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Laser Ignition of Engines – A Contribution to Environmental Protection and a Challenge to Laser Technology

Invited Paper

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Abstract – **The technique of laser ignition via a plasma spark has reached a high degree of maturity. It allows the improvement of performance of large MW gas engines: higher ignition pressures, capability for ignition of leanest mixtures, lower NO_x content in the exhaust, higher efficiency, better running smoothness (COV coefficient of variation), potential longer durability, however higher cost until now. The application towards implementation in cars, especially in case of direct gasoline injection, still suffers from several problems, e.g. the requirement of specification for a wide operation temperature range, the necessary compactness and, of course being even more crucial in this case, cost. Application towards turbine and rocket ignition is also under development. For all these cases of innovative ignition systems improvements or even better, novel developments in laser technology are required. Besides some concepts for central lasers emitting ns pulses to be distributed to several ignition points, different versions of laser sparkplugs have been developed as a more compact alternative. The most advanced ones potentially will be pumped by 2-D power VCSELs (vertical cavity surface emitting laser) arrays which can be easily and cheaply collimated and coupled into the laser medium. Temperature sensitivity of the whole system pump diode and Q-switched solid-state laser still represents a major challenge.**

Keywords – **Laser plasma, laser sparkplug, laser ignition of engines, Q-switched Nd:YAG laser, diode pumping by VCSELs**

I. INTRODUCTION

Since the first – as seen from today's perspective – inadequate attempts of igniting engines by a laser (a CO_2 laser in this case) [1], tremendous advances in laser technology as well as technical understanding of the plasma interaction processes [2] have been made. Highlights are i) the development of compact solid-state lasers, especially Nd:YAG [3] (e.g. microchip lasers [4], ceramic laser materials [5]) associated with high perfection in Q-switching for the generation of ns-pulses [6]. Monolithic arrangements of Cr^{4+}:YAG [7] and Nd^{3+}:YAG are most elegant and robust; ii) The development of compatible powerful quasi-continuous wave (qcw, pulse duration in the 100-µs regime) pump diodes with emission @ ~808 nm is a second most important step towards the realization of a real laser sparkplug. Since several years, high-power diode lasers with peak power >500 W are commercially available (e.g. 600 W JENOPTIK, JOLD-600-QPXF-2P2 as employed by Kofler [8]) and allow the generation of ns-pulses with energies up to 20 mJ [9]. Presently, high-power qcw 2-dimensionally stacked vertical cavity surface emitting lasers (VCSELs) become available and have the potential to revolutionize the concept of diode pumping of such solid-state lasers [10, 11].

Non-resonant laser plasma ignition is the most likely candidate for a successful commercial system of laser ignition [2]. It offers clear advantages: i) Within a range of wavelengths one may choose the best one rather freely (as seen from all aspects like laser material, efficiency, complexity, size, operational lifetime, cost). ii) Due to the nature of non-linearity, the relevant process of plasma breakdown will only happen in a high intensity region, i.e. in or near the focus which may be placed at any position according to engineering aspects as long as optics allows it (focal size for instance). This is most important for internal combustion engines, i.e. Otto engines in this context. iii) There might be a third advantage relevant for direct fuel injection gasoline engines: Due to the difference of plasma formation threshold of gases and condensed matter (~500 versus ~1 GW/cm^2) the laser spark can "search" for fuel droplets, even if the location slightly changes according to a change of engine parameters. iv) Furthermore, in case of lean mixtures the higher temperature of a laser plasma compared to an electrical spark becomes a useful feature for more reliable ignition [12], associated with the fact that a ns-plasma cannot be extinguished easily via turbulences. The advantages of laser ignition vs. conventional spark emission have been discussed frequently [13, 14]. The favorable pressure dependence certainly is one major motivation followed by the absence of electrode erosion, earlier onset and decrease of combustion time [15, 16]. To realize the full potential of laser ignition, special engine development for this purpose would be required which, to our knowledge, never anywhere has been carried out so far. The goal of creating a

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long-lived ignition device of acceptable price fulfilling all specifications with respect to operational and ambient parameters and which clearly reduces service cost going along with the mentioned advantages has not been demonstrated in any respect until now.

