Radiation shielding calculations for the ALS upgrade project

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May 30th 2023

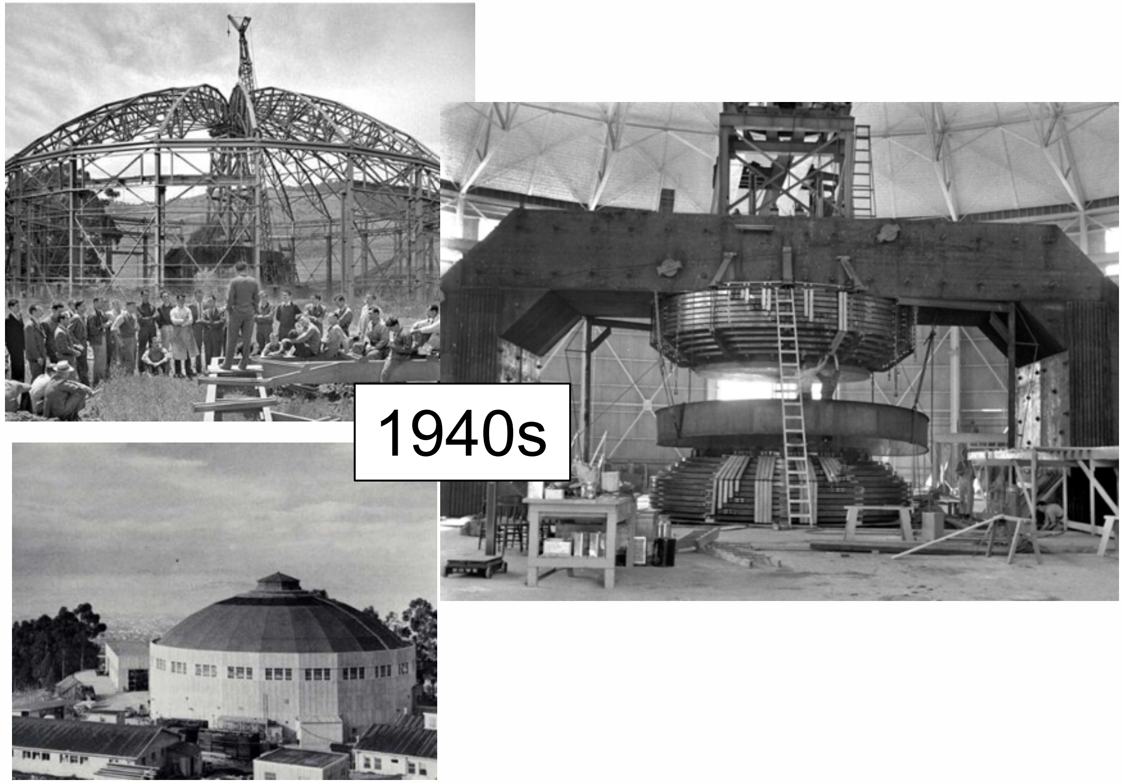
RADSYNCH23 - ESRF, Grenoble, 2023

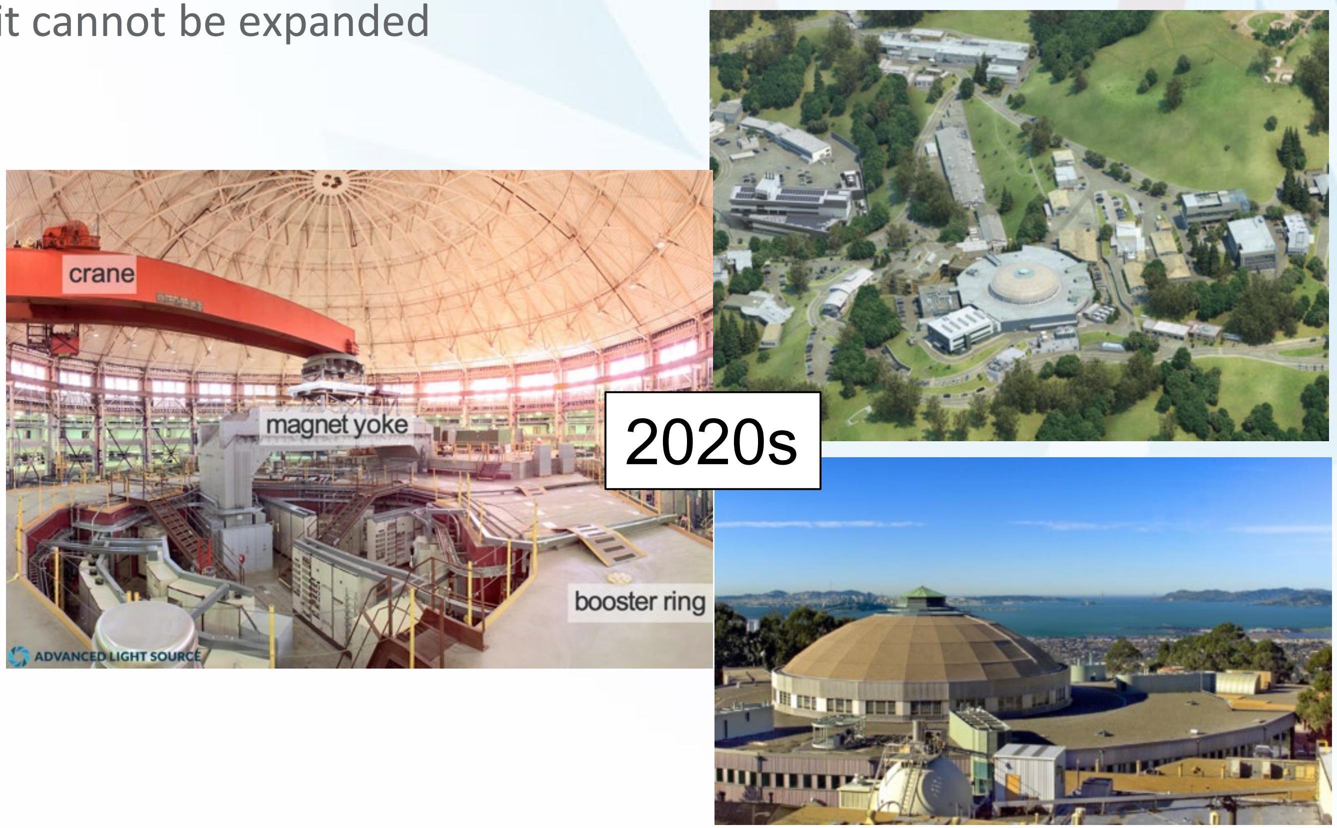
Outline

- Overview of current and upgraded ALS
- ALS-U radiation hazards
- Shielding policy
- Accelerator Shielding: existing, retrofit and new shielding
- Shielding calculations methods
- Overview of shielding requirements

Overview of the ALS facility

- Built between 1987-1993, it incorporates the dome of the Lawrence’s 184-inch cyclotron
- Small facility, constrained by hills and other buildings it cannot be expanded

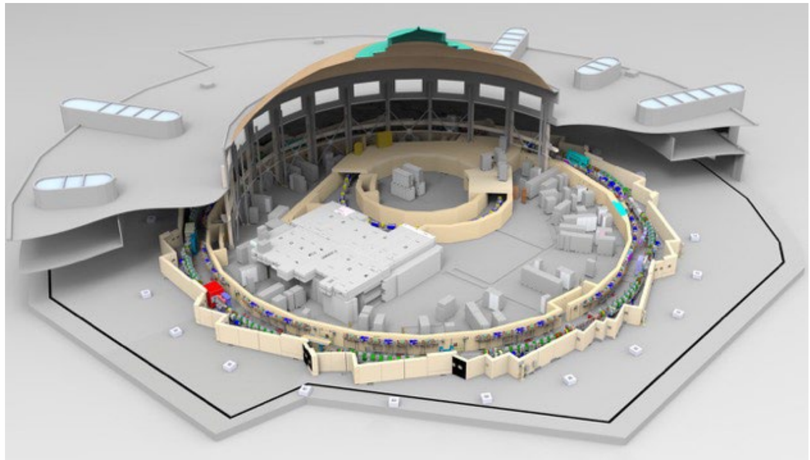


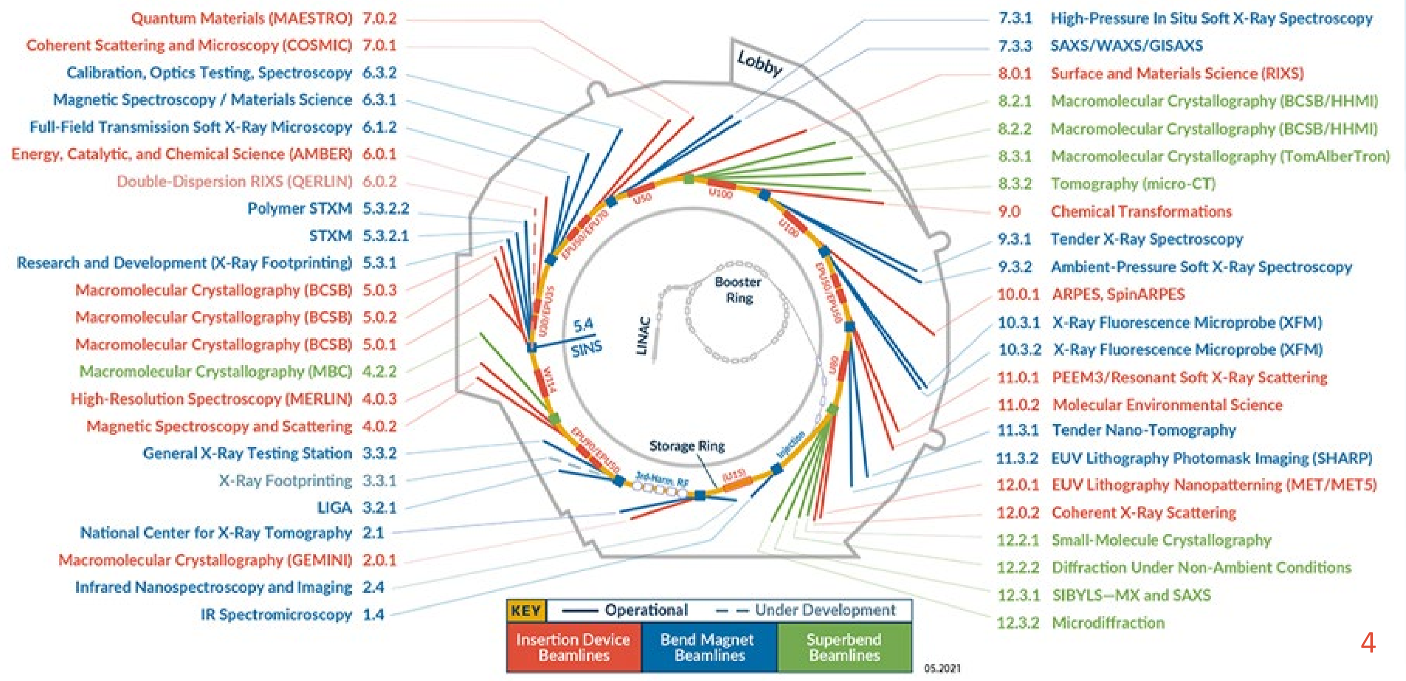


Overview of the ALS facility

- Accelerators: Linac (50 MeV), booster and storage ring (1.9 GeV), 500 mA
- 46 beamlines, including infra-red
- Mainly developed for soft X-ray science, it has added, over time, hard X-ray beamlines
  - storage ring circumference ~197 m
  - storage ring tunnel width varies between 4 to 8 meters (inner to ratchet wall)
  - experimental floor space is limited, **no first-optics enclosures**

17 insertion device beamlines
20 bend magnet beamlines
9 super-bend magnet beamlines



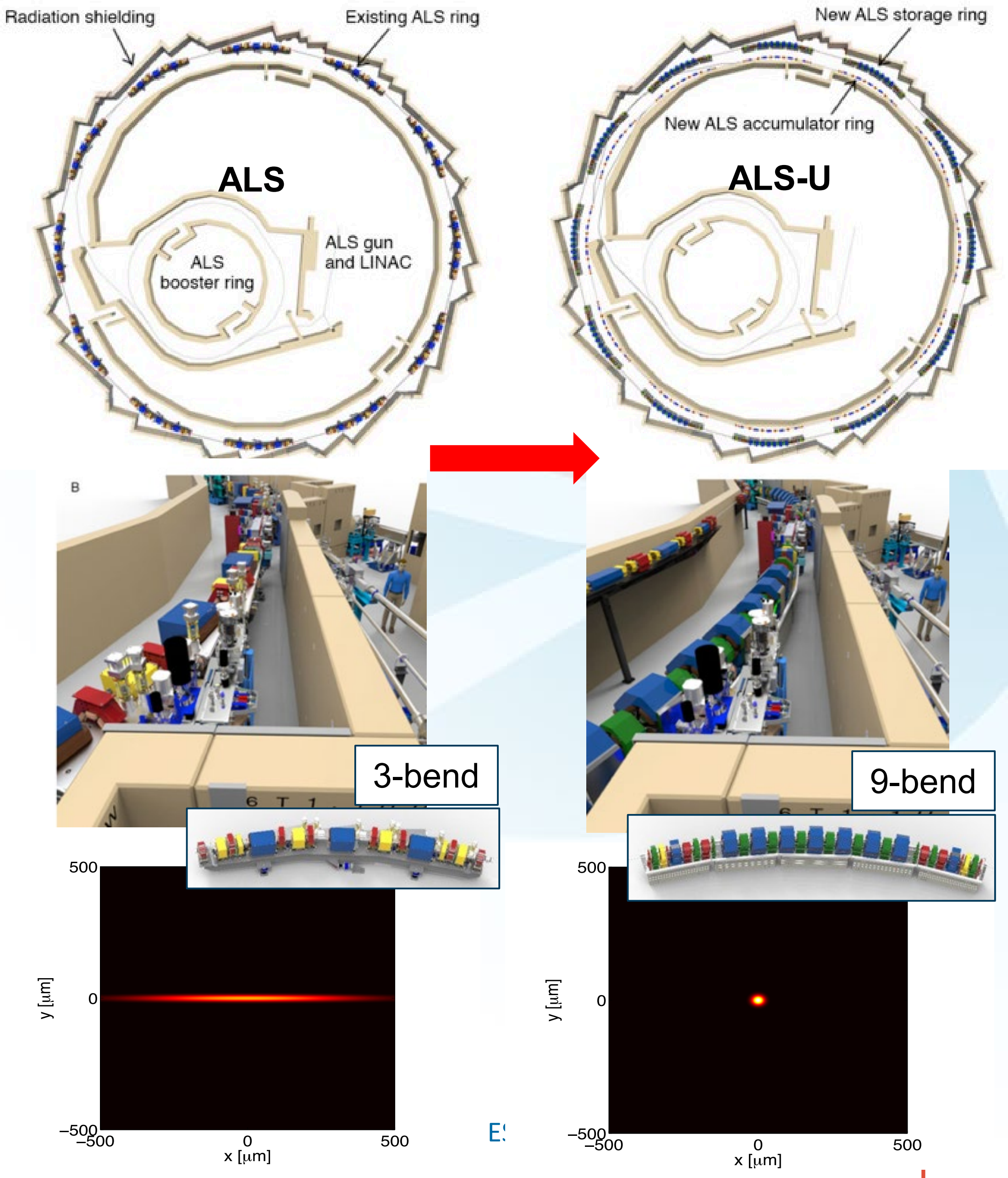


ALS → ALS-U: accelerators

- Upgrade goals: ***reduced*** $\boldsymbol{\varepsilon_x}$ and ***increased brightness***
- Addition of accumulator, new storage ring, new transfer lines
- New SR: from 3-bend arc to 9-bend achromat lattice

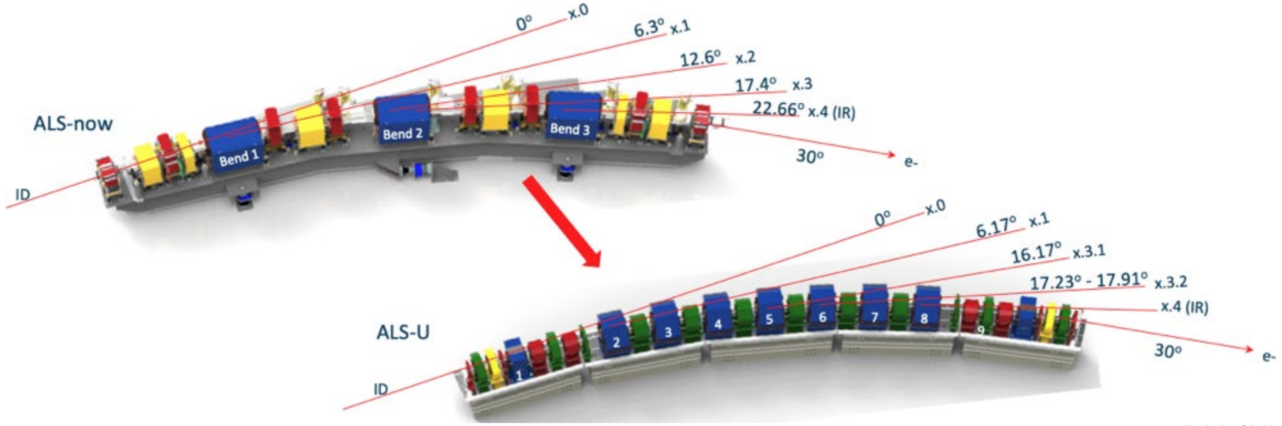
Parameter	Current ALS	Future ALS
Electron energy	1.9 GeV	2.0 GeV
Beam current	500 mA	500 mA
Horizontal emittance	2,000 pm rad	<75 pm rad
Vertical emittance	30 pm rad	<75 pm rad
Beam size at insertion-device center (σ_x/σ_y)	251 / 9 μm	$\leq$14 / $\leq$14 μm
Beam size at bend source points (σ_x/σ_y)	40 / 7 μm	$\leq$7 / $\leq$10 μm
Energy spread	$9.7\times10^{-4}\frac{\Delta E}{E}$	$\approx 1\times10^{-3}\frac{\Delta E}{E}$
Typical bunch length (fwhm)	60–70 ps	100–120 ps
Circumference	196.8 m	≈196.5 m
Number of main bend magnets per sector	3	9

Performance Measure	Threshold
Storage ring energy	$\geq$ 1.9 GeV
Beam current	> 25 mA
Horizontal emittance	< 150 pm rad
Calculated brightness at 1 keV	> 2.0 x 10^{19}
Number of feature MBA beamlines installed	2

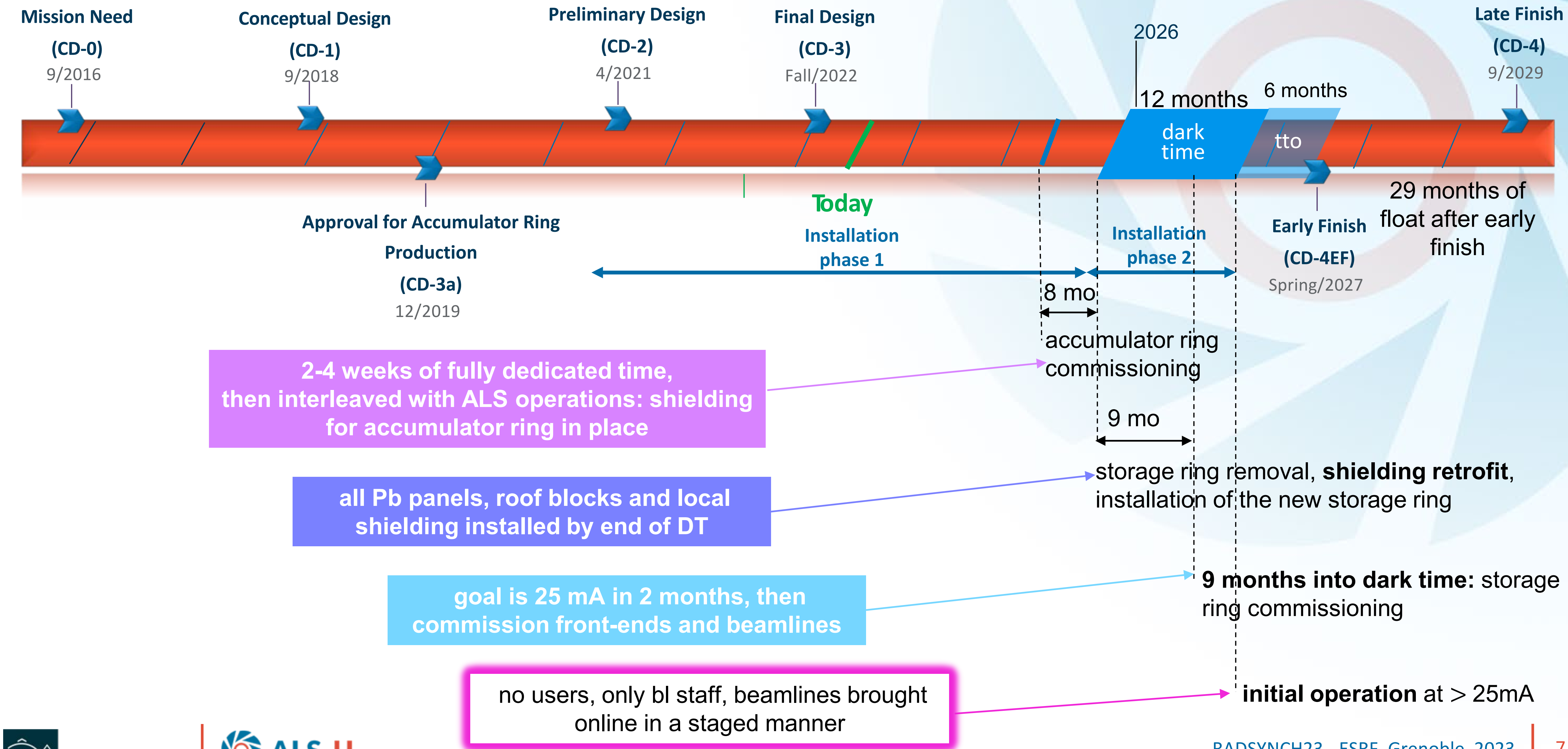


ALS → ALS-U: beamlines

- 4 new ID beamlines, 2 of which will have 2 new insertion devices:
  - 1 full length (4m) in-vacuum undulator (IVID) for the Tender beamline, B_{peak} = 1.3 T, λ = 19 mm, gap = 4.3 mm
  - 1 full length (4m) Apple II type undulator (EPU) for the FLEXON beamline, B_{eff} = 0.985 T (planar)
- Bend magnets fields all decrease and cryo-magnets are replaced with permanent magnets
- All bend-magnet sources move → realignment of 24 beamlines



