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Interaction of the 5 MeV electron beam with the matter in the AREAL photoelectron gun facility experimental hall

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Abstract. The interaction of the AREAL photoelectron gun beam with the matter was simulated applying particle tracking software. The produced secondary particle fluxes produced at the certain places of interest within the AREAL facility experimental hall was calculated utilizing the data obtained by electron beam diagnostic system; particularly Faraday Cups (FC) and YAG screen stations. Absorbed dose rate has been measured by high precision ion chamber dosimeter capable to measure radiation produced by high frequency pulsed source. The comparison of the simulation and dose measurement results allows validation of the calculation methods and beam diagnostic data. Particularly ion chamber measurement of the dose creates opportunity to estimate the beam energy spread more accurately.

Keywords: Photoelectron gun beam, Faraday Cup, ion chamber dosimeter.

1. Introduction

The development of the modern large scale projects of X-ray Free Electron Lasers (FEL) like FLASH, European XFEL and LCLS that put stringent conditions on electron beam quality was probably the main reason bringing the laser driven photo-electronic RF guns into the focus of scientific research since they allow generation of short electron bunches with low emittances suitable for the injection into low emittance linear accelerators. [1-3]. The Photo Injector Test Facility (PITZ) at the DESY was created aiming at testing and optimization of the sources of high brightness electron beams for future free electron lasers and linear colliders [4]. REGAE the Relativistic Electron Gun for Atomic Exploration is a another small electron accelerator build and at DESY in order to provide high quality electron bunches for time resolved diffraction experiments and serves as test facility for accelerator research. The AREAL linear accelerator is designed to provide an ultra-short electron pulses with small emittance [5]. The photo-electronic RF gun of AREAL produces an electron beam with the energy of 2-5MeV and bunch charge of 10-250pC that is being used for the several material and life science irradiation experiments [6,7] along with accelerator and particles beam physics research. The secondary radiation has been generated when the electron beam interacts with the material on the beam trajectory (beam dump target, beam pipe walls, detectors and beam diagnostic equipment). In current study low energy electron beam interaction with matter has been investigated applying both numerical simulation and experimental measurements methods. For the determination of radiation field (radiation dose and its spatial and angular distribution in the AREAL machine hall and neighboring rooms) by computer simulation of the beam interaction with matter has been performed along with the direct measurement of the radiation dose rates. FLUKA Monte Carlo particle transport code has been used [8].

The radiation dose simulations using digital simulation computer codes are necessary for the design and development of the adequate radiation shielding and for the planning of the radiation protection measures in stages of the particle accelerator construction, operation and update. A general consensus exists, that Monte-Carlo codes, such as FLUKA, EGS4, GEANT, MCNPX and MARS provide accurate results for shielding design purposes, in particular for complicated three-dimensional geometries [9]. The choice of the FLUKA code is based on the consideration that an operational up to date version of the code is available and FLUKA gives an opportunity to track the particles to the low energies consuming reasonably affordable computational resources and time.

FLUKA has been in use widely for radiation protection related research and development in the CERN, SLAC, CEBAF and other accelerator centers [10-12].

In the result of the primary electron beam interaction with the matter the following sources of the secondary radiation: beam dump, FC, YAG screen targets, beam-pipe walls, vacuum windows and air have been considered during the computer modeling of the radiation field in the experimental hall of the low energy electron facility AREAL. Beam characteristics obtained by beam diagnostic measurement and hall equipment geometry have beam taken into account accurately in numerical simulations based on FLUKA particle tracking code. Dose measurements by high precision ion chamber dose meter have been carried out and satisfactory agreement between measurement results and the numerical simulation results has been found.

Since dose measurements prove the reliability of simulation results the radiation shielding contraction design and creation as well as the radiation safety procedures development have been realized in routinely manner based on numerical simulation data.

Both calculation data based on numerical simulation and dose measurement proved that radiation dose levels in the AREAL machine hall and experimental rooms were under the control and conform completely the radiation safety requirements for equipment and personal.

