Summary

This work can be considered a first approach to the world of synchrotron machines. That field implies a lot of disciplines; in this work the focus will be in the radiological protection and all that surround it.

A synchrotron can be understood as a huge microscope that produces the desired light to develop research and development for companies or for public investigation in many fields of interest. ALBA synchrotron is the only one here in Spain, and it is the synchrotron of reference to do this work.

The utilization of this kind of installation also produces undesired radiation. That radiation can be dangerous if it is not adequately dealt. For that reason the main objective of this work is to calculate the total annual (or in a period of time) dose produced by ALBA synchrotron.

It was necessary to understand the physics behind ionizing radiations and to implement it in a code. In this work are described or referenced all of the assumptions and coefficients used to do it.

The values calculated from the simulations are verified, with measured dose obtained from the network of detectors that ALBA has, with a very good match. These results are far away from causing damage to the workers.

At the end of this work there are also possible future working to keep developing that topic.
Determination of the Total Annual Dose emitted by the ALBA Synchrotron

Daniel Sabio Ruiz
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Introduction

Objectives

The main objective of this work is the determination of the total annual dose emitted by the synchrotron light source accelerator ALBA in a cloud of points around the facility, using semi-empirical models used in the design of its shielding. Moreover, the results calculated will be verified with the data measured by the working network of ALBA detectors.

Scope of this project

To achieve the objectives of this work, the following actions will be developed:

- To describe the creation, operation and the implications (risks and application) of a synchrotron particle accelerator, focusing in ALBA facility.
- To study the physics related with the radiological protection and the laws involved.
- To study the model and the algorithms used in ALBA synchrotron to calculate the dose that verify the shielding.
- To implement this algorithm in a new language, making its use easier, with a more intuitive interface and adapted to the operational inputs.
- To analyse the results of the algorithm and verify it with the measured data by the network of detectors of surveillance.
Determination of the Total Annual Dose emitted by the ALBA Synchrotron

Daniel Sabio Ruiz
Chapter 1

Synchrotron ALBA facility

1.1 Description

ALBA is a facility located in a technological park in Cerdanyola del Valles, (Barcelona). Managed by the Consortium for the Construction, Equipping and Exploitation of the Synchrotron Light Source (CELLS), it is funded in equal parts by the Spanish and the Catalonian Administration. The figure 1.1 shows the evolution of the project.

![Figure 1.1: Cronology of ALBA.](Image)

Information Source: ALBA’s website

It is a 3rd generation Synchrotron Light built to produce synchrotron light in a broad spectrum which covers from microwaves to hard X-rays, that is used for a lot kind of scientist and industrial users to study fundamental properties of matter, chemical and electronic properties.
The majors applications are:

- Medical therapy: the X-rays emitted by a synchrotron can be applied to medical imaging and certain therapies.
- Molecular biology: for studying proteins, viruses and helping to design new medicine.
- Material sciences: for studying the properties of materials.
- Environmental sciences: for determining the structure of pollutants.

ALBA is a first class radioactive facility with authorisation to operate, as establish the ministerial order [7].

1.2 Main parts

When a charged particle is accelerated it produces electromagnetic radiation, if the acceleration is parallel to the velocity it is called bremsstrahlung radiation and if the acceleration is radial it is called synchrotron radiation.

In the case of ALBA, this synchrotron radiation is produced by electrons. Those are accelerated in the LINAC up to 110 MeV to be injected into the Booster Ring, where electrons are further accelerated to 3 GeV. Then they are transferred into the Storage Ring, keeping it making turns inside it, to produce the synchrotron light used in the experiments.

The accelerator machines are shielded between walls, represented in horizontal view in figure 1.2. For more detailed information see annex B.2.

![Figure 1.2: Schematic lay-out of ALBA Accelerator.](image)

*Source: Left (Original), Right ([1])*
1.2.1 LINAC (LINear ACcelerator)

The Linac is where the electrons acquire energy moving on a linear path. The equation that defines this variation of energy is:

\[
\frac{dW}{dt} = \frac{dz}{dt} \cdot \frac{dp}{dt} = q \cdot \frac{dz}{dt} \cdot (E + \frac{dz}{dt} \times B) \tag{1.1}
\]

As is shown in the equation, the energy can be gained using electric fields or magnetic fields, in a synchrotron the electric fields are used for accelerations and magnetic fields for focusing and bending the beam.

There are several methods to accelerate a particle using electric fields; the method implemented in ALBA is using a radio frequency (RF) linac. It consist in a RF power source that provides an electromagnetic wave with the desired frequency, this wave is conducted to a metallic cavity, which have to concentrate the induced electric field in the beam area, minimize losses of RF power and control the limiting factors, in order to produce a resonance with the wave frequency. To do all of this is necessary a very accurate geometry. When particles pass through this cavity, with an appropriate phase, it is accelerated.

![Figure 1.3: Schematic of RF working.](source: [2])

The solution of the Maxwell equation for electromagnetic waves in this medium describe the electric field induced in a cavity with the following equation. For more detailed information see [2].

\[
E(x, y, z, t) = E(x, y, z, t) \cdot \exp(-j\omega t) \tag{1.2}
\]

The first term is function of space and the second one is function of time oscillating at frequency \(\frac{\omega}{2\pi}\). Then the energy gain of a particle q on axis at phase \(\theta\) is obtained with the integral of the electric field along the cavity length.

\[
\Delta W = \int_0^L q \cdot E(x, y, z, t) \cdot \exp(-j\omega t) \tag{1.3}
\]
The ALBA Linac, which is 12 m long, accelerates the electrons produced by a thermo-ionic gun up to 15 MeV using standing waves cavities. Later using two travelling waves sections with constant RF gradient they are accelerated up to 110 MeV to inject it into the Booster, for more detailed information see [6].

