Ion beams delivered by two accelerating gaps for industrial and therapeutic applications

V. Nassisi, D. Delle Side, M.De Marco and L. Velardi
Department of Physics, University of Salento, Laboratorio di Elettronica Applicata e Strumentazione, LEAS I.N.F.N. sect. of Lecce, C.P. 193, 73100 Lecce, Italy vincenzo.nassisi@le.infn.it
F. Paladini
Department of Physics, University of Salento, I.N.F.N. sect. of Lecce, C.P. 193, 73100 Lecce, Italy
G. Buccolieri
Dipartimento di Scienza dei Materiali, University of Salento, I.N.F.N. sect. of Lecce, C.P. 193, 73100 Lecce, Italy

Abstract

Laser ion sources offer the possibility to get ion beams utilizable to improve particle accelerators. Today many laboratories, as well as the LEAS, are involved to develop accelerators of very contained dimensions, easy to be installed in little laboratories and hospitals. Pulsed lasers at intensities of the order of 10^8 W/cm^2 and of ns pulse duration, interacting with solid matter in vacuum, produce plasma of high temperature and density. The charge state distribution of the plasma generates high electric fields which accelerate ions along the normal to the target surface. The energy of emitted ions has a shifted Maxwell-Boltzmann distribution which depends on the ion charge state. To increase the ion energy, a post-acceleration system can be employed by means of high voltage power supplies of about 100 kV. The post acceleration system results a good method to obtain high ion currents using a not expensive system and the final ion beams find interesting applications in the field of the ion implantations, hadrontherapy, scientific applications and industrial use. In this work we study the electromagnetic and geometric properties, like the emittance of the beams delivered by Cu target. Plasma's characterization was performed using a Faraday cup for the electromagnetic characteristics, while for the geometric ones by adopting a pepper pot system. Applying 60 kV of accelerating voltage and a laser irradiance of 0.1 GW/cm^2, we obtain 5.5 mA of output current and a normalized beam emittance of 0.2 π mm mrad. The brightness of the beams was 137 mA(p mm mrad)$^{-2}$.

INTRODUCTION

It is known that the presence of specific doped ions can significantly modify the properties of many materials. Today, the use of laser sources facilitates the improvement of ion beams of moderate energy and good geometric qualities. They are more and more used for the production of innovative electronic materials[1], biomedical materials[2, 3], new radio-pharmacy[4, 5], hadrontherapy applications[6] and to improve the oxidation resistance of many materials [7].

Currently, a widely adopted technique to generate ions consists in the application of electron beams directed on solid target which etches the material[8]. Another method exploits the electron cyclotron resonance applied to gases. The application of pulsed laser ablation (PLA) technique (the one that we adopt in this work) allows to get ions from solid targets, without any previous preparation, whose energy can be easily increased by post acceleration systems[9-11]. Today it is possible to arrange power laser beams. So, an intense laser beam focused onto metal targets generates laser-induced plasma[12]. In this way, plasma can be generated from many materials, also from refractory ones[13-14].

Laser-generated plasmas favour the ion acceleration along the normal to the target surface. At intensities of the order of 108 W/cm2 and ns pulse duration, the laser interaction with solid matter in vacuum produces hot plasmas at high temperature and densities, of the order of tens eV and 1017 electrons/cm3 [15].

The thermal interactions, the adiabatic expansion in vacuum and the Coulomb interactions are responsible of the primary ion acceleration in plasma[16]. By applying post acceleration, it is possible to extract specific charged particles and to increase their energy. This idea can be applied to plasmas of moderate density thanks to their low electric conductivity, that it is also influenced by the value of the particle energy[17]. Therefore, to extract charges from plasma it is necessary to choose very low density plasmas in order to overcome the conducting phase and to avoid short-circuits inside the chamber. Besides, the presence of high energy particles can inhibit the breakdowns owing to the low influence of the external electric fields on particle trajectories.

The percentage of ionization in the plasma plume in LIS sources is not very high, but it is sufficient to get ion beams of high intensity. Besides, in these apparatus, applying a high laser repetition rate and a high power vacuum system, the output ion beam can become continuous. The maximum percentage of the ionized material is found near the target and it is of about 16% with respect to the total ablated material [11]. The ionizing process is due to the photoionization and to the absorbed laser energy via bremsstrahlung[9]. The plume temperature recorded can get values of hundred thousand Kelvin[13]. Besides, the total ion beam energy depends on the particle charge state, on the intrinsic particle energy and primarily on the applied voltages, which provide the accelerating fields. In this work, to increase the acceleration without increasing the value of the potential power supply, we add a second accelerating gap. It is worth noticing that the maximum value of the potential applicable to the apparatus mainly depends by the chamber volume, by its geometry and morphology. Then, we developed an accelerator composted by two independent accelerating sectors, using an excimer laser to get PLA from pure Cu target. By a suitable Faraday cup and a pepper pot system, we characterized the extracted charges and the geometric quality of the beams.

