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Preliminary communication

Status report: Nanodosimetry of carbon ion beam at HIL

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ABSTRACT

We present preliminary data for measured distributions of ionization cluster size produced by carbon ions in tissue equivalent media. The experiments were carried out with a beam of 92 MeV carbon ions from the U200p cyclotron at the Heavy Ion Laboratory (HIL), University of Warsaw, and nitrogen targets using the so-called Jet Counter set-up.

1. Background

Great effort has gone into understanding the effects of ionizing radiation on living organisms. In particular in nanosites, such as DNA molecules, ionizing radiation induces elementary electric charges in the form of single or clustered charges. In living cells, radiation may cause reparable or irreparable DNA damage. This knowledge is nowadays used in photon beam radiotherapy.[1] However, with the progress of accelerator technology new methods, which use heavy charged particles forming a beam of radiation, are coming into use. One of the most interesting choices are carbon ions.[2] However, there is no way to perform an experiment showing single event effects in living tissue or water. The only way to gain this knowledge is to make a Monte Carlo simulation or an experimental model. A pioneer experimental work was done in 1976 by Pszona.[3] In some recent papers, this approach has been well applied to alpha particles[4–7] and low energy electrons.[8,9] The present paper presents first results of experimental modelling of the interaction of carbon ions with nanosites comparable in size to a short segment of a DNA molecule (unit density 1 g/cm^3). The main emphasis is placed on the formation of charge clusters induced by 53 and 73 MeV ions passing through the sensitive volume of nitrogen gas at low pressure. These energies are close to the Bragg peak, which are of the greatest interest in terms of biological effectiveness of charged particles in radiotherapy.

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2. Materials and methods

The main device used in the experiments was an ion counting nanodosimeter called a Jet Counter (JC), which has been developed and improved over the past two decades by a group from the National Centre for Nuclear Research, Poland.[4,7] The JC consists of an interaction chamber (IC) where a sensitive volume with nanometric dimensions is created by expansion of a gas (preferably nitrogen) jet from reservoir R injected by piezoelectric valve PZ (see Fig. 1). Nitrogen molecules are ionized by single carbon ions passing the sensitive volume by forming ionization clusters of different sizes. The frequency of formation for a given size cluster is stored on an event-by-event basis with a known total efficiency of about $\eta \approx 40\%$. This value is a product of efficiency of ion extraction, ion guiding to ion detector and ion detector itself.[7]

The method of determining the density of gas jet injected into the IC is based on measurements of electron transmission and has been described in detail in the following paper.[7] The electron transmission curves were determined for two sizes of the sensitive volume of nitrogen released to the IC in a single injection. The size ratio was set at 1:2, which should provide a similar ratio of mass-per-area of gas target.

As shown in Fig. 2, the duration and location of the maximum density (minimum transmission) hardly depend on the amount of gas injected. However, the minimum value is variable and is different in each case. For the calculation the period of 340 μs was chosen, wherein the density changes by no more than 5% around the mean value. Mean values appear in Fig. 2 as curve labels. Also, the period of 340 μs is the time window in which the JC is ready for measurement and waits for the arrival of a single ionizing particle.

The source of carbon ions was the U200p cyclotron operated by the Heavy Ion Laboratory, University of Warsaw. The primary energy of the carbon ion beam was 92 MeV. The beam impinged on a thick gold foil and ions scattered at an angle of 45° entered the JC, as shown in Fig. 3. During dosimetric measurements the energy spectra of carbon ions leaving the IC were collected. A silicon detector was used to measure the energy spectrum of particles and trigger the acquisition system of the JC.

Due to the limited beam time that was available for the experiment, it was decided that the measurements would be carried out for four cases. Two beam energies of ions and two sizes of simulated nanosites (two target densities) were chosen.

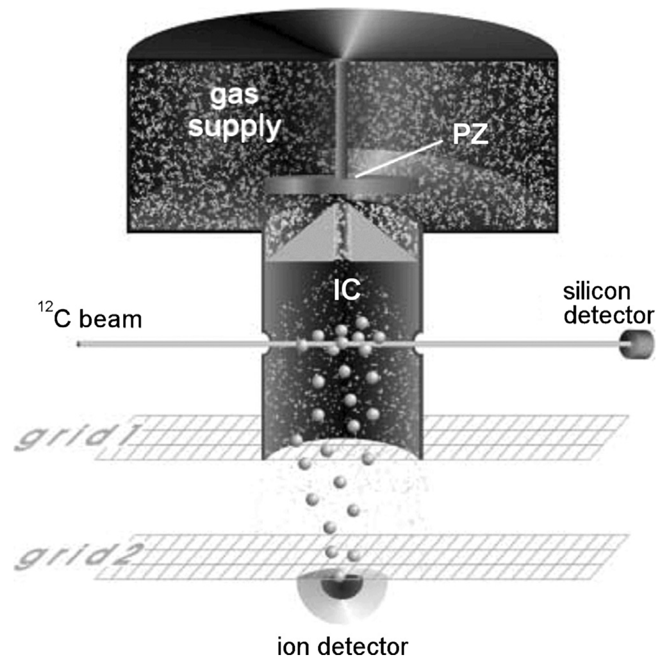

Fig. 1 – Schematic view of the Jet Counter.

