7. Radiation Safety

7.1 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]. An *ionizing radiation* is the radiation that causes the ionization of the interacting matter. Ionizing radiation can be classified in two categories: *immediately ionizing radiation* and *indirect (oblique) ionizing radiation*.
Immediately ionizing radiation consists of charged particles the kinetic energy of which is enough for making ionization while colliding with the atoms of the material. As examples of this can be α - and β - radiations of radio-nuclides, proton and electron radiations of the accelerators, etc.
Oblique ionizing radiation consists of not charged (neutral) particles that produce the origination of charged particles enabling immediately the ionization. Examples of oblique ionizing radiation are neutron and photon radiations.
Ionizing radiation, by interacting with the matter, transfers its energy to it with small but finite portions. The transferred energy is realizing in the processes of ionization, excitation, elastic collisions; part of the energy goes to the increasing of the mass rest of irradiating matter. The energy, which remains in considered volume, compounds *absorbed radiation energy*. In a dosimetry, however, in absorbed energy do not include a radiation energy expended on augmentation of a rest mass of irradiated material.

Radiation and radioactivity levels. Radiation and radioactivity levels of CANDLE light source need to be judged against the reference levels in order to estimate the overall health risk they represent. Reference levels relating to radiation safety established by the Parliament of Republic of Armenia are based on internationally accepted recommendations. A possible set of guidelines against which the significance of exposure to radiation near an accelerator may be judged is given in Table 7.1.1 [2].

Table 7.1.1 Guidelines to the significance of exposure to radiation.

Exposure	Significance
3.5Sv(sievert)	50% chance of survival
> 1 Sv	Serious to lethal
> 50 mSv	Requiring medical checks
50 $mSv \cdot y^{-1}$	Occupational dose limit
15 – 50 $mSv \cdot y^{-1}$	Strict dose control necessary
5 – 15 $mSv \cdot y^{-1}$	Professional exposure
< 5 $mSv \cdot y^{-1}$	Minimum control necessary
1 $mSv \cdot y^{-1}$	Natural background
<1 $mSv \cdot y^{-1}$	Insignificant

The dose levels considered in this table are those to a person rather than that existing near machine. The annual occupational dose limit of 15 $mSv \cdot y^{-1}$ was considered as the upper limit for the exposure of radiation workers of CANDLE not exceeding the radiation limits currently in application in the European accelerator centers (e.g., CERN - 15 $mSv \cdot y^{-1}$, DIAMOND - 20 mSv·y^{-1}) [3], and taking as a basis a mortality risk factor due to radiation induced cancers of 10^{-2} per Sv. However, the occupational dose limit for the general public and non-radiation workers was considered to be at the level of 1 mSv·y^{-1} that corresponds to average natural background level as recommended by the International Commission on Radiological Protection (ICRP) [4].

Operation Schedule and Normal Beam Loss Estimates.
The annual CANDLE storage ring operation schedule is dictated by the experimental scientific program, facilities start-up and machine development. The expected CANDLE storage ring operation schedules an one-month start-up prior to a 10-month scientific program. Machine development is scheduled for 1 day per week during the 10 months scientific program.
For the nominal circulating current in the booster of 5 mA, the 3 GeV electron beam is injected into the ring at average rate of 4.0×10^{10} electrons/s. With 2 Hz repetition rate and 640 ns particle revolution time in booster, this corresponds to 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 synchrotron radiation that is replenished by the RF system. The lifetime of the stored beam in CANDLE storage ring is 18.4 hours, so the stored electron current will slowly decay (by e = 2.72 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 mA to 350 mA (normal operation mode) or after continuous replenishment of the stored current as its decay below 95% ("top-up" operation mode).

Normal operation mode. In the normal operation mode, the storage ring will be fresh filled twice per day, each 12 hours, from 0 mA to 350 mA. The stored current in 12 hours will then decay slowly from 350 mA to 180mA, and the 180 mA 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 7.1.2 [5].

Table 7.1.2 Annual CANDLE operation schedule .

