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ON THE POSSIBILITY OF LASER GENERATING QUASI-MONOCHROMATIC ION BUNCHES VIA ULTRATHIN TARGETS NANO-STRUCTURING

Abstract

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On the Possibility of Laser Generating Quasi-Monochromatic Ion Bunches via Ultrathin Targets Nano-Structuring

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I. INTRODUCTION

The laser-driven acceleration of ions has, in the recent ten years, gained considerable attention[1–22], especially due to the extremely scientifically relevant applications in which ion bunches of energy ranging from a few to hundreds of MeV might be successfully employed. Among the most important, hadrontheraphy[23–31] and Inertial Confinement Fusion (ICF)[32,33] are surely worth mentioning. In hadrontheraphy, ion beams with proper characteristics can be successfully employed in order to irradiate tumoral tissues and to destroy the metastasis, thus preventing cancer growth. In ICF, ion bunches are expected to be usefully employed in order to externally ignite the fusion fuel, thus allowing to relax the extreme compression requirements on fusion capsules, which are at present some the most relevant difficulties characterizing laser-assisted fusion research. Furthermore, ion bunches of high energy can also be successfully employed as an invaluable and unique diagnostic tool to efficiently monitor the characteristics of extremely rapidly varying electromagnetic fields, with a technique known as proton imaging[34–37].

Despite laser-accelerated hadron bunches possess unique and highly spectacular characteristics, such as a low divergence and an ultra-low emittance, which are typically of the order of $10°$ and below 0.004 mm · mrad[38,39], respectively, they also suffer of many drawbacks which at present strongly prevent them from being employed in many applications, as extensively discussed in[40]. Among them, the almost thermal feature typically characterizing laser-accelerated ion spectra is probably one of the most serious problem to be overcome, as applications conversely require the employment of quasi-monoenergetic ion bunches, a relative energy dispersion $\Delta E/E$ (full width half maximum) below 2% being a standard request.

Unfortunately, reducing the laser-accelerated relative energy spread from almost 100% to that required for applications in absolutely not an easy task. Recent efforts in such direction have experimentally proved the possibility of generating laser-accelerated ions with relative energy spread of roughly 25%[41] and 17%[42] with an approach based on the micro-structuring of solid, thin foils of μm thickness.

Here, we would like to focus our attention on presenting a combined theoretical and numerical investigation of the conditions which might be expected to be sufficient in order to achieve the experimental generation of quasi-monochromatic, multi-MeV ion bunches with the help of a present-day, fs laser system. The reason why we turn our attention towards fs, table-top, laser systems relies on the compactness of such sources, which allows a significantly lower both environmental & economical impact with respect to ps, hundreds of Joules per shot facilities. Furthermore, conversely from ps laser systems, which are intrinsically single shot in nature, fs sources can operate at high repetition rates which, at present, can be up to 10 Hz, and this might therefore be considered as a more favorable condition towards the employment of such sources in medical therapy. At the same time, we will turn our attention towards the employment of ultrathin targets, i.e. of solid foils of thickness below 1 μm which, as long as fs laser pulses are employed, have been proved to effectively lead to the laser-generation of hadron jets with energy significantly higher than that achievable by irradiation of μm-thick foils[12,17].

The paper is organized as follows. In Sec. II we will discuss the conditions for achieving laser-generation of quasi-monochromatic ion bunches, to which we will refer as Quasi-Monochromaticity Conditions (QMC). Such QMC will be formulated in terms of four physical parameters which depend on the specific laser-target setup adopted and whose preliminary characterization will be given in Sec. III. Subsequently, in Sec. IV we will present the results of preliminary, two dimensional, PIC simulations which indicate that with a laser-target setup in which the solid foil design is oriented by the four QMC it is possible to achieve, with a fs, present-day laser system, the generation of multi-MeV ion bunches with a relative energy spread of roughly 11%. Furthermore, on the basis of the combined theoretical and numerical analysis presented, we will also propose, in Sec. V, an experimentally new and feasible approach towards the generation of laser-driven, quasi-monochromatic ion bunches which relies on the nano-structuring of a solid foil. Finally, in Sec. VI, we will turn to discussing the comparison between the approach here presented and those described in[41] and in[42], while Sec. VII is devoted to presenting our conclusions.

