FLUKA SIMULATIONS OF THE LOSS OF THE STORED ELECTRON BEAM AT BESSY *

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Abstract

The synchrotron light source BESSY consists of a 50 MeV microtron, a full energy synchrotron and a 1.9 GeV storage ring. At synchrotron light sources the accidental loss of the stored beam can occur several times a year. This could mean a considerable risk for the users because of the bremsstrahlung flash coming through the open beamshutters. This is to our knowledge the first time, that this occurences are discussed in detail for synchrotron light sources. We used the particle interaction and transport code FLUKA for the calculations in different scenarios. We present here additional radiation safety measures based on the FLUKA results that decrease the possible personal dose from those beam losses below 1 mSv/year. Comparisons of the FLUKA results with semi - empiric formulas for radiation through lateral shielding are presented too.

INTRODUCTION

The storage ring BESSY II is in operation since 1998 and since 1999 used for a regular scientific program with synchrotron radiation. It has an extended double bend achromat lattice with a 16-fold symmetry. Up to 14 straight sections are suited for the installation for wigglers, undulators and wave length shifters (WLS). Two sections are used for the rf system and the injection septum. The full energy booster (1.9 GeV) operates in 10 Hz and is used asynchronously to fill the storage ring with bunch trains of 300 nsec. The short injection periods ($<$ 2 min and 3 to 5 times a day) are crucial for the annual radiation dose outside the shielding wall.

The electron losses at the vacuum system causes γ - radiation, giant - resonance neutrons quasi - deuteron fission neutrons and neutrons from photo - pion production. (The maximum of the energy spectrum of both γ and neutron radiation is at about 1 MeV).

In every beam line angle at the closest transversal distance to the machine a stationary γ und neutron measurement system is installed outside the shielding wall in the experimental hall. The detectors are a ionisation chamber and a BF_3 counter and are sufficient to measure the pulsed γ and neutron radiation during injection without loss of information. The measurement period is dependent of the dose rate and can be reduced down to 1 sec automatically. The data are accumulated by a PC every minute.

The measurement system is in operation since 1998 and we found values between of 0.8 - 1.2 mSv/year at the sections 2 - 15 and 3.8 (1998) - 2.2 mSv/year (2002) at the injection septum (section 1) with falling tendency because the machine test periods have been reduced. The values include the natural annual dose which is 0.6 mSv/a in Berlin.

The synchrotron radiation has a critcal energy of 2.5 keV (dipols), 2 keV (wigglers) and 1 keV (undulators), so it is completely absorbed in the vacuum system with 2 mm stainless steel. The critical energy at WLS beamlines rises up to 10 keV, so at these beamlines are located within hutches with a lead screening up to 5 mm.

At the ID beamlines the 8 m gas target of the straight section causes in forward direction 300 mSv/h gas bremsstrahlung at 10^{-7} Pa and 1.7 GeV in a cone with an angle of 0.6 mrad ($2/\gamma$). At ID beamlines with a mirror chamber this radiation is absorbed with 30 cm Pb in forward direction. ID beamlines without a mirror chamber are secured by a personal interlock system.

So from the considered contributions to the personal dose the limit of 1 mSv/a for non - radiation workers is hold in the experimental hall.

What we discuss now is the contribution of the accidental loss of the stored beam with opened beamshutters which occurs about 50 times a year at BESSY.

ACCIDENTAL BEAM LOSSES

At BESSY the electrons lose 170 keV per cycle within the convolution time of 840 nsec which is 10^{-4} of the nominal energy of the storage ring. Dependent of tune and chromaticity the storage ring accept electrons within max. 5 % of the nominal energy. That means that the electrons will be outside the dynamical aperture within 500 cycles or 0.4 msec if the rf system is switched off by a failure function or by an interlock circuit.

Beam losses are also caused by failures of power supplies or the control system. If the power supply circuit of the main ring dipoles is switched off, it lasts 700 msec (RL circuit) until the current is zero.

From

$$x(s_0) = \theta \cdot \frac{\beta(s_0)}{2 \tan \pi Q} \qquad (1)$$

and $Q_x = 17.8, Q_y = 6.7$ $\beta_x^{max} = 17\mathrm{m}, \beta_y^{max} = 20\mathrm{m}$ one gets the orbit change x where the distortion kick θ occurs. So in the horizontal and vertical direction a kick at a high β location of approximately 1 mrad is necessary for an orbit change of 10 mm, which is usual sufficient for a beam dump.

So if we compare this with the deflection angle of a BESSY dipole of 196 mrad, we can estimate, that a beam loss will occure within 3.6/32 msec if the power supply of the 32 main dipoles is switched off. (The dipoles are

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located at places where the horizontal β_x function is maximal). This means too, that the primary particles cannot reach the experimental hall through a 0^0 insertion device beam line because at the time of the beam loss almost the complete magnetic field of the dipoles still deflects the electrons.

