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PROPOSAL FOR A NEW TYPE OF ACCELERATOR FOR ELECTRONS AND PROTONS

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Abstract. A new laser-based acceleration structure for protons, with characteristics appropriate for the radio therapy is proposed in the present work. The structure is designed in two stages of acceleration – the first one accelerates electrons to GeV energies and the second one uses these electrons in order to accelerate protons in the hundreds of MeV range. It uses commercial available pulsed lasers and it is expected to have the geometrical sizes that fit into a usual oncological treatment room. The accelerated proton beams have energies of hundreds of MeV with a medium to large spread, a high repetition rate, geometrical dimensions and emittance adequate for a small size medical accelerator facility. The present proposal is mainly an attempt coming from the medical community to bring into the attention of accelerator scientists the huge need for small size treatment accelerators, nowadays feasible grace to the last decades progress in laser technologies.

Key words: pulsed laser, two-phase acceleration, accelerated electron beam, capillary device, “bubbles” of accelerated electrons.

1. INTRODUCTION

A major technical challenge of the hadrontherapy field is the reduction in the sizes of the protons and carbon ions accelerators as well of the radiotherapy devices. The huge progress in the high power laser technology in the last decades is mainly due to the advent of the Chirped Pulse Amplification (CPA) technique. It opens a realistic perspective for designing small size medical accelerators for protons and heavier ions. Two proton acceleration concepts which might lead to compact and cheap alternatives to the conventional radio-frequency accelerators and could solve the “one room accelerator” problem are discussed in the literature – the laser-driven ion acceleration in the Target Normal Sheath Acceleration (TNSA) process that is discussed since the 1970’s [1] and the Laser Wakefield Acceleration (LWFA) proposed by Tajima and Dawson [2].

In this paper it is advanced the idea to combine LWFA and TNSA techniques in order to design a two-step acceleration structure that can deliver a beam of protons with energies in the 100 MeV ranges, intensities and geometrical characteristics required by radio therapeutic oncological treatments. In the first step a pulsed laser beam increases the energy of a free electrons beam by a LWFA mechanism (Section 3.1 and Fig. 3) while in the second step the pulsed beam of electrons obtained in the first stage increases the energy of a proton beam originating from a small energy ion source by a mechanism similar to the one of TNSA (Section 3.2). According to our knowledge, this is the first time when such a two-stage laser based acceleration system is proposed, and we strongly address the accelerator community to investigate its technological feasibility.

2. PRESENT STATUS: TNSA AND LWFA

2.1. TNSA

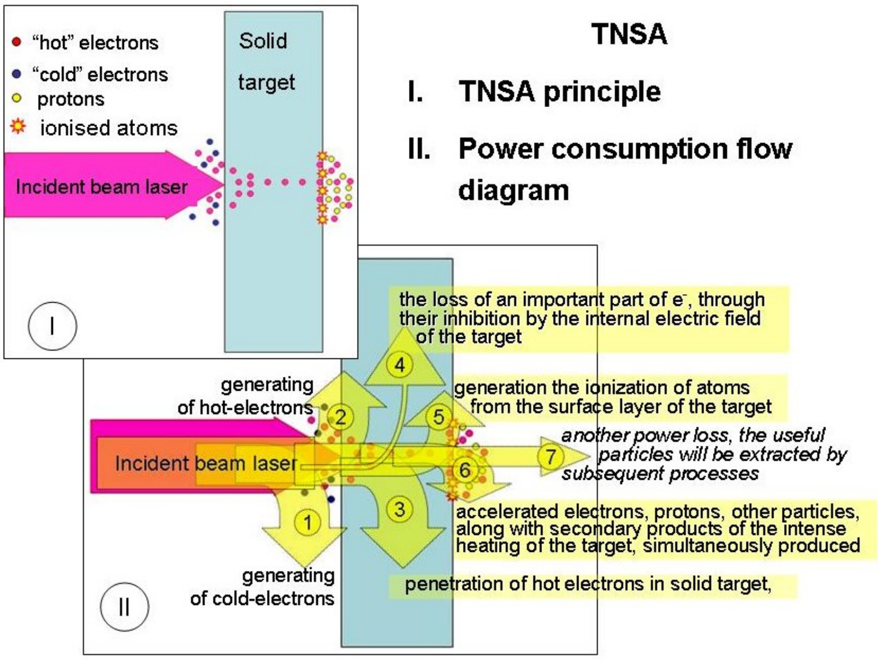

Fig. 1 – Schematic representation of the TNSA mechanism and the corresponding laser beam power consumption flow diagram [15, 16].