ALS-U timeline



Summary of Radiation Hazards

- Radiation hazards do not change in type, only in severity

increasing

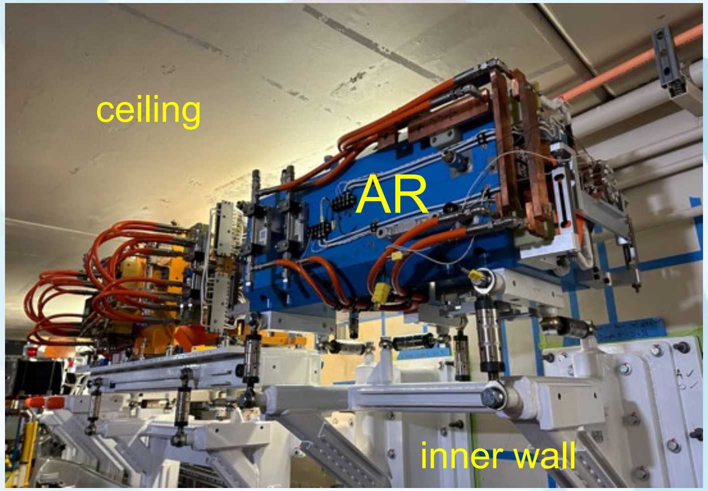
- 5x more losses due to reduced beam lifetime (0.5 h from 4 h)
- increased swap-out incident charge: 1 nC → 30 nC
- electron beam power density increases
- AR is an additional source, placed on inner wall and close to ceiling
- additional transfer lines

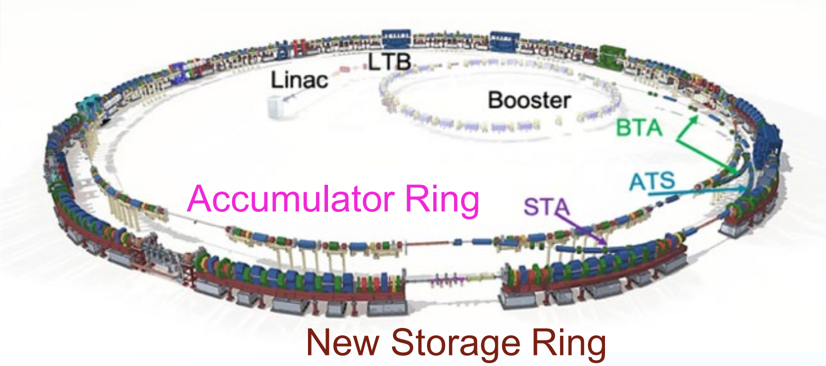
decreasing

- improved injection efficiency into the storage ring: 50% → 99.8%
- collimators will intercept 95% of losses reducing losses elsewhere to < 5%
- significantly lower B-fields at bend beamlines will result in decreased radiation

stationary

- SR gas bremsstrahlung comparable to or less than present one, after commissioning due to neg coating of all vacuum chambers
- at the existing ID beamlines B-fields will be reduced by increasing gaps due to thermal load and to keep same shielding as much as possible



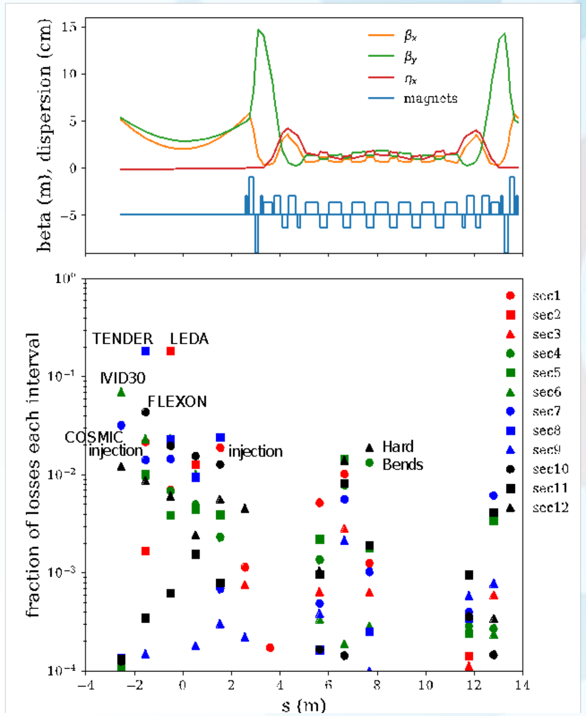


Beam losses

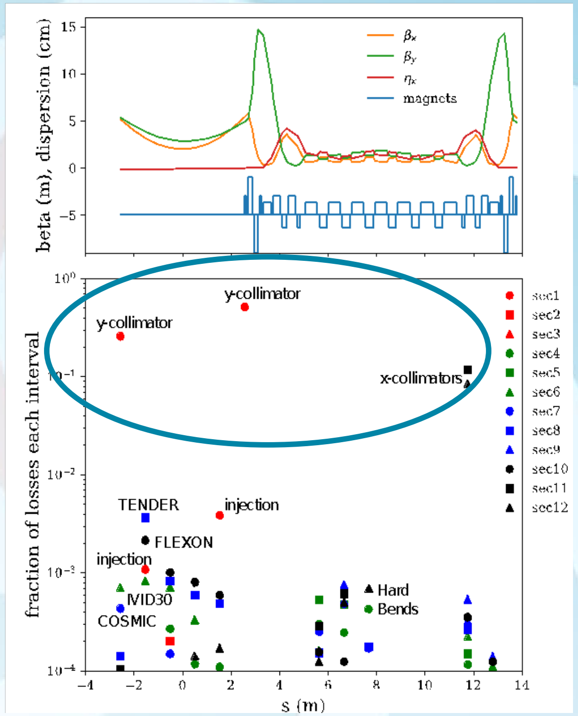
- **Injector chain**: loss fractions and patterns remain unchanged, but 5x higher repetition rate in swap out mode
- **Accumulator ring**:
  - **0.017 nC/s lost mainly at 2 collimators**
- **Storage ring:**
  - **0.5 h lifetime (Touschek + gas) → 0.18 nC/s lost**
  - swap-out losses: 0.2% of 30 nC/30s
  - fill-mode losses: 2.16 nC in 15 minutes
- **Abnormal events:**
  - loss of injected beam in a photon beamline (30 nC)
  - loss of full stored and injected beam away from collimators (330 nC in SR, 30 nC in AR)
  - reduced collimators efficiency (from 95% to 50%)
  - increased gas pressure (MPS trips at 5 nT in straight sections)

Storage Ring

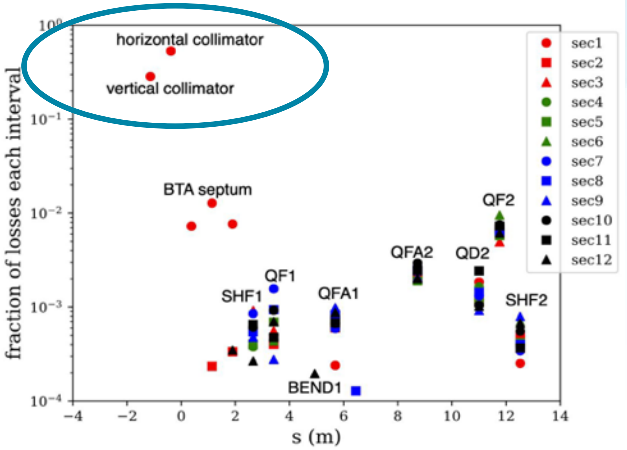
without collimators



with collimators



Accumulator Ring



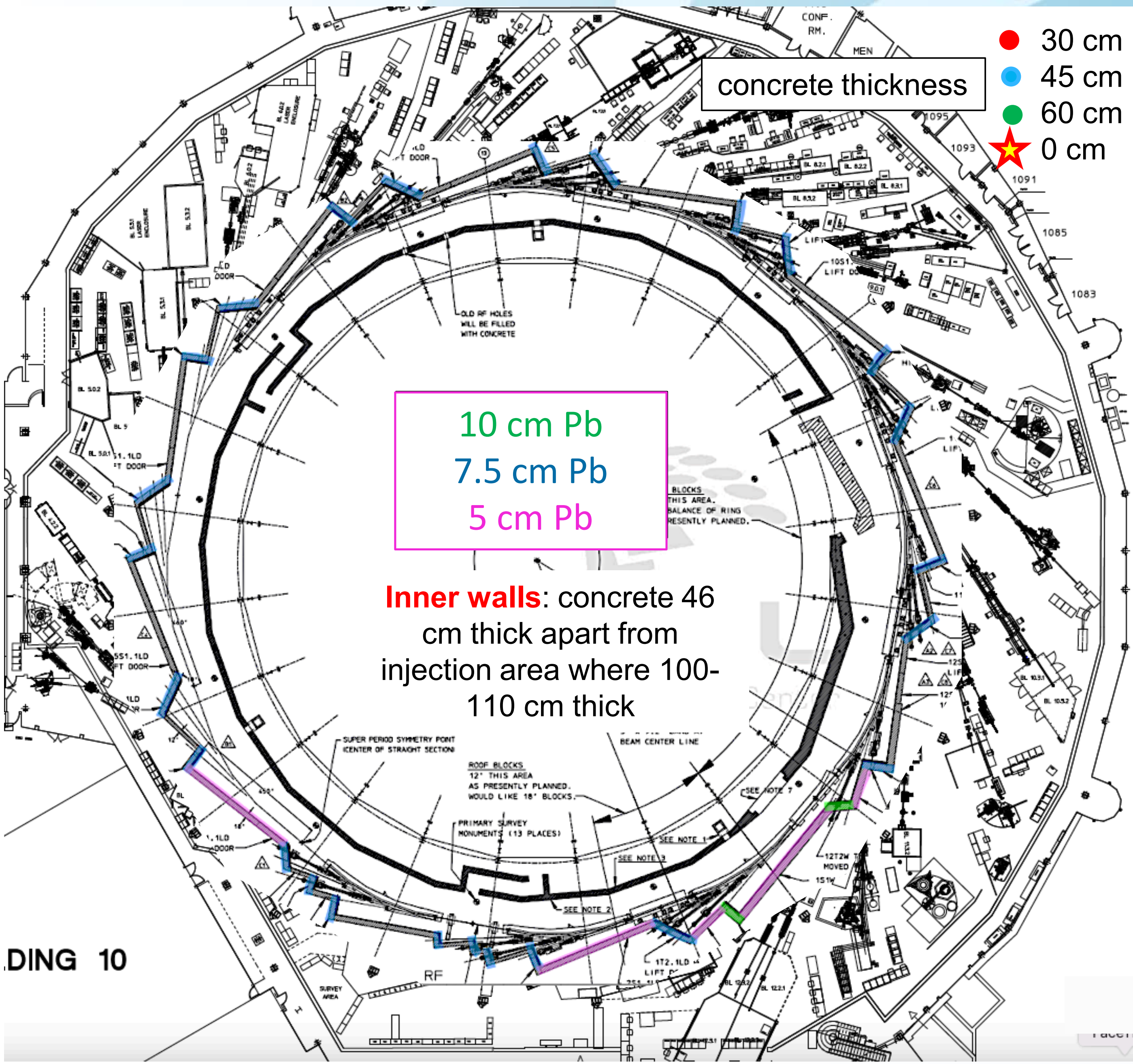
Parameter	ALS	ALS-U
Electron energy	1.9 GeV	2.0 GeV
Injection efficiency	≈50 %	≥99 %
Stored beam losses	0.5×10^{12} electrons/hour	2×10^{12} electrons/hour
Top-off injection shot	1 nC	30 nC

Shielding policy

- A major facility modification drives re-evaluation of the existing policy (1 µSv/h, 0.4 mSv/event)
- New shielding policy developed to stay below DOE limits and ALARA, using dosimetry data collected over the years
- **ALS-U, post commissioning phase goal:** keep controlled area classification and remove radiation areas with shielding retrofit
- **Shielding design goal**
  - 5 µSv/h with an ALARA goal of 0.5 µSv/h on the experimental floor
  - 1 mSv/event for incident scenarios
- **Commissioning phase**: all staff classified as radiation worker with dosimeter
- When dosimetry data accumulated over time reach a **steady state**, if exposures are low enough, worker classification and badging will be re-assessed

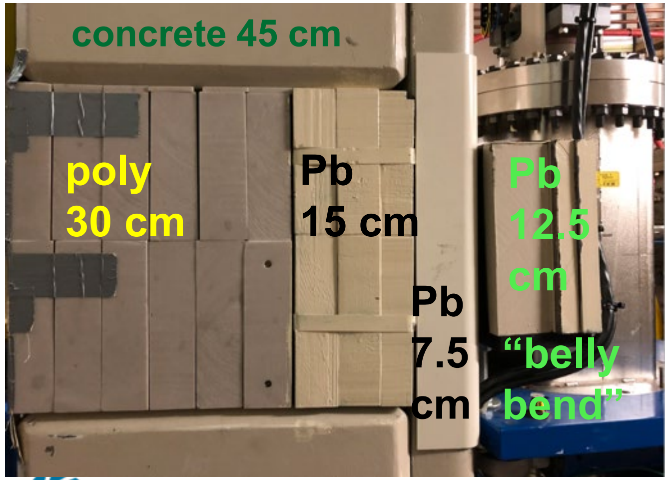
Shielding challenges

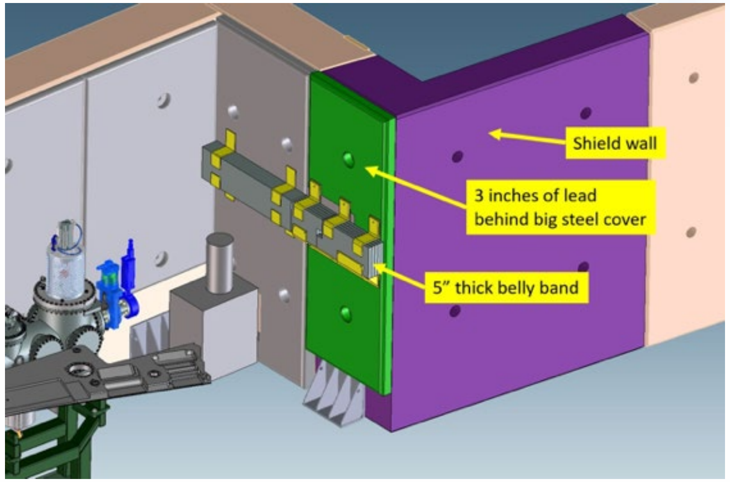
- **ALS-U is not a green field facility and there is no possibility to expand or rebuild**
- Shielding walls (material and thickness) not standard for all sectors
- Several simulations needed for different layouts and radiation sources



Front-end and wall plugs at beamlines ports

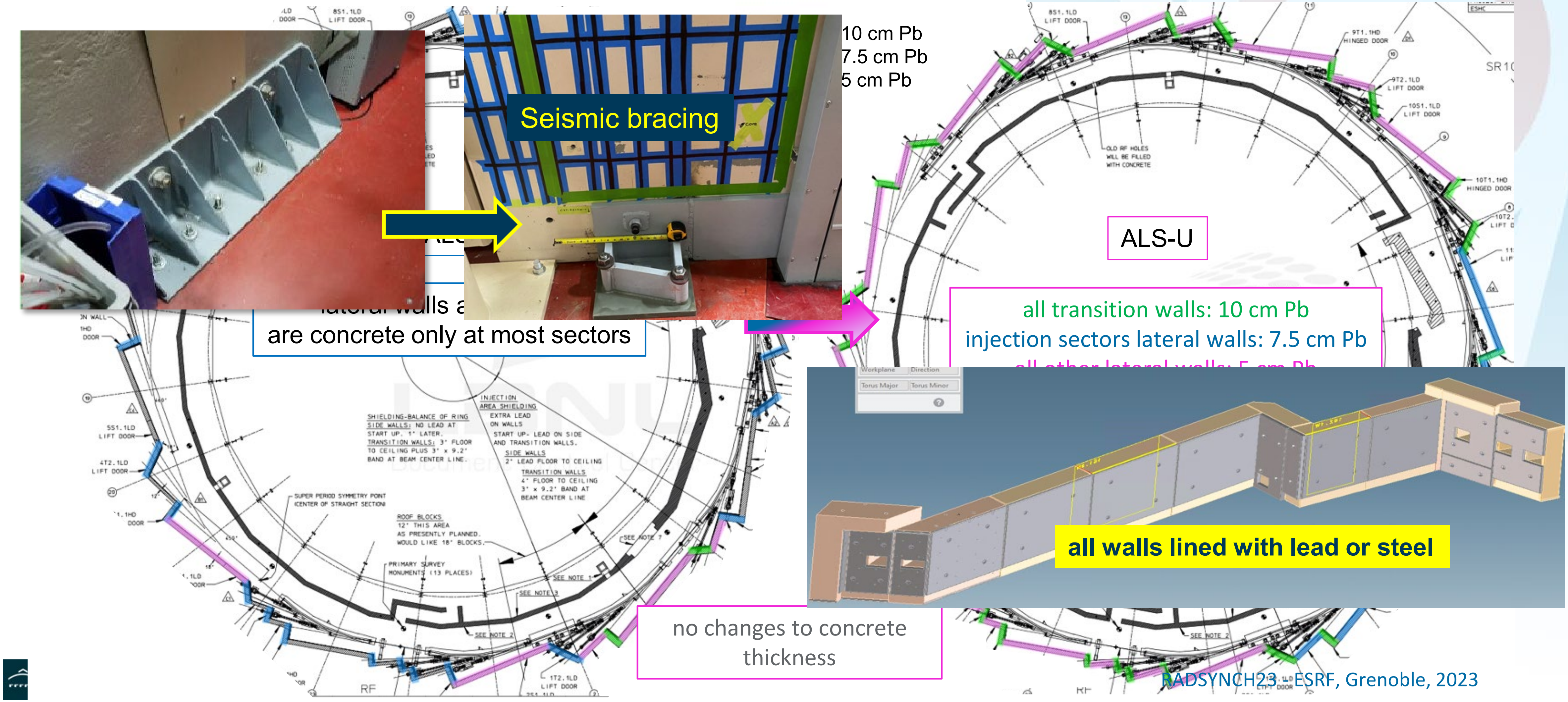
- At beamline ports through the shield wall, concrete is replaced with Pb and polyethylene
- Front-ends have Pb belly bands that vary from 7.5 to 12.5 cm, local shielding to shadow the storage rings from the beamline ports: mainly Pb, some W
- Shielding layout varies front-end by front-end, depending on installed equipment as the space is very limited
- **Validation of present shielding installation for ALS-U operation**





