

Advances in laser drilling technology from DeepU Project

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ABSTRACT

The potential of geothermal resources is currently constrained by existing drilling technology. To address this issue, the DeepU Project is investigating the application of laser and cryogenic gas for drilling deep wells (>4 km) to realise a U-shaped closed-loop geothermal heat exchanger. This work presents the latest results from laboratory-scale laser drilling experiments utilising a newly designed and manufactured drilling system. This technology includes a 30kW laser source and optics, a drilling string, a drilling head, a flushing system and a few secondary systems necessary for successful rock penetration. Laser-rock interactions were examined, such as thermal spallation, melting and vaporisation on 50x35x15cm slabs of granite, sandstone, limestone and basalt. These phenomena were studied with advanced analytical techniques like thermography, photogrammetry, and electron microscopy. In order to understand the physical nature of the drilling process and potential benefits, such as vitrification of borehole walls. This multidisciplinary approach allowed to describe the most efficient rock removal mechanism – the thermal spallation. The power density thresholds for spallation, melting and vaporization were determined. In the performed experiments (30kW laser), the 15cm thick slabs of rocks were penetrated with a diameter of c. 10cm. This proves that laser drilling is possible and can be scaled up to drill larger wells. Subsequently, we evaluated the feasibility and efficiency of the laser drilling, allowing for a direct comparison with traditional mechanical drilling methods. This work has demonstrated that laser drilling technology is a promising alternative, capable of reducing well completion costs while being environmentally friendly. In the near future, it may not only unlock the true potential of deep geothermal resources but also reduce

cost of drilling for all geothermal systems and deep storages.

1. INTRODUCTION

The energy transition theme has become a daily topic in the world and for human society's hunger for energy. Increased energy availability and use has meant prosperity in many countries. Still, it has shown its cost to the environment, resulting in the overproduction of greenhouse gases and its debated effects. Energy production and use account for more than 75% of the European Union's greenhouse gas emissions, and similar figures appear in many industrialized areas, so energy transition and decarbonization of energy technologies go hand in hand. Continuously renewable, CO₂-neutral, clean, affordable, and modern energy for the benefit of all people has been set as the 7th of the United Nations Sustainable Development Goals (SDG). Our ability to meet the 1.5°C climate goal agreed upon at COP21 in Paris almost a decade ago requires fast progress in energy transition. This implies expanding infrastructures, changing regulatory frameworks and market designs, and delivering the institutional and human resource capacities needed to support the energy transition. Not least, it requires continuous technological development of renewable energy. Expanding renewables in regions and countries outside leading markets and scaling up renewables other than solar PV are two key priorities for meeting decarbonization goals (IRENA, 2024).

For many years, geothermal energy has played a minor role in the energy scenario. Its numerous and crucial advantages disappear compared to its current production, which accounts for less than 1% of the international energy demand. More importantly, the sector lacked the capacity to convince people that its vast potential may be unlocked with novel technologies. The perspective has recently changed. As IEA (2024) stated, "Advances in technology are

opening new horizons for geothermal, promising to make it an attractive option for countries and companies all around the world. [...] If geothermal can follow in the footsteps of innovation success stories such as solar PV, wind, EVs and batteries, it can become a cornerstone of tomorrow's electricity and heat systems as a dispatchable and clean source of energy."

Among the unconventional geothermal alternatives, Deep Heat exchangers (DHE), Advanced Closed-loop Systems (ACL), or Advanced Geothermal Systems (AGS) are gaining momentum. There are many names for a single concept: the heat exchange at deep depth via the circulation of a working fluid - namely water while other fluids are being considered in various system designs - within a closed-loop, deep borehole, or pipe. The hot rock and geothermal fluid, even in low-permeability formations, surrounding the pipes at deep depths heat the working fluid by conduction. The main advantages of DHE are their versatility, replicability, predictability, low water consumption, and limited development risks related to resource availability. Its technological challenges are engineering-related. The main primary one stems from the considerable drilling length required to create sufficient heat transfer area in the subsurface. Another challenge, calling for improved project designs and operating patterns, is the limiting production temperature declines over time.

