High Throughput Structuring: Basics, Limitations and Needs

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Outline

Introduction

Theoretical considerations
- Volume ablation rates
- Optimum repetition rates
- Maximum volume ablation rates

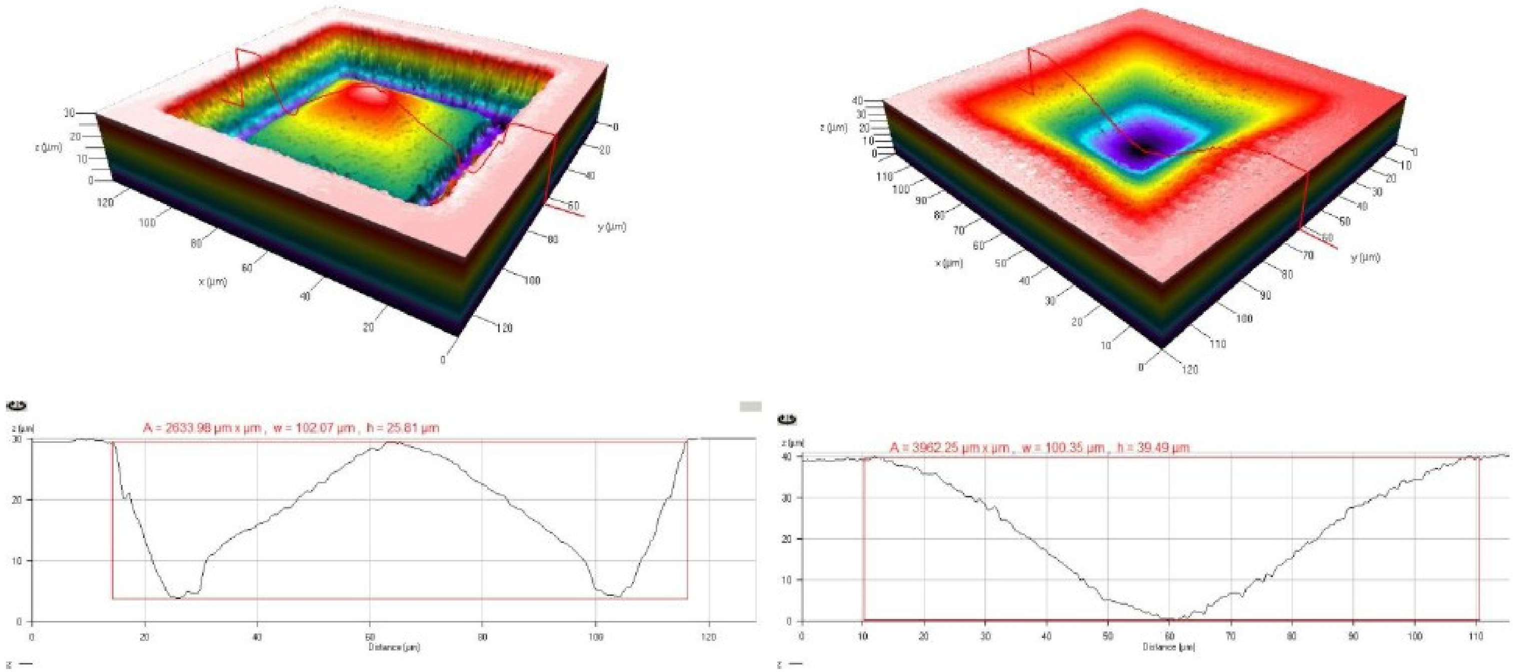
Beam Shaping Optics

Limiting factors

Needs

Conclusions

Surface Microstructures



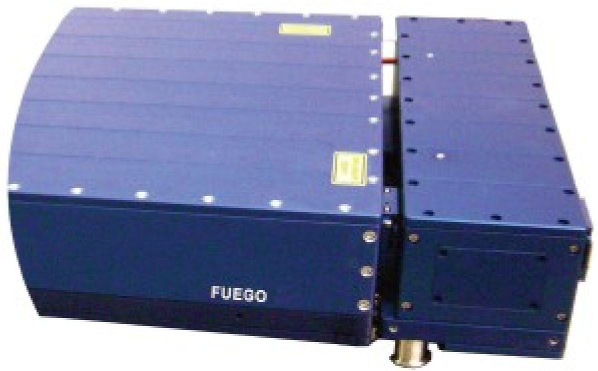
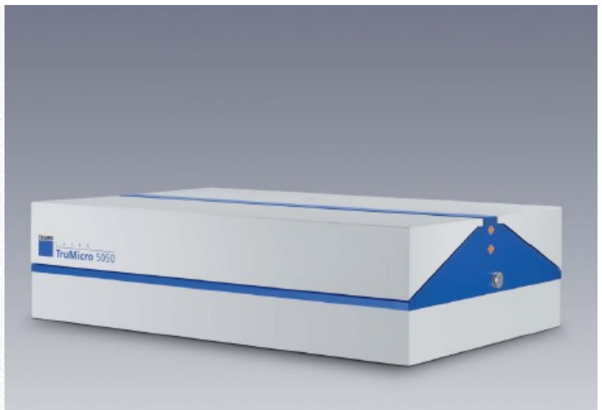
Goal: Generation of surface microstructures in the range of 100 µm.

High throughput means ablation volumes of a few mm³/min

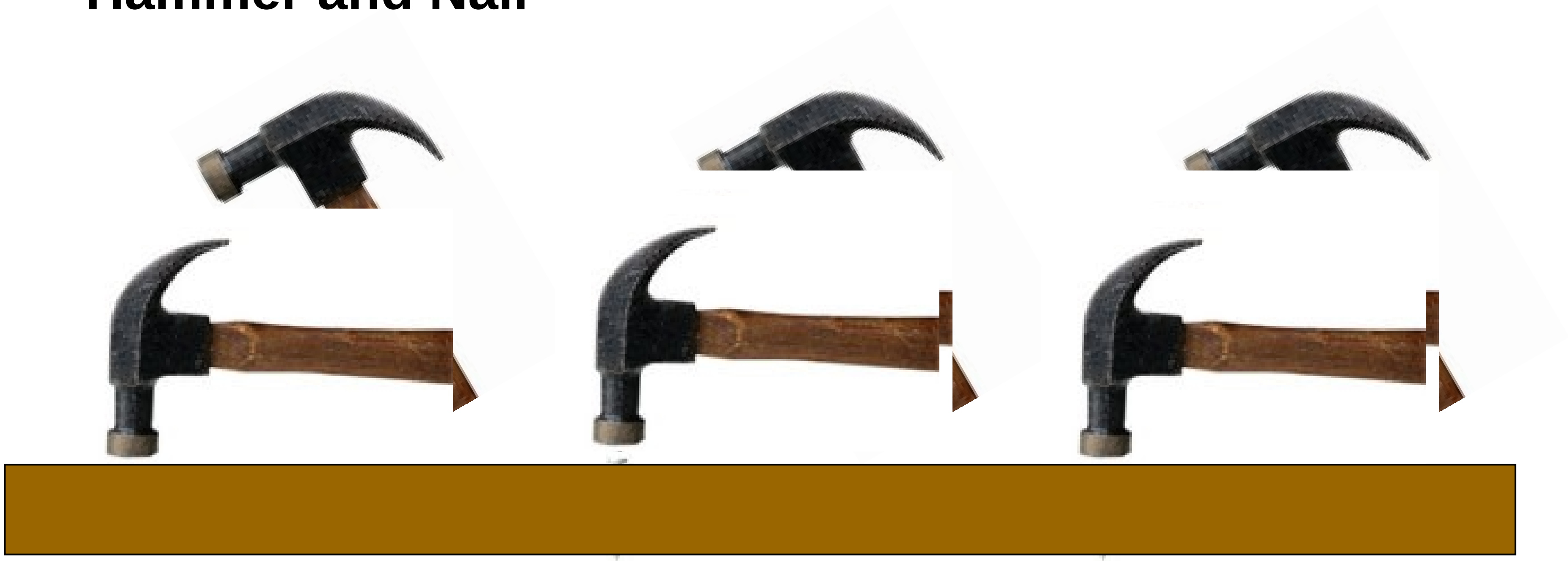
- with adequate surface roughness
- no oxidation of the surface
- geometrical precise

Picosecond laser systems a promising candidate to fulfill this requirements.

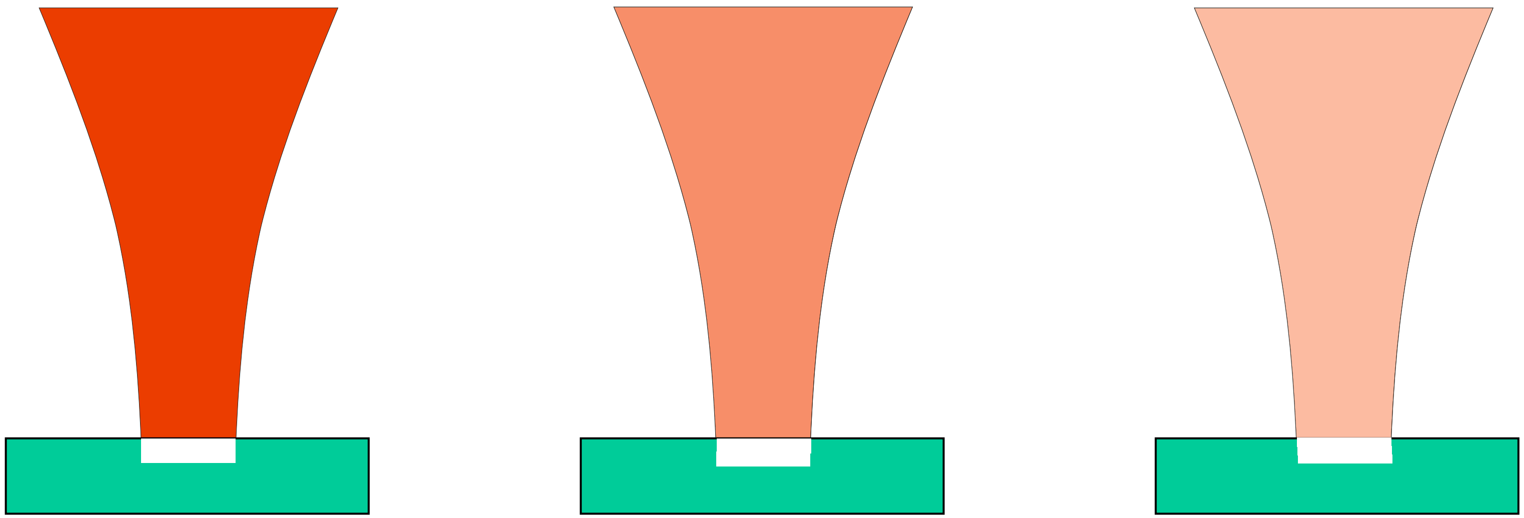
High Power ps systems

tbwp FUEGO	Lumera Hyper Rapid	TrueMicro 5050
		
$P_{av} > 45\ W$	$P_{av} > 45\ W$	$P_{av} = 50\ W$
f_{rep} $200\ kHz – 8\ MHz$	f_{rep} $200\ kHz – 1\ MHz$	$f_{rep} = 200\ kHz$
$\Delta\tau = 10\ ps$	$\Delta\tau < 15\ ps$	$\Delta\tau < 10\ ps$
$M^2 < 1.3$	$M^2 < 1.5$	$M^2 < 1.3$