EXPERIMENTAL SEUPS

To get PLA from solid targets we utilised a Compex 205 excimer laser operating in the UV range. Its maximum output energy is 600 mJ. It works at 248 nm wavelength, 25 ns of pulse duration and the maximum repetition rate is 50 Hz. The laser beam streaks the solid targets and it generates plasma in a vacuum chamber, Fig. 1. Particularly, inside the vacuum chamber, it is placed an expansion chamber (EC) closed around to the target support. The plasma expands inside the expansion chamber and, since there isn't any electric field, breakdowns are absent. The length of expansion chamber (18 cm) was sufficient to decrease the plasma density. The target, as well as the expansion chamber, is connected to a power supply of positive bias voltage. Four capacitors of 1 nF stabilize the accelerating voltage during the fast ion extraction. Thanks to the plasma expansion, the charges reach the extremity of the expansion chamber. This chamber extremity is drilled by a 1.5 cm hole to allow the ion extraction.

A pierce ground electrode is placed at 3 cm distance from the expansion chamber. After this electrode an another one, placed at 2 cm from the ground electrode and connected to a power supply of negative bias voltage, is utilized as third electrode and also as Faraday cup collector. The angle formed by the laser beam with respect to the normal to the target surface is 70o. During our measurements the laser spot area onto the target surface is fixed at 0.005 cm2 for all experimental conditions. The third electrode is connected to the oscilloscope by a high voltage capacitor (2 nF) and a voltage attenuator, x20, in order to separate the oscilloscope from the high voltage and to suit the electric signal to oscilloscope input voltage. The value of the capacitors (4 nF) applied to stabilize the

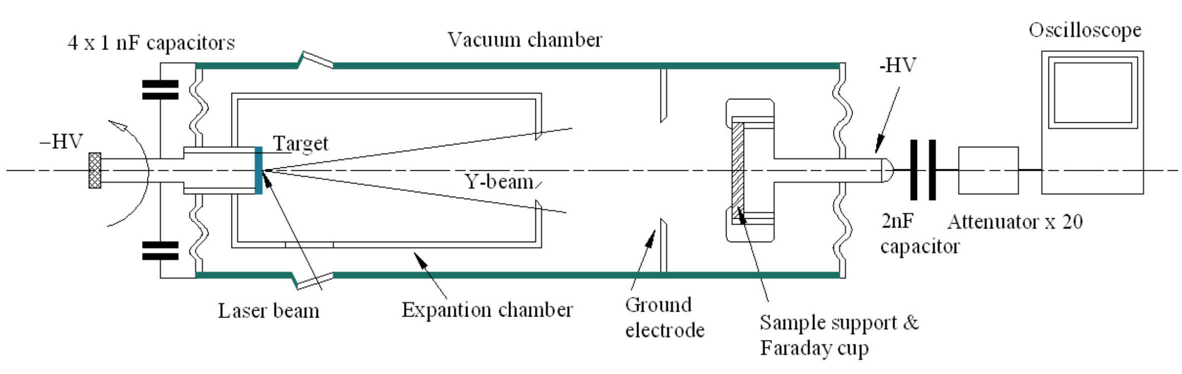

Fig. 1: Schematic drawing of the experimental apparatus

accelerating voltage and the one of the capacitors (2 nF) used to separate the oscilloscope from the high voltage were calculated assuming a storage charge higher that the extracted one. Under this condition, the accelerating voltages during the charge extraction is constant as well as the oscilloscope is able to record the real signal. At 40kV the stabilized capacitors store a charge of about 160 μC, while at 20kV the separating capacitors store a charge of about 40 μC. As it is possible to see in the next section, the total charge extracted in this experiment is about 10 μC, value quite little with respect to the storage ones.
By theoretical consideration, the maximum accelerating voltage applicable in this configuration can increase up to 160 kV.
The third electrode that we use also as Faraday cup. This last is not able to support the suppressing electrode on the cup collector and therefore secondary electron emission, caused by high ion energy, was present. In this configuration, we are aware that the output current values are about 20% higher than the real ones[19].
The laser irradiance used to produce ion beams was 1.0x108 W/cm2 and the target was pure (99.99%) disk of Cu.

