Argonne NATIONAL LABORATORY

Radiation Shielding of Beamlines of APS-U

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APS-U, ESH-RPP

Radsynch, ESRF 30 May-2 June 2023

APS-U

Number of sectors: 40

Beam Energy: 6 GeV

Beam Current: 200 mA

Max. single bunch current: > 4.2 mA

Circumference: 1103.608 meters

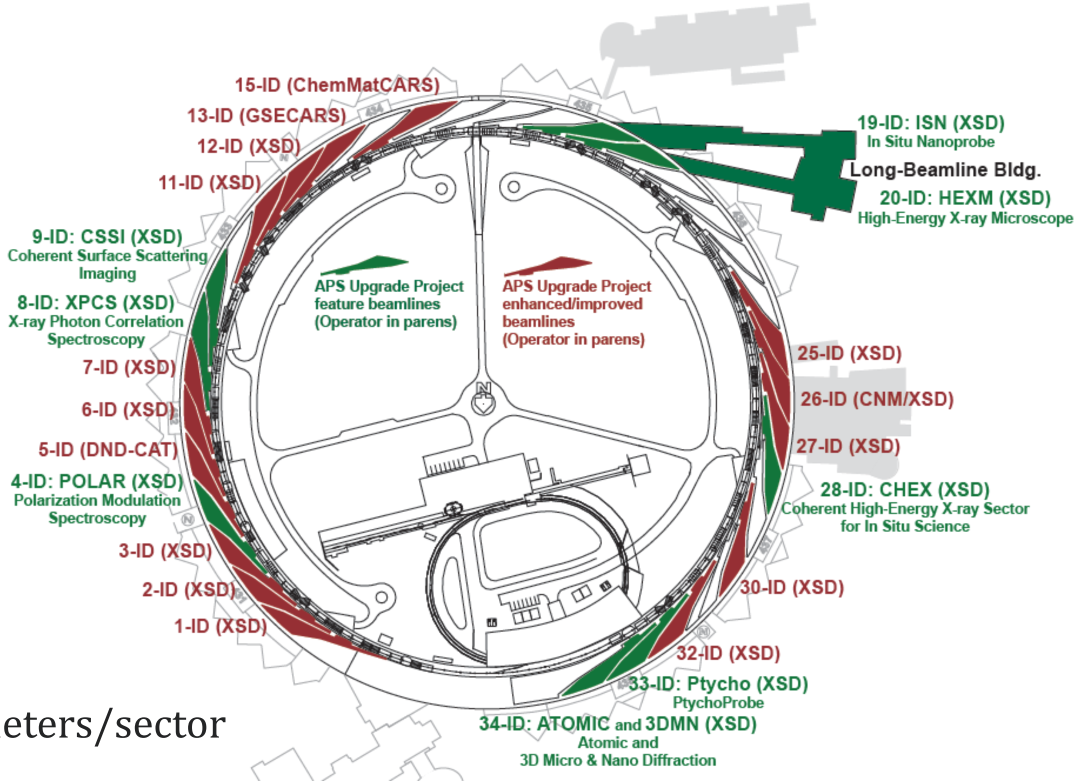
Main RF frequency: 352.055 MHz

Minimum bunch spacing: 11.36 ns

48 to 324 uniformly-spaced bunches

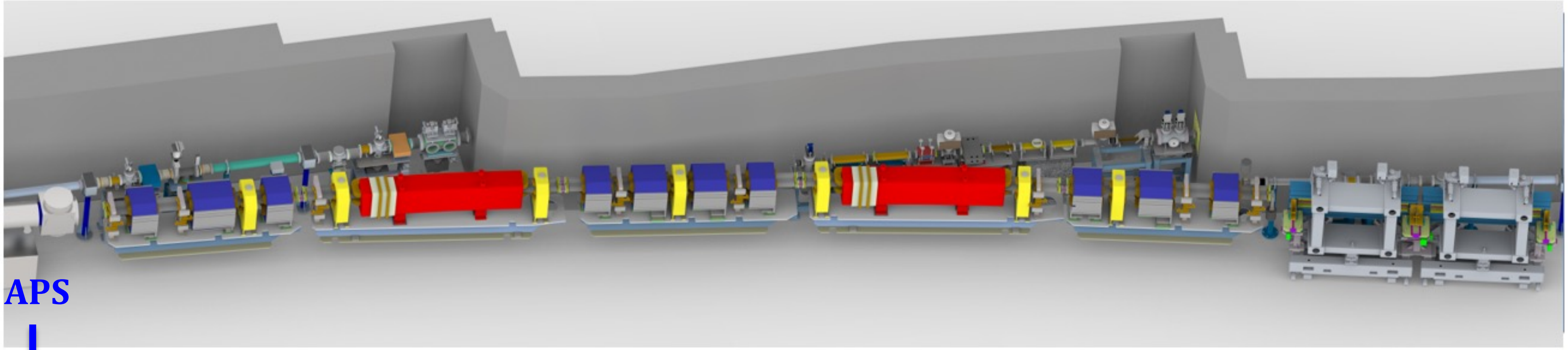
Space available for ID hardware: 5.4 meters/sector

Horizontal on-axis swap-out injection

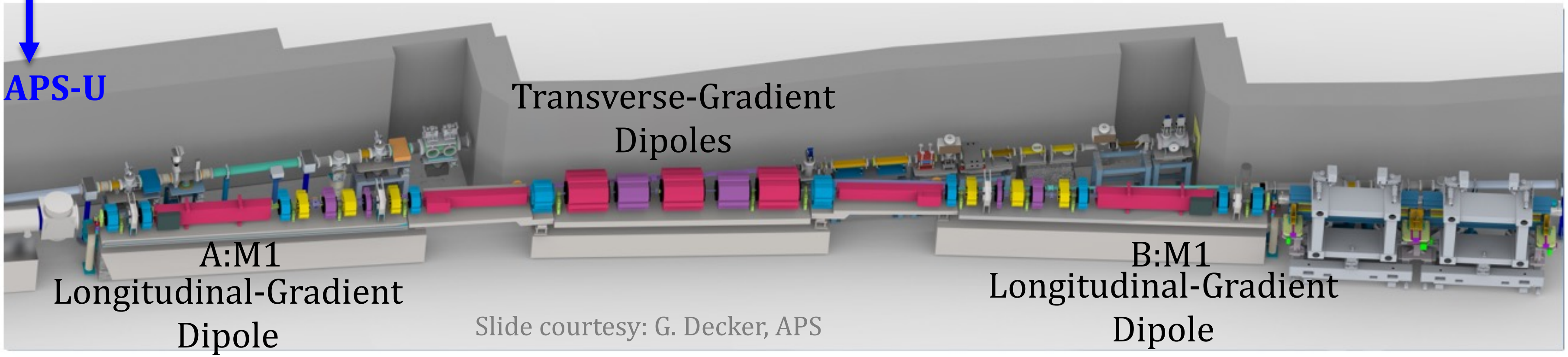


8 new beamlines, 15 enhanced beamlines

APS to APS-U

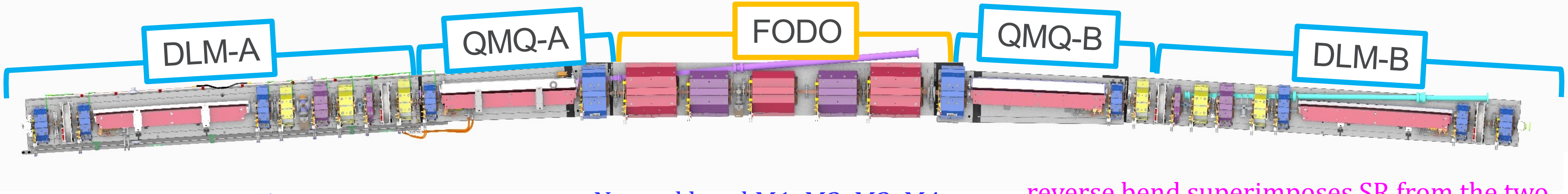


7 GeV, 100 mA, 3100 pm-rad → 6 GeV, 200 mA, 32 - 42 pm-rad



APS-U storage ring lattice

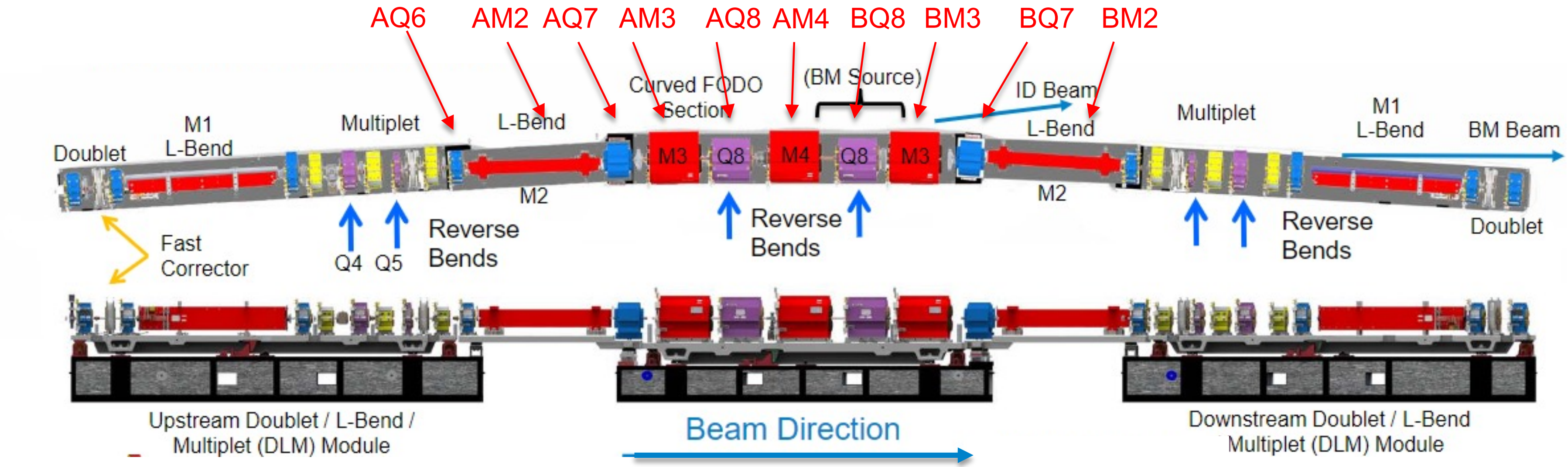
Each sector contains 33 arc magnets; 27.6 meters/sector



Focusing Q1, Q4, Q5, Q7, Q8, S2
Defocusing Q2, Q3, Q6, M3, M4, S1, S3

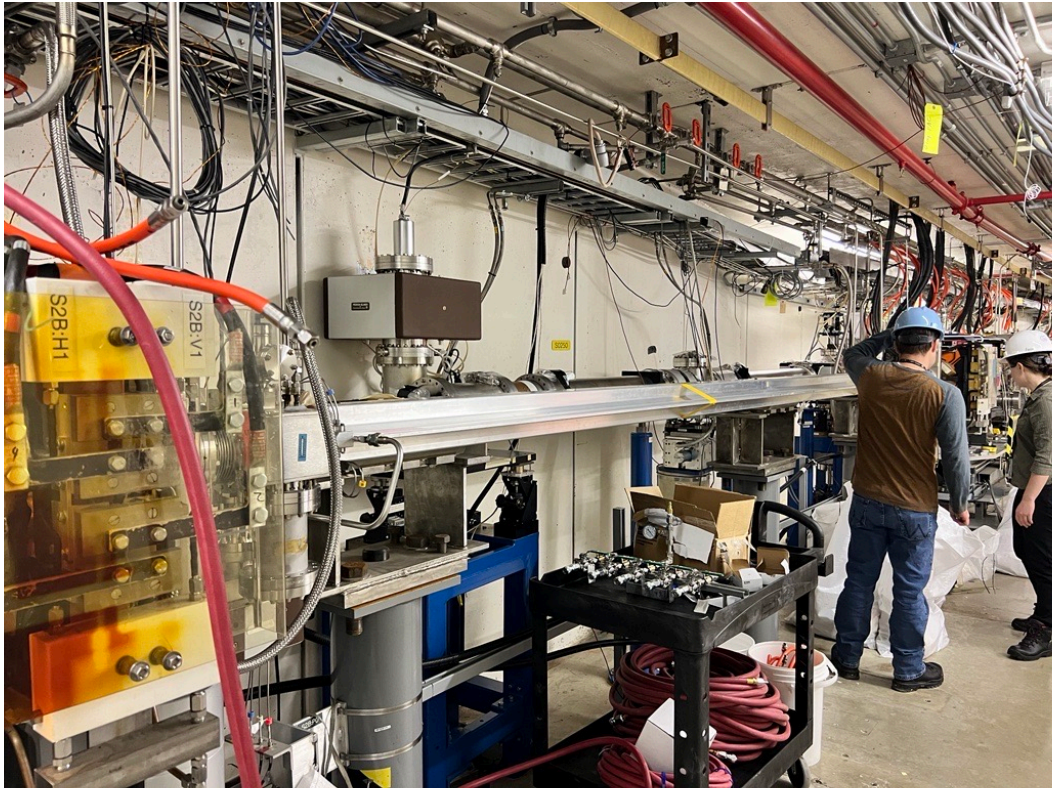
Normal bend M1, M2, M3, M4
Reverse bend Q4, Q5, Q8

reverse bend superimposes SR from the two dipoles (M4 and M3) and the Q8 (weak dipole)



Slide courtesy, Glenn Decker and Jason Carter

Tunnel is empty!