A. Pump schemes and pump sources for laser sparkplugs

In this paper, other ignition concepts not based on plasma sparks like thermal ignition, or such which do not rely on separate laser pulse formation at every single cylinder (usually by diode-pumped Q-switched solid-state lasers), i.e. “optical sparkplugs”, are not treated (compare Fig.1). Nevertheless it should be mentioned that a successful approach for laser ignition via a central (commercial) laser, followed by a multiplexer of the laser scanner type distributing pulses into fibers which address the various cylinders of a large gas engine, has been reported several times by A. Yalin et al. [17]. The ignition pulses are propagated via thick step-index fibers into which laser pulses are coupled by low numerical aperture lenses allowing to finally focus enough tightly that plasma is formed. Despite the bulkiness of the system with rather large fiber radii of curvature it represents a viable approach which is highly robust and unaffected by temperature changes with respect to laser performance. Nevertheless, according to our opinion, it cannot represent a solution for automotive implementation!

Laser sparkplugs (see Figs. 2 and 3), in general, require pump diodes whose temperature dependent emission has to match with the laser material absorption. Therefore the engine environment represents a major problem with respect to elevated, and even worse, varying temperature as well as vibrations and pollution. Only in case of remote (i.e. fiber-coupled) longitudinal diode pumping, this negative influence can be ruled out to a major extent. In this case solely the solid-state laser is exposed to the elevated temperature in the vicinity of the cylinder walls (<100°C) and the other mentioned influences. Kofler et al. and Taira et al. have successfully followed this concept [18,19]. The latter group has recently published the first automotive operation of a laser ignited engine.

Another approach has been successfully performed by Carynthian Tech Research (CTR): they followed the concept of transversal pumping [20]. According to their reports [21], the setup is extremely unaffected by engine vibrations. However, the temperature inherent problem exists, associated with rather high cost of this solution. Hence it is no wonder that broad commercial application still is missing.

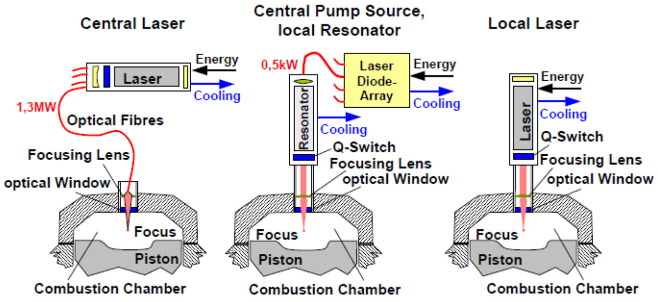

Fig. 1. Schematic drawings of ignition laser-cylinder concepts: (left) a central laser (any suitable type) can be employed with beam transportation to every cylinder, potentially involving a multiplexer; (center) a passively Q-switched solid-state laser is mounted to every cylinder just like a sparkplug, however being pumped remotely via (standard) optical fiber; multiplexing of the pump being possible; (right) a local laser represents a real optical spark plug, and each cylinder is equipped (Graphics: AVL).

Fig. 2. Different laser sparkplugs developed by pioneering research groups: a) Laser Ignition Group Vienna University of Technology, Vienna, Austria [8], b) Institute of Molecular Science, Okazaki, Japan [19], both longitudinally fiber-coupled diode pumped Q-switched Nd:YAG lasers.

B. High-power qcw VCSELs as pump sources for laser sparkplugs

Recently, mainly cost-oriented considerations, but also technical advances, led to a change of concept from fiber-based remote pumping via edge emitter arrays to the use of newly developed so-called power VCSELs ([10,11]; these homepages of Princeton Optronics and ULM Photonics, respectively, give comprehensive evidence for many following statements). Thereby, among other advantages, the symmetry of pump laser arrays is in the focus of attention: edge emitter arrays usually consist of one row of ~20 emitters (aperture around 1×5 µm^2) with ~ 50–100 µm periodicity, i.e. a very elongated arrangement of light sources. Collimation to form a round pump beam represents some challenge applying the laws of classical optics. Opposed to that, VCSELs are 2-dimensionally arranged; hence the problem of collimation optics is much more relaxed. Additionally, direct mounting of the pump laser onto the laser sparkplug will improve simplicity and eventually cost, provided operation at elevated or, even more problematic, variable operation temperature T_{pump} due to direct mounting on the cylinder head of an engine can be tolerated.

