Shielding calculation with FLUKA for the design of LOREA Beamline at ALBA Synchrotron

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1. Context
1.1 Description of ALBA

- **CELLS**: Consortium for the Construction the Exploitation of the Synchrotron Light Laboratory

- **ALBA Synchotron**: particle accelerator located near Barcelona city generating bright beams of synchrotron radiation. ALBA accelerates *electrons* up to 3 GeV.
1.1 Description of ALBA

**LINAC**
*Electron beam*
*110 MeV*

**BOOSTER**
*110 MeV to 3 GeV*

**STORAGE RING**
*3 GeV stored electron beam*
*130 mA (currently) - designed for 400 mA*
*270 m perimeter*
1.1 Description of ALBA

- In the Storage Ring, electrons are curved by Bending Magnets emitting a powerful source of X-Rays: the **synchrotron radiation**.
- At each **Beamline (BL)**, Insertion Devices (ID) produces synchrotron radiation used by scientists for a wide range of **experiments**.
- **LOREA** is the 9th BL designed at ALBA and will be dedicated to low-energy ultra-high-resolution angular photoemission for complex materials.
1.2 Goal of the study

**Objective:**

- Design LOREA Beamline shielding elements using FLUKA code
- Guarantee public access zone\(^1\) outside the shielding in operation

\(^1\) *public access zone: equivalent dose rates below 0.5 μSv/h, derived from the dose limit for non-exposed workers, assuming 2000 h/year*
2. Methodology
2.1 Define the geometry

**LOREA Optical Hutch geometry:**
1 side wall T (1.5 m normal concrete)
1 side wall S
1 back wall B
1 roof R

**Target:**
2° inclined Mirror M1 (Copper)
2.2 Define the source(s)

Main sources of radiation at LOREA:

- **Source of radiation**

  - **Gas Bremsstrahlung**: Electromagnetic cascade produced by the interaction of the e- beam with the residual gas inside the vacuum chamber. Depend on the Current Intensity (mA), the e- Energy (3GeV), the pressure and composition inside the vacuum chamber.

  - **Insertion Device Undulator**: serie of magnets bending the electron beam producing synchrotron radiation. Radiation depends on the Undulator parameters and directly proportional to the current intensity.
2.2 Define the source(s)

1. Gas Bremsstrahlung source

**Beam:** Electron 3 GeV

**Target:** Residual gas inside a 8.62 m length straight section

**Average pressure** in the straight section: $1.4 \times 10^{-9}$ mbar (design value) but calculations performed at atmospheric pressure (1 atm) and then scaled at design value

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Relative pressure (%)</th>
<th>Partial pressure (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>80</td>
<td>$1.12 \times 10^{-9}$</td>
</tr>
<tr>
<td>CO</td>
<td>10</td>
<td>$1.4 \times 10^{-10}$</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>5</td>
<td>$7 \times 10^{-11}$</td>
</tr>
<tr>
<td>Ar</td>
<td>3</td>
<td>$4.2 \times 10^{-11}$</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>2</td>
<td>$2.8 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

Electron beam
1. Gas Bremsstrahlung source:

- The flux obtained is actually the source for the LOREA shielding calculation with the 1st copper Mirror as target.

*Photon flux (photons/s) for 400 mA e- beam, scored with USRBDX at the end of the straight section*
2.2 Define the source(s)

2. Insertion Device source

Use of `hsource.f` sub routine to read histogram and used for the Shielding Calculation with the Beamline 1st Mirror as main Target

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Maximum ID photon flux (analytic calculation by ALBA Accelerator division)

- **Flux (Ph/s/0.1%BW)**
- **Energy (eV)**

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Flux (Ph/s/0.1%BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.E+16</td>
</tr>
<tr>
<td>10</td>
<td>1.E+13</td>
</tr>
<tr>
<td>100</td>
<td>1.E+10</td>
</tr>
<tr>
<td>1000</td>
<td>1.E+07</td>
</tr>
<tr>
<td>10000</td>
<td>1.E+04</td>
</tr>
<tr>
<td>100000</td>
<td>1.E+01</td>
</tr>
<tr>
<td>1000000</td>
<td>1.E-02</td>
</tr>
<tr>
<td>10000000</td>
<td>1.E-05</td>
</tr>
<tr>
<td>100000000</td>
<td>1.E-08</td>
</tr>
</tbody>
</table>

- **Flux (Ph/s/0.1%BW)**
- **Energy (eV)**

**Histogram Energy / Probability**

- **Undulator ID**

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- `# CREATE SOURCE` for
- `# DEFINE SOURCE` for
- `SUBROUTINE SOURCE (SOURCE)`
- `INCLUDE 'uflhesp.c'
- `INCLUDE 'uflhesp.h'
- `INCLUDE 'uflhesp.f'

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- Copyright (C) 1990-2016 by Alfredo Ferrari & Paolo Sala
- All Rights Reserved.

- New source for FLUUA; Fluka 2016;
- Created on 07 January 1990 by Alfredo Ferrari & Paolo Sala
- Last change on 17-05-16 by Alfredo Ferrari

- This is just an example of a possible user written source routine.
- Note that the beam card still has some meaning - in the scoring the
  maximum momentum used in deciding the binning is taken from the
  beam momentum. Other beam card parameters are obsolete.

