4.10 Radiation Safety

This section describes the shielding requirements to guarantee radiation safety at the SBLC collider. The most important considerations here are, of course, the impact of the collider operation on the environment, i.e. conceivable radiation levels outside of the accelerator housing in areas accessible to the public and possible activation of soil and ground water. Other aspects are the safe working conditions for the operations personnel charged with repair and maintenance of the installations in the service tunnel.

The beam power in each of the two colliding beams (7 MW) is such that great care must be taken to avoid an uncontrolled loss of the beams. Such loss could immediately lead to a local destruction of the accelerator components and with this to an automatic cessation of operation. For equipment safety alone the monitoring of beam current along the machine is an absolute necessity, such that in case of unexpected significant loss ($> 1\,\%$) pulsing of the accelerator is interrupted instantly. Moreover, radiation monitoring in the accelerator housing will detect losses of much smaller magnitude such that corrective action can be taken in time.

The worst conceivable scenario is the failure of the beam loss interrupt system and the local deposition of a large amount of beam power, but just not large enough to significantly damage the accelerator and thereby terminate operation. Shielding of the produced radiation in such a case must be sufficient to avoid any significant radiation in the outside world.

The case of total beam loss in a small area will lead to immediate destruction of part of the accelerator and is harmless in comparison, as far as the maximum radiation dose is concerned. Particular attemtion must be paid to the beam dumps and the collimators for the spent beam close to the interaction point, because here all the beam power will be deposited during routine operation.

4.10.1 Radiation Levels on the Earth Surface Above the Tunnel

The most penetrating particles above the position of beam loss are high energy neutrons. For a point loss or a loss which occurs over only a few meters along the accelerator, the dose equivalent on the earth surface can be calculated with a simple formula given in [1], a report which also summarizes experimental and theoretical results. The thickness of the earth cover on top of the accelerator tunnel has an average value of 14 m. The smallest coverage will be 8 m. If a local beam loss would be as large as $0.1\,\%$ and would remain undetected and uncorrected, the radiation level at the surface would be $5{\cdot}10^{-8}$ Sv/h (0.005 mrem/h or $40\,\%$ of the natural background). With 5000 hours of operation per year, such radiation could, if left uncorrected, lead to an annual dose of 250 μSv ($17\,\%$ of the legally permitted local radiation level). But such a continuous loss as assumed here would be produced by a continuous loss of 8 kW of high energy radiation in the tunnel, a huge signal for the above mentioned radiation monitors. Such a situation would be immediately corrected!

The beam dumps will be positioned below DESY ground and have an earth coverage of at least 11 m (each additional thickness of 1.3 m reduces the rate from high energy neutrons by a factor of 10). With such shielding thickness the dose rate at the the surface can be made smaller than the natural background.

Another dose component at the earth surface is due to muons produced by beam losses along the accelerator. Muons are only created within a small cone in the beam direction, but they have a very large range. The doses were estimated by means of data given in [2]. First calculations of the conceivable dose rates show them to be small compared to the natural background. Muons from the beam dumps can be avoided at the surface by bending the beams downwards before they enter the dumps.

4.10.2 Radiation Levels in the Service Tunnel

Parallel to the accelerator tunnel (inside diameter 2.5 m) there is a service tunnel (inside diameter 4 m) which houses the klystron transmitters, power supplies, water cooling systems and all sensitive control and monitoring electronics. Continuous and unrestricted access also during times of collider operation must be available for the personnel charged with maintenance and repair work. It is therefore imperative that radiation levels in this service tunnel be low enough for radiation workers even under conditions of faulty accelerator operation.

The axis' of both tunnels are 9.5 m apart, such that more than 6 m of earth and concrete will separate both tunnels. Considering the numbers given above, it is evident that neutron doses in the service tunnel are just by a factor of 34 larger than those on the earth surface under comparable machine conditions:

- An undetected continuous beam loss of 0.1 % will lead to a maximum dose rate of 1.7 μSv/h (less than 15 times the natural background).

- Even for a local beam loss of 10 %, which might temporarily occur at collimator positions, the radiation level in the service tunnel would be only 0.17 mSv, still safely allowing access for a radiation worker.

- The beam dump will be located far enough away from the service tunnel such that radiation levels from that source can be neglected.

Other radiators in the service tunnel are the 150 MW klystrons, which need lead shielding around the collectors.

4.10.3 Activation of the Main Beam Dump

It was shown in section 4.7.9 that a dump made essentially of graphite and backed by aluminium is capable of handling a 7 MW beam. Such a dump has the additional advantage that the number of produced neutrons and its residual radioactivity are smaller than with any other material. In the following the activity of a pure carbon dump is estimated together with the dose rate near it after a long period of operation.

Nuclide	Saturation Activity [Bq]
^{11}C	$5 \cdot 10^{15}$
^{7}Be	$7 \cdot 10^{13}$
^{3}H	$7 \cdot 10^{12}$

Table 4.10.1: *Saturation activities in the Carbon beam dump.*

We assume an electromagnetic cascade completely developed in carbon, then the yield Y of a nuclide per incoming primary electron (energy E_0) is

$$Y(E_0) = \frac{L\rho}{A} \int_0^{E_0} \sigma(k) l\prime(k) dk \qquad (4.10.1)$$

Here $\sigma(k)$ is the cross section of the nuclear reaction as a function of photon energy, $l\prime(k)$ the differential track length, and L, ρ, and Δ are Avogadro's number, density and atomic weight of the material. Approximation of cascade theory is especially valid at high energies, therefore we can write

$$l\prime(k) \approx 0.572 \frac{X_0 E_0}{k^2} \qquad (4.10.2)$$

where X_0 is the radiation length.