To overcome these limits and make DHE projects economically viable, the DeepU technology focuses on demonstrating at the lab scale the feasibility of using a combined laser/cryogenic gas drilling action. DeepU states for "Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation", a European project launched in 2022 and ending by 2025. The developed technology aims to optimize the drilling process and reduce drilling costs by increasing the penetration rates and avoiding wear of the drilling head as it is a non-contact method. Its laboratory-scale demonstration produces the information required for assessing the technological, environmental, and economic sustainability and defining the potential and commercial attractiveness of the proposed solution.

2. EXPERIMENTAL DESIGN AND METHODS

The laboratory set-up for rock melting/vaporization and vitrification was prepared. A press container was set to perform the first laboratory tests with the novel lightweight laser and gas processing drill head, equipped with monitoring devices (Fig. 1a). A series of laboratory-scale experiments were performed with the Ytterbium fiber laser with a wavelength of $1070 \pm 10 \text{ nm}$, operating continuously within a power range of 170-30000W (Fig. 1b).

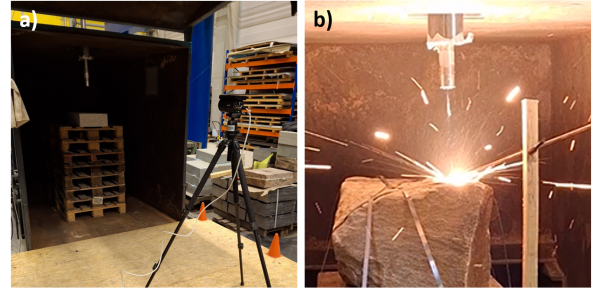


Figure 1: Picture of experimental setup (a), and picture taken during thermal spallation laser drilling test (b)

Three lithologies were selected for laser tests: granite, sandstone, and limestone. Representative samples were characterized in detail (thermo-physical properties). The rock materials were analyzed by optical microscopy (OM) and electron microscopy (SEM-EDS) to characterize the petrological characteristics of the pre- and post-lasing samples. X-ray powder diffraction (XRPD), and vibrational spectroscopies (Raman) were performed on samples to fully determine the mineral composition, specific microstructural elements, and new phases. Samples of granite, sandstone and limestone with dimensions of $500 \times 350 \times 150 \text{ mm}$ are being tested. These three lithologies were selected as the first to be tested because they represent the hardest rocks (granite) to be drilled at deep depth, and the most common geothermal reservoir rocks (sandstone and limestone). A thermo-camera FLIR GF77a with HSM mode monitored the lasing process and allowed gas visualization. The liberated gases were analyzed with a Raman spectrometer while the cuttings removed from the borehole were collected and characterized. The morphology of craters and boreholes was analyzed with photogrammetry, which allowed the estimate of efficiency parameters such as rate of penetration (ROP) and specific energy (S_e), defined by the following formulas:

$$ROP = \frac{h}{t_i} \left(\frac{\text{mm}}{\text{s}} \right), \left(\frac{\text{m}}{\text{h}} \right) \quad [1]$$

where, h is the depth (mm) of the borehole measured from the deepest point, and t_i is the irradiation time (s):

$$S_e = \frac{Pt_i}{V} \left(\frac{\text{kJ}}{\text{cm}^3} \right) \quad [2]$$

where P is laser power (W), t_i is the irradiation time (s) and V is the volume of removed rock (cm^3).

The preliminary laser drilling experiments were performed on 5cm cubic samples (Fig. 2a), applying the optical system described by Cerwenka et al., (2020). The second type of laser test was performed with a novel DeepU laser drilling head equipped with an optical system and two sets of nuzzles for cooling and cleaning the cuttings (Fig. 2b). The samples used for these tests were rock slabs ($50 \times 30 \times 15 \text{ cm}$). Around 100 single-lasing tests were performed to investigate the impact of different parameters.

