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

A. Devienne[1]

[1] Health & Safety Department, ALBA Synchrotron light source, Barcelona, Spain

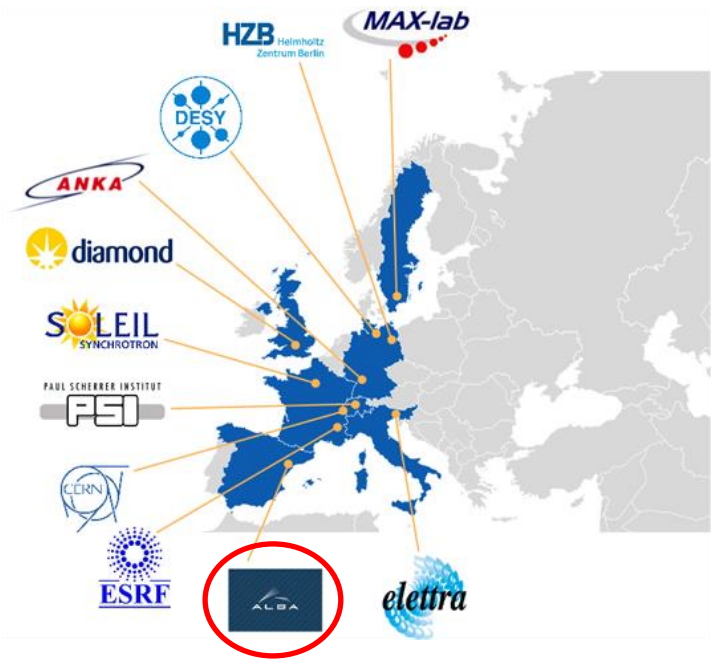
Contents

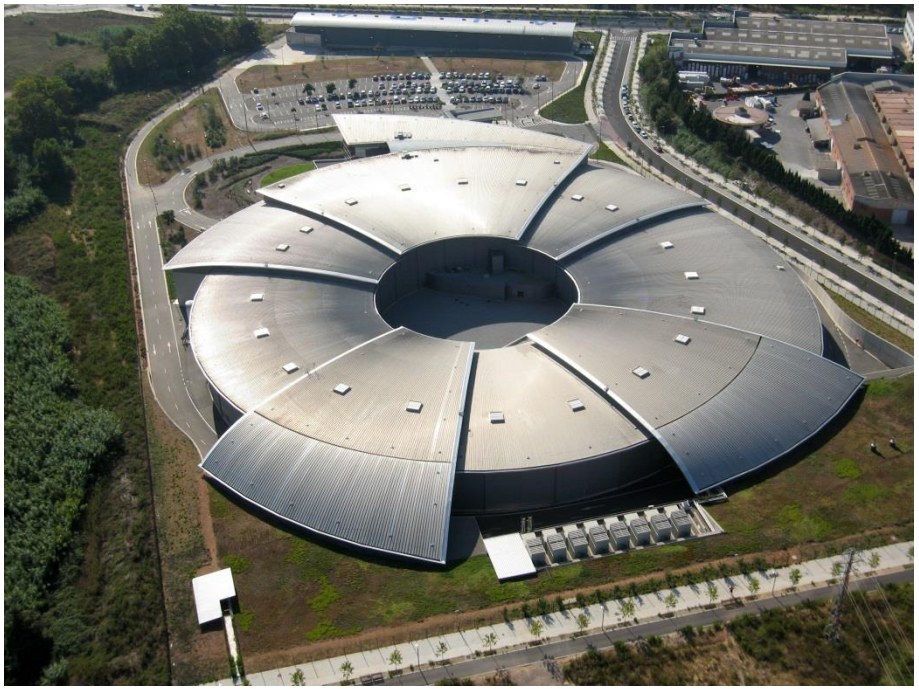
1. Context

1.1 Description of ALBA

- **CELLS**: **C**onsortium for the **C**onstruction the **E**xploitation of the **S**ynchrotron **L**ight **L**aboratory