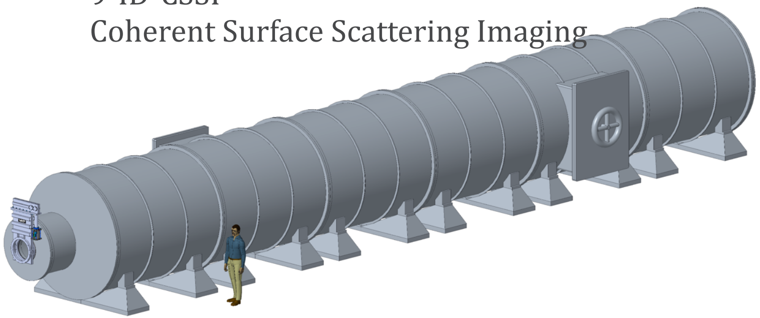
As of April 24, APS has entered the dark time

Shielding philosophy of APS

- Ensure shielding of all enclosures are adequate with the strongest source for worst case scenarios
- Identify an ID that can serve as the bounding source
  - Superconducting and planar undulators in APS-U
- Make exceptions for special beamlines
  - 9-ID-CSSI, 19-ID-ISN
- Monochromatic beam enclosures are assumed to be pink beam enclosures
- Assume 0.1% BW for monochromatic beams
  - Overly conservative use for higher harmonics
- Target dose: 0.5 mrem/h [10CFR835]

Difficult to augment the shielding of the enclosures.

9-ID-CSSI
Coherent Surface Scattering Imaging



19-ID-ISN In Situ Nanoprobe in the long beamline building

Synchrotron radiation shielding

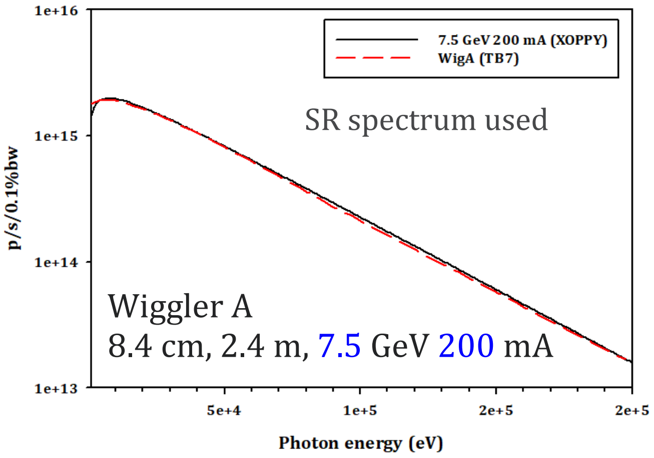
APS shielding and assumptions used

Station Type	Upstream	Lateral	Roof	Downstream
ID White	19	19	12	50 (100 locally)
BM White	8	8	6	9 (24 locally)
ID Pink	10	10	6	12
BM Pink	6	6	4	7

All dimensions in mm

Station type	Beam transport scenarios			Shutter/stops	
	Air (SR)	Solid (SR)	Solid (GB)	W	Pb
ID White	12	21	45	180	300
BM White	6	11	12	180	300
ID Pink	8	12	-	60	
BM Pink	5	7	-	21	

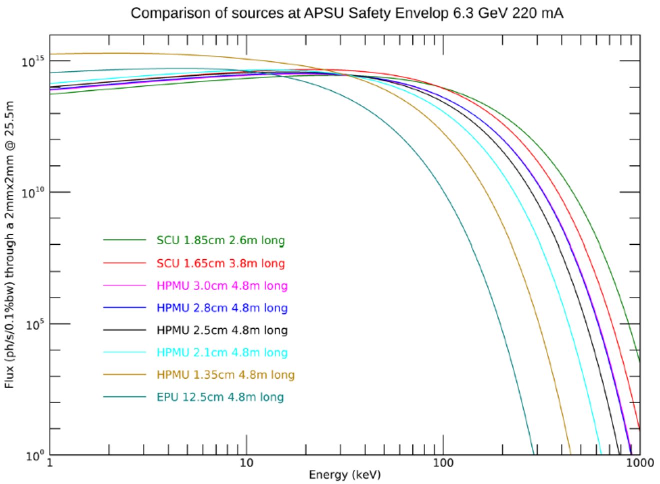
- PHOTON for SR shielding
- XOP for source term for a wiggler
  - Artificially increased by 10x
  - 0.1% BW for DCM beams
- EGS for GB shielding
  - 15 m (ID), 23 cm (BM), 1nT pressure
  - 7 GeV, 300 mA

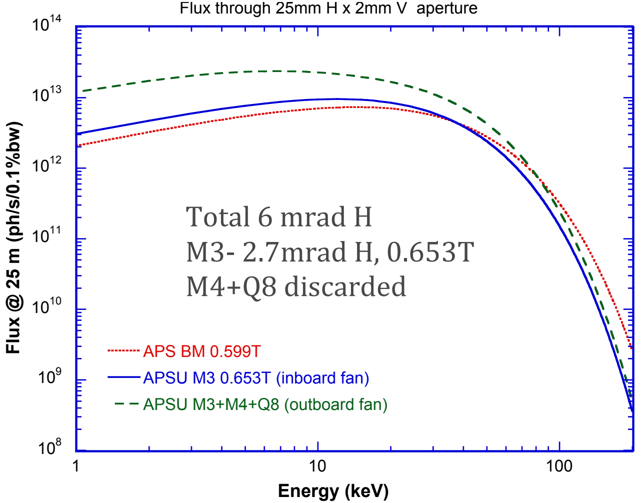


Sources of SR in APS-U

APS-U safety envelope for SR shielding 6.3 GeV 220 mA

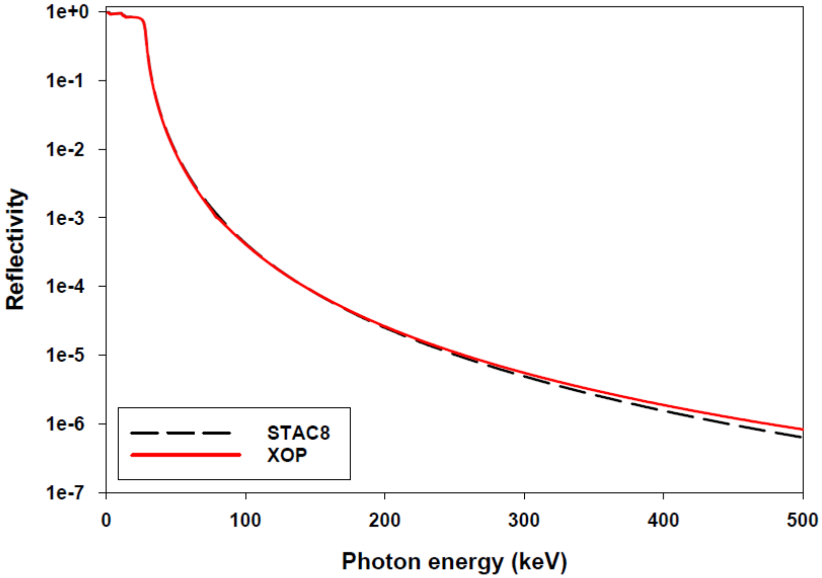
Period (cm)	K_{eff}	B_{eff} (T)	N	Ec (keV)	
1.35	0.389	0.309	350	8.2	
1.40	0.436	0.333	338	8.8	
2.10	1.309	0.667	224	17.6	
2.30	1.610	0.749	206	19.8	
2.50	1.914	0.820	188	21.6	
2.70	2.282	0.905	174	23.9	
2.80	2.459	0.940	168	24.8	
3.00	2.664	0.951	158	25.1	U2.8
3.30	2.891	0.938	144	24.8	U3.0
1.65	1.697	1.101	230	29.1	SCU165
1.85	2.342	1.356	140	35.8	SCU185
12.50	5.266	0.451	36	11.9	
12.50	3.865	0.331	36	8.7	





Shielding methodology for APS-U

- White beam from XOP using Wiggler approximation (for ID)
  - Agrees well with STAC8 source spectrum
- All solid scattering calculations carried out by STAC8
  - Air scattering calculations using FLUKA/PHITS
- $4k/\gamma$ x $1/\gamma$ and 2 mm x 2mm at 25 m apertures for ID
- 2.7 mradH fan for BM
- Pink beam from Pt coated mirror at 1 mradian
  - Nominal angles would be 2-3 mradian
- Reflectivity is calculated by STAC8
  - Matches very well with XOP data
- Mirror roughness is ignored
- Polarization is ignored
- Effective dose is estimated using STAC8, FLUKA and PHITS
  - XOP white beam, STAC8 pink beam as inputs for FLUKA, PHITS
- All GB calculations using FLUKA



Monochromatic beam DCM

- Monochromatic beam extracted from white beam
- BW of fundamental energy can be as high as 0.1%
  - enhanced BW expected from crystals that are asymmetric, imperfect, strained or bent Laue
- Bandwidths (BW) from XOP calculations
  - Both crystals are assumed to be cryogenically cooled
  - Lower the crystal temperature, higher is the Debye-Waller factor and wider is the bandwidth
- Can be calculated by*

$$\frac{\Delta E}{E} = \left(\frac{\lambda}{\sin\theta}\right)^2 \frac{r_e C F_H e^{-m}}{\pi V}$$

- λ is the wavelength of the photon, θ is the angle of scattering, r_e is classical electron radius, C is the polarization factor (assumed to be 1.0 here), F_H is the crystal structure factor taken to be $4f$, where f is the mean atomic scattering factor as tabulated in the International table for crystallography, e^{-m} is the temperature factor and V is unit cell volume of a Si crystal taken as 160.1 Å^3.