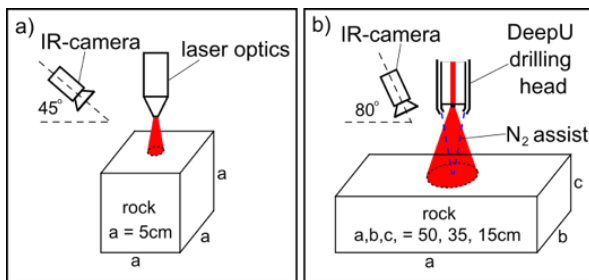


Figure 2: Schematic drawing of preliminary laser tests setup (a), and DeepU laser drilling head setup (b).

3. RESULTS

Preliminary laser tests confirmed three main processes occurring during the lasing of rocks: thermal spallation, melting, and vaporization (Brian C. Gahan et al., 2001; Xu et al., 2003; Buckstegge et al., 2016; Bharatish et al., 2019; Gowida et al., 2023) as shown in Fig. 3. These processes are controlled chiefly by power density (P_p), irradiation time (t_i), and lithology (structure, chemical and mineralogical composition). The P_p thresholds between apparent processes were quantified allowing for accurate predictions. Two drilling regimes have been observed and distinguished: 1) rock removal due to thermal spallation or 2) matter removal via melting-vaporization. Thermal spallation is driven by the thermal expansion of minerals and the mechanical bucking of rock fragments. It occurs at relatively low temperatures, $\sim 500^\circ\text{C}$, and is energetically efficient and thus can drill boreholes with larger diameters ($> 5\text{ cm}$ for 30 kW DeepU laser). However, the process of spallation produces cuttings (spalls) that must be efficiently removed from the borehole to sustain constant penetration. Melting and vaporization occur at higher temperatures $> 2100^\circ\text{C}$, and rock removal is achieved through the vaporization of earlier molten material. Therefore, it requires much more energy than thermal spallation. The achieved vaporized borehole diameter is currently $< 1\text{ cm}$.

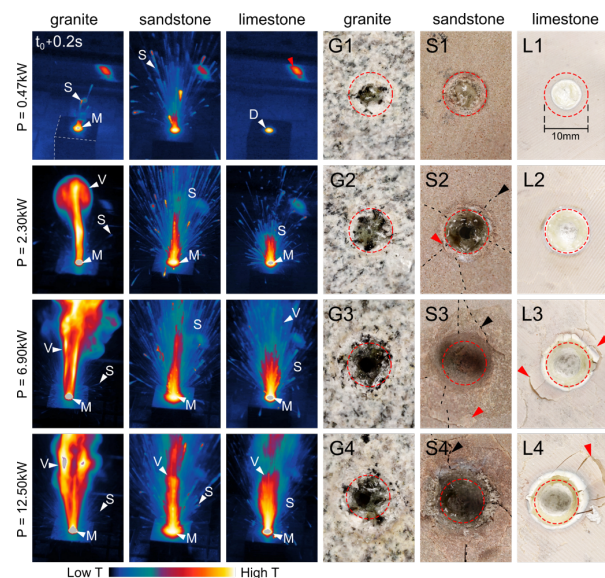


Figure 3: IR images of the drilling process at $t=0.2\text{ s}$ (left) and pictures of the corresponding craters (right). S – spallation, M – melting, V – vaporization, red and black arrows indicate fractures.

