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LATERAL DOSE DISTRIBUTION OF PROTON BEAMS AT ENERGIES FROM 4 TO 11 MeV

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Abstract — The distribution of imparted energy deposited at distance from the axis of a proton beam, i.e. the lateral distribution of absorbed dose, is determined by measurement of the light emission in nitrogen at the wavelengths of 391.4 nm and 337.1 nm in single photon counting technique. Results for the proton energies 4, 8 and 11 MeV are given.

INTRODUCTION

Measurements with proton beams were performed in the energy range from 4 to 11 MeV in nitrogen, to evaluate the distribution of absorbed dose in a plane perpendicular to the beam axis, i.e. the lateral distribution of absorbed dose. The energy deposition was measured by observation of the intensity of the emitted fluorescent light in single photon counting technique. Two transitions of the molecular nitrogen were observed, the (0,0) transition of the first negative system at a wavelength of 391.4 nm and the (0,0) transition of the second positive system at 337.1 nm. The excitation cross section of the first negative system is, for electron energies in excess of 25 eV, proportional to the total ionisation cross section[1], and it is, therefore, possible to evaluate the number of ion pairs from observation of this transition. The transition at 337.1 nm is excited nearly exclusively by low energy electrons[2]; therefore it is suitable for assessing their contribution to the electron fluence.

The main advantage of the method is, apart from the high spatial resolution, that it avoids the disturbances of the radiation field that arise if charged particle detectors are used. The need to correct for collision quenching is a disadvantage of the method, if — in the case of energetic protons — the pressure in the collision chamber must be increased to keep its size within reasonable limits.

The experimental system is based on the equipment and experience of Ibach and colleagues at the GSF who have earlier performed corresponding measurements with protons of energies below 2 MeV[3].

EXPERIMENTAL ASSEMBLY

The approximately parallel proton beam enters the collision volume from the left (Figure 1); its cross section is defined by an orifice of 1 mm diameter in a foil of tantalum. Scattered protons are rejected from the collision volume by a second orifice of diameter 1 mm. After traversing the collision volume the total beam is absorbed in a Faraday cup to determine the current. Two 1 μm Havar foils separate the nitrogen flushed chamber from the vacuum of the beam guide system and from the vacuum of the Faraday cup. The energy loss of the protons within the gas of the collision volume is less than 2% in all measurements. The chamber is separated from the photon counting equipment by a quartz glass window which is located between the lenses and the slit diaphragm. The collision chamber is connected to a gas flow system with pressure adjustable from 1 Pa to 100 kPa. A lens system collects the photons from a rectangular cylinder of cross section 0.2–2 mm and approximate length 120 mm (diameter of the collision volume) on to the photomultiplier.

The cylinder is orthogonal to the beam, and the

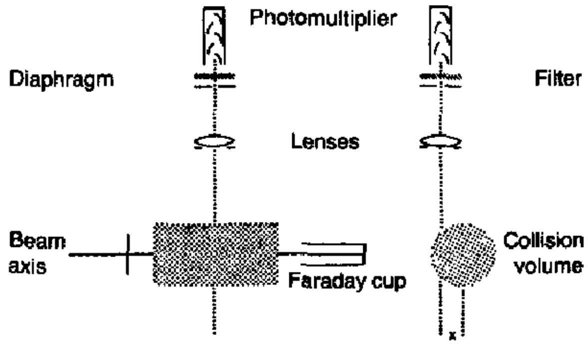

Figure 1. Diagram of the experimental system in a horizontal plane parallel to the beam axis (left panel) and in a plane perpendicular to the beam axis (right panel). The diagram is not to scale; (see text for actual dimensions).

long sides of its cross section are parallel to the beam.The distance between the beam and the cylinder, i.e. the lateral distance, can be varied mechanically; in addition the 'effective' distance is varied by changing the nitrogen pressure. To observe the chosen transition, two interference filters with full width at half maximum of the transmission of 6.9 nm (first negative system) and 5.3 nm (second positive system) were employed. The photons were detected by an ultraviolet-sensitive photomultiplier in single photon counting technique. To evaluate the response of the photon detection system at 391.4 nm, the transition was excited by well collimated monoenergetic electron beams. If the condition of single collisions is guaranteed the fluence rate of photons can be deduced from the knowledge of the excitation cross sections and the electron current. Since the calibration measurements were restricted to the transition at 391.4 nm, the detection efficiency at 337.1 nm had to be calculated by accounting for the transmission factors through the various components of the optical system.

