Development of NCLR's 1 kW XeCl laser

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ABSTRACT

For several years NCLR is working on a 1 kW, 1kHz XeCl laser. Improvement of the beam quality at high power levels enabled us to do large-scale application experiments and industrial applications become feasible. The base for the good beam quality is a homogeneous discharge. It starts with a smooth gas flow from a classical flow loop. The combination of X-ray pre-ionization and the sophisticated spiker-sustainer circuit guarantees a stable discharge with a long optical pulse (250 ns). Due to the gentle discharge only weak shock waves are formed that are damped within 800 μs. An unstable resonator gives a nearly diffraction limited beam. We are now finding a market for this laser. Hole drilling is one of the most promising applications. We can drill holes of 10 to 100 μm diameter at a very fast production rate of up to 1000 holes per second. The holes can be drilled in many different materials: metals like aluminum, titanium, steel and nickel alloys, but also plastics, ceramics, glass and composites. The good results encouraged us to design a commercial version of the laser.

Keywords: High Power 1kW Excimer XeCl-laser

1. INTRODUCTION

The development from a single shot experiment to an industrial XeCl-laser operating at 1 kHz repetition rate is far from trivial. Reliability and lifetime of components are crucial items for a commercial apparatus. From three aspects of the laser will be discussed how they contribute to reliable operation. These are: 1) the classical flow loop, 2) the X-ray pre-ionization and 3) the spiker-sustainer circuit. Years of engineering gradually lead to the 1 kW operation. The laser is already mature enough to do large-scale application experiments. E.g., in a collaboration with British Aerospace we have drilled millions of 50 μm holes in 1mm thick aluminum. With a Dutch machine building conglomerate, we are doing a research program to explore the possibilities of the excimer laser. Also the American aircraft industries are anxious to learn about the excimer laser. The versatility of the laser is demonstrated with some samples of holes drilled in various materials. Also drilling at very shallow angle is possible.

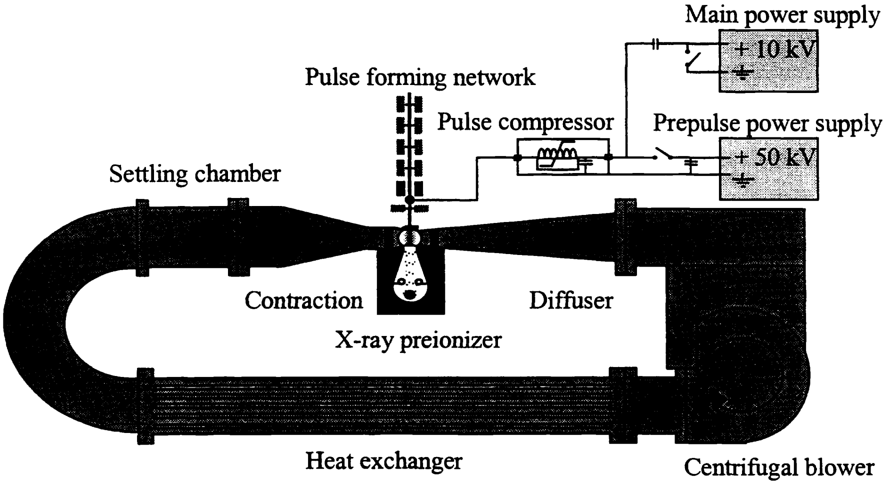

Figure 1: Schematic overview of the laser set-up.

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2. FLOWLOOP

A schematic overview of our laser is given in figure 1. The flow loop is a classical design with wide bends and a centrifugal blower. It is an efficient way to create a laminar flow. Starting from the blower the gas goes first through the heat exchanger. About 70 kW of heat has to be removed as the discharge dissipates maximum 50 kW (to reach 1 kW UV-power with at least 2 % efficiency) and the blower adds another 20 kW to circulate the gas. Provisions were made to install a settling chamber to suppress any turbulence but this appeared to be not necessary. After the contraction section the flow velocity between the electrodes is 70 m/s. The discharge volume is 80 cm length by 3 cm electrode gap by 3 cm width, determined by the X-ray window. A speed of 70 m/s over 3 cm with gives a clearing ratio of 2.3 at 1 kHz. Behind the discharge the diffuser reduces the flow speed and then the gas enters the blower again.

