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This report results from a contract tasking Vienna University of Technology as follows: 1) Theoretical Assessment: The reflectivity of a plasma, at least at the radiation of a carbon dioxide laser depends strongly on the number of free electrons per unit volume. The latter electron density is known from the literature for the case of a metal vapor plasma in deep penetration laser welding or drilling for the case of plasma shielding. So by comparing theoretical work on plasma shielding in the case of deep penetration welding and the outcomings of the arc models, arc currents can be estimated, where electron densities become comparable to those which cause plasma shielding in laser welding and where the desired mirror action can be expected.

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Intermediate Report on

**Feasibility Study of the Plasma Mirror Concept for  
High Power Lasers**

Work package 4

European Office of Aerospace Research and Development

Award No. FA 8655-05-1-3045

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High Power Laser Technology

Arsenal Obj. 207, Franz-Grill-Straße 1

1030 Vienna, Austria

<http://www.tuwien.ac.at>

# 1 Introduction

The aim of this report is to clarify the cause and nature of phenomena observed during the preceding work packages of the actual project that are described in the intermediate report on work packages 2 and 3 [1]. The actual project initially was devoted to investigate the possibility to switch the optical path of a high power carbon dioxide laser with the help of a plasma. That consideration is based on the fact that depending upon several laser and plasma parameters different processes occur during laser–plasma interaction: At electron densities below  $10^{16} \text{ cm}^{-3}$  the plasma is transparent for the radiation of CO<sub>2</sub>-lasers with a wavelength of  $10.6 \mu\text{m}$ , but at considerably higher electron densities a strong absorption of the radiation by the plasma occurs. As has been pointed out in the first intermediate report [2] a further increase of electron density to about  $10^{19} \text{ cm}^{-3}$  can even lead to resonance with the plasma frequency resulting in strong reflection of the laser beam.

Obviously the first idea was to realize a setup consisting of a plasma with controllable parameters that can act as a switchable mirror and therefore deflect respectively transmit the high power laser radiation. Apart from other difficulties (regarding for example the flatness of the reflecting plasma surface) the high electron densities required for this task cannot be reached practically as has been suggested in the preceding report [2]. Therefore the objective of the project was modified to develop a possibility to allow the plasma to be switched between full transmission and strong absorption. Such a device would not be capable of reflecting a high power laser beam in a directed manner but could instead be used as a kind of Q-switch for carbon dioxide lasers.

Theoretical considerations carried out during the frame work of the first work package yielded promising results concerning a realization of such a device. For an experimental verification of the theoretical predictions a laser induced plasma was ignited in argon atmosphere in a process very similar to laser beam welding. This plasma was used to sim-

ulate the arc plasma and was penetrated by a CO<sub>2</sub>-probe laser beam. The attenuation of the probe laser beam penetrating the plasma was detected at different experimental conditions. For a range of parameters strong absorption of the CO<sub>2</sub>-radiation could be observed as expected from theory. But during the experiments that were part of work package 2 and 3 some phenomena occurred that were not fully understood. Those phenomena as well as possible explanations will be discussed in the course of this report.

## 2 Plasma formation during deep penetration laser welding

As described above the intention of the experiments was to measure the absorption a CO<sub>2</sub>-laser beam experiences when penetrating a plasma plume. The plasma was generated in a process similar to laser welding in argon atmosphere and replaced the originally intended arc plasma.

As is known from deep penetration laser welding a laser beam with an intensity higher than a certain threshold intensity (in the order of  $10^6 \frac{\text{W}}{\text{cm}^2}$ ) impinging on a metallic surface causes evaporation and leads to the generation of a metal vapor plasma and the formation of a capillary in the workpiece called keyhole. Plasma resides inside as well as outside the keyhole, called *keyhole plasma* and *plasma plume*, respectively.

For deep penetration laser welding the plasma – consisting of metal vapour, ionized atoms and free electrons – is essential since it contributes to the absorption of laser radiation via inverse bremsstrahlung absorption and the transfer of laser energy to the workpiece. On the other hand the plasma plume can absorb, scatter and refract the laser beam leading to undesirable welding results. It is for example found that the plasma enlarges the diameter of the focused laser beam and the focus position shifts downwards [3, 4]. To alleviate the problems caused by the plasma plume an inert gas such as argon or helium is injected to reduce the size of the plasma plume and ensure proper welding results. Compared with argon the use of helium leads to a significantly smaller plasma plume [5, 6].

