# T.3: Radiation physics studies at Indus-1 synchrotron radiation source for radiation protection in high energy electron accelerators

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## 1. Introduction

Electron accelerators are widely used world over for various applications in industry, medicine and in basic and applied research. The electron energy used for industrial and medical applications is up to ~10 MeV. For research applications, the energy may extend to very high values (hundreds of MeV, GeV or TeV). High energy accelerators are on the rise as they are powerful tools to search the yet to be seen elementary particles, thereby unraveling the hidden realities of the universe. Livingston in 1962 in his famous "Livingston Plot" predicted a ten-fold increase in particle energy, every six years, which was confirmed by Panosky [1] two decades later who brought out a revised plot, which is shown in Fig.T.3.1.

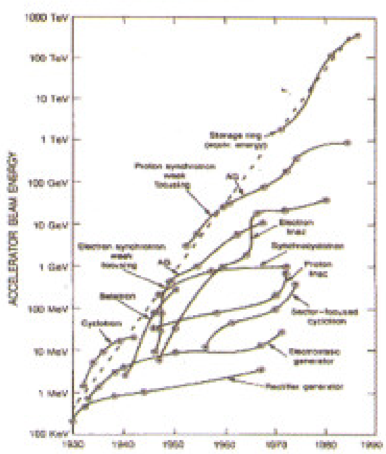


*Fig.T.3.1: Livingston Plot: Envelope of the curves suggests a ten-fold increase in particle energy, every 6 years.*

High energy electron accelerators are widely used at several laboratories in order to produce intense synchrotron radiation from storage rings [2]. High energy electrons are preferred for the production of synchrotron radiation due to its very low rest mass, in comparison with other fundamental particles and hence they can be accelerated to relativistic velocities easily unlike other charged particles.

When the high energy electrons interact with accelerator structures, residual gas molecules in the vacuum chamber, experimental targets etc, bremsstrahlung x-rays [3,4] are produced [5]. These x-rays have a broad spectrum extending up to the kinetic energy of the electron beam. Bremsstrahlung x-rays are the main radiation hazard in any high energy electron accelerator. These x-rays may further induce photo nuclear reactions within the interacting material and as a result several secondary particulate radiations like neutrons, protons, muons etc. may be generated. Thus the increase in the primary particle energy poses a great challenge in radiation protection due to the complex radiological conditions existing in such accelerators and lack of proper dosimetric systems [6].

Conventionally, radiation dosimetry and shielding aspects had been limited to radiation of few MeV, whose primary sources were mainly, naturally occurring radio-isotopes, nuclear fuel cycle operations like mining, milling, nuclear reactor operation, fuel reprocessing and x-ray generators used in diagnostic radiology and research. With the increase in the electron energy and the subsequent production of high energy bremstrahlung x-rays, the conventional dosimetric and radiation shielding concepts may not provide adequate safety to personnel in such accelerator environment. This is basically due to the difference in the interaction mechanism of this high energy radiation with matter, as compared to low energy radiations, up to few MeV.

When a photon with energy far above the pair production threshold (1.02 MeV) is incident on a medium, an energetic electron and photon are formed, as pair production is the dominant interaction mechanism at high photon energies. Subsequently, the energetic electron and positron radiate out photons and these photons in turn produce further pairs giving rise to a cascade (or shower) of electrons, positrons and photons resulting in an electromagnetic shower [5]. H.J. Bhabha, in his work on theory of cosmic ray showers, calculated the number of particles (electrons and positrons) emerging from a lead plate of 5 cm on 100 GeV electron bombardment to be 1000 or more [6]. An example of a massive shower generated when a 10 GeV electron is incident on a target of tungsten is shown in Fig.T.3.2.

