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FLUKA CALCULATIONS OF GAMMA SPECTRA AT BESSY *

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Abstract

Since 22nd October 2012 the synchrotron light source BESSY is operated in top-up mode. Losses of electrons during injection cause an electromagnetic cascade, that consists of high energetic photons of the bremsstrahlung, and secondary electrons and positrons from the pair creations. The bremsstrahlung spectrum has a maximum at 1.022 MeV owing to pair creations. The spectrum has a high energetic tail, that reaches up to the electron energy of 1.7 GeV at BESSY. The low energy part of the electromagnetic cascade is produced by compton scattering or the photo - effect. Due to the opened beamshutters during top-up injections, the low energetic part of the bremsstrahlung spectrum can reach the experimental hall. We used the particle interaction and transport code FLUKA for the calculations of both the fluence and the dose distribution. We calculated the gamma spectra of the radiation through the shielding walls and through the front-ends. We discussed the question whether additional safety measures are necessary for top-up operation due to the low energy part of the spectrum. From our calculations we determined the correction factors for our ionisation chambers of the ambient dose measurement system.

INTRODUCTION

The storage ring BESSY 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. 14 straight sections have been used for the installation of wigglers, undulators and wave length shifters (WLS). Two sections are used for the rf system and the injection septum. In 2011 the microtron has been replaced by a 50 MeV linac which is operated as preinjector for the synchrotron. This measure makes much higher charges in a single bunch possible and it was one of the prerequisites for the top-up operation [1]. The installation of a cryogenic in-vacuum undulator is in preparation (EMIL project). Hutches are only necessary at the WLS and the cryogenic in-vacuum undulator. At all other beamlines the synchrotron radiation is absorbed in the vacuum system because of the low critical energy which is about 2.5 keV at dipole beamlines and about 1 keV at W/U beamlines. Up to now there are 51 beamlines in operation. An overview of BESSY is given in Figure 1 the most important machine parameters are shown in table 1.

At every ratchet 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. Measurement errors of neutron monitors are possible due to high energetic neutrons [2], that are not detectable by standard neutron monitors and by dead - time effects due to pulsed radiation [3]. These papers include correction factors [2] and correction formulas [3] for these errors.

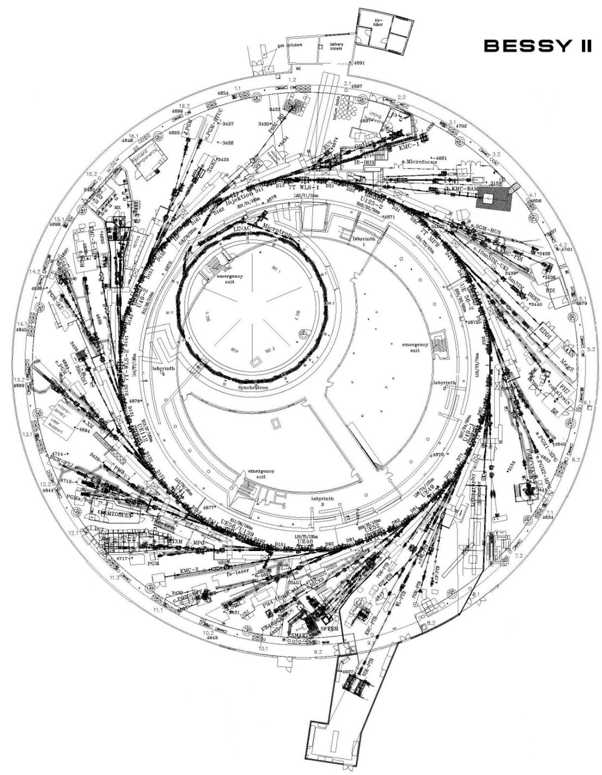

Figure 1: BESSY II.

Table 1: Machine Parameters

Linac energy	50 MeV
Charge per pulse	2 nC
Booster energy	0.2 - 1.9 GeV
Stored beam energy	1.7 GeV
Booster circumference	96 m
Storage ring circumference	240 m
Max. injection frequency	10 Hz
Max. top-up inj. frequency	0.1 Hz
Stored current	300 mA
Stored charge	1.5E12 e-
Lifetime at 300 mA	7 h

We discuss in this paper the contribution of the high energy photons that cannot be detected by our gamma monitors. This is the first time that such an investigation is conducted at a synchrotron light source.

