Dependence of power density and energy fluence on ablation rates and LIBS observation thresholds for laser-irradiated ITER relevant materials

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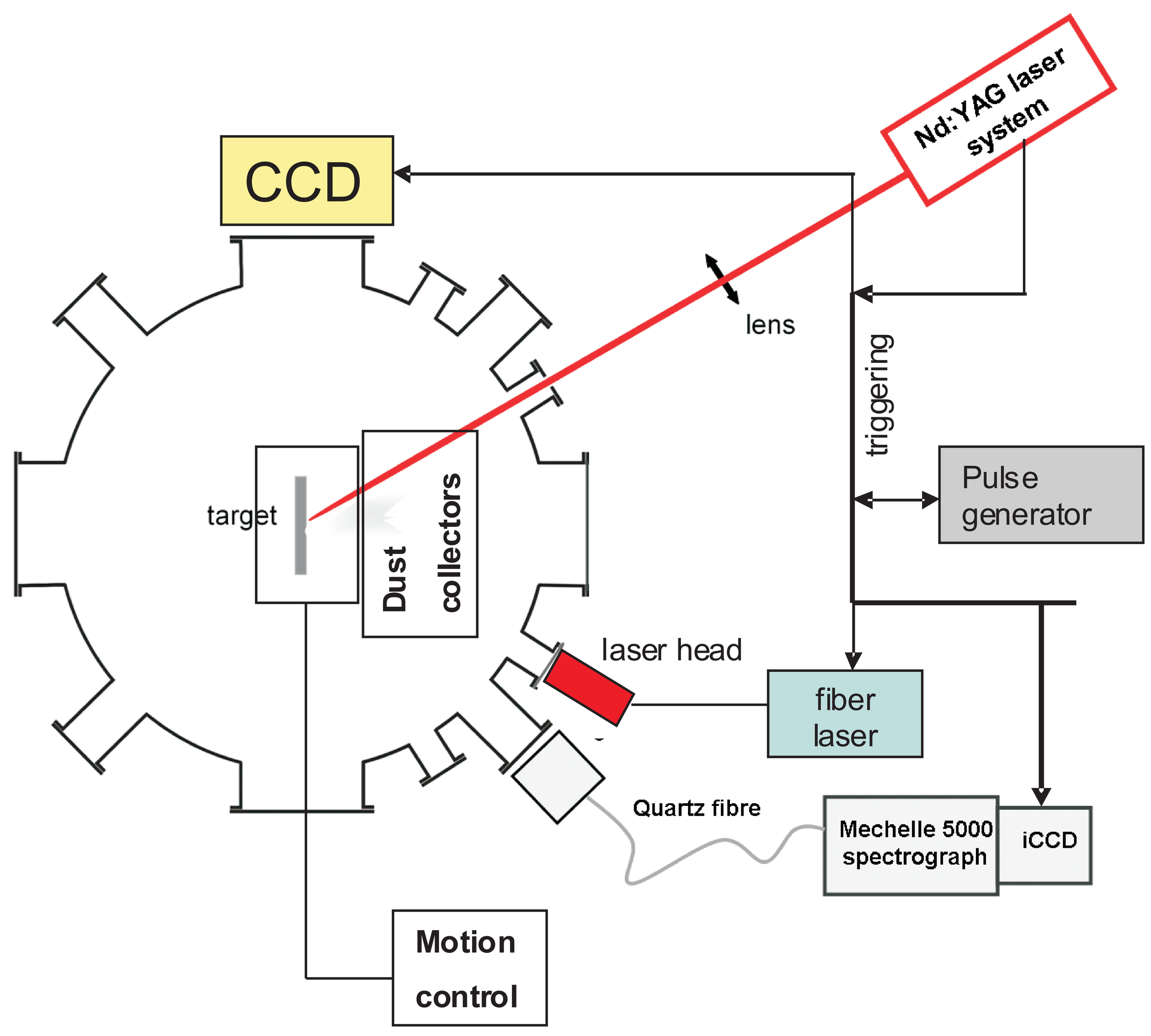
ABSTRACT