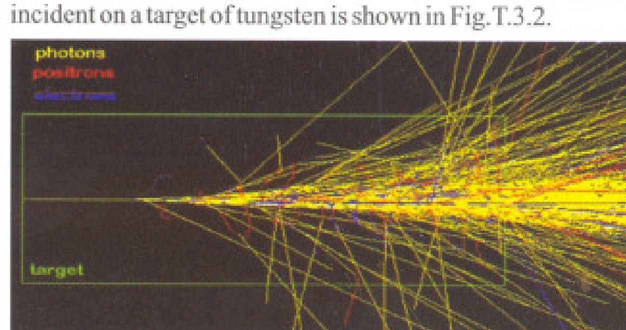


*Fig.T.3.2: A massive electromagnetic shower simulated in a block of tungsten target on 10 GeV electron incidence.*

As a result of the shower generation, the particle fluence increases with depth of the interacting medium and their mean energy decreases. Therefore the energy deposition in the medium increases with depth, giving rise to a build up in the radiation absorbed dose (energy absorbed per unit mass of the medium). As the mean energy of photon in the medium reduces to a low value, the pair production and Compton scattering compete at certain depth [7] in the medium, beyond which dose build up dose not take place and hence the dose will fall off almost exponentially owing to Compton and photoelectric effect. The whole process would therefore result in a depth dose curve in the interacting medium with a rising and falling edge. The depth at which the maximum dose ($D_{max}$) occurs is the shower maximum ($X_{max}$) of the electro-magnetic shower.

Conventional radiation monitors, usually calibrated in terms of personal dose equivalent, $H_p(10)$ [8] when used to monitor such high energy photon radiation do not indicate the true dose received by the worker as they show only the dose equivalent at a depth of 10 mm in tissue. Thus the absorbed dose and hence the dose equivalent (a quantity used in personnel radiation protection) in a high energy photon field would be higher than the dose equivalent indicated by a conventional radiation survey meter.

Studies were carried out at in the high energy photon radiation field at Indus-1 Synchrotron Radiation Source (SRS) to find out the dose equivalent build up factor experimentally with conventional survey meters and water phantom, simulating a human body. Emphasis has been given to measurements using water phantoms, as human body contains about 62 % water [9], and can be applied for all practical radiation protection purposes. Monte-Carlo simulations were also carried out to simulate the experimentally observed dose build up factors. Dose build up factors as a function of the depth in water phantom was then estimated from which a high energy correction factor for radiation monitors is deduced.

## 2. Preliminary observations on cascade development around Indus-1

A set of 31 observations on the electro-magnetic cascade development and the subsequent radiation dose build up in different media were made with three different radiation monitors around Indus-1 SRS. The following three radiation monitors were used for the measurement:

1. Victoreen survey meter (Model 450P, USA),
2. Pulsed x-ray monitor (Model WM10, ED, BARC, India) and
3. RADMON survey meter (Model 701, Nucleonix, India).

All these monitors have a tested, near flat energy response from ~60 keV to 1.25 MeV.

In the experiment, a number of observations were made within the shielded enclosures at various locations around the storage ring of Indus-1 during the storage mode of operation. To see the dose build up, various media were interposed between the source (storage ring) and the monitors and the response was noted. The dose rate build up factors were then found out from the response with build up medium to the response from the bare monitor. It has been observed that all the monitors showed dose rate build up with the build up medium in front of the monitors. The measured dose rate build up factors [10] varied in the range 1.9 to 4.5, which are pictorially shown in Fig.T.3.3. These observations refer to various values of stored current on different days and for different build up media like water phantom, tissue phantom, steel of few mm etc. This clearly demonstrated the shower generation within the media and indicated that all the radiation monitors studied are underestimating the radiation dose within the shielded enclosure.