II. QUASI-MONOCHROMATICITY CONDITIONS

The theoretical discussion we present relies on the preliminary observation that laser-generation of quasi-monochromatic ion bunches is a process which inherently must rely on the employment of multi-specie targets. In fact, as long as the irradiated foil consists of only a one-layer target, the energy spectrum of the accelerated ions is essentially thermal, as theoretical analysis of the "plasma expansion into vacuum" problem predict (see, for example,[19–22] and references therein) and experiments confirm. In the following, we will restrict our investigation to double-layer targets, in which a substrate will be covered on one side by a dopant layer, and the foil is assumed to be laser-irradiated on the substrate uncovered side. In order to achieve the laser-generation of quasi-monochromatic ion bunches with such kind of targets one therefore needs to ensure the dopant plasma expansion timescale to be much shorter than the substrate one. This condition, as long as one introduces the substrate and the dopant ion plasma frequencies, given, in MKSA units, by $\omega_{\rm si} = \sqrt{n_{\rm s} Z_{\rm s} e^2/\epsilon_0 A_{\rm s} m_{\rm p}}$ and by $\omega_{\rm di} = \sqrt{n_{\rm s} Z_{\rm d} e^2/\epsilon_0 A_{\rm d} m_{\rm p}}$, respectively, where $Z_{\rm s}$ and $Z_{\rm d}$ are the substrate and the dopant charge states, $A_{\rm s}$ and $A_{\rm d}$ their respective mass numbers, e the modulus of the electron charge, $m_{\rm p}$ the proton mass and ϵ_0 the vacuum absolute dielectric constant, can be written as $\omega_{\rm si}/\omega_{\rm di} \ll 1$ or, equivalently, as

$$\frac{Z_{\rm s}/A_{\rm s}}{Z_{\rm d}/A_{\rm d}} \ll 1, \tag{1}$$

to which in the following we will as "first quasi-monochromaticity condition". In the regime described by Eq. (1), laser-irradiation of the substrate thus leads, on the back of the target, to the formation of an electric field structure which is thus capable of accelerating the dopant layer ions on a timescale which is significantly faster than the one on which substrate explosion takes place. Practically, the fulfilment of condition (1) corresponds to separating the role of the *accelerator*, which in our case is played by the laser-irradiated substrate foil, from the role of the *accelerated material*, which in our scheme is played by the dopant layer. Our goal is thus to achieve laser acceleration of the dopant layer so as to produce a quasi-monoenergetic ion bunch.

In order to accomplish to such a task, we observe that the longitudinal electric field structures which, due to the laser-matter interaction, are induced at the back of the target are expected to possess very strong field gradients along a direction orthogonal to the foil surface. Therefore, the ions of a dopant layer of finite thickness δ would experience a non uniform electric field. In particular, if we denote with L the longitudinal scale over which the electric field component which is responsible for ion acceleration varies, the maximum difference between the accelerating fields experienced by any two dopant ions can be taken to be of the order of δ/L. Correspondingly, quasi-monochromatic acceleration of the dopant layer ions might occur only as long as

$$\delta/L \ll 1, \tag{2}$$

to which in the following we will refer as "second quasi-monochromaticity condition".

Furthermore, the longitudinal electric field which is responsible for ion acceleration is strongly non-uniform even in the transverse - i.e. parallel to target surface - direction. Let us assume, with a very simplified estimate, that laser irradiation of the substrate leads, on the back of the target, to the formation of a roughly cylindrically-symmetric, longitudinal electric field structure whose transverse spatial scale will thus be denoted with R. Quasi-monochromatic laser acceleration of the dopant layer ions might thus occur only as long as the dopant consists of small disks of radius r_0 satisfying

$$r_0/R \ll 1, \tag{3}$$

to which we will refer as "third quasi-monochromaticity condition".