* X-Ray monochromators, T. Matsushita and H. Hashizume, Handbook on synchrotron radiation, North Holland Pub. Co (1983)

Reflection	ΔE/E (eq)	ΔE/E (XOP)	dE/E
Si(111)	1.17E-04	1.37E-04	**1.00E-03**
Si(333)	7.75E-06	8.54E-06	**1.11E-04**
Si(444)	4.66E-06	5.22E-06	**6.25E-05**
Si(555)	3.00E-06	1.63E-06	**4.00E-05**
Si(777)	3.74E-07	4.50E-07	**2.04E-05**

dE/E is used as DCM BW for shielding
- **8-55 times higher than the ΔE/E**

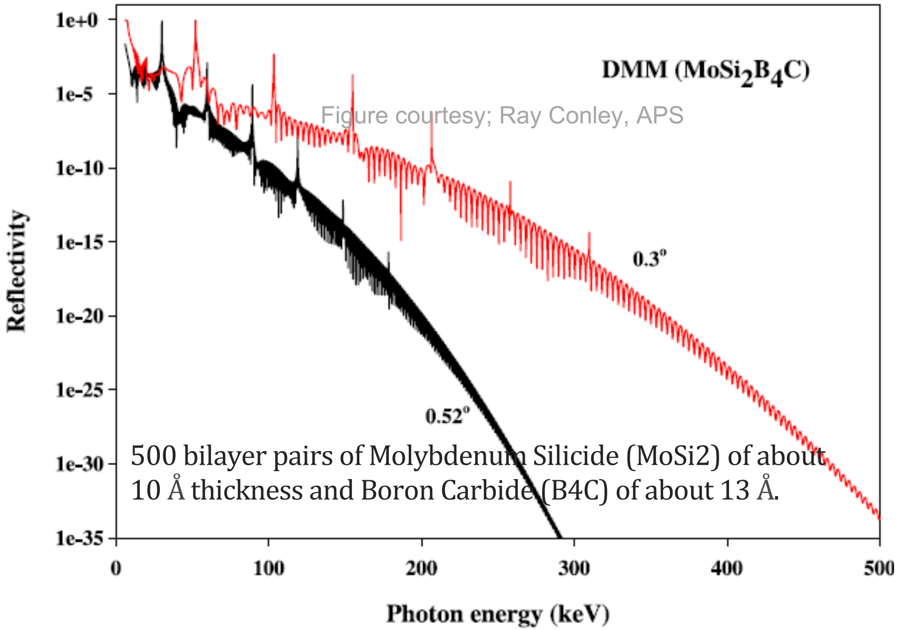
Fundamental energy set at 0.1%

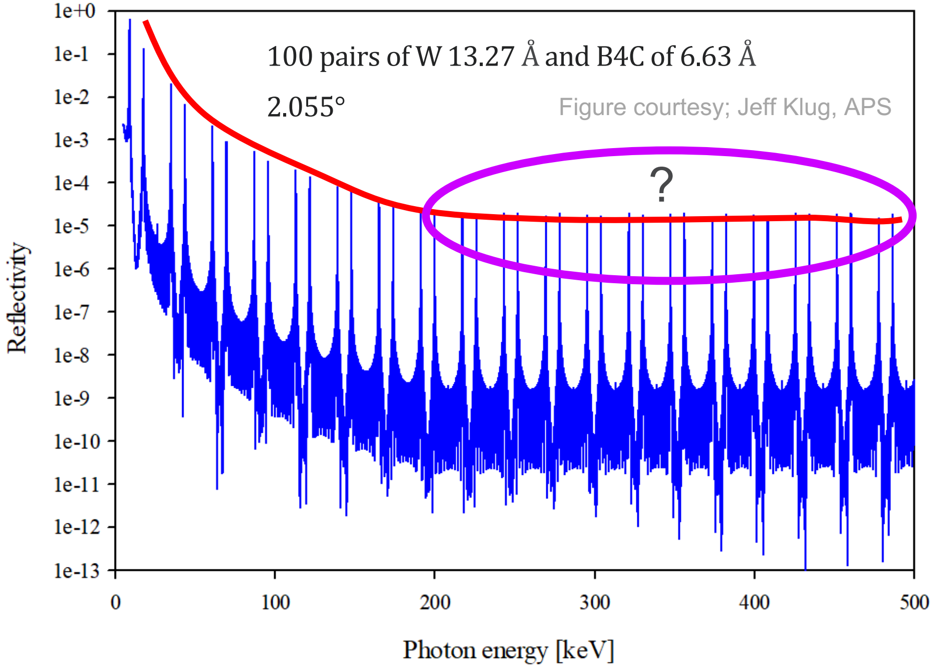
BW of higher harmonics scaled as $\left(\frac{\lambda}{\sin\theta}\right)^2$

XOP data; courtesy; L. Berman (NSLS-II)
dE/E data: Courtesy, D. Haeffner, APS

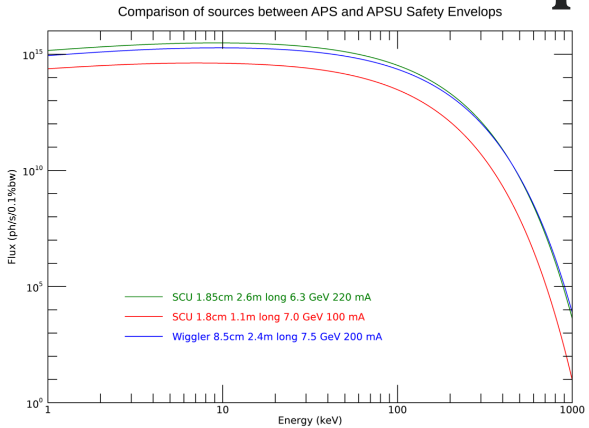
Double Multilayer Monochromator in APS-U

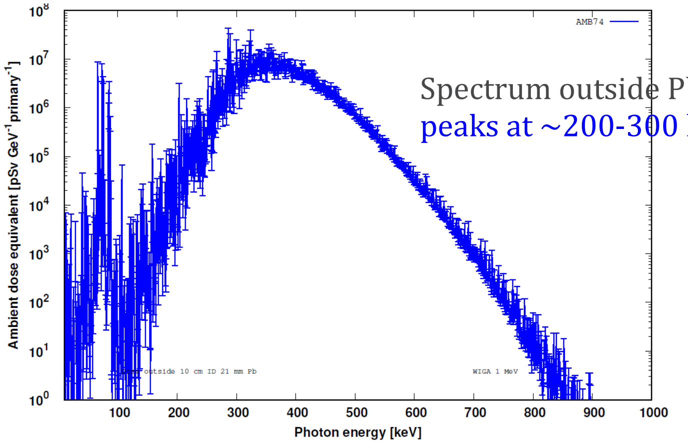
- APS-U will use Double Multilayer Monochromators in a few beamlines
- Reflectivity can be very high for higher energies
- No straightforward way to find the worst case
- Calculations are done on a case-by-case basis



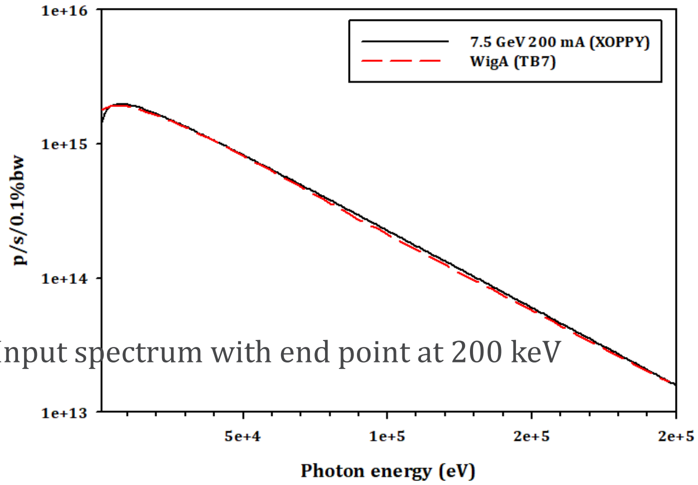


Effect of source end point

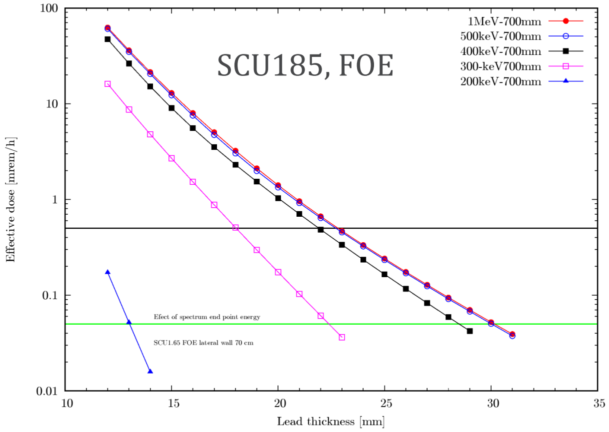




Spectrum outside Pb shield
peaks at ~200-300 keV

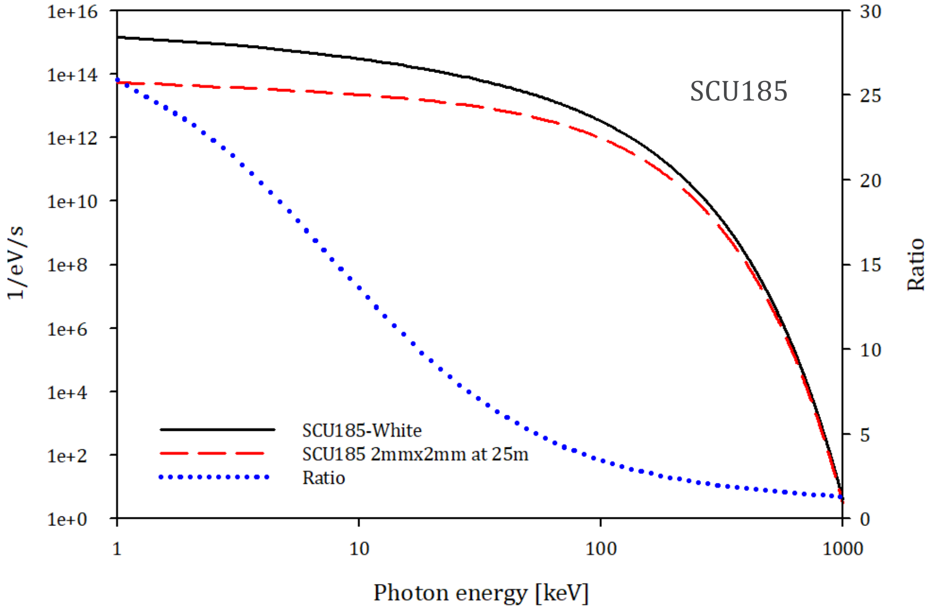


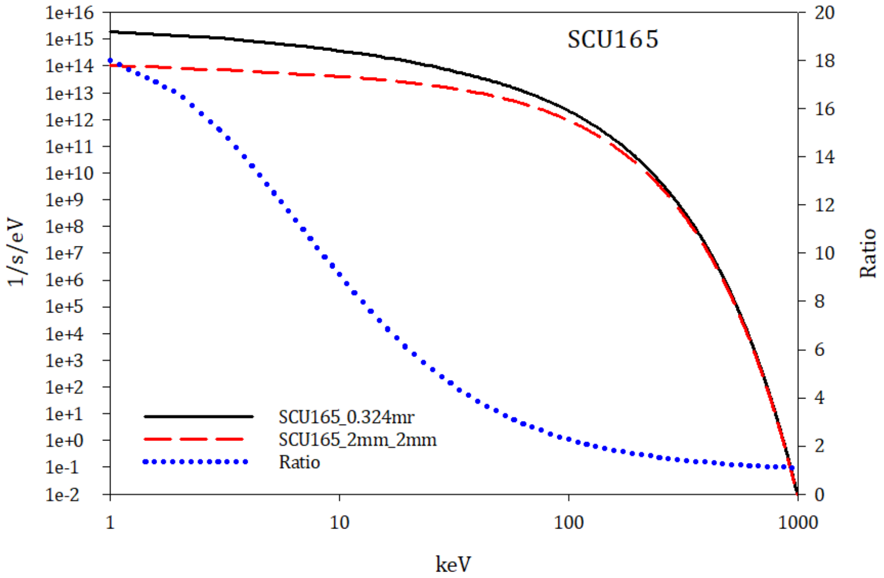
Input spectrum with end point at 200 keV



SCU185, FOE

Reduced source strengths





- With a 2mm x 2mm exit slit at 25m, the source strengths have reduced
- Exit mask will then be a credited control

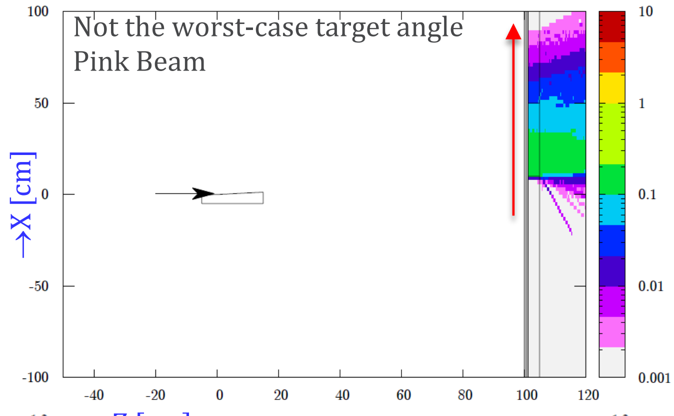
Required and recommended Pb thicknesses

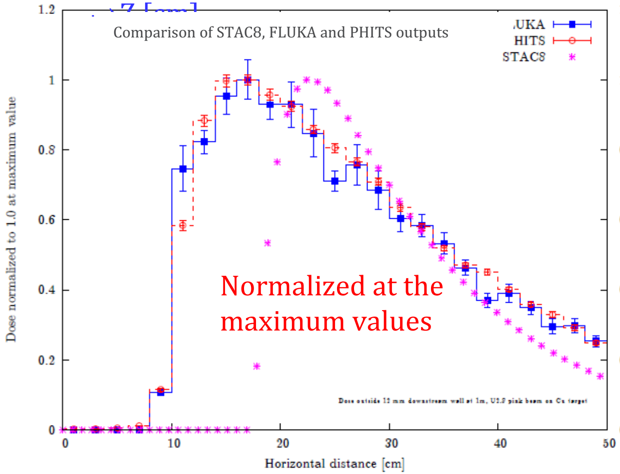
Enclosure	Distance	Pb thickness	SCU185		SCU165		U2.8	
	cm	mm	Req	Rec	Req	Rec	Req	Rec
FOE Lateral	70	19	30	39	23	30	17	23
FOE roof	100	12	28	36	21	28	16	21
FOE d/s wall	100	50 (100)	92	110	70	85	54	66
PBE Lateral	70	10	10	13	10	12	9	11
PBE Roof	100	6	10	13	9	11	9	11
PBE d/s wall	100	12	36	46	28	36	22	28

