ON THE LOW ENERGY ELECTRON BEAM APPLICATIONS IN BIOPHYSICS AND MATERIALS SCIENCES AT CANDLE

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AREAL electron linac at the CANDLE SRI provides electron beam with the energy 2 - 5 MeV. The beam is being used as an irradiation source in the number of material science and life science experiments.

Direct application of the electron beam for the irradiation experiments allows achievement of high absorbed doses. For the accurate definition of the absorbed dose parameters Monte Carlo modelling of the particle transport has been performed. Simulation results should be combined with the beam parameters measurements.

The report 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.

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. [V. M. Tsakanov, et al., NIM A, v.829, pp. 248-253, 2016.

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AREAL ELECTRON 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
Laser wavelength	258 nm
Laser beam diameter	2.0 mm

Absorbed Dose Rate from Charged Particle Beam

The absorbed dose is defined as the mean energy imparted by ionizing radiation to matter of mass *m* in a elementary volume *V* by:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

$$\dot{D} = \frac{\dot{\varphi} A(-dE/dx)\Delta x}{\rho A \Delta x} = \dot{\varphi}\left(-\frac{dE}{\rho\, dx}\right)$$

$\dot{D}$ = dose rate

$\dot{\varphi}$ = fluence rate ($cm^{-2}\, s^{-1}$)

ρ= density

A = area

Mass stopping power

$$(S/\rho)_{tot} = \frac{1}{\rho}\frac{dE_K}{dx} \quad (\mathrm{MeV \cdot cm^2/g})$$

$$(S/\rho)_{tot} = (S/\rho)_{col} + (S/\rho)_{rad}$$

$$D = \phi (S/\rho)_{col}$$

1. INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Stopping Powers for Electrons and Positrons, Rep. 37, ICRU, Bethesda, MD (1984).
2. Fundamental Quantities and Units for Ionizing Radiation, Rep. 60, ICRU, Bethesda, MD (1998).

STOPPING POWER

The Bethe theory is used to calculate stopping powers for electrons and positrons. The complete mass collisional stopping power for electrons and positrons, according to ICRU Report No. 37, is

$$\frac{S_{\mathrm{col}}}{\rho} = \frac{N_A Z}{A} \frac{\pi r_0^2 2 m_e c^2}{\beta^2} [\ln(E_K/I)^2 + \ln(1+\tau/2) + F^{\pm}(\tau) - \delta]$$

for electrons $$F^{-}(\tau) = (1-\beta^2)[1 + \tau^2/8 - (2\tau+1)\ln 2]$$

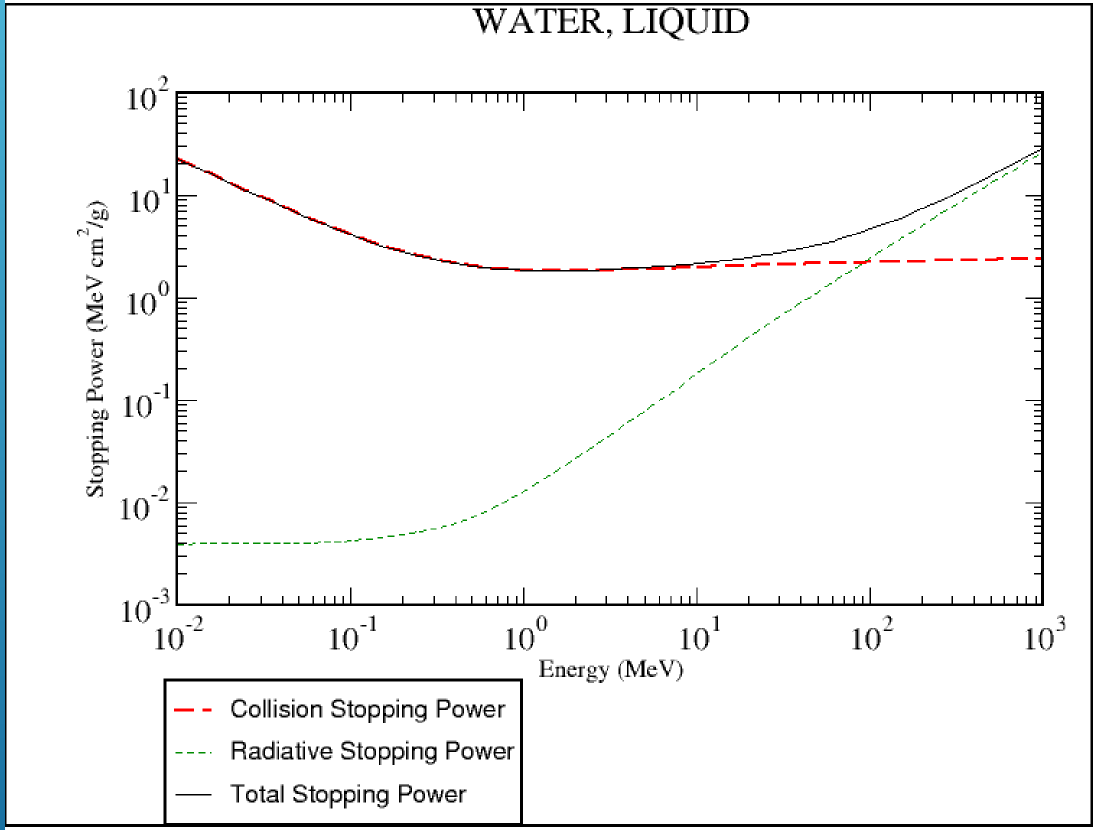
for positrons $$F^{+}(\tau) = 2\ln 2 - (\beta^2/12)[23 + 14/(\tau+2) + 10/(\tau+2)^2 + 4/(\tau+2)^3]$$

