ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Lecce

INFN/FM-03/01
18 Aprile 2003

MOVABLE FARADAY CUP MEASUREMENTS FOR ION BEAMS CHARACTERIZATION

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Abstract

In this article we present the results of a non-equilibrium laser-plasma generated by an ultraviolet excimer laser. These studies are very important to develop new ion sources via laser-plasma technique (LPT). All measurements were realized at fixed laser energy of 70 mJ. It was concentrated on a 0.004 cm^2 spot by a convergent focal lens of 15 cm focal length. The target utilized was a disc of Cu of 99.99% pure and to detect the plasma flow pulse at different positions along drift tube, we developed an 8 cm in diameter movable Faraday cup. Analyzing the time-of-flight (TOF) pulse we was able to distinguish the electron pulse, the suprathermal ions and the thermal evolution of the plasma. Besides, applying a breakdown voltage as polarizing voltage to the Faraday cup, we characterized the neutral component. To determine the efficiency of the system on particles production, we measured the total etched material per pulse, 0.235 μg, and the fractional ionization, 10%. The flux distribution was measured by an optical transmission analysis of a Cu deposited film on a glass substrate. The ablation process expelled particles with an initial velocity of 34 km/s while the maximum ions concentration was emitted after 1 μs with a mean velocity of about 20 km/s. During the propagation the plasma longitudinal dimension changed from 7.5 cm near the target (8 cm) to 31 cm near the cup (40 cm). At low distances, the cup waveforms presented a plateau due to the high dense plasma which gets the space charge regime governed by the Child-Langmuir law. By our results the maximum charge distribution was generated at the target and it decreased with the distance.

*Published by **SIS–Pubblicazioni***
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1. Introduction

The multiple charged ion generation[1, 2], the realization of micro-machine and the deposition of thin films of complex materials [3, 4] can be now achieved by pulsed laser ablation (PLA). PLA is even widely used in mass spectroscopy and in surface modification[3, 5] This technique is in fast expansion since the eighties in coincidence with the commercialisation of powerful laser sources. The high temperature plasma that can be obtained by this technique[6] creates ions at high charge state which favours the generation of ion beams able to feed large ion accelerators. Recently the technique of laser ion source (LIS) is applied in light ion beam generation devotes to a new bio-medicine field, the hadrotherapy[7].

This technique has also the advantage to generate ions of many elements because of the laser beam acts directly on solid materials instead to the conventional sources EBIS and ECR which operate mainly on evaporated materials.

LISs are dependent on produced plasma that in his turn is generated from a small spot. This characteristics favours the control of the geometric characteristic of the ion beams.

When a high power laser beam impinges on a solid target, its energy is absorbed resulting in electron excitation of the atoms near the surface enhancing rapidly the target temperature. An part of the absorbed energy is released to the emitted ions, atoms, clusters and electrons and even soft X rays. These last propagate in the space generating electrons from the metal chamber walls in a few nanoseconds in coincident with the laser pulse. Instead, the particles of the evaporated material go away from the target and the hot electrons are the first particles result free to escape from the target. The remaining particles, due to their high concentration, implicate a low Debye length which limits the evolving electric field area until the plasma expands. When the Debye length becomes comparable to the plasma dimension a fraction of the ions will be accelerated at high velocity[8]. Now, a hot plasma expands in vacuum. After laser irradiation, due to the high target temperature and the expansion in vacuum, the plasma undergoes to an adiabatic expansion where the plasma oscillations enhance the ion energies up to some keV[9].

In these experiments it is very complex to know the plasma characteristics. Many studies have been carried out to predict the film profile and the chemical dynamic usually considering the generated gas fairly neutral [10]. To generate high good quality ion beams, it is necessary to enhance the plasma ionisation particles in order to get an easier ion acceleration or to increase the output current.

Previous experiments described in recent papers[6, 11] have reported on the ion etching thresholds, angular emission, ion and neutral emission, ion energy distribution and characteristics of ion beams.

The goal of this article consists in to determinate the plasma temperature and the drift velocity during its expansion, and to diagnostic the neutral component. The experimental values were recorded by a movable Faraday cup and the depositing of a thin film on a glass substrate and by analysing the cup current waveforms under short-circuit regime.

2. Thermodynamic theory

The interaction of an incident laser radiation on target materials results in electronic excitation of the atoms near the surface. In PLA experiments the laser fluences are very high which bring instantly the target to liquid phase at its thermodynamic critical temperature, T_{tc} . From the thermally activated target, we have the expansion of the plasma. Its particles escape from the target surface with velocity $v_x \geq 0$ normal to the target. For low particle density values the escaping velocity v_x remains approximately constant, on the contrary for high density, it has been demonstrated [12] that the particles, emitted with velocity $v_x \geq 0$, are undergone to collisions sufficiently to modify their initial velocity v_x in order to get also negative values, namely $-\infty < v_x < +\infty$. This phase or Knudsen-layer [KL] phase occurs near the target surface where the particles collide at least two or three time. As far as the *y*- and *z*-direction velocities, they assume values corresponding to $-\infty < v_y, v_z < +\infty$ with average values $< v_y >$ and $< v_z >$ equal to zero. Therefore, the initial velocity distribution function on the surface results to be:

$$f_t \propto \exp\left[-\frac{2E + mv_x^2}{2kT_t}\right] \cdot \exp\left[-m\frac{v_y^2 + v_z^2}{2kT_t}\right] \tag{1}$$

and the average velocity in the *x*-direction is estimated to be:

$$< v_x > = \left[\frac{2kT_t}{\pi m}\right] \tag{2}$$

with T_t the target temperature, *k* the Boltzmann constant and *E* the total internal energy of the particles.

