THE STORY
OF THE WATER JET GUIDED LASER

Who would have thought that the fusion of light and water would result in a new machining technology capable of cutting through the hardest of materials at highest precision and quality? This is the amazing story of how Bernold Richerzhagen, Synova's founder, demonstrated the feasibility of such a concept for the first time in history in a Swiss laboratory in 1993. It is an invention that had revolutionized laser machining in the aviation, diamond and semi-conductor industries

Bernold Richerzhagen had a vision of how combining features from water jet and laser to cut materials. After years of research, he invented a hybrid method of machining. Patented in 1994, the LMJ MicroJet® (LMJ) technology combines a laser with a low-pressure hair-thin water jet that guides the laser beam by means of total internal reflection in a manner like a conventional optical fiber.

Richerzhagen's technology differs fundamentally from either high-pressure water jet cutting or conventional laser machining. The low water pressure is insufficient to cut through the material. Instead, it is the laser energy that melts and vaporizes it. The guiding of laser in a water jet results in simultaneous cooling with virtually no resulting heat damage to the material.

It is of historical interest that Richerzhagen got inspiration for his invention from a light and water experiment conducted almost two centuries ago.

First Light and Water Jet Combination

This experiment, which took place 180 years ago, demonstrated the first example of "fusion" between light and water.

Professor Daniel Colladon, at Geneva University, entertained lecture halls with an optical phenomenon known as 'light guiding' based on total internal reflection. He demonstrated one such model at the Observatory of Arts and Sciences of Paris in October **1841**.

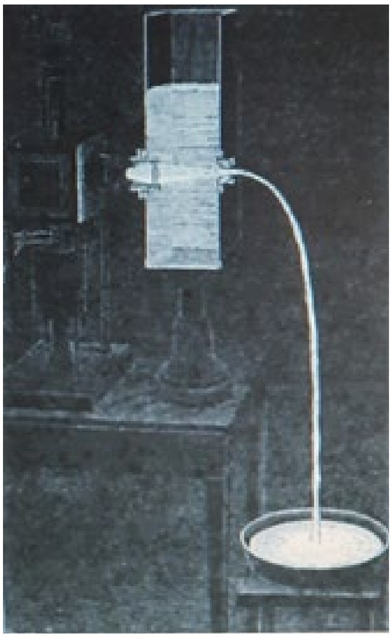

Fig. 1: Colladon's water fountain with light coupled into and guided by the laminar flow of water

Colladon's model used an electric arc light as a light source. A lens focused the light through the water tank and along a jet squirting out a hole in the other side. When the light rays in the water glanced the edge of the jet at a certain angle, total internal reflection trapped them in the liquid. The rays bounced along the curving arc of the water jet until it splashed in a collection pan. In effect, the light followed the curve of the water.

The first application of this invention was to illuminate water fountains, such as during the World Exposition in **1889** in Paris:

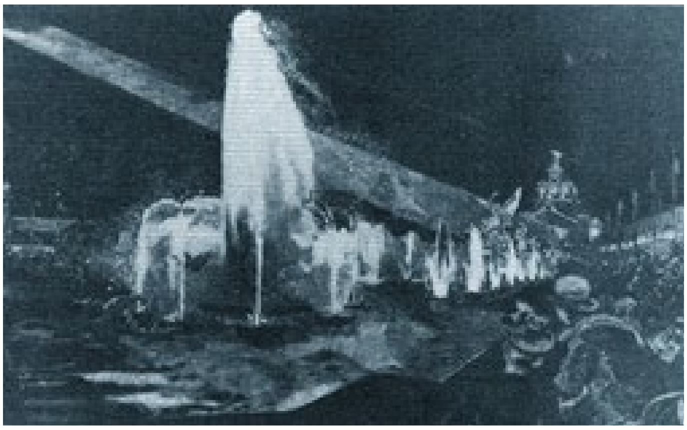

Fig. 2: Illuminated water fountain at 1889 Paris World Exposition

Of course, the same effect of light guiding happens in an optical fiber. Thus, Colladon is also known as the "father" of the optical fiber.