1.2.2 Booster Ring

The Booster Ring is a set of machines, which form a circular trajectory, that increase the energy of the electrons at each turn. To do this is used a FODO type lattice that consist in a unit cell composed by a bending magnet (dipole) together with a focusing and one defocusing quadrupole. Eight of these cells units are distributed in each quadrant of a four-fould symmetry, together with two matching cell, composed by sextupoles.

The circumference of ALBA Booster is 249.6 m. In a 3.125 Hz rate it accelerates the electrons from 110 MeV to 3 GeV in a ramp of 145 ms to transfer it to the Storage Ring and then it ramps down for the next injection of the Linac, for more detailed information see [6].
1.2.3 Storage Ring

The Storage Ring has the same principle as Booster Ring, with the difference that it only needs compensate the energy lost in each turn. Also it is where the beam is modified to achieve the desired parameters to do the experiments.

Table 1.1: Magnets in each ring.

<table>
<thead>
<tr>
<th></th>
<th>Booster Ring</th>
<th>Storage Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>60</td>
<td>112</td>
</tr>
<tr>
<td>Sextupole</td>
<td>16</td>
<td>120</td>
</tr>
</tbody>
</table>

The energy is lost in form of light and radiation, the light is voluntary produced with wigglers to be used in the experiments and the radiation is shielded to protect the facility and the people, that topic will be developed later.

A wiggler is a series of short bending magnets with alternating field excitation. It is used to generate more synchrotron radiation light and to manipulate beam parameters, among others.

![Figure 1.6: Schematic of a wiggler.](Spring8 synchrotron website)

The circumference of ALBA Storage Ring is 268.8 m long.
Chapter 2

Physical Interactions

The main disadvantage of a synchrotron machine is that it generates undesired radiation. This radiation comes from the interaction of a particle (primary or secondary) or photons with the matter (machine or facility).

2.1 Interaction between electrons and matter

2.1.1 Inelastic collision

An electron transfers energy to an orbital electron when they collide in an inelastic way. In function of the transferred energy:

- If the energy is sufficient, the second electron is excited and it goes to a higher orbital.
- If the energy is higher, the orbital electron leaves the atom. It means that this released electron can also interact with matter and the atom is ionized, that often implies highly reactivity.

The empty space generated is filled with other orbital electron, which emit a photon.

2.1.2 Bremsstrahlung radiation

As is mentioned in section 1.2, electromagnetic radiation is produced when a charge particle change his movement. It happens when an electron interacts with the electric field generated by an atomic nucleus. This nucleus can be from the tube pipe, then this type of radiation is called solid bremsstrahlung, or it can be from the residual gas inside the vacuum chamber, then this type is called gas bremsstrahlung.
2.2 Interaction between neutrons and matter

Neutrons can also produce elastic and inelastic collisions or be absorbed by an atomic nucleus. It may produce ionization, in the first case, or an isotope change, in the second one, and if this isotope is not stable it will produce ionizing radiation.

2.3 Interaction between photons and matter

2.3.1 Photo-electric effect

An electron can be removed from an orbital of the inner shells if a photon with enough energy (threshold frequency) impact with it.

2.3.2 Compton scattering

It is an inelastic collision of a photon with the boundary electrons.

2.3.3 Pair production

A photon with high energy (at least $E = 2 \cdot m_e c^2 = 1.022 \text{ MeV}$) can produce an electron and a positron when it interacts with the Coulomb field of an atomic nucleus, the probability of this conversion increase with the energy. This production is completely symmetric and follows the Einstein’s equation $E = m \cdot c^2$.

$$\gamma \rightarrow e^- + e^+$$ (2.1)

2.4 Electromagnetic cascade

All of these effects listed above can happen consecutively, as a result of the interactions of one primary particle with high energy until the energy of secondary particles is too low to produce more reactions. This chain of events is named electromagnetic cascade. The length of this event depends on the energy and on the material where the particles are interacting.

$$\frac{dE}{dx} = - \frac{1}{L_R} \cdot E$$ (2.2)

$$E_x = E_0 \cdot \exp\left(-\frac{x}{L_R}\right)$$ (2.3)

$dE/dx$: Average rate of energy loss per cm path length

$L_R$: Radiation length of the material. It can be interpreted as the average thickness of
material that reduces the mean energy of the charged particle by a factor $e$. The value $L_R$ for electrons in lead is 0.56 cm, for iron it is 1.8 cm and for aluminium it is 8.9 cm. For more detailed information see [8].

![Figure 2.1: Schematic of electromagnetic cascade.](Source: Radiation Protection Dosimetry Oxford journals website)

2.5 Interaction between ionizing radiation and matter

These interactions explained above can produce, directly or indirectly, ionizing radiation, which is energy transmitted through the space or through material medium that can ionize atoms or molecules, and break chemical bounds.