2. Numerical simulation study of radiation field at AREAL

The goal of this study is determination of the radiation dose at linear accelerator AREAL (≤5MeV) facility and the comparison of the numerical simulation results with those of experimental measurements. The detailed characteristics of geometry have been taken into account. The computer program based on the FLUKA particle tracking simulation code was created and used to simulate radiation dose of electron beam with 3.7MeV energy. The custom routines in FORTRAN language were programmed to define 3D magnetic field in FLUKA, output beam parameters and input parameters of the primary electron beam respectively. Obtaining simulation results in a format suitable to compare with data measured in the experiment via Faraday Cup (which measures beam charge), YAG screen (which measures beam profile) and dosimeter (ion chamber) is possible only using custom routines.

The beam electrons interact with materials located on the trajectory (beam dump target, vacuum chamber walls, detectors and diagnostic equipment), which leads to the generation of secondary radiation. Therefore, to determine the radiation dose field FLUKA particle transport code (based on Monte Carlo algorithm) has been used. Range of applications of FLUKA used in current study covers particle accelerator shielding, target design, dosimetry, detector design, etc. Since it is based on modern physical models, FLUKA can simulate the interaction and propagation in a matter of beam electron initiated electromagnetic shower comprising of photons and electrons down to 1 keV.

FLUKA can handle complex geometries and track correctly charged particles in the presence of magnetic or electric fields which is important in accelerator related tasks, particularly that feature was used in the current study to transport the beam through the focusing solenoid and bending dipole magnets field.

The SimpleGeo package is used to obtain a radiation profile on the electron beam line and 2D plot of dose distribution. The entire assembly model of the AREAL premises and facilities is shown in Fig. 1, as it was developed with the help of SimpleGeo 4.3 software tool integrated with FLUKA that allows creating geometric models for FLUKA in flexible and straightforward way.

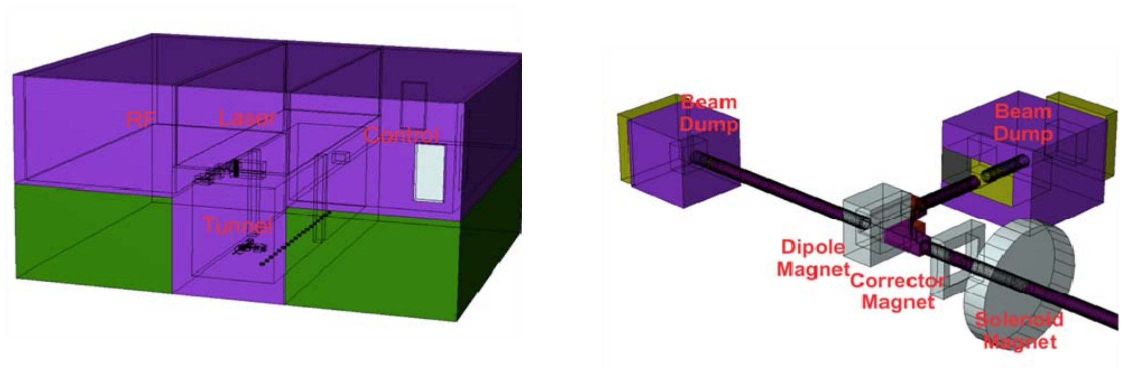

Fig. 1. The geometric model of the AREAL machine hall and neighboring rooms (left) and accelerator facility equipment (right) used in FLUKA simulations.

The simulated electron beam had a Gaussian profile with Full width at Half Maximum (FWHM) 2.3-3.2mm in the x and y direction, respectively and energy spread 1%. The numerical calculations are performed using the parameters of the electron beam given in Table 1.