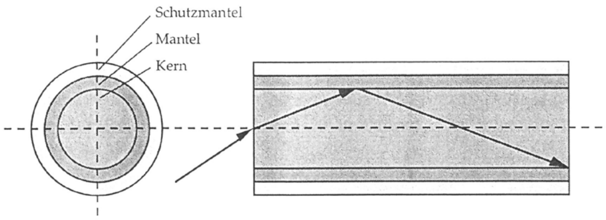

Fig. 3: Total reflection of light in an optical fiber

Richerzhagen visualized a modified form of an optical transmission system. Instead of white light, he would use a laser beam in a water jet similar to Colladon's experiments, but much smaller and at higher pressure.

Attempts at Combining Laser and Water Jet

In the 1980s attempts were made to combine both technologies, laser and water jet, in one hybrid process.

The only known patent application at this time is from Aesculap, Germany **(DE 3643284 December 1986)**. It described a set up to couple a laser beam in a water jet for medical applications by creating a water jet directly around a laser fiber tip.

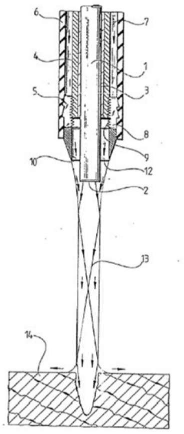

Fig. 4: Aesculap patent design

This design has a major disadvantage: the water pressure and flow rate must be kept very low or otherwise the jet gets immediately turbulent. Therefore, it is not applicable for industrial applications.

ETA (Switzerland) tried to couple a laser beam into a conventional water jet nozzle but quickly damaged the nozzles and they gave the concept. Trumpf (Germany) made some theoretical estimates and concluded that a combination of water jet and laser would be energetically inefficient.

None of these attempts were successful. Not a single product was developed. There was no commercial version of a water jet guided laser on the market.

Laser-cooled Dental Hand Tool

Richerzhagen found the incentive for developing a water guided laser from an unlikely source. The Centre d'Application Laser (later renamed Institut d'Optique Appliquée) received funding for a laser project for dental applications.

After getting his master's in mechanical engineering from RWTH Aachen, Richerzhagen started work on this project while studying for his PhD degree. His task was to develop a laser energy transmission system for dental applications (removal of carious).

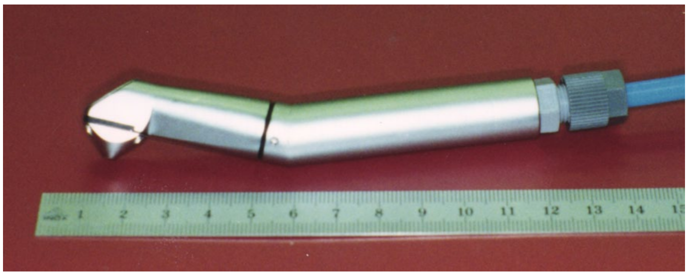

Fig. 5: Dental hand tool with water jet guided laser

Richerzhagen considered two options to cool the tooth during laser drilling. One was with a water spray. The other with a water jet, in which the laser is guided by total reflection. Although Colladon discovered this phenomenon 180 years ago, it had never been implemented with a laser for machining.

Richerzhagen decided to pursue this solution because there were immense advantages in a water jet guided laser: parallel laser beam, long focus and very efficient cooling so that thermal damages can be avoided (the nerf in the tooth is very sensitive to temperature changes).

The lasers available for the tests in the EPFL laser lab were first a dye laser emitting at 635 nm and subsequently an infrared YAG laser at 1064 nm.

Richerzhagen constructed his first prototype to couple a laser beam with a water jet. It consisted of the following components:

- Pulsed laser (dye liquid laser, later YAG infrared laser)
- Water pump (10 bar)
- Water chamber with de-ionized water
- High pressure water jet nozzle (100 microns diameter)

Richerzhagen's set up was based on the well-known theory of quasi-stationary flow of water to achieve a stable and laminar flow in a free water jet. This enabled a constant, homogeneous acceleration of the water from the chamber until it passes through the nozzle. A window was placed to close the water chamber but allow the laser beam to pass through the water.

The basic difference from the Aesculap set up was to (a) separate the optics and the water jet coupling and (b) use high quality nozzles to generate a stable water jet. The laser was focused through a window in a water chamber onto a water jet nozzle and coupled into the water jet that was ejected from the nozzle.