Fig. 3. Different laser sparkplugs developed worldwide: Concept Carynthian Tech Research Villach / AVL Graz, Austria, based on transversally diode-pumped Q-switched Nd:YAG laser [20].

An increase of T_{pump} has at least a threefold impact on the performance of laser diodes: the output power will be reduced; the lifetime of the device will shrink and the emission wavelength will become slightly longer. The mode characteristics might also vary, however this does not follow such a clear pattern. In [10], as an example, the L-I curves for a qcw array at 808 nm at different T_{pump} are depicted. Changing from 20°C to 85°C @ 50A current is reported to result in a linear drop of the maximum output from ~50W to ~25W, i.e. to one half! In good agreement with this measurement, an empirical rule for the reduction of output power can be found in the literature [22]: 0.8% per degree C (20° to 90°C).

The lifetime of VCSELs can lie above 1 Mio. hours (corresponding to >100 yrs) decreasing exponentially, however, with rising T_{pump} [23]. This may lead to a value <1/10 of this time span for a realistic T_{pump} rise, i.e. >10 yrs, and hence can be considered to be still sufficient.

The dependency of the mean emitted wavelength for a VCSEL typically lies in the range of 0.06 nm/°C [23,24]. This means, a diode emitting @ 804 nm at RT will emit @ 808 nm at 77°C. It depends on the specific application, if this change can be estimated small or large. In any case, the T_{pump} dependence of the VCSEL with respect to emitted wavelength is clearly smaller than for the edge emitter ("classical laser diode"), amounting 0.3 nm/°C [25].

If a certain narrow absorption line should be met, e.g. like the 808 nm-line of Nd:YAG, the T_{pump} dependence has to be considered in any case. For a high power VCSEL sufficient cooling not only has to be provided for the sake of the diode conservation (lifetime!), but also a decent temporal stability of operation temperature, otherwise the wavelength may leave the desired emission range and, for instance, cannot be absorbed any more by Nd:YAG. As a matter of fact, cooling stringently must be not only efficient, but also constant over time!

C. Influence of temperature on Q-switched Nd:YAG laser performance

Under engine-like operation conditions, the laser sparkplug being in immediate contact with the cylinder will work at crystal temperatures T_{las} up to 120°C and hence the question of T_{las} influence on laser performance has to be investigated. For this purpose we carried out a series of experiments employing a heatable and adjustable laser crystal holder among other necessary components in the setup. In order to reduce any T_{las}-related effects of the pump beam absorption, the emission wavelength of the diode was set 0.6 nm over the maximum absorption to a T_{las} insensitive point (Fig. 4a)). A clear dependence of the Q-switched output pulse energy could be measured in different open and monolithic setups [18]. Consequences of this and other results will be discussed further down.

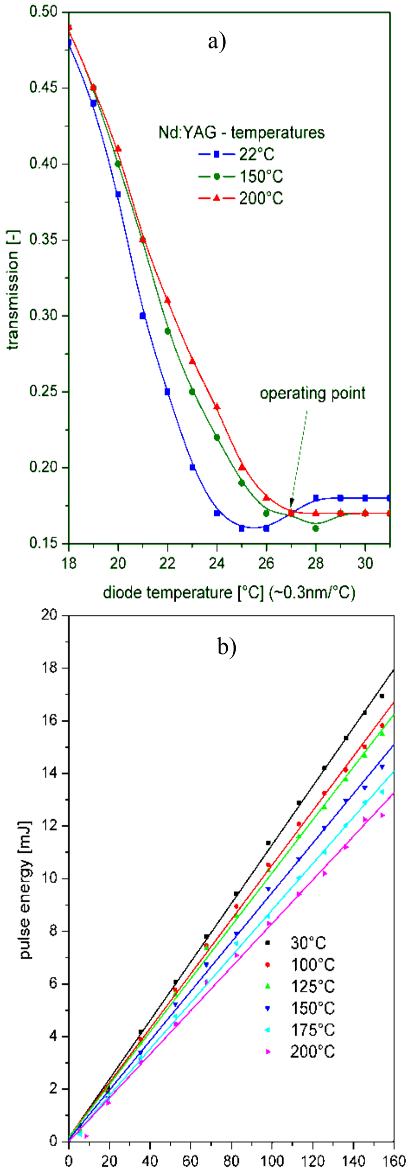

Fig. 4. a) Transmission of pump light through 5 mm long Nd:YAG crystal at different crystal temperatures T_{las} vs. pump diode temperature T_{pump}. At T_{pump} = 27°C, pump transmission showed minmum T_{las} dependence (⇒ diode operating point); b) Output versus input energy slopes of monolithic laser setup for different T_{las}.