In research on ablative laser removal of fuel and co-deposits from PFCs, the parameters of removal are commonly expressed in dependence of laser energy flux defined as J/cm^2 and calculated for single laser pulses or series of pulses. Due to variety of recently available laser systems for removal applications, which can provide pulses from broad ranges of energy and time, this approach is no longer sufficient. The limitations of the fluence model is especially clear when comparing removal with the use of short pulse Nd:YAG lasers operating in single nanoseconds and a part of J regime and fiber lasers operating in the regime of one hundred nanoseconds pulse duration and single mJ energy.
To complete the fluence model and make it applicable for assessment of the laser removal efficiency, the information on laser power density should be included into it. It is obvious that especially for longer and low energetic pulses, the decreasing power density can have deteriorating influence on ablation rate even for high energy fluence. While the removal process can be monitored by the LIBS, the power density threshold for the correct LIBS characterization should be determined.
The contribution includes a comparative experimental study on the influence of the laser power density and energy flux on the ablation rate for Nd:YAG and Yb:fiber laser systems. The ablation rate in function of fluence is estimated for various power densities from a wide range from 10^6 to 10^{10} W/cm^2 by the means of profilometry of laser induded craters. The thresholds for LIBS observation are estimated with the Mechelle 5000 spectrometer. As the targets for the laser irradiation there were used various C, W and Al (as beryllium analogue) samples.

EXPERIMENTAL SETUP



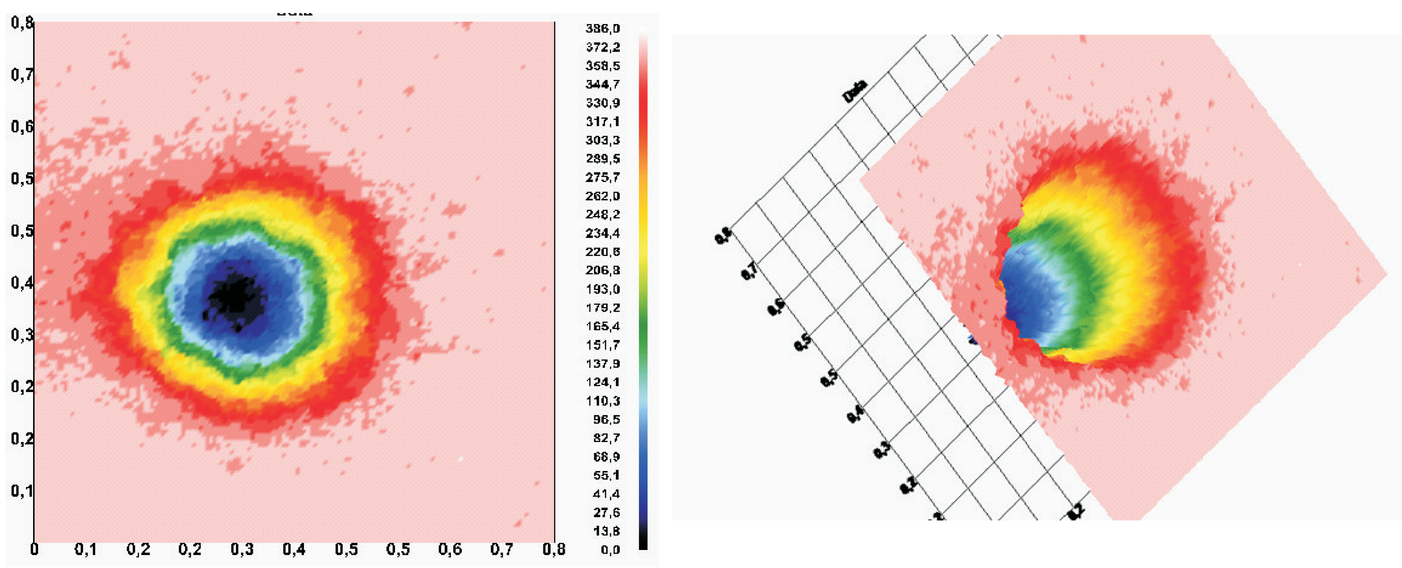
The recent experiental setup at the IPPLM contains two lasers:
- Nd:YAG delivering 3 ns, 0.6 mJ pulses at 1064 nm and up to 10 Hz repetition rate which allows for obtaining high peak power in range of 10^{11} W/cm^2 but rather low average power of 6 W
- Yb:fiber laser with 1mJ, 100 ns pulses at the repetition rate 2 100 kHz with flexible both energy in the pulse and repetition rate control which offers obtaining the averege power of 200 W and peak power inn range of 10 MW/cm^2.

