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Bulk Shielding Evaluation of 4th Generation Storage Ring in Korea

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  - 4GSR (4th Generation Storage Ring) construction project of Korea
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  - By Semi-empirical formula, SHIELD11 code (in Conceptual Design Report stage)
  - By FLUKA code (in Technical Design Report stage, on-going) → Showing Preliminary Results

- Summary

Introduction: What is 4GSR light source?

- Next Generation Storage Ring

  : e-beam emittance improvement about 50 ~ 100 times compared to 3rd Generation Storage Ring (3GSR)
- Terms for Next Generation Storage Ring

  - USR : Ultimate Storage Ring, this term was first used in 2000.

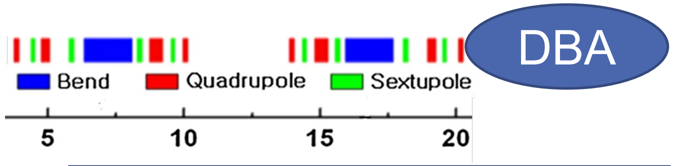
  - DLSR : Diffraction Limited Storage ring

  - 4GSR : 4th Generation Storage Ring
- Lattice(Cell structure) of Storage Ring

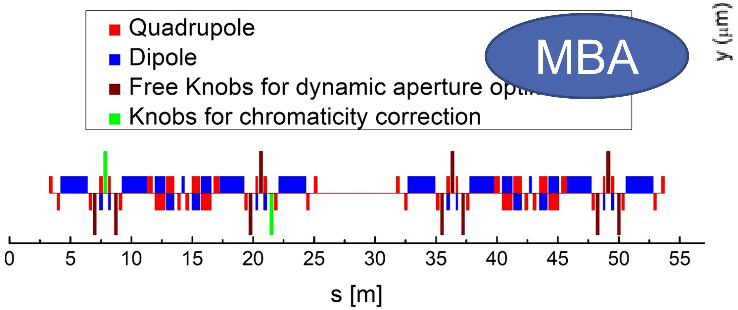
  - 3GSR : DBA (Double Bend Acromat) or

    TBA (Triple Bend Acromat)

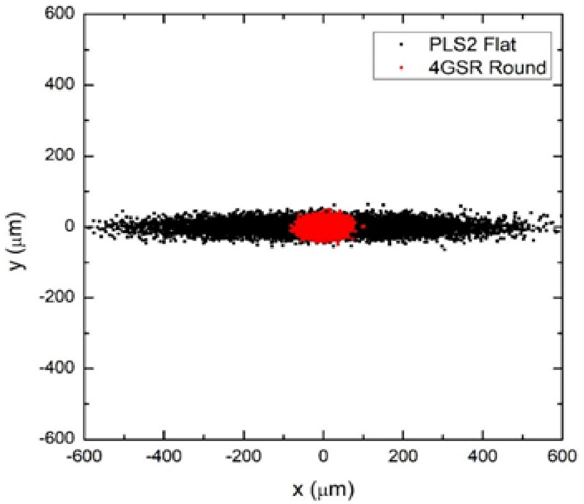
  - 4GSR : MBA (Multi-Bend Acromat)



Magnet elements in single cells of PLS-II[1]



Magnet elements in two cells of KOREA-4GSR[1]



Comparison of beam shape between PLS-II and 4GSR [2]

[1] J. Lee et al., "Storage rings in Korea as synchrotron radiation source", J. Korean. Phys. Soc. 80, 859 (2022)
[2] Pohang Accelerator Laboratory, "Conceptual Design Report of 4GSR", PAL-PUB-2000-004, 2000.

Introduction: Worldwide Next Generation SR

	Name	Beam energy (GeV)	Circumference (m)	Emittance (nm·rad)	Status
New	MAX-IV (Sweden)	3	528	0.33	In Operation
	SIRIUS (Brazil)	3	518.4	0.25	In Operation
	HEPS (China)	6	1360.4	0.059	
	SLiT-J (Japan)	3	354	0.93	
Upgrade (from 3GSR to 4GSR)	ESRF-EBS (EU)	6	844.4	4 → 0.13	In Operation
	APS-U (USA)	7 → 6	1,104	3.1 → 0.042	
	ALS-U (USA)	2	196.8	2 → 0.07	
	SPring-8-II (Japan)	8 → 6	1,436	2.4 → 0.149	
	SLS-II (Swiss)	3 → 3.5	290.4	5 → 0.13	
	Diamond II (UK)	3 → 3.5	561.6	2.8 → 0.125	
	SOLEIL II (France)	2.75	353.1	3.7 → 0.072	
	PETRA-IV (Germany)	6	2,304	1 → 0.02	
	ELETTRA 2.0 (Italy)	2	259.2	7 → 0.25	

Introduction: 4GSR project in Korea

- History

  - 2019. 10 : Start a Conceptual Design of 4GSR by PAL/KBSI/KAERI collaboration

  - 2020. 5 : Determine a construction site as ‘Cheongju’

  - 2020. 6 : Publish a Conceptual Design Report (CDR)[1]

  - 2021. 7 : Determine a institution to conduct construction project as KBSI (Korea Basic Science Institute)

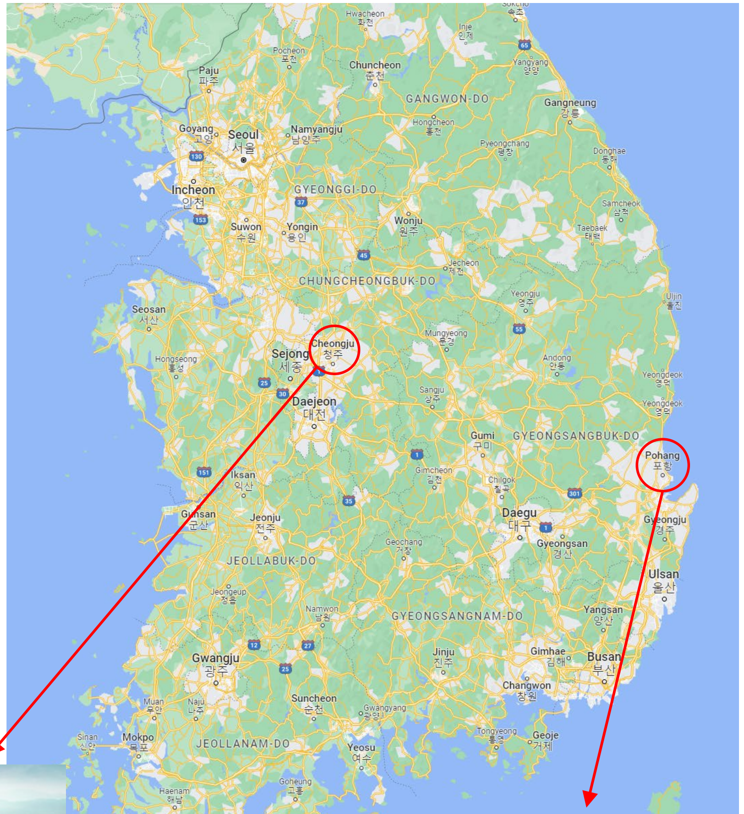
  - 2021. 7 (~ 2027. 6) : Start a construction project, ‘Multipurpose Synchrotron Radiation Construction Project’

- Counterpart in the construction project

  - KBSI : Building & Infrastructure

  - PAL : Accelerator & Beamline

  (+ Radiation Shielding, Radiation Protection System)



[1] Pohang Accelerator Laboratory, “Conceptual Design Report of 4GSR”, PAL-PUB-2000-004, 2000.

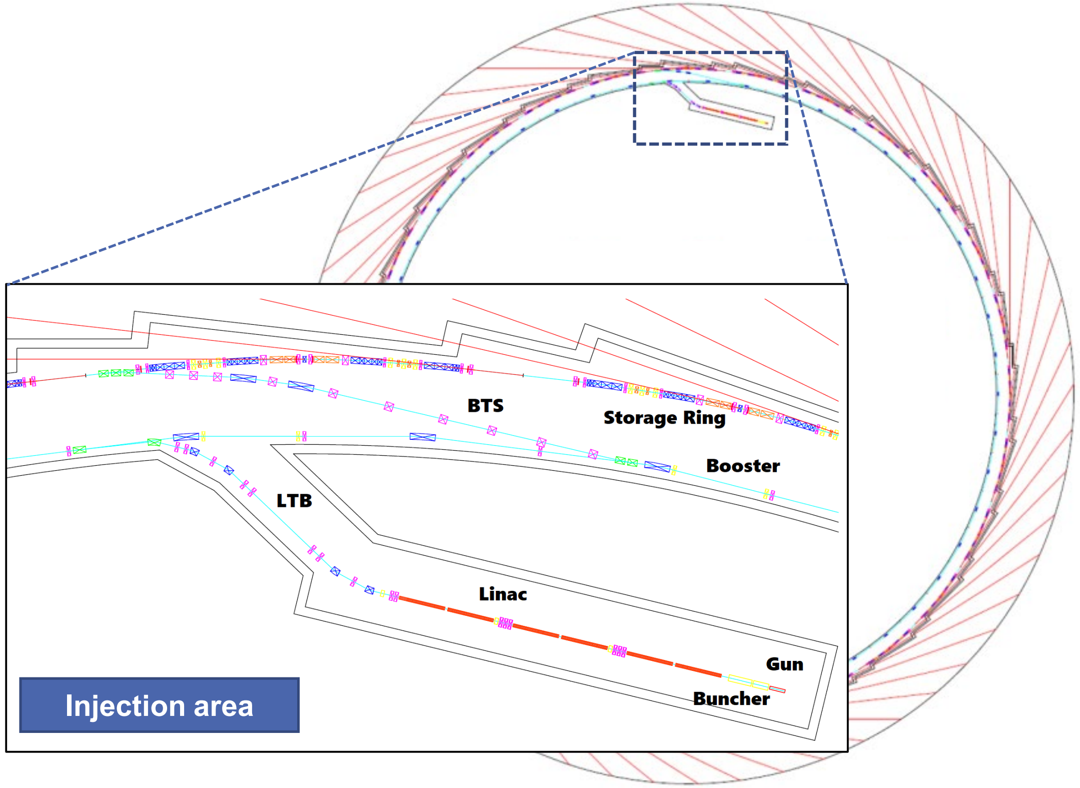
Introduction: Specification of 4GSR in Korea

- Specification (in CDR)

	Category	Value
SR	Beam Energy	**4 GeV**
	Stored Current	**400 mA**
	Ring Circumference	**798.8 m**
	Symmetry	28
	Straight Section No.	28
	Straight Section length	6.5 m
	Dipole magnet No.	28 x 7 = 196
	Emittance	**58 pm rad**
Booster	Energy	0.2 GeV to 4 GeV
	Circumference	756.86 m
	Revolution time	2.52 μs

- Plan view (in CDR)

: Booster Ring & Storage Ring in same tunnel



Beam direction : counter-clockwise

- 10 Beamlines will be constructed in end of construction project.