	Operation Schedule	Number of Electrons	Electron Fraction
Start-Up	5 fills/hour of 0 to 350 mA, 3 hours/day, 14 days/month	$0.4 \cdot 10^{15}$	24%
Scientific Program	2 fills/day of 0 to 350 mA, 26 days/month, 10 months/y	$1.1 \cdot 10^{15}$	65%
Machine Development	2 fills/week of 0 to 350 mA 4 weeks/month, 10 months/y	$0.17 \cdot 10^{15}$	11%
Sum	11 months per year	$1.67 \cdot 10^{15}$	100%

The one month duration start-up program implies on 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 1.1×10^{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-month scientific program in total.
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 remaining 40% ($8.4 \cdot 10^{11}$ particles) is damped.

"Top-up" injection mode. The finite stored electron beam lifetime in the main ring results in the exponential decay of the stored current with the time. The number of particles lost in the ring is then given by:

$$N_{lost} = N_0 \left[1 - \exp(-t/\tau)\right], \tag{7.1}$$

where $N_0 = 1.575 \cdot 10^{12}$ is the number of initial stored particles (350 mA circulating current), τ = 18.4 hours is the beam lifetime, t is the time. The "top-up" injection mode implies the replenishment of the stored current as it reduces the designed current below 95%. The period, during which the intensity of the stored beam decreases by 5%, amounts 0.95 hour. The number of lost particles during this period is $7.87 \cdot 10^{10}$. Thus, in each hour ("top-up" injection mode) the booster synchrotron provides the injection of a 3 GeV electron beam with pulse current of about 50 μA. Fig. 7.1.1 shows schematically the stored current variation in the ring in "top-up" injection mode.

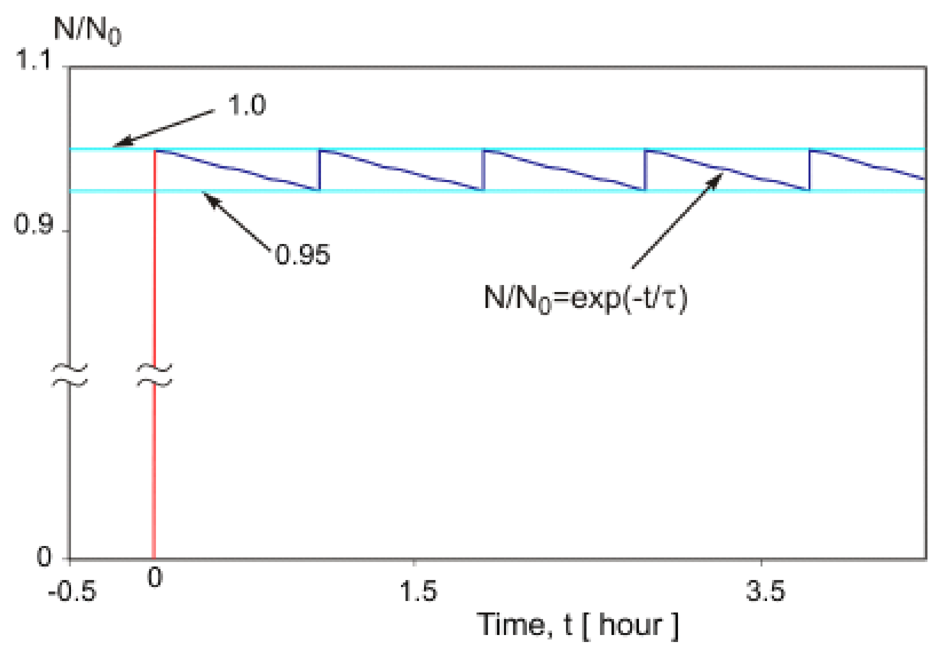

Fig. 7.1.1 The stored beam time structure in "top-up" injection mode.