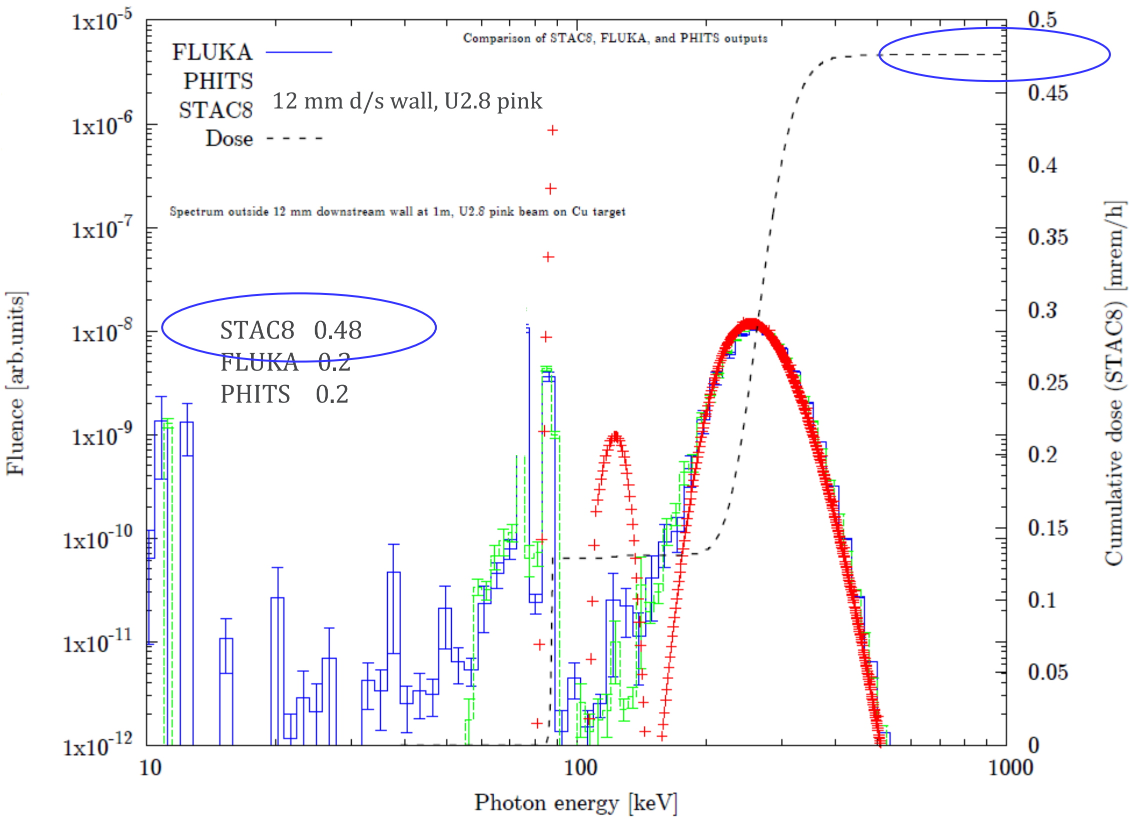
All sources with 2mm x 2mm exit slit

Req: Required thickness to achieve 0.5 mrem/h
Rec: Recommended thickness to achieve 0.05 mrem/h

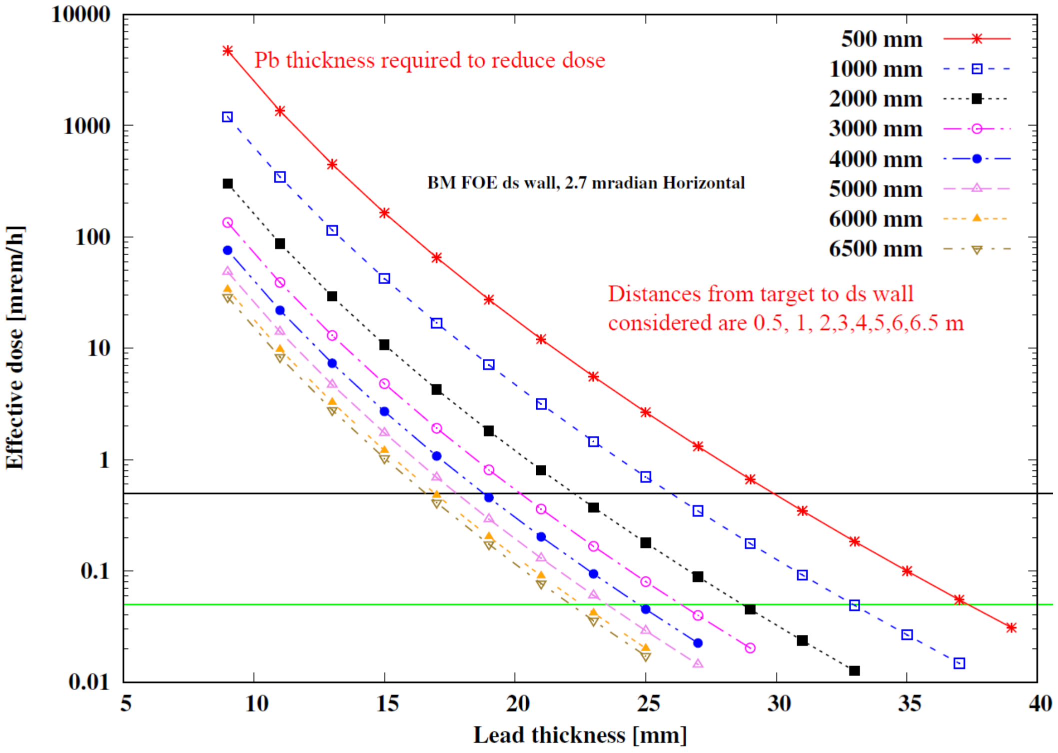
STAC8, FLUKA and PHITS results; pink beam d/s wall

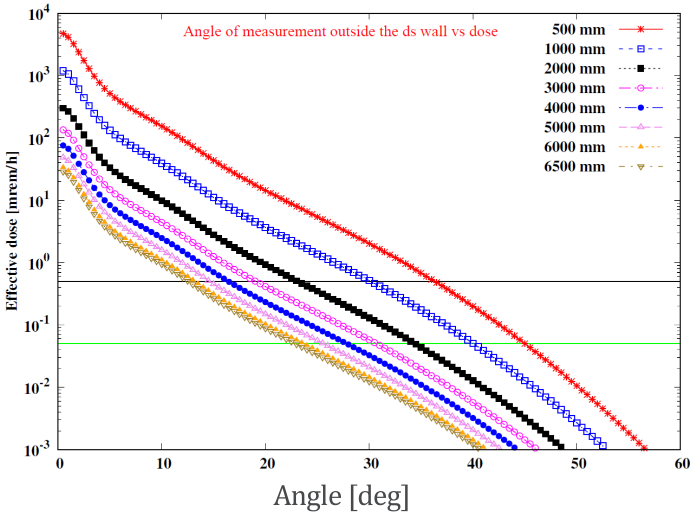


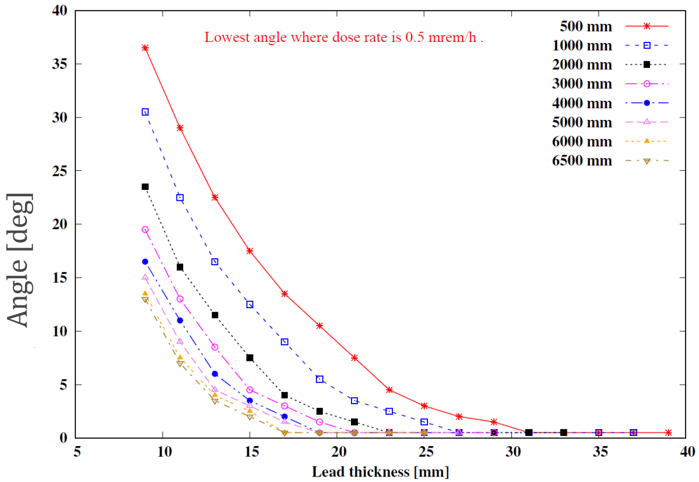




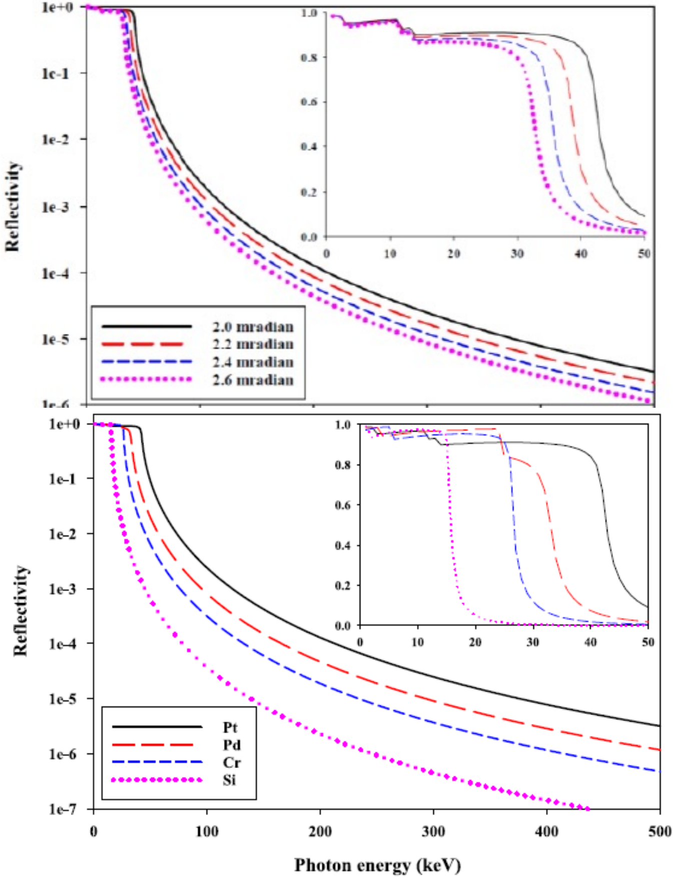
BM Outside downstream wall

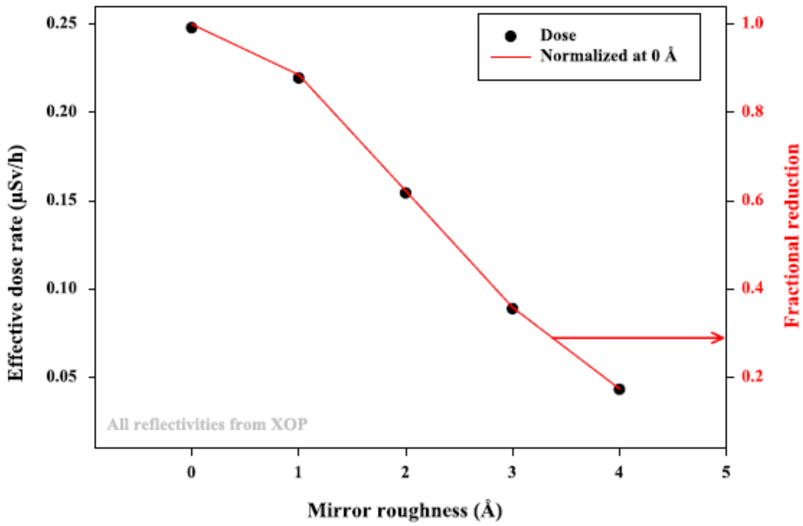






Mirror angle and roughness

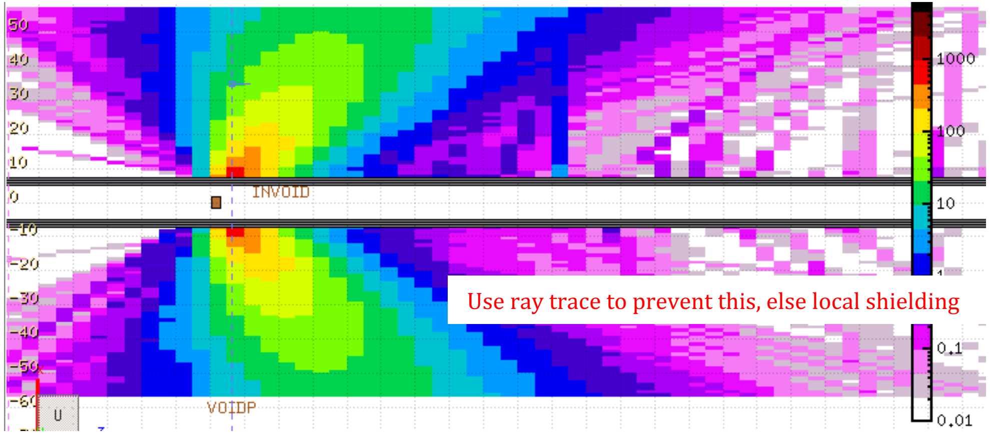




Not worst case			Worst case
Mirror Angle	**STAC8**	**FLUKA**	**STAC8**
1.0	0.48	0.2	37.0
2.0	0.02	0.01	3.4
3.0	0.005	0.003	0.4