Hammer and Nail



One high energy puls <-> several low energy pulses

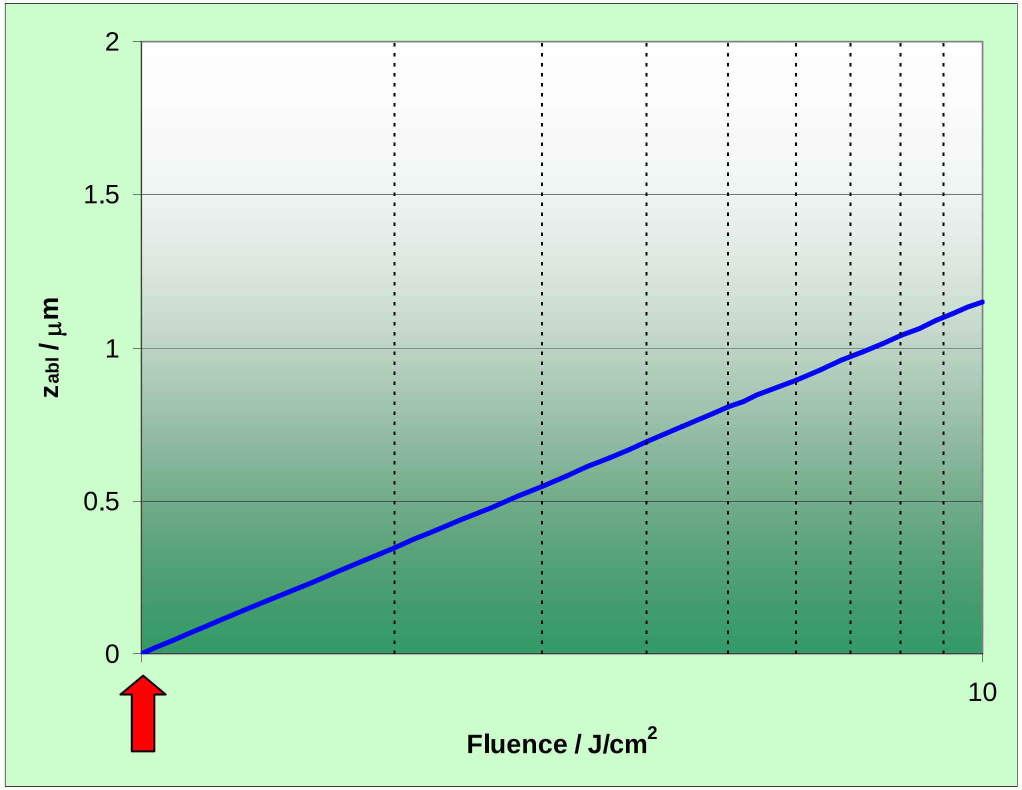


$\Delta V_1 \quad \leq ? \geq \quad \Delta V_2 \quad \leq ? \geq \quad \Delta V_3$

Is it better to distribute the energy among several pulses?

If yes, what is the optimum pulse number?

Ablation of metals with short and ultrashort pulses



Threshold Fluence ϕ_{th}

The logarithmic law:

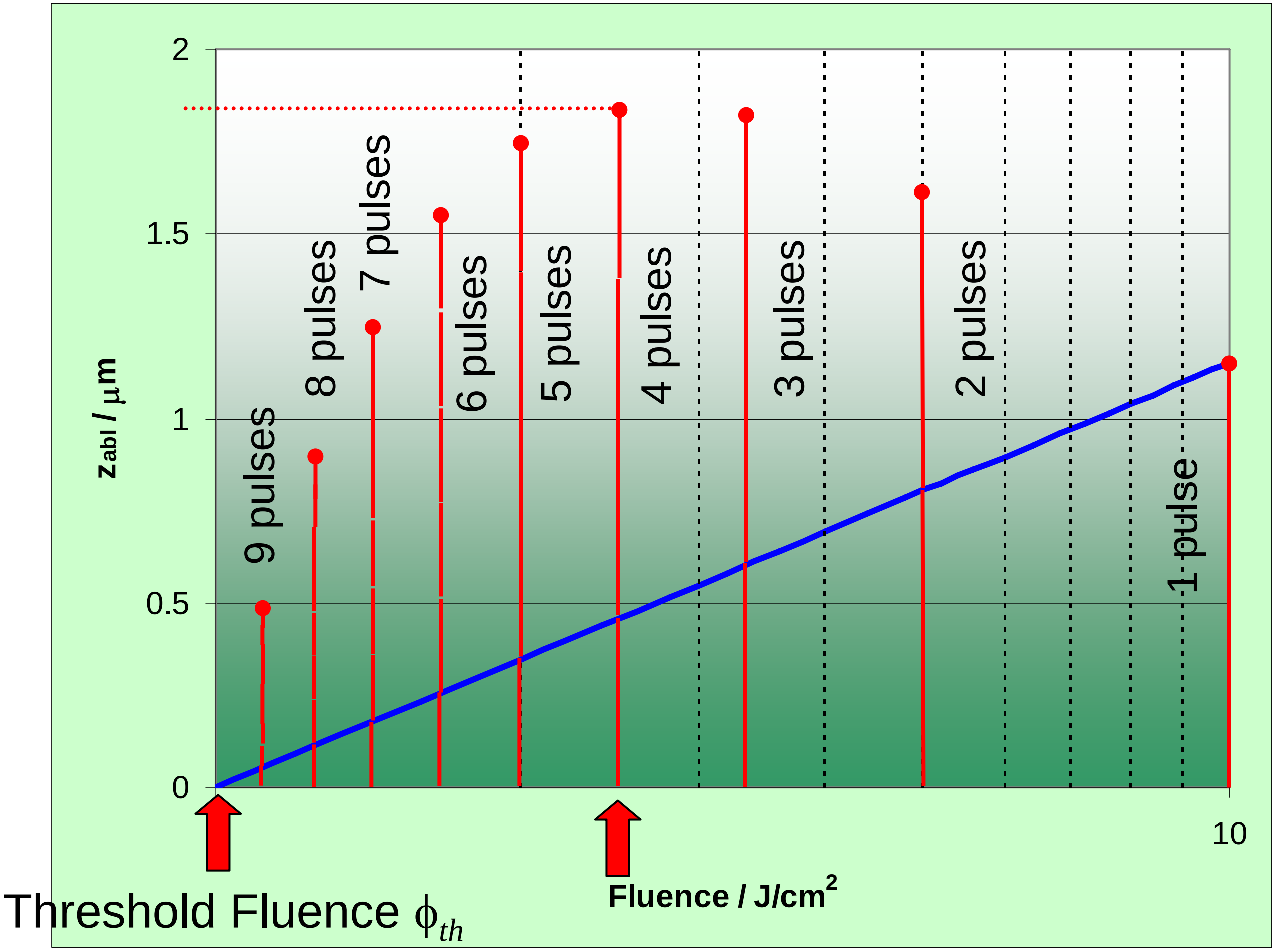
$$z_{abl} = \delta \cdot \ln\left(\frac{\phi}{\phi_{th}}\right)$$

δ: Penetration depth

The logarithmic law has often been reported and confirmed in the literature.

We concentrate on metals and assume that a laser pulse does not influence the physical parameters of the surface for the next pulse.

Distribute the same energy among several equal pulses

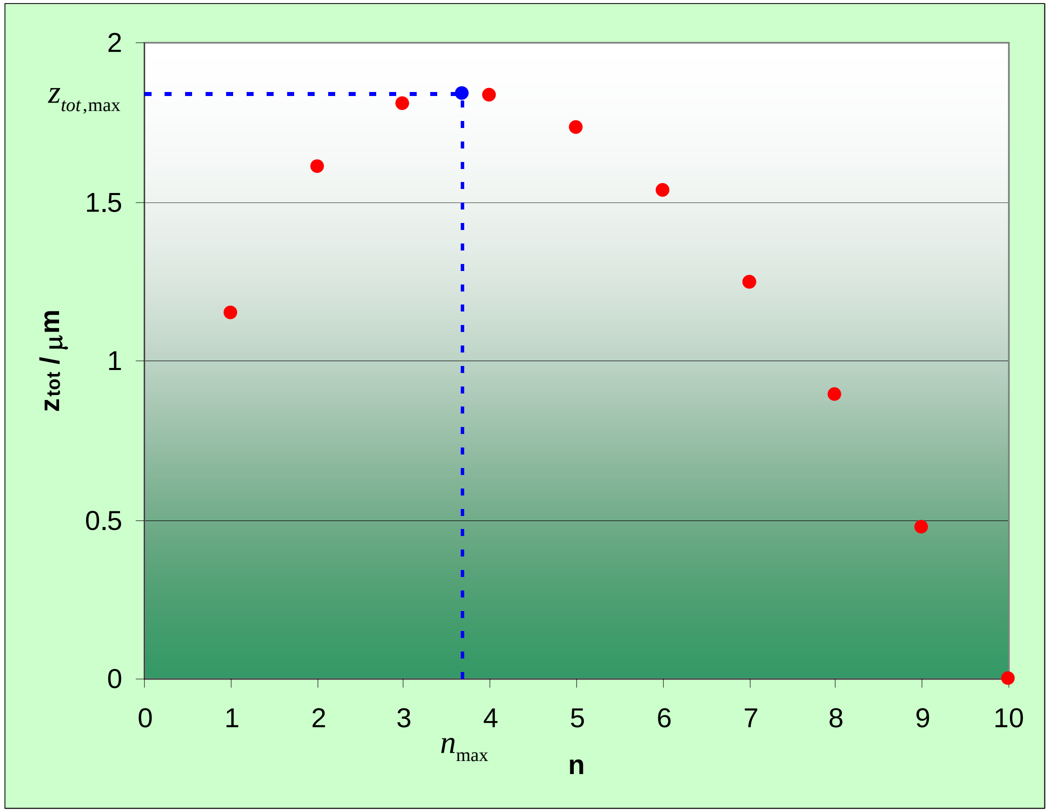


$$z_{abl} = \delta \cdot \ln\left(\frac{\phi}{\phi_{th}}\right)$$

δ: Penetration depth

There exist an optimum pulse number to reach the maximum ablation depth.