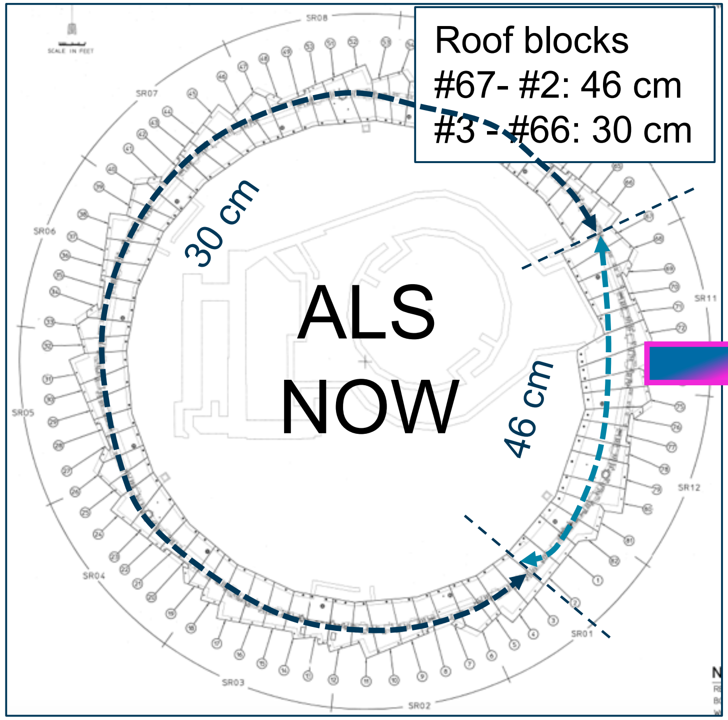
Storage Ring Tunnel: ALARA shielding retrofit

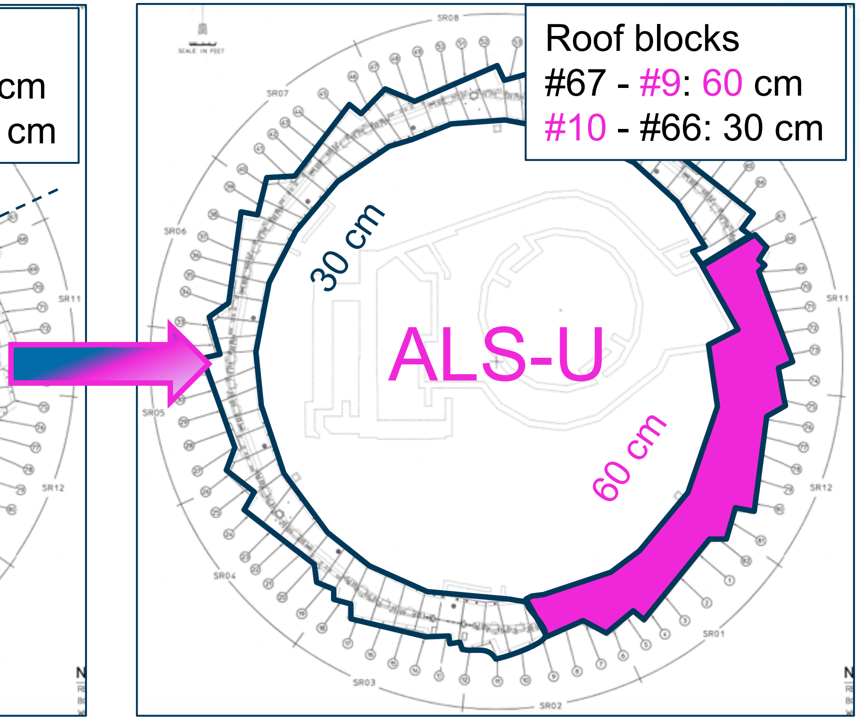
- ALS-U will retrofit the existing shielding within the scope of the Seismic Retrofit required by the new seismic code
- Proposal to add Pb/Steel panels to the ratchet walls where missing

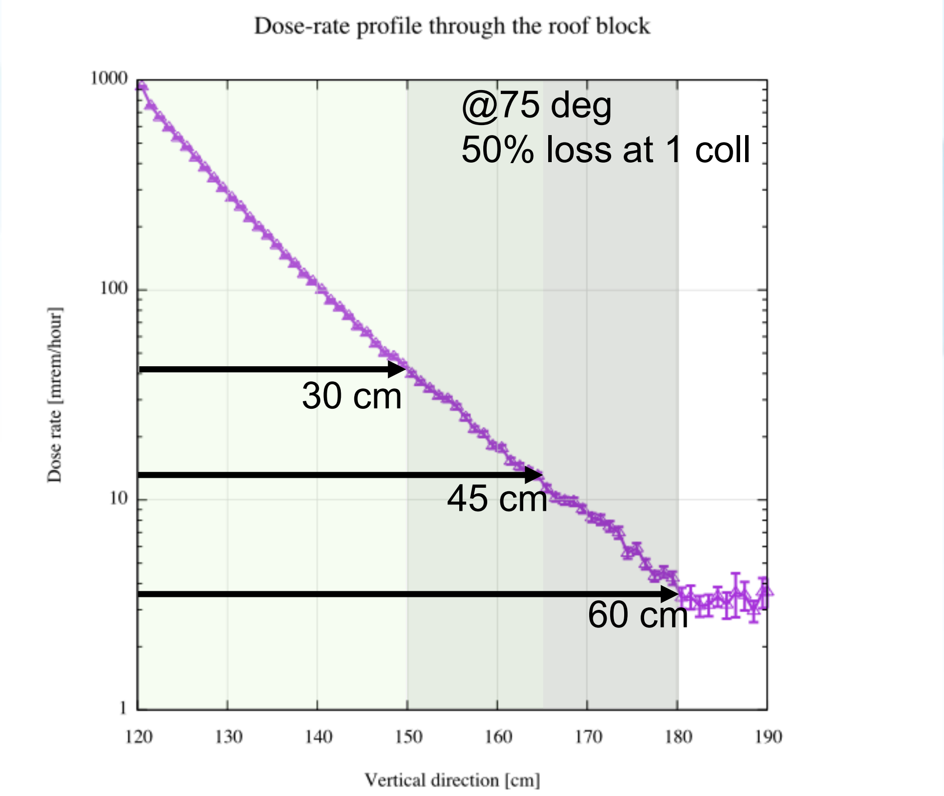


Storage ring shielding: roof blocks

- In the seismic evaluation also thicker roof blocks have been considered, with the plan to increase 26 blocks: 60 cm thick (from the current 30 cm - 45 cm), all other blocks will remain 30 cm thick
- Project decision to retrofit only above injection, 60 cm was chosen for seismic analysis and retrofit planning





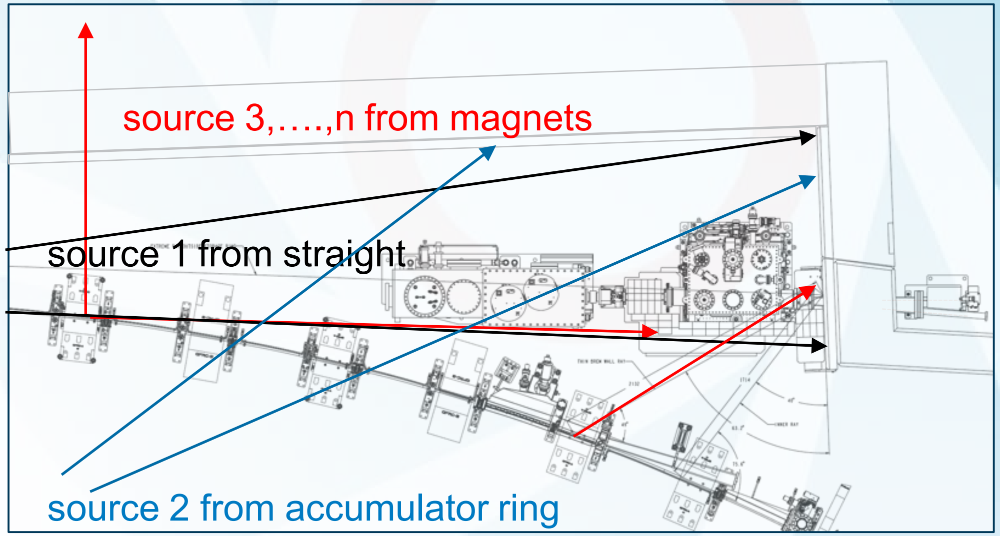


General methodology

- **Motivation**: several different geometry layouts, need for a quick tool to reduce number of detailed MC simulations and adaptable in case of design changes
- **Method**: Semi-analytical method, tailored for existing shielding
  - MC simulations to generate source terms and attenuation lengths in pure materials and layered materials, for several targets and as a function of angles in cylindrical geometry
  - analytical calculations using

$$H(\theta, r, d, \lambda) = \frac{H_1(\theta)}{(r+d)^2} \exp\left[-\frac{d}{\lambda_1(\theta)}\right] + \frac{H_2(\theta)}{(r+d)^2} \exp\left[-\frac{d}{\lambda_2(\theta)}\right]$$

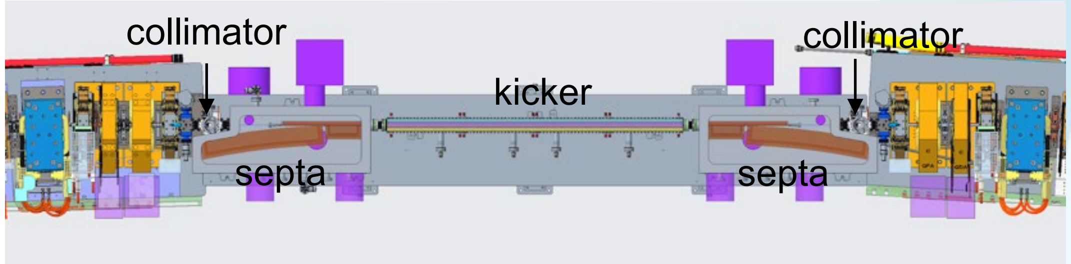
- **Objective: create look-up tables for radiation type, target type and shielding material** so that shielding thickness can be calculated without having to run time-consuming simulations
- Realistic simulations used only for specific cases: labyrinths, penetrations, complex layouts



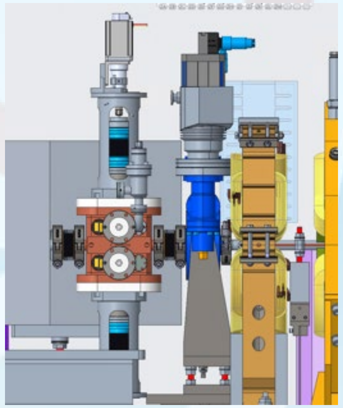
Given concrete thickness:
- which sources (loss type, distance, angle)?
- how much lead or steel for lateral wall?
- how much lead for side wall?
- how much lead/iron for local shielding?

Key references

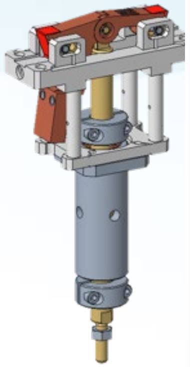
S. Agosteo et al. Nucl. Instr. and Meth. B 265 (2007), 581-598
S. H. Rokni et al. Rad. Prot. Dosim. 115 (2005), 200-206

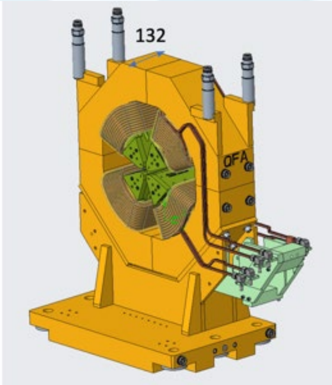


- **Monte Carlo simulations with FLUKA:**
  - 2 GeV electron beam on 3 targets representative of ALS-U loss points: collimators, septa/ID, magnets
  - spectra and doses from 0 to 90 degrees in cylindrical-symmetry geometry, bin size optimized to decrease CPU time while keeping < 5% statistical error
  - shielding represented by either **pure concrete** or **Pb + concrete** or **Steel + concrete**
  - separated simulations to remove cross-talks from neutrons generated at 0 degrees that would not contribute to 90-degrees dose

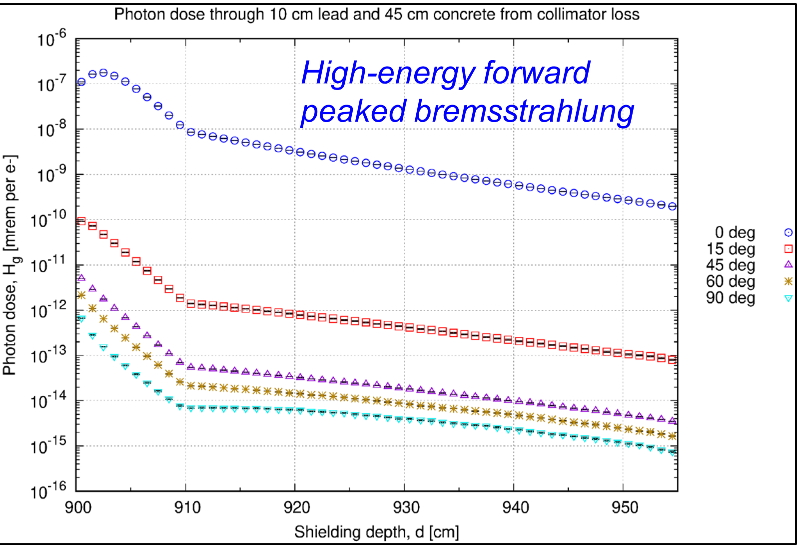


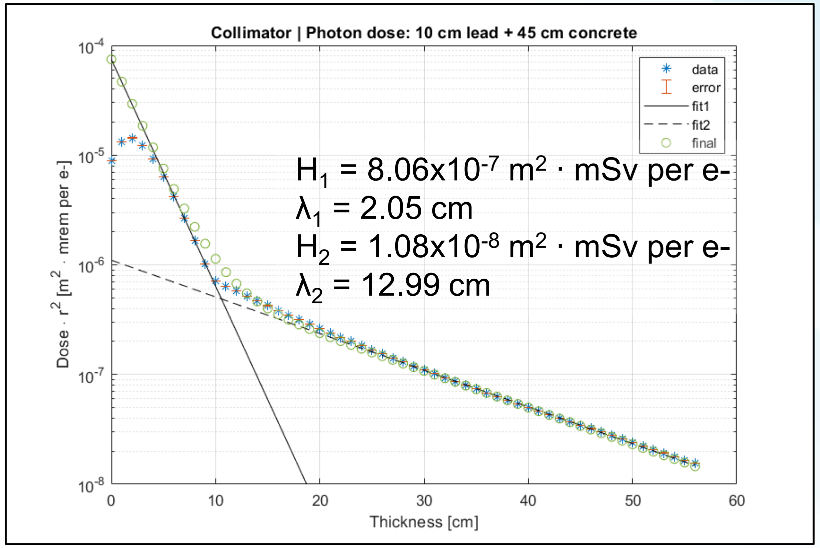
- **Analytical analysis with Matlab:**
  - dose attenuation curve fit with double exponential formula to get $H_{1,2}$ and $\lambda_{1,2}$
  - script to calculate dose where input parameters are: target type, loss intensity, angle, shielding material, distance, dose goal (optional)

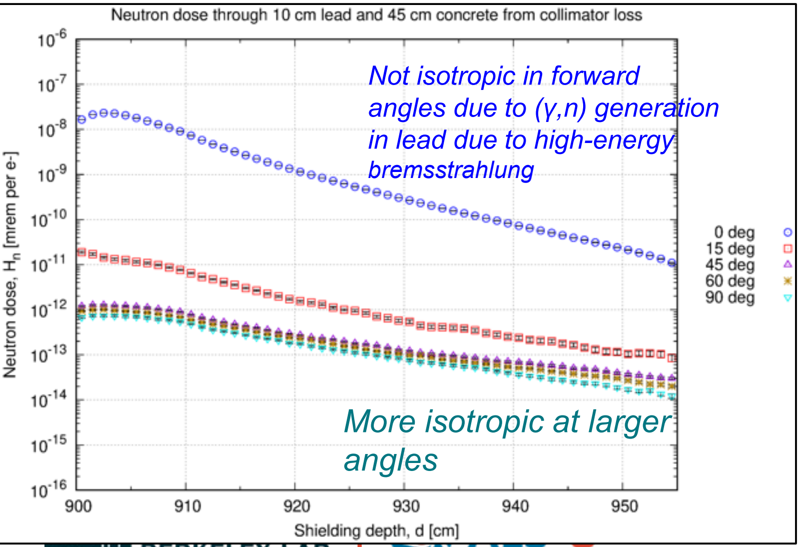


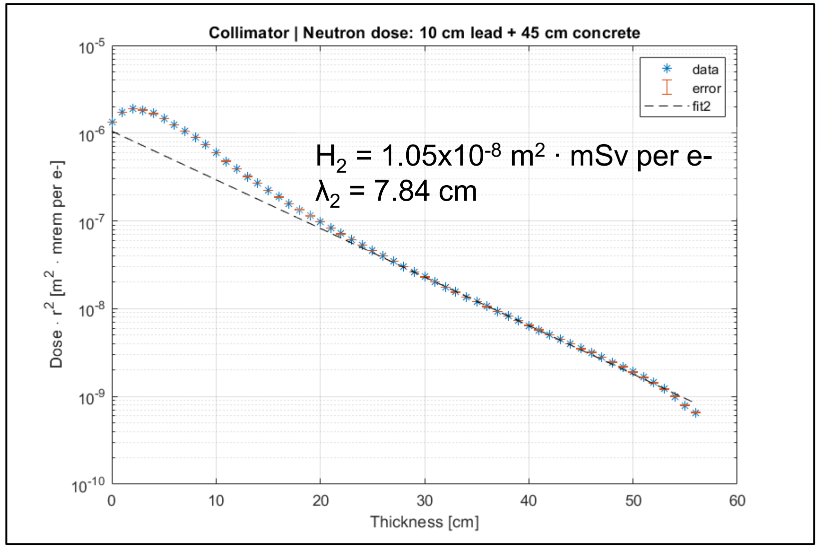


Dose attenuation curves: fit









Photon and neutron dose through 10 cm lead and 45 cm concrete for beam loss on a collimator

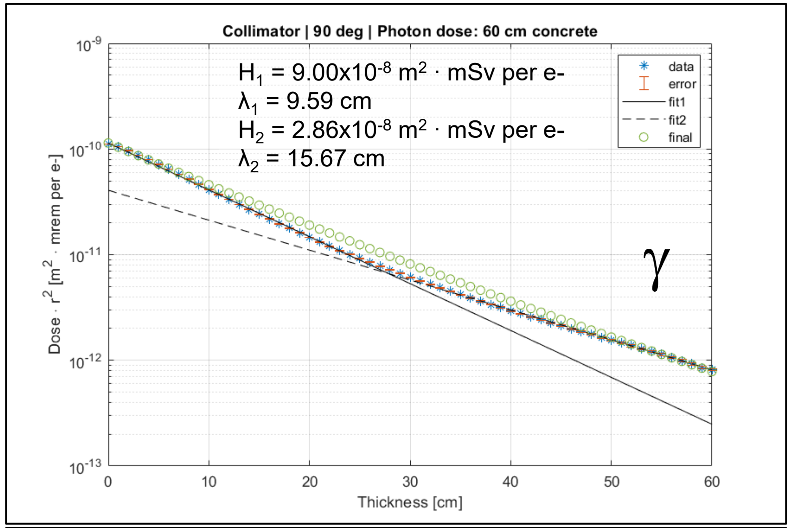
- Photons: two attenuation lengths λ_1 and λ_2 corresponding to Pb and concrete
- Neutrons: build-up region within starting ~10-20 cm followed by equilibrium attenuation length λ_{eq}

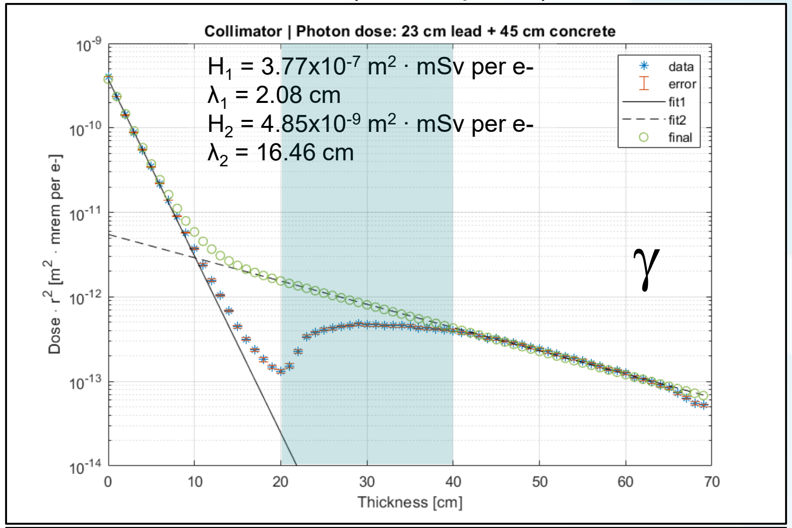
Examples of fitting and obtaining H and λ