Additionally the interaction between plasma and laser radiation can lead to further heating and ionization of the plasma and an increase of absorption of laser energy. Depending on laser power density this may result in the plasma frequency exceeding the radiation frequency and therefore reflection of the laser energy and a decrease of plasma

temperature [6]. Furthermore the vaporization rate at the workpiece decreases since less energy reaches the target due to plasma reflection. This process is called *plasma shielding*. The critical laser power density for plasma shielding is depending, among other parameters, on the type and flow rate of the shielding gas [7].

Plasma plume properties and the absorption of laser energy by the plasma during laser welding have been studied extensively both theoretically and experimentally, see for example [5, 8, 9, 10, 11, 12, 13] and references therein. The experimental investigation of the keyhole plasma is of course more difficult, two different attempts are described in [11, 14].

It is generally assumed that the plasma plume above the keyhole is a mixture of metal vapour and shielding gas, i.e. the plasma consists of ionized metal vapour diluted with the shielding gas, with the fraction of shielding gas increasing with the distance from the surface of the workpiece and the laser axis. However there are results that do not confirm this assumption: It is reported that when argon is used as shielding gas there are actually two different plasmas present, argon plasma and metal vapour plasma, which due to diffusion contain a certain amount of the second component [8], but do not mix. These findings are also supported by models indicating that the argon plasma contributes to absorption leading to a total absorption rate of up to 33 percent of the laser radiation [9]. Helium does not show this behaviour because of its higher ionization energy.

### 3 Summary of experimental results

The results of the experiments carried out during work packages 2 and 3 which are comprehensively described in intermediate report 2 [1] are summarized here. Figure 3.1 shows the setup used for the experiments schematically. A continuous wave CO<sub>2</sub>-laser with a maximum output power of 3 kW is focussed onto a moving metallic target. With

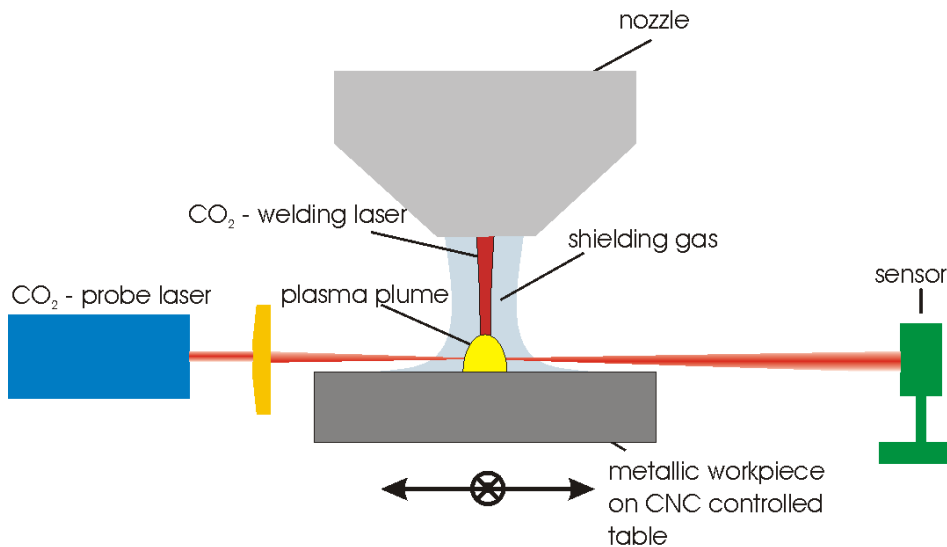


Fig. 3.1: Schematic setup of the transmission measurements (side view).

a focus diameter of about  $300 \mu\text{m}$  this corresponds to a power density of  $4.2 \cdot 10^6 \frac{\text{W}}{\text{cm}^2}$ . Due to this power density material is vaporized and a plasma ignites. A CO<sub>2</sub>-probe laser beam parallel to the metallic target is directed onto this plasma and the transmitted radiation hits a fast detector. The dependency of the detector's signal from several parameters like laser power or shielding gas flow is observed. As a shielding gas argon is injected by either a welding nozzle or a hardening nozzle. The two nozzles have different geometries: The hardening nozzle has a bigger outlet-diameter and is positioned at a

greater distance from the workpiece surface. A sketch showing the respective dimensions is depicted in figure 3.2.