Radiation Safety Control Policy (Same policy with 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

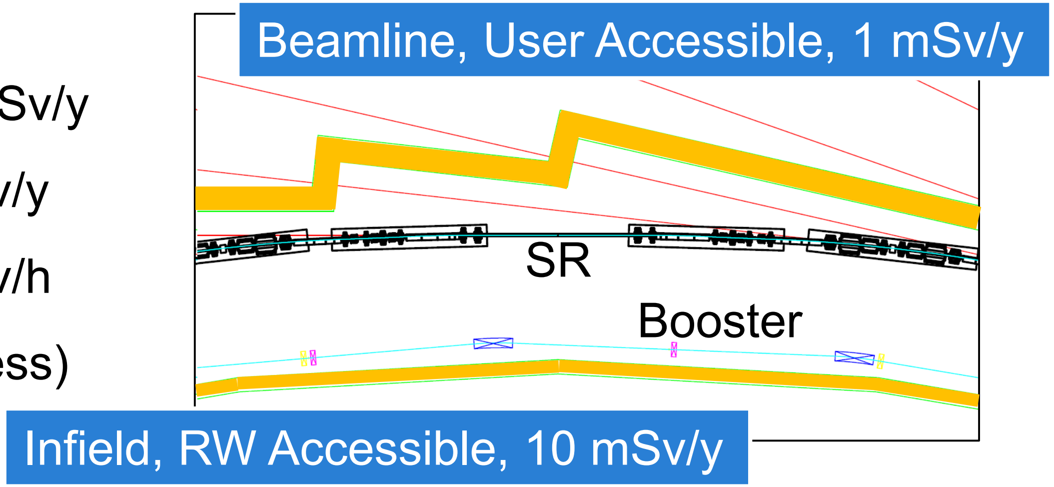
  (Normal Operation)

  - RW accessible area : 10 mSv/y, ½ of dose limit based on ALARA
  - User accessible area : 1 mSv/y

  (In Accident) 1 mSv within 1 h for single event

- Area (Zone) 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)



Beam Loss Scenario

- Stored beam energy & current : **4 GeV, 400 mA** (= 6.65 x 10^{12} electrons)
- SR operation mode : **Top-up**
- Top-up operation cycle : **240 hr = 10 day = 1 operation shift** : every 2 weeks

  → First injection is full-injection, and thereafter a 7200 top-up injection occur every 2 min
- Loss rate of stored current (distributed loss around SR considering Touschek lifetime)

  : **4 mA during 2 min** (= 6.65 x 10^{10} electrons)
- Electron energy increasing in Booster : **200 MeV to 4 GeV → 4 GeV assumption**
- Loss fraction in booster (distributed loss around Booster) : **2%** (H.J. Moe's assumption for APS booster[1])
- Beam loss fraction during injection : **10%** (Injection efficiency : **90%**)

  → **½ of loss** is occurred **at injection position**, septum magnet

  ½ of loss is **distributed around SR** (or Booster)

Loss fraction in Booster
- SIRIUS : 20% [2]
- NSLS-II : 10 ~ 20% [3]

[1] H.J. Moe, "Advanced Photon Source: Radiological Design Considerations", APS-LS-141 Revised, 1991.
[2] R. Madacki et al., "Sirius Bulk Shielding", in Proceedings of Radsynch13, 8-10 May 2013, BNL, USA.
[3] J. Choi, in private communication, 2021.

Beam Loss Scenario

- Estimation of injection efficiency in shielding design

  - According to accumulation of operation experience and improvement of injection device performance, the assumption of injection efficiency in the recent shielding design tends to be set high.

    (Booster injection) SIRIUS[1] : 80%, APS-U [2] : 80%, BESSY-VSR [3] : 90%,

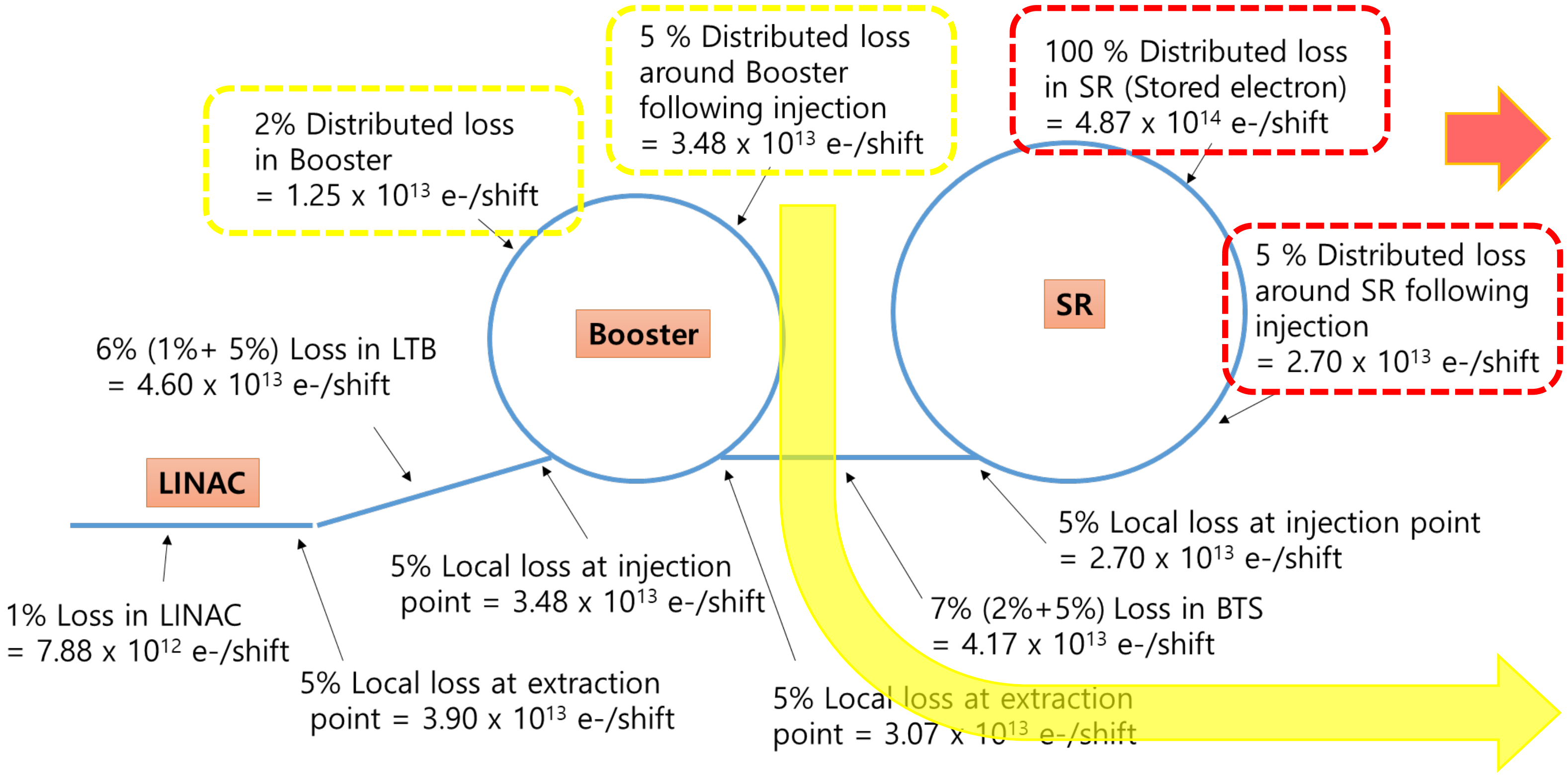
    SPring-8-II [4] : 85%, NSLS-II [5,6] : > 90%

    (LINAC injection) MAX-IV [7] : 50%

We assumed **90% injection efficiency** for 4GSR in Korea.

[1] R. Madacki et al., "Sirius Bulk Shielding", in Proceedings of Radsynch13, 8-10 May 2013, BNL, USA.
[2] B.J. Micklich, "Radiation Physics Issues for the Advanced Photon Source Upgrade", in Proceedings of Radsynch15, 3-5 June 2015, DESY, Germany.
[3] Y. Bergmann et al., "Radiation Protection Issues of BESSY VSR", in Proceeding of Radsynch19, 22-24 May 2019, MAX-IV, Sweden.
[4] RIKEN SPring-8 Center, "SPring-8-II Conceptual Design Report", RIKEN, November 2014.
[5] J. Choi, in private communication, 2021.
[6] G.M. Wang et al., "NSLS-II Storage Ring Injection Optimization", IPAC2015, Richmond, VA, USA
[7] MAX IV Facility, "Detailed Design Report on the MAX IV Facility, Chapter 7: MAX IV Shielding", MAX IV Facility, August 2010.

Beam Loss Scenario



Conceptual drawing of beam loss during 1 shift of 4GSR in Korea
(Booster & SR are sharing the same tunnel enclosure.)

- Number of lost electrons (Power) for distributed loss around SR
  : **5.14 x 10^{14} e-/shift** (**381.1 mW**)

  8.3 shift/year = 2000 hr/year
  → **4.28 x 10^{15} e-/year** (**3.174 W**)

- Number of lost electrons (Power) for distributed loss around Booster
  : **4.73 x 10^{13} e-/shift** (**10.6 mW**)

  8.3 shift/year = 2000 hr/year
  → **3.94 x 10^{14} e-/year** (**88.3 mW**)

Two Different Areas in SR-Booster Tunnel

- Beam loss in 'Non-injection area'

  : SR distributed + Booster distributed

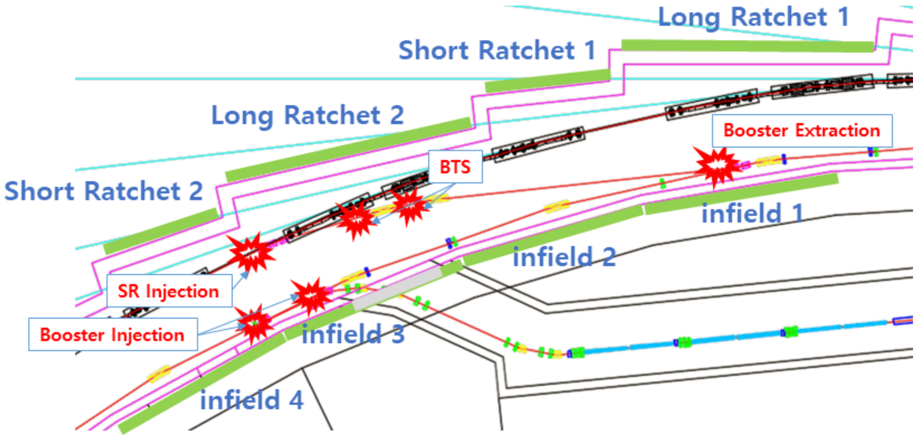
- Beam loss in 'Injection area'