The daily loss of the particles in the storage ring then amounts of about $2 \cdot 10^{12}$ particles and exceeds the daily loss of $1.52 \cdot 10^{12}$ particles in normal operation mode (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 Fig. 7.2. The loss of particles during the injection is expected basically at the injection septum (25%) and kicker (25%). The rest 50% of loss is expected uniformly distributed around the ring at the locations with small aperture. The stored beam particle losses is expected to dominate in horizontal plane, so 30% loss associates with focusing quadrupoles, 30% at the locations with small aperture and the rest 40% at the insertion devices.

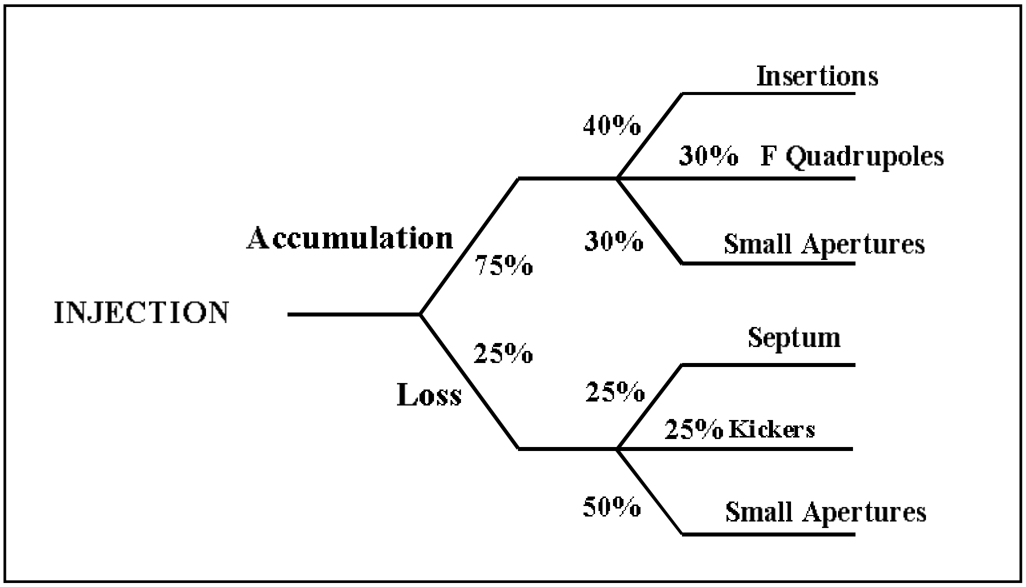

Fig. 7.1.2 Diagram of the expected electron beam losses in CANDLE ("top-up" mode).

In addition to the above normal beam losses, abnormal beam losses should be considered in the shielding design. Abnormal beam losses are most likely due to the beam mis-steering (*e.g.*, a mismatch between the beam and ring lattice, RF trip, loss of magnet power supply, *etc.*) and are less likely due to interlocked safety system failure (*e.g.*, the current limiting devices fail and a beam is injected at a power higher than normal) [6]. Abnormal beam losses generally result in persistent high dose rates outside the ring wall during injection (if not detected and terminated) and instantaneous doses during stored beam. Since the regulations and standards in this area are not complete, it is the synchrotron radiation facility's responsibility to carefully identify which abnormal beam loss scenarios are likely or credible, to define the dose limits against which the shielding is designed, and to implement the mitigation measures for the credible scenarios.

7.2 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. If the limiting apertures are already identified then due to not uniform distribution of the radiation in the storage ring the concrete walls of the ring should have different thickness in different locations. For example, the locations with heavy losses, *e.g.*, the injection septum and the stored beam dump, have thicker walls and/or additional local shielding (*e.g.*, lead). Shielding blocks placed in and near the beamlines, *i.e.*, the injection stopper and shadow wall are necessary to shadow these penetrations from forward bremsstrahlung and neutrons generated in the ring. Therefore, ray trace studies via Monte-Carlo simulations are implemented for the circular wall and penetration shielding design, particularly when local heavy-metal blocks are used to complement the circular wall shielding. The estimation of the necessary uniform circular shielding wall for the CANDLE storage ring is based on the conservative approach.

