Shielding calculations for the design of new Beamlines at ALBA Synchrotron

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Abstract

ALBA is a Spanish synchrotron facility formed with a 3 GeV electron synchrotron accelerator generating bright beams of synchrotron radiation, located near Barcelona.
At ALBA, electrons are first accelerated in a 110 MeV linear accelerator LINAC, and then injected in a synchrotron accelerator named Booster which increases the energy up to 3 GeV. Finally, the electron beam is stored in a synchrotron Storage Ring with a current up to 400 mA emitting a bright beam of synchrotron radiation. Both the Booster and the Storage Ring are located inside the same concrete shielding area called Tunnel, while the LINAC is located in a separated concrete shielding called Bunker. Outside the Tunnel shielding, and tangentially to the Storage Ring, are located the experimental research laboratories named Beamlines, where scientists receive synchrotron light by the mean of dipole magnets or insertion devices, for a wide variety of experiments. At present ALBA has 8 Beamlines installed, 1 Beamline under construction, and 2 Beamlines in the design stage.
This paper details the design of the shielding elements of the new Beamline under construction called LOREA, a soft X-ray beamline dedicated to low-energy ultra-high-resolution angle-resolved photoemission for complex materials. The shielding calculations are performed using FLUKA Monte Carlo code and aim at quantifying the total dose produced by the different sources of radiation at the Beamline in operation. In particular, it studies the dose generated by the gas bremsstrahlung radiation resulting from the interaction of the 3 GeV electron beam with the residual gas of the storage ring vacuum chamber, and compares it to the dose generated by the insertion device radiation flux. The objective of the FLUKA simulations performed in this work is to design all the beamline shielding elements (back wall, side wall, roof, shadow shielding, collimators and beam stops) to ensure a public dose (dose rate lower than 0.5 μSv/h) outside the shielding during Beamline operation.

1. Introduction

The objective of this document is to describe the results of the shielding calculations made for LOREA Beamline, a soft X-ray beamline dedicated to low-energy ultra-high-resolution angle-resolved photoemission for complex material, to ensure a public zone outside the shielding in operation with dose rates below 0.5 μSv/h. It will guarantee that the annual dose outside the shielding will be below the dose limit for non-exposed workers of 1 mSv/year, assuming 2000 working hours per year.

2. Material and methods

2.1 Hypothesis

The Monte Carlo code used for these calculations is FLUKA code version 2011.2c.5 [1],[2]. Like for ALBA phase I Beamlines [3], the following parameters are used for the calculations:

- Electron energy: 3 GeV
- Stored beam current: 400 mA
- Length medium straight section: 8.62 m
- Average pressure in the straight section: 5.0×10^{-9} mbar, with the residual gas composition given in Table 1

Molecule	Relative pressure (%)	Partial pressure (mbar)
H_2	80	1.12×10^{-9}
CO	10	1.4×10^{-10}
CO_2	5	7×10^{-11}
Noble gases	3	4.2×10^{-11}
H_2O	2	2.8×10^{-11}

Table 1 - Residual gas composition in the straight sections, used for the bremsstrahlung shielding calculations. The partial pressures in the third column correspond to a total pressure of 1.4×10-9 mbar (design value).

Following the recommendations of ALBA phase I Beamline shielding report [3], the shielding calculations for LOREA Beamline are performed with an average pressure in the straight section of 5×10^{-9} mbar, and maximum permitted total dose rates outside LOREA shielding below 0.5 µSv/h. This will guarantee that at the design pressure of 1.4×10-9 mbar, the dose rates outside the hutch will be close to natural background, while allowing the Beamline to operate at higher pressure values without surpassing the public access classification.

2.2 LOREA Geometry

The LOREA optics hutch has one sidewall outward (S) at a distance of 90 cm from the beam axis and one sidewall inward (T) at a minimum distance of 78 cm making frontier with the Tunnel side wall. The first element of the optics inside the hutch is a mirror whose reflecting surface faces the inward wall and is 2º inclined (see Fig. 1) with respect to the incoming white beam. The outward wall (S) sidewall has a length of 480 cm. At the end of the optical hutch is located the Backwall (B). At 340 cm height is located the roof (R, not shown in Fig. 1).