Finally, it is worth observing that, even if conditions (1), (2) and (3) were satisfied, the quasi-monochromatic character of the laser-accelerated dopant ions spectrum might also be affected by their self, repulsive electric field. Despite the latter might be expected to be at least partially shielded by the cold electron cloud accompanying the accelerated ions, its contribution to the spectrum widening might be significantly reduced also by properly controlling the dopant layer density. In fact, if for the sake of simplicity we restrict ourselves to an unidimensional treatment and introduce the electron, the substrate ion and the dopant ion densities, given by $n_{\rm e}$, $n_{\rm s}$ and $n_{\rm d}$, respectively, together with a coordinate axis x oriented along the outward normal to the back target surface, Poisson equation, in MKSA units, reads

$$\frac{{\rm d}E}{{\rm d}x} = \frac{e}{\epsilon_0}(Z_{\rm s}n_{\rm s} + Z_{\rm d}n_{\rm d} - n_{\rm e}),$$

where we have denoted with e the absolute value of the electron charge. By taking the x-coordinate axis origin to be located on the substrate symmetry plane, and by denoting with a the substrate thickness, one has

$$E(\frac{a}{2}+\delta) - E(0) = \frac{e}{\epsilon_0}(Z_{\rm s}n_{\rm s}\frac{a}{2} - \int_0^{a/2+\delta} n_{\rm e}\ {\rm d}x + Z_{\rm d}n_{\rm d}\delta) = E_{\rm s} + E_{\rm d},$$

where we have introduced the quantities $E_{\rm s}$ and $E_{\rm d}$, given by

$$E_{\rm s} = \frac{e}{\epsilon_0}(Z_{\rm s}n_{\rm s}\frac{a}{2} - \int_0^{a/2+\delta} n_{\rm e}\ {\rm d}x) \quad \text{and by} \quad E_{\rm d} = \frac{e}{\epsilon_0}(Z_{\rm d}n_{\rm d}\delta),$$

respectively. Note that $E_{\rm s}$ corresponds to the electric field which is responsible for the ion acceleration process of the dopant layer, while the quantity $E_{\rm d}$ represents the self, repulsive ion bunch electric field. It is also worth to observe that the accelerating field depends on the local charge separation occurring inside the substrate and is in fact proportional to the term $\int_0^{a/2+\delta} n_{\rm e}\ {\rm d}x$, which represents half of the total number of electrons per unit surface which are confined inside the target. Therefore, the dopant self repulsive field can be neglected if compared with the accelerating field as long as one has

$$\eta = \frac{E_{\rm d}}{E_{\rm s}} = \frac{Z_{\rm d}n_{\rm d}\delta}{E_{\rm s}} \ll 1, \tag{4}$$

to which in the following we will refer as "fourth quasi-monochromaticity condition".

III. CHARACTERIZATION OF THE PARAMETERS SPACE AS A FUNCTION OF THE LASER-TARGET SETUP

The formulation of the four QMC implies the characterization, in terms of the parameters defining a specific laser-target setup, of the substrate charge-to-mass ratio $Z_{\rm s}/A_{\rm s}$, of the longitudinal and of the transverse spatial scales over which the accelerating electric field changes, which have been denoted in Sec. II with L and R, respectively, and of the accelerating electric field amplitude $E_{\rm s}$. This Section is therefore devoted to presenting a preliminary discussion of such characterization.