Distribute the same energy among several equal pulses



$$z_{tot} = n \cdot \delta \cdot \ln\left(\frac{\phi_{tot}}{n \cdot \phi_{th}}\right)$$

$$\frac{dz_{tot}}{dn} = 0 \quad \rightarrow \quad n_{\max}$$

$$\Rightarrow \quad n_{\max} = \frac{1}{e} \cdot \frac{\phi_{tot}}{\phi_{th}}$$

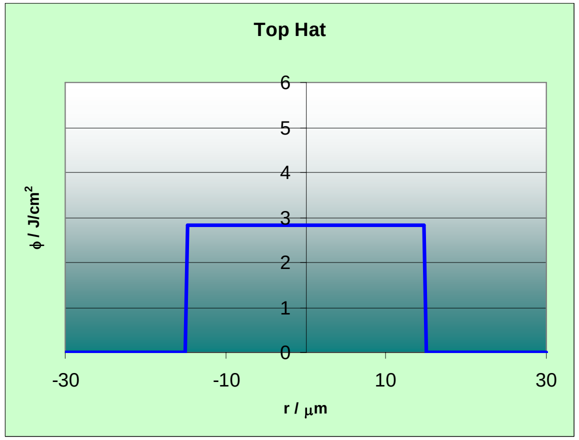
$$\Rightarrow \quad z_{tot,\max} = \frac{1}{e} \cdot \delta \cdot \frac{\phi_{tot}}{\phi_{th}}$$

Remark:
The above result for $n_{\max}$ is not automatically a nonnegative integer. For an exact calculation this has to be taken into account.

Which volume can be ablated by one Pulse

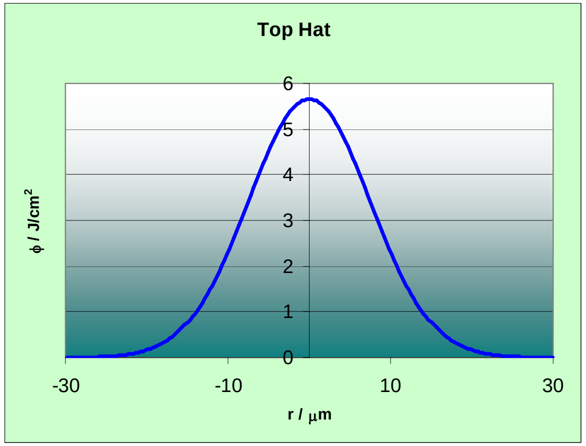
Pulse energy: E_p Spot radius: w_0

Top Hat:



$$\phi(r)=\begin{cases}\dfrac{E_p}{\pi\cdot w_0^2} & r\le w_0\\ 0 & r>w_0\end{cases}$$

Gaussian beam:



$$\phi(r)=\phi_0\cdot e^{-2\cdot\frac{r^2}{w_0^2}}$$

$$\phi_0=\frac{2\cdot E_p}{\pi\cdot w_0^2}$$

Introducing into: $z_{tot}(r)=n\cdot\delta\cdot\ln\left(\dfrac{\phi(r)}{n\cdot\phi_{th}}\right)$

Which volume can be ablated by one Pulse

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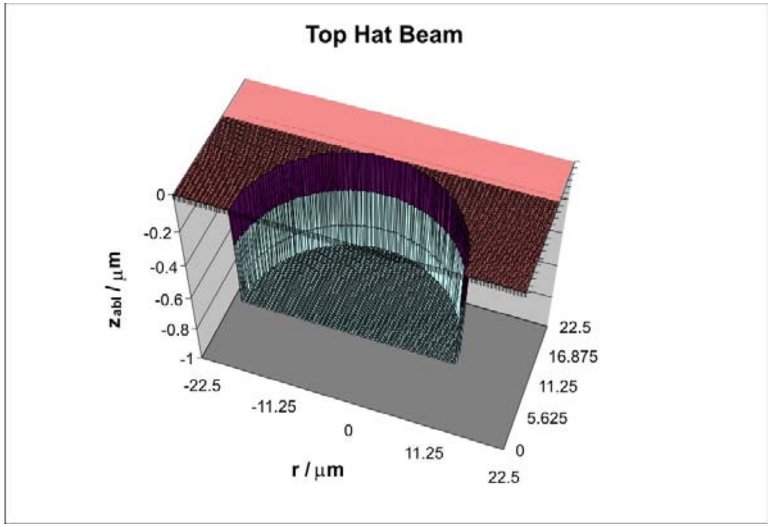
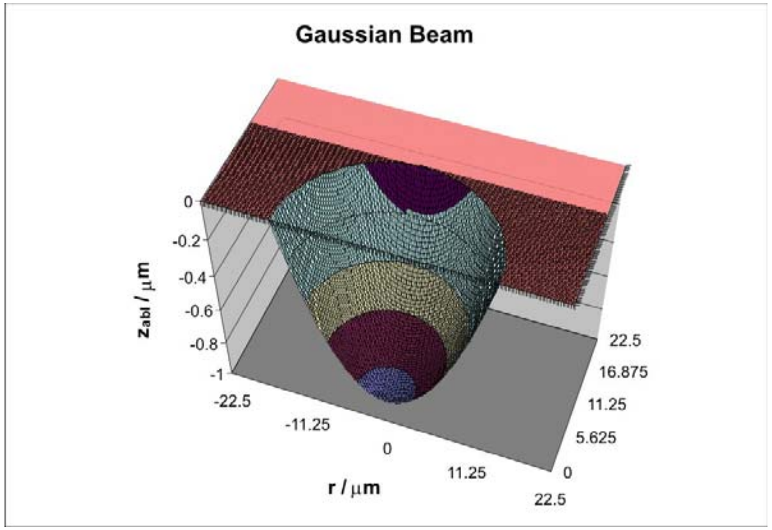
Top Hat:



$$z_{abl}(r)=\begin{cases}\delta\cdot\ln\left(\dfrac{\phi}{\phi_{th}}\right) & r\le w_0\\ 0 & r>w_0\end{cases}$$

Gaussian beam:



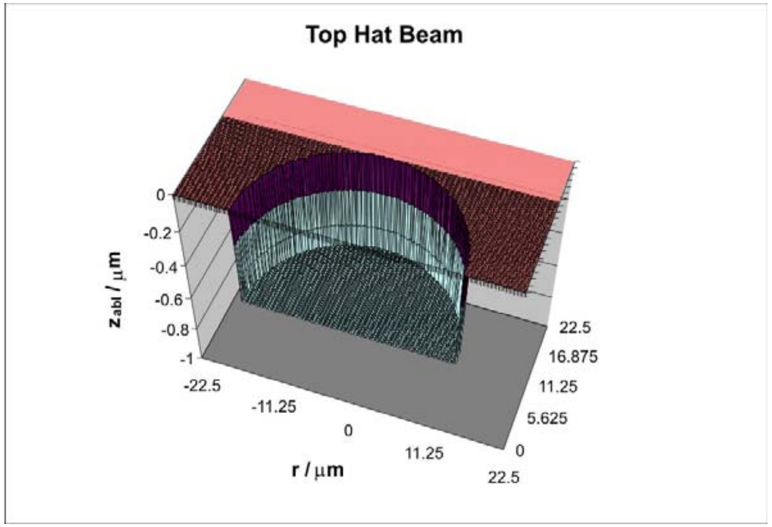
$$z_{abl}(r)=\begin{cases}\delta\cdot\left(\ln\left(\dfrac{\phi_0}{\phi_{th}}\right)-2\cdot\dfrac{r^2}{w_0^2}\right) & r\le R\\ 0 & r>R\end{cases}$$

with: $R=\dfrac{w_0}{\sqrt{2}}\cdot\sqrt{\dfrac{\phi_0}{\phi_{th}}}$

Which volume can be ablated by one Pulse

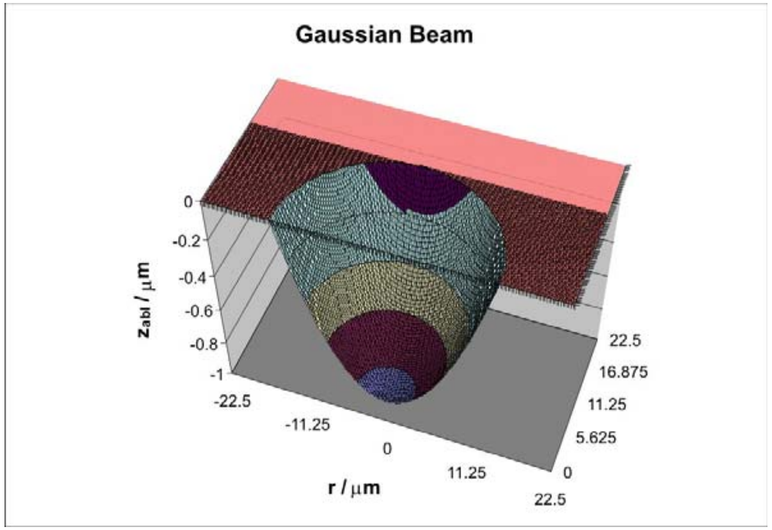
Pulse energy: E_p Spot radius: w_0

Top Hat:



$$\Delta V = \pi \cdot w_0^2 \cdot z_{abl}$$
$$= \pi \cdot w_0^2 \cdot \delta \cdot \ln\left(\frac{\phi}{\phi_{th}}\right)$$

Gaussian beam:



$$\Delta V = \int_0^{2\pi}\int_0^{R} z_{abl}(r) \cdot r \cdot dr \cdot d\pi$$
$$= \frac{1}{4} \cdot \pi \cdot \delta \cdot w_0^2 \cdot \ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

Which volume can be ablated at a constant power

Average Power: P_{av} Spot radius: w_0 Repetition rate: f

Top Hat:

$$\Delta V = \pi \cdot w_0^2 \cdot \delta \cdot \ln\left(\frac{\phi}{\phi_{th}}\right)$$

