Mathematical modelling the interaction of laser pulse with substance for the tasks of proton therapy

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Abstract. In this paper, we discuss using laser plasma as a source of high-energy ions for the purposes of hadron (proton) therapy. Hadron therapy (HT) is a modern, high-precision form of radiation therapy that uses protons to irradiate diseased tissue. HT has received the greatest use for the fight against cancer. The high accuracy of cancer cell damage, together with the gentlest impact on healthy organs and normal tissues, the absence or mild side effects, make proton therapy indispensable where the tumour is located next to the vital organs, in paediatrics, where the anatomical location of the tumour makes it impossible for surgical removal and use of photon therapy will place the patient at an unacceptable risk. In our work we present the results of mathematical modelling of laser pulse with substance. Computer modelling gives the chance of selection of parameters of a laser pulse and target, for more exact focusing of a pulse and obtaining the set energy of ions.

1. Introduction
Lasers are sources of the strongest electromagnetic radiation under terrestrial conditions. This gave impetus to extensive theoretical and experimental studies of ion acceleration using high-power lasers. The most important applications of fast ion beams generated in the laserplasma interaction are hadron therapy for oncological diseases.

By the end of 2017 almost 200’000 patients had been treated world wide with Particle Therapy. About 170500 have been treated with protons, about 25700 with C-ions and about 3500 with He, ions and other ions.[1] 80+ treatment rooms to be operational in Europe by 2020. [4]. The use of ionising radiation to treat cancer has a long history. Many types of radiation have been employed to achieve control of tumour viability. The depthdose profile of four current types of external beam radiations a ‘low’ linear energy transfer (LET) beam of photons, two ‘high’ LET unmodified and spread-out Bragg peak (SOBP) beams of protons, and carbon ions are compared in Figure 1. [2].

The above data indicate a huge difference in the distribution of the radiation dose received from different sources. The main advantage of using proton and carbon particle beams is that the dose of radiation increases very slowly with increasing penetration depth and reaches a sharp maximum at the point (target) at which the beam stops. In this point, the time of interaction of an ion with a medium increases due to a decrease in its velocity, which leads to increase in the ionization of the atoms of the medium. This will ultimately lead to an unrepairable double-strand break of a larger number of DNA molecules. Thus, tumours can be targeted more accurately whilst minimizing damage in adjacent normal tissues. Currently, proton/12C ion beams have been used for the treatment of various tumours, including radio resistant tumours.
close to radiosensitive organs, base of skull and spine tumours, eye tumours, paediatric tumours, lung, prostate and other cancers. [4] The treatment has been successful, giving high local control rate achieving 90 % or higher 5-year local control in some cases and 90% or higher 5-year patient survival for some cancers [3]. To realize the full potential advantage partial therapy, the range of proton/ carbon particle beams in patients’ need to be predicted as accurate as possible in the treatment planning and delivery process. Uncertainties in the exact position of the distal dose gradient arise from a) organ motion, b) setup and anatomical variations, c) dose calculation approximations, and d) biological considerations. At the Massachusetts General Hospital (MGH), treatment planning assumes an uncertainty in the proton beam range of 3.5% of the range plus an additional 1mm. Other centres follow similar margin recipes [6]. Of especial interest is the carbon-ion beams, since the LET of carbon beams is larger than that of proton beams, the Relative Biological Effectiveness (RBE) is 2-3 times greater for carbon ions, it permits it to deliver a sufficient dose to the target with minimal damage to adjacent healthy tissues. This is a huge advantage in the treatment of radiation-resistant tumours [4]. The effect of the tail, which develops because of fragmentation due to nuclear interaction with atoms, is clinically insignificant, because fragments deliver only low doses with a predominantly low LET component. Carbon ions offer potential radiobiological advantages such as: reduced oxygen enhancement ratio (OER), which makes them highly effective for photon-resistant, hypoxic tumours; reduced repair capacity; decreased cell-cycle dependence; and possibly higher immunological responses owing to predominant occurrence of double-strand DNA breaks in the body [2],[5].

In this article we presented the mechanism of acceleration ions - Columb explosion. We demonstrate the results of 3D PIC and 2D PIC simulations of the ultra short high irradiance laser pulse interaction with targets where the plasma containing multicomponent cluster targets is imbedded in an underdense plasma [7].

2. Columb explosion
Clusters, which correspond to a specific class of targets for laser radiation interaction with matter, are sub-wavelength pieces of solid. According to the properties of the laser-cluster interaction, the gas of clusters occupies an intermediate position between gaseous and solid (foil) targets. On one hand, the electromagnetic wave can penetrate deep into the depth of the cluster cloud target. On the other hand, the radiation interaction with individual cluster demonstrates processes typical for the laser interaction with solid targets. A cluster is characterized by its material, size, and internal structure.

Generation of fast ions during the Coulomb explosion of a cluster irradiated by a laser pulse
is assumed to be the main mechanism for ion acceleration at moderate laser intensities.

