Activation Calculation for the Robinson Wiggler at the Metrology Light Source
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Abstract

The Physikalisch-Technische Bundesanstalt (PTB) operates an electron storage ring, the Metrology Light Source (MLS), at the location of BESSY II with an operating energy from 105 MeV up to 630 MeV.

An important parameter for users of synchrotron radiation is the lifetime of the stored beam. At the MLS the lifetime is dominated by the Touschek effect. To increase the lifetime different methods are possible. One of them is the installation of a Robinson Wiggler, which is preferred at the MLS for different reasons [4]. The design studies of the RW are already done [5].

Due to the selected material which contains a high amount of Cobalt it is important to clarify potential radiation hazard by activation.

A simulation using FLUKA Monte Carlo code and the resulting activation are presented in the following.

1. Introduction

Germany’s national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB), is using synchrotron radiation for metrology and related applications. Therefore they operate its own storage ring in the surrounding of the BESSY II storage ring in Berlin Adlershof since 2008. It’s called the Metrology Light Source (MLS) and is designed, built and operated by the Helmholtz-Zentrum Berlin. The MLS can be operated at any energy between 50 MeV and 629 MeV, while the stored current can be varied from 200 mA down to a single electron. In Fig. 1 the schematic layout of the MLS is given as well as some key parameters in Table 1.

<table>
<thead>
<tr>
<th>MLS – Key Parameter</th>
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<tbody>
<tr>
<td>Energy E</td>
<td>[MeV]</td>
</tr>
<tr>
<td>Circumference</td>
<td>[m]</td>
</tr>
<tr>
<td>Beam Current I</td>
<td>[mA]</td>
</tr>
<tr>
<td>Beam Lifetime (150 mA)</td>
<td>[h]</td>
</tr>
<tr>
<td>Cavity Voltage</td>
<td>[kV]</td>
</tr>
<tr>
<td>Horizontal Emittance</td>
<td>[nm rad]</td>
</tr>
<tr>
<td>Magnetic Field B</td>
<td>[T]</td>
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<tr>
<td>Bending Radius R</td>
<td>[m]</td>
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</table>

For users of synchrotron radiation the lifetime is a fundamental value. In 2012 the lifetime at the MLS was about 3.5 hours at 150 mA in the standard user optic. After changing the magnet optics in 2014 the lifetime was about 6 hours at 150 mA [3]. As it was illustrated in different papers [3, 4] the lifetime at the MLS is dominated by the Touschek effect. To increase the lifetime the Touschek lifetime has to be improved. The Touschek lifetime depends linearly on bunch size and length. So one solution for an existing accelerator is the installation of an insertion device which consists of combined function magnets. Such a device is called a Robinson Wiggler.
For the installation at the MLS there is only one straight section left. This section has a length of 2.5 m which reduces the length of the designed Robinson Wiggler of 1.74 m. The design studies [5] show that the normal conducting Robinson Wiggler will consist of twelve poles (including the end poles). To achieve the necessary high field strengths a Cobalt-Iron steel (AFK502) is used for the yoke. This compound consist of 49% iron, 49% cobalt and 2% vanadium. The high amount of cobalt might get activated by beam losses in the material so a study has to be conducted to clarify this.

1. Neutron Spectrum and Activation

Activation is a serious hazard since the radiation remains after switching off the accelerator. The consequences are additional radiation expositions. At electron accelerators electron losses cause bremsstrahlung which may lead to nuclear reaction and thus to neutron radiation and activation. The interaction between two particles is generally described by means of a cross section. The cross section corresponds to the area effectively seen by the incident particle which causes the specific reaction. The cross section is a measure that a particle conduct a nuclear reaction. For neutrons the cross section for capture decrease exponentially with the energy (Fig. 2). Especially thermalized neutrons have a very high cross section for (n, γ) reaction.

![Fig. 2 - cross section of cobalt-59 for (n, γ) reaction](image)

A closer look at the neutron spectrum after a total beam loss at the Robinson Wiggler of the MLS (Fig. 3) the thermal neutron component of the spectrum is clearly visible. These thermal neutrons, moderated by backscattering from the concrete shielding, can be captured in the atomic nucleus from the target material which causes an emission of gamma quants.

![Fig. 3 - neutron spectrum (logarithmic in eV) after a total beam loss at the Robinson Wiggler of the MLS](image)
For thermal neutron capture the high cobalt content of the yoke is of great importance because the cross section of cobalt for slower neutrons is much higher than e.g. for iron or vanadium (Table 2). The generated activation after switching off the accelerator is an indicator of a possible waiting time or protection against exposition.

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount in yoke</th>
<th>( \sigma(n,\gamma) ) (25 meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>49%</td>
<td>2.6 barns</td>
</tr>
<tr>
<td>Co</td>
<td>49%</td>
<td>37.2 barns</td>
</tr>
<tr>
<td>V</td>
<td>2%</td>
<td>4.8 barns</td>
</tr>
</tbody>
</table>

_table 2 – comparison between Fe, Co and V amount in yoke and neutron cross section at 25 meV_

The activation rate \( \dot{N}^+ \) depends on the cross section \( \sigma \) \( (E_p) \), the flux density \( \Phi \) \( (E_p,r) \), the mass number \( A \) and the density of the nuclei \( \rho \):

\[
\dot{N}^+ = \frac{\rho N_A}{A} \int_0^{E_p} \sigma(E_p) \cdot \Phi(E_p, r) \cdot dE_p dV.
\]

(1)

where \( E_p \) is the energy of the photons.

