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# Passively cooled Cr:YAG Q-switched Yb:YAG micro-laser delivering continuously tunable high repetition rate bursts of short pulses

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## ABSTRACT

Some applications like range finding, optical counter measures or engine ignition, require lasers capable of delivering high repetition rate bursts of nanosecond pulses with hundreds of microjoules to a few millijoules in terms of energy per pulse.

We have developed such a diode pumped Yb:YAG micro-laser with an oscillator comprised of a 2-mm long 10% at-doped Yb:YAG crystal followed by a Cr:YAG passive Q-switch with an initial transmittance of 85 %. The laser plano-concave cavity is 5-cm long. This oscillator emits 250  $\mu$ J to 300  $\mu$ J per pulse, with a 3 – 5 ns pulse duration, with an intra-burst pulse repetition frequency that can be tuned continuously from 1 kHz to 20 kHz by increasing the pump power.

The pumping diode laser is operated in quasi continuous wave regime, emitting 1-ms to 10-ms long pulses with up to 20 W peak power. This qcw pumping results in the emission of a burst of pulses at high repetition rate for the duration of this pump long pulse. These pump pulses, and consequently the bursts of nanosecond pulses, are repeated at very low frequency, between 1 Hz and 5 Hz, so that the average power to handle doesn't require active cooling.

This oscillator is then amplified to the millijoule level in a second 3-mm long Yb:YAG crystal pumped by a synchronous qcw emitting diode laser.

**Keywords:** solid state laser, passive Q-switch, Yb:YAG, Cr:YAG, high repetition rate, nanosecond pulses, passive cooling

## 1. INTRODUCTION

The main application motivating the development of this laser source is aircraft engine ignition. It is most often triggered by spark plugs, but there are some issues and risks due to low ignition efficiency of standard spark plugs when temperature or pressure are low. Laser ignition can be an alternate solution to improve this efficiency in these difficult circumstances.

Different approaches exist to induce ignition: thermal or photochemical effects, requiring additional chemical species absorbing the laser radiation in the engine chamber mix, but these can impair the combustion process. Breakdown ignition is often preferred as it doesn't require such additional species. Resonant breakdown ignition is very demanding in terms of spectral properties of the laser source (narrow linewidth tunable ultraviolet lasers fitting exactly the absorption lines of the molecules involved in the combustion process) and non-resonant schemes are easier in terms of laser wavelength choice.

That's the reason why non-resonant laser breakdown ignition is the most promising technique and is widely studied<sup>1,2</sup>. even if it requires very short pulses, shorter than 1 ns if possible, and the threshold is generally around a few millijoules with 1 ns pulses<sup>3</sup> with very good beam quality in order to achieve > 100 GW/cm<sup>2</sup> in terms of laser irradiance. This threshold increases with the pulse duration and can reach tens of millijoules for 10-ns pulses.

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In order to improve the efficiency of engine ignition techniques, we chose to study multi-pulse laser ignition, as it was demonstrated to increase the efficiency of a laser spark plug<sup>4</sup>. Cumulative effects from double pulses have also been observed, optimal pulse spacing being in the order of 100  $\mu\text{s}$ <sup>5</sup>, but up to now, no conclusive demonstration of multi-pulse laser ignition has really been presented.

Passive Q-switch of solid state lasers like Nd:YAG or Yb:YAG is an interesting solution to generate such short pulse duration high repetition rate laser radiation. Nd:YAG lasers Q-switched by Cr:YAG have already been tested for engine ignition<sup>4</sup>. However, due to its narrow band of absorption and limited doping concentration, Nd:YAG laser pumping requires powerful wavelength stabilized diode lasers.

Another laser medium of interest is Yb:YAG with much broader absorption bands. It delivers promising results: 10 – 20 ns pulses with a few hundred  $\mu\text{J}$  energy per pulse at a few kHz repetition frequency have been demonstrated in 2015<sup>6</sup>. Bursts of shorter pulses of 1.5 - 3 ns duration with around 1 mJ per pulse and internal burst repetition frequency up to 10 kHz have also been reported<sup>7</sup>. 3 – 7 ns duration pulses with high repetition frequency up to 15 kHz have been reported for lower energy per pulse, in the order of 150  $\mu\text{J}$ <sup>8</sup>. Finally, microchip lasers with 400 – 600 ps pulse duration and up to 30 kHz repetition frequency but only 50  $\mu\text{J}$  per pulse have been demonstrated<sup>9</sup>. All these results have been obtained using composite Yb:YAG/Cr:YAG crystals.

