Invited Paper

CO_2 Laser with 65MW pulses and 100kW power, concept and first steps of development

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Abstract

From theoretical considerations it is well known that pulsed CO_2 lasers with beam peak powers of 50 MW and a pulse length of 20 µs should be able to launch small satellites. To overcome limitations from ultra high power densities in a single laser source, a new concept proposes a beam source which consists of several individual laser systems. Short laser pulses emitted by 16 Q-switched CO_2 laser sources with more than 50 MW power, as of coaxial electrode geometry with excellent beam power to volume ratio, will be combined on a common optical beam path to form a longer single pulse as required. Coaxial lasers have already been built successfully, although without Q-switching.

As a main component of the above concept a new optical beam switching element – a "plasma mirror" - which can withstand ultra high power densities that must serve as a Q switch and as a beam path switch is proposed. From the literature it is well known that very dense plasmas are able to reflect an incoming laser beam totally if the plasma frequency, depending on the electron density, equals the laser radiation frequency. As a first step for the development of such a device the absorptivity and reflectivity of iron argon plasmas for CO_2 laser beams has been studied theoretically and experimentally by the authors with the result, that for plasma electron densities of 10^{17} cm^{-3} nearly 100% are absorbed due to "inverse bremsstrahlung", but that the plasma frequency and thus reflectivity can not be reached, since the electron density is too small in plasmas as contained in electrical arcs.

1. Introduction

Carbon dioxide lasers are relatively simple devices that do not use poisonous gases and show a relatively high efficiency of practically 20%. Since they have also reached a high degree of industrial maturity they are used all over the world for high power applications, mainly in production technology. Of specific importance especially for the car industry is deep penetration welding that can only be accomplished in an efficient way if a plasma is ignited in the evaporated metal. Plasma formation is also important for beam energy propulsion as shown by the Lightcraft concept. The feasibility of this concept has already been demonstrated by the US Air Force. Theoretical considerations /1/ have shown that carbon dioxide lasers with at least a beam power of

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100 kW, a pulse width of 20 µs and a repetition frequency of 100 Hertz, that yield peak beam powers of 50 Megawatt are necessary for a successful launching of small satellites.

For the latter purpose one of the authors developed a concept that uses 16 carbon dioxide lasers each with Q-switching and a repetition rate of 100 Hertz and an average beam power of 6.5 kW. These lasers are coupled in such a way that the pulses of all lasers propagate on one common optical path (see Fig. 1). Since firing of each individual laser is delayed by a time roughly equal to the pulse width with respect to its neighbouring laser a quasi long pulse operation is obtained. With a pulse width of the individual lasers of a round 1 µs that might be achieved with Q-switching, the 16 lasers mentioned above could yield a length of the quasi long pulses of 16 µs or a little bit more. With a repetition frequency of the pulsed lasers of 100 Hertz, a peak power of 65 Megawatt is obtained by each individual laser and during the duration of the quasi long pulses of the overall assembly of 16 lasers.