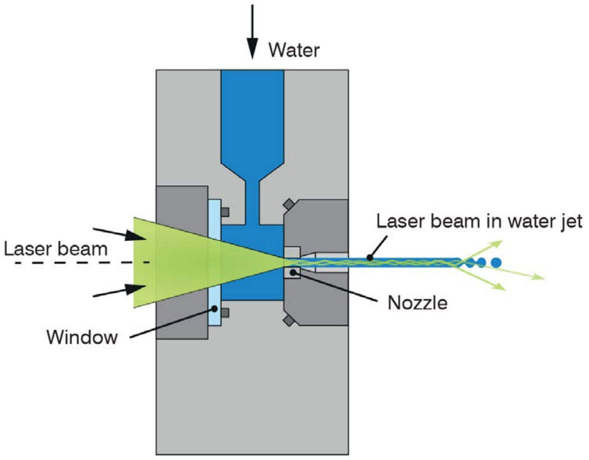

Fig. 6: Coupling unit model

Richerzhagen's coupling unit had mixed results. Though his calculations and simulations showed that all light should pass through the nozzle, the nozzles failed quickly. In effect, this set up was resulting in damaged nozzles as was the case with the ETA set up.

While working on his PhD project, Richerzhagen had prepared a patent application (FR 2 676 913, May 1991) in the name of LASAG (part of Swatch group that had co-financed the EPFL lab). This application described a water jet guided system based on the above concept of having a large chamber for quasi-stationary flow of water.

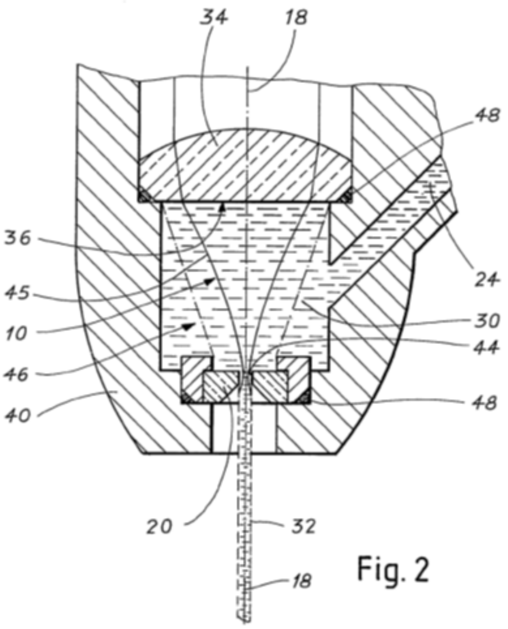

Fig. 7: Schematic of water jet guided system with large water chamber

Thermal Defocusing Effect

Richerzhagen was now focused on why nozzles were getting damaged. Two years of intensive research from 1992 till 1993 led to important scientific discoveries.

Richerzhagen's approach lay in designing a series of experiments to understand why the laser beam was not getting properly focused in the nozzle. The objective of his first experiment was to study what takes place when a transparent chamber containing water absorbs energy from a laser pulse.

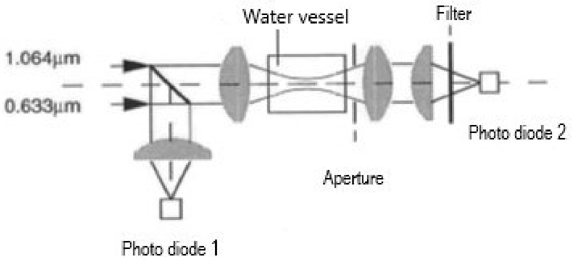

Fig. 8: Set-up to measure intensities of 2 laser beams passing through water:

Richerzhagen's experiment used two laser sources: a ND: YAG laser (1064nm, 200 microseconds pulse width) and a continuous low-power Helium-Neon laser (633nm). Photo diode 1 measured the signal amplitude of the YAG laser.

Both beams passed through an achromat lens designed to bring the two wave lengths to the same focal point in the water. After leaving the water, the two beams passed through an aperture, lenses and a filter that only allowed the Helium-Neon laser beam to pass through to photo diode 2.

Studying the signals from the two photo diodes on a digital oscilloscope, Richerzhagen made an interesting observation. During and after the 200 microsecond ND: YAG laser pulse, the helium-neon signal registered a loss in intensity.

