Abstract

The superconductive cavities of the proposed TESLA collider are cooled by liquid helium. The coolant is continuously transported within a loop consisting of accelerator structures in the tunnel and a cooling plant outside. In shut-down periods a storage outside the tunnel is also possible. Therefore the activation of the helium may be of radiological importance. The only activation product is tritium $^3$H. A mean loss of $3 \cdot 10^{-4}$ of the total beam current of $2 \cdot 10^{14}$ electrons (positrons) per second per linac leads to a saturation activity of $2 \cdot 10^{16}$ Bq (1/2 Ci) for the whole TESLA facility. Taking into account a realistic operation time of 20 years with 5000 hours per year and the total coolant inventory of some 90 tons a specific activity of 70 Bq/g is obtained. The German regulation does not require a license for possession of and handling with radioactive substances with a specific activity less than 100 Bq/g.
1 Introduction

The beam loss along the active parts of the TESLA linacs will be very low, otherwise the low temperatures can not be maintained. But it is not zero, a certain activation of materials near to the beam can be expected though such an activation will be of no important radiological concern. Special attention is only necessary on the activation of the helium because it is a liquid and will be transported continuously within a loop consisting of accelerator structures in the tunnel and a cooling plant outside. In shut-down periods a storage outside the tunnel is also possible. The only nuclide which can be produced is the tritium $^3$H. Unfortunately it has a long half-life of 12.3 years, and it is a $\beta^-$-emitter with a maximum $\beta^-$ energy of 20 keV which makes it very difficult to measure. Liquid helium is kept near to the beam, therefore tritium is produced predominantly by photons from the electromagnetic cascade initiated by lost electrons. The considered reaction is $^4$He$(\gamma,p)^3$H. Its threshold is 20 MeV. Not considered is the tritium production in pipe walls from where the tritium could diffuse into the helium in principle.

In the following the cross section of the reaction is discussed. The proposed cryostat is drastically simplified so that its geometry is suitable for a Monte Carlo calculation. Photon track length distributions are calculated in different helium regions. These values together with a reasonable beam loss give the tritium activities at saturation.

Other sources of tritium production are not considered. Especially, if rf-produced dark current in the cavities contains a large amount of photons above 20 MeV, then this effect will also contribute. But we have no quantitative information concerning this source (intensity, spectral and angular distributions) at present. Perhaps the necessary data can be gained at the TESLA Test Facility in the near future.

2 The calculations

The photon-produced saturation activity (in Bq) in a given region of interest is

$$A_s = I n \int_{k_{th}}^{\infty} \sigma(k) \frac{d\Lambda}{dk}(k) \, dk$$  \hspace{1cm} (1)

where $I$ is the number of primary electrons/s hitting the system, $n$ the number of helium atoms/cm$^3$ in the region, $\sigma$ the total cross section (cm$^2$), and $d\Lambda/dk$ the differential track length distribution (cm/MeV) in that region as a function of photon energy $k$.

2.1 Activation cross-section

We use the cross section from [Exfor], it is a compilation of 6 measurements. Other measurements [Ber71, Mey70] are in good agreement with it. The curve is displayed in fig.1A. It has the typical shape of a simple reaction up to 100 MeV. The onset of $\pi$ production is visible only by a change of the slope, interaction with n-p pairs (quasideuteron disintegration) does not show up at all. The
Figure 1: A) The total cross-section of the tritium production $^4\text{He}(\gamma,p)^3\text{H}$ as a function of photon energy $k$. Points: measurements. Solid line: used parametrization (see text). B) Differential track length per primary electron in the first inner helium region as a function of photon energy $k$. 
reason is that in an interaction at higher energies the remaining 3 nucleons are not kept bound together so that the production of tritium is prevented. Probably for the same reason the Δ resonance does not give a further contribution. The integral of equ.(1) is calculated by means of a parametrization of the cross-section with a double exponential

\[ \sigma(k) = \sigma_1 e^{-k/k_1} + \sigma_2 e^{-k/k_2} \]

where \( \sigma_1 = 5.84 \) mbarn, \( k_1 = 19.9 \) MeV, \( \sigma_2 = 0.0198 \) mbarn and \( k_2 = 126 \) MeV are the parameters (shown as solid line in fig.1A).

2.2 Photon spectrum

The calculation of the track length distribution is performed with the Monte Carlo code FLUKA-98 [Fas98] in a pure electromagnetic mode. The spectrum is displayed in fig.1B with the same energy axis as for the cross-section. It can easily be seen that the contributions to the activation integral equ.(1) derive from the energy region below 100 MeV only.

2.3 Geometry of the cryomodule

The proposed cryostat [Wol99] for cavities is shown in fig.2. Such a complicated geometry is not very suitable for a Monte Carlo calculation, neither it is necessary to take all the details into account. The development of the electromagnetic shower in bulk material is rather insensitive to the arrangement of the masses under question as far as only the production of secondary particles is interesting. The approximate amount of material per meter is given in tab.1. These materials are pressed into a geometry with cylindrical symmetry around the beam but preserving the densities and the masses per meter. The result is described by tab.2 which gives the radii of the cylindrical regions. The system is positioned on the axis of a tunnel with concrete walls at 250-280 cm radius. The total length is 15 m divided into 5 parts of 3 m each. The incoming beam is ring-shaped with

<table>
<thead>
<tr>
<th>material</th>
<th>specification</th>
<th>mass/length [kg/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>helium</td>
<td>cavity</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>2 K phase</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2 K forward</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>2 K return</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>4.5 K forward</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>4.5 K return</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>70 K forward + return</td>
<td>0.13</td>
</tr>
<tr>
<td>niobium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>titanium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kryoperm</td>
<td>(70% Ni, 15% Fe, 4.5% Cu, ...)</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>assumed to be Ni</td>
<td></td>
</tr>
<tr>
<td>cryostat</td>
<td>material other than He, Nb, Ti, kryoperm</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>assumed to be iron</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Radii of cylindrical regions representing the simplified cryostat.

