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Novel geothermal drilling for developing deep heat exchangers: the DeepU Project

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ABSTRACT

The principal concept of the European DeepU project pertains to an innovative drilling technology poised to redefine the parameters of geothermal development and utilization through improved access to deep geothermal resources. The overarching objective is to establish a deep (>4 km) closed-loop connection in the form of a U-tube exchanger, achieved by developing rapid and efficient laser drilling technology, thus augmenting the availability of deep geothermal resources for low-carbon heating and potential power generation. This document presents the most recent findings from laboratory-scale laser drilling experiments conducted with a newly designed and manufactured drilling system.

A laser drill head has been integrated with specialized drill strings that facilitate the coupled action of laser and cryogenic gas, effectively spalling, melting, evaporating, and cooling even the hardest rocks. The fine particles of the drilled rock are expelled to the surface in the gas stream via the borehole annulus. Detailed temperature control analysis and innovative laser lenses are employed to convey heat and sustain drilling. Additionally, it is essential that gases remain cryogenic across extended distances.

Laboratory tests with the novel lightweight laser and gas processing drill head were conducted within a press container equipped with monitoring devices. Both an optical camera and a thermal camera monitor the process. The prototype drill head has been developed, merging the laser system with a novel drill-string design capable of enduring the combined action of laser and cryogenic gas. The interactions between the laser and rock, including thermal spallation, melting, and vaporization, were examined utilizing advanced analytical techniques such as thermography, photogrammetry, and electron microscopy to elucidate the physical nature of the drilling process. Subsequently, the feasibility and efficiency of laser drilling were evaluated, allowing for a direct comparison with conventional mechanical drilling methods. Under the current laser configuration, spallation emerges as the most efficient mechanism for rock removal and penetration, while melting and evaporation act as secondary processes. The flow of cryogenic gas facilitates drilling by effectively evacuating spalled particles. The meticulous optimization of laser parameters and experimental setups, in conjunction with microscopic examinations of the drilled rocks, has unveiled macro- and micro-scale phenomena that contribute to the successful development of this innovative drilling method. Additionally, the project assesses the potential for exploitation and economic implications of the developed drilling technology through numerical simulations calibrated according to laboratory data. Furthermore, the legislative considerations and environmental standards pertinent to the proposed solution are also evaluated.

The high-risk innovation presented in DeepU can potentially make geothermal energy systems accessible everywhere in a targeted and demand-oriented manner. It would provide a complementary approach and an alternative solution to traditional energy storage, power and heat generation, thus decentralizing the energy supply in areas currently considered uneconomic.

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 very large depths 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 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 stands for "Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation", a European research 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 productive drilling time by 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. THE CONCEPT AND THE EXPERIMENTAL APPROACH

In the DeepU concept of work, a laser drill head is combined with special drill strings sustaining the coupled action of laser and cryogenic gas, and it is responsible for spalling, melting, evaporating, and cooling even the hardest rocks. The resultant fine particles are transported to the surface by the gas stream within the well's annulus, in much the same way conventional rotary drilling achieves hole cleaning. Specific temperature control analysis and innovative laser lenses convey the heat and sustain drilling. In addition, gases are kept cryogenic over a long distance (Fig. 1a).