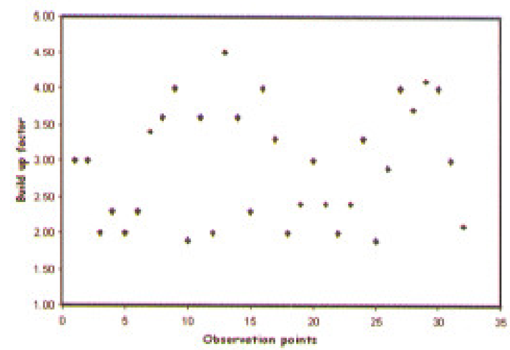


*Fig.T.3.3 Dose build up factors observed for 31 observations around Indus-1.*

## 3. Systematic measurements on radiation dose build up

Based on the preliminary observations on the radiation dose build up around the storage ring, systematic measurements were performed at the front-end (the interface between the storage ring and a beam line) exit and near the bending magnet-3 (BM-3) using water phantom and Victoreen survey meter.

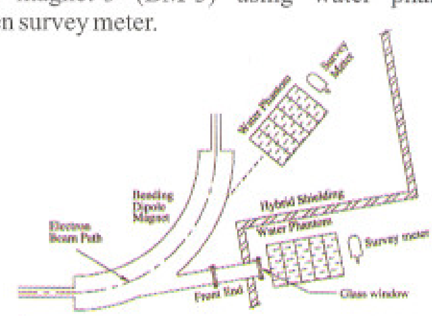


*Fig.T.3.4: Schematic diagram of the experimental set-up for depth dose measurements.*

The Victoreen survey meter was used to get the depth dose profile in water so as to see how the dose profile varies with depth of a human body when exposed to the photon radiation. Measurements were done at 10 mA of stored current in the ring. The schematic diagram of the experimental set up for studying the depth dose profile is shown in Fig.T.3.4.

In the radiation field near the bending magnet, the survey meter response was noted by varying the thickness of water slab. Since it was difficult to surround or immerse the instruments in water, as it is to be done ideally, water slabs were kept in front of the survey meter. Similar experiment was carried out at the front-end exit. The depth dose profiles obtained near the bending magnet and at the front- end are shown in Fig.T.3.5 [11].

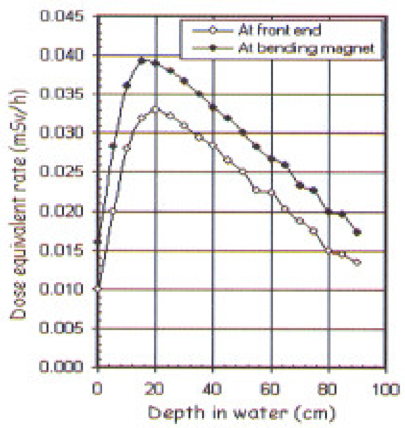


*Fig.T.3.5: Depth dose curves measured at bending magnet and front- end (of BM-3) of Indus-1 SRS.*

The depth dose profiles indicated that at the bending magnet, the maximum dose equivalent rate occurred at about 15 cm, giving a dose build up factor of 2.5 w.r.t. the bare monitor. At the front-end location, the dose equivalent rate peaked at a depth of 20 cm, with a dose build up factor of 3.3. To confirm the dose build up in another medium and with other type of detectors, measurements were performed with copper as the build up medium and $CaSO_4$(Dy) TLD as the detector, which confirmed the same [12].

## 4. Monte Carlo Simulations of depth dose around the Storage Ring

Experimental observations discussed above were simulated using the Monte Carlo codes : EGS-4 [13] and EGSnrc [14]. Experimental depth dose curves obtained from the measurements with Victoreen survey meter indicated spectral variations at different locations around the storage ring. Therefore a different approach was adopted to simulate the experimental conditions which enable explain the experimental results.

A pencil beam of 450 MeV electrons is allowed to be incident on different thicknesses of semi-infinite copper target and the emergent bremsstrahlung spectra are scored in air in the forward direction with a central axis scoring radius of 5 mm. Copper is selected because the structural materials in and around the accelerator are of medium atomic number. The bremsstrahlung spectra obtained from 3 mm, 50 mm and 100 mm copper targets are shown in Fig.T.3.6. (Spectra from other thicknesses are not shown due to mix-up of spectral data in the figure).