Energy	3.7 MeV
Direct bunch charge FC1	250 pC
Bent bunch charge FC2	36 pC
Bunch length	0.4-9 ps
Norm. emittance	≤0.5 mm-mrad
RMS energy spread	≤1.5%
Repetition rate	12

Table 1: Beam parameters

In this work, experimental measured data of dose rate by ion chamber and diagnostic equipment FC and YAG screens are compared with those of FLUKA simulations. FLUKA does not have built-in scoring cards letting comparison of simulation with experiments. For that reason, custom routines were developed in order to modify FLUKA source code and obtain the data, which could be compared with experiments. Routines were used to simulate electron beam matching as close as possible to AREAL beam bunch and magnetic field of solenoid, corrector and dipole magnets. Also FLUKA output format has been changed to get the beam particles information such as coordinates, momentum and particle type at FC and YAG screen detectors region. In addition, several FLUKA routines (magfld.f, mgdraw.f, source.f) were modified to match AREAL setup geometry. For the accurate modeling of the AREAL linear accelerator beam interaction with the environment numerical simulation with FLUKA is performed applying the special settings by activating the following FLUKA command cards:

- DEFAULTS card - issued the PRECISIO scenario for the precision simulations;
- SOURCE card - to generate distribution for source particles (beam profile, directional and energy distribution). This command activates calls to the user routine source.f
- EMF-CUT card - to establish secondary electron and photon transport. The cut off energy of particle transport was set at 6 keV.
- USERDUMP card - the routine writes a complete information of dump (type of particles, trajectory, particles energy). This command activates calls to the user routine mgdraw.f
- MAGFLD card - to use a magnetic field map.

The simulated electron beam had a Gaussian profile with Full width at Half Maximum (FWHM) equal to 2.3-3.2 mm in the x and y direction respectively and the energy spread 1%.

3. Experimental Setup

An ionization chamber survey meter dosimeter is being used routinely for the experimental measurement of dose rate in the machine tunnel. The instrument consists of air-opened 600 cm^3 large volume ionization chamber and low noise ampere meter circuit that provide high precision and a wide range of measurements of the ambient dose equivalent H*(10), directional dose equivalent H(0.07Ω) and their rates. Since ionization chamber is integrating device it can cope with high frequency gamma and beta radiation pulses produced by RF gun beam. Technical specification of dosimeter is given in Table 2.

Dose rate range Dose range	*0μSv/h- 2000 mSv/h* *0-2000μSv*
Photon energy range Beta energy range	*6keV to 7.5MeV* *60keV to 2MeV*
Sensitive volume Lateral shielding Face entry window	*600* cm^3 disposable, *550* mg/cm^2 *3.3* mg/cm^2 (metal covered PETP foil)
Accuracy Linearity	*<15%* ±5%

Table 2: Technical specifications of survey meter

Dose rate in tunnel is obtained by measurement using STEP OD-01 survey meter dosimeter at several different locations. Fig. 2 shows schematic layout of tunnel of the AREAL and the locations where dose rate was measured. AREAL linac with beam diagnostic system consists of the laser driven RF gun, focusing solenoid, bending magnet, corrector magnet, Faraday Cups (FC) and YAG screen. One of FC is located at the end of the curved pipe after the vacuum window and second one (an insert able FC and YAG screen) are installed after the bending magnet in straight section.

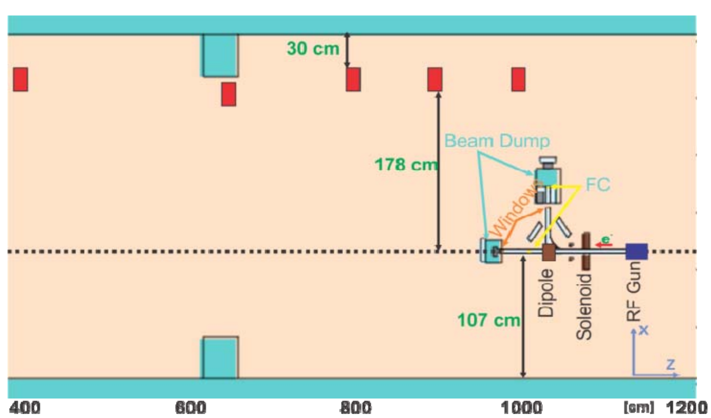

Fig. 2. Layout of the AREAL linear in the horizotal (X,Z) plane Z axis points to the electron beam propagation primary direction. The red triangles show the positions of the dosimeter.