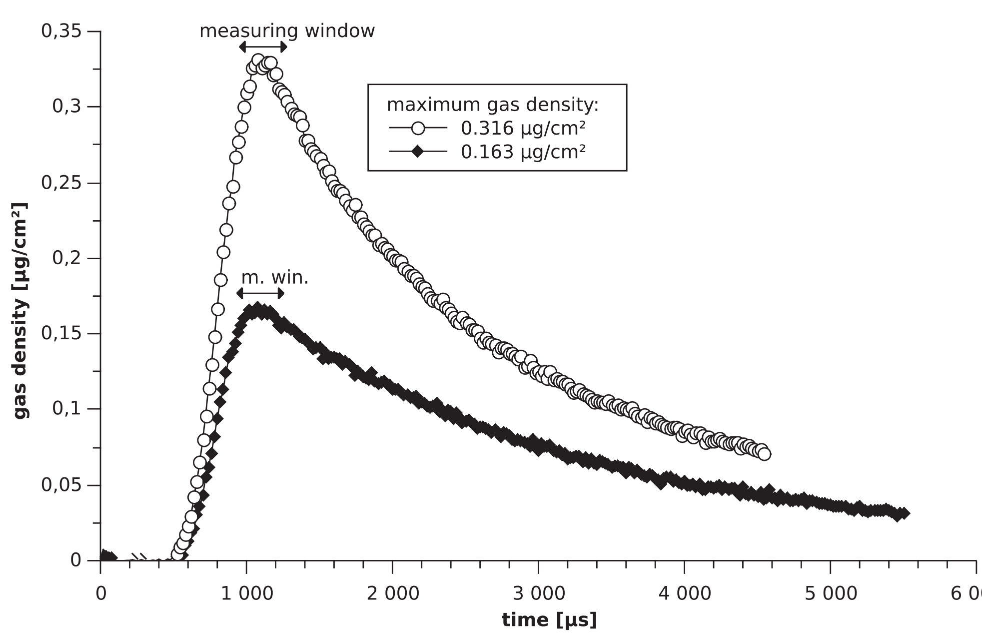

Fig. 2 – Time dependence of instantaneous mass-per-area of nitrogen jet released into the interaction chamber. Maximum gas density is the value of the actual nitrogen target.

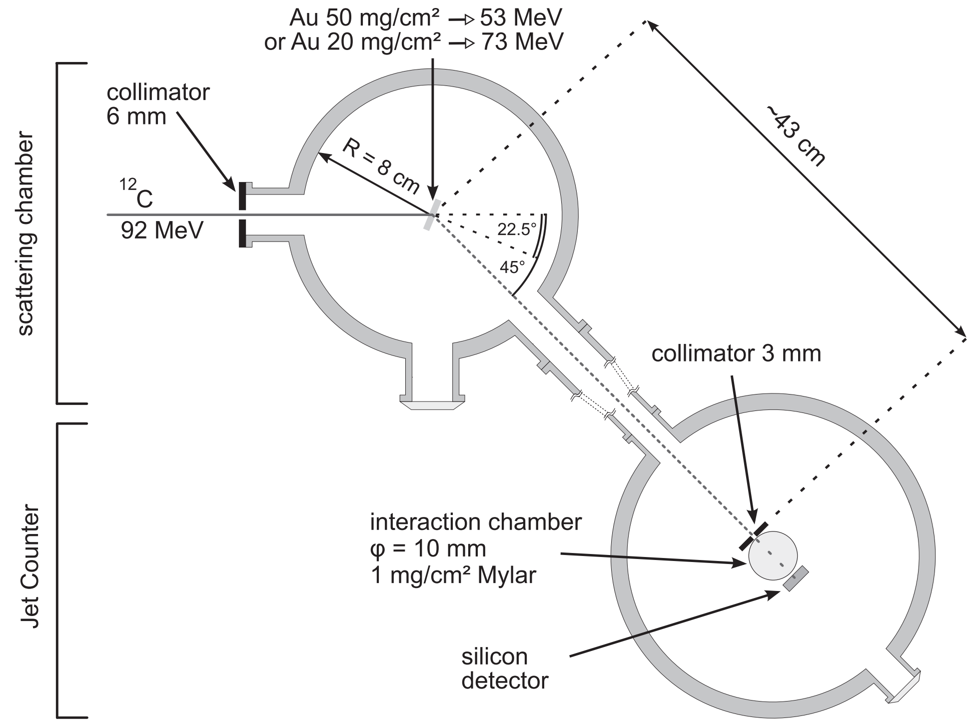

Fig. 3 – Schematic view of the whole setup used in experiment.