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 azimuthal position of the ring. The daily particle loss is taken $2 \cdot 10^{12}$ ("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 use the DOSRZnrc user code [7] of series EGSnrc code [8] based on EGS4 [9] with certain improvements and additions. The input parameters for DOSRZnrc code were chosen as the followings. A point source of an electron with 3 GeV primary energy on Z-axis is incident from the front. The distance of the point source from the front of the target is 10 cm. The radius of the beam at the front of the target is 43.46 μm which is equivalent to the radius of the ring the surface of which is equal to those of the ellipse with radii σ_x = 266 μm and σ_y = 28.4 μm. The electron and photon cutoff energies for transport are 0.6688 MeV and 0.010 MeV respectively.

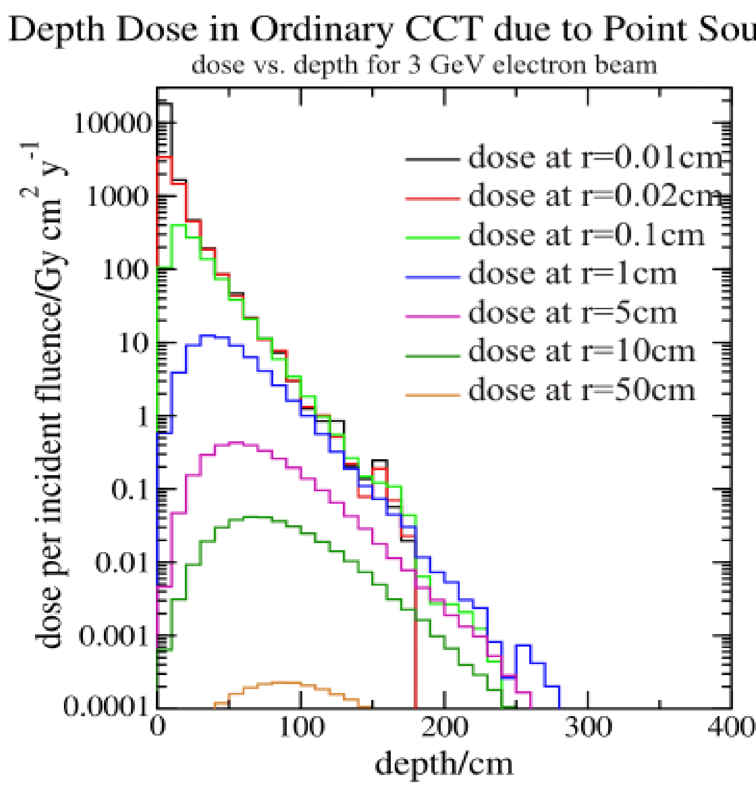

Fig.7.2.1 Annual dose rate induced by 3 GeV electron beam in ordinary concrete (CCT).

The longitudinal dose rate induced by the lost electrons during a year for "top-up" operation mode of CANDLE facility is presented in Fig. 7.2.1. Using this dose dependence on the absorber thickness one can assess the thickness of the tunnel wall of the ring by taking into account the overall health risk guidelines presented in Table 7.1. Indeed, Fig. 7.3 shows that to have the natural background level of radiation 1 $mSv.y^{-1}$ behind the wall of storage ring, the wall thickness should 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 $\theta = 66^o$. This is clearly illustrated on Fig. 7.2.2. The 240 cm of the electron beam penetration depth then corresponds to wall thickness of about 1m.

