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Analysis of the Temporal and Spatial Properties of Platinum Plasma Using Pulsed Nd:YAG and CO_2 lasers

Zahraa Adel Mohammed[1] and Wissam Hasan Mahdi[2]

[1,2] Physics Department, College of Education for women
zahraae.aljanabi@student.uokufa.edu.iq،University of Kufa
*Corresponding author email: wisam.alajeeli@uokufa.edu.iq

تحليل الخصائص الزمنية والمكانية لبلازما البلاتين باستخدام الليزر النبضي Nd:YAG وCO2

زهراء عادل محمد1 ، وسام حسن مهدي 2
zahraae.aljanabi@student.uokufa.edu.iq،جامعةالكوفة, كلية التربية للبنات
wisam.alajeeli@uokufa.edu.iq،جامعةالكوفة ,كلية التربية للبنات

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ABSTRACT

Background:

The impact of laser light and pulse duration on the hydrodynamic properties of plasma was studied in terms of electron temperature (T_e), ion temperature (T_i), and ion rate (Z*).

Materials and methods:

The study was carried out in two stages: in the first phase, five energy levels of the Nd:YAG laser (1, 3, 5, 7, 9 J) and a pulse duration of (10 ns) were used at Full Width at Half Maximum (FWHM). In the second phase, five energy levels of the CO2 laser (1, 3, 5, 7, 9 J) with a (10 ns) pulse duration .

Results:

It was observed that at energy values of (1, 3, 5, 7, 9) J for the Nd:YAG laser with a 10 ns pulse duration, the electron temperature ranged from (214.79 to 690.97) eV. While the electron temperatures as a result of Co2 laser is ranged between (84.93 to 414.99) eV.

Conclusion:

We observe the electron temperatures of platinum plasma produced as a result of the ND:YAG laser was produced with with the same levels were higher than the electron temperatures of platinum plasma produced using a CO_2 laser.

Keywords: The platinum plasma; ND:YAG laser; CO2 laser; laser produced plasma (LPP), X-rays; MED103.

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INTRODUCTION

Plasma is considered the fourth matter state alongside the other common states: solid, liquid, and gas. Plasma can exhibit behavior characteristic of each of these three more common states depending on its density and temperature. It can be described as a quasi-neutral gas made up of neutral and charged particles that behaves collectively [1]. Platinum is used as a solid target to form laser-produced plasma within the soft X-ray range of the water window, making it suitable for imaging living cells with microscopy.[2]

Laser-produced plasma is one of the most effective methods, using a solid, liquid, or gas target. The emission spectrum is influenced by electron temperature (Te), ion temperature (Ti), as well as the densities of electrons and ions, and the type of target material [3]. Plasmas generated from elements with higher atomic numbers emit shorter wavelengths due to unresolved transitions between the n=4 to n=4 and n=4 to n=5 levels [4]. The plasma generated by the laser is extremely dense and hot. Laser-produced plasma has been applied in various fields[5], such as microscopy and lithography[6]. The most important technological application of laser-produced plasma in industry is X − ray lithography [7].

X-ray lithography has been proposed as a method for manufacturing dense, fine electronic circuits [8-9]. Microscopy, on the other hand, is an advanced technique that uses X-rays in the spectral "water window" region ($2.3 < \lambda < 4.4$ nm) to image biological samples and various materials with high precision. This technique allows for studying the fine structure of materials at the nanometer scale. In the spectral "carbon window" region ($4.5 < \lambda < 5.0$ nm), there is a unique capability of soft X-rays to examine thick layers of organic and other carbon-containing materials [10]. Extreme ultraviolet (EUV) and soft X-ray sources have been developed for use in several prominent fields, including 3D both single-shot flash imaging and imaging of microscopic biological structures, such as living cells within organisms[11].