For carbon only three nuclides have to be considered: ^{11}C (Half life 20 min), ^{7}Be (54 d), and ^{3}H (12.3 a). Their saturation activity in Bq is calculated which equals the number of produced nuclei per second. A full power operation of 7 MW is assumed to produce a saturation activity of ^{11}C, a mean power of 2 MW for the production of ^{7}Be and a mean power of 0.5 MW averaged over 25 years for calculating this magnitude for ^{3}H. The photon cross sections are mainly taken from [3, 4, 5] ; a small tail is added to the cross section curves to cover the photon energy range up to 200 MeV. The resulting saturation activities are given in Table 4.11.1.

A tritium activity of $7 \cdot 10^{12}$ Bq or 0.02 g produced in 25 years of operation is easily absorbed by the graphite (together with 1 g of stable hydrogen produced by nuclear processes), its absorption capacity is about $0.3 Ncm^3/g$ at room temperature. If part of it is exhaled due to elevated temperatures during operation it will be removed by the tunnel ventilation and presents no radiological hazard. The dose rate due to the residual activities of Table 4.11.1 is calculated taking roughly into account the extension of the source and the shielding effect of the surrounding aluminium. Immediately after stopping operation the ^{11}C gives a very high dose rate of 25 Sv/h at a distance of 1 m. After a cooling period of 3 h the dose rate is determined by the ^{7}Be which amounts to 10 mSv/h and decreases with the half life of 54 d. After a very long cooling period the dose rate is determined at a much lower level by the ^{22}Na activity produced in the backing aluminium (half life 2 a). The dose rate can be reduced by lead shields if necessary, depending on the position of the dump.

4.10.4 Activations Outside the Tunnel

The carbon/aluminium dumps described in this report are designed to absorb the total beam power of the two beams. In actual collider operation a significant amount (about 10 %) has to be absorbed by collimators in the spent beam capture system for the positron source. These locations will be under DESY land and will have special shielding added. But except for these deliberate scraping losses at these collimators all beam power is dissipated in the dumps. Energetic neutrons produced in these dumps might penetrate the dump, lead shields and the concrete walls of the structures which house the dumps. These neutrons can then in turn activate soil and ground water. The resulting saturation activations under the assumption of no additional shielding have been calulated (see [6]. The results can be summarized as follows.

Saturation activity is essentially given by the product of neutron fluence and cross section, integrated over the neutron spectrum. The neutron fluence spectrum generated in a thick target is well known by measurements and calculations for primary protons. For high energy primary electrons no experimental results are available. Therefore we studied the shape of the neutron spectrum by preliminary calculations using the MC code FLUKA 92 for a thick target and as a function of concrete side shieldings. It turned out that the spectrum shape is independent of the shield for concrete thickness larger than 60 cm and that it is very similar to the neutron spectrum produced by primary protons. This can be expected. Neutrons in the relevant range up to 200 MeV are produced by intranuclear cascades (initiated by particles below 0.5 - 1 GeV) and by low energy nuclear reactions in the thick target and in the concrete or sand shield, rather independent of the high energy process. The spectrum was normalized in such a way that its total dose equivalent equals the dose of electron- produced neutrons given in [1] (which in turn is based on measurements and calculations).

When one considers nuclear reactions in the soil and ground water initiated by fast neutrons from an *unshielded* beam dump, radioactive nuclides with very short life time are of less interest, because of the time necessary to come in possible contact with people. Nuclides with very long life times are also of less interest, because of the low dose rates associated with long life times. The cross sections for the producing reactions of the interesting nuclides are not all accurately known. But since neutron induced reactions are known to be similar to proton induced reactions, the cross sections of the latter can be reasonably substituted.

The resulting saturation activity, assuming an unrealistic continuous 7 MW operation throughout the year, in the soil near the beam dump is, ^{7}Be: 6400 Bq/g, ^{22}Na: 12000 Bq/g, ^{55}Fe: 3000 Bq/g, ^{45}Ca: 300 Bq/g and ^{54}Mn: 150 Bq/g. Apparently these numbers present no radiological problem: The nuclides are permanently attached to solid soil and are neither accessible nor movable. With a half life for all of them smaller than 3 years, 40 years after final shutdown of the accelerator all remaining activities will be smaller than the natural activity of sand.

Accelerator-produced nuclides could also be expected in the ground water due to spallation of oxygen and leaching of nuclides produced in the soil. The somewhat complex situation is described and analyzed in [6]. As a result, only ^{22}Na and ^{3}H might be found in ground water. This has been confirmed by experiment [7]. If we assume that the slowly moving ground water will be close the beam dump for 100 days, the calculated activity concentration will be 320 Bq/g and 1400 Bq/g, respectively. These numbers would be of concern only, if the drinking water for people is taken without dilution from a well in the immediate vicinity of the beam dump (they would be 5000 times as large as legally permitted for general consumption). This is an extremely unlikely scenario, since the beam dumps are under DESY land and there will be no wells in their immediate vicinity. A large dilution factor could therefore be reasonably assumed in practice. But it would also be very simple to add concrete shielding around the beam dump and reduce the water activity concentration there by a factor of 5000: One meter of heavy concrete gives a reduction factor of 30 for fast neutrons. Therefore 2.5 m of added shielding would already suffice.

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