3.1 Laser-induced thermal spallation

The DeepU thermal spallation experiments (Fig. 2b) were performed at a fixed diameter (5 cm) and power (26 kW), which corresponds to a power density of 1325 W/cm^2 . Based on preliminary experiments (Fig. 4) the predominant processes expected to occur are melting-spallation and spallation. The IR-records allowed to estimate the average temperature of spallation for granite as 550°C shown in Fig. 5, consistent with previous studies (Kant et al., 2017; Rossi et al., 2020). with a noticeable strongly heterogeneous temperature distribution within the laser beam spot. This heterogeneity is a result of the radiation absorbance of various minerals and gaussian distribution of power intensity within laser beam spot. The average spallation temperature of sandstone is lower (400°C) than that of granite due to the higher modal content of quartz which is known for enhance rock fracturing with increasing temperature (Alcock et al., 2023). The $\alpha \leftrightarrow \beta$ phase transition in quartz is followed by significant change in cell volume and elastic properties at around 570°C (Li and Chou, 2022). Therefore, the higher quartz content increases the intensity of spallation, simultaneously decreasing the temperature. Sandstones can be effectively penetrated with laser-induced thermal spallation. Thermal spallation in limestone is visible only within the first second of irradiation, soon after the temperature exceeds 2100°C (IR camera limit), which indicates the initiation of CaO melting from previously decomposed calcite and its vaporization. However, the melting-evaporation at a diameter of 5 cm does not effectively remove the material. To support thermal spallation in limestone, the rock was immersed in water for 48 h. Subsequent laser tests were performed on fully saturated limestone. Thermal spallation in saturated limestone was successfully achieved at an average temperature of 180°C . The borehole created by the

laser drilling of saturated limestone is shown in Fig. 6c SL.

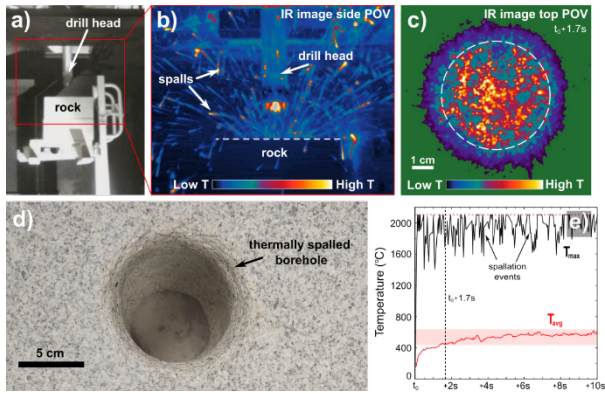


Figure 5: Photograph of the experimental setup (a) used to test DeepU drilling head. IR images of the thermal spallation drilling, side point of view (b), and top point of view (c). Photograph of the thermally spalled borehole, depth 150mm, diameter ~80mm (d). The temporal temperature of laser drilling, T_{max} – the maximum recorded temperature at a single point, T_{avg} – the average temperature in beam spot area (e).

3.2 Efficiency of DeepU laser drilling

The craters drilled with the DeepU setup were further analyzed to estimate the spalling process's efficiency. The rock slabs of granite and sandstone were drilled through the entire thickness of 150 mm (Fig. 6a,b). Complete penetration of the limestone slab has not been archived so far with thermal spallation (Fig. 6c). The specific energy calculated for granite is 6.35 kJ/cm^3 , while for sandstone 2.86 kJ/cm^3 . The thermal spallation for limestone was hampered within 1s, and melting-vaporization was initiated (Fig. 6c). Therefore, the obtained S_e value is significantly higher (86.67 kJ/cm^3) than other lithologies. However, spallation can be induced and sustained by saturating the limestone with water (Fig. 6c SL), that reduces S_e to 16.25 kJ/cm^3 . The maximum ROP archived was 4.2, 7.2, and 1.4 mm/s for granite, sandstone, and saturated limestone, which corresponds to 15, 26, and 5 m/h, respectively. Comparison of the parameters is shown in Fig. 6d.