Being $< v_x >$ different to zero, it can be regarded as a velocity of the center of mass (COM). Then, taking in account the collisions, the initial *x*-direction velocities decrease as well as the longitudinal temperature of the plasma becomes lower than the target one. Now we have the KL distribution function of the form:

$$f_{KL}(v_x, v_y, v_z) \propto \exp\left[-\frac{2E + m(v_x - v_d)^2}{2kT_{KL}}\right] \cdot \exp\left[-m\frac{v_y^2 + v_z^2}{2kT_{KL}}\right] \tag{3}$$

where v_d represents the COM velocity.

In PLA experiments the laser fluence is enough high that the high excited atoms at the surface change the physical properties of the target that should be regarded as a dense gas composed by energetic particles which contribute to ablate material. The temporal behaviour of the neutral components cannot be measured by electromagnetic probes, while temporal behaviour of charged particles can be studied by time of flight (TOF) signals recorded by Faraday cups.

In fact, to evaluate the ion distribution flux along the *x*-axis the Eq. (3) have to be integrated on v_y and v_z over the interval $B_0 = \left\{ v_y, v_z \in \Re^2 : 0 \le \sqrt{v^2_y + v^2_z} \le \frac{R}{x} v_x \right\}$, where R is the cup radius and x is the cup-target distance. Applying the polar coordinates to Eq. (3) we have:

$$f_{KL}(v_x) \propto \exp\left[-\frac{E}{kT_{KL}} - \frac{m}{2kT_{KL}} (v_x - v_d)^2 \right] \cdot g(v_x) \qquad (4)$$

with

$$g(v_x) \propto 2\pi \int_0^{\frac{R}{x}v_x} v_n \exp\left[-m \frac{v_n^2}{2kT_{KL}} \right] dv_n \,, \qquad B_0 \to B_0^{|} = \left\{ \varphi \in [0, 2\pi[, v_n \in \left[0, \frac{R}{x} v_x \right] \right.$$

where $v_n = \sqrt{v_y^2 + v_z^2}$ is the transversal velocity.

Under our experiment conditions, the plasma is generated approximately from a small spot on the target and, as a consequence, at *x* distance the particles arrive after a time *t*.

Then substituting v_x with x/t and dv_x with xdt/t^2 in the Eq. (4), the ion current recorded by the cup assumes the form:

$$I \propto \frac{1}{t^2} \exp\left[-\frac{E}{kT_{KL}} - \frac{m}{2kT_{KL}} \left(\frac{x}{t} - v_d \right)^2 \right] \cdot g\left(\frac{x}{t} \right) \qquad (4')$$

Under the condition of low solid angle, $g(x/t)$ can be approximated to $\propto 1/t^2$ so the cup current simplifies to

$$I \propto \frac{1}{t^4} \exp\left[-\frac{E}{kT_{KL}} - \frac{m}{2kT_{KL}} \left(\frac{x}{t} - v_d \right)^2 \right] \qquad (5)$$

3. Experimental apparatus

Before to complete the accelerating section, we performed experiments on plasma generation in order to characterize it. We utilised an interaction chamber very versatile. It is sealed by two quartz windows and two flanges indispensable for laser beam propagation inside the chamber, and to connect the chamber to the vacuum system, respectively, Fig. 1. The quartz windows are tilted of 70° with respect to the axis of the chamber. The target support was a stem mounted on the chamber. An homemade XeCl excimer laser (λ= 308 nm) having a 20 ns pulse produces material ablation depositing a bunch energy of 70 mJ. To focus the laser beam on the target a 15 cm focal length lens (L) was used which comprised the laser beam on the target surface on a 0.004 cm^2 spot.

This laser spot size was measured by a careful evaluation of the signal of a photodiode having a slit and placed on the focal plane of the 15 cm length. By finely translating the photodiode with a step of 0.05 mm we obtained an accurate profile of the laser intensity, both in the horizontal and vertical direction with respect to the lens axis. By the width at half maximum of the measured profiles, we assumed 0.004 cm^2 as spot dimension.

The chamber is equipped with a drift tube of 8 cm in diameter placed normally to the target.

An movable Faraday cup as ion collector (IC) was developed to reveal the electromagnetic characteristics of the generated plasma. To do this, a polarising voltage was applied to the cup of negative value by a separating capacitor of 5μF. The cup signal was closed on an load resistor of 50 Ω connected to a voltage divider having an attenuation factor of 25. In this way we are able to collect the positive specimen. Figure 2 shows the Faraday cup connected to the electric circuit. The polarising voltage played an important role particularly for measurements performed near the source of the ablation material owing to short-circuits formation.

The ion output current I_I is a fraction of the total cup output current I_C and it is governed by the following expression time-depending,

$$I_I(t) = I_C(t)[1 - \sigma(t)] = \frac{V_C(t)}{R_{Load}}[1 - \sigma(t)]$$

where $\sigma(t)$ is the secondary ion-electron emission function. In our experiments we considers $\sigma(t) \approx 0$ due to the low ejected particle energy.

4. Experimental results

Our measurements were performed moving the Faraday cup along the drift tube until 40 cm from the plasma source. At the maximum distance the plasma flow was detected by the cup with a bias voltage, V_C, until 700 V without to observe substantial changing with respect to lower bias voltage. In these measurements the recorded waveforms show the start peak at left-hand side and the ion collection at the right-hand side, Fig. 3. The former represents the electron emission due to UV and X-ray beams incident on the cup collector which releases electrons, the latter instead is due to the ion collected. The solid line represents the experimental result while the data points is the Maxwell-Boltzmann distribution defined in Eq. (4’) with longitudinal KL temperature T_{KL}= 500000 K and flow velocity v_d = 9300 m/s. From Fig. 3 one can observe that the Maxwell-Boltzmann distribution with the chosen velocity of the ion flow and KL temperature fits fairly well the experimental result. By experimental data recorded at 30, 25, 20, 15, 12, 10, 8 cm it has been possible to determinate the evolution of the longitudinally values of the temperature and the ion flow velocity, see Tab. (1).