As first, it is worth observing that the substrate charge-to-mass ratio depends on the ionization state of the bulk ions. The latter might thus expected to depend on the laser electric field, and to thus be a function of the pulse intensity $I_{\rm L}$, i.e.

$$\frac{Z_{\rm s}}{A_{\rm s}} = \frac{Z_{\rm s}}{A_{\rm s}}(I_{\rm L})$$

In order to characterize the electric field structure driving the dopant ions acceleration process, we schematize the target after the laser-matter interaction as a uniformly ionized plasma in which the ions are cold while the electron energies are thermally distributed with mean energy given by $k_{\rm B}T_{\rm e}$, where $k_{\rm B}$ is the Boltzmann constant and $T_{\rm e}$ the electron temperature. In the framework of such simplified description, the longitudinal component of the electric field which, at the back of the target, is responsible for the acceleration of the dopant layer ions has a longitudinal spatial scale which can thus be taken to be of the order of the hot electrons Debye length (see[19] and references therein), i.e. $L \approx \lambda_{\rm d}$. In order to clarify the laser-target setup parameters on which the quantity L depends we thus observe that the hot electron Debye length is given, in MKSA units, by $\lambda_{\rm d} = \sqrt{\epsilon_0 k_{\rm B}T_{\rm e}/n_0e^2}$, where where n_0 is the average hot electron density inside the target. Therefore, the accelerating electric field spatial scale L depends on the two parameters $k_B T_e$ and n_0. The former, being the hot electrons average energy, might be expected to be proportional to the laser intensity I_L and, as the target is ultrathin, also to the substrate thickness a[12,17]. For what regards the average hot electron density, we might expect it to be proportional to the total hot electron number N_0, and to the volume the negatively charged particles occupy, the latter being given by $V \approx \pi R_d^2 a$, with R_d the Debye sheath radius. The total number of hot electrons can be taken to be roughly equal to the total energy delivered by the laser pulse divided by the average hot electron energy, i.e. $N_0 \approx \alpha U_L / k_B T_e$, where α is the electron absorption coefficient. Furthermore, for what regards the volume occupied by the hot electrons, one might observe that the Debye sheath radius R_d can be taken to be of the order of[22] $R_d \approx w_0 + a \tan \theta_e$, where $\theta_e \approx 25°$ is the typically reported hot electron half angle divergence inside the target, thus, for ultrathin targets for which $a/w_0 \ll 1$, we have $R_d \approx w_0$. Therefore, the average hot electron density n_0 might be expected to be a function of the substrate thickness and of the laser waist, energy and intensity, i.e. $n_0 = n_0(a, w_0, U_L, I_L)$. This implies that the hot electron Debye length, and thus the spatial scale of the longitudinal component of the Debye sheath electric field, might be expected to be functions of the substrate thickness and of the laser waist, energy and intensity, i.e.

$$L = L(a, w_0, U_L, I_L).$$

For what regards the accelerating electric field gradient transverse spatial scale R, we observe that at present there is neither theoretical nor numerical modeling describing the dependence of such quantity on the parameters characterizing the laser-target setup. Due to this lack of information, in what follows we will thus take R to coincide with the Debye sheath radius which, because of the above discussion, for ultrathin targets might be expected to be taken to be of the order of the laser pulse waist w_0, i.e. $R \approx w_0$. However, in principle we might expect

$$R = R(w_0).$$

Finally, for what regards the characterization of the accelerating electric field amplitude E_s, we might observe that, within the simplified schematization we are adopting, the electric field at the back of the target can be taken to be of the order of (see again[19] and references therein) $E_s \approx \sqrt{n_f/n_0}\,(k_B T_e/\lambda_d)$, where n_f is the hot electron density at the ion substrate boundary. Thus, following the above discussion, we might expect

$$E_s = E_s(a, w_0, U_L, I_L).$$

The effective characterization of the QMC parameters L, Z_s/A_s R and E_s as a function of the specific laser-target setup requires an extensive and quite complex numerical investigation which is at present scheduled. Preliminary, one-dimensional PIC simulations indicate that laser irradiation of a 100 nm, six times ionized C substrate at solid density with a 25 fs pulse at peak intensity of 10^{21} W/cm^2 leads, on the back of the target, to the formation of an electric field structure longitudinally uniform over a spatial scale of roughly 3 nm and with peak amplitude of $E_s \approx 10^{13}$ V/m.

