Passive and real-time radiation monitoring at FEL facilities using Radiochromic Films, Bubble detectors and Thermoluminescent Dosimeters

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Abstract

Free Electron Laser, FLASH (Free Electron Laser in Hamburg) at DESY is driven by a 1.25 GeV superconducting electron linac. During its operation FLASH produces parasitic (pulsed) radiations made of gamma rays (bremsstrahlung) and photoneutrons, caused by the interaction of field emission- and dark-current induced electrons with the accelerator components. A myriad of microelectronics-based instrumentations, prone to detrimental radiation effects are located inside the tunnel, in close proximity of the beam line. During 2006-2009 at FLASH we have carried out extensive gamma and neutron dosimetry measurements at various critical locations in the 260 m long linac containment tunnel using TLD-600 and TLD-700 dosimeters and Gaf-EBT radiochromic films. We also developed a novel "quasi-real-time" detector for the assessment pulsed gamma (bremsstrahlung) rays for shielding efficacy studies. Our paper highlights several important radiation detection and dosimetry experiments including performance testing of a "shielded container" for the protection of radiation sensitive microelectronic instruments.

1. FLASH (Free Electron Laser in Hamburg)

1.1. Operation and construction principles

On 27 April 2006 FLASH started its routine operation. FLASH produces high brilliance vacuum-ultraviolet (λ = 10 nm) light, used in a myriad of basic and applied scientific research projects conducted by German and international scientific communities. FLASH is driven by a 1.25 GeV superconducting electron linac made of ultra pure Niobium cavities developed on state-of-the-art TESLA (Tera Electron volt Superconducting Linear Accelerator) technology [1]. The schematic diagram of the 260 m long FLASH facility showing important components is shown in Figure 1.

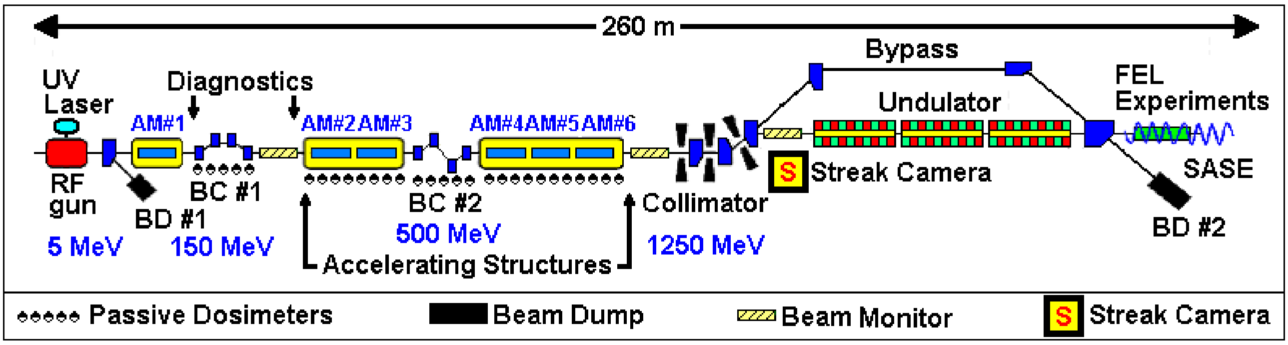

Fig.1 –Schematic diagram of the FLASH facility showing the location of Passive dosimeters,Beam dumps,Beam Loss Monitors and the shielded container housing Streak camera.

The RF gun of FLASH includes high quantum efficiency Cesium Telluride (Cs_2Te) photo-cathode excited by a pulsed (f = 1.3 GHz) UV laser (λ = 260 nm) beam, thereby emitting photoelectrons [2]. These photoelectrons are accelerated to 5 MeV by the 1½ cell cavity situated in the RF gun, injected to accelerator module 1 (AM #1) and accelerated to 150 MeV. This beam is further guided to 2nd (AM #2) and 3rd (AM #3) modules via 1st bunch compressor (BC #1) and accelerated to 500 MeV. The resulting beam is delivered to 4th (AM #4), 5th (AM #5) and 6th (AM #6) modules via 2nd bunch compressor (BC #2) reaching the final energy of 1250 MeV. The highest energy electron beam is guided to the 27 m long undulator array made of permanent magnets (NdFeB) via collimator, producing the self-amplified spontaneous emission (SASE) [3]. The SASE-free electron laser (FEL) beam is guided to the dedicated FEL experiment hall after undergoing the diagnostic procedure. The main accelerating (linac) structures are housed in an adequately shielded containment hall made of standard concrete (ρ = 2.38 gcm^{-3}) complying the radiological safety requirements. The rest of the facility is situated in a 5 m diameter underground concrete tunnel. Evidently, the beam dumps (BD #1 and BD #2) are strong sources of prompt gamma and neutron radiations, hence, are located underground. Important characteristics of FLASH are highlighted in Table 1.