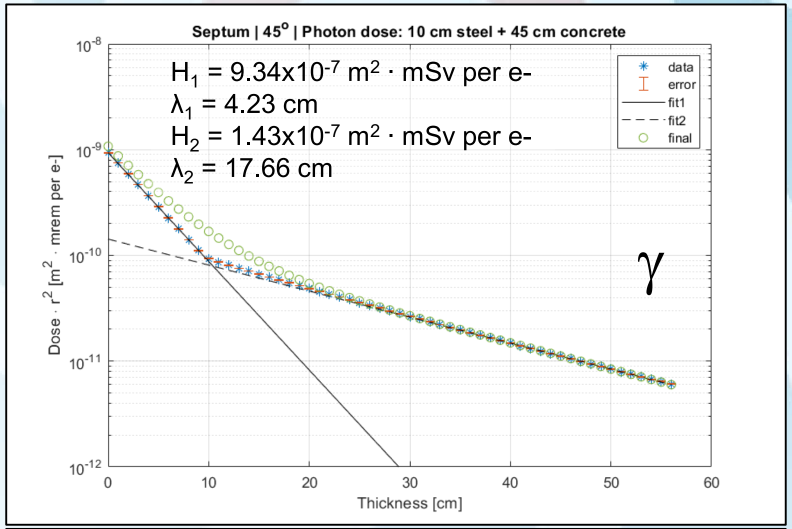
90° dose curves with only concrete shielding (i.e., roof)

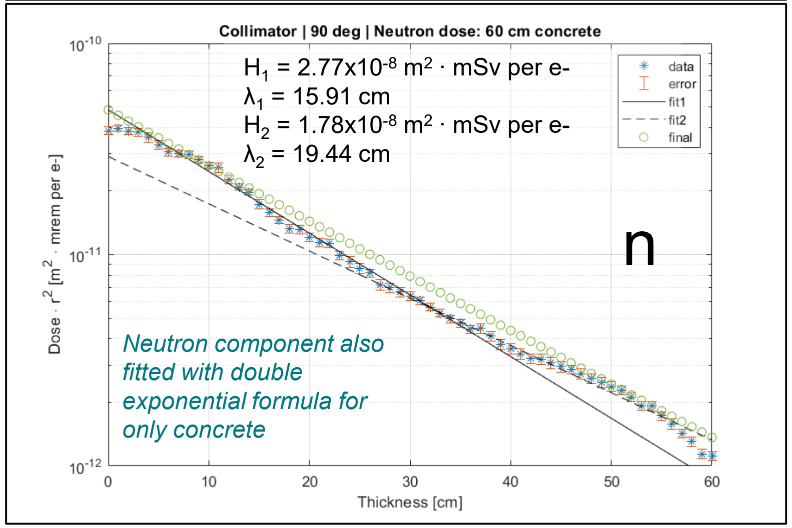
45° dose curves for 23 cm Pb (bb+Pb panel) and 45 cm concrete

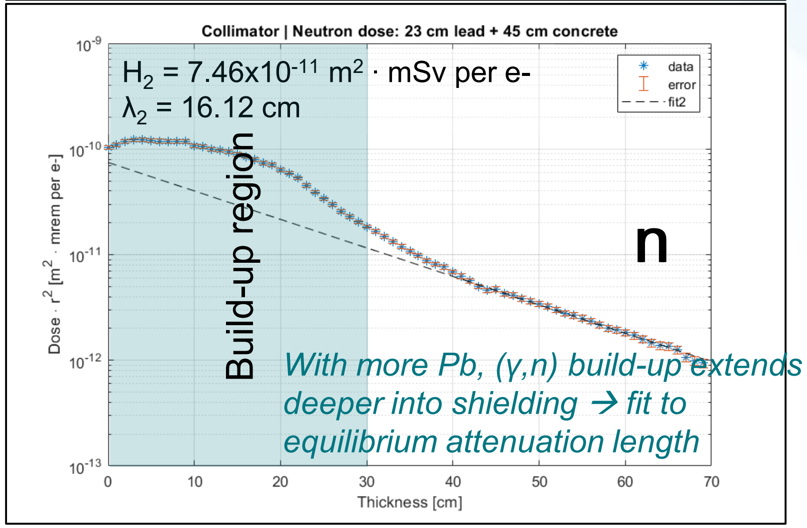
45° dose curves for 10 cm steel and 45 cm concrete

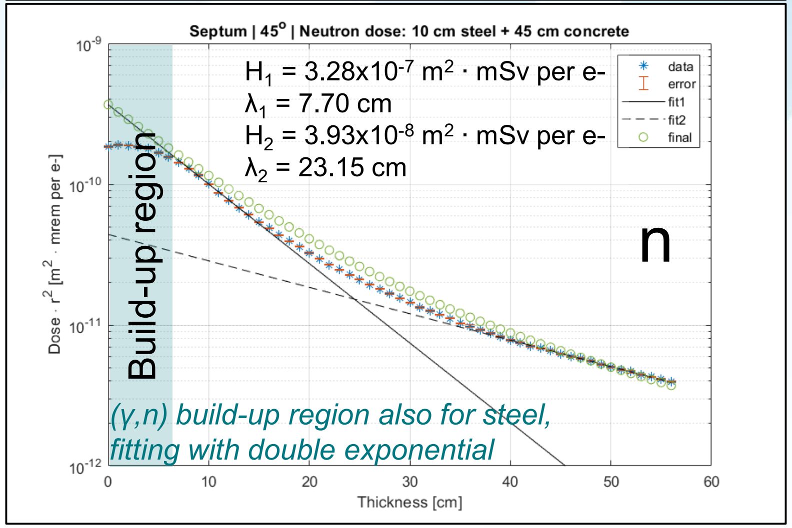




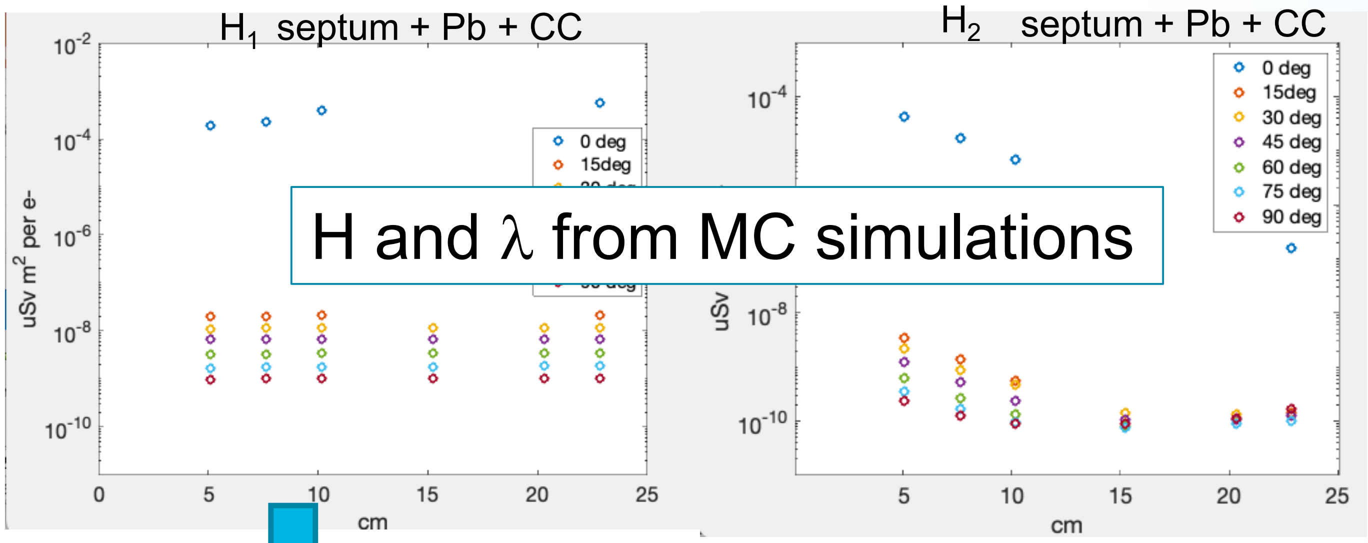








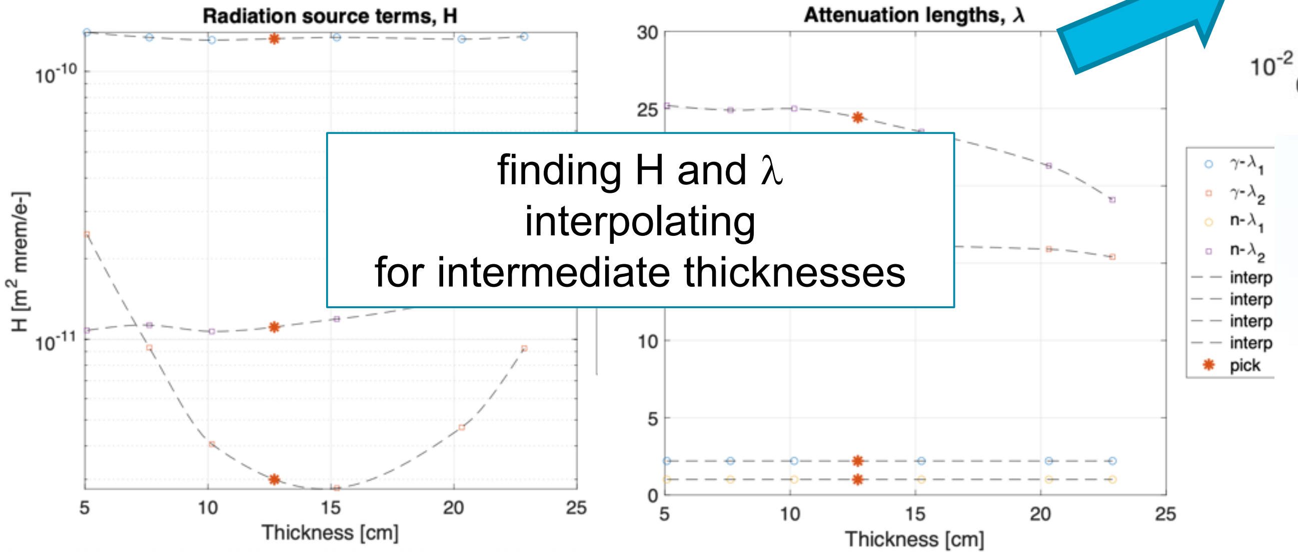
Workflow



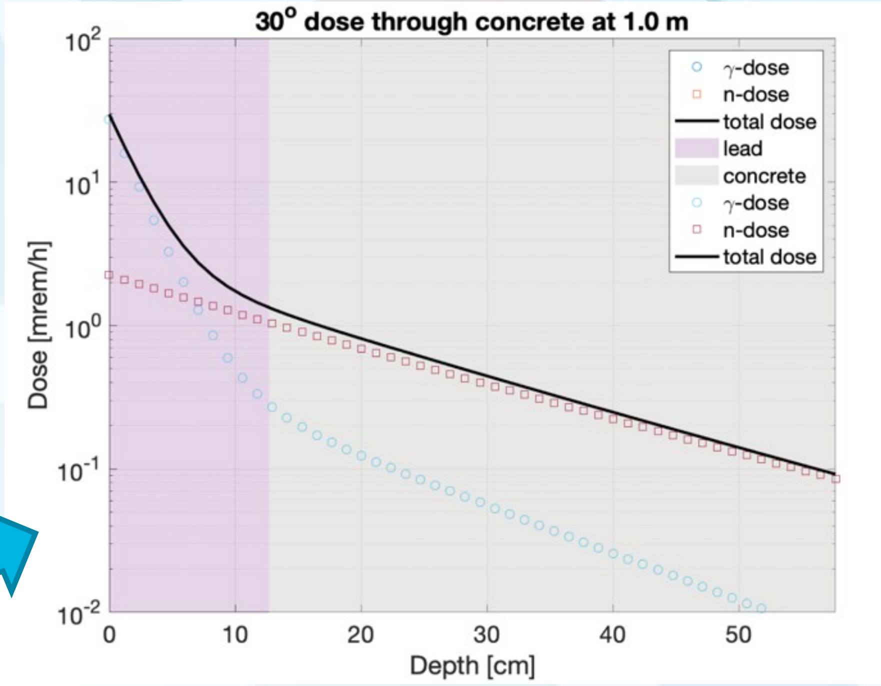
H and λ from MC simulations

Input

Target type
Shielding materials
Shielding thickness
distance
angle

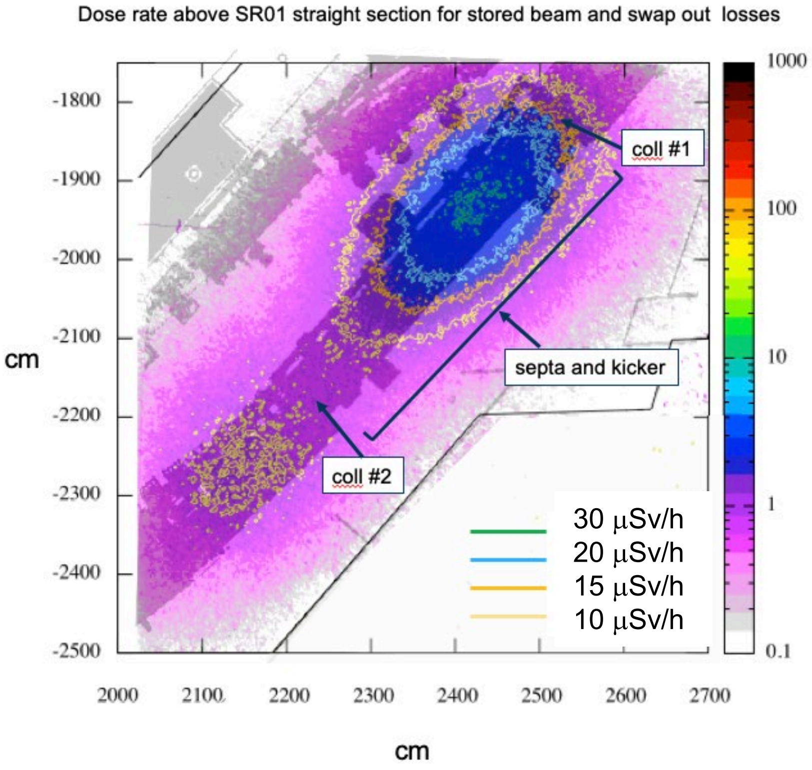


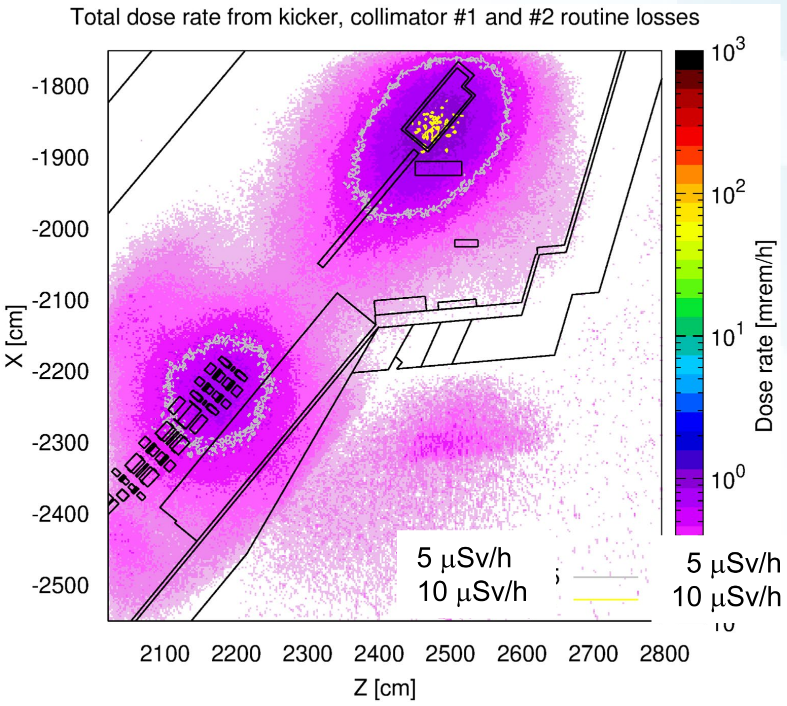
finding H and λ
interpolating
for intermediate thicknesses

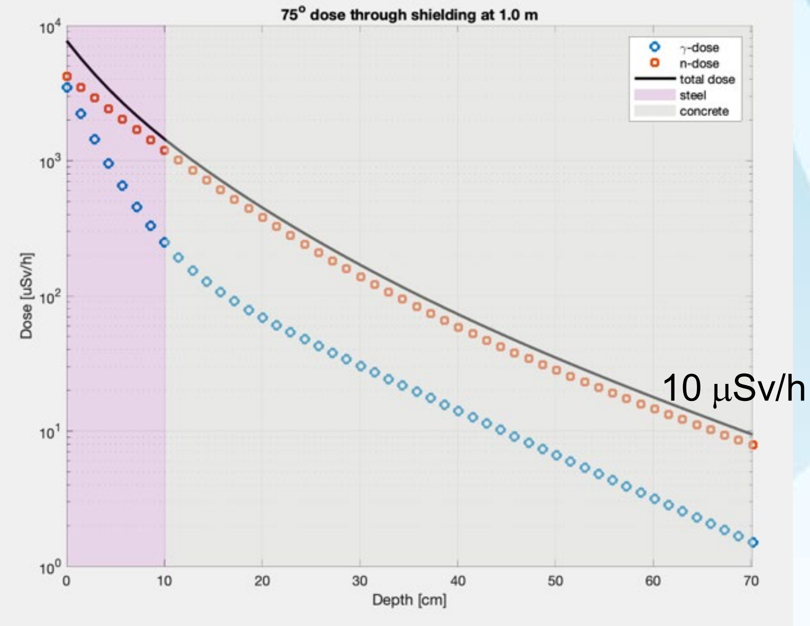


Comparison with realistic-geometry simulations (1)

calculated 10 cm steel to add to 60 cm CC to lower dose from 30 to 10 uSv/h

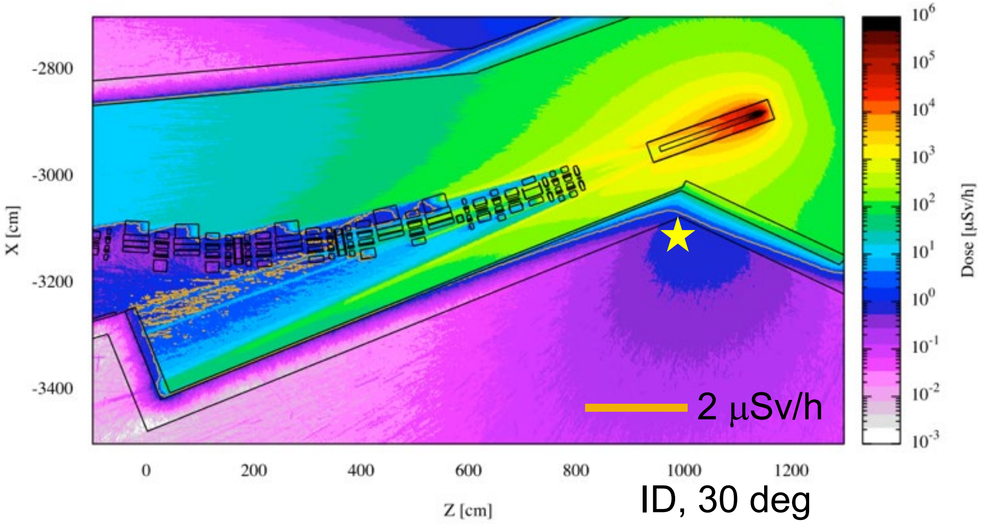






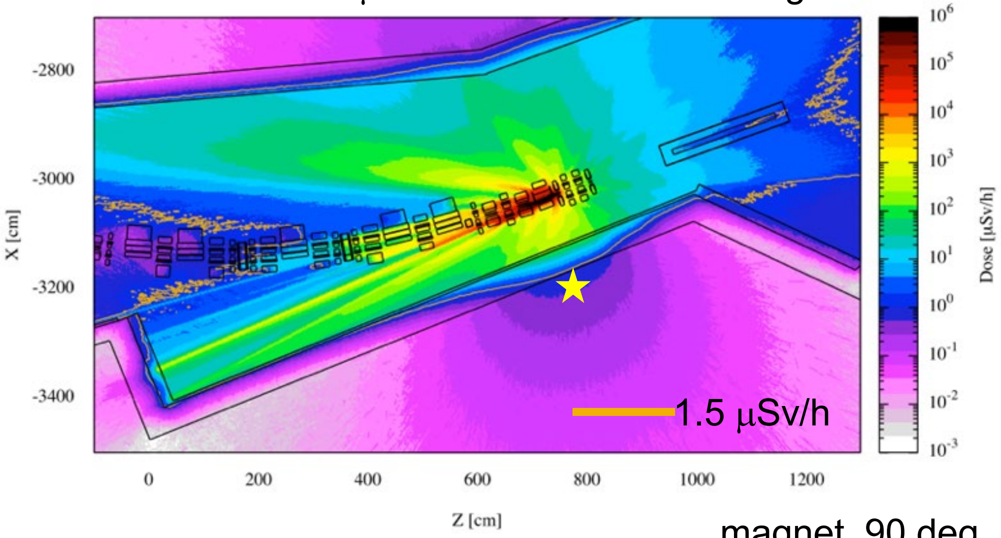
Comparison with realistic-geometry simulations (2)

calculated 2 μSv/h outside the shielding



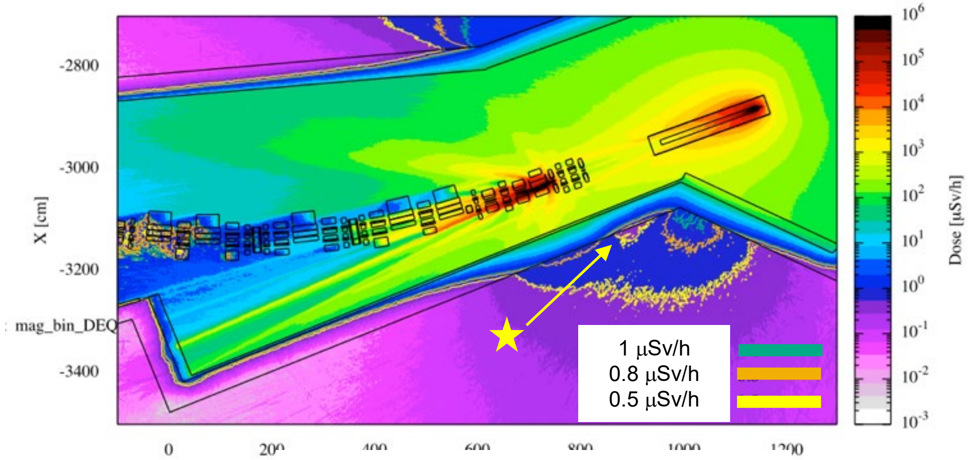
ID, 30 deg

calculated 1.5 μSv/h outside the shielding



magnet, 90 deg

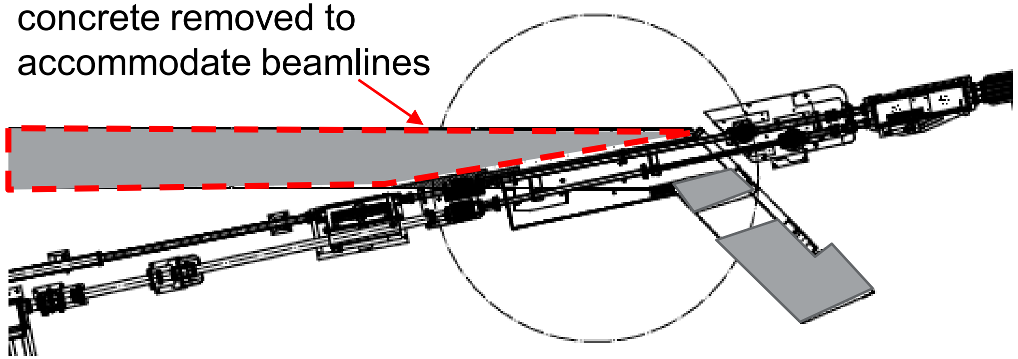
calculated 0.8 μSv/h outside the shielding