IV. NUMERICAL SIMULATIONS RESULTS

The theoretical discussion presented thus indicates that the laser-driven generation of quasi-monochromatic ion bunches might be expected to rely on the fulfilment of four QMC which, as long as double-layer targets are employed, become equivalent to the the system of Equations (1), (2), (3) and (4).

In order to validate the theoretical predictions, we have thus run two sets of PIC simulations with laser-foil setups in which the target design was oriented by the four QMC. All the runs performed are 2D in the Cartesian coordinates and 3D in the particles' momenta, while the box resolution is equal to 0.67 nm in both directions. The laser pulse is, in both simulation sets, Gaussian in both space and time, with a pulse waist and a duration given by $w_0 = 4$ μm and $\tau_L = 25$ fs, respectively, and a peak intensity of 8×10^{19} W/cm^2. The target substrate in both the simulation sets consists of a three times ionized, 100 nm thick Al foil at density equal to 3 g/cm^3. Following the preliminary characterization of the QMC parameters discussed in Sec. III, we have thus adopted a dopant layer consisting of a 400 nm diameter Hydrogen microdot, whose thickness is taken to be equal to 4 nm in the first set of simulations and to 2 nm in the second set. The density of the dopant layer has been chosen to be equal to 0.3 g/cm^3. Electron pre-pulse heating has been artificially modeled by assigning the specie an initial temperature of 3 keV. It is worth to note that the choices adopted, which have been forced by computational reasons, are not optimal for what regards the fourth quasi-monochromaticity condition, i.e. Eq. (4).

The spectrum of the laser-accelerated protons typically obtained in each of the two simulation sets is shown, at two different times, in Figs. 1 and 2. At is clear from both figures, the parameters chosen have proved, on a numerical simulation basis, to lead to the laser-generation of a proton bunch with a remarkable quasi-monochromaticity.

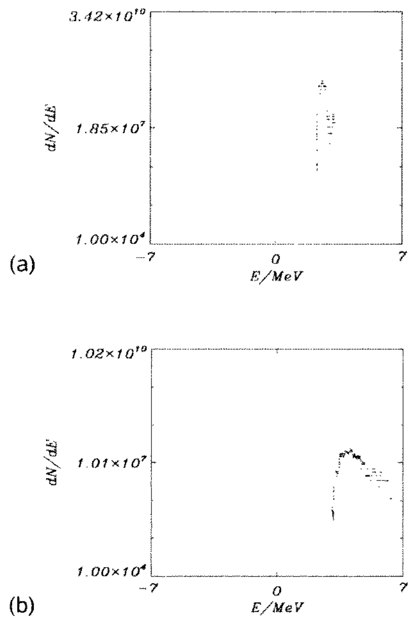

FIG. 1: Simulated energy spectrum of the proton bunch at 180 fs (panel (a)) and 300 fs (panel (b)). The proton disk thickness is 4 nm.

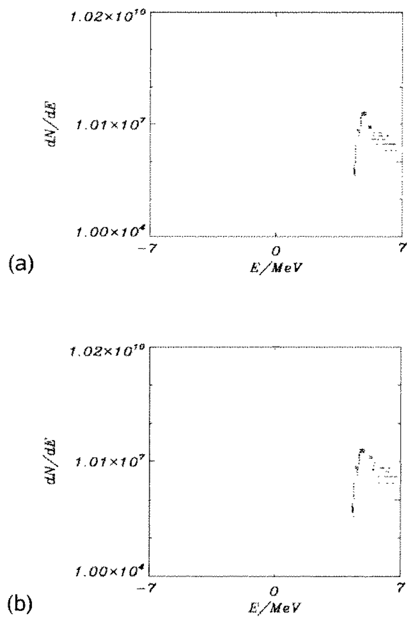

FIG. 2: Simulated energy spectrum of the proton bunch at 266 fs (panel (a)) and 400 fs (panel (b)). The proton disk thickness is 2 nm.