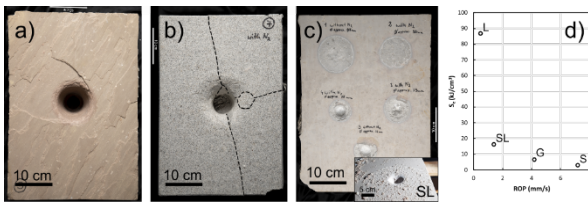


Figure 6: Photographs of penetrated rock slabs of sandstone (a), granite (b) and rock slab of limestone after lasing tests (c). Graph showing efficiency of laser drilling for selected lithologies (d) for sandstone (S), granite (G), limestone (L) and saturated limestone (SL).

4. CONCLUSIONS

To address the results of the laser tests, two concepts for the drilling were developed: 1) the drilling head is adjusted to melt and evaporate the rock operating in the high-temperature environment (Fig. 4a), resulting in a vitrified layer on the borehole walls and 2) the drilling head is optimized to thermally spall the rock at a specific temperature range and efficiently remove all spalls from the borehole (Fig. 4b). Since commercially available laser power does not allow for the application of melting-vaporization as a primary rock removal process for drilling boreholes $> 5 \text{ cm}$, the second (Fig. 4b) concept was realized for further tests.

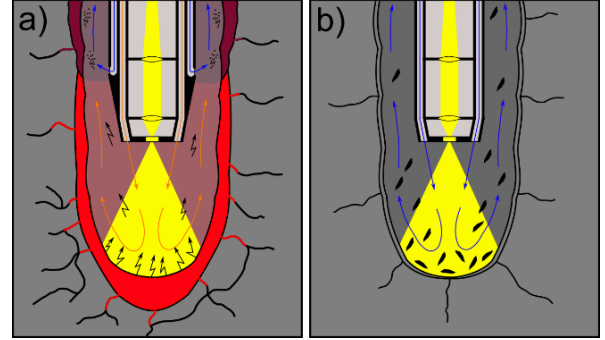


Figure 4: Schematic drawing of DeepU drilling concept for drilling with melting and vaporization (a) and thermal spallation (b).

Laser drilling offers a perspective in deep drilling for heat exchangers at depths where traditional drilling technologies face many problems due to demands on equipment, life-span of drill string components (most notably drill bits) resulting in higher levels of Non-Productive Time (NPT), and increased completion costs. Although laser drilling is a proven technology, its application to geothermal production has been hindered by traditional open-loop geothermal production's requirements to preserve or even enlarge (EGS) rock fractures. This limitation is overcome in closed-loop systems, and the laser drilling technological challenge becomes primarily related to cooling the drill head and flushing the melted rocks out of the borehole from a deep depth.

The current DeepU project results show the robustness of the proposed approach and indicate the effectiveness of the path taken to achieve all the set goals. Laser drilling proves very effective in hard, crystalline rocks, which are the most common at deep depths, and may result in optimal drilling targets where rich radiogenic heat is present, as in many areas of Europe and worldwide. In limestone, the most difficult to drill by laser, laboratory experiments showed an improved drilling efficacy in water-saturated conditions. The laser drilling rate can be kept constant while penetrating different formations by anticipating petrophysical and rheological variation through adequate sensor systems and then adapting laser and gas properties. Overall, laser drilling provides a higher penetration rate than traditional drilling, thanks to good ROP (50% higher than rotary technologies) and much lower (essentially

null) NPT. The laser-drilled boreholes are vertical and have a constant diameter, favoring rapid casing and potentially coiling, provided suitable (high conductivity) coil material is identified. In some conditions, depending on rock and mineral assemblage and saturation level, vitrification might prove effective in reinforcing the borehole stability and obtaining borehole impermeability, potentially providing completed wells. Drilling noise is very low, and vibrations are scarce or null.

Our research has shown that laser drilling technology is a viable alternative to conventional drilling and deserves further development and innovation. It is proficient at diminishing well completion costs while adhering to environmental sustainability goals. However, the entire laboratory demonstration and the design of the full-scale facility will take a few more months to complete. In the foreseeable future, DeepU technology will hopefully unveil the true potential of deep geothermal resources and decrease the expenses associated with drilling for deep geothermal systems and deep heat storage.

DISCLAMER

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