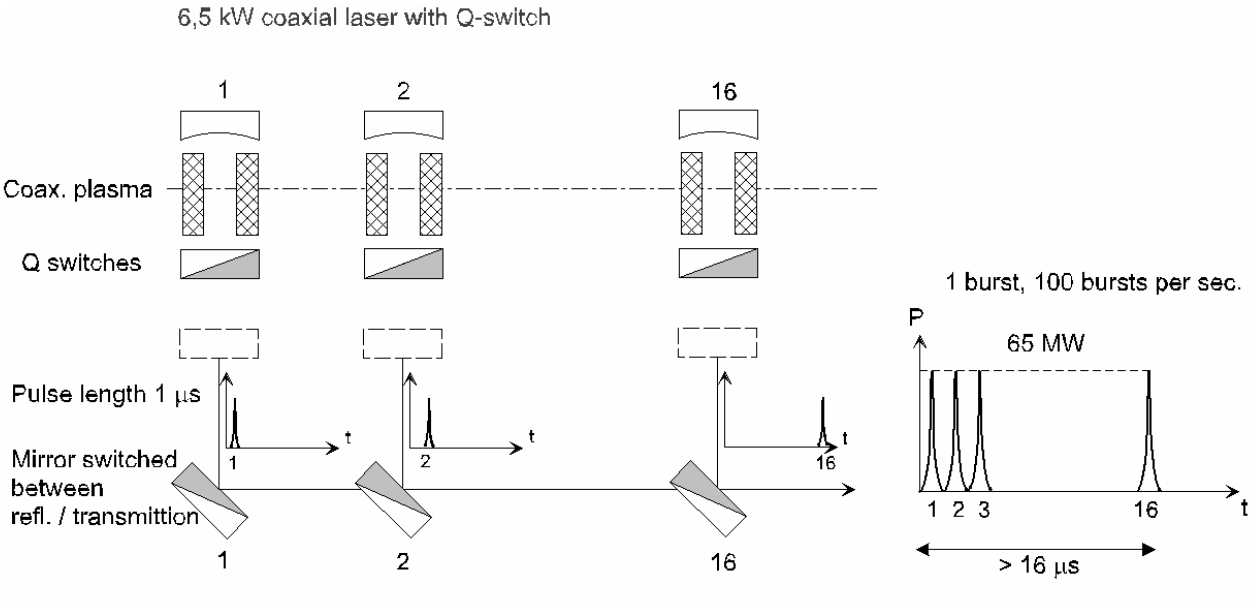

Fig. 1 Overall layout of the 100 kW laser beam and temporal structure of the pulsed radiation

Main elements of the latter construction are the plasma modules of the 16 individual lasers, the resonators and the Q-switches and finally the coupling system that generates finally the quasi long pulses.

Concerning the plasma module the applicants have built carbon dioxide lasers with coaxial electrodes and an annular plasma and RF-excitation with a beam power of 6 kW. Cooling is done by a fast gas flow through water cooled heat exchangers. These lasers use ordinary stable resonators with a 100% reflecting mirror that is in principle flat, but contains a concave semitoroidal structure and a flat and partly transmissive output window. With the latter resonator a beam that showed 100% rotational symmetry and could be focused to a spot with a diameter of few hundred micrometers has been generated (see Fig. 2). Theoretical estimations have shown that the laser construction shows an outstanding ratio of power to volume since a beam power of 12 kW could be obtained with a plasma diameter of 12 cm on a length of 30 cm. Nevertheless the plasma must be cooled with a gas flow of 7000m^3/h /2/.