RESULTS

In the LEAS experiments the value of the laser intensity utilised is of the order 108 W/cm2 which is sufficient to generate plasma and to produce ions without forming breakdowns at maximum accelerating voltage used.
Fig. 2 shows typical time of flight (TOF) spectra obtained from the Cu target detecting the ion emission with the Faraday cup placed at 23cm distance from the target. The vertical axis represents the output current. The maximum output current is reached with 40 and 20 kV, respectively on the first gap (target-ground electrode) and second one (ground electrode-Faraday cup). In Fig. 2 shows three curves at 60, 40 and 30 kV of total voltage. Space charge effects are present at low accelerating voltage applied on the first gap. So, considering only the TOF curves out of the charge domination effects, we obtain the behaviour of the accelerated charge with respect to the accelerating voltage (Fig. 3). From these results we can observe the absence of a saturation phase. In fact the curves of the Fig 3 have a growing trend with respect to the applied voltage. The growing trend on the first gap voltage are larger than the ones dependent on the second gap voltage. Theoretically, it is expected to

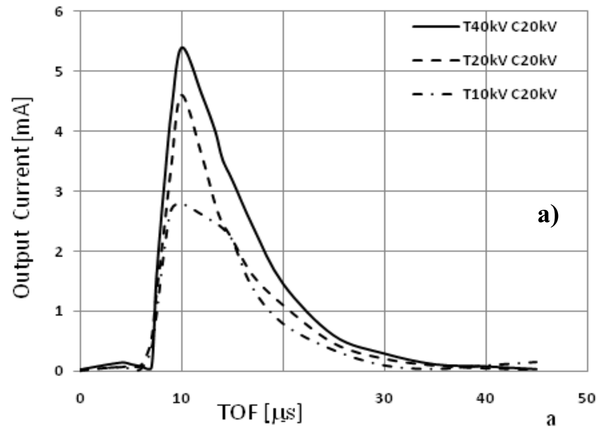

Fig. 2: Waveform of the output current at different accelerating voltages: for Cu target. Laser irradiance 0.1 GW/cm^2.

observe a constant trend for the curves dependent principally on the voltages of the second acceleration gap because the charge is already extracted and its value ought to be constant. We can ascribe this behaviour to secondary emission of electrons from the cup collector because we are not able to prevent this emission, owing to the absence of the suppressing electrode on the Faraday cup. So we expect that the real charge must be increased of about 20% for the used voltage values.
With a fixed voltage of 20 kV in the second gap, the extraction current increased with the varying of the voltage applied on first gap, reaching 150% at the maximum voltage of 40 kV respect to the value obtained at 0 kV. This result implies a strong dependence of the extraction efficiency on the first stage voltage. Since the anode consists of a cylinder with a hole at its end (1.5 cm in diameter) in order to let the ions to escape. By simulation results, the electric field strength near the hole increased with respect to the applied voltage. This fact can enlarge the extracting volume inside the anode and as a consequence the extraction efficiency. Cu target at zero voltage produced ion beams containing 1.2x10^{11} ions/pulse (0.7x10^{11} ions/cm^2). Instead, applying accelerating voltages of 40 and 20 kV in the first and second accelerating gap, respectively, we obtained an increase of the ion dose up to 3.4x10^{11} ions/pulse, (2x10^{11} ions/cm^2) for the Cu target.
In this work we performed also emittance measurements of the beam by the pepper pot technique[19, 20]. To introduce the emittance concept we present the case of an ideal beam generally called laminar beam. A beam which ray trajectories do not occupy the space of other trajectories is laminar. Therefore, a paraxial beam has got rays all parallel, a convergent o

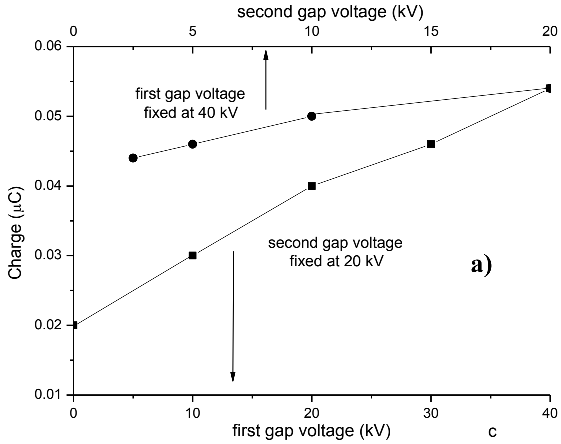

Fig. 3: Output charge on accelerating voltages for Cu target. Laser irradiance: 0.1 GW/cm^2.