  : SR distributed + Booster distributed

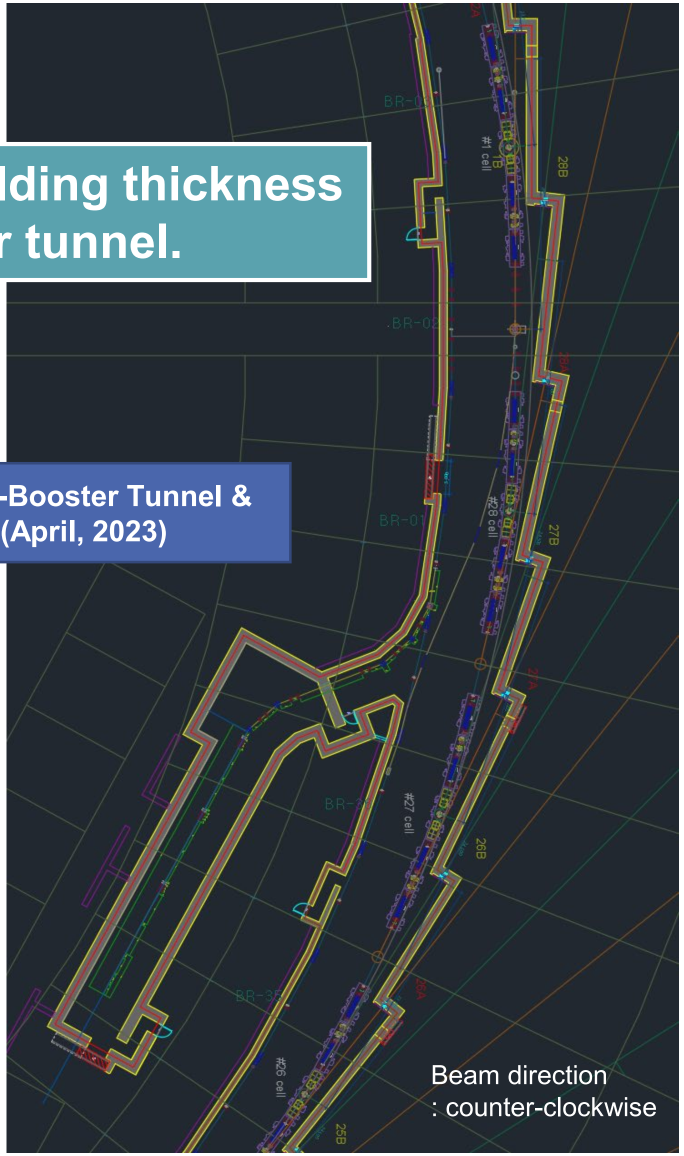
  + SR injection + BTS(Booster-to-SR) distributed

  + Booster extraction + Booster injection

We designed different shielding thickness for two areas in SR-booster tunnel.



Injection area in SR-Booster Tunnel (in CDR stage)



Injection area in SR-Booster Tunnel & Linac Tunnel (April, 2023)

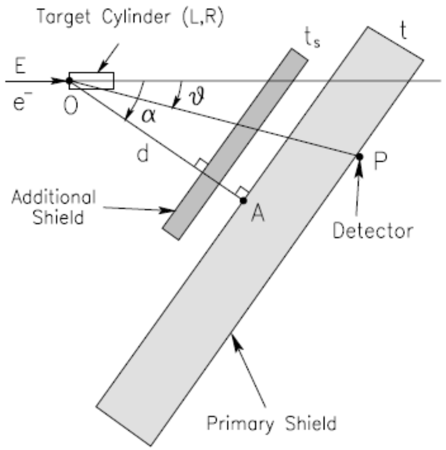
Method of Bulk Shielding: SHIELD11 code[1]

- Code for performing shielding analyses around a high-energy electron accelerator
- Developed by W.R. Nelson and T.M. Jenkins (Stanford Linear Accelerator Center)
- Simple **analytic expression** for production and attenuation of photons and neutrons resulting from electron striking thick targets

- Photon and neutron group into five components
  - **GRN** : Giant-Resonance Neutron, $0.1 < E_n < 20$ MeV
  - **MID** : Mid-Energy Neutron, $20 < E_n < 100$ MeV
  - **HEN** : High-Energy Neutron, $E_n > 100$ MeV
  - **GamD** : Direct Gamma, by EM shower
  - **GamI** : Indirect Gamma, 25% of HEN dose rate

[1] W.R. Nelson and T.M. Jenkins, “The SHIELD11 Computer Code”, SLAC-R-737, 2005

- Geometry



Available (built-in) material
1) Concrete (2.35 g/cm^3)
2) Fe (7.87 g/cm^3)
3) Pb (11.35 g/cm^3)

Steps for Bulk Shielding Design of SR-Booster Tunnel

- Three steps for bulk shielding design

1st step: Simplification of geometry to be **circular** by **SHIELD11**

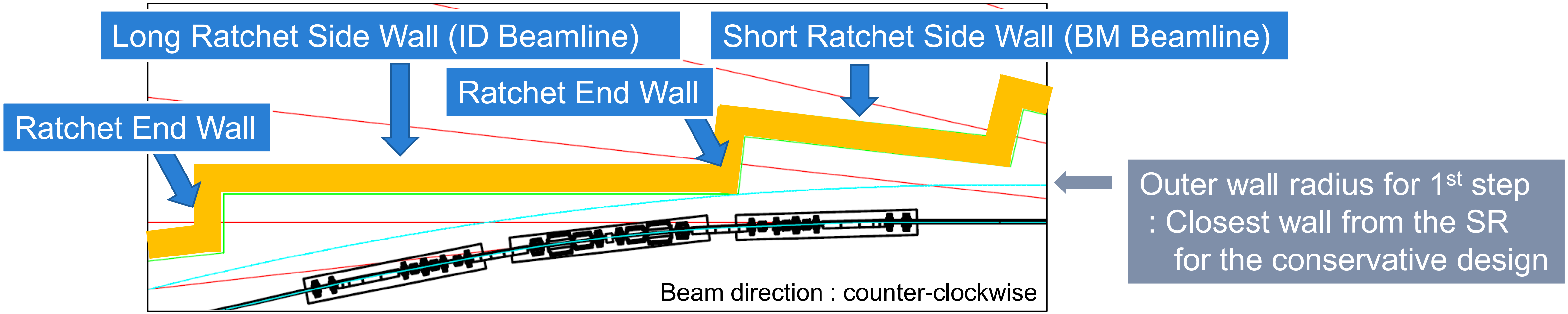
→ Estimation of **required shielding thickness**

2nd step: Consideration of **real ratchet structure** for the side wall & end wall by **SHIELD11**

→ Checking the possibility to **reduce the shielding thickness** for the **side wall** with local shield

→ Determination of the **sufficient shielding thickness** for the **end wall**

3rd step: Comparison and verification of SHIELD11 results by **FLUKA code (On-going)**



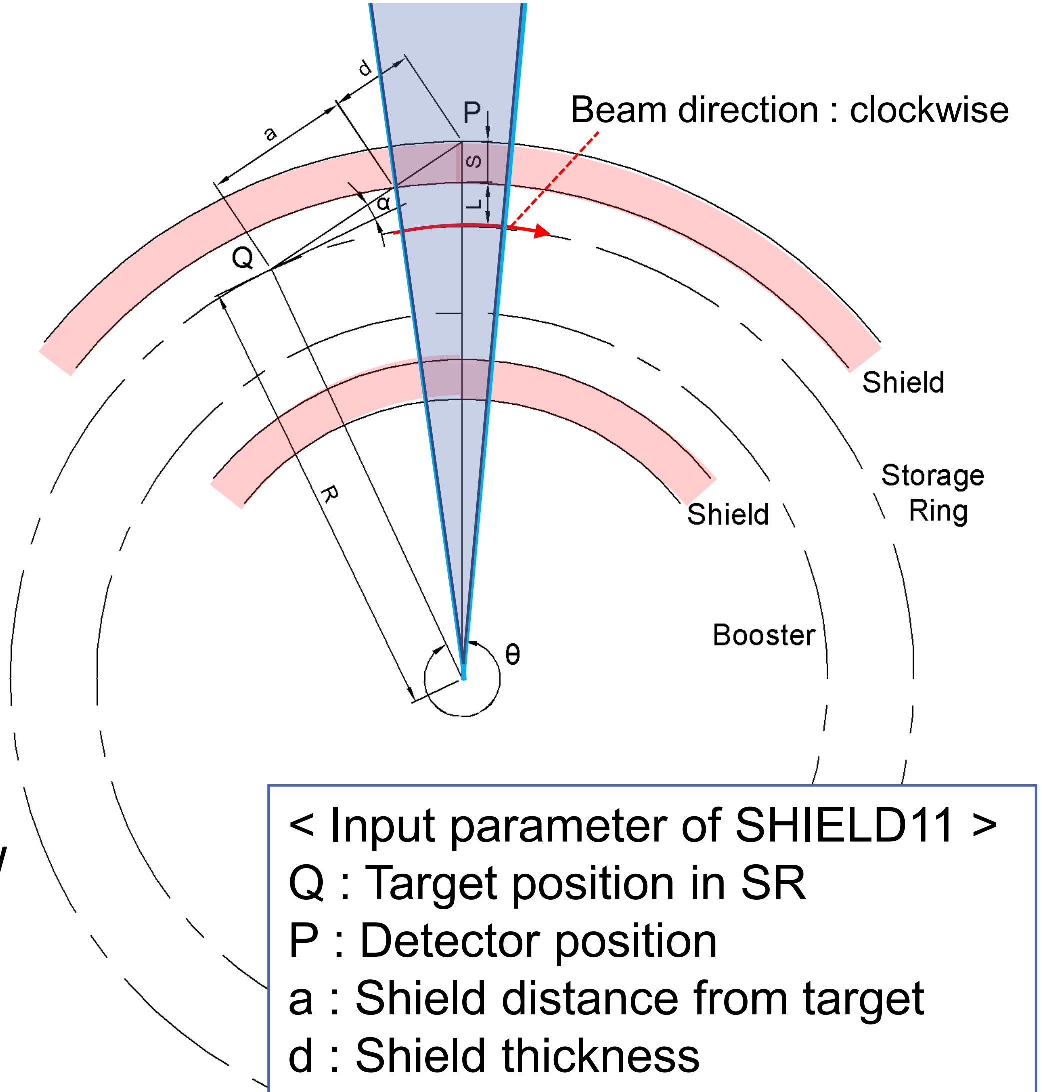
Bulk Shielding: 1st step

- Dimension for circular assumption (in CDR)
  - Radius of SR : 125.2 m
  - Radius of Booster : 120.5 m
  - Distance between SR to outer wall : 1.1 m (closest)
  - Distance between Booster to inner wall : 0.5 m
- Number of target : 3600 (Angle bin, $\Delta\theta$: 0.1°)
- Lost power in each target of SR : 381.1 / 3600 = 0.106 mW
  (per shift) Booster : 10.6 / 3600 = 0.003 mW
- Dose at detector position, P (behind tunnel wall)

$$\dot{H}_P = \sum_{\Delta\theta=1}^{3600} \dot{H}_{\Delta\theta,SR} + \sum_{\Delta\theta=1}^{3600} \dot{H}_{\Delta\theta,Booster}$$

