

## ABSORBED DOSE DETERMINATION IN CONVENTIONAL AND LASER-DRIVEN HADRON CLINICAL BEAMS USING ELECTRICAL CHARGE MEASUREMENTS

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*Abstract.* The energies recommended by IAEA TRS 398 for therapeutic hadron beams range from 50 to 250 MeV for protons and from 100 to 450 MeV/u for carbon ions. At present such energies are supplied by conventional cyclotron, synchrocyclotron, synchrotron and linac type accelerators. As an alternative to conventional accelerator beams, laser-driven carbon ion/proton therapy beams have been developed. The parameter which characterizes the interaction of the clinical particle beams with the target is represented by the absorbed dose in the tumors. This paper presents a procedure for measuring the electric charge with ionization chambers as to determine the absorbed dose in clinical hadron beams.

*Keywords:* absorbed dose to water, ionization chamber, hadron therapy beam, hadron dosimetry, expanded uncertainty.

### 1. INTRODUCTION

The 10 PW (150 J, 15 fs) APOLLON Laser system which is now under construction on Magurele Platform close to Bucharest [1], creates the premises for its application in generation of therapeutic hadron beams with energies of 50 to 250 MeV for protons and energies of 100 to 450 MeV/u, for carbon ions [2]. In this regard it may be possible to skip the stage of utilizing conventional accelerators (cyclotron, synchrotron, synchrocyclotron and linac) including the already in design-phase compact accelerators, *i.e.* FFAG, DWA and cyclinac, and directly pass to the alternative of using laser-driven carbon ion/proton therapy beams.

Such an alternative is based on the fact that the experimental research on the Target Normal Sheath Acceleration (TNSA) mechanism has shown that protons may be accelerated to a kinetic energy of about 70 MeV (4 cm range in water) [3], and C<sup>6+</sup> carbon ions may be accelerated to an energy of 525 MeV (about 44 MeV/u,

0.6 cm range in water) through Brake-Out Afterburner (BOA) acceleration mechanisms [4] with the first experimental demonstration. Moreover, computer simulations showed that by using the Radiation Pressure Acceleration (RPA) mechanism for protons, energies output rises up to 2.5 GeV and for carbon ions ( $C^{6+}$ ) the obtained energy is up to 1 GeV/u, *i.e.* more than twice the recommended energy of 450 MeV ( $\approx 28.6$  cm range in water) [5]. These values are ten times greater than the recommended energy of 250 MeV ( $\approx 37.4$  cm range in water). The 10 PW Laser is a potential hadron source in the ultra-relativistic operation regime ( $a_L \geq 100$  [6]). Employing the RPA mechanism with the 10 PW APOLLON Laser may generate clinical hadron beams with the energies required for radiotherapy [7].

INFLPR houses a High Energy Secondary Standard Dosimetry Lab-STARDOOR, accredited by the Romanian Accreditation Association (RENAR), capable of running tests and calibrations in high energy photon, electron and neutron beams, according to SR EN ISO/CEI 17025:2005 [8]. The dosimetric measurements developed in this laboratory are traceable to the reference (primary) standard developed and maintained by PTB-Braunschweig (German Federal Institute of Physics and Metrology).

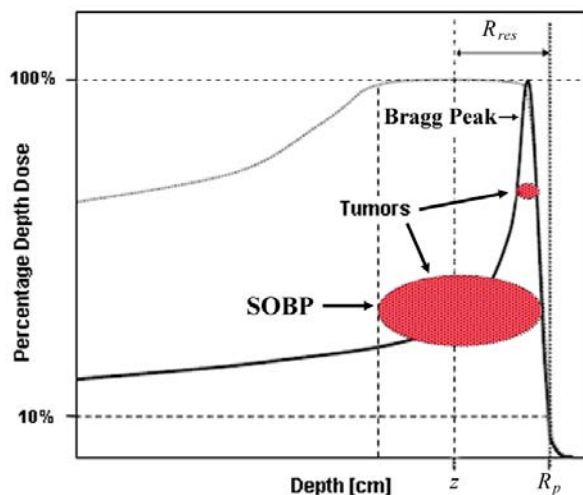


Fig. 1 – Definitions of practical range  $R_p$  and residual range  $R_{res}$ .