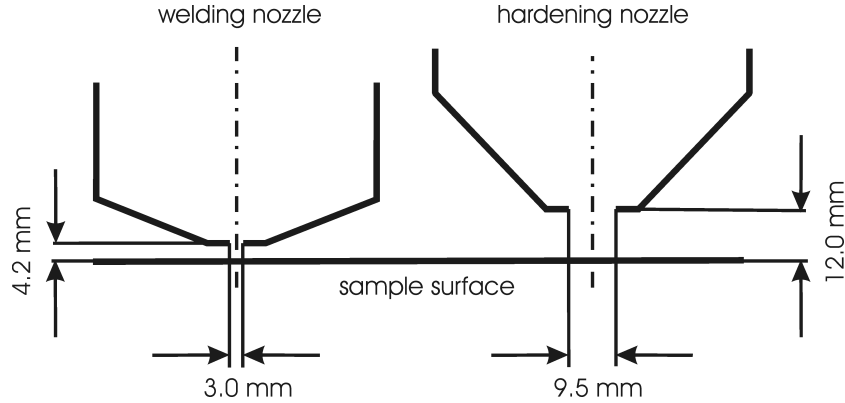


Fig. 3.2: Outlet diameter and working position of the two nozzle types.

Left: Welding-nozzle; outlet-diameter=3 mm @ 4.2 mm from focus position.

Right: Hardening-nozzle; outlet-diameter=9.5 mm @ 12 mm from focus position.

The experiments indicate that the different nozzle geometries have very strong influence on the results: With the welding nozzle a bluish plasma was ignited and a strongly fluctuating signal was recorded by the detector (see figure 3.3 left) that did not allow to confirm any absorption of the probe laser beam. The process was accompanied by the generation of welding seams in the stainless steel targets. (Experimental parameters: laser power 1300-3000 W; sample velocity 6-15 mm/s; argon flow rate 12 litres/minute.)

Quite different findings were attained with the hardening nozzle (experimental parameters: laser power 1000-3000 W; sample velocity 5-12 mm/s; argon flow rate 12-60 litres/minute): Some measurements showed results similar to the ones with welding nozzle, but often a very bright and glaring plasma occurred. Whenever this happened a very low transmission (in some experiments clearly below 10 percent) was detected (see figure 3.3 right), and additionally no welding seam was generated in the metallic target. This indicates that the high power laser beam is blocked off from the surface of the target. Similar effects can be observed during plasma shielding. But in contrast to plasma shielding, which occurs only at high laser power densities, the strong absorption accompanied by glaring plasma generation described here occurs preferably at lower laser powers. Specifically at a laser power of 1500 W nearly all measurements showed the



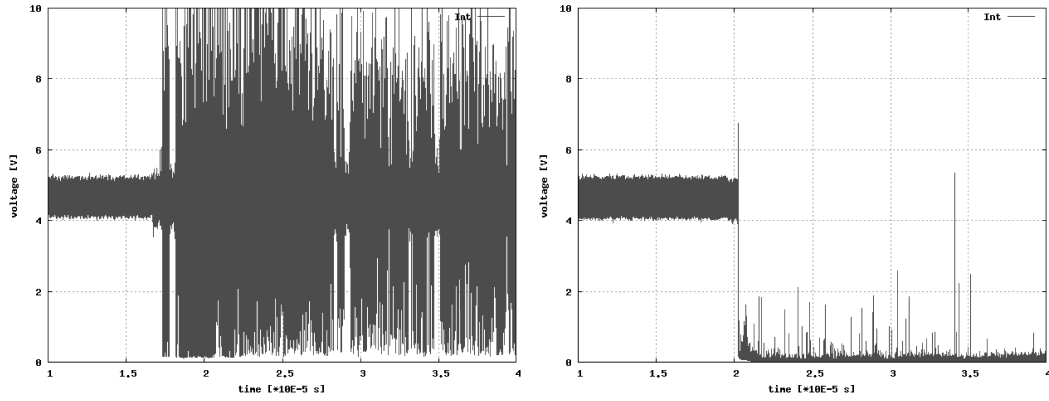


Fig. 3.3: Typical detector-signals.

Left: Strongly fluctuating signal during bluish plasma emission.

Right: Strong absorption during glaring plasma emission.

The left part of the pictures shows the signal without plasma present.

strongly absorbing, glaring plasma, only at a very high gas flow rate of 60 litres/minute a welding seam was generated in the target. At higher laser powers there seemed to be a range of shielding gas flow rates (between approximately 10 and 20 litres/minute) where the plasma's behaviour was unpredictable. Data suggest that at higher power levels a lower shielding gas flow is needed to prevent a glaring plasma.