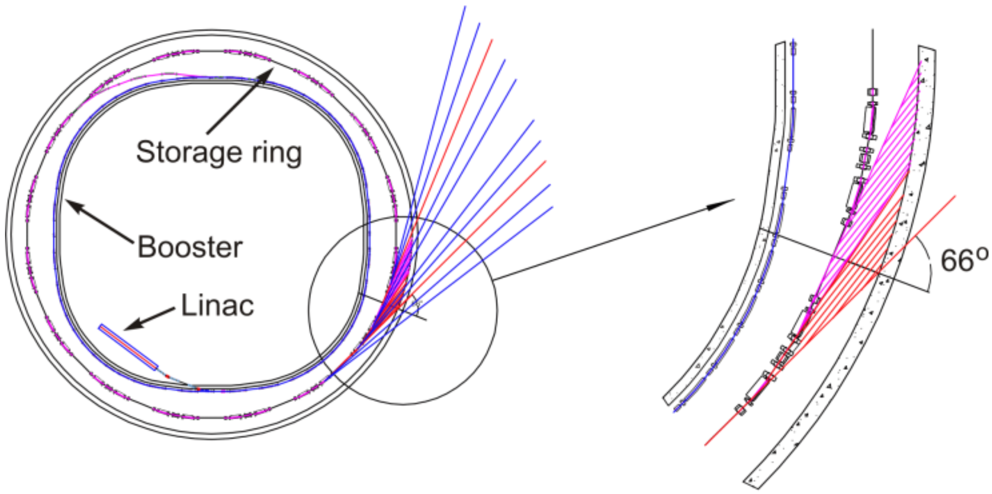

Fig. 7.2.2 Schematic layout of CANDLE and beamline section.

The radial dose rate for the above discussed case is presented in Fig. 7.2.3. As one can see from the Figure the radial dose spread is rather narrow. The natural background of radiation level in lateral direction of the beam is provided by R = 10 cm ordinary concrete absorber.

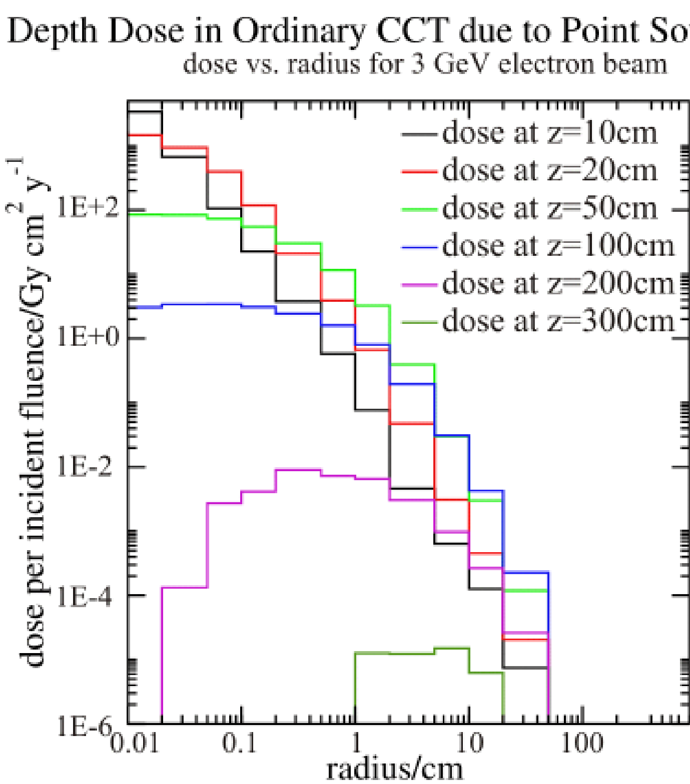

Fig. 7.2.3 Radial annual dose rate induced by 3 GeV electron beam in ordinary concrete.

Synchrotron radiation. Due to the complicated energy spectrum of the synchrotron radiation and the fast-changing attenuation coefficients of materials for photons < 100 keV, the phenomenological estimation methods are not effective for synchrotron radiation shielding design [6]. Our first approach to the problem of calculation of CANDLE bending magnets synchrotron radiation induced radioactivity levels is to use again the DOSRZnrc code [7]. 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 $\Delta\theta/2 = 22.5\ mrad$. The vertical angular size of the photon spot on the wall may be taken equal to $1/\gamma$. 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 should 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 = 1.04 cm.