The existence of the 10 PW laser source will require the extension of the STARDOOR Laboratory functions, in order to develop tests and calibrations for clinical proton and carbon ion beams. The distribution of the proton and carbon ion absorbed doses in depth (Fig. 1) are characterized by a low dose in the plateau area followed by a narrow area of Bragg peak at the end of the practical range,  $R_p$ , in the medium.

That is defined as the depth to which the dose has decreased to 90 % of the maximum dose. The quality parameter of the hadron beams is considered the residual range, defined as,  $R_{res} = z - R_p$ , where  $z$  is the measurement depth.

When the hadron energy that enters the medium is modulated in order to produce an extended Bragg peak, the ratio plateau to peak decreases but the biological efficiency reduces these disadvantages (Fig. 2) [9].

Out of the three reference dosimetry techniques for clinical hadron beams – calorimetry, Faraday cup and ionization chamber dosimetry – the STARDOOR Laboratory aims at first to develop on the ionizing chamber-based dosimetry.

This paper presents a measurement procedure to determine the absorbed dose to water in clinical hadron beams by measuring the electric charge based on synthesis from worldwide experience.

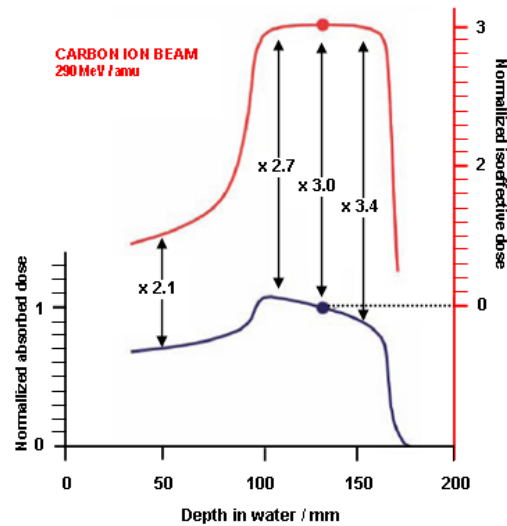


Fig. 2 – Biologically equivalent spread out Bragg Peaks (SOBP<sub>s</sub>).

The symbol for charge is  $q$  and the unit ‘coulomb’ [ $C = A \times s$ ] in SI and in the unit of CGS is esu, franklin (Fr) or statcoulomb (statC) and  $Fr$  or  $statC = \sqrt{g \times cm^3 \times s^{-2}} = 3.3356 \times 10^{-10} C$ . Elementary charge has:  $e = 4.803 \times 10^{-10} esu = 1.602 \times 10^{-19} C$ .

## 2. METHODS AND MATERIALS. ELECTRIC CHARGE MEASUREMENTS

The ionization method is used to determine the absorbed dose to water by means of ionization chambers. Such ionization chambers, cylindrical or plane-parallel type, may be used for absolute (reference) dosimetry and relative dosimetry in clinical beams. The volume of the ionization chamber cavity is filled

with ambient air. The absorbed dose is determined by measuring the electric charge,  $q$ , in [C] and the absorbed dose rate is determined by measuring the ionizing current  $I$ , in [A].

The electric charge  $q$ , generated by the radiation of quality  $Q$  in the sensitive air mass of the chamber, is proportional to the mean absorbed dose to air in the cavity of an ionization chamber,  $\bar{D}_{air}$  [Gy], and the mass of air in the chamber cavity,  $m_{air}$  [kg], by relationship

$$q[\text{C}] = \frac{m_{air}}{(\bar{W}_{air}/e)} \bar{D}_{air} [\text{Gy}]. \quad (1)$$

In relation (1),  $(\bar{W}_{air}/e)$  is the mean energy required to produce an ion pair in air per unit charge, measured in [J/C] and  $m_{air} = \rho_{air} \times V_{eff}$ , where  $\rho$  is the air density in the standard conditions of temperature and pressure and  $V_{eff}$  is the effective air volume in the chamber collecting ions.

