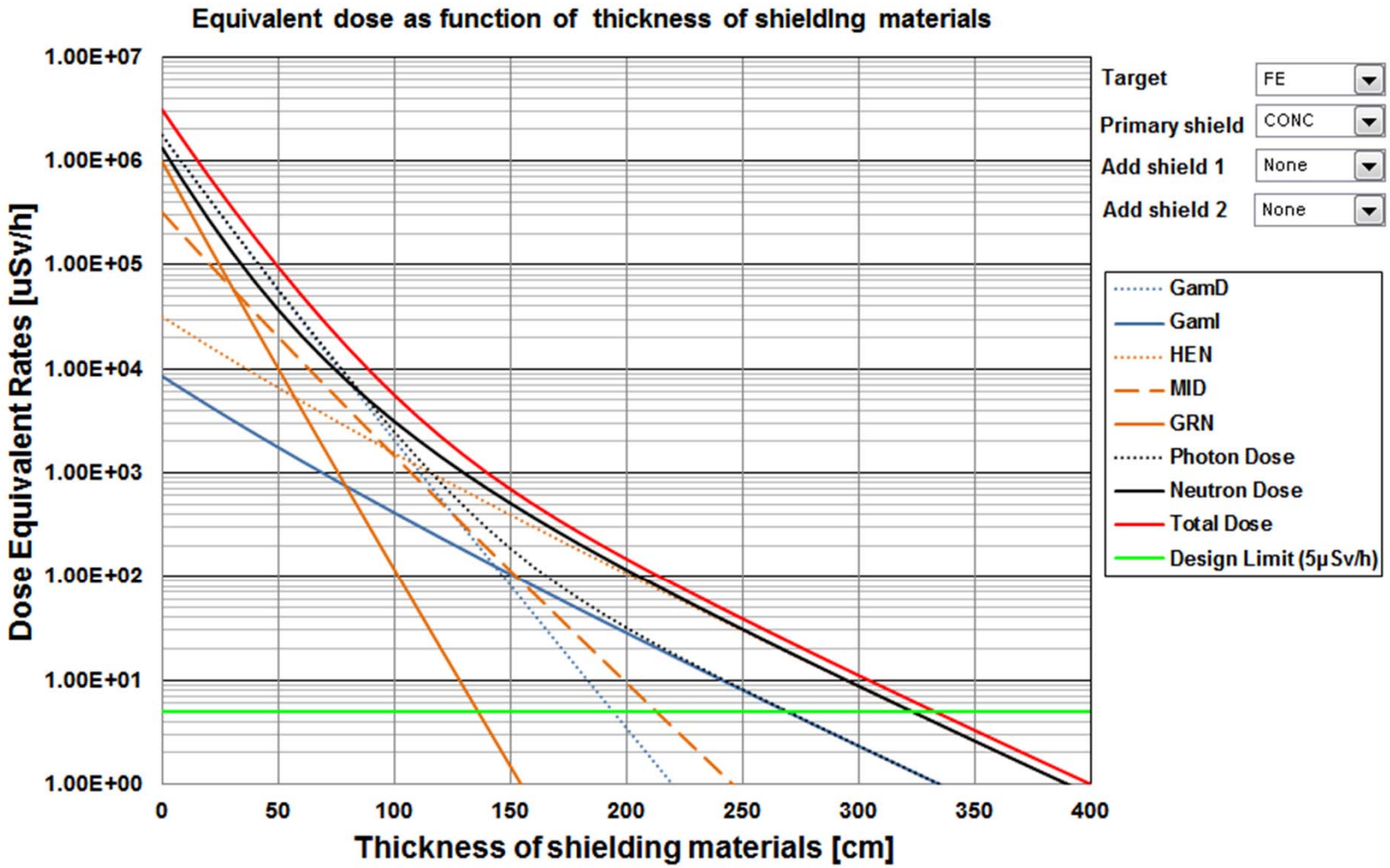
← **Enter your input**

Target items

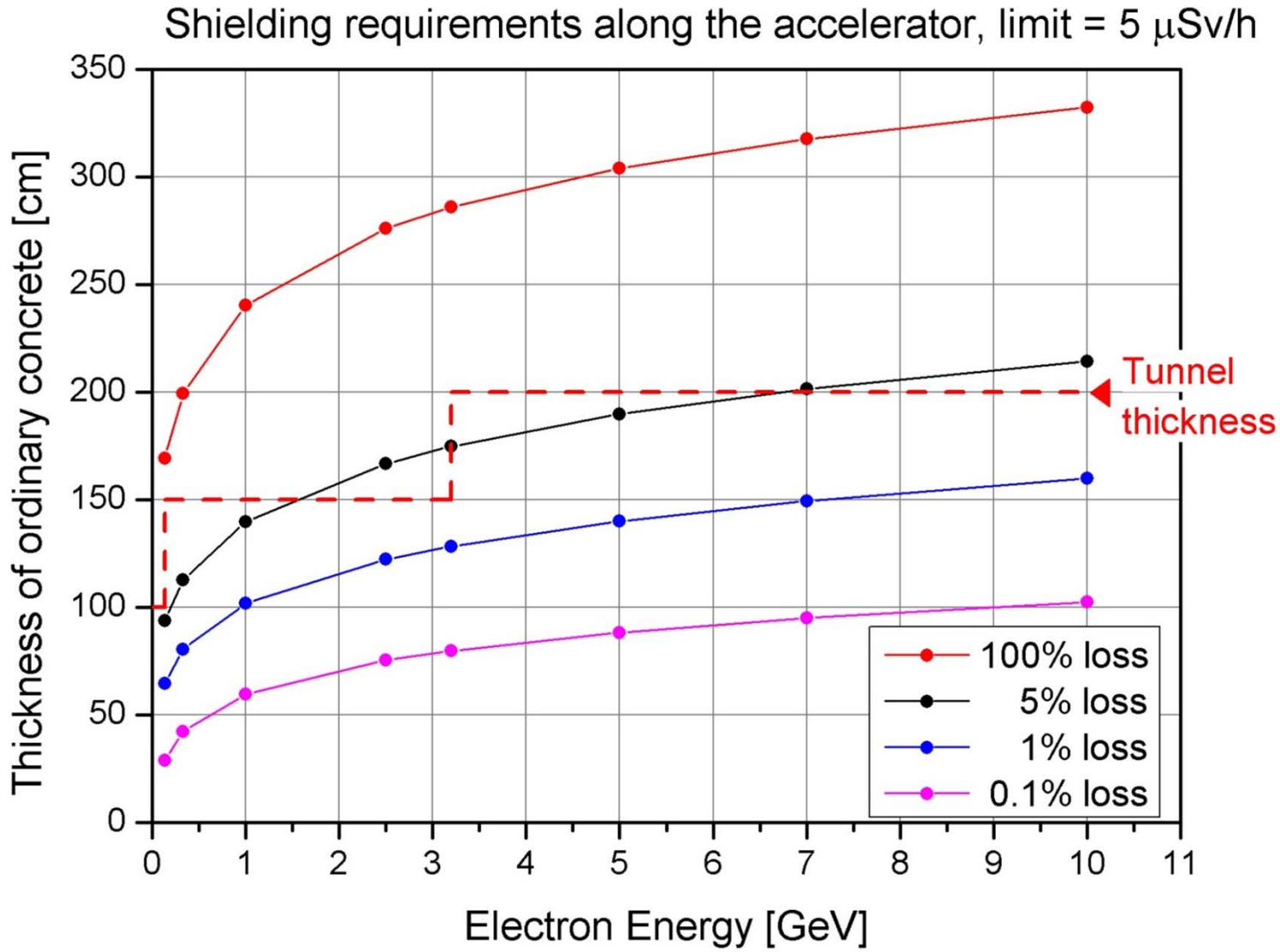
e^(−(0.959*sqrt(θ)))	e^(−θ/72.2)
0.000209736	0.339

Methods for shielding design

□ SHIELD11_PAL.xls, 12 Dec. 2012, Edited by J.H. Oh and H.S. Lee



Tunnel thickness

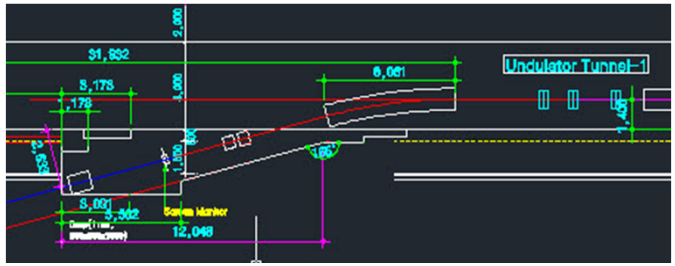


Tunnel thickness

□ Determine the different thickness according to the electron energy

Section	Electron energy [GeV]	Thickness of the concrete [cm]
Injector	0.139	100 (*L), 150 (R)
Linac	< 3	150 (L, R)
	3 ~ 10	200 (L, R)
SX undulator	3.15	150 (L, R)
HX undulator	10	200 (L, R)

