DOSIMETRY AND MICRODOSIMETRY OF PHASOTRON THERAPY PROTON BEAMS

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Absorbed dose measurements in JINR therapeutic proton beams are performed with air- and tissue -equivalent (A-150) ionization chambers.The accuracy achieved on the base of the calibration at the reference ^{60}Co source at Prague and using the parameters recommended in the code of practice is about 3%. Spatial dose distribution measurements are assured also with the help of some other devices like silicon, diamond and thermoluminescent detectors. Depth dose distributions established by means of different types of detectors agreed well and showed that the distortion caused by differences in energy responses are for the proton beams studied insignificant. Microdosimetric studies in the proton beams have been performed with solid state nuclear track detectors (SSNTD). Chemically etched polyallyldiglycolcarbonate has been used to determine the importance of secondary particles with linear energy transfer (LET) above 10 keV per μm. An example of the calibration of this LET spectrometer with heavier charged particles is presented. Linear energy spectra of secondary charged particles are presented, their contribution to the absorbed dose relatively to primary proton ionization losses is estimated.

1.INTRODUCTION

Radiation therapy with a proton beam has a number important advantages as compared to conventional photon and electron beams. The proton beam allows the maximum absorbed dose to be confined to the treatment volume while the dose to surrounding normal tissues is minimal. Realization of these advantages requires the knowledge of dosimetric characteristics of a beam as precise and complete as possible. This contribution describes the dosimetry and microdosimetry studies performed in the JINR therapeutic proton beams, i.e. with proton energies between 70 and 250 MeV [1,2].

2.EXPERIMENTAL

2.1. Therapeutic proton beams

The phasotron of the LNP JINR accelerates protons primarily to an energy of about 660 MeV, about 10^{13} protons per second can be produced. The clinical-physical facility consists of four treatment rooms designated for proton therapy, one for neutron and another one for negative pion irradiation. Proton beams with primary energies between 70 and 250 MeV can be produced. A system of collimators, lenses, energy degraders, and filters permits the formation of beams with variable depth-dose and profile distributions.

2.2.Dosimetry methods used and studied

- ***Ionization chambers***

Two types of ionization chambers are used for absorbed dose measurements in proton beams;
- thimble air- filled air-equivalent chambers VAK-251 or VAK-253 (volumes 50 or 1500 mm^3, resp.),
- tissue equivalent (A-150) thimble chambers with the volume 1420 mm^3, filled with air or propane based tissue equivalent gas mixture.

Their calibration is performed regularly using the ^{60}Co source of the therapeutic gamma unit, placed in another cabin of the clinical-physical facility, in accordance with the „Code of Practice for Clinical Proton Dosimetry“ [3]. The ^{60}Co source was calibrated against the primary standard of Czech Republic installed at DRD NPI ASCR, with the accuracy 1.3%. [11]

- ***Thermoluminescent detectors***

Three types of thermoluminescent detectors have been used to determine dosimetric characteristics in proton beams : ^{7}LiF, $CaSO_4$:Dy, and czech alumophosphate glasses. They were always irradiated in sets of at least six detectors. Each set was covered from both sides by 2 mm of Teflon. They were also calibrated in the primary ^{60}Co photon beam in Prague.

- ***Detectors for spatial distribution measurements***

The most convenient detectors to establish the spatial distributions in proton beams are miniature silicon and diamond detectors. There are several types of Si-diodes available in our laboratories: Li-drifted (volume up to several mm^3) are used at relatively low dose rates, industrial produced diodes (KD-208 or KD-209, diameter 1mm, thickness 0.2 mm) were chosen for higher dose rate measurements. Diamond crystal detector (volume from 1 to 5 mm^3, the thickness up to 0.4 mm) has a roughly the same sensitivity as silicon one, they are more tissue equivalent and also more stable to radiation [4]. Both these types of detectors are

implanted in automatized systems directed through a personal computer.

- ***Spectrometer of LET based on a SSNTD***

Polyallyldiglycolcarbonate available from Pershore Moulding Ltd., UK, has been used for the LET-spectrometry. The detector samples are etched in the 5 N NaOH solution at 70° C. Before etching, each sample is irradiated in a corner with ^{252}Cf fission fragments and ^{241}Am alpha particles to check the exact conditions of etching and to determine the bulk etching rate and the thickness of the layer removed by etching. This thickness was about 17 μm. Etch rate ratio $V = V_T/V_B$; (where V_T is the track etch rate and V_B is the bulk etch rate) is established through the determination of track parameters by means of an automatic optical image analyzer LUCIA II based on a Leitz microscope [5]. The tracks with minor axes larger than 5 μm are taken into account. There are several possible procedures to establish V from track parameters, the final optimization is performed through the comparison of the removed layer thickness, recalculated from the V-value with that directly measured through the fission fragment tracks diameter. The obtained spectra of V-values are corrected for the critical angle of the registration and transformed to LET spectra on the basis of the calibration performed by means of heavy charged particles. Available LET region situates between 100 and 6000 $MeV.cm^2.g^{-1}$ [5,6]. The LET spectra enables to calculate dose and dose equivalent distributions corresponding to secondary particles the tracks of which are revealed. The integral values of the dose, D, resp. the dose equivalent, H, are obtained from these distributions as:

$$D = \int (dN/dL)*L*dL; \text{ resp.}$$

$$H = \int (dN/dL)*L*Q(L)*dL,$$

where dN/dL is number of tracks in a LET interval; L is the value of LET; and Q(L) is the quality factor corresponding to the value of L.