In figure 3.4 a comparison of stainless steel targets can be seen. In one case (a) a welding seam was generated in the target, in the other case (b) a strongly absorbing plasma occurred.

With the use of a camera the plasma was observed during the welding process. Figure 3.5 shows the plasma plumes in the case when a welding seam is generated (left) and when strong absorption occurs (right). It can be seen that the bright, glaring plasma is bigger than the bluish one and extends farther from the workpiece surface. In addition the glaring plasma plume in contrast to the bluish plasma is very stable and maintains constant size during the process. It should be mentioned that sometimes the process started with a bluish plasma (accompanied by the generation of a welding seam) and then switched to show the glaring appearance, but the reversed procedure could not be observed.

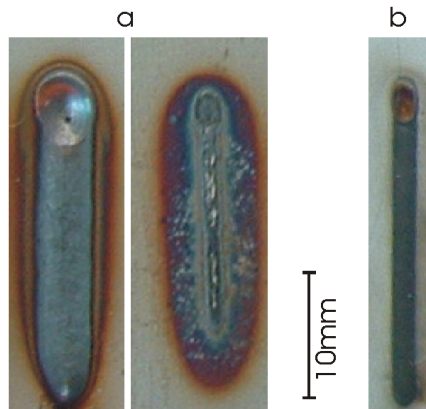


Fig. 3.4: Stainless steel targets (3 mm thick).

(a): Bluish plasma,  $P=1900$  W,  $v=10$  mm/s,  $s=60$ l/min (front/back view).

(b): Glaring plasma,  $P=1900$  W,  $v=10$  mm/s,  $s=30$ l/min.

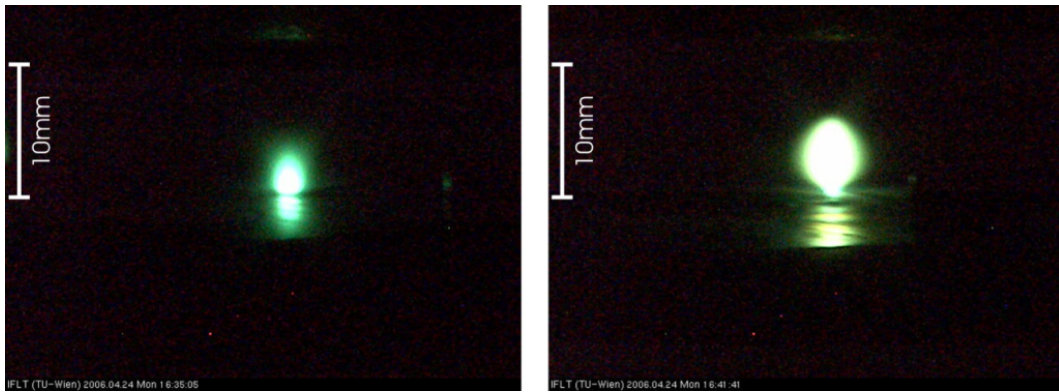


Fig. 3.5: Plasma plume images.

Bottom left: bluish,  $P=1900$  W,  $s=20$  l/min.

Bottom right: glaring,  $P=1500$  W,  $s=20$  l/min.

## 4 Interpretation of results

### 4.1 Description of unexpected phenomena

The measurements described above showed that the plasma can absorb laser radiation to a large amount. Insofar the theoretical considerations were confirmed. Nonetheless some unexpected phenomena occurred and left open questions:

- The strong absorption accompanied by the bright, glaring plasma occurred preferably at lower laser powers. Normally such a plasma appearance is known from plasma shielding which only occurs at high laser intensities.
- Furthermore the observed strong absorption could only be generated with the use of the hardening nozzle, with the welding nozzle only the regular behaviour with generation of a welding seam occurred.
- It is questionable how the glaring plasma can be maintained. From the marks generated on the surface of the metallic targets during the bright plasma appearance it can be concluded that if at all only a very small amount of metal was vaporized.
- The composition of the plasma in the case of glaring in contrast to bluish appearance is unknown. According to [8] a bluish metal vapour plasma and a pinkish argon plasma can be observed during deep penetration laser welding. We assume that the glaring appearance of the plasma in our experiments is caused by an argon plasma at high temperature while the bluish appearance can be attributed to a metal vapour plasma.
- The mechanism of the transition from weakly absorbing bluish plasma to a plasma with high absorption and luminescence is unclear.