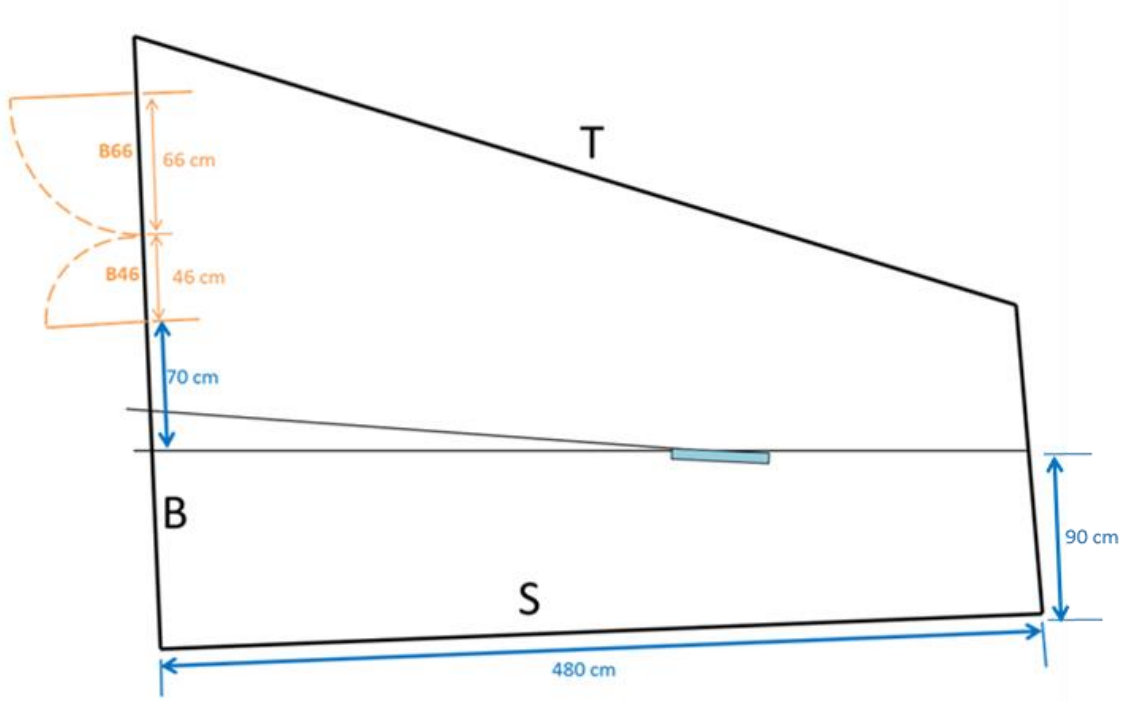

Fig. 1- Schematic layout of the LOREA optical hutch

2.3 FLUKA Parameters

The main parameters used for the LOREA shielding calculation are:

- DEFAULT card set to PRECISIO.
- EMFCUT to set Cut-off production to 100 keV for electrons and positrons, and 1 keV for photons.
- PHOTONUCLEAR card activated in all material to activate gamma interactions with nuclei.

The gas bremsstrahlung source shielding calculation is performed in FLUKA at atmospheric pressure and then scale to real average pressure in the straight section 5×10^{-9} mbar. In addition, the following parameters are used in the 8.62 m medium straight section [4],[5]:

- MULSOPT card to suppress multiple scattering in the gas target
- EMFCUT to suppress Moller/Bhabha scattering in the straight section
- EMFCUT to get rid of primary electron beam at the end of the straight section

Finally, the USERBIN card has been used to plot dose equivalent through DOSE-EQ parameter (dose maps in Fig. 2, Fig. 3, Fig. 4 and Fig. 5)

3. Results and discussion

3.1 LOREA shielding calculation

3.2.1 Optical hutch shielding elements

Table 2 shows the results of shielding calculations made for LOREA summarizing the recommendations of the optical hutch shielding elements:

Shielding Elements	Shielding thicknesses and material recommendation for the LOREA optics hutch walls and roof (mm)	Corresponding vacuum in straight section for 0.5 µSv/h (mbar)
Side wall (S)	20 mm lead + 50 mm polyethylene	2.5×10^{-8}
Roof (R)	15 mm lead	2.5×10^{-8}
Back wall (B)	60 mm lead + local shielding (see Table 3): ▪ 50 mm lead (OH backwall central reinforcement) ▪ 105 mm lead (OH-to-EH guillotine) ▪ 50 mm lead (Local Pb screen 1 behind mirror) ▪ 20 mm lead (Local Pb screen 2 behind slits)	5.0×10^{-8}

Table 2 - Summary of shielding requirements for the optical hutch

In addition, Table 3 details the list of local shielding elements to be foreseen in the optical hutch, with their expected minimum dimensions taking into account LOREA current optical design.

#	Shielding Elements	Height (cm)	Width (cm)	Thickness (cm)	Material
1	Tunnel-to-OH guillotine	35.5	30.5	2	lead
2	Local Pb screen 1 behind mirror	65	70	5	lead
3	Local Pb screen 2 behind slits	45	45	2	lead
4	Central reinforcement Pb screen 2	10	10	2	lead
5	OH-to-EH guillotine	22	22	10.5	lead
6	OH backwall central reinforcement	100	100	5	lead

Table 3 - list of LOREA local shielding elements with expected minimum dimensions

3.2.2 Scattered gas bremsstrahlung case

This section shows the Monte Carlo simulation results used to determine the required lead wall and roof thicknesses for scattered gas bremsstrahlung and LOREA Beamline geometry.