The mean energy of the carbon ion beam hitting the silicon detector was 50 and 70.5 MeV for 50 and 20 mg/cm^2 gold foils, respectively. As shown in Fig. 4 the spectra of the carbon ions are strongly broadened due to straggling effects. Also, it should be noted that the particles undergo an additional scattering on the walls of the interaction chamber before they reach the detector. However, at the moment of production of the ionization clusters, they had only passed through one wall, so that their energy is slightly higher. Calculations show that for slower ions, a single Mylar foil (1 mg/cm^2) degraded its energy by approximately 3 MeV, while for the faster ions only by 2 MeV.

Due to the pulsed nature of the ion beam and also the pulsed nature of the JC operation, it was necessary to synchronize them to achieve the highest possible efficiency of the whole system. This was accomplished by an additional electronics system shown in Fig. 5. This allows the cyclotron RF signal to trigger the PZ valve of the JC in a moment which provides the highest beam intensity during the measurement time window of JC.

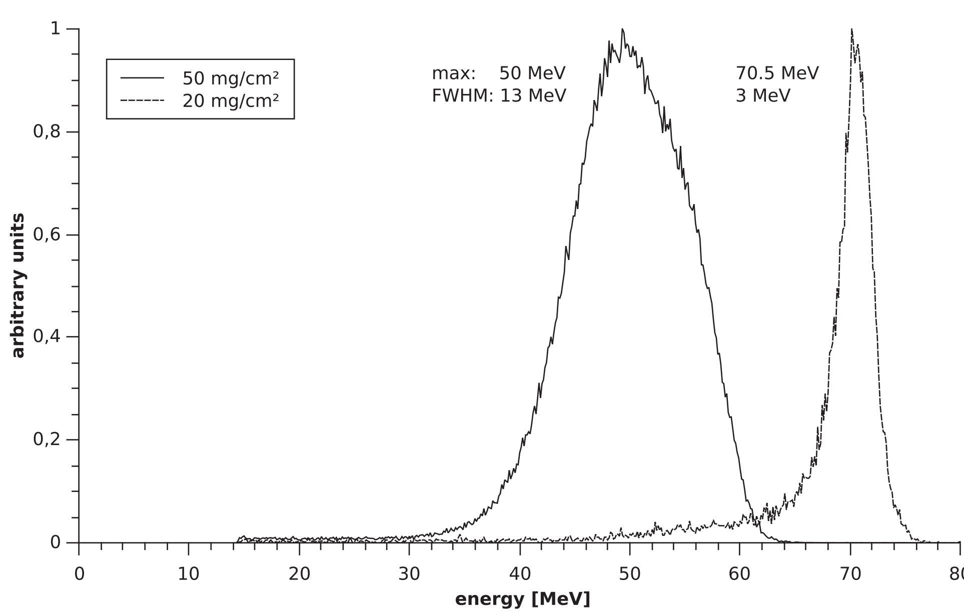

Fig. 4 – Measured energy spectra of carbon ions hitting the silicon detector.

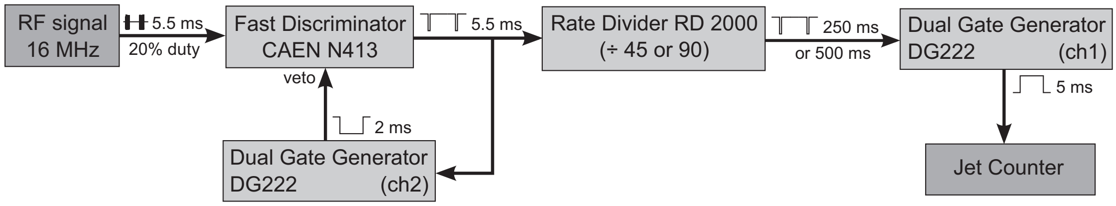

Fig. 5 – Electronic system used for synchronization of the cyclotron and Jet Counter device.

