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A Review and Comparison of Three Unconventional Drilling Technologies

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ABSTRACT

There are three fundamental drilling and rock excavating mechanisms: mechanically induced stress, thermal induced stresses, fusion and vaporization, and chemical reactions and almost all drilling and rock excavation methods can be categorized into the three groups (Maurer 1968, Maurer 1980). The rotary drilling bit, the most common drilling technology today, attacks rock with mechanically induced stress and is usually called the conventional drilling technology. Novel or unconventional drilling technologies refer to methods which attach rock with the other three mechanisms.

Scientists and engineers have been trying to improve or replace rotary drilling bits with novel methods ever since 1930s and many concepts were invented and tested in 1960s. However, due to significant improvements of roller cone bits and the invention of PDC bits in 1970s, the drilling technology with rotary bits has been continuously enhanced and meets petroleum or natural gas drilling requirements for most of time. Percussive hammers and abrasive jet drills also developed and applied in petroleum drilling, coal mining, and tunnel excavation as good supplements for rotary drilling bits in this phase. So, the research on other drilling technologies ceased since 1980s. This situation did not change until 2000s when geothermal energy gradually weights more in energy strategy in many countries in the global carbon-reduction trend. High-quality geothermal energy is stored in hot dry rock which is usually granite with more than 150°C and neither roller cone bits or PDC bits could perform efficiently in these hot and hard rocks. In order to improve the geothermal energy drilling efficiency, scientists and engineers regained enthusiasm on unconventional drilling technologies.

Based on literature review and on-site survey, this paper chooses three unconventional drilling technologies, the plasma drilling, the electrical discharge drilling, and the laser drilling from dozens of novel drilling concepts and will further review the recent advances of the three technologies. Theories and rock excavating mechanisms will be firstly introduced respectively; recent engineering efforts with test data will be exposed and discussed. The three alternative drilling technologies are chosen because they all require a considerable amount of electricity which leads to challenge of power transmission even though the way they attack rock vary. They all show potentials to replace rotary drilling bits so in the end readiness and challenges of the three technologies will be evaluated and discussed.

A method to evaluate drilling technologies was established in (Pierce et al. 1996) considering below 6 functions which are necessary to provide a useful hole:

- Transmission of energy to the system-rock interface
- Reduction of the rock
- Removal of the rock
- Maintenance of the borehole (formation stability) while drilling
- Control of formation fluids (well control)
- Preservation of the borehole (completion)

In this review, a similar method will be used to evaluate the technical readiness and foreseeable challenges in future for plasma drilling, electrical discharge drilling, and laser drilling.

1. INTRODUCTION

In the 21st century, with the trend of global energy conservation and carbon emission reduction, the proportion of geothermal energy in the energy strategies of many countries is gradually increasing. However, hot dry rock resources are located in deep strata (3000-10000m), with high rock hardness, usually granite with a temperature of more than 150℃. The formation pressure is also higher, and the drillability of rocks is poor. While the traditional drilling method (mechanical gear, transmission device, drill, etc.) has basically developed to the limit state, with little space for efficiency improvement. In the drilling of deep and ultra-deep Wells, there are more and more problems, such as slow speed, long cycle, high cost, short bit life and poor quality of drilling body. On the one hand, many scholars study the use of torque impactor, air hammer, water hammer and other auxiliary instruments with traditional drill to increase the life of the bit. On the other hand, more and more novel drilling technology has been developed. For high hardness rocks, novel drilling technology can reduce rock hardness and improve rock crushing efficiency.

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Novel drilling usually refers to alternative methods which attack rock with thermal energy, electrical energy, chemical energy, etc. rather than conventional rotary drilling bits with mechanical energy. Research on novel drilling technologies has been conducted ever since 1960s with considerable achievements. This paper will only focus on three novel drilling technologies: the plasma drilling, the electrical impulse drilling, and the laser drilling. The working principle and the rock disintegration mechanism for each of the three technologies will be described respectively and then recent research activities and engineering efforts in the past 20 years will be introduced and discussed. In the end, the three novel drilling technologies will be compared and evaluated regarding to the technical readiness, concerns, and challenges.

2. PLASMA DRILLING

Rock Disintegration Mechanism. Plasma torch, also called as plasma generator, is a device to generate high temperature plasma jet. As shown in Figure 1, the working gas is ionized and a plasma arc is generated in between the cathode and the anode, the working gas then is heated by the plasma arc and ejected out the torch in form of plasma jet.