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 [10]:

$$dN_{ph} = d\varepsilon \Delta\theta \frac{\sqrt{3}}{2\pi} \frac{\alpha\gamma}{\varepsilon_c} \frac{I}{e} \int_{\varepsilon/\varepsilon_c}^{\infty} K_{5/3}(y)dy\,, \tag{7.2}$$

with $I = 350mA$ beam current, $\alpha = 1/137$, e is the electron charge, ε is the photon energy, ε_c is the critical photon energy for the bending magnet synchrotron radiation, $K_n(x)$ is the Macdonald function. The photon number spectral density distribution versus energy incident on the wall is presented on Figure 7.2.4.

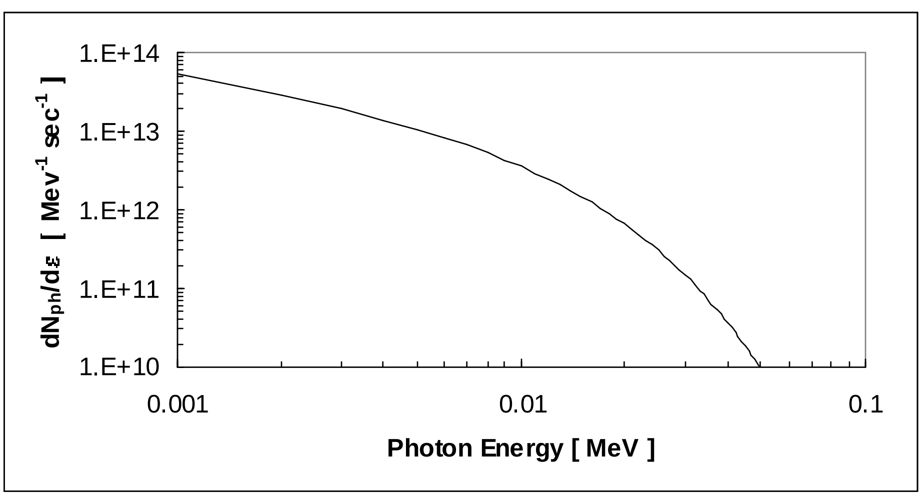

Fig. 7.2.4 The spectral photon flux density distribution versus energy.

The results of radiation dose induced by synchrotron radiation from CANDLE dipoles are given in Fig. 7.2.5 for downstream dose distribution. The downstream dose per incident photon flux of energies from 1 keV to 50 keV 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.

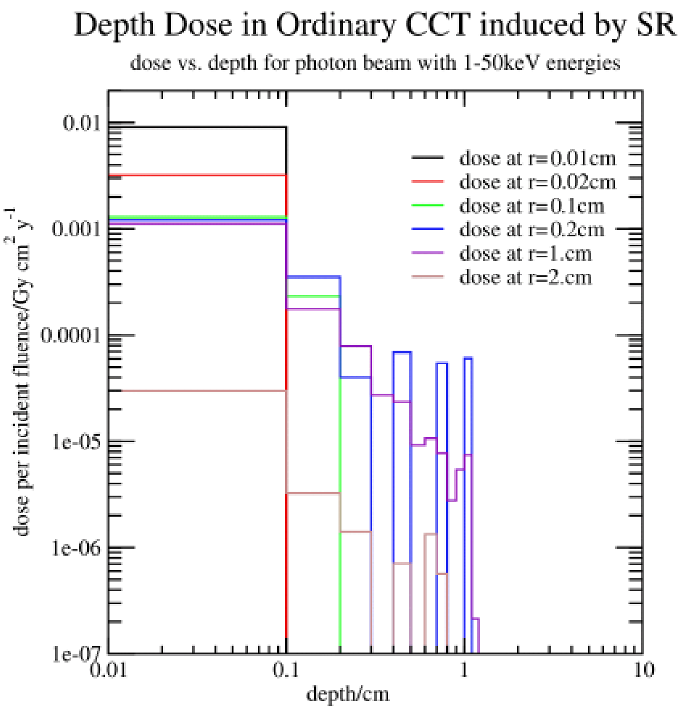

Fig. 7.2.5 Downstream dose distribution for CANDLE shielding (concrete).