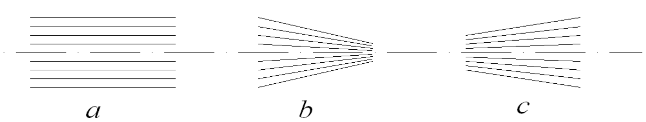

Fig. 4: Example of laminar beams. a: paraxial; b: convergent; c: divergent.

divergent beam have got rays all convergent or divergent, respectively as shown in Fig. 4.
Assuming the propagation direction of the beam along the *z* axis, the *x*-plane emittance ε_x is $1/\pi$ times the area A_x in the xx' trace plane (*TPx*) occupied by the points representing the beam particles at a given value of *z*, namely:

$$\varepsilon_x = \frac{A_x}{\pi} \tag{1}$$

In the phase plane (*PPx*), the area of the particle is defined as:

$$A_x^o = \iint_{f_2^o \neq 0} dx dp_x = m_o c \beta\gamma A_x \tag{2}$$

where f_2^o is the distribution function of the particles, mo is the rest mass of the particles and $\beta = v/c$ and $\gamma = 1/(1-\beta^2)^{1/2}$.
Actually, it is necessary to define an invariant quantity of the motion called normalized emittance e_{nx} in the *TPx*. Therefore, by Liouville's theorem it is known that the area occupied by the particle beam in *PPx* is an invariant quantity and the normalised emittance can assume the form:

$$\varepsilon_{nx} = \beta\gamma\varepsilon_x \tag{3}$$

and in the trace plane *yy'* we have:

$$\varepsilon_{ny} = \beta\gamma\varepsilon_y \tag{4}$$

We exploit the pepper pot method to measure the emittance.

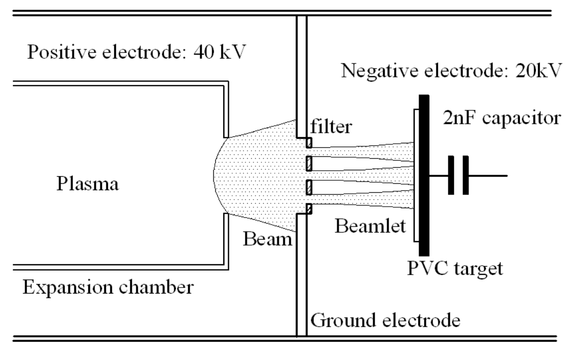

Fig. 5: Sketch of the pepper pot system .

Fig. 5 shows a sketch of the system. The mask has 5 holes of 1 mm in diameter and it was fixed on the ground electrode. One hole is in the centre of the mask and 4 holes are at 3.5 mm from the centre. We used as screen radio-chromic films type EBT, placed on the third electrode at a distance of 2 cm respect to the mask.
Radio-chromic detectors involve the direct impression of a material by the absorption of energetic radiation, without requiring latent chemical, optical, or thermal development or amplification. A radio-chromic film changes its optical density as a function of the absorbed dose. This property and the relative ease of use, led to adopt these detectors as simple ion beam transverse properties diagnostic tools.
So, the ion beam after the mask imprinted the radio-chromic film and then it was possible to measure the divergence of all beamlets. The divergence values allowed to determinate the beam area A_x in the *TPx*. We applied 250 ion shots to imprint the radio-chromic films.
Fig. 6 shows a photo of the impressed radio-chromic film after 250 shots, at 40 kV of total accelerating voltage.
We measured the emittance for different values of accelerating voltage. We fixed the accelerating volt-