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TOP-UP OPERATION

Since 22nd October 2012 BESSY is operated in top-up mode. The storage ring current for this mode is 300 mA. This was also the maximum current of the former decay mode. The shorter life time at higher current made it necessary to increase the injection efficiency from 30 % to 90 % to keep the number of injected electrons/year constant in comparison with the former decay mode. The annual dose through the shielding walls depends on the number of electrons injected per year. For that reason top-up is not a method to compensate reduced lifetimes (e.g. because of in-vacuum undulators) by permanent injections. Top-up injections occur at opened beamshutters so we installed interlock save exclusion areas close to the front - end. These areas are only accessible if every beamshutter of this section is closed and no injection is made. Located in these areas (Fig. 2) are the mirror chambers that separates the synchrotron radiation from the bremsstrahlung, the lead absorber for the gas bremsstrahlung (30 cm) and for scattered bremsstrahlung in forward direction respectively.

Figure 2: BESSY experimental hall front end restricted area.

Besides the bremsstrahlung absorber we placed a white PE cylinder for the usage of an albedo dosimeter (Fig. 2). The albedo dosimeters are not accurate because of the minimum detectable dose of 100 μSv but they can detect the effects of crash conditions. Because of the possible errors of the radiation monitoring we used the injection efficiency to control the top - up injections. This is much more accurate and faster than the usage of radiation monitors. The injection efficiency η is defined by:

$$\eta = \frac{\Delta I_{SR}}{I_{SY} \cdot 2.4} \tag{1}$$

η is measured shot by shot and averaged over a 4 h period. If the 4 h - average is below 90 % the deviation is compensated by a penalty time (decay mode), if $\eta < 60\%$ the top - up operation is stopped immediately and the storage ring is operated in decay mode. Before top - up can be started again, at least one injection shot must be > 60% with closed beamshutters.

All measures are planned to hold the 1 mSv/a limit in the accessible part of the experimental hall as it was before during the decay - mode. But this has to be proven during the test operation phase. A detailled description of the radiation protection issues of the top-up operation is given in [4].

Table 2: Top-up Safety Measures

Linac charge limit	2 nC/shot
Booster frequency limit	1 Hz
Injection frequency limit	0.1 Hz
I_{SY} < 0.3 mA	SY beam not extracted
I_{SR} < 200 mA	no top - up injections
I_{SR} > 300 mA	injection stops
η < 60%	top - up stops
η < 90% in 4 h	penalty time decay mode
Lifetime at 300 mA < 5 h	SY beam not extracted

FLUKA CALCULATIONS

We calculated the photon fluence spectra as photons per primary/(GeV · sr · cm^2) with FLUKA [5]. To obtain the integral binned results multiply these values have to be multiplied by the energy difference of the respective bin and by 2π for one-way scoring. We used a logarithmic binning up to the gamma energy of 1.7 GeV and down to 10 keV. In our spectra Figures the group fluences are divided by the lethargy interval $\lg E_{i+1} - \lg E_i$ (i is the respective bin number). We use boundary crossing estimators with different detector areas. To increase the statistics we used parallel computing and merged the resulting data. The Figures are made with Flair, and the calculations described so far are included in the norm to process the data files. The calculation of the integral binned results and from them the dose values / energy bin is made with our program specgam which uses the subroutine deq99c.f [6]. This subroutine contains the fluence to dose conversion factors [7] and is included in FLUKA since 2008. We integrated the doses up to the maximum energy of our ionisation chambers (7 MeV) and beyond, to calculate the part of the dose that cannot be detected by them. The shielding wall in forward direction at the beamline angles consists of a 5 cm lead screen and 1 m haematite concrete, in the transversal direction the shielding wall consists of 1 m ordinary concrete or close to the front - ends of 0.8 m heavy concrete. As the first scenario we considered a beam loss at the steel tube of the straight section downstream the planned cryogenic in-vacuum undulator at an angle of 1 mrad. The calculations are conducted with magnetic fields in the dipole chambers. The gamma dose/primary e- for this scenario is shown in Fig. 3.