But, effective angle to dose: < 10° (θ = 353° ~ 3°)

Effective target location to dose at position P

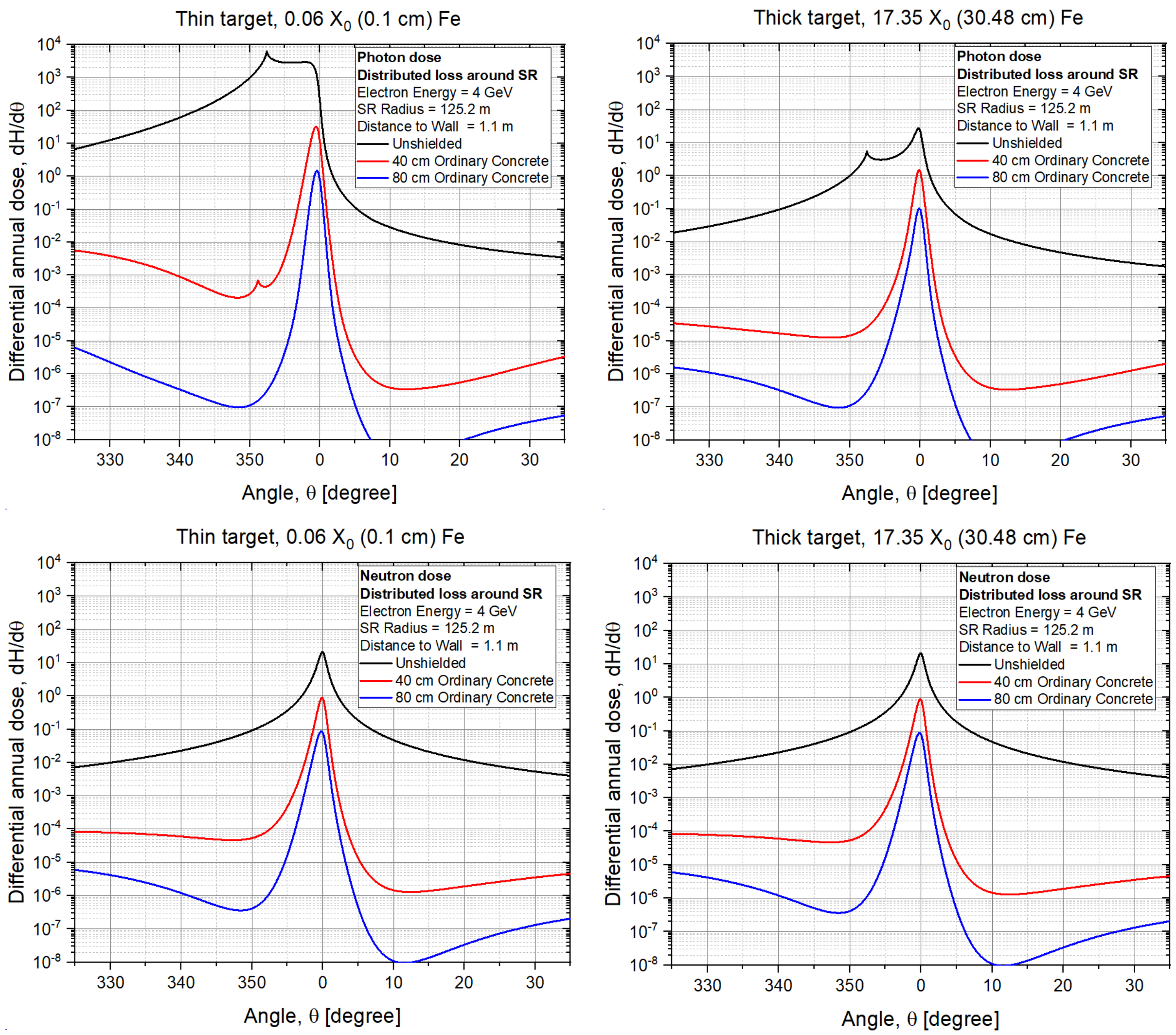


< Input parameter of SHIELD11 >
Q : Target position in SR
P : Detector position
a : Shield distance from target
d : Shield thickness
α : Angle of detector

Target Assumption for SHIELD11

Photon dose

Neutron dose



Thin target

Thick target

- Thin target vs. Thick target for outer wall
  - Photon dose decreases as the target thickness increases.
  - Neutron dose is similar.
  - As the concrete thickness increases, the dose contribution at the point closest to the target is highest.

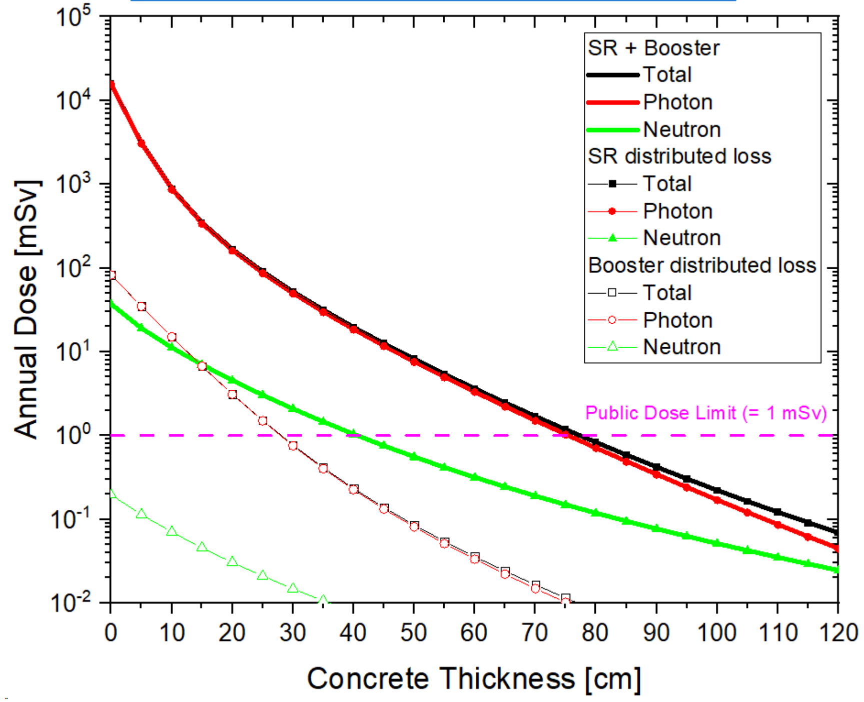
- Target assumption

  : From consideration of magnet dimension,

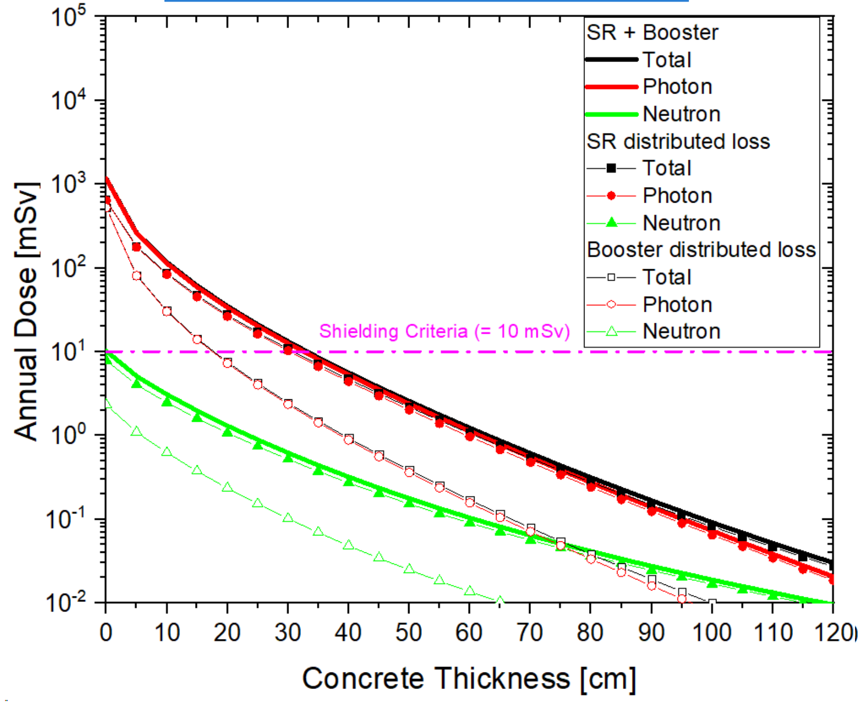
  → **3 cm** or **10 cm** thick **Iron**

Annual Dose Changes according to Wall Thickness

Outer sidewall to beamline



Inner sidewall to infield



- Photon dose is dominant to decide the thickness of tunnel wall.
- Even with inner wall that is closer to the booster, the dose caused by SR beam loss is greater.

  But, it could be changed if the different loss fraction in booster is applied.

