

Article

Synthesis of Nickel-Based Nanoparticles by Pulsed Laser Ablation in Liquids: Correlations between Laser Beam Power, Size Distribution and Cavitation Bubble Lifetime

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Abstract: Pulsed laser ablation in liquids (PLAL) is a colloidal synthesis technique attracting significant interest from the scientific community due to the quality of the nanoparticles being produced. In this type of synthesis protocol, the cavitation bubble plays a vital role during the synthesis of nanoparticles. This work studied the effect of the laser beam power on cavitation bubble lifetime. Three different laser beam power values (5.8 W, 7.5 W and 10.5 W) were used to irradiate a pure nickel target in de-ionized (DI) water to synthesize nickel-based nanoparticles. The optimal repetition rate maximizing the production of nanoparticles was determined by atomic emission spectroscopy for each laser beam power. It was determined that the optimal repetition rate increased exponentially with laser beam power, while the cavitation bubble lifetime decreased logarithmically with the laser beam power. Moreover, the effect of the laser beam power on the cavitation bubble lifetime also had an effect on the size distribution of the nanoparticles being produced; the smallest size distribution was obtained at the highest laser beam power.

Keywords: nanoparticles; cavitation bubble; laser ablation



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1. Introduction

The prefix ‘nano’ is referred to a Greek prefix meaning ‘dwarf’ or something very small and depicts one thousand millionth of a meter (10^{-9} m). The word “nanotechnology” was coined in 1974 by Norio Taniguchi (1912–1999), a Japanese Professor from Tokyo University of Science, who was the first to define the word as: “nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule”. Then, it was redefined by the National Nanotechnology Initiative as “the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications” [1]. At this scale, surface effects and quantum effects become important [2–4]. Indeed, by reducing the size of a material to the nanometer scale, the surface area to volume ratio of the particle increases, leading to a situation in which surface atoms dominate the nanoparticle properties. Algebraically, the fraction of atoms at the surface scales with the surface to volume ratio. As atoms on surfaces have fewer neighbors compared to those in the bulk, this makes nanoparticles dramatically different from the same substances in bulk form. Consequently, material properties such as thermal, mechanical, optical and electronic properties undergo size and shape effects that scale generally with the surface to volume ratio. Additionally, quantum effects start appearing when the thermal energy kT becomes smaller than the energy spacing between two successive energy levels. This occurs when the size of the particle is reduced. Indeed, by shrinking the size of the particle, the density of states decreases, and consequently, the splitting between two successive energy levels increases. The quantization of the energy levels in a nanoparticle is similar to the classic ‘particle in a box problem,’ but now to the extent where the nano is the size of

the box itself. This means that nanoparticle size now plays a significant role in terms of electronic characteristics.