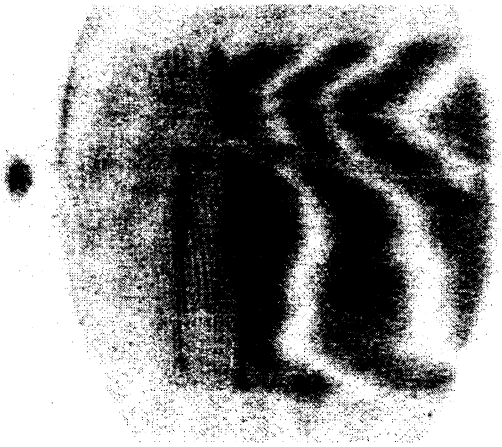

Figure 2: Interferogram of the discharge area

With an interferometer set-up the quality of the gas flow is examined. The interferogram is shown in figure 2. On the left side of the interferogram you see no interference pattern indicating that after the discharge the gas is turbulent. From the right you see fresh and homogeneous gas entering the discharge area. The boundary with the turbulent used gas is very sharp. From the speed of the boundary a gas velocity of 70 m/s is measured. A closer look shows that the gas stays homogeneous during the discharge. Distortion starts about 1μs after the discharge. Even then narrow fringes are still visible at close separation indicating a strong temperature gradient in a non-turbulent gas.

A shock wave bouncing between the electrodes is also visible, see the step in the fringes in the upper half of the interferogram. This shock wave travels with the speed of sound and is damped within 800 μs. In our system we don't need to take special precautions to achieve this damping. Probably the shock waves in our laser are weak because of our smooth and matched discharge (see section 3). Up to 1 kHz the gas homogeneity gives no limitation for the laser performance.

3. X-RAY PREIONISATION

The stability of the gas discharge depends strongly on the start conditions. As discussed before the flow loop guarantees fresh and homogeneous gas with no density variations caused by turbulence or temperature gradients. Besides a homogeneous gas distribution a homogeneous electron distribution is necessary too, to ensure simultaneous breakdown of the discharge along the whole length of the laser (80 cm). This homogeneous electron distribution is applied by a pre-ionization pulse. Usually this pre-ionization is done by a UV-pulse. In our system is chosen for X-ray pre-ionization, because this has several advantages.

UV is produced by small sparks near the electrodes of the laser. These sparks give distortion of the gas flow and of the electrical field distribution between the electrodes. X-rays are generated in an external source and the radiation enters the discharge volume trough a window in a solid and smooth electrode. Therefore the gas flow and the electric field are not disturbed.

X-rays penetrate deep into the laser gas and give a homogeneous pre-ionization. UV is strongly absorbed and near the sparks the pre-ionization is much stronger then at the opposite electrode.

The spark plugs for UV-pre-ionization erode and contaminate the laser gas. This hampers the chemistry in the discharge and the output energy will be lower. The dust that is formed destroys the laser mirrors. The external X-ray source gives zero pollution to the laser gas and increases the lifetime of the gas.

The X-rays come from an external source and penetrate trough a window. This gives a well-collimated X-ray beam that pre-ionizes only the discharge area. The width of the discharge is determined by the X-ray window and depends less on the exact geometry of the electrical field distribution. With UV-pre-ionization the whole volume between the electrodes is pre-ionized and the width of the discharge is very sensitive to the shape of the electrodes and the applied voltage.

At the end of the lifetime of the spark plugs, the entire laser vessel has to be opened to change them. The cathode in the X-ray source can be changed very quickly without opening the laser vessel.

A drawback for X-ray is that the X-ray source is more complex then a spark plug.