We can observe that at the lowest distance analysed, the flow velocity and the KL temperature were very low. At higher distances the flow velocity increased while the temperature remained approximately constant. This behaviour can be ascribed to the very dense initial plasma and its rapid expansion that favours the drift velocity due to the coulomb contribute[13].

As far as the ion time duration, we measured the ion pulse duration at FWHM on distance. Considering the ion peak velocity, we estimated the ion plasma extension. Figure 4 shows the ion plasma extension as a function of the distance. By extrapolation the experimental data, one can observe that at the source the ion plasma extension was of 2.8 cm and it increased as the distance increased.

It was very difficult to analyse the results at distance very low. Due to high plasma density, the bias voltage of the cup became insufficient to collect the plasma ions. Typical waveform shows the rise-time of the collection, a plateau and a fall-time. The rise-time and fall-time regions represent the saturation conditions. Fig. 5 shows the experimental results obtained at 8 cm distance with bias voltage of 225, 250, 275, 300, 325, 350 and 375 V. In all the waveforms of Fig. 5, the onset time and the tail time coincide, while the plateau level increased as the bias voltage increased. In this case due to the Child-Langmuir law the maximum current is limited by the space charge regime [14]. At bias voltage higher than 275 V an other phenomenon is present; the breakdown of the plasma which short-circuits the IC to ground after about 12 μs from laser action, bringing the cup output voltage equal to the bias voltage. These phenomena were also observed at higher distance but with bias voltage also higher. We have this behaviour due to the presence of neutral components that during the plasma expansion they decrease their density increasing the breakdown voltage values. At 6 cm distance, the higher plasma density did not allow to detect the global plasma pulse because of the gas breakdown just present at the pulse onset time.

The ablation process expelled particles with an initial velocity of 34 km/s while the maximum ions concentration got a formation velocity of about 20 km/s. Plotting the rise-time values of the ion pulses as a function of the distance we estimated the time formation in order to get the maximum ion concentration at the source, Fig. 6. By fitting the above data with a second order polynomial and putting the distance equal to zero, we found the initial rise-time corresponding to about 1 μs. This very important result is interesting to diagnostic the physical properties of the source. We can suppose that the rise-time value is dependent on thermal characteristics of the target material and laser characteristics.

At low distances we observed also the presence of a positive peak due to the suprathermal effect. The expelling velocity was estimate to be of 55 km/s but its intensity was very low with respect to the plasma one. Figure 7 shows the plasma signal at 6 cm away the source showing the suprathermal[8] signal and three ion current at 50, 100 and 150 V. One can note that the suprathermal peak intensity did not change as the bias voltage changed indicating a particle suprathermal kinetic energy higher than the bias one. In fact, it results of 1keV. The suprathermal peak is not present at distance larger than 10 cm due to the isotropic emission of the suprathermal particles.

The total ejected material, containing both neutral and charged particles, was estimated by measuring the mass of the target before and after the laser irradiation by means of a highly sensitive digital balance (Sartorius ME215S). Due to the low ejected material per pulse, the laser irradiation consisted of 2000 shots. The ablation rate was 0.235 μg/pulse, that is 2.2_10^{15} atoms/pulse.

To evaluate the angular distribution of the ejected particles at about 2.1 cm from the target we placed a glass substrate in order to deposit a film. During the deposition the target was continuously rotated in order to avoid the plasma flux deviation owing to the progressive modification of the crater. The film distribution was determined by measuring the optical transmittance of the deposition by a He-Ne laser as light source and a IR photodiode as detector. The deposited film was translated while the laser and the photodiode were take blockaded. To estimate the film profile a 0.2 mm pinhole was placed in front the detector. The input (I_{in}) and output (I_{out}) intensities are linked by the well known relation

$$I_{out} = I_{in} e^{-\alpha s} \qquad (6)$$

where s is the film thickness and α is the absorption coefficient (6.85_10^5 cm^{-1}) of the deposited film at He-Ne wavelength. The profile of the deposited material is shown in Fig. 8. As it can be seen, the ejected material had a symmetric distribution and a narrow directionality (FWHM= ±35°).

By the above measurements we can assert that only at distance lower than about 5 cm the cup is able to detect all the particles. At larger distances the total ions is calculated by the ion signals recorded by the cup and corrected by the emission profile. At the lowest measurable distance the ion concentration was 2.2x10^{14} ions which implies an ionisation factor of 10%.

Taking in account the angular distribution and the cup signal, Fig. 9 shows the ion concentration as a function of the distance. Its behaviour decreases as the distance increases indicating an higher ion concentration at the source.

Particularly at low value distances, we increased the cup polarization voltage up to 700 V in order to provoke short-circuits inside to the ejected gas. During the short-circuit the output voltage recorded by the cup increased at its maximum value. Its time duration is much higher than the ion one. In fact, at the source it was about 300 μs while at 20 cm distance was 150 μs. At higher distances than 20 cm, nevertheless the maximum applied voltage we did not observe short-circuits likely due to the low concentration of the particles. An example of the breakdown process is shown in Fig. 10 at 20 cm distance and 700 V applied.