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



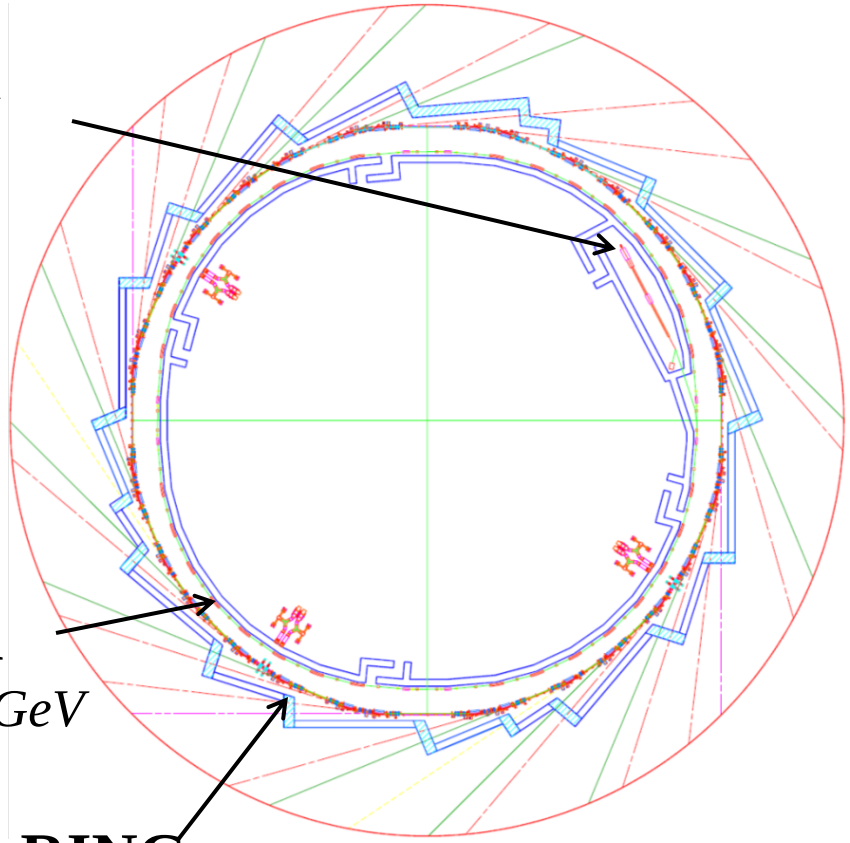


1.1 Description of ALBA

LINAC

Electron beam

110 MeV



BOOSTER

110 MeV to 3 GeV

STORAGE RING

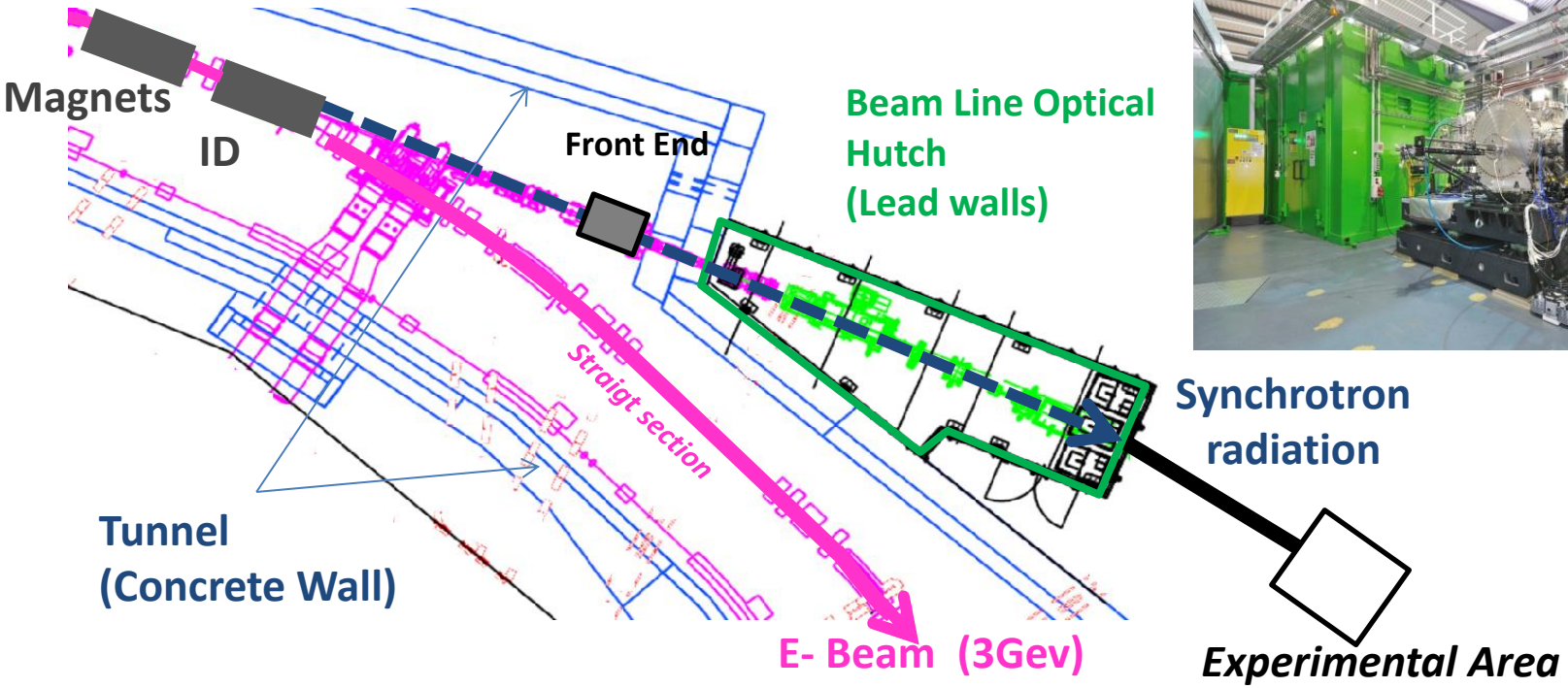
3 GeV stored electron beam

130 mA (currently) - designed for 400 mA

270 m perimeter

1.1 Description of ALBA

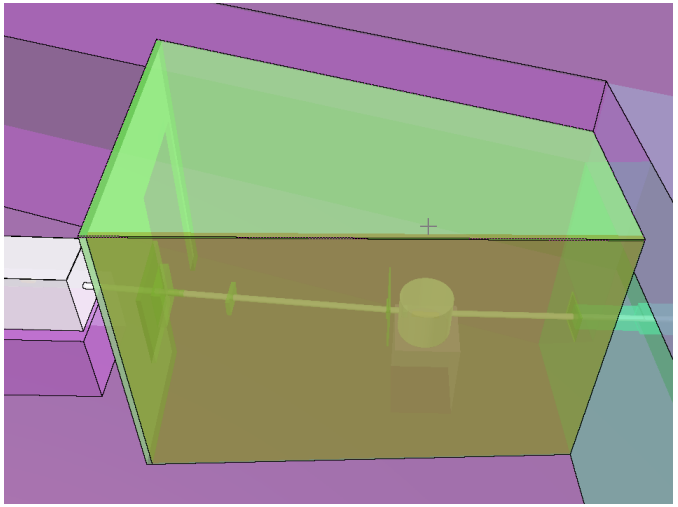
- In the Storage Ring, electrons are curved by Bending Magnets emitting a powerful source of X-Rays: the **synchrotron radiation**.
- At each **Beamline (BL)**, Insertion Devices (ID) produces synchrotron radiation used by scientists for a wide range of **experiments**
- **LOREA** is the 9th BL designed 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

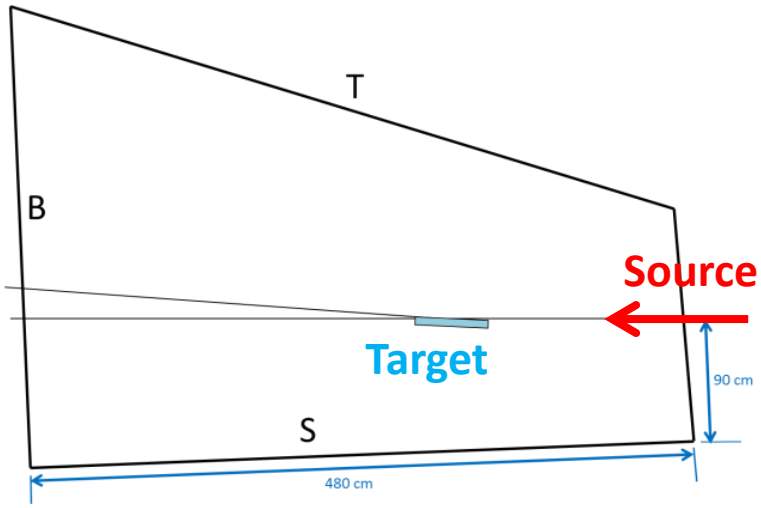
2.1 Define the geometry

LOREA Optical Hutch geometry:

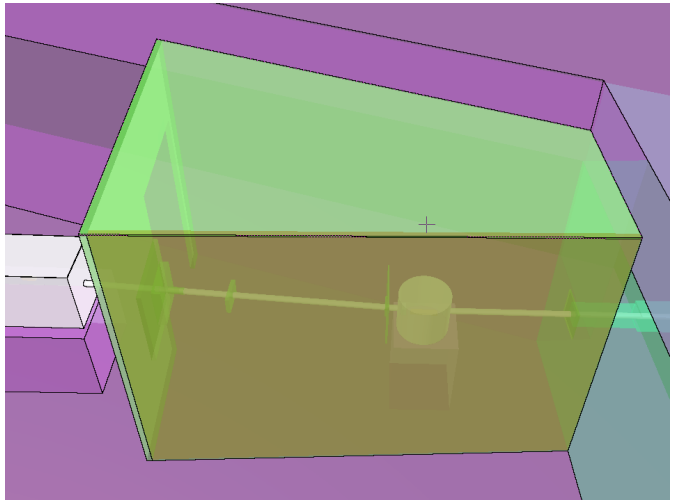
1 side wall T (1.5 m normal concrete)
1 side wall S
1 back wall B
1 roof R

Target :

