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# Optimization of key parameters for efficient processing with 100 W femtosecond lasers

E. Audouard[a,*], G. Mincuzzi[b], A. Letan[a], K. Gaudfrin[b], K. Mischichik[a], C. Hönninger[a], R. Kling[b], E. Mottay[a], J. Lopez[c]

[a]AMPLITUDE SYSTEMES, 33600 Pessac, France
[b]ALPHANOV, 33400 Talence, France
[c]UNIV BORDEAUX, CNRS, CEA, CELIA UMR5107, 33405 Talence, France

**Abstract**

Thanks to high average power, 100 W and more, and high repetition rate, it is possible today to achieve high throughput with femtosecond lasers, providing that the operating parameters are finely tuned to the application. Femtosecond lasers play a key role in these processes, due to their ability to high quality micro processing thanks to their specific shape of deposited energy. A clear understanding of all the processing steps necessary to optimize the processing speed is a main challenge for industrial development. Indeed, laser parameters are not independent of beam engineering devices and their synchronization with the laser (beam deflection, beam scanning and beam shaping). Pulses energies, laser repetition rates have to be precisely settled according to the time and spatial sequences of pulses superposition resulting from beam delivery on the sample. A bad choice of parameters can lead to energy waste and poor process efficiency.

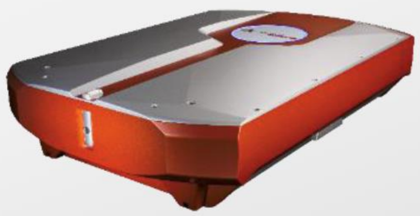
Keywords: femtosecond processing, High speed processing, High power processing, beam engineering, processing optimization.

## 1. Introduction

Industrial femtosecond laser over 100W generating pulses as short as 500 fs, pulse energies >300µJ, and pulse peak powers on the order of 1GW (see figure 1) brings new opportunities to develop high throughput applications. Moreover,

* *Corresponding author.*
*E-mail address: eaudouard@amplitude-systemes.com .*

the concept developed by Amplitude Systèmes is highly flexible in pulse repetition rate. For example, femtosecond pulse trains in a parameter range reaching from 300kHz over 2MHz to 40MHz can be covered with pulse energies of >300µJ, 50µJ, and 2.5µJ, respectively. The high energies are interesting to translate high average power into high throughput by beam splitting or beam parallelization. On the other hand, high pulse repetition rates, burst mode operation and synchronization to a polygon scanner are possible. Pulse-to-pulse modulation up to 2MHz pulse repetition rate is possible with an integrated modulator as well. The high peak power femtosecond pulses can be converted to the green or UV spectral region with high efficiencies.



| Tangor ultrafast laser | |
|---|---|
| Pulse energy | 300 µJ |
| Average power | 100 W |
| Pulse duration | 500 fs |
| Repetition rate | 0 – 2 MHz |
| Footprint | 68 x 56 cm |

Fig. 1: TANGOR Laser standard specifications

## 2. High power laser concept

Industrial femtosecond lasers with pulse duration of less than 500 fs were limited to average powers of a few tens of Watt. Two main laser architectures represent this type of lasers: femtosecond lasers based on regenerative amplifiers or fiber based amplifiers.

Amplitude Systèmes has developed a hybrid fiber-seeded-crystal-booster amplifier to achieve a femtosecond laser platform with the ability to deliver >100W average power, with high pulse energies and flexible repetition rate operation. The principle of such hybrid system is schematically presented in figure 2. A compact and powerful femtosecond fiber technology is used as a base of the concept and an innovative crystal-based booster amplifier is added for power and energy scaling. The interface between both technologies in terms of output parameters of the fiber-based seed laser and the input parameters of the crystal-based booster amplifier is flexible and can be selected to meet specific output parameters. Typically, a seed laser power of a few Watts average power is sufficient to obtain >100W from the amplifier.