The beam energy measurement has been conducted using 900 degree bending magnet, which is located after the focusing solenoid. The energy spread is calculated using a bunch horizontal size on the YAG screen. Table 1 gives the parameters of the electron beam obtained by beam diagnostic measurement when the dose rates in the tunnel have been measured.

It is found that the dose rate varies in the tunnel depending on whether the bending magnet is switch on or off. Therefore, two series of the dose rate measurement results have been obtained corresponding to two cases when the bending magnet is switched on and when it is switched off. In Fig. 3 shows the measurement results in both straight and bent beams cases. The position of the exit of RF gun coincides with Z = 0 coordinate. On each bar of the plot, the dosimeter position and dose rate values are indicated.

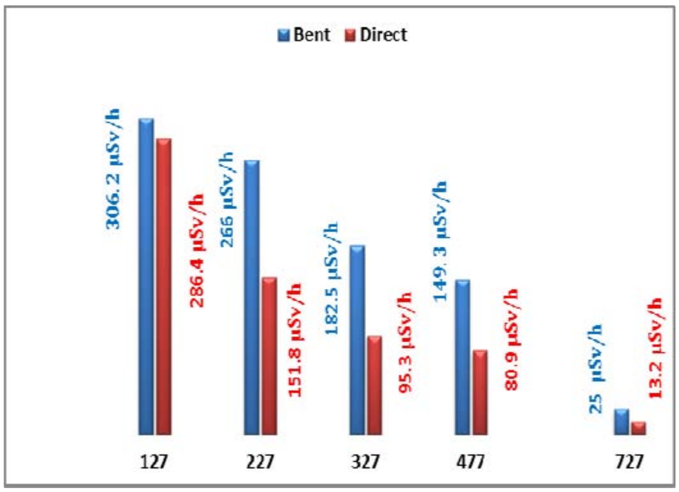

Fig. 3. Measured dose for the various positions of the dosimeter corresponding to the straight beam (blue) and bent beam (red).

4. FLUKA simulation results comparison with experiment

Fig. 4 shows the beam profile and the distribution of the energy distribution in three different positions.

Fig. 4a, 4c and 4e demonstrate electron beam transverse profile evolution along curved beam line. Fig. 4a shows the profile of the initial electron beam (x, y) at the end of the RF gun. Fig. 4c depicts the 90 degree bent beam profile after bending magnet. Its horizontal width increased due to dispersion. Fig. 4e demonstrates beam profile in the cross sectional plane of the FC located on the bent beam section at 20cm distance from vacuum window inside the dump. Because of interactions of the beam electrons in the 50 µm tick Titanium window 20 cm width air gap numerous halo electrons come to existence filling the beam pipe inner volume.

Fig. 4b, 4d and 4f demonstrate energy distribution of the electron beam at (mentioned above) three different positions. The histograms are normalized to maximum of the first histogram (referring the primary beam). The bent beam (Fig. 4d) contains only 74 % of the initial number of the particles. Comparing Fig. 4b with Fig. 4d one can conclude that 90 degree bending preserves the beam initial energy spread (FWHM is ~2.7%). It can be seen that only 21% of initial particles survive the interaction processes when the beam propagates through the Titanium window and 20 cm air layer.

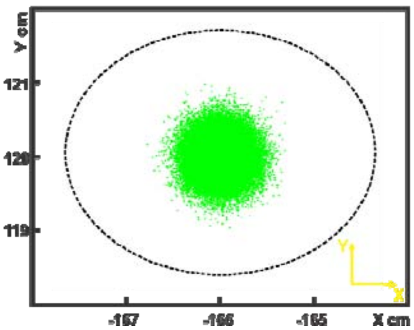

Fig. 4a. The profile of the initial electron beam (x,y) at the end of the RF gun.