The disadvantage of X-ray pre-ionization is the bad name of X-ray radiation. However with only a few mm of lead the entire radiation is shielded with no hazard for people or environment.

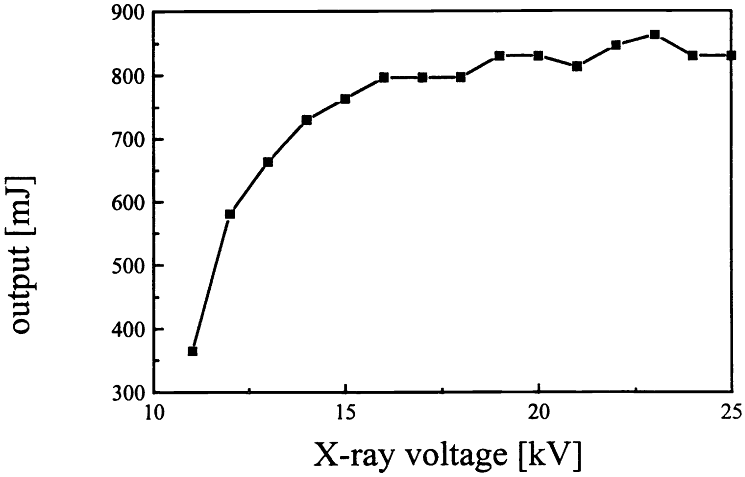

Figure 3: Laser output as function of the X-ray voltage

The current in the X-ray source is space charge limited, so the yield of X-rays is proportional with the voltage to the power 7/2. In figure 3 it is shown that the laser output saturates above 16 kV. The actual X-ray anode voltage is transformed up 7 times, so the X-ray photon energy will be maximum 112 keV at this power supply voltage. Below 16 kV the discharge is filamentary because of insufficient pre-ionization. Once you have sufficient overlap of individual electron avalanches you can not gain output by applying more pre-ionization.

4. SPIKER-SUSTAINER CIRCUIT

A characteristic of a steady burning gas discharge is a constant voltage across the electrodes independent of the current. However, at the high pressure (5 bar) and the high current (40 kA) needed for laser operation the discharge is unstable. Therefore a gas discharge excimer laser can be operated pulsed only. (At low power also RF-pumped CW excimer lasers exist.) A capacitor has to be charged to twice the steady state voltage of the gas discharge to match the gas discharge. In that case the capacitor discharges completely in one single current pulse without ringing. On the other hand, for the breakdown of the gas a much higher voltage is needed, typically 4 to 6 times the steady state voltage.

With a simple circuit consisting of a capacitor coupled with a switch and some unavoidable self-inductance to the laser electrodes these two demands can never be fulfilled simultaneously. Either the voltage on the capacitor is too low, resulting in a poor breakdown of the gas, or the voltage is too high, resulting in ringing of the current. Nevertheless, commercial excimer lasers use such a simple circuit. The discharge is very unstable, the beam quality is poor and the optical pulse duration of such laser is typically 20 ns.

In our laser we use a spiker-sustainer circuit as indicated in figure 4. The spiker gives a high voltage with a very fast rise time for homogeneous breakdown of the laser gas. Then the sustainer delivers energy under matched conditions to sustain the discharge. With this circuit we obtain a long optical pulse duration of 250 ns.