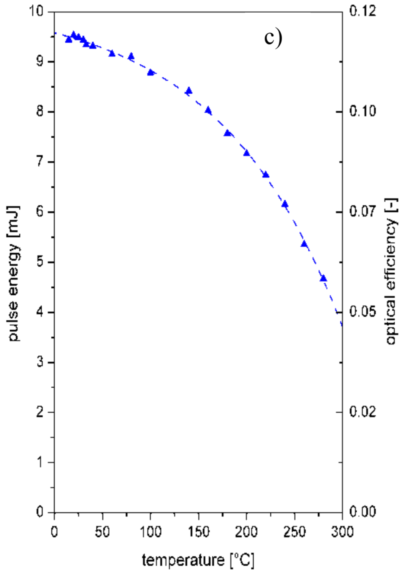

Fig. 4 (continued). c) Influence of T_{las} on the optical efficiency expressed via pulse energy; (pump duration 300 µs, and pump power 278 W).

Fig. 4b) shows results attained with the monolithic crystal setup being placed in the heater. The graphs represent energy slopes at several T_{las}. It is remarkable that all slopes seem to originate at zero, which would mean that the laser had no lasing offset. This is explainable by the pump light adjustment to the respective conditions which results in the effect, that always the same intensity was achieved in the pumped volume. In other words, the pumped volume scaled with the energy.

The graph in Fig. 4c) traces the optical efficiency as a function of T_{las} which shows accelerated decrease beyond 150°C. This finding clearly recommends cooling for higher T_{las} ranges.

Generally, while heating up the crystal, the pulse formation time shifted continuously to later timings. Since the working point of the laser was already close to the falling edge of the pump phase, the incoupling geometry had to be readjusted to maintain laser operation (see Fig. 5). This means, in terms of the pump light intensity distribution in the crystal that the radiation needed to be focused to smaller volumes, similar as if the pump power would be reduced.

A closer look on the beam profiles via a beam profiler reveals that the decrease in efficiency is accompanied by a decrease in beam diameter as well as in mode order, which can be ascribed to the reduced pump volume. Fig. 6 depicts these findings in dependence of T_{las}. At RT (1) the laser was running in a nearly perfect cylindrical TEM_{10} mode yielding a wide and energetic beam. A distinct decrease in beam cross section was already observed at 100°C (4), however, the laser was still operating in the same mode. Around 125°C (5), the beam profile started to jump into the fundamental mode which strongly constricted the beam diameter. On basis of the non-normalized profiles taken by the profiler it is discernible, that the maximum intensity in the center stayed at a constant level for all temperatures. Additionally, an increase in pulse duration was observable from 1.3 ns at room temperature to 2.0 ns at 200°C.

It is a fact that the gain in the crystal decreases with T_{las}. The reason for this efficiency drop may lie in several competing mechanisms: i) Florescence lifetime: Kaminskii reports no changes in the radiative lifetime for a 0.3 at%-doped Nd:YAG within T_{las} up to 600°C [26], however, he also points out that for doping levels near or in the concentration quenching regime the lifetime does not remain constant with increasing T_{las} [27]. Minor changes over a range of 160°C (−80°C to +80°C) were observed by [28] and [29] assuming a homogeneous lifetime reduction with increasing T_{las}; ii) Stimulated emission cross section: [28,30] report a linear decrease in the emission cross section of Nd:YAG in a range between −80°C and +80°C with a slope of $\sim 0.3\times10^{-19}$ $cm^2/100°C$; iii) Changes in the crystalline field due to thermal expansion → changes in the Stark splitting; iv) Thermal (homogeneous) line broadening [31]; v) Cr^{4+}:YAG: the above mentioned considerations are also valid, moreover T_{las} might be more influential since Chromium is a transition metal ion; vi) Coated dielectric mirrors: the thickness and the refractive index of such a stack of layers changes with T_{las} which also leads to thermal stress. This may affect the resonator; vii) Boltzmann occupation of the lower laser level can be neglected within that T_{las} range, since a 1% occupation will not be reached below 350°C (for comparison, in Yb:YAG, a typical quasi-three level system, a population of 1 % is reached already at -100°C). On the other hand, at the excited state, it may cause statistic population differences between the $^4F_{3/2}$ state and the several energetically close positioned multiplets ($^4F_{5/2}$, $^2H_{9/2}$,…).

