THE SHIELDING DESIGN OF THE METROLOGY LIGHT SOURCE *

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Abstract

MLS will consist of a 100 MeV microtron and a 600 MeV electron storage ring. The investigations of the radiation types occuring at those machines dependent of the electron energy, target and shielding materials, observating angles and geometric aspects are well established, often condensed in semi - empiric formulas and in good agreement with the results of Monte Carlo codes like FLUKA for lateral shielding. But as important as the pure physical aspects of radiation are for a shielding design the operating times and modes and the considerations of possible crash scenarios. We present here an approach of considering failure operating probabilities at electron storage rings based on years of radiation and operating observations of BESSY I and BESSY II for the shielding design of MLS. Comparisons of FLUKA calculations with the used semi - empiric formulas are presented too.

INTRODUCTION

The Physikalisch - Technische Bundesanstalt (PTB) needs a low energy storage ring as primary radiation normal for photon energies in a spectral range from ultraviolet to extreme ultraviolet to accomplish her tasks as a governmental metrologic institution. The optimal technical solution is to build a low energy compact storage ring with an electron energy from 200 MeV to 600 MeV close to BESSY II in Berlin - Adlershof. The concept was developed in cooperation with BESSY [1].

The preinjector will be a 100 MeV race track microtron, the acceleration to max. 600 MeV is resolved in the storage ring through ramping. Microtron and storage ring will be located in two different bunkers, so access to the microtron is possible during operation of the storage ring for i.e. attendance work. Access to the storage ring during operation of the microtron is not necessary.

The guidelines given by the EURATOM are now law in the most member states of the European Community and since 2001 in Germany. The most important change was the decrease of the personal dose limit for non radiation workers from 5 mSv/a to 1 mSv/a.

We decided to hold this limit within the experimental hall (surveillance area). The local dose limit for the general area (outside the buildung) are unchanged and 0.3 mSv/a for the indirect radiation, 1 mSv/a for direct radiation. The two bunkers are restricted area during operation because the dose rate limit respective to the german law of $\dot{H} > 3\mathrm{mSv/h}$ can be exceeded.
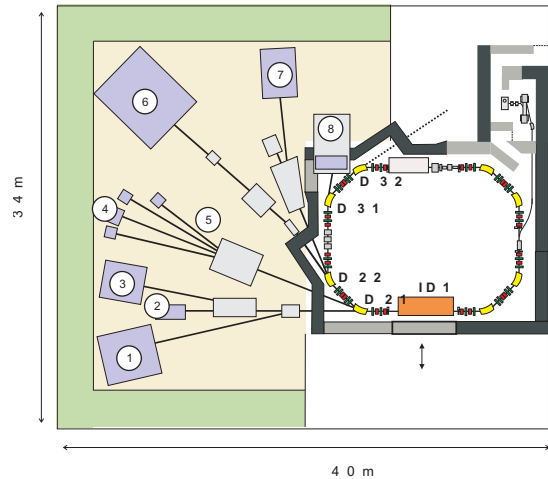
Figure 1: MLS view; the infrared experiment(8) is located on the roof; shielding black: heavy concrete, blue-green normal concrete

The roof of storage ring and micotron bunker is used for technical installations and so should be as accessible as the experimental hall with similar doses.

MACHINE PARAMETERS

The storage ring has a rectangular shape with four straight sections with pairwise different length. The two short straight sections are used for the rf and the injection septum, the two longer sections offer place for two undulators.

Microtron

Table 1: Microtron parameters

Maximum energy:	100 MeV
Number of cycles:	19
ΔE / cycle:	5.3 MeV
Pulse current :	10 mA
Rf frequency :	2.9986 GHz
Pulse length :	100 nsec - 1 μsec
Max. rep. rate :	10 Hz
Energy spread :	0.1 MeV
Emitance :	0.1 mm mrad
Dipole field :	1.13 T

Such microtrons are used at the storage rings MAX I in Lund, Sweden and at ASTRID in Aarhus, Denmark. Both microtrons are identical and are offered now by Danfysik A/S commercially.

Storage ring

Table 2: Storage ring parameters

Injection energy :	100 MeV
Energy :	200 - 600 MeV
Current :	1 electron - 200 mA
Max. Current / bunch :	3.3 mA / bunch
Energy loss / cycle :	7.53 keV / cycle
Circumference :	48 m
Straight sections :	2 x 6 m, 2 x 2.25 m
Natural emitance :	85 nm rad
Number of dipoles :	8
Max. dipole field :	1.3 T

At 100 MeV the transversal damping times of the betatron oscillations during the injection are about 5 sec. Therefore a classical injection scheme would require an injection repetition rate of 0.2 Hz. M. Erikson developed at MAX I a different injection scheme using transversal stacking [2] which will be used at MLS too. With this injection method the repetiton rate is 10 Hz and the max. current of 200 mA is injected within 30 sec as optimal case as it is possible at MAX I. The 10 Hz injection scheme increases the electron losses considerable.