This is why nanomaterials have different chemical, physical and biological properties compared to their bulk counterpart. Among these nanomaterials, nickel/nickel oxide (Ni/NiO) nanoparticles have gained substantial interest from the scientific community because they combine magnetic properties with catalytic properties. Indeed, Ni/NiO nanoparticles have been used as hydrogen evolution reaction (HER) catalysts for water splitting reactions by attaching the NiO/Ni heterostructure to the carbon nanotube (CNT) network [5]. Ni/NiO can also be used as a photocatalyst to degrade water pollutants [6]. Nickel-based catalysts are cheap compared to noble metals because nickel is more abundant in the earth's crust than noble metals [7]. Indeed, the crustal abundance of nickel is 26.6 ppm [8], while it is 1.3×10^{-3} ppm for gold [9] and 3.7×10^{-5} ppm for platinum [10]. This is why several groups have been working on the synthesis of nickel-based nanoparticles. For example, Jaji et al. prepared nickel-based nanoparticles using the one-pot solvothermal synthesis method, which involves a chemical reaction at a high temperature and a high reaction time [11]. Heilmann et al. reported the synthesis of Ni nanoparticles via a synthetic route, which requires several chemical reactions of nickel acetylacetonate as a precursor, oleylamine as the reducing agent and solvent, dibenzyl ether as the co-solvent and trioctylphosphine as the stabilizer [12]. Using a thermal decomposition technique, Liu et al. produced shuriken-shaped nickel nanoparticles, utilizing acetylacetonate as the precursor and oleylamine as both the solvent and reductant. The process was conducted at a temperature of 200 °C, involving multiple chemicals and reaction steps. They synthesized face-centered cubic nickel nanostructures with an average size of around 150 nm [13]. Kim et al. employed a comparable method to produce nickel nanoparticles through a hydrothermal approach, utilizing Nickel (II) chloride hexahydrate as a precursor and the borane-ammonia complex as the reducing agent under various temperatures ranging from 80 to 140 degrees Celsius. They observed that the influence of NaCl and KCl on the crystal growth rate led to the formation of spherical Ni particles, with size distributions from ~298 nm to ~1082 nm for NaCl and from ~359 nm to ~605 nm for KCl, respectively [14]. Woodard et al. synthesized nickel nanoparticles through the breakdown of nickelocene ($\text{Ni}(\text{Cp})_2$) in a continuous-flow, low-pressure, non-thermal plasma environment composed of argon and hydrogen (Ar-H_2). While their system was unable to yield completely carbon-free Ni nanoparticles, they managed to control the properties of the synthesized nanomaterials, including their chemical composition, size distribution and structure [15]. Zahra et al. synthesized NiO nanoparticles through a sol-gel process facilitated by a polyol medium. This method involved using nickel nitrate hexahydrate as the starting material, a mixture of isopropyl alcohol and water as the solvent and glycerol to make the polyol medium. The process was completed by subjecting the materials to calcination at temperatures varying between 500 and 900 °C. They were able to synthesize the face-centered cubic structure of nickel oxide. However, high aggregation of particles resulted in the formation of flakes of irregular sizes and shapes [16]. Shin et al. reported the production of nickel nanoparticles from LiNiO_2 (a cathode material). First, NiSO_4 , derived from leaching and purification, underwent liquid reduction with hydrazine monohydrate ($\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$) in a 10:3 volume ratio for 10 min, forming a nickel hydrazine complex. Then, adding sodium hydroxide in a 10:1.25–1.5 weight ratio to this complex and reacting at 80 °C for 15 min resulted in the synthesis of nickel particles [17].

Besides wet-chemical routes, pulsed laser ablation in liquids (PLAL) is an interesting alternative to synthesize Ni/NiO nanoparticles (Table 1). Indeed, the main advantage of PLAL over other techniques is the surface's purity of nanoparticles being produced by relying on electrostatic repulsion, instead of steric repulsion like wet-chemistry does. PLAL uses a pulsed high-energy laser beam that is focused on a solid target material totally submerged into a liquid solvent [18–20]. When the laser pulse strikes the target, it creates a plasma plume containing the ionized species from the target and solvent [21,22]. When the plasma cools down, it releases its heat to the surrounding solvent, which leads to the

formation of a cavitation bubble [23,24]. The high temperatures and pressures inside the bubble can cause structural changes within the nanoparticles, leading to the formation of new phases or stoichiometries [25]. The lifetime of these bubbles is known to be influenced by various factors, such as the laser pulse duration, the target, and the properties of the solvent. This paper examines the relationship between laser beam power, cavitation bubble lifetime and the size distribution of the Ni/NiO nanoparticles being produced.