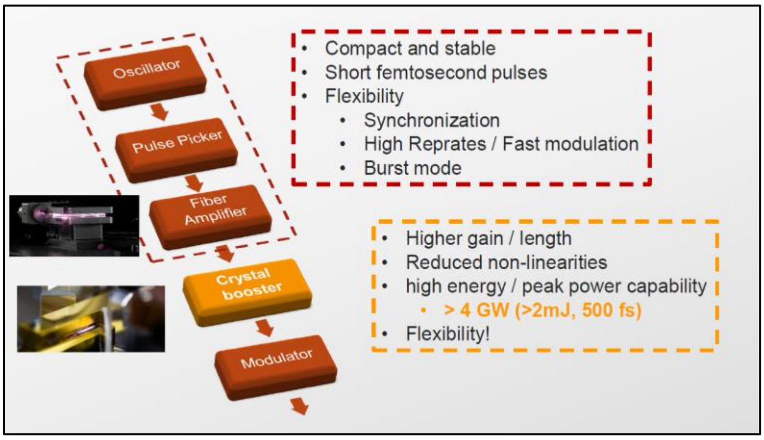



Fig. 2: Hybrid fiber/crystal technology for high power TANGOR laser

Thermal management is a crucial point in the crystal-based booster amplifier in order to minimize thermally induced aberrations and maintain an excellent beam quality. High power and high brightness pump diodes are well suited to pump crystal amplifiers in a rod geometry, however, the output power per rod is typically limited to roughly 20 to 40 W to maintain excellent beam quality. The use of sequential rod amplifiers is then a well-known concept for power scaling, but leads to a rather complicated setup in terms of number of components and for adjustment when increasing the number of amplifier stages. A multi-rod concept, developed in collaboration with the Fraunhofer Institute of Laser Technology (ILT) in Aachen, offers an elegant solution, where only one laser crystal and a common set of optics is used for the shaping and imaging of pump sources, and for the amplifier beam path. This elegant concept significantly reduces the number of optical components and the complexity of alignment compared to a more typical sequential rod set up.

In the Amplitude Systemes architecture up to 7 fiber-coupled high brightness pump diodes are used achieving output powers exceeding 150W. The slab-geometry of the crystal facilitates thermal management and maintains an excellent beam quality of $M^2<1.2$. The low non-linearity in the amplifier allows for femtosecond pulses to be directly amplified at high pulse repetition rates resulting in a few µJ pulse energy at 40MHz pulse repetition rate. When applying chirped pulse amplification, energy scaling to >300µJ can be obtained at a pulse repetition rate of 350kHz. The extremely short pulse duration of 400-fs is enabled thanks to the fiber-based seed laser which is essentially maintained in the crystal-based booster. The beam profiles of the seed laser and the amplifier are also shown to confirm the excellent beam quality of the high power femtosecond laser with an $M^2$-value below 1.2.

For use of such lasers with high repetition rate, the role of the synchronization of laser pulses with the operating system (scanners, translation stages…) becomes crucial for process optimization.

The specific architecture of amplitude lasers (figure 2) allow a high degree of flexibility in possible operating modes. For example, a bunch of pulses can be used. It is a definite number of amplified pulses at the pulse picker period and selected by the modulator (via a gate function). Pulse bunch can be generated synchronous to the process. It has a 25 ns jitter due to the oscillator period. The signal can be gated or modulated in amplitude. Any duty cycle can be chosen, for instance 90 %. The modulation speed is typically 2 MHz pulse to pulse and can be more with a certain loss of contrast. Figure 3 shows example of controlling signals.