With the number of irradiation periods \( v \), the irradiation time \( t_b \), the decay time \( t_k \) and the decay constant \( \lambda \) the resulting activation can be determined:

\[
A_v = \dot{N}^+ \cdot \left[ 1 - e^{-\lambda t_b} \right] \cdot \frac{1 - e^{-\lambda t_k}}{1 - e^{-\lambda (t_b+t_k)}}.
\]

(2)

\[
\lambda = \frac{ln 2}{T_{1/2}},
\]

(3)

where \( T_{1/2} \) is the half-life period.

With the resulting activation the gamma dose rate can be evaluated:

\[
\frac{d\Phi}{dt} = \Gamma \cdot \frac{1}{r^2} \cdot A,
\]

(4)

and \( \Gamma \) is the isotope dependent radiation constant.

The activation rate \( \dot{N}^+ \) can also be calculated by the Monte-Carlo-Code FLUKA using the option RESNUCLEII. By calculations with FLUKA the generated resnucle file outputs the number of nuclei produced per primary particle. With the activation equation it is possible to calculate manually the activation contribution. For many different components this procedure is very complex and intense in time.

With a self-written user routine aktiv2.f [6] which contained the activation equation and many of the common radionuclides with their mass number \( A \) and atomic number \( Z \) and its specific activation it is possible to identify the occurred radionuclides. Furthermore the activation after a specified half-life period is printed out.
3. Results and Conclusion

To get an impression of the activation at the Robinson Wiggler we consider a total beam loss at the water cooled aluminum vacuum chamber caused by an electron beam of 100 MeV at an angle of 1 mrad. We suppose the standard user mode with 200 mA per injection and 1800 injections per year with an efficiency of approximately 20%. This corresponds to a loss of 18E14 electrons per year.

To calculate the activation “by hand” we assume that the cross section of Cobalt is predominant for the interaction with neutrons whereas the other materials are negligible. The number of the incident neutrons \( N_0 \) per year and yoke were determined by FLUKA. The number of neutrons \( N(x) \) left after crossing the target with the thickness \( x \) can be defined with:

\[
N(x) = N_0 \cdot e^{-\rho_T x}.
\]  

(4)

Here \( \rho_T \) is the particle density of the target material with the mass density \( \rho \) and molar mass \( M \):

\[
\rho_T = \frac{N_A \rho}{M}.
\]  

(5)

In this case the number of neutrons \( N(x) \) is extremely small. This leads to the conclusion that nearly all neutrons interact with the yoke material.

With the program aktiv2.f [6] it is clearly identifiable that the most important radionuclide at this scenario is Cobalt-60. The long half-life period of 5.27 years indicates that an existing activation will decrease slowly.

One important question for components of an accelerator is the further use after removal. To release the wiggler for recycling the limitation in the German Radiation Protection Ordinance has to be obeyed. The activation limit for Co-60 for recycling is 0.6 Bq/g. In our case the limit is exceeded by a factor of 2.3 and in future after removal from the storage ring it has to be used in radiologically controlled areas again or stored as a weak activated component.

Another important aspect is the access to the storage ring immediately after operation whether the access is unexpected or planned. For this the resulting dose rate for different decay times is a good indicator. There is a possibility to simulate the activation and the dose rate directly in one step with FLUKA (RADDECAY) in consideration of different decay times (cooling times). Fig. 4 shows the dose equivalent rate after an irradiation time of one year with decay times of one second, one day, three months and one year. After one year decay time the dose rate due to activation compared to the dose rate immediately after switch off the beam is lower by about one order of magnitude.

For questions of activation and dose rates programs like FLUKA or self-written programs like aktiv2.f can simplify these calculations and save time. In order to verify the results it is a good idea to calculate these values with well-known equations and compare them with the results of the programs. In doing so one gets an impression if the calculations are in the right magnitude or not.

In the case of the Robinson Wiggler the calculations fit well together as you can see in Table 3. The deviation of the activation may be explained with the rough calculation “by hand” based on assumptions. The cross section of cobalt is certainly the predominant for the interaction with the neutrons but all other materials were neglected.

<table>
<thead>
<tr>
<th>Activation rate [Bq/cm3]</th>
<th>dose rate [pSv/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation by Hand</td>
<td>3.12</td>
</tr>
<tr>
<td>Calculation by program</td>
<td>12</td>
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</tbody>
</table>

*Table 3 – comparison of the results calculated “by hand” and with program*
4. Summary

At the Metrology Light Source in Berlin a new device will be implemented. A Robinson Wiggler should improve the lifetime of the electron storage ring between 60% and 100% (depending on operation mode). The design studies for the Robinson Wiggler are almost completed. An important question to clarify was the activation after operation. For access after switch off the machine there is no attention which should be paid to a waiting time or protection against exposition. For a removal from the storage ring after operating life it has to be used in radiologically controlled areas again or stored as a weak activated component. A recycling is at the earliest after a waiting period of at least 6.5 years possible. So before a new component will be constructed it is also important to think about potential complications after the operating life.

References