In the literature, Nguyen et al. explored how varying liquid depths affected the behavior of cavitation bubbles created by nanosecond pulsed laser ablation in liquids (ns-PLAL), using high-speed laser stroboscopic videography. They found that, if the liquid depth is significantly less than the maximum bubble radius, the bubble breaks through the liquid surface, shortening its lifespan and blocking secondary shock wave generation. For liquid depths slightly less to several times greater than the bubble's maximum radius, the bubble's growth and collapse are asymmetrical, elongating during expansion and flattening during collapse. A liquid jet forms during bubble contraction, impacting a rigid boundary and causing additional force on the target. Following this, the bubble takes on a toroidal shape, and at its smallest contraction, it emits multiple shock waves from various points along the torus. With deeper liquids, these secondary shock waves are more concentric, delivering a stronger impulse to the solid target [26]. Long et al. conducted a similar study by analyzing cavitation bubble dynamics using a high-resolution stroboscopic shadowgraphy system. They studied how the liquid height affects the evolution and growth of the bubbles, and they concluded that the laser fluence is mainly responsible for the speed of the emitted shockwaves, and the effects of the liquid height are negligible when the height is between 0.5 mm and 4 mm. They further concluded that, when the liquid height is less than the maximum radius of the bubble, the expanding cavitation bubble contacts the liquid–air interface [27]. Letzel et al. reported that a defined number of pulses changed the target's surface geometry as well as the dynamics of cavitation bubbles. They also found that the mass concentration within the cavitation bubble decreases with the number of laser pulses [28]. Peng et al. studied the simulation of the collapse process of a cavitation bubble near a rigid boundary. According to their simulation, the maximum pressure, collapse velocity, and collapse temperature increased with the distance between the cavitation bubble and the rigid boundary [29]. Sasaki et al. observed the effect of external pressure on the cavitation bubble during PLAL. According to their study, the external pressure to the ambient liquid affects cavitation bubble dynamics, bubble temperature and the lifetime of the cavitation bubble [30]. Wang et al. reported the effects of the solvent's surface tension and initial input energy on the cavitation bubble. Their simulation indicates that the collapse pressure, velocity and temperature increase with the surface tension. The parameter most influenced is the collapse pressure, whereas the collapse temperature is the least affected. The simulation shows similar effects for the cavitation bubble collapsing near a neutral wall [31]. Yuan et al. investigated the effects of wall wettability on the collapse of cavitation bubbles. Their simulation of single-bubble collapse near a neutral wall aligns well with the Rayleigh–Plesset results. Additionally, they showed that the interaction forces on a cavitation bubble are different with different surface wettability. A hydrophilic surface creates a repulsive force between the wall and the bubble, causing both the size and pressure of the high-pressure region above the bubble to decrease. Conversely, a hydrophobic surface creates an attractive force between the wall and the cavitation bubble, and the attractive force accelerates the collapse of the cavitation bubble. The simulation also showed that the collapse time of a cavitation bubble is significantly shorter near a hydrophobic wall compared to a hydrophilic wall when the bubble is close to the wall. Conversely, if the bubble is outside the wall's influence, its lifetime is similar regardless of the wall's wettability [32]. All these previous studies help to understand the formation and collapse of the cavitation bubbles. However, the effect of the laser beam power on the cavitation bubble lifetime was not studied in detail, and this was the main reason behind this investigation.

Table 1. List of main papers discussing the synthesis of Ni or NiO or Ni/NiO nanoparticles (NPs) by PLAL.

Authors	Laser	Fluence (J/cm ²)	Solvent	Wavelength (nm)	Duration (min)	Rep. Rate (Hz)	Results
Ma et al. [33]	Nd:YAG	3.2, 10.5, 19.9	De-Ionized (DI) water		60	10	NiO NPs
Mardis et al. [34]	Nd:YAG		Liquid CO ₂	1064	15	10	Ni NPs
Safa et al. [35]	Nd:YAG	0.6, 0.8, 1, 1.2	Distilled water	1064		10	NiO NPs
Mahfouz et al. [36]	Nd:YAG		Water	532	2–15	10	NiO NPs
Khashan et al. [37]	Nd:YAG		DI water	1064	10, 20	1	NiO NPs
Lasemi et al. [38]	Nd:YAG		Water, Ethanol, Butanol, Isopropanol	532		20	Ni/NiO NPs
Musaev et al. [39]	Nitrogen laser	50	Distilled water	337		5	Ni NPs
Mostafa et al. [40]	Nd:YAG		Pure water	1064		10	NiO NPs
Gondal et al. [41]	Nd:YAG		H ₂ O ₂	355	30	10	NiO NPs
Jung et al. [42]	Nd:YAG		DI water, Methanol, Hexane	1064	20	10	Ni, Ni/NiO NPs
Gellini et al. [43]	Nd:YAG	2.5	Pure water	1064	20	10	NiO NPs
Lee et al. [44]	Nd:YAG		Methanol, DI water, Hexane	1064		10	Ni NPs
Arboleda et al. [45]	Ti:sapphire	90	Water, n-heptane	800	9	1000	Ni NPs
This work	Nd:YAG	70, 90, 130	DI water	1064	5	100–8000	Ni/NiO NPs