Furthermore, the two simulation sets numerically confirm the theoretical prediction which is summarized by the second QMC, i.e. that reducing the dopant disk thickness increases the proton spectrum quasi-monochromaticity. In particular, as it is shown in Fig. 2, the employment of a 2 nm Hydrogen disk is numerically predicted to lead to the

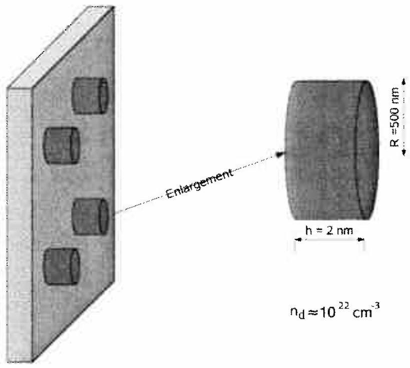

FIG. 3: Sketch of the nano-structured target proposed.

production of a proton bunch with a peak in the energy spectrum at roughly 5 MeV and with a relative energy spread of about 11%.

V. NANO-STRUCTURED TARGET DESCRIPTION

On the basis of the combined theoretical and numerical discussion presented, we are thus now capable of describing a feasible setup in order to experimentally test the proposed scheme. For such scope, we suggest the employment of a double-layer, ultrathin target to be nano-structured on one side as qualitatively shown in Fig. 3.

In particular, in order to satisfy all the four QMC, we propose the employment of a 100 nm thick Au substrate and to implant on one of its sides cylindrically-symmetric, 500 nm of diameter, 2 nm thick CH nano-dots at density of about 10^{22} cm^{-3}, the latter corresponding, in terms of H matter density, to roughly 0.02 g/cm^{-3}.

VI. DISCUSSION

Finally, in this Section we turn to comparing the approach here theoretically discussed with the experimental ones described in[41] and[42].

TABLE I: Comparison, in terms of QMC verified, of the experiments discussed in[41], in[42] with the present experimental proposal.

QMC	Experiment[41]	Experiment[42]	Present proposal
(1)	√	√	√
(1)	-	√	√
(2)	√	-	√
(3)	-	-	√

The comparison, summarized in Table I, illustrates that, differently from the experiments described in[41] and[42], the present experimental proposal satisfies all the four QMC. Correspondingly, with respect to such works, the present scheme is numerically found to lead to a significant reduction of the accelerated ions relative energy spread. It should be also observed that, similarly to[42] but conversely from[41], in our simulations the peak in the ion energy distribution function is located in the high energy tail of the spectrum. This implies the acceleration of the majority of the ion population of the dopant layer up to the maximum energy which might be expected to be achievable with the specific laser system adopted.

VII. CONCLUSIONS

In conclusion, we have theoretically discussed the conditions which might be expected to be sufficient in order to achieve the laser-generation of quasi-monochromatic ion bunches with present-day, fs laser systems. For that purposes, four QMC conditions have been identified. Preliminary, two dimensional, PIC numerical simulation indicate that with a laser-foil setup in which the target design is oriented by such four QMC it is possible to achieve the laser-generation of multi-MeV ions with a relative energy spread (full width half maximum) of about 11%. On such basis, a feasible setup in order to experimentally test the theoretical predictions is therefore proposed. Finally, the present scheme is compared with the experimental approaches described in[41] and[42].