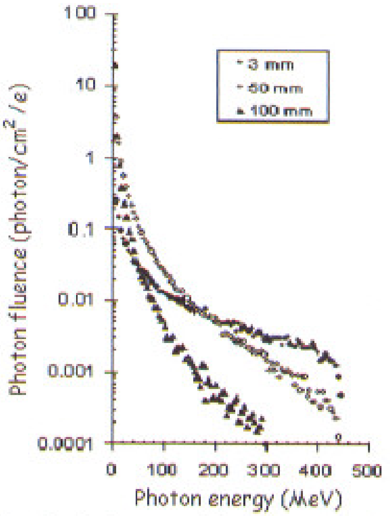


*Fig.T.3.6: Simulated bremsstrahlung spectra obtained from different thickness of Cu target on 450 MeV electron incidence (using EGS-4).*

It can be seen from Fig.T.3.6 that the spectrum from 3mm Cu (thin target) is more populated on the high energy side compared to the other two. For thick targets, the low energy component dominates due to the spectral degradation on account of interaction within the Cu target itself. These spectra of photons are allowed to be incident as a broad parallel beam on water phantom and the depth dose in water is scored. For the depth dose calculation, total histories of 10 millions are used to have better statistical accuracy. For electron and photon transport, cut-off energies used were 0.521 MeV for electrons and 0.01 MeV for photons. The statistical accuracy obtained in all the simulations was within ±1 %. The simulated depth dose curves obtained is shown in Fig.T.3.7. The top curve corresponds to spectrum from 3 mm Cu and the bottom one is from 100 mm thick Cu.

One can see from the depth dose curves that dose maximum ($D_{max}$) and the shower maximum ($X_{max}$) decreases as one moves from a thin target to a thick target. The dose build up factors are calculated as the ratio of $D_{max}$ to the dose at 1 cm depth in water from the simulated depth dose curves. The $X_{max}$ corresponding to $D_{max}$ is also noted in each case. The

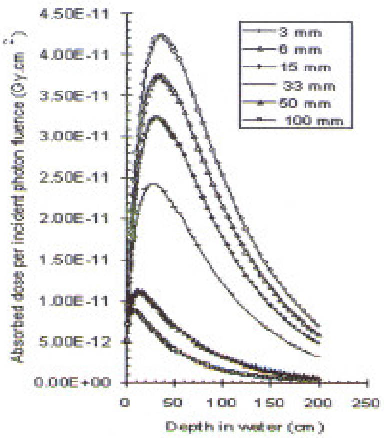


*Fig.T.3.7: Simulated depth dose curves in water phantom for different incident bremsstrahlung spectra from Cu targets of different thickness obtained from 450 MeV electron incidence (using EGSnrc).*

average energy of the incident photon spectra and the calculated dose build up factors plotted as a function of the shower maximum, $X_{max}$ is shown in Fig. T.3.8.

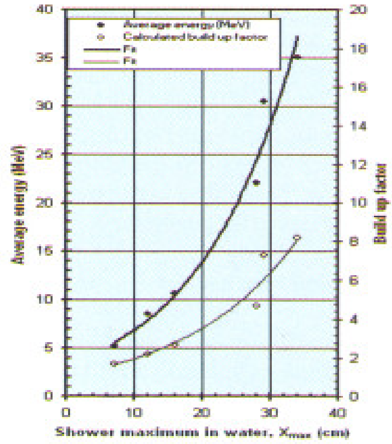


*Fig.T.3.8: Calculated dose build up factor & average energy of incident bremsstrahlung spectra as a function of the shower maximum.*

## 5. Results of the simulations and comparison with measurements

From Fig.T.3.8, the shower maximum and the build up factor is seen to increase with the average energy of the incident photon spectrum. Moreover, as the shower maximum increases, the build up factor also is seen to increase. An exponential fit to the average energy as a function of the $X_{max}$ assumes the following form.

$$E_{avg}(MeV) = 3.41e^{0.07X_{max}} \quad (1)$$

It follows that,

$$X_{max} = \frac{1}{0.07}\ln\left(\frac{E_{avg}}{3.41}\right) \quad (2)$$

The above equation says that at an average energy of 3.41 MeV, $X_{max} = 0$ and hence dose build up in water does not take place below this energy.

