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ABSORBED DOSE CHARACTERISTICS FOR IRRADIATION EXPERIMENTS AT AREAL 5 MeV ELECTRON LINAC

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Abstract

Existing electron photogun facility at the CANDLE SRI currently can provide electron beam with the energy up to 5 MeV. The beam is being used as an irradiation source in the number of material science and life science experiments. Performed beam particle tracking simulations along with intensive application of the beam diagnostic instruments (bending magnet, YAG stations, Faraday cups) allow control of the experimental samples' irradiation parameters, particularly exposure times for given dose as well as absorbed dose spatial distribution.

Direct application of the electron beam for the irradiation experiments allows achievement of high absorbed dose. For the calculation of the irradiation parameters of the experimental sample particle transport simulation results should be combined with the beam current measurements by Faraday Cup (FC). Dose measurements and the comparison with digital simulations using various initial parameters (Transverse size, divergence and energy spread) permit to pin down their actual values.

INTRODUCTION

Numerous experiments on material science and radiation biology have been carried out at the AREAL linear accelerator aiming at investigation of the effect of the irradiation by the 5 MeV electron beam on the material or on organic sample [1]. The experimental programs scope includes though not limited to the issues a) The production of point defects (NV centres) in diamonds for hypersensitive magnetometry; b) The study of ultrafast electron beam induced non-equilibrium processes in semiconductors; c) Dose-rate effects of ultrashort pulsed electron beam irradiation on DNA damage/repair in human cancer cells [2-5]. The paper is focused on the methods of the calculation of experimental sample irradiation parameters based on beam parameters measurement and numerical simulation study of the electron beam interaction with the medium.

ELECTRON BEAM PARAMETERS AND ABSORBED DOSE

AREAL electron linac can produce clean and controllable 2-5 MeV electron beam with 30- 250 pC pulse charge and 1- 20 Hz repetition rate [6]. The main parameters of the electron beam are can be monitored and manipulated to apply precise irradiation dose for the experimental sample. AREAL uses photogun driven by 0.45 ps laser pulses thus conditioning short bunch duration taking into account that RF wavelength is 0.1 m. Main parameters of the AREAL electron beam are presented in Table 1.

Table 1: AREAL Beam Parameters

Energy	2–5 MeV
Pulse charge	30–250 pC
Pulse length	0.45 ps
Norm. emittance	≤ 0.5 mm-mrad
RMS energy spread	≤1.5 %
Pulse repetition rate	1-20 Hz
RF frequency	3 GHz

Following the recommendations of the International Commission on Radiation Units and Measurements (ICRU) one can find out absorbed dose from electrons by the formula $D = \varphi\left({}^{S}/_{\rho}\right)_{col}$, where φ is electrons fluence (in 1/cm^2 units) and $\left({}^{S}/_{\rho}\right)_{col}$ (in MeV cm^2/g units) is the mass collision stopping power, resulting from electron interactions with the orbital electrons in atoms [7,8]. The resulting formula for the absorbed dose rate will be: $\dot{D}\left[\frac{Gy}{s}\right] = \frac{Q[pC]\cdot n[Hz]}{e[C]\cdot A[\mathrm{cm}^2]} \times \left(\frac{S}{\rho}\right)_{col}\left[\frac{MeV\cdot cm^2}{g}\right] \times 10^{-3}$.

Here $Q[pC]$ is the pulse charge in picocoulombs, $n[Hz]$ is repetition rate $e[C]$ is electron charge and $A[\mathrm{cm}^2]$ is beam spot size area at the sample surface. Since particles distributions are nearly Gaussian both in transverse vertical and horizontal directions A can be calculated as the area limited by ellipse $A = \frac{\pi}{4}XY$, where X *and* Y are beam spot sizes (FWHM) in horizontal and vertical directions.

BEAM PARAMETERS MEASUREMENTS

Advanced Research Electron Accelerator Laboratory (AREAL) based on photo cathode RF gun has been constructed at CANDLE.

The AREAL RF photogun experimental operation provides the electron bunches with up to 4.8 MeV energy and 5 nC mean current. The gun section contains the focusing solenoid, magnetic spectrometer, horizontal/vertical corrector magnet, Faraday Cups (FC) and YAG screens with cameras. The charge of individual bunches was measured using two FCs.

The beam energy and the energy spread measurements have been performed using the magnetic spectrometer

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located downstream the gun focusing solenoid. The spectrometer consists of 90° bending dipole magnet and the YAG screen station. The beam absolute energy is determined by measuring the beam position on the YAG screen with respect to the central trajectory position, which was calibrated with particle tracking simulations using the measured dipole magnetic field distribution. The energy spread is evaluated using the beam horizontal profile on the YAG screen. The horizontal width of the distribution is determined by the width of the energy distribution.