3.RESULTS; DISCUSSION

- ***Absorbed dose measurements***

The absolute absorbed dose measurements are performed by means of ionization chambers. The absorbed dose calibration factor for a proton beam A_{cal} may be obtained from the calibration of the ionization chamber in a ^{60}Co reference beam using the relation:

$$A_{cal} = N_k * C_p,$$

where C_p, the proton conversion factor may be obtained using the formulae [3]:

$$C_p = A_{wall} * [(\bar{S}/\rho)_{air}^{tissue}]_p * k \text{ , where}$$

$$k = (1-g) * \frac{(W_{air}/e)_p}{(W_{air}/e)_\gamma} * \frac{[(\bar{\mu}_{en}/\rho)_{air}^{A-150}]_\gamma}{[(\bar{L}/\rho)_{air}^{A-150}]_\gamma}$$

where

- (1 - g) - correction to bremsstrahlung in the air in the ^{60}Co ;
- A_{wall} is the wall perturbation factor that takes into account absorption and scattering of γ -rays produced in the ionization chamber walls.
- $(W_{air}/e)_p$ and $(W_{air}/e)_\gamma$ - the average energy required to produce an ion pair in dry air for γ -rays and protons;
- $[(\bar{\mu}/\rho)_{air}^{A-150}]_\gamma$ - the ratio between the mean mass energy absorption coefficients of the chamber wall material and the air for γ -rays ;
- $[(\bar{L}/\rho)_{air}^{A-150}]_\gamma$ - the ratio between the mean restricted collision mass stopping powers of the chamber wall material and the air for γ -rays; and
- $(\bar{S}/\rho)_{air}^{tissue}]_p$ - the ratio of the mass stopping powers of tissue to air for the proton beam.

The values of all coefficients used are presented in the Table 1.

The results of measurements with ionization chambers have been compared with the results of several other institution during national and international intercomparisons [12]. In all cases our results agreed with the reference values, the maximum differences did not exceed 2 %. The uncertainty of JINR proton beam dosimetry using the parameters presented and recommended in [3] is estimated not to be worse than 3 %. This accuracy meets the international requirements for the therapeutic proton beam dosimetry. Relative dose measurements can be performed also with TLD. It is however necessary to verify their energy response to the protons of different energies. The results of such studies executed in JINR proton beams are presented in Table 2. One can see there that these responses are very close to the unity. This property allows them to be used for beam profile, depth dose and other measurements in proton beams.

A_{wall}	0.99±0.01
(1-g)	0.997 [3]
$[(\bar{\mu}/\rho)^{A-150}_{air}]_{\gamma}$	1.101 (0.1 %) [3]
$[(\bar{L}/\rho)^{A-150}_{air}]_{\gamma}$	1.145 (0.1 %) [3]
$(\bar{S}/\rho)^{tissue}_{air}]_{p}$	1.130 [7]

Proton energy, MeV	200	200	250	250
$(W_{air}/e)_p$, JC^{-1}	35.2 (4%) [3]	34.1 (2%) [8]	34.2±0.5 [9]	34.8 (2%) [10]
$(W_{air}/e)_p/(W_{air}/e)_{\gamma}$	1.0362 [3]	1.01 [8]	1.007 [9]	1.024 [10]
K	0.9934	0.9863	0.9654	0.9817
C_0	1.1113	1.0832	1.0800	1.0982
A_{cal}*10^7 Gy/C	1.970	1.921	1.915	1.947

Table 1 : The absorbed dose rate calibration factors of the TE-chamber for proton beams

E_{p_0}, MeV	LiF	Al-P glasses	$CaSO_4$
179±18	1.01±0.08	0.96±0.06	1.04±0.06
160±18	0.98±0.06	0.94±0.08	0.90±0.09
131±16	-	0.99±0.04	1.06±0.06
90±18	1.11±0.09	1.02±0.05	0.96±0.07
55±16	-	1.01±0.06	0.93±0.07

Table 2 : Relative responses of TLDs to the protons of therapeutic beams

- ***Spatial dose distributions measurements***

Three dosimetry methods have been compared to follow depth dose distributions in a proton beam : air-equivalent ionization chamber, silicon diode and diamond detector. The results obtained are presented in Fig. 1. The primary proton energy was 200 MeV, the dose rate about 4 mGy.s^{-1} (0.25 Gy per minute). All curves were normalized at the point on the surface of water phantom, one can see in the Fig.1 that all distributions agree well up to the region of Bragg peak. It can be concluded that the distortion caused by possible differences in the energy dependence of studied detectors is for our proton beams insignificant.