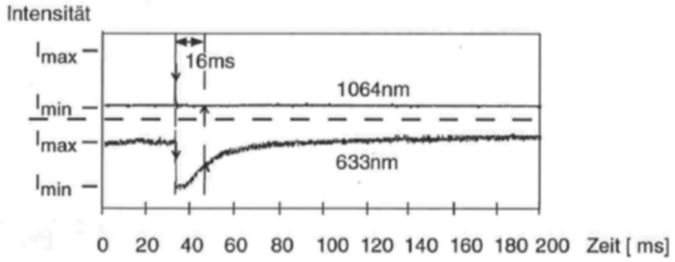

Fig. 9: He-Ne laser signal loss due to water absorbing ND: YAG laser pulse energy

Richerzhagen finally found a physical explanation for this occurrence. During each pulse, the water absorbs a small part of the laser energy. This energy is converted to heat. Due to the temperature increase in water, the refractive index also changes.

This generates a so-called 'negative lens'. A certain time after the laser pulse, the water cools down due to heat exchange processes such as heat conduction and convection. As a result, the refractive index rises again to its original level. The thermal-induced lens loses its effect. This phenomenon is known as thermal blooming or thermal defocusing.

During the 200 microseconds laser pulse, the water in the chamber between the window and nozzle (5 mm) was practically still. There were water speeds sufficient for convection during the pulse duration only in the zone over the nozzle hole and in the nozzle itself.

The observation of increase in the transmission losses of the coupling system with increasing pulse energy led to the hypothesis that thermal defocusing caused the coupling problems mentioned. This defocusing caused the beam to widen and the position of the focal point to shift.

Thus, a significant part of the energy was outside the theoretical focal point. This energy struck the front surface of the nozzle and damaged it. This process took place during the laser pulse and clear traces of the laser radiation were found on the damaged nozzles.

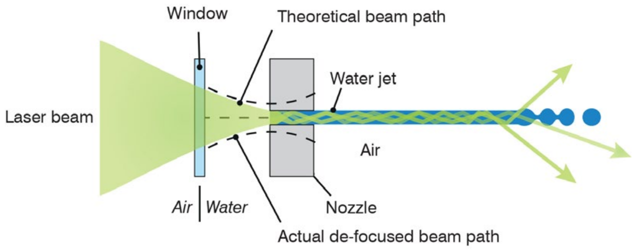

Fig. 10: Theoretical versus actual defocused beam path

Study and Correction of Thermal De-focusing

After establishing the impact of increase in water temperature on the intensity of a laser signal, Richerzhagen's next task was to measure the changes in the laser beam profile as it passed through the water.

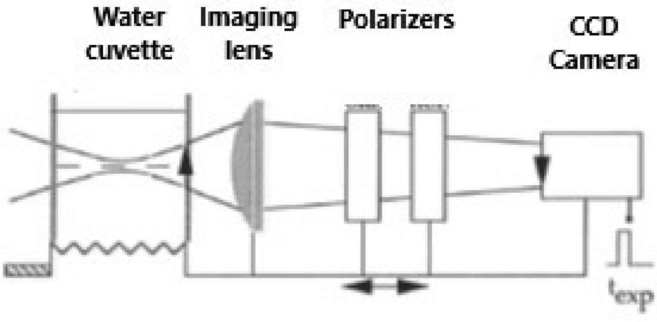

Fig. 11: Set-up to measure beam waist as a function of position and time during a laser pulse

In this experimental set-up, Richerzhagen used a pulsed laser source with a pulse duration of 200 micro-seconds. The laser beam was focused in a water vessel with two glass windows. The output window could be moved axially so that the focal point of the beam was always on this window.

Imaging optics magnified the beam and two polarizers served to reduce the laser power without distorting the intensity profile. The camera had adjustable shutter speeds down to 1 micro-second and the imaging optics enabled a resolution of 2.2 microns.

Richerzhagen automated the entire set-up. He only had to enter the values for the time increment steps and shutter opening time into a PC. The measurement took place in several stages. After setting the shutter opening time, the camera recorded the first 10 frames at 10 different axial positions at the start of the 200 micro-second laser pulse.

He repeated the measurements at different shutter opening times until he reached the end of the laser pulse. Image processing software was used to display the laser beam profile for every time increment from the start till the end of the pulse.

The below images show the measuring results for a time frame from the beginning of the laser pulse (Fig. 12a) and at the end of the laser pulse (Fig. 12b).

