RADIATION SAFETY CONSIDERATIONS FOR CANDLE LIGHT SOURCE

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Abstract

The radiation and radioactivity levels, induced by a 3 GeV nominal energy, 350mA circulating current electron beam in the CANDLE storage ring, are studied. The radiation safety requirements for the facility, as well as the main features of the Machine and Personnel Protection Systems are discussed. Monte-Carlo simulation based on EGSnrc code is performed to determine the concentrated dose of radiation and the shielding requirements.

1 GENERAL CONSIDERATIONS

As a consequence of the interaction between radiation and matter, energy is transferred from the radiation field to the matter. The energy transferred to electrons may be sufficient to make the charge separation [1]. *Ionising radiation* -the radiation that causes the ionisation of the interacting matter- by interacting with the matter transfers the energy with small but finite portions.

1.1 Radiation and Radioactivity Levels

The annual occupational dose limit of 50 mSv·y^{-1} was considered as an upper limit for the exposure of radiation workers as recommended by the International Commission on Radiological Protection (ICRP) and is based on a mortality risk factor due to radiation induced cancers of 10^{-2} per Sv [2,3]. Occupational dose limit for the general public and non-radiation workers should be at the average natural background level [4] of 1 mSv·y^{-1}.

1.2 Operation Schedule and Normal Beam Loss Estimates

The annual CANDLE storage ring operation schedule is dictated by the experimental scientific program (10 month), facilities start-up (1 month) and machine development (1 day per week). For the nominal circulating current of 5mA in the booster, the 3 GeV electron beam is injected into the ring at the average rate of $4.0\text{x}10^{10}$ electrons/s. With 2 Hz repetition rate and 640 ns particle revolution times in booster, this corresponds to the average current of 6.4 nA. The power transmitted to storage ring is then 19.2 W. In less than 1 minute the current of 350 mA is stored in the main ring. Particles in the storage ring lose the energy to SR that is replenished by the RF system. The lifetime of the stored beam in CANDLE storage ring is $\tau = 18.4$ hours, so the stored electron current will slowly decay (by $e = 2.71$ times in 18.4 hours). The beam current of 350 mA is restored via the beam damp after 12 hours and fresh filling of the storage ring from 0 to 350 mA (normal operation mode) or continuous replenishment of the stored current as its decay below 95% ("top-up" operation mode).

1.2.1 Normal operation mode

In a normal operation mode, the storage ring will be fresh filled twice per day each 12 hours, from 0 to 350 mA. The stored current in 12 hours will then decay slowly from 350 to 180mA, and the 180mA pulse current beam will be extracted and damped before the fresh filling. The stored current of 350 mA corresponds to $1.575{\cdot}10^{12}$ circulating electrons in storage ring. With the conservative approach of 75% injection efficiency, the number of electrons injected into the storage ring per filling time is $2.1{\cdot}10^{12}$. The number of particles lost during a fresh filling (injection period) is $0.53{\cdot}10^{12}$, while the number of stored particles lost in the storage ring in 12 hours is $0.76{\cdot}10^{12}$. The preliminary annual CANDLE operation schedule is given in Table 1. The one month duration start-up program implies in average about 200 storage ring fillings with the total number of injected electrons of $4{\cdot}10^{14}$. The number of electrons injected into the CANDLE ring during the 10-month scientific program is $1.1{\cdot}10^{15}$ (520 fresh fillings). The machine development program is estimated for 2 fills per week ($4.2{\cdot}10^{12}$ injected electrons), or 80 fills within 10 months scientific program in total.

Table 1: Annual CANDLE operation schedule

	Operation Schedule	No of Electrons	Electron Fraction
Start-Up	5fills/h of 0-350mA, 3 h/d, 14 d/m	$0.4{\cdot}10^{15}$	24%
Scientific Program	2fills/d of 0 -350mA, 26 d/m, 10 m/y	$1.1{\cdot}10^{15}$	65%
Machine Develop.	2fills/w of 0-350mA, 4 w/m, 10 m/y	$0.17{\cdot}10^{15}$	11%
Sum	11 months per year	$1.67{\cdot}10^{15}$	100%

All electrons injected into the ring are lost either during the short injection period or during the long stored beam period. From the total injected beam of $2.1{\cdot}10^{12}$ particles, 25% ($5.3{\cdot}10^{11}$ particles) is lost during the injection period, 35% ($7.6{\cdot}10^{11}$ particles) - during 12 hours of beam storage, and the rest 40% ($8.4{\cdot}10^{11}$ particles) is damped**.**

1.2.2 "Top-up" injection mode

The finite stored electron beam lifetime in the ring results in the exponential decay of the current during the time. The number of particles lost is then given by:

$$N_{lost} = N_0\left[1 - \exp(-t/\tau)\right], \quad (1)$$

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where N_0=1.575·10^{12} is the number of initial stored particles (350mA circulating current), t is the time. The “top-up” injection mode implies the replenishment of the stored current as it reduces below 95% of the design current (0.95 hour, 7.87·10^{10} particles lost). Thus, almost every one hour the booster synchrotron provides the injection of a 3GeV electron beam with pulse current of about 50 μA. Figure 1 shows schematically the stored current variation in the ring in “top-up” injection mode.