Solid target in beam transport sections

Location	Pb	SCU185	SCU185	SCU165	U2.8	U3.0
		Wide aperture	2 mm x 2mm aperture			
	mm	mrem/h				
ID WBT	21	1445*	916	99	10	11
ID PBT	12	26	12	4.5	1.5	1.5



Pb thickness required to get 0.5 mrem/h

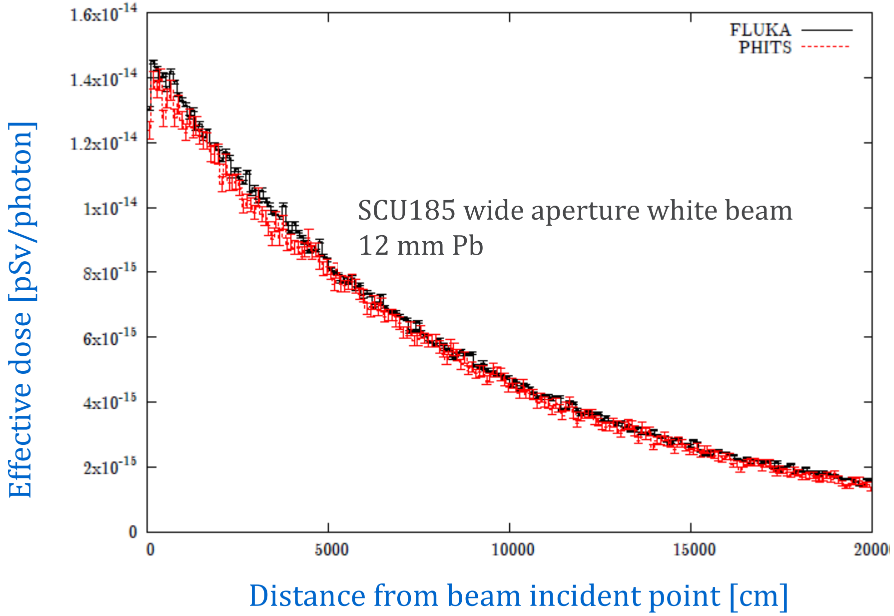
Source	WBT	PBT
SCU185	97	18
SCU165	88	15
U2.8	29	13
U3.0	30	13

W(P)BT: White (Pink) beam transport

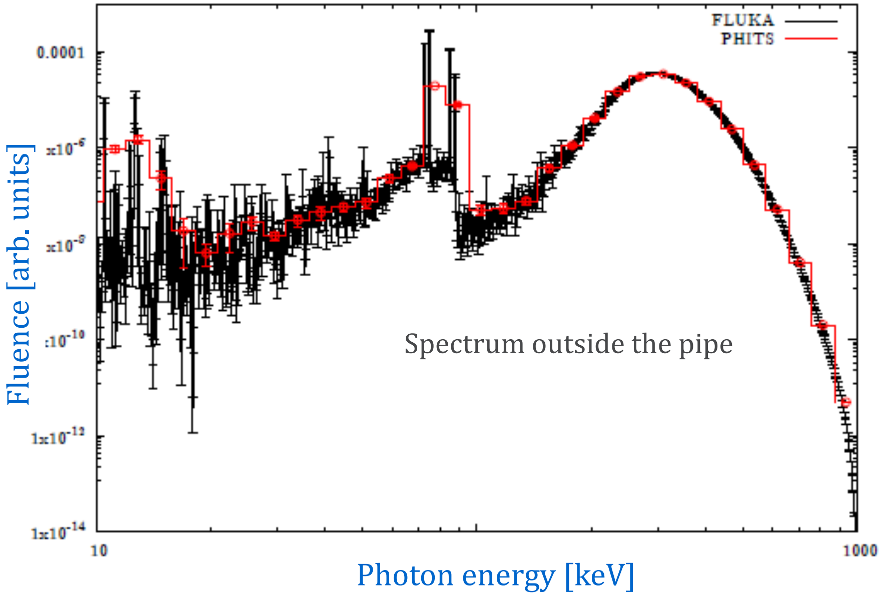
Dose and spectrum from air scattering

Dry air in 200 m long 10 cm ID transport pipe with SCU185 wide aperture as source

Dose outside shield (FLUKA and PHITS)



Photon spectrum outside shield (FLUKA and PHITS)



Similar shape was observed in an air-scattering experiment

Dose from air scattering; SR sources

Dose (mrem/h) due to SCU185 wide aperture SR scattering in an air column

Configuration	Distance (cm)	Pb (mm)	FLUKA	PHITS
ID WBT	5.0	21 (For solid target)	0.95±0.01	1.04±0.08
ID WBT	5.0	12	51.9±0.2	52.9±1.6
ID PBT	5.0	8	0.15	0.13

Source	Effective dose (mrem/h)
SCU185	29.4
SCU165	3.8
U2.8	0.4
U3.0	0.4

FLUKA results for 12 mm Pb shield (WBT) at 5 cm with 2mm x 2mm apertures sources

Vacuum interlocks/radiation monitor will be installed to limit the duration of loss of vacuum accidents

Dose outside shutters/stops with SR source

- All shutters are redundant
  - With 18 cm of W or 30 cm Pb for ID white beam, dose rates are less than 0.05 mrem/h with SCU185 wide aperture source
    - For both shutters and stops
- Stationary stops are not redundant but are under configuration control
- SCU pink beams require more than the recommended beam stop thicknesses
- With planar undulators with 2mm x 2mm aperture, 60 mm W keeps the dose rate below 0.05 mrem/h

Dose outside ID pink beam stops (60 mm W)

Source	Dose (mrem/h)
SCU185	46
SCU185	29
SCU165	1.4
U2.8	0.06

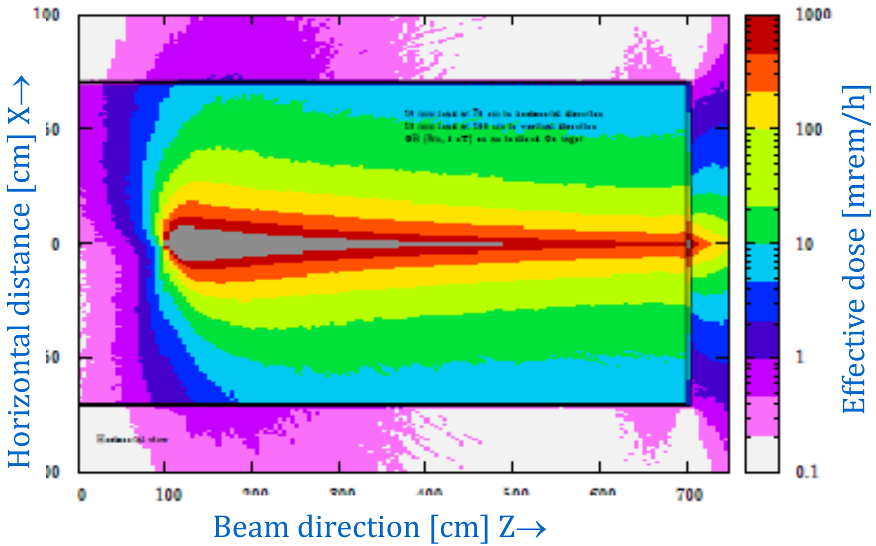
With 2mm x 2mm aperture (applies to SCU185 29, SCU165 1.4, U2.8 0.06)

Conclusion and recommendation on SR shielding

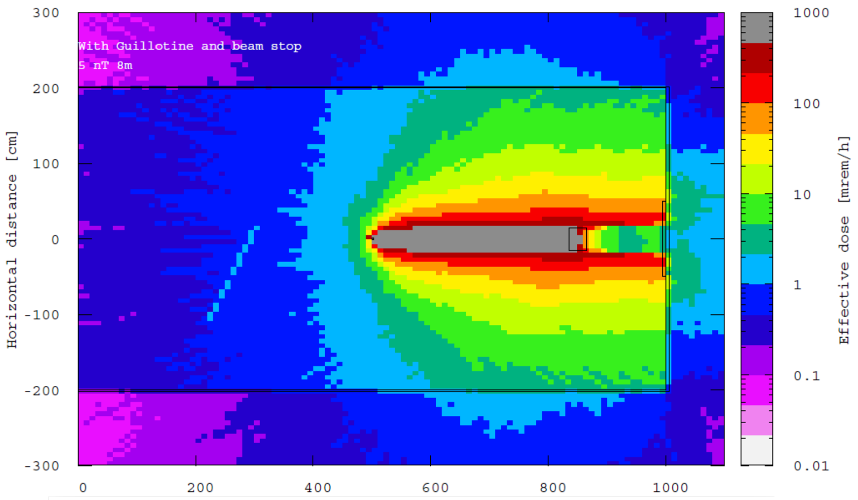
- STAC8 results are ~2.0-2.5 times higher than FLUKA/PHITS results
- For ID beamlines
  - Current shielding is inadequate for use of SCU 1.85 cm period length as the bounding source
  - Use U2.8/U3.0 with 2 mm x 2mm exit slit at 25 m
  - Analyze downstream walls to estimate additional lead panel thickness
  - Superconducting undulator beamlines will be analyzed separately
- For BM beamlines
  - Analyze downstream walls (for both white and pink) to estimate additional lead panel thickness
- No solid targets in the beam transport sections
- Install vacuum interlocks to minimize duration of vacuum excursion, or area radiation monitors to close shutters

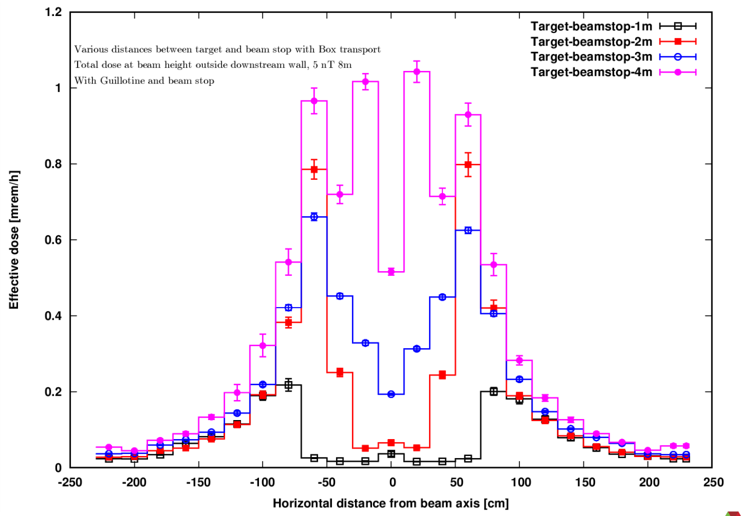
Gas Bremsstrahlung in ID beamlines

GB in ID FOE



Enclosure	Distance (cm)	Pb shield (mm)	GB dose mrem/h
FOE lateral wall	70	19	0.9
FOE roof	100	12	0.8
FOE d/s wall (local)	100	100	27
FOE d/s wall	100	50	335