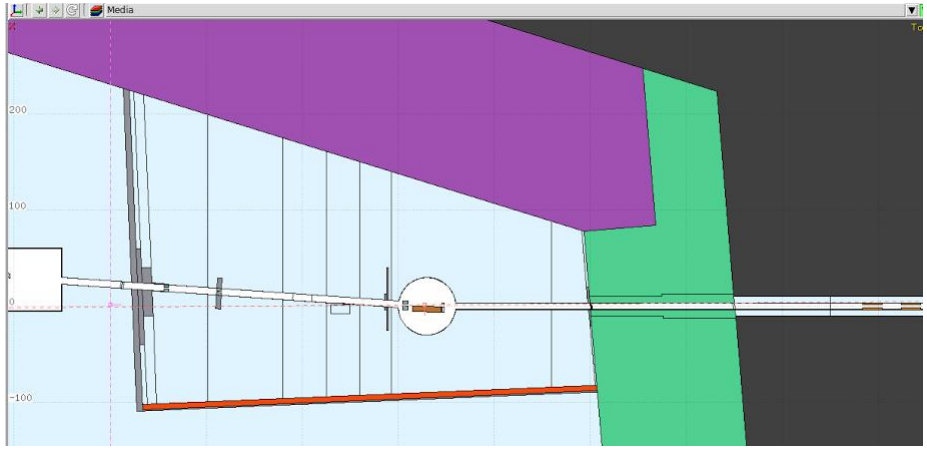
2° inclined Mirror M1 (Copper)



Simplified LOREA Optical Hutch drawing



LOREA Optical Hutch FLUKA 3D view



LOREA Optical Hutch FLUKA 2D top view

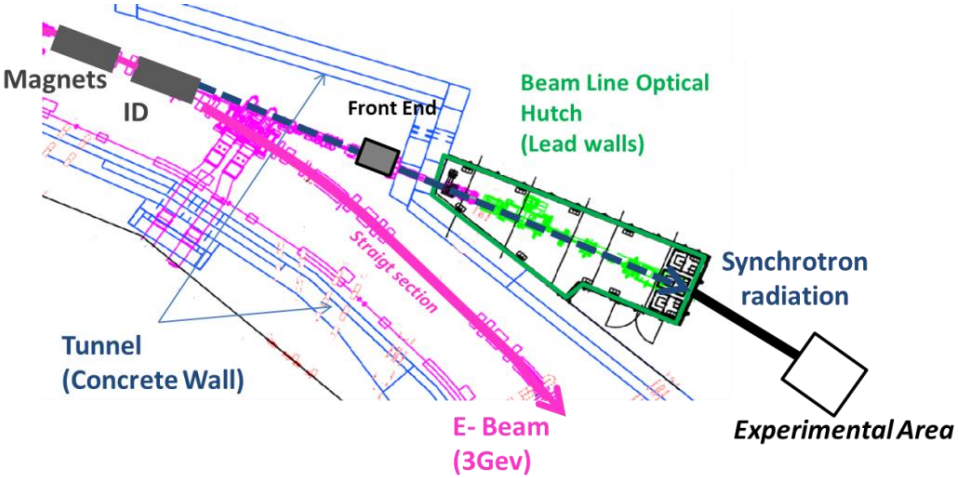
2.2 Define the source(s)

- **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

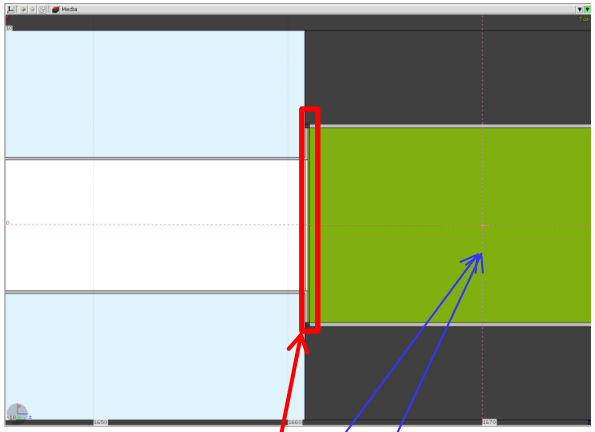


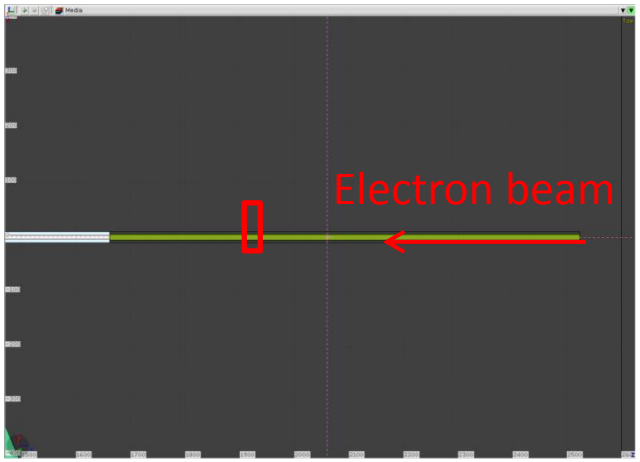
2.2 Define the source(s)

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: 1.4×10^{-9} mbar (design value) but calculations performed at atmospheric pressure (1 atm) and then scaled at design value

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}
Ar	3	4.2×10^{-11}
H_2O	2	2.8×10^{-11}