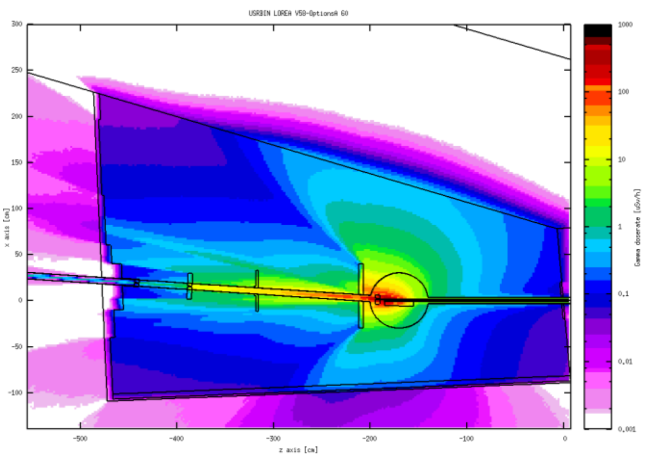

Fig. 2 - Photon dose rate map (in µSv/h) from scattered bremsstrahlung

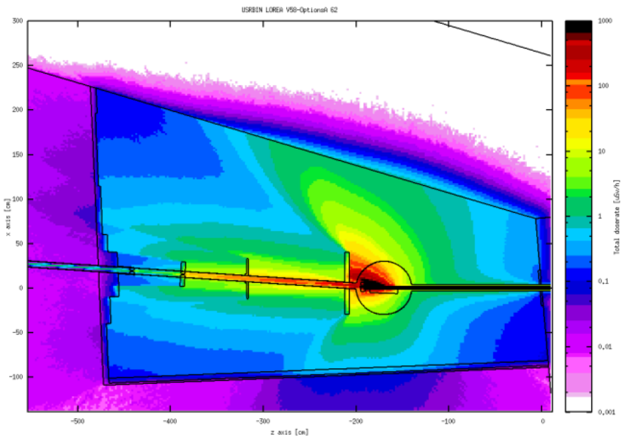

Fig. 4 - Total dose rate map (in µSv/h) from scattered bremsstrahlung

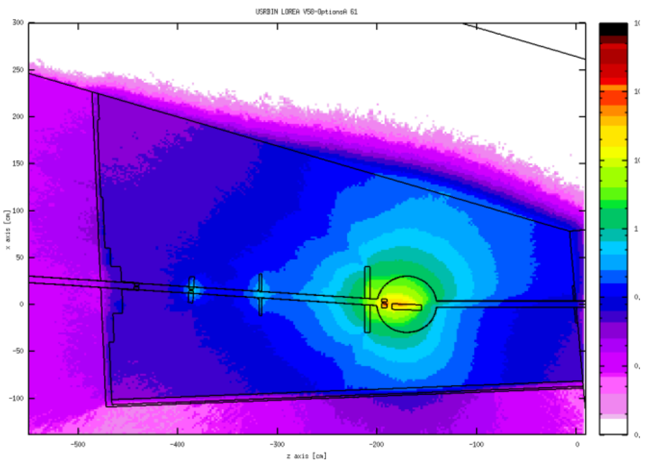

Fig. 3 - Neutron dose rate map (in µSv/h) from scattered bremsstrahlung

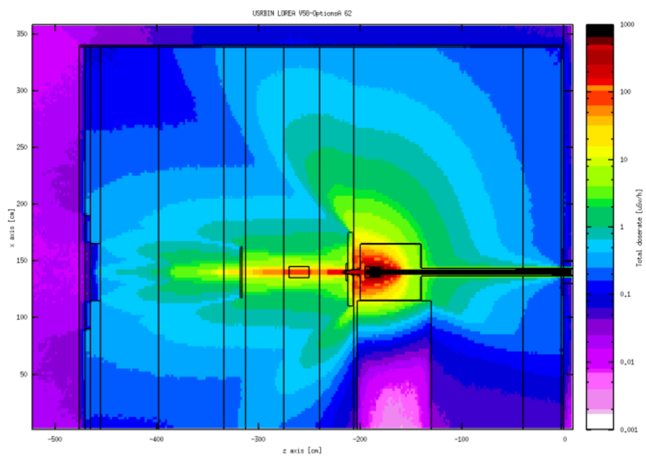

Fig. 5 - Vertical profile at the beam axis position of the total dose rate map (in µSv/h) from scattered bremsstrahlung

Fig. 2, Fig. 3 and Fig. 4, show respectively the photon, neutron and total equivalent dose rates at 140 cm height (level of the primary beam). Fig. 5 shows the transversal total dose rate map (in µSv/h) from scattered bremsstrahlung with real LOREA geometry and shielding. The geometry used for the calculation was LOREA Beamline geometry (Fig. 1) including Table 2 and Table 3 shielding elements and using a gas bremsstrahlung source. It can be observed that the maximum total dose rate outside LOREA optical hutch is 0.1 µSv/h (for 5.0×10^{-9} mbar), allowing a maximum value for the pressure in the straight section of 2.5×10^{-8} mbar for 0.5 µSv/h.

3.2.3 Synchrotron radiation from ID case

In the general shielding report of phase I Beamlines [3], it has been calculated that the shielding requirements for scattered synchrotron radiation for a EU62 Undulator (CIRCE ID, Soft X-Ray Beamline ID similar to LOREA ID) are largely met by the shielding thicknesses required for scattered bremsstrahlung.