For beam losses caused by failures of the power supply or control system of other magnets (steerer, quadrupoles, sextupoles) we can estimate the time until the beam is lost < 1 msec with similar arguments.

In the average the electrons are lost by crossing the vacuum chamber at places where the β - function is large and / or the aperture is small around the ring.

If we consider the annual dose, we can assume that the annual electron losses are divided around the ring. But for a single event one cannot make this approximation. Because it is impossible to give a limit of electron losses at a given straight section or other place in an electron storage ring due to a single beam dump, we consider the situation conservativly and assume, that at a single event all electrons are lost at one place as a point source.

FLUKA SIMULATIONS

The consequences of a beam loss with open beam shutters has to be investigated with a Monte Carlo program [1] because the intensity of the resulting radiation field in the experimental hall has to be known as a function of the area. Semi - empirical formulas e.g for labyrinths are not applicable for these calculations.

At the BESSY beamline angles we have three openings for beam lines at 0^0 from insertion devices, 4^0 and 6.7^0 from the first dipol. The shielding wall in forward direction at the beamline angles consist of a 5 cm lead screen (beam height $\pm$ 20 cm) and 1 m heavy concrete.

There is also the possibility of using a 2^0 beamline of the second dipole, but this occurs up to now at only two sections. The beamline from the second dipole has to pass through the side shielding wall with a length of 8 m, so the risks of the accidental beam losses are far less because of collimating effect. We focus in the following on the situation in forward direction at the beamline angle.

Because of the correct inclusion of collimating and stray radiation effects, we use real beamline geometries with collimators and variabel cross sections at both dipole and insertion device beamlines. From the beam line types used at BESSY we used that with the largest aperture for the FLUKA calculations. The origin of the diagrams is located at the end of the straight section (at the beginning of dipole 1). The dipoles are not included, but can be localized as gaps between the machine beamline pieces.

Neutron doses caused by the accidental beam losses in forward direction are more than an order of magnitude lower than the γ doses and not considered in the following.

Scenarios

The most important scenario (see fig. 1) is the calculation of the electron - photon cascade in forward direction along the 0^0 beamline which passes through the first dipole too. We use here a 2.0 cm thick (radius 2.5 cm) target on which the electron beam ($10^{12} e^-$ of 1.7 GeV) hits at normal incident. Such a scenario can occure if the electron beam hits the vacuum chamber (d = 2 mm) of the first dipol at half of the deflection angle, a thin hindrance in the vacuum tube or a misaligned insertion device vacuum chamber in combination with a wrong four magnet bump.

This scenario is conservative because the target has approximately the thickness of the radiation length of iron (1.8 cm), that means two thirds of the energy can pass through the dipol as bremsstrahlung flash and the target is thin enough, so that it has no self absorption. These thickness was used also by Ferrari et al. [4] to maximize the bremstrahlung in forward direction.

At the 0^0 beamline we use a steel box with a 15 cm thick piece of silicon to modelize the mirror chamber. The absorber for the bremsstrahlung is of lead (30 cm) within a lead wall (10 cm) to absorb stray radiation. On the left and right hand side of the bremsstrahlung absorber are two lead stripes (thickness 5 cm, length 30 cm, height 10 cm) perpendicular to the stray aborber and parallel to the beamline.

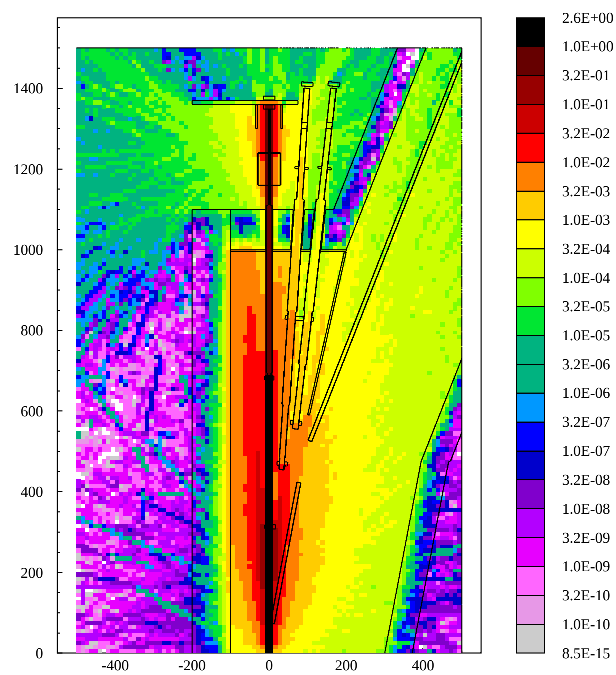

Figure 1: $\phi = 0^0 \gamma$ radiation, dose in Sv/ dump (10^{12} electrons)

The source term of the γ radiation for a target in forward direction was investigated by several authors [2], [3], [4] but their results differ at almost two orders of magnitude. One reason of this is that the detector or the binning geometry does not match with the small angle cone (2/γ) in which the bremsstrahlung is emmitted. Therefore small detectors has to be used to investigate the geometrical spread of this type of radiation. But this decreases the statistics or increases the computing time. Another reason is that so called thick targets are used, whose self absorption in forward direction is considerable. In the case of thin unshielded targets the correct inclusion of the low energy part of the electron - photon cascade and the correct inclusion of β doses at close distances seems questionable.