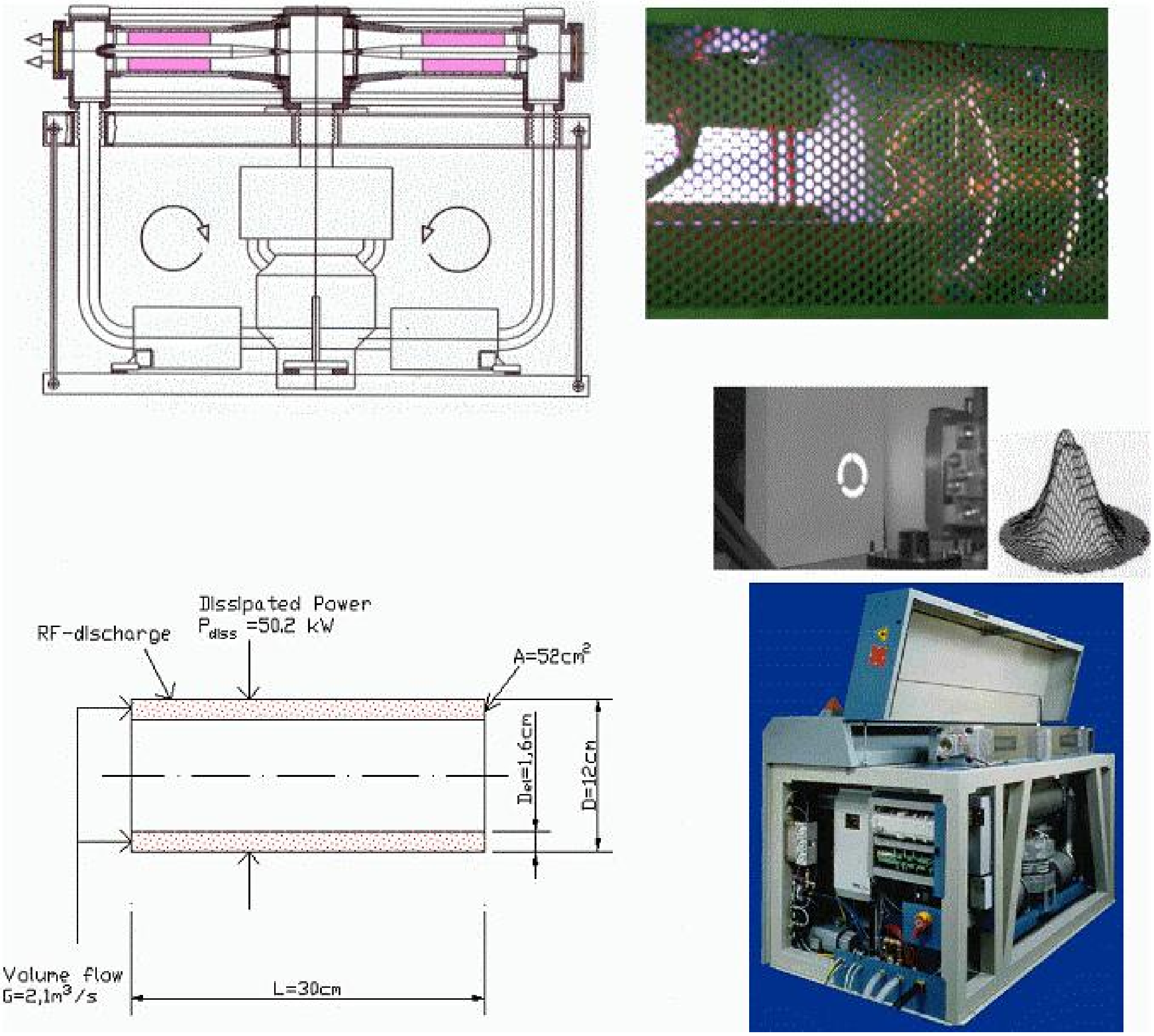

Fig. 2. Coaxial laser (top left: construction scheme, right: plasma; bottom left: dimensions for 12kW beam energy, right middle: unfocused beam, focused beam; bottom right: overall view of the laser

Concerning Q-switching, several successful experiments have been reported in the literature whereas a pulse width of 250 ns has been reached. It is expected that by optimization even 1 µs or more could be reached /3/. Concerning coupling of carbon dioxide lasers, coherent coupling of CW-carbon dioxide laser has been successfully demonstrated by the department of the authors. Coupling of pulsed lasers in the way as proposed above has been demonstrated successfully by the authors department, although the latter has used up to now only a small number of lasers, by the way not of carbon dioxide type, but of diode type /4/. Nevertheless the application to coupling of carbon dioxide lasers as described above seems to be feasible.

Summarizing for all constituents of the desired pulsed 100 kW carbon dioxide laser as the light amplifying plasma, the beam forming resonator, the pulse generating Q-switch and the coupling system that yields the high peak power and quasi long pulse length, concepts are available and have in principle been experimentally proved either by the author or by others.

In the case of the above concept for the generation of relatively long high peak power pulses by a system of 16 coupled carbon dioxide lasers, the pulses show a certain structure (see Fig. 1) since they are composed from 16 subsequent microsecond pulses. The question if this property of the system is disadvantageous for the launching of satellites can not be answered by the authors due to the missing experience with laser beam propulsion. Anyway a certain temporal overlapping of the pulses generated by the individual lasers could result in a shape of the quasi long pulses delivered by the coupled system where the beam power remains nearly constant during these pulses.

In order to realize the above concept, a mirror is strongly desired, that can switch quickly between full transmission and total blocking.

Any mechanical movement of the mirrors must be totally excluded due to their low speed, Since optical materials cannot withstand easily the power densities involved here, a new solution must be found where a manifold of mirrors, which can be switched between total transmission and total reflection, must be used. Such a solution could be provided by the well known phenomenon of “Plasma shielding” that appears in deep penetration laser welding and drilling where ionisation of evaporated metal leads initially to a largely enhanced absorption but with rising degree of ionisation to total reflection of the laser beam. Based on this principle a new “plasma mirror” could consist in principle of several pairs of electrodes that allows a laser beam passing through without any hindrance (see Fig. 3).