Gaussian beam:

$$\Delta V = \frac{1}{4} \cdot \pi \cdot \delta \cdot w_0^2 \cdot \ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

$$E_p = \frac{P_{av}}{f}$$

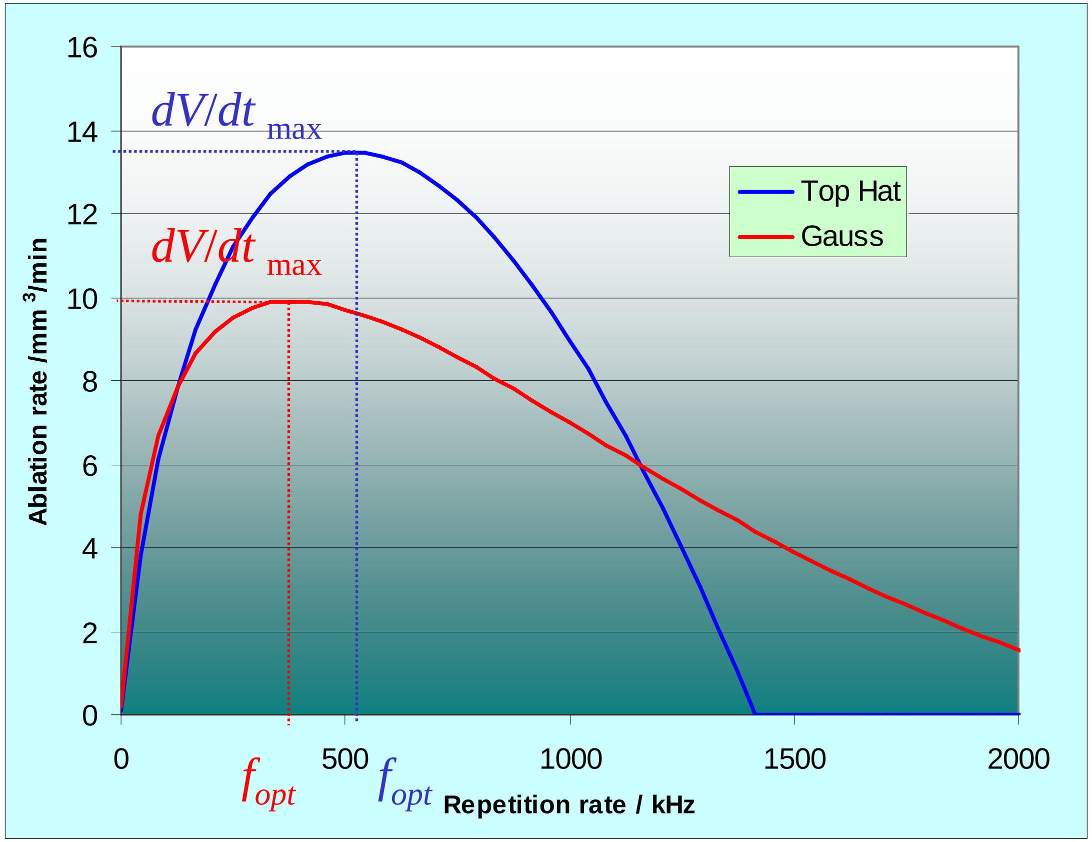
leads to: $\phi = \dfrac{P_{av}}{f \cdot \pi \cdot w_0^2}$ and $\phi_0 = \dfrac{2 \cdot P_{av}}{f \cdot \pi \cdot w_0^2}$

With $\dot{V} = f \cdot \Delta V$ follows:

$$\dot{V} = \pi \cdot w_0^2 \cdot \delta \cdot \boxed{f} \cdot \ln\left(\frac{P_{av}}{\boxed{f} \cdot \pi \cdot w_0^2 \cdot \phi_{th}}\right)$$

$$\dot{V} = \frac{1}{4} \cdot \pi \cdot w_0^2 \cdot \delta \cdot \boxed{f} \cdot \ln^2\left(\frac{2 \cdot P_{av}}{\boxed{f} \cdot \pi \cdot w_0^2 \cdot \phi_{th}}\right)$$

Ablation rate as a function of the repetition rate



$$P_{av} = 10\,W, \;\; w_0 = 15\;\mu m$$

$$\phi_{th} = 1\,\frac{J}{cm^2}$$

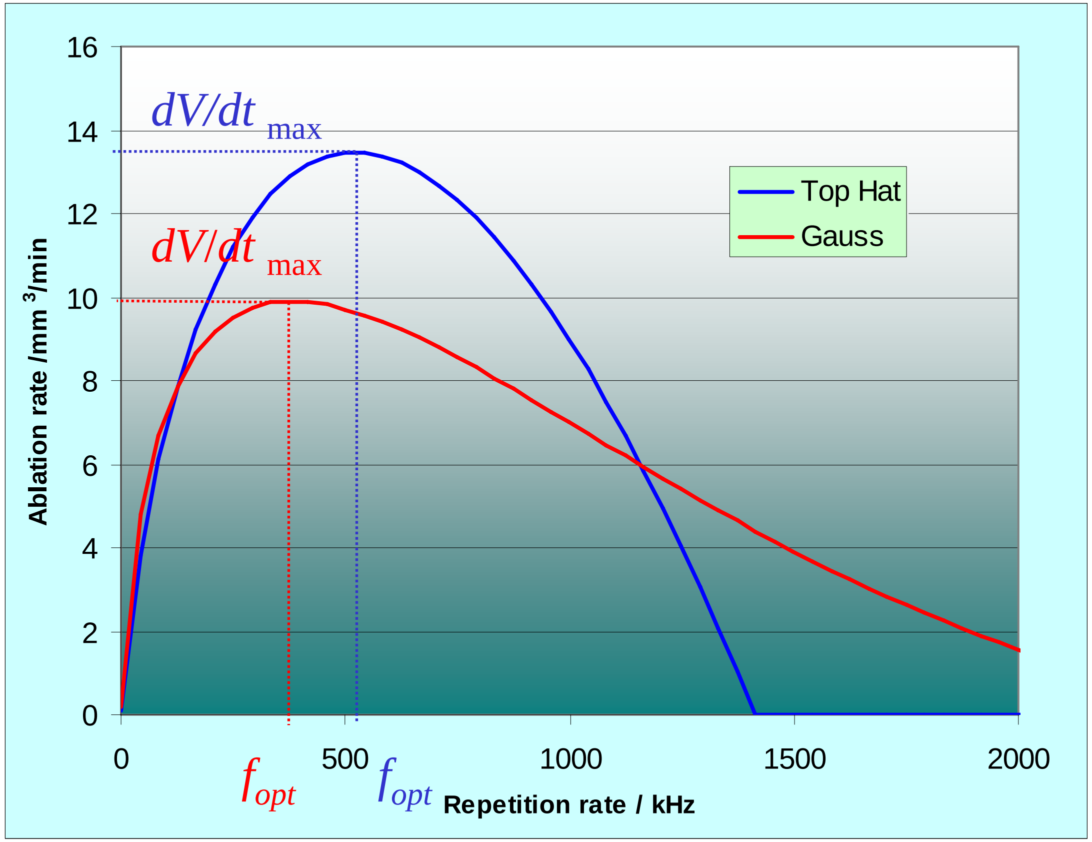
$$\delta = 0.61\;\mu m$$

There exist an optimum repetition rate f_{opt} going with a maximum ablation rate.

The Top Hat beam shape shows an about 35% higher ablation rate.

For a Gaussian beam shape working at a too high repetition rate is preferred compared to a too low repetition rate.

Ablation rate as a function of the repetition rate



$$P_{av} = 10\,W, \quad w_0 = 15\,\mu m$$

$$\phi_{th} = 1\,\frac{J}{cm^2}$$

$$\delta = 0.61\,\mu m$$

Top Hat:

$$f_{opt} = \frac{1}{e} \cdot \frac{\boxed{P_{av}}}{\pi \cdot \boxed{w_0^2} \cdot \phi_{th}}$$

$$\dot{V}_{\max} = \frac{\delta}{e} \cdot \frac{\boxed{P_{av}}}{\phi_{th}}$$

Gauss:

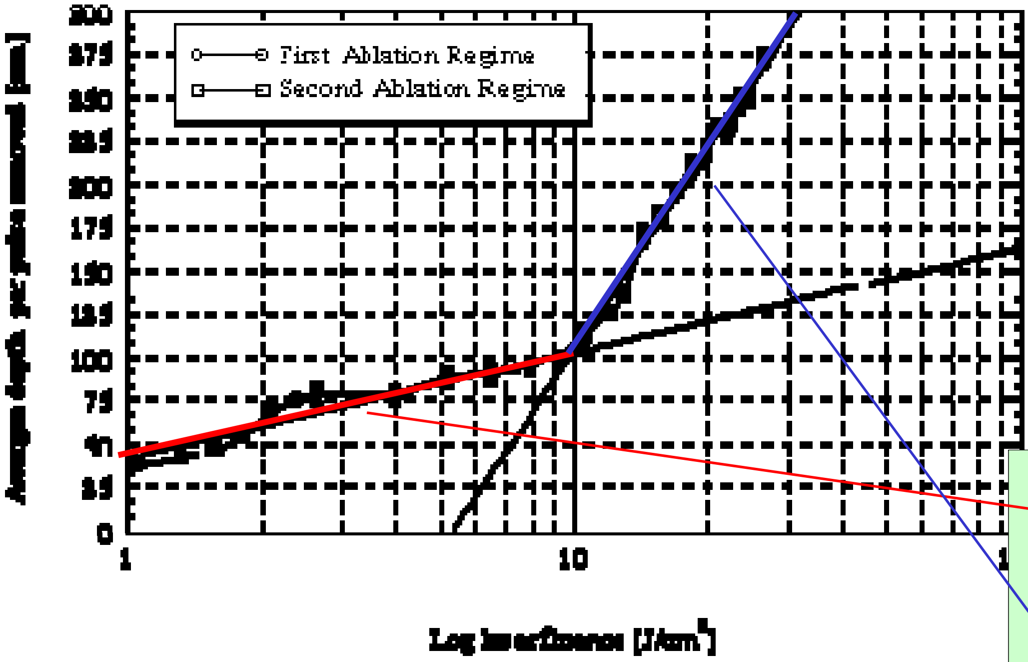
$$f_{opt} = \frac{1}{e^2} \cdot \frac{2 \cdot \boxed{P_{av}}}{\pi \cdot \boxed{w_0^2} \cdot \phi_{th}}$$

$$\dot{V}_{\max} = 2 \cdot \frac{\delta}{e^2} \cdot \frac{\boxed{P_{av}}}{\phi_{th}}$$

Optimum repetition rate and maximum ablation rate directly scale with the average power.
Optimum repetition rate directly scales with $1/w_0{}^2$, i.e. smaller spots lead to higher optimum repetition rates.

Ultrashort laser pulses

Ablation of stainless steel with $\Delta\tau = 150\ fs$.