2. Synthesis–Experimental Details

A Q-switched Nd: YAG laser, emitting at 1064 nm, from Electro Scientific Industries, was used to irradiate a solid Ni target totally submerged in de-ionized (DI) water (Figure 1A). The laser beam power was precisely controlled, with power values set at 5.8 W, 7.5 W and 10.5 W. Additionally, the repetition rate was tuned from 0.1 kHz to 8 kHz. This adjustment in the repetition rate had an influence on the pulse duration, which varied slightly from 70 to 200 nanoseconds. The top-down irradiation setup illustrated in Figure 1A included a gold-coated mirror placed on the beam path at a 45-degree angle with respect to the laser rail to convert the horizontal laser beam into a vertical one. The distance between the lens and the target was adjusted to match the focal length of the lens (83 mm) to minimize the surface area of the beam spot size on the target. The laser's beam spot size on the surface of the target was measured to be around ~100 µm in diameter. The fluences of the laser beam at the varying power settings were calculated to be approximately 70 J/cm² at 5.8 W, 90 J/cm² at 7.5 W and 130 J/cm² at 10.5 W. All these fluence levels were significantly above the laser fluences used to synthesize nickel-based nanoparticles reported by Liu and his group [46]. For the target, a high-purity cylindrical nickel pellet was used, measuring 6.3 mm in height and diameter and composed of 99.995% nickel (supplied by Kurt J. Lesker). This target was placed in a 50 mL round glass beaker, which served as the container for the experiment. The nickel pellet (Figure 1B) was submerged into 5 mL of DI water, resulting in a water level approximately 2.5 mm above the target surface. The irradiation lasted for 5 min.

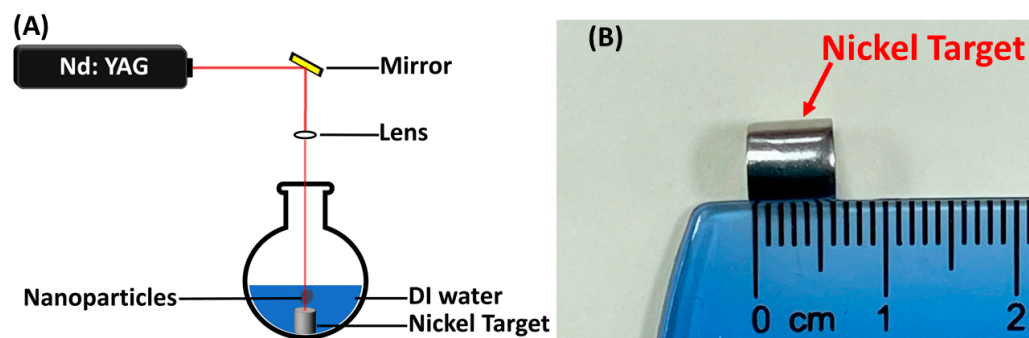


Figure 1. (A) Sketch displaying the pulsed laser ablation in liquid set-up used in this investigation. It is a top-down PLAL synthesis protocol. (B) The target is a cylindrical pellet made of pure Ni (@ 99.995% from Kurt Lesker).

3. Results and Discussion

The atomic emission spectroscopy (AES) analysis (4210 MP-AES, Agilent, Santa Clara, CA, USA) was a crucial component of our investigation to determine the effect of the repetition rate on the production of nanoparticles. From this analysis, the best repetition rate maximizing the production of nanoparticles was determined. Indeed, the AES results revealed a clear pattern: as the laser's repetition rate increased, the concentration of nanoparticles in the solution initially rose, to reach a maximum range, before gradually decreasing. This trend can be explained by the interaction of the laser beam with the Ni target within the solvent. When the pulsed laser beam hit the target (beam ON), it ionized the target and the solvent around the ablation zone, creating a plasma. This plasma, confined within the liquid medium, reached a temperature of approximately 5000 K [47]. However, when the beam was OFF, the plasma could not be sustained and cooled down, transferring the heat to the surrounding solvent and vaporizing it, leading to the formation of a cavitation bubble. Due to the pressure of the liquid on the cavitation bubble, the cavitation bubble finally collapsed, releasing the nanoparticles within the solvent [48].