## 4.2 Argon plasma formation

Investigation of literature yielded the following clue: According to [15] a CO<sub>2</sub>-laser intensity of about  $10^9 \frac{\text{W}}{\text{cm}^2}$  is necessary for the generation of a stationary plasma in argon at a pressure of 1 bar. An initial electron density  $n_e$  of  $10^3 \text{ cm}^{-3}$  is assumed for this assessment. Since the maximum laser intensity of our experiments only amounts to about  $4 \cdot 10^6 \frac{\text{W}}{\text{cm}^2}$  no stationary argon plasma should be possible. Nevertheless it is reported [15] that such plasmas can occur during deep penetration laser welding with continuous wave CO<sub>2</sub>-lasers at considerably lower intensities of some  $10^6 \frac{\text{W}}{\text{cm}^2}$ . In this case the argon plasma is initiated by the metal vapour plasma present during laser welding. The argon plasma shows strong luminescence and can detach from and levitate above the target surface. Due to the fact that this plasma shows strong absorption of the CO<sub>2</sub>-radiation it is possible that the intensity at the target surface falls below the threshold intensity for metal vaporization. This means that the metal vapour plasma extinguishes and in case of laser welding the welding process stops. Nevertheless the argon plasma remains maintained even if the target is removed. When the laser beam is interrupted the argon plasma extinguishes and can only be re-ignited with the help of a metal vapour plasma.

The generation of the stationary argon plasma by means of a metal vapour plasma can be described with electron diffusion and electron-ion-collisions [15]. For the development of a plasma it is necessary that more free electrons are generated per unit time than are lost due to diffusion or recombination, i.e.  $\frac{dn_e}{dt} > 0$  ( $n_e$  = free electron density). The diffusion losses are proportional to the *diffusion coefficient*  $D$ . This coefficient is reduced by about two orders of magnitude during the transition from electronic to *ambipolar diffusion*.

In a plasma the electrons can move at a higher velocity (and therefore have a higher diffusion coefficient) than ions which have a much larger mass. This means that electrons move into an area with lower degree of ionization much faster than ions and therefore ions and electrons are spatially separated. This leads to the buildup of an electrical field in the plasma that slows down the free electrons and accelerates the ions, until electrons and ions show the same diffusion velocity. For laser-plasma interaction this so called

ambipolar diffusion has to be considered when the *Debye-Length*  $r_D$  is smaller than the laser focus radius  $r_F$ .

$$r_D = \sqrt{\frac{\varepsilon_0 k T_e}{e^2 n_e}} < r_F \quad (4.1)$$

In the presence of a metal vapour plasma (with an electron density  $n_e > 10^{15} \text{ cm}^{-3}$ ) the above condition is met (focus radius  $r_F > 100 \text{ }\mu\text{m}$ ) and a strongly reduced diffusion occurs.

Because of the Ramsauer-Townsend-effect the collision frequency between electrons and neutral noble gas atoms is low in the appropriate electron energy range ( $k \cdot T_e \simeq 1 \text{ eV}$ ) and the electron-ion collisions dominate the inverse bremsstrahlung absorption. The electron collision frequency is a function of the plasma's electron temperature and is furthermore proportional to the ion density  $n_i$  which is equal to the free electron density  $n_e$ . The *plasma absorption coefficient*  $\alpha$  must be proportional to the electron collision frequency as well as to the electron density. Therefore at the given electron density the plasma absorption coefficient already shows quadratic dependence on the electron density:

$$\alpha \sim n_e^2 \quad (4.2)$$

The low diffusion together with the quadratic increase of the absorption coefficient with electron density can lead to the formation of an argon plasma that is stable and no longer dependent upon the metal vapour plasma.

The threshold intensity for the ignition of the argon plasma depends on the initial free electron density, as can be seen in figure 4.1: At higher electron densities a lower laser intensity is necessary to ignite the argon plasma. After ignition of the metal vapour plasma the respective threshold intensity is in the order of  $10^6 - 10^7 \frac{\text{W}}{\text{cm}^2}$ . It is reported that such an argon plasma was generated during deep penetration laser welding with a 2 kW CW  $\text{CO}_2$ -laser at a laser intensity of  $4 \cdot 10^6 \frac{\text{W}}{\text{cm}^2}$  when argon was feeded with a side nozzle [15].