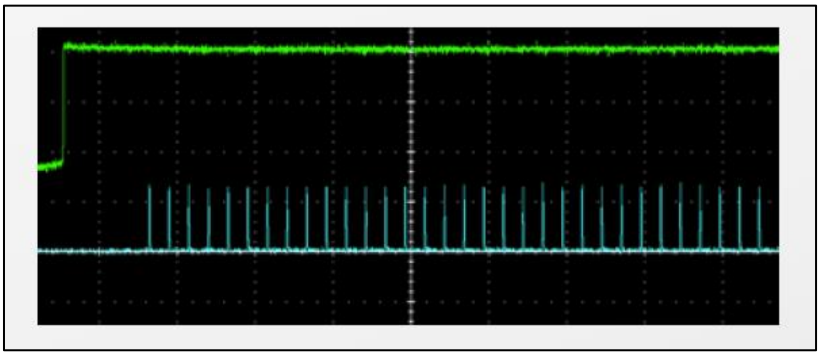


Fig. 3: Illustration of bunch of pulses operating mode. The blue signal is the resulting bunch after 1 Mhz pulse picker trigger input. The green signal is the modulator gate input.

Typically, this operating mode can be used when the process need a definite number of pulses on the sample to obtain a precise machining depth. If the material ablation rate is known, the resulting depth obtained by the bunch of pulses can be easily predicted.

Another useful operating mode is the burst mode operation. It is a definite number of amplified pulses at the oscillator period, separated by 25 ns for a 40 MHz oscillator as mentioned above. Bursts are generated by user control of the pulse picker trigger input (see figure 2). Energy is redistributed between the sub-pulses. So with the same laser power and the same repetition rate, lower peak intensity per each pulse is seen by the material. Typical signals are shown in figure 4. As the time interval between pulses is smaller, there is less time for heat diffusion during the process and thus efficient heat accumulation is obtained. This burst mode can useful in some specific cases such as to obtain a better energy deposition in glass processing or a higher surface quality in metal processing.

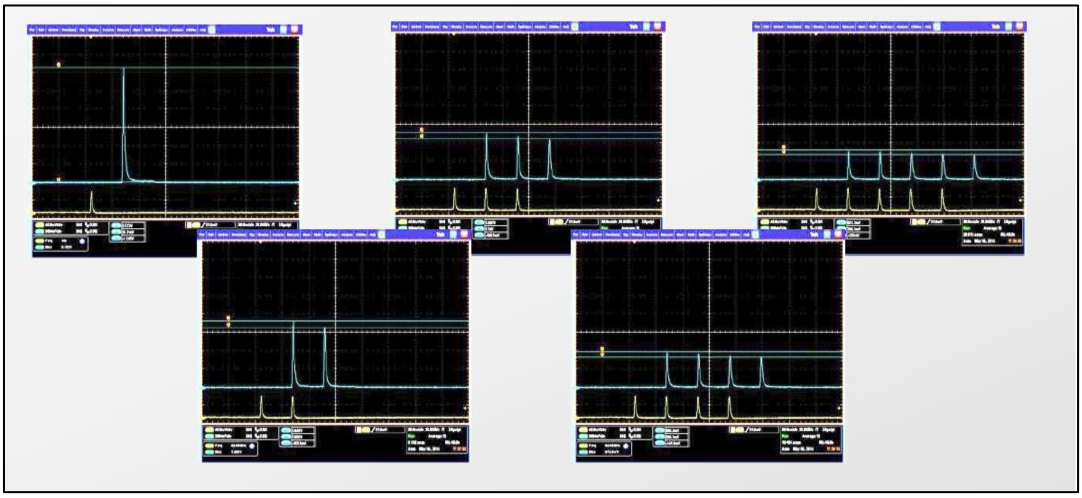


Fig. 4: Illustration of burst operating mode. Bursts are generated by pulse picker trigger input, the main pulse energy is redistributed in several sub pulses.

**3. Application fields**

Thanks to high average power, 100 W and more, and high repetition rate, it is possible today to achieve high throughput with femtosecond lasers, providing that the operating parameters are finely tuned to the application. Femtosecond lasers play a key role in these processes, due to their ability to high quality micro processing thanks to their specific shape of deposited energy. They perform high thickness holes (up to 1 mm) with arbitrary shapes, zero-conicity cutting, high speed surface functionalization. They allow also to minimize added stress to materials and surface roughness and burr. Several tenths of MHz for laser repetition rates and several hundreds of meters per second for beam speed are available. More than 100 m/s is then possible for laser surface structuring. As mentioned above, the synchronization of operating tools after the laser with the laser is crucial, not only to take advantage of the possibility of high speed processing, but also to prevent new thermal mechanisms occurring when two pulses are either spatially or temporally overlapping.