MATERIALS AND WORKING METHODS

Platinum element with atomic number 78 was used, where two lasers were focused in two stages, the first is an ND laser and the second is a CO laser, using the Medusa program, where data was entered regarding the laser used, such as laser power and wavelength, as well as the target geometry, such as its shape, as a cylindrical platinum target was used, and its atomic number. The program produced a file containing all the plasma properties, from the temperature of the electrons and ions, to the ion rate, pressure, and speed. Using the MATLAB program, the results were analyzed and plotted.

RESULTS AND DISCUSSION

A modified version of MEDUSA (103MED) was used to study the effect of laser pulse energy J (1, 3, 5, 7 and 9) and laser pulse duration of 5 ns on the hydrodynamic properties. The study involved using an Nd: YAG laser with a wavelength of 1064nm and a CO_2 laser with a wavelength of 10600 nm, both focused on a spot with a radius of 20 µm, targeting a platinum (Pt) element with an atomic number Z=78 and a diameter of 90 µm, shaped as a cylindrical geometric target. The laser beam is directed at an angle of 90 degrees (perpendicular) to the target. The grid was divided into 400 cells, and the simulation time was set to 100 ns, with results recorded at a time interval of 1 ns between each time step. During the program's execution, changes in hydrodynamic properties are recorded as a function of time across all 400 grid cells or as a function of distance across all time steps.

When using an Nd: YAG laser with a pulse duration of 10 ns, the laser power density ranges between (0.795×10^{13}–7.162×10^{13}) W/cm ^{2} . The electron temperature (T_e) and ion temperature (T_i) increase with the increase in energy (E), recording the highest values for T_i and T_e at 585.79eV and 690.97 eV , respectively. In the case of the CO_2 laser with a pulse duration of 10 ns, the electron temperature ranges between (84.93 – 414.99) eV, while the ion temperature ranges between (81.35 – 319.59) eV with in the energy range of J (1, 3, 5, 7 and 9). Table 1 includes the energy values for the Nd: YAG laser at a pulse duration of 10 ns, the power density of the Nd: YAG laser, the maximum electron temperature (T_e), ion temperature (T_i), the average ionization at the maximum electron temperature (Z^*), the maximum average ionization at the maximum electron temperature (Z max), the logarithm of electron density (Log n_e), as well as the time and distance at which the electron temperature reaches its maximum value. It was observed that, at a pulse duration of 5 ns, increasing the energy results in an increase in the laser power density, and with the increase in laser power density, the maximum electron temperature also increases, ranging between 214.97 eV and 690.97 eV.

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Table (1) The maximum electron and ion temperatures (Te , Ti) and the average ionization Z* for the Nd: YAG laser with a wavelength of 1064 nm at a pulse duration of 10 ns.

Laser energy (J)	Laser power density $(Wcm^{-2})x10^{13}$	T_e (eV)	T_i (eV)	Z* max	Z*	Log n_e (cm^{-3})	Time (ns)	Distance (μm)
1	0.795	214.79	199.02	34.48	33.59	19.98	16.005	134.54
3	2.387	434.81	365.38	43.97	43.08	19.84	13.002	131.11
5	3.978	552.26	446.65	46.96	45.31	20.02	11.007	120.53
7	5.570	620.90	491.3	48.90	47.59	19.86	11.005	141.59
9	7.162	690.97	585.79	51.88	51.25	20.10	17.006	169.24

The maximum ion temperature increases with the rise in the power density of the Nd:YAG laser, ranging from(199.02 to 585.79) eV. The ion rate at the maximum electron temperature (Z*) also increases with the power density of the Nd:YAG laser, ranging from 33.59 to 51.25. The maximum ion rate (Z* max) increases with higher laser power density, ranging from 34.48 to 51.88. It was observed from the values of the ion rate at the maximum electron temperature (Z*) and the maximum ion rate (Z* max) that the ion rate at the maximum electron temperature is very close to the maximum ion rate. It was also noted that reaching the maximum electron temperature occurs after the pulse duration ends and at a distance from the target surface due to the target thickness of 90 μm, with distances ranging from 134.54 to 169.24 μm.