As mentioned previously, the increase in efficiency of engine ignition by multi-pulse lasers will require repetition rates higher than 10 kHz in order to achieve optimum spacing between the pulses.

In this paper, we developed a laser source delivering 3 - 4 ns duration pulses at a repetition frequency that can be tuned up to 20 kHz and an energy per pulse of 270 – 300  $\mu\text{J}$ . An additional Yb:YAG amplifier can then increase the energy per pulse to the millijoule level. This source is perfect to investigate the optimum parameters of multi-pulse engine ignition, as its repetition rate (hence pulse-to-pulse spacing) can be tuned continuously.

It is also an interesting laser source for other applications, such as range finding. Furthermore, if used to pumped frequency converters to the mid- infrared, optical counter measures or spectroscopic measurement can be addressed too.

Another advantage of this source, as will be detailed later on, is its passive cooling configuration that results in compactness and light weight with good portability and integration potential.

## 2. LASER SOURCE ARCHITECTURE

The laser is in a Master Oscillator Power Amplifier (MOPA) configuration as detailed in Fig. 1. Both the Master Oscillator and the Power Amplifier stages are pumped by diode lasers with a continuous wave power level of 40 W and 70 W respectively. The laser diode beams are collimated and then focused in the laser media with a x2 magnification. The output fiber of the laser diodes being 105  $\mu\text{m}$  in diameter, the pump beams are 210- $\mu\text{m}$  diameter in the laser media.

In the optimization process of the laser source, we compared different Yb:YAG and Cr:YAG crystals, as well as oscillator cavity output couplers (OC). The Yb:YAG crystals are 5x5 mm square section and 1-mm to 3-mm long. Ytterbium dopant concentration is either 10 at. % or 20 at. %. Cr:YAG crystal with 5x5 mm square section have been supplied with initial transmission  $T_0$  ranging from 80 % to 90 %. Multiple output couplers have been supplied and tested, with reflectivity  $R_{OC}$  ranging from 50 % to 90 % (corresponding to output coupler transmission  $T_{OC}$  varying from 10 to 50 %). Both flat mirrors and concave mirrors are available. The concave mirrors have a radius of curvature of 70 mm and the flat mirrors can be used when the thermal load in the Yb:YAG crystal of the oscillator is sufficient to establish a thermal lens that stabilizes the plane-parallel laser cavity.

We used non composite crystals to reduce the cost of the experiment, and to be able to switch laser and passive Q-switch crystals easily, in order to compare the different pairs of crystals in the oscillator. As we'll detail later on, the use of passive cooling allows for such a non-composite crystal configuration. However, to operate at higher average power levels with stronger thermal effects, efficient active cooling would probably be required, as we observed fast decay of the laser performances and strong increase in the laser threshold when thermal load and Yb:YAG crystal temperature were increased. For instance, the laser operation couldn't be achieved in the continuous wave regime with such a non-composite crystal configuration, as even active cooling was not sufficient to extract heat efficiently from the laser medium.