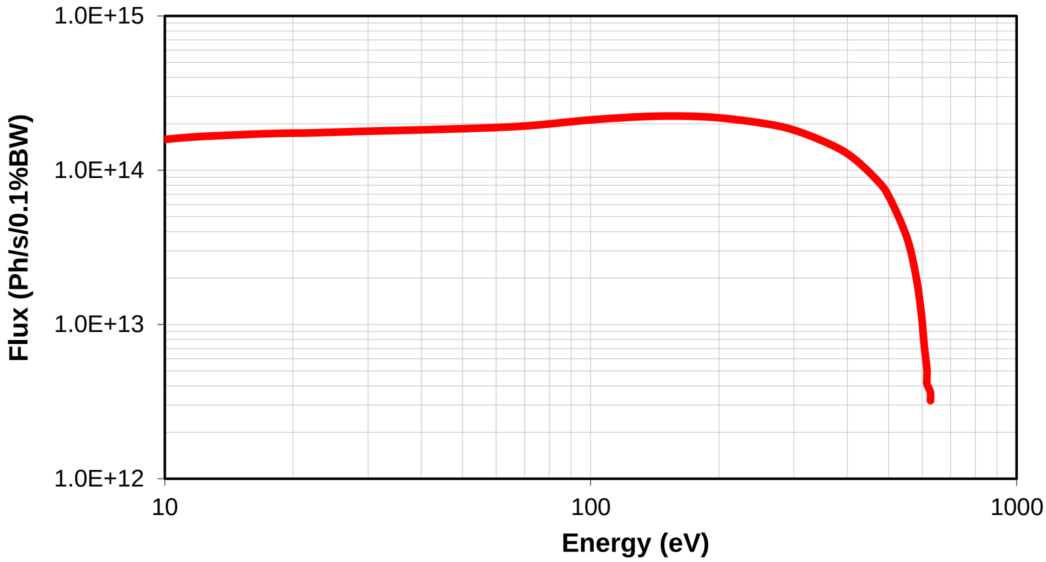

Fig. 6 – LOREA ID Undulator photon flux source

The results obtained with FLUKA with LOREA Insertion Device photon flux source (Fig. 6) have confirmed that for LOREA the shielding requirements for scattered synchrotron radiation is largely covered by the shielding thicknesses required for scattered bremsstrahlung. Indeed, LOREA will operate with a photon flux below 1 keV.

3.2 Collimation system and beam stops

The LOREA Beamline is a soft X-ray Beamline. The optics hutch will only include the first optical element, the horizontally deflecting mirror, M1, together with the slits and diagnostic elements on the pink beam line. The monochromator chamber itself will be installed outside the optics hutch, in an unshielded environment. Without any beam stops or collimators, an important amount of scattered radiation from the mirror would escape from the optics hutch through the pink beam hole in the hutch backwall. Therefore, a collimation system is needed.

3.2.1 M1 bremsstrahlung beamstop

To optimize the shielding thicknesses, it is recommended to place 10×10 mm² Tungsten bremsstrahlung beamstop in-vacuum just after M1, which will constitute the main scattering source in the optical hutch together with the mirror itself. The recommendation for LOREA is that the tungsten beamstop should have at least a 50 mm thickness and the aperture should be lower than 14×14 mm² to act like a collimator.

3.2.2 Double collimator

The amount of scattered radiation from the mirror that can escape through the pipe can be seen in Fig. 7 (blue line), showing the scattered bremsstrahlung spectrum transported outside the optical hutch without collimator. The collimation system consists in a double collimator and its effect can be seen on Fig. 7 (red line), producing a significant attenuation of the photon flux by a factor 10. Consequently, it is recommended for LOREA to place a double collimator system to reduce the photon flux escaping through the beam pipe hole.

