Laser-IORT: a laser-driven source of relativistic electrons suitable for Intra-Operative Radiation Therapy of tumors

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Abstract. In a recent experiment [1] a high efficiency regime of stable electron acceleration to kinetic energies ranging from 10 to 40 MeV has been achieved. The main parameters of the electron bunches are comparable with those of bunches provided by commercial Radio-Frequency based Linacs currently used in Hospitals for Intra-Operative Radiation Therapy (IORT). IORT is an emerging technique applied in operating theaters during the surgical treatment of tumors. Performances and structure of a potential laser-driven Hospital accelerator are compared in detail with the ones of several commercial devices. A number of possible advantages of the laser based technique are also discussed.

Keywords: Laser-plasma accelerators, Intra-Operative Radiation Therapy, Electron accelerators for radiotherapy
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INTRODUCTION

Plasma-based electron accelerators have attracted in the last years an increasing attention from the scientific community, crosswise from plasma and laser physicist up to particle physicist working at the big accelerator facilities [2]. The possibility to achieve GeV electron energies in centimeter distance is appealing for the field of particle physics, as it enables to counter the huge cost and dimension requirements of large colliders like LHC or SLAC. However, it represents also a tool for which a prompt and useful application in fields like nuclear physics and medicine can be reasonably considered. In fact, while for accelerated electron bunches to reach above-GeV energy with high charge and low emittance it takes a pushed-to-extreme development of laser systems and targets and it represents a continued challenge, electron sources from laser-plasmas with energy of few ten's of MeV are attainable in a wide number of laboratories [3]. It follows that research in this way can be conducted with greater accessibility and consequently the optimization of the acceleration output is investigated with much more efficiency. In this framework, the possibility to build a laser-driven source of electrons with energy of a few tens of MeV turns out to be much more appealing and useful for consideration of various practical applications.

Relativistic electron beams are directly used for various purposes. The fields of employment related to medicine are however the most relevant in terms of oriented research. Electron accelerators are used in hospitals either as a clinical tool, in the radiotherapy treatment of oncological diseases [4], and to sterilize medical products from typical contamination by microorganisms on the surfaces of medical instruments [5]. In the following, we will mainly consider the radiotherapeutic application: electrons are in fact used for the treatment of superficial tumors in external-beam radio-therapy (RT) or in the so-called Intra-Operative Radiation Therapy (IORT) directly on the tumor bed during the

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surgical resection procedure [6, 7]. The paper is organized as follows: first, the IORT technique is briefly introduced and the requirements for the dose to be released to the patient are stated; then a comparison between the conventional radio-frequency-based medical linacs and a particularly efficient laser-plasma electron source are considered. Finally, the likely benefits from a laser-plasma electron accelerator for RT and IORT treatments are discussed, with an outlook on the possible implementation of a laser-plasma-based IORT facility.

THE INTRA-OPERATIVE RADIATION THERAPY (IORT) FOR CANCER TREATMENT

Due to the constant increase of tumor occurrences in worldwide population, clinical treatments based on radio-therapy (RT) with bunches of relativistic electrons are very frequently performed as auxiliary therapy to surgical removal of oncologic diseases. Advances in radio-frequency based linear accelerators (RF-linacs) have made several major industrial suppliers (Varian, Siemens, Sordina, Philips and many others) produce medical devices capable of producing electron bunches with energy from 2 to $\sim$50 MeV to release dose rates in the treated region of tens of Gy/min. Besides the external RT performed after the surgical removal of the tumor mass, a technique called Intra-Operative Radiation-Therapy (IORT) is an innovative additional option, which consists in direct irradiation of residual specific areas of a tumor bed during a surgical procedure. IORT enables irradiation of a limited volume of tissue next to the tumor area (it has been observed that the 85% of recurrences happen in the scar tissue area [4]) with a major visual control of the target volume and mapping of the irradiation field, from which the surrounding healthy structures can be displaced. In IORT treatments, a typical dose of the order of 20 Gy/min is released in sequences of electron bunches from a RF-linac. From the biologic point of view, single-dose IORT effectiveness is hypothesized to be two to three times the one of fractionated radiotherapy, so that 15 Gy of IORT is equivalent to 30-45 Gy of fractionated external beam irradiation [8].