Similarly the exponential fit to the build up factor assumes the form,

$$BF = 1.08\exp\left(X_{max}/16.9\right) \quad (3)$$

where $X_{max}$ is the shower maximum in water in cm. The simulated build up factor enables us to compare with the experimental values. Table T.3.1 gives the comparison of the experimental and the simulated build up factors as a function of the shower maximum, $X_{max}$.

*Table.T.3.1: Comparison of dose build up factor from experiments and simulations.*

| Location | Shower maximum (cm) | Build up factor | |
|---|---|---|---|
| | Measured | Measured* | Simulated** |
| Bending magnet | 15.0 | 2.5 | 2.6 |
| Front end | 20.0 | 3.3 | 3.5 |

* From Fig. T.3.5 ** From Equation 3

It is seen from the table that the simulated and experimental build up factors are in very good agreement. The difference in the average energy (representing the incident spectrum) explains the different shower maxima and build up factors observed during the measurement. Due to electron interaction within the accelerator structures (thickness of the absorber may vary depending upon the angle of incidence, position of the beam about the closed orbit, beam current etc.), the emerging spectra would be different and hence the depth at which dose maximum occurs will vary. Since the minimum vacuum envelope thickness the electron beam encounters is about a few millimeter, the average energy of the photons is about a few tens of MeV. For instance, from 3 mm Cu, the value is ~33 MeV, which gives a shower maximum beyond 30 cm in water. Therefore at $X_{max}$= 30 cm in water, the approximate size of a human body, a dose build up factor of 6.4 is obtained from equation 3. This build up factor can be used as a conservative high energy correction (multiplication) factor for the monitor reading in the high energy photon radiation field within the shielded enclosures of Indus-1.

A thought was given to surround the ion chamber detectors used within the shielded enclosures of the monitor by a proper build up material with thickness giving rise to the same build up factor. But it was felt that it could give rise to underestimation in a photon field where the spectrum is softer. Therefore it is safer to correct the instrument response manually with the suggested correction factor.

### 6. Effectiveness of the correction factor outside the shield

In order to see the applicability of the high energy response correction factor for the radiation monitors outside the shielded enclosures of Indus-1, the energy spectra in the direct and the transmitted photon field were measured using a 2" x 2" BGO (Bismuth Germanate) detector during the storage mode of Indus-1 operation. The direct spectrum was obtained from the storage ring through a hole (~100mm dia) in the shielding and for the transmitted spectrum, a lead block of 80 mm thick was used to block the hole in the shielding. The spectra obtained are presented in Fig.T.3.9 [15]

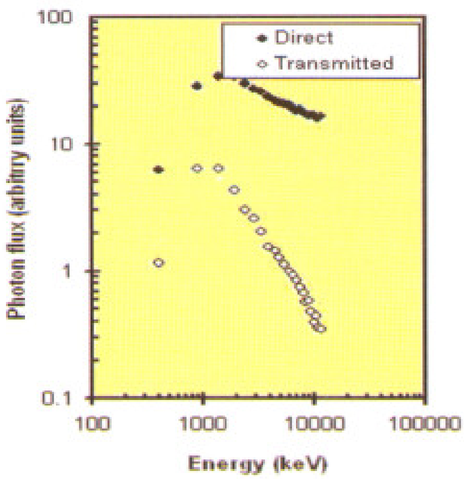


*Fig.T.3.9: Measured direct and transmitted bremsstrahlung spectra (through 80 mm Pb) from Indus-1 (BM-1side).*

The trend of the direct spectrum indicates that it is extending to very high energies. However, the average energy of the transmitted spectrum was estimated to be 3.3 MeV, which is less than 3.41 MeV, below which no build up takes place in water (from eq.3). Therefore, the correction factor suggested for the monitor response within the shielded enclosures does not apply behind the present hybrid shielding (80 mm lead + 80 mm mild steel) of the storage ring. Bremsstrahlung x-ray energy estimation outside the shield was also carried out using TLD badge, which gave an effective energy of 2.18 MeV [16]