As a matter of fact there is little, sometimes even controversial sounding literature dealing with lasers operating at higher T_{las}. Bass et al. and Kimmelma et al. deal with a flashlamp-pumped resp. a longitudinally diode-pumped laser [32,33]. Both groups report an increase in pulse energy with increasing T_{las}. This results from their fixed incoupling setup, which probably leads to longer pump durations under thermal load and, therefore, to higher energy storage in the crystal.

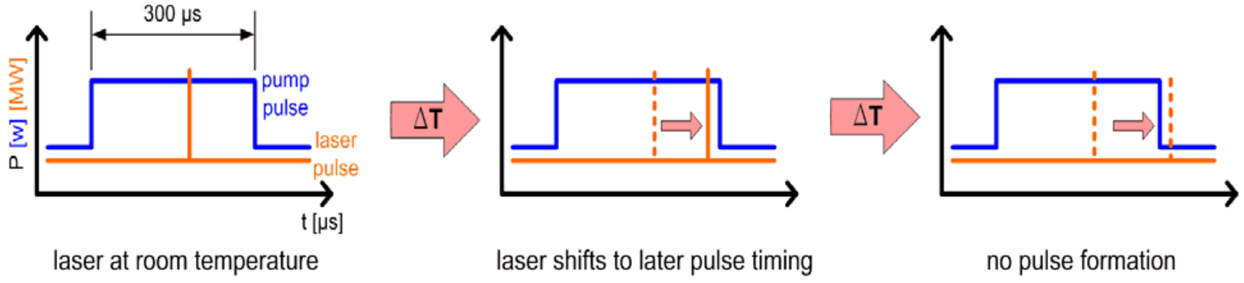

Fig. 5. Pulse formation timing at fixed incoupling geometry depending on crystal temperature T_{las}. With increasing T_{las} it shifts to later times, first leading to increased pulse energy (more optical pump energy stored in resonator). Eventually, after the pump phase is exceeded, pulse formation will fail.

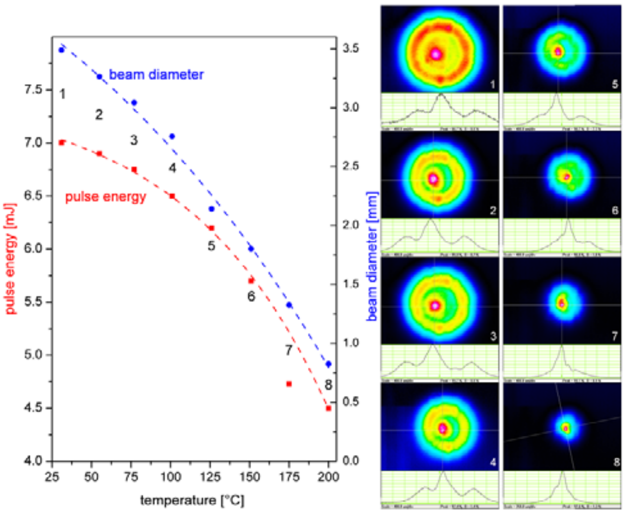

Fig. 6. Temperature (T_{las}-) dependence of pulse energy and corresponding beam diameters. The numbers between the graphs indicate discrete points of measurement of beam profiles (@ 50 cm distance) from which values of beam diameter were taken (monolithic resonator) [8].