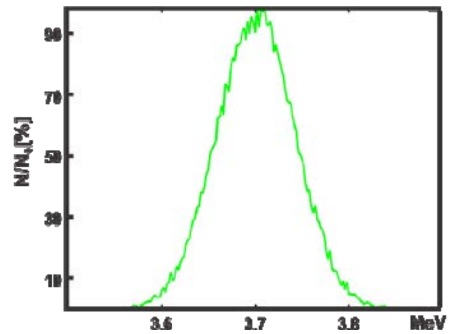

Fig. 4b. The energy distribution of the electron beam at the end of gun.

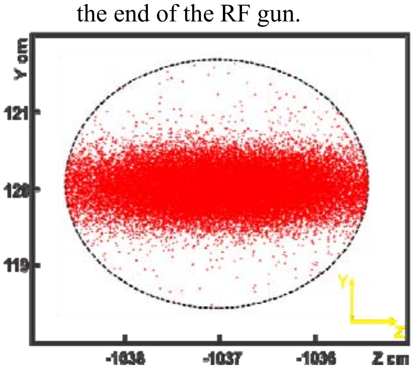

Fig. 4c. The beam profile in the plane of the YAG screen target located between bending magnet and the vacuum window.

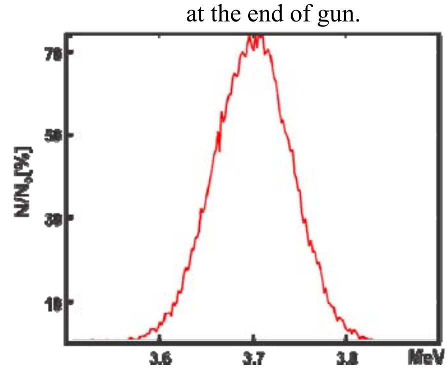

Fig. 4d. The energy distribution of the electron beam at the YAG screen target located between bending magnet and the vacuum window.

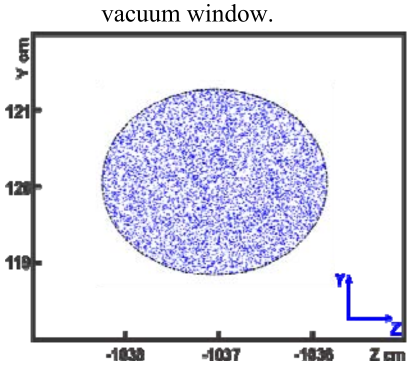

Fig. 4e. The beam profile in the cross sectional plane of the FC located on the bent beam section at 20cm distance from vacuum window inside the dump.

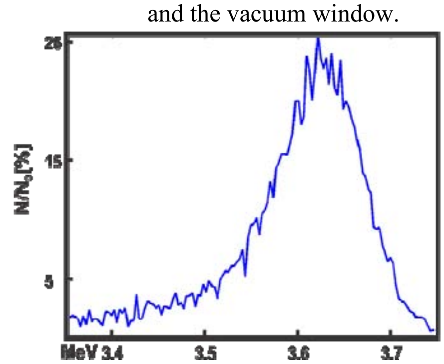

Fig. 4f. The energy distribution of the electron beam at the FC located on the bent beam section at 20cm distance from vacuum window inside the dump.

Fig. 5 and Fig. 6 illustrate that taking 1% RMS for beam energy spread in numerical simulations yields dose rates values closer to those of obtained by measurements. One of the reasons of some mismatch between measured and simulation results is the fact that it is virtually impossible to take into account precisely in digital models some elements of geometry such as PC or cables and other infrastructure equipment.