The energy comes from an unstable atom of nucleus that emits it. This emission is radioactive if includes alpha or beta particles, gamma rays or conversion electrons. This stochastic process is named radioactive decays or radioactivity. The unit of radioactivity in the SI is the Becquerel (Bq), it is defined as the quantity of radioactive material in which one nucleus decays per second.

This kind of energy is harmful and it is mandatory be careful with the exposure to it, there are different forms to evaluate it.

2.5.1 Absorbed dose

It is the concentration of energy deposited per mass as a result of an exposure to ionizing radiation. It is used to directly evaluate the effect of the radiation in the inanimate matter. SI units: $\text{Grey} = \text{Joule/kg}$

2.5.2 Equivalent dose

It represents the probability of cause serious damage in a human body. It is based on the absorbed dose, taking into account the biological effectiveness of the radiation, which is dependent on the radiation type and energy. SI units: $\text{Sievert} = \text{Joule/kg}$

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2.5.3 Effective dose

It is the tissue-weighted sum of the equivalent doses of all organs and tissues of the body. This tissue weighting factor takes into account the absorbed dose to all organs of the body, the relative harm level of the radiation and the sensitivities of each organ to radiation. 

Sievert = Joule/kg
Chapter 3

Radiological protection

It is obligatory guarantee that all the people that work in a facility that produce radiation has limited his exposure, by law [9], in order to prevent accidents. Moreover, all the facilities that produces ionizing radiation must follow the ALARA principle. It is an acronym for "as low as (is) reasonably achievable" which means to make every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, taking into account all the parameters that applies. For more detailed information see [10].

3.1 Workers

There are the limits to the effective dose, in function of the worker, that they can be exposed in their job:

- Exposed worker:
  - Type A: Can be exposed to $20 \text{ mSv/year}$ averaged for 5 years periods, with a maximum dose of $50 \text{ mSv}$ per official year.
  - Type B: Can receive a maximum dose of $6 \text{ mSv/year}$ per official year.

- Non exposed workers, general public and women during pregnancy can be exposed to $1 \text{ mSv}$ per official year.

3.2 Working areas

Also working areas are classified in function of the radiation in it to determinate which exposed workers can go inside it, For more detailed information see [9].

- Watched Zone: There is a dose level between $1 \text{ mSv}$ and $6 \text{ mSv}$ per official year.
- Controlled Zone: There is a dose level higher than $6 \text{ mSv}$ per official year.

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– Limit Access Zone: dose higher than 100 $mSv$ for 5 years.
– Prohibited Access Zone: high dose in a single exposition.

Of course the time that one worker need to be in one zone is decisive to define the type of this zone.

To control the exposure of the workers, all of them use personnel dosimeters and the dose in each area with radiation is measured with detectors.

All of those limits do not have into account the natural radiation that there are in the Earth, coming from different sources; the biggest part of it comes from the nature. The worldwide average dose is 2.4 $mSv/year$.

**Figure 3.1:** Average contribution of different sources to natural background radiation
Chapter 4

Selection of installation points for the calculation of the dose

The primary source of ionising radiation, in a working synchrotron, comes from the escape of electrons of his ideal orbit inside the vacuum pipe.

The points represented in the figure 4.1 are where the electrons have more probabilities to escape. Those points and the probability associated to each one of it were deduced experimentally from the experience in others synchrotron facilities and adapted to ALBA.

Figure 4.1: Electrons loss points at the ALBA accelerator.
Source: [4]
Those points are where the different models are applied to calculate the contribution to the dose at certain distance of those points, see figure 4.2.

**Figure 4.2:** Dose point directions with respect to the electrons trajectory.  
*Source: [1]*

### 4.1 Calculation of the electron losses

The number of electrons lost at each machine point due to regular losses is estimated by the following equation.

\[
\text{epsLOSS}_i = \text{epsOUT}_{i-1} \cdot \text{loss}_i \tag{4.1}
\]

**Figure 4.3:** Electron flux diagram.  
*Source: [4]*

Definitions:

- **i**: Each lost point.

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• eps: Electrons per second.
• epsLOSSi: Electrons per second lost in the point "i".
• epsOUTi: Electrons per second that correctly through the point "i".
• lossi: the percentage of electrons which are regularly lost in the point "i".

Estimations:

• epsOUT0: Electrons per second coming from de thermo-ionic gun.
• Loss percentages are predicted from the experience of others synchrotron and then adapted by K.Ott to ALBA.

Table 4.1: Equations applied to synchrotron ALBA.