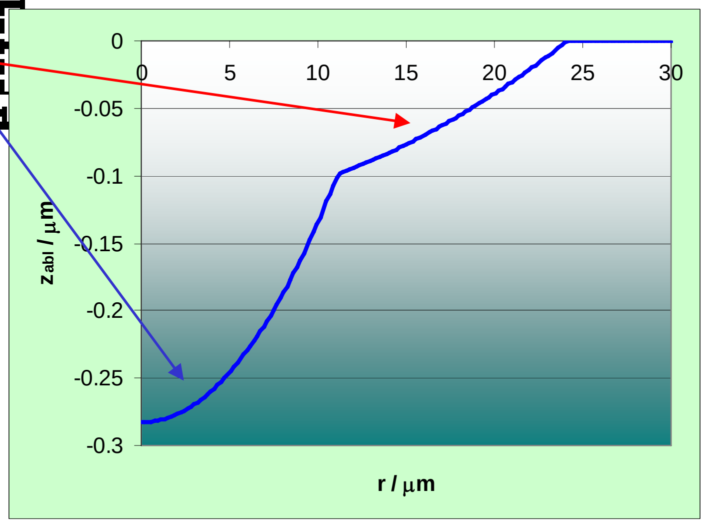


From NCLA Galway, Ireland

Two regimes:

$$\phi_{th,1} = 0.16 \frac{J}{cm^2}; \quad \delta_1 = 0.0242\ \mu m$$

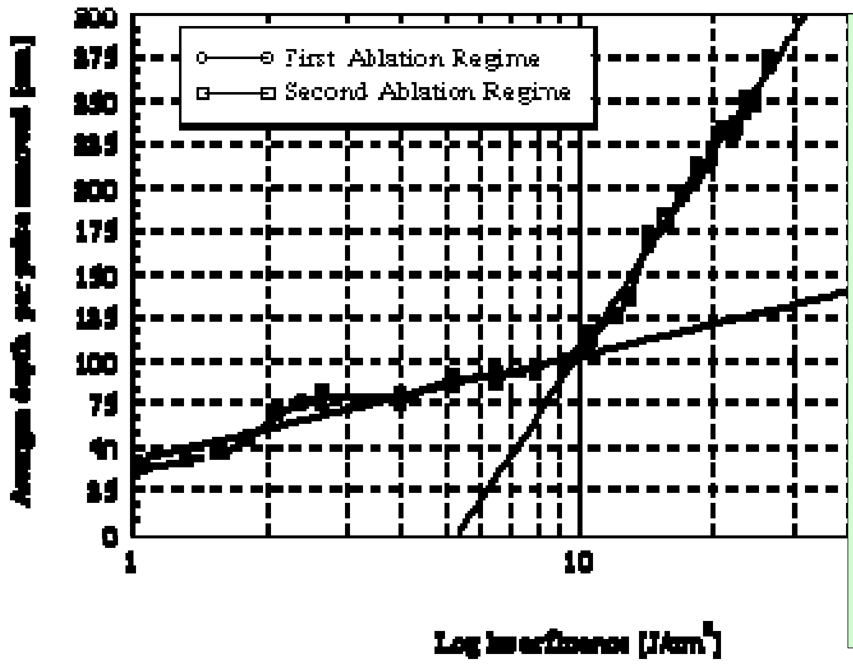
$$\phi_{th,2} = 5.2 \frac{J}{cm^2}; \quad \delta_2 = 0.167\ \mu m$$

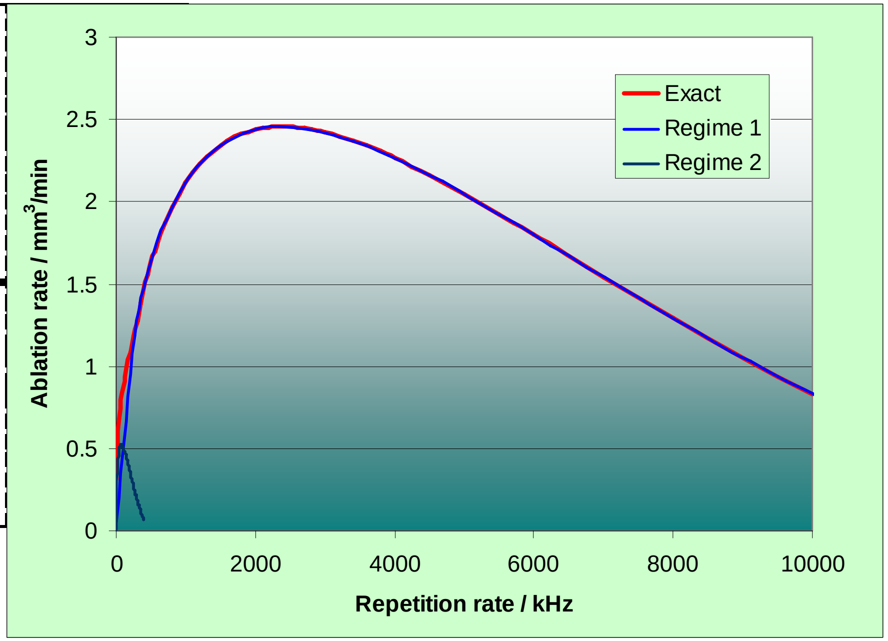


Does this change the obtained results?

Ultrashort laser pulses

Ablation of stainless steel with $\Delta\tau = 150\ fs$.

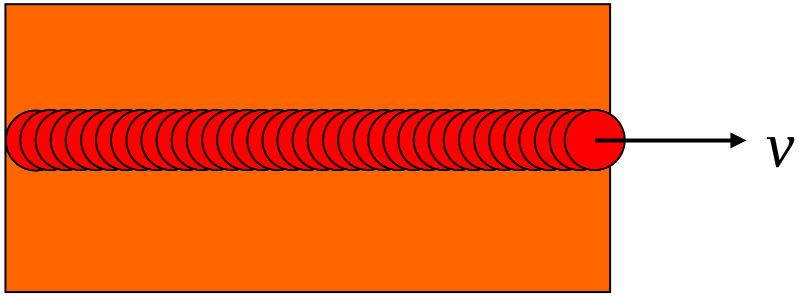




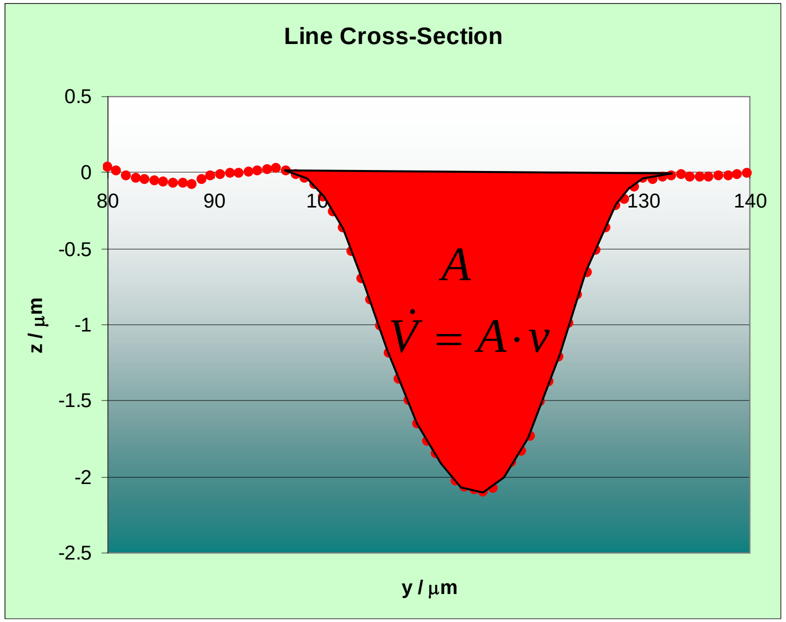
The exact curve equals the curve of the first regime. Differences are only observed for very low repetition rates.

And in reality?

Marking lines in a polished copper surface:



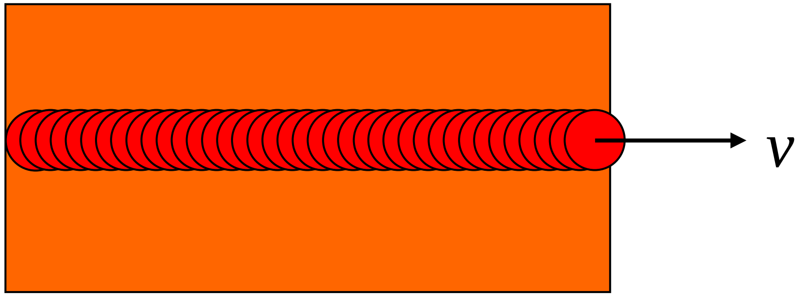
$P_{av} = 3\ W$
$w_0 = 20\ \mu m$
pitch = $0.5\ \mu m$
$M^2 = 1.3$ (Gaussian Beam)
$\Delta\tau = 12\ ps$
$\lambda = 1064\ nm$



Generate a set of lines at constant average power with different repetition rates and adapted speed to guarantee a constant pitch.

And in reality?

Marking lines in a polished copper surface:



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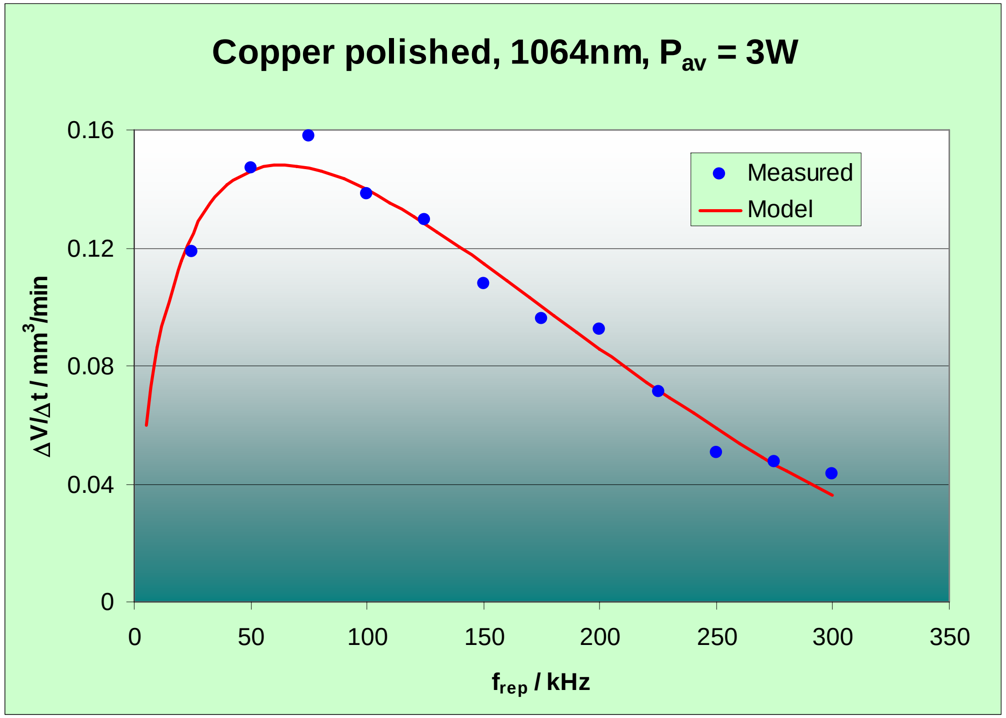
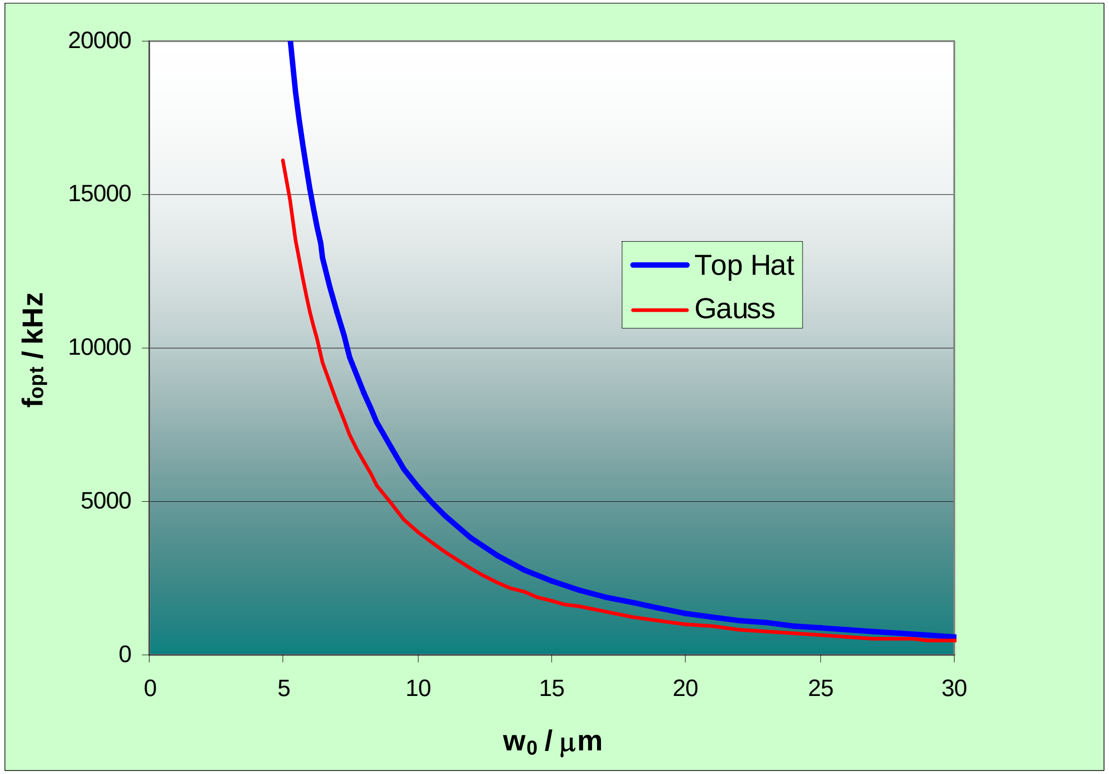


