Computer simulation in proton therapy

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Abstract. The ionising radiation as a method of cancer treatment has a long history. Any types of radiation have been employed to achieve control of tumour viability such as a ‘low’ linear energy transfer (LET) beam of photons, two ‘high’ LET unmodified and spread-out Bragg peak (SOBP) beams of protons. Per the end of 2018, about 190036 patients have been treated with protons [1), 93 facilities in clinical operation worldwide in April 2020 (2). The unattainable goal so far is the creation and implementation of such a treatment plan in which the target volume receives 100 % of the prescribed dose and healthy surrounding tissue 0%. The goal of modern science to find ways to “optimised” treatment plan especially in childhood cancer, where the preservation of healthy tissue surrounding the tumour is especially important. In our work we presented the results of a calculated experiment of the interaction of a laser impulse with various targets and showed the dependence of energy distribution from the target types.

1. Introduction
The use of ionizing radiation to treat cancer has a long history. Various types of radiation have been and are being used to achieve control over tumor viability. However, proton therapy can be an effective, and sometimes the only, method for treating many types of tumors, including tumors of the prostate, brain and spinal cord, head and neck, lungs, and gastrointestinal tract. Due to its peculiarities, this type of therapy is the preferred option in many cases in the treatment of tumors in children. At the end of 2017, almost 200,000 patients were treated with elementary therapy. About 170,500 patients were treated with protons, about 25,700 with carbon ions, and about 3,500 with helium, pions and other ions. (1) In traditional radiation therapy, streams pass through the tumor, while irradiating nearby healthy organs and tissues. When using proton therapy, the radiation is extremely concentrated on the pathological focus, which significantly reduces the effect on the surrounding healthy organs and tissues. They are significantly reduced, but unfortunately, are not completely excluded, in terms of the severity and frequency of occurrence of side effects. This expands the possibilities of treating elderly and debilitated patients, reduces the risk of secondary cancers, and significantly preserves the patient’s quality of life. The depth-dose profile of four current types of external beam radiation - a photon beam with a ‘low’ linear energy transfer (LET), two unmodified beams with a ‘high’ LET, and extended Bragg peak proton beams (SOBP) and carbon ions - are compared at Figure 1. (2)

The main advantage of using beams of protons and carbon particles is that the radiation dose increases very slowly with increasing depth of penetration and reaches a sharp maximum in the pathological focus where the beam stops. At this point, the time of interaction of the ion with the medium increases due to a decrease in its velocity, which leads to an increase in
the ionization of the atoms of the medium, which ultimately leads to an unrecoverable double-stranded break of a larger number of DNA molecules. Damage to the nucleus occurs at a dose of 1 to 2 Gy. If both DNA strands break, the cell is unable to restore them and dies. In the event of damage to one helix, the mechanism of molecule recovery is activated, which increases the percentage of restored cells. Proton therapy has potential radiobiological benefits, such as reduced oxygen enhancement ratio (OER), making it highly effective for photon-resistant hypoxic tumors; reduced repair capacity; reduced dependence on the cell cycle; and, possibly, a higher immunological response due to the predominant occurrence of double-stranded DNA breaks in the body Figure 2, 3, 4. (2.5)

\[
\text{(RBE)} = \frac{D_y}{D_x}
\]

where \(D_y\) is the dose delivered by X-rays or gamma rays; \(D_x\) the dose delivered by the ions in question, which is required to achieve a similar biological effect. The \(D_y\) dose standard is the dose of an artificial source of photons \(^{60}\text{Co}\) RBE = 1. \(RBE(\text{proton}) \approx 1.1\text{RBE}\)

To realize the full potential benefits of proton therapy, the proton beam range must be predicted as accurately as possible during treatment planning and delivery. Uncertainties in the exact position of the distal dose gradient arise from a) organ movement, b) tuning and anatomical variations, c) approximate dose calculations, and d) biological considerations. A prime example is the use of proton therapy for chordoma and chondrosarcoma. When localized at the base of the skull, surgical resection may be technically difficult or impossible, and postoperative radiotherapy is required for a large neoplasm. However, proximity to critical structures can be difficult to deliver doses of sufficient intensity. According to the literature data, the proton therapy allows increasing the dose - median dose was 73.8 Gy (RBE; range 68.4-79.2 Gy), while
the sharp dose gradient limits toxicity to critical normal tissues. Median follow-up was 37 months. The 3-year local control and progression-free survival was 86% and 81%.

Mathematical modeling makes it possible to make a virtual environment and conduct an experiment that allows you to select a parameter to obtain the necessary ion energies. Task of mathematical modeling facilitates selection of laser pulse parameters and creation of targets for obtaining fast ions. Here we present the results of one numerical experiment.

2. Mathematical model
In this section we presented the computer simulation result of the interaction laser pulse with multiclusteres plasma. Our purpose is to receive the accelerated protons.

Interaction of intense laser pulses with the cluster targets has raised a great interest since a long ago. The laser cluster interaction shows many specific features, which can be encountered in both the gas and solid materials. The clusters have their own characteristics as well.

We observed two competitive effects. The first effect is the laser light incoherent scattering on individual clusters. It leads to the laser pulse spreading and its energy attenuation. The second effect appears due to the change of the mean refractive index. It may result in the self-guided laser propagation.

The dimensions of the simulation box are $300\lambda \times 50\lambda$, the numerical mesh size being $\lambda/20$. The diameter of the cluster is $0.75\lambda$ The total number of quasiparticles is $10^6$. The ion to electron mass ratio is 1836 (hydrogen plasma). The electron density corresponds to $\omega_{pe}/\omega = 400$. A circularly polarized laser pulse is launched from the left boundary of the simulation box. The laser gaussian pulse has a amplitude $a = 10$, with $Lx = 100$, $Ly = 12$. 

**Figure 3.** Definition of relative biological effectiveness (RBE), illustrated for cell survival curves

**Figure 4.** Curves of RBE and OER as functions of LET
The figure shows the distribution of the electric field at the moment of pulse passage, the formation of three jets is visible, that is, we form three directions of accelerated ions, which allows you to process three targets. Fast ions are accelerated due to the combination of the Coulomb explosion and the electric charge separation mean electric field up to the energy 10 MeV.

3. Conclusion
The counter-play of the laser pulse scattering in the case of relatively low power pulse laser propagating through the cloud of large diameter clusters and the laser pulse self-focusing in the small diameter high density cluster cloud results in: fast electron generation occurs due to the vacuum heating and direct laser acceleration; fast ion are generated due to the Coulomb explosion and in the mean electric field formed by the electric charge separation.

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