* L : left side toward beam direction, R : right side

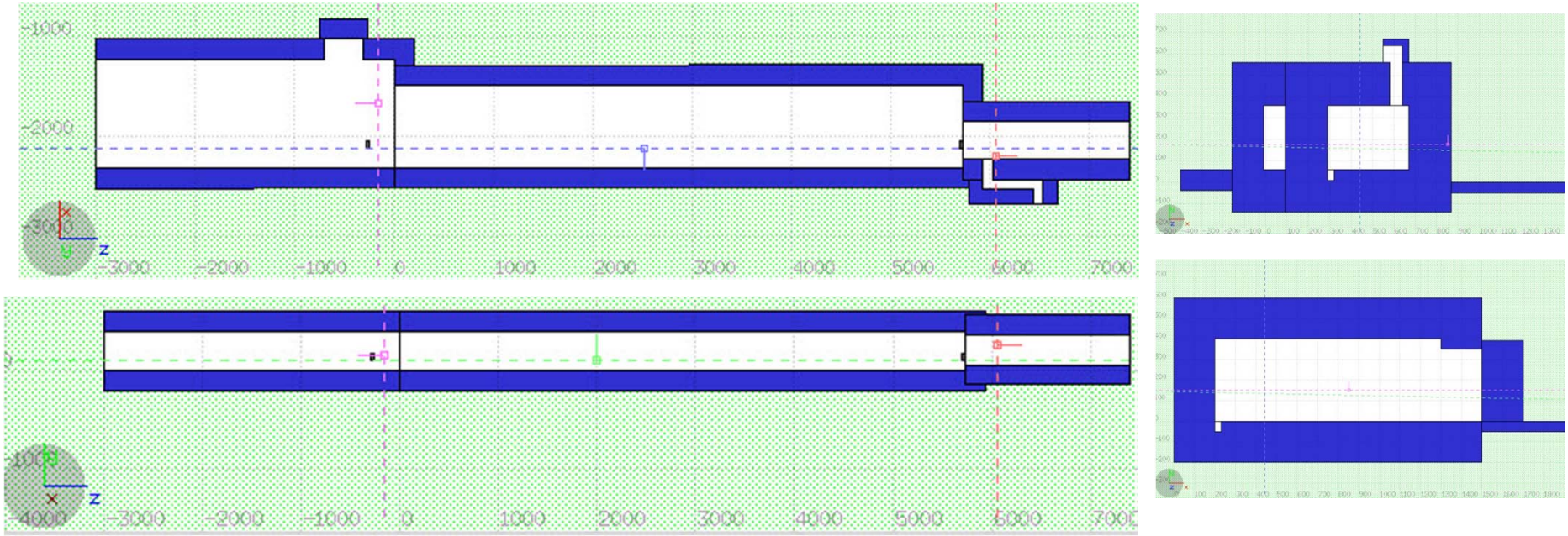


□ Main beam dump (80 x 80 x 100 cm^3 iron) installed at the pit

: changing beam direction using main dump magnet

Tunnel entrance (Door, Maze) & Ducts

< Example - FLUKA geometry >



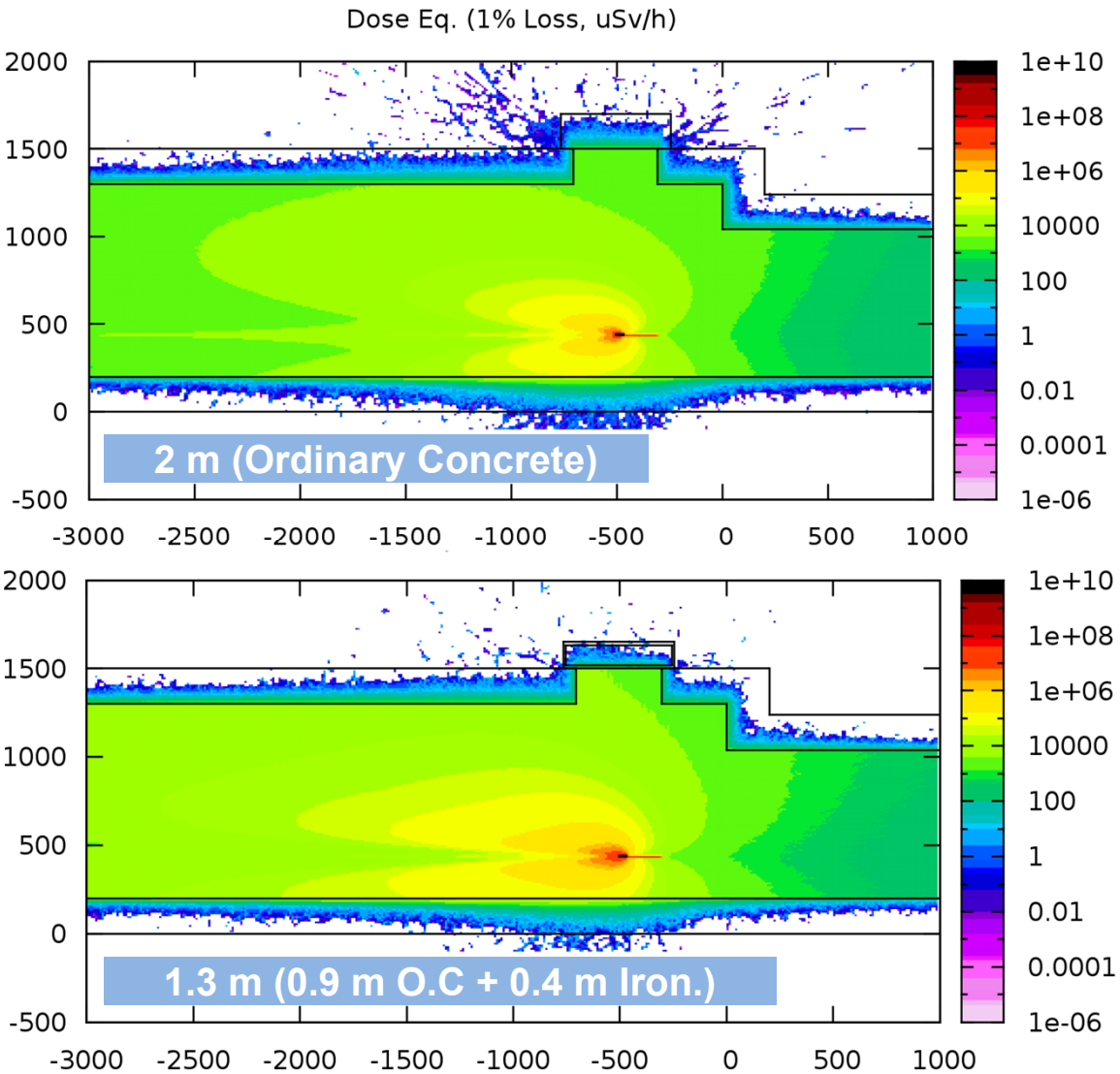
- Location : End of linac, BTL, Start of HX undulator tunnel
- 1 sliding door, 1 maze entrance, several maze ducts at tunnel roof
- Target thickness : 36 cm iron ≈ 17.3 r.l. (critical size of neutron)
- Electron energy : 10 GeV

Tunnel entrance : Door, Maze

< Example of sliding door >

- Gap bet. door and floor, bet. door and tunnel wall : 5 mm
- Overlap length : 60 cm (upper, both sides)
- Thick iron target
- 2.4 W loss (1%, 2 bunches)