Indeed, the process set up has to be modified to obtain the same results as in low repetition /low power case, to maintain for instance the pulse overlap defined for the determined process. Two options are then possible, depending on laser parameters: to speed also the operating tools, by using for instance polygonal scanners for keeping the same energy density on sample, or to use multiple beams for distributing the energy on several laser spots. Figure 5 show a schematic view of application field in function of laser pulse repetition and pulse energy.

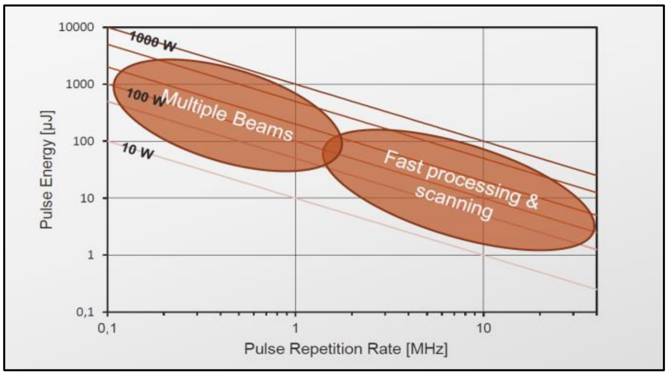



Fig. 5: schematic representation of application field in function of laser parameters

A clear understanding of all the processing steps necessary to optimize the processing speed is a main challenge for industrial development. Indeed, laser parameters are not independent of beam engineering devices (beam deflection, beam scanning and beam shaping). Pulses energies, laser repetition rates have to be precisely settled according to the time and spatial sequences of pulses superposition resulting from beam delivery on the sample. A bad choice of parameters can lead to energy waste and poor process efficiency. In particular, the role of heat accumulation has to be controlled since it can either help the ablation process or degrade the quality.

In the purpose of finding the key parameters for both high aspect ratio processing and high throughput, some optimizations are rather trivial, some are not. In the following, we will investigate some results that can be obtained with a polygonal scanner.

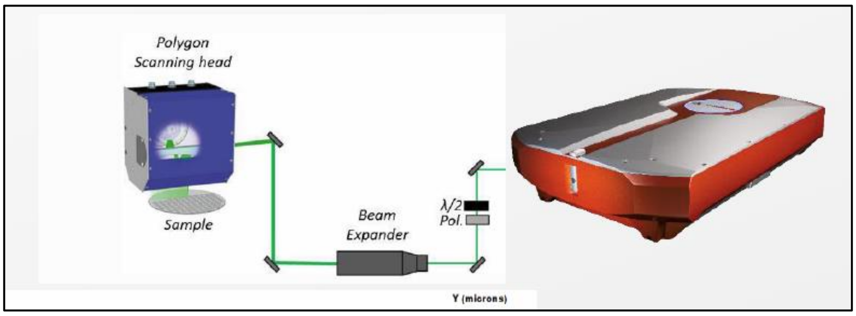



Fig. 6: High speed processing with polygonal scanner

### *3.1. High speed cutting*

A previously presented simple engineering model (see Audouard et al. 2016) describing ultra-fast ablation can be useful to predict results without numerous empirical tests. In the widely-used case of stainless steel, the model allows a quick estimation of the multi-passes profiles and the cutting speed for a determinate thickness sample. For a typical case of 2 MHz repetition rate for 100 W laser power, with a beam waist $w_0$= 20 µm and an energy density (fluence) of 4 J/cm2, and using a polygonal scanner speed of v= 25 m/s, meaning a pulse overlap of 70 %, we obtain a cutting depth of 100 µm for typically 400 passes (see figure 7). The cutting speed is thus 60 mm/s for a 100 µm thick sample. Notice that the previous given time is a “physical time”, *i.e.* the time needed if the laser is always processing. It is obviously not the case for every cutting set up and this value give an estimation of the possible gain for optimizing mechanical, synchronization and computer times.