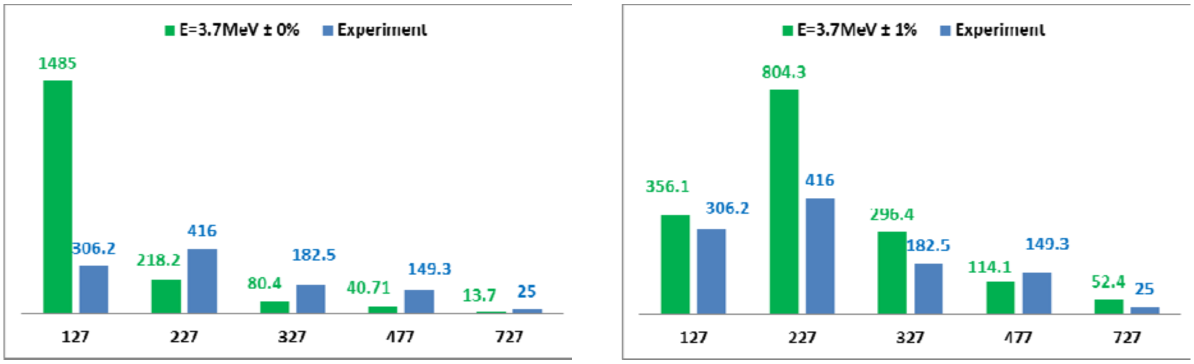

Fig. 5. Calculated and measured dose rates in μSv/hr for the some position of the dosimeter for bent beam, when primary energy spread was 0%(left) and when energy spread was 1% RMS (right). Horizontal axis shows distance from the gun exit in cm.

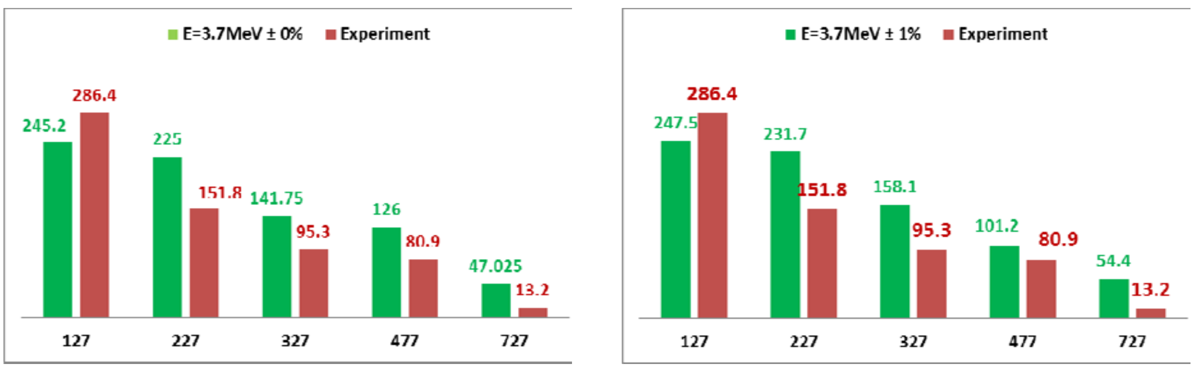

Fig. 6. Calculated and measured dose rates in μSv/hr for the some position of the dosimeter for straight beam, when primary energy spread was 0%(left) and when energy spread was 1% RMS (right). Horizontal axis shows distance from the gun exit in cm.

5. Conclusions

FLUKA simulations of the secondary radiation field at AREAL machine hall and experimental rooms were performed. Input parameters for the simulation beam derived from the beam diagnostic measurements (e.g. beam current is given by FC measurement). Radiation measurement was performed using ion chamber that can measure gamma, electron and positron fluxes produced by pulsed source. Dose rate measurement results have been compared with the values of numerical simulations and satisfactory agreement has been found thus validating the choice of simulation method. Dose measurement data was used to improve the accuracy of the beam diagnostic data. Particularly it was found that the beam initial energy spread was about 1.5%. Dose rates continuous measurement with ion chamber helps monitor and control the radiation level. Radiation Safety considerations imply monitoring and management of the radiation level within the machine hall and neighboring rooms. At the current stage of the AREAL development, the beam energy is in the range of 5 MeV, well below the threshold of the neutron, production channel via giant dipole mechanism. Therefore, eventually only gamma component of the penetrating radiation exist taking into account electrons and positrons short paths at those energies. Numerical simulation and dose measurement gave data allowing development of the necessary radiation shielding and protection walls and proved that radiation dose levels in the AREAL machine hall and experimental rooms conform the radiation safety requirements for equipment and personal.

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