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[1] K. Krushelnick, Phys. Plasmas **7**, 2055 (2000).
[2] S. P. Hatchett *et al.*, Phys. Plasmas **7**, 2076 (2000).
[3] R. A. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000).
[4] H. Habara *et al.*, Phys. Rev. E **69**, 036407 (2004).
[5] P. McKenna *et al.*, Phys. Rev. E **70**, 036405 (2004).
[6] M. Borghesi *et al.*, Phys. Plasmas **9**, 2214 (2002).
[7] L. Romagnani *et al.*, Phys. Rev. Lett. **95** 195001, (2005).
[8] F. Cornolti *et al.*, Phys.Rev. E **71**, 056407 (2005).
[9] A. J. Mackinnon *et al.*, Phys. Rev. Lett. **97** 045001, (2006).
[10] M. Kaluza *et al.*, Phys. Rev. Lett. **93**, 045003 (2004).
[11] L. Romagnani *et al.*, Phys. Rev. Lett. **95**, 195001 (2005).
[12] T. Ceccotti *et al.*, Phys. Rev. Lett. **99**, 185002 (2007).
[13] L. Yin *et al.*, Phys. Plas. **14**, 056706 (2007).
[14] Q. L. Dong, Z. M. Sheng, M. Y. Yu and J. Zhang, Phys. Rev. E **68**, 026408 (2003).
[15] D. Neely *et al.* Appl. Phys. Lett **89**, 021502 (2006).
[16] A. P. L. Robinson and P. Gibbon, Phys. Rev. E **75**, 015401(R) (2007).
[17] P. Antici *et al.*, Phys. Plasmas **14**, 030701 (2007).
[18] M. Allen *et al.*, Phys, ReV. Lett. **93** 265004 (2004).
[19] S. Betti, F. Ceccherini, F. Cornolti and F. Pegoraro, Plasma Phys. Contr. Fusion **47**, 521-529 (2005).
[20] F. Ceccherini, S. Betti, F. Cornolti and F. Pegoraro, Laser Phys. **16**, 594-599 (2006).
[21] P. Mora, Phys. Rev. E **72**, 056401 (2005).
[22] J. Fuchs *et al.* Nature Physics **2**, 48 (2006).
[23] S.V. Bulanov *et al.* Phys. Lett. A **299**, 240 (2002).
[24] S.V. Bulanov and V. S. Khoroshkov, Plasma. Phys. Rep. **28**, 453 (2002).
[25] T. Zh. Esirkepov *et al.*, Phys. Rev Lett. **89**, 175003 (2002).
[26] R. Orecchia *et al.*, Critical Reviews in Oncology/Hemathology **51**, 81 (2004).
[27] A. Brahme, Int. J. Radiat. Oncol. Biol. Phys. **58**, 603 (2004).
[28] W. K. Weyrather and J. Debus, Clinical Oncology **15**, s23 (2003).
[29] H. Tsujii, Eur. J. Cancer **37**, s251 (2004).
[30] R. Orecchia *et al.*, Eur. J. Cancer **34**, 459 (1998).
[31] U. Amaldi, Analysis **1**, 1 (2003).
[32] S. Atzeni and J. Meyer-ter-vehn, *The physics of inertial confinement fusion, beam plasma interaction, hydrodynamics, hot dense matter*, Clarendon press, Oxford (2004).
[33] M. Roth *et al.*, Phys. Rev. Lett. **86**, 436 (2001).
[34] M. Borghesi *et al.*, Phys. Plasmas **9**, 2214 (2002).

[35] M. Borghesi *et al.*, Phys. Rev. Lett. **92**, 055003 (2004).
[36] F. Califano, F. Pegoraro and S. V. Bulanov, Phys. Rev. E **68**, 066406 (2003).
[37] M. Borghesi *et al.*, Phys. Rev. Lett. **88**, 135002 (2004).
[38] T. E. Cowan *et al.*, Phys. Rev. Lett. **92**, 204801 (2004).
[39] A. J. Kemp *et al.*, Phys. Rev. E **75**, 056401 (2007).
[40] U. Linz and J. Alonso, Phys. Rev. ST **10**, 094801 (2007).
[41] H. Schwoerer *et al.*, Nature **439**, 445 (2006).
[42] B. M. Hegelich *et al.*, Nature **439**, 441 (2006).