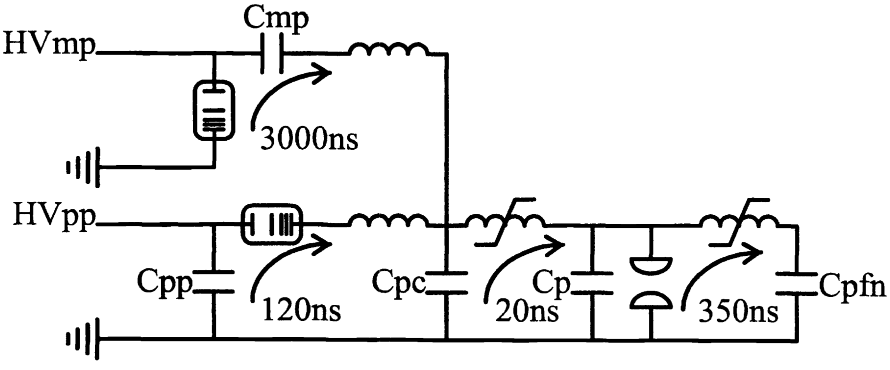

Figure 4: Spiker-sustainer circuit

The trick with the spiker-sustainer circuit is that charge is relative slowly transferred from storage capacitors Cmp en Cpp to capacitors close to the laser head. This gives a low load on the thyratrons, the active high voltage switches, and this guarantees a long lifetime of these thyratrons. The capacitors close to the laser, Cp and Cpfn are special low inductance capacitors to enable a fast current rise time through the discharge. The spiker and the sustainer voltages are separated by passive magnetic switches. The circuit works as follows: In 3 μs the charge from the storage capacitor Cmp is transferred to the pulse forming network Cpfn, close to the laser head. Then the spiker thyratron fires and the charge from the storage capacitor Cpp is transferred to the intermediate capacitor Cpc of the pulse compressor. When the ferrites of the saturable inductor in the pulse compressor saturate, the charge transfer form Cpc to the peaking capacitors Cp at the laser electrodes is 6 times faster then the charge transfer from Cpp to Cpc. Between Cpfn and Cp ferrites are placed in a racetrack geometry. When this saturable inductor saturates a current from Cpfn (640nf) to Cp (3.2nf) rings up the voltage on Cp to a high voltage at which the breakdown of the laser occurs. Then the current continues through the laser and in a single pulse of 350 ns the pulse forming network discharges. As shown in figure 5, the optical pulse follows the current pulse (after a built up time) till the end of the current pulse. This indicates that the discharge is stable till the end of the pulse

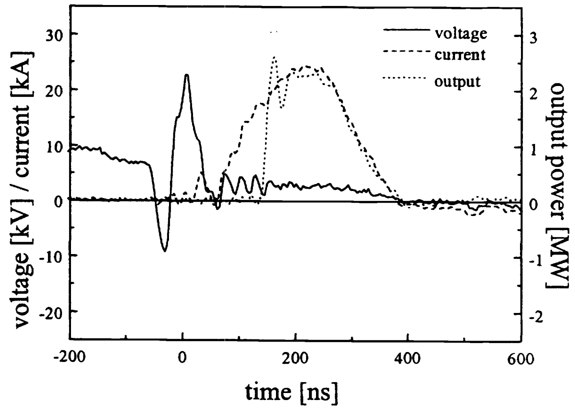

Figure 5: Typical waveforms

5. BEAM QUALITY

For high power lasers the beam quality is very important because it determines to what extent the power can really be used. The homogeneous discharge with the long pulse duration in combination with an unstable resonator gives an excellent beam quality of 1.3 times the diffraction limit. This achievement is so important that a separate contribution to this conference is dedicated to this subject. See: "On the optical quality of NCLR's 1 kW, 1 kHz XeCl excimer laser" by Ramon Hofstra.

6. APPLICATIONS

In the early days of the XeCl laser lithography was thought to be the most important application. However this market has passed the XeCl laser (308 nm) and has directly moved on to the KrF laser (248 nm) and the ArF laser (193 nm) and will maybe go to the F_2 (157 nm) laser. However in the race to shorter wavelengths the high power XeCl laser can come back for the production of soft X-rays (13 nm). This radiation can be produced by a laser induced plasma on a target like e.g. Tungsten. A big problem with solid targets is the contamination of the focussing lens by particles. This problem can be solved by using other targets, e.g. Xenon clusters or water droplets.

Another application in the semiconductor industry is the annealing of flat panel displays. The top layer a silicon wafer can be transformed from amorphous to (poly-)crystalline with high intensity excimer radiation.