An interesting aspect observed during the irradiation was that the cavitation bubble formed by the laser pulse acted as a shield, preventing subsequent laser pulses from effectively reaching the target [25,49]. The data indicated that the maximum concentration of nanoparticles was achieved at repetition rates of 1.6 ± 0.2 kHz @ 5.8 W, 1.9 ± 0.2 kHz @ 7.5 W and 3.8 ± 0.2 kHz @ 10.5 W (Figure 2). These correspond to a total number of pulses of 480,000, 570,000 and 1,140,000 at 1.6 kHz, 1.9 kHz and 3.8 kHz, respectively. When the repetition rate exceeded those optimal values, the laser beam interacted with the cavitation bubble and not the target, leading to a decrease in nanoparticle production. This observation allowed us to estimate the lifetime of the cavitation bubble by taking the reciprocal value of the optimal repetition rate, which was 0.64 ± 0.06 ms @ 5.8 W, 0.53 ± 0.04 ms @ 7.5 W and 0.26 ± 0.01 ms @ 10.5 W. These values are in agreement with the literature. Indeed, the cavitation bubble lifetimes generally ranged from microseconds to milliseconds, depending on the laser parameters used during the synthesis [25,50–52].

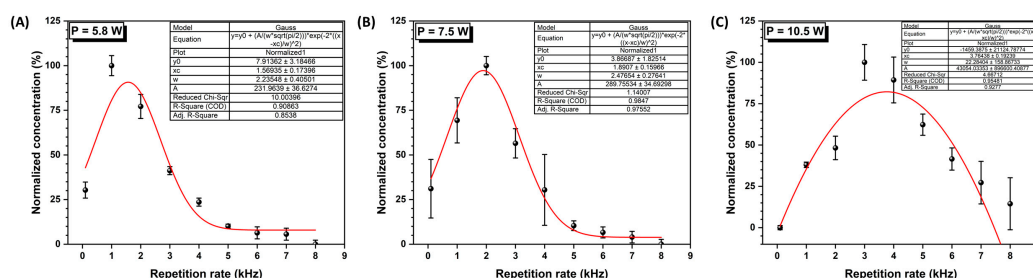


Figure 2. Concentration of the colloids measured at different repetition rates for each laser beam power used (A) P = 5.8 W, (B) P = 7.5 W and (C) P = 10.5 W.

Afterwards, X-ray diffraction (XRD) was conducted with a Rigaku Miniflex 600 to determine the structural properties of the Ni/NiO nanoparticles produced at the best repetition rate for each of the selected powers (1.6 kHz @ 5.8 W, 1.9 kHz @ 7.5 W and 3.8 kHz @ 10.5 W). After synthesis, these colloids underwent centrifugation using a Sorvall Legend Micro 17 (Thermo Scientific, Waltham, MA, USA). The precipitates were then carefully dried onto silicon wafers for detailed examination. Significantly, as seen in Figure 3, the XRD patterns show diffraction peaks at 2θ angles of 37.2° , 43.1° and 62.8° across all three samples. These peaks are indicative of the (1 1 1), (2 0 0) and (2 2 0) lattice planes of NiO, confirming its presence within all the samples. Additionally, the patterns exhibited peaks at 44.4° , 51.8° and 76.3° , corresponding to the (1 1 1), (2 0 0) and (2 2 0) lattice planes of Ni. Furthermore, the peak observed in all three samples at 69.12° is attributed to the silicon wafer substrate onto which the nanoparticles were deposited. The intensity of the XRD peak is related to the number of atoms in the crystal that are capable of scattering X-rays. From Figure 3, it is obvious that the intensity of the Ni peaks is much larger than the intensity of NiO peaks, confirming that Ni is the dominant phase compared to NiO; therefore, the presence of NiO could only be due to the surface oxidation of the Ni core [53].

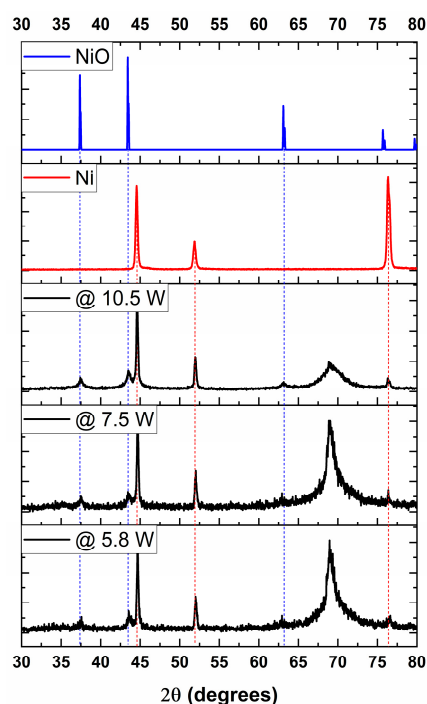


Figure 3. XRD patterns of the Ni-based nanoparticles synthesized by PLAL under the following conditions: 1.6 kHz @ $P = 5.8$ W, 1.9 kHz @ $P = 7.5$ W and 3.8 kHz @ $P = 10.5$ W. The XRD pattern of the pure Ni target as well as the NiO reference from the Ruff database (Ruff ID = R080121.9) are indicated for comparison purposes. The peak @ 69° belongs to the silicon substrate.