  (With 20% distributed loss assumption in booster, dose by SR ≈ dose by booster)

Required Wall Thickness : by SHIELD 11, 1^{st} Step

Position	Concrete Wall Thickness [cm]	Annual Dose [mSv]		
		Sum (SR+Booster)	SR distributed	Booster distributed
Outer Sidewall	**80**	0.83	0.82	< 0.01
	85	0.59	0.58	< 0.01
Inner Sidewall	35	8.52	7.03	1.49
	40	5.60	4.68	0.92

Required thickness of sidewall
- 80 cm concrete for outer wall
- 40 cm concrete for inner wall
: considering the ambiguity of Booster distributed loss
(safe up to 20% loss assumption)

Bulk Shielding: by SHIELD11, 2nd step

- Consideration of 'Real Ratchet' structure
- **Number of target (electron loss position)** : 6

  P1 : Straight section to consider the end wall shielding caused the forward-peaking bremsstrahlung photon

  P2 ~ P6 : **After the quadrupole located downstream of dipole** (**based on the experience of PLS-II**)
- Lost power per shift in each target of SR : 381.1 / 28 / 6 = 2.26 mW

- Approach for sidewall

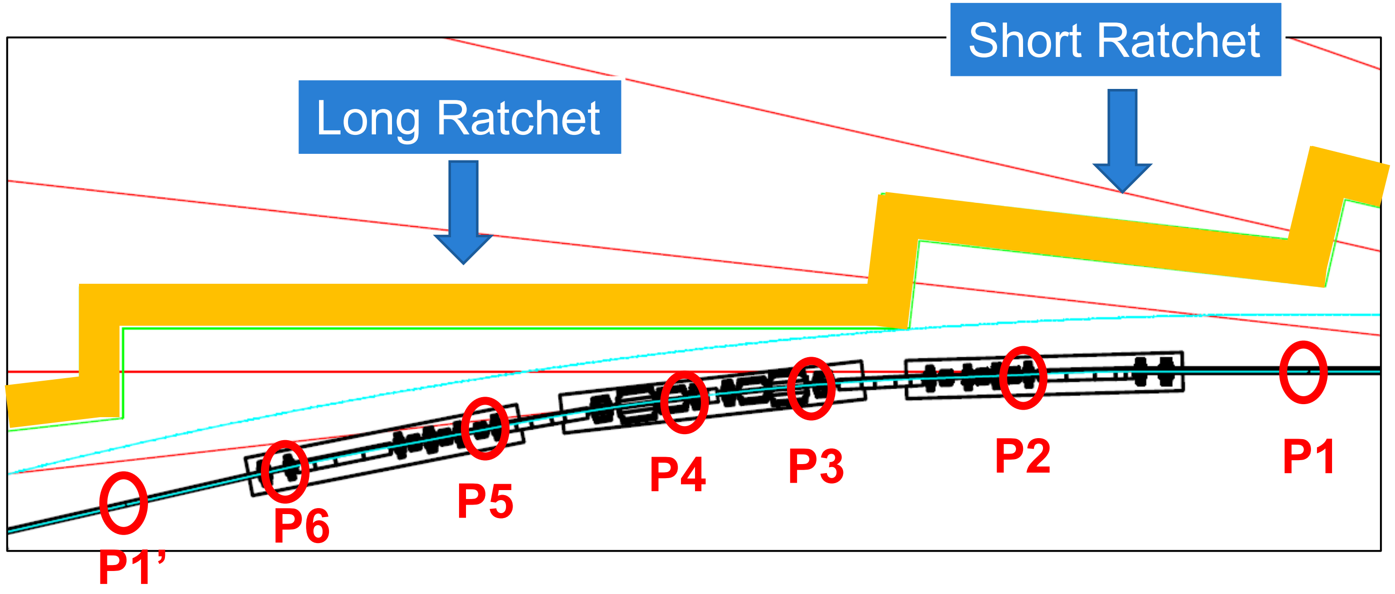
  : Reduction of outer sidewall thickness

  (80 cm → 70 cm) with local shield

  installation at closest wall

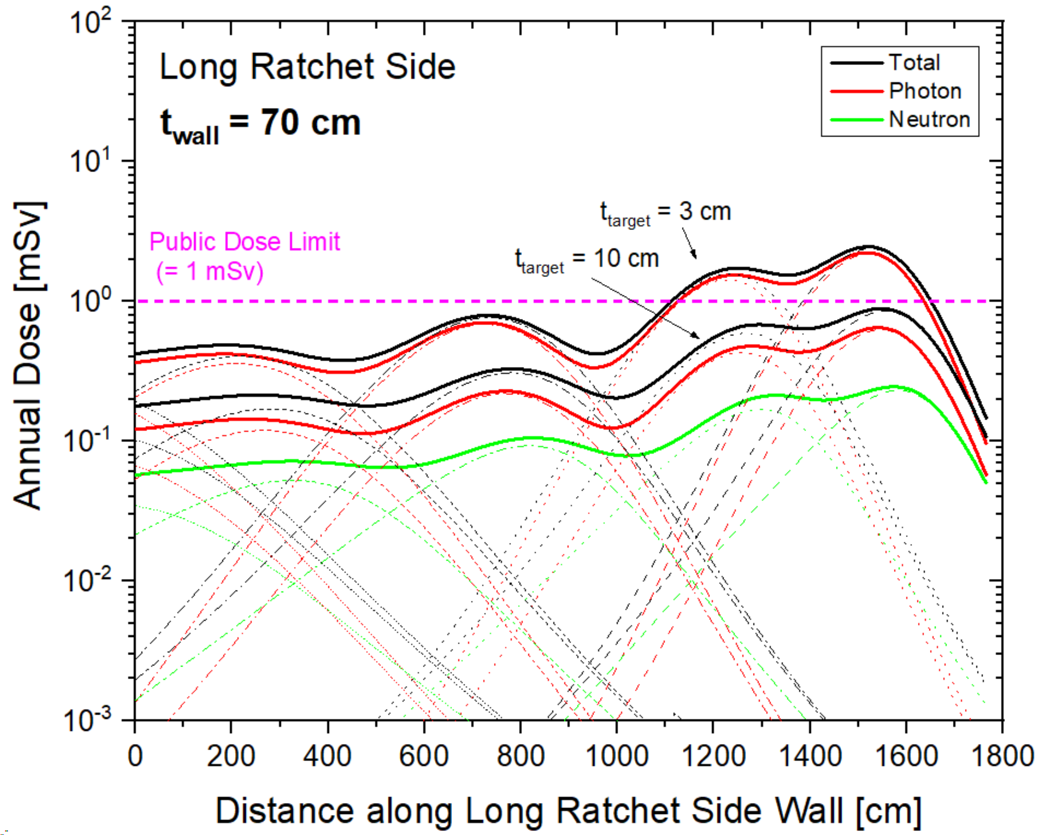
  → Size of local shield ?

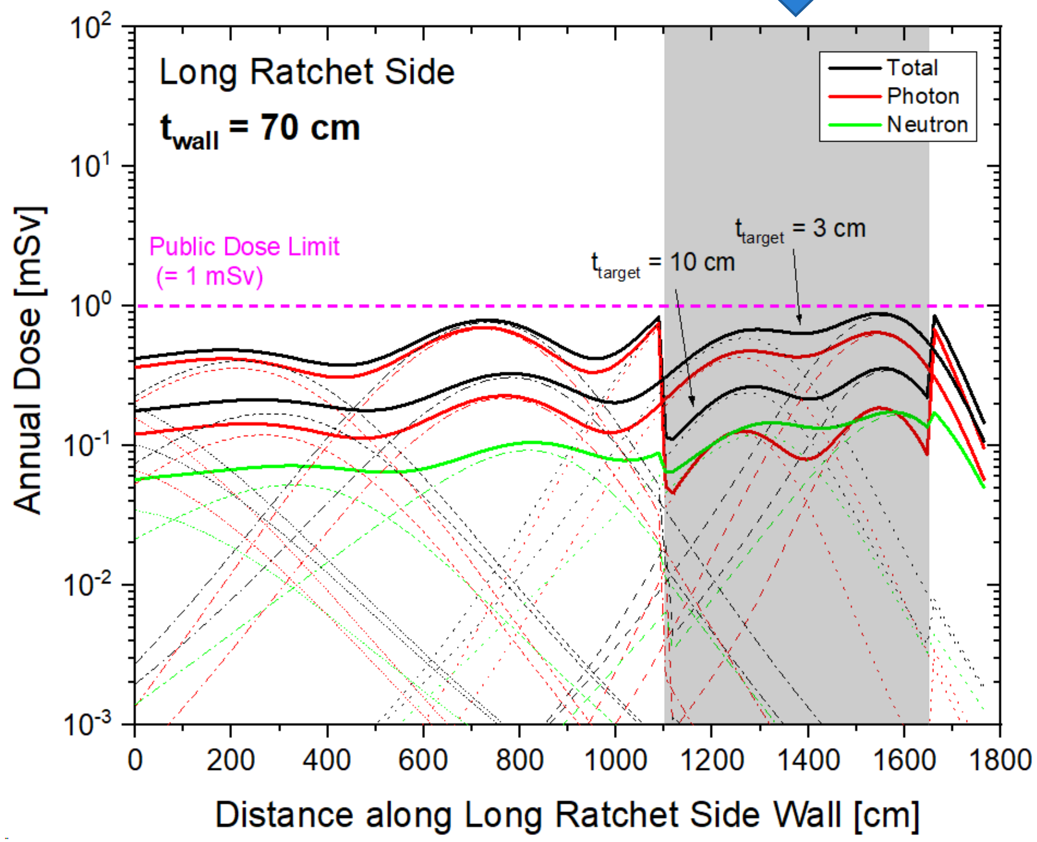
  (NOT accepted in TDR stage)

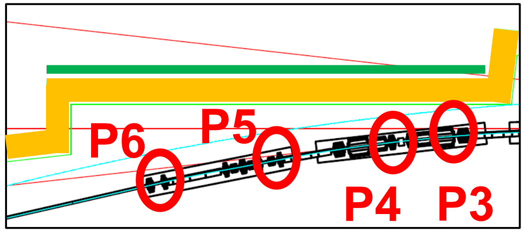


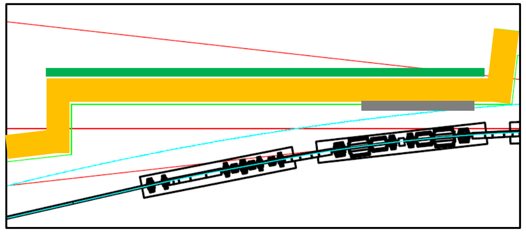
Example of SHIELD11 results, 2nd step

5 cm lead, 5.5 m local







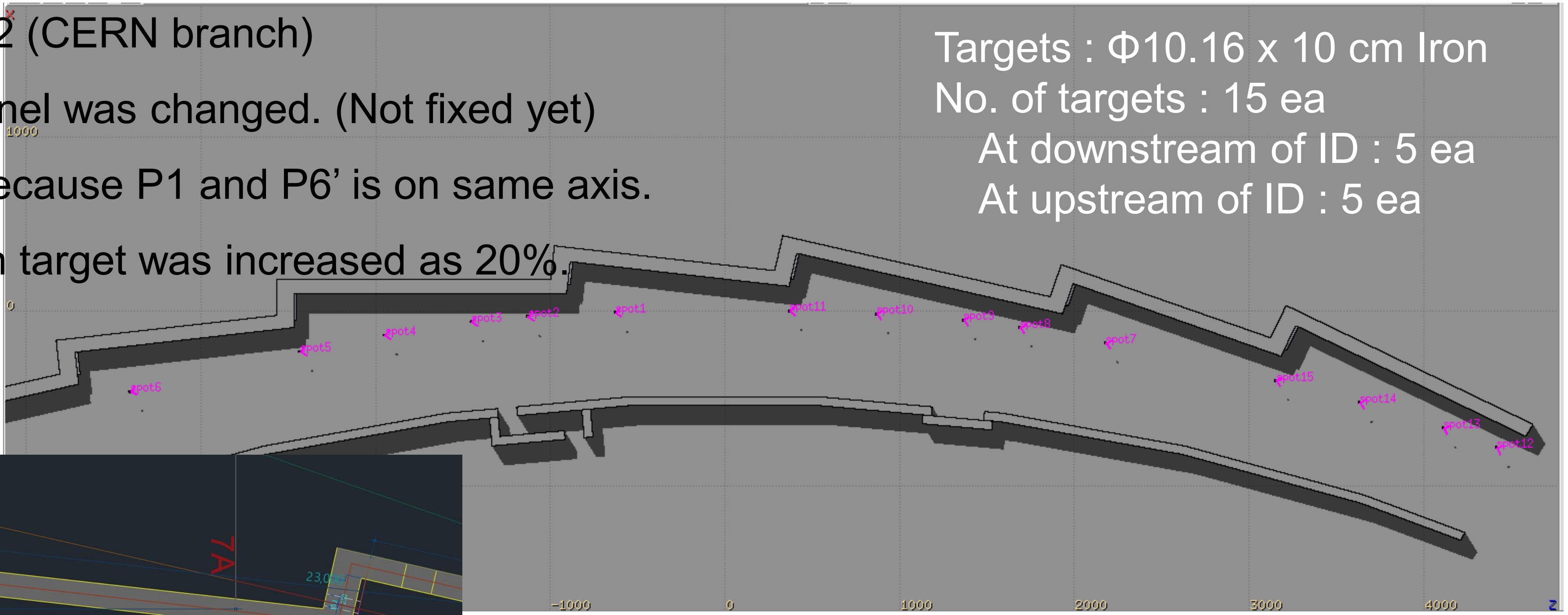


Bulk Shielding : FLUKA code

Preliminary result !