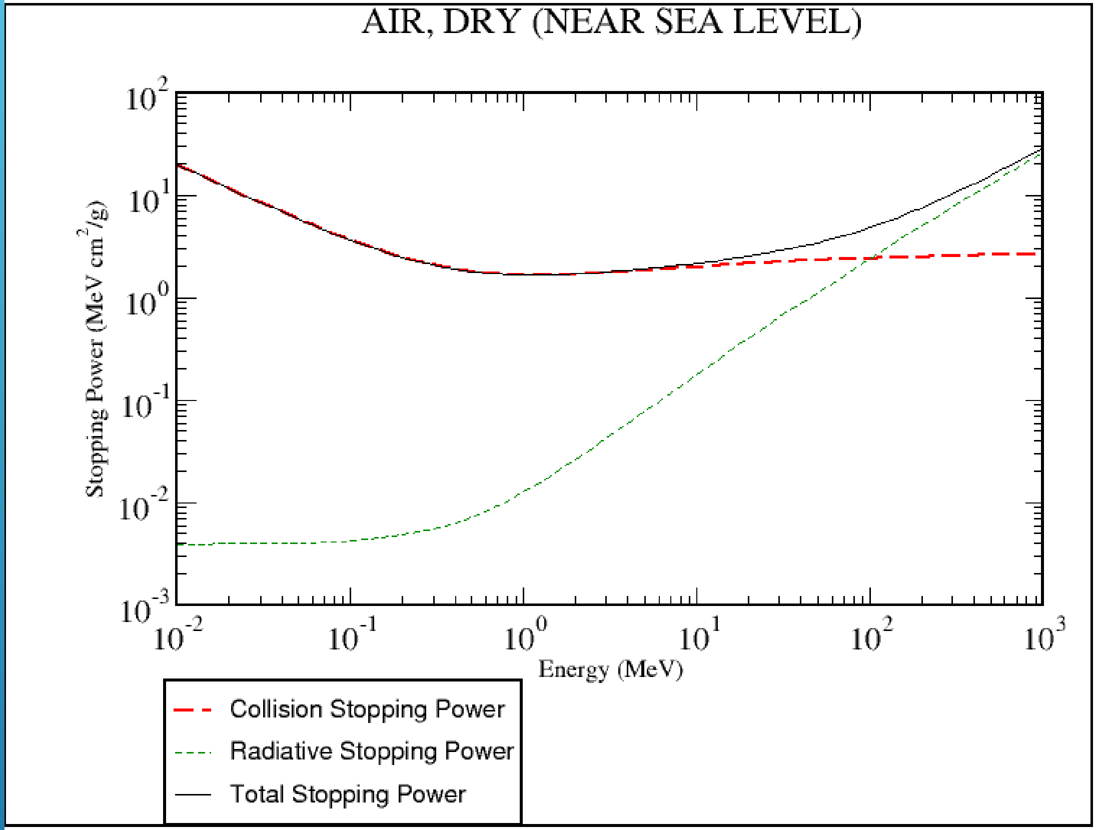
$$\tau = E_K/m_e c^2 \text{ and } \beta = \upsilon/c.$$

The Bethe–Heitler theory leads to the following formula for the mass radiative stopping power:

$$\frac{S_{\mathrm{rad}}}{\rho} = \sigma_0 \frac{N_A Z^2}{A} (E_K + m_e c^2) \bar{B}_r$$

STOPPING POWER





NIST Standard Reference Database 124

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ESTAR: Stopping Powers and Range Tables for Electrons
WATER, LIQUID

Kinetic Energy MeV	Collision Stp. Pow. MeV cm2/g	Radiative Stp. Pow. MeV c m2/g	CSDA Range g/cm2
1.000E-02	2.256E+01	3.898E-03	2.515E-04
1.500E+00	1.822E+00	1.942E-02	7.075E-01
1.750E+00	1.821E+00	2.303E-02	8.432E-01
2.000E+00	1.824E+00	2.678E-02	9.785E-01
2.500E+00	1.834E+00	3.468E-02	1.247E+00
3.000E+00	1.846E+00	4.299E-02	1.514E+00
3.500E+00	1.858E+00	5.164E-02	1.777E+00
4.000E+00	1.870E+00	6.058E-02	2.037E+00
4.500E+00	1.882E+00	6.976E-02	2.295E+00
9.000E+00	1.956E+00	1.601E-01	4.506E+00

Kinetic Energy (MeV)	Collision Stopping Power (MeV cm^2/g)

Water

3.100E+00	1.848E+00
3.500E+00	1.858E+00

Photographic emulsion

3.100E+00	1.334E+00
3.500E+00	1.347E+00

Air, dry (near sea level)

3.100E+00	1.745E+00
3.500E+00	1.766E+00

Polypropylene

3.100E+00	1.923E+00
3.500E+00	1.933E+00

Absorbed dose rate

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 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.

Absorbed dose rates achieved with the 3.6 MeV beam:

$\dot{D}\left[\frac{Gy}{s}\right] = 34.1$(strait beam) and $\dot{D}\left[\frac{Gy}{s}\right] = 1.74$ (bent beam);

Peak dose rates with 0.45 ps pulse duration:

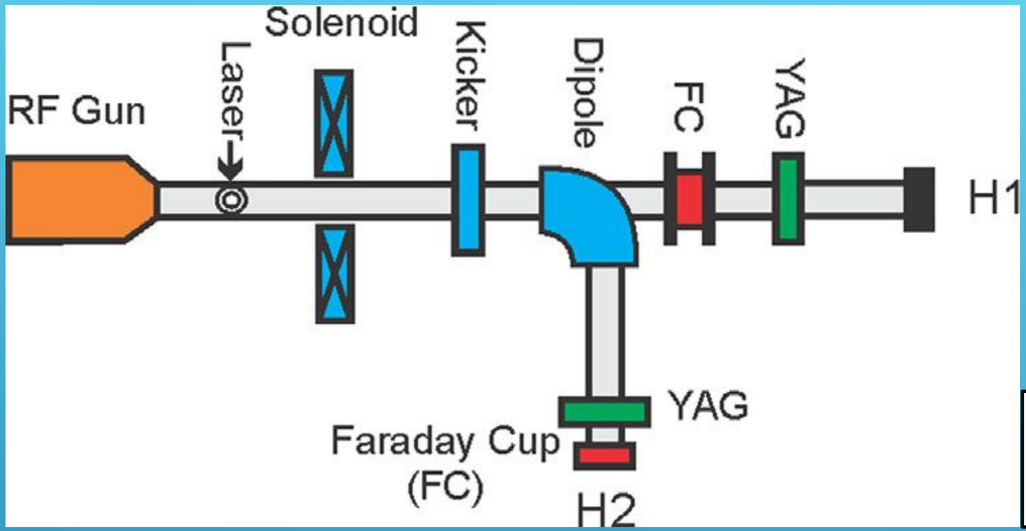
$\dot{D}\left[\frac{Gy}{s}\right] = 3.8\times 10^{12}$(strait beam) and $\dot{D}\left[\frac{Gy}{s}\right] = 0.19\times 10^{12}$ (bent beam);