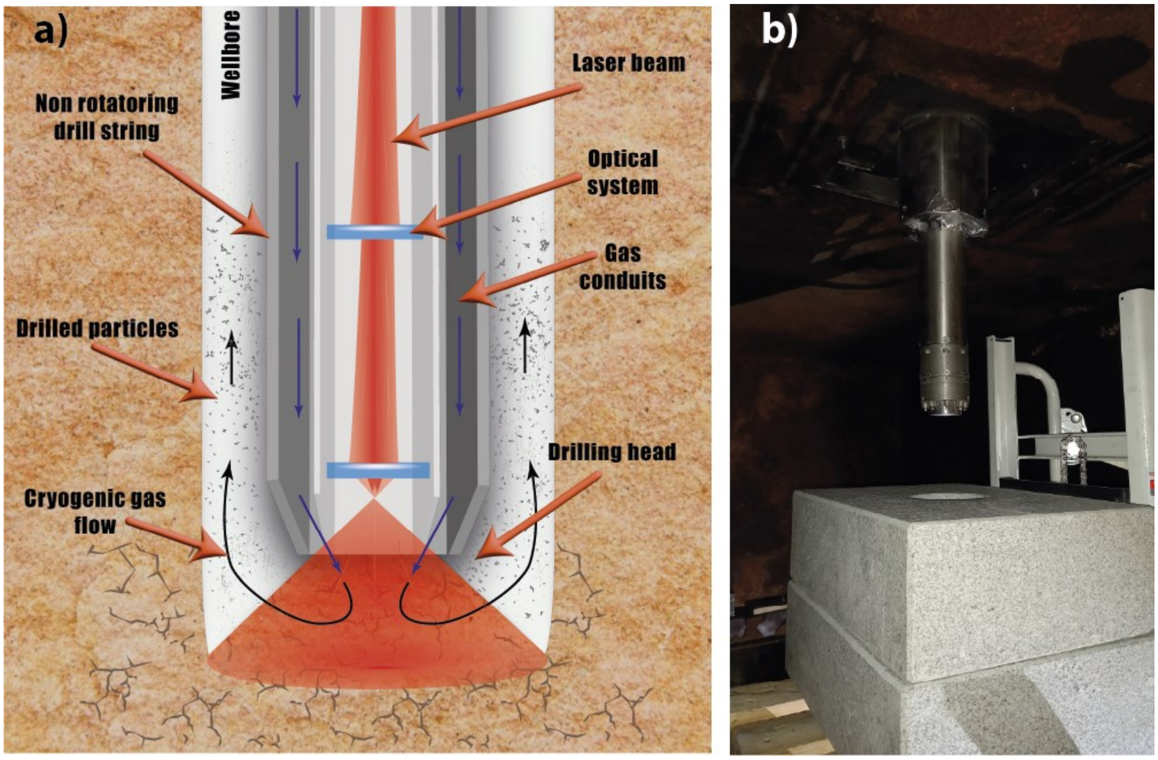

Figure 1: Schematic drawing of the drilling head and drill string in action (a), photograph of a drill string with drilling head (b).

First, the technological developments in the DeepU project led to the design and manufacturing of the drill string capable of conveying the laser beam downwards (outer tube 100 mm, inner tube 60 mm). The project also considered possible alternatives to convey the cryogenic gas flow (e.g., flexible cryotubes). In addition, four gases (argon Ar, krypton Kr, helium He, and nitrogen N) were considered as potential cryogenic gases for the innovative DeepU technology, and Nitrogen was selected.

The laboratory set-up for rock spallation, melting/vaporization and vitrification was prepared. A press container was adapted as a safe housing for laser experiments. This container was set to perform the first laboratory tests with the novel lightweight laser and gas processing drill head (Fig. 1b), equipped with monitoring devices. A series of laboratory-scale experiments were performed with the Ytterbium fiber laser with a wavelength of 1070±10nm, operating continuously within a power range of 170-30000W. Three lithologies were selected for laser tests: granite, sandstone, and limestone. These three lithologies were selected because they represent the hardest rocks (granite) to be drilled at deep depth, and the most common geothermal reservoir rocks (sandstone and limestone). The lithic materials were also analyzed by optical microscopy (OM) and electron microscopy (SEM-EDS) to characterize the mineralogical-petrographic and microstructural characteristics of the pre- and post-vaporizing/melting effects. X-ray powder diffraction (XRPD), solid-state NMR (MAS-SS-NMR), and vibrational spectroscopies (FTIR, Raman) were performed on microvolumes of samples to fully determine the mineralogical nature, specific microstructural elements, and neoformation phases. 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:

$$ROP = \frac{h}{t_i}\left(\frac{mm}{s}\right) \quad (1)$$

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

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

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 5 cm 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 nuzzels for cooling and cleaning the cuttings (Fig. 2b). The samples used for these tests were rock slabs (50 x 30 x 15 cm). Around 100 single-lasing tests were performed to investigate the impact of different parameters.