The requests for a RF-linac are mainly oriented to guarantee stability and reliability of the electron bunches, while the overall dimensions and weight limit the flexibility of usage and the cost of the device exceeds the economic supportability by small medical centers or underdeveloped countries. IORT treatments can be performed either with non-dedicated RF-linacs or with IORT-dedicated RF linacs. In the first case, the used device is the same as the ones everyday used for radiotherapy with external beam, and are not specifically designated for IORT treatment; they must be placed in a radio-protected environment for safety reasons and then often require the transportation of the anesthetized patient during the surgery from a zone to another of the hospital, with consequent logistic and clinical drawbacks. IORT-dedicated linacs are on the contrary rather compact and mobile, and are housed inside the operating room. An example of such a device is represented by the NOVAC7 (by Hitesys), the LIAC (by Sordina) and the Mobetron (by IntraOp).

The most challenging technical issues related to a RF-based medical linac are the limitation of maximum electron energy to a few tens of MeV, due to the extent of the radiant head up to the ceiling, the ultra-high-vacuum technology required for the cavity and the related components, and the need of using ad-hoc diffusors and applicators for the original produced electron beam in order to obtain the desired divergence on the target.

Furthermore, a RF-linac has to be used in a surgery room and specific equipment are mandatory to satisfy the surgical-theatre requirements to access and operate in a clean environment while preserving either safety radiation protection of personnel and easy performances of control and manoeuvre.

THE LASER-DRIVEN ELECTRON SOURCE

A recent experiment of laser-driven electron acceleration in supersonic gas-jet target demonstrated that the suitability for medical uses of the produced electron source can be pursued with a laser system of moderate intensity. In fact, a regime of electron acceleration of high efficiency was found using a 10 TW laser and a supersonic jet of Helium at the SLIC laboratory of CEA/Saclay (France) [1].

The table-top accelerator set-up in the experiment, described in Ref. [1], was capable of delivering high-charge (about 1 nC per Joule of laser energy), reproducible, fairly collimated, and quasi-monochromatic electron bunches in an unprecedented efficient way, as testified by the photo-activation measurements performed with bremsstrahlung photons generated out of the accelerated electrons. The electron peak energy ranged in the 10-45 MeV interval, with a FWHM energy spread of 8 MeV. This kind of spectrum is suitable for a relevant class of cancer therapy.

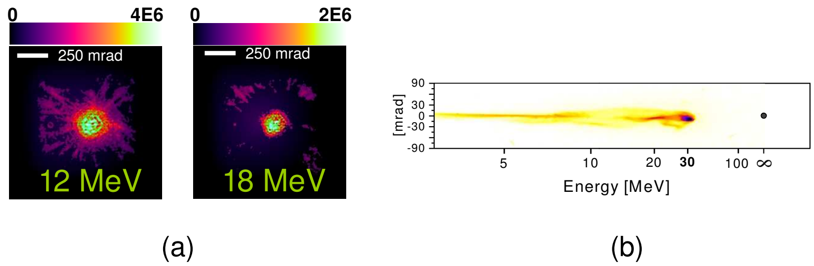

FIGURE 1. Angular and spectral distribution of the electron bunches accelerated in the laser-gas-jet experiment described in the text. (a) Angular distribution for the selected energies of 12 and 18 MeV. (b) Electron spectrum recorded with a magnetic spectrometer for shot with a 2 mm-diameter supersonic helium nozzle as target.

Figure 1 shows a typical angular and spectral composition of the accelerated electron bunches, after de-convolution of experimental data from the radiochromic film-stack device SHEEBA [9] and analysis of the signal from a magnetic spectrometer.

With this experiment, laser driven electron acceleration approaches the stage of suitability for medical uses, in particular for Intra-Operative Radiation Therapy (IORT) of tumors [6, 7]. Comparison of the main parameters of electron bunches produced by two commercial RF Hospital accelerators for IORT treatment and those of this laser driven accelerator is shown in the Table 1.

TABLE 1. Performances of two commercial medical linacs compared with the experimental laser-driven electron accelerator.