Very good agreement with the developed model:

$\phi_{th} = 1.07\ J/cm^2$

$\delta = 0.033\ \mu m$

What does this mean for an average Power of 50 W



Top Hat:

$$\dot{V}_{\max} = \frac{\delta}{e} \cdot \frac{P_{av}}{\phi_{th}} = 3.4 \frac{mm^3}{\min}$$

Gauss:

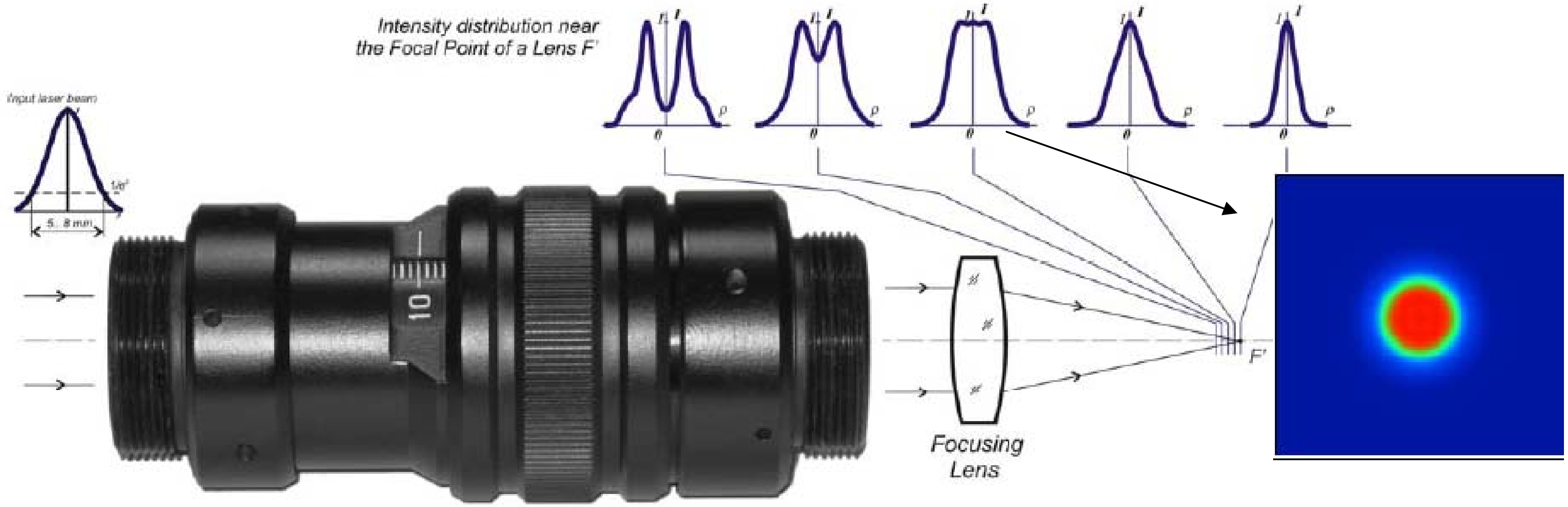
$$\dot{V}_{\max} = 2 \cdot \frac{\delta}{e^2} \cdot \frac{P_{av}}{\phi_{th}} = 2.5 \frac{mm^3}{\min}$$

For small spot sizes repetition rates of several MHz are required to obtain maximum ablation rates.

For lower repetition rates, the spot size has to be increased.

A Top Hat distribution will be more efficient than a Gaussian Beam.

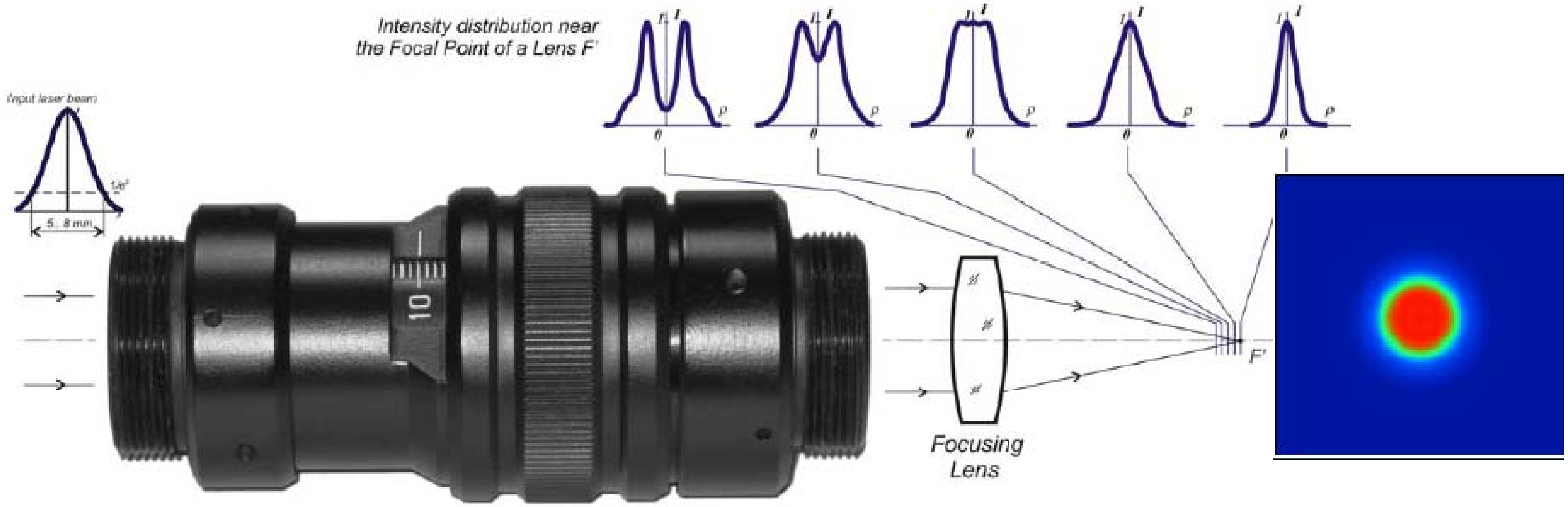
Top Hat: Pi-Shaper (Moltech)

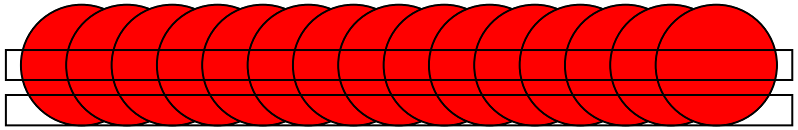


The Top Hat distribution is only achieved over a small distance in front of the focal plane. Therefore only suited for scanners whit a significantly reduced scan field.

A spot diameter of about $50\ \mu m$ can be achieved with a $f = 50\ mm$ lens. This spot corresponds approximately to the spot limit.

Top Hat: Pi-Shaper (Moltech)



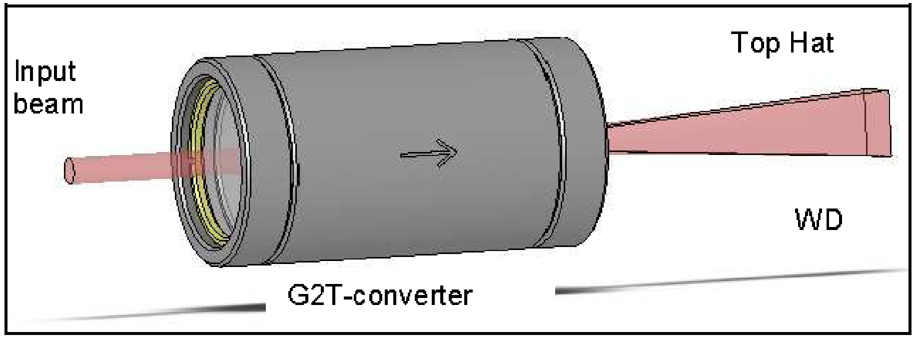


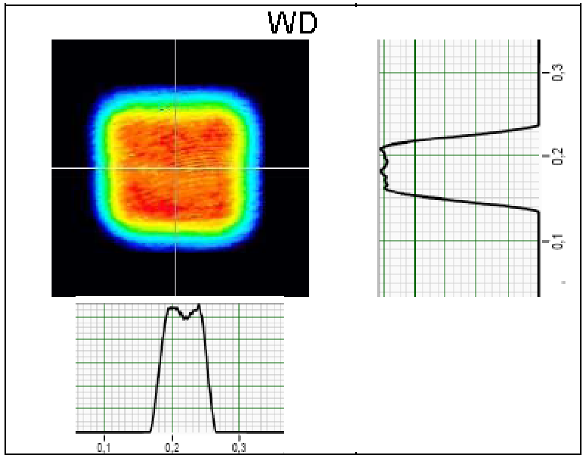
When a round top hat beam moves over a surface more energy per area is deposited in the center of the line than at the borders.