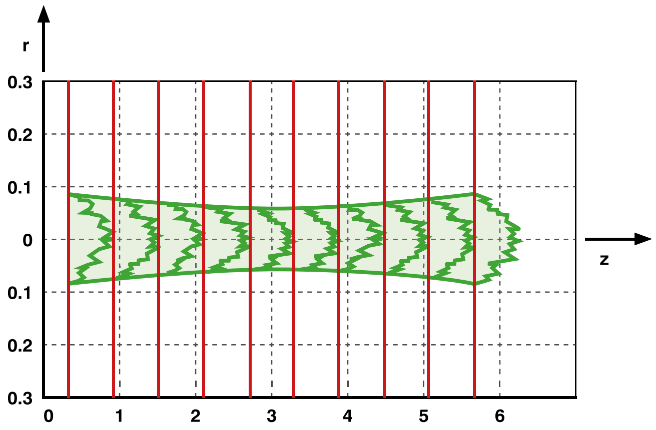

Fig. 12a: Beam waist at t = 0 microseconds

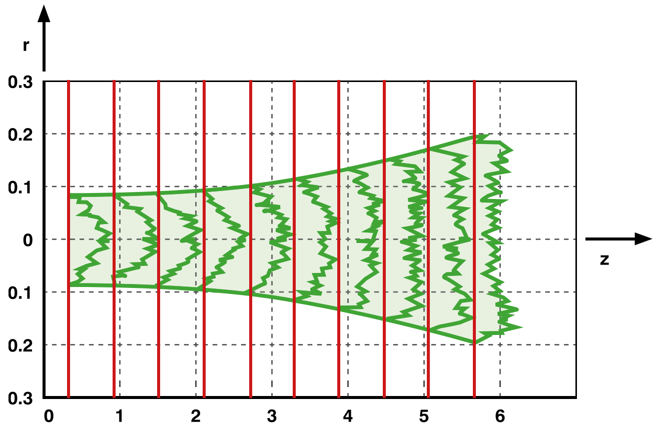

Fig. 12b: Beam waist at t = 200 microseconds

The waist diameter which is less than 0.2 millimeters at the start of the pulse doubles to 0.4 millimeters towards the end of the laser pulse.

Having established experimentally the reason why nozzles were getting damaged, Richerzhagen's research took a new direction in order to confirm his theory theoretically, meaning by mathematical calculations.

First, it was important to know the refractive index in function of the temperature. Seeing that previous measurements on the refractive index of water as a function of temperature were not precise enough at 1064 nm, he decided upon an experimental set-up to obtain accurate data that would enable a comparison with a numerical simulation of this phenomenon.

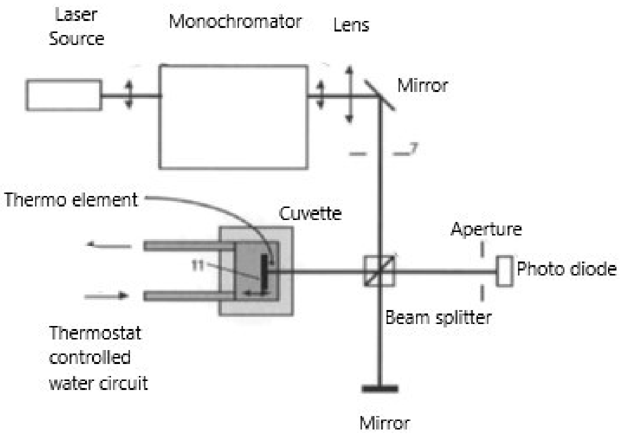

Fig. 13: Modified Michelson interferometer set-up to measure refractive index change as function of water temperature

Richerzhagen designed a set-up based on a Michelson Interferometer, a configuration used for optical interferometry. Using a beam splitter, a light source is split into two arms. Each of these beams is then reflected to the splitter which combines their amplitudes and transmits to a photo diode. The two beams are superposed, and they show an interference in function of the phase of the two waves (the two beams).

The resulting wave can be zero (half wavelength) or doubled (1 wavelength) or in between. One arm of the splitter was connected to a mirror placed in a glass vessel or cuvette. The refractive index was calculated by moving the mirror a precise distance and measuring the interference signal at the photo diode.