In the experiments due to properties of the power amplification and pulse formation in the Nd:YAG laser, the Nd:YAG laser is the main source of triggering in the system. The laser triggers the Mechelle spectrometer, the CCD camera and the pulse generator which is the triggering souce for the fiber laser.
Mechelle 5000 spectrometer equipped with the Istar CCD camera allows for the observation of the optical spectra in 200-1000 nm range with good spectral and time resolution which allows for the observation of the evolution of the soectrum of the expanding laser-plasma cloud.
The high resolution (2400x2400 pixels) fast CCD camera allows for observation of the laser produced dust with time frame down to 10 us. The photos are most often taken ~40 us after the laser impact due to the maximum of the production after this delay.
The samples including graphite TEXTOR limiter and W:C AUG divertor samples as well as various calibrated samples are mounted on the 1D motion stage in the vacuum chamber. The position of the sample may be adjusted manually or with the use of a PC system which also allows for motion with a velocity given by a maths formula.The chamber besides of allowingto obtain the pressure of 10^{-5} mbarr is equipped with two micrometer valves which allows to introduce the ambient of a mix of gasses. In recent experiments Ar, He, O, H, N and their mixes were used with pressures from a part of Pa to a few hundreds of Hpa.
The part of work presented in this contribution mainly includes the investigation of the laser induced craters which were measured by the means of Nanovea profilometer. With the application of the XY motorized stage and Z detector head, the pofilometer allows for obtaining 3D images with the XY resolution of 25 nm on 50 mm distance and 2.5 nm depth resolution on 1.2 mm total detpth which is satisfactory for the number of laser pulses in the experiments.

FIBER LASER ON THE GRAPHITE SUBSTRATE

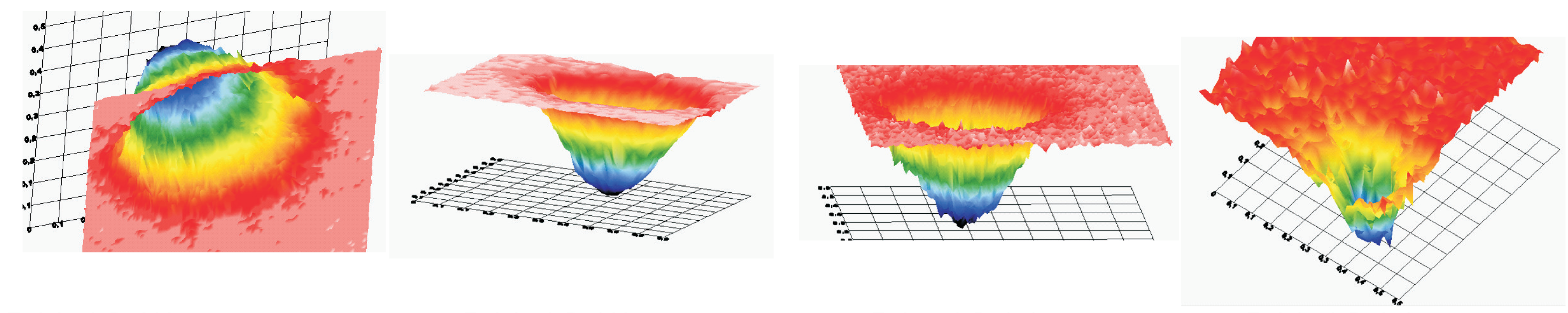
The idea of the experiments with the fiber laser was basically to perform two series of laser shots:
(1) with the constant repetition rate but with variable pulse energy which illustrated the behaviour of the phenomena in conditions of variable both power density and fluence
(2) with constant energy in the laser pulse but with variable repetition rate which illustrated the behaviour of the phenomena in conditions of the constant power density but with variable total fluence.
The first series were performed with irradiation time of 20 s, the second one with 10 s.

THE PROFILES FOR VARIABLE POWER DENSITY



E=1mJ, D=370um, H=366 um, P_{den} 10MW/cm^2

The experiments were performed with decreasing energy in a pulse tarting from 1 mJ down to 0.1 mJ in 20 second series. The irradiation resulted in power density on the target from the range from 1 to 10 MW/cm^2 while the beam was focussed to approximately 350-400 um.
After the series of pulses the laser induced craters where measured with the use of profilometry. The craters had regular gausoid shapes which confirms the high quality of the beam and suggests the linear dependence of the power density on the removal rate.
The picture on the left presents a colour height "map" of the crater and its 3D profile. The crater on the left was induced by 1 mJ pulses.
The craters shown below illustrate the evolution of the crater with decreasing power density.