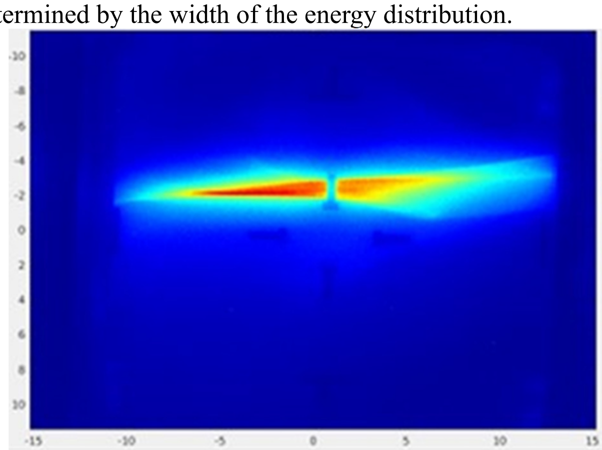
Figure 1: YAG screen image of the beam.

Dedicated software has been created at CANDLE that allows digital processing of the YAG screen image of the AREAL beam and to derive digital values of the beam particles transverse distributions parameters. Figure 1 presents the 250 pC charge beam profile at the YAG screen in the bended beam (dipole magnet is switched on) section. The corresponding beam energy is about 4.2 MeV and the energy spread is below 1.5%. Beam transverse profile measurements results have been used to calculate absorbed dose spatial distribution. The particles energy spread is dominated by an uncorrelated contribution, which is decreasing with acceleration being inversely proportional to beam energy. Compact sized experimental samples have been irradiated by 2 - 4.8 MeV electron beam at the AREALThe samples were exposed to the beam at a distance 3 cm from the exit port. At those positions typical beam spot sizes were 15 mm in diameter for strait beam and 15 mm × 35 mm for bended one. For radiation biology experiments the objects of the larger size have been used by positioning them in 40 cm distance from the beam exit window.

Beam profiles have been visualized and quantities of particles distributions were being estimated using YAG screen stations both in strait and bended beam sections.

For the beam charge measurement beam has been focused on the FC entrance window by manipulating the solenoid magnets current. Thus routinely 250 pC charge was being measured for the strait beam (see Fig. 2) and at least 30 pC value has been obtained for the bended beam.

While pulse charge is being measured by FC permanently, finding out the beam spot sizes at experimental sample position is not trivial problem. For the later purpose thin glass plates are being irradiated by electron beam at the experimental sample frontal position for 30 minutes. Obtained image is gradually faded within a few days, however allows estimation of the beam spot sizes (Fig. 3). The image is permanent one if quartz is used instead of ordinary glass.

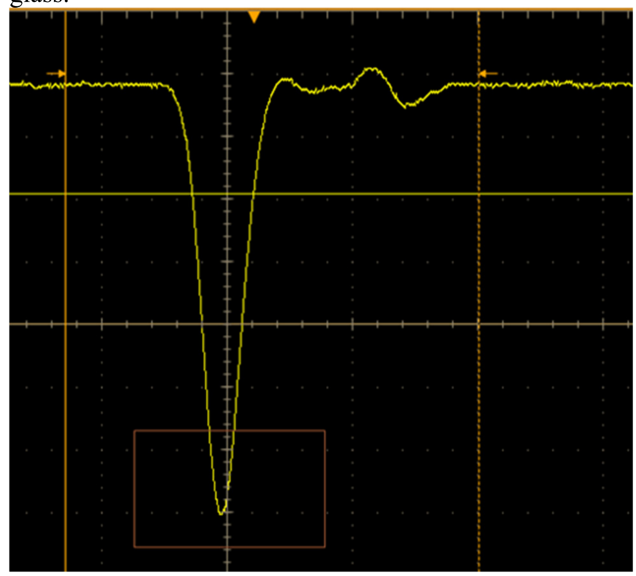
Figure 2: Inversed signal from the FC that corresponds to 280 pC electron beam pulse charge.

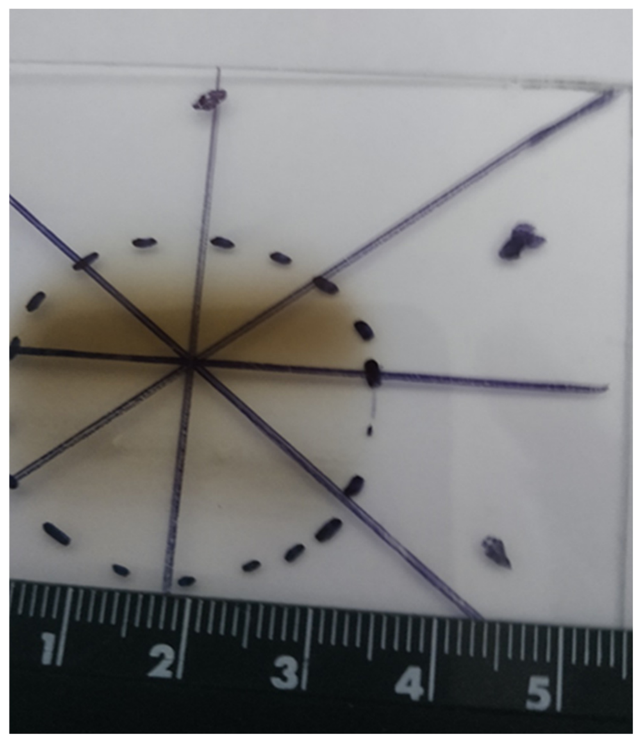

Figure 3: Electron beam image on the glass plate (bent beam) at the sample location.