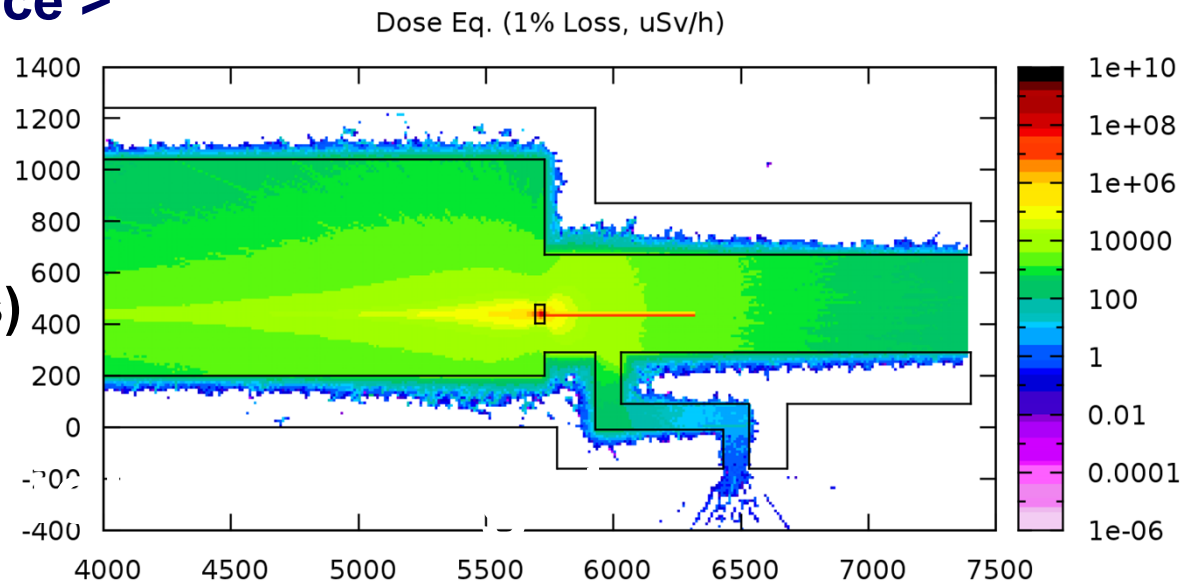
⇒ Detailed door design are discussing with the door making company.

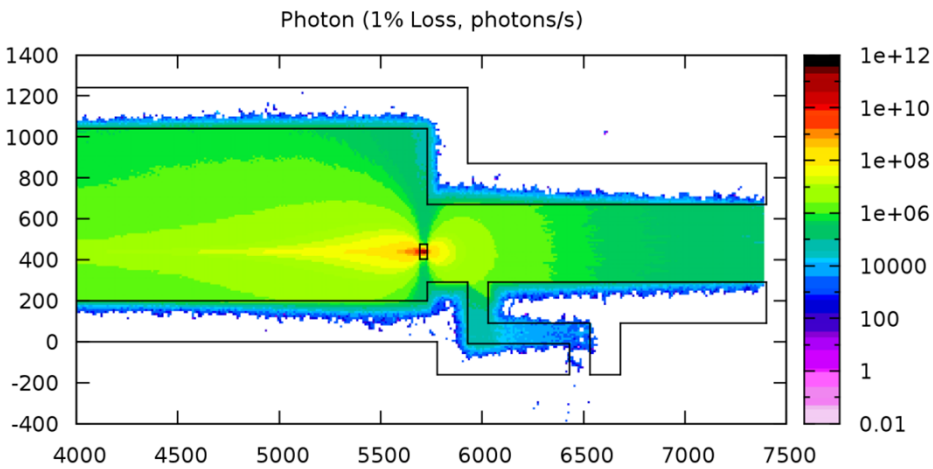


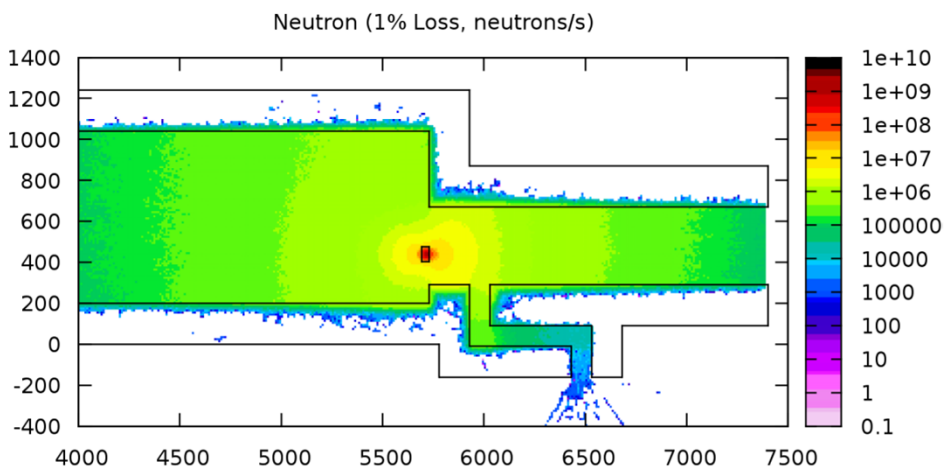
Tunnel entrance : Door, Maze

< Example of maze entrance >

- Thick iron target
  : Quadrupole Magnet
- 2.4 W loss (1%, 2 bunches)



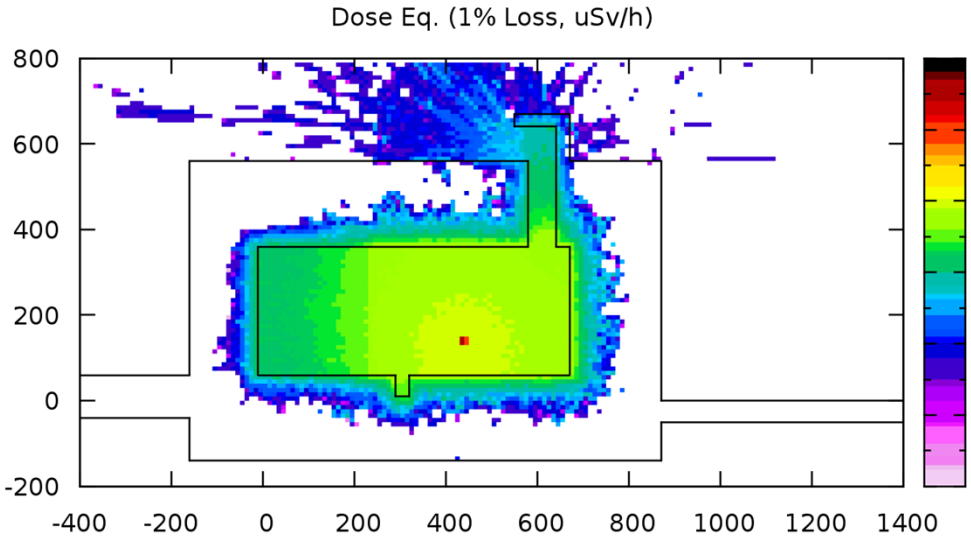




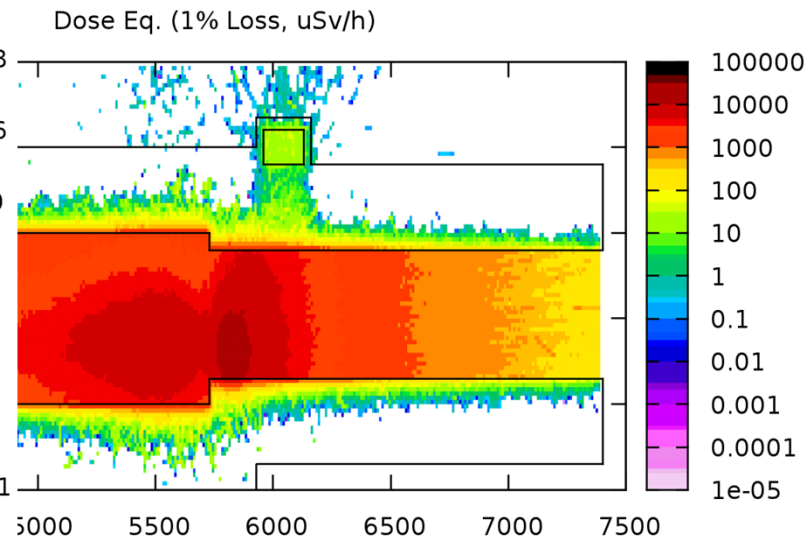
Maze duct

< Example of maze duct at tunnel roof >

- Upstream, Distance from target : 2.3 m, Size : 1.7 m (W) x 0.8 m (H)