OPERATING OF MLS

For shielding design purposes, one has to distinguish between two cases of storage ring (synchrotron) operation:

a) The machine is used just to inject and produce synchrotron radiation (user mode).

b) The machine is used for machine tests, machine experiments and some phases of the commissioning (machine test mode).

The two modes differ considerable in electron losses and crash probabilities:

Table 3: Operating times,modes a: user, b: machine tests

Mode	a	b
Weeks of operating / year	40	12
Injections / day	5	10
Injections / year	1200	600
Operating of the microtron / injection [m]	<10	<20
Operating of the microtron / year [h]	200	200

ELECTRON LOSSES

The losses during acceleration in the microtron we estimate from respective numbers of the BESSY microtron as 70 %. These losses occure during the first cycles at lower energies, so we assume the energy of the losses as 15 MeV. The electrons leave the microtron after 19 cycles with the energy of 100 MeV. The electron losses during ramping are neglectable $< 10^{-4}$ in comparison with the losses during injection and are not considered further.

Electron losses occur in the transferline between microtron and storage ring with a percentage of approximately 10 % which we divide at one half in the microtron bunker and the other half in the storage ring bunker. The pulse length is 150 nsec and shorter than the revolution time of the electrons in the storage ring of 160 nsec so the injection is conducted as single turn injection. The storage ring is operated with the rf frequency of 500 MHz, and the microtron with 3 GHz. The electron losses due to the rebunching in the storage ring are typically 50 %. The main cause of electron losses in the storage ring is the inefficiency of the injection according to the transversal stacking. From the minimum injection time of 30 sec one can estimate that the total electron losses in the storage ring are 98.7 %. The electron losses in the storage ring are divided in the relation 4:6 between injection septum and four point sources.

FAILURE HANDLING

The electron losses presented in the previous section are the optimal case, the total losses the worst case. To prognosticate the annual dose, we have to estimate, how often per year the electron losses during injection are higher than the optimal case and how large the ammount of these increased losses is. We use an approach which has proved to be very successful for the prediction of annual doses at BESSY II [3].

We define P_U as the failure function probability for the user mode, P_M for the machine test mode and t_{max} is the operation time of the microtron with 200 h/a for user operation and machine tests respective. We get then expressions for the effective annual operating times of the machine component i (transferline 1 and 2, septum, point sources storage ring) for both normal and crash operation for user and machine test mode.

$$t_i^{normal} = t_{max} \cdot \prod_{k=1}^{i} (1 - P_{U/M}) \tag{1}$$

$$t_i^{crash} = t_{max} \cdot P_{U/M} \cdot \prod_{k=1}^{i-1} (1 - P_{U/M}) \tag{2}$$

The probabilites P_U and P_M we get from the comparison of the minimum injection time with the respective annual average injection times [2]. One of the reasons of the accuracy of this approach compared with the usual arbitrary estimates of the duration of crash szenarios is the fact, that electron storage rings are never operated optimized to minimum injection times. This is because injection times are usual short and the requirements of the users in respect of i.e. orbit accuracy and stability have priority.

PHYSICAL ASPECTS

The main contribution of the radiation doses at electron storage rings causes from the electron losses during the short injection periods. When electrons hit under small angles the vacuum system bremsstrahlung is produced. This bremsstrahlung causes electron positron pair production and therefore an electron photon cascade with a maximum energy at about 1 MeV [6]. The bremsstrahlung also causes with (γ,n) processes giant resonance neutrons and fast neutrons with quasi deuteron fission. The threshold energy for the photo - pion process is 150 MeV, so this process is neglectable for this consideration. The energy spectrum of the giant resonance neutrons is mainly determined by the material of the target (vacuum system) and in the case of steel (iron) it is similar to the Cf spectrum with a maximum at 1 MeV [5]. The cross - section for the quasi deuteron fission is an order of magnitude lower than that of the giant resonance neutron production. To calculate the effective cross - section for the production of the quasi - deuteron fission spectrum one has to fold the respective energy dependent cross section with the spectrum of the bremsstrahlung. Hence the spectrum of neutrons is strongly increased at energies around few MeV. Even we take into account the lower attenuation coefficients for the quasi deuteron fission neutrons and concrete, the contribution of them to the total neutron dose is lower than 5 % outside the shielding wall for this machine. So we can restrict our consideration of neutrons to giant resonance neutrons with good accuracy.