The result will be a groove with a round shaped cross section.

Quite hard to adjust.

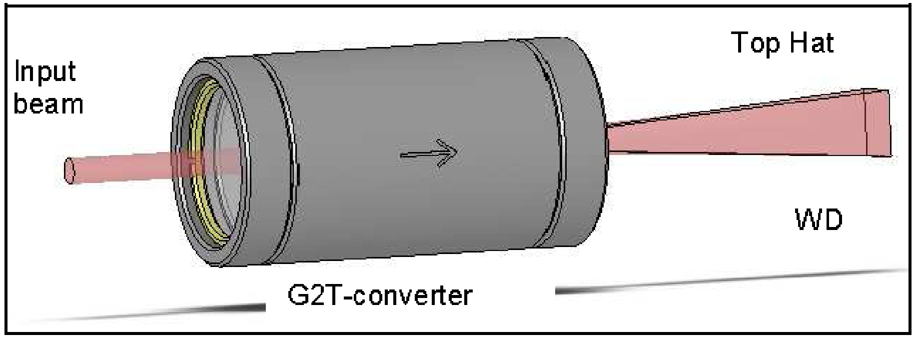
Top Hat: Gauss to Top Hat Converter g_2T (Limo)

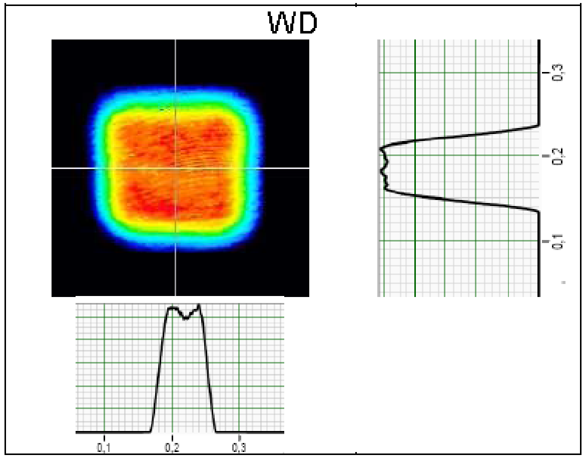




g2T® - module		Field size[1] (top hat[5] mm)	Working distance[1] WD (mm)	Depth of Focus[2] DOF (mm)	Input beam diameter[3,4] (FW1/e²; mm)
g2T_1064_0.06x0.06	(410.211)	0.06 x 0.06	25	± 0.04	2 ± 0.2
g2T_1064_0.1x0.1	(410.212)	0.1 x 0.1	48	± 0.05	3 ± 0.3
g2T_1064_0.18x0.18	(410.214)	0.18 x 0.18	100	± 0.4	3 ± 0.3
g2T_1064_0.37x0.37	(410.216)	0.37 x 0.37	206	± 1.2	3 ± 0.3
g2T_1064_0.5x0.5	(410.217)	0.5 x 0.5	46	± 0.2	4 ± 0.3
g2T_1064_1x1	(410.220)	1.0 x 1.0	97	± 0.6	4 ± 0.3
g2T_1064_2x2	(410.221)	2.0 x 2.0	193	± 3	4 ± 0.3
g2T_1064_2.5x2.5	(410.222)	2.5 x 2.5	239	± 4	4 ± 0.3
g2T_1064_3x3	(410.223)	3.0 x 3.0	284	± 6	4 ± 0.3
g2T_1064_4.8x4.8	(410.225)	4.8 x 4.8	97	± 1.8	4 ± 0.3
g2T_1064_9.6x9.6	(410.230)	9.6 x 9.6	196	± 13	4 ± 0.3

Top Hat: Gauss to Top Hat Converter g_2T (Limo)





Would produce grooves with rectangular cross section.

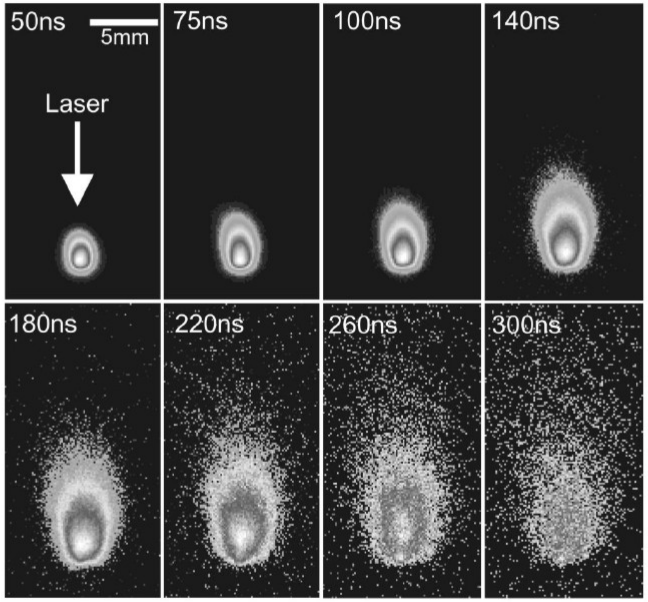
Achievable spot sizes are limited to $60\ \mu m$.

The depth of focus is quite small.

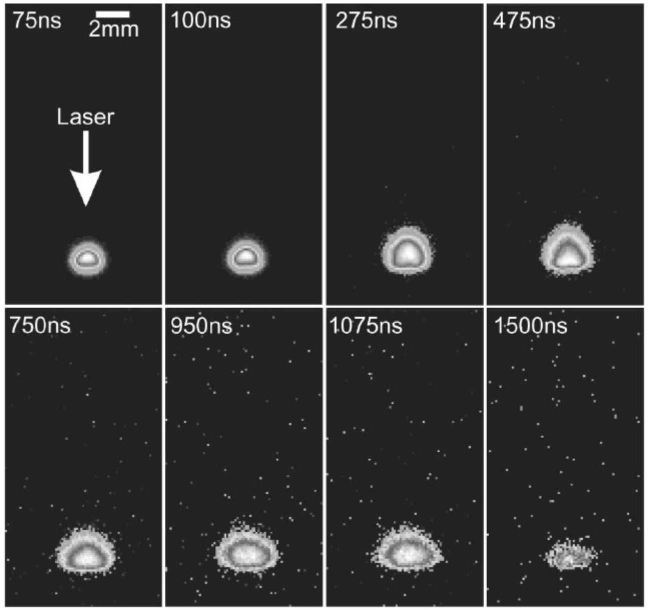
Not suited for operation with scanners, i.e. moving work piece.

Influencing and limiting factors

Plasma generation:



Vacuum 10^{-6} $mbar$



Low pressure: 260 $mbar$

Typical lifetime of the plasma plume in air is in the range of μs corresponding to a repetition in the range of 1 MHz.

To avoid plasma shielding, the next pulse at the same location should appear after the lifetime of the plasma plume -> reduction of the repetition rate or fast moving of the laser beam.

Influencing and limiting factors

Surface heating:

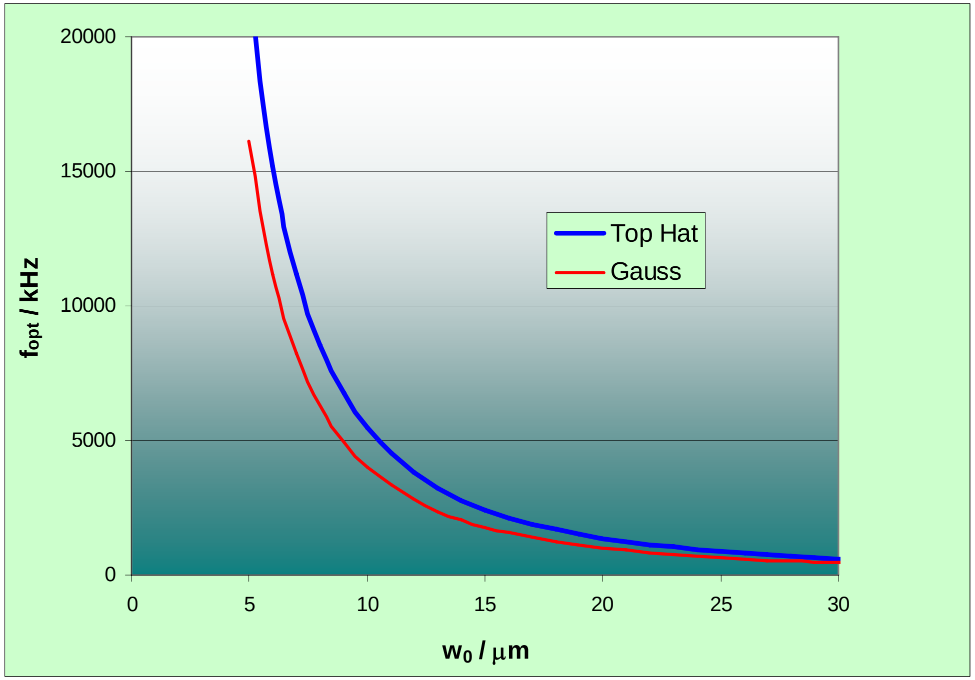
Even in the case of ultrashort pulses, always a part of the energy is converted to heat in the material.

For high average powers this can lead to surface melting effects, when the laser energy is concentrated to too low lateral dimension.

-> The laser energy has to be spread over a certain area of the surface, i.e. the laser spot has to be moved over the surface.

From a repetition rate of about 1 MHz on, the beam spot should be moved by about one spot diameter from pulse to pulse.

What does this mean for an average Power of 50 W



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Gauss:

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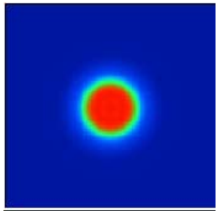
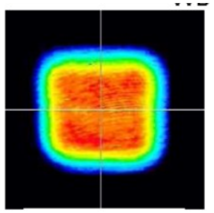


$w_0 = 25\ \mu m$

$f_{opt} \approx 870\ kHz$

$v_{Beam} \approx 22\ \frac{m}{s}$

Today scanners can not reach marking speeds in the range of $20\ m/s$ with an $f = 50\ mm$ Optic.