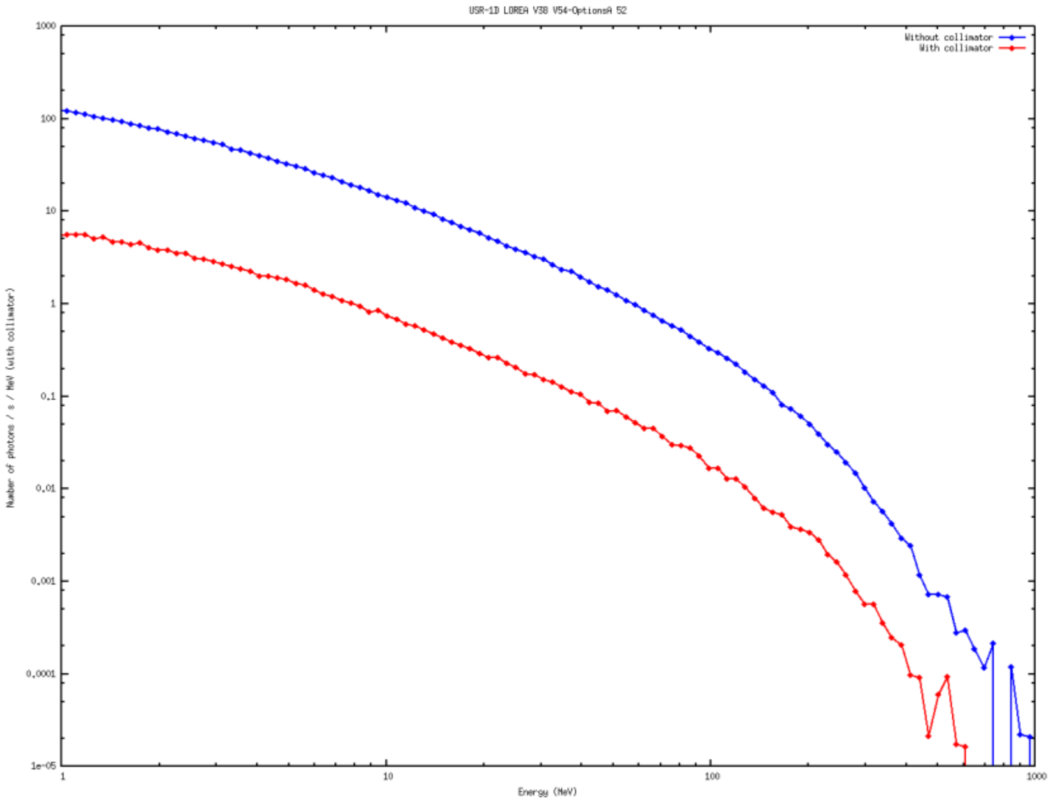

Fig. 7 - Transmitted scattered bremsstrahlung spectrum through the beampipe hole in the backwall (Photons / s /MeV); blue curve: no collimation; red curve: double collimator

For LOREA shielding calculations, a 1st collimator block (5 cm of Tungsten) has been located in vacuum at 90 cm upstream of the back wall, and a 2nd collimator block (5 cm of Tungsten) located in vacuum at 30 cm upstream of the back wall, both with a 12 (horizontal) x 15 (vertical) mm² full aperture. At the level of the 1st block a 5 cm lead screen should be placed outside the vacuum chamber to screen the hole in the back wall from all radiation sources of scattering (mirror, beam stop, slits). Around the beam pipe, between the 2nd tungsten collimator block and the back wall, 0.6 cm of lead screen should also be foreseen to avoid any scattered radiation to enter the beam pipe.

3.2.3 Monochromator beamstop

Finally, even if dose rates are again sufficiently small around monochromator it is advisable, like it has been done in phase I Beamline shielding report [3], to foresee a small tungsten stop 50x50 mm² (with a thickness of 3 cm) behind the first crystal, since the monochromator will be located outside the optical hutch in an unshielded environment.

3.3 Access door optimization

The design of the optical hutch requires the access door to be on the backwall, because of space limitations in the sidewalls. The door will be a double frame door with a special effort to be done in the chicane design. Indeed joints in a back wall are always more difficult to deal with because radiation more or less directly hits the joints. The door should allow a 1 meter free pass, and will be composed by a 1st frame door B46 of 46 cm wide letting a 40 cm free pass, and a 2nd frame door B66 of 66 cm wide letting a 60 cm free pass (see door in orange in Fig. 1). Door B46 should have the same thickness of the backwall (60 mm of lead) since it is the closest door to the white beam axis. For door B66, an optimization has been done to check the radiation protection implication of reducing its thickness to 40 mm of lead to make it less heavy. This can be achieved by reinforcing the shadow shielding Local Pb screen 1 (element 2 in Table 3), taking into account its location (116 cm offset between the closest limit of door B66 from the white beam axis) and the radiation levels calculated. The final recommendations for the shielding of LOREA optical hutch door is shown in Table 4.

Door	**Shielding**	**Corresponding vacuum in straight section for 0.5 µSv/h (mbar)**
B46	60 mm lead	5.0×10^{-8}
B66	40 mm lead	6.2×10^{-8}

Table 4 - Summary of shielding requirements for the optical hutch door

4. Conclusion

Shielding calculations have been done at ALBA Synchrotron with Monte Carlo code FLUKA to determine the shielding required for LOREA Beamline, a soft X-ray beamline dedicated to study low-energy ultra-high-resolution angle-resolved photoemission for complex materials. In particular, the calculations have taken into account the radiation produced by LOREA insertion device, and the gas bremsstrahlung radiation produced by the interaction of the Storage Ring electron beam with the residual gas inside the vacuum chamber. The results obtained with a radiation protection approach show the dimension, thickness and material recommended for LOREA shielding (optical hutch, local shielding, stoppers, collimator), to ensure a public zone outside the shielding during Beamline operation with dose rate below 0.5 µSv/h. A proper commissioning should be performed before operating the beamline to validate LOREA shielding from a radiation protection point of view, with a special attention given to the door located on the optical hutch backwall.

References

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