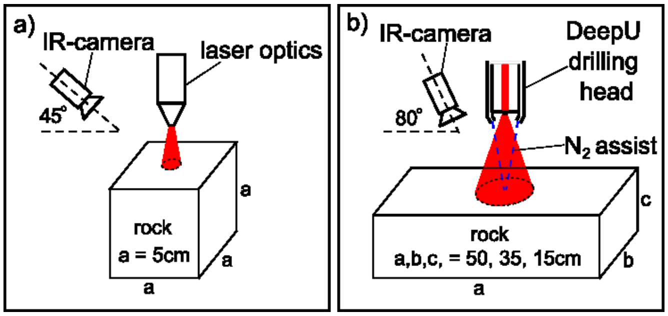

Figure 2: Schematic drawing of preliminary laser tests setup (a), and DeepU laser drilling head setup (b).

Preliminary laser tests confirmed the three main processes occurring during the lasing of rocks: thermal spallation, melting, and vaporization (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 (Pρ), irradiation time (t_i), and lithology (structure, chemical and mineralogical composition). The Pρ 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, ~500°C, and is energetically efficient and thus can drill boreholes with larger diameters (> 5 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°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 < 1cm.

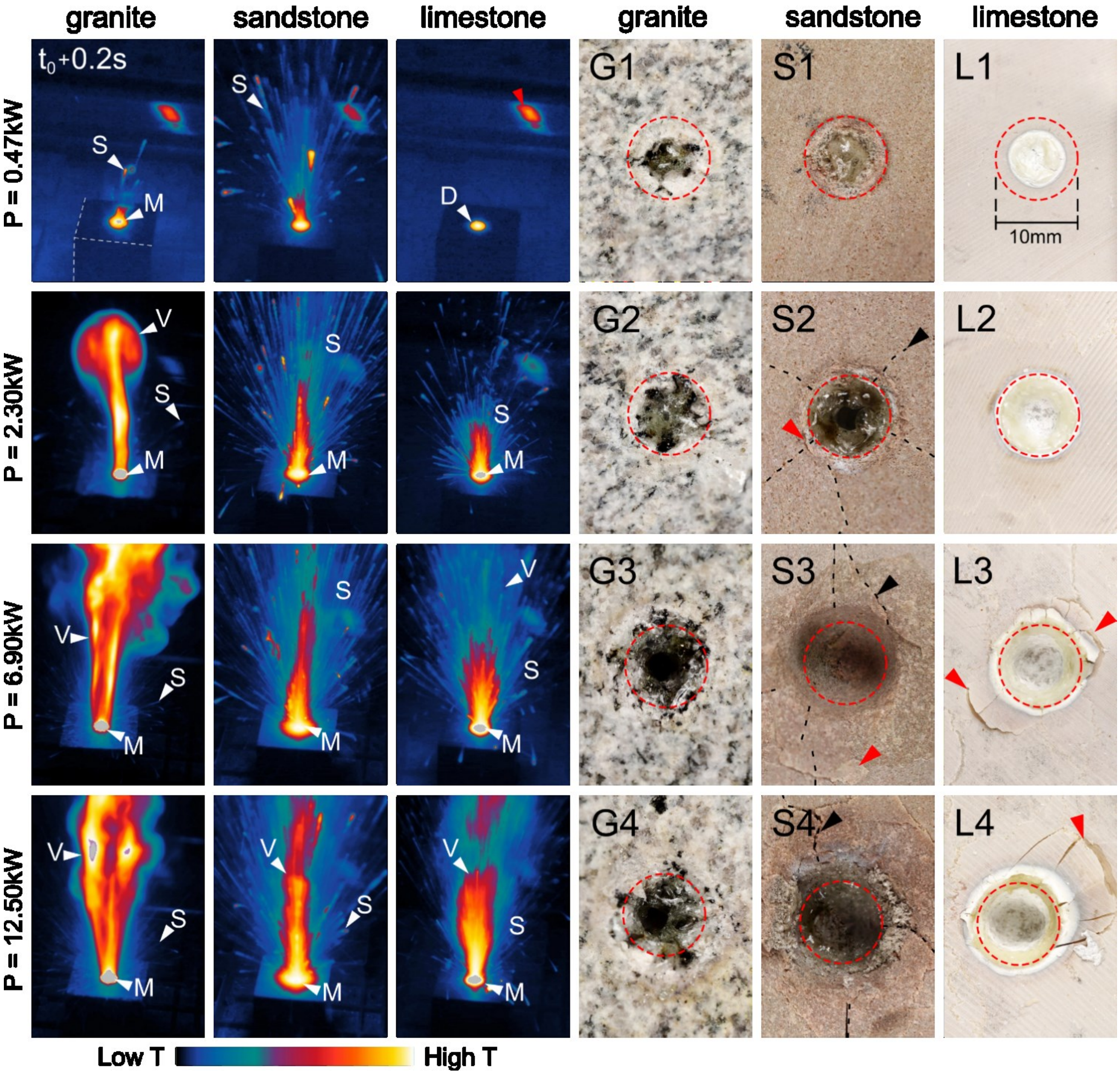

Figure 3: IR images of the drilling process at t=0.2s (left) and pictures of the corresponding craters (right). S – spallation, M – melting, V – vaporization. Arrows indicate spallation-induced fractures, shearing (red), tensile (black). Red circles mark beam spots.

3. DEEPU LASER DRILLING SYSTEM

To address the results of the preliminary 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 cm, the second (Fig. 4b) concept was realized for further tests.

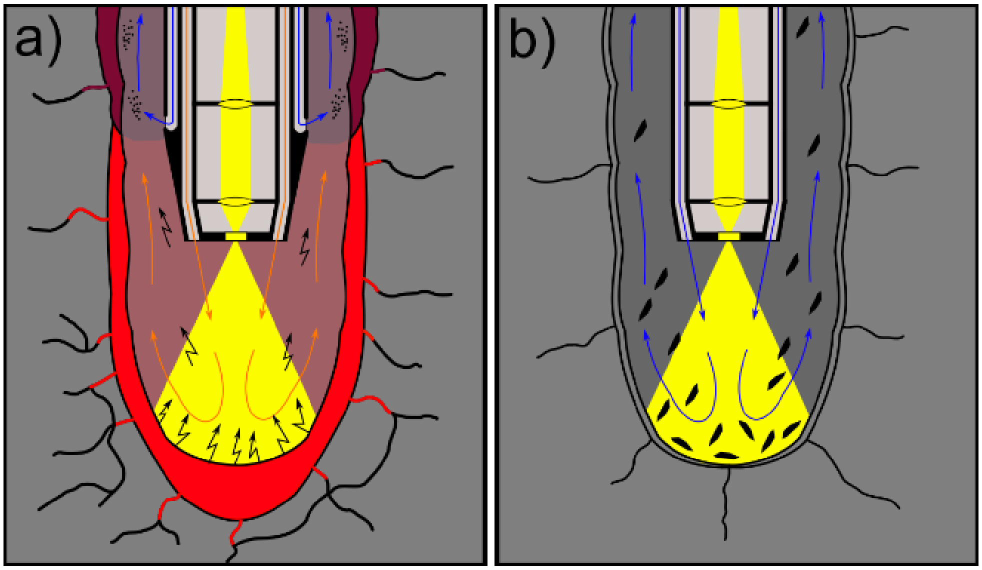

Figure 4: Schematic drawing of DeepU drilling concept for drilling with melting and vaporization (a) and thermal spallation (b).

3.1 Laser-induced thermal spallation

The DeepU thermal spallation experiments (Fig. 5) 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 enabled an estimation of the average spallation temperature for granite at 550 °C (Fig. 5), aligning with prior studies (Kant et al., 2017; Rossi et al., 2020), and revealing a highly heterogeneous temperature distribution within the laser beam spot. This heterogeneity is a result of the radiation absorbance of various minerals and the Gaussian distribution of power intensity within the 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 enhancing rock fracturing with increasing temperature (Alcock et al., 2023). The α ↔ β phase transition in quartz is followed by a 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 melting and vaporization. However, the melting-evaporation at a diameter of 5 cm does not effectively remove the material. The rock was submerged in water for a duration of 48 hours to facilitate thermal spallation in limestone. Subsequent laser tests were performed on fully saturated limestone. Thermal spallation in saturated limestone was achieved at an average temperature of 180 °C. The borehole created by the laser drilling of saturated limestone is shown in Fig. 6c SL.