Subsequently, scanning electron microscopy (SEM) analysis was performed on the nanoparticles synthesized under optimal conditions (1.6 kHz @ 5.8 W, 1.9 kHz @ 7.5 W and 3.8 kHz @ 10.5 W) to determine their size and shape (Figure 4). This analysis was performed using a JEOL JSM7000F SEM system (JEOL Ltd., Tokyo, Japan) operated at an acceleration voltage of 15 kV. The SEM images, presented in Figure 4, show the spherical shape of the nanoparticles for all the analyzed samples. From Figure 4, a trend was observed between the laser beam power and the size of the nanoparticles. Indeed, as power increased, the size of the nanoparticles decreased. Quantitatively, Figure 4 also presents the size distribution corresponding to each SEM image. The average sizes of the nanoparticles prepared at 5.8 W, 7.5 W and 10.5 W was analyzed by ImageJ software (version 1.53t) and were determined as 49 ± 18 nm, 19 ± 6 nm and 8 ± 3 nm, respectively. The diameters of the nanoparticles

were measured manually one particle at a time by ImageJ software (version 1.53t). The repetition rates 1.6 kHz, 1.9 kHz and 3.8 kHz were used at powers 5.8 W, 7.5 W and 10.5 W, respectively, to maximize the productivity of the nanoparticles.

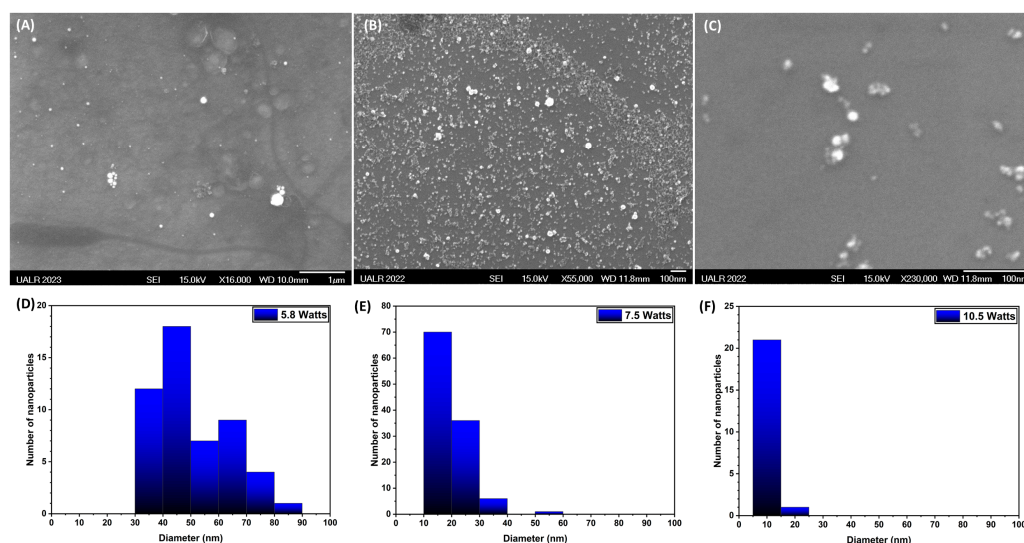


Figure 4. SEM images of the Ni-based nanoparticles synthesized by PLAL under the following conditions: (A) 1.6 kHz @ P = 5.8 W (energy per pulse = 3.62 mJ), (B) 1.9 kHz @ P = 7.5 W (energy per pulse = 3.95 mJ) and (C) 3.8 kHz @ P = 10.5 W (energy per pulse = 2.76 mJ). Size distribution of the Ni-based nanoparticles prepared by PLAL under the following conditions: (D) 1.6 kHz @ P = 5.8 W, (E) 1.9 kHz @ P = 7.5 W and (F) 3.8 kHz @ P = 10.5 W.