The measurements were carried out in a controlled laboratory environment. The laser source was coupled to a monochromator, a device designed to ensure that the laser wavelength and intensity were within a very tight wavelength spectrum to assure a strong interference effect.

The lenses and aperture corrected any astigmatism caused by the monochromator. The glass vessel was thermally insulated, so that the water temperature remains constant during the one-minute measuring process. An external circuit keeps the water heated.

The measurement cycle was long. After heating the water in the glass vessel to a specific temperature, there was an hour wait for the water temperature to stabilize. The measuring process consisted of moving the mirror in the water a specific length and measuring the interference signal. Measurements were carried out for water temperatures from 20°C to 60°C to record the refractive index for each temperature.

The results were significant enough to be published in the journal Applied Physics in 1996 and to become part of the "Handbook of Chemistry and Physics."

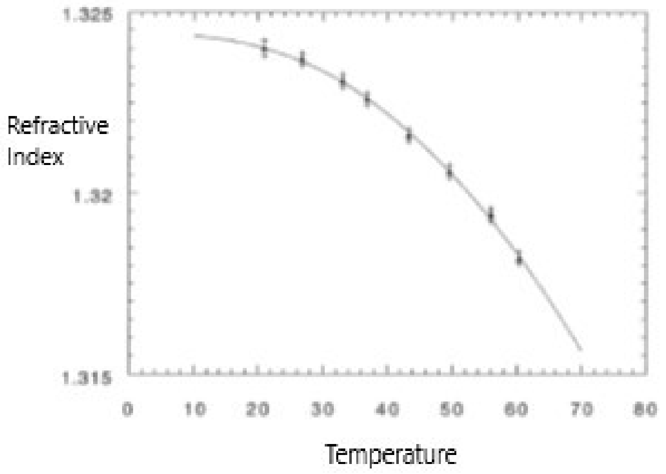

Fig. 14: Change in refractive index as a function of water temperature

Having found the most accurate method of establishing the relationship between the refractive index and the water temperature, Richerzhagen went a step further. He decided to confirm the hypothesis of thermal defocusing and reproduce his experimental measurements of beam profiles under thermal defocusing through **numerical simulation**. In the process, he metamorphosed from engineer to scientist.

Richerzhagen's methodology was based on combining something known as **Finite Element** analysis with **Raytracing process**. In a simplified form, his simulation was based on a laser beam passing through a grid of finite elements and its path being influenced by different refractive indices.

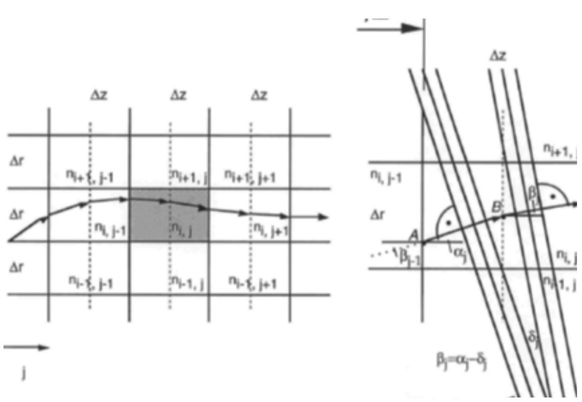

Fig. 15: Principle of Richerzhagen's Finite-Element-Raytracing Method

The above graphic on the left shows the calculated beam path in a magnified matrix grid of finite elements. The above graphic on the right shows the changes in the ray path at the entrance "A" of an element (applying the Snell law, at passing from one element to the axial neighbor element), in the center of the element "B" (tilting of the wave fronts due to the difference in refractive index of the two radial neighbor elements). The deviation at point "C" is again calculated like point "A". Based on the above numerical calculations, that have been proven in mathematical calculable models such as gradient index fibers, the graphics below show the simulated beam profiles.