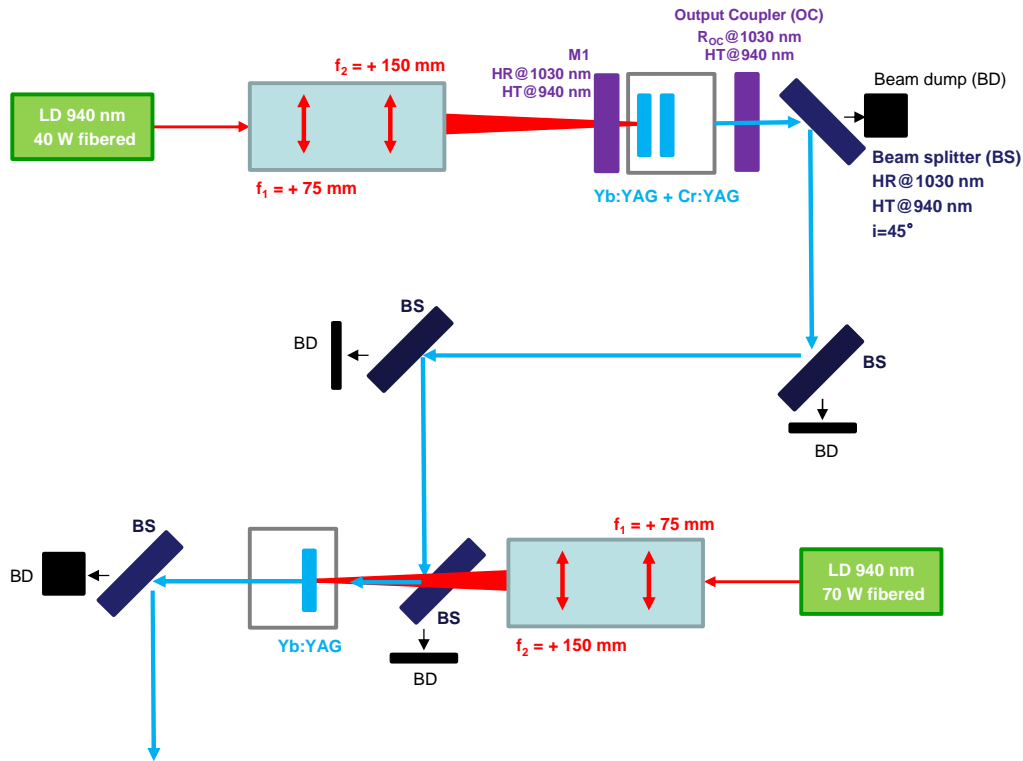


Figure 1. Laser source architecture. A Cr:YAG passively Q-switched Yb:YAG master oscillator (MO) is followed by an Yb:YAG power amplifier (PA) to achieve the expected laser performances.

### 3. LASER DIODE PUMPING OPTIMIZATION

The laser diodes used for pumping are nLight element<sup>®</sup> series fiber coupled modules, e3 type for the 40 W DL and e6 type for the 70 W DL. Both are coupled in a 105  $\mu\text{m}$  and 0.22 NA fiber. The 105  $\mu\text{m}$  output of the fiber is magnified into a 210  $\mu\text{m}$  diameter pump beam using a +75 mm collimating achromatic convergent doublet and a +150 mm focusing achromatic convergent doublet from Thorlabs. Fig.2 presents the setup of pumping diode lasers as well as a visual of the diode packages themselves.

The beam diameter of the pump lasers has been measured using a WincamD beam viewer. It fits the 210  $\mu\text{m}$  diameter expected, taking into account the magnification of the collimating and focusing optics.

As the beams from the laser diodes are extremely divergent, we developed a very accurate alignment process without which it was impossible to achieve laser emission. We use a reference beam given by an He-Ne laser (5 mW at 633 nm) but the issue is to overlap the He-Ne laser beam with the laser diode beam.

The method we used is summarized in Fig. 4. Two reference pinholes were used to overlap the He-Ne laser beam and the diode laser beam: first one is directly drilled in a sheet of paper at the focal point of the diode laser beam, and second one is positioned between the collimating and focusing lenses, visualizing the overlap of the beams on a WincamD beam viewer.

The He-Ne beam is then aligned on pinholes #1 and #2 and used as a reference beam to align the laser oscillator components. A similar alignment procedure is used to position the crystal and to overlap the seed beam from the oscillator with the laser diode pump beam in the Yb:YAG amplifier.

A P(I) characterization of the laser diodes emission was performed. The 40-W diode delivers up to 36.6 W. It can be increased even more to 38 W by cooling down the laser diode to 15°C, but condensation can appear at such a low temperature. We operate the diode maintaining it at ambient temperature of 23°C with a maximum power of 36 W.