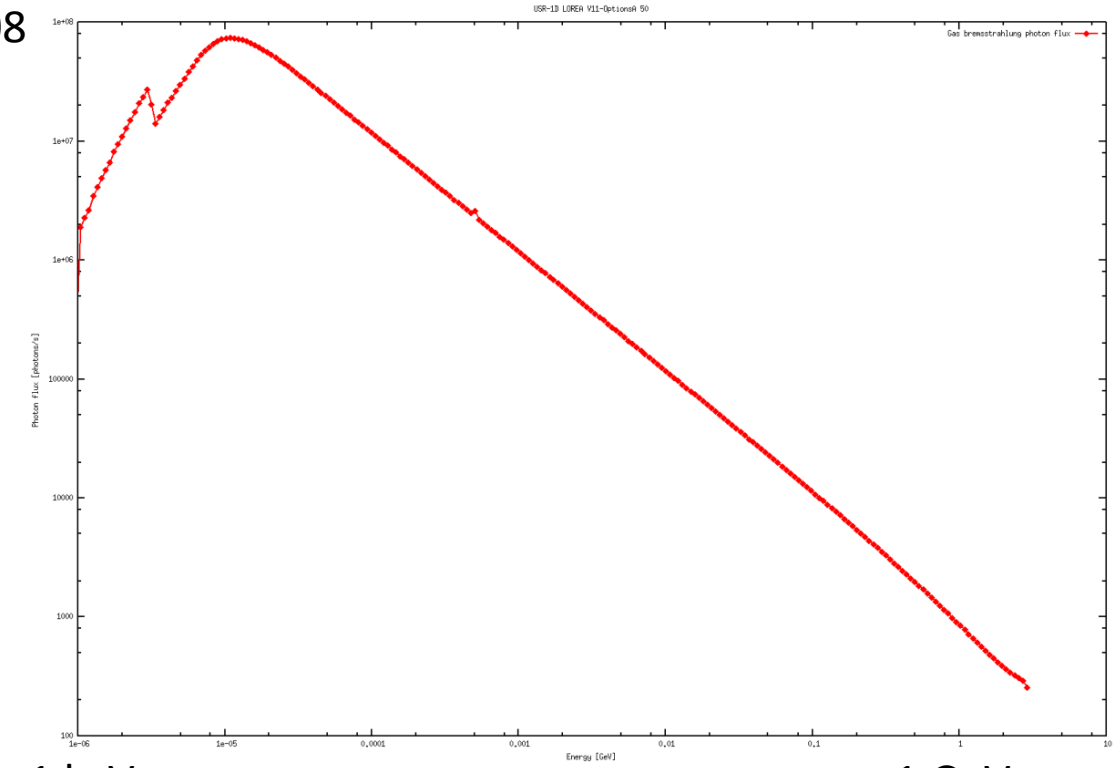



```
Suppress multiple scattering in the air target
MULSOPT                                                                                    Type:  ▾
                                                                                           e-e+ steps: 0                                                   Optimize: off ▾
                                                                                           Mat: AIRPLOW ▾                                                  h/μ Corr: No corrections ▾                                   e-e+ Corr: no MCS ▾
                                                                                                                                                           to Mat: AIRPLOW ▾                                            Step: 0.
                h/μ steps: 0
Suppress Moller/Bhabha scattering in the air column.
EMFCUT                                                                                     Type: ELPO-THR ▾                                                e-e+ Brem: 0.0                                               γ Bhabha/Moller: 4.0
                                                                                           Mat: AIRPLOW ▾                                                  to Mat: AIRPLOW ▾                                            Step:
                Photonuc: 0.0
---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
Get rid of charged particles that were produced in the air column.
EMFCUT                                                                                     Type: transport ▾
                                                                                           e-e+ Threshold: Kinetic ▾                                       e-e+ Ekin: 4.0                                               γ: 0.000001
                                                                                           Reg: TUB_KILL ▾                                                 to Reg: TUB_KILL ▾                                           Step:
```

2.2 Define the source(s)

1. Gas Bremsstrahlung source:

1e+08



1 keV

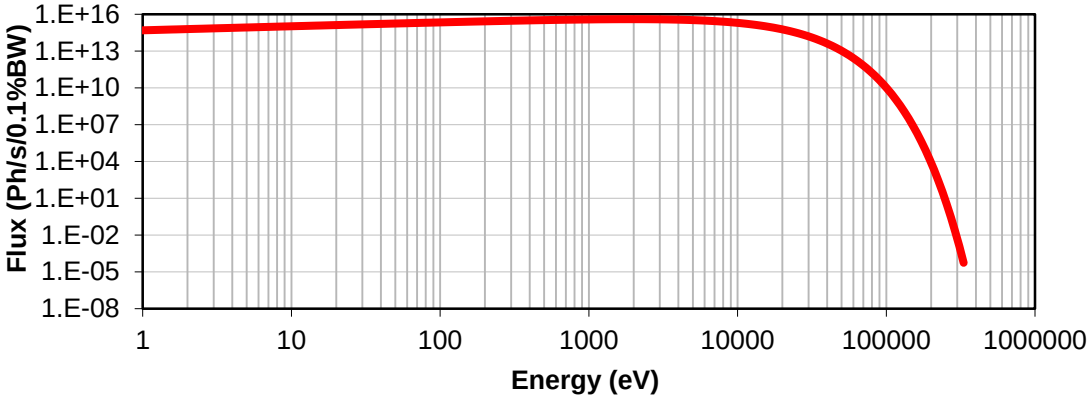
1 GeV

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

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

2.2 Define the source(s)

2. Insertion Device source



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

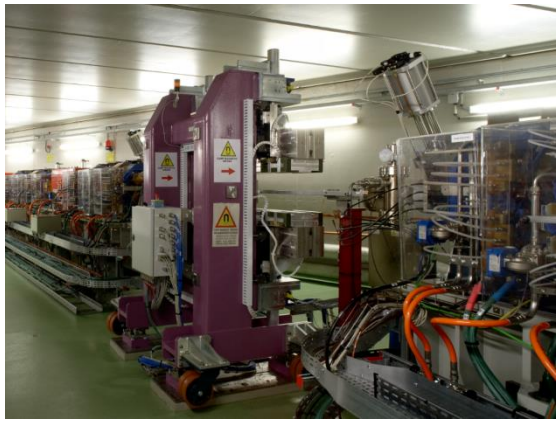
Use of **hsource.f** sub routine to read histogram and used for the Shielding Calculation with the Beamline 1st Mirror as main Target

```
*$ CREATE SOURCE.FOR
*COPY SOURCE
*
*=== source ==========================================================*
*
      SUBROUTINE SOURCE ( NOMORE )

      INCLUDE '(DBLPRC)'
      INCLUDE '(DIMPAR)'
      INCLUDE '(IOUNIT)'
*
*----------------------------------------------------------------------*
*                                                                      *
*     Copyright (C) 1990-2010      by    Alfredo Ferrari & Paola Sala  *
*     All Rights Reserved.                                             *
*                                                                      *
*                                                                      *
*     New source for FLUKA9x-FLUKA20xy:                                *
*                                                                      *
*     Created on 07 January 1990   by    Alfredo Ferrari & Paola Sala  *
*                                                   Infn - Milan       *
*                                                                      *
*     Last change on  17-Oct-10    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:                                              *
*                                                                      *
*             Nomore = if > 0 the run will be terminated               *
*                                                                      *
*  Read source term from a histogram                                   *
*     Author: Vasilis.Vlachoudis@cern.ch                               *
*                                                                      *
*----------------------------------------------------------------------*
```

```
# Histogram with 3 variable bins
# First line should be zero to define the lower energy limit
# Eupper Value
#E(GeV)          pi
0.0000000009     0
0.000000001 0.003030342
1.14E-09    0.003164945
1.2996E-09  0.003305461
1.48154E-09 0.003452141
1.68896E-09 0.003605244
1.92541E-09 0.003765042
2.19497E-09 0.003931811
2.50227E-09 0.004105841
2.85259E-09 0.004287431
3.25195E-09 0.004476888
3.70722E-09 0.00467453
4.22623E-09 0.004880684
4.8179E-09  0.005095686
5.49241E-09 0.005319883
6.26135E-09 0.005553627
7.13794E-09 0.005797281
8.13725E-09 0.006051213
9.27646E-09 0.006315798
```

Histogram Energy / Probability



Undulator ID

2.3 Define FLUKA cards

Some FLUKA cards used for the simulations:

- DEFAULTS: New-defaults card

```
Set the defaults for precision simulations
DEFAULTS                                                    NEW-DEFA ▾
```

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

```
Low-Mat cross sections
LOW-MAT                                                     Mat: ALUMINUM ▾
LOW-MAT                                                     Mat: ARGON ▾
```

- EMF: Activate Electromagnetic FLUKA transport

```
Activates ElectroMagnetic FLUKA: transport of electrons, positrons and photons
EMF                                                         ON ▾
```