To compare our calculations we use therefore the paper of Dinter et al [5], who investigated the dose behind beam absorber in forward direction. This geometry correspond with the situation at the 0^0 beamline behind the 30 cm lead bremsstrahlung absorber. With E = 1.7 GeV and 10^{12} electrons we get from [5] for dose behind this absorber 20 μSv/dump. This is close to our value of 8.5 μSv/dump. If we include our 2 cm iron target in the formula of Dinter et al. [5] (with good accuracy as copper, because no iron attenuation coefficient was given), we get 10.5 μ/dump which is in good agreement with our value.

As the next scenario (see fig. 2) we consider the electron beam hitting the vacuum chamber of stainless steel with d = 2 mm at an angle of $\phi = 2^0$ between dipole 1 and dipole 2. This results in effective thickness of 5.7 cm is sufficient for the electron - photon cascade to develop and it has no transverse self absorption. The dump doses > 300 μSv/dump are located in a transversal distance < 0.5m of the dipole beamlines in the experimental hall. At the end of the dipole beamlines is a beamstop located with 10 cm lead thickness. At these place the mirror chamber of the dipole beamline is located in the reality too.

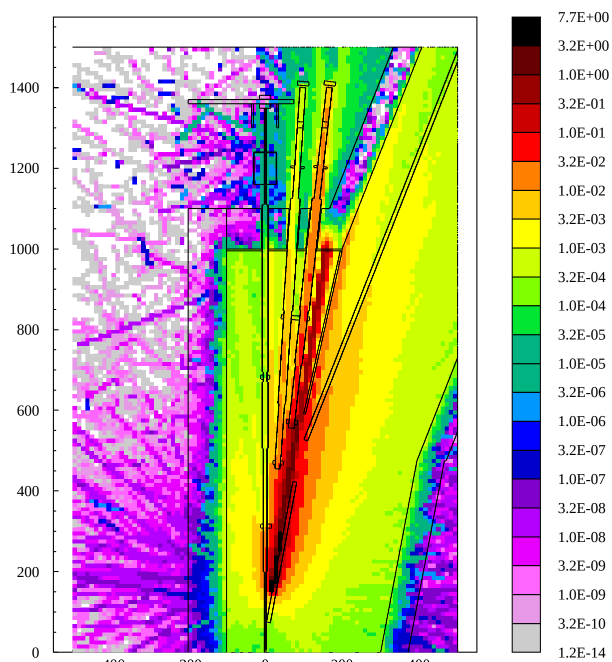

Figure 2: $\phi = 2^0\gamma$ radiation, dose in Sv/dump (10^{12} electrons)

As last scenario we set the point source behind dipol 2. As scenario parameters we use again the hitting angle $\phi = 2^0$, target material iron, thickness d = 2 mm, $d_{eff} = 5.7$ cm or 3.3 radiation lengths.

The three openings of the beamlines are screened by a lead stripe with the length of 4 m, thickness 5 cm and height of 10 cm within the storage ring tunnel.

So from accidental beam losses downstream of dipole 2 the radiation field does not exceed 0.3 mSv/dump.

RESULTING SAFETY MEASURES

We decided, to divide the experimental hall in a large area where the annual personal dose is $<$ 1 mSv/a and sixteen small control areas, which are accessible for BESSY staff only.

The borderlines of the 16 control areas are defined by the following criterions: a) The dose for a single beam dump has to be $<$ 1 mSv/dump for the worst case scenario at the border of the control area. b) The annual dose of all beam dumps has to be lower than 1 mSv/section if the 50 dumps/year are divided to all 16 sections equally at the border of the control area.

From a) and b) results the maximum dump dose in the border of the control area as $<$ 0.3 mSv/dump. According to this dose limit a fence was installed from the corner of the shielding wall to the lead screen. This lead screen against stray radiation was broadened to the left side. From the right edge of this lead screen the fence was installed 2 m parallel to the shielding wall. The enclosure of the area was completed by installing a door between the right dipol beamline and the shielding wall.

In the few cases where the 0^0 wiggler/undulator beamline has no mirror chamber (or the mirror chamber is far downstream) the complete beamline is surrounded by a fence. In the case of wave length shifter beamlines the complete beamline is enclosed in a hutch, so no further installations are necessary.

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