NUMERICAL SIMULATION WITH FLUKA

Measured beam parameters along with experimental sample geometry, position and material composition data enables one to estimate absorbed dose. More accurate definition of the absorbed dose and its distribution in the

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volume of the irradiated material can be obtained with numerical modelling.

Absorbed dose in the sample by the electron has been calculated using the particle transport simulation modelling code FLUKA [9]. Digital simulations to take into account accurately the beam scattering within the vacuum window material (Titanium) and in the air. The results of beam parameters measurements used for simulations include:

- Beam current measurements by Faraday cup;
- Beam transverse profile imaging by YAG screen and camera station;
- Focusing solenoid magnet current adjustment and definition of the beam minimal spot sizes;
- Beam energy and energy spread measurement by spectrometer consisting of dipole magnet and YAG screen system.

The processing of the YAG screen image reveals that the beam has Gaussian distribution of electrons along horizontal and vertical directions, i.e., perpendicular to the beam direction. Default function of FLUKA does not let one to simulate the beam with required parameters. Default function is designed to calculate physical quantity per electron that gives only integral values of absorbed dose. Therefore, a custom user routine was programed in FORTRAN language. The program is able to generate beam with the parameters and distributions that actually available at AREAL linear accelerator. Digital simulations extended to take into account accurately the beam scattering within the vacuum window material (Titanium) and within the air.

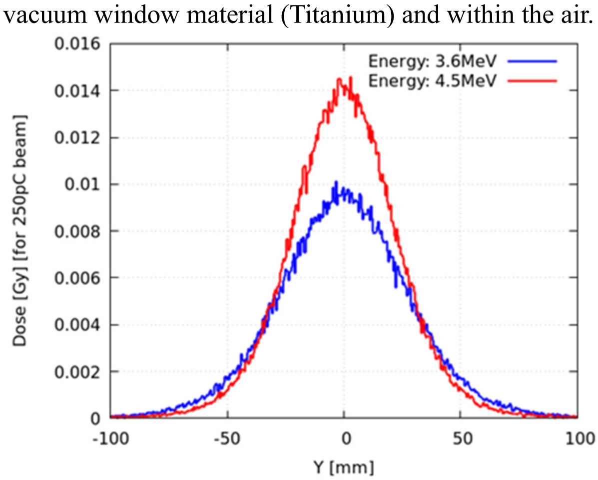

Figure 4: Dose distribution along vertical axis. Distributions are normalized per 250 pC.

Figures 4 and 5 show the results of the FLUKA simulations of the beam interaction with the biological sample model (water filled cylinder with 5 cm diameter and 20 cm height) positioned at 40 cm distance from the vacuum window vertical to beam propagation direction. Note, that the origin of the coordinate system coincides with the geometrical centrum of the cylinder. Dose distributions become narrower and shift deeper within the volume of the experimental sample with the increase of the impact beam energy. Note, that in Continuous Slowdown Approximation (CSDA) model electron range in the water is 2.0 cm for 3.6 MeV energy and 2.5 cm for 4.5 MeV energy [7].

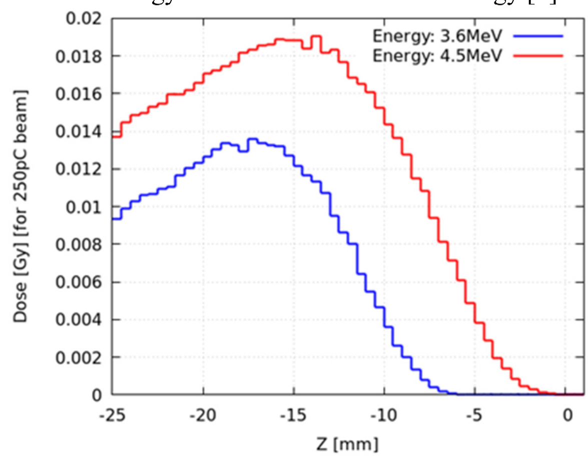

Figure 5: Dose distribution along Z axis, pointing to beam propagation direction. Distributions are normalized per 250 pC.

CONCLUSION

FLUKA simulations have been performed aimed at calculation of the required exposure time to provide necessary irradiation dose for the given beam parameters (energy, current, spatial sizes and divergence).

Input parameters for FLUKA simulations of the electron beam interaction with experimental sample have been defined relying on two sets of the data. Beam parameters measurements results have been combined with the sample geometrical and composition parameters allowing calculation of the absorbed dose within the experimental sample volume. However, digital modelling by Monte Carlo particle transport code proved to be more instrumental method for precise definition of the absorbed dose and its distribution within the experimental sample volume.

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