The processes that can lead to the formation of a stable argon plasma under some experimental conditions can be summarized as follows:

- For the direct ignition of a plasma in argon (ionization energy 15.8 eV) a laser

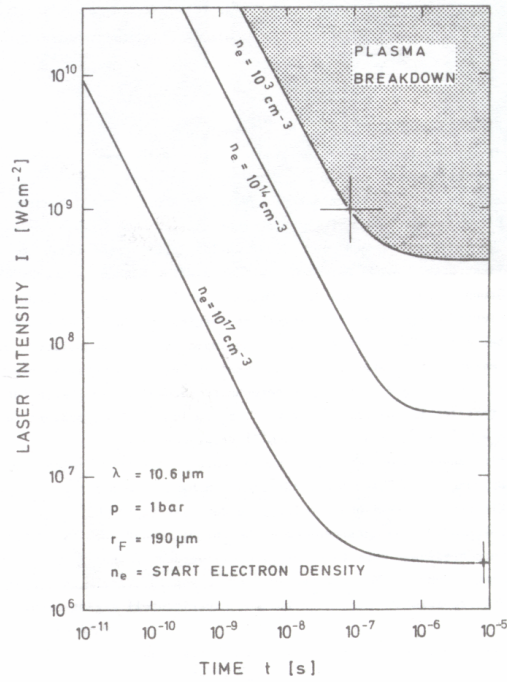


Fig. 4.1: Threshold intensity for the ignition of an argon plasma for different initial free electron densities over laser pulse duration  $t$  [15]. Values for continuous wave operation are approximated by the values for long pulse duration ( $10^{-5}$  s).

intensity of approximately  $10^9 \frac{\text{W}}{\text{cm}^2}$  would be necessary, a value about three orders of magnitude higher than the given intensity.

- The laser radiation of about  $10^6 \frac{\text{W}}{\text{cm}^2}$  impinging on a metallic target leads to vaporization and to the formation of a metal vapour plasma via thermal processes (ionization energy of iron: 7.9 eV). This plasma is heated by the laser radiation via inverse bremsstrahlung processes and the number of free electrons is increased.
- The presence of free electrons in the argon atmosphere reduces the required laser intensity for argon plasma ignition. For some experimental parameters (i.e. laser intensities, argon flow rates, nozzle geometries) an argon plasma can be ignited.
- The argon plasma is heated by inverse bremsstrahlung absorption of laser radiation leading to an increasing free electron density. Since the plasma's absorption coefficient shows quadratic dependence on free electron density high absorption values can occur. Together with a strongly reduced (ambipolar) diffusion this can

lead to a stable argon plasma that is independent of the metal vapour plasma.

### 4.3 Clarification of observed phenomena

It seems plausible that the effects observed during our experiments can be attributed to the generation of an argon plasma in the way described above. The strong absorption of the plasma as well as its glaring appearance correspond to the reported properties of argon plasmas. The fact that such a plasma is independent of the existence of a metal vapour plasma as well as its strong absorption for CO<sub>2</sub>-laser radiation can explain both the absence of distinct marks on the surface of the metallic target material and the mechanism maintaining the plasma. The laser intensities in our experiments also show good agreement to the reported parameters, although in our case the argon is coaxially fed in contrast to the side-nozzle used in [15].

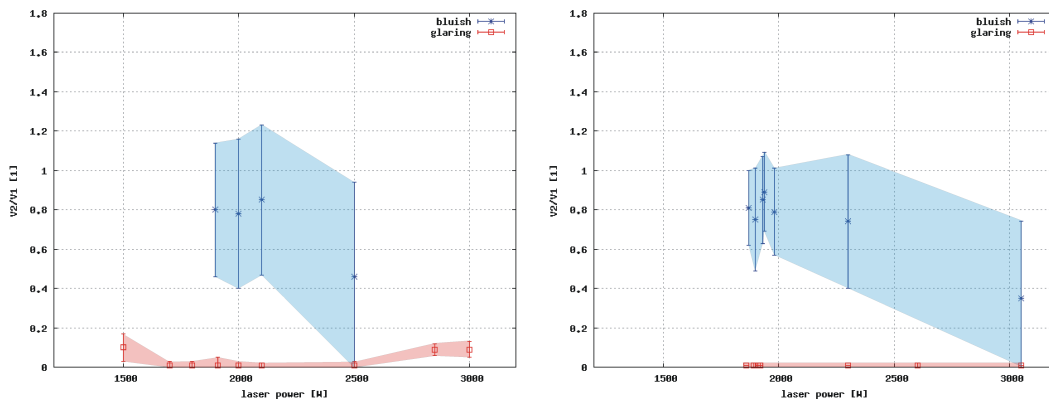


Fig. 4.2: The ratio  $V_2/V_1$  over laser power. Experiments with hardening nozzle, different sample velocities  $v$  and argon flow rates  $s$ .