- Used version : FLUKA 4-3.2 (CERN branch)
- Layout of accelerator & tunnel was changed. (Not fixed yet)
- Target at P1 wasn't used because P1 and P6' is on same axis.
- Lost power per shift in each target was increased as 20%.

  : 2.26 mW → 2.72 mW

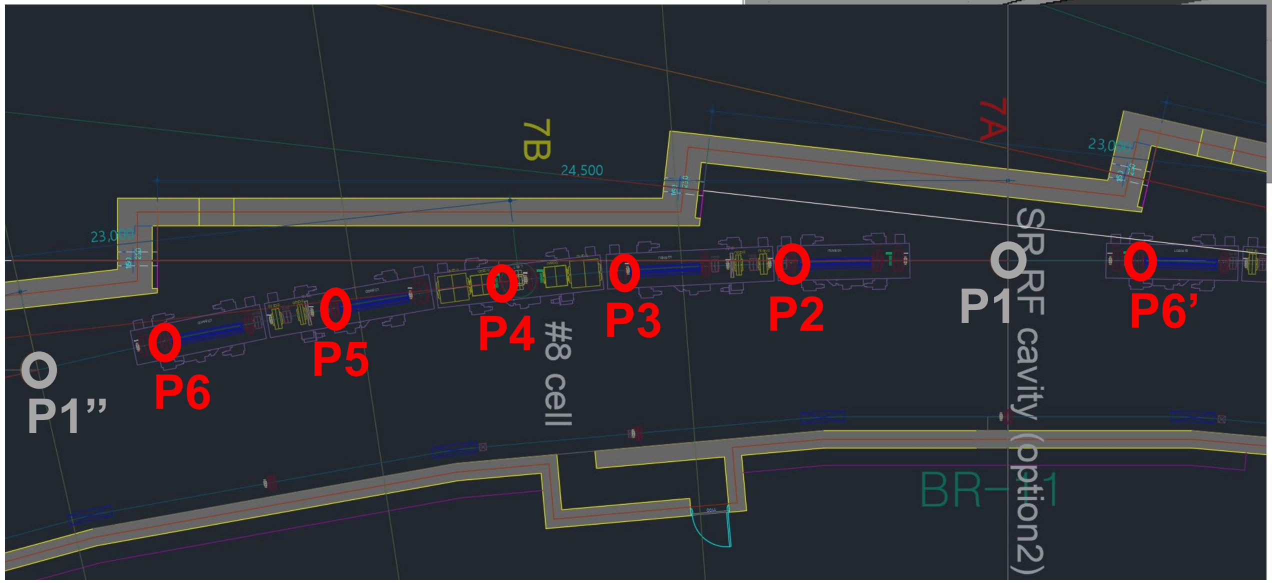


Targets : Φ10.16 x 10 cm Iron

No. of targets : 15 ea

At downstream of ID : 5 ea

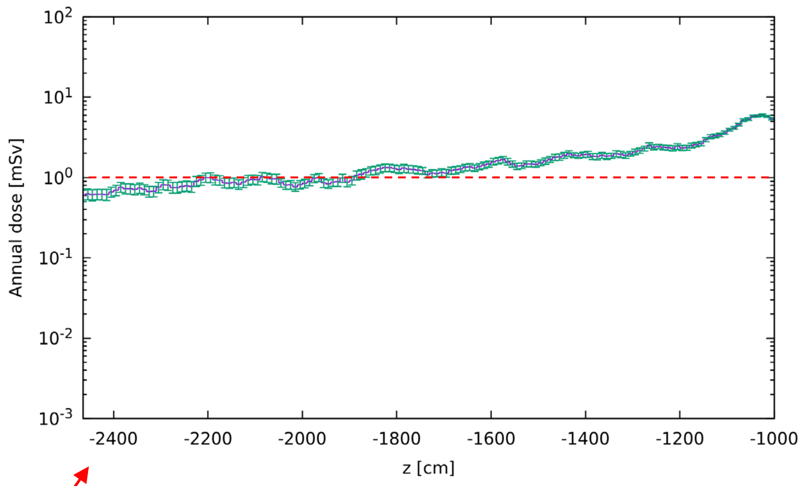
At upstream of ID : 5 ea

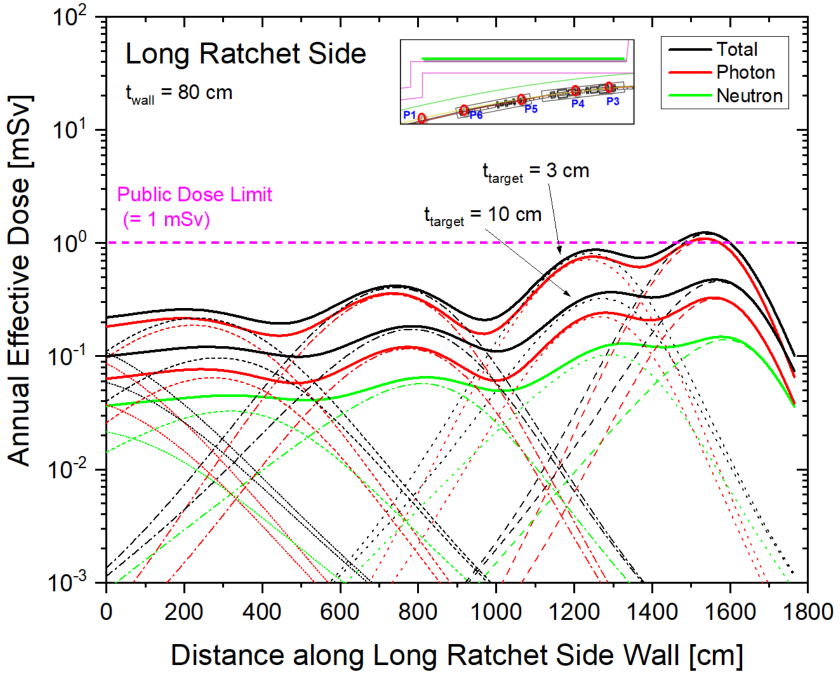


- Side Wall : 80 cm thick Ordinary Concrete (∵ SR-to-side wall distance was reduced.)
- End Wall : 100 cm thick Ordinary Concrete + 15 cm thick Lead
- Inner Wall to infield : 50 cm (∵ Booster-to-inner wall distance was reduced.)
- Roof : 50 cm

Bulk Shielding : FLUKA code

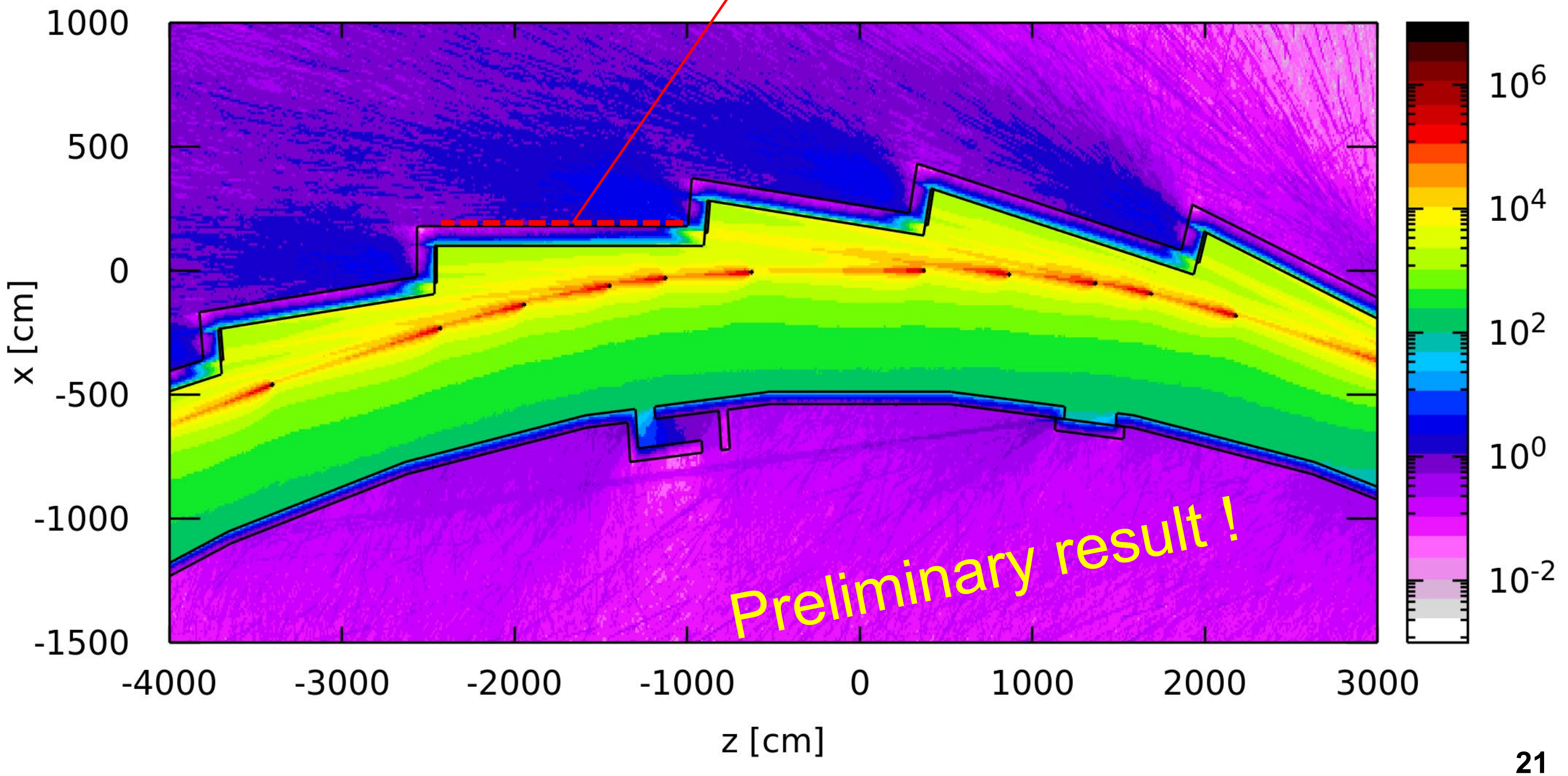
- Comparison with SHIELD11 results for 80 cm thick sidewall
  - Two results are similar, even beam loss point and geometries were not same.