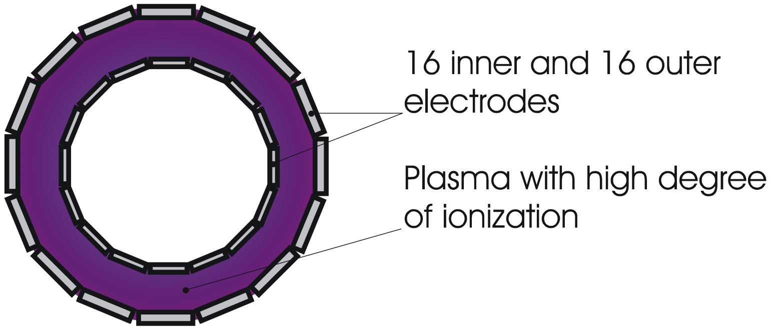

Fig. 3 Plasma mirror

Nevertheless if sufficiently high voltages are applied to the electrodes or if energy is supplied to the volume between the electrodes in any other way, a plasma is ignited and may under certain conditions reflect the laser beam totally. The usual random delay of ignition can be avoided by a certain pre-ionisation, for instance by UV radiation. The typical build up time of a plasma is limited by the transit time of the electrons that is in the order of magnitude of 10^{-7} s/cm. The latter device can withstand high laser power and be switched between total transmission and 100 % reflection and allows a sufficiently fast switching. In detail the plasma mirror could use coaxial electrodes as shown by Fig. 3., matched to the hollow cylindrical beam as described above. Both electrodes must be divided into a number of segments that serve to supply electrical energy to the plasma uniformly around the full circumference of the device thus avoiding the constriction of the plasma to a certain location on the electrodes.

2. Theoretical considerations

2.1 Absorption by Inverse Bremsstrahlung

In principle plasmas can absorb laser radiation due to absorption of light by the atoms and ions and by the acceleration of free electrons by the electrical field of the light wave.

The first mechanism can be excluded in the case of carbon dioxide lasers since the quantum energy of 0.1 eV is too low to excite atomic energy levels. Concerning electrons, in the absence of collisions with atoms they can not acquire energy from the electrical field of the light wave due to the 90° phase shift between the electrical field strength and the speed of the electrons according to Newton´s law. Nevertheless if the electrons undergo collisions with neutral atoms or ions, a resonance absorption appears if the collision frequency of the electrons equals the light frequency, a phenomenon called “inverse bremsstrahlung”. The mechanism of the latter phenomenon is based on the reversal of the electrons movement after hitting an atom. In the case of the resonance mentioned just before also the direction of the electrical field reverses after the collision what means that the electron is not only accelerated by the electrical field of the wave on its way from one collision to the next but also on the way back after the collision (see Fig. 4)

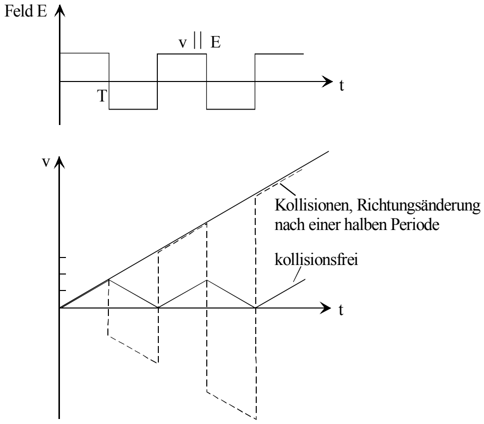

Fig. 4 Permanent acceleration of an electron due to “inverse bremsstrahlung”

It should be mentioned that the latter resonance absorption takes place not only for an electron collision frequency equal to the laser frequency, but already starts at very much lower collision frequencies since the velocity distribution of the electrons gives rise to a certain fraction of the electrons that show much higher collision frequencies that equal the resonance frequency of the laser radiation. Clearly the latter amount of the electrons is rising with rising collision frequency.

2.2 Electron collision frequency in a plasma

The electron collision frequency v_c is composed from the frequency of collisions with neutral atoms V_{cg} and with ions V_{ci}, whereas the first one depends mainly on the speed of the electrons given by the electron temperature T_e and the mean free path of the atoms given by the atom density n_g and remains practically constant with rising electron density.