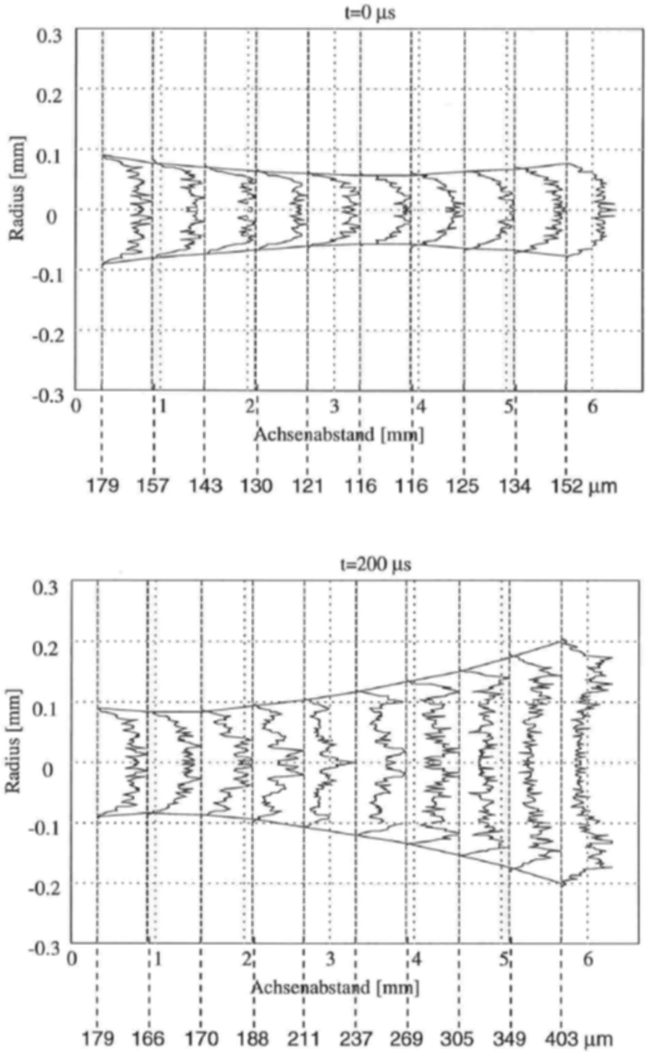

Fig. 16: Simulated beam profiles at t = 0 microseconds and t = 200 microseconds

Richerzhagen's theoretical simulation results were extremely close to those obtained in his earlier practical experiments, without any fitting factor. The findings were significant enough to be published in the journal 'Applied Physics' (1996) and in the journal 'Optical Engineering' (1996).

The agreement between measurement and theory enabled Richerzhagen to make reliable theoretical predictions of the thermal defocusing effect. Eventually, the results of this work led to a modification of the coupling system that avoided transmission losses. He had developed a coupling unit that did not damage nozzles.

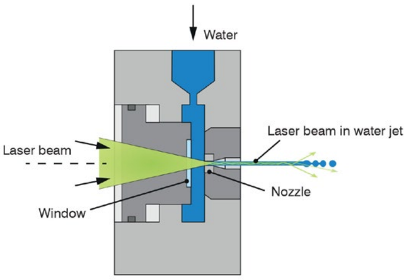

Fig. 17a: Modified coupling unit schematic

Fig. 17b: Coupling unit

The above improved coupling unit design was the first system to guide a high-power laser beam in a water jet to ablate material. Even high coupling energies of up to two joules per pulse did not damage the nozzle. The overall efficiency remained constant at 87%.

With these works Richerzhagen had demonstrated the feasibility of a water jet guided laser capable of ablating material for the first time in history in 1993.

Based on his coupling unit concept, Richerzhagen designed a water jet guided hand tool for dental applications.

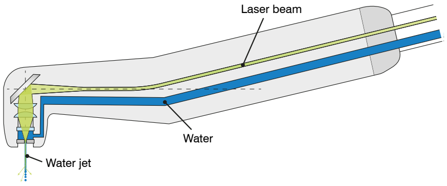

Fig. 18: Schematic of water-cooled dental tool

The initial employment of this new process and hand piece in dental medicine has shown its superiority in many ways. For one thing, the laser energy for the ablation is available at more than 4 centimeters.

For another, there is a constant cooling of the tissue with the water jet. As a result, the dentist has a greater working distance between the hand piece and the tooth which allowed him to make deeper cavities in the tooth.

The successful execution of the dental laser hand tool project provided the basis for Richerzhagen to complete his doctoral thesis by May 1994.

The Industrialisation of Water Jet Guided Laser: SYNOVA S.A.

Richerzhagen had the advantage of being a scientist as well as an engineer. As a result, many of his patents were based on theoretical simulations backed by practical working prototypes. Starting from the developed laser hand tool and coupling unit concept, he started designing a processing machine that employed the concept of the water jet coupled laser.