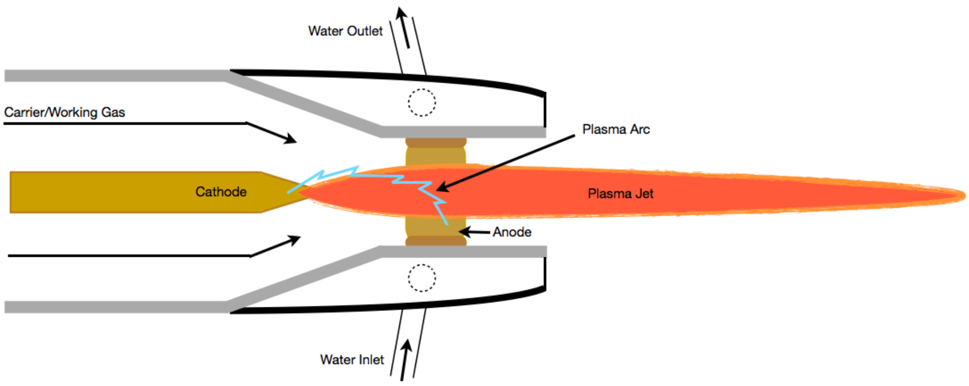


Figure 1: The schematic diagram of a plasma torch.

The temperature of plasma jet could be up to 10,000K, so there could be three possible modes of rock disintegration: spallation, fusion, and evaporation (Kocis et al. 2015). When the temperature of plasma jet applied on a rock exceeds the fusion or vaporization temperature, the rock will be melted or vaporized directly; otherwise, the plasma jet will heat up the rock and cause thermal stress due to the temperature differential and the non-homogeneity, which could be big enough to spall the rock.

Researchers from GA Drilling AS company further performed rock disintegration test applying plasma torch on various types of rock including limestone, sandstone, halite, granite and quartzite, and noticed that the most effective disintegration mode varies with the type of rock (Kocis et al. 2015a). The result is summarized in Table 1.

Table 1 Rock types and the most effective disintegration mode by plasma drilling (Kocis et al. 2015a).

Rock Types	Most Effective Disintegration Mode	Reasons
Quartzite	Spallation	High internal stress due to metamorphic changes
Limestone sandstone	Fusion	Low macroscopic internal stress
Halite	Evaporation	Low boiling temperature of 1686K

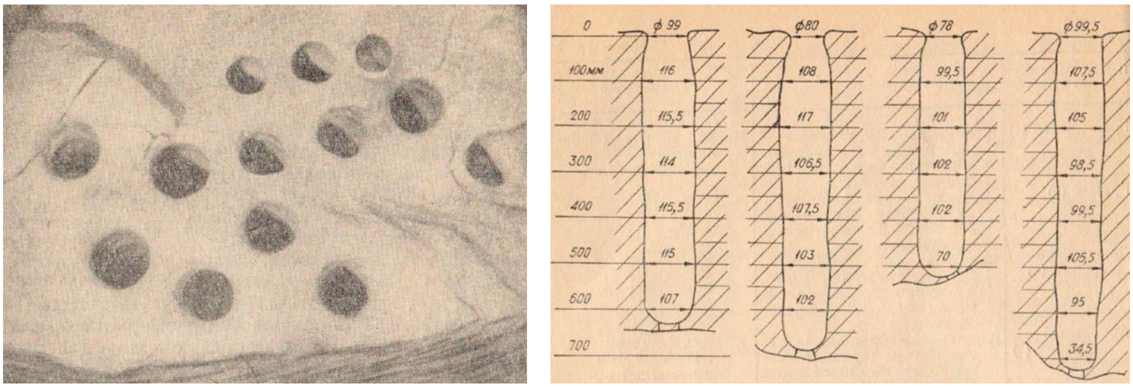
Researchers from ENN Energy Research Institute also have performed some rock disintegration test with a 50kW off-the-shelf plasma torch and noticed that the rock could be disintegrated by plasma torch in a combined mode, especially when there is air or water cooling applied on the rock surface as shown in Figure 2.

(a) Fusion mode only

(b) Combination of fusion and spallation with water cooling

Figure 2: Modes of rock disintegration by plasma torch applied on basalt.