Beam transport sections

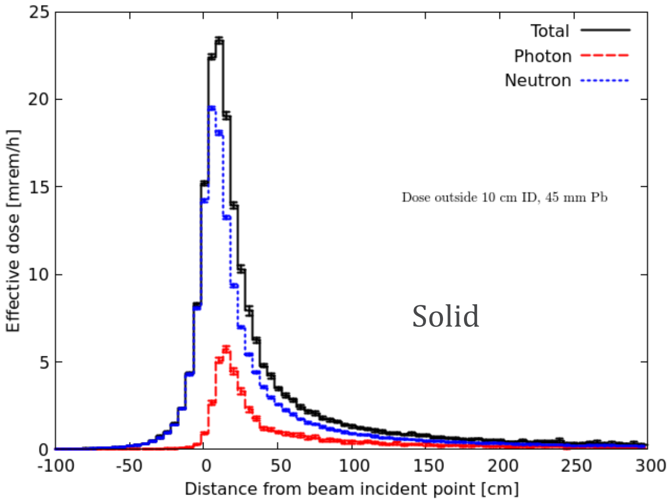
Solid target in White Beam Transport

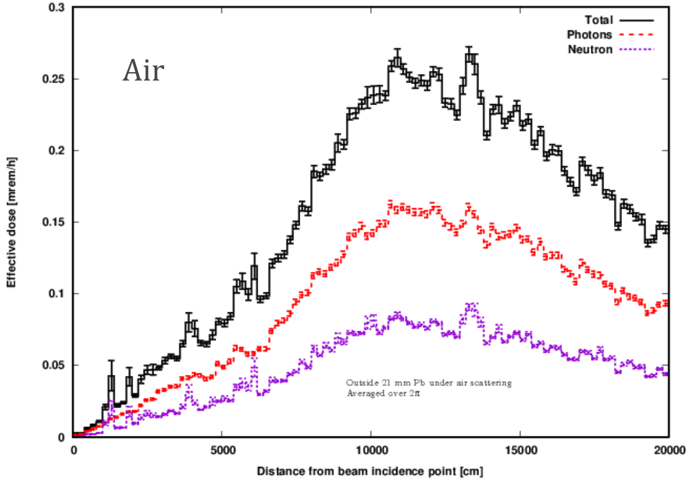
Location	Pb (mm)	Dose (mrem/h)
ID WBT	21	84.1±3.8
ID WBT	45	23.3±0.2

21 mm → for SR
45 mm → for GB

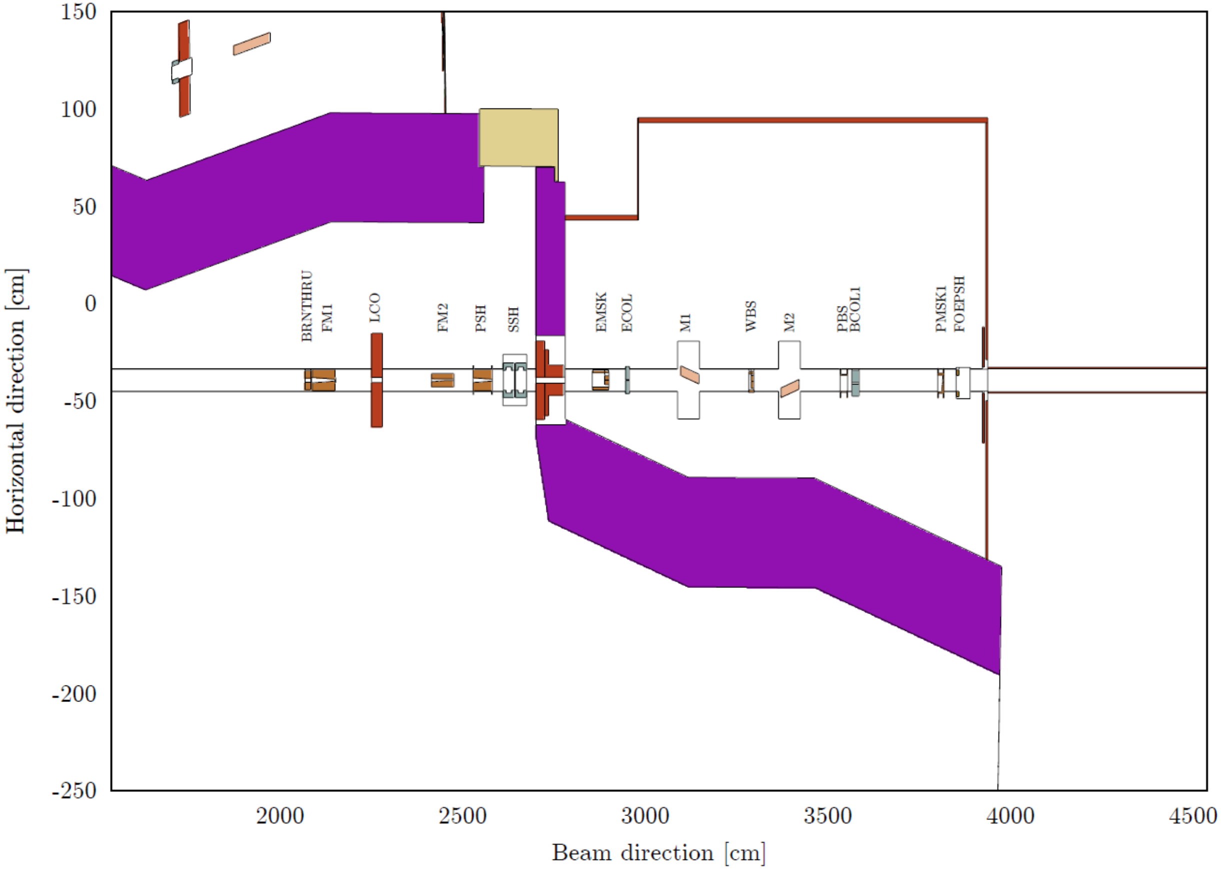
Air in White Beam Transport

Location	Pb (mm)	Dose (mrem/h)
ID WBT	21	0.14
ID WBT	12	0.31

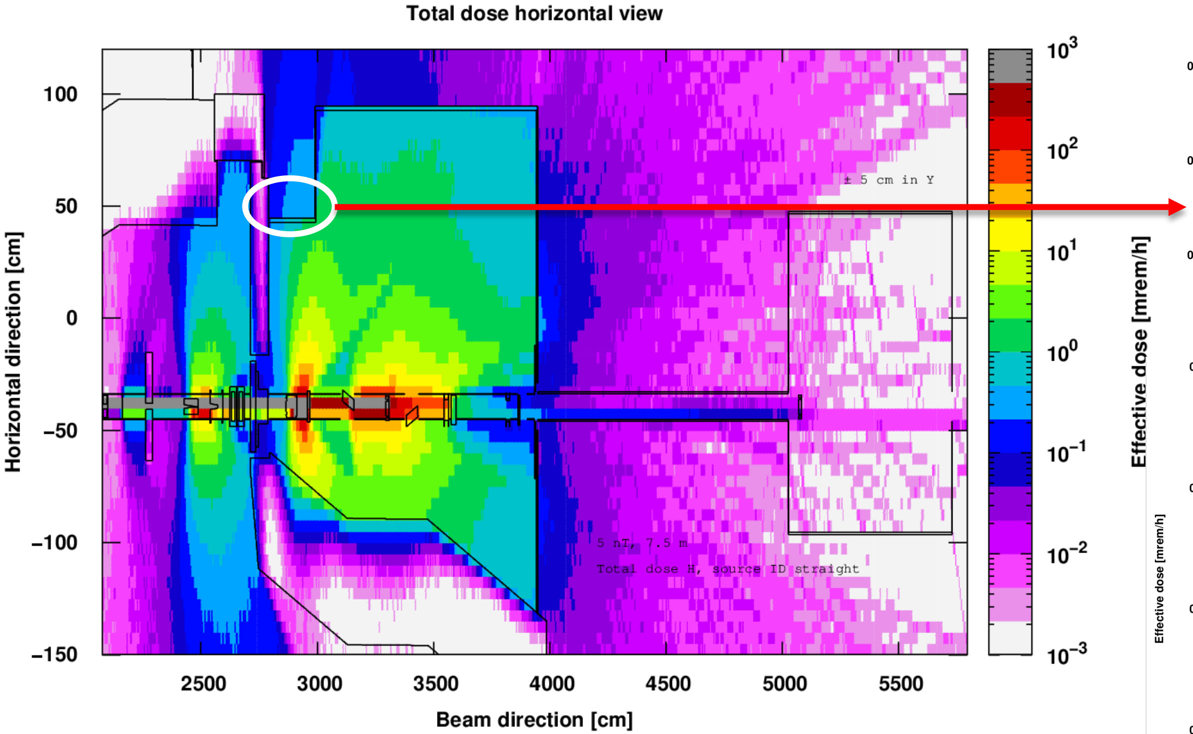


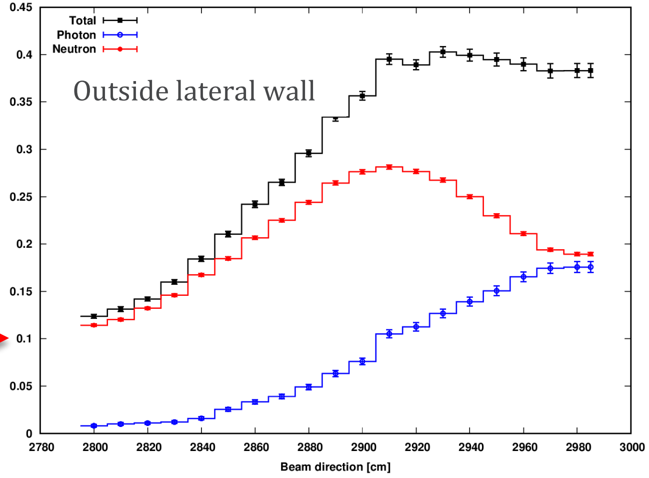


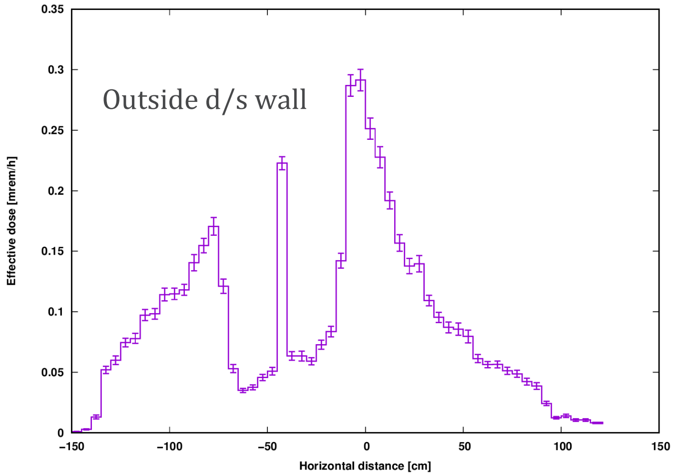
High Heat Load ID beamline Full geometry