Left:  $v=10$  mm/s,  $s=171$ /min. Right:  $v=12$  mm/s,  $s=121$ /min.

It is still unsettled why under the same experimental parameters sometimes the regular behaviour known from deep penetration laser welding was observed and sometimes the glaring argon plasma occurred. Presumably fluctuating conditions of shielding gas flow rate or laser power (possibly during the onset of laser radiation) are responsible for this behaviour. The fact that the glaring plasma could not be produced with the welding nozzle indicates that the argon flow rate has strong influence on whether an argon plasma is ignited or not. Figure 4.2 shows the results of measurements of the ratio  $\frac{V_2}{V_1}$  of the

detector signals with ( $V_2$ ) and without ( $V_1$ ) plasma present over laser power. (The experimental details are described in the intermediate report on work packages 2 and 3 [1].) This ratio is a measure for the amount of probe laser power absorbed or refracted by the plasma. It can be seen that over a large laser power range either bluish metal vapour plasma (data points plotted in blue) or glaring argon plasma (data points plotted in red) could be observed at the same experimental parameters. While the ratio is low and stays more or less constant for argon plasma it is considerably higher for metal vapour plasma and drops with rising laser power. The latter fact can be attributed to an increase of absorption in the metal vapour plasma at higher laser powers which is caused by further plasma heating and ionization and an extension of plasma plume dimensions [6]. The ratios detected for argon plasma indicate absorption (or refraction) of more than 90 percent of the incident probe laser radiation. The reduction of the detected signal caused by the plasma cannot solely be attributed to absorption since the plasma also refracts the radiation of the probe laser and therefore contributes to the reduction of the signal.

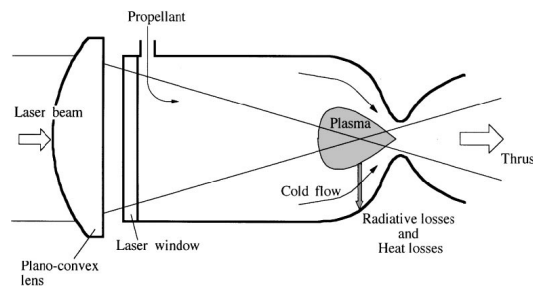


Fig. 4.3: Sketch of laser thruster propulsion [17].

It should be mentioned that plasmas very similar to the argon plasma described here have been investigated in the context of laser thruster propulsion, see for example [16, 17, 18, 19, 20, 21, 22, 23]. In that context the term 'laser sustained plasma' (LSP) is used. In those experiments generally a plasma is ignited in a flow of propellant gas (often by means of an ignition rod made of tungsten) and sustained with a high power  $\text{CO}_2$ -laser (see figure 4.3). This plasma absorbs the laser power and is used to heat the propellant (for example argon or nitrogen) to produce thrust. For different experimental parameters laser absorption rates between 55 and 97 percent are reported for argon plasmas. Some experiments have shown that the LSP is stable for only certain combinations of plasma



pressure, flow rate and laser power [20].