Dose Equivalent XY

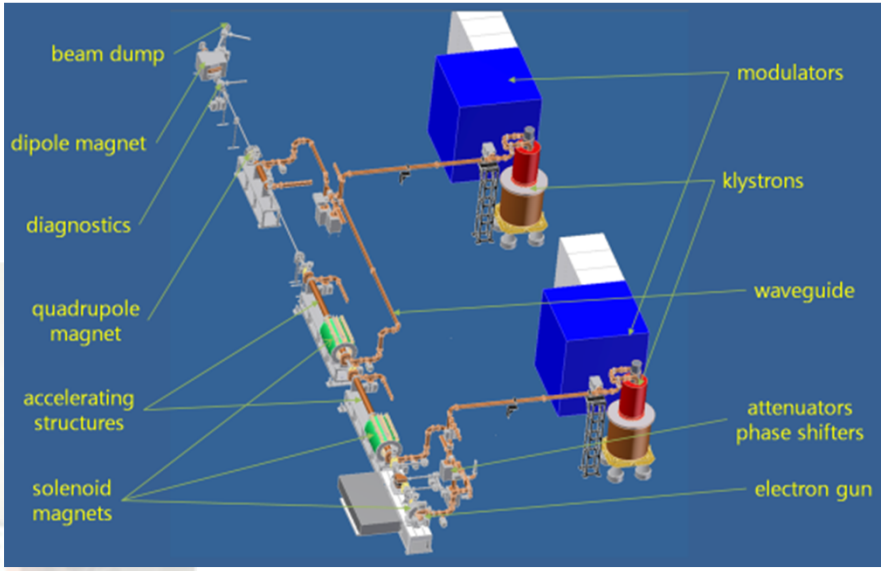


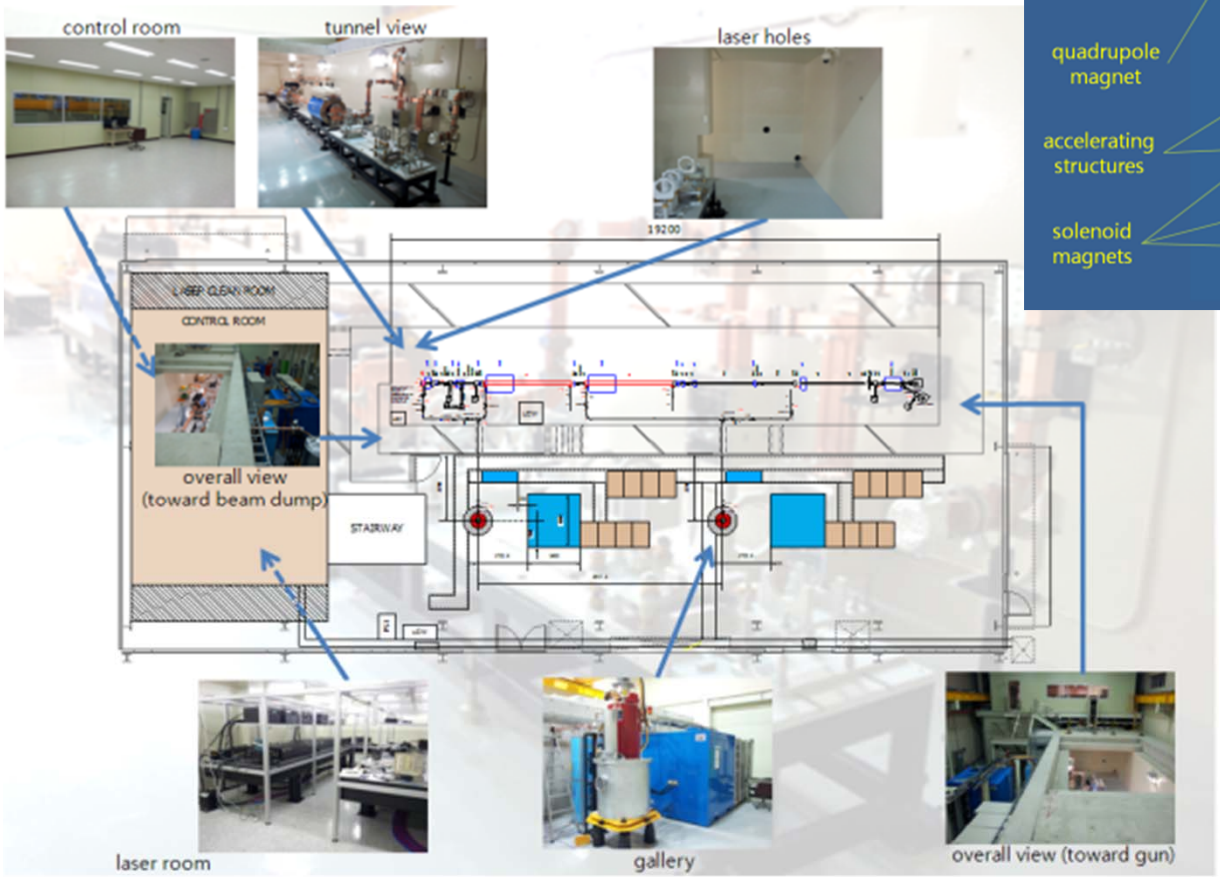
Dose Equivalent XZ

- The periphery of the duct which have high radiation dose will be set as the radiologically-controlled area

ITF: Injector Test Facility

- Beam energy : 0.139 GeV
- Beam charge : 0.2 nC
- Repetition rate : 60 Hz





- Tunnel thickness

  forward : 150 cm

  left side : 150 cm

  right side : 100 cm

  roof : 60 cm

ITF: Injector Test Facility

Inside of the tunnel

Klystron Gallery

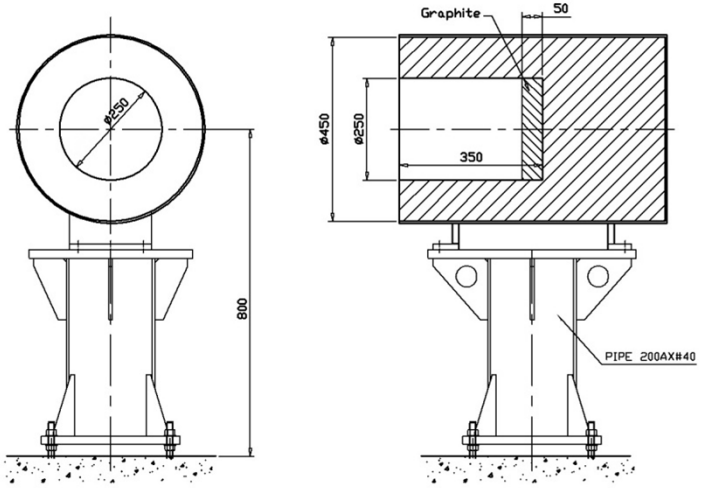
ITF: Injector Test Facility

< Beam dump >

- Material : Graphite + Lead
- Total length : 650 mm

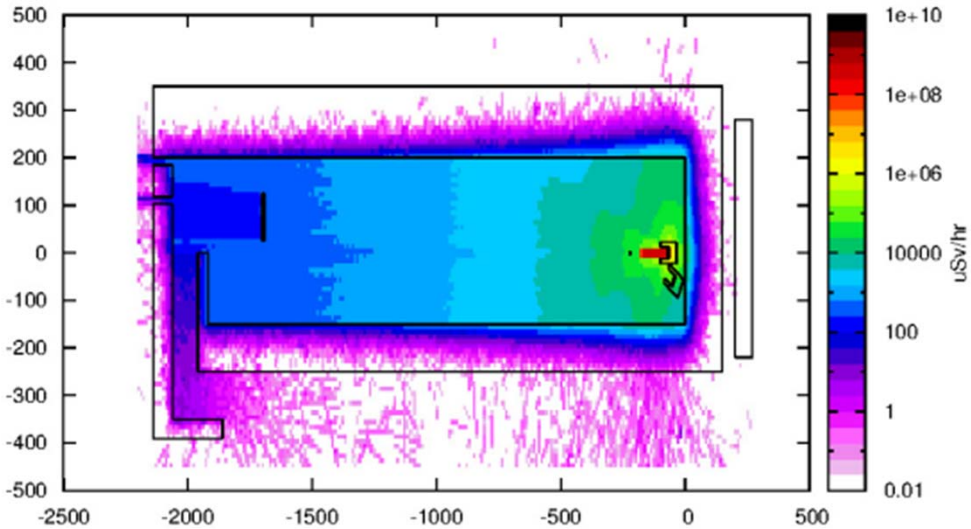
< Faraday cup >

- Material : 6061 Al alloy
- Size : Φ2.5 cm x 14.4 cm

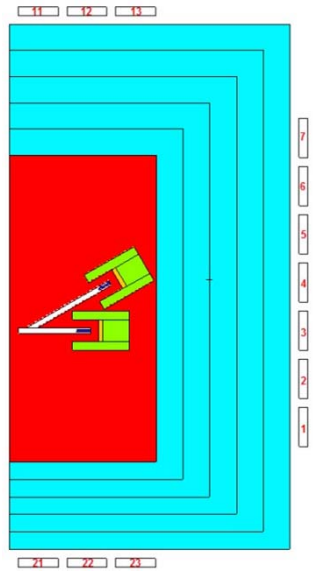


Prohibit approaching to the tunnel roof during ITF operation !!