Nevertheless the electron/ion collision frequency does not depend on the atomic density but on the ion density the latter being equal to the electron density n_e and therefore rises linearly with rising electron density.

A practical value for the electron collision frequency for an iron vapour plasma with $n_g = 0{,}5 \cdot 10^{19}$[cm^{-3}] is 10 ^{12} [s^{-1}].

Eventually the electron collision frequency rising with rising electron density in the plasma equals the laser radiation frequency, in the case of carbon dioxide laser $1{,}78 \cdot 10^{14}$[s^{-1}] and then full resonance absorption takes place due to “inverse bremsstrahlung”.

If the gas density for an iron vapour plasma is $0{,}5 \cdot 10^{19}$ / cm^3 (6 times lower than the atomic density in air) full resonance would be obtained for an electron density a little bit above 10^{19} / cm^3. The latter situation is not feasible. So if a realistic degree of ionisation of 1% is assumed, an electron density of 10^{17}[cm^{-3}] could be achieved being relatively far away from perfect resonance yielding a certain but not maximum absorption by “inverse bremsstrahlung”.

2.3 Absorption coefficient

The absorption coefficient α [1/cm] must depend on the number of electron movements forth and back where the electron is always accelerated by the electrical field of the light wave, that means it must be proportional to the electron collision frequency discussed above and must also be proportional to the number of electrons.

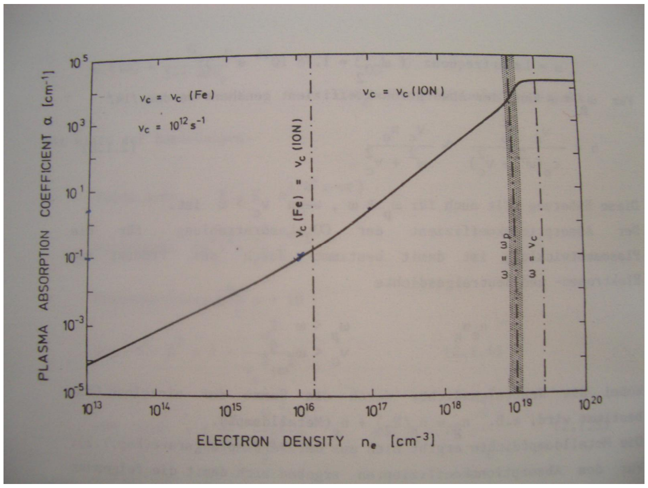

Fig. 5 Plasma absorption dependent on electron density for iron $n_g = 0{,}5 \cdot 10^{17}$[cm-3] /1/

Theoretical calculations show that for the iron plasma with an atomic density of 0,5 x10^{19} [cm^{-3}], a case that corresponds to the plasma built up during deep penetration laser welding, the latter absorption coefficient changes between 0,1 and 3 if the electron density rises from 10^{16} /cm^3 to 10^{17} /cm^3, (see Fig. 5), what means that a laser beam travelling through the plasma with a thickness of 1 cm suffers practically from no attenuation for the case of 10^{16} electrons / $\mathrm{cm}^{3,}$ but is practically extincted (90% absorption) if the electron density rises by one order of magnitude. So the plasma can obviously be used as a switch for a carbon dioxide laser radiation since the change of electron density that is determined by the voltage applied to the plasma changes the behaviour of the plasma from transmissive to blocking.

It should be mentioned that in the case of a resonance between the plasma frequency, that is determined solely by the electron density, strong reflection takes place a phenomenon well known from the reflection of short wave radio signals at the Heavyside layer. In the case of oscillations with the plasma frequency, the electrons move collectively with respect to the ions and resemble thus an electrical dipole that emits electromagnetic radiation with the frequency of movement, that means the plasma frequency. If the latter oscillations are excited by a laser light wave with a frequency equal to the plasma frequency, the latter dipole radiation shows the same frequency and acts thus as a reflection of the incident light wave. Nevertheless this phenomenon appears only at an electron density in the order of magnitude of 10^{19}/cm^3 and is thus hardly feasible, quite similar to the situation of full resonance in the case of the “inverse bremsstrahlung”. At that point it should also be mentioned that in the case of deep penetration welding with high laser intensity a very dense plasma forms at the surface of the workpiece, that absorbs the whole laser beam energy and allows thus no beam energy to reach the surface of the workpiece any more, thus interrupting the vaporization and the welding process. The latter phenomenon is often confused with a reflection of the laser beam by the plasma that takes place due to totally different reasons namely as mentioned above a resonance between laser light frequency and the plasma frequency.