<table>
<thead>
<tr>
<th>Loss points</th>
<th>i</th>
<th>lossi</th>
<th>epsLOSSi [eps]</th>
<th>epsOUTi [eps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-buncher</td>
<td>0</td>
<td>0%</td>
<td>1.540E+11</td>
<td></td>
</tr>
<tr>
<td>First acceleration</td>
<td>1</td>
<td>10%</td>
<td>1.540E+10</td>
<td>1.386E+11</td>
</tr>
<tr>
<td>Second acceleration</td>
<td>2</td>
<td>10%</td>
<td>1.386E+10</td>
<td>1.247E+11</td>
</tr>
<tr>
<td>Linac-to-booster transfer line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linac tunnel</td>
<td>3</td>
<td>5%</td>
<td>6.237E+09</td>
<td>1.185E+11</td>
</tr>
<tr>
<td>Booster tunnel</td>
<td>4</td>
<td>5%</td>
<td>5.925E+09</td>
<td>1.126E+11</td>
</tr>
<tr>
<td>Booster</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection septum</td>
<td>5</td>
<td>20%</td>
<td>2.252E+10</td>
<td>9.006E+10</td>
</tr>
<tr>
<td>Extraction septum</td>
<td>6</td>
<td>15%</td>
<td>1.689E+10</td>
<td>7.318E+10</td>
</tr>
<tr>
<td>Point sources (25)</td>
<td>7</td>
<td>15%</td>
<td>1.689E+10</td>
<td>5.629E+10</td>
</tr>
<tr>
<td>Extraction septum</td>
<td>8</td>
<td>15%</td>
<td>8.443E+09</td>
<td>4.785E+10</td>
</tr>
<tr>
<td>Booster-to-storage transfer line</td>
<td>9</td>
<td>5%</td>
<td>2.392E+09</td>
<td>4.545E+10</td>
</tr>
<tr>
<td>Before bending magnets</td>
<td>10</td>
<td>5%</td>
<td>2.273E+09</td>
<td>4.318E+10</td>
</tr>
<tr>
<td>After bending magnets</td>
<td>11</td>
<td>25%</td>
<td>1.080E+10</td>
<td>3.239E+10</td>
</tr>
<tr>
<td>Point sources (27)</td>
<td>12</td>
<td>25%</td>
<td>8.096E+09</td>
<td>2.429E+10</td>
</tr>
</tbody>
</table>

For more detailed information see [4].

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Chapter 5

Modelling of the dose calculation

To ensure that the specifications of radiological protection listed before, in the page number 23, will be accomplished, it is mandatory calculate the dose that will be produced by the facility before built it and monitoring it with detectors, when it is operating, to verify the results.

The semi-empirical model used to calculate the contribution to the dose generate by electrons lost is deterministic and deduced from the experience of others installations and from Monte Carlo simulations. The result of combine these two knowledge is the following generic equation.

\[
H_e [Sv/e] = H_0 \left( \frac{1}{r|m|} \right)^2 \cdot \left( \frac{E[GeV]}{k} \right)^{\alpha} \cdot M_i \tag{5.1}
\]

\[
M_i = exp(-\lambda_i[cm^2g^{-1}] \cdot (x_i \rho_i [g \cdot cm^{-2}]))) \tag{5.2}
\]

Figure 5.1: Target-shielding geometry layout.

Source: [5]
Where:

- $H_e [Sv/e]$ is the dose per primary electron
- $H_a [Sv/e]$ is the dose after the lead shielding
- $r [m]$ is the distance of the loss point to the place where the dose is calculated.
- $E [GeV]$ is the electron energy.
- $M_i$ is the attenuation produced by a shielding material.
- $x_i [cm]$ is the thickness of the shielding material.
- $\rho_i [g \cdot cm^{-3}]$ is the density of the shielding material, see table 5.1

The others parameters takes different values depending on the geometry and which event is taking into account. For more detailed information see [5].

<table>
<thead>
<tr>
<th>Shielding material</th>
<th>$\rho [g \cdot cm^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND concrete</td>
<td>2.4</td>
</tr>
<tr>
<td>Sand</td>
<td>1.6</td>
</tr>
<tr>
<td>HD concrete</td>
<td>3.2</td>
</tr>
<tr>
<td>Lead</td>
<td>11.35</td>
</tr>
<tr>
<td>Copper</td>
<td>8.92</td>
</tr>
<tr>
<td>Iron</td>
<td>7.86</td>
</tr>
</tbody>
</table>

### 5.1 Electromagnetic Particles

#### 5.1.1 Dose point in the electron direction

The dose is computed for two cases:

- $t = 0.2 cm$ and $\psi = 2^\circ$. Then $H_0$ is $1.0 \cdot 10^{-12} [Sv/e]$
- $t = 1 cm$ and $\psi = 90^\circ$. Then $H_0$ is $4.5 \cdot 10^{-13} [Sv/e]$

$$H_e [Sv/e] = H_a \left( \frac{1}{r[m]} \right)^2 \cdot \left( \frac{E[GeV]}{0.1} \right)^{1.47} \cdot \exp \left( -0.19 \cdot \left( \frac{t}{\sin \theta} \right) - 1 \right) \cdot M_2 \quad (5.3)$$

The details of this parametrization are given in [11].
5.1.2 Inclined target and dose point out of electron direction

The dose is computed for two target thicknesses $t = 0.2$ cm and $t = 1$ cm in different observation angles $\theta = 7.5^\circ$, $25^\circ$ and $90^\circ$, with a fixed target angle $\phi = -2^\circ$. The details of this parameterization are given in [12].

$$H_e[Sv/e] = H_a \left( \frac{1}{r[m]} \right)^2 \cdot \left( \frac{E[GeV]}{5} \right)^{\alpha} \cdot \exp(-\lambda_2[cm^2/g^{-1}] \cdot (x_2 \rho_2[g \cdot cm^{-2}] - 75)) \quad (5.4)$$