But semiconductors is not the only market. Lasers are well established in material processing. For example the CO_2 laser is widely used for cutting or welding metals. The YAG-laser is gaining market because of its shorter wavelength and therefore more precise cut.

The excimer is the logical successor since with an even shorter wavelength finer structures can be made. Also the higher photon energy is beneficial especially for cutting or drilling plastics. The 1 kW XeCl laser enters a completely new region of material processing. From figure 6 can be seen that the laser is very suitable for micro machining, like drilling small holes, and for shock hardening. With hole drilling we have some experience that will be explained in the next sections. For shock hardening we must still explore the possibilities. The region of the laser possibilities extents the scope of the figure with known applications. We expect that some completely new applications will become possible with this laser.

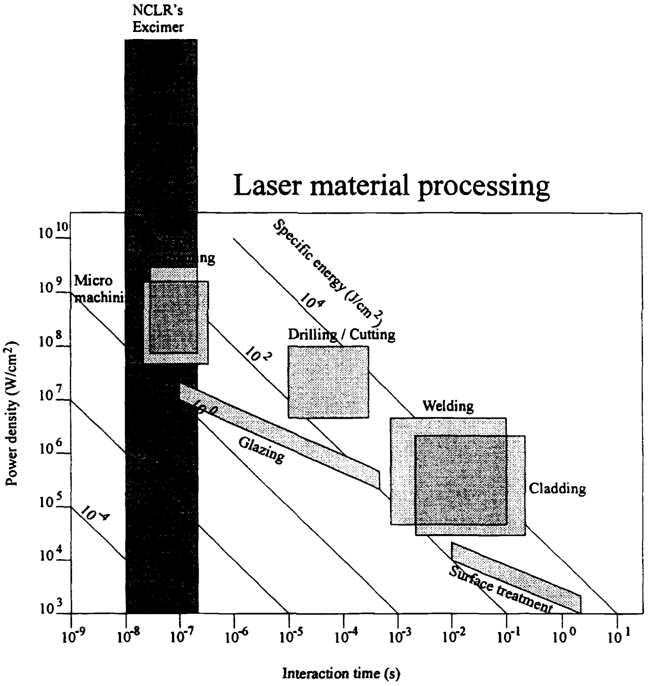

Figure 6: Interactions of laser with material

In this paper we focus on hole-drilling. For example, in airplane wings many millions of small holes can be used for boundary layer suction. With this technique the amount of turbulence at and behind the wing can be reduced, witch leads to enormous fuel savings. The holes must be small, about 50 µm, or they will create turbulence instead of reducing it. With a few million holes per square meter a porous surface is made. An inward directed flow pulls the boundary layer of the airflow towards the surface.

Another aircraft application is drilling holes in liners and turbine blades in the engines. Through these holes cooling air can be flown to protect the components for the heat in the engine.

Another application of holes is the production of sieves. For sieves the holes must have smooth walls and a certain tapering. Once a particle has gone through the smallest diameter at the entrance of the sieve, it must have a free way to exit the sieve, or the sieve will be clogged up.

Small and precise holes are needed as nozzles for various applications. In inkjet printers the size and shape of the hole is very important for a good dosage of the ink. The same applies for the fuel injectors in diesel engines.

7. PARALLEL DRILLING

The size of the laser beam is 30 x 30 mm^2 and the energy per pulse is 1 J. If this energy is focussed in one spot you will get a big and terrible hole as 1 J is far too much energy. The nicest way to drill holes is percussion drilling with 0.5 to 5 mJ energy per pulse and several pulses to drill through. The energy per pulse determines the size of the hole. The number of shots is dependent on the kind of material and the material thickness. For Aluminum about 20 shots per mm thickness are needed, for Titanium or steel about 120 shot per mm are needed. Quartz or ceramics require several 100's of shots. To be able to use the energy of the laser efficiently, the laser beam must be split in many separate foci. There are two ways to do this, with a lens array or with a holographic beam splitter.