Engineering Efforts. Back in 1970s, researchers in Institute of Theoretical and Applied Mechanics S.A. Khristianovich SB RAS (ITAM) in USSR innovatively tried to drill holes with plasma torches with 100kW power and some results are shown in Figure 3. Unfortunately, their research was interrupted by the national power shortage in 1980s and was never resumed.



(a) Top views of plasma drilled holes **(b) Cross-section views of plasma drilled holes**

Figure 3: Holes drilled with plasma torch by ITAM in 1970s.

The stability of well drilled by plasma torch has also been studied. Researchers have shown that one of the main problems as the drilling depth increases is the wellbore instability. Lab tests were performed, and it is concluded that core-size rock samples interact with temperature that is generated from plasma torch promoting the initiation and propagation of fractures (Bazargan et al. 2015).

Researchers in ENN Science and Technology Development Co. Ltd. have performed similar lab test and noticed that the reaction of rock samples vary with the type of rocks. As shown in Figure 4 basalt was melted by the plasma torch with an even glassy surface; however, granite was melted with an uneven glassy surface and deep cracks were initiated and propagated. Properties of the vitrification of rocks were further studied as listed in Table 2 to validate the concept of completing wells with the vitrification. Unfortunately, the vitrification of rock is too brittle to withhold the downhole pressure even though there is an engineering solution to keep the glassy surface smooth.

(a) Basalt **(b) Granite**

Figure 4: Holes evacuated by 50kW off-the-shelf plasma torches.

Table 2 Comparison of hardness of rock samples and their vitrification melted by plasma torch.

Rock Samples	Hardness (HV)
granite	1619.1
basalt	1007.3
vitrification of rock	691.0

Researchers from GA Drilling AS company customized the plasma torch design to generate an area-wide jet flow in order to improve the hole quality. The shape of plasma jet flow of GA's torch is compared with conventional ones in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The engineers from GA company further designed the drilling tool implementing the plasma torch and the drilling method, i.e. the bottom hole assembly (Kocis et al. 2015b, Kocis et al 2016). The prototype of the tool has been tested and is ready for Environment Testing (Kocis et al. 2015a).

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(a) Narrow plasma jet flow **(b) Area-wide plasma jet flow**

Figure 5: Comparison between the of plasma jet flows of a conventional torch and the G A optimized torch (Bazargan et al. 2015).

3. ELECTRICAL IMPULSE DRILLING

Rock Disintegration Mechanism. Electrical Impulse (EI) drilling is also named plasma channel drilling by some researchers because a plasma channel forms in the rock while an electrical impulse is discharged via a pair of electrodes applied on the rock and the impulse could break down the solid dielectric.

As shown in Figure 6, there are two key factors to ensure breakdown happens in the rock rather than the surrounding fluid: 1) the front edge has to be short enough, only in which case the rock is electrically weaker than water or even than drilling fluid; 2) the voltage impulse needs to be high enough to breakdown the rock (Ushakov et al. 2019). There are multiple ways to generate the required electrical impulse and a Marx generator is the most commonly used by researchers due to the simplicity and reliability. An electrical circuit of a typical Marx generator is presented in Figure 7.

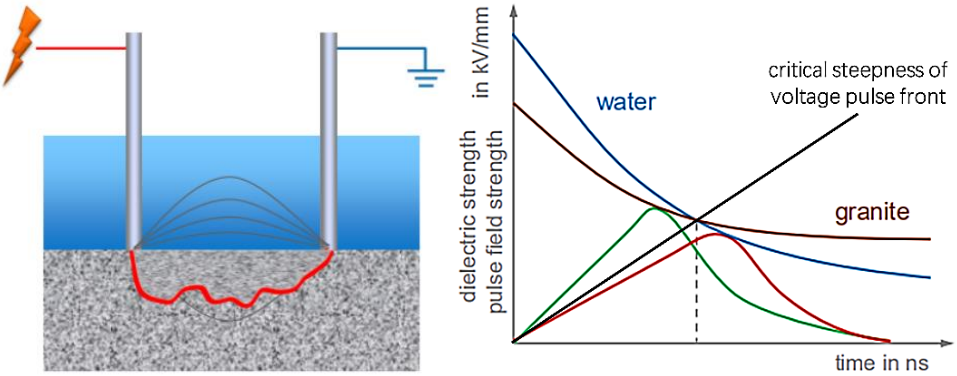

Figure 6: Working principle of electrical impulse (Voigt et al. 2016).