SHIELD11 in CDR stage

Total DER [mSv/year]



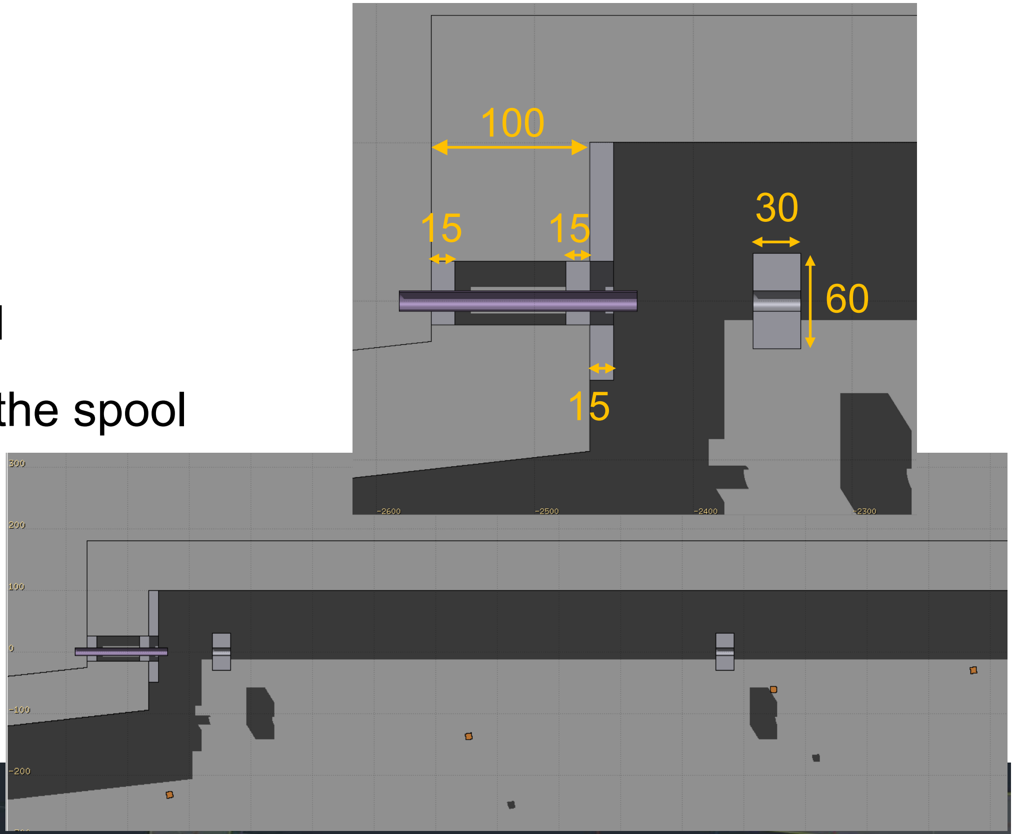
Bulk Shielding : FLUKA code

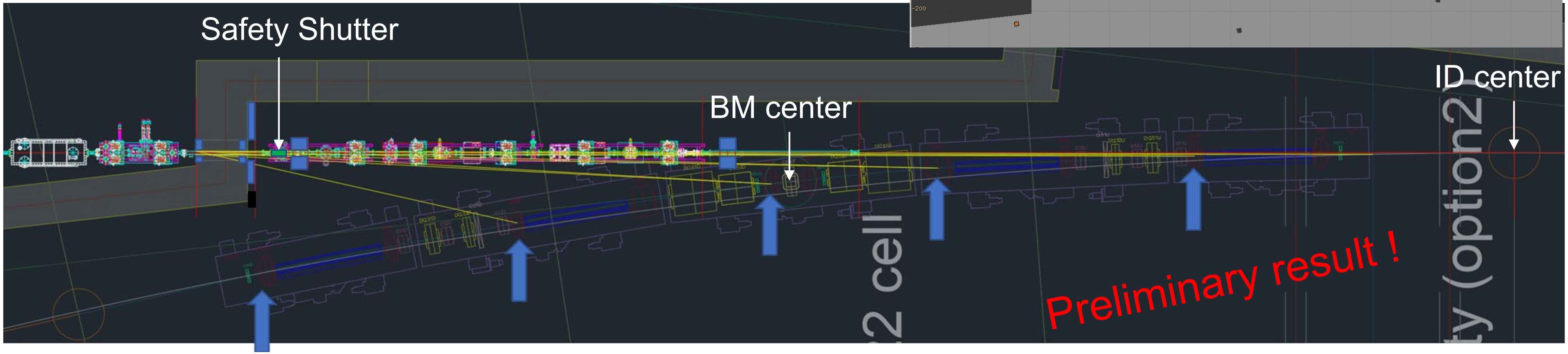
- Concept Design of End Wall & Lead Collimators in Front-end

  - End Wall : 30 cm-thick Lead, to replace 100 cm concrete at the spool

  - Collimators : 2 collimators, 30 cm-thick Lead

    1 as close as to SR, 1 in front of Safety Shutter





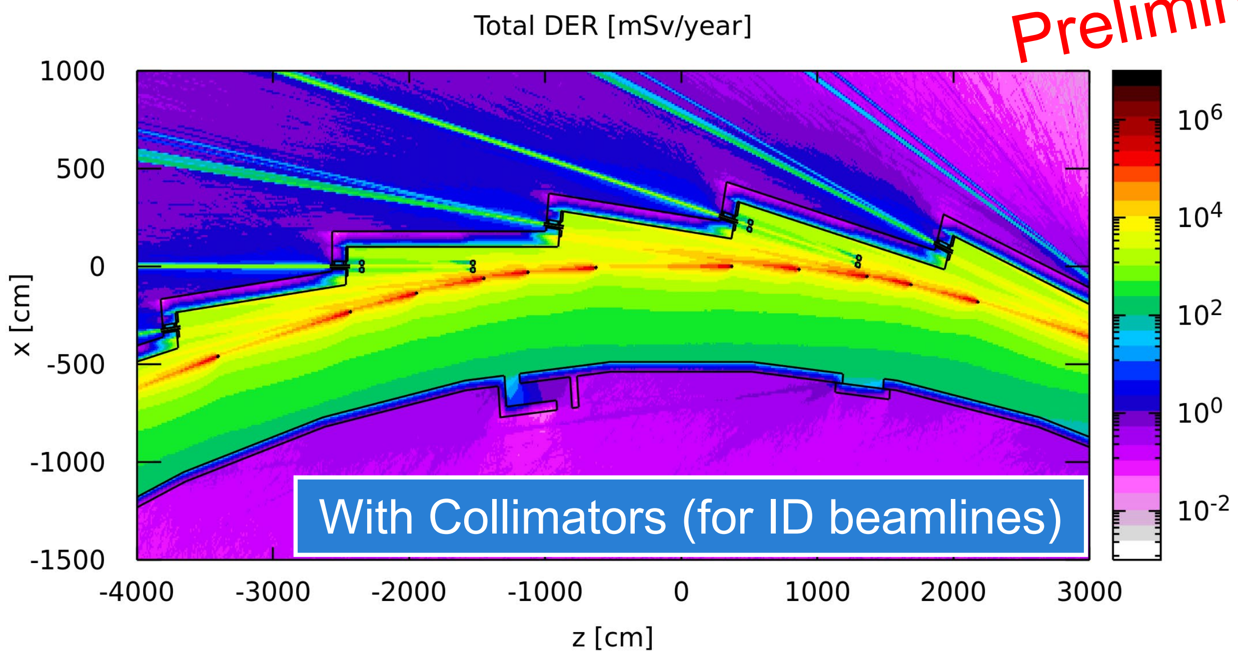
Bulk Shielding : FLUKA code

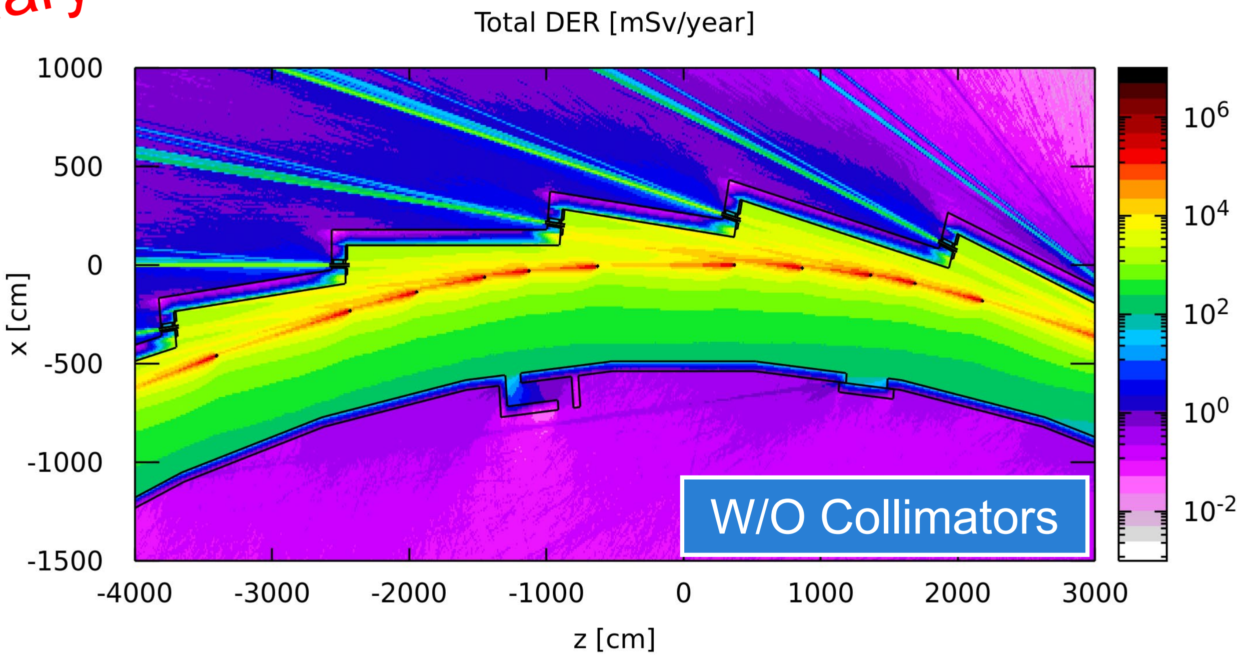
- Results for End Wall & Lead Collimators in Front-end

  - The position of collimators is sufficiently effective.