Dose per pulse:

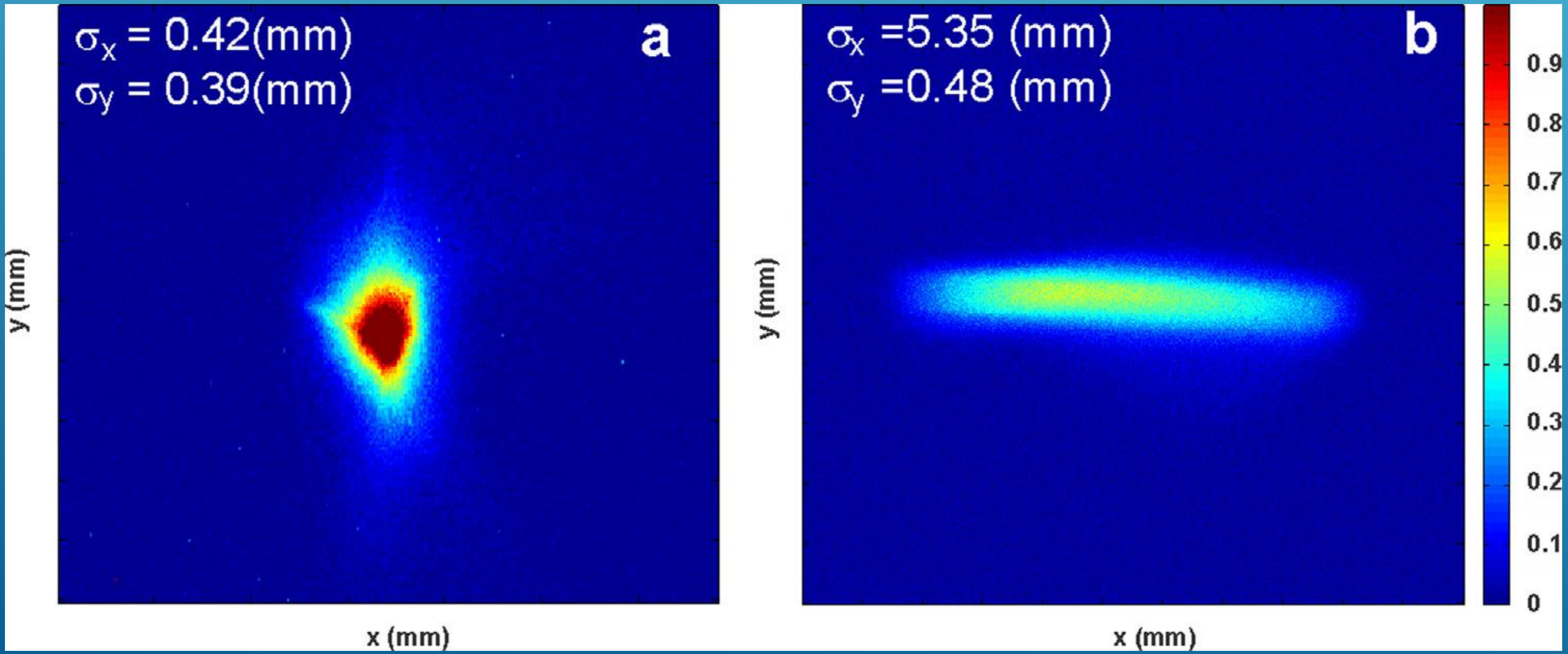
$\mathrm{D}[Gy] = 1.7$(strait beam) and $\mathrm{D}[Gy] = 0.087$ (bent beam);

BEAM PARAMETERS MEASUREMENTS

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.