The stability of the colloidal solutions containing the nanoparticles synthesized under the following conditions 1.6 kHz @ 5.8 W, 1.9 kHz @ 7.5 W and 3.8 kHz @ 10.5 W was also determined. To assess the colloidal stability, the zeta potential was measured [51]. The zeta potential was measured using the NanoBrook 90Plus Zeta from Brookhaven Instruments Corporation (Holtsville, NY, USA), as illustrated in Figure 5. The zeta potential is a critical parameter in colloid science, reflecting the degree of electrostatic repulsion or attraction between particles in suspension, and it is also an indicator of the potential for particle aggregation or flocculation in the colloid. Higher absolute values of zeta potential generally indicate greater stability of the colloidal system, as the electrostatic repulsion prevents the particles from agglomerating. For the samples synthesized at 1.6 kHz @ 5.8 W, 1.9 kHz @ 7.5 W and 3.8 kHz @ 10.5 W, the zeta potential values were measured to be around $\xi = 24$ mV, 16 mV and 17 mV, respectively. A solution is typically considered unstable if its zeta potential is less than $|30 \text{ mV}|$, as this lower potential indicates insufficient electrostatic repulsion to prevent particle agglomeration. Conversely, a zeta potential greater than $|30 \text{ mV}|$ indicates a stable colloidal system [54]. Given the measured values in our study, it can be inferred that the colloids synthesized under the tested conditions were unstable, as indicated by their zeta potentials being below the threshold of $|30 \text{ mV}|$. This suggests a propensity for the particles to flocculate or agglomerate over time. This problem can be solved by ultrasonication to breakdown the agglomerates, if the sample needs to be used days or weeks after their synthesis.

Figure 6A,B demonstrates the relationship between laser beam power and the cavitation bubble's lifetime, specifically for power values ranging from ~5 W to ~11 W. The results showed that when the laser beam power increased, the optimal repetition rate maximizing the nanoparticle's production increased exponentially, while the lifetime of the cavitation bubble decreased. The underlying mechanism of this observation can be understood through the Rayleigh–Plesset equation, which is given by $P = P_0 (R_0/R)^{3\gamma}$, where γ is the heat capacity ratio, and P is the pressure within the cavitation bubble at some radius R [55–57]. Indeed, when the power of the laser beam is increased, there is a corresponding

increase in the laser fluence. This increase in fluence leads to an increase in the initial radius of the cavitation bubble (Figure 7) [55]. According to the Rayleigh–Plesset equation, a larger bubble radius decreases the internal pressure of the bubble. This decreased pressure, in turn, causes the bubble to collapse more quickly. This rapid collapse has a significant effect on the particle's size. Indeed, a quicker release of nanoparticles into the colloidal solution means smaller nanoparticles.

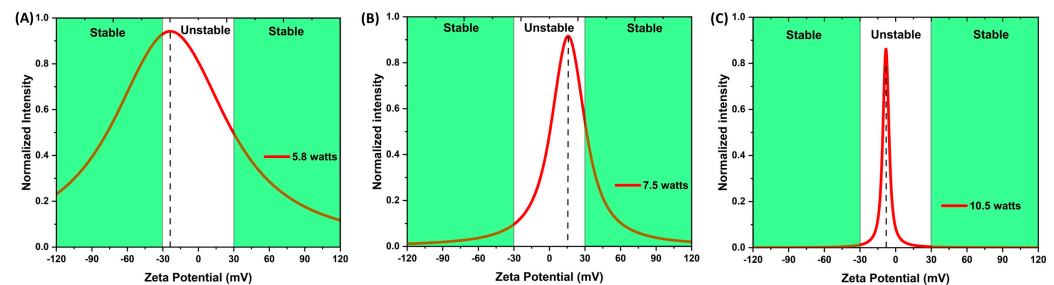


Figure 5. Zeta potential of the colloids synthesized by PLAL under the following conditions: (A) 1.6 kHz @ $P = 5.8$ W, (B) 1.9 kHz @ $P = 7.5$ W and (C) 3.8 kHz @ $P = 10.5$ W.