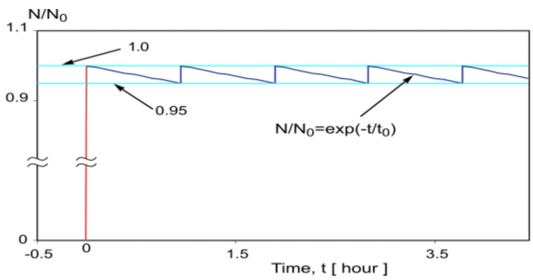

Figure 1: The stored beam time structure in “top-up” injection mode.

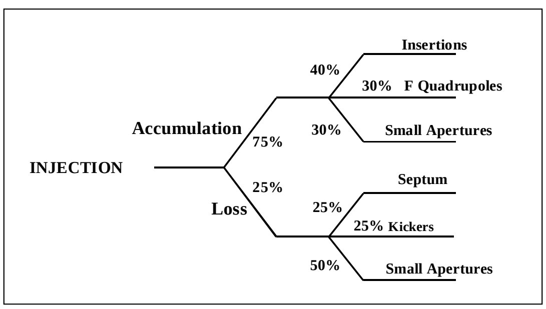

Figure 2: Diagram of the expected electron beam losses in CANDLE (“top-up” mode).

The daily loss of the particles in the storage ring is then amounts of about 2·10^{12} particles and is exceeds the daily loss in normal operation mode 1.52·10^{12} particles (two fillings per day). The diagram of the expected beam losses related to CANDLE storage ring operation in “top-up” injection mode is given in Figure 2.

2 RADIATION SHIELDING REQUIREMENTS

The beam losses in the ring will create an electromagnetic shower in the ring components, producing bremsstrahlung photons and neutrons, which generally dictate the ring shielding design. Ray trace studies via Monte-Carlo simulations are implemented for the circular wall and penetration shielding design because of their different thickness in different locations [5].

2.1 Electron Beam Losses

The estimation of the necessary uniform circular shielding wall for the CANDLE storage ring is based on the conservative approach that the daily electron beam loss is localized at the reference azimuth position of the ring. The daily particle loss is taken 2·10^{12} (“top-up” injection mode) as the most conservative.

To illustrate the storage ring shielding design, the longitudinal (Z) and radial (R) depth dose rates are calculated for ordinary concrete. In our calculations, for the pure electromagnetic part of the cascade, actually we have used the DOSRZnrc code [6]. The input parameters for DOSRZnrc code were chosen as followings. A point source of an electron with 3 GeV primary energy on Z-axis is incident from front. The distance of the point source from the front of the target is 10cm. The equivalent beam radius at the front of the target is 43.46μm. The electron and photon cut-off energies for transport are 0.6688MeV and 0.010MeV respectively.

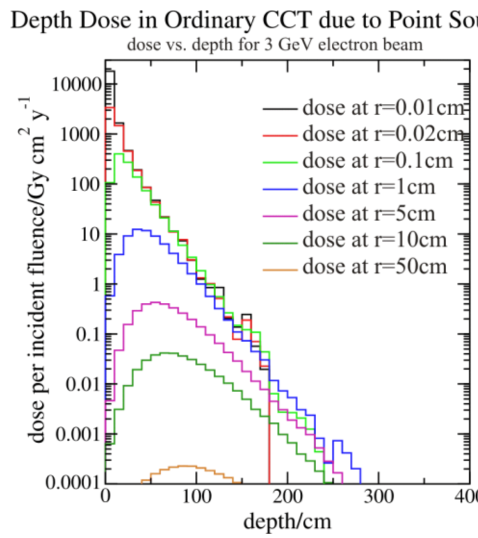

Figure 3: Annual dose rate induced by 3 GeV electron beam in ordinary concrete (CCT).

The annual longitudinal dose rate induced by lost electrons for “top-up” operation mode of CANDLE facility is presented in Figure 3. Figure 3 shows that to have the natural background level of radiation 1 mSv.y^{-1} behind the wall of storage ring, the wall thickness have to be 240 cm. This is the most conservative case because the calculations are carried out for “top-up” operating mode. In fact, the beam loss is basically directed tangentially to the reference orbit so that the angle between the radius of circular shielding wall and the incident electron beam is $\theta = 66^o$. The 240cm of the electron beam penetration depth then corresponds to wall thickness of about 1m.