Table 2 shows the effect of increasing the power density of the CO_2 laser with a pulse duration of 10 ns on the maximum electron temperature. With increased power density of the CO2 laser, the maximum electron temperature rises, ranging from (84.93 to 414.99) eV. The maximum ion temperature also increases with the CO_2 laser power density, ranging from (81.35 to 319.59) eV. The ion rate at the maximum electron temperature and the maximum ion rate increase with the laser power density, and the maximum electron temperature is reached after the pulse duration ends and is located farther from the target surface.

Comparing the results obtained using the Nd: YAG laser with those obtained using the CO_2 laser at a laser pulse duration of 10 ns, it is observed that the values of maximum electron and ion temperatures using the CO_2 laser are significantly lower than those when using the Nd: YAG laser. Similarly, the ion rate at the maximum electron temperature and the maximum ion rate are lower than those with the Nd:YAG laser. This is due to the difference in the wavelengths of the two lasers used, as an increase

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in laser wavelength reduces the maximum electron and ion temperatures as well as the ion rate at the maximum electron temperature and the maximum ion rate.

Table (2) The maximum electron and ion temperatures (T_e , T_i) and the average ionization Z^* for the CO_2 laser with a wavelength of 10600 nm at a pulse duration of 10 ns.

Laser energy (J)	Laser power density (Wcm^{-2})x10^{13}	T_e (eV)	T_i (eV)	Z*	Z* max	Log n_e (cm^{-3})	Time (ns)	Distance (µm)
1	0.795	84.93	81.35	20.58	21.04	19.95	17.008	207.86
3	2.387	164.84	152.54	29.24	30.02	19.81	17.004	244.2
5	3.978	249.40	218.23	34.87	35.68	19.63	17.002	281.17
7	5.570	333.52	274.73	38.64	39.44	19.50	17.008	303.70
9	7.162	414.99	319.59	40.84	42.10	19.52	16.008	292.98

Figure1 shows the variation of the maximum electron temperature with the power density for the ND:YAG laser and CO_2 laser at a pulse duration of 10 ns. The Nd:YAG laser appears in black and grows faster compared to the CO_2 laser (in red), indicating that the Nd:YAG laser raises electron temperature at a faster rate with increasing power density than the CO_2 laser. Overall, it can be concluded that the Nd:YAG laser is more effective at raising electron temperature at the same power density compared to the CO_2 laser.

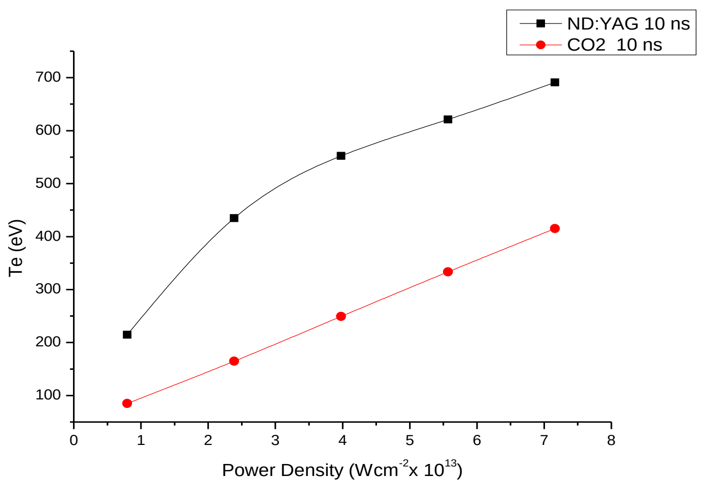

Figure (1) The variation of the maximum electron temperature with power density for the Nd:YAG laser and CO_2 laser at a pulse duration of 10 ns