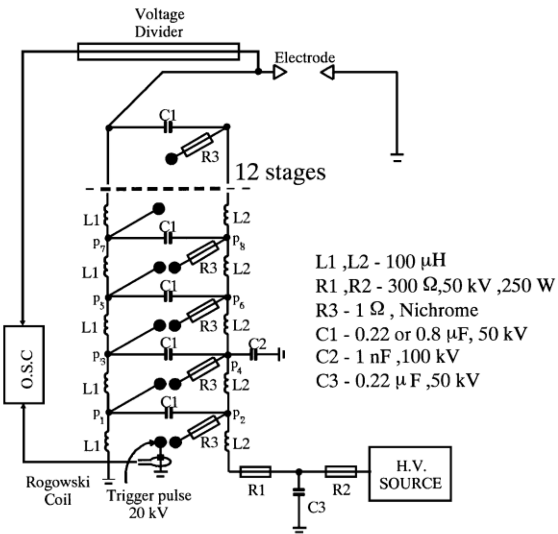

Figure 7: Electrical circuit of a typical Marx generator used for EI (Inoue et al. 1999).

The discharge process can be further divided into three phases (Cho et al. 2014 and Cho et al. 2016) and the energy distribution is as shown in Figure 8:

- Phase I: the time of front edge of the impulse and there is no current generated in this phase.
- Phase II: breakdown in rock happens and the plasma channel is formed in the rock and thus some electrical energy is consumed.
- Phase III: the plasma channel expands together with the increase of current; the high current in the plasma channel immediately heats up the rock and causes high thermal stress, which breaks the rock efficiently.

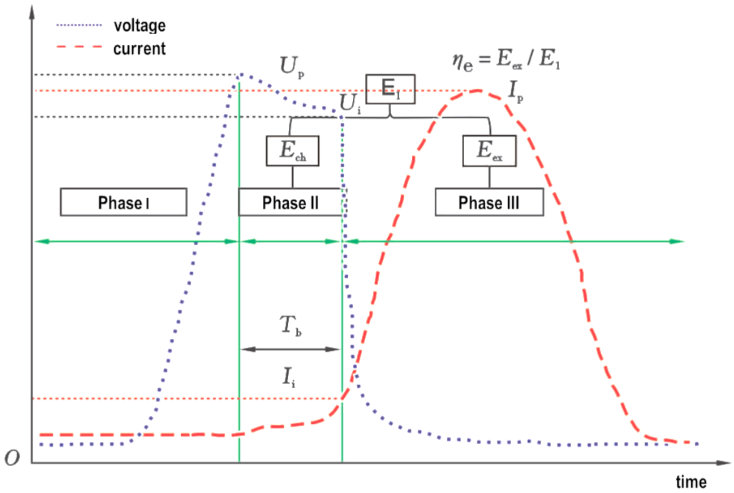

Figure 8: The 3 phases in discharge process (Zhu et al. 2020).

Engineering Efforts. The EI technology was innovatively applied to rock excavation and drilling by researchers in Tomsk Polytechnic University in 1960s, however, this technology was not paid enough attention under the conditions of planned economy and the Cold War (Ushakov et al. 2019). With the disassembly of USSR, this technology was spread to the world and further studied since 21st century.

In early 2000s, researchers from University of Strathclyde developed a lab prototype drilling tool based on the EI technology and performed some lab drilling test (Timoshkin et al. 2003, Timoshkin et al. 2004). The prototype tool was able to cut clearly defined circular holes in sandstone with a speed of up to 16 cm/min, as shown in Figure 9. However, the lab prototype only proves the concept of drilling of small diameter holes (3.5-15 cm) for sidetrack creation and multilateral drilling, there was still a lot of engineering work needed to implement the impulse-generation infrastructure into the bottom hole assembly.

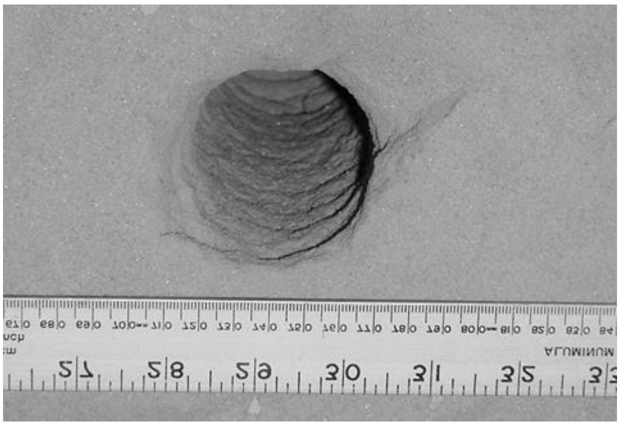

Figure 9: A 50mm hole drilled in the yellow sandstone (Timoshkin et al. 2003).