During a Coulomb explosion, electrons are pushed out of the cluster by the radiation pressure of an intense electromagnetic wave. As a result, a cloud of positively charged ions accelerated due to Coulomb repulsion of likely charged particles is produced. The energy of fast ions is proportional to the electrostatic potential of the positively charged ion cloud. For relatively small clusters and high laser intensities, ions and electrons are pushed forward by the radiation pressure of the electromagnetic wave. [8]

2.1. Results of the 2D computer simulation with proton cluster

In this subsection we presented the computer simulation result of the interaction laser pulse with cluster. Our purpose is to receive the accelerated ions. We consider the region

The dimensions of the simulation box are $70\lambda \times 70\lambda$, the numerical mesh size being $\lambda/20$. The diameter of the cluster is $2.5\lambda$. The total number of quasiparticles is $10^4$. The cluster is initially located at $x = 30\lambda$. The ion to electron mass ratio is 1836 (hydrogen plasma). The electron density corresponds to $\omega_{pe}/\omega = 4$. A circularly polarized laser pulse is launched from the left boundary of the simulation box. The laser pulse has an amplitude $a = 100$, is correspondent the $1.37 \times 10^{22} \text{W/cm}^2$.

![Figure 2. The electron density at the initial time](image1)

![Figure 3. The Coulomb explosion.](image2)

![Figure 4. The phase plane. Homogeneous expansion of the ions.](image3)

On the figure 3 we see the coulomb explosion. We know that the ion energy grows proportionally to $t^{1/3}$ power
2.2. Results of the 2D computer simulation with carbon cluster

Try to compare the result of computer simulation proton cluster and carbon cluster under the same condition.

The dimensions of the simulation box are $70\lambda \times 70\lambda$, the numerical mesh size being $\lambda/20$. The diameter of the cluster is $2.5\lambda$. The total number of quasiparticles is $10^4$. The cluster is initially located at $x = 30\lambda$. The ion to electron mass ratio is 12001. A circularly polarized laser pulse is launched from the left boundary of the simulation box. The laser pulse has an amplitude $a = 100$, and is correspondent to the $1.37 \times 10^{22} W/cm^2$. We see that in this case process develops more slowly as ions of carbon fabrics it is heavier. However, they bear on themselves big energy. Follows, to note that if we increase amplitude by 3 times, then ions will move a whole

![Figure 5. The ion density at the final time](image)

2.3. Results of the 3D computer simulation

We assume that the critical parameter of an intense EM wave interaction with a cluster is the ratio between the minimal energy, which is necessary to separate charges, and the typical kinetic energy acquired by all the electrons in the EM wave on a distance of the order of the cluster diameter

$$\epsilon_{\text{min}}/\epsilon_k = \pi/5 r_e/\lambda (\omega_{pe}/\omega)/a$$

where $a = eE/(m_e c)$ is the dimensionless amplitude of the EM wave. If this parameter is much less than one, we have a 'pure' Coulomb explosion, i.e. all the electrons abandon the cluster within a few EM wave periods.

The 'pure' Coulomb explosion is demonstrated in this subsection. We considered the cube region $-1 \leq z \leq 1, -1 \leq y \leq 1, -1 \leq x \leq 1$. The linearly polarized semi-infinite $1\mu m$ laser pulse propagates in the $x$-axis direction. Its peak intensity is $1.37 \times 10^{20} W/cm^2$, corresponding to the dimensionless amplitude $a = eE_z/(m_e c\omega) = 10$ (at $\lambda = 1\mu m$). The pulse front length is $3\lambda$. The cluster with diameter 0.2$\mu m$ is placed in the cubic simulation box with edge size $10.2\lambda$. We assume that the cluster is a drop of an ideal hydrogen overcritical plasma, $n_e = 100n_{cr}$. Grid size is $1024^3$, total number of quasiparticles is $3 \times 10^6$. We see that all the electrons abandon the cluster within a couple of laser periods. Stripped protons undergo the Coulomb explosion and acquire energy. Their spectrum is shown in Fig. 5.

We see that ion take a high energy. The energy is equal 5.2 MeV.
3. Conclusion
Results of a computing experiment of a vzaimodestviye of a super short and super strong laser impulse with substance are presented in our article. Receiving a precise dosage of ions of high energy was shown. Ions of high energy are applied in medicine (proton therapies). It should be noted that taking into account fast development of technologies and creation of heavy-duty lasers, the possibility of use of proton therapy for treatment of various diseases is extending rapidly.

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References
[1] PTCOG Patient Treatment Statistics https://www.ptcog.ch/
[2] Dosanjh M, Bernier J 2018 Advances in Particle Therapy: A Multidisciplinary Approach Series in Medical Physics and Biomedical Engineering CRC Press 9,170 282
[3] Younghyun Lee, Ryuichi Okayasu 2018 Strategies to Enhance Radiosensitivity to Heavy Ion Radiation Therapy International Journal of Particle Therapy Summer 5 1 114-121
[4] Fraile LM 2018 Proton therapy and nuclear techniques for oncology
[5] Mording EJ, Kastan MB, Kirsch DG Jul 2013 Strategies for optimizing the response of cancer and normal tissues to radiation Nat Rev Drug Discov 12 7 526542.

[6] Paganetti H Jun 2012 Range uncertainties in proton therapy and the role of Monte Carlo simulations Phys Med Biol. 7 57 11 R99R117.

[7] E. Y. Echkina, I. N. Inovenkov, T. Z. Esirkepov et al. 2009 Propagation of the high power laser pulse in multicomponent cluster targets Laser Physics 19 228230.

[8] E. Yu Echkina, I. N. Inovenkov, T. Zh Esirkepov, F. Pegoraro, M. Borghesi, and S. V. Bulanov. 2010 Dependence of the ion energy on the parameters of the laser pulse and target in the radiation pressure dominated regime of acceleration. Plasma Physics Reports, 36(1), 1732.