<table>
<thead>
<tr>
<th>$t$ [cm]</th>
<th>$\theta$ [°]</th>
<th>$H_0$ [Sv/e]</th>
<th>$H_a$ [Sv/e]</th>
<th>$\alpha$</th>
<th>*Shielding material</th>
<th>$\lambda_2$ [cm$^2 \cdot g^{-1}$]</th>
<th>$\theta=7.5^\circ$</th>
<th>$\theta=90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>7.5</td>
<td>2.60E-12</td>
<td>2.30E-13</td>
<td>0.61</td>
<td>*</td>
<td></td>
<td>0.044</td>
<td>0.044</td>
</tr>
<tr>
<td>0.2</td>
<td>25</td>
<td>6.90E-13</td>
<td>3.50E-15</td>
<td>0.52</td>
<td>Lead</td>
<td></td>
<td>0.024</td>
<td>0.031</td>
</tr>
<tr>
<td>0.2</td>
<td>90</td>
<td>9.90E-14</td>
<td>1.30E-17</td>
<td>0.51</td>
<td>Iron</td>
<td></td>
<td>0.024</td>
<td>0.027</td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
<td>1.20E-12</td>
<td>1.50E-13</td>
<td>1.05</td>
<td>HD concrete</td>
<td></td>
<td>0.024</td>
<td>0.027</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>5.30E-13</td>
<td>3.50E-14</td>
<td>0.97</td>
<td>ND concrete</td>
<td></td>
<td>0.02</td>
<td>0.025</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>1.30E-13</td>
<td>4.40E-16</td>
<td>0.95</td>
<td>Sand</td>
<td></td>
<td>0.019</td>
<td>0.025</td>
</tr>
</tbody>
</table>

5.1.3 Dose point out of electron direction and perpendicular target

This parametrization estimates the dose when the electron hits the target perpendicularly. The dose is computed for observation angles from $\theta = 5^\circ$ to $\theta = 100^\circ$. The details of this parameterization are given in [12].

$$H_e[Sv/e] = 1.5 \cdot 10^{-9} \left( \frac{1}{r[m]} \right)^2 \cdot (E[GeV])^{1.56} \cdot M_1 \cdot M_2 \quad (5.5)$$

$$\lambda_i = \frac{1}{a \cdot \log(E[GeV]) + b} \quad (5.6)$$

Table 5.2: Parameters of Eq. 5.4.

Source: [5]

<table>
<thead>
<tr>
<th>Material</th>
<th>a [g $\cdot$ cm$^{-2}$ $\cdot$ GeV$^{-1}$]</th>
<th>b [g $\cdot$ cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND concrete</td>
<td>5.33</td>
<td>39.6</td>
</tr>
<tr>
<td>Sand</td>
<td>5.33</td>
<td>39.6</td>
</tr>
<tr>
<td>HD concrete</td>
<td>5.74</td>
<td>31</td>
</tr>
<tr>
<td>Lead</td>
<td>0</td>
<td>18.3</td>
</tr>
<tr>
<td>Cooper</td>
<td>0</td>
<td>28.3</td>
</tr>
</tbody>
</table>

Table 5.3: Parameters of Eq. 5.6.

Source: [5]
5.2 Neutrons

When an electron hits a target, in function of its energy, two parametrizations can be characterized to determine the dose (outside shielding material) produced by neutrons.

5.2.1 Giant-resonance neutrons

This parametrization is used for incident electron energies larger than 0.1 GeV. The details of this parametrization are given in [12].

\[ H_e[Sv/e] = 0.3 \cdot 4 \cdot 10^{-10} \left( \frac{1}{4\pi r[m]} \right)^2 \cdot (E[GeV]) \cdot M_1 \cdot M_2 \]  

(5.7)

Table 5.4: Attenuation coefficient of \( M_1 \) and \( M_2 \) of Eq. 5.7.

Source: [5]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \lambda ) [cm(^2\cdot g^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND concrete</td>
<td>0.027</td>
</tr>
<tr>
<td>Sand</td>
<td>0.033</td>
</tr>
<tr>
<td>HD concrete</td>
<td>0.024</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0044</td>
</tr>
<tr>
<td>Copper</td>
<td>0</td>
</tr>
<tr>
<td>Iron</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

5.2.2 High-energy neutrons

This parametrization is used for incident electron energies larger than 0.4 GeV. The details of this parametrization are given in [12].

\[ H_e[Sv/e] = H_0 \cdot \left( \frac{1}{r[m]} \right)^2 \cdot (E[GeV]) \cdot M_1 \cdot M_2 \]  

(5.8)

Table 5.5: Coefficients of Eq. 5.8.

Source: [5]

<table>
<thead>
<tr>
<th>Material</th>
<th>( H_0 ) [Sv/e]</th>
<th>( \lambda ) [cm(^2\cdot g^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND concrete</td>
<td>4.00E-17</td>
<td>100</td>
</tr>
<tr>
<td>Sand</td>
<td>4.00E-17</td>
<td>100</td>
</tr>
<tr>
<td>HD concrete</td>
<td>4.00E-17</td>
<td>110</td>
</tr>
<tr>
<td>Lead</td>
<td>2.40E-17</td>
<td>222.79</td>
</tr>
<tr>
<td>Copper</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Iron</td>
<td>4.00E-17</td>
<td>170</td>
</tr>
</tbody>
</table>
Chapter 6

Operating mode of ALBA and measured values of radiological surveillance network

As everybody knows, the reality is more complex than the theory. For this reason the real values need to be adapted to the hypothesis, that are used in a model.

6.1 Operating mode

The synchrotron ALBA can work 24 hours/day all the days. To do it there are workers with rotating schedules of 8 hours/turn.