From 2007 to 2014, researchers from Technische Universität Dresden (TUD) performed some feasibility study of EI for deep drilling application with optimizing and testing EI drilling bits. In this phase of study, they developed multiple prototypes of EI bits and drilled a variety type of rocks in lab. The drilling fluid they used contains bentonite but not all necessary polymers in a typical drilling mud. This is already a significant advance as all previous EI drilling tests were performed in deionized water, tap water, or engine oil which are all electrically stronger and more unlikely to discharge. Even though the drilling fluid in the tests still misses some polymers but it is certainly more similar as the real drilling environment than all previous tests. Multiple sizes and types of rock including granite were drilled with EI bits and the hole quality is comparable to the holes drilled by a rotary bit as shown in Figure 10. In the oil-based mud (OBM), a rate of penetration of 1 m/hr was achieved in granite and it could be faster in sandstone.

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(a) look of a downhole drilled by rotary bit **(b) look of a hole drilled by the EI bit in OBM**

Figure 10: Hole quality drilled by rotary bit and EI bit (Anders et al. 2015).

Recently, the research team designed an EI drilling system which is fully compatible with the traditional drill string as shown in Figure 11. The EI drilling system includes a power generation module with a turbine and a mud generator to generate power in downhole by use of the dynamic energy of drilling fluid. Then the power is transferred to the rectifier and the impulse generator, and eventually is sent to the electrodes in shape of impulse. The electrode module is the EI drilling bit, which replaces the rotary drilling bit. All the electrical modules are packed in a double-walled housing, the annulus of which allows drilling fluid to pass as traditional rotary bit drilling.

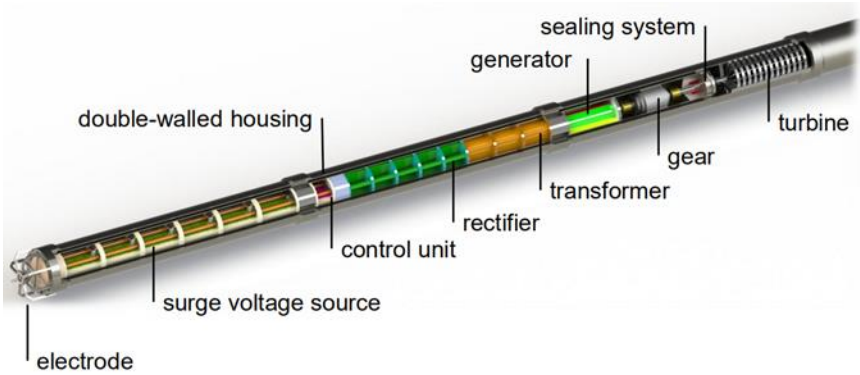


Figure 11: EI drilling concept designed in TUD (Voigt et al. 2019).

An engineering prototype based on this concept was developed at TUD with the housing outer diameter of 370mm and a drilling test was performed on an outdoor rig in 2017. The test only lasted for a short time with very little penetration of rock due to the system complexity and unreliability. Unfortunately, there was no more budget for this project to improve reliability and resolve design issues and no further test was performed since then. The test rig and the drilling debris are shown in Figure 12.

(a) the outdoor test rig **(b) cutting debris in the test**

Figure 12: The outdoor test rig used and the cutting debris in the EI drilling test conducted by TUD (Voigt et al. 2019).

Research Activities. Studies on EI continue even though no further engineering efforts has been performed since the TUD test. The erosion rate and erosion mechanism of electrode under high-pulsed current discharge was studied and it was concluded that the complex electrochemistry reaction, which is induced by the high-temperature arc in water, is a significant cause resulting in more serious erosion in water (Liu et al. 2016).

The influences of environmental pressure and temperature were studied, and the results can be concluded in Figure 13.