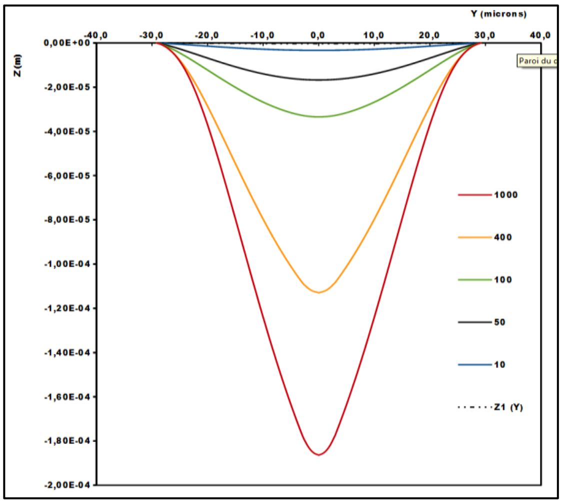



Fig. 7: Calculated estimation of stainless steel cutting with polygonal scanner (speed 25 m/s, beam diameter 40 µm), for laser of 100 W and 2 MHz.

In the presented case, due to the high fluence used, the process efficiency is around 0.2 $mm^3$/min/W which is no more than the obtained value with conventional scanner. The cutting conicity is near 10° which is rather high for many applications. As we will see below, higher repetition rate has to be used to maintain high ablation efficiency. It’s theoretically more efficient to use higher repetition rate rather than higher fluence for the same power. The logarithmic variation of ablation depth with fluence explains this discrepancy. But, for high repetition rate, heat accumulation occurs and leads to severe degradation of cutting quality due to thermal effects.

The conicity correction is a critical subject, and a dedicated operating tool, like trepanning head, has to be involved in the set up. Trepanning systems are using oblique beams which allow to reduce the conicity. But this approach is not easily compatible with a polygonal scanner. New processing technics have thus to be defined. In the following we show the role of beam angle in the cutting results.

Examples of machined groove profiles are presented in figure 8 using a standard set up with a standard galvo scanner. Pictures are taken from the optical microscope after sample cut. Laser parameters are: pulse energy of 61 µJ, laser repetition rate of 250 kHz. The scan speed is 1.2 m/s thus the pulse overlap is 82 %. The number of passes is 100. In the case (a), the laser beam is normal to the sample surface, in the case (b), the beam has an 8° angle with the normal to the surface, in the direction indicated on the figure. The groove profile in figure 2a exhibits the classical conical shape meanwhile in figure 2b we observe that the oblique beam seriously affects the groove shape. The conicity is higher for the left side but is lowered down to quasi 0° for the right side. Indeed, this correction vanishes in the deeper part of the groove, where the profile seems to take the direction of the reflected beam into the hole in formation. This deeper effect will reduce the cutting efficiency of an oblique beam. We can make the assumption that it is linked with multiple reflections inside the groove, and then significantly affected by beam polarization. Nevertheless it has to be taken into account in the final machining procedure (drilling or cutting).