Parameter	Value
Length (m)	260
End energy (GeV)	1.25
Number of modules	6
Number of cavities	48
Cavity type	TESLA
Cavity temperature (K)	2
Number of RF stations	4
Location of RF Stations	External
Gradient (MV/m)	16 - 21
QF (unloaded)	5.0E+09
Repitation rate (Hz)	5 - 10
RF pulse length (ms)	1.33
Beam pulse length (ms)	0.80
Wavelength (nm)	10
Peak power (kW)	208

Table 1 – Important physical characteristics of FLASH.

1.2. Radiation field characterisation

During the operation of high-energy electron linac driving FLASH there are two main types of radiation (parasitic) fields are of great concern: (a) Dark current (DC). The stary electrons in the RF gun are the source of DC. The intensity of DC is primarily depended on the surface characteristics of the photo-cathode [2]. During machine operation both primary beam and DC electrons are simultaneously accelerated. However, due to their random emission probabilities, a substantial number of transversally emitted DC electrons hit the beam line parts resulting in high parasitic radiation fields near AM #1 and BC #1. (b) Field emission (FE). When a high voltage gradient (> 10 MVm^{-1}) introduced across the superconducting niobium cavity, spurious electrons are emitted (FE), accelerated within the cavity, hit internal wall producing secondary radiation. The scenarios of radiation production pathways caused by field emission are shown in Figure 2.

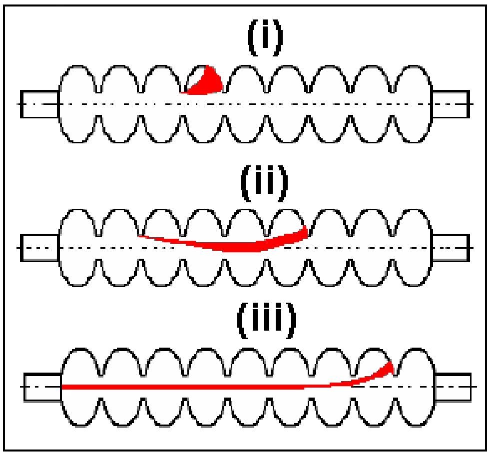

Fig.2 –Field Emission induced radiation production scenarios within niobium cavity.

Scenario (i): Production and subsequent acceleration of FE electrons within the same cavity cell. This results in production intense flux of low-energy bremsstrahlung (x-ray). Scenario (ii): Acceleration of FE electrons created in the neighboring cell of the same cavity and resulting in production of medium-energy bremsstrahlung. Scenario (iii): Acceleration of FE electrons originated from a distant cavity to high energy thereby production of high-energy bremsstrahlung as well as photoneutrons [4].

Evidently, the FE electrons are the primary source of unwanted (parasitic) ionizing radiation form accelerating cavities when placed under a high voltage gradient. The FE phenomenon is interpreted by Nordheim-Fowler equation [**5**] as given below:

$$J_{FN} = (C/\phi)(ßE)^2 exp(-B\phi^{3/2}/ßE) \qquad (1)$$

Where, J_{FN} [Acm^{-2}], ϕ [eV], ß and E [Vm^{-1}] stand for field emission current density, work faction of the surface material (Niobium) and voltage gradient respectively. Furthermore, B [Vm^{-1}] and C [AV^{-1}] are material specific constants.

2. Radiation Detection Devices

2.1. Passive radiation detectors

Three types of integrating type passive radiation detectors were used in our investigations. (a) Radiochromic film [6]: radiochromic films (RF) are made of a thin foil coated with radiosensitive material and sandwiched between two transparent polyester foils. Exposure to gamma rays causes coloration of the film. The optical density of the exposed film is proportional to gamma dose. (b) Superheated emulsion (bubble) dosimeter [7]: Microscopic droplets of selected organic material are suspended in polymer gel matrix and encapsulated in small polystyrene vials. The droplets explode to larger bubbles (visible by naked eye) when exposed to neutrons. Number of bubbles counted is proportional to neutron dose (kerma), the method is explained in details elsewhere [8]. (**c**) Thermoluminescent dosimeter (TLD): The TLD-700 (^{7}LiF:Ti,Mg) and TLD-600 (^{6}LiF:Ti,Mg) are widely used in high-energy accelerator dosimetry [9].The TL-glow curve deconvolution technique was used to estimate the neutron and gamma doses explicitly [10, 11].