As the second scenario we considered a beam loss downstream the second dipole. The produced bremsstrahlung penetrates the side wall of the tunnel and reaches the place where our ionisation chambers are located. Again the beam hits the vacuum tube at an angle of 1 mrad. The gamma dose/primary e- is shown in Fig. 4.

RESULTS

In the following H_{7-} and H_{7+} means the integrated doses from the spectra for energies < 7 MeV and > 7 MeV respectively and H_{Σ} is the dose that results from the full integral of the spectrum. From the first scenario we calculated the

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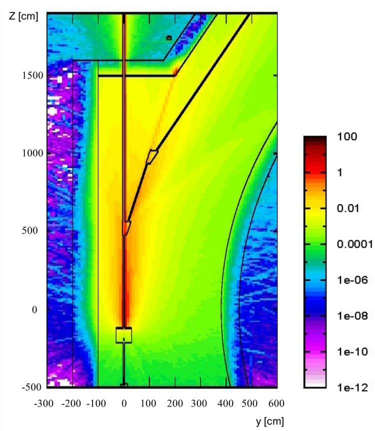

Figure 3: Gamma dose rate from one point source in straight section in pSv/primary.

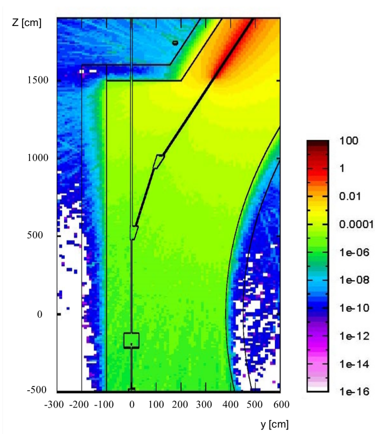

Figure 4: Gamma dose rate from one point source behind dipole in pSv/primary.

energy spectra of the photons that pass the aperture of the ratchet end wall (Fig. 5).

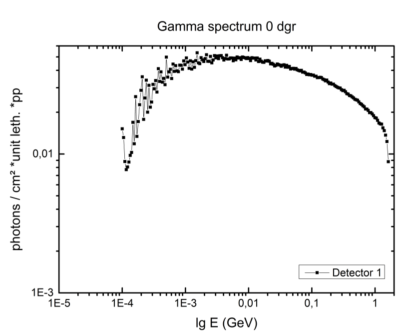

Figure 5: Gamma spectrum in forward direction.

From the first scenario we got $H_{7-}/H_{\Sigma} = 0.058$ or 17.2 as correction factor. From the second scenario we calculated the energy spectrum of photons inside the tunnel (red curve in Fig 6) and that who penetrated the wall (black curve in Fig 6).

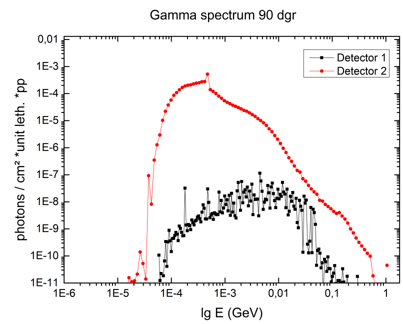

Figure 6: Gamma spectra in transversal direction.

From the first scenario get $H_{7-}/H_{\Sigma} = 0.374$ or 2.67 as correction factor for the spectrum outside the wall. Inside the tunnel we have $H_{7-}/H_{\Sigma} = 0.967$ or 1.034 as correction factor in the transversal direction. The ratchet end wall at BESSY reduces the gamma radiation in forward direction by five orders of magnitude (as well as the beamshutters), so at the location of the ionisation chambers the transversal radiation is more important and the correction factor for this direction should be used. In Berlin the natural gamma background is 0.6 mSv/a. The highest gamma value in the experimental hall at BESSY was in 2013 0.82 mSv/a, which was reached at the injection septum. When we subtract the natural background we have 0.22 mSv/a which is corrected 0.59 mSv/a but it is still low if we consider that this is the value for 6000 h/a of acclerator operation and the maximum stay is 2000 h/a.

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