D. Gas engine results and perspectives

The proven advantages of laser ignition of large scale, stationary gas engines lie, according to the joint experience of the two cooperating groups (TU Vienna and IIT Kanpur) and in correspondence with the literature [34],[35], in some increase in efficiency (comp. Fig. 7, where higher in-cylinder pressure and earlier heat release are the favorable features compared to spark ignition SI), clearly better engine performance expressed by the coefficient of variation COV of the IMEP as shown in Fig. 8, also allowing lower idle speed, better ignition of lean mixtures, lesser exhaust of NO_x and HC.

Presently, to a large extent it is cost-related arguments which prohibit the introduction of laser ignition LI to gas engines at a commercial level. Longterm performance also is still on the stake. With the abundance of natural gas in the present world, a strong motivation is set to employ gas engines on a large scale and simultaneously develop specific models optimized for LI. Exploitation of the high knocking resistance of this fuel paired with the special capability of LI to ignite high pressure gas mixtures would allow impressive further improvements of performance. The upcoming of a mixture of hydrogen and methane, named Hythane, would even more stimulate such an approach. Hydrogen [38],[39] allows for lower MIE and higher λ_{equ} and goes along with faster flame front propagation. All these features are favorable towards exploiting the best properties of LI.

E. Strategies for reducing the required laser pulse energy in order to save costs

Both, the increase of ignition pressure and the increase of ignition temperature reduce the potentially required pulse energy as shown in Fig. 9. For stoichiometric and slightly lean methane-air mixtures MIE is always smaller than MPE, i.e. every plasma spark will lead to ignition. Turbulence represents an adverse effect, it cannot extinguish plasma formation (opposed to SI), however it can prevent ignition [41].

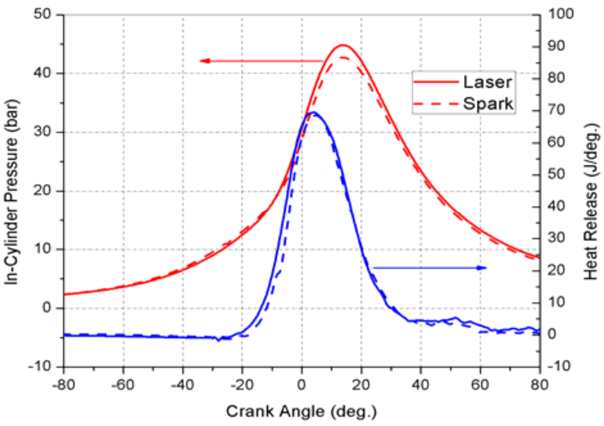

Fig. 7. Comparison of in-cylinder pressure and heat release rate for LI and SI for wide open throttle (WOT) at 1500 rev/min, air-fuel equivalence ratio $\lambda_{equ} = 1.2$ [36].

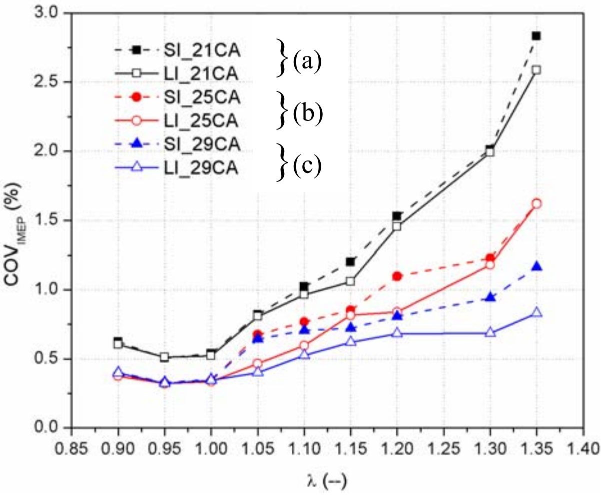

Fig. 8. Coefficient of variation COV of IMEP for LI vis-à-vis SI w.r.t. λ_{equ} at ignition timings of (a) 210 BTDC, (b) 250 BTDC, and (c) 290 BTDC; (IMEP…indicated mean effective pressure, BTDC…before top dead center) [37].

Shorter pulses in the ns regime, i.e. ≤1 ns compared to several ns, also allow a slight reduction of pulse energy because less pulse energy is transmitted before plasma is created which absorbs 100% of the beam energy arriving later [41].