In case that the volume  $V_{eff}$  of the ionization chamber cavity is precisely known, one may define the cavity air calibration factor of the ionization chamber by the relation:

$$N_{D,air} = \frac{\bar{D}_{air}}{M_Q} = \frac{1}{m_{air}} \cdot \frac{\bar{W}_{air}}{e} = \frac{1}{\rho V_{eff}} \cdot \frac{\bar{W}_{air}}{e}, \quad (2)$$

where  $M_Q$  is the ionization chamber signal in [C] for the dose.

Equation (2) shows clearly that the calibration factor  $N_{D,air}$  depends only on the volume of the air in the cavity  $V_{eff}$  and it is independent of the radiation quality  $Q$ . That means that  $N_{D,air,Q} = N_{D,air,Q_0}$  where  $Q_0$  is the reference beam quality, *i.e.*  $^{60}\text{Co}$   $\gamma$  radiation beam, and  $Q$  can be the quality of the photon and electron beams.

For a radiation therapy beam one may consider that the volume  $V_{eff}$  is not known accurately enough and consequently  $N_{D,air}$  needs to be determined from the calibration factor of the air cavity starting from the dosimetric factors which are directly proportional to the measured electric charge. Such factors are the followings:  $X$  – exposure,  $K_{air}$  – air kerma,  $D_{air}$  – the mean absorbed dose to air and  $D_w$  – the absorbed dose to water. These are defined by the calculation relation:

$$q/m = X_0 = \varepsilon^{-1} \cdot (1-g) \cdot h \cdot K_{air,Q_0} = \varepsilon^{-1} \cdot D_{air} = (\varepsilon \cdot \eta \cdot p_Q)^{-1} \cdot D_{w,Q_0}, \quad (3)$$

where:  $m = m_{air}$ ,  $\varepsilon = \bar{W}_{air}/e$ , which was defined above,  $g$  is bremsstrahlung fraction, that depends on the electron kinetic energy and  $\eta = S_{w,air}$  is the ratio of restricted collision stopping powers of water to air and  $h$  and  $p_Q$  is defined in TRS 398.

The measuring units for the four dosimetric quantities are as follows. The unit for exposure  $X$  is coulomb per kilogram [C/kg]. In SI, the unit for exposure is simply  $2.58 \times 10^{-4}$  C/kg of air and in CGS the unit is the roentgen,  $1 \text{ R} = 1 \text{ esu/cm}^3$  of air;  $1 \text{ R} = 2.58 \times 10^{-4}$  C/kg of air. The unit for quantities  $D_{air}$ ,  $K_{air}$  and  $D_w$  in SI is joule per kilogram [J/kg]. The special name for this unit is the gray (Gy),  $1 \text{ Gy} = 1 \text{ J} \times \text{kg}^{-1}$ . In CGS, the unit for these quantities is the centigray (cGy),  $1 \text{ cGy} = 10^{-2} \text{ J} \times \text{kg}^{-1}$ .

The ionization chambers used to determine the absorbed dose to water need to be calibrated in a radiation beam of quality  $Q_0$  ( $= {}^{60}\text{Co}$   $\gamma$  beam). The first factor is the exposure calibration factor of an ionization chamber  $N_{X,Q_0}$  [R/C]. This is defined as  $N_{X,Q_0} = X_{Q_0}/M_{Q_0}$  where  $X_{Q_0}$  is the exposure at a point P in air in the absence of the chamber and  $M_{Q_0}$  is the chamber meter reading when the chamber is centered at point P and is corrected for: standard temperature, pressure, humidity and recombination.