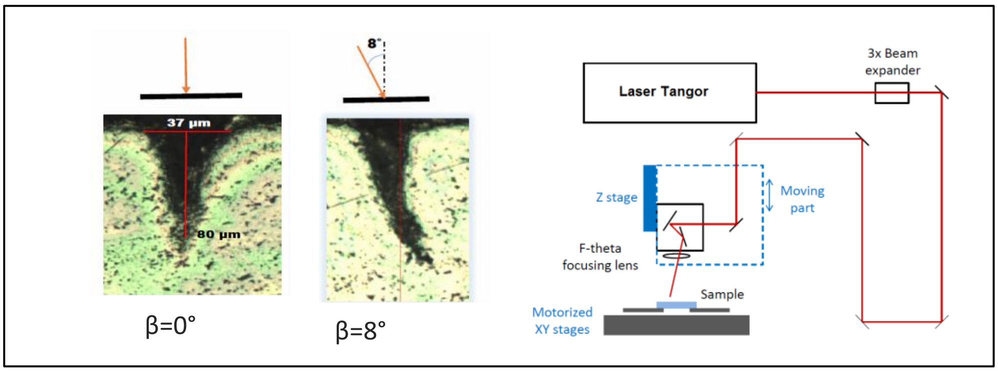



Fig. 8: normal and oblique line cutting with conventional scanner. pulse energy 61 µJ, laser repetition rate 250 kHz, scan speed 1.2m/s (pulse overlap is 82 %), number of passes 100. Two examples of results with normal beam (0°) and oblique beam (8°)

### 3.2 High speed surfacing

Surface functionalization is a rapidly growing application for industrial ultrafast lasers. There is an increasing interest for high throughput surface processing, especially for texturing and engraving large manufacturing tools for different industrial fields such injection molding, embossing and printing. Hydrophobic and hydrophilic surfaces, colored or deep black metal surfaces can now be industrially produced. The engraving speed is continuously improving following developments in beam scanning technology and high average power industrial ultrafast lasers. These surfaces are quite hard to produce since it is necessary to have a good compromise between high removal rate and high quality issues (low roughness, burr-free, narrow heat affected zone). Short pulse lasers are commonly used for this application but the main limitation is the uncontrolled melting of the processed area at average power (typically 50 W). The removal rate with short pulse lasers is about 0,25 $mm^3$/min/W with conventional scanner. In this context, presented ultrashort high power technology combined with polygonal scanner is able to overcome this limitation since it is possible to achieve high throughput and outstanding processing quality at the same time, providing that the operating parameters are finely tuned to the application in order to minimize the thermal load into the target material. In particular, one key parameter is the pulse-to-pulse overlap which depends on the scanning velocity, the spot size, and the repetition rate but also the line-to-line overlap which has to be settled to optimize the depth and roughness.

In figure 9, we present results on surface engraving of stainless steel with a TANGOR system up to 80 W and 7 MHz. In this case, the removal rate per Watt reach 0,45 $mm^3$/min/W.

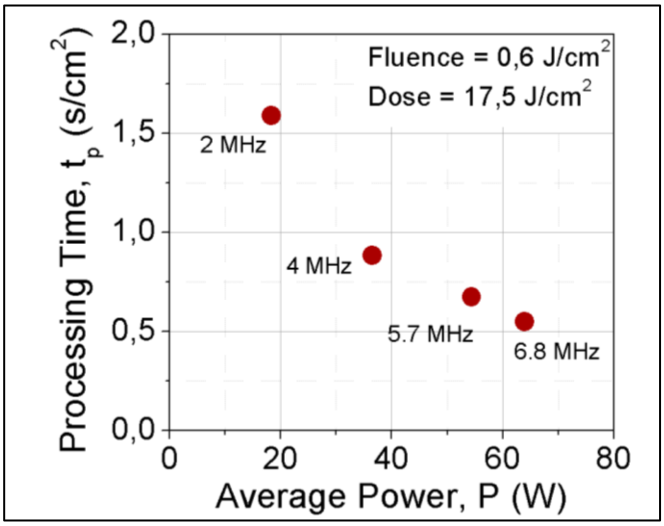



Fig. 9: Processing time versus average power for surfacing with a polygonal scanner

## 4. Conclusion

Thanks to high average power, 100 W and more, and high repetition rate, it is possible today to achieve high throughput with femtosecond lasers, providing that the operating parameters are finely tuned to the application. Femtosecond lasers play a key role in these processes, due to their ability to high quality micro processing thanks to their specific shape of deposited energy. They perform zero-conicity cutting and high speed surface functionalization with up to 0,45 $mm^3$/min/W. They allow also to minimize added stress to materials and surface roughness and burr. Several tenths of MHz for laser repetition rates and several hundreds of meters per second for beam speed are available. More than 100 m/s is then possible for laser surface structuring

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