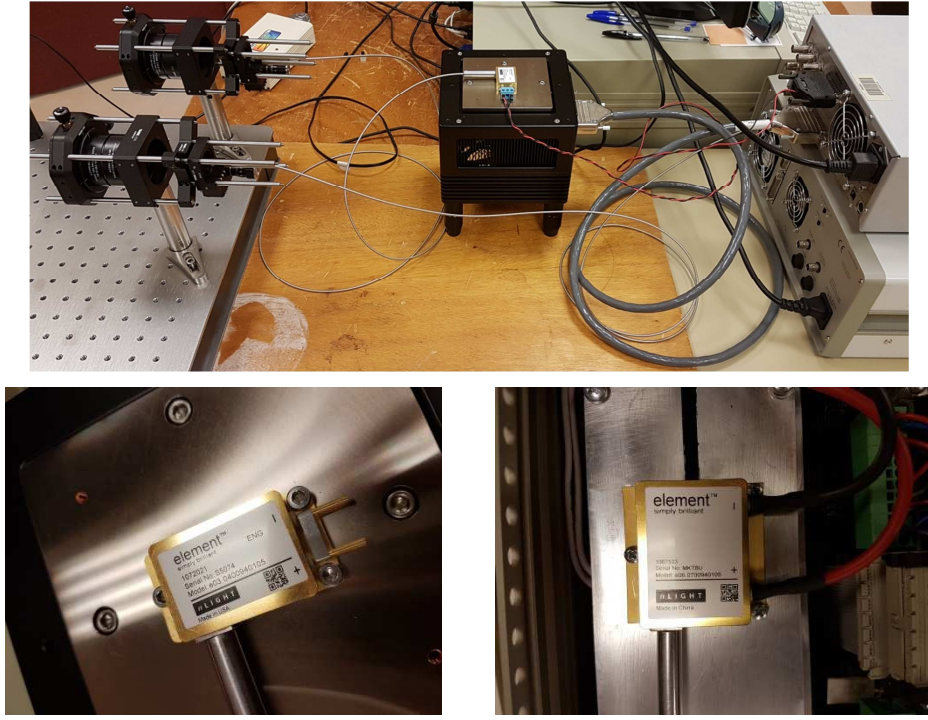


Figure 2. nLight diode lasers used for pumping the MOPA architecture. The diode lasers are mounted on thermo-electric coolers and focused in the Yb:YAG crystals by two pairs of achromatic convergent doublets, visible on the left of the picture. The black and aluminum-plated TEC of the 40-W diode laser is visible in the middle of the picture. The drivers of the diode lasers are on the right part of the picture. The metal protected fibers are also visible. On the bottom part of the figure, zooms on the diode laser packages are visible.

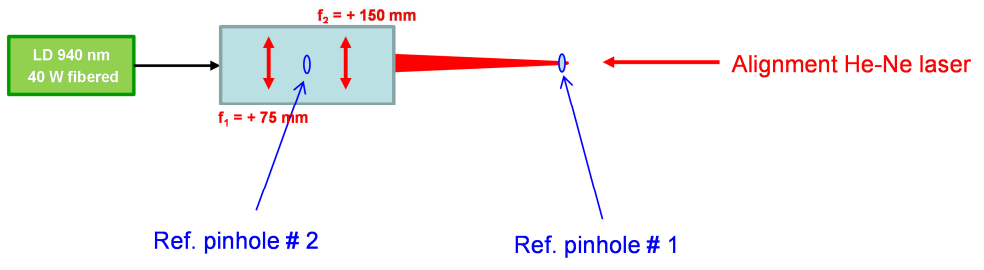
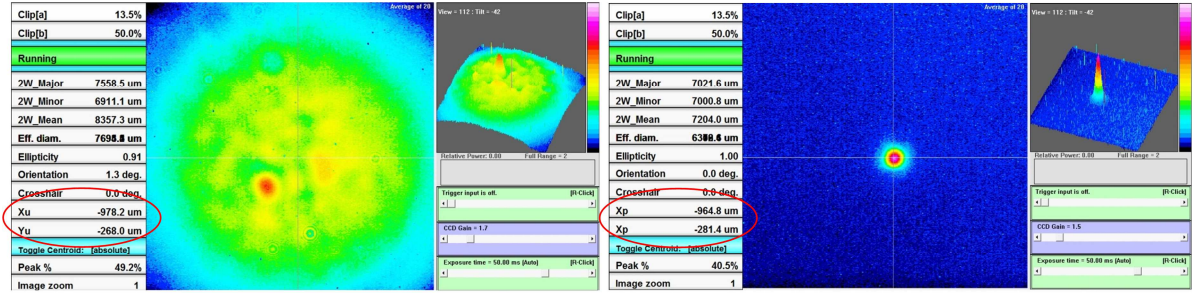