E=0.9mJ, D=360um, H=240 um, P_{den} 9.4MW/cm^2

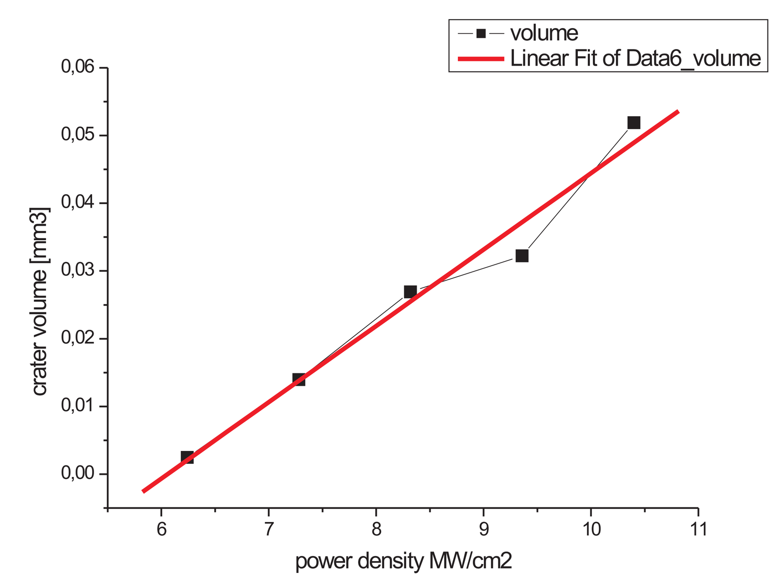
E=0.8mJ, D=360um, H=212 um, P_{den} 8.3MW/cm^2

E=0.7mJ, D=350um, H=110 um, P_{den} 7.3MW/cm^2

E=0.6mJ, D=250um, H=38 um, P_{den} 6.2MW/cm^2

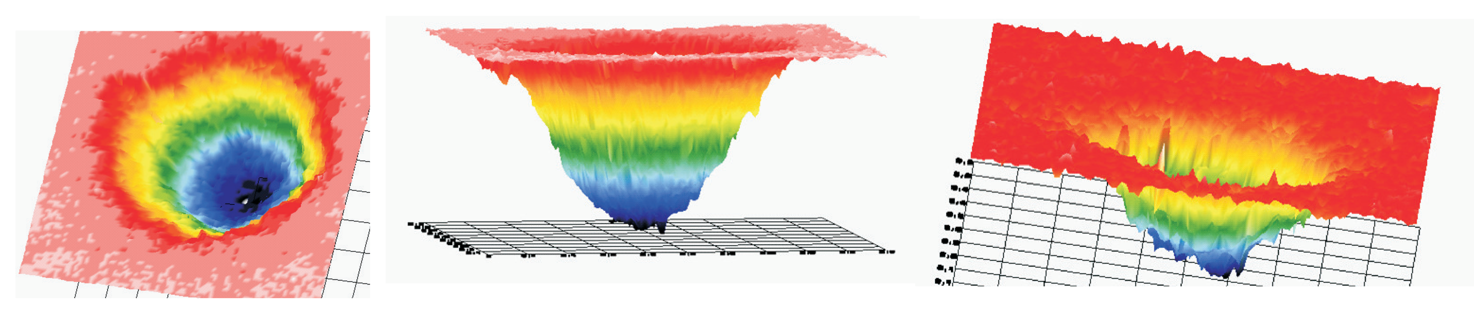
POWER DENSITY DEPENDENCE

The obtained results allowed for estimation of the relation between power density and volume of the laser induced crater. The points on the graph were easily fitted by a linear function. The dependence is presented in figure on the right.
Estimation of the curve allowed for calculation of the threshold power density for interaction with this type of laser which equals ~5.9-6 MW/cm^2. The calculated threshold is consistent with profilometry measurements which did not show the presence of a crator for power densities below the threshold.



REPETITION RATE (FLUENCE) DEPENDENCE

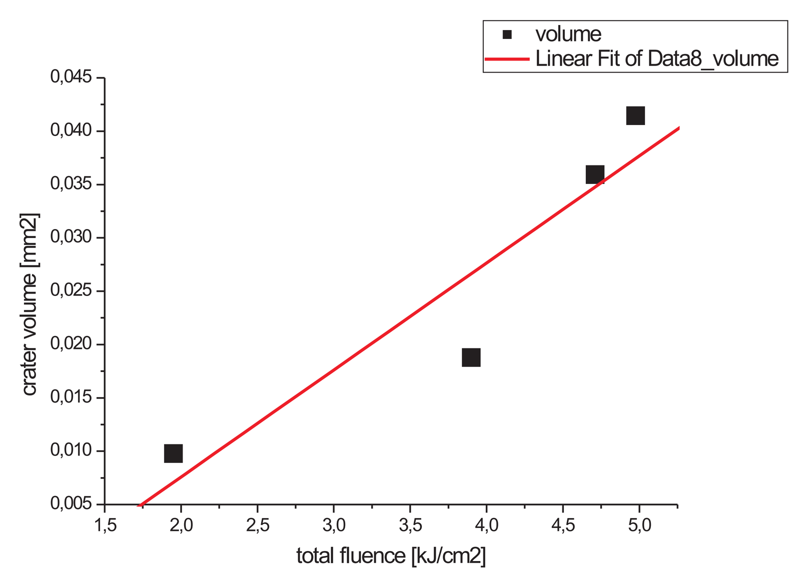
The second part of the experiment with the fiber laser included was to measure the craters depth in function of the repetition rate of the pulses of constant power density obtained in previous experiments for the maximum pulse energy. The sample craters obtaine d for various repetition rate are shown below.