The second factor is the air kerma calibration factor  $N_{K,Q_0}$  [Gy/C] defined as  $N_{K,Q_0} = K_{air,Q_0}/M_{Q_0}$ , where  $M_{Q_0}$  is the reading of the dosimeter, during calibration in  ${}^{60}\text{Co}$  beam. Based on relations (3), the result is that the calibration factors  $N_{X_0}$  for exposure [R] can be converted to calibration factors  $N_{K,Q_0}$  for air kerma [Gy] by the relation:

$$N_{K,Q_0} = N_{X_0} \cdot (\overline{W}_{air} / e) \cdot (1 - g)^{-1}. \quad (4)$$

The third factor is the cavity air calibration factor  $N_{D,air}$  defined as  $N_{D,air} = D_{air}/M_Q$  [Gy/C]. According to formalism  $N_{D,air}$  for the determination of the absorbed dose to water  $D_w$ , it can be determined from the factor  $N_{K,Q_0}$  or as per the formalism  $N_{D,w}$  from the fourth factor which is  $N_{D,w,Q_0}$  [Gy/C],

$$N_{D,air,Q_0} = N_{D,w,Q_0} / (s_{w,air} \cdot p_Q)_{Q_0}, \quad (5)$$

called the absorbed dose to water calibration factor and defined as  $N_{D,w,Q_0} = D_{w,Q_0}/M_{Q_0}$  where  $M_{Q_0}$  is the reading of the dosimeter under reference conditions used in the standard laboratory.

ICRU 59 recommends the calibration factors  $N_{X,Q_0}$ ,  $N_{K,Q_0}$  and  $N_{D,w,Q}$  for the proton beam dosimetry. TRS 398 recommends the calibration factor  $N_{D,w,Q_0}$  for the ion and proton beam dosimetry.

By dividing the elements of the equation (3) by  $M_{Q_0}$ , using the calibration factors defined above and the perturbation factors  $h_{att}$ ,  $h_m$  and  $h_{cel}$  [2], one may obtain the relation (6) for the calibration factor  $N_{D,air,Q_0}$

$$N_{D,air,Q_0} = N_{K,air,Q_0} \cdot (1 - g) \cdot h_{att} \cdot h_m \cdot h_{cel}, \quad (6)$$

where the meaning of the factors,  $h_{att}$ ,  $h_m$  and  $h_{cel}$ , marked by  $k_{att}$ ,  $k_m$  and  $k_{cel}$ , was given in [2, 10, 11].

The passage from the absorbed dose in air  $D_{air,Q_0}$ , to the absorbed dose to water,  $D_w$  is made by the application of Bragg-Gray principle [2]. According to the principle, the absorbed dose to water is

$$D_{w,Q_0} = M_{Q_0} \cdot N_{D_{air,Q_0}} \cdot (s_{w,air})_{Q_0} \cdot p_{Q_0}, \quad (7)$$

where  $p_{Q_0} = (p_{cav} \times p_{dis} \times p_{wall} \times p_{cel})_{Q_0}$  is overall perturbation factor of the ionization chamber for phantom measurements at the  $Q_0$  quality beam (TRS 398). Applying the formalism,  $N_{D,w}$  the absorbed dose to water at the reference depth  $z_{ref}$  in water for a reference beam of quality  $Q_0$ , and in the absence of ionization chamber, is given by:

$$D_{w,Q_0} = M_{Q_0} \cdot N_{D,w,Q_0}. \quad (8)$$

The identity of the two formalisms (7) and (8) for the same quality  $Q_0$  leads to the expression:

$$N_{D,w,Q_0} = N_{D_{air,Q_0}} \cdot (s_{w,air})_{Q_0} \cdot p_{Q_0}. \quad (9)$$