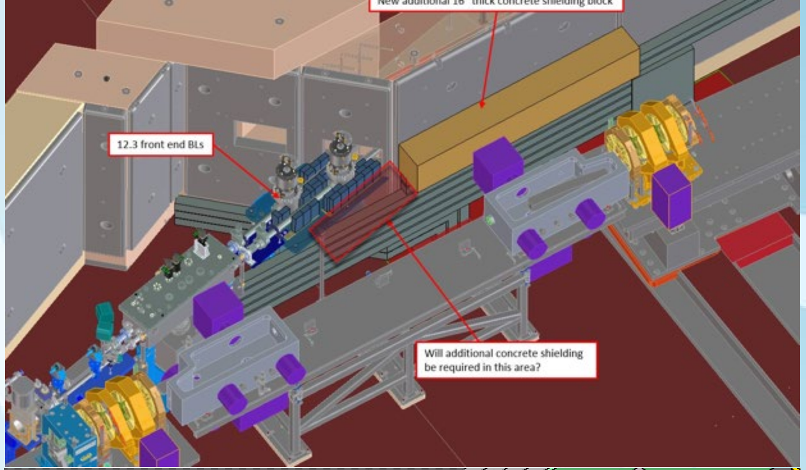
magnet, 90 deg + ID, 30 deg

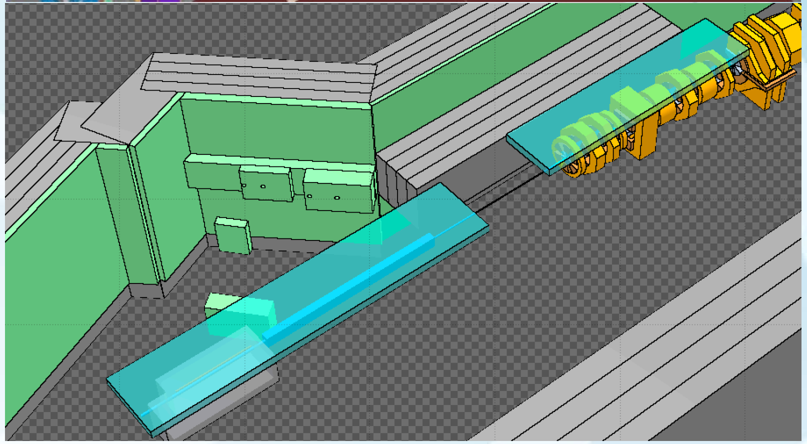
SR01 special case

concrete removed to accommodate beamlines



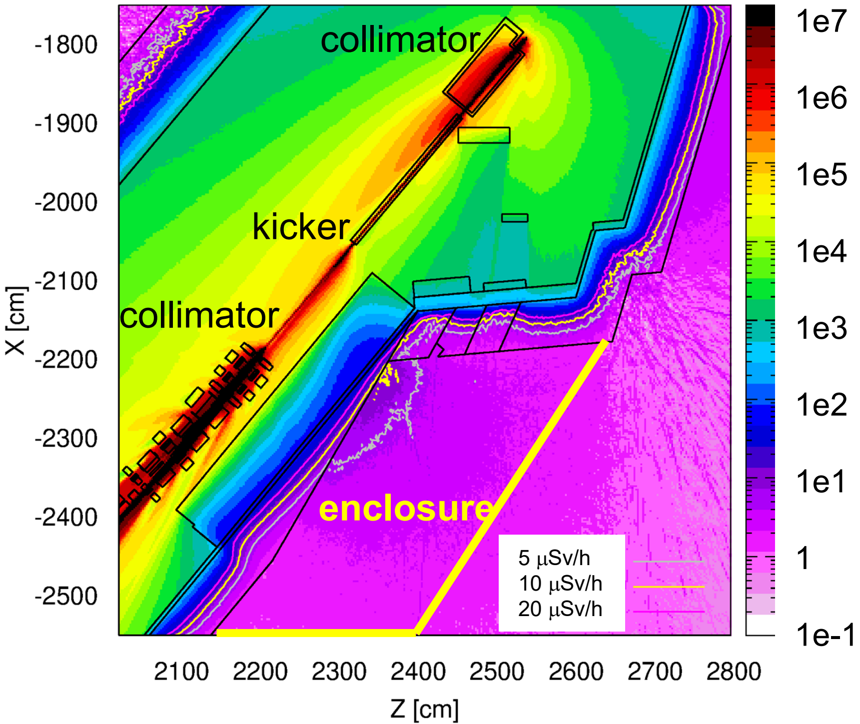
supplemental CC shielding thickness was calculated with toolkit and then realistic simulations ran to confirm





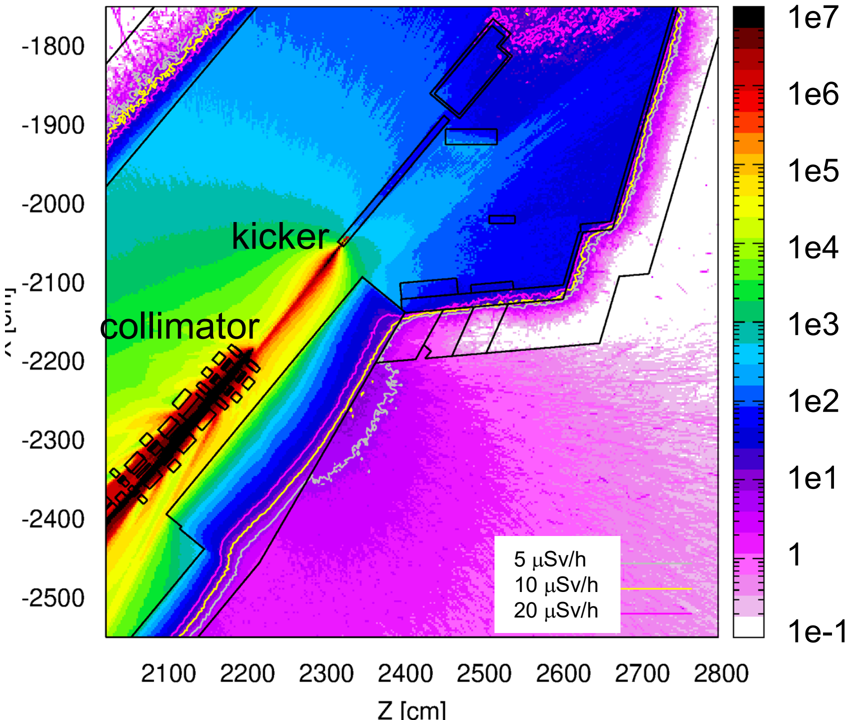
70 cm CC + 5 cm Pb → 5 - 10 μSv/h

Total dose rate from kicker, collimator #1 and #2 routine losses

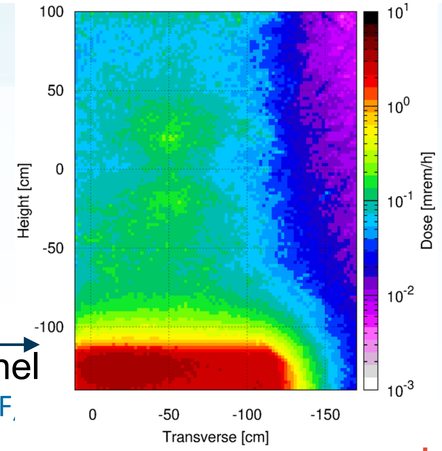


70 cm CC 5 → 10 μSv/h (no collimator #1 loss)

Total dose rate from kicker, collimator #1 and #2 routine losses

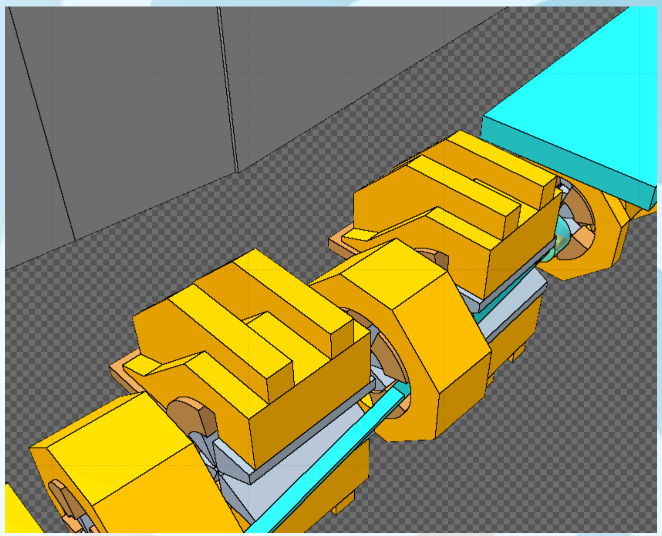


effect of Pb panel on trans wall

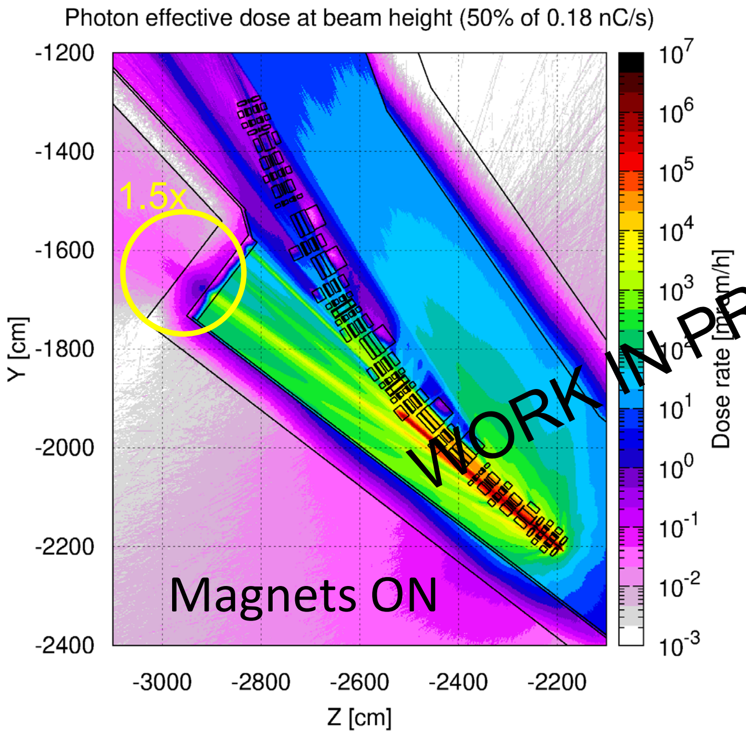


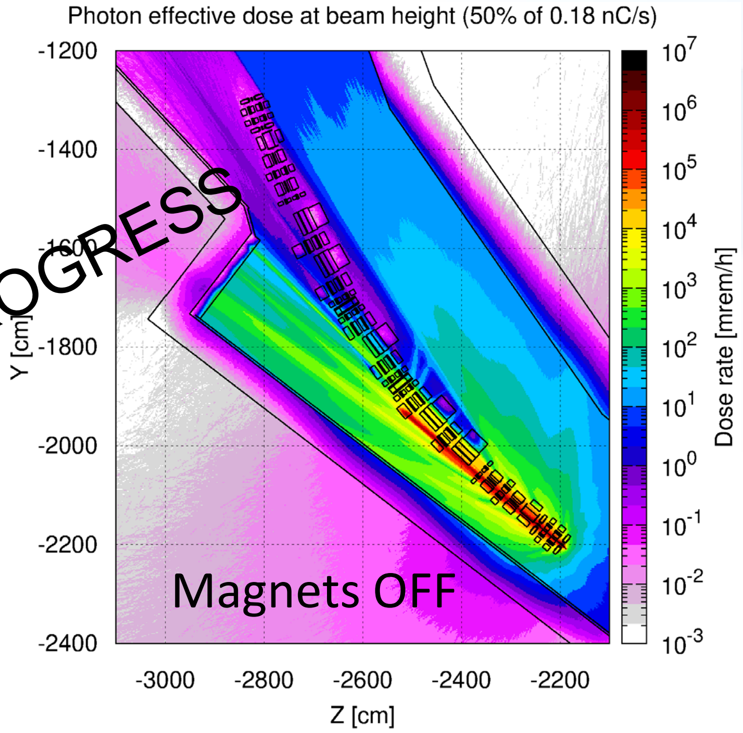
no panel

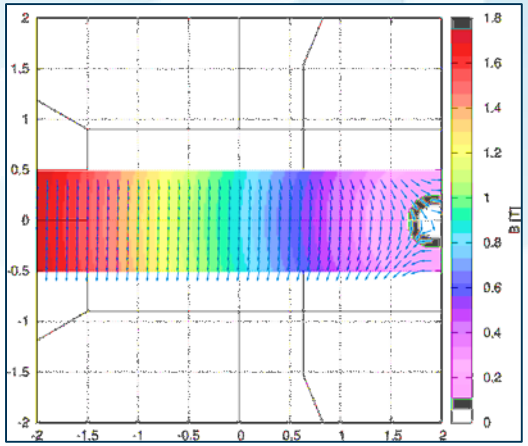
Effect of magnetic fields on dose



- Implemented B-fields for magnets, including focusing effect of combined-function magnets



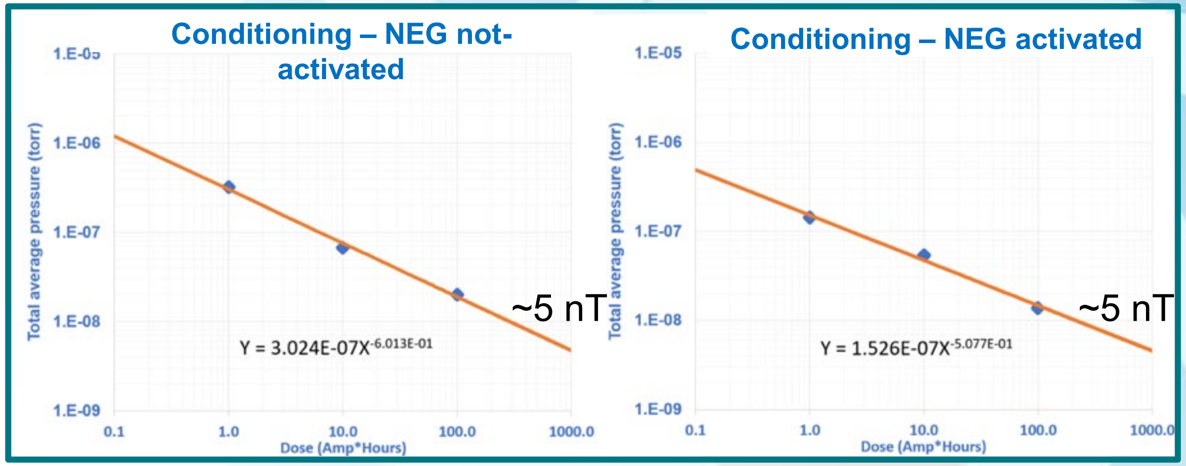


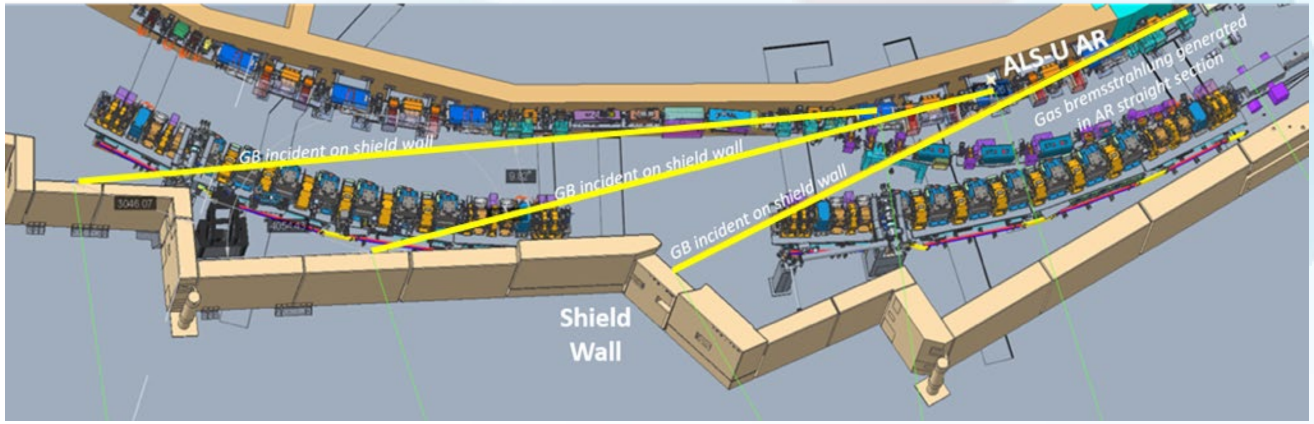


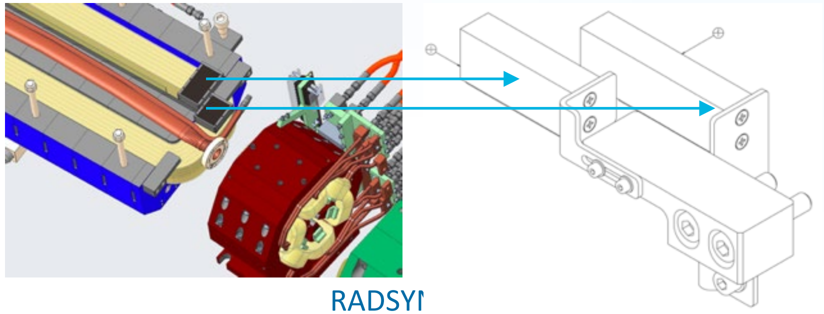
Gas bremsstrahlung (GB)

- GB from SR already shielded with Pb belly bands and with collimators and stops along the beamlines
- GB from AR directed towards ratchet walls at ~2 m
- Calculations for 14 nTorr (50 nTorr abnormal), air composition instead of residual gas
- Lengths: 9.6 m and 2.8 m
- Unshielded dose > 10 μSv/hour (nominal pressure)
- Shielding requirements: local tungsten blocks at dipole exit