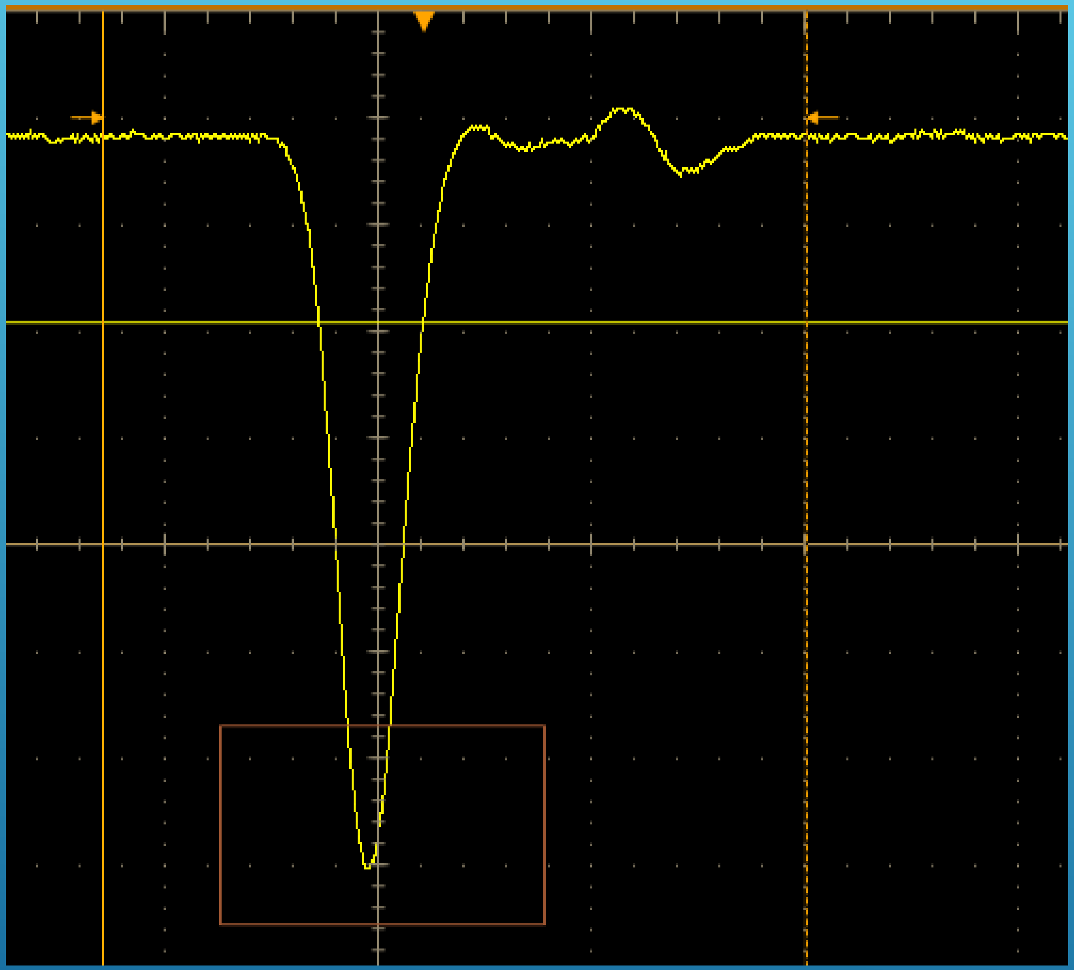


AREAL RF photogun linac layout with experimental stations H1 and H2.



Electron beam transverse profiles for the strait(a) and bent (b) beams.

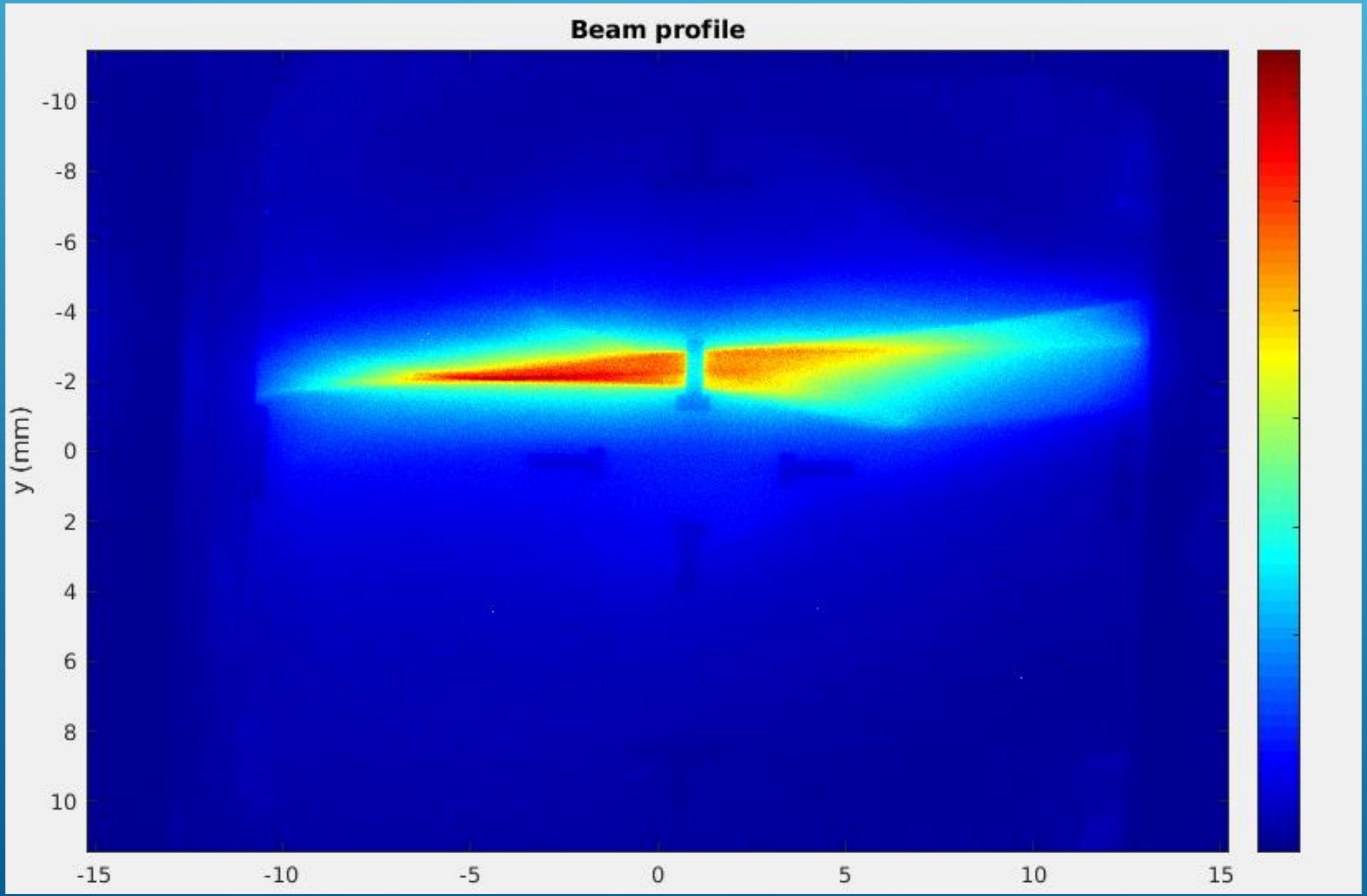
Pulse charge measurement



Signal from FC that corresponds to 280 pC pulse charge.

For the beam charge measurement it has been focused on the Faraday Cup (FC) entrance window by manipulating the solenoid magnets current. Thus routinely 250 pC charge was being measured for the strait beam and at least 30 pC value has been obtained for the bended beam. Those charges correspond to number of electrons 1.6×10^9 and 1.9×10^8 (Pulse length is 450 fs).

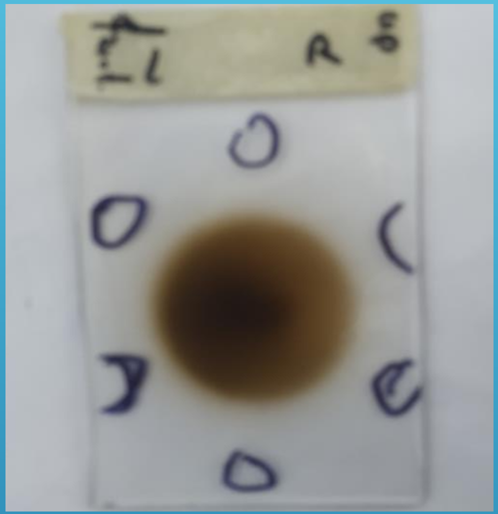
The spectrometer consists of 90° bending dipole magnet and the YAG screen station. The beam absolute energy is determined by measuring the beam position on the YAG screen with respect to the central trajectory position, which was calibrated with particle tracking simulations using the measured dipole 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.