- PHOTONUC: Activate photonuclear interaction

```
PHOTONUCLEAR INTERACTIONS
PHOTONUC
E>0.7GeV On ▾        Type: ▾
                     Δ resonance On ▾        Quasi D On ▾        All E: off ▾
                     Mat: LEAD ▾             to Mat: ▾           Giant Dipole On ▾
                                                                 Step:
```

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

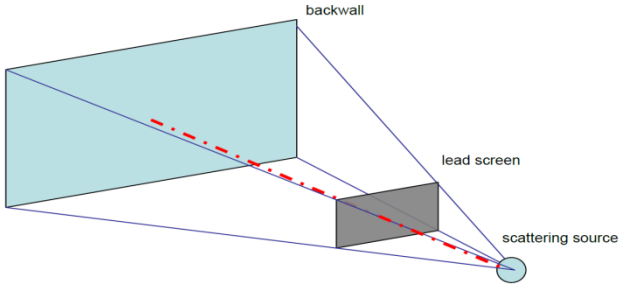
```
gamma a 1kev
EMFCUT                Type: PROD-CUT ▾
                      e-e+ Threshold: Kinetic ▾        e-e+ Ekin: 0.0005        γ: 0.000001
Fudgem: 0.0           Mat: LEAD ▾                      to Mat: ▾                Step:
```

- BIASING: no biasing card used

3. Results

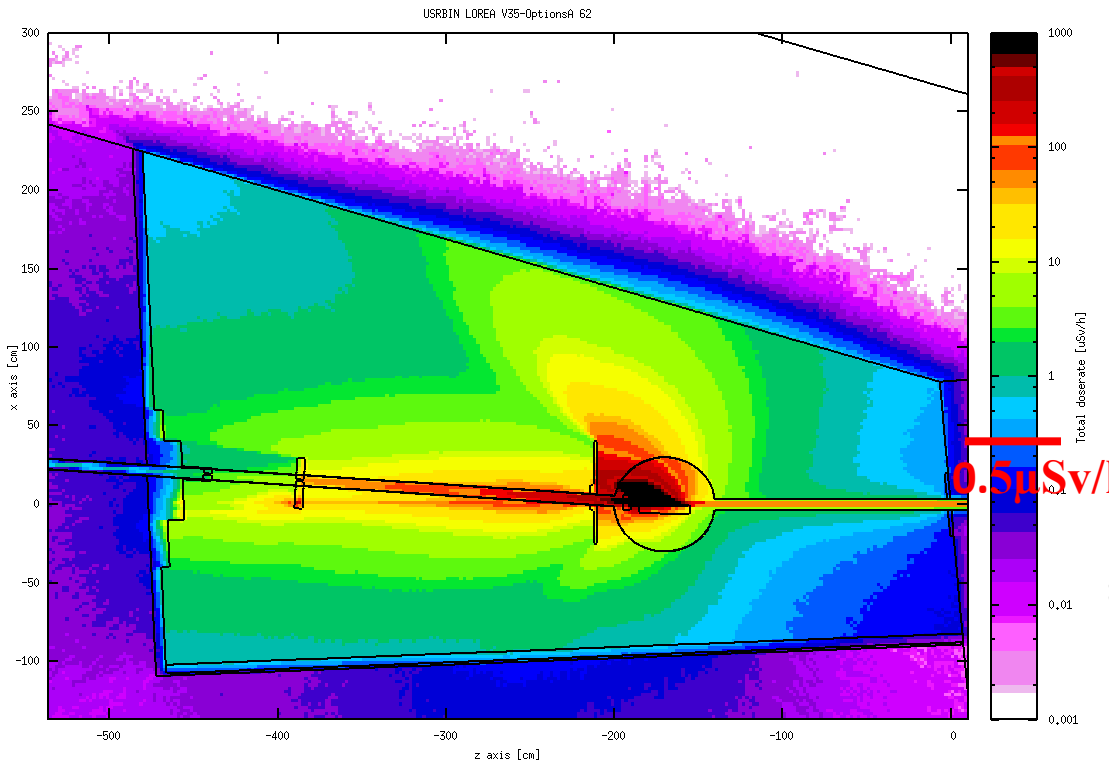
3. Results

- **Shielding elements summary after thickness optimization:**

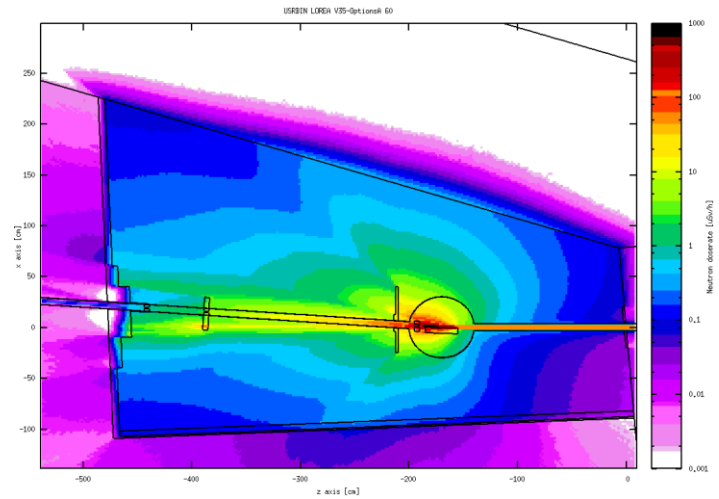
Shielding thicknesses and material recommendation for the LOREA optics hutch wall and roof (mm)	*Corresponding vacuum in straight section for 0.5 μSv/h (mbar)*
Wall S (side wall)	
15 mm lead + 50 mm polyethylene	1.25×10^{-8}
Roof	
15 mm lead	1.25×10^{-8}
Wall B (back wall)	
60 mm of lead + 50 mm of lead in central 1 m^2 + 105 mm of lead Opt-to-Exp guillotine + 20 mm of lead local screen behind mirror + 20 mm other white beam scattering source	1.25×10^{-8} 

3.1 Gas Bremsstralhung source

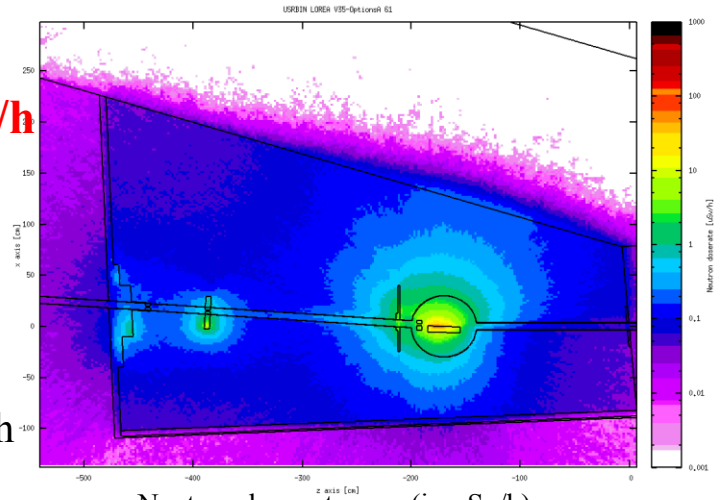
Gas Bremsstralung source case equivalent dose rate maps (DOSE-EQ) - horizontal view at beam level -