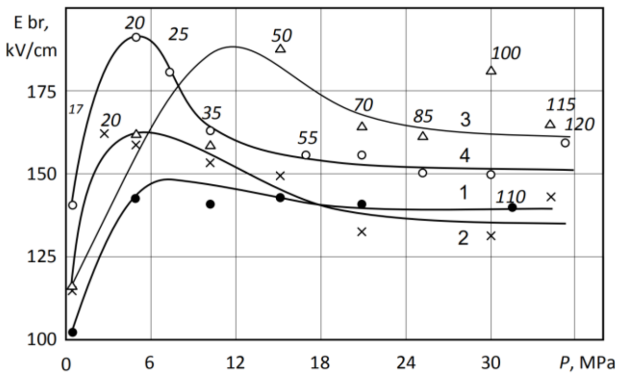
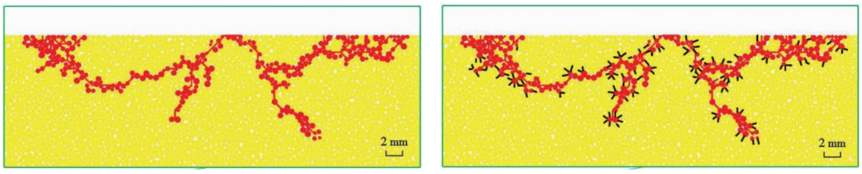
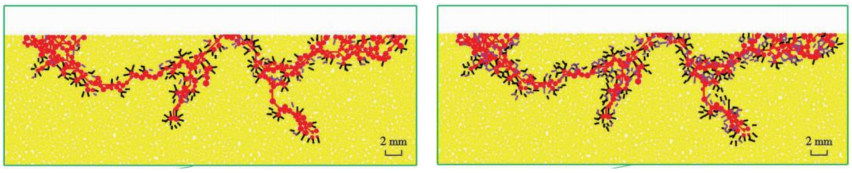


Figure 13: Dependence of the electrical strength of rocks on the pressure and temperature for sandstone (1), limestone (2), granite (3), and drilling fluid (4), values next to the points indicate the temperature (Ushakov et al. 2019).

The formation and expansion of plasma channel in the rock was studied by means of numerical simulations (Zhu et al. 2020), and some results are shown in Figure 14. The rock breaking state and forms were studied and the strategy to improve energy utilization rate was proposed (Li et al. 2018, Li et al. 2019).



(a) t=0 μs **(b) t=0.20 μs**

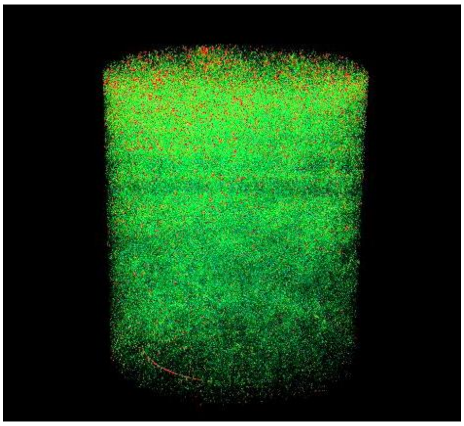


(c) t=0.30 μs **(d) t=0.50 μs**

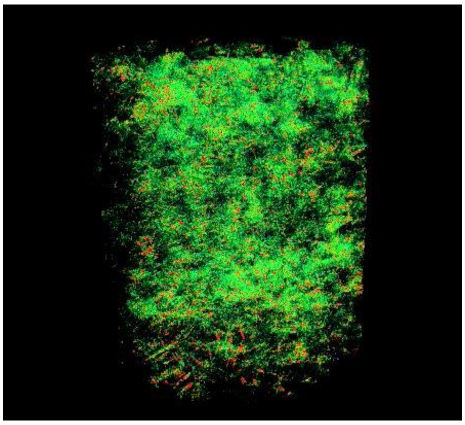
Figure 14: Plasma channel expansion in rock with no formation pressure (from Zhu et al. 2020).

4. LASER DRILLING

Rock Disintegration Mechanism. The laser beam impact rock with controlled thermal energy and generates a compressive stress field. CT Scanning visualization indicates a high degree of microfracture formation and aggregation generated by laser heating as shown in Figure 15. The profile of the laser beam can be controlled precisely with customized lens package to improve the rock weakening or breaking efficiency and optimize the borehole profile as well.