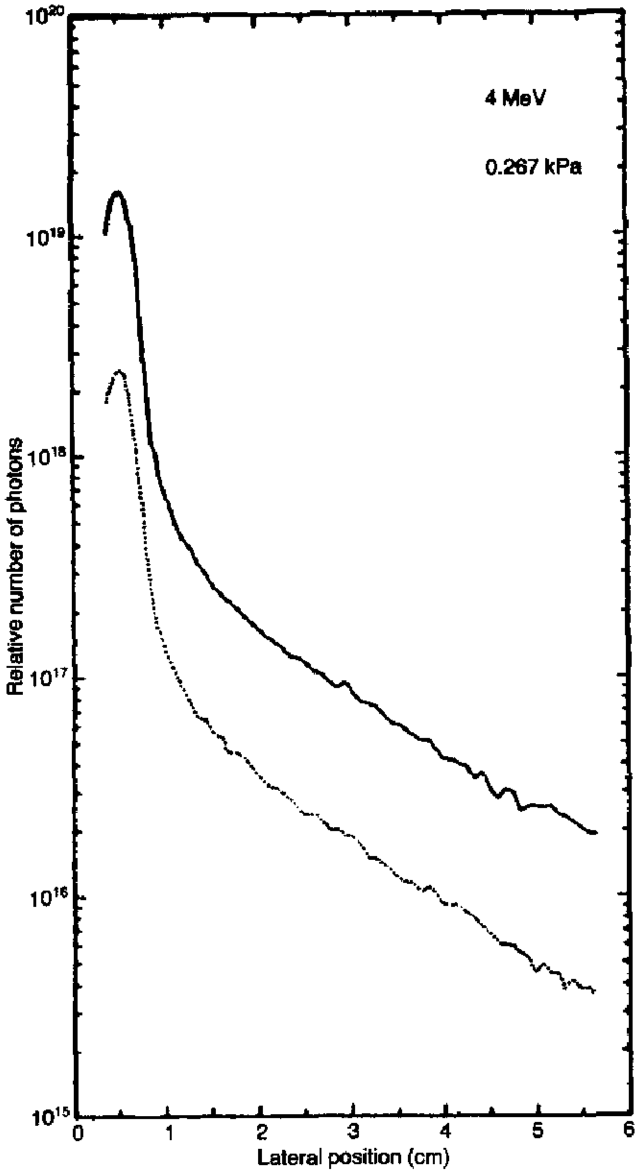

Figure 2. Relative number of photons versus the lateral position, i.e. the position of the axis of the optical system with respect to the proton beam axis. For the assessment of standard errors see Laßmann[4].

RESULTS

In Figure 2 the raw data of a typical measurement are given, corrected merely for collision quenching. These data have been obtained with 4 MeV protons at a nitrogen pressure of 0.267 kPa. The relative number of photons is shown in its dependence on lateral position. The peak of the curve corresponds to the axis of the proton beam. To achieve better resolution close to the beam axis and to simulate larger distances, added measurements at reduced and increased pressures were performed. Two sets of the resulting data are given in Figure 3 on a logarithmic abscissa scale. The number of photons and the radial distance, i.e. the distance between proton beam axis and the axis of the optical system, are scaled to the nitrogen density 1 $g.cm^{-3}$.

To deduce the emission density $\varepsilon(r)$, i.e. the number of photons emitted per volume element, from the measured data the 'Abel inversion' needs to be performed. Most of the procedures available suffer from instabilities, if the experimental data are of limited precision. Therefore, an alternative method equivalent to the Abel inversion has been applied which uses an optimisation algorithm with constraints. As constraint on the solution the evident condition of monotonous decrease of the emission density with increasing distance was chosen. The inversions were performed separately for each pressure value, and the emission densities so obtained were then combined. The results for 4 MeV and 11 MeV protons are given in Figure 4. The corresponding data for 8 MeV protons are given in Figure 5.

The results demonstrate the advantages of the light emission measurements; the lateral distances that were examined extend for 11 MeV protons from about 1 nm to about 4 µm, and the emission density was determined over about eight orders of magnitude. An error analysis indicates an accuracy of about 20% for the ordinate values, which corresponds to about 10% for the distances[4].