<table>
<thead>
<tr>
<th>Material</th>
<th>Inner radius [cm]</th>
<th>Outer radius [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>vacuum</td>
<td>0</td>
<td>5.0</td>
</tr>
<tr>
<td>niobium</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td>helium</td>
<td>5.6</td>
<td>8.7</td>
</tr>
<tr>
<td>titanium</td>
<td>8.7</td>
<td>9.4</td>
</tr>
<tr>
<td>nickel</td>
<td>9.4</td>
<td>9.7</td>
</tr>
<tr>
<td>vacuum</td>
<td>9.7</td>
<td>45.0</td>
</tr>
<tr>
<td>helium</td>
<td>45.0</td>
<td>45.4</td>
</tr>
<tr>
<td>iron</td>
<td>45.4</td>
<td>47.0</td>
</tr>
</tbody>
</table>

$r = 5.0$-$5.6$ cm to simulate a beam loss hitting the niobium. Assuming a linear dependance on the primary beam energy we take a main energy of 120 GeV for the whole TESLA facility.

Figure 2: Cross section of cryomodule [Wol99].

Beside the cryostats for cavities, also quadrupole magnets are cooled by liquid helium. Their total length is 1250 m whereas the cryostats for all cavities have a length of 20900 m. Therefore the presence of the magnets is neglected.
2.4 Beam loss

The assumed beam loss is rather arbitrary, generally it will be very low. We assume a loss of only $3 \times 10^{-4}$ along the active length of one linac. The reason is the following: for the proposed intensity of $2 \times 10^{14}$ e/s the beam loss results in $5.7 \times 10^{6}$ e/s per meter and at 120 GeV a power loss of 0.11 W/m. This number is small compared with the dynamic heat load of about 1 W/m, so it will not influence the operation of the cryogenic plant. It will also not be detected by a beam loss monitor. Therefore we can assume that this beam loss of $6 \times 10^{10}$ e/s per linac remains undetected and occurs permanently.

3 Results

The number of tritium nuclei per one 120 GeV electron are entered into tab.3 for the 10 helium regions\(^1\) (The total number of helium nuclei per volume is $n = 2.1 \times 10^{22}$ cm\(^{-3}\)). With the assumed continuous beam loss of $6 \times 10^{10}$ e/s per linac the total saturation activity is $2 \times 10^{10}$ Bq (0.5 Ci) for the whole TESLA facility. This is 4000 times the “Freigrenze” (exemption value) according to the German Radiation Protection Regulation.

\begin{table}[h]
\centering
\begin{tabular}{ccc}
\hline
\textbf{region $\Delta r$ [cm]} & \textbf{region $\Delta z$ [m]} & \textbf{number of $^3$H nuclei} \\
\hline
5.6 - 8.7 & 0 - 3 & $1.5 \times 10^{-1}$ \\
& 3 - 6 & $5.6 \times 10^{-3}$ \\
& 6 - 9 & $1.9 \times 10^{-3}$ \\
& 9 - 12 & $8.2 \times 10^{-4}$ \\
& 12 - 15 & $3.5 \times 10^{-4}$ \\
45.0 - 45.4 & 0 - 3 & $3.3 \times 10^{-3}$ \\
& 3 - 6 & $1.1 \times 10^{-3}$ \\
& 6 - 9 & $1.7 \times 10^{-4}$ \\
& 9 - 12 & $3.6 \times 10^{-5}$ \\
& 12 - 15 & $1.0 \times 10^{-5}$ \\
\hline
\textbf{total} & & $1.7 \times 10^{-1}$ \\
\hline
\end{tabular}
\caption{Number of produced tritium nuclei per one 120 GeV electron in the helium regions.}
\end{table}

Hydrogen in 2 K und 4 K helium is solid. The produced tritium is fine-grained distributed in the liquid, it has a very low density and is transported together with the liquid; it remains in the closed system. There are low-temperature absorbers installed in the cryohalls. Here, tritium could be collected, but it can not be detected outside the pipes. Apparently it is difficult to predict the way in which it is distributed and collected. The simplest assumption is an equal distribution in the whole helium inventory of 90800 kg, this gives a specific saturation activity of 220 Bq/g.

\(^1\)A second FLUKA calculation was done using the option RESNUCLEi that gives the number of residual nuclei directly. The results are a one order of magnitude less compared to the values in tab.3. This is due to an inelastic photo cross-section for $^4$He very different to that $^4$(He,$\gamma$,p)$^3$H cross-section shown in fig.1A.
Saturation for tritium means a continuous operation during 20-30 years, which is impossible at a beam power of 8 MW. A more realistic mode of operation could be a half year’s operation at 8 MW followed by a shutdown of half year, and this during 20 years. It would yield a specific activity of about 70 Bq/g at the end of this period, with otherwise the same assumptions as above. This value is below 100 Bq/g. For possession of and handling with radioactive substances with a specific activity less than 100 Bq/g a license is not required according to the German regulation.

References


[Fas98] A. Fasso, A. Ferrari, J. Ranft, P. Sala, FLUKA-98

[Exfor] IAEA Nuclear Data Services http://iaeand.iaea.or.at/exfor/