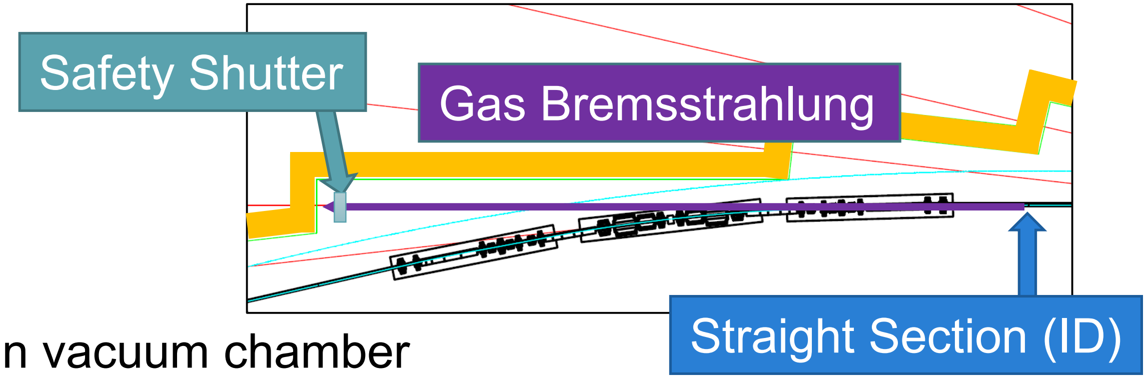
    → Collimator size and location will be determined in conjunction with beamline detailed design.

Preliminary result !





Thickness of Safety Shutter



- Need to consider the 'Gas Bremsstrahlung'

  - Produced by stored electrons interact with residual gas in vacuum chamber

  - These photons generated at insertion device (ID) position can be increased the dose at photon beamline

- Using the semi-empirical formula

$$\dot{H} = 1.7 \times 10^{-16} E^{2.43} \frac{p}{p_{atm}} IL \left(\frac{10 + L/2}{d} \right)^2$$ (Tromba's Eq. [1])

$$\dot{H} = 2.5 \times 10^{-27} \left(\frac{E}{0.511} \right)^{2.67} \frac{L}{d(L+d)} I \frac{p}{p_0}$$ (Ferrari's Eq. [2])

E : electron energy [MeV]

p/p_{atm}, p/p_0 : pressure ratio (p_{atm} : 760 Torr, p_0 : 10^{-9} Torr)

I : beam current [e^-/sec]

- Results : $\dot{H}$ < 0.5 μSv/h (= 1 mSv/yr)

	Straight (Undulator)	Bending (Dipole)
Length of air path, L [m]	8.1	2.9
Distance from dose point to air path, d [m]	25.3	24.9
Bremsstrahlung dose rate [Sv/h]	0.59 (Tromba's Eq.) 1.12 (Ferrari's Eq.)	0.15 (Tromba's Eq.) 0.49 (Ferrari's Eq.)
Dose behind 31 cm-thick Lead* [μSv/h]	0.48 (Ferrari's Eq.)	0.21 (Ferrari's Eq.)

* Tungsten 23 cm is the same shielding performance.

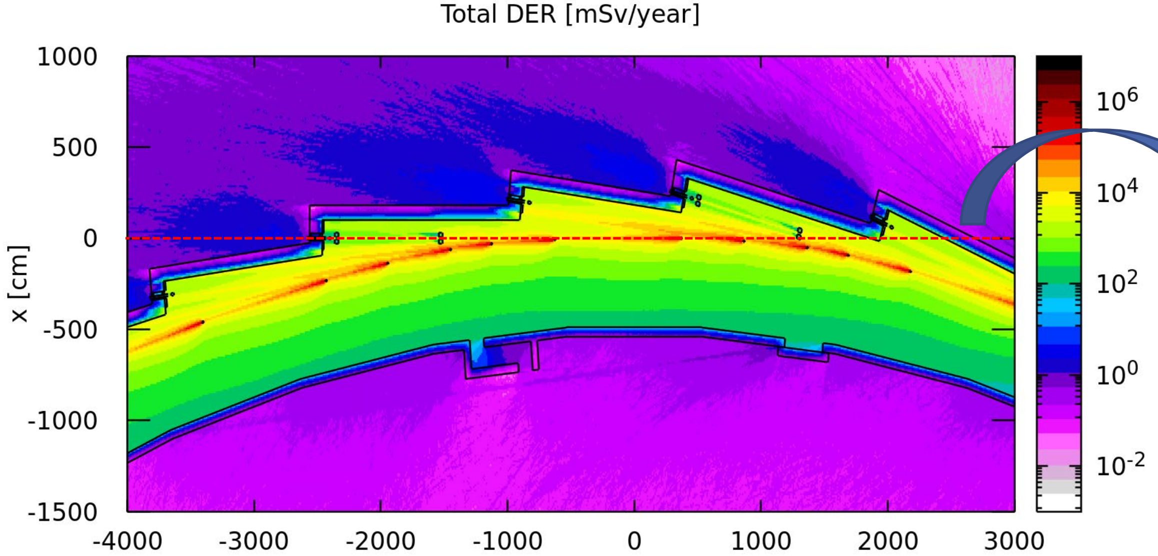
[1] G. Tromba and A. Rindi, Nucl. Instrum. Meth. A 292, 700 (1990)
[2] A. Ferrari et al., Nucl. Instrum. Meth. B 83, 518 (1993)

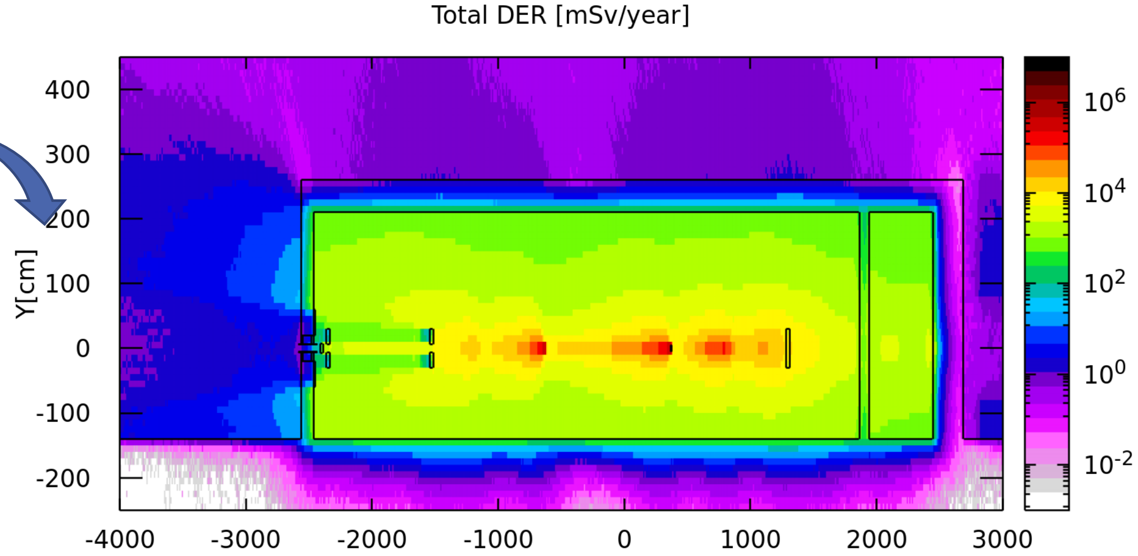
Bulk Shielding : FLUKA code

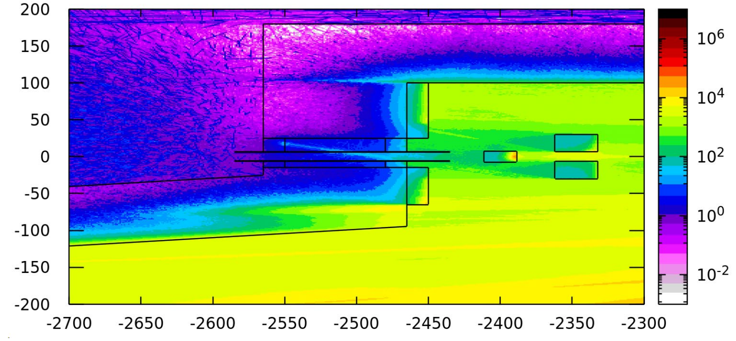
Preliminary result !

- Safety Shutter : Tungsten 23 cm is effective to block the forward-peaking bremsstrahlung photons

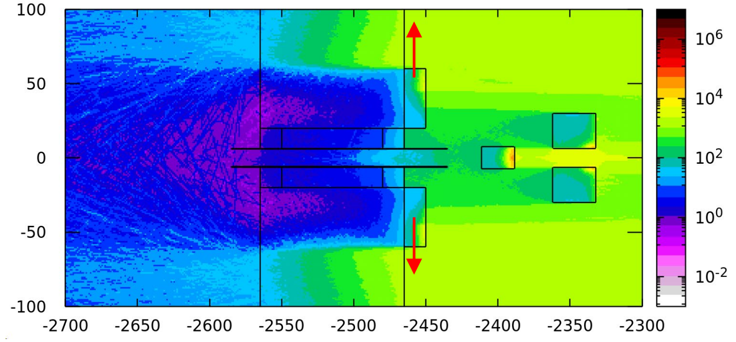
(GB evaluation by FLUKA will be performed later.)







Plan view



Vertical view

Up-down direction of front Pb : need to be extended

Summary of Bulk Shielding for SR-Booster Tunnel

(March, 2023)

Wall Components	Non-injection Area	Injection Area
Side Wall	80 cm Concrete	100 cm Concrete
End Wall	100 cm Concrete + 15 cm Lead	110 cm Concrete + 15 cm Lead
Inner Wall to Infield	50 cm Concrete	70 cm Concrete
Roof	50 cm Concrete	70 cm Concrete

- FLUKA calculation is on-going.

- FLUKA calculation is ready to start.

Summary

- The **required bulk shielding thickness of a 4GSR in KOREA** was evaluated by **SHIELD11 & FLUKA code**.
- The **radiation control policy** in accordance with Korean regulations and the **beam loss scenario** were **established**.; **High injection efficiency, 90%**, was assumed reflecting recent trends.
- The **SHIELD11 and FLUKA results showed good agreement** for bulk shielding evaluation
- The **final tunnel design** may changed slightly since accelerator design is in progress, but the **established design approach will continue to be used** in the future.

Thank you for your attention !!

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