Accumulator Ring



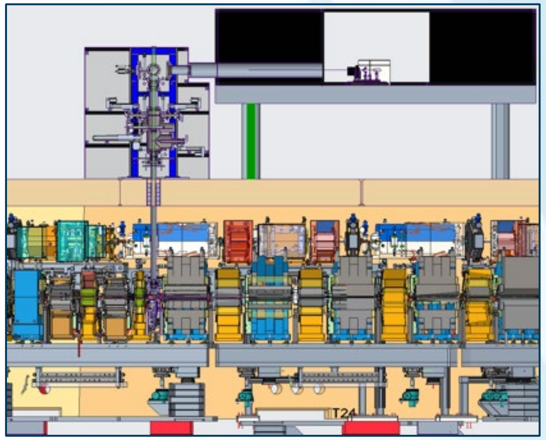


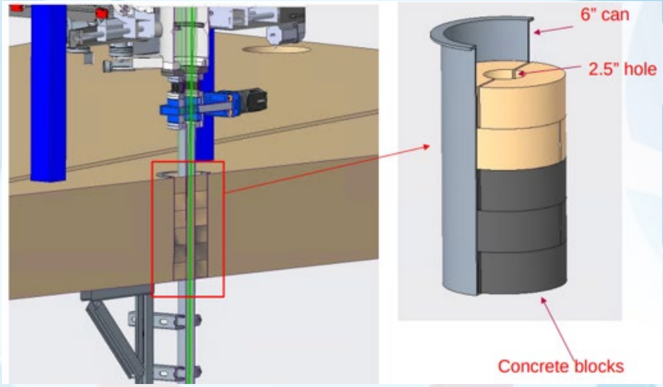


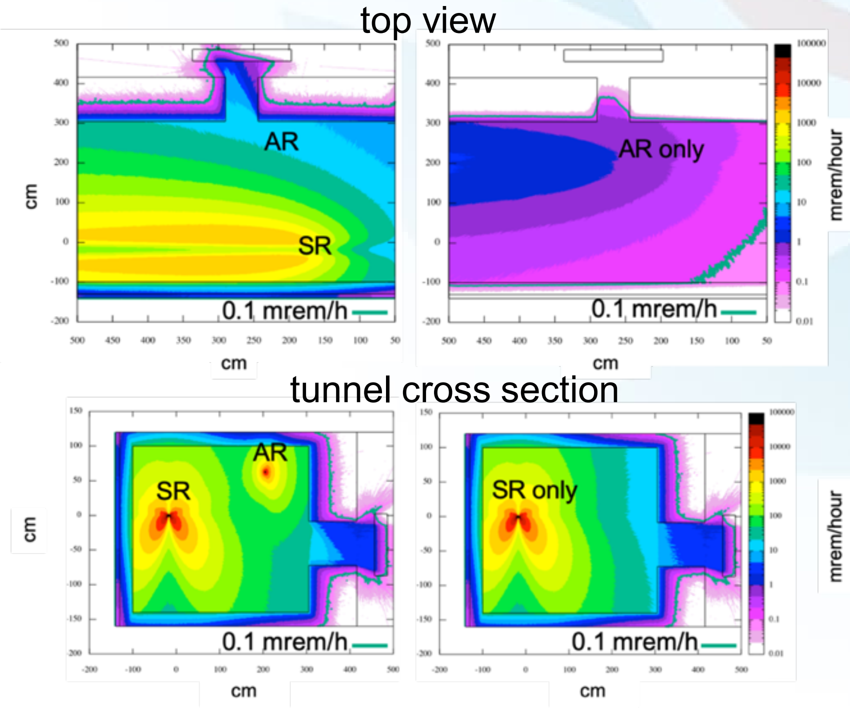
RADSYN

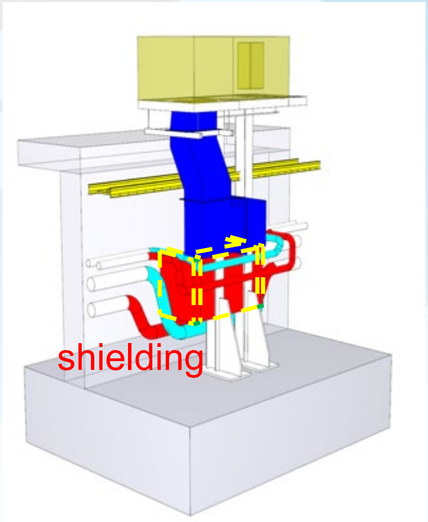
Penetrations

- Diagnostics beamlines on roof blocks, need for two 15 cm diameter penetrations, concrete plug around vacuum pipe and dog-house shielding above the penetration
- HVAC: 50 cm x 50 cm apertures in the inner wall. Already drilled and shielding has been commissioned, concrete blocks with steel and polyethylene wings
- Electrical (Φ < 15 cm): no shielding but at no more than 30 cm height; existing ones at ceiling level on the inner wall all already closed or will be before AR commissioning



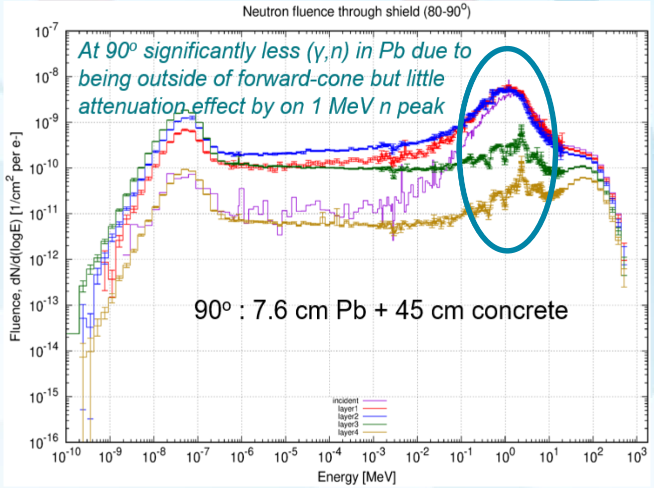






Accelerator shielding requirements

- With the 30-60 cm ratchet walls, shielding retrofit assumptions on Pb thickness adequate to meet design goals on the experimental floor, **with local shielding:**
  - **10 cm** steel "car-port" to cover the collimator areas for lateral shielding
  - **Pb** in the fwd direction, in addition to Pb panels and belly bands for all transition walls, also at floor level
  - W blocks in AR dipoles
- **Steel panels** to be used on side walls
- In general side walls panel can start 30 cm above the floor
- Doses on the unmodified roof blocks (30 cm) can be as high as 15 μSv/hour without any retrofit and access to the roof will be limited with exclusion zones and regulated with badge entrance
- Doses on retrofitted blocks (60 cm) will be below limits, except for the collimator area
- All calculations include several safety factors: loss input x2, no effective shielding length for angle > 60 deg, gas pressure 3x higher, used 50% of total losses at 1 collimator at a time



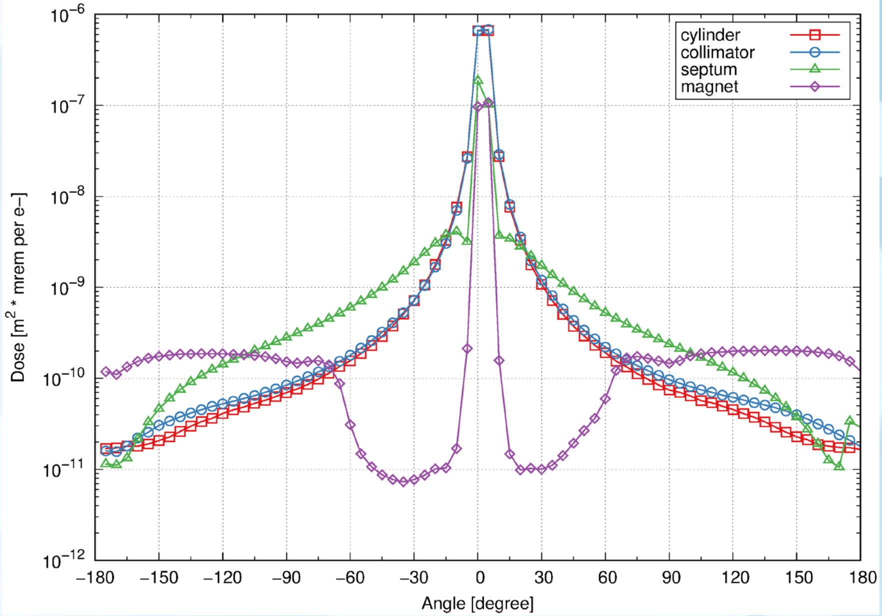
Conclusions

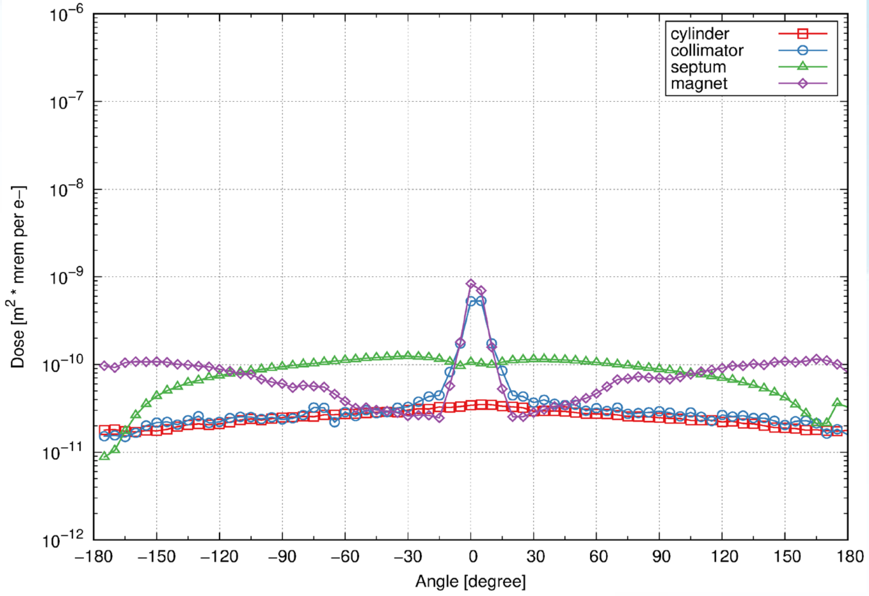
- Developed a semi-analytical toolkit to calculate dose and shielding requirements without having to re-run MC simulations (after the initial effort)
- Benchmarked with realistic layout simulations: for angles > 60 deg results are very close, it slightly overestimates by a factor 1.5 – 2 at small angles, which is expected due to the lower attenuation of the forward showers
- Useful for most shielding calculations, still realistic simulations are needed for complex layouts
- Limited to the ALS-U case, not a universal tool!


THANK YOU

Targets

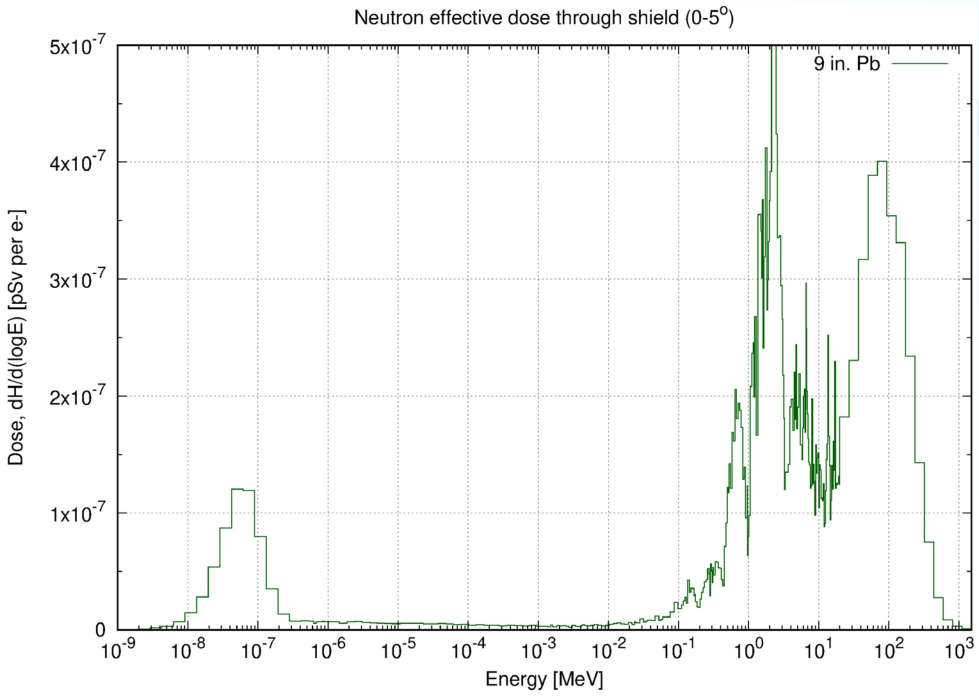
- Collimator (followed by magnets) is 6 cm long, height of 1 cm, depth of 1.35 cm, curvature radius of 4.25 cm
  - along the beam axis, the thickness is 4 cm or ~3 X_0 (Cu radiation length is 1.436 cm)
  - at the beam axis, the lateral thickness is 0.5 R_m (Molière radius is 1.568 cm)
- Septum is 6 cm high, the wall thickness 2 cm, the length is 100 cm and the electron beam is incident with a grazing angle of 1 mrad
- Magnet: coils inner diameter is 5.8 cm, outer diameter is 20.8 cm, + 5 cm yoke, 40 cm long (beam first interacts with a 0.135 cm thick stainless-steel pipe)





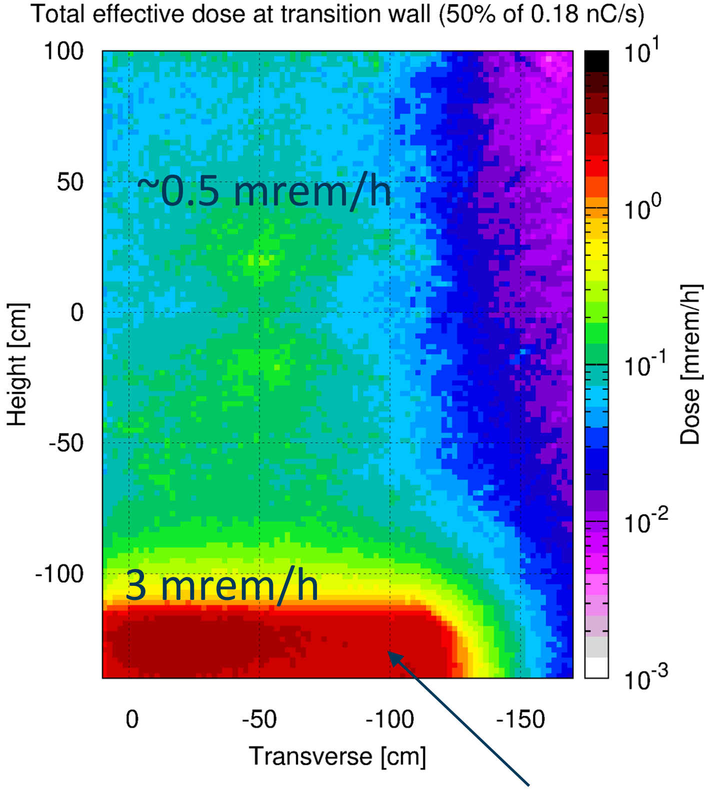
Neutron dose

- Dose vs energy for neutrons exiting the transition wall concrete

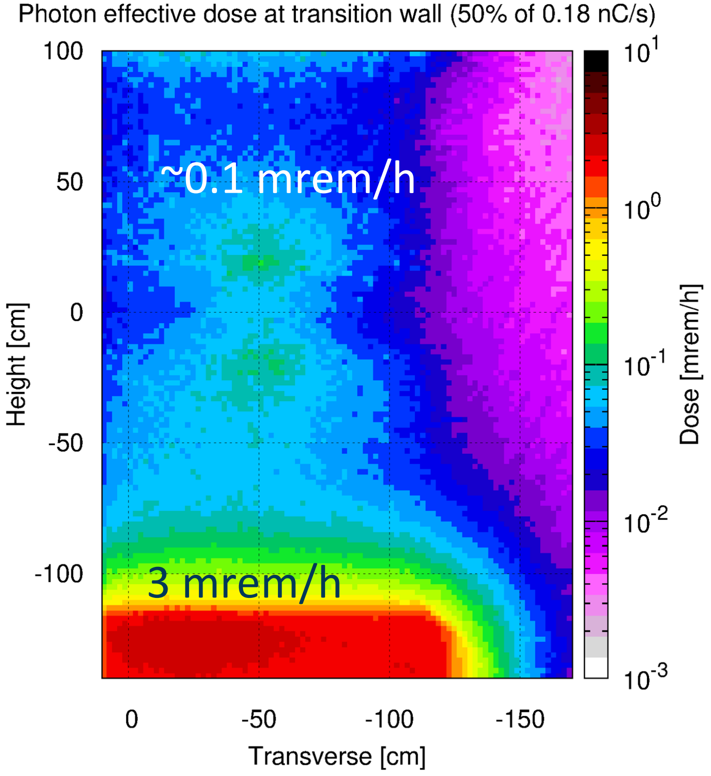


Looking at the transition wall from outside: Dose rate

Total dose rate



Photon only



Very clearly observe the effect of the Pb panel not reaching completely to the floor

Swap-out radiation hazards

- An errant electron bunch train reaching the experimental floor through a beamline for both ALS/ALS-U would result in a very high dose

30 nC e- beam, 2 GeV on the white beam mask

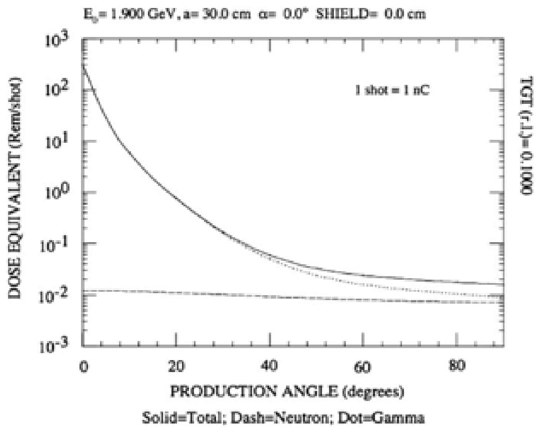
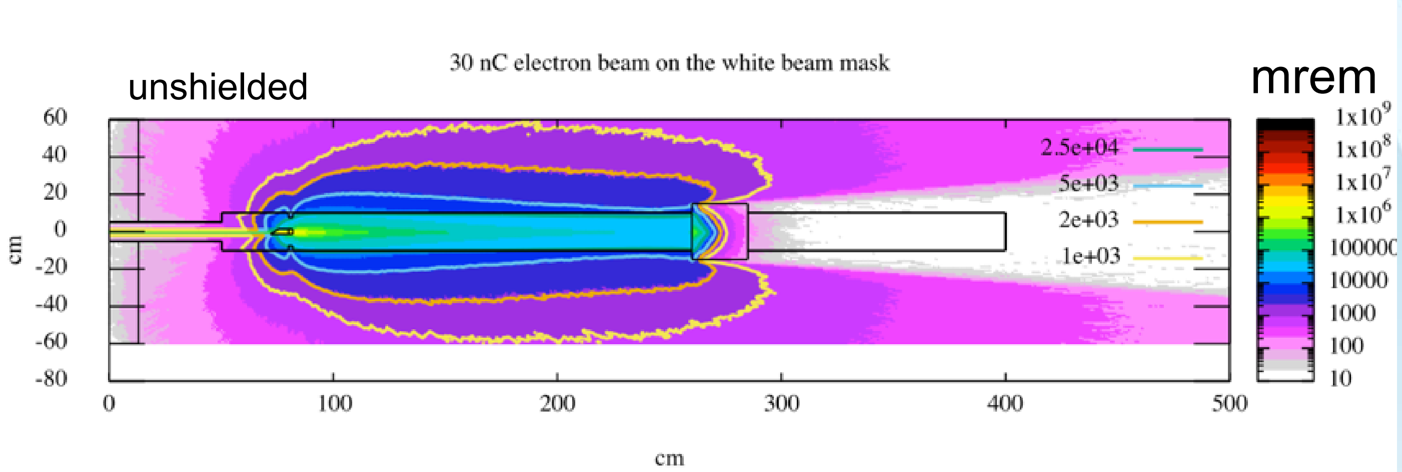
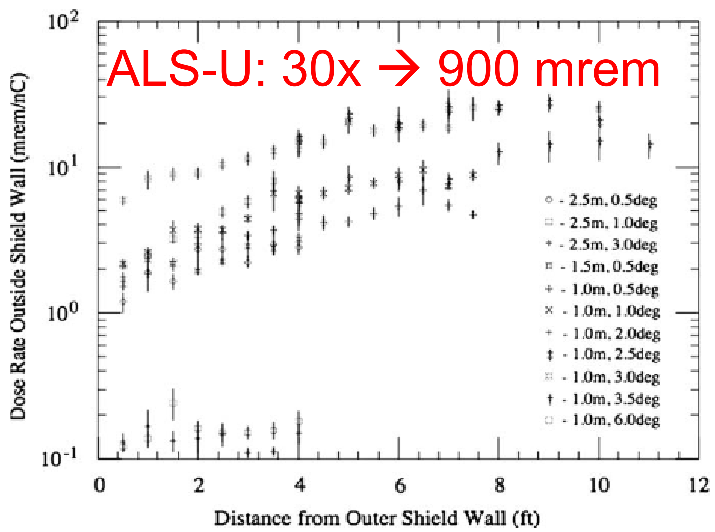


Fig. 6. Dose from a 1.9 GeV, 1 nC electron beam hitting an optimum thin target radiator. Dose is calculated as a function of incident electron beam angle and at a distance of 30 cm from the target. Results were calculated with the SLAC SHIELD11 [12] analytic model.