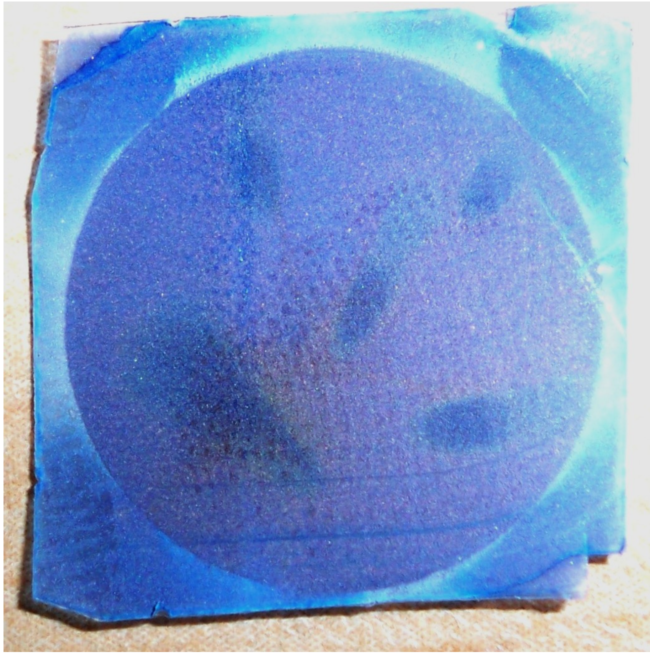

Fig. 6: Photo of the impressed radio-chromic film after 250 shots, at 40 kV of total accelerating voltage.

age of the second gap at 20 kV, while the one of the first gap was put at 10, 20, 30 and 40 kV. So, the obtained values of the area in the *TPx* resulted of 613, 545, 525 and 435 mm mrad for 30, 40, 50 and 60 kV of total accelerating field, respectively (table I). Considering that ,

$$\varepsilon_{nx} = \beta\gamma\varepsilon_x$$

by applying Eq. 1 and 3 we found the normalized emittance values.

For all the applied voltage values, the normalized emittance resulted constant: ε_{nx}=0.2π mm mrad. Therefore, to estimate the total properties of the delivered beams, it is necessary to introduce the concept of brightness. The brightness is the ratio between the current and the emittance along *x*- and *y*-axis. Generally assuming ε_x equal to ε_y, the normalised brightness becomes:

$$B_n = \frac{I}{\varepsilon_{nx}^2} \quad (5)$$

By equation 5, at the current peak (5.5 mA), the brightness values resulted of 137 mA(π mm mrad)$^{-2}$ at 60 kV of accelerating voltage.

In conclusion, this apparatus due to the low emittance and high current is very promising to be used to fed large accelerators. The challenge of the moment is to get accelerators of dimensions so small that can be easily deployed in little laboratories and hospitals.

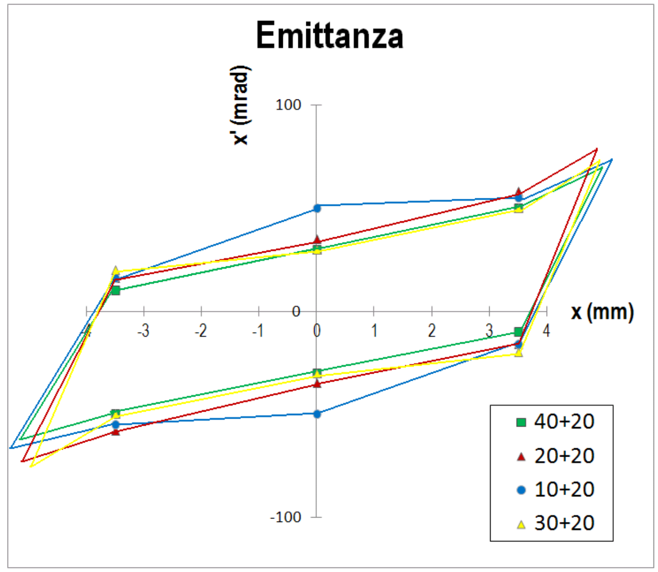

Fig. 7: Emittance diagram in the trace plane for different accelerating voltage values.

DISCUSSION AND CONCLUSION

The post-acceleration of ions emitted from laser-generated plasma can be developed to obtain small and compact accelerating machines. The output current can easily increase on accelerating voltage. The applied voltage can cause breakdowns and for this reason the design of the chamber is very important (primarily its dimensions and morphology). We have also demonstrated that by two gap of acceleration it is possible to increase the ion energy avoiding

	Emittance			
Voltages (kV)	40+20	30+20	20+20	10+20
ε_x (mm mrad)	435	525	545	613
ε_{nx} (π mm mrad)	**0,196**	**0,220**	**0,200**	**0,197**

Table I

to apply only one acceleration voltage of high value. Increasing the voltage of the first accelerating gap, we increased substantially the efficiency of the extracted current due to the rise of the electric field and extracting volume inside the EC. The charge extracted without electric fields was 0.7×10^{11} ions/cm^2. At the maximum accelerating voltage the ion dose was 2×10^{11} ions/cm^2, and the corresponding peak current was 5.5 mA. We also measured the geometric characteristics of the beam utilising the pepper pot method. We calculated the normalized emittance of our beams to be of $\varepsilon_{nx} = 0.2\ \pi$ mm mrad. Therefore, the brightness values resulted of 137 mA(π mm mrad)$^{-2}$.