2.4 Degree of ionisation

The number of electrons and ions per unit volume in a plasma is determined mainly by the electron temperature, whereas at an electron temperature of 10.000°C a degree of ionisation of 1% is safely reached, what means that one out of 100 atom is ionised.

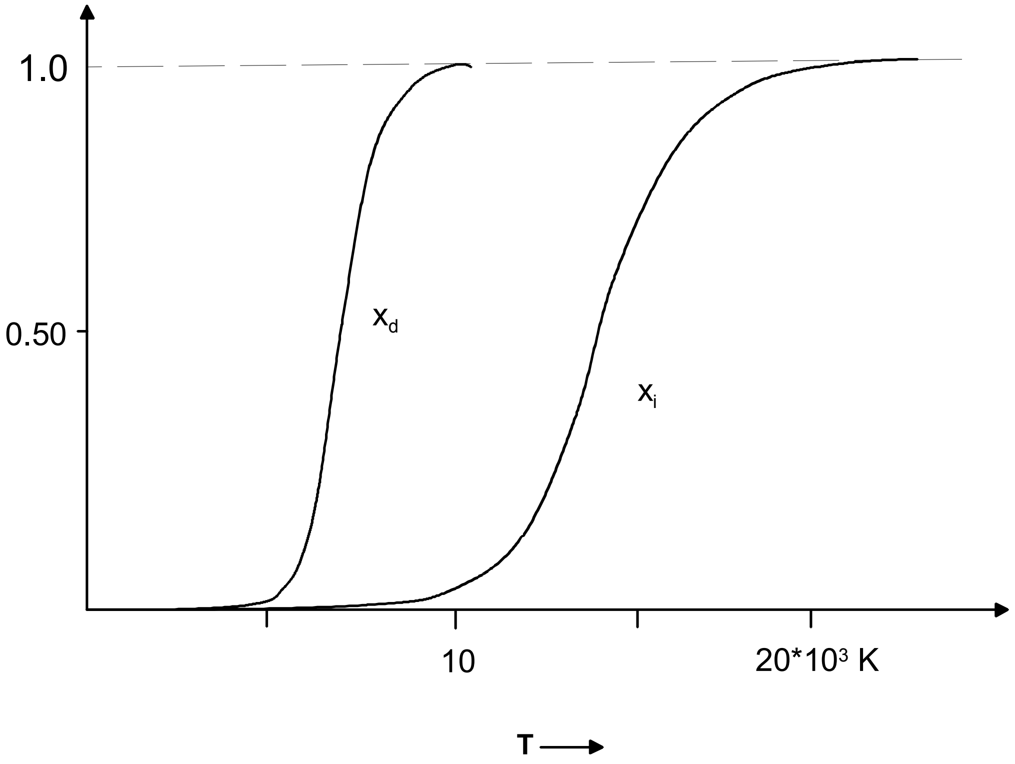

Fig 6. Degree of ionisation X_i for N_2 at atmospheric pressure dependent of the electron temperature

If for atmospheric pressure in air a particle number of $0{,}5 \cdot 10^{19}$ / cm^3 is assumed, the above degree of ionisation leads to an electron density of 10^{17} / cm^3, what means according to above strong absorption for carbon dioxide laser radiation. The question is how an electron temperature around 10.000 K can be reached in an arc.

2.5 Electron temperature

The most simple model of an electrical arc is the so called “channel model” that assumes that the plasma body has a cylindrical shape with an radius R and the length L that extends between the electrodes. In the latter channel neutral gas atoms and a much smaller amount of electrons and an equal number of positive ions are present. The electron temperature equals the gas temperature T and due to an electrical voltage U applied to the electrodes a current I is maintained, so an electrical power $U \cdot I$ is supplied to the arc per unit time. The latter energy is dissipated mainly by radiation given by σT^4 per unit surface and also by energy flowing to the electrodes, whereas the latter energy losses are neglected here for the sake of simplicity.