2.2. Active (real-time) radiation detector

Using common radiochromic film (Model: EBT3, Manufacturer: International Specialty Product, NJ, USA) we have developed a gamma detector (GAMMA CUBE) as depicted in Figure 3 [12].

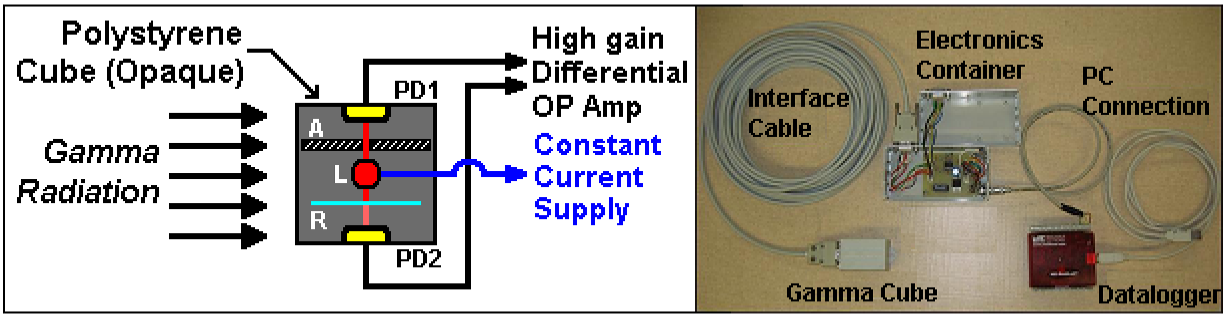

Fig.3 –Principle of real-time gamma monitor GAMMA CUBE (left) and photograph of the prototype (right).

An aluminum aperture (A) and a piece of radiochromic film (R) were mounted in a 2×2×2 cm^3 opaque polystyrene cube. Two PIN photodiodes ere mounted facing the aperture (PD1) and the radiochromic film (PD2) and a high power red LED (L) placed in between. The photodiodes were connected to a high gain differential operational amplifier and the LED was powered by a constant current supply. While exposed to gamma radiation, the radiochromic filmstrip turns darker causing a change of illumination levels detected by the photodiodes, resulting in an output voltage difference across the photodiode pairs, which is further enhanced by the high gain differential operational amplifier. The output is multiplied by the experimentally estimated "calibration factor" to give the time depended gamma dose.

3. Radiation Measurement Examples

3.1. Radiation Measurement at Accelerating Modules

WE have used thermoluminescence dosimeters and bubble detectors to estimate neutron and gamma doses near the selected accelerating module (AM #5) operating in field emission mode (RF gun switched off).

Five pairs of TLD-700 chip and temperature stabilized bubble detector (Model: BDPND, Manufacturer: Bubble Technology Industries, Calk River, Canada) were attached to the surface of the module container tank in order to detect the photoneutrons generated via the giant dipole resonant (GDR) reaction [9]. Each pair was aligned to the centre of the 1st (C1), 2nd (C2), 4th (C4), 6th (C6) and 8th (C8) cavity in the module. The module (AM #5) was exclusively powered on to voltage gradient levels of 17.5, 20, 25 and 29 MVm^{-1}, whereas, the rest of the modules was switched off. The duration of dosimeter exposure per run was 8 hours. Furthermore, for each run unexposed sets of dosimeter pairs were deployed. The bubble detectors [8] and TLD chips [9] were evaluated; the results are depicted in Figures 4 and 5.

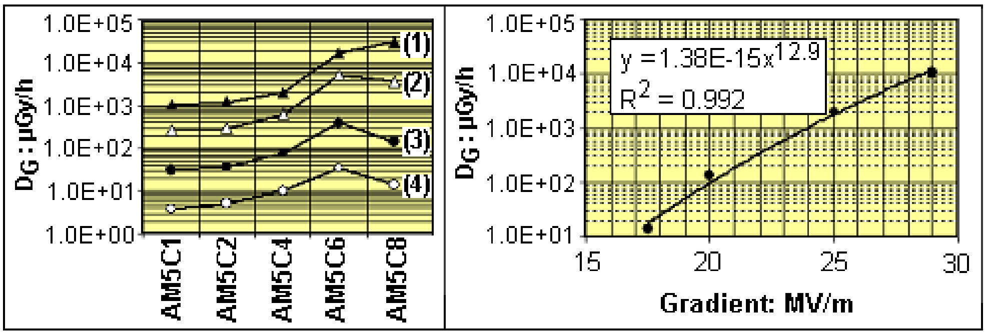

Fig.4 –Gamma dose rates near the cavities of AM #5 running at voltage gradient of 29 MV/m (1), 25 MV/m (2), 20 MV/m (3) and 17.5 MV/m evaluated using TLD-700 dosimeter chips (left). The average gammadose rate(all 8 cavities) plotted as a power function of gradient (right).