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



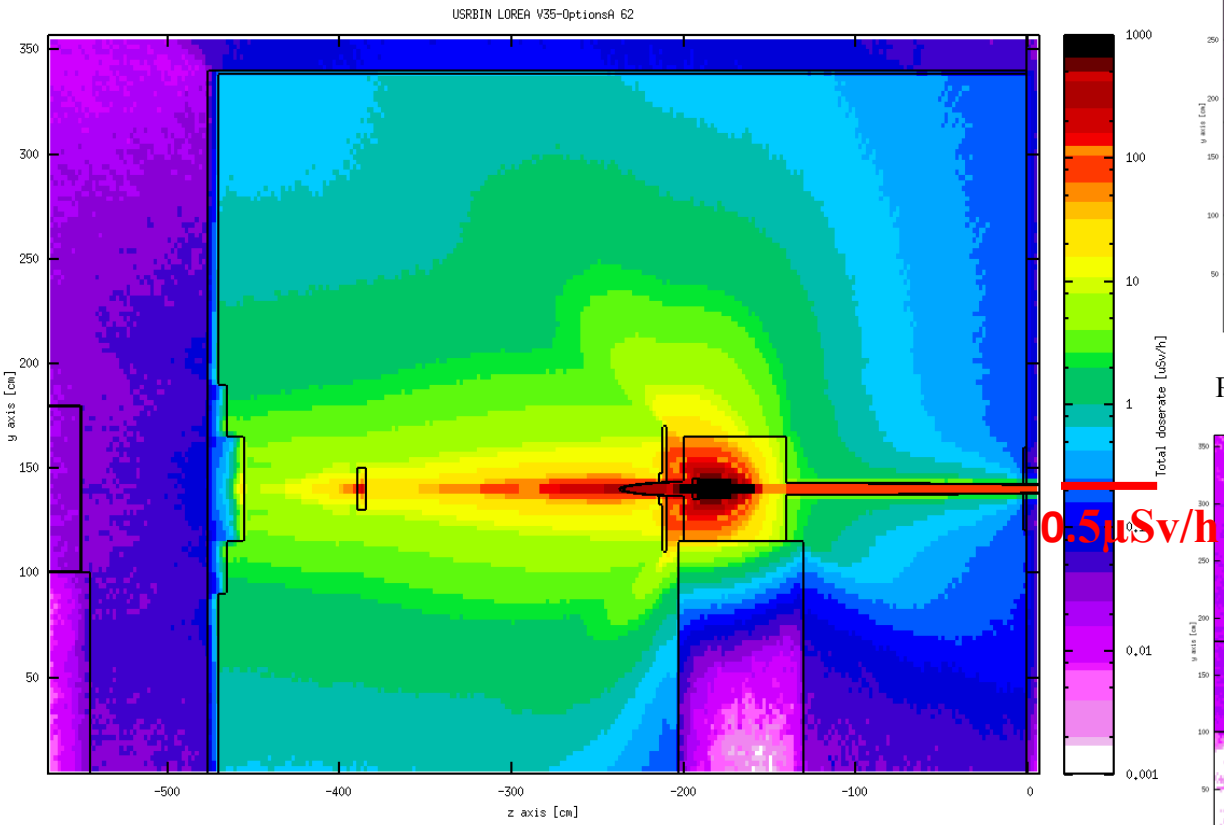
Photon dose rate map (in µSv/h)



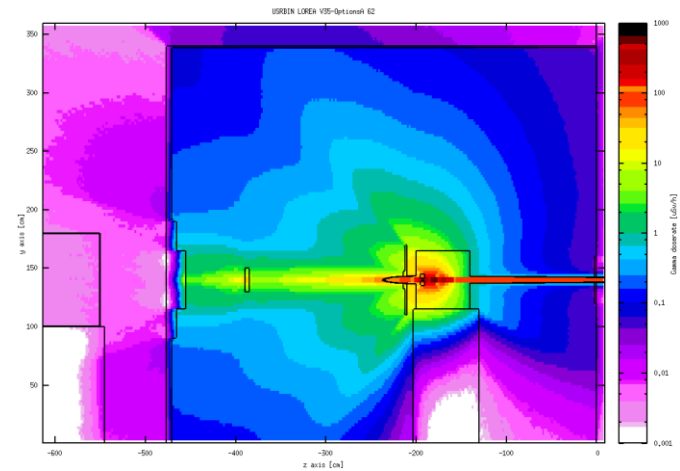
Neutron dose rate map (in µSv/h)

3.1 Gas Bremsstralhung source

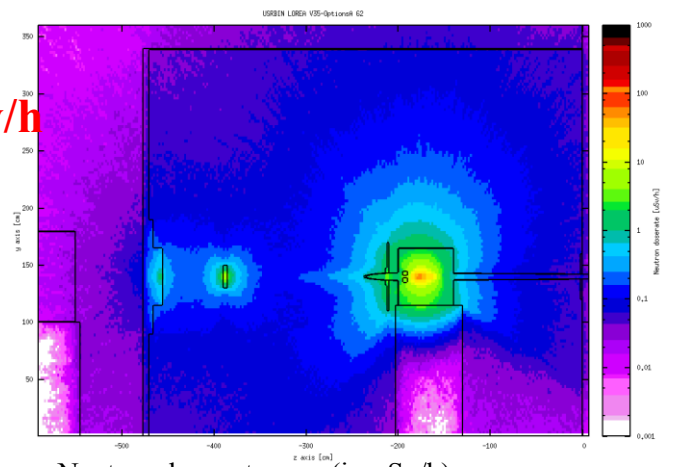
- **Gas Bremsstralung** source case equivalent dose rate maps (DOSE-EQ) - vertical view at beam level -



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



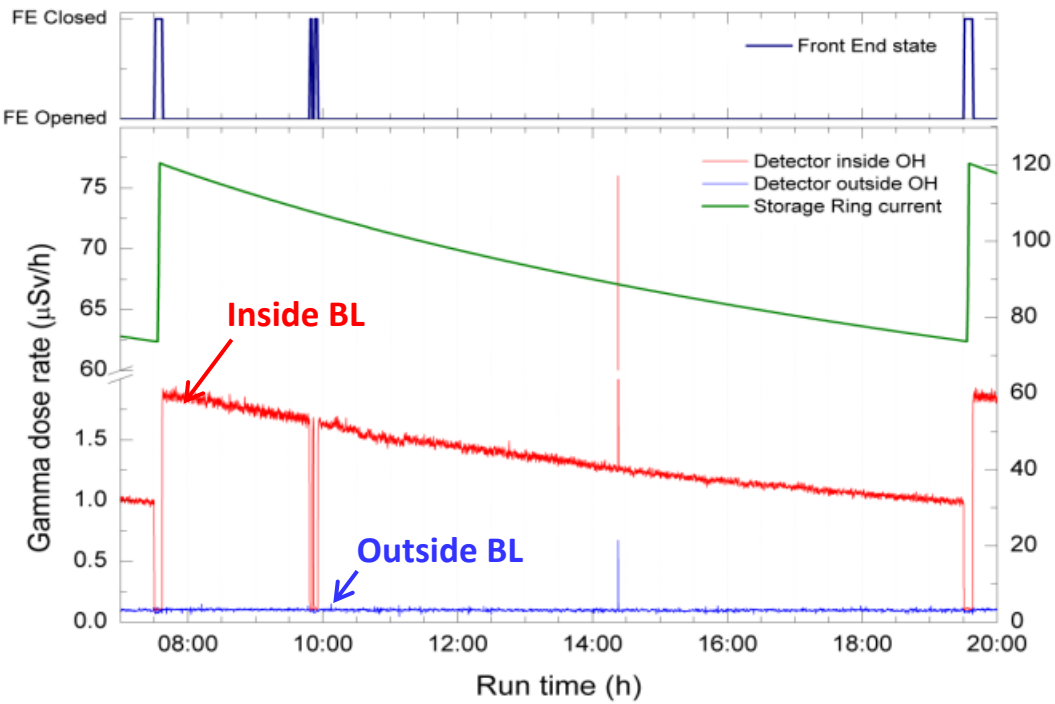
Photon dose rate map (in µSv/h)