5. Conclusion remarks

This work report on important results of an expanding plasma produced by the pulsed laser irradiation with a copper target. Due to the fast target modification and to the non-equilibrium phenomenon the plasma characterization was very complex. At low distances the plasma flow presented two peak explicable within the contest of two-temperature model. The fast suprathermal peak travel with a velocity of about 55 km/s corresponding to a particle energy of about 1keV. The slower peak, corresponding to the thermal distribution, had got a mean velocity of 20 km/s. The ion distribution was growing with the distance and at the source it resulted of about 1 μs time duration. As far as the ion time duration, it was also growing with the distance and at the source it was of about 2.8 cm. Instead, the neutral component was more extended. It was estimated to be 300 μs near the source and decreases at 150 μm at 20 cm from the target.

The KL temperature was approximately constant along the drift tube while the mean COM velocity increased as the distance increased. The maximum value at 40 cm distance was 9300 m/s.

The ionisation percentage instead increased as the distance decreased due to recombination processes during the plasma expansion. We was not able to measured the ionisation at 6 cm distance due to plasma breakdown. The highest measured value was 10% at 8 cm distance. The ionisation reduced to 5% at 40 cm distance.

6. Acknowledgments

The authors are pleased to acknowledge the excellent technical support of F. De Donno, V. Nicolardi.

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Figure captions

Fig. 1: Experimental apparatus.

Fig. 2: Faraday cup. D=8 cm, R_{Load}=50 Ω, Voltage divider attenuator 25.

Fig. 3. Typical TOF signal of laser-induced Cu ions at 40 cm distance away from the target. Data points Maxwell-Boltzmann fit with T_{KL} = 500000K and flow velocity 9300m/s.

Fig. 4. Ion plasma extension (FWHM) on distance.

Fig. 5. TOF signal of laser-induced Cu ions at 8 cm distance away from the target. Data points Maxwell-Boltzmann fit with T_{KL} = 370000K and flow velocity 1800m/s.

Fig. 6. Ion pulse rise-time as a function of the distance.

Fig. 7. Plasma signal at 6 cm distance away from the target containing the suprathermal signal and three ion currents at 50, 100 and 150 V.

Fig. 8. Angular distribution of the ablated material.

Fig. 9. Charge measurement along the drift tube. _ experimental values; _ expected values.

Fig. 10. Example of breakdown recorded at 20 cm distance with 700 V of polarization voltage. The mean time duration is valuable to be 150 µs.

Tab. 1. Results of the longitudinally temperature and ion flow velocity on target-cup distance.

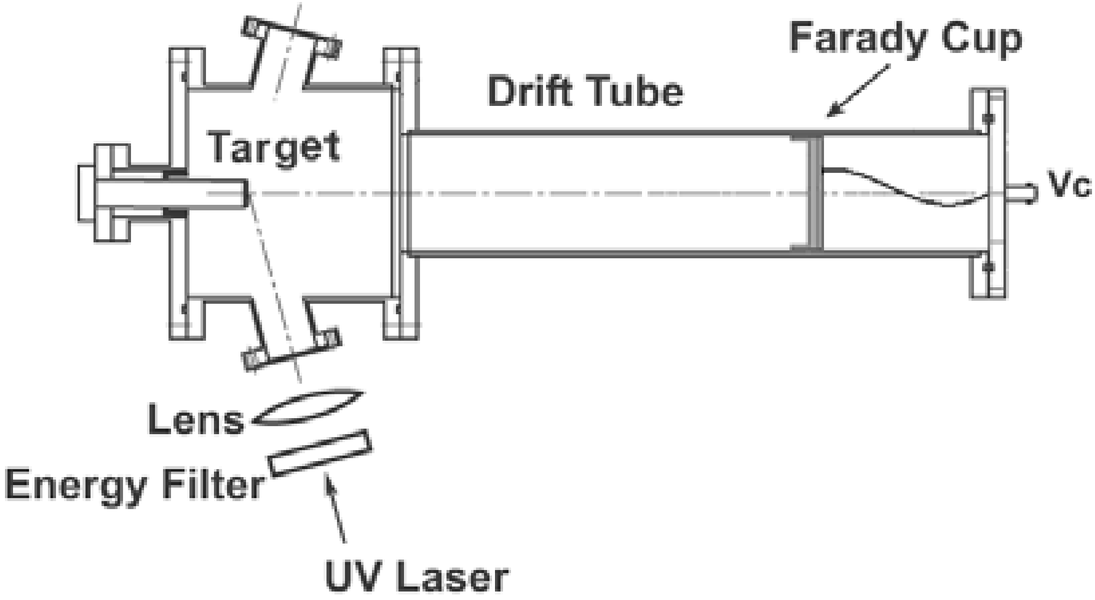
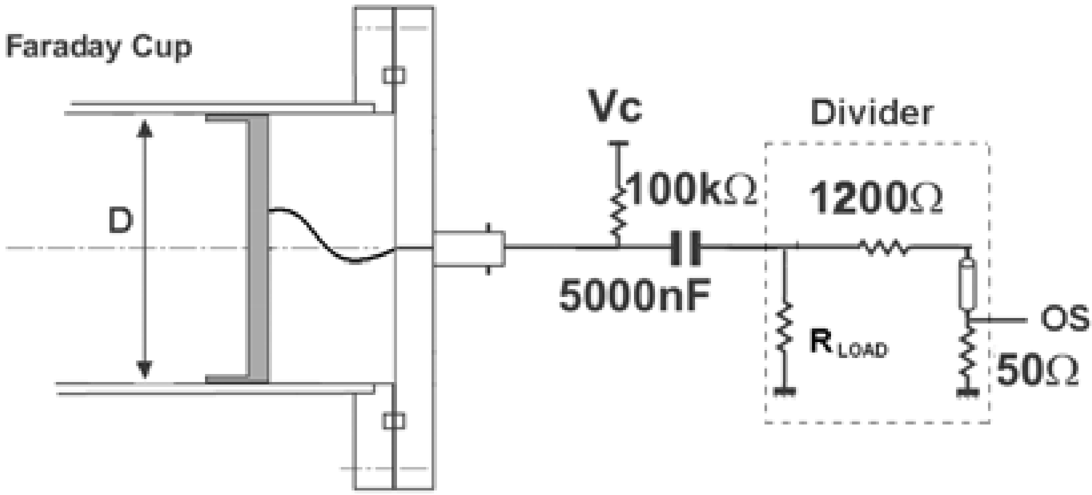


Fig. 1 - Nassisi – J. Appl. Phys.