Figure 2 illustrates the behavior of the maximum ion temperature values as a function of the laser power density at energy levels of (1, 3, 5, 7, 9)J with a pulse duration of

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10 ns. The Nd:YAG laser appears in black and grows faster compared to the CO_2 laser (in red), indicating that the Nd:YAG laser raises electron temperature at a faster rate with increasing power density than the CO_2 laser. Overall, it can be concluded that the Nd:YAG laser is more effective at raising electron temperature at the same power density compared to the CO_2 laser. It was observed from Figures (1) and (2) that the behavior of the maximum electron temperature and the maximum ion temperature when using two different lasers at the same energy levels and a pulse duration of 10 ns is very similar.

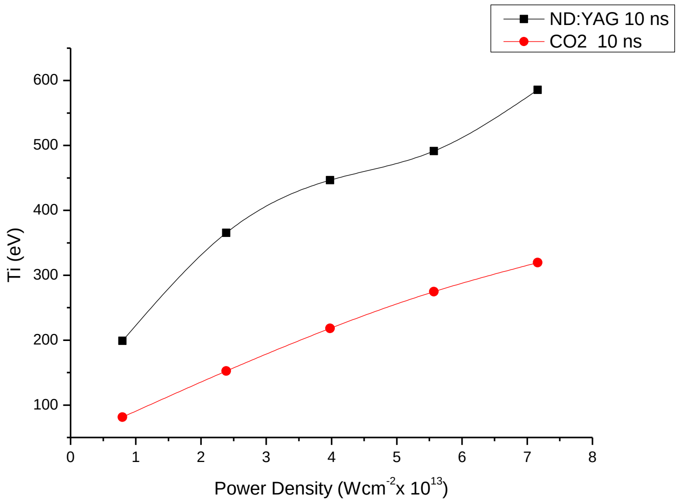

Figure (2) The variation of the maximum ion temperature with power density for the Nd:YAG laser and CO_2 laser at a pulse duration of 5 ns

At a pulse duration of 10 ns, as the energy increases, the laser power density also increases, leading to a rise in electron temperature. Figure (3) A illustrates the temporal and spatial variation of temperature with changes in the energy of the Nd:YAG laser. At an energy of 1J, it was observed that the electron temperature starts from 20 eV and reaches a maximum value of 214 eV. The highest electron temperature is found in a very small region of the plasma, close to the surface of the target, while the dominant temperature in the plasma is around (20-40) eV, at an energy of 3 J, it was observed that the electron temperature starts from 50 eV and reaches a maximum value of 434 eV. The maximum electron temperature occurs in a very small region of the plasma and close to the target surface, but the dominant temperature in the plasma ranges between 50-100 eV. At an energy of 5 J, it was observed that the electron temperature starts from 50 eV and reaches a maximum value of 552 eV. The maximum electron temperature occurs in a very small region of the plasma and farther from the target surface, while the dominant temperature in the plasma ranges between 50-150 eV.

Figure (3) B illustrates the temporal and spatial variation of electron temperature with changes in the energy of the CO_2 laser. At an energy of 1J, it was observed that the

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electron temperature starts from 10 eV and reaches a maximum value of 84 eV. The highest electron temperature occurs in a very small region of the plasma, located far from the surface of the target, while the dominant temperature in the plasma is around 10 eV. At an energy of 3J , the electron temperature begins at 20 eV and increases to a maximum of 164 eV. The highest electron temperature occurs in a very small region of the plasma, located far from the surface of the target, while the dominant temperature in the plasma is around 20 eV. At an energy of 5J , the electron temperature begins at 50 eV and increases to a maximum of 249 eV. The highest electron temperature occurs in a very small region of the plasma, located far from the surface of the target, while the dominant temperature in the plasma is around 50 eV.