DISCUSSION

In a rough approximation absorbed dose is often assumed to decrease with the inverse square of the radial distance. The diagrams of Figure 6 suggest a somewhat steeper decline than this approximation. A comparison of the emission densities at 391.4 nm and 337.1 nm indicates a somewhat larger relative contribution of low energy electrons close to the beam axis. At larger distances the relative contribution appears to be roughly constant. Monte Carlo simulations by Lappa[5,6] support this finding. A corresponding observation is not made in experiments performed with electron beams[4]; in these experiments the relative contribution of low energy electrons appeared to be constant within the entire region of energy deposition. A comparison between experiment and simulation is given for 8 MeV protons in Figure 5. The transport code was based on a program developed by Zaider *et al*[6] for the simulation of proton tracks in water. The applicability of the code was extended to energies up to 20 MeV primarily by implementation of the binary encounter approximation of Rudd *et al*[8] for the calculation of the emission of secondary electrons. The results for water were related to nitrogen by scaling. The agreement at large distances is good. The difference at small distances reflects the fact that the results obtained in this study correspond to a finite width of the proton beam; this makes the contribution of the energy deposits right on the proton trajectory visible, while the corresponding contribution is not visible in the plot for the simulations. The integrals, however, agree.

The comparison of the present results with earlier experimental data is limited by the fact that these are restricted to lower or higher proton energies. Toburen[9] has derived radial dose distributions for uranium ions of 5.9 MeV per nucleon from microdosimetric measurements which he performed with two simulated site sizes. The results deduced from the two series of measurements were not consistent. The radial dose distribution which he deduced from the measurements with a simulated site size of 500 nm is, when rescaled, in good agreement with the results obtained in this study; the profile he obtained from the measurements with the smaller site size of 125 nm are somewhat broader at small distances, and more narrow at distances beyond 100 nm. As seen in Figure 7, the profiles determined by Mills and Rossi[10] are generally somewhat more narrow than the results obtained in this study. So far no