2.2 Synchrotron Radiation

Our first approach to the problem of calculation of CANDLE bending magnets synchrotron radiation induced radioactivity levels is to use again the DOSRZnrc code. As the input parameters for the code one should give the distance Δl of the point source from the front of the concrete shielding and the radius R of the beam at the front of concrete target. The beam horizontal size is determined by the width of window and is equal to Δx =

10cm on the wall surface placed approximately at the distance equal to Δl =20m from the photon source. Then the angular size of the spot of the beamline on concrete wall is equal to $\Delta\theta/2 = 22.5\ mrad$. $1/\gamma$ vertical angular size of the photon spot on the wall may be taken . Thus the vertical size of the beam can be determined from the relation: $\Delta y/20\ \sim\ 1/\gamma$. Because of the axial symmetry request of the code we have to use the equivalent radius of the beam on the concrete wall that can be got from the equality of the rectangular and circular areas of the beam spots on the concrete wall $\Delta x \Delta y = \pi R^2$, so R = 1.04cm.

The number of photons is also a numerical basis for the calculation of the synchrotron radiation radioactivity as the input parameter, which can reach the outward concrete shielding wall of the building from the open bending beam-line window. The spectral photon flux incident on the wall is given by [7]:

$$dN_{ph} = d\varepsilon \Delta\theta \frac{\sqrt{3}}{2\pi} \frac{\alpha\gamma}{\varepsilon_c} \frac{I}{e} \int_{\varepsilon/\varepsilon_c}^{\infty} K_{5/3}(y) dy\,, \qquad (2)$$

with $I = 350mA$ beam current, $\alpha = 1/137$, e is the electron charge, ε is photon energy, ε_c is the critical photon energy for the bending magnet synchrotron radiation, $K_n(x)$ is the Macdonald function. The results of radiation dose induced by synchrotron radiation from CANDLE dipoles are given in Figure 4 for downstream dose distribution. The downstream dose per incident photon flux of energies from 1keV to 50keV at 0.1 cm depth of ordinary concrete already reaches to the value of 1 mGy cm^2 y^{-1}, which is the natural background level. In comparison with the 3 GeV electron beam induced radiation level that is negligible.

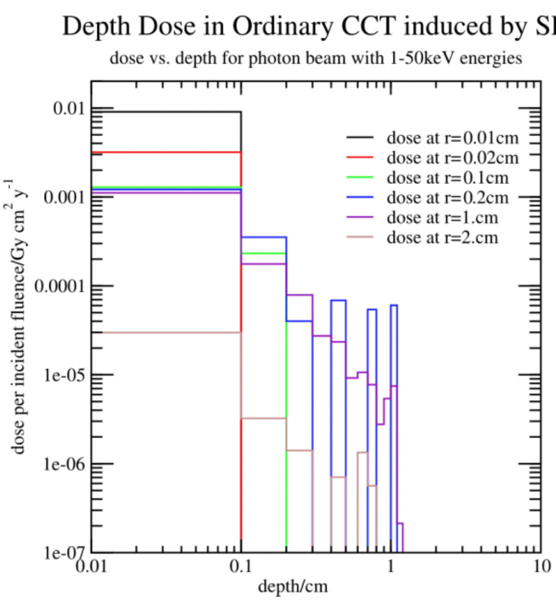

Figure 4: Downstream dose distribution for CANDLE shielding (ordinary concrete).

3 BEAMLINE PERSONNEL PROTECTION

The main approach to radiation safety considerations for CANDLE X-ray beamlines is illustrated on Figure 5.

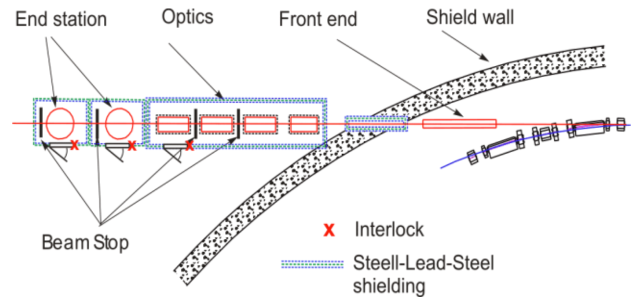

Figure 5: The radiation safety scheme adopted for CANDLE X-ray beamline.

The beamline components will generally intercept not only synchrotron radiation but also gas bremsstrahlung [5]. Scattered photons, as well as photo neutrons induced by gas bremsstrahlung, need to be considered in the beamline shielding design. The hutch walls and beampipes need to be thick enough to attenuate the scattered radiation from these components. Whether it is the scattered gas bremsstrahlung or scattered synchrotron radiation that will dictate the shielding design depends on the characteristics of the individual beamline and its layout, as well as the photon source characteristics. The appropriate approach for each individual case will be done separately in parallel of the user demand.

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