There are two operation modes when the synchrotron is working:

- User operation: The synchrotron provides the desired light to do the experiments.
- Machine operation: It is used to run some tests to the machines.

The available values to do this work are from year 2013, the month of July was selected to discuss the operation modes because it is the most homogeneous month. For more detailed information see annex B.1.

6.1.1 Storage Ring current

The model suppose that a current is injected in the synchrotron every certain hours with a specific filling time, for the two modes of operations. But the reality is not homogeneous, the image 6.1 shows the variability in the current of the Storage Ring of synchrotron ALBA in the month of July of 2013.
A new code was developed by the author of this work, Daniel Sabio Ruiz, to know the parameters mentioned before. This code analyse all the injections and extract the parameters related to each one, then the final numbers are extracted of the average of all data.

The theoretical values predicted are very similar with some considerations listed below the table.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Theoretical</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection [mA]</td>
<td>400</td>
<td>97.24</td>
</tr>
<tr>
<td>Every [h]</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>Filling time [min]</td>
<td>7.5</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 6.1: Storage Rinc current parameters.

Source: Original

Considerations:

- The injection predicted is the maximum capacity of the synchrotron ALBA. In July of 2013 the average of the current is around 100 mA (see figure 6.1)

- The machine operation is a mode of work of synchrotron to run some tests, that can be very different each time.

Figure 6.1: Storage Ring Current.

Source: ALBA synchrotron
6.2 Natural Radiation

As was shown in the graphic of the figure 3.1 there are a natural radiation in all the Earth.

In August of 2013 the synchrotron ALBA was stop, but the detectors are always working. For this reason, these measured values was used to know the natural radiation in each point where the detectors are placed to discriminate it in the future measures.

Figure 6.2: Average gamma natural dose expressed in $\mu$Sv/day.

Source: Original

The values are the average of gamma radiation in August of 2013, at each point.

Daniel Sabio Ruiz
6.3 Gamma radiation dose

The following figure shows the average measured net dose contribution in July of 2013 in all gamma detectors of ALBA.

![Figure 6.3: Average gamma dose expressed in $\mu$Sv/day. Source: Original](image)

The value of detector EH20 is excluded from the calculations because it is probably an anomaly caused from an experiment or something similar.

These values will be used in chapter 8 to verify the gamma radiation calculated in the simulations.
Chapter 7

Implementation of dose calculation model in shielding design

The model explained in chapter 5 was used in the design of the shielding of ALBA synchrotron, in reference with the radiological protection. It was implemented in a code, which was wrote in C language by Klaus Ott.

Nevertheless, that code is not very friendly for the people that wants to use it, because it is necessary know how it works and know about C language to modify the inputs and for read the results produced.

For these reasons another code, using the previous one, was developed by the author of this work, Daniel Sabio Ruiz, during his internship in ALBA synchrotron in the summer of 2013.

That second code was wrote in MS Excel with some modifications to adapt it. It is more intuitive than the first one and it can be used for people that do not know about programming following the instructions listed here [13].

Obviously, the same results will be obtained if the same inputs are given to the two codes.

Moreover, another code was developed for the author of this work to adapt the operational data of the ALBA synchrotron to the inputs of the model. This is more explained in the section 6.1.1.

This process is represented in the following figure 7.1.
Figure 7.1: Scheme of the development of the codes
Chapter 8

Verification of the code with measured values

The code mentioned before calculates the total equivalent, in a period of time, dose emitted by a synchrotron light source accelerators (from the linac to the storage ring) using MS Excel, applying the model explained in chapter 5. As inputs it need:

- The probability of loss electrons at each point. (Explained in Chapter 4)
- The energy of electrons. Defined by design (From 90 keV to 3 GeV).
- Injection parameter. (Explained in section 6.1.1)
- The total probability of a successful injection of an electron bunch from the Linac gun into the Storage Ring for the two modes of operation. (See [4])
- The shielding material and its properties.
- The thickness of the walls and the distance to the point where calculate the dose. (See table 8.1)

Table 8.1: Example of some inputs.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1st Shielding layer</th>
<th>2nd Shielding layer</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Thickness [cm]</td>
<td>Material</td>
</tr>
<tr>
<td>Backward</td>
<td>HD concrete</td>
<td>100</td>
<td>1290</td>
</tr>
<tr>
<td>Forward</td>
<td>Lead</td>
<td>10</td>
<td>HD concrete</td>
</tr>
<tr>
<td>Inward</td>
<td>ND concrete</td>
<td>100</td>
<td>298</td>
</tr>
<tr>
<td>Outward</td>
<td>HD concrete</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Upward</td>
<td>HD concrete</td>
<td>100</td>
<td>260</td>
</tr>
</tbody>
</table>

Source: Original
8.1 Simulations

All the simulations are calculated using the input data of July of 2013 (explained in section 6.1) to obtain the ambient dose for this month of reference.

The code was executed adapting the distances to the position of some gamma detectors, to calculate the gamma dose generated by the electrons when they interact with some magnets. For more detailed information about the distances used in the simulations see annex B.3.

However, it uses models to calculate the dose in different specific directions, for these reason some assumptions must be taken with the distances chosen in the following tables:

- The outward distances are the minimum distance between the detector and the respective rings. It means that the program calculates doses with the assumption that there are all the types of magnets producing outward dose at minimum distance. (conservative assumption)

- The thickness of the wall is always the distance travelled by the particle when it through this. (conservative assumption)

- The forward distances are the minimum distance between the detector and the first type magnet in that direction.