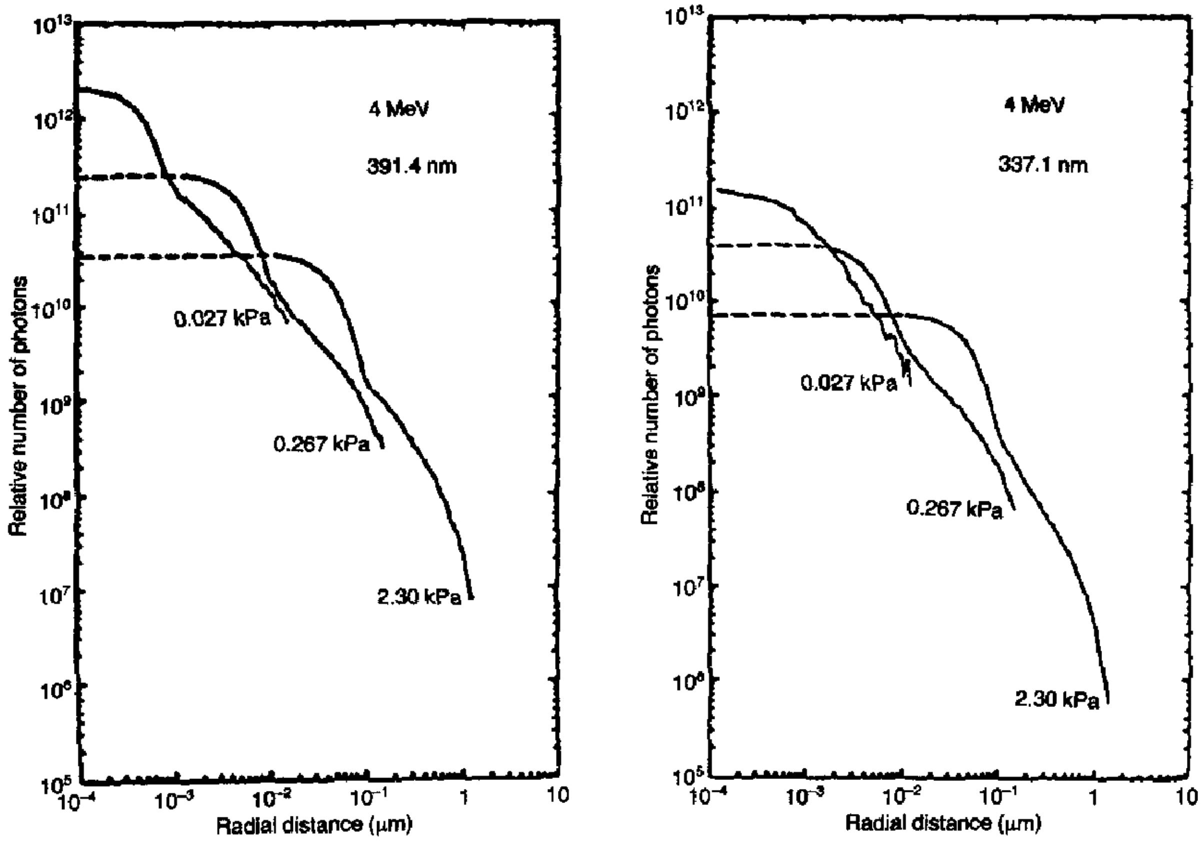

Figure 3. Relative number of photons versus distance between proton beam axis and axis of the optical system i.e. data before the 'Abel inversion'. The measurements were performed at different nitrogen gas pressures; the number of photons and the distances are referred to gas density 1 $g.cm^{-3}$.

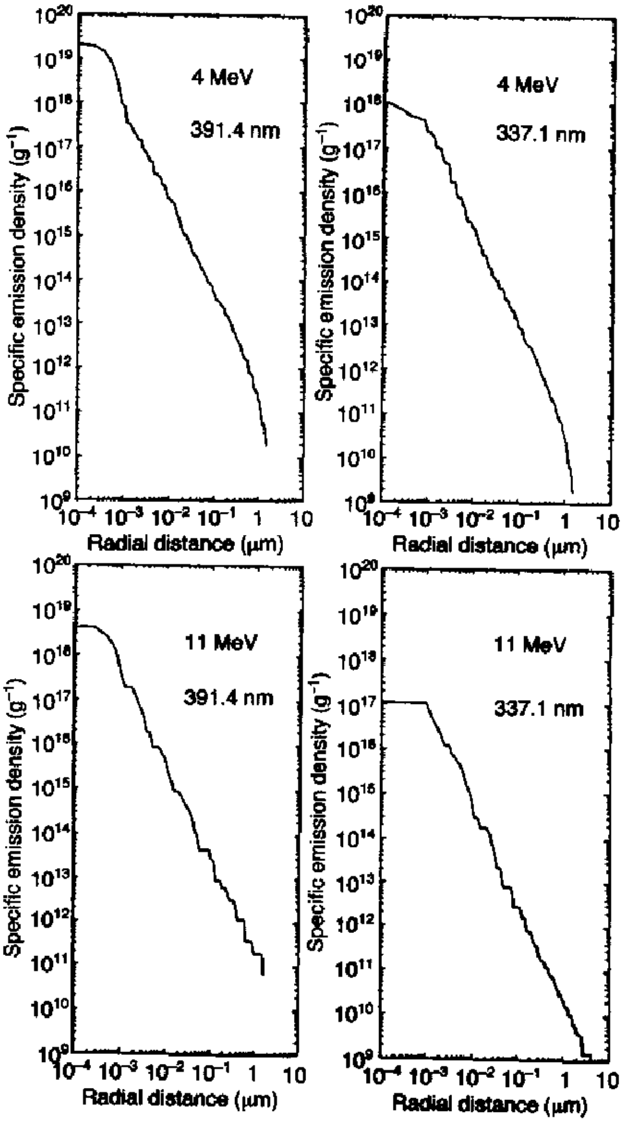

Figure 4. Specific emission density in nitrogen as a function of radial distance; emission density and distance refer to gas density 1g.cm^{-3}.