From an energy-balance perspective, TNSA appears as a sequence of processes of losing the energy of the incident laser beam in stages that do not serve entirely to accelerate target electrons, as it is schematically shown in Fig. 1. Examples are generation of hot-electrons, penetration of these electrons in solid target and the loss of an important part of them through their inhibition by the internal electric field of the target, ionization of atoms from the surface layer of the target, etc. It is observed experimentally that TNSA simultaneously produces accelerated electrons, accelerated protons, other particles, along with secondary products of the intense heating of the target scattered in a quasi-hemispheric volume. From this volume, the useful particles must be extracted by subsequent processes, implying another power loss [15, 16].

Although beams of accelerated protons have been produced by TNSA, proving the principle of this technique, there is still a long way ahead to reach the proton beam parameters required by medical therapy.

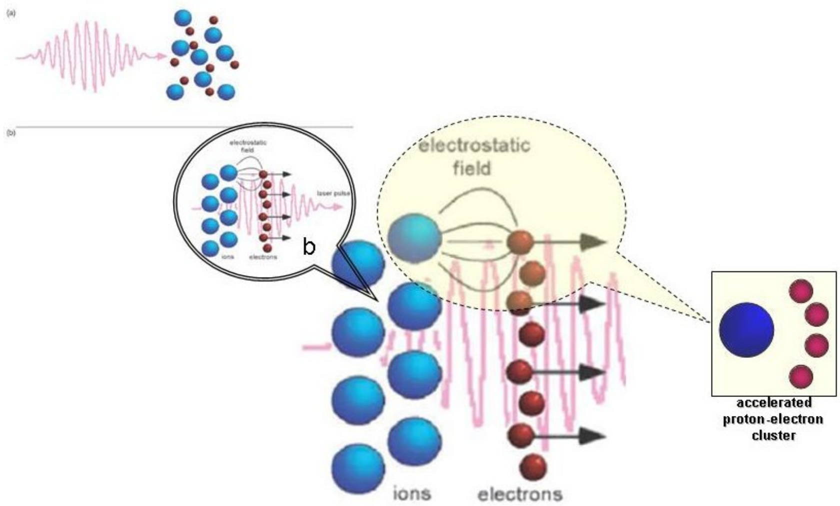

Fig. 2 – TNSA, generation of electrons and ions [14] with the electrostatic field created between them – a schematic representation [14].

As the schematic view of the TNSA mechanism presented in Fig. 2 shows, the laser-driven electrical field between electrons and ions is the one responsible for creating a "tractor" force on the ions (protons). This process from TNSA, can be seen as ion acceleration produced by the electron cloud, an idea exploited in the present proposal for the second stage of the accelerator – the proton acceleration from tens of keV to 100 MeV range. Since the required equipment for hadrontherapy has to be relatively cheap and adaptable to the possibilities and needs of the medical oncology in a short time period, we propose a TNSA – inspired technique for increasing the energy of protons. It would require lasers with pulse power in the tens of TW range which are commercially available nowadays and have "tabletop" dimensions.

2.2. LWFA

LWFA technology has usually two ways of implementation, as illustrated in Fig. 3. In the first (and most often proposed) one, a pulsed laser beam is injected into a capillary (glass or other material) placed in a cell with gas whereby pumping Hydrogen [7, 10, 12], Helium [6, 10] or Nitrogen [9, 10] into it.