For calculation of the dose behind lateral shielding we used for the acceleration losses within the microtron the paper of Swanson [4]. For the electron - photon cascade of the accelerated electrons we used the paper of [6] for 90^0 ([7] for 0^0) observation angle because the authors investigated the behavior of an electron beam hitting a vacuum chamber which is the worst case in transversal direction. Other authors used so called optimal thick targets which used to be thick also in transversal direction which causes considerable self absorption. Because the lowest energy in [6] is 150 MeV we checked the applicability of the given semi - empirical formulas by [6] at 100 MeV which are based on EGS4 calculations with FLUKA [8]. As energy cuts we used 500 keV for charged particles and 10 keV for photons.

We investigated the source term H_A behind $75\mathrm{g/cm}^2$ normal concrete in 1 m distance at the observating angle $\theta = 90^0$. As target we used an iron plate 2 mm thick, hitting angle $\phi = 2^0$, with an effective thickness of 5.7 cm. The radiation length is 1.7 cm, so the electron - photon cascade could develope.

$$H_A = H_{A1} \cdot \left(\frac{E}{E_0} \right)^\alpha \qquad (3)$$

with H_{A1} at 1 GeV, E in GeV, $E_0 = 1$ GeV.

From the fit we get $H_{A1} = 2.037 \cdot 10^{-17}\mathrm{Sv}/e^-$ and $\alpha=$ 0.924. At 100 MeV this is within a factor 1.3 of the extrapolation of [6] but we get a stronger energy dependence.
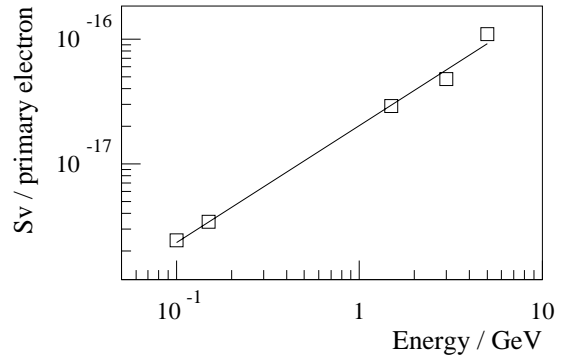

Figure 2: $90^0\gamma$ radiation, iron, $\phi = 2^0$, $d = 2$ mm, $d_{eff} = 5.7$ cm, source term H_A behind $75\mathrm{g/cm}^2$ concrete, dose in Sv/ primary electron

RESULTS

The outer wall of the storage ring is dimensioned 1 m normal concrete and at the beamline angles and the forward direction at quadrants 1 und 4 with 1 m heavy concrete and a 10 cm lead stripe (beam height $\pm$ 20 cm). The outer wall of the microtron is dimensioned 1 m heavy concrete. The roofs of both storage ring and microtron are 1 m thick. The roofs are of heavy concrete.

Table 4: Storage ring, point source transversal outside

$\gamma - \dot{H}_1$	$5.30e - 04$	Sv/h	$\gamma - \dot{H}_S$	$2.14e - 06$	Sv/h
$\gamma - H_U$	$2.14e - 05$	Sv/a	$\gamma - H_M$	$1.07e - 05$	Sv/a
$\gamma - \dot{H}_1^{tot}$	$2.16e - 03$	Sv/h	$\gamma - \dot{H}_S^{tot}$	$8.74e - 06$	Sv/h
$\gamma - H_U^{tot}$	$9.74e - 05$	Sv/a	$\gamma - H_M^{tot}$	$6.63e - 05$	Sv/a
$giant_n - \dot{H}_1$	$2.86e - 02$	Sv/h	$giant_n - \dot{H}_S$	$1.10e - 05$	Sv/h
$giant_n - H_U$	$1.10e - 04$	Sv/a	$giant_n - H_M$	$5.51e - 05$	Sv/a
$giant_n - \dot{H}_1^{tot}$	$1.17e - 01$	Sv/h	$giant_n - \dot{H}_S^{tot}$	$4.48e - 05$	Sv/h
$giant_n - H_U^{tot}$	$4.99e - 04$	Sv/a	$giant_n - H_M^{tot}$	$3.40e - 04$	Sv/a

The complete calculated annual local dose is 1.20 mSv/a transversal behind normal concrete and 0.4 mSv/a in forward direction at the beamline angles behind heavy concrete.

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