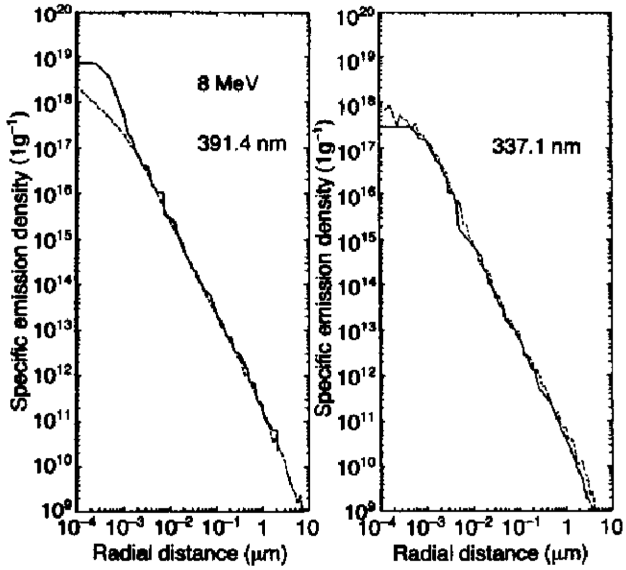

Figure 5. Specific emission density versus radial distance; both quantities refer to gas density 1 g.cm^{-3}. Comparison of experiment (——) and Monte Carlo simulation (---).

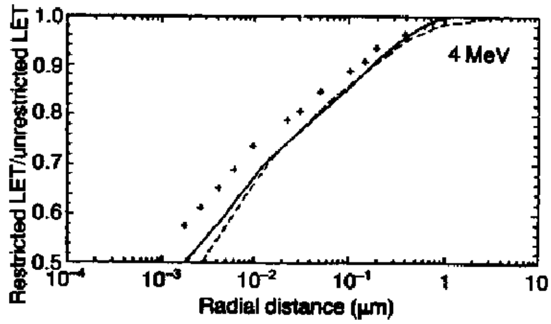

Figure 7. Radial-restricted LET divided by unrestricted LET versus radial distance. The crosses represent measurements of Mills and Rossi (1980)[10] in tissue equivalent gas. The solid line is derived from the measurements in nitrogen of this study. The broken line gives the results of a Monte Carlo simulation for water; the code is a modification of the program of Zaider *et al* (1983)[7].

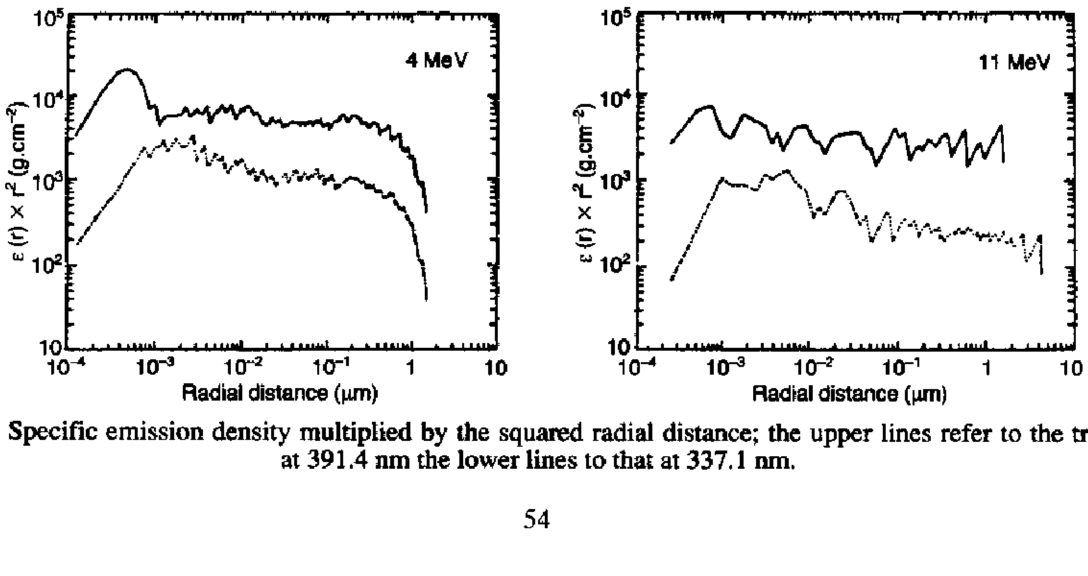

Figure 6. Specific emission density multiplied by the squared radial distance; the upper lines refer to the transition at 391.4 nm the lower lines to that at 337.1 nm.

explanation for this difference, which can not solely be due to the finite width of the proton beam in the experiment, has been derived.

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