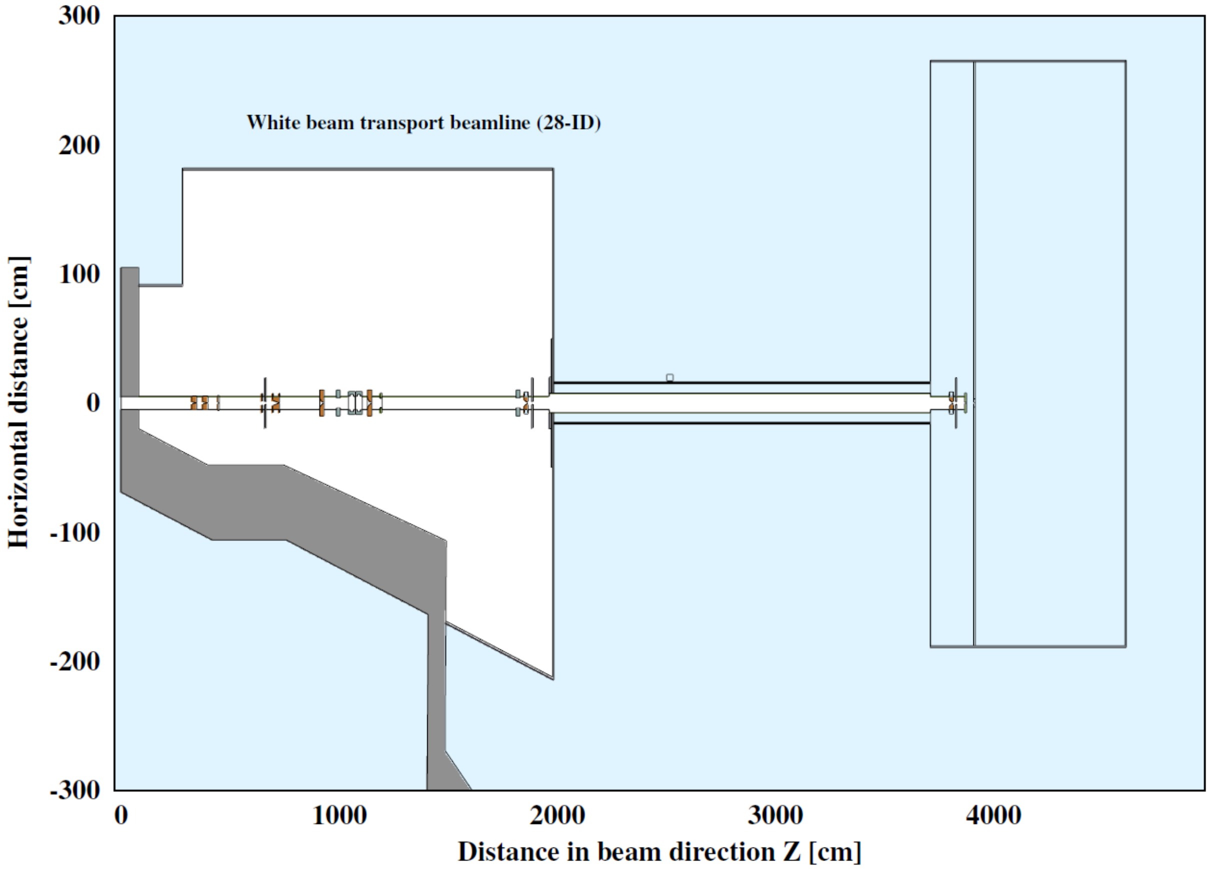
High Heat Load ID beamline



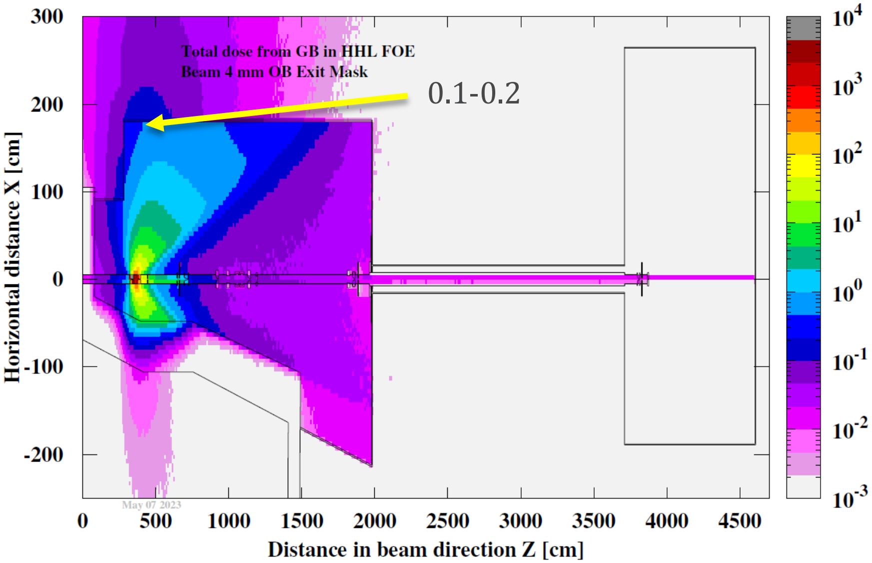


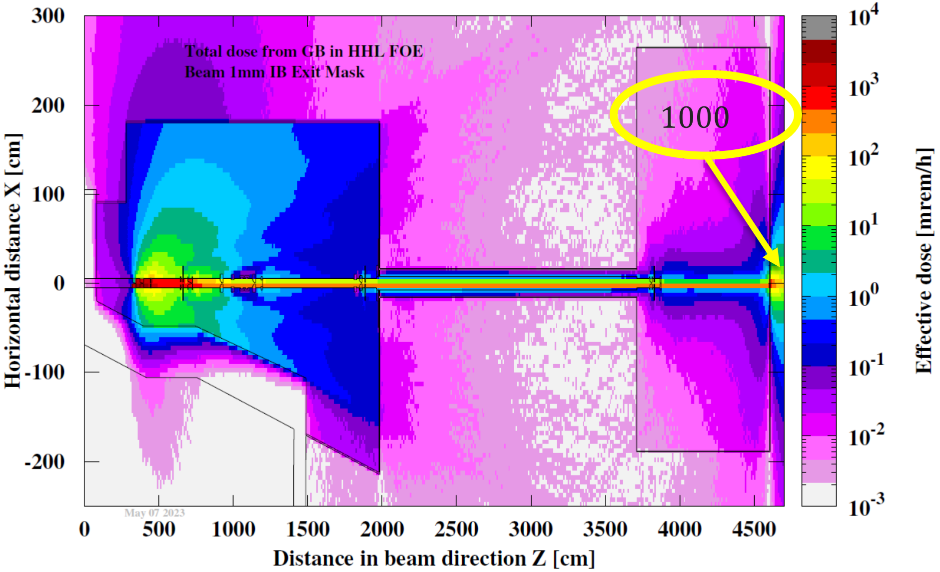


28-ID, HHL, white beam beyond FOE

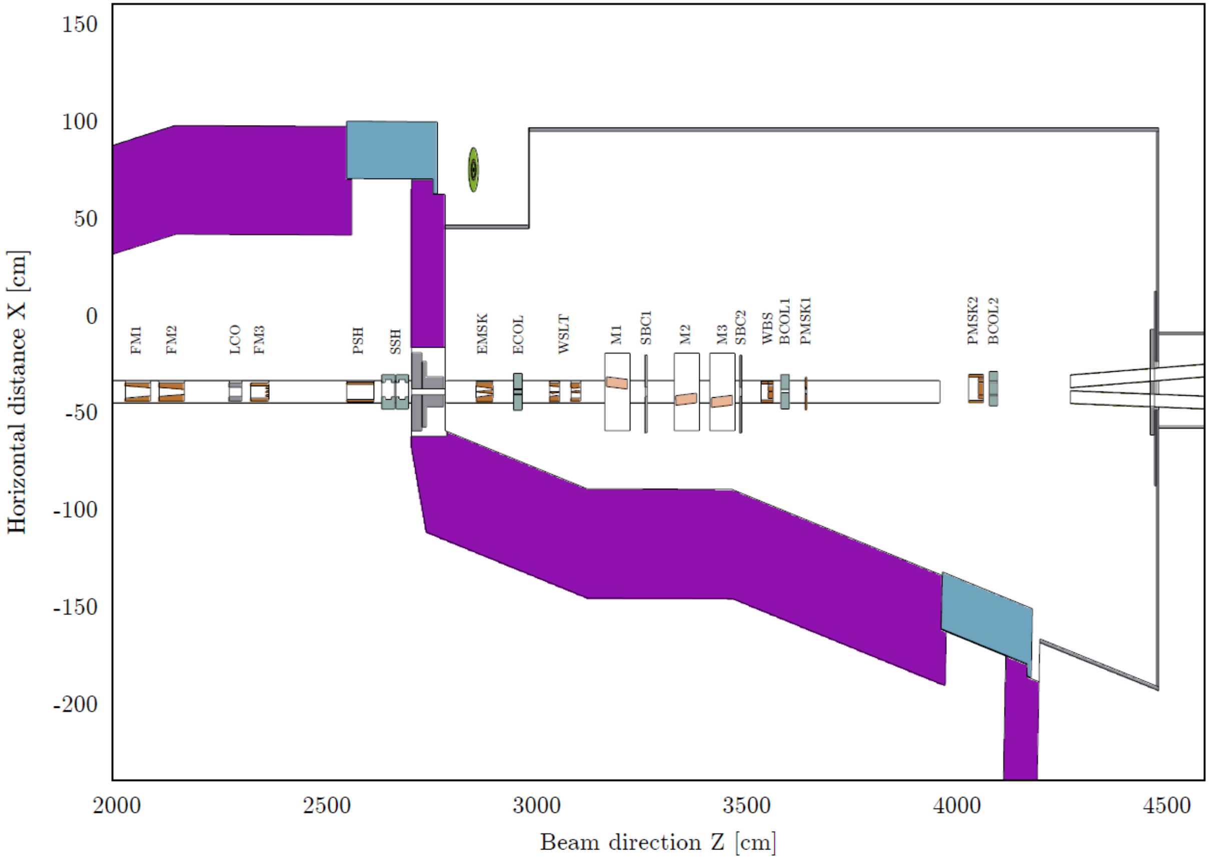


28-ID, HHL, white beam beyond FOE



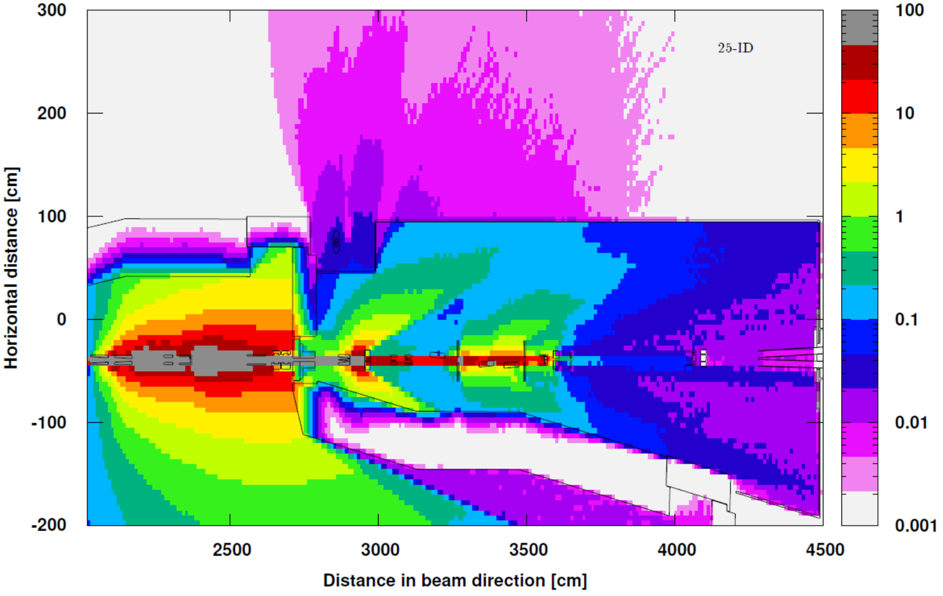


Canted ID beamline, full geometry

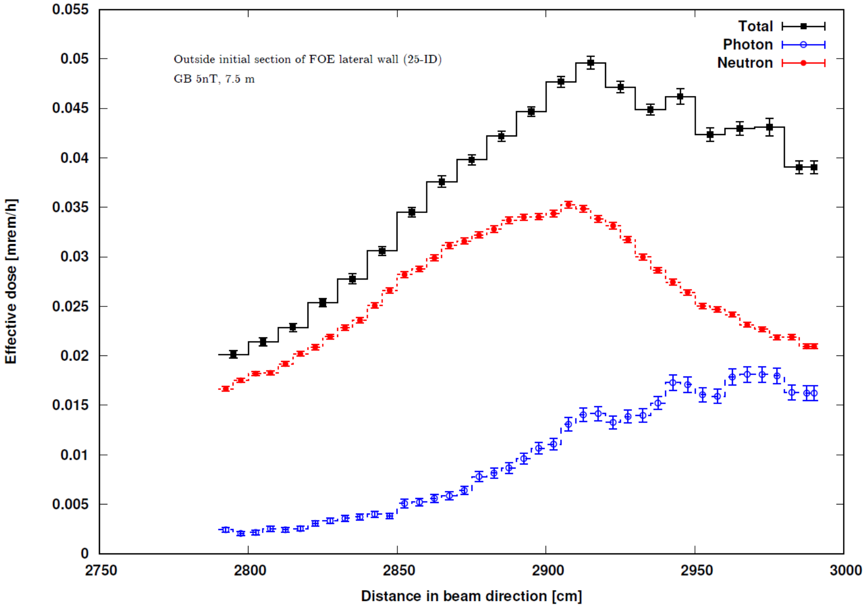


Canted ID beamline

Horizontal view



Outside lateral wall



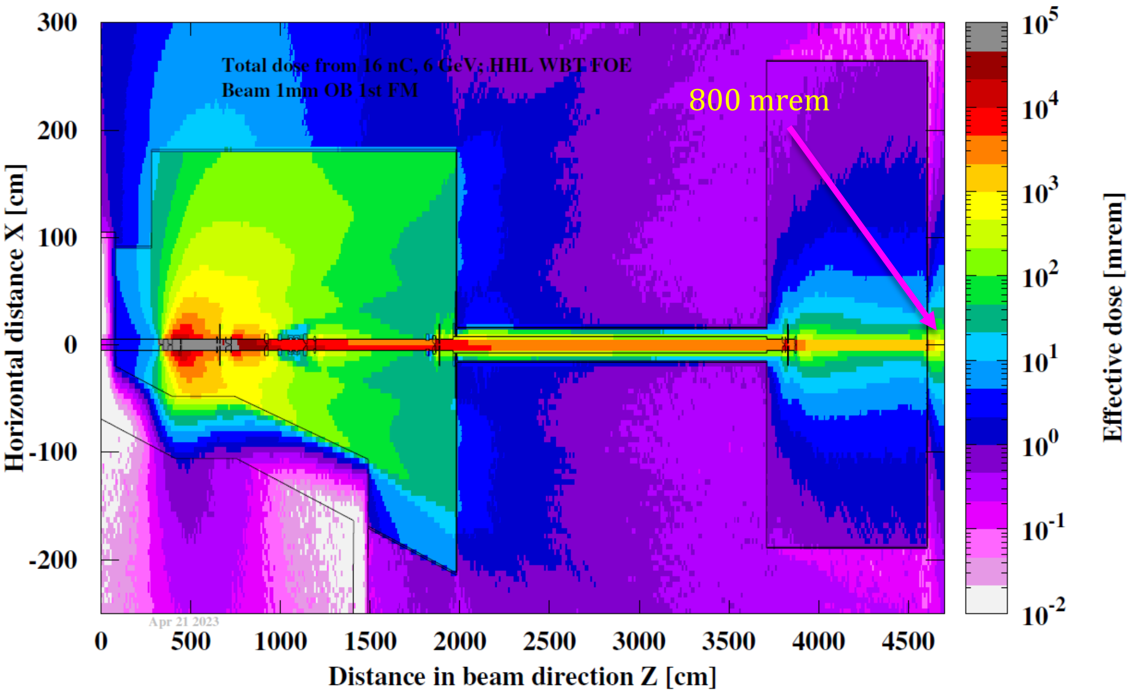
Conclusions

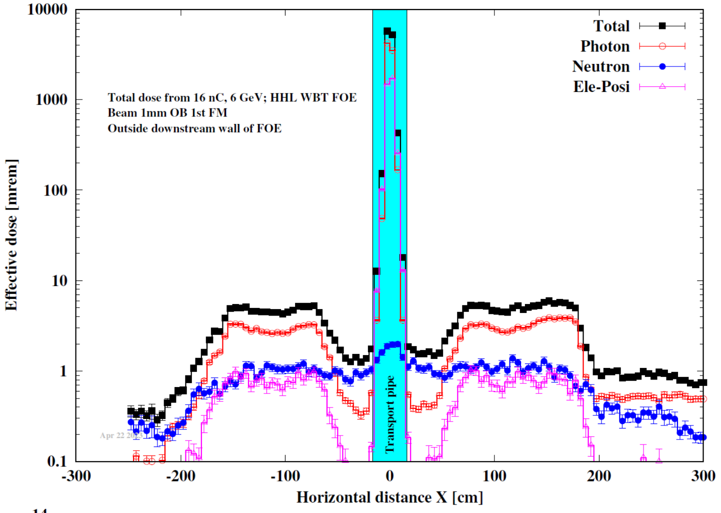
- Include all radiation safety components and personal protection components in beamline radiation shielding calculations
- To keep dose rates outside the downstream walls either identify mirror configurations or add additional lead shielding

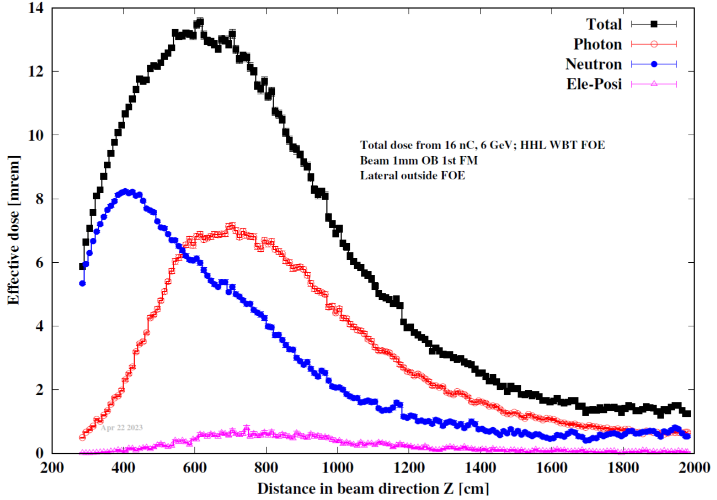
Off-normal electrons in FOE

High Heat Load ID beam line

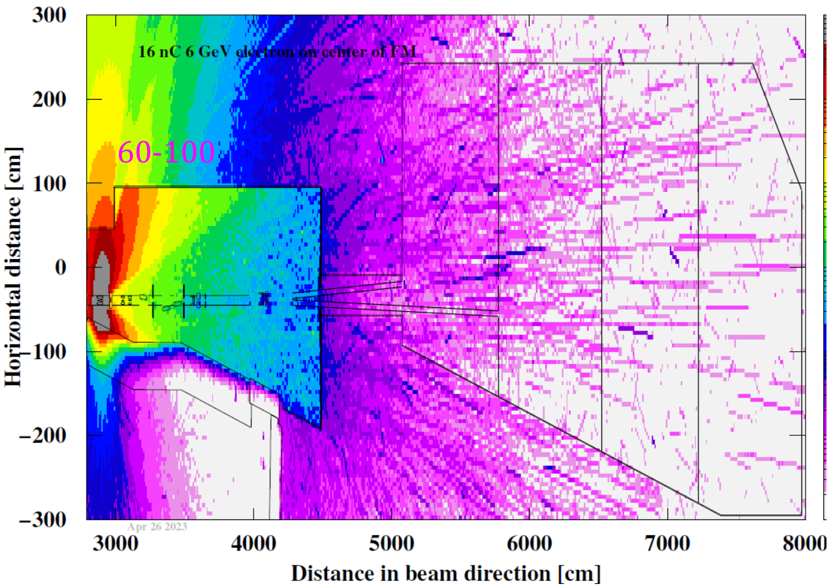