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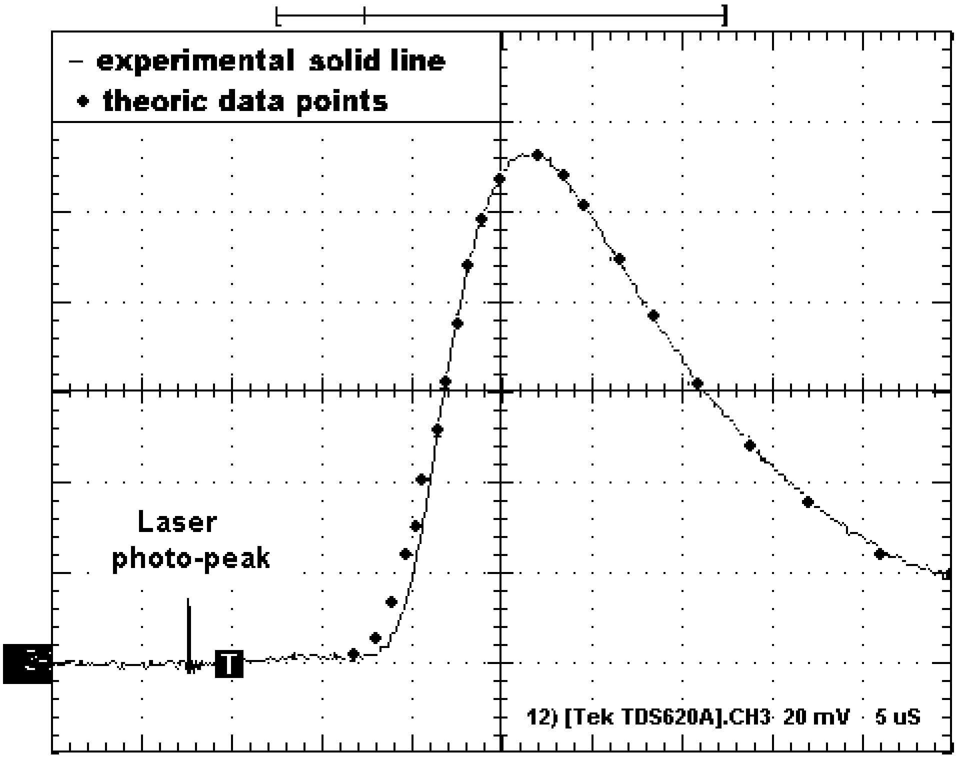

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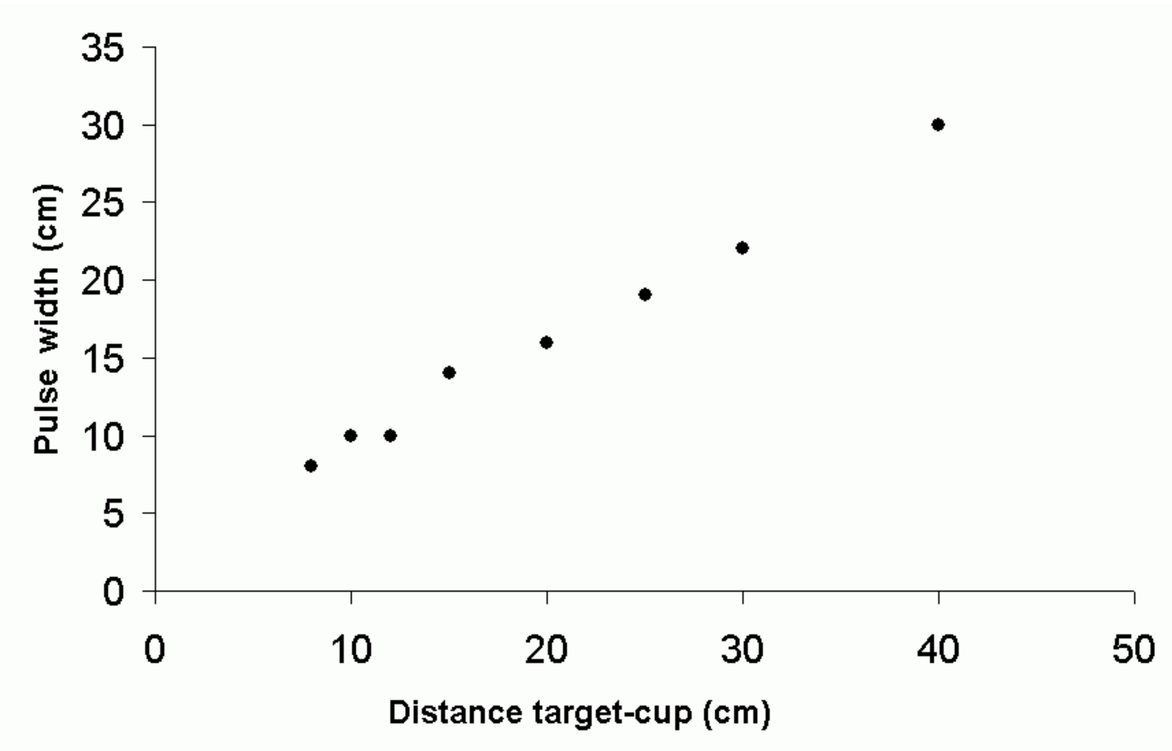