Figure 3. Top: beam profile of the laser diode after its focal point when pinhole #2 is not present (left) and when pinhole #2 is present (right). The pinhole can be brought exactly at the center of the laser diode beam profile with better than 15- $\mu$ m positioning accuracy. The locations of the pinholes used to align the He-Ne reference beam are indicated in the bottom part of the figure.

As the diodes are not wavelength stabilized, the laser diode wavelength also increases with current, and eventually exits the absorption band of Yb:YAG when the power is maximum. As Yb:YAG doesn't absorb light at a wavelength higher than 945 nm, the maximum values of current will not be useful for our purpose.

The 70-W laser diode presents similar behavior, only at higher maximum emitted power of course. To avoid condensation on the diode package in this case, the power from this laser diode has to be limited to 58 W. If we increase the power higher, condensation impairs the cooling process sufficiently for the diode to overheat rapidly.

#### 4. YB:YAG/CR:YAG MASTER OSCILLATOR CHARACTERIZATION

##### 4.1 Characterization of the Yb:YAG crystals absorption

Due to the simultaneous variation of the diode laser power and wavelength, we have to measure the effective absorption of the Yb:YAG crystal to know exactly the amount of power absorbed in the laser medium. We aperture the laser beam with a 1-mm diameter pinhole, extracting only a few percents of the laser diode power and compare this power before and after the Yb:YAG crystal to assess its absorption.

We observe a maximum absorbed power of around 27 W for a current of 12 A, demonstrating that increasing the laser diode current to its maximum value of 15 A is not needed (see Fig. 4).

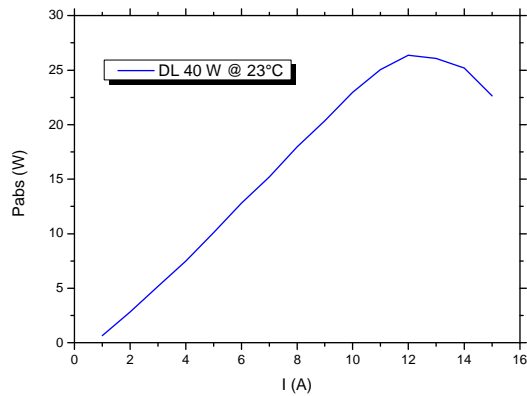


Figure 4. Pump power absorbed in a 10 at. % doped 2-mm length Yb:YAG crystal vs. current for the 40-W emitting laser diode.

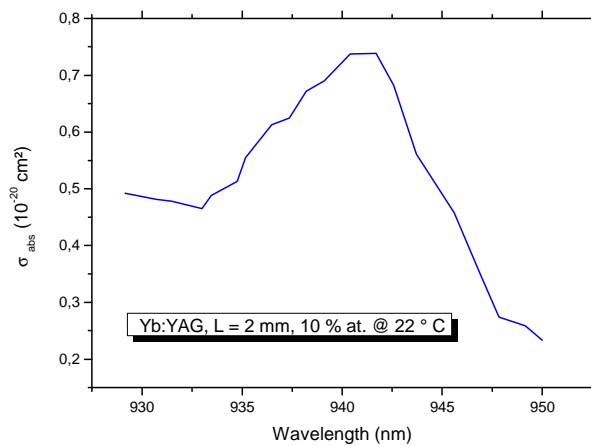


Figure 5. Absorption cross section vs. wavelength for a 10 at. % doped 2-mm length Yb:YAG crystal.

We are also able to infer the absorption cross section vs. wavelength of the laser diode for our Yb:YAG crystal thanks to these measurements (see Fig. 5). We find very similar results to the ones presented in the literature<sup>10</sup>.

Similar measurements done on the 70-W laser diode used to pump the PA stage reveal that the wavelength dramatically increases as soon as the diode current reaches 11 A.