$$U \cdot I = 2\,\pi R\,\sigma T^4 \qquad (1)$$

If it is assumed that the electrical power input to the arc with a radius of 1 mm and a length of 1mm is 1kW, an electron temperature equal to the gas temperature (again the most simple approximation) of roughly 7000 K is obtained. The latter temperature is not sufficient to generate the degree of ionisation mentioned above that leads to strong absorption of carbon dioxide laser radiation in the plasma. So keeping the electrical power input constant, additional heating of the plasma is necessary to obtain the desired electron temperature and ionization degree.It is obvious that in the plasmas that are built up during deep penetration welding with their strong absorption of dioxide laser radiation the latter degree of ionisation must be present, what means that the electron temperature must be in the order of magnitude of 10.000 K. For continuous CO2 laser welding of steel reported plasma plume temperatures vary between 8000 K and 14000 K, corresponding electron densities between 10^{15} cm^{-3} and 10^{18} cm^{-3} [5]. The reason for this difference between arc and plasma plume is that the laser welding plasma is ignited in a hot gas generated by a vaporization of the workpiece to be welded.Thus a welding plasma plume would be well suited as a switch for CO_2 laser radiation rather than an electrical arc.

3.Experimental investigations

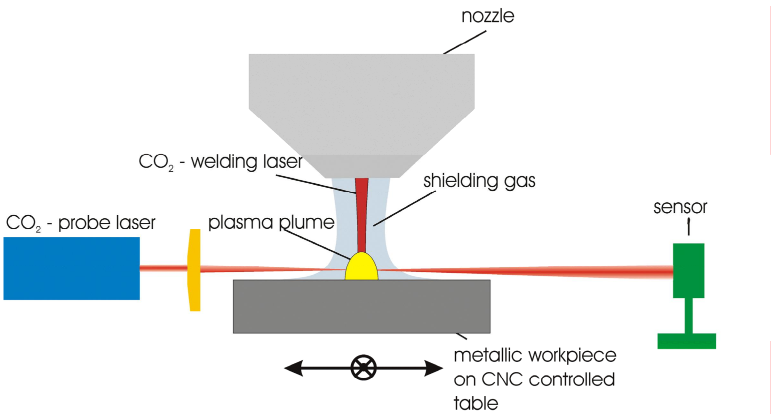

Fig. 7 Setup for the measurement of observation of a CO_2 laser beam by the plasma plume generated during deep penetration welding

In order to investigate the reflection, transmission and absorption of a plasma plume a deep penetration laser welding set-up has been used, where the welding laser beam is focused to the surface of a metallic workpiece, thus generating a plasma plume and a laser of low power crosses then the latter, whereas the transmitted power is registered by a suitable detector device. It should be mentioned, that only one position of the probe laser beam with respect to the surface of the workpiece or the processing head has been used. Since the properties of the plasma may change between the workpiece and nozzle of the processing head, the results of the measurements described below do not show the full variation of the plasma properties along the processing laser beam. The processing laser of carbon dioxide laser type had a beam power of 1 - 3kW, the workpiece was steel, the probe laser was also of carbon dioxide laser type, had a beam power of 25W and the detector was a multiple heterojunction photovoltaic device. Focusing of the probe laser on the plasma has been carried out with a zinc selenide lens. Two kind of protective gas nozzles have been used, one usually employed for deep penetration welding and one with a wider opening designed for hardening purpose. Argon has been used as protective gas. In principal two kinds of luminosity have been observed, first a bright bluish plasma and second a glaring plasma. Both kinds of luminosity are shown in Fig. 8.

Fig. 8 Bluish plasma (left) and glaring plasma (right)

The first kind of luminosity was associated with the formation of a weld seam and the second, the glaring one was associated with weak heat input to the workpiece with mere melting only at the surface. Nevertheless, a low laser power around 1500 W and the use of the hardening nozzle with a wider argon stream resulted in the appearance of the glaring plasma. Unfortunately, even under equal conditions both kinds of plasmas can be obtained, whereas the change form one to the other kind can take place even during the experiment

Both kinds of plasma showed an attenuation of a probe laser beam (see Fig. 9) but after the transition to a glaring plasma the transmission of the probe laser beam decreased to practically zero, that means 100% absorption.