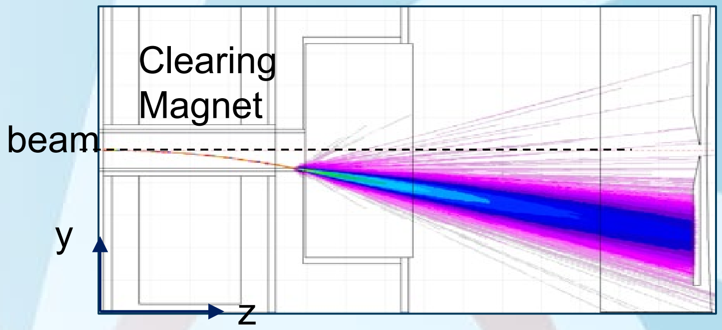
ALS-U: 30x



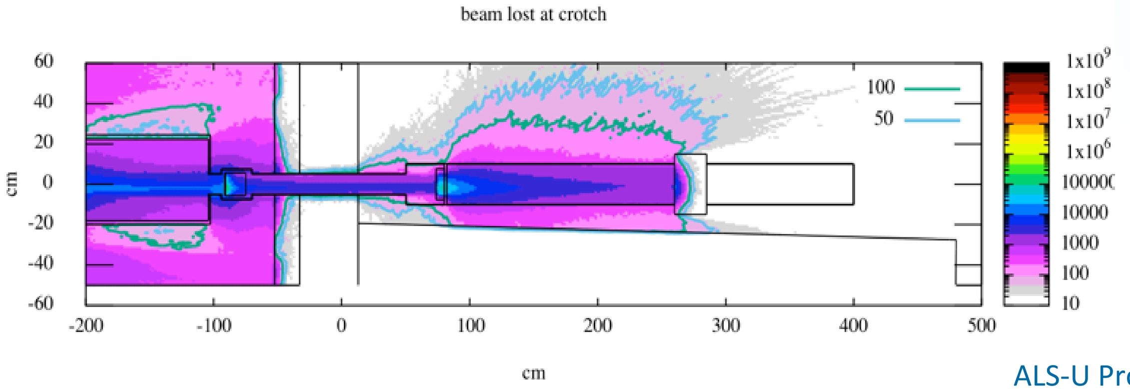
- An errant electron bunch train lost inside the shield walls with open shutters would generate bremsstrahlung that propagates along the beamline and generates high doses on the experimental floor



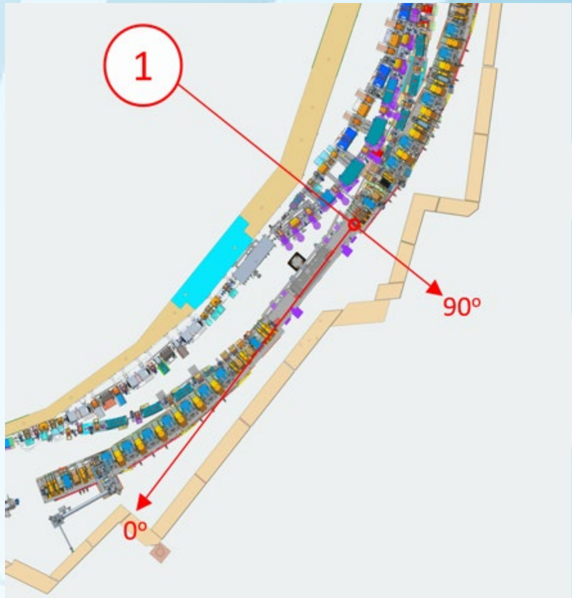
Swap out controls and mitigations



- Presently, at the ALS, several controls are in place to prevent it and mitigate its consequences: top-off credited apertures (TOCAs), beam energy and current interlocks, shielding and interlocked radiation monitors. The positions of the TOCAs have been determined with extensive tracking simulations that took a couple years and required well defined specifications of all magnets
- ALS-U, while keeping all the other controls, has decided to use clearing magnets instead of the TOCAs: the clearing magnets are now in baseline, and preliminary RP analyses have demonstrated the benefit of this strategy
- A full analysis has been performed specifically for beamline 5.0 (wiggler) and has been internally reviewed
- More analyses are needed to evaluate existing shielding and potential need for improvement

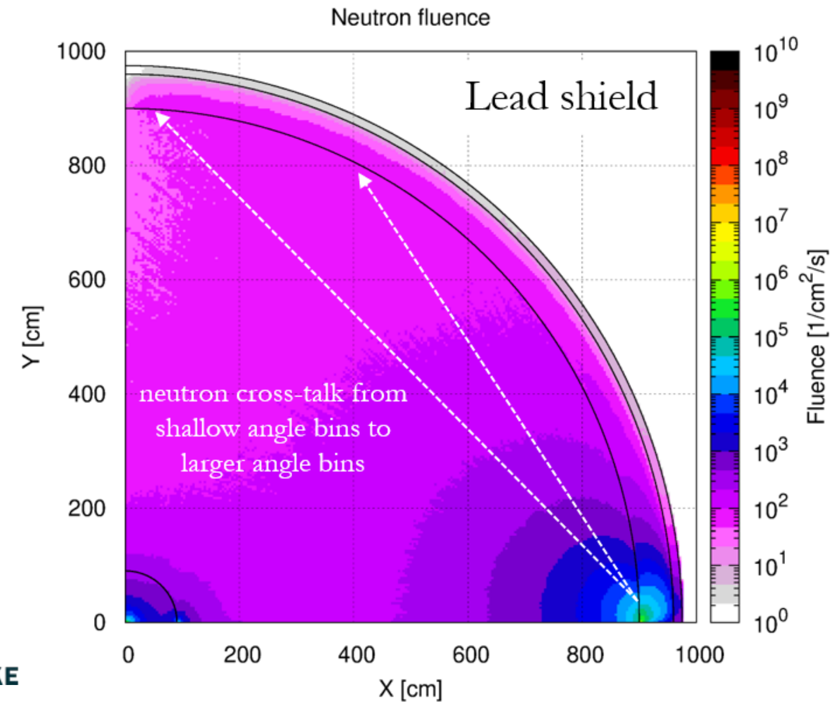


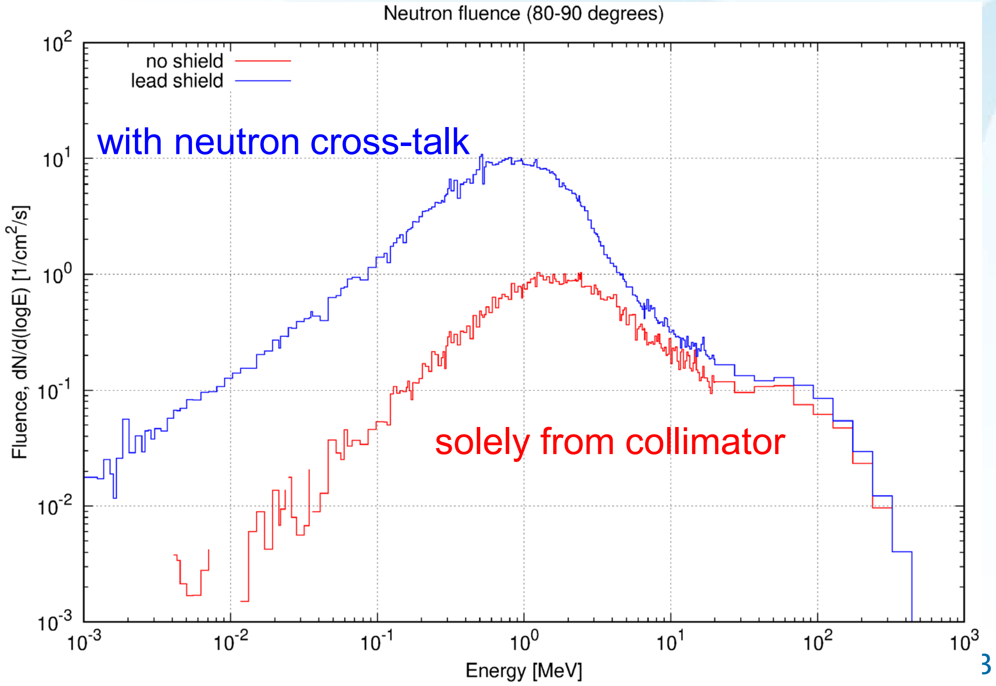
Neutron cross-talk



Back-scattered neutrons from (γ,n) generated in forward angles due to high-energy bremsstrahlung lead to overestimate of neutron source term and underestimate of attenuation length at lateral angles

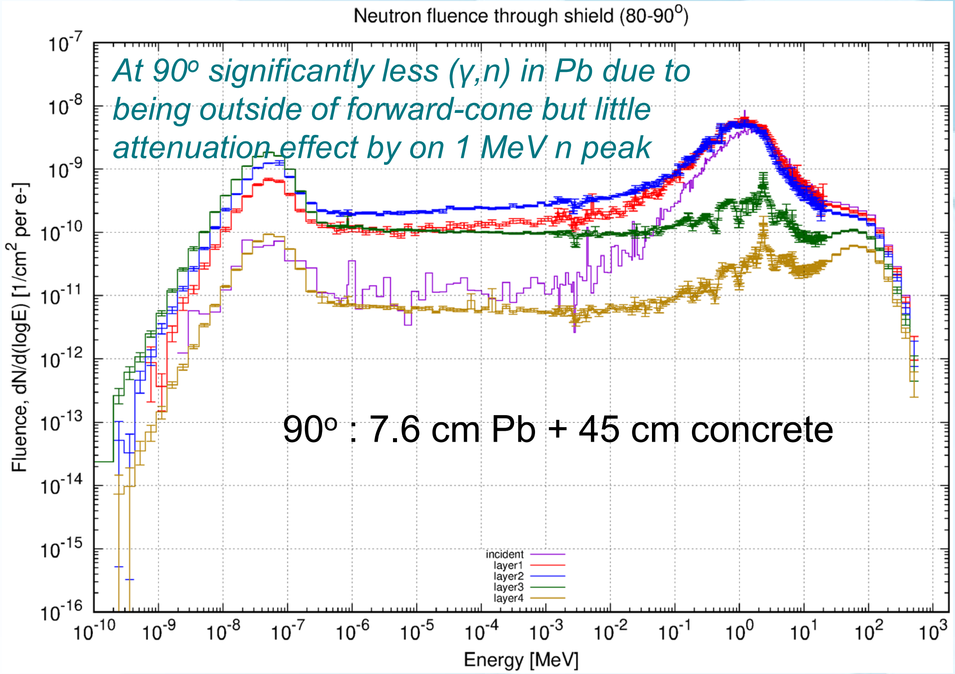
Solution: Substitute shielding at 0-30° to blackhole in the simulation and run separately for larger angles 30-90°

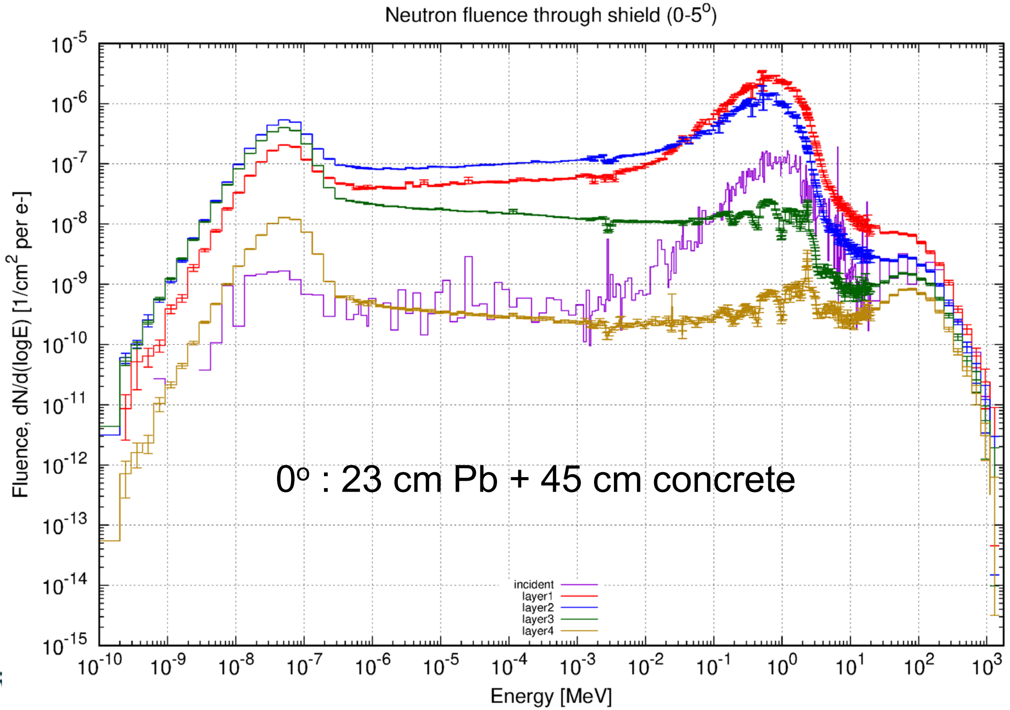


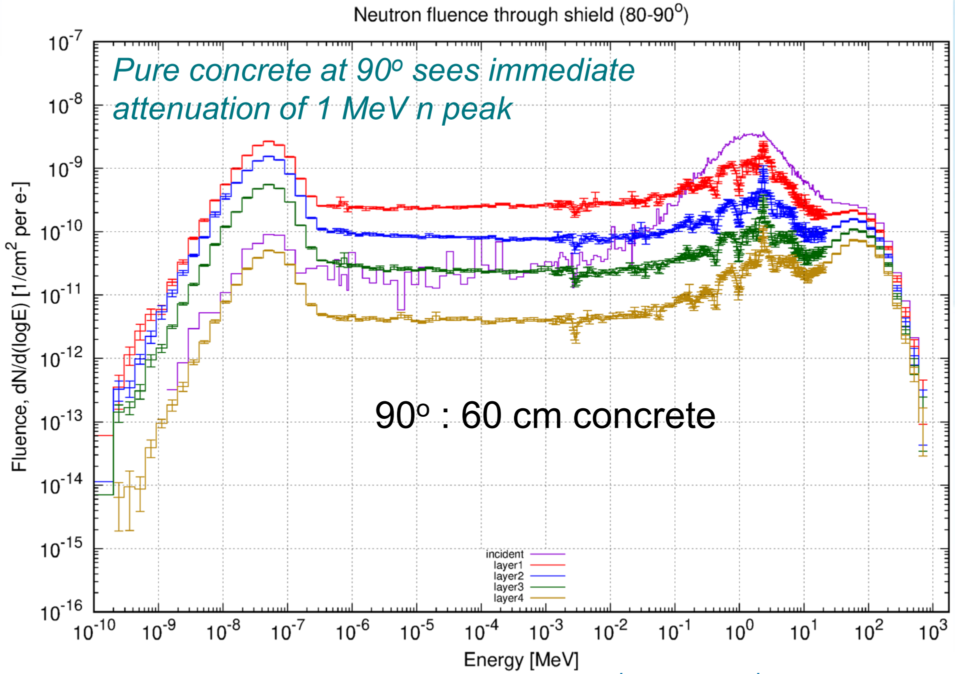


Neutron energy spectra

At 0º large number MeV-range neutrons are generated via (γ,n) from forward-peaked high-energy bremsstrahlung within Pb shielding as seen below