< FLUKA >

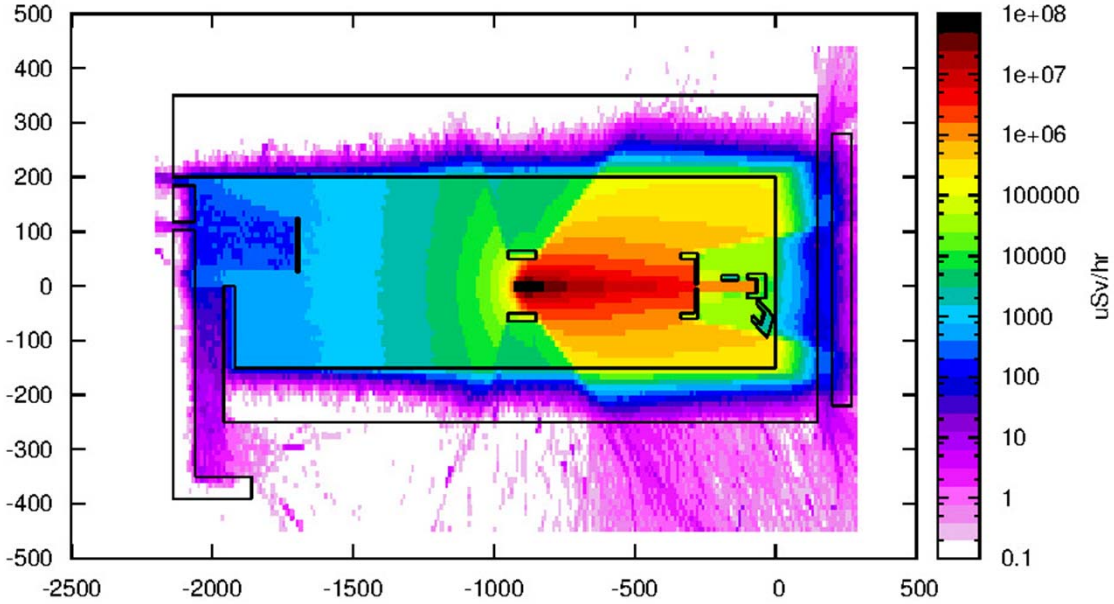


< MCNPX >

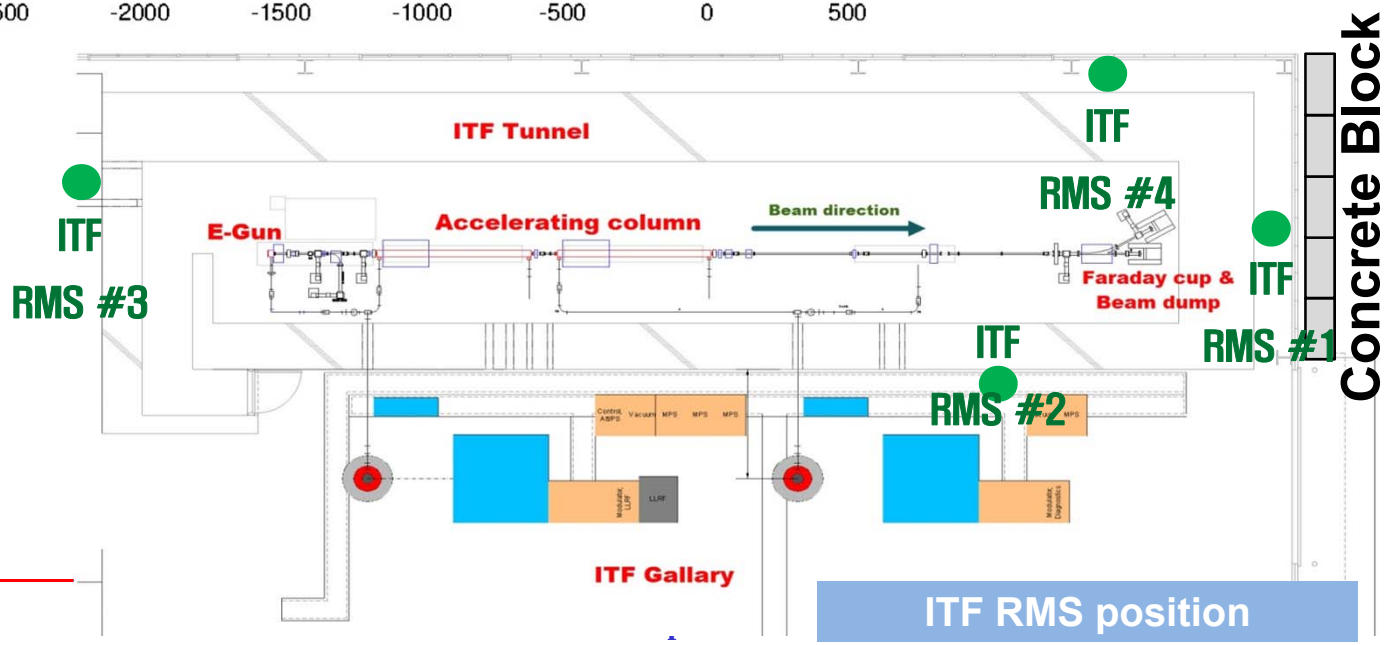


Beam direction	Total doserate [μSv/h] (Photon doserate)
Forward	0.15±0.15 (0.01±0.01)
Left	< 0.01 (< 0.01)
Right	0.63±0.25 (0.17±0.02)
Upper	6.43±0.51 (2.99±0.09)

ITF: Injector Test Facility



FLUKA result for accidental case : 100% beam loss is occurred after two accelerating structure