A rather innovative idea was pursued when mixing two colors, e.g. the fundamental laser wavelength and its second harmonic, as it was shown in detail by Schwarz in her thesis [42]. It is remarkable that a mixture of fundamental (70% of pulse energy) and second harmonic (30%) wavelengths of a pulsed (5 ns) Nd:YAG laser yielded the lowest threshold. The corresponding plasma intensity values represent the highest plasma formation efficiency. This effect of superposition of laser fields with different wavelength is discussed theoretically in the paper [43] being proven by a series of experimental results.

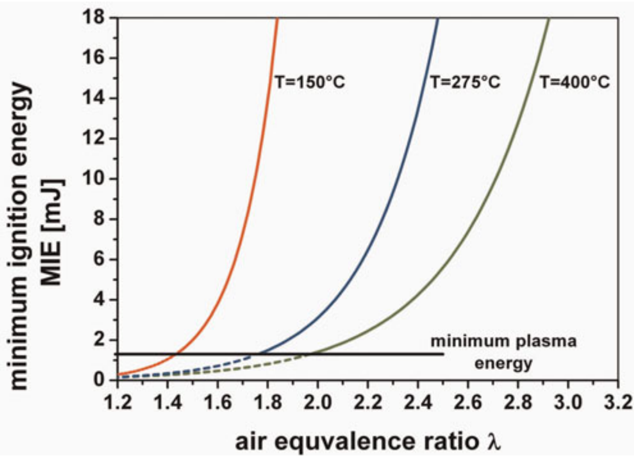

Fig. 9. Minimum ignition energy MIE vs. equivalence ratio λ_{equ} at three ignition temperatures T. MIE and minimum plasma energy MPE are mainly defined by the ignition pressure (p = 20 bar in this measurement) and the focal volume. The MPE is independent of T [40].

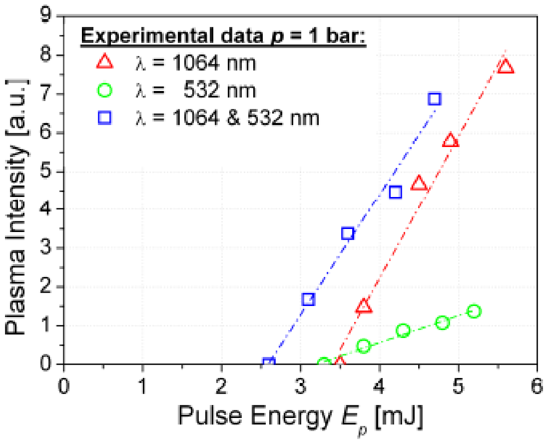

Fig. 10. Plasma intensity representing plasma energy vs. pulse energy of fundamental (1064 nm), second harmonic (532 nm) and a mixture of both. The latter yields the highest plasma formation efficiency.

Out of the reasons mentioned before it seems interesting to pursue experiments on dual wavelength lasers with independent control of both outputs, e.g. a coaxial-geometry tunable dual-wavelength flashlamp pumped Nd:YAG laser [44]. In these experiments we have developed Nd:YAG laser that oscillates in a single active crystal on basis of excitation by a single pump pulse with a single pumped arrangement at two chosen lines in the range 1.06 µm - 1.44 µm (1.06, 1.32, 1.34, 1.36, 1.44 µm). The accumulated total output reached up to ~0.42 J. The two beams could be generated competitionless in two coaxially arranged and optically separated parts of the Nd:YAG rod, each one provided with its own resonator with independent energy, time and wavelength control. As an essential advantage, the focusing effect by the external Nd:YAG crystal part increases the pump energy density (~2½ times) into the internal part and thus facilitates strongly the generation therein at weaker lasing lines. Experimental measurements and computer simulation of the laser operation were carried out, including free-lasing and combined free-lasing with Q-switching. Adequately adapted, this concept potentially may open up new possibilities for applications in laser ignition.

The following two Figs. 10 and 11 allow a short description of the simple setup for such a two-wavelength laser and illustrate some performance data, verified by computer simulations.