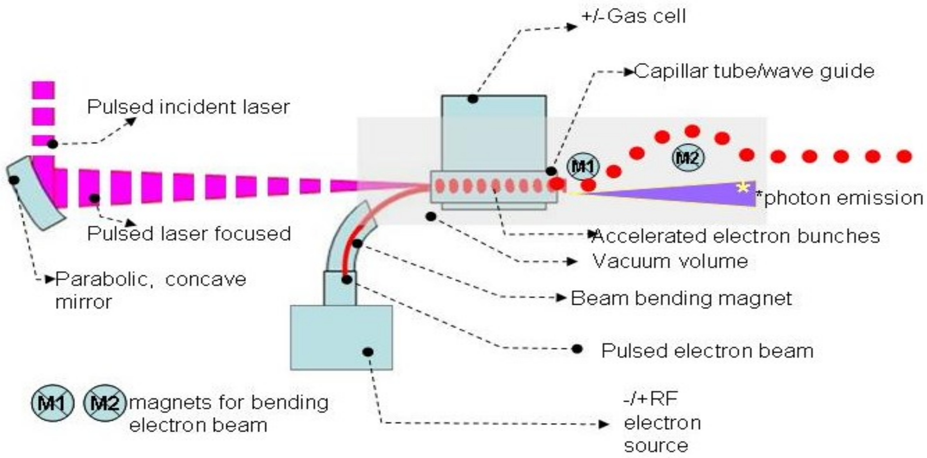

Fig. 3 – Schematic representation of the LWFA-based accelerator in the two versions discussed in the text. By using the external electron source the gas cell is no longer needed simplifying the acceleration model [12, 13 and 8]. See text for details.

The laser beam ionizes this gas producing ionized gas bubbles and electrons, particles that are subsequently separated. In the second approach, are injected simultaneously in the capillary a pulsed laser beam and an electron beam (produced by another source of electrons) with the same frequency, but in counter-phase, generating bunches of accelerated electrons.

In both acceleration methods, TNSA and LWFA, are produced also accordable Bremsstrahlung radiation and radiation with even lower frequency (terahertz) [5] that have to be separated from the beams of electrons and protons through a magnetic stirring. In a medical facility it is worth to develop techniques for using these radiations for macroscopic and/or microscopic Imagistics [22].

In LWBA-based electron acceleration scenario presented in Fig. 3, a critical problem discussed by several authors, refers to the synchronization of the pulses of electrons with the pulses of photons of the incident laser beam. Khachatryan *et al.*, [3] have introduced the concept of “distance of capturing” as the distance between a cluster of electrons and the beginning of the next pulse of photons, as a key parameter in adjusting the time distribution of the pulses of photons and electrons. There are several studies in the literature approaching from an experimental perspective the acceleration of electrons to the GeV energies by using LWFA techniques with TW lasers. We present in Table 1 the main features of the incident laser beams and the emerging beams of accelerated electrons, together with the characteristics of the capillary tube in which acceleration is produced, as are reported in Ref. [5–14].

Table 1

Ref.	**laser**	**Pulse/ fs**	**Energy**	**W/cm^2**	**Freq. Hz**	**gas**	**plasma density [cm^{-3}]**	**output electrons energy**	**ang. div.**	**Capill. diam.**	**Capill. length**
5	10–50 TW	40	> 1.3 J/pulse	10^{18}	–	–	2.7×10^{18}	1 GeV	–	190 µm, 225 µm, 310 µm	33 mm
6	40–TW	30	–	10^{19}	10	He_2	1.5×10^{19}	300MeV	100 µrad	–	–
7	40 TW	35–45	0.12 J	10^{18}	–	H_2	1.2×10^{18}	1–10 GV/m	–	50 µm	1.2–8.1 cm
8	16 TW	40	–	–	–	–	–	300 MeV	–	–	–
9	–	100 – 500	3.5 kJ	1.5×10^{16}–10^{19}	–	N_2	–	1 GeV up to 1 TeV	–	100 µm	less than 10 cm
10	–	20	150 mJ	1.5×10^{16}	100	H_2 or He_2	–	50–250 MeV -	–	–	–
11	10 PW	224	–	–	–	–	2.7×10^{17}– 2.2×10^{16}	10 GeV	–	–	–
12	55 TW	55	3.2–4.2 J	10^{17}– 2.9×10^{18}	–	H_2	2.2×10^{18}– 3.2×10^{17}	900MeV	3.5 mrad	200–300µm	33 mm
13	18 TW	42	750	–	–	–	–	200–300 MeV	–	–	–
14	–	45	$4\cdot10^4$ J cm^2	–	–	H_2	$3 \cdot 10^{18}$	200 MeV 1 GeV	–	200 µm or 300 µm	15 mm –33 mm

The last column of Table 1 shows that the length of the Capillary tube needed to reach GeV energies for the electron beams is smaller than 10 cm, a very important fact regarding the small geometrical dimensions required by the medical accelerators. Overall, a tabletop laser with power of tens of TW combined with a small size keV electron accelerator and tens of cm long Capillary could provide a pulsed beam of GeV electrons in a room of few square meters, a convenient size for the current medical facilities.