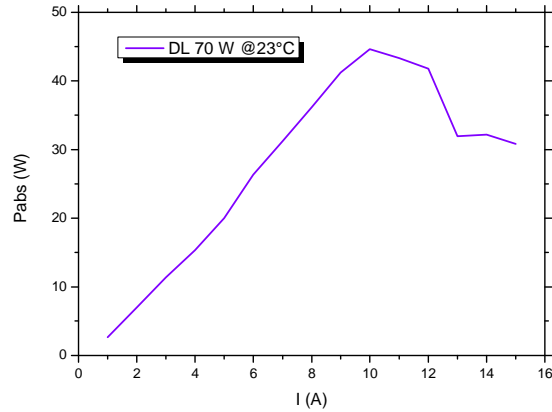


Figure 6. Pump power absorbed in a 10 at. % doped 2-mm length Yb:YAG crystal vs. current for the 70-W emitting laser diode.

This laser diode has to be operated at a current of 10 A to deliver its maximum level of absorbed pump power in an Yb:YAG crystal (see Fig. 6). Advantageously, limiting the operation to this level of current, we don't have to deal with the condensation effects mentioned before, and we can operate the diode laser without having to deal with any issue in terms of heat dissipation.

#### 4.2 Characterization of the master oscillator emission

After testing the available pairs of Yb:YAG crystals and Cr:YAG crystals, we found a nice architecture for the laser oscillator which is obtained using a 10 at. % doped 2-mm length Yb:YAG crystal, a 85 % initial transmission Cr:YAG crystal and a  $R = 70\%$  at 1030 nm concave output coupler with a radius of curvature of 70 mm. The cavity length is 5 cm to ensure optimal overlap of the pump and laser beams in the Yb:YAG and constant beam diameter in the Cr:YAG crystal.

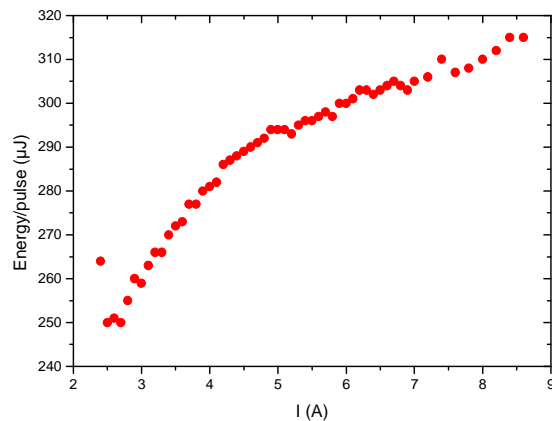


Figure 7. Energy per pulse emitted by the laser oscillator vs. 40-W pump laser diode current.



We operate the oscillator in a “burst emission regime”, where 3-ms duration qcw pump pulses were used. During these 3 ms of pumping, a burst of short pulses is emitted by the laser with an energy per pulse around 270  $\mu$ J, slightly increasing with the pump power level (see Fig. 7). The duration of these pulses is measured between 3 and 4 ns. More importantly, the number of pulses emitted during the 3-ms long pump pulse increases with pump power, as can be observed in Fig. 8, resulting in an increase of the “local” intra-burst repetition frequency of these pulses (see Fig. 9).

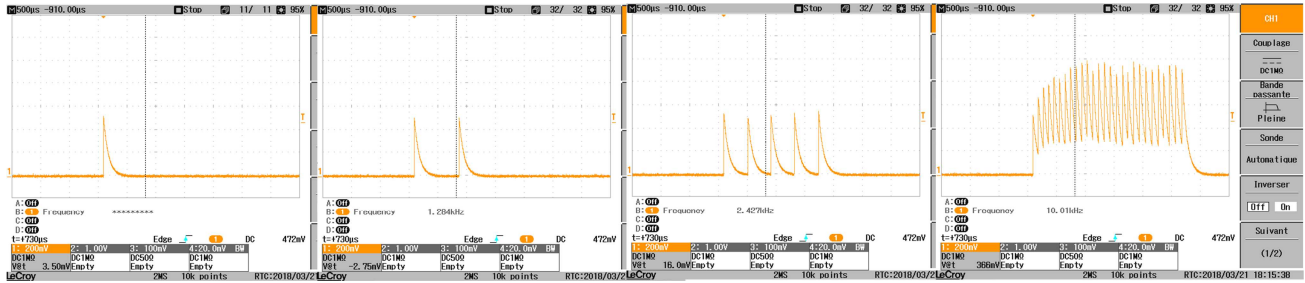


Figure 8. Bursts of pulses emitted by the laser oscillator during one long pump pulse for increasing values of pump power: the number of pulses emitted during the 3-ms long pump pulse increases from 1 to more than 60.