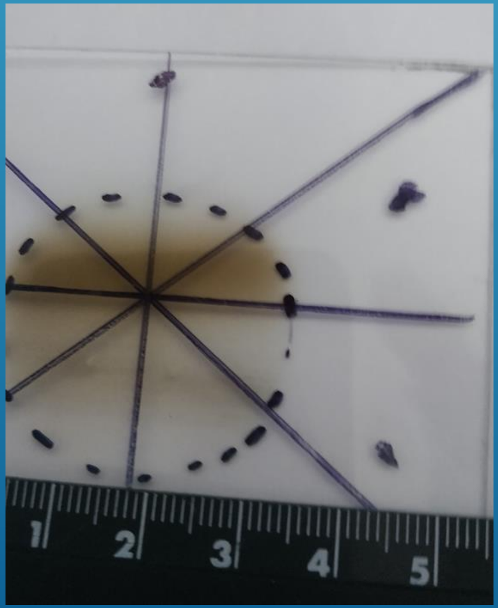


Beam profile at the YAG screen in the bended beam (dipole magnet is switched on) section. The corresponding beam energy is about 4.2 MeV, energy spread is below 1.5%.

Electron beam image on glass plate at sample location

Obtained image is gradually faded within a few days, however allows estimation of the beam spot sizes . The image is permanent one if quartz is used instead of ordinary glass.





The 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.

NUMERICAL SIMULATION WITH FLUKA

More accurate definition of the absorbed dose and its distribution in the volume of the irradiated material can be obtained with numerical modelling.

Absorbed dose in the sample through the electron has been calculated using the particle transport modelling code FLUKA

. 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.

NUMERICAL SIMULATION WITH FLUKA

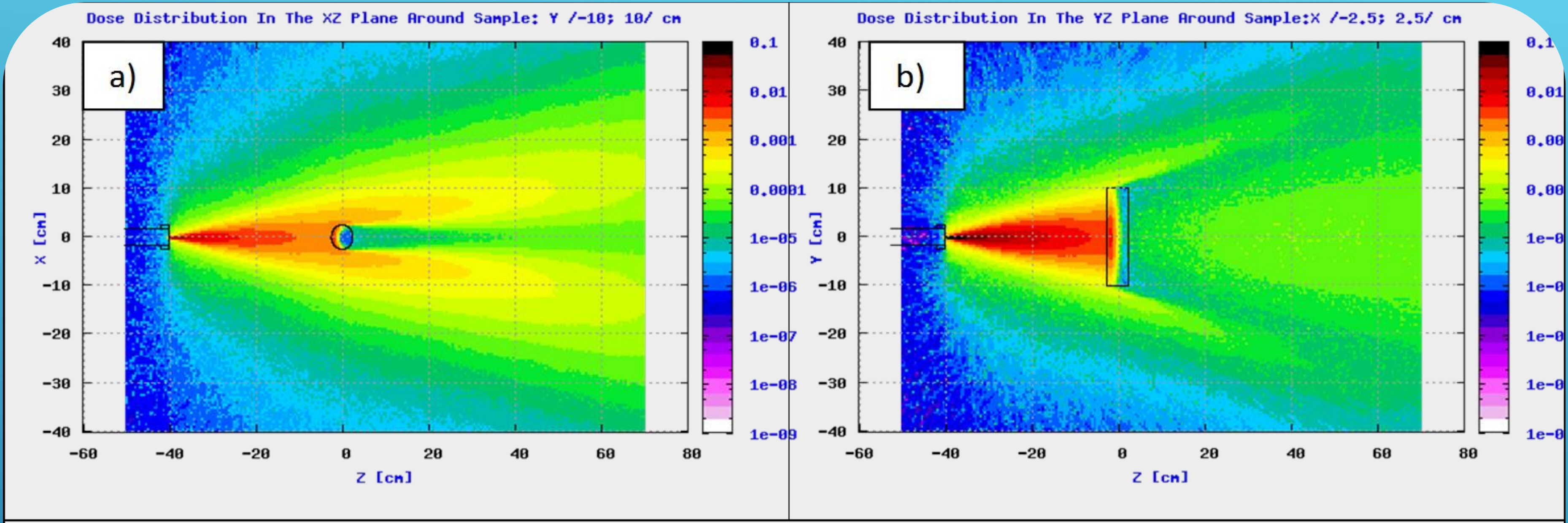
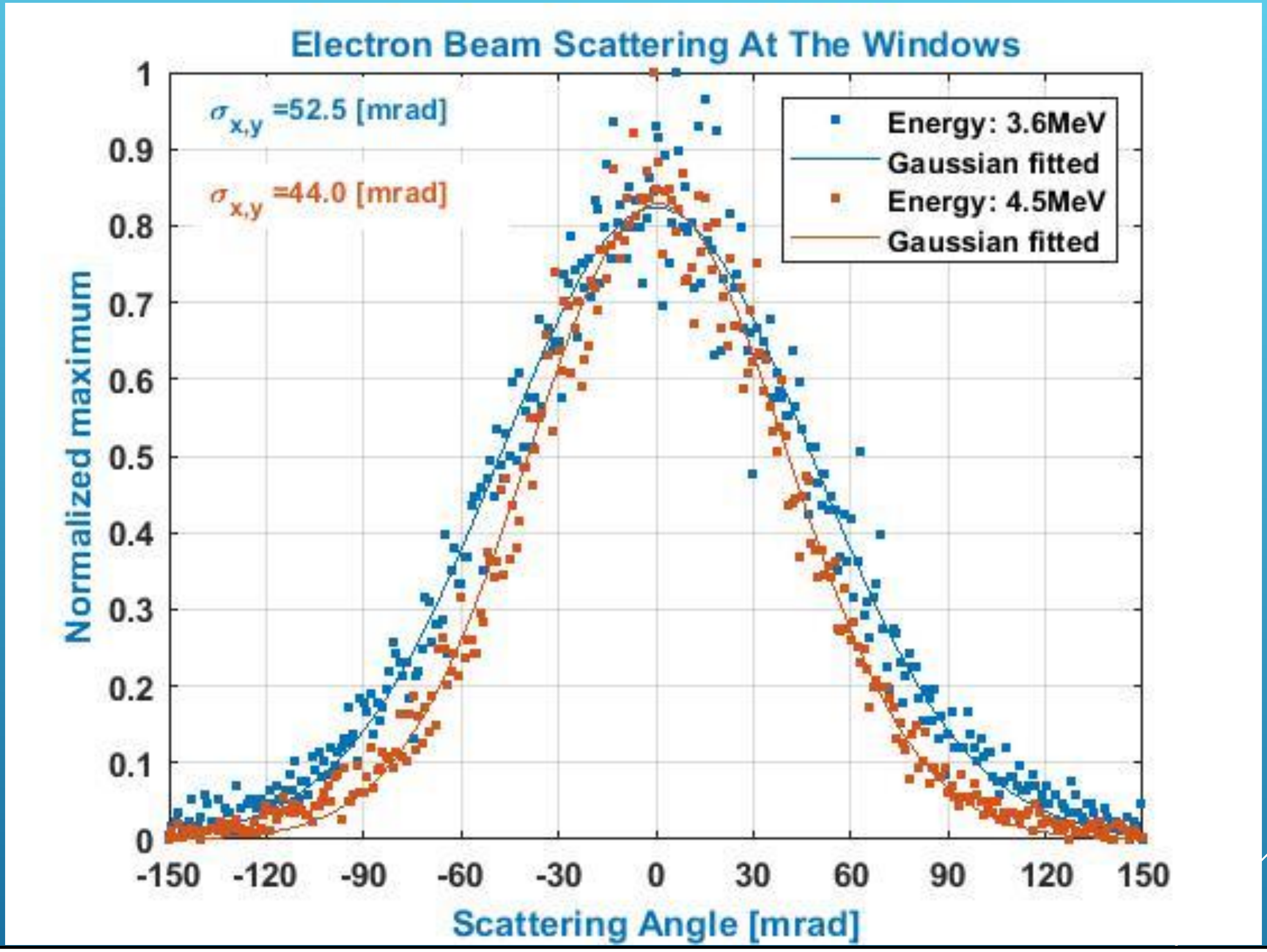