3. DESCRIPTION OF THE ACCELERATION MODEL

3.1. THE FIRST STAGE OF ACCELERATION: ACCELERATE ELECTRONS BY USING PHOTONS

In the proposed model, we consider a pulsed laser with the power between 10 to 40 TW, Ti:sapphire or Nd:glass laser, infrared beam, 1,05 μm or 0,8 μm wavelength, pulse duration between 20 fs to 40 fs, energy per pulse ranged from 120 mJ to 150 mJ, power dissipation on the surface varied between 10^{16} W/cm^2 to 10^{18} W/cm^2, the pulse frequency between 10 Hz to 100 Hz. Laser photons are focused at the entrance (by a parabolic, concave mirror) and injected into a glass capillary (capillary diameter about 200 microns, length between 12 mm to 100 mm) simple or integrated in a cell gas. This injection generates an intense ionization produced by the action of the laser pulse on the gas cell (hydrogen, 25 mbar in average), or it is simultaneous with an external pulsed electron beam (accelerated by an external small accelerator with the same frequency but in counter-phase, with an energy of approximate 3 MeV, charge of 100 pC, a pulse duration 11 fs [11], 27 fs [10] or 100 fs [3]). The laser beam creates a region of cavitations followed by a Wakefield, electrons move around the bubble and are injected behind the laser pulses, as described for example in [20]. A smaller electron density occurs on the beam axis due to the ponderomotive forces, as discussed for example in [21].

Electrons, either injected from an external source, or produced by the pulsed laser interaction with the gas in capillary, are structured in space as bunches or “bouquets” of electrons. For the protection of capillaries, these electrons are confined near the central axis, minimizing the energy losses [3–17]. The energy transfer takes place in the interaction between photons coming from the laser and the electrons injected, through a process similar to the Compton Effect.

When exiting the capillary, the short bunches of electrons have few microns in diameter with high energy (hundreds of MeV [3] or 1–2 GeV [11]), the charge 0.5 nC/1fs, the angular divergence of the electron beam emerging ranging between 100 microrad and 3.5 mrad.

Even during their route through the capillary, the electrons bunches can emit X-rays or high-frequency waves (THz). In order to be used in the following stage of acceleration (acceleration of protons) the electron beam must be separated from the beam of electromagnetic radiation by employing a magnetic field (0.25-1T [6, 12]). As described in [21], the electron beam will generate also an axial current, which can lead to a thoroidal magnetic field with mega-Gauss amplitude that can produce spurious effects into a radiation treatment facility environment.

3.2. THE SECOND STAGE: ACCELERATE PROTONS BY USING ELECTRONS

The pulsed beam of electrons accelerated at 1 GeV in the first stage is injected in counter-phase with a pulsed proton beam of low energy (MeV) into a “proton acceleration tunnel”. Protons are produced by a low energy source-accelerator configuration as shown schematically in Fig. 4. By the Coulomb attraction, a tractor force acts on the protons due to the electron bunches. It is important to underline the conditions in which the phenomenon of towing is likely to occur with high efficiency:

(i) the pulses of electrons and protons have the same frequency;

(ii) the pulses of electrons and protons are in counter-phase;

(iii) the intensity of a bunch of electrons is sufficiently large to be able to attract and accelerate protons bouquet to an energy required for a proton beam dedicated to the proton therapy.

The current intensity of protons should be at the level of nA, *i.e*. a mean value of about 10^{10}–10^{12} proton/s on average per cycle. In the treatment, 2 Gy dose in a field of 25×25 cm^2 in 2 minutes, leads to approximately 5×10^{11} protons that must be delivered in the distal layer [18, 19].

When the “bouquets” of electrons reach an energy of hundreds of MeV, it will be injected a proton pulsed beam with an energy of 1–3 MeV produced by a source, and this beam is curved in to the direction of the electron beam by coils. The protons are attracted to the “bouquets” of electrons and in this place they act as a tractor beam, which results from the initial acceleration of electrons. Protons are left behind because of inertia.

The process of acceleration of protons lasts until their energy is high enough for medical treatments (~250 MeV), then the electrons are stripped away magnetically, generating at the end of the process two pulsed beams with closed energies. Electron beam can be reused, by reinjection into the process for the first phase of acceleration. A schematic representation of the entire process is given in Fig. 4.