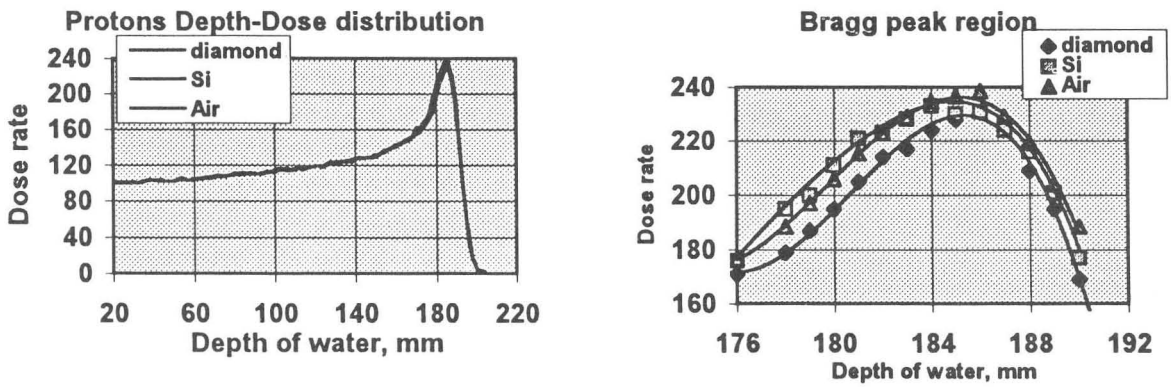

Figure 1 : Depth dose profiles measurements in 200 MeV proton beam : a) full range; b) Bragg peak

- ***Microdosimetry studies in proton beams***

The methodology of LET-spectrometry is in more details described in our previous works [5,6]. To demonstrate the possibilities of it, we present in Figure 2 the LET spectrum of ^{12}C ions with the energy of 100 MeV per amu. One can see there that all particles are registered very close to the value of

LET in tissue, with practically 100% efficiency. The LET spectra of secondary particles created through the interaction of primary protons with the energy of 200 MeV are presented in the Fig. 3.

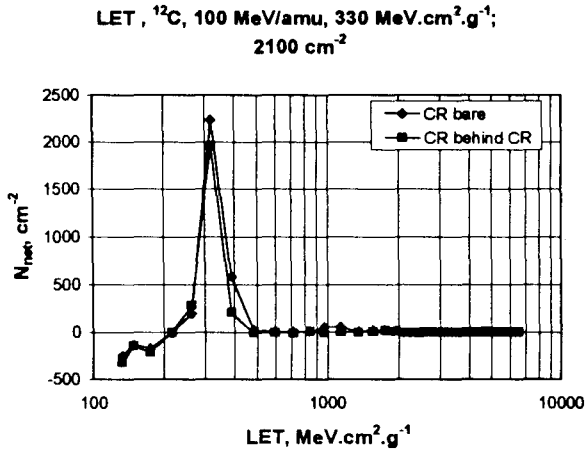

Figure 2 : LET spectra of ^{12}C ions with the energy of 100 MeV per amu

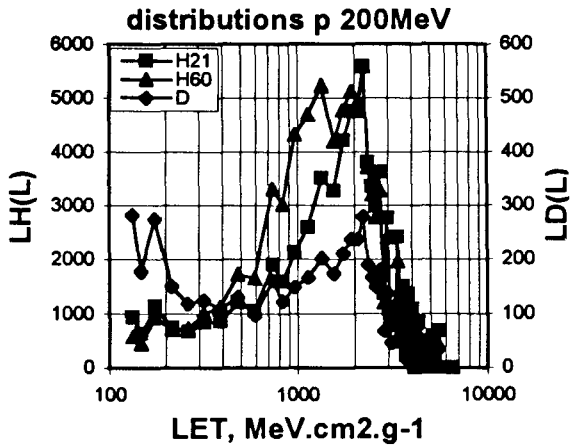

Figure 3 : Microdosimetric distributions of the dose and the dose equivalent due to the secondary particles created through the interactions of 200 MeV protons; H21(60)-QF from ICRP 21(60) [13].

As mentioned above, the LET spectra as presented in Figure 3 permits to calculate the dose and the dose equivalent due to the registered secondary particles. It was found out that the contribution of such particles to the total absorbed dose is not negligible. It increases, as could be expected, with the proton energy. Relatively to the ionization losses it represents 1.2 % at 85 MeV, but already 2.7 % at 200 MeV. These values agree well with the results established by means of a tissue-equivalent proportional counter [14]. When expressed as adopted in radiation protection, the relative dose equivalent due to secondary particles with high LET values approaches to 20 % at 200 MeV primary proton energy. Of course, quality factor defined for radiation protection purposes is not appropriate to express relative biological efficiency in radiotherapy. Nevertheless the values given are high enough to explain the radiotherapy biological efficiency of high energy protons estimated up to 1.2 [15].

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