By applying the IAEA formalism [2, 10, 11, 12–15] based on  $N_{D,w}$  we observe that the absorbed dose to water,  $D_w$ , at the reference depth  $z_{ref}$  in water for any quality of beam  $Q$  (bosons, leptons and hadrons) is given by the relation:

$$D_{w,Q} = M_{Q,corr} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \quad (10')$$

$$k_{Q,Q_0} = \frac{[(s_{w,air})(\overline{W}_{air}/e)p_Q]_Q}{[(s_{w,air})(\overline{W}_{air}/e)p_Q]_{Q_0}}, \quad (11)$$

where  $M_{Q,corr}$  [C] is the reading of the dosimeter with the reference chamber positioned at  $z_{ref}$ , and corrected for temperature and pressure, electrometer calibration, polarity effect and ion recombination as described in TRS 398.  $N_{D,w,Q_0}$  [Gy/C] is the calibration factor in terms of absorbed dose to water for the dosimeter at the reference quality  $Q_0$  and  $k_{Q,Q_0}$  is a chamber specific factor which corrects for the difference between the reference beam quality  $Q_0$  and the actual beam quality  $Q$ . When the reference quality  $Q_0$  is  $^{60}\text{Co}$   $\gamma$  beam the factor  $k_{Q,Q_0}$  is denoted by  $k_Q$ .

### 3. RESULTS IN REFERENCE CONDITIONS

For the parameters of the beam of quality  $Q_0$  ( $\equiv {}^{60}\text{Co}$   $\gamma$  beam) TRS 398 recommends the following values and uncertainties ( $1\sigma$ ):  $(S_{w,air})_{Q_0} = 1.133 \pm 0.1\%$ ,  $(\bar{W}_{air}/e)_{Q_0} = 33.97 \text{ J/C} \pm 0.2\%$ , for dry air and  $p_{Q_0}$  is a function of the ionization chamber type. For example, note:  $p_{Q_0} = 1.010; 1.009; 0.994; 0.982$  and  $0.979$  for Ross, Markus, Farmer, PTW30001 and PTW30011 ionization chambers respectively. In the case of proton beam quality ‘ $Q_p$ ’, the recommended values and uncertainties ( $1\sigma$ ) are:  $(S_{w,air})_{Q_p}$  calculated depending on of energy, with  $1\%$  uncertainty.

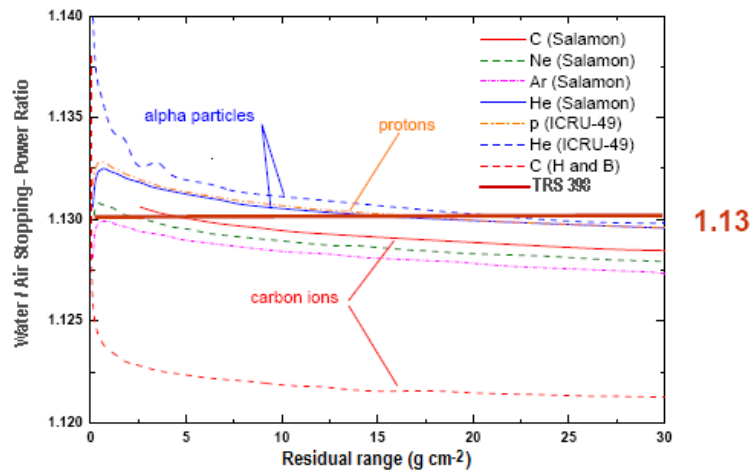


Fig. 3 – Stopping-power ratio for proton and ion beams.

For proton beams, the  $S_{w,air}$  value depends on proton energy. It is assessed using the residual range  $R_{res}$  that is dependent on energy according to TRS 398  $(S_{w,air})_{Q_p} = a + b \times R_{res} + (c/R_{res})$ , where  $a = 1.137$ ;  $b = -4.3 \times 10^{-5}$  and  $c = 1.84 \cdot 10^{-3} \times (\bar{W}_{air}/e)_{Q_p} = 34.23 \text{ J/C} \pm 0.4\%$  and  $(\bar{W}_{air}/e)_{Q_p} = 34.8 \text{ J/C} \pm 0.7\%$  for dry air and  $p_{Q_p} = 1 \pm 0.7\%$  [2]. TRS 398 recommends for all heavy-ion beams ions:  $(\bar{W}_{air}/e)_{Q_i} = 34.50 \text{ J/C} \pm 1.5\%$ ,  $(s_{w,air})_{Q_i} = 1.13 \pm 2\%$  and  $p_{Q_i} = 1.0 \pm 1\%$ .