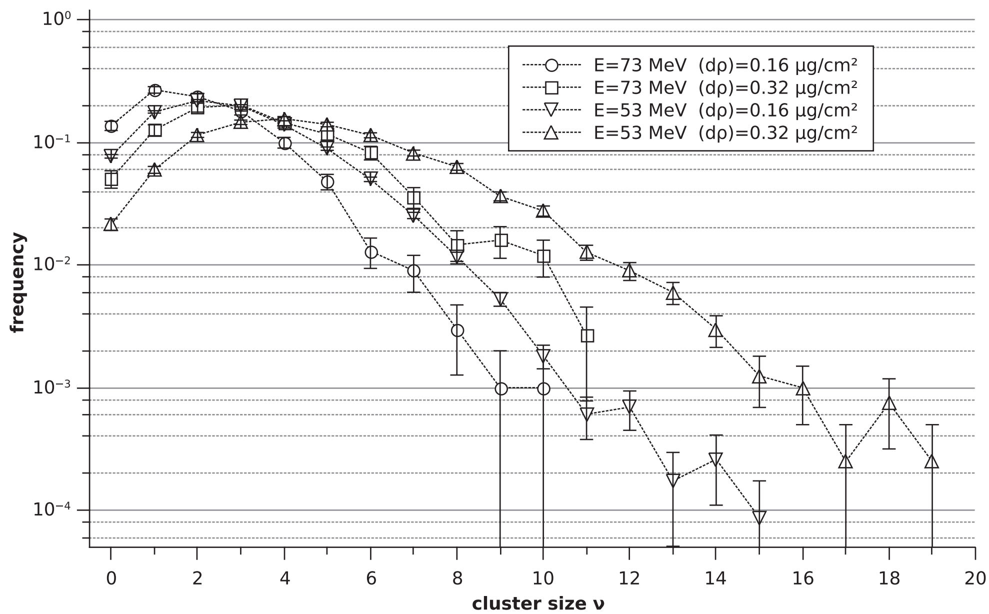

Fig. 6 – Measured distributions of ionization cluster size produced by carbon ions.

3. Results and discussion

The frequency cluster size distributions obtained in the experiment are shown in Fig. 6. Unfortunately, the small number of registered events leads to significant statistical errors for large values of the cluster size. Production of a large cluster is a very rare event, so a larger number of such cases would require a significant extension of the data collection time or improvement in system efficiency. As the available beam time is limited, we should rather focus on the second option and increase the efficiency of the system. The very low intensity of the scattered beam could be easily increased by reducing the scattering angle to 22.5°, which will be done in the next experiment.

The MC simulations were performed for similar experiment with a few MeV alpha particles[6,7] and low energy electrons.[7] MC code for carbon ions is still under development and yet to be compared with extended experimental results.

Using the experimental frequency distributions, important descriptors of radiation quality were determined. The first moment of the distribution, M_1, describes the mean cluster size equal to the mean number of ion pairs formed by a single particle track in the sensitive volume of the interaction chamber. Also, M_1 can be assumed to be equivalent to the absorbed dose D (for radiobiology) and to charge (for nanoelectronics).[7]

As the ions were detected with known efficiency of about $\eta \approx 40\%$, the mean cluster size at efficiency of 100% is equal to: $M_1\ (100\%) = M_1(\eta)/\eta$.[10] The results of this calculation are presented in Table 1. It is clear to see that carbon ions at the measured energies can produce on average more than two ionizations on the DNA scale, and as a result may produce double strand breaking (DSB) in DNA with probability close to 1.

An important parameter defining the radiation quality that may be extracted from the measured frequency distributions is the probability of forming cluster size $\nu = 1$, $P_1(Q)$. P_1 relates to the formation of single strand breaks (SSB) of DNA. Also the cumulative distribution function is the sum of the distribution function $F_2 = \sum_{i=2}^{\infty} P_i(Q)$. The cumulative distribution function F_2 describing the probability of forming cluster size $\nu \geq 2$ could

Table 1 – Mean cluster size extracted from the distributions of ionization cluster size produced by carbon ions.

Energy (MeV)	$d\rho$ (μg/cm^2)	M_1 (exp.)	M_1 (100%)
53	0.16	2.88	7.20
	0.32	4.86	12.15
73	0.16	2.11	5.28
	0.32	3.45	8.63

be related to radiobiological data describing the formation of double strand breaks (DSB) of DNA. Direct extraction of these parameters is not possible as the measured distribution must be converted to 100% efficiency.

4. Conclusions

In the experiments performed here the distributions of cluster size produced by carbon ions were measured. The measurements were carried out for ion energies of 53 and 73 MeV, respectively. For each energy, two densities of gas were selected, 0.16 $\mu g/cm^2$ and 0.32 $\mu g/cm^2$, respectively. The obtained results clearly show that the Jet Counter facility is capable of taking nanodosimetric measurements for heavy ion beams in a wide range of parameters. This means that the main aim of the experiment was fully achieved. In addition, the experiment showed that the intensity of the beam guided to the nanodosimeter can be safely increased in order to fully exploit the device performance.

The experience gained in these measurements will be useful when performing modifications for the next experiment, which will allow us to investigate more cases and to collect better statistics in each of them. These new data will be used to compare experimental results with Monte Carlo simulations.

Conflict of interest

None declared.

Financial disclosure

None declared.

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