Accelerator type	IORT-NOVAC7	LIAC	Laser-driven accelerator
Producer	HITESYS SpA	SORDINA SpA	ref. [1]
Electron energy	$\leq$ 10 MeV (3, 5, 7, 9 MeV)	$\leq$ 12 MeV (4, 6, 9, 12 MeV)	$\geq$ 10 MeV (10 - 45 MeV)
Peak current	1.5 mA	1.5 mA	>1.6 kA
Bunch duration	4 μs	1.2 μs	$<$ 1 ps
Bunch charge	6 nC	1.8 nC	1.6 nC
Repetition rate	5 Hz	5-20 Hz	10 Hz
Mean current	30 nA @ 5 Hz	18 nA @ 10 Hz	16 nA @ 10 Hz
Delivered energy (1 min.)	18 J @ 9 MeV	14 J @ 12 MeV	21 J @ 20 MeV

Most of the performances of the experimental laser driven electron accelerator set-up at CEA-Saclay are comparable with presently used conventional accelerators. The new ultrashort laser-driven electron source thus opens also an exciting field of basic bio-medical research. The investigation of the radiobiological effects induced by a LPA source on biological samples has been proposed for funding at the Italian Ministry of Health in the framework of the Young Researchers Call 2008 [10].

LASER-IORT

As it emerges from the comparison, most of the performances of the experimental laser driven electron accelerator set-up at CEA-Saclay are comparable with presently used conventional accelerators, including the dose delivered for each shot. However, the electron bunch duration is about six orders of magnitude shorter in the case of the LPA. Consequently, the peak current is 10^6 times higher. In addition, it has to be noted that electrons from a LPA have an intrinsic angular divergence of a few hundreds of mrad. This feature, that represents a drawback in the framework of competition with large-scale accelerators like the CERN's LHC, is in this case an advantage: in fact, standard RF-linacs need the produced electron beams to be widened and then collimated to 2 to 8 cm diameters.

The dose rate delivered by the electron beams accelerated in the CEA/Saclay laser-plasma cathode can be evaluated by multiplying their "effective fluence" on irradiation target by the mass stopping power for water [11]: $D = (\varepsilon/e) \cdot$

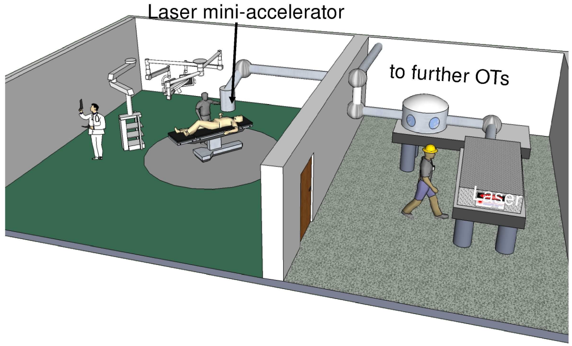

FIGURE 2. Schematic view of an operating theatre geared with laser-IORT equipment.

$(I/A)\cdot(dE/\rho dx)$ in which ε is the fraction of electrons that reach the target, e is the electron charge, I is the current, A is the target cross section $dE/\rho dx$ describe the energy loss in a medium with density ρ. For a water phantom, $\rho = 1$ g/cm^3 and $dE/dx \sim 2$ MeV/cm. Considering 2 nC of charge at 10 Hz, the 10% of which reaches a region of 25x25 cm^2 of the patient (standard value for external RT), it implies that the released dose rate is approximately 0.1 Gy/min, i.e. more than one over twenty the clinical request. However, if smaller areas of treatments are considered, like the ones irradiated during IORT procedures of 4 to 6 cm diameter [12], significant dose rates for medical purposes can be reached once that an adequate repetition rate is provided.

Furthermore, a laser-based mini-accelerator can overcome most of the requirements listed in section 1, since it can be contained in a “box” of sizes 20-40 cm, it can deliver electrons of energy even 10 times higher than a conventional linac, it doesn’t require UHV and doesn’t require high power suppliers inside the operating theatre (OT). The laser can in fact be located outside the OT in a way that its maintenance and repair can be acted without facing the problem of OT sterility. It is only needed that the laser beam could reach the Laser-linac through an evacuated (not UHV) pipe. Finally, just one laser can supply several OT’s, while in case of Laser-linac failure, the “box” can be easily removed from the OT by medical operators, checked and repaired outside.

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