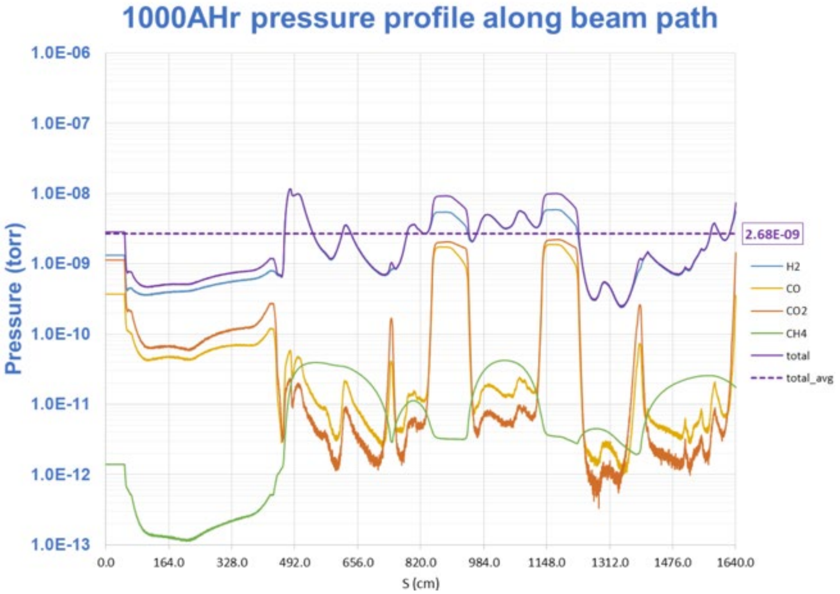


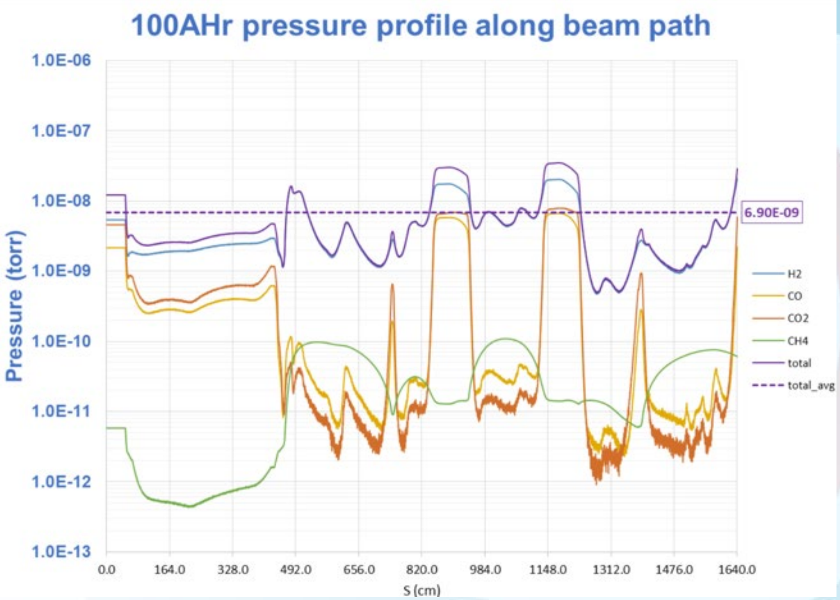


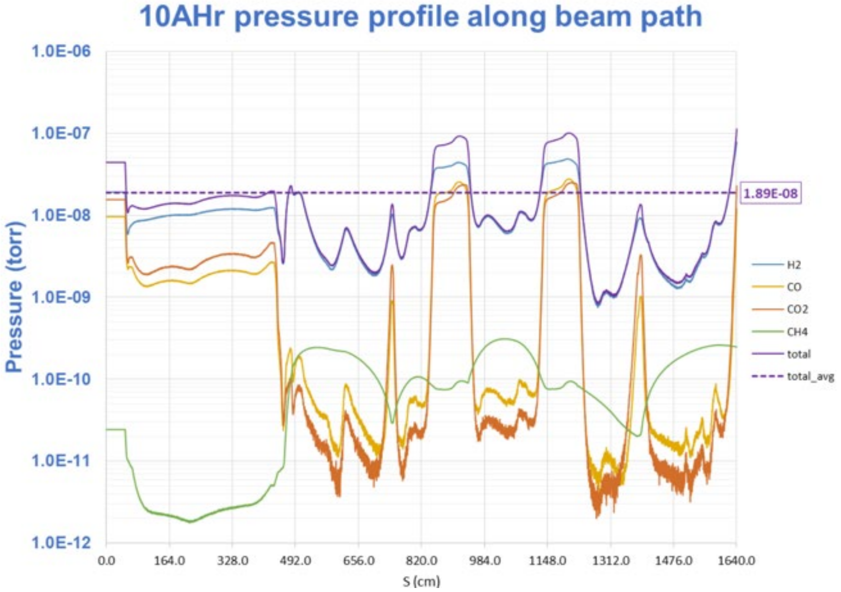


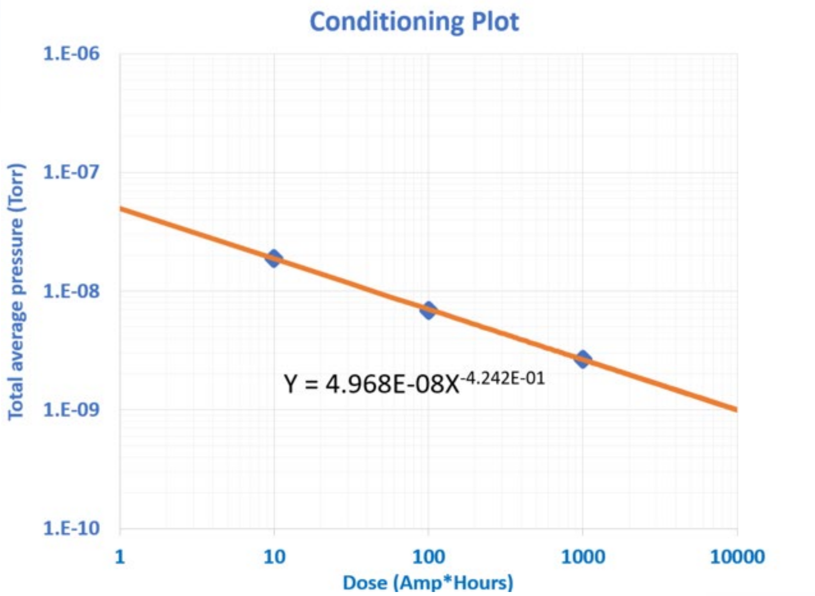
BEI

SR Dynamic pressure profile





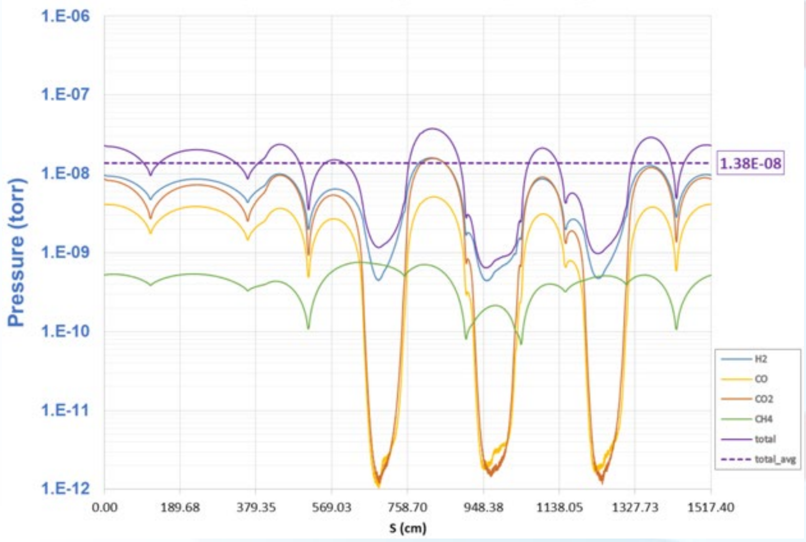




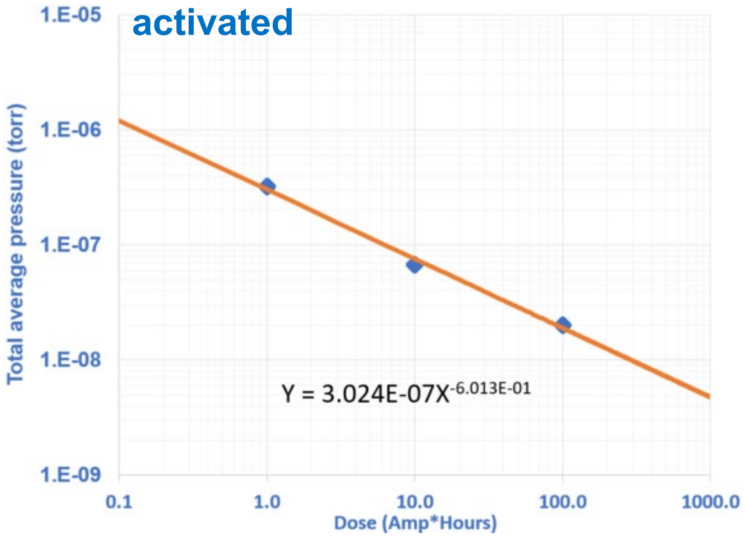
AR dynamic pressure profile

Pressure @ 100 AHr – NEG not-activated

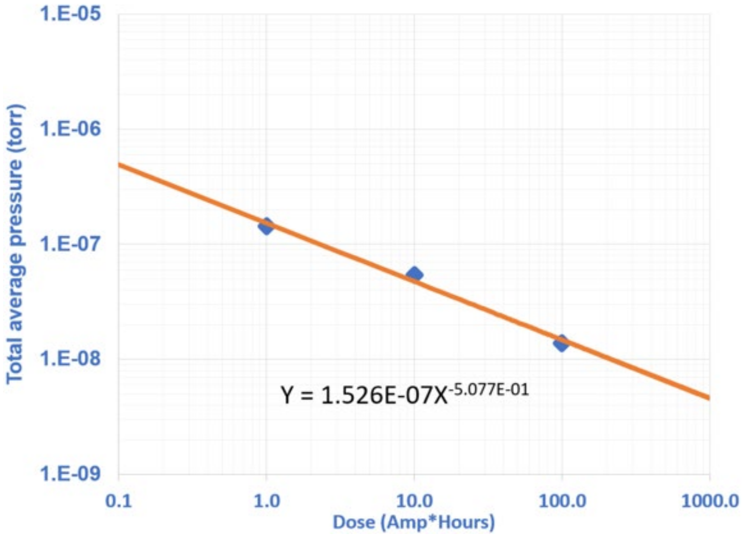
Pressure @ 100 AHr – NEG activated



Conditioning – NEG not-activated



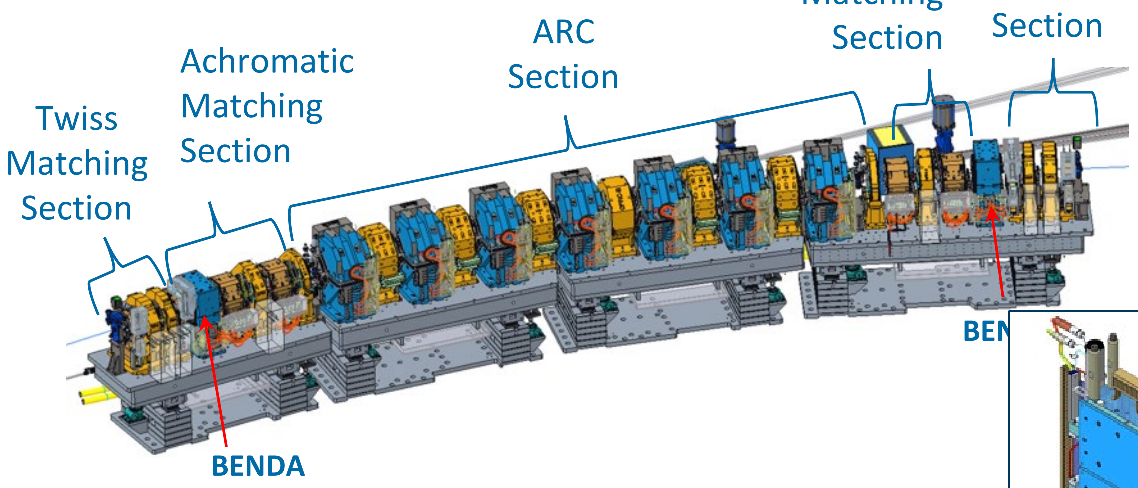
Conditioning – NEG activated

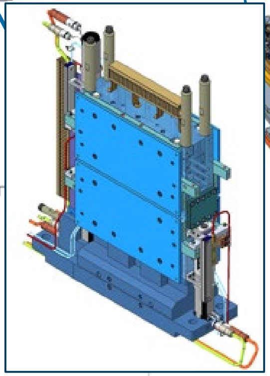


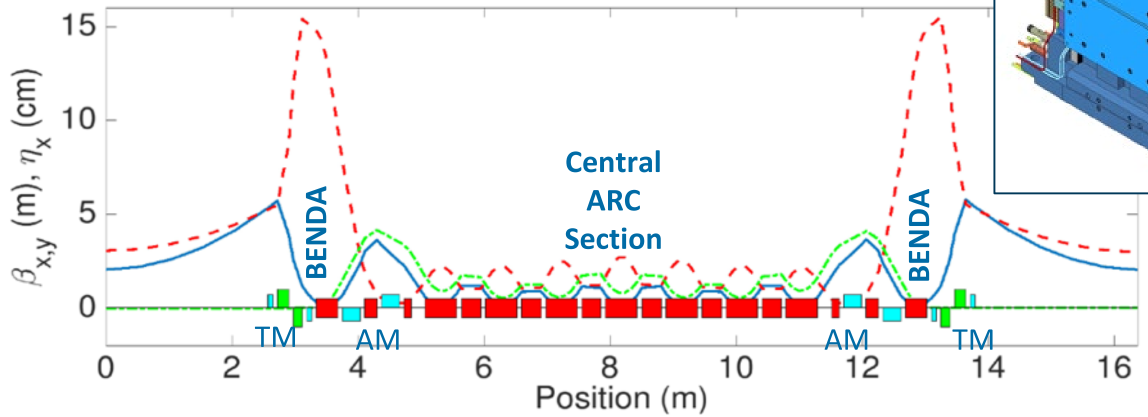
SR arcs divided in 2 different sector structures

Charge #4

Standard Arc

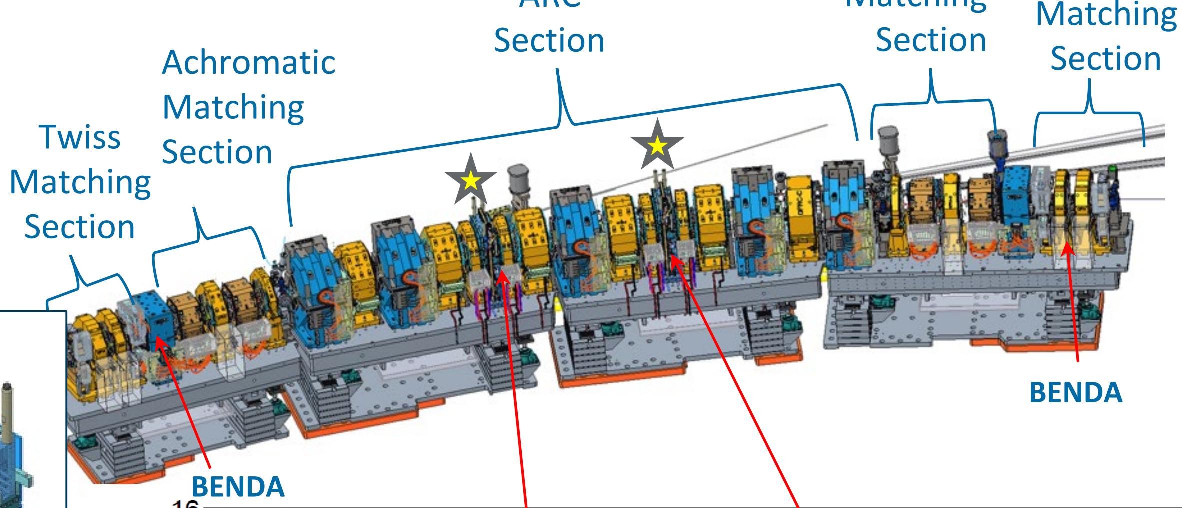


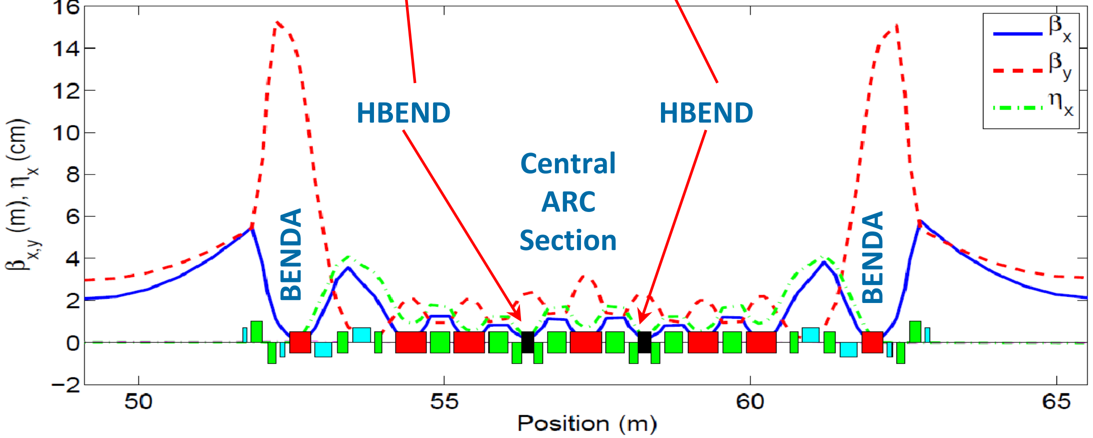




Reference image of standard machine lattice functions illustrating placement with respect to the BENDA magnets.

HBEND Arc



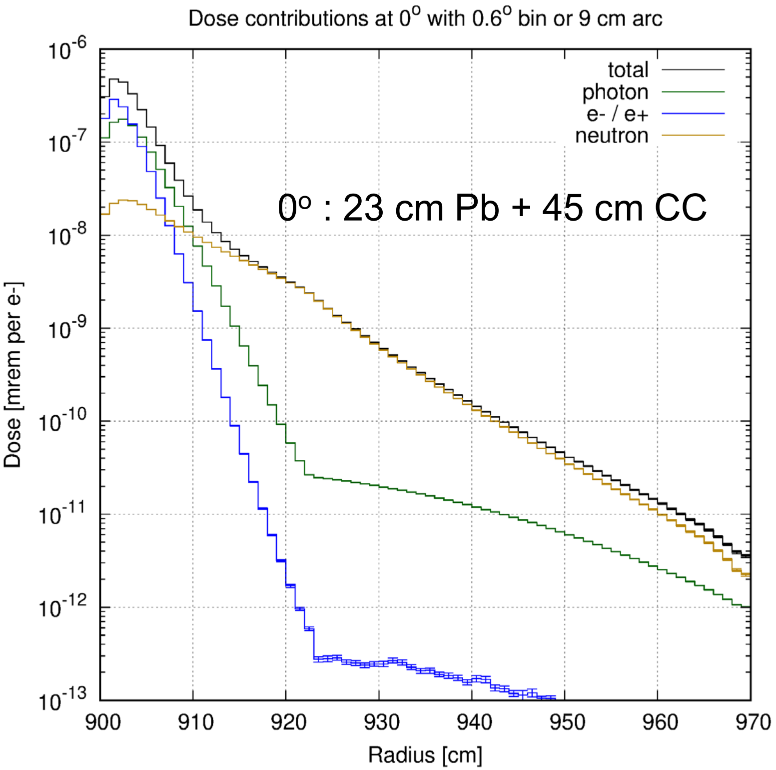


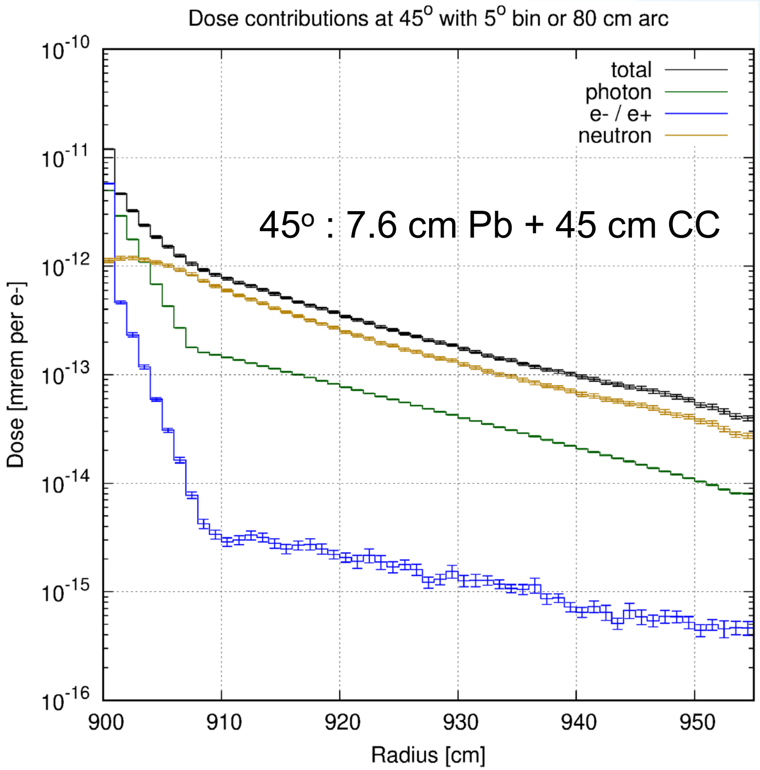
Reference image of HBEND lattice functions illustrating placement with respect to the BENDA magnets.

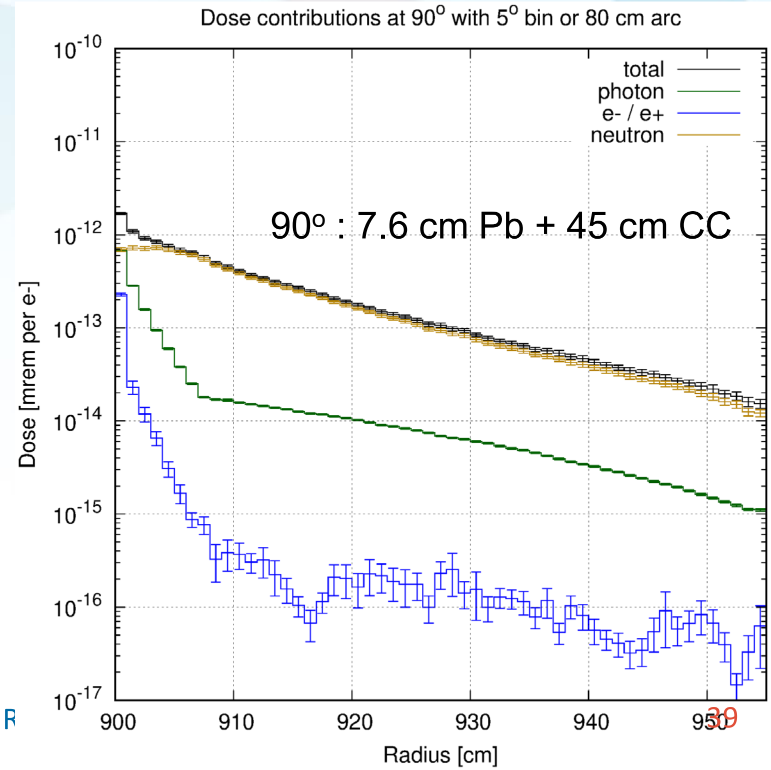
Courtesy Lerche-Swenson, ALS-U CD-3 Review presentation

Dose contribution from electrons & positrons

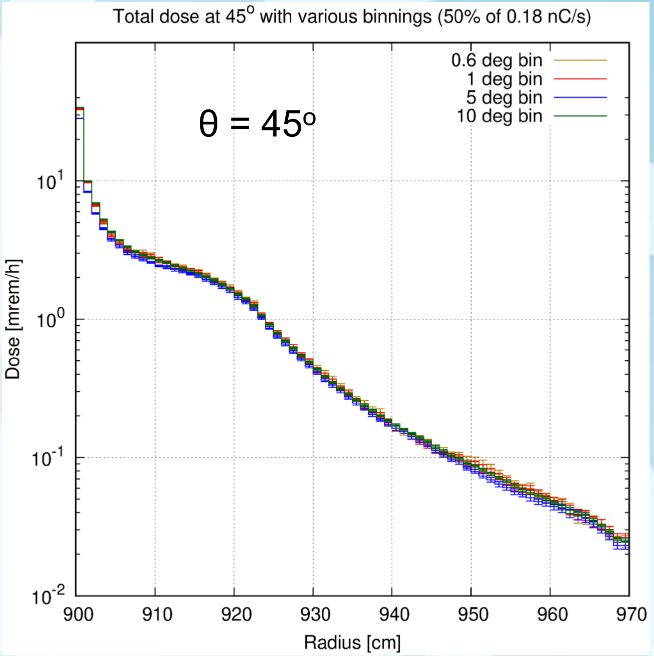
- Electrons & positron dose outside shielding is at least an order of magnitude less than photon and neutron dose







Effect of binning size on dose



FLUKA geometry uses R = 9 m, so choice of bin size can underestimate the dose at shallow angles…

- Underestimate of the dose at 0° and slight disagreement at 15°
- Good agreement of the dose at 30°, 45° and 90°

Solution: Use small 0.6° binning for forward angles and 5° binning is acceptable at lateral angles