The same situation is with the radial dependence of the dose level. One can see from the Fig. 7.2.6 that the lateral spread of the radiation of photons is almost not changed being comparable with the lateral dimensions of incident beam (1.04 cm).

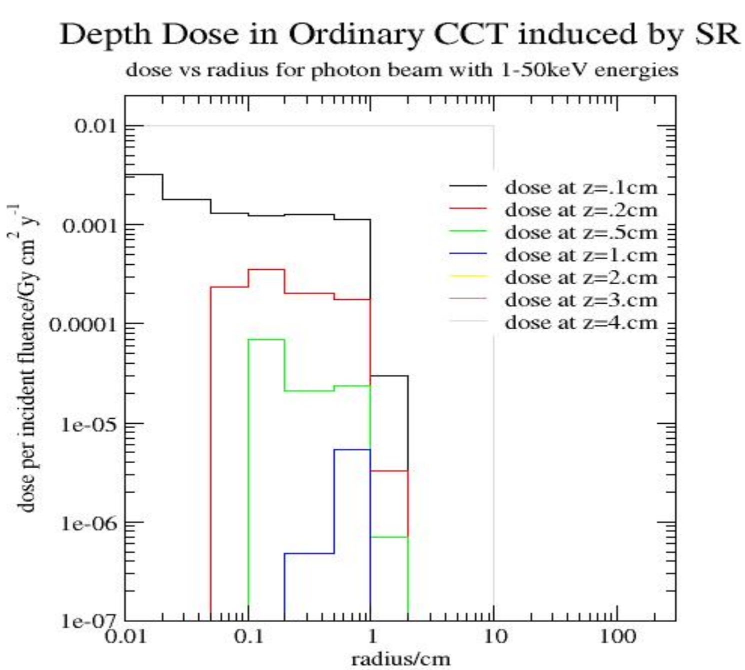

Fig. 7.2.6 Radial dose distribution for CANDLE shielding (concrete).

In addition to the hutch wall and beam pipe shielding, attention should be paid to synchrotron radiation streaming through ventilation and cable penetrations in the hutch, as well as ground shine under the hutch doors, in particular for insertion device beamlines at CANDLE facility.

Neutrons contribution. Because photons have substantially larger nuclear cross-sections than electrons, neutrons and other particles resulting from inelastic nuclear reactions are produced mainly by the photon component of the EM shower. Three photoneutron production processes are important at high-energy electron facilities: g*iant resonance production, pseudo-deuteron production, photo-pion production.* While substantially less numerous than giant resonance neutrons, the photopion neutrons are very penetrating and will be the component of the initial radiation field from a target (with the exception of muons at very high energies) that determines the radiation fields outside very thick shields. Photons and giant resonance neutrons dominate the field inside shielding enclosures and remain a significant component behind moderate shielding. For example, a 60 cm lateral concrete shielding of a 3 GeV electron beam line with average beam power of 5 W can be considered as moderate [11]. For CANDLE the beam power amounts 19 W, which exceeds this considered value by a factor of about 4 for the same 3 GeV electron beam nominal energy. It is reasonable to make rough estimation of the moderate lateral concrete shielding thickness for CANDLE just multiplying 60 cm by a factor 4 which will amount 240 cm. This conclusion is in excellent agreement with the results of our Monte Carlo calculations.

For neutrons with energies above ~20 MeV the best shielding configuration consists of a layer of high-*Z* material, such as lead or steel, followed by a low-*Z* shield with high hydrogen content (≈1%) - most often concrete.