The three first detectors used for the tables, 8.2-8.3-8.4, was selected because there are as near as possible to the walls of the synchrotron, there are not behind an experimental hutch and there are in different positions around ALBA. (See annex B.2 or B.3).

Table 8.2: Adjusted values for EH16 detector and results for the month of reference. 
*Source: Original*

<table>
<thead>
<tr>
<th>Loss point</th>
<th>Magnet</th>
<th>Distance [cm]</th>
<th>Gamma Dose [μSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Ring</td>
<td>Dipole</td>
<td>579</td>
<td>2197</td>
</tr>
<tr>
<td></td>
<td>Quadrupole</td>
<td>579</td>
<td>1879</td>
</tr>
<tr>
<td>Storage Ring</td>
<td>Dipole</td>
<td>232</td>
<td>1185</td>
</tr>
<tr>
<td></td>
<td>Wiggler</td>
<td>232</td>
<td>1836</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Daniel Sabio Ruiz
### Table 8.3: Adjusted values for EH03 detector and results for the month of reference.  
*Source: Original*  

<table>
<thead>
<tr>
<th>Loss point</th>
<th>Magnet</th>
<th>Distance [cm]</th>
<th>Gamma Dose [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Ring</td>
<td>Dipole</td>
<td>463</td>
<td>3.66E-01</td>
</tr>
<tr>
<td></td>
<td>Quadrupole</td>
<td>463</td>
<td>8.17E-02</td>
</tr>
<tr>
<td>Storage Ring</td>
<td>Dipole</td>
<td>217</td>
<td>2.88E+00</td>
</tr>
<tr>
<td></td>
<td>Wiggler</td>
<td>217</td>
<td>4.77E-01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4.24</strong></td>
</tr>
</tbody>
</table>

### Table 8.4: Adjusted values for EH27 detector and results for the month of reference.  
*Source: Original*  

<table>
<thead>
<tr>
<th>Loss point</th>
<th>Magnet</th>
<th>Distance [cm]</th>
<th>Gamma Dose [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Ring</td>
<td>Dipole</td>
<td>579</td>
<td>2.34E-01</td>
</tr>
<tr>
<td></td>
<td>Quadrupole</td>
<td>579</td>
<td>5.22E-02</td>
</tr>
<tr>
<td>Storage Ring</td>
<td>Dipole</td>
<td>289</td>
<td>1.62E+00</td>
</tr>
<tr>
<td></td>
<td>Wiggler</td>
<td>232</td>
<td>2.69E-01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>2.84</strong></td>
</tr>
</tbody>
</table>

The following simulations use the detector that is near the injection point between Linac-Booster (table 8.5) and Booster-Storage (table 8.6), respectively. In order to check also others loss points and others types of parametrizations.

The directions that have not distances is because there are too long, there are not that type of magnet in that direction or the direction is not pointing to the detector.

### Table 8.5: Adjusted values for EH07 detector and results for the month of reference.  
*Source: Original*  

<table>
<thead>
<tr>
<th>Loss point</th>
<th>Magnet</th>
<th>Distance [cm]</th>
<th>Gamma Dose [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Ring</td>
<td>Dipole</td>
<td>839</td>
<td>1.11E-01</td>
</tr>
<tr>
<td></td>
<td>Quadrupole</td>
<td>839</td>
<td>2.49E-02</td>
</tr>
<tr>
<td>Storage Ring</td>
<td>Dipole</td>
<td>1142</td>
<td>1.97E-01</td>
</tr>
<tr>
<td></td>
<td>Wiggler</td>
<td>1446</td>
<td>5.11E-03</td>
</tr>
<tr>
<td>Transferline 2</td>
<td></td>
<td>2530</td>
<td>8.63E-02</td>
</tr>
<tr>
<td>Injection</td>
<td></td>
<td>1937</td>
<td>2.85E-02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>0.55</strong></td>
</tr>
</tbody>
</table>
Table 8.6: Adjusted values for EH33 detector and results for the month of reference.
Source: Original

<table>
<thead>
<tr>
<th>Loss point</th>
<th>Magnet</th>
<th>Distance [cm]</th>
<th>Gamma Dose [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Ring Dipole</td>
<td>665</td>
<td>2356</td>
<td>1.77E-01, 2.47E-06</td>
</tr>
<tr>
<td>Quadrupole Dipole</td>
<td>665</td>
<td>2038</td>
<td>3.96E-02, 1.78E-01</td>
</tr>
<tr>
<td>Storage Ring Dipole</td>
<td>1113</td>
<td>1157</td>
<td>2.09E-01, 6.02E-03</td>
</tr>
<tr>
<td>Wiggler</td>
<td>1345</td>
<td>1345</td>
<td>6.02E-03</td>
</tr>
<tr>
<td>Extraction septum</td>
<td>2255</td>
<td>2255</td>
<td>1.51E-14</td>
</tr>
<tr>
<td>Transferline 1</td>
<td>1157</td>
<td>1157</td>
<td>1.03E-07</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>593</td>
<td>593</td>
<td>2.16E-21</td>
</tr>
<tr>
<td>Injection septum</td>
<td>246</td>
<td>246</td>
<td>4.35E-07</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1.52</td>
</tr>
</tbody>
</table>

8.2 Verification of the values

Using the measured values exposed in the section 6.3 it can be verified the results obtained with the simulations.