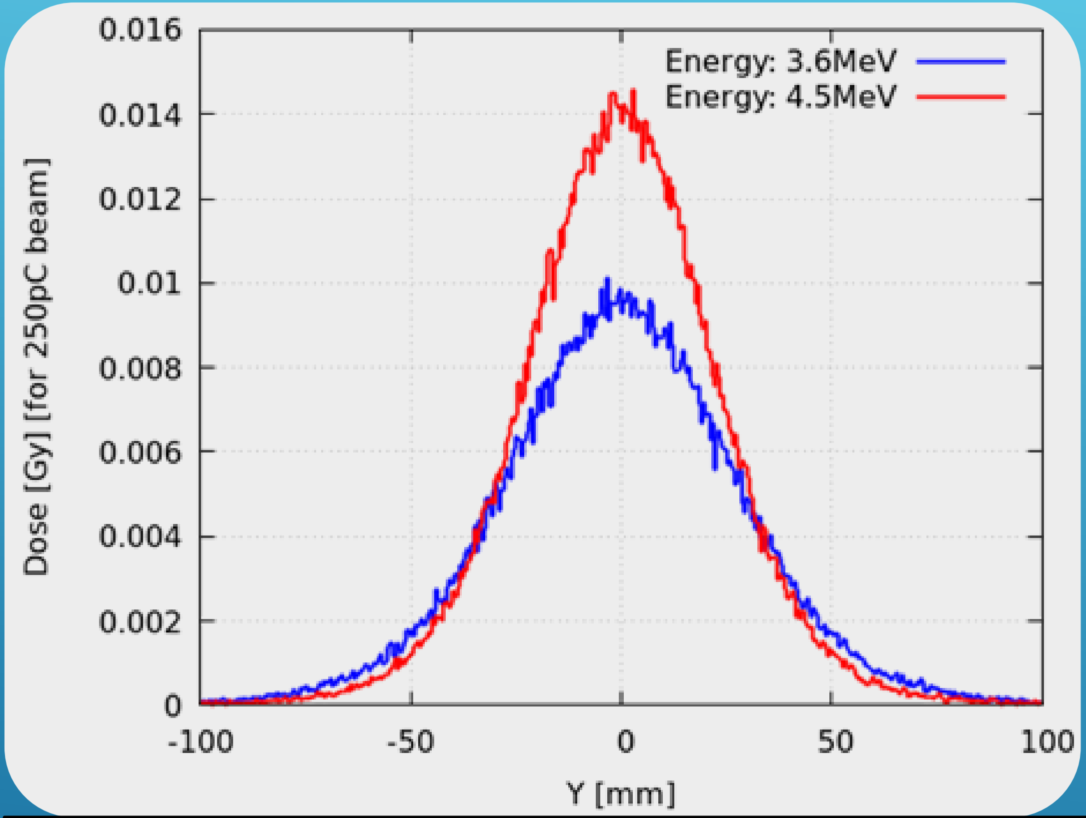
Figure 1: The dose distribution in the experimental station region. Here 1a) is the dose distribution in the horizontal XZ plane for 250 pC with the integration over the vertical Y axis within the range of the cylinder height 20cm and 1b) is the dose distribution in the vertical YZ plane for 250 pC with the integration over the horizontal X-axis within the range of the cylinder diameter 5 cm.