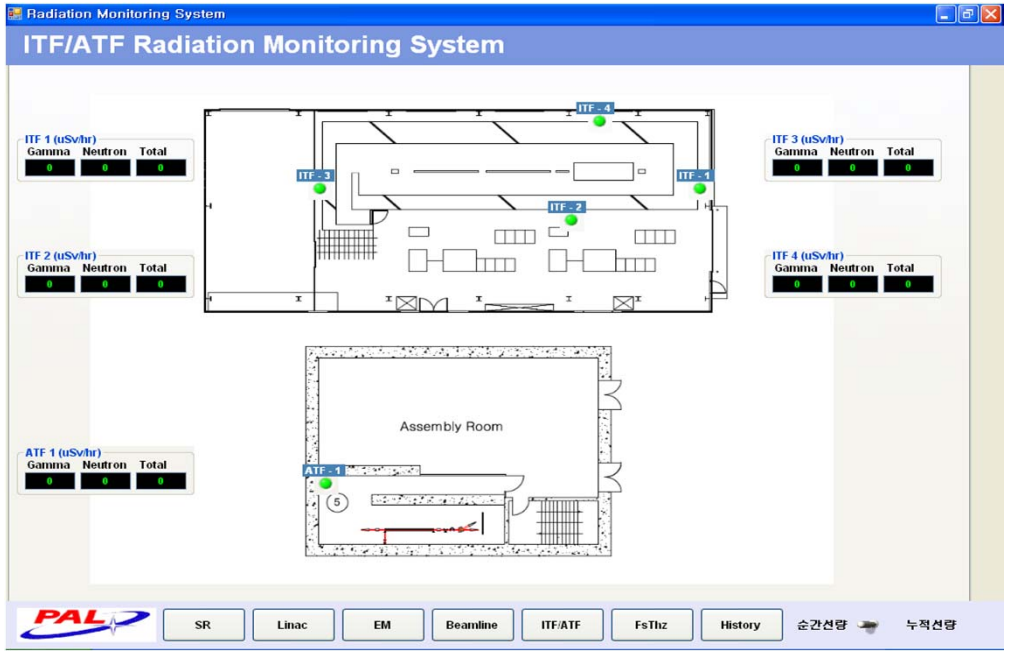


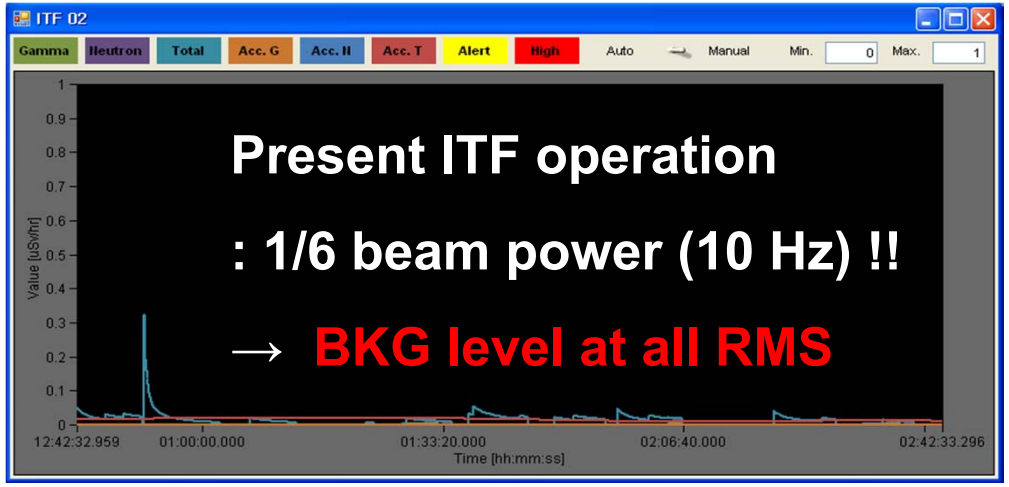
ITF RMS position

ITF: Injector Test Facility

- Detector for photon (ion chamber)
  - Far West Tech., Inc.
  - HPI 6035B
  - Energy range
    : 80 keV ~ 1.6 MeV (within 30%)
  - Range : 0.1 mR/h ~ 100 mR/h
  - Sensitivity : 1,200 CPM/mR/h

- Detector for neutron (AB remmeter)
  - Far West Tech., Inc.
  - HPI 6065
  - Energy range
    : Thermal to 15 MeV
  - Range : BKG ~ 10,000 mrem/h
  - Sensitivity : 12,000 counts/mrem





ATF: Accelerating column Test Facility

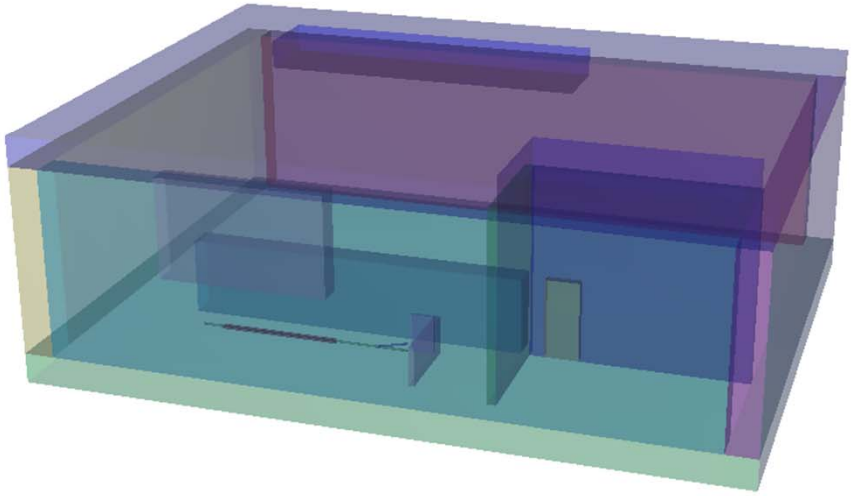
< Location >

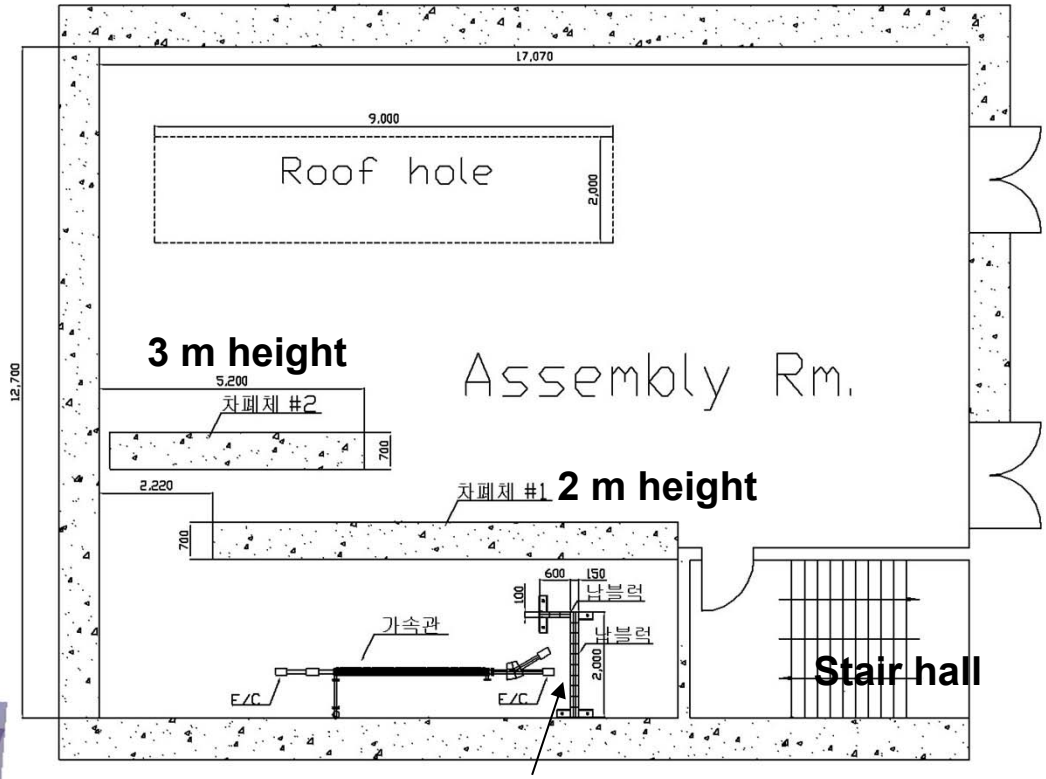
: PLS-II linac assembly room

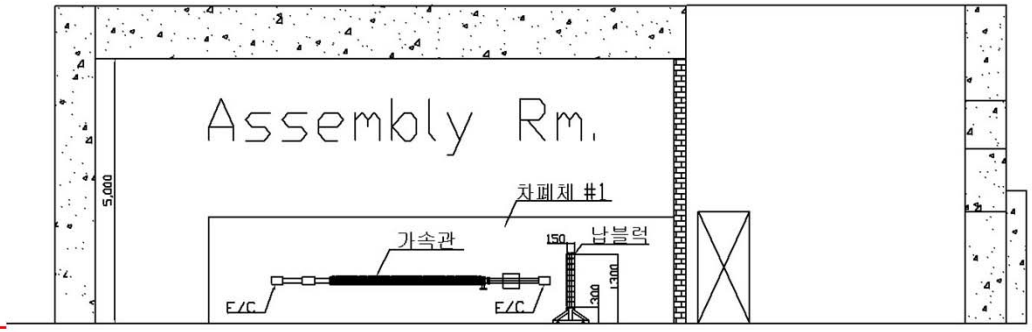
< Testing accelerating columns >

: RI (Research Instruments), Mitsubishi, IHEP (Institute of High Energy Physics), 비츠로

< Source > : dark current !