For ion beams TRS 398 recommends one fixed value  $(S_{w,air})_{Q_i} = 1.130$  ( $\pm 2\%$ ) neglecting any dependence with residual range (Fig. 3 [2]) due to lack of the experimental values. The quality factor  $k_Q$  values are calculated as a function of the proton energy in [2]. As an example, note: for  $R_{res} = 1, 10, 20, 30$  cm, PTW 30010 Farmer chamber  $k_Q$  is 1.031, 1.029, 1.029 and 1.028 respectively, and Markus plan parallel chamber  $k_Q$  is 1.004, 1.002, 1.002 and 1.001 respectively.

For ion beams the quality factor  $k_Q$  is 1.003 for PTW 34001 Roos chamber and  $k_Q$  is 1.004 for PTW 34001 Markus [2].

#### 4. UNCERTAINTIES

The accuracy and precision of absorbed dose measurements  $D_{w,Q}$  are given by the combined uncertainty  $u_c(D_{w,Q})$  that is calculated from the type A uncertainty of the electric charge  $M_Q$ , and the type B uncertainties of  $N_{D,w,Q_0}$  and  $k_{Q,Q_0}$  by means of relation:

$$u_c(D_{w,q}) = (u_A^2(M_Q) + u_B^2(N_{D,w,Q_0}) + u_B^2(k_Q))^{1/2}. \quad (12)$$

Table 1

Estimate relative uncertainties (in %) for the quality factors for proton and carbon ion beams [IAEA TRS 398]

Protons	Cylindrical chambers		Plane-parallel chambers	
	protons	<sup>60</sup> Co + protons	protons	<sup>60</sup> Co + protons
$s_{w,air}$	1.0	1.2	1.0	1.2
$\bar{W}_{air}/e$	0.4	0.5	0.4	0.5
$p_Q$ (combined)	0.8	1.1	0.7	1.7
Total uncertainty in $k_{Q,Q_0}$	–	1.7	–	2.1
<hr/>				
Light ions	Cylindrical chambers		Plane-parallel chambers	
	light ions	<sup>60</sup> Co + light ions	light ions	<sup>60</sup> Co + light ions
$s_{w,air}$	2.0	2.1	2.0	2.1
$\bar{W}_{air}/e$	1.5	1.5	1.5	1.5
$p_Q$ (combined)	1.0	1.0	1.0	1.8
Total uncertainty in $k_{Q,Q_0}$	–	2.8	–	3.2

For therapy employing hadrons the protocols recommends the use of cylindrical ionization chambers because the uncertainties related to the correction factors are smaller and because they use the depth  $z \geq 0.5 \text{ g/cm}^2$  for protons and  $z \geq 2 \text{ g/cm}^2$  for carbon ions. At lower depth, plan-parallel chamber are required. Table 1 shows such uncertainties [16, 17].

#### 5. CONCLUSIONS

By fully satisfying TRS 398 recommendations and applying the three formalisms based on exposure, air kerma and absorbed dose to water the authors presented an ionization method for determining the absorbed dose to water in standard conditions, employing electrometer measurements of a single parameter – the electric charge.



Ionization chambers calibrated in the beam of a  $^{60}\text{Co}$  source by a primary standard laboratory using the ionometric method, could be used in present day for the absorbed dose to water assessment for therapeutic proton and ion beams delivered by charged particle accelerators.

The energies of protons and carbon ions were set at the values stated in TRS 398 considering that those values can be obtained with the operation of the 10 PW laser in ultra-relativistic regime using the radiation pressure acceleration (RPA) mechanism.

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