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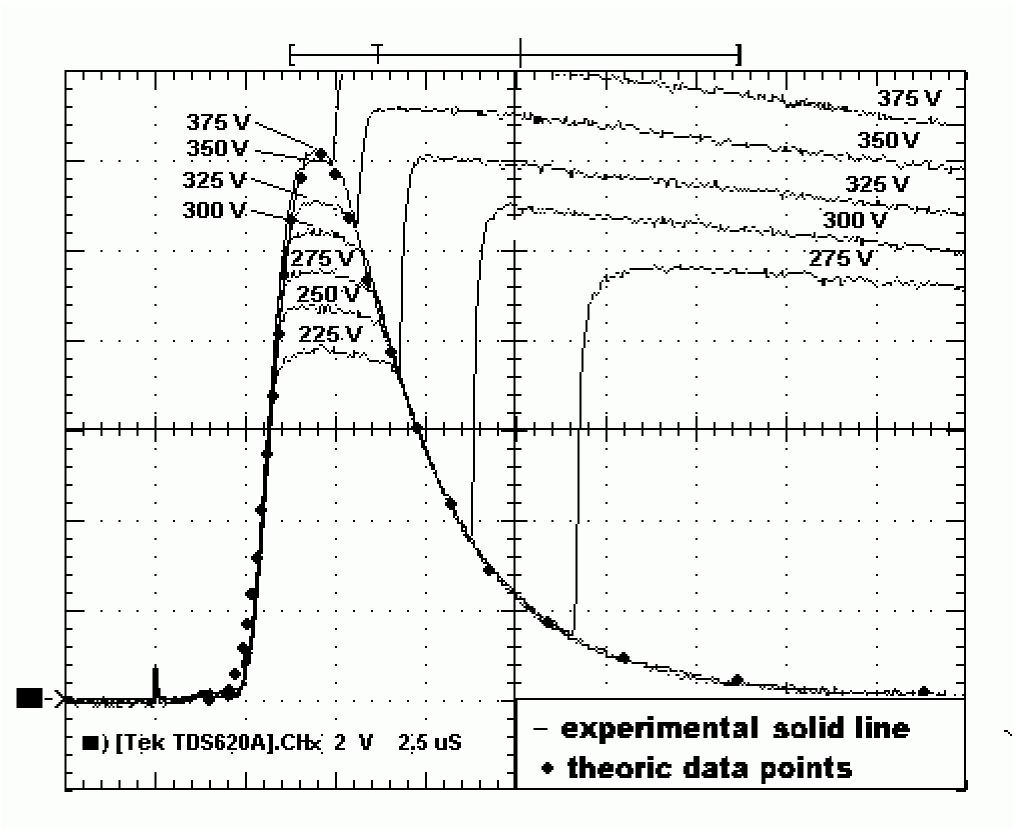

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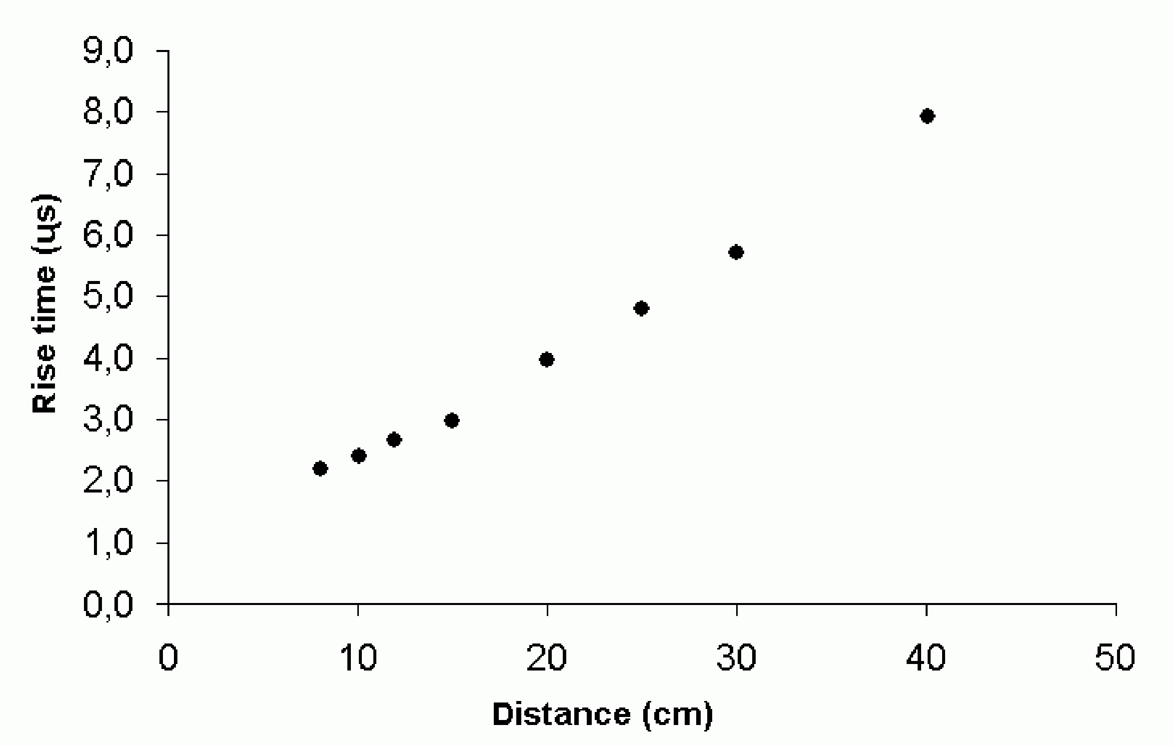

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Fig. 6 - Nassisi – J. Appl. Phys.