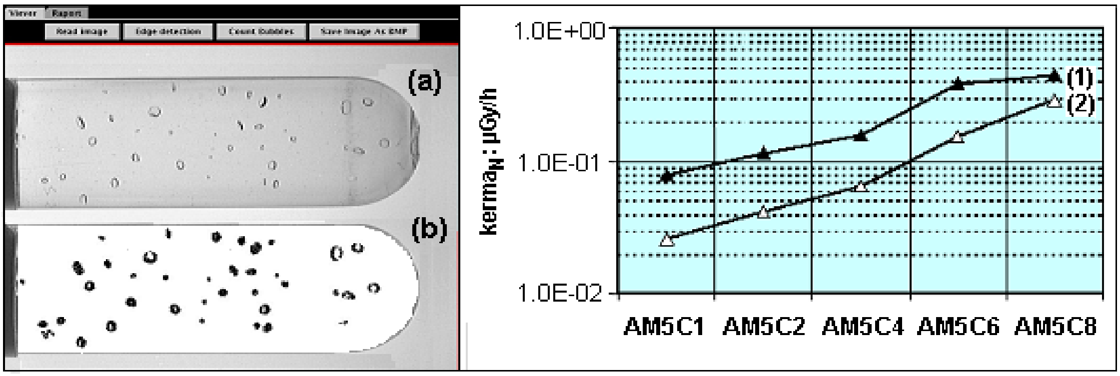

Fig.5 –The digital photograph of BDPND type bubble detector showing the bubbles formed after neutron exposure near AM #5 (a); the "edge corrected" image of the bubbles (b) for automatic bubble counting algorithm (ABCA) deveoped elsewhere [13] (left) Neutron kerma rates near the cavities of AM #5 running at voltage gradient of 29 MV/m (1) and 25 MV/m (2) evaluated from bubble counting data using ABCA(right).

3.2. Radiation Measurement-along FLASH Linac

Strips (2×2 cm^2) of radiochromic film (Model: EBT 2) were packed in small Mylar satchels, wrapped in aluminum (heat reflecting and light tight) tapes and attached to equatorial plane of the accelerator modules, including bunch compressors at every meter, along the entire accelerating structure (Figure 1). After a continuous (routine) FLASH operation of eight weeks the filmstrips were retrieved and the optical densities (OD) evaluated using a laboratory densitometer (Model: DensiX, Manufacturer: PTW, Freiburg, Germany). The integrated gamma doses were evaluated from OD of the films. The results are depicted in Figure 6.

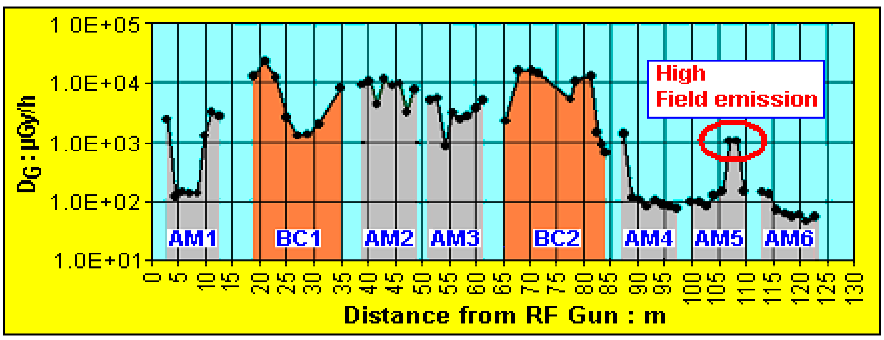

Fig.6 –Gamma doserates along the accelerating structure of FLASH evaluated using radiochromic films.Cavity (AM5-C7) producing high field emission causing enhanced gamma dose rate is identfied.

3.3. Radiation Measurement in real time using GAMMA CUBE

A Femtosecond Streak Camera (Model: C6138-FESCA-200, Manufacturer: Hamamatsu, Japan) was installed in FLASH tunnel for electron beam diagnostic purpose (Figure 1). The Streak Camera (S) is made of high-quality optoelectronic as well as microelectronic circuitry, highly susceptible to ionizing radiation. Therefore, the S-Camera was housed in a shielded-container to cut off the radiation exposure to a safe level, thereby lowering the probability of irreversible radiation damage of the device [14].