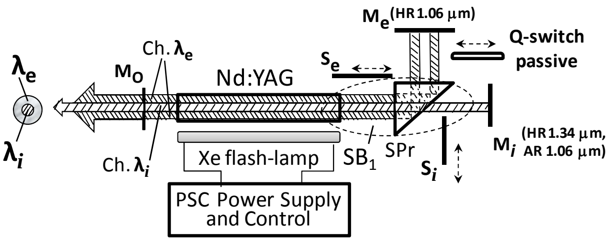

Fig. 11. Schematic presentation of the optical scheme of the developed tunable two-wavelength coaxial-geometry Nd:YAG laser using a hole-prism SPr separator and spectrally selective mirrors in the resonators.

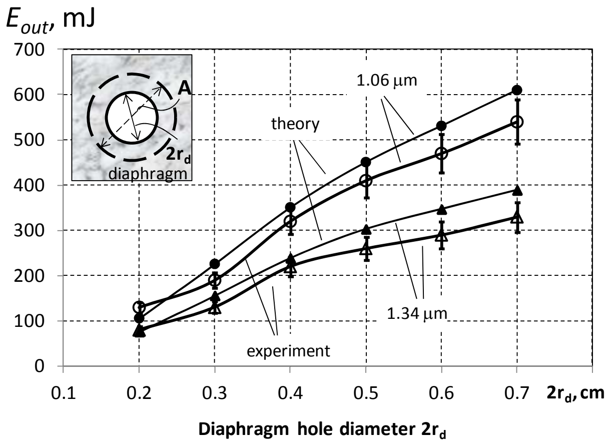

Fig. 12. Measured laser pulse energies for the two wavelengths, 1.06 µm and 1.34 µm, represented by the sequences of points and connecting thick curves versus different diameters for the holes in the diaphragm introduced into the resonator varying from 0.2 cm to 0.7 cm. In the same figure, the thin lines and corresponding points describe the corresponding computed energies.

II. CONCLUSION

Laser ignition via non-resonant plasma spark generation can be applied successfully for the ignition of internal combustion engines as well as of turbines and even rockets. Development for stationary MW (natural) gas engines has reached the highest status of maturity and was demonstrated to work successfully. Increase of fuel efficiency via the possibility to ignite leaner mixtures by laser sparks combined with higher ignition pressures, reductions of NO_x emission and increase of smoothness of engine performance (COV value) have been the most outstanding results so far.

In the course of search for the best and most reliable as well as acceptably priced solution, different strategies have been pursued: i) Central (commercial) ns ignition lasers with transportation of multiplexed beams via mirrors or better thick optical fibers (e.g. Colorado State University); ii) Transversally diode-pumped Q-switched Nd:YAG lasers representing one version of laser sparkplug (AVL/CTR); iii) Remotely longitudinally diode-pumped (via fiber propagated pump pulses) Q-switched monolithic Nd:YAG laser (TU Vienna/GE Jenbacher and Institute for Molecular Science, Okazaki/Denso); iv) Directly longitudinally diode-pumped monolithic Q-switched Nd:YAG laser (e.g. Bosch). Especially with solution iii) and in the context of stationary gas engines, requirements for varying ambient parameters, especially temperature changes, are not very stringent. The diodes can be placed remote, and the laser sparkplug can be maintained at a certain elevated temperature.

Based on literature review and specific experiments, it was demonstrated that the temperature effect on both major sparkplug components, the pump diode array (preferentially VCSELs) as well as the Q-switched solid-state laser, is non-negligible. Both will have to be operated at elevated temperature to be kept constant for the diodes, while for the laser a compromise between cold-starting properties and equilibrium temperature has to be found. This will be one of the most stringent problems in the context of car engine laser ignition, for which a large span of operation temperatures, a compact solution (prohibiting “laser diodes in the trunk”) and moderate prices have to be met simultaneously. Furthermore, due to the non-existence of specific automotive gas engines, presently the advantages of laser ignition cannot be exploited. Solutions to the improvement of direct injection gasoline automotive engines are not well developed so far.

In case of turbines and rocketry, laser ignition is rather close to the beginnings. Ignition pressures are low (around 1 bar), focal distances long and hence laser pulse energy demands are much higher. In case of rockets, price is not so much the limitation compared to weight and power consumption.

Finally, in this paper strategies for reducing laser energy required to ignite plasma sparks have been discussed. Two-color approaches have proven to allow lower plasma thresholds. Hence a new coaxial dual wavelength Nd:YAG laser concept was presented in short and discussed.

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