In conclusion, this study have demonstrated that our apparatus can be produce ion beam with good quality, such as low emittance value and high current. For this reason it is very promising to be used to fed large accelerators.

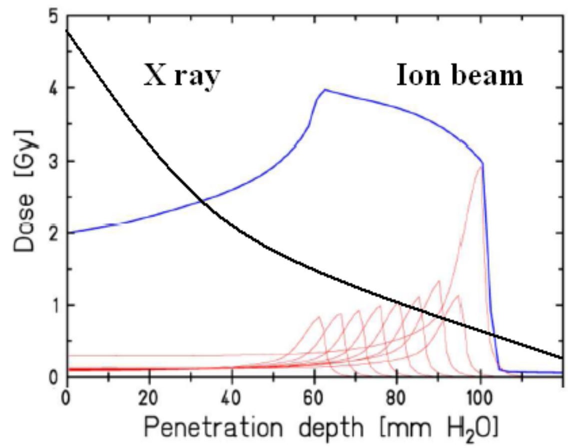

Fig. 10: Example of absorbed doses by an equivalent tissue. X ray deposits them energy along the penetration; ion beam deposits them energy at a depth.

Acknowledgments

The work was supported by the Fifth National Committee of INFN by experiment LILIA.

REFERENCES

[1] A. Lorusso, V. Nassisi, L. Velardi, G. Congedo, Nucl. Instrum. Meth., B 266 (2008) 2486-89.
[2] A. Lorusso, L. Velardi, V. Nassisi, L. Torrisi, D. Margarone, A. Mezzasalma and A. Rainò, Rad. Eff. Def. Solids, 163, 447 (2008)
[3] Z.L. Yu, Surface & Coatings Technology 201, 8006 (2007)
[4] H. Takeda, J.H. Billen, S. Nath, J.E. Stoval, R.L. Wood, L.M. Young. Proc. IEEE Part. Accel. Conf. 2, 1140 (1995)
[5] M.A. Fortin, F. Marion, B.L. Stansfield, R.W. Paynter, A. Sarkissian, B. Terrealt, ad Surf. and Coatings Technology, 200, 996 (2005)
[6] L.Picardi et al. Proc. EPAC '94, p. 864 (1994).
[7] F. Noli, A. Lagoyannis, P. Misaelides, Nucl. Instrum. Methods. Phys. Res. B266, 2437 (2008).
[8] R. Becker, Rev. Sci. Instrum., 69, 623 (1998).
[9] A. Luches, M. Martino, V. Nassisi, A. Pecoraro and A. Perrone, Nucl. Instrum. Methods. Phys. Res., A322, 166 (1992).
[10] A. Beloglazov, V. Nassisi, M. Primavera, Rev Sci. Instrum., 66, 3883 (1995)
[11] V. Nassisi and A. Pedone, Rev. Sci. Instrum. 74, 68 (2003).
[12] F. Belloni, D. Doria, A. Lorusso, and V. Nassisi, Rev. Sci. Instrum., 75, 4763 (2004).
[13] D. Bleiner, A. Bogaerts, F. Belloni and V. Nassisi, Appl. Phys., 101, 83301 (2007)
[14] A. Lorusso, L. Velardi, V. Nassisi, F. Paladini, A. M. Visco, N. Campo, L. Torrisi, D. Margarone, L. Giuffrida, A. Rainò, Nucl. Instrum. Meth. B266, 2490 (2008)
[15] L. Torrisi, F. Caridi, L. Giuffrida, Nucl. Instr. and Methods in Physics Res., B268 2285, (2010)
[16] L. Torrisi, S. Gammino, L. Andò and L. Laska, J. Appl. Phys., 91(5), 4685 (2002)
[17] A. Lorusso, M.V. Siciliano, L. Velardi V. Nassisi, Nucl. Instrum. Meth., A614, 169 (2010)
[18] A. Lorusso, M.V. Siciliano, L. Velardi V. Nassisi, Appl. Phys., A101, 179 (2010)
[19] J.G. Wang, D.X. Wang and M. Reiser, Nucl. Instrum. Meth. A307, 190 (1991)
[20] V. Nassisi and E. Giannico, Rev. Sci. Instrum., 70, 3277 (1999).
[21] (www.srim.org)