We have recorded the gamma dose level inside and outside of the container in real-time for a duration of 65 hours using the GAMMA CUBE detector. The device set up and results are depicted in Figure 7.

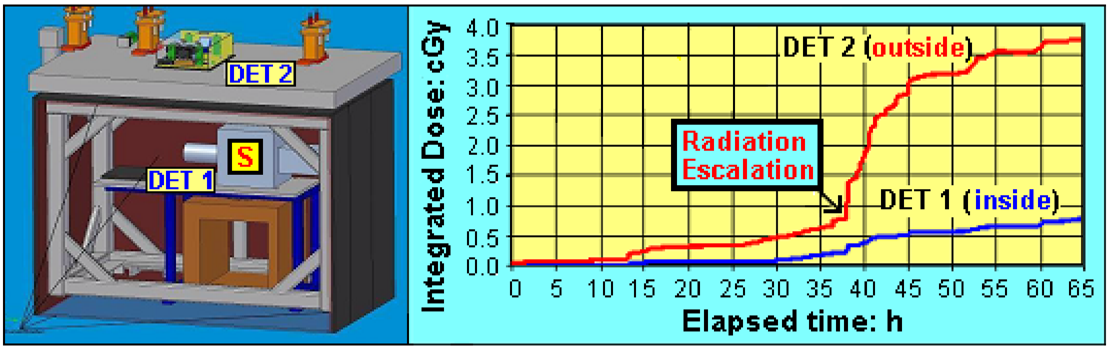

Fig.7 –Location of the Streak Camera (S) and GAMMA CUBE detctors inside (DET 1) and outside (DET 2) of the shielded container (left) and the plot of integrated gamma doses as functions of elapsed time (right).

4. Results and Discussion

In this paper the authors have highlighted the radiation environment of FLASH during routine operation. The energy loss of dark current from the RF gun and field emission from the superconducting cavities made of high purity Niobium found to be primary sources of parasitic radiation dose (Figure 2).

Thermoluminescence dosimeters and superheated emulsion (bubble) detectors were used to record gamma and neutron doses (kerma) respectively near the cavities operating at different voltage gradients. Gamma dose rises at escalating rate with increasing gradient (Figure 4). This vindicates the Nordheim-Fowler theory of field emission. On the other hand, the photoneutron dose rises at a much lower rate, starting from gradient of 25 MV/m (Figure 5).

A gamma dose rate mapping along the entire accelerating structure (Figure 1) of FLASH was carried out using strips of radiochromic film. The results reveal “high dose zones” near bunch compressors and cavities producing high field emission electrons. The intense stray radiation field in the vicinity of bunch compressors and accelerator modules (Figure 6) could be detrimental to electronic instrumentations located in FLASH tunnel.

A novel quasi real-time gamma dose monitoring device (GAMMA CUBE) has been developed using EBT2 type radiochromic film and patented under German Patent Number: 10 2007 056 989 (Figure 3). The GAMMA CUBE was used monitor the radiation exposure at the internal external wall surface a shielding container housing a Streak camera, made of sophisticated microelectronic components vulnerable to ionizing radiation (Figure 7). Furthermore, one can visualize the sudden radiation escalation form the real-time plot of the gamma dose. The gamma-shielding efficacy of the container wall was calculated as the ratio of the gamma dose rates and found to be 0.19 (Figure 7).

5. Summary and Conclusion

High-energy electron (lepton) linear accelerators driving free electron lasers like FLASH emit bremsstrahlung photons as well as GDR (Giant Dipole resonant) photoneutrons as parasitic radiation. These are caused by interaction of dark current and accelerated field emission electrons with accelerator components. Dosimetry experiments carried out at FLASH using radiochromic films, TLD chips and bubble detectors demonstrated that radiation dose from bremsstrahlung photons found to be more than four orders of magnitude higher than that from photoneutrons.

An accurate dose mapping procedure along the accelerator structure was carried out in order to identify high radiation producing zones as well as cavities producing strong field emission induced gamma rays.

This was performed in a very cost effective way by placing small radiochromic-filmstrips (total number of 120) on external wall module tanks and bunch compressor sections. The filmstrips were exposed during a routine FLASH operation period of eight weeks. The results were utilized to develop an effective radiological safety protocol for FLASH.

The radiation fields existing in electron linac environment are of pulsating nature. The conventional radiation monitoring instruments suffer from "pulse pile up" effect, hence, are unsuitable for detection of the above. We have circumvented this major shortcoming by implementing the quasi real-time gamma dosimeter GAMMA CUBE based on radiochromic films. Evidently, broad applications of GAMMA CUBE in the radiation detection and dosimetry purposes at medical linac facilities are envisaged.

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