He recognized the advantages of the water jet guided laser for material processing:

- No Material Damages (no HAZ – Heat Affected Zone)
- No burrs
- Very Large Thickness Range
- Tight, parallel kerfs (>25 μm) - meaning no taper
- High Cutting Speed - Low J/mm3
- Wide Range of Materials

Richerzhagen wrote his first own patent in German on water jet guided laser technology in 1994 when he was still employed at the EPFL. The water jet guided laser patent (called "Stauraumfrei") was registered in 1995 as European application (EP7629481).

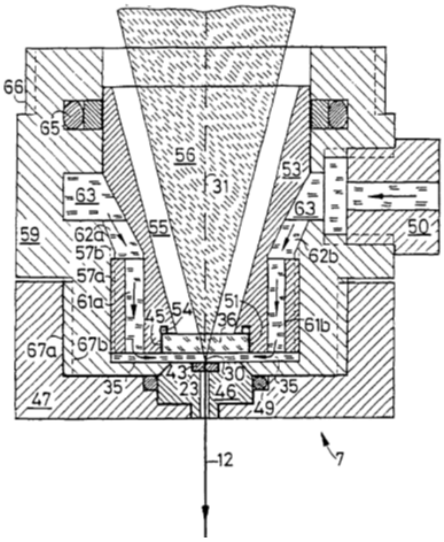

Fig. 19: Schematic of coupling unit in patent application

Richerzhagen developed a first machine tool based on his invention in his first company, an engineering office, between **1995** and **1996**, in the Science Parc of the EPFL.

Fig. 20: Machine 001

Richerzhagen won several Swiss and international awards for his pioneering inventions. He founded Synova SA in May 1997 to commercialize his technology.

Synova received its first order for a water jet guided laser machine (called JPS 1000) in 1998. This machine was delivered in 1999.

Later, Synova moved from near infrared to green wavelength because of higher absorption in some specific materials such as Diamond, Copper, Ceramics or Sapphire and because of lower absorption in water meaning less energy losses in the water jet. However, the fundamental relations are still valid and building a very thin, disc-type water chamber to control the thermal effects is still today the condition for a successful coupling of any laser in liquid jets.

Today's water jet laser systems

Synova's team has constantly researched, improved, and optimized and industrialized its machines, systems, and solutions. As far as industrial applications are concerned, Synova's R&D and Engineering teams are innovating in three areas:

While holding the same tight tolerances as in the smaller machines, a new generation of mechanical platforms is bigger and more rugged. For example, the 5-axis XLS laser cutting system has a 1000 x 1000 x 750 mm workspace.

Fig. 21: Richerzhagen next to LCS 305 designed to machine milling cutters and turbine blades

To enable the laser head to machine bores and slots in workpieces where the access space is limited, key components such as the optical head and coupling unit have been miniaturized.

Figure 22: Compact optical head and miniaturized coupling unit

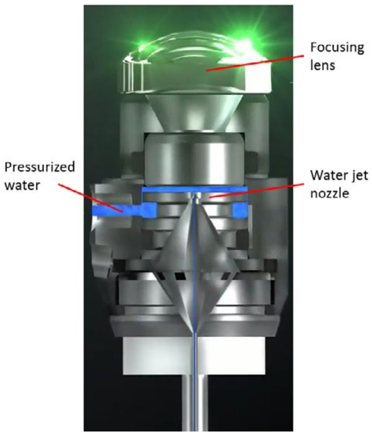

Fig. 23: Coupling unit cross-section

Finally, various sophisticated Industry 4.0 sensors and software enable reliable 2D- or 3D-machining, for example shaping of facets on raw diamond stones thus doing away with the need for skilled labour for polishing gems. A future EU-funded project is to implement AI into the LMJ process for auto-correction in machining of arbitrary 3D shapes. In more ways than one, Richerzhagen's invention has been a game changer in the precision machining of hard and sensitive materials.

Richerzhagen has laid the basics for a new machining technology which is being increasingly applied in many industry sectors to process various materials, often high-tech materials such as ceramic matrix composites or CVD tools requiring a high quality of surface finish. Leading research institutes globally have started to develop applications with the water jet laser technology. The future looks bright for the evolution of this technology.