$2w_0 = 60\ \mu m$

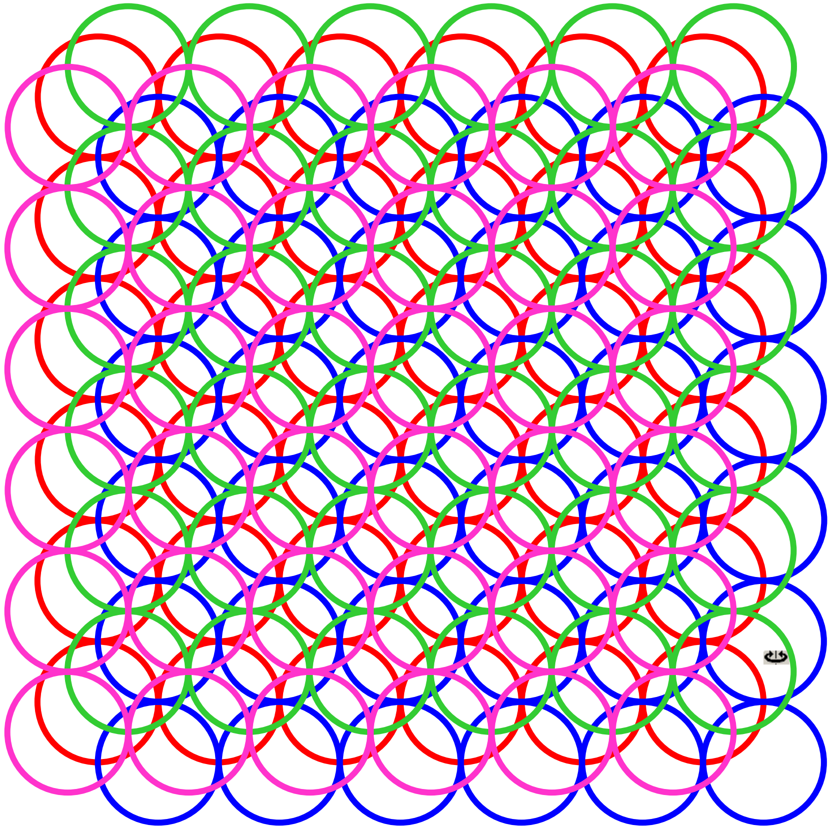
$f_{opt} \approx 480\ kHz$

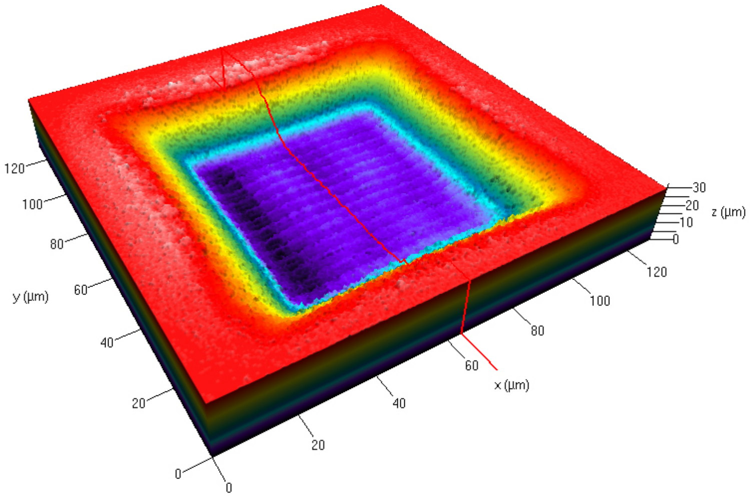
$v_{Beam} \approx 28\ \frac{m}{s}$

Speed in the range of $30\ m/s$ of the work piece for structures in the range of $100\ \mu m$??

Structuring with single Gaussian spots

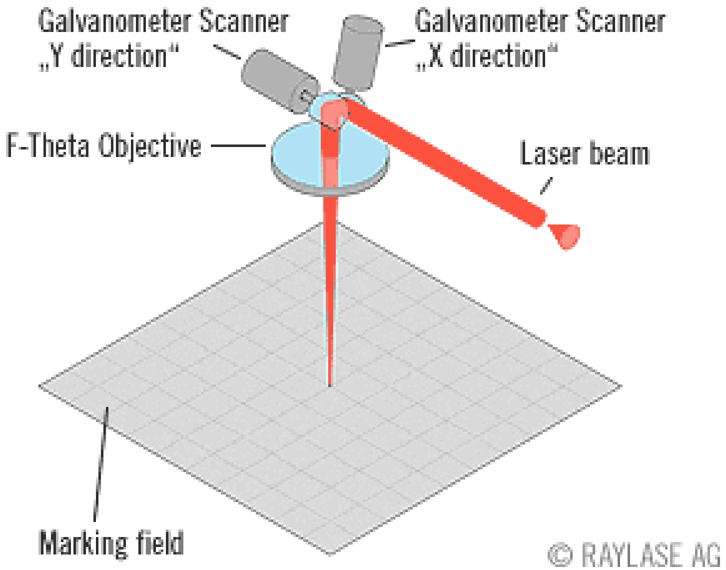
Structuring with single layers

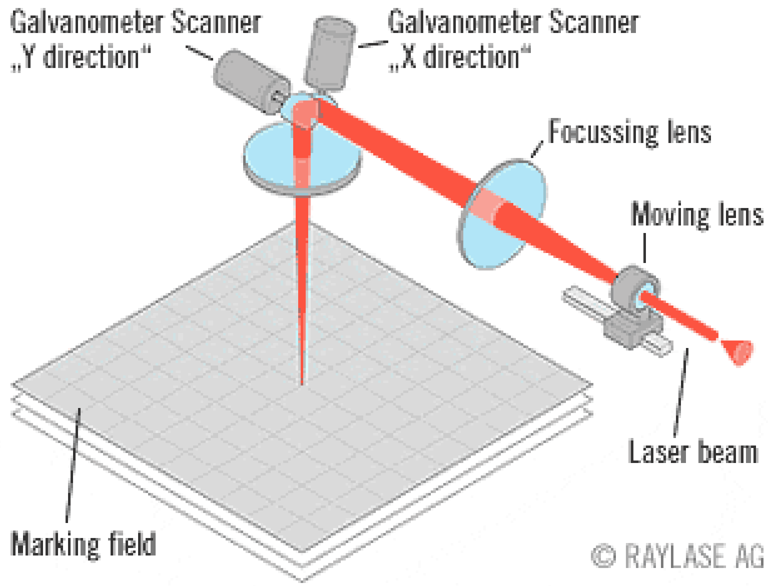




Good results concerning precision and roughness are achieved.
Resolution of at least ¼ of the beam diameter is required.
For a $100\ \mu m$ structure the beam diameter should not be bigger than $15\ \mu m$.

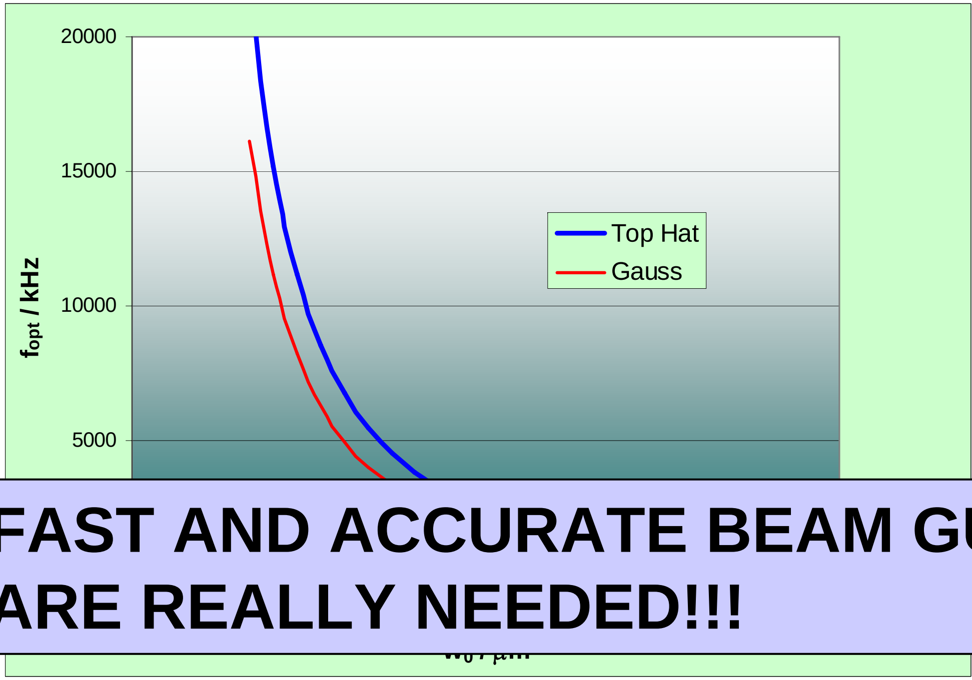
Galvo scanner systems





The scanner axes should be driven closed loop controlled and should be triggered with the laser repetition rate.

What does this mean for an average Power of 50 W



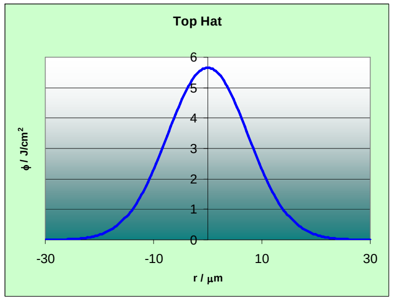
Top Hat:

$$\dot{V}_{\max} = \frac{\delta}{e} \cdot \frac{P_{av}}{\phi_{th}} = 3.4 \frac{mm^3}{\min}$$

Gauss:

$$\dot{V}_{\max} = 2 \cdot \frac{\delta}{e^2} \cdot \frac{P_{av}}{\phi_{th}} = 2.5 \frac{mm^3}{\min}$$

FAST AND ACCURATE BEAM GUIDING SYSTEMS ARE REALLY NEEDED!!!



$$w_0 = 7.5\ \mu m$$

$$f_{opt} \approx 7100\ kHz$$

$$v_{Beam} \approx 110\ \tfrac{m}{s}$$

To achieve a spot diameter of $15\ \mu m$, a scanner optics of $f = 50\ \mu m$ has to be used.

There is absolutely no scanning system on the market which can achieve this speed with a resolution of $3\ \mu m$.

Conclusions

Based on the logarithmic ablation law we can find expressions for the ablated volume as a function of the average power and the repetition rate.

These expressions show that there exist optimum repetition rates (at a given average power) to achieve maximum volume ablation rates.

In the case of ps-laserpulses these optimum frequencies lies in the range of a few MHz for an average power of $50\ W$ and a spot radius of about $10\ \mu m$.
The maximum ablation rates amount several mm^3/min.

There is a great lack of beam guiding systems to really take benefit of these high average powers.

With beam conversion optics the optimum repetition rate can be reduced to several $100\ kHz$.
Beam guiding is still a problem.
Not well suited for 3d micro structuring.

Today, we can not really take benefit of the currently available high average power system, for 3d micro structuring.

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Thank you for your attention

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