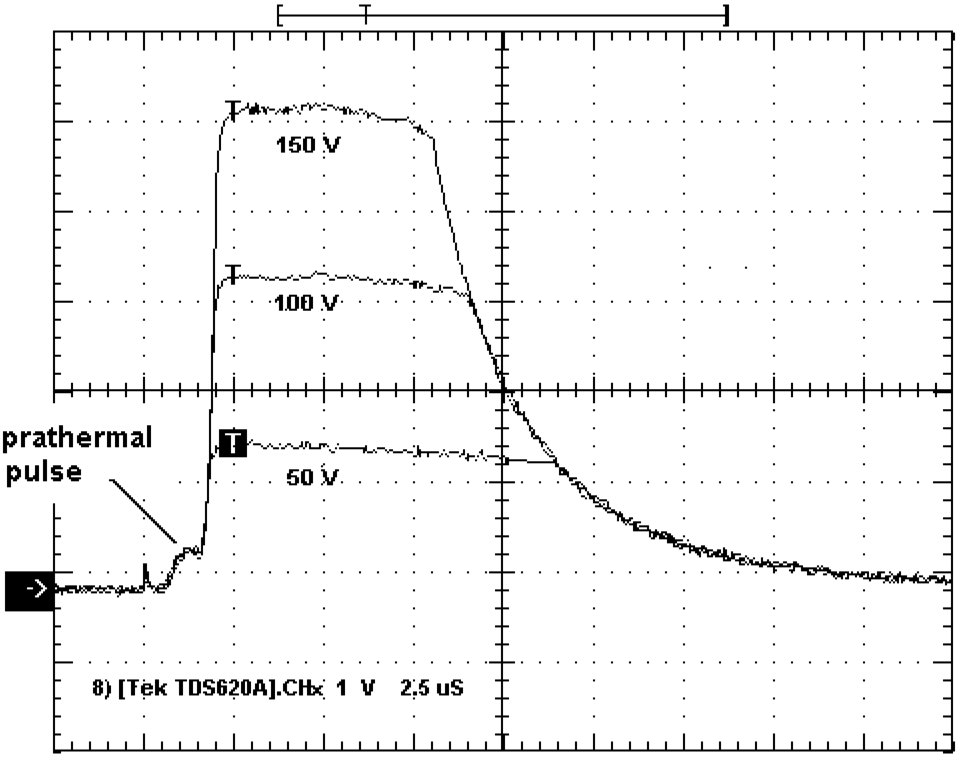


Fig. 7 - Nassisi – J. Appl. Phys.