Due to the distance factor and large physical size of a shower in concrete (large X_0: 10.7cm for shielding concrete), it can result in extremely high radiation levels in occupied areas. In the framework of a model in which only the production of secondary photons and neutrons is taken into account (e.g., semi-empirical shielding code SHIELD11 [12]), *i.e.* muons are not considered, we can make assumption based on a “thick target” concept, requiring that the electromagnetic shower be fully developed in the target. This implies that the radius should be greater than 1 Moliere unit and longer than 10 radiation lengths in a given material. These conditions are more than satisfied for the results of our calculations: 240 cm thick ordinary concrete shield which amounts ~20X_0 and is enough to dissolve the low energy neutrons contribution. Indeed, the dose equivalent at the given point can be estimated (for example in the framework of a pure point source/line-of-sight model - or Moyer Model - summarized in [13] which is directly applicable to the shielding of GeV range proton accelerators and also can be used at electron accelerators [14]) as follows:

$$D = H_0\left(\frac{E_e}{E_0}\right)^{0.8}\frac{\exp[-(r-r_0)/\lambda]}{r^2}, \qquad (7.3)$$

where E_e is the electron energy, E_0 is 1 GeV, H_0 is the dose-equivalent normalization constant with the value 1.1×10^{-15} Sv.m^2.GeV^{-1} per electron and λ for concrete is 42g.cm^{-2}, r= 240 cm which in our case coincides with the line-of sight distance in the shield and also with beam axis, r_0 = 0 for our simplest case. By substituting these parameters with their values into formula (7.3) and taking into account the annual particles losses from the storage ring we obtain D = 0.66 μSv.cm^2. GeV^{-1}.y^{-1} for the resonance neutrons induced dose equivalent behind 240 cm concrete shield, which is insignificant (see Table 7.1).

7.3 Beamline Personnel Protection.

Synchrotron radiation beamlines can be classified in two categories: hard X-ray (> a few keV), which generally is at a line-of-sight path to the stored beam, and vacuum ultra-violet/soft X-ray (VUV) beamlines. The experimental stations at X-ray beamlines are lead- or iron-shielded enclosures (experimental hutches), which are large enough for experimenters to access. On the other hand, the VUV or soft X-rays, arising from synchrotron radiation reflected from mirrors at large angles, is so soft that the experiment has to be performed inside a vacuum container. Thus, the vacuum chamber beampipe itself can easily attenuate and contain the VUV light. Fig. 7.3.1 illustrates the main approach to radiation safety considerations for CANDLE X-ray beamlines.

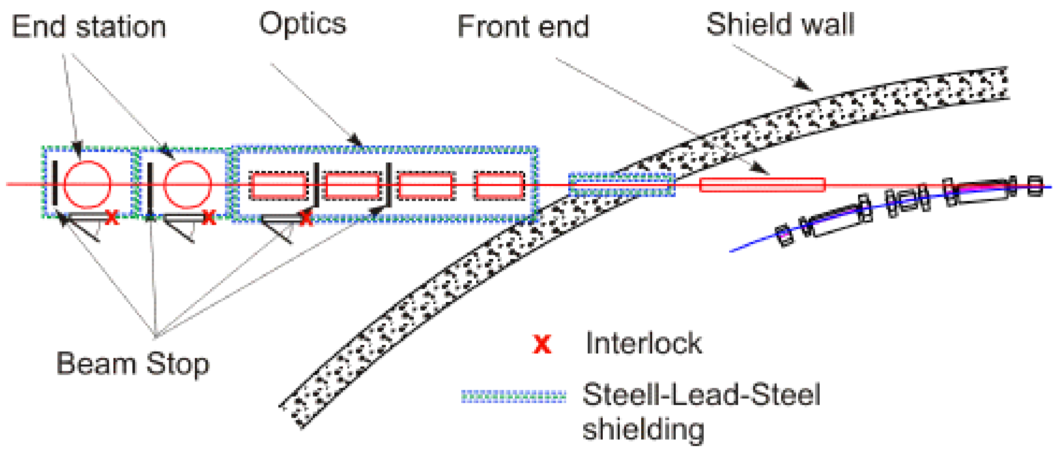

Fig. 7.3.1 The radiation safety scheme adopted for CANDLE X-ray beamline.

The beamline components will generally intercept not only synchrotron radiation but also gas bremsstrahlung. 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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