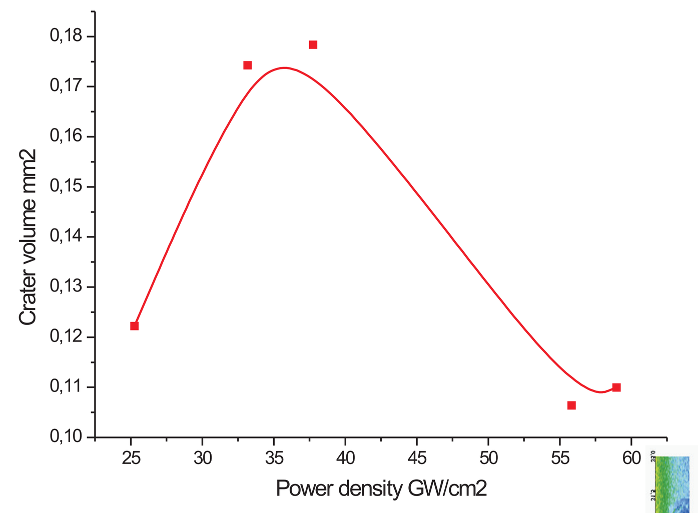


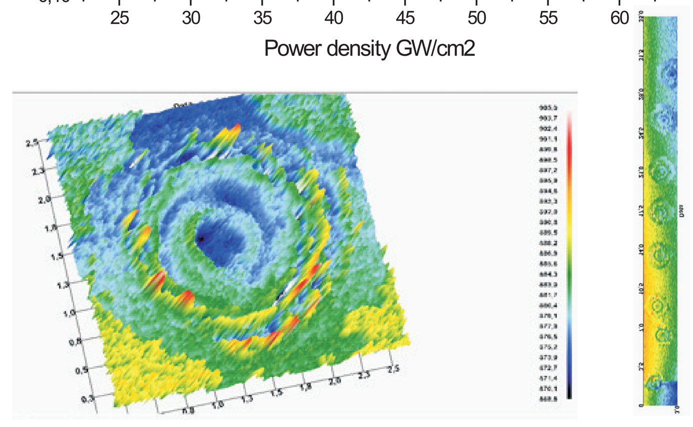
E=1 mJ, D=400um, H= 250,Rep. rate 100 kHz

E=1 mJ, D=390um, H= 228,Rep. rate 90 kHz

E=1 mJ, D=350um, H= 77,Rep. rate 60 kHz







Nd:YAG LASER ON THE GRAPHITE AND ALUMINUM SUBSTRATES

The interaction of the Nd:YAG irradiation was tested on carbon and aluminum substrates in vacuum, in 100 Pa and in atmospheric pressure. The pressure had a big impact on the surface area and the depth of the craters. While in vacuum the craters were deep and narrow, in the ambient atmosphere, the screening effect of laser generated plasma led to formation of shallow craters with larger diameters. In vacuum, the craters in the graphite had a diameter of a part of a micrometer and could reach a large depths of a few hundreds of micrometer. The dependence of the power density on the volume for a constant pulse energy is not straightforward as in case of the fiber laser. The dependence taken for the narrow region in vicinity of focal point is shown on the left. The graph shows that there is a optimal focussing regime which allows to obtain the highest crater volume. Such a crater is not extremely deep which takes place when the power density is higher, but the bigger crater diameter makes the volume considerably larger.
The experiments on the aluminum plate shows the morphology of the craters which takes form of the interferometric rings. This surface structure due to its optical properties may introduce errors to the measurements of the profilometer and should be further investigated. A sample crater and the whole plate with craters are shown on the left.

CONCLUSION

Operating in different power density regimes results in quite different phenomena leading to crater formation which can be learly seen by the means of profilometry. The difference is especially important when the power density is high enough that it produces big amounts of plasma resulted from interaction with the gaseous atmosphere.
Results allow for estimation of the power density threshold for the process of the removalof graphite with a fiber laser which may very useful, especially that this threshold is significatly higher than it is for a standard codeposit.