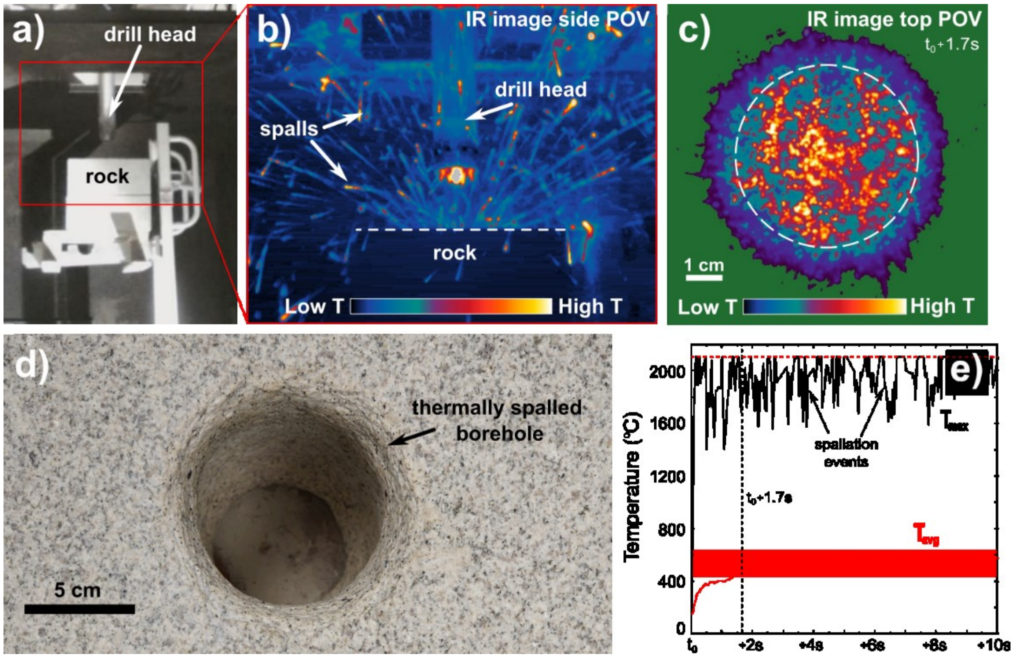

Figure 5: Photograph of the experimental setup (a) used to test DeepU drilling head, IR images of the thermal spallation drilling, side point of view (b), and top point of view (c). Photograph of the thermally spalled borehole, depth 150 mm, diameter ~80 mm (d). The temporal temperature of laser drilling, 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, and for sandstone it is 2.86 kJ/cm^3. The thermal spallation for limestone was hampered within 1 s, and melting-vaporization was initiated (Fig. 6c). Therefore, the obtained S_e value is significantly higher (86.67 kJ/cm^3) than for other lithologies. However, spallation can be induced and sustained by saturating the limestone with water (Fig. 6c SL), which reduces S_e to 16.25 kJ/cm^3. The maximum ROP achieved was 4.2, 7.2, and 1.4 mm/s for granite, sandstone, and saturated limestone, corresponding to 15, 26, and 5 m/h, respectively. A comparison of the parameters is shown in Fig. 6d.

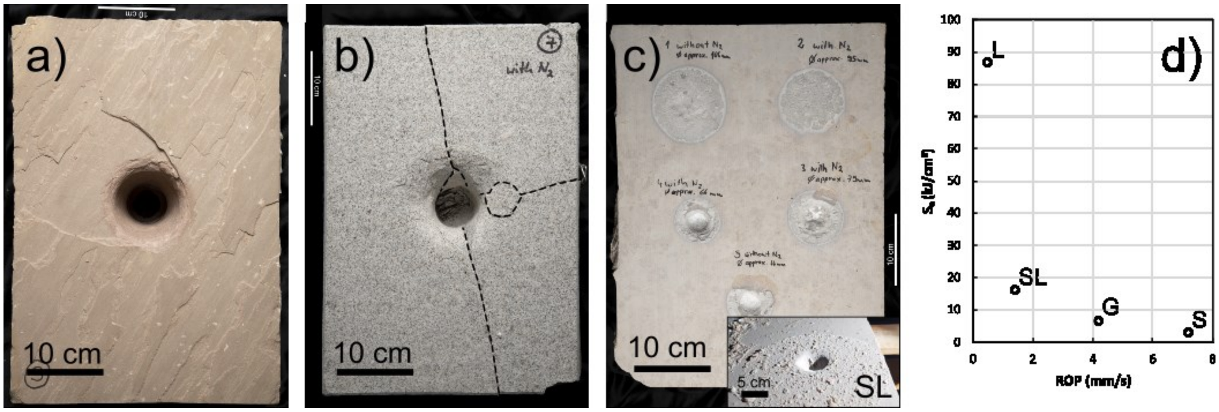

Figure 6: Photographs of penetrated rock slabs of sandstone (a), granite (b), limestone after lasing tests (c). Graph showing the efficiency of laser drilling for selected lithologies (d) for sandstone (S), granite (G), limestone (L) and saturated limestone (SL).