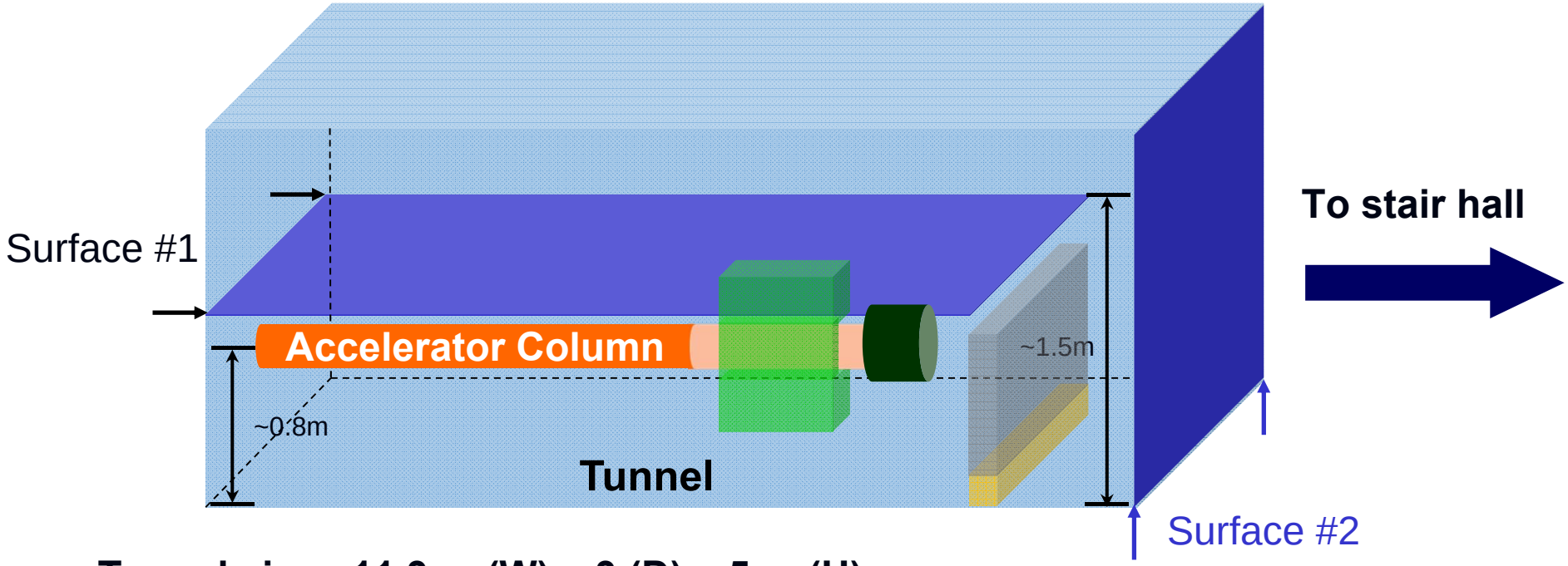
ATF: Accelerating column Test Facility

- Dark current estimation from our RF group

  : max. 90 MeV (30 MV/m, 3 m length), 1 pA (first) ⇒ 1 nA (now)

  after dose measurement

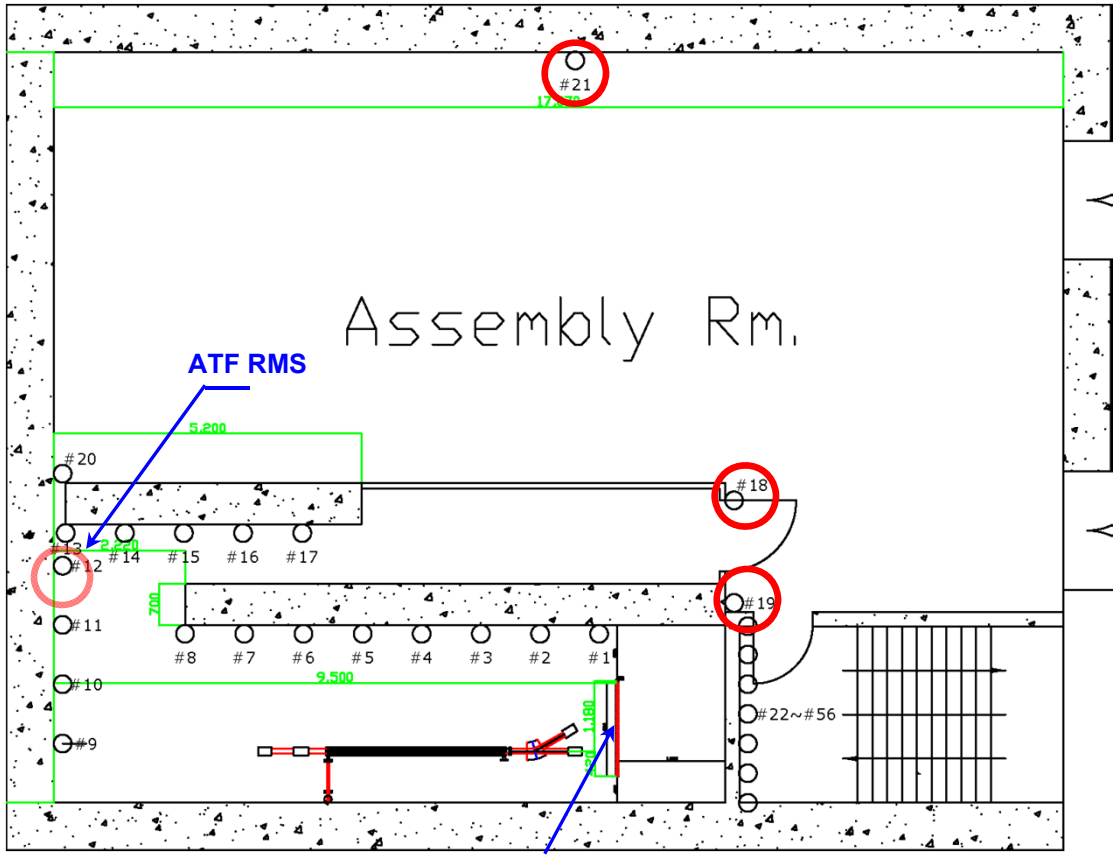
- Location of OSLN measurement



Tunnel size : 11.3 m (W) x 3 (D) x 5 m (H)

ATF: Accelerating column Test Facility

< Surface #1 – RI accelerating column>



10 cm Pb!! (5 cm Pb required from MCNPX calculation with assuming of 1 pA, 2 μSv/h at stair hall)

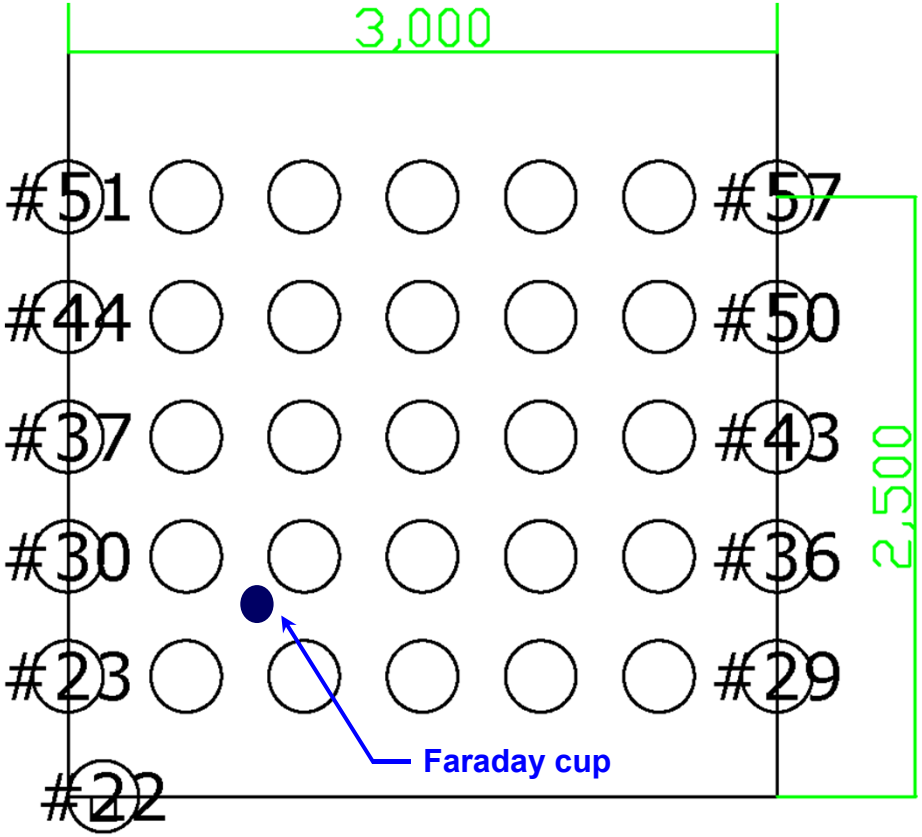
OSLN no.	DDE [1] [mSv]	DR [2] [μSv/h]
1	60.06	347.2
2	68.87	398.1
3	41.24	238.4
4	19.89	115.0
5	12.07	69.8
6	10.33	59.7
7	7.87	45.5
8	7.04	40.7
9	1.99	11.5
10	3.14	18.2
11	2.88	16.6
12	2.27	13.1
13	1.67	9.7
14	0.65	3.8
15	0.43	2.5
16	0.46	2.7
17	0.5	2.9
18	0.45	2.6
19	0.7	4.0
20	0.15	0.9
21	0.2	1.2