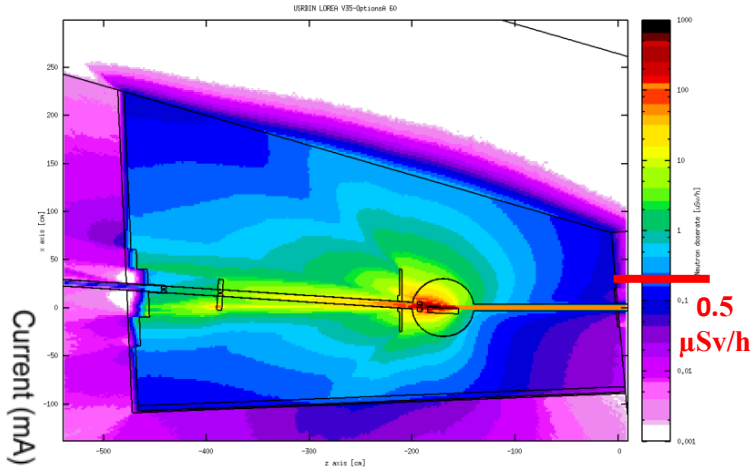
Neutron dose rate map (in µSv/h)

3.1 Gas Bremsstralhung source

- **Comparison with experimental data from ALBA beamlines**



Gamma dose rate measurements at BOREAS BL compared with storage ring current and FE state

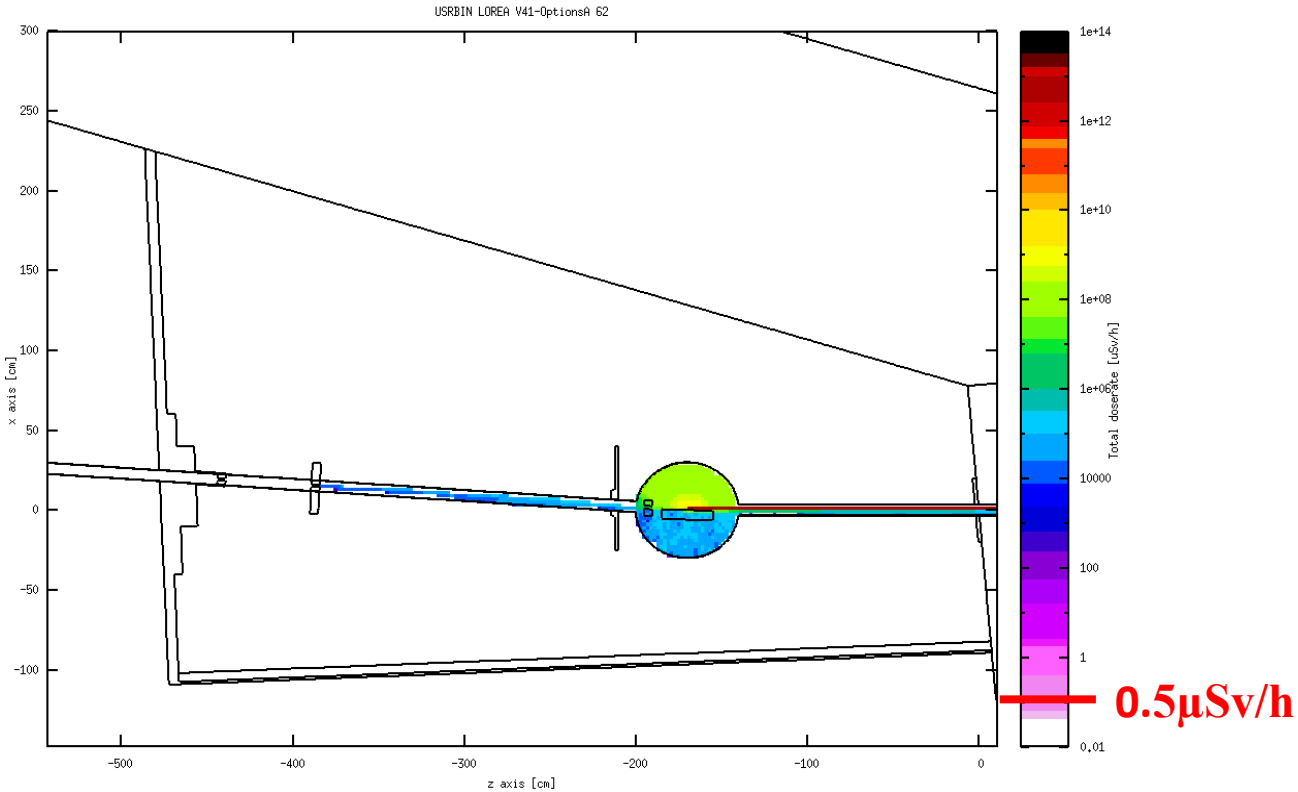


Gamma dose rate map (in µSv/h) from scattered bremsstrahlung at LOREA at 400 mA

✓ 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):



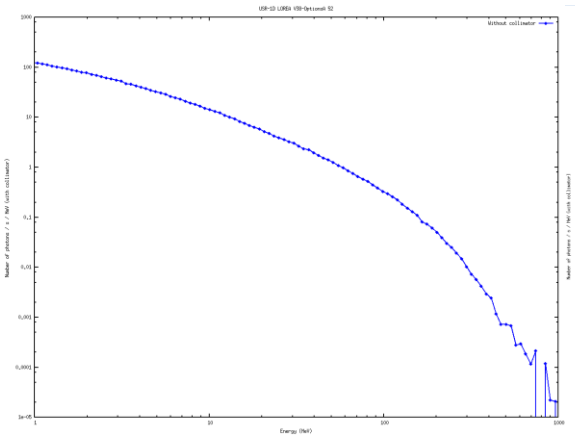
Total dose rate map (in µSv/h) from ID Undulator source

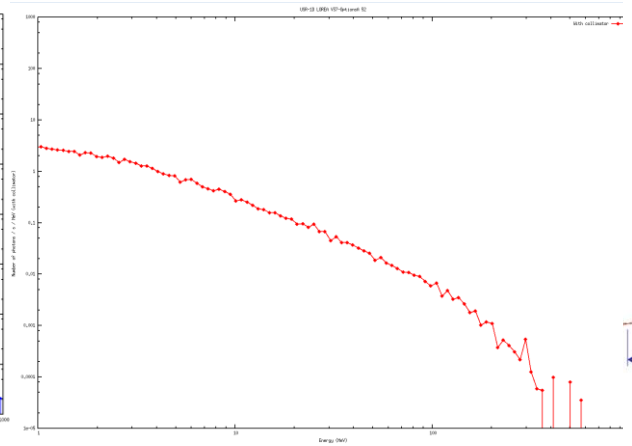
✓ **Shielding requirements for scattered synchrotron radiation are largely met by the shielding thicknesses required for scattered bremsstrahlung**.