NUMERICAL SIMULATION WITH FLUKA

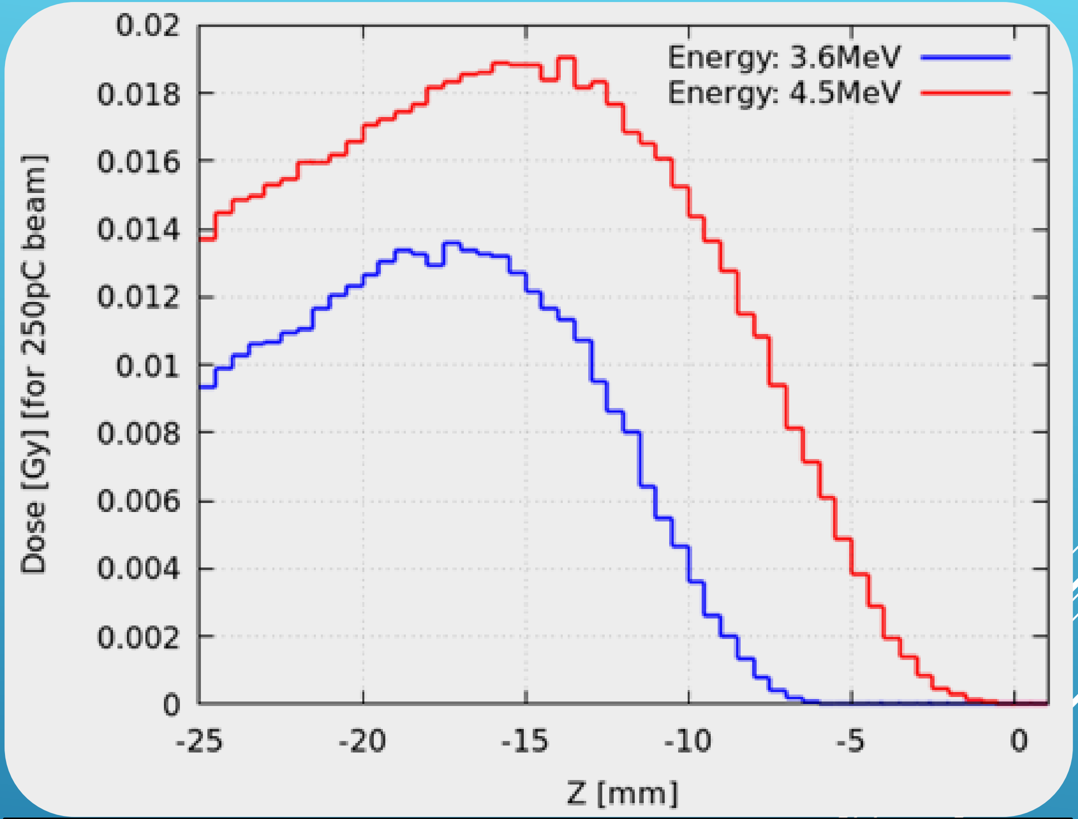


Electron beam scattering at the vacuum window(Ti, 20 μm)