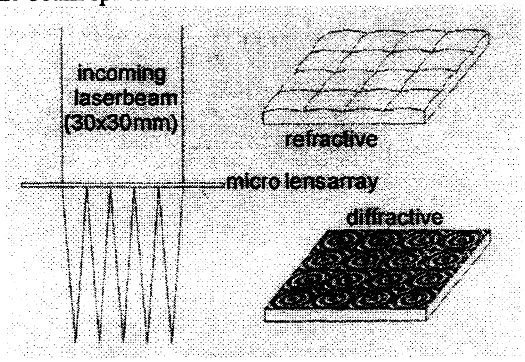

Figure 7: Multiple foci with a lens array

The lens array consists of a plate with an array of small lenses as shown in figure 7. Each lens takes a small part out of the beam and makes a focus. The lenses can be stacked orthogonal or hexagonal. With the square orthogonal configuration it is easy to step to the next block. The hexagonal configuration gives a better filling of the surface. It is best to have circular lenses because these give the best focus. A square lens gives a cross-shaped focus with a large fraction of the energy in unwanted side lobes. The lenses can be made in two configurations. Curved surfaces can form a classic refractive lens. A diffractive lens consists of circular steps to make phase shifts leading to a focus.

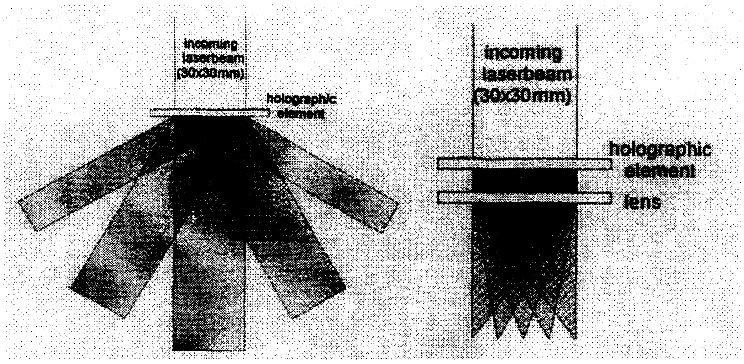

Figure 8: Multiple foci with a holographic beam splitter

The second way to split the beam is with a holographic element. Like in the diffractive lens array a phase distribution can be made that results in multiple beams exiting the hologram at certain angles as shown in figure 8. A simple lens focuses these beams in multiple foci. It is not easy to design the phase distribution because a simple algorithm does not exist. The phase distribution has to be designed in an iteration process. Then the next problem is the fabrication of the hologram with its very fine structures. The big advantage of a holographic beam splitter is that every sub-beam is an image of the whole incoming beam. Therefore every sub-beam has the same energy and will drill a hole of equal size. With the lens array the lenses at the edge are likely to have somewhat less energy resulting in smaller holes and some losses occur because the beam has to be masked to match the discrete number of lenses. With the holographic beam splitter the exact shape of the beam and the falling energy at the edges are irrelevant, as long as the phase profile of the beam is flat and the intensity gradients are not too big.

The drilling rate can be very large. E.g., to drill 50 μm holes in 1 mm thick aluminum we need 20 shots with 5 mJ of energy. With a laser power of 1J per pulse and 1 kHz repetition rate we can, in principle, do 200 holes in parallel and 50 sessions per second resulting in 10,000 holes per second. In practice we have to deal with the fill factor of the lens array or the efficiency of the holographic beam splitter, losses in the optics and time to move the work piece. In practice at least 1,000 holes per second is achievable.

8. EXAMPLES OF SEVERAL MATERIALS

To show the versatility of the laser some examples of holes in several materials are given. Figure 9 gives a view of a large area filled with 50 μm holes at 500 μm spacing in stainless steel. The plate is 200μm thick. This plate is drilled with the use of a lens array.