Electron and proton groups should be introduced in the acceleration tunnel in counter-phase at a distance greater than 5.29×10^{-11} m to avoid the formation of dipoles [21]. Between the groups of electrons and protons appear Coulomb interactions (“Coulomb explosion” [21]) that will lead to slower electrons and the protons will increase their speed by the principle of energy conservation. To describe the second phase of acceleration we must take into account the attractive force exerted between the two distributions of charges and the tractor force actions of electrons on the proton bounces, as shown in Fig. 5.

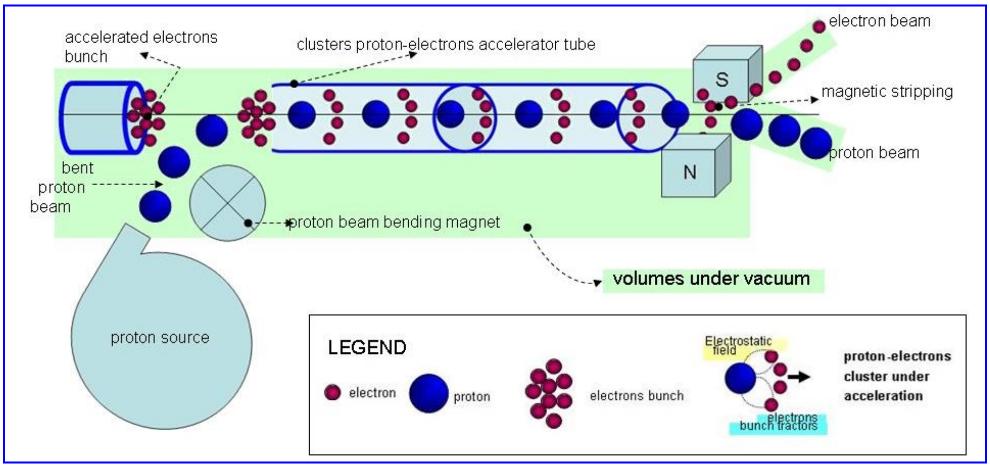

Fig. 4 – The schematic representation of the second step of accelerating protons by using electrons.

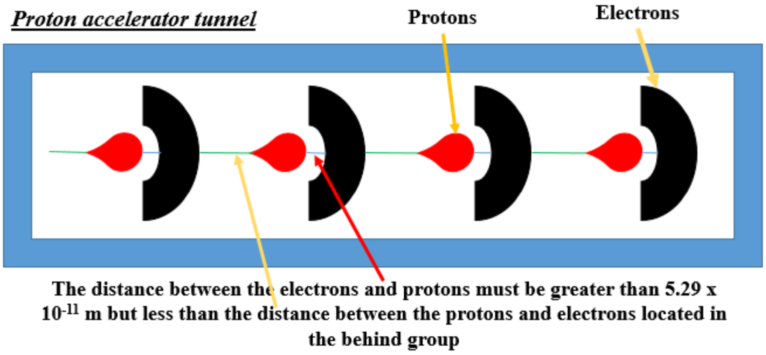

Fig. 5 – Goups of GeV electrons and protons on the accelerator tunnel.
The relevant geometrical distances are shown.

In the current models, the distance of 5.29×10^{-11} m is theoretically valid only if the clouds of charge are very dense and small – *i.e.* are considered as two point-like electrical charges [21]. More realistic models are expected to provide predictions leading to the basic engineering concept of this accelerator structure.

4. CONCLUSIONS

A two-stage accelerator structure for protons based on the LWFA and TNSA principles is proposed in the present paper. The proposal is motivated by the huge need of small size protons accelerator for the treatment of cancer by irradiation. Major reduction in the sizes of the TW lasers (table-top lasers nowadays) make the aim of this work hopeful. The advantages of the proposed accelerator structure are the very small sizes and mass in comparison with the known cyclotrons which can lead to build up proton-therapy facility with size and mass approximately equal to that of an electron accelerators currently used in hospitals. Another advantage of the proposed facility is the possibility to use it in conventional radiotherapy with X ray and electrons and also for medical imaging with tunable X ray and terahertz radiation. This proposal is made by a team of scientists working into a radiation treatment facility having a deep conviction that the accelerator experts will consider its technical feasibility in details.

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