5. PERSPECTIVE FOR THE COMMERCIAL DEVELOPMENT: THE ENVIRONMENTAL AND ECONOMIC ASPECTS

While drilling is at the heart of the project, DeepU also addresses environmental regulation and operational design aspects to analyze the exploitation potential and its economics.

To pave the road to the development of the DeepU laser and cryogenic gas drilling method, the legislation and regulations governing the health and safety of drilling personnel, equipment and drill sites, the use of industrial-scale lasers, the assessment of environmental impact, and the requirements for mitigation measures applicable to the development of deep drilling projects are crucial. These aspects have been tracked down to understand the current state of the art in the context of applicable regulations (Pasquali et al., 2023) and to identify barriers to the potential future development of the DeepU technology, but also to highlight the opportunities that such a new drilling method may bring in the context of reduced environmental and health and safety conditions associated with the DeepU drilling and completion compared to the existing drilling and completion methodologies. Two key tools were applied: a Failure Mode and Effects Analysis (FMEA) and an Environmental Health and Safety (EHS) Risk Assessment. The FMEA, used to identify the potential modes of failure of the individual technology components, provides mitigation strategies to allow the DeepU technology to progress to the next stage of development. Such mitigations were framed as part of ongoing recommendations in a Technology Roadmap, which captures the necessary next steps to be undertaken to address any remaining challenges that may be present for future commercialization. The EHS Risk Assessment is being used to address the main challenges highlighted to ensure the achievement of regulatory and legislative compliance. The EHS assessment compares existing operational requirements of the onshore drilling process, general health and safety, and environmental and licensing aspects associated with conventional (mechanical) deep drilling projects to define key EHS indicators for the DeepU, non-mechanical drilling method. Key EHS process differences are being highlighted, and recommendations with respect to the requirements for achieving potential future acceptance from regulators are considered, ensuring that DeepU technologies remain at the forefront of innovation while upholding the highest standards of EHS.

A preliminary technological and market analysis is also carried out to transition DeepU solutions from the laboratory to field-testing. It is based on the simulated operation of DHE and its comparison with traditional open-loop systems. Using TOUGH2 for the open-loop system and COMSOL 6.2 for the closed-loop system, geothermal prospects defined to supply hot fluids for a high (≈ 10 MWe, T ≈ 300 °C) and a medium (≈ 5 MWe, T ≈ 135 °C) enthalpy power plants in open-loop systems are being compared to closed-loop solutions, considering different reservoir lithologies, temperature and pressure conditions. The case study sites are already known by literature and suitable for a conventional geothermal project. Various closed-loop geometrical designs (U-tube, multi-length, radiator, co-axial) have been analyzed, depending on the specific application, subsurface conditions, and desired heat exchange efficiency. The simulation helps define the optimal design for mitigating thermal decline and energy production from DHE systems. Moreover, some critical factors are being identified besides the most obvious ones (working fluid flow rate with respect to the heat flow, operating time, and flow direction), such as thermal insulation and rugosity of wells and pressure conditions to manage flashing effects. Thanks to simulation results, it will be possible to complete the computation of the Levelized Cost of Energy, electricity and heat, supported by the definition of investment and operating costs from literature review and partners' expertise.

6. CONCLUSIONS

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. Laser drilling has been researched before in combination with mechanical drilling and as a stand-alone 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 very large 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 offers a more consistent and predictable ROP, compared to conventional mechanical drilling, and virtually eliminates NPT, associated with tripping. 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 reducing 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 be confirmed in field tests to unveil the true potential of deep geothermal resources and decrease the expenses associated with drilling for deep geothermal systems and deep heat storage.

7. ACKNOWLEDGMENTS AND DISCLAIMER

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