(a) Pre-laser



(b) Post-laser

Figure 15: 1mm Cross section CT scan on rock sample pre-laser and post-laser processing

Engineering Efforts. The attempts to apply laser to rock destruction could retrospect to 1960s, however laser drilling technology developed very slowly subjected to the immaturity and complexity of the CO2 laser (Maurer 1980). In 2002, the MRACL laser and the Nuvonyx high power diode laser was tested and validated for the ability of destroying and drilling through a rock (Graves 2002). The innovation that opened up the prospect of commercializing laser drilling was the introduction of a 10kW fiber laser in 2008 and a year later the FORO Energy company was founded to develop a laser drilling technology that could create a commercial grade borehole (Zediker 2014a, Zediker 2014b).

One of the key technical challenges FORO Energy has resolved is to develop the long-distance optic fiber by suppressing the Stimulated Brillounin Scattering (SBS). SBS is a non-linear phenomenon that occurs in optic fibers which can cause the optical power to be reflected back toward the laser system and so the length and diameter of the optic fiber was a limitation for laser drilling before. Optic Fibers developed by FORO Energy could transfer 20 kW laser up to 4km.

There are five key components in the prototype developed by FORO:

- The laser unit, the equipment on surface to generate laser with electricity power.
- The optical slip ring, the critical components to transmit the laser from the still optic cable to the rotating optic cable which is installed in the drill string.
- The fiber optic cable, it transmits the laser from surface to downhole.
- The downhole connector as shown in Figure 16 (a), it connects the optic cable to the optic package,
- The optic package as shown in Figure 16 (b), it contains a set of optical lenses to adjust the laser beam profile and angle. The optic package is installed upon the connector.

(a) downhole connector **(b) high-pressure optic package**

Figure 16: The downhole connector and optic package developed by FORO

The optic package is about 1-inch diameter and 3-inch long, which is compact enough to be installed on a PDC bit. The FORO Energy further developed a PDC-laser hybrid bit and validated the drilling ability as shown in Figure 17. The FORO Energy even developed an electric motor for the PDC-laser hybrid bit, which allows laser cable to go through and provides torque to the bits as well (Grubb et al. 2017).

The laser drilling utilizes a compressed gas such as air or nitrogen to assist in the process to maintain efficient transmission of the light. Laser drilling is feasible in the presence of drilling fluid or water, however, the specific method and system has yet to be developed.

(a) PDC-laser hybrid bit **(b) Hole drilled by the bit**

Figure 17: The PDC-laser hybrid bit invented by FORO and the hole drilled by the hybrid bit (Zediker 2014a).

5. CONCLUSIONS

Rock disintegration mechanisms and recent engineering advances of the three novel drilling technologies have been introduced and discussed. None of the three novel drilling is mature enough for commercialization and each technology still faces many challenges. In order to evaluate potentials and readiness of the three novel drilling technologies, a similar method as established in (Pierce et al. 1996) was deployed. Seven aspects of concern are discussed and compared as shown in Table 3.

According to the table, technical challenges and readiness of the three novel drilling technologies can be concluded as below:

- Plasma Drilling, there are many technical obstacles to overcome and even though they could be resolved, there are still many limitations in drilling depth due to the worst hole quality and incompatibility with drilling mud. This technology has the most foreseeable engineering challenges and lowest readiness.

- EI Drilling, the only critical challenge is to generate enough power in downhole, which could be up to 20kW. Theoretically this can be achieved with multi-stage mud turbine and mud generator. The EI drilling could be fully compatible with current drilling system once the power is resolved. So this is the most promising novel drilling technology attracting most researchers and engineers.

- Laser Drilling, currently this technology is more mature than the others, but the available length of fiber (fibers up to 6 or more km are producible) and the management of wellbore pressure are both outstanding challenges of this technology.

Table 3 Comparison of the three novel drilling technologies.

Aspects of Concern	Plasma Torch	Electrical Impulse	Laser
Rock disintegration mechanism	fusion & spallation (combined)	spallation	fusion & spallation (controllable)
Power Mode in downhole	DC(>100A)	impulse voltage	laser
Difficulty of power acquisition in downhole	from surface, challenging	possibly generated in downhole	from surface, challenging
Others to be transmitted to downhole	working gas cooling water	no	no
Hybrid Bit	impossible	possible	possible and tested
Hole quality	Bad	Decent	Good
Function in downhole HP	extremely difficult	yes and tested	theoretically yes
Working with drilling mud	No	feasible	feasible

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