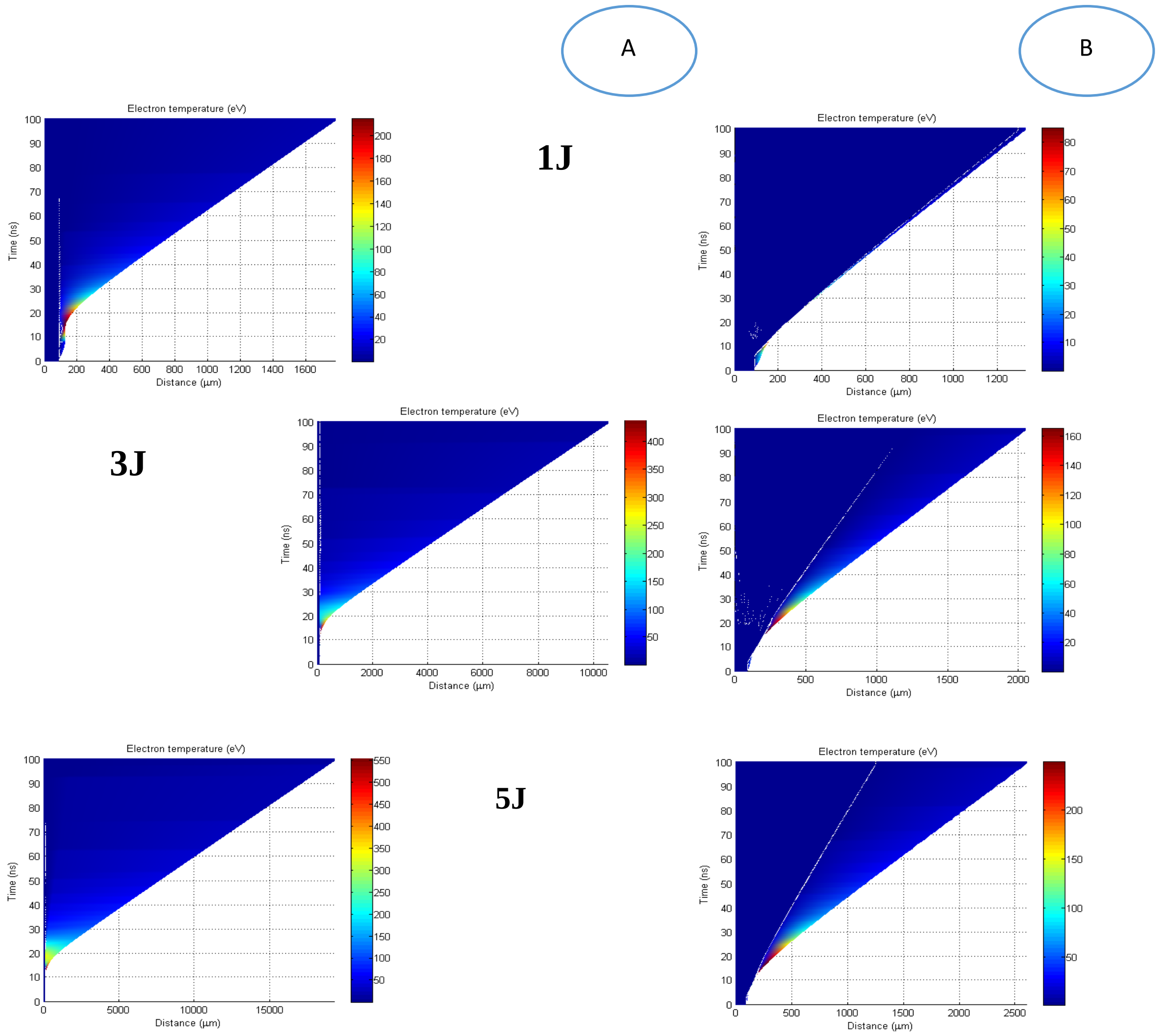

Figure (3) Temporal and Spatial Variation of Electron Temperature Using Energies (1, 3 ,5) J at Pulse Duration 10 ns A- using ND:YAG laser B- using CO_2 laser