Table 8.7: Values for the month of reference around Storage Ring.
Source: Original

<table>
<thead>
<tr>
<th>Detector</th>
<th>Simulation [µSv]</th>
<th>Measured [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH16</td>
<td>3.62</td>
<td>1.29</td>
</tr>
<tr>
<td>EH03</td>
<td>4.24</td>
<td>1.43</td>
</tr>
<tr>
<td>EH27</td>
<td>2.84</td>
<td>1.33</td>
</tr>
</tbody>
</table>

It is a very good result taking into consideration the conservatives assumptions that the code use with the distances to the magnets, thickness of the walls, electrons lost, among others, to ensure the radiological protection of the workers.

The numbers shown an average coefficient of 2.6 between the measured values and the simulated values. It can be considered as a safety coefficient.

Table 8.8: Values for the month of reference at the injection points.
Source: Original

<table>
<thead>
<tr>
<th>Detector</th>
<th>Simulation [µSv]</th>
<th>Measured [µSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH07</td>
<td>0.55</td>
<td>0.62</td>
</tr>
<tr>
<td>EH33</td>
<td>1.15</td>
<td>1.02</td>
</tr>
</tbody>
</table>

More approximate results are obtained using this other parametrization.
Chapter 9

Conclusions and future working

Tasks performed

During the first stage of the work, the applications and the physics that there are behind a synchrotron particle accelerator have been studied. Making special focus on the radiological protection.

In a second stage, the program used in ALBA synchrotron for the shielding design and for the calculation of the dose has been studied and redesigned. Making it more user-friendly and intuitive.

In a third stage, an algorithm has been designed to adapt the program to the different operational data of the installation. In order to be able to calculate the produced dose and then verify the results.

Finally, in a fourth stage, the data measured in the gamma radiation surveillance network around the ALBA synchrotron has been analysed and compared with the results of simulations.

Conclusions

The main objective of this work is the calculation of the total annual dose emitted by ALBA synchrotron in a set of points. And this objective has been verified with experimental measurements.

The already existing algorithm of calculation has been improved and expanded. Nowadays, ALBA is using the program developed and explained in this work.

In short, it can be considered that the initial challenges have been realized and overcome.

Daniel Sabio Ruiz
Possible future working

The future working can be divided in two areas.

More acquisition data in ALBA synchrotron.

- To characterise, more accurately, every element in a coordinate system to know their exact location. This would allow a more precise measure of the distances and this would also allow avoiding the simplification of the thickness of the wall as distance to be travelled by the particle when it through this.

- To place a temporary experimental surveillance network in lost points to adjust the probability of leakage of electrons.

Modifications and improvements of the model and its implementation:

- To implement the system of coordinates mentioned above in a graphical interface that allows to decide at which point the dose will be calculated. In order to avoid the manual modifications of the distances and to avoid also the calculation of the dose in all points, saving computer time and money.

- To adjust the coefficients used in the model, by the comparison of the results obtained with other methods of calculation as methods of Monte Carlo, for instance the FLUKA program.
Annex A

Budget

The following cost is an estimation of how expensive is make this kind of work, which do not have experimental work. Without taking into account taxes or the price of the detectors installed in ALBA.

A.1 Office supplies

The office supplies are the computer used to do this work and the software used. The amortized value is calculated using a service life of five years and a period of time dedicated to this work of half year.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Original value [€]</th>
<th>Amortized value [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Pavilion dv7 Notebook PC</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Office Professional 2010</td>
<td>719</td>
<td>71.9</td>
</tr>
<tr>
<td>TeXstudio software</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MiKTeX software</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>171.9</td>
</tr>
</tbody>
</table>
A.2 Human resources

The human resources have also a price in the professional world.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost per hour [€/h]</th>
<th>Hours [h]</th>
<th>Cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training and research</td>
<td>25</td>
<td>100</td>
<td>2500</td>
</tr>
<tr>
<td>Simulation and writing</td>
<td>25</td>
<td>350</td>
<td>8750</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>11250</strong></td>
</tr>
</tbody>
</table>

A.3 Other costs

There are other costs associated to this work. Part of this work was did in the synchrotron ALBA facility, that implied:

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost per week [€/w]</th>
<th>Weeks [w]</th>
<th>Cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trips</td>
<td>60</td>
<td>4</td>
<td>240</td>
</tr>
<tr>
<td>Meals</td>
<td>45</td>
<td>4</td>
<td>180</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>420</strong></td>
</tr>
</tbody>
</table>

A.4 Total budget

Taking into account all the previous costs, the total cost of this work is:

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office supplies</td>
<td>171.9</td>
</tr>
<tr>
<td>Human resources</td>
<td>11250</td>
</tr>
<tr>
<td>Other costs</td>
<td>420</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11841.9</strong></td>
</tr>
</tbody>
</table>

Daniel Sabio Ruiz
Annex B

List of documents

B.1 ALBA operational schedule of year 2013
B.2 Installation drawing of ALBA
B.3 Installation drawing of ALBA with distances
Determination of the Total Annual Dose emitted by the ALBA Synchrotron
Bibliography


[9] Royal Decree. Real decreto 783/2001, de 6 de julio por el que se aprueba el reglamento sobre protección sanitaria contra radiaciones ionizantes, 2001. 23