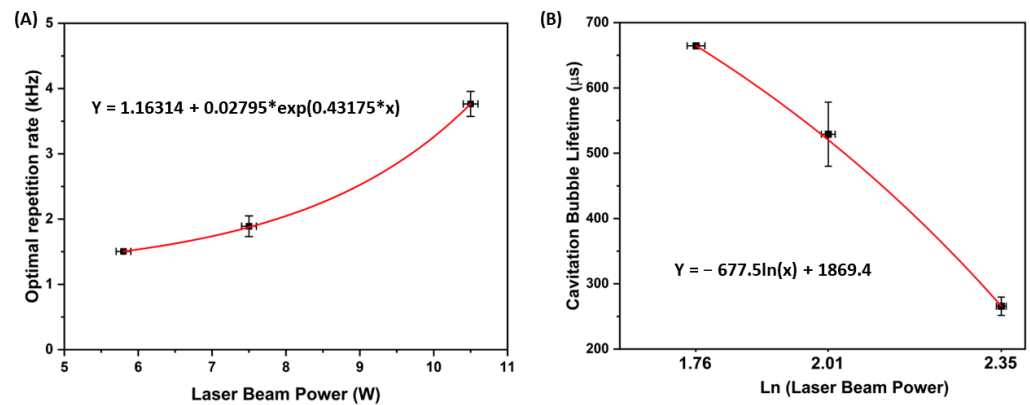


Figure 6. (A) Optimal repetition rate versus laser beam power. (B) Cavitation bubble lifetime versus laser beam power.

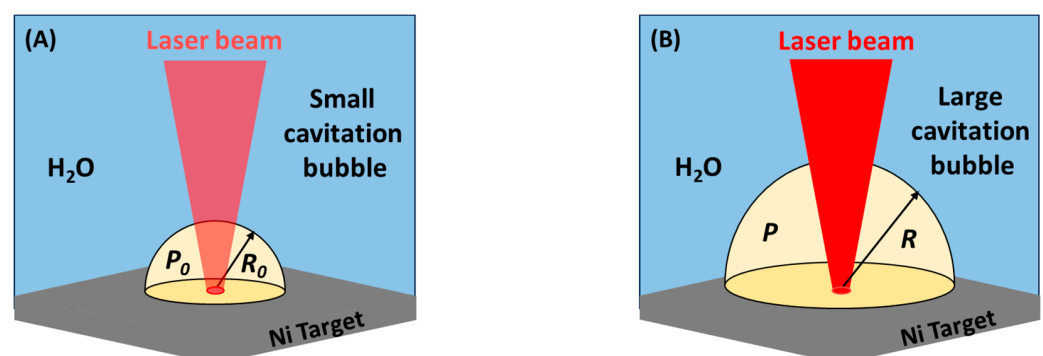


Figure 7. Sketch explaining the correlation between laser beam power and cavitation bubble radius: (A) low laser beam power; (B) high laser beam power.

4. Conclusions

In conclusion, Ni/NiO nanoparticles were synthesized by using the PLAL technique at three different laser beam power values (5.8 W, 7.5 W and 10.5 W). The presence of NiO and Ni within the nanoparticles was confirmed by XRD analysis. The SEM analysis demonstrated the spherical shape of the nanoparticles as well as a clear correlation between laser beam power and nanoparticle size distribution: the larger the power value, the

smaller the size distribution. The zeta potential measurements indicated that the colloids synthesized under our test conditions were relatively unstable with time, demonstrating a tendency for particle aggregation. The AES analysis revealed that the concentration of nanoparticles in colloids varies with the laser's repetition rate, following a gaussian distribution. This is due to the cavitation bubble protecting the target from subsequent laser pulses. This observation offers a pathway to maximize the production of nanoparticles by PLAL. A repetition rate within the kHz regime seems to be required to maximize the production when using a nanosecond laser irradiating an immobile target. Additionally, the optimal repetition rate, defined as the repetition rate maximizing the productivity of nanoparticles, increased exponentially with the laser beam power. The laser used to carry out this work allowed us to probe a relatively limited power range from ~5 W to ~11 W. Therefore, further investigation is needed to check the validity of the exponential relationship between the optimal repetition rate with the laser beam power at high power values, as well as the logarithmic relationship between the cavitation bubble lifetime with the laser beam power at higher power values. Finally, the study of the relationship between laser beam power and cavitation bubble lifetime, as analyzed through the Rayleigh–Plesset equation, has provided essential insights into the dynamics of bubble growth and collapse. This understanding is crucial to optimize the PLAL synthesis protocol and better control the size of the produced nanoparticles.

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