At a pulse duration of 10 ns, increasing the energy results in an increase in the laser power density, which consequently raises the ion temperature. At a pulse duration of 10 ns, as the energy increases, the laser power density also increases, leading to a rise in ion temperature. Figure (4) A illustrates the temporal and spatial variation of temperature with changes in the energy of the Nd:YAG laser. At an energy of 1J, it was observed that the ion temperature starts from 20 eV and reaches a maximum value of 199 eV. The maximum ion temperature occurs in a very small region of the plasma and is far from the target surface, while the dominant temperature in the plasma is around 20-40 eV. At an energy of 3 J, it was observed that the ion temperature starts from 50 eV and reaches a maximum value of 365 eV.

The maximum ion temperature occurs in a very small region of the plasma and is far from the target surface, but the dominant temperature in the plasma is around 50-100 eV. At an energy of 5 J, it was observed that the ion temperature starts from 50 eV and reaches a maximum value of 446 eV. The maximum ion temperature occurs in a very small region of the plasma and is far from the target surface, but the dominant temperature in the plasma is around 50-150 eV.

Figure (3) B illustrates the temporal and spatial variation of electron temperature with changes in the energy of the CO_2 laser .At an energy of 1J, it was observed that the electron temperature starts from 10 eV and reaches a maximum value of 8 eV. The highest electron temperature occurs in a very small region of the plasma, located far from the surface of the target, while the dominant temperature in the plasma is around 10 eV. At an energy of (3 , 5) J, it was observed that the ion temperature starts from 20 eV and reaches a maximum value of (152 , 218) eV. The maximum ion temperature occurs in a very small region of the plasma and is far from the target surface, while the dominant temperature in the plasma is around 20 eV.

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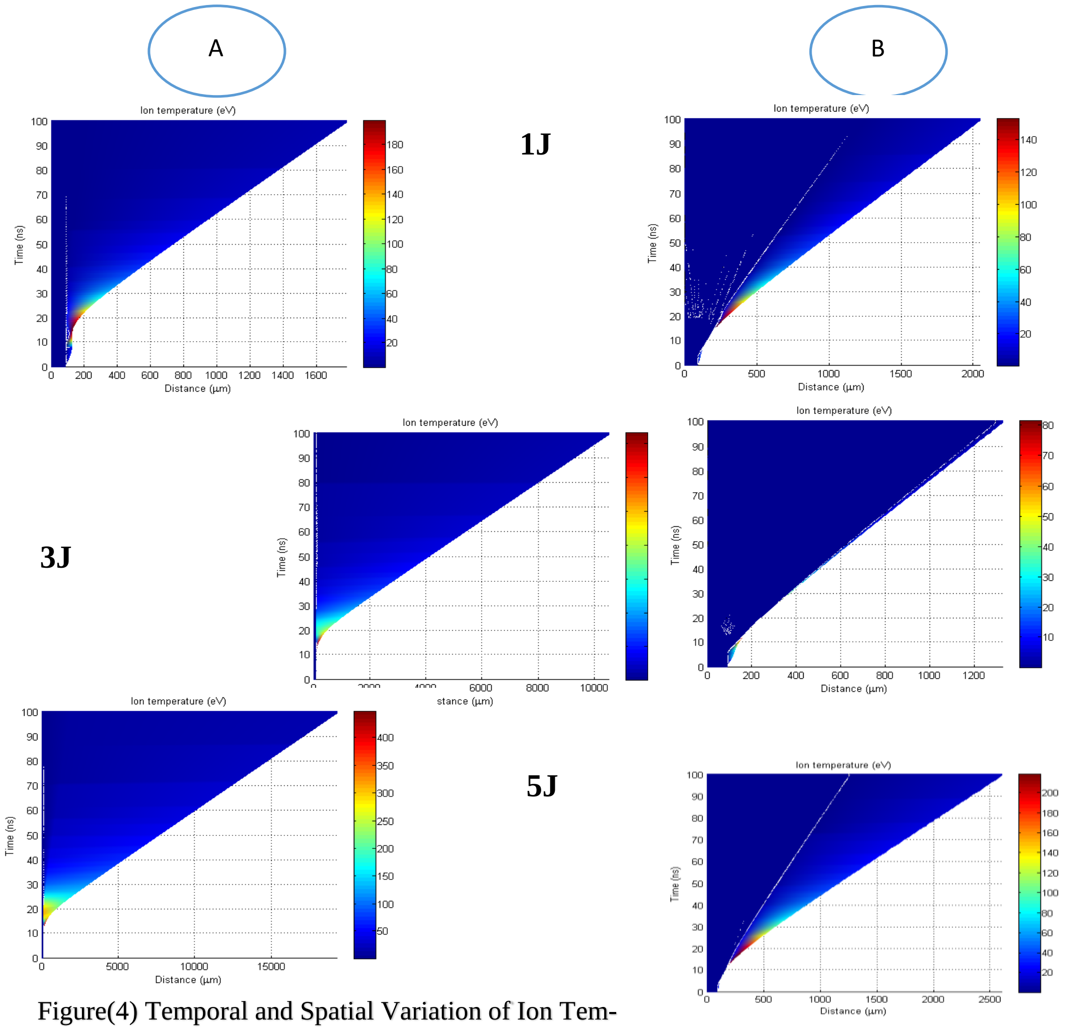