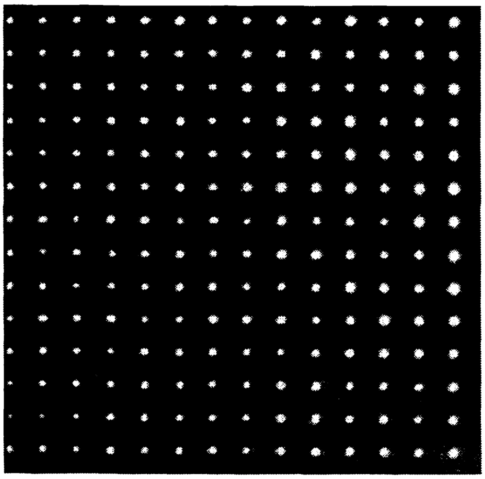

Figure 9: Array of holes drilled in stainless steel

Aluminum is very easy to drill holes in, probably because of the low melting point. It takes about 20 shots to drill trough a 1 mm plate. Other metals like Titanium, Nickel or stainless steel all take about 120 shots to drill 1 mm thickness. Also other materials can be drilled. For plastics it is important to have sufficient absorption. Clear PVC is hard to drill. Kapton (polyamide) is a yellow plastic in witch very nice holes can be drilled. In figure 10 a hole in alumina is shown. A row of holes is drilled and afterwards the ceramic plate is broken along the perforated line. We tried the same in quartz. This should be impossible since quartz is transparent for 308 nm radiation. Nevertheless figure 11 shows a nice hole. Only at the top the quartz plate didn't break in the plane of the holes.

Figure 10: Hole drilled in 1 mm Al_2O_3,
entrance 275 μm, exit 100μm,
pulse energy 75 mJ, 500 pulses,

Figure 11: Hole drilled in 1 mm quartz
entrance 145 μm, exit 50 μm
pulse energy 3.5 mJ, 120 pulses

Next we tried to drill under an angle. In figure 12 you see a hole in Al_2O_3 under 45 degrees. In figure 13 a hole is drilled under 15 degrees with the surface. Both holes are in 1 mm Al_2O_3 plate. A line of holes was drilled and the plate was broken along that line. Drilling under an angle gives no problems with reflection of the beam. Apparently the short wavelength gives a good incoupling of the beam. The number of shots needed to drill though is proportional to the effective thickness that increases with the reciprocal sine of the angle. Especially in figure 13 you can see that the sharp edges are well conserved.

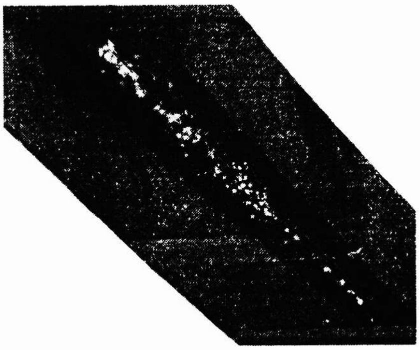

Figure 12: Hole in Al_2O_3 at 45 degrees

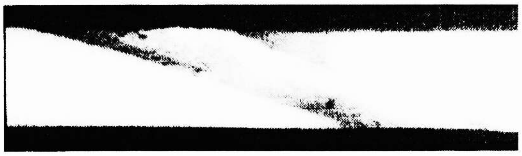

Figure 13: Hole in Al_2O_3 at 15 degrees

9. CONCLUSION

We have a highly sophisticated, unique and versatile piece of equipment. The laser enters a new region of output power at short wavelength with unexplored possibilities. Especially hole drilling is an important application. Almost every material can be drilled successfully but a research program is needed for every material to find the right parameters. Many holes can be drilled in parallel at very high production speed. The perforation of airplane wings for boundary layer suction can be done on a practical time scale with the high average power of 1 kW, but it will still take days. The market looks promising for a 1 kW excimer laser, so we are designing now an industrial version. In the summer of next year we hope to have this laser ready for tests in an industrial environment.