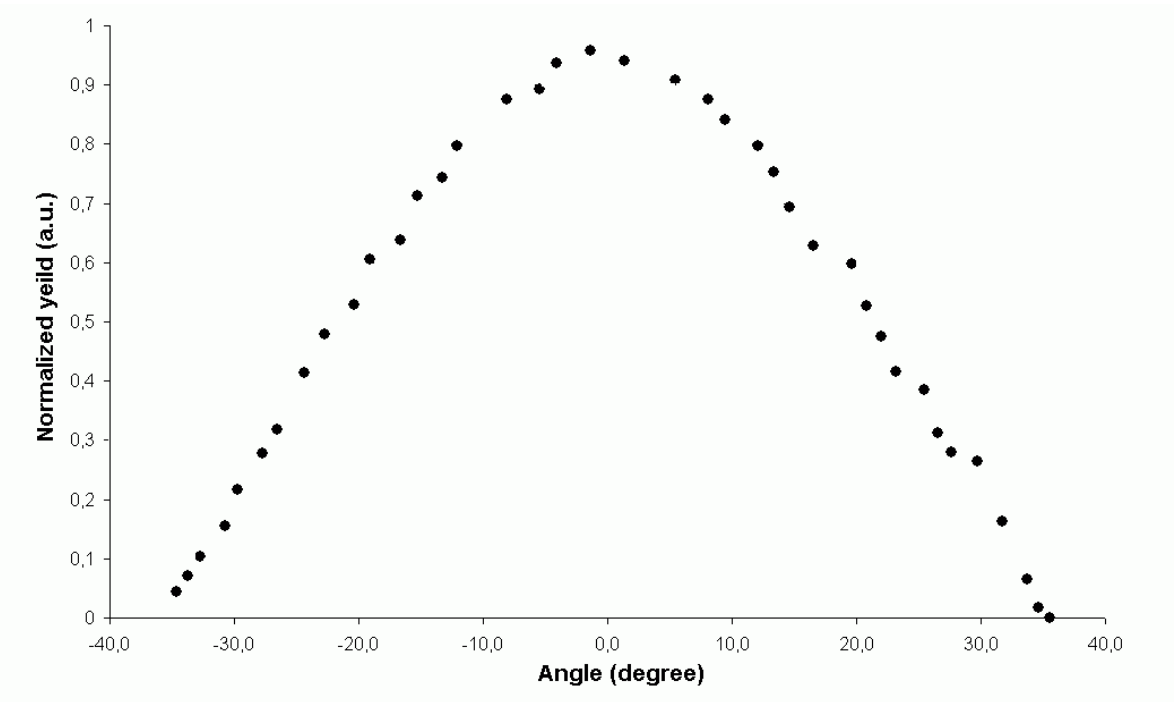
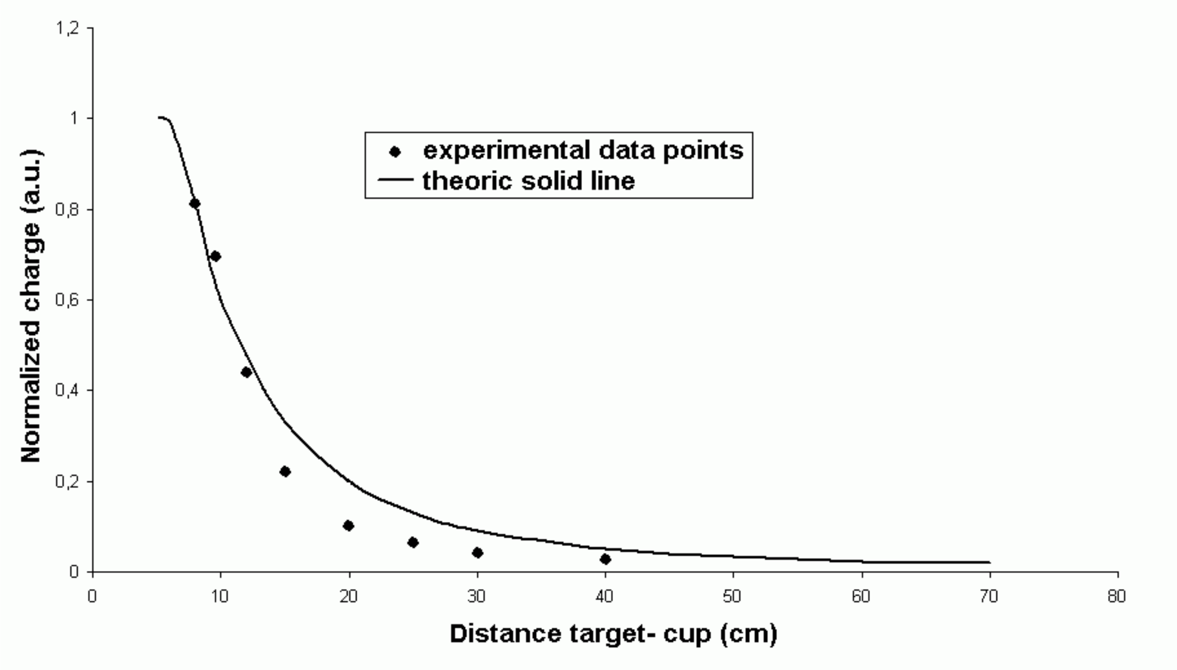


Fig. 8 - Nassisi – J. Appl. Phys.



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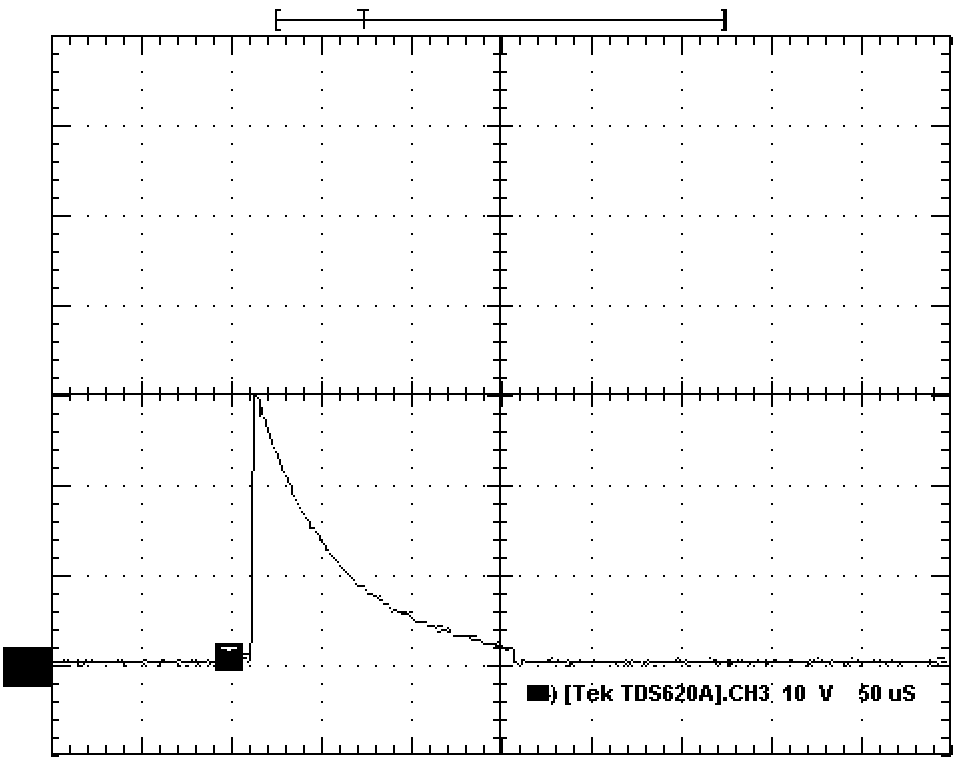

Fig. 10 - Nassisi – J. Appl. Phys.

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Distance target-cup (cm)	Mean velocity (m/s)	Temperature (K)
8	1800	370000
10	2000	550000
12	3500	550000
15	5200	520000
20	5800	530000
25	7000	530000
30	7700	480000
40	9300	500000