### 7. Dose build up experiments outside shielding of Indus-1

A set of dose build up study was carried out outside the shielded enclosure of Indus-1 to ensure no dose build up in the transmitted photon field through shield as predicted by eq.3 and the spectrum measurements. For this study, integrating type of dosimeters were used with different build up media for sufficiently large time in order to obtain meaningful results. Table. T.3.2 summaries the results.

*Table.T.3.2: Mesured dose build up factors in the direct and transmitted bremsstrahlung photon field at Indus-1.*

| Field conditions | Dose rate without buildup | Dose rate with buildup / material | Buildup factor |
|---|---|---|---|
| Direct photons in the forward direction from storage ring (BM-1 side) | 1.0 mR/h | 3.0 mR/h / 5mm iron | 3.0 |
| | 1.0 mR/h | 2.0 mR/h / 100 mm water | 2.0 |
| Transmitted photons through 50 cm concrete in the forward direction. (BM-1 side) | 0.5 mR/h | 0.4 mR/h / 5 mm iron | 0.8 |
| | 255 mR* | 185 mR* / 100 mm water | 0.73 |
| | 380 mR* | 280 mR* / 100 mm water | 0.74 |

*Data from DRD (Integrating type)

It can be seen from the table that the dose build up factor is greater than 1 in the direct photon field, whereas it is less than 1 in the transmitted photon field, through 50 cm concrete. Compared with concrete, the present hybrid shielding comprising of mild steel and lead has higher atomic number and hence energy degradation will be more dominant. Therefore the build up factor would be much more less than what is observed for concrete.

### 8. Summary and conclusions

The experiments on radiation dose build up in and around Indus-1 storage ring was carried out with different radiation detectors and build up medium. The results show that radiation dose increases in the build up medium up to certain depth and declines thereafter in the radiation field around the storage ring within the shielded enclosure and in the streaming radiation field, in accessible areas. Specific studies with a 30 cm water phantom, simulating a human body in the high energy photon radiation field from Indus-1 suggests that conventional radiation monitors when used for radiation dose measurements in high energy bremsstrahlung radiation field, the dose received by the radiation worker is underestimated many fold than $H_p(10)$, the personnel dose equivalent measured by the conventional monitors. The build up of radiation dose was attributed to the generation of electro-magnetic shower within the build up medium, usually initiated when a high energy photon or electron far above the pair-production threshold is incident on the medium. Based on the dose build up experiments and Monte-Carlo calculations, a high energy correction factor of 6.4 was obtained for the radiation monitors within the shielded enclosures and in the streaming high energy field. This correction is only for application in personnel radiation protection as the factor is deduced based on dose measurements and simulations in water phantom. Applicability of the correction factor was checked outside the shielding by spectrum measurements and dose build up measurements. It is found that no correction needs to be applied for radiation monitors outside the shielded enclosure except at streaming bremsstrahlung photon field. It is concluded from the study that

1. Conventional radiation monitors and dosimeters underestimate dose in high energy photon radiation environment near high energy electron accelerators by many factors.
2. Proper correction needs to be applied to the monitor reading when measured within the shielded enclosure or in the streaming radiation field in order to estimate the dose equivalent correctly.
3. Since radiation dose build up takes place in a material medium when high energy photons are incident, shielding should be sufficiently greater than the shower maximum ($X_{max}$) in the shield material. Otherwise, high energy photons contribute to the radiation field significantly in accessible areas, which is not desirable.
4. Any non-uniformity or gaps in the shielding structure around the ring can result in streaming of high energy photons to accessible areas.
5. The present study suggests that the presence of high energy photons in accessible areas can be detected by observing radiation dose build up in radiation detectors with proper build up media thereby adequate control measures can be enforced.

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