White beam beyond the FOE

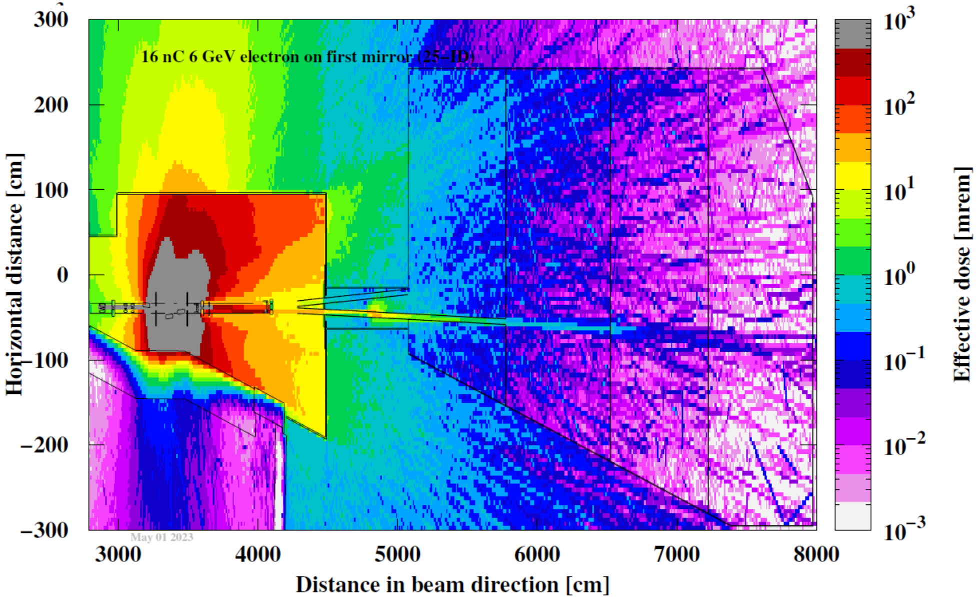




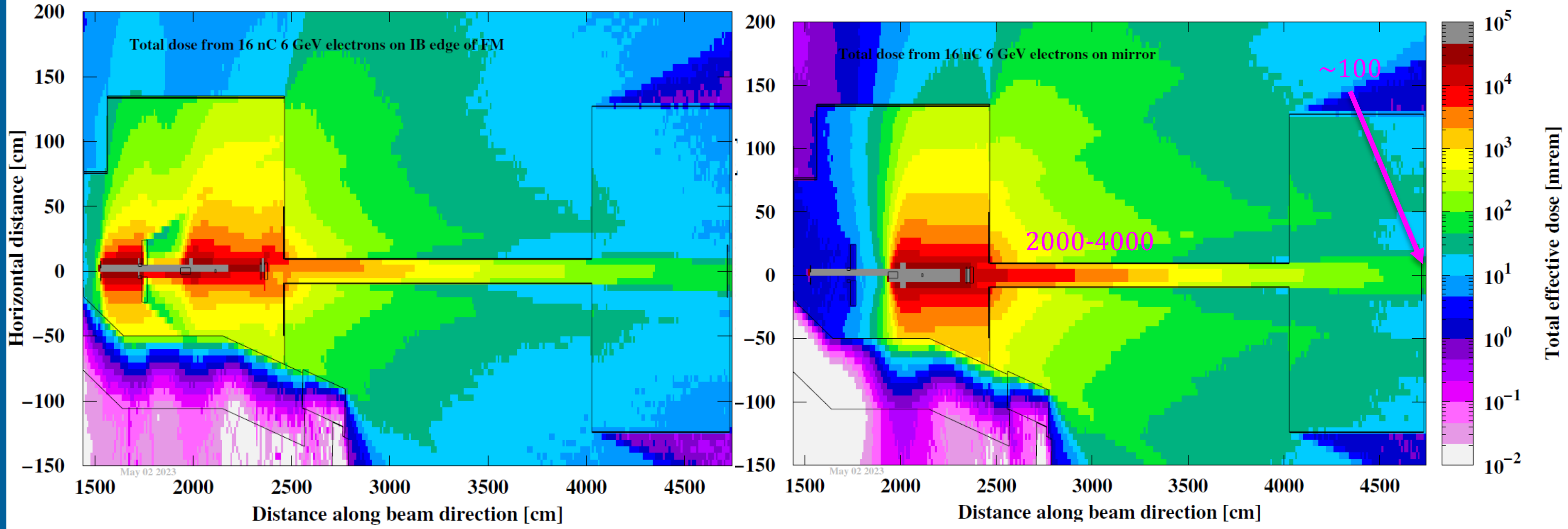


Canted ID beam line





BM beamline


Total dose from 16 nC 6 GeV electrons on IB edge of FM
Total dose from 16 nC 6 GeV electrons on mirror
~100
2000-4000
Horizontal distance [cm]
Distance along beam direction [cm]
Distance along beam direction [cm]
Total effective dose [mrem]
May 02 2023
May 02 2023
200
150
100
50
0
−50
−100
−150
1500
2000
2500
3000
3500
4000
4500
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}

Conclusions

- Particle tracking has not shown any possibility of electrons entering the FOE
- Multiple safety systems will prevent such a scenario
  - Check for the presence of stored beam in the storage ring
  - Check for energy match between booster and storage ring
  - Prohibit injection if magnets have current or voltage outside of prescribed limits

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