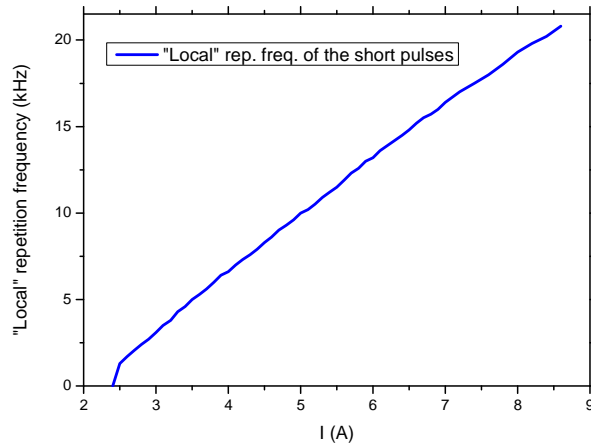


Figure 9. “Local” intra-burst repetition frequency of the 4-ns duration pulses as the pump power increases.

This oscillator is perfect for engine ignition tests, as the high repetition frequency of the pulses during one burst can be tuned continuously, without significant change in the pulse duration and in the pulse energy.

Amplifying these bursts of pulses in a second Yb:YAG crystal pumped by the 70-W laser diode, as indicated in Fig. 1, we are able to scale the energy per pulse up to 1 mJ, without changing the sequences of pulses emitted.

### 4.3 Passive cooling operation of the master oscillator

In these tests, we chose to pump the oscillator with 3-ms long pulses repeated at 1 - 5 Hz, in order to keep the average power below 500 mW. The maximum output power of the pump laser diode we use is 20 W absorbed power. Only a maximum of 60 mJ per 3-ms pulse are absorbed in the Yb:YAG crystal and the result is an average absorbed power of 60 - 300 mW, depending on the exact value of the long pump pulse repetition frequency between 1 and 5 Hz.

The resulting average pump power absorbed in the laser medium induces very low temperature elevation, even when the Yb:YAG crystal is not actively cooled, as it was the case in our experiments.



Operation of Yb:YAG in continuous wave regime or with qcw pumping but for higher levels of absorbed pump power (exceeding 1 W for instance) is not really achievable in our configuration where the Yb:YAG and Cr:YAG are separate crystals. Use of composite crystals where the Yb:YAG and Cr:YAG are diffusion bonded is necessary to provide better heat extraction and maintain laser operation above threshold for higher levels of average pump power.

Hopefully, for the purpose of engine ignition, we just need bursts of pulses and we can operate the laser in a quasi-continuous wave regime, with very low average pump power. Passive cooling is sufficient and laser medium heating doesn't impair the laser performances.

## 5. CONCLUSION

We developed a high repetition rate diode pumped Yb:YAG laser oscillator that can be used to study the effects of cumulated pulses on the engine ignition process. Passive cooling of this oscillator is sufficient as laser medium heating is very limited, the laser being operated at low average pump power levels.

This oscillator generates 3-ms long bursts of pulses repeated at 1- 5 Hz, with a repetition frequency of the pulses within these 3 ms that increases from 1 to 20 kHz when the pump power is increased. Energy per pulse is around 270  $\mu$ J.

Amplification of this laser oscillator in a second Yb:YAG crystal allows to generate up to 1 mJ per pulse without changing the sequences of pulses emitted.

Ongoing work of investigating the use of Cr:YAG crystals with lower initial transmission (< 80 %) should result in the generation of shorter pulses, much closer to the 1-ns optimum duration. Development of a simple numerical model to simulate the generation of pulses should allow to predict the pulse duration and energy for a given laser oscillator architecture.

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