3.3 Collimation system

- **Collimation system:**

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





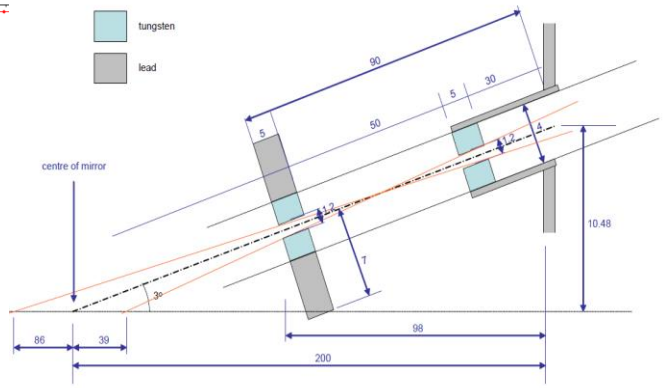


Figure A2 – Principle of the double collimation system (not to scale; all dimensions are in cm).

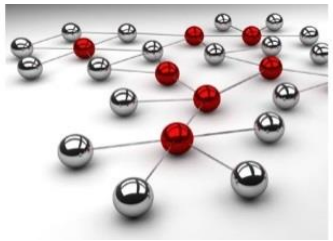
Transmitted scattered bremsstrahlung spectrum through the beampipe hole in the backwall; blue curve: no collimation; red curve: double collimator

→ **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 particules, 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 separeted input files, each one with a different thickness? **- not done -**

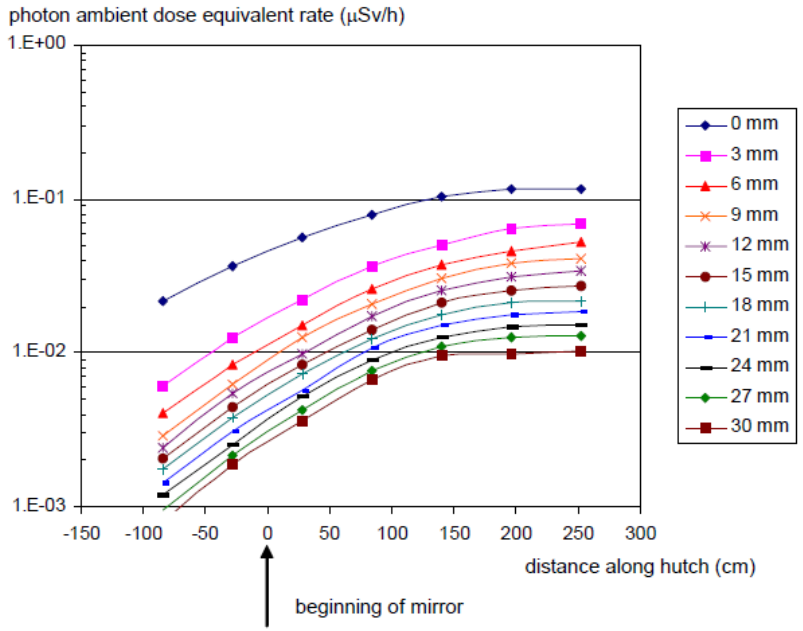
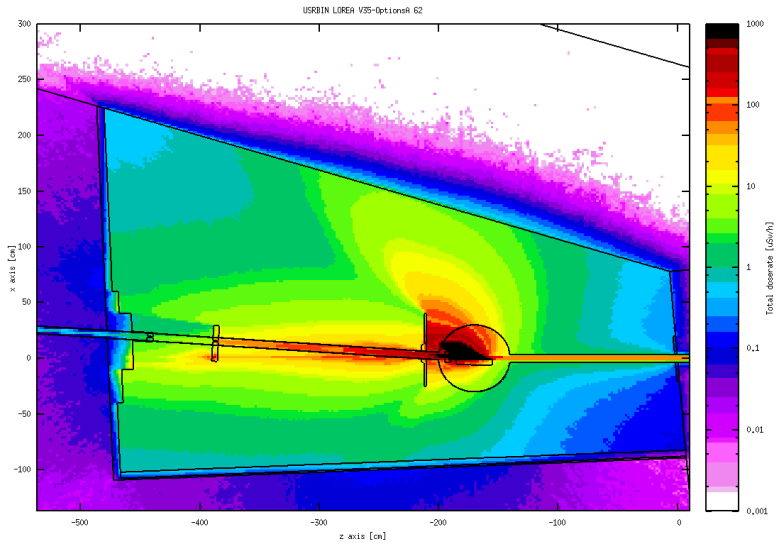


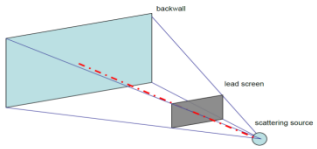
Figure 2 – Photon ambient dose equivalent rates behind the optics hutch side wall A, as a function of the distance along the hutch, for different lead thicknesses of the hutch side wall.

Conclusions

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



Total dose rate map (in µSv/h) from scattered bremsstrahlung at LOREA

Shielding thicknesses and material recommendation for the LOREA optics hutch wall and roof (mm)	*Corresponding vacuum in straight section for 0.5 µSv/h (mbar)*
Wall S	
15 mm lead + 50 mm polyethylene	1.25×10^{-8}
Roof	
15 mm lead	1.25×10^{-8}
Wall B	
60 mm of lead + 50 mm of lead in central 1 m^2 + 105 mm of lead Opt-to-Exp guillotine + 20 mm of lead local screen behind mirror + 20 mm other white beam scattering source	1.25×10^{-8} 

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!

Acknowledgement:

- ALBA Accelerator and Computing division
- FLUKA Team & forum

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

References:

- [1] "The FLUKA code: Description and benchmarking" G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)
- [2] "FLUKA: a multi-particle transport code" A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11,SLAC-R-773
- [4] Gas Bremsstrahlung Considerations in the Shielding Design of the
- Advanced Photon Source Synchrotron Radiation Beam Lines, Nisy E. Ipe, Alberto Fasso , SLAC–PUB–6452
- [5] Impact of gas bremsstrahlung on synchrotron radiation beamline shielding
- at the advanced photon source, Nisy E. Ipe, Alberto Fasso SLAC–PUB–6410,
- [6] Shielding of Beamlines at ALBA: Comparison between different types of bremsstrahlung, P. Berkvens. ALBA internal report.