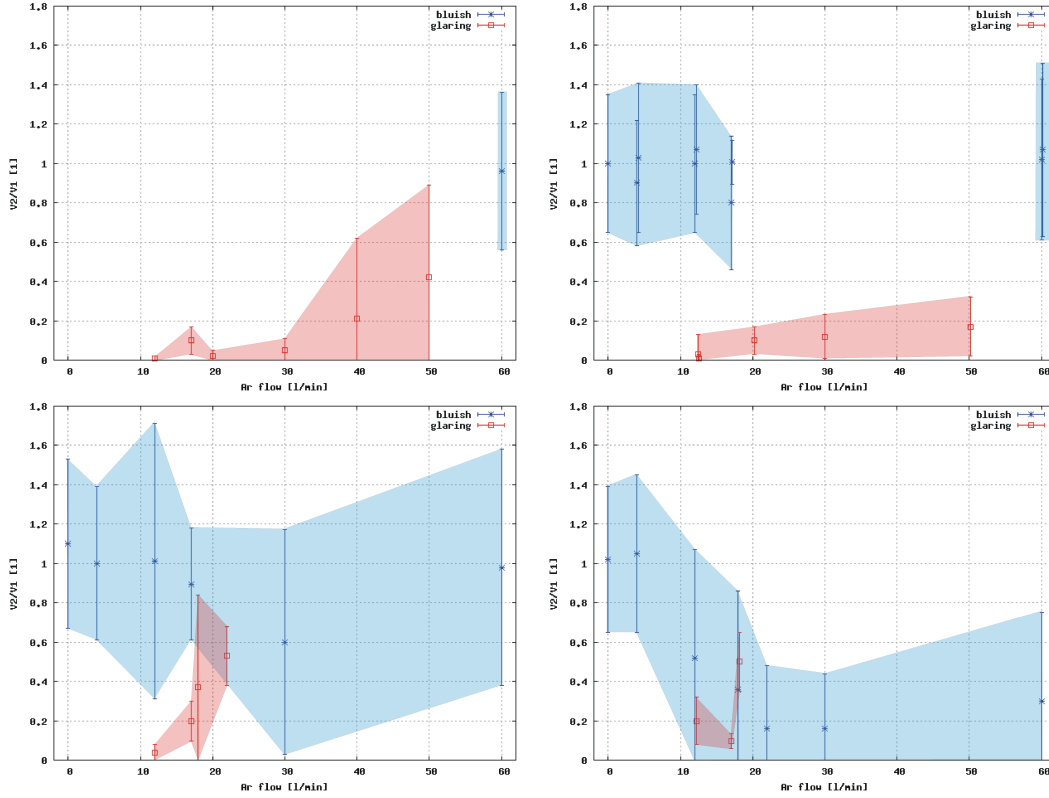


Fig. 4.4: The ratio  $V_2/V_1$  over shielding gas flow rate for different laser powers  $P$ . Sample velocity=10 mm/s.  
 Top left:  $P=1500$  W. Top right:  $P=1900$  W.  
 Bottom left:  $P=2400$  W. Bottom right:  $P=3000$  W.

The latter report seems to confirm the observation of our experiments. Figure 4.4 shows the measured ratios  $\frac{V_2}{V_1}$  over argon flow rate for four different laser powers. These measurements suggest that at higher laser powers the range for argon flow rates allowing the generation of argon plasma is smaller than for lower laser powers.

In the case when argon plasma is present the ratio  $\frac{V_2}{V_1}$  shows the tendency to increase with the flow rate. It is assumed that at high flow rates the plasma is at least partially blown away by the shielding gas allowing the probe laser to reach the detector increasingly unhindered. This would explain the rising of the detected ratio with flow rate.

It is still questionable why at a relatively low laser power of 1500 W all experiments (with the exception of one measurement at a very high argon flow rate) showed the generation of an argon plasma. Maybe the combination of this power with the way the argon flows at the given nozzle geometry leads to a very stable argon plasma. Another rather speculative possibility is that at such a low power the laser intensity is not sufficient to produce a keyhole and vaporization occurs at the planar surface of the target. Therefore the metal vapour is directed mainly into the vertical direction and thus directly into the laser beam, whereas after keyhole formation the vapour expulsion happens in a tilted manner due to the angle of the keyhole front wall [24]. This could lead to different free electron densities in the laser beam and therefore to varying threshold intensities for argon plasma ignition.

## 5 Conclusions

During the experiments conducted for the previous work packages of the actual project some phenomena occurred that were not fully understood at the time. The last part of the project was devoted to a clarification of those experimental findings. An investigation of appropriate literature yielded a model that can explain the observed phenomena quite well: It turned out that the observed phenomena can be attributed to an argon plasma that is ignited with the help of a metal vapour plasma and afterwards is sustained by the radiation of the CO<sub>2</sub>-laser. The metal vapour plasma is required to provide the free electron density necessary for the ignition of the argon plasma. After ignition the argon plasma is independent of the metal vapour plasma and keeps maintained for some experimental parameters. It has been shown that the amount of a CO<sub>2</sub>-probe-laser beam transmitted through this plasma is very low, in some cases the beam was absorbed or refracted almost completely by the plasma. After the main CO<sub>2</sub>-laser is turned off the argon plasma vanishes and the probe laser beam is transmitted unhindered. Possibly this could be utilized to realize a device that allows to quickly switch high power CO<sub>2</sub>-lasers.

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