Figure(4) Temporal and Spatial Variation of Ion Temperature Using Energies (1, 3) J at Pulse Duration 10 ns A- using ND:YAG laser B- using CO_2 laser

CONCLUSION

Using a laser with a shorter wavelength provides better results. When using both Nd:YAG laser and CO_2 lasers, it is observed that the Nd:YAG laser yields higher temperatures due to its shorter wavelength. The temperature of electrons and ions increases with the increase in laser power density, i.e., by increasing laser energy or reducing laser pulse duration. The high temperature is concentrated near the target surface and occurs after the laser pulse duration ends.

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Conflict of interests:

There is no conflict of interest

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الخلاصة:

مقدمة:

تم دراسة تأثير ضوء الليزر ومدة النبضة على الخواص الهيدروديناميكية للبلازما من حيث درجة حرارة الإلكترون (Te) و درجة حرارة الأيون (Ti)ومعدل الأيون .(Z*)

طريقة العمل:

أجريت الدراسة على مرحلتين: في المرحلة الأولى، تم استخدام خمسة مستويات طاقة لليزر 1) Nd:YAG، 3، 5، 7 ، 9 (لومدة نبضة 10ns عند FWHM لوحظ أنه عند قيم طاقة (1,3,5,7,9) لليزر Nd:YAG مع مدة نبضة 10ns، تراوحت درجة حرارة الإلكترون من (214.79 إلى 690.97) إلكترون فولت. في المرحلة الثانية، تم استخدام خمسة مستويات طاقة لليزر 1 CO2، 3، 5، 7 ، J 9 مع مدة نبضة 10ns، مما أدى إلى نطاق أقصى لدرجة حرارة الإلكترون (84.93 إلى 414.93) إلكترون فولت.

الاستنتاجات:

نلاحظ أن درجات حرارة الإلكترون في بلازما البلاتين المنتجة باستخدام ليزر ND:YAG بنفس مستويات الطاقة كانت أعلى من درجات حرارة الإلكترون في بلازما البلاتين المنتجة باستخدام ليزر CO2

الكلمات المفتاحية :

بلازما البلاتين ، ليزر نديميوم ياك ، ليزر ثنائي اوكسيد الكاربون ، بلازما المنتجة بالليزر ، الاشعة السينية ، برنامج الميدوسا .

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