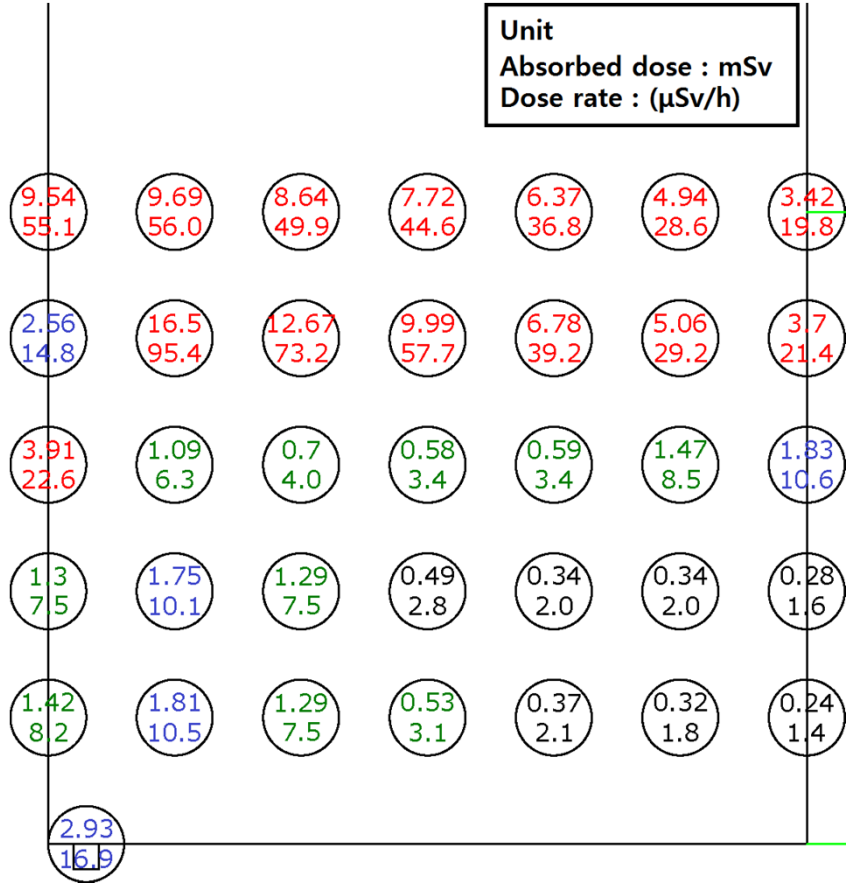
[1] DDE : Deep Dose Equivalent

[2] DR : Dose Rate (Operation Time : 173h)

ATF: Accelerating column Test Facility

< Surface #2 – RI accelerating column>





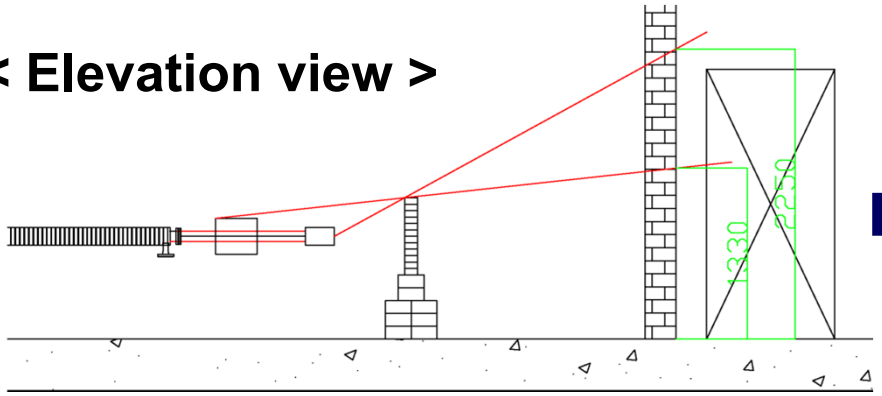
MCNPX result : 2 μSv/h at stair hall on surface #2 with assumption of 1 pA

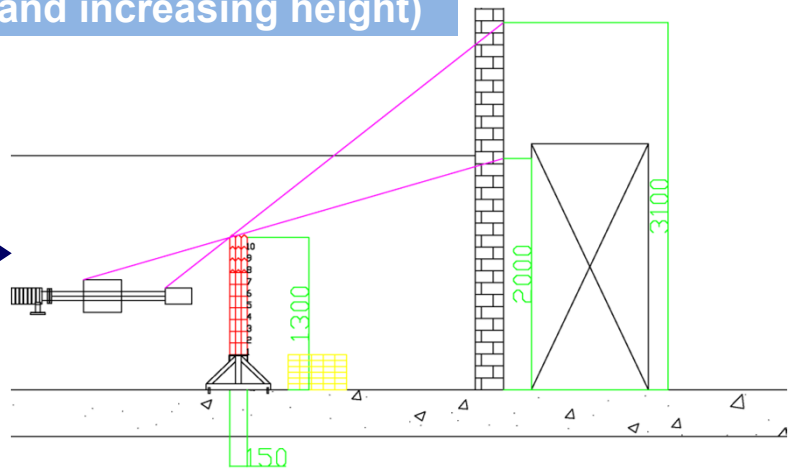
ATF: Accelerating column Test Facility

Before

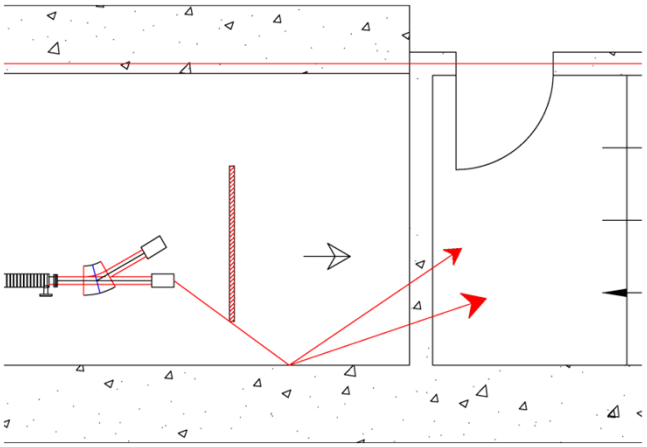
After (15 cm thickness Pb and increasing height)

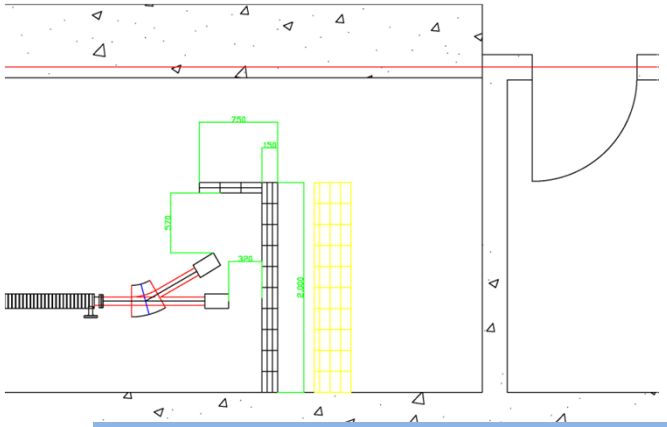
< Elevation view >





< Plan view >





After (Add more Pb shield)

Now, we test the Mitsubishi column with OSLN measuring !!

❑ Conclusion

- **The shielding design of the linac and undulator tunnel of PAL-XFEL**
  - Three normal beam loss scenario was established.
    : full beam loss at main beam dump, low power beam loss at linac & undulator, low power beam loss at several dumps
  - Bulk tunnel thickness was determined using semi-empirical formula, SHIELD11.
    : Ee > 3.2 GeV, 2 m tunnel thickness
  - Complicated tunnel structures like entrance and duct were analyzed using Monte Carlo code, FLUKA.

- **Test facility ITF**
  - Beam dump for ITF was designed.
  - Additional shields(Pb, Concrete) were required under accidental scenario.
  - Radiation Monitoring System were installed at the ITF.
    : BKG level under the present ITF operation (1/6 of full power)

❑ Conclusion

- **Test facility ATF**
  - Tested accelerating column of RI (research instrument) with OSNL measurement
    : Additional Pb shield design was changed.
  - Next accelerating column of Mitsubishi are testing now.

Present statue of PAL-XFEL

26. Nov. 2012

1. May. 2013

Thank you for your attention !!

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