- Output variables:
  - **Homo** = 1 if > 0 the run will be terminated
  - Read source term from a histogram
  - Author: Vassilis.Vlasopoulos@cern.ch
2.3 Define FLUKA cards

Some FLUKA cards used for the simulations:

- **DEFAULTS**: New-defaults card

  ![DEFAULTS](image)

- **LOW-MAT**: Correspondence between FLUKA materials and low energy neutron cross sections

  ![LOW-MAT](image)

- **EMF**: Activate Electromagnetic FLUKA transport

  ![EMF](image)

- **PHOTONUC**: Activate photonuclear interaction

  ![PHOTONUC](image)

- **EMFCUT**: Energy threshold production: 1 keV for photon and 500 keV for electron and positron

  ![EMFCUT](image)

- **BIASING**: no biasing card used
3. Results
3. Results

- Shielding elements summary after thickness optimization:

<table>
<thead>
<tr>
<th>Shielding thicknesses and material recommendation for the LOREA optics hutch wall and roof (mm)</th>
<th>Corresponding vacuum in straight section for 0.5 μSv/h (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall S (side wall)</strong></td>
<td></td>
</tr>
<tr>
<td>15 mm lead + 50 mm polyethylene</td>
<td>1.25 × 10⁻⁸</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
</tr>
<tr>
<td>15 mm lead</td>
<td>1.25 × 10⁻⁸</td>
</tr>
<tr>
<td><strong>Wall B (back wall)</strong></td>
<td></td>
</tr>
<tr>
<td>60 mm of lead</td>
<td>1.25 × 10⁻⁸</td>
</tr>
<tr>
<td>+ 50 mm of lead in central 1 m²</td>
<td></td>
</tr>
<tr>
<td>+ 105 mm of lead Opt-to-Exp guillotine</td>
<td></td>
</tr>
<tr>
<td>+ 20 mm of lead local screen behind mirror</td>
<td></td>
</tr>
<tr>
<td>+ 20 mm other white beam scattering source</td>
<td></td>
</tr>
</tbody>
</table>
3.1 Gas Bremsstrahlung source

Gas Bremsstrahlung source case equivalent dose rate maps (DOSE-EQ) - horizontal view at beam level -

Total dose rate map (in µSv/h) from scattered bremsstrahlung with real LOREA geometry and shielding

Photon dose rate map (in µSv/h)

Neutron dose rate map (in µSv/h)

0.5µSv/h
3.1 Gas Bremsstrahlung source

- **Gas Bremsstrahlung** source case equivalent dose rate maps (DOSE-EQ) - vertical view at beam level -

- Total dose rate map (in $\mu$Sv/h) from scattered bremsstrahlung with real LOREA geometry and shielding

- Photon dose rate map (in $\mu$Sv/h)

- Neutron dose rate map (in $\mu$Sv/h)

Total dose rate map (in $\mu$Sv/h) from scattered bremsstrahlung with real LOREA geometry and shielding
3.1 Gas Bremsstrahlung source

- Comparison with experimental data from ALBA beamlines

- Results obtained with FLUKA are in agreement with experimental data from a similar Beamline at ALBA (few µSv/h current inside the Optical Hutch - proportional to the electron beam - and background reading outside)
3.2 Synchrotron radiation source

- **ID Undulator** dose rate maps (at 400 mA):

![Dose Rate Map](image)

Total dose rate map (in $\mu$Sv/h) from ID Undulator source

- **Shielding requirements for scattered synchrotron radiation** are largely met by the shielding thicknesses required for scattered bremsstrahlung.
3.3 Collimation system

• Collimation system:

From the results, it has been seen that an important amount of gas bremsstrahlung scattered radiation will escape from the optics hutch through the pink beam hole in the backwall. Consequently a collimation system is needed:

Transmitted scattered bremsstrahlung spectrum through the beampipe hole in the backwall; blue curve: no collimation; red curve: double collimator

→ Reduction of a factor 15 of the scattered bremsstrahlung radiation escaping from the Optical Hutch through the beampipe
4. Open points & conclusion
4. Open points

1. **Time of calculation**: 0.3 ms per primary particle, 1e+08 primary sent per cycles, 10 cycles per run
   - 3 to 4 days for each run in 1 CPU
   - 10-15% statistical error after the shielding

   a) Statistic improved by **parallelization** of the simulations via Batch system to cluster: split into 48 inputs – **done** –

   b) Use of **biaising** (in particular playing with importance inside the shielding element) could allow better statistic in regions of interest - **not done** –

   c) Use the intermediate results (**tracking** all particles, x, y, z, dx, dy, dz, energy, weight) as a source, via user routine source.f, to save CPU time - **not done** –
4. Open points

2. Results compatible with GEANT4 results used for the design of a similar Beamline at ALBA. – done -

3. Possibility in FLUKA to test different thicknesses for the shieldings without going through separated input files, each one with a different thickness? - not done -
Conclusions

- FLUKA is a **powerful code** for the design of Synchrotron Beamline shielding (Radioprotection)

![Total dose rate map](image)

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*Summary of shielding requirements for LOREA optical hutch*

- **The next step is to** implement the open points solutions to save CPU time and improve statistics
Thank you for your attention!

Email: adevienne@cells.es
ALBA Website: www.albasynchrotron.es

Acknowledgement:
- ALBA Accelerator and Computing division
- FLUKA Team & forum
References:

- [5] Impact of gas bremsstrahlung on synchrotron radiation beamline shielding at the advanced photon source, Nisy E. Ipe, Alberto Fasso SLAC–PUB–6410,