NUMERICAL SIMULATION WITH FLUKA

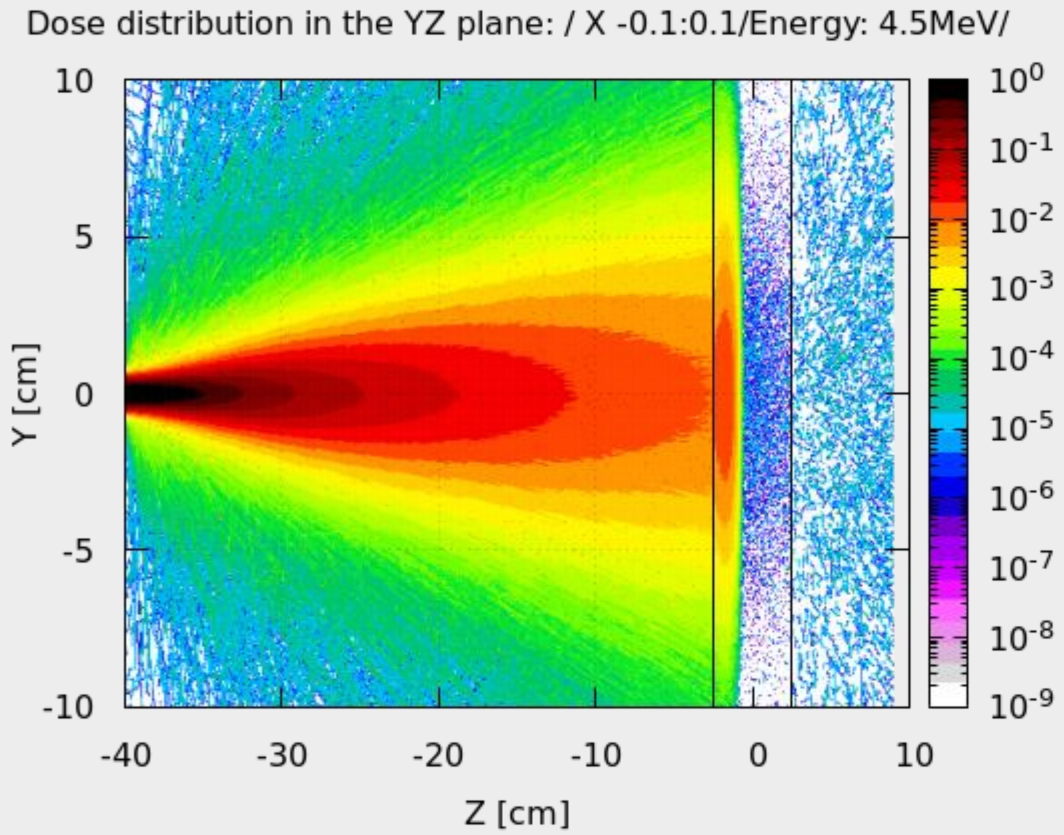


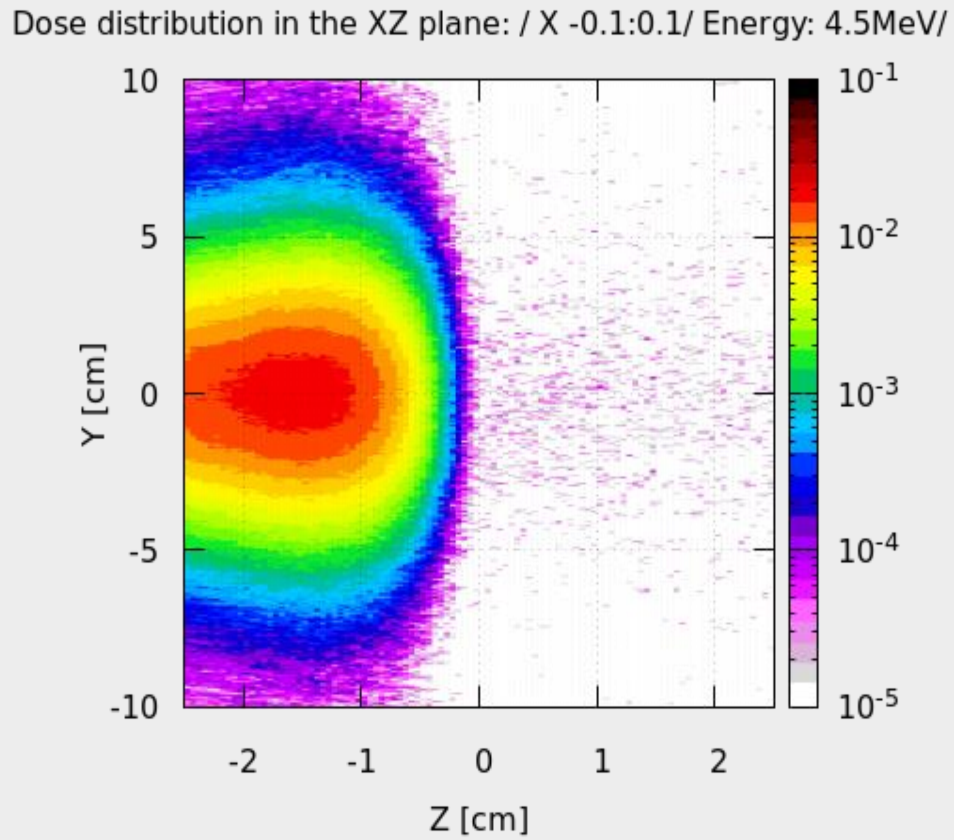
Dose distribution along vertical axis Distributions are normalized per 250 pC.



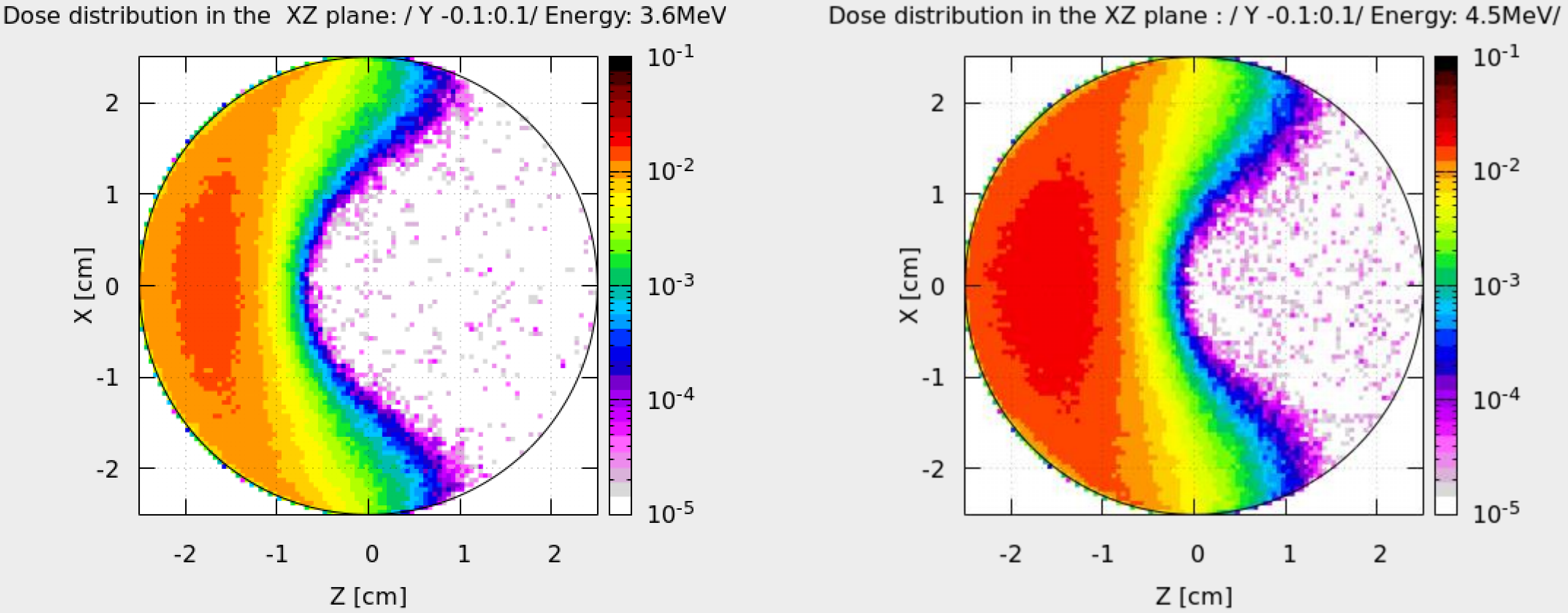
Dose distribution along Z axis, pointing to beam direction. Distributions are normalized per 250 pC.

NUMERICAL SIMULATION WITH FLUKA





NUMERICAL SIMULATION WITH FLUKA



TIME STRUCTURE OF THE e- BEAM AND ABSORBED DOSE

Pulse width – 0.45 ps
Mean dose rate – 34.1 Gy/s (100 Gy/s maximum)
Intra-pulse dose rate - 3.8×10^{12} Gy/s
Dose per pulse DPP – 1.7 Gy
Pulse repetition frequency PRF – 20 Hz
RF frequency – 3 GHz

Ultrahigh dose rate - Radiation delivered with mean dose rate of > ~40 Gy/s
FLASH-RT - Ultrahigh dose rate RT that presents decreased damage to normal tissues compared to RT delivered with conventional dose rate of ~0.04 Gy/s.

PERSPECTIVES

- Energy upgrade to 10 MeV (to increase range in water to 5 cm)
- Improve beam parameters (emittance, pulse charge, pulse length)
- Obtain dosimeter based on mm size parallel plain ion chamber
- Develop dedicated simulation software using FLUKA and TOPAS codes
- Develop and create a new beam focusing system (solenoid and quadrupole doublet magnets, etc)

THANK YOU FOR ATTENTION!