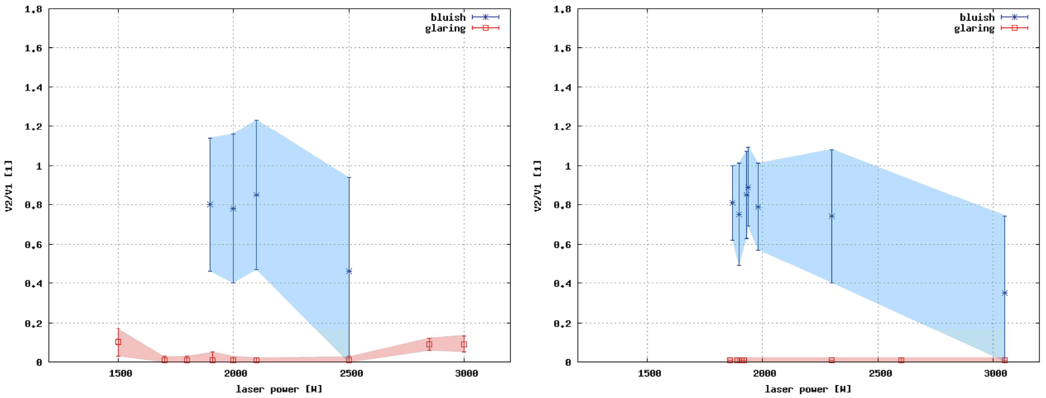

Fig. 9 Transmission in the case of a bluish plasma (high transmission) and of a glaring plasma (low transmission) for different laser powers (horizontal axis laser power, vertical axis relative magnitude of detected signal compared to the signal without any plasma)

An explanation of the above observation must be based on the effect that two kinds of gases are present, namely the vapour of the workpiece and. and argon, both gases having different ionisation energies where the ionisation energy of argon is two times larger than tat of iron. Dependent of the relative contribution of both elements in the plasma, different plasma temperatures are obtained. Due to the different temperatures also the degree of ionisation and the electron density changes and in consequence different luminosities appear. The differences of electron densities also influences the absorption due to inverse bremsstrahlung as explained above.

So under the conditions of the glaring plasma obtained with a hardening optics and a strong flow of protective argon gas practically 100% attenuation of the probe laser beam can be obtained thus making this kind of plasma a feasible switch for carbon dioxide laser radiations whereas practically no absorption takes place if the plasma is operated at a low energy level but rises to nearly to 100% and blocks the probe laser radiation if sufficient energy is supplied to the plasma plume. As mentioned above this behaviour must be observed quite similarly in the case of an electrical arc where switching between transmission and blocking and is realised by changing the current level.

4. Acknowledgement

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5. Conclusions

For the above concept of a carbon dioxide laser with ultra high pulses for ablative propulsion purposes switches for carbon dioxide laser beams are desired that can withstand very high beam powers and that allow a fast switching action, whereas for the purpose of Q-switching simple blocking is necessary and for the combination of several beams on one common pass reflection is necessary. It has been argued that switches of the latter kind can be realised with plasmas for instance of electrical arcs that show under certain conditions strong reflectivity since it is well known that plasma plumes that are generated during deep penetration welding and are similar to an electrical arc can interrupt the welding process due to shielding action.

Theoretical considerations show that with a plasma plume as obtained during deep penetration welding a high degree of reflectivity can not be obtained but nevertheless strong absorption of carbon dioxide radiation may take place under feasible conditions. Therefore it points out that plasmas as they are contained in the plasma plume are not suited for redirecting the laser beam as it is necessary for the combination of several laser beams on a common path, but they can well be used for Q-switching as it is also necessary for the above concept of a pulsed ultra high power laser.

Experimental investigations showed that under certain circumstances in fact the plasma plume generated during deep penetration welding can show practically 100% absorption for the radiation of a carbon dioxide laser and is thus well suited for a beam switching as it is needed for Q-switched lasers.

Finally it should be mentioned that the use of the plasma for internal blocking of the resonator asks for a very fast extinction of plasma in order to unlock the resonator and to generate a beam pulse.

The time constant of the extinction of the plasma after the end of the energy supply to the latter is given by the time of diffusion of the electrons. The latter can possibly be strong by